Measurement of Large Transverse Momentum Hadrons and Constraints on Medium Opacity Parameters

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The PHENIX experiment has measured $\pi^0$'s in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, with good statistics for transverse momentum, $p_T$, up to 20 GeV/c. A fivefold suppression is found, which is essentially constant for $5 < p_T < 20$ GeV/c. While the production of high $p_T$ pions in high energy p+p collisions is well described in the framework of perturbative QCD, production in ultra-relativistic heavy ion collisions involves additional degrees of freedom related to the opacity of the deconfined medium produced in the collisions. The uncertainties of the latest measurement are small enough to constrain model-dependent opacity-related parameters, such as the transport coefficient of the medium, $\hat{q}$ or initial gluon density $dN_g/dy$ at the level of $\pm 20$-25% (one standard deviation), by applying a statistical method proposed. From the dependence of the suppression level to the number of participant nucleons, we have also confirmed that the energy loss increases as $p_T$ of partons increases. The latest PHENIX result on high transverse momentum hadrons are presented, and the property of the medium created in the collisions is discussed in detail.

1. INTRODUCTION

It has now been established that novel form of matter is created in the ultra-relativistic heavy-ion collisions at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory [1]. Hard scattering of individual partons is a particularly important probe of the evolution of the medium created in these collisions, as it occurs at early stages of the collision and produces high-$p_T$ observables. The observation of jet quenching [2, 3] has motivated a great deal of theoretical and experimental work in an attempt to understand the source of this effect. Suppression exhibited in measured spectra is currently attributed to energy loss of fast moving partons as they traverse the medium, prior to fragmentation into observed particles. There are two sources of energy loss considered responsible: coherent medium-dependent gluon bremsstrahlung and collisional energy loss.

A number of models have been used to predict the energy loss seen in heavy-ion collisions, representing a variety of implementations of the collision geometry and the degree to which they represent the two sources of energy loss (for example, see [4] and references therein). In most cases, these models can be characterized by a single input parameter. The input parameter typically describes the opacity of the medium; the more opaque the medium, the greater the energy loss and therefore the greater the suppression observed. We report on recent PHENIX measurements of high-$p_T$ hadrons, including the impact the results have on constraining several popular models.

2. PHENIX MEASUREMENT OF HIGH PT HADRONS

The PHENIX detector [5] is used to measure $\pi^0$'s via their decay to photons using an electromagnetic calorimeter (EMC) that covers $|\eta| < 0.35$. The EMC consists of eight sectors, each covering $\pi/8$ in azimuth, using two detector technologies: Pb-scintillating (PbSc) sampling calorimeter (six sectors) and Pb-glass (PbGl) Cherenkov calorimeter (two sectors). The cell size $\Delta\phi \times \Delta\eta$ of the calorimeter is $0.011^2$ and $0.0075^2$ for the PbSc and PbGl, respectively. For heavy-ion collisions, the centrality (degree of overlap between nuclei) of the collision is measured using the correlation between the charged multiplicity measured in the Beam-Beam Counters (BBCs) and the energy deposited in the zero-degree calorimeters (ZDCs).

We have measured the $\pi^0$ spectrum in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV [6] and 62.4 GeV [7], as shown in Figure 1. The measured cross-sections show quite good agreement with pQCD calculations, which provides an important baseline for comparison with heavy ion collisions as well as establishes the fact that we indeed observe hard-scattering in RHIC collisions.
Neutral pion spectra have been measured in both Au+Au and Cu+Cu collisions, as a function of centrality of the collision[8,9]. When this spectra are compared to that of p+p collisions scaled by the appropriate number of binary parton-parton collisions, an important suppression pattern is revealed. For peripheral collisions, we observe suppression of produced particles as large as a factor of five, and approximately independent of pT for the high-pT regime. The suppression seen in nuclear collisions is characterized by the nuclear modification factor, RAA:

\[ R_{AA} = \frac{1/N_{\text{cut}} d^2 N/dydp_T}{\langle T_{AB} \rangle d^2 \sigma_{pp}/dydp_T} \]  

(1)

where \( \sigma_{pp} \) is the production cross-section in p+p collisions, and \( \langle T_{AB} \rangle \) is the nuclear thickness function averaged over a range of impact parameters in the particular centrality, calculated with a Glauber Model. The RAA for neutral pions in Au+Au collisions has been measured by PHENIX most recently in 2004 [8] and is shown in Figure 2.

In order to use the RAA to shed light on energy loss in the medium, we note that for pT > 5.0 GeV/c both the p+p and Au+Au spectra behave as a power law. This allows a reinterpretation of the suppression as an effective fractional energy loss, \( S_{\text{loss}} = 1 - R_{AA}^{1/(n-2)} \). \( S_{\text{loss}} \) is expected to be proportional to a power of the number of participant nucleons, \( N_{\text{part}} \). We fit the \( N_{\text{part}} \) dependence of the RAA integrated over two different pT ranges with the function \( R_{AA} = (1 - S_0 N_{\text{part}}^a)^{-2} \). The result is shown in the right panel of Figure 2. The RAA versus centrality does not appear to saturate, and the fit gives us \( a = 0.58 \pm 0.07(0.56 \pm 0.07) \), \( S_0 = (8.3 \pm 3.3) \times 10^{-3}(9.2 \pm 4.9) \times 10^{-3} \) for pT > 5 GeV/c (pT > 10 GeV/c). Both the Gyulassy-Levai-Vitev (GLV) model and parton quenching model (PQM) predict a \( \approx 2/3 \). All this evidence points to the implication that the energy loss experienced by partons moving through the medium increases with pT.
3. QUANTITATIVE ANALYSIS

A new statistical analysis has been proposed to help constrain models, using a complete description of all experimental uncertainties [4]. Given a model prediction that depends on a single input parameter \( p, \mu(p) \), a fit is performed on the data by varying \( p \) and the most likely range of values are determined at the one and two \( \sigma \) levels. This fit involves careful categorization of uncertainties: Type A, point-to-point uncorrelated (statistical) errors; Type B, point-to-point correlated errors; and Type C, globally correlated errors. We then seek to minimize the \( \chi^2 \) statistic:

\[
\tilde{\chi}^2(\epsilon_b, \epsilon_c, p) = \sum_{i=1}^{n} \left( \frac{(y_i^2 + \epsilon_b \sigma_b_i + \epsilon_c y_i \sigma_c - \mu_i(p))^2}{\tilde{\sigma}_i^2} + \epsilon_b^2 + \epsilon_c^2 \right)
\]

\[
\tilde{\sigma}_i^2 = \sigma_i(y_i^2 + \epsilon_b \sigma_b_i + \epsilon_c y_i \sigma_c)/y_i
\]

where \( \epsilon_b \) and \( \epsilon_c \) are the fractions of the Type B and C errors that displace all points together. It is important to note that this procedure accounts for only the experimental uncertainties.

As an example, this analysis has been applied to the 0-5\% most central \( R_{AA} \) measurements using PQM [4]. PQM is a Monte Carlo model based on the quenching weights from the BDMPS model. It is characterized by a single parameter, \( \langle \hat{q} \rangle \), which quantifies the average transverse momentum transferred from the medium to the parton per unit mean free path. The result of varying \( \langle \hat{q} \rangle \) and fitting to the \( R_{AA} \) data is shown in Figure 3. The data constrains \( \langle \hat{q} \rangle \) as \( 13.2^{+2.1}_{-3.2}^{+6.3}_{-5.2} \) GeV\(^2\)/fm at the one and two \( \sigma \) levels. Similar analysis has been performed on several other popular energy-loss models, producing similar constraints on their input parameters [4].
Figure 3: Fits of PQM to $\pi^0$ $R_{AA}$ for 0-5% central events in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. LEFT: Neutral pion $R_{AA}$, shown with the resulting PQM predictions as $\langle \hat{q} \rangle$ is varied. RIGHT: Chi-squared of the PQM fit as a function of $\langle \hat{q} \rangle$. The red dot indicates the minimum.

4. SUMMARY

PHENIX has measured high-$p_T$ ($1 < p_T < 20$ GeV/c) hadrons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. In the most central collisions and above $p_T \simeq 5$ GeV/c, we observe a suppression of hadrons of a factor of approximately five. This suppression remains constant out to the highest accessible $p_T$. The pattern of suppression as seen in the $R_{AA}$ measurement suggests that the energy loss suffered by the partons produced in these collisions is proportional to $p_T$: we find that the integrated $R_{AA}$ does not saturate with the number of participants, the data are consistent with an $S_{loss} \propto N_{part}^n$, and the high-$p_T$ spectra follows the same power law from p+p to Au+Au (with $n \simeq 8.1$). Most importantly, the precision of our $R_{AA}$ measurement allows for the application of a quantitative approach to finding constraints to existing models. Incorporating all experimental uncertainties into this analysis, we are able to constrain the single input parameters for several popular models to 10-20% at the one standard deviation level.

References

[1] K. Adcox et al. Formation of dense partonic matter in relativistic nucleus nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration. Nucl. Phys., A757:184–283, 2005.
[2] Stephen Scott Adler et al. Modifications to di-jet hadron pair correlations in Au + Au collisions at $\sqrt{s_{NN}} = 200$-GeV. Phys. Rev. Lett., 97:052301, 2006.
[3] A. Adare et al. Dihadron azimuthal correlations in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Phys. Rev., C78:014901, 2008.
[4] A. Adare et al. Quantitative Constraints on the Opacity of Hot Partonic Matter from Semi-Inclusive Single High Transverse Momentum Pion Suppression in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Phys. Rev., C77:064907, 2008.
[5] D. P. Morrison et al. The PHENIX experiment at RHIC. Nucl. Phys., A638:565–570, 1998.
[6] A. Adare et al. Inclusive cross section and double helicity asymmetry for $\pi^0$ production in p+p collisions at $\sqrt{s} = 200$ GeV: Implications for the polarized gluon distribution in the proton. *Phys. Rev.*, D76:051106, 2007.

[7] A. Adare et al. Inclusive cross section and double helicity asymmetry for $\pi^0$ production in p+p collisions at $\sqrt{s} = 62.4$ GeV. 2008. arXiv:hep-ex/0810.0701.

[8] A. Adare et al. Suppression pattern of neutral pions at high transverse momentum in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and constraints on medium transport coefficients. 2008. Accepted for publication in *Phys. Rev. Lett.*

[9] A. Adare et al. Energy dependence of pi-zero production in Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4$, 62.4, and 200 GeV. 2008.
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