Suppression of Hadrons with Large Transverse Momentum in Central Au+Au Collisions at $\sqrt{s_{NN}} = 130$ GeV


1Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
2Bhabha Atomic Research Centre, Bombay 400 085, India
3Brookhaven National Laboratory, Upton, NY 11973-5000, USA
4Department of Physics, Banaras Hindu University, Varanasi 221005, India
5University of California - Riverside, Riverside, CA 92521, USA
6China Institute of Atomic Energy (CIAE), Beijing, People’s Republic of China
7Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
8Columbia University, New York, NY 10027 and Nevis Laboratories, Irvington, NY 10533, USA
9Florida State University, Tallahassee, FL 32306, USA
10Georgia State University, Atlanta, GA 30303, USA
11Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan
Transverse momentum spectra for charged hadrons and for neutral pions in the range $1 \text{ GeV/c} < p_T < 5 \text{ GeV/c}$ have been measured by the PHENIX experiment at RHIC in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 130 \text{ GeV}$. At high $p_T$ the spectra from peripheral nuclear collisions are consistent with scaling the spectra from p+p collisions by the average number of binary nucleon-nucleon collisions. The spectra from central collisions are significantly suppressed when compared to the binary-scaled p+p expectation, and also when compared to similarly binary-scaled peripheral collisions, indicating a novel nuclear medium effect in central nuclear collisions at RHIC energies.

PACS numbers: 25.75.Dw

Ultrarelativistic heavy ion collisions provide the opportunity to study strongly interacting matter at high temperature and density. At Brookhaven National Laboratory’s Relativistic Heavy Ion Collider (RHIC), nuclei as heavy as gold (Au) are accelerated to energies of $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$ per nucleon-nucleon pair. In the early stages of a central collision, energy densities are expected to be sufficient to dissolve normal nuclear matter into a phase of deconfined quarks and gluons, the “Quark Gluon Plasma” (QGP). The PHENIX experiment is designed to investigate nuclear collisions with a wide variety of probes, focusing primarily on those produced in the early stages of the collision.

Of particular interest are the products of parton scatterings with large momentum transfer (“hard scatterings”). In p+p collisions hard-scattered partons fragment into jets of hadrons; these fragments are the primary source of hadrons at high transverse momentum ($p_T$), typically above $\sim 2 \text{ GeV/c}$. In a high-energy nuclear collision hard scattering will occur at the earliest time during the collision, well before the QGP is expected to form, and thus the scattered partons will subsequently experience the strongly interacting medium created in the collision. These partons are expected to lose energy in hot and dense nuclear matter through gluon bremsstrahlung, effectively quenching jet produc-
scales with the number of nucleons participating in the collision, is smaller than one since the bulk of particle production in central and peripheral classes of Au+Au collisions at RHIC is enhanced compared to binary scaling. The ratio, the ratio, $R_{AA}(p_T) = \frac{(1/N_{coll}) d^2N^{A+A}/dp_Tdq}{(N_{binary})/\sigma_{inel}^{N+N} d^2\sigma^{N+N}/dp_Tdq}$, in the absence of nuclear modifications to hard scattering, will be unity; thus departures from this value will be a signature for nuclear medium effects. Previous measurements indicate that for $p_T$ below 2 GeV/c, $R_{AA}$ is smaller than one since the bulk of particle production scales with the number of nucleons participating in the reaction. For $p_T$ above 2 GeV/c, particle production in p+A collisions is enhanced compared to binary scaling, commonly referred to as the “Cronin effect.”

Parton shadowing as measured in lepton+A collisions is also expected to modify the hadron spectra in p+A and A+A compared to binary scaling.

We examine high-$p_T$ spectra of charged hadrons and neutral pions measured by the PHENIX experiment in a central and a peripheral class of Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV. These data are obtained with the central spectrometer, which consists of two arms, “east” and “west,” each covering $\Delta \phi = 90^\circ$ and $|\eta| < 0.35$. The arms are positioned outside an axially-symmetric magnetic field centered around the beam axis.

Charged particles are reconstructed using a drift chamber (DC) and two layers of multi-wire proportional chambers with pad-readout (PC1, PC3) in the east arm. The DC measures the particle trajectories between 2.0 and 2.4 m radius in the plane perpendicular to the beam axis. A matching hit in PC1 at $\sim 2.5$ m, together with location of the collision vertex, fixes the polar angle. Particle momenta are determined with a resolution of $\delta p/p \simeq 0.6\% \oplus 3.6\% p$ (GeV/c). The absolute momentum scale is known to better than 2%. Trajectories are confirmed by requiring a matching hit within a $\pm 2\sigma$ window (about 2.5 cm) in PC3 at a radius of 5 m, which eliminates nearly all secondary tracks from decays and interactions in material. The remaining background is due primarily to accidental associations. The level of background to signal is negligible below $p_T < 2$ GeV/c, rises to 1/10 at 3.5 GeV/c, and reaches 1/1 at 6 GeV/c. This background is measured statistically, by swapping the z-coordinate of the PC3 hits, and subtracted from the yield.

Corrections for acceptance, reconstruction efficiency, decays in flight, momentum resolution, and dead areas are determined using a full GEANT simulation. Simulated single particles are embedded in real events to model the effect of detector occupancy. In peripheral Au+Au collisions the track reconstruction efficiency exceeds 98%, while it is reduced to 68 ± 6% for central collisions, independent of momentum. Corrections due to finite momentum resolution are negligible at low $p_T$ and rise to the level of 30% at 5 GeV/c. The systematic errors (Table 1) are dominated by the uncertainty in the Monte Carlo description of the detector, including the dead areas and the momentum resolution.

Neutral pions are measured via their $\pi^0 \rightarrow \gamma \gamma$ decay. Two separate analyses are performed, the first using a lead-scintillator (PbSc) sampling calorimeter in half ($\Delta \phi = 45^\circ$) of the east arm aperture and the second with a lead-glass Cerenkov (PbGl) calorimeter in a quarter ($\Delta \phi = 22.5^\circ$) of the east arm aperture. The two analyses have very different systematics, and Figure 1 shows the agreement of their final $\pi^0$ spectra.

In both analyses, the yield in $p_T$ is determined by integrating the subtracted $m_{\gamma\gamma}$ distribution from the vertex are estimated by GEANT simulation to be 6-8%. The dominant sources of error are the uncertainty in the particle identification, the effect of energy smearing, and the peak extraction procedure. Their relative contributions to the total errors (see Table 1) differ for the two analyses.

Event classification is provided by the combination of two beam-beam counters (BBC’s) and two zero-degree arms, “east” and “west”, each covering $\Delta \phi \sim 90^\circ$ and $|\eta| < 0.35$. The arms are positioned outside an axially-symmetric magnetic field centered around the beam axis.

Charged particles are reconstructed using a drift chamber (DC) and two layers of multi-wire proportional chambers with pad-readout (PC1, PC3) in the east arm. The DC measures the particle trajectories between 2.0 and 2.4 m radius in the plane perpendicular to the beam axis. A matching hit in PC1 at $\sim 2.5$ m, together with location of the collision vertex, fixes the polar angle. Particle momenta are determined with a resolution of $\delta p/p \simeq 0.6\% \oplus 3.6\% p$ (GeV/c). The absolute momentum scale is known to better than 2%. Trajectories are confirmed by requiring a matching hit within a $\pm 2\sigma$ window (about 2.5 cm) in PC3 at a radius of 5 m, which eliminates nearly all secondary tracks from decays and interactions in material. The remaining background is due primarily to accidental associations. The level of background to signal is negligible below $p_T < 2$ GeV/c, rises to 1/10 at 3.5 GeV/c, and reaches 1/1 at 6 GeV/c. This background is measured statistically, by swapping the z-coordinate of the PC3 hits, and subtracted from the yield.

Corrections for acceptance, reconstruction efficiency, decays in flight, momentum resolution, and dead areas are determined using a full GEANT simulation. Simulated single particles are embedded in real events to model the effect of detector occupancy. In peripheral Au+Au collisions the track reconstruction efficiency exceeds 98%, while it is reduced to 68 ± 6% for central collisions, independent of momentum. Corrections due to finite momentum resolution are negligible at low $p_T$ and rise to the level of 30% at 5 GeV/c. The systematic errors (Table 1) are dominated by the uncertainty in the Monte Carlo description of the detector, including the dead areas and the momentum resolution.

Neutral pions are measured via their $\pi^0 \rightarrow \gamma \gamma$ decay. Two separate analyses are performed, the first using a lead-scintillator (PbSc) sampling calorimeter in half ($\Delta \phi = 45^\circ$) of the west arm aperture and the second with a lead-glass Cerenkov (PbGl) calorimeter in a quarter ($\Delta \phi = 22.5^\circ$) of the east arm aperture. The two analyses have very different systematics, and Figure 1 shows the agreement of their final $\pi^0$ spectra.

In both analyses, the yield in $p_T$ is determined by integrating the subtracted $m_{\gamma\gamma}$ distribution from the vertex area estimated by GEANT simulation to be 6-8%. The dominant sources of error are the uncertainty in the particle identification, the effect of energy smearing, and the peak extraction procedure. Their relative contributions to the total errors (see Table 1) differ for the two analyses.

Event classification is provided by the combination of two beam-beam counters (BBC’s) and two zero-degree
calorimeters (ZDC’s). We present data from two event samples, central and peripheral. The central sample covers the 0–10% most central fraction of the geometrical Au+Au cross-section, while the peripheral sample contains events in the 60–80% selection. Using a Glauber model combined with a simulation of the BBC and ZDC responses, we estimate \( \langle N_{\text{binary}} \rangle = 905 \pm 96 \) for the central sample, \( \langle N_{\text{binary}} \rangle = 20 \pm 6 \) for the peripheral sample, and 45 ± 13 for the ratio between them. The errors include the uncertainties in the parameters used in the Glauber model, as well as in the fraction of the total geometrical cross section (92 ± 4%) seen by the interaction trigger.

The \( p_T \) distributions for charged hadrons and neutral pions are shown for both centrality classes in Fig. 1. In this figure, those following, and Table I, the systematic errors shown are the quadrature sums of conservatively estimated limits on several independent errors and represent upper bounds on standard deviations. They are also substantially correlated between points.

The data are compared to the binary-scaled yield from N+N collisions. Since no N+N data exist at 1.96 GeV/c, we parameterize the cross section \( \sigma(d^2\sigma/d\eta d\eta_T) \) for \( (h^+ + h^-)/2 \) as \( A/(1 + p_T/p_0)^\alpha \). We determine the parameters \( A=330 \text{ mb/GeV}^2/c^2 \), \( p_0=1.72 \text{ GeV/c} \), and \( n=12.4 \) by interpolating between results from p+p collisions at the ISR and \( \sqrt{s}=130 \text{ GeV} \), and from Au+Au collisions at the SpS and the Tevatron. The systematic error in the N+N reference (Table I) is due to the error in the absolute normalization of the data used and in the interpolation technique. For neutral pions we scale the charged hadron cross section by the charged pion to charged hadron ratio \( \pi/h \) observed at the ISR. This was found to be 0.63 ± 0.06 nearly independent of \( p_T \) above 1.5 GeV/c.

For \( p_T > 2 \text{ GeV/c} \) the binary-scaling prediction agrees with the data from peripheral collisions for both charged and neutral pions, while for central collisions the data lie noticeably below the prediction. To examine this difference more directly, we plot the ratio \( R_{AA} \) for central collisions in Fig. 2. For the charged spectrum \( R_{AA} \) rises up to 2 GeV/c, as expected; but above 2 GeV/c \( R_{AA} \) remains significantly below unity for both spectra.

The depletion is quite striking, since the production of high-\( p_T \) hadrons in p+A collisions at fixed-target energies is known to be enhanced compared to the binary-scaling expectation for \( p_T > 2 \text{ GeV/c} \), i.e., the Cronin effect. A similar enhancement has also been observed in heavy ion collisions at lower energies, as shown in Fig. 2. Phenomenological calculations including shadowing and the Cronin effect predicted that for central Au+Au collisions at \( \sqrt{s_{NN}} = 130 \text{ GeV} \), \( R_{AA} > 1 \) for hadron spectra in the \( p_T \) range 3–9 GeV/c with a peak value of \( R_{AA} \approx 1.3 \) at 4 GeV/c.

Above 2 GeV/c \( R_{AA} \) is lower for pions than for charged hadrons, which implies that the \( \pi/h \) ratio is smaller in central RHIC Au+Au collisions than in ISR p+p collisions. This is consistent with identified charged hadron spectra measured by PHENIX for which a large yield of protons and antiprotons is observed at \( p_T \sim 2 \text{ GeV/c} \).

We can also examine the spectra from central collisions for modifications at high \( p_T \) by comparing them to the spectra from peripheral collisions after dividing each by the corresponding values of \( \langle N_{\text{binary}} \rangle \). The central-to-peripheral ratio is a useful complement to \( R_{AA} \), since it should be unity in the limit of point-like scaling. Many of the experimental uncertainties are reduced in this ratio (see Table I). Additionally, the uncertainty induced by the p+p interpolation is eliminated, albeit at the expense of incurring that in \( \langle N_{\text{binary}} \rangle \) for the peripheral class. We note that there may be effects from the centrality dependence of nuclear shadowing and/or the Cronin effect that would also be present in this comparison.

The central-to-peripheral ratios are plotted in Fig. 3. Like \( R_{AA} \) this ratio is below unity at all observed \( p_T \) for both charged hadrons and neutral pions, indicating a suppression of the yield per N+N collision in central collisions relative to peripheral. The difference between the two ratios implies that the \( \pi/h \) ratio is smaller in central collisions than in peripheral.

We have presented spectra for charged hadrons and neutral pions measured at 90° from central and peripheral Au+Au collisions in the PHENIX experiment at RHIC. Above \( p_T \sim 2 \text{ GeV/c} \), the spectra from peripheral collisions appear to be consistent (albeit within a substantial systematic error) with a simple, incoherent sum of underlying N+N collisions. The spectra from central collisions, in contrast, are systematically below the scaled N+N expectation, both when compared to data from p+p collisions and to spectra from Au+Au peripheral collisions. The suppression in central collisions is in qualitative agreement with the predictions of energy loss by scattered partons traversing a dense medium. However, other nuclear medium effects should be understood before a quantitative conclusion can be drawn. Measurements in p+A at RHIC can help in this direction.

We thank the staff of the RHIC project, Collider-Accelerator, and Physics Departments at BNL and the staff of PHENIX participating institutions for their vital contributions. We acknowledge support from the Department of Energy and NSF (U.S.A.), Monbusho and STA (Japan), RAS, RMAE, and RMS (Russia), BMBF, DAAD, and AVH (Germany), FRN, NFR, and the Wallenberg Foundation (Sweden), MIST and NSERC (Canada), CNPq and FAPESP (Brazil), IN2P3/CNRS (France), DAE and DST (India), LG-YF, KRF and KOSEF (Korea), and the US-Israel Binational Science Foundation.
Deceased
† Not a participating institution.
[12] We use the Woods-Saxon parameters radius = 6.38 ± 0.27 fm, diffusivity = 0.53 ± 0.01 fm [B. Hahn, D.G. Ravenhall and R. Hofstadter, Phys. Rev. 101, 1131 (1956)], and σ_{inel}^{N+N} = 40 ± 3 mb.
[13] The error due to model uncertainties is 2% [5]. An additional 3.5% error results from time dependencies in the centrality selection over the large data sample.

FIG. 1. The yields per event at mid-rapidity for charged hadrons (left) and neutral pions (right) are shown as a function of p_{T} for 60–80% (lower) and 0–10% (upper) event samples. The error bars indicate the statistical errors on the yield; the surrounding brackets indicate the systematic errors. Also shown are the N+N references for charged hadrons and neutral pions, each scaled up by ⟨N_{binary}⟩ for the class. The bands indicate the uncertainty in the N+N reference and in the ⟨N_{binary}⟩.

FIG. 2. The ratio R_{AA} for charged hadrons and neutral pions (weighted average of PbSc and PbGl results) in central Au+Au collisions. The error bars indicate the statistical errors on the measurement. The surrounding bands [shaded for π^0's, brackets for (h^+ + h^-)/2] are the quadrature sums of (i) the systematic errors on the measurement, (ii) the uncertainty in the N+N reference, and (iii) the uncertainty in ⟨N_{binary}⟩. Also shown are the ratio of inclusive cross sections in α+α compared to p+p at \sqrt{s_{NN}} = 31 GeV [18], and spectra from central Pb+Pb, Pb+Au compared to p+p collisions at \sqrt{s_{NN}} = 17 GeV [17] shown as a band indicating the range of uncertainty.
FIG. 3. Ratio of yield per event in central vs peripheral Au+Au collisions, with each divided by \( \langle N_{\text{binary}} \rangle \) for that class. For \( \pi^0 \) the weighted average of PbSc and PbGl results is shown. The error bars indicate the statistical errors on the spectra. The surrounding bands [shaded for \( \pi^0 \)'s, brackets for \( \langle h^+ + h^- \rangle /2 \)] are the quadrature sums of (i) the parts of the systematic errors on the spectra that do not cancel in the ratio, and (ii) the uncertainty in \( \langle N_{\text{binary}} \rangle \) (see Table I).

<table>
<thead>
<tr>
<th>Sys. error:</th>
<th>Yield ( p_T ) [GeV/c]</th>
<th>Cent/Per ( p_T ) [GeV/c]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h ) data</td>
<td>27% 0.5 8% all</td>
<td>16-18% 0.8-3.5</td>
</tr>
<tr>
<td>( \pi^+ ) data</td>
<td>25% 1.2 24% 1.2</td>
<td></td>
</tr>
<tr>
<td>(PbSc)</td>
<td>35% 3.7 33% 3.2</td>
<td></td>
</tr>
<tr>
<td>(PbGl)</td>
<td>52% 3.7 40% 2.7</td>
<td></td>
</tr>
<tr>
<td>( \pi^0 ) data</td>
<td>33% 1.2 32% 1.2</td>
<td></td>
</tr>
<tr>
<td>(combined)</td>
<td>30% 3.7 24% 2.7</td>
<td></td>
</tr>
<tr>
<td>N+N ref.</td>
<td>20% 1.0 N/A</td>
<td></td>
</tr>
<tr>
<td>35% 5.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( \langle N_{\text{binary}} \rangle \) 29% all

central 11% all

peripheral 30% all