

## 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

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For Au + Au collisions at 200 GeV, we measure neutral pion production 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/ $c$ . Experimental uncertainties are small enough to constrain any model-dependent parametrization for the transport coefficient of the medium, e.g.,  $\langle \hat{q} \rangle$  in the parton quenching model. The spectral shape is similar for all collision classes, and the suppression does not saturate in Au + Au collisions.

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Large transverse momentum ( $p_T$ ) hadrons originate primarily from the fragmentation of hard scattered quarks or gluons. In high energy  $p + p$  collisions, this is well described in the framework of perturbative QCD [1]. In ultrarelativistic heavy ion collisions, such hard scatterings occur in the early phase of the reaction, and the transiting partons serve as probes of the strongly interacting medium produced in the collisions. Lattice QCD predicts a phase transition to a plasma of deconfined quarks and gluons, which induces gluon radiation from the scattered parton and depletes hadron production at high  $p_T$  (“jet quenching”) [2,3]. The measurements in Au + Au collisions at Relativistic Heavy Ion Collider (RHIC) showed suppressed hadron yields in central collisions [4] as predicted [5,6], and motivated advanced theoretical studies of radiative energy loss.

All energy loss models must incorporate the space-time evolution of the medium, as it is not static, and the initial distribution of the partons throughout the medium. Models generally also include an input parameter for the medium density and/or the coupling. Different assumptions in the various models lead to similar descriptions of the  $\pi^0$  suppression with different model-dependent parameters [7,8]. For instance, the Parton Quenching model (PQM) is a Monte Carlo program using the quenching weights from Baier-Dokshitzer-Mueller-Peigne-Schiff (BDMPS) [5] that combines the coupling strength with the color-charge density to create a single transport coefficient, often referred to as  $\langle \hat{q} \rangle$  [9,10], which gives the  $\langle p_T^2 \rangle$  transferred from the medium to the parton per mean free path.

Establishing the magnitude,  $p_T$  and centrality dependence of the suppression pattern up to the highest possible  $p_T$  is crucial to constrain the theoretical models and separate contributions of initial and final state effects from the energy loss mechanism. As neutral pions can be identified up to very high  $p_T$ , their suppression and its centrality (average pathlength) dependence puts important con-

straints on the energy loss. Whereas di-hadron suppression at high  $p_T$  may be somewhat more sensitive to medium opacity [11] than single hadron suppression, such improvement is contingent upon theoretical and experimental, statistical and systematic uncertainties.

This Letter reports on the measurement of  $\pi^0$ s up to  $p_T = 20$  GeV/ $c$  in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV at RHIC, using the high statistics data taken in 2004. The results are used to extract the  $\langle \hat{q} \rangle$  parameter of the PQM model for the most central collisions.

The analysis used  $1.03 \times 10^9$  minimum bias events taken by the PHENIX experiment [12]. Collision centrality was determined from the correlation between the number of charged particles detected in the Beam-Beam Counters (BBC,  $3.0 < |\eta| < 3.9$ ) and the energy measured in the Zero Degree Calorimeters (ZDC). A Glauber model Monte Carlo program with a simulation of the BBC and ZDC responses was used to estimate the average number of participating nucleons ( $\langle N_{\text{part}} \rangle$ ) and binary nucleon-nucleon collisions ( $\langle N_{\text{coll}} \rangle$ ) for each centrality bin [13].

Neutral pions were measured in the  $\pi^0 \rightarrow \gamma\gamma$  decay channel with the photons reconstructed in the Electromagnetic Calorimeter (EMCal) located in the two central arms of PHENIX ( $|\eta| \leq 0.35$ ). The EMCal [14] consists of two subsystems: six sectors of lead-scintillator sandwich calorimeter (PbSc) and two sectors of lead-glass Čerenkov calorimeter (PbGl) at the radial distance of about 5 m. The fine segmentation of the EMCal ( $\delta\phi \times \delta\eta \sim 0.01 \times 0.01$  for PbSc and  $\sim 0.008 \times 0.008$  for PbGl) ensures that the two photons from a  $\pi^0 \rightarrow \gamma\gamma$  decay are well resolved up to  $p_T^{\pi^0} \approx 12$  (PbSc) and 16 (PbGl) GeV/ $c$ . Data from the two subsystems were analyzed separately, and the fully corrected results were combined.

Details of the analysis including extraction of the raw  $\pi^0$  yield, correction for acceptance, detector response, reconstruction efficiency have been described elsewhere [15,16]. In this analysis, the higher  $p_T$  range required an additional

TABLE I. Summary of the systematic uncertainties on the  $\pi^0$  yield extracted independently with the PbSc (PbG) electromagnetic calorimeters. The last row is the total systematic uncertainty on the combined spectra.

$p_T$ (GeV/c)	2	6	10	16
uncertainty source	PbSc (PbG)			
yield extraction (%)	3.0 (4.1)	3.0 (4.1)	3.0 (4.1)	3.0 (4.1)
PID efficiency (%)	3.5 (3.9)	3.5 (3.5)	3.5 (3.7)	3.5 (3.9)
Energy scale (%)	6.7 (9.0)	8.0 (9.2)	8.0 (8.2)	8.0 (12.3)
Acceptance (%)	1.5 (4.1)	1.5 (4.1)	1.5 (4.1)	1.5 (4.1)
$\pi^0$ merging (%)	... (...)	... (...)	4.4 (...)	28 (4.8)
Conversion (%)	3.0 (2.5)	3.0 (2.5)	3.0 (2.5)	3.0 (2.5)
off-vertex $\pi^0$ (%)	1.5 (1.5)	1.5 (1.5)	1.5 (1.5)	1.5 (1.5)
Total (%)	8.7 (12)	9.8 (11)	11 (11)	30 (15)
PbSc and PbG combined: Total (%)	7.0	7.5	7.6	14

correction for losses in the observed (raw)  $\pi^0$ s due to “cluster merging.”

With increasing  $p_T^{\pi^0}$ , the minimum opening angle of the two photons decreases, and eventually they will be reconstructed as a single cluster. Such “merging” reaches 50% of the total raw yield at  $p_T = 14$  GeV/c in the PbSc and at  $p_T = 18$  GeV/c in the PbG. Merged clusters were rejected by various shower profile cuts, and the loss was determined by simulated  $\pi^0$ s embedded into real events and analyzed with the same cuts. The systematic uncertainties were estimated by comparing  $\pi^0$  yields in the PbSc extracted in bins of asymmetry  $|E_{\gamma_1} - E_{\gamma_2}|/(E_{\gamma_1} + E_{\gamma_2})$  and also by comparing yields in the PbSc and PbG.

We considered two sources of  $\pi^0$ s not coming from the vertex (off-vertex  $\pi^0$ ): those produced by hadrons interacting with detector material (instrumental background) and feed-down products from weak decay of higher mass hadrons (physics background). Based upon simulations both types of background were found to be negligible ( $< 1\%$  at  $p_T > 2.0$  GeV/c) except for  $\pi^0$ s from  $K_S^0$  decay ( $\approx 3\%$  of  $\pi^0$  yield for  $p_T > 1$  GeV/c), which has been subtracted from the data. Finally, the yields were corrected to the center of the  $p_T$  bins using the local slope.

The main sources of systematic uncertainties are yield extraction, efficiency corrections, energy scale, and merging, none of which exhibits a significant centrality dependence. The PbSc and PbG have quite different systematics with all but one of them (off-vertex  $\pi^0$ ) uncorrelated. Therefore, when combining their results, the total error is reduced in the weighted average of the two independent measurements. The final systematic uncertainties (1 standard deviation) on the spectra are shown in Table I.

The top panel of Fig. 1 shows the  $\pi^0$  invariant yield for all centralities and minimum bias, combined from the independent PbSc and PbG measurements which now extend to  $p_T \sim 20$  GeV/c, 6 GeV/c higher than those published earlier [15]. In the overlap region, the results are consistent with the ones in [15] while the errors are reduced by a factor of 2 to 2.5. The bottom panel shows the

consistency of the PbSc and PbG results. The spectra are similar at all centralities: when fitting  $p_T > 5$  GeV/c with a power-law function ( $\propto p_T^{-n}$ ), the exponents vary from  $n = 8.00 \pm 0.12$  in 0–5% to  $n = 8.06 \pm 0.08$  in the 80–92% (most peripheral) bin. Note that  $n = 8.22 \pm 0.09$  in  $p + p$  collisions. The errors are combined statistical errors and systematic uncertainties.

To quantify the comparison of spectra in heavy ion and  $p + p$  collisions, the nuclear modification factor

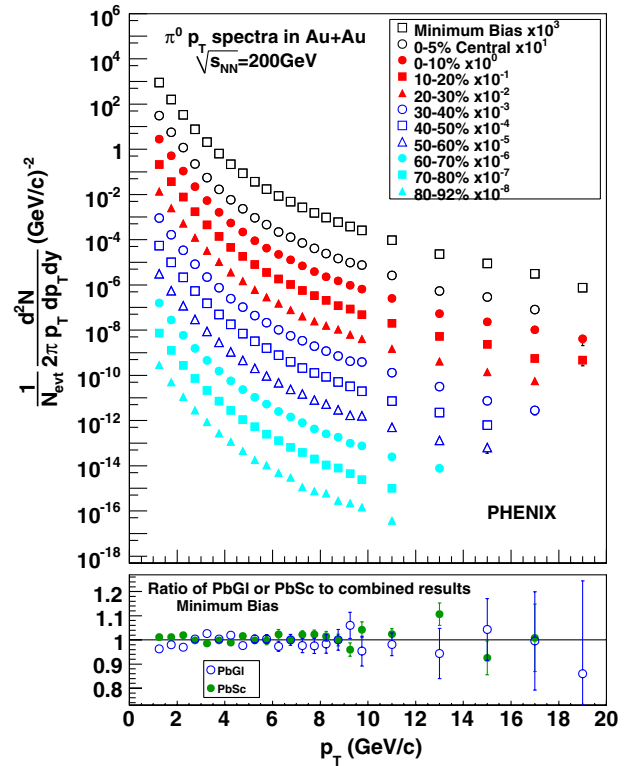


FIG. 1 (color online). Top:  $\pi^0$  invariant yields for all centralities and minimum bias. Bottom: ratios of the (separately analyzed) PbSc and PbG yields to the combined minimum bias invariant yield, which is shown in the top panel.



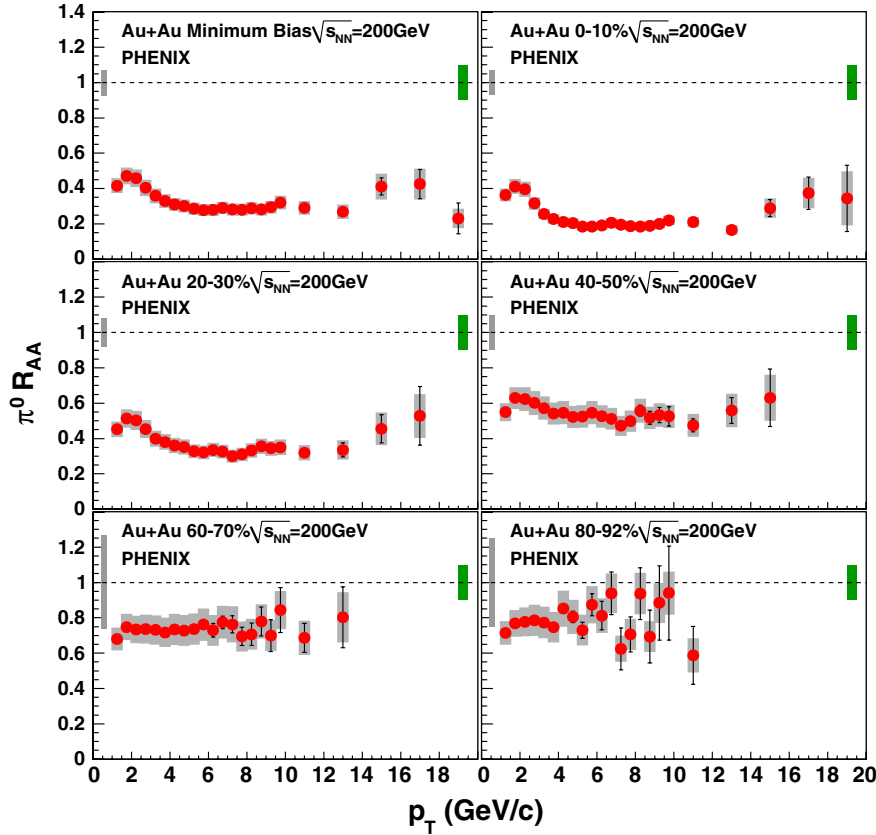


FIG. 2 (color online). Nuclear modification factor ( $R_{AA}$ ) for  $\pi^0$ s. Error bars are statistical and  $p_T$ -uncorrelated errors, boxes around the points indicate  $p_T$ -correlated errors. Single box around  $R_{AA} = 1$  on the left is the error due to  $N_{\text{coll}}$ , whereas the single box on the right is the overall normalization error of the  $p + p$  reference spectrum.

$$R_{AA} = \frac{1/N_{\text{evt}} d^2N/dydp_T}{\langle T_{AB} \rangle d^2\sigma_{pp}/dydp_T} \quad (1)$$

is used, where  $\sigma_{pp}$  is the production cross section of the particle in  $p + p$  collisions, and  $\langle T_{AB} \rangle$  is the nuclear thickness function averaged over a range of impact parameters for the given centrality, calculated within a Glauber model [13]. Figures 2 and 3 show  $R_{AA}$  for  $\pi^0$  at different centralities. The reference  $p + p$  yield was obtained from the 2005 (Run-5) RHIC  $p + p$  measurement [17].

$R_{AA}$  reaches  $\sim 0.2$  in 0–10% centrality at  $p_T > 5$  GeV/ $c$  with very little (if any)  $p_T$  dependence. This trend is compatible with most current energy loss models but not with a semiopaque medium assumption, where  $R_{AA}$  would decrease with increasing  $p_T$  [7]. While its magnitude changes, the suppression pattern itself is remarkably similar at all centralities suggesting that the bulk  $R_{AA}$  (integrated over azimuth) is sensitive only to the  $N_{\text{part}}$  but not to the specific geometry. Consequently, study of the  $p_T$ -integrated  $R_{AA}$  vs centrality is instructive.

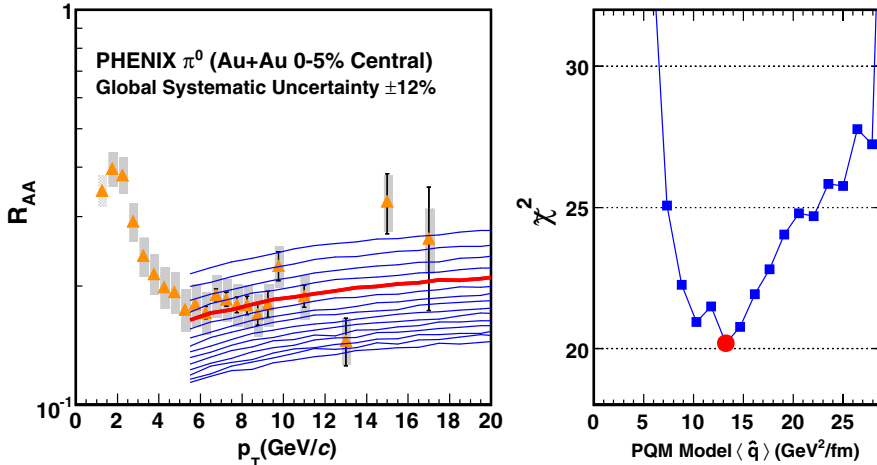


FIG. 3 (color online). Left:  $\pi^0 R_{AA}$  for the most central (0–5%) Au + Au collisions and PQM model calculations for different values of  $\langle \hat{q} \rangle$ . Right:  $\chi^2(\epsilon_b, \epsilon_c, p)$  distribution for the corresponding values of  $\langle \hat{q} \rangle$ . The bold (red) curve in the left panel and the round (red) point in the right panel are the best fit values.

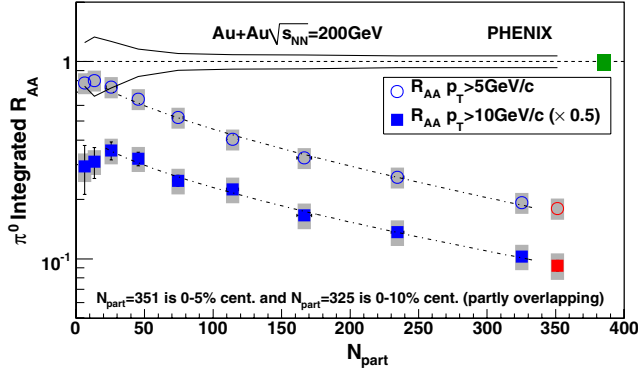


FIG. 4 (color online). Integrated nuclear modification factor ( $R_{AA}$ ) for  $\pi^0$  as a function of collision centrality expressed in terms of  $N_{part}$ . The error bars/bands are the same as in Fig. 2. The two lines at unity show the errors on  $\langle N_{coll} \rangle$ . The last two points correspond to partially overlapping centrality bins. The dashed lines show the fit explained in the text.

Figure 4 shows  $R_{AA}$  for  $\pi^0$ s integrated above  $p_T > 5$  GeV/c, and  $p_T > 10$  GeV/c, as a function of centrality. The last two points indicate overlapping 0–10% and 0–5% bins. In both cases, the suppression increases monotonically with  $N_{part}$  without any sign of saturation, suggesting that larger colliding systems (such as  $U + U$  planned at RHIC) should exhibit even more suppression.

The common power-law behavior ( $\propto p_T^{-n}$ ) in  $p + p$  and Au + Au allows the suppression to be reinterpreted as a fractional energy loss  $S_{loss} = 1 - R_{AA}^{1/(n-2)}$  where  $n$  is the power-law exponent, and we found that  $S_{loss} \propto N_{part}^a$  [15,18]. Fitting the integrated  $R_{AA}$  with a function  $R_{AA} = (1 - S_0 N_{part}^a)^{n-2}$ , where  $n$  is fixed as 8.1, gives  $a = 0.57 \pm 0.13$  for  $N_{part} > 20$  for  $p_T > 5$  GeV/c, and  $a = 0.55 \pm 0.14$  for  $p_T > 10$  GeV/c. The fit does not take errors on  $p + p$  luminosity into account. The Gyulassy-Levai-Vitev (GLV) [6] and PQM [10] models predict that  $a \approx 2/3$ , which is consistent with the data. The fitted values of  $S_0$  are  $(9.0 \pm 6.1) \times 10^{-3}$  and  $(9.4 \pm 7.3) \times 10^{-3}$  for  $p_T > 5$  GeV/c and  $p_T > 10$  GeV/c, respectively. The fits are shown as dashed lines in Fig. 4.

We use the highest centrality (0–5%)  $R_{AA}$  data as shown in Fig. 3 to constrain the PQM model parameter  $\langle \hat{q} \rangle$ . This must be done with careful consideration of the various, partially coupled error sources, leading to necessary refinement beyond a naive least square analysis. We calculate

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

using theory curves  $\mu_i(p)$  with different values of the input parameter  $p$ , i.e.,  $\langle \hat{q} \rangle$  in the PQM model.  $p_T$ -uncorrelated, statistical  $\oplus$  systematic errors are  $\sigma_i$ ,  $p_T$ -correlated errors are  $\sigma_{b_i}$  (boxes on Figs. 2 and 3), while uniform fractional

shifts of all points are given by  $\sigma_c$ . All the measured values  $y_i$  are allowed to shift by the same fraction,  $\epsilon_b$ , of their systematic error  $\sigma_{b_i}$  from the nominal values. The  $\epsilon_c$  is a similar correlated fraction of  $\sigma_c$ , and  $\tilde{\sigma}_i = \sigma_i(y_i + \epsilon_b \sigma_{b_i} + \epsilon_c y_i \sigma_c)/y_i$  is the point-to-point random error scaled by the multiplicative shift, so that the fractional error is unchanged by the shift, which is true for the present measurement. The best fit,  $\tilde{\chi}_{min}^2$ , the minimum of  $\tilde{\chi}^2(\epsilon_b, \epsilon_c, p)$  by variation of  $\epsilon_b$ ,  $\epsilon_c$ , and  $p$ , is found by standard methods. Further details are given in [16]. The right panel of Fig. 3 shows the minima of  $\tilde{\chi}^2(\epsilon_b, \epsilon_c, p)$  by varying  $\epsilon_b$  and  $\epsilon_c$  for a wide range of values of the PQM model transport coefficient,  $\langle \hat{q} \rangle$ . Our data constrain  $\langle \hat{q} \rangle$  as  $13.2_{-3.2}^{+2.1}$  and  $_{-5.2}^{+6.3}$  GeV<sup>2</sup>/fm at the 1 and 2 standard deviation levels. These constraints include only the experimental uncertainties and do not account for the large model-dependent differences in the quenching scenario and description of the medium. Extracting fundamental model-independent properties of the medium from the present data requires resolution of ambiguities and open questions in the models themselves, which also will have to account simultaneously for the  $p_T$  and centrality (average path-length) dependence. This work demonstrates the power of data for pion production in constraining the energy loss of partons. The large  $\langle \hat{q} \rangle$  suggests that the matter consists of strongly coupled partons.

The  $R_{AA}(p_T)$  for 0–5% was fitted with a simple linear function in the entire  $p_T > 5$  GeV/c range as well: the slope of the fit is  $0.0017_{-0.0039}^{+0.0035}$  and  $_{-0.0076}^{+0.0070}$  c/GeV at the 1 and 2 standard deviation levels [16]. The fact that  $R_{AA}$  as well as the power ( $n$ ) for all spectra from  $p + p$  to Au + Au are essentially constant proves that the dominant term in energy loss is proportional to  $p_T$ .

In summary, PHENIX has measured neutral pions in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV at mid rapidity in the transverse momentum range of  $1 < p_T < 20$  GeV/c, analyzing high statistics data taken in 2004. The shape of the spectra is similar for all centralities, as is the shape of  $R_{AA}(p_T)$  at  $p_T > 5$  GeV/c. In central collisions, the yield is suppressed by a factor of  $\sim 5$  at 5 GeV/c compared to the binary scaled  $p + p$  reference, and the suppression prevails with little or no change up to 20 GeV/c. The integrated  $R_{AA}$  vs centrality does not saturate at this nuclear size; also, the predicted  $S_{loss} \propto N_{part}^{2/3}$  [6,10] is consistent with our data. In this picture, the energy loss increases with  $p_T$ . Using the 0–5% (most central)  $R_{AA}$ , we find that the transport coefficient  $\langle \hat{q} \rangle$  of the PQM model is constrained to  $13.2_{-3.2}^{+2.1}$  ( $_{-5.2}^{+6.3}$ ) GeV<sup>2</sup>/fm at the one (two)  $\sigma$  level. The experimental evidence for a high transport coefficient, derived with remarkable accuracy due to high quality data and sophisticated new analysis, as presented here and in [16], reveals a totally nontrivial feature of the dense QCD medium created at RHIC. The shape of the spectra and the suppression pattern

indicate that the dominant term in energy loss is proportional to  $p_T$ .

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