

## Transverse-Momentum and Collision-Energy Dependence of High- $p_T$ Hadron Suppression in Au + Au Collisions at Ultrarelativistic Energies

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We report high statistics measurements of inclusive charged hadron production in Au + Au and  $p + p$  collisions at  $\sqrt{s_{NN}} = 200$  GeV. A large, approximately constant hadron suppression is observed in central Au + Au collisions for  $5 < p_T < 12$  GeV/ $c$ . The collision energy dependence of the yields and the centrality and  $p_T$  dependence of the suppression provide stringent constraints on theoretical models of suppression. Models incorporating initial-state gluon saturation or partonic energy loss in dense matter are largely consistent with observations. We observe no evidence of  $p_T$ -dependent suppression, which may be expected from models incorporating jet attenuation in cold nuclear matter or scattering of fragmentation hadrons.

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High energy partons propagating through matter are predicted to lose energy via induced gluon radiation, with the total energy loss strongly dependent on the color charge density of the medium [1]. This process can pro-

vide a sensitive probe of the hot and dense matter generated early in ultrarelativistic nuclear collisions, when a plasma of deconfined quarks and gluons may form. The hard scattering and subsequent fragmentation of partons

generates jets of correlated hadrons. In nuclear collisions, jets may be studied via observables such as high transverse momentum (high  $p_T$ ) hadronic inclusive spectra [2] and correlations. Several striking high  $p_T$  phenomena have been observed at the BNL Relativistic Heavy Ion Collider (RHIC) [3–7], including strong suppression of inclusive hadron production [3–5]. These phenomena are consistent with large partonic energy loss in high energy density matter [1,8–11] though other mechanisms have been proposed, including gluon saturation in the initial nuclear wave function [12], attenuation of jet formation in cold nuclear matter [13], and scattering of fragmentation hadrons [14]. Additional measurements are required to discriminate among these pictures and to isolate effects due to final-state partonic energy loss.

We report high statistics measurements by the STAR Collaboration of the inclusive charged hadron yield  $(h^+ + h^-)/2$  (defined as the summed yields of primary  $\pi^\pm$ ,  $K^\pm$ ,  $p$ , and  $\bar{p}$ ) in Au + Au collisions and nonsingly diffractive (NSD)  $p + p$  collisions at nucleon-nucleon center of mass energy  $\sqrt{s_{NN}} = 200$  GeV. The Au + Au data extend considerably the  $p_T$  range of earlier charged hadron suppression studies, and the  $p + p$  data are the first such measurement at this energy. Comparisons are made to several theoretical models. The high precision and broad kinematic coverage of the data significantly constrain the possible mechanisms of hadron suppression. In addition, the energy dependence of the yields may be sensitive to gluon shadowing at low Bjorken  $x$  in heavy nuclei.

We compare the data to two calculations based on hard parton scattering evaluated via perturbative QCD (pQCD-I [15] and pQCD-II [9]) and to a calculation extending the saturation model to high momentum transfer [12]. Both pQCD models for Au + Au collisions incorporate nuclear shadowing, the Cronin effect [16], and partonic energy loss, but with different formulations. pQCD-I results excluding one or more nuclear effects are also shown. Neither pQCD calculation includes non-perturbative effects that generate particle species-dependent differences for  $p_T < 5$  GeV/ $c$  [15,17].

Charged particle trajectories were measured in the STAR time projection chamber (TPC) [18]. The magnetic field was 0.5 T, resulting in a factor of 3 improvement in  $p_T$  resolution at high  $p_T$  relative to [3,6]. After event selection cuts, the Au + Au dataset comprised  $1.7 \times 10^6$  minimum bias events ( $97 \pm 3\%$  of the geometric cross section  $\sigma_{\text{geom}}^{\text{AuAu}}$ ) and  $1.5 \times 10^6$  central events (10% of  $\sigma_{\text{geom}}^{\text{AuAu}}$ ). Centrality selection and analysis of spectra follow Ref. [3]. Background at high  $p_T$  is dominated by weak decay products, with correction factors calculated using STAR measurements of  $\Lambda(+\Sigma^0)$  and  $K_s^0$  for  $p_T < 6$  GeV/ $c$  [19] and assuming constant yield ratios  $\Lambda(+\Sigma^0)/(h^+ + h^-)$  and  $K_s^0/(h^+ + h^-)$  for  $p_T > 6$  GeV/ $c$ . The  $\Lambda(+\Sigma^0)$  yield was scaled by a fac-

TABLE I. Multiplicative correction factors applied to the measured yields at  $p_T = 10$  GeV/ $c$  for  $p + p$  and Au + Au data. Factors vary by approximately 5% within  $4 < p_T < 12$  GeV/ $c$  and have similar uncertainties.

	Tracking	Background	$p_T$ resolution
$p + p$	$1.18 \pm 0.07$	$0.90 \pm 0.08$	$0.89^{+0.05}_{-0.05}$
Au + Au 60%–80%	$1.11 \pm 0.06$	$0.95 \pm 0.05$	$0.97^{+0.03}_{-0.05}$
Au + Au 0%–5%	$1.25 \pm 0.06$	$0.94 \pm 0.06$	$0.95^{+0.05}_{-0.05}$

tor of 1.4 to account for  $\Sigma^+$  decays. Table I summarizes the correction factors at high  $p_T$ .

After event selection cuts, the  $p + p$  dataset comprised  $5 \times 10^6$  mainly NSD events, triggered on the coincidence of two beam-beam counters (BBCs). The BBCs are annular scintillator detectors situated  $\pm 3.5$  m from the interaction region, covering pseudorapidity  $3.3 < |\eta| < 5.0$ . A van der Meer scan [20] measured the BBC trigger cross section to be  $26.1 \pm 0.2(\text{stat}) \pm 1.8(\text{syst})$  mb. The BBC trigger was simulated using PYTHIA [21] and HERWIG [22] events passed through a GEANT detector model. The PYTHIA trigger cross section is 27 mb, consistent with measurement, of which 0.7 mb results from singly diffractive events. The PYTHIA and HERWIG simulations show that the trigger accepts  $87\% \pm 8\%$  of all NSD events containing a TPC track, with negligible track  $p_T$  dependence. Noninteraction backgrounds contributed  $3\% \pm 2\%$  of the trigger rate. The high  $p + p$  interaction rate generated significant pileup in the TPC. Valid tracks matched an in-time hit in the central trigger barrel (CTB [18]) surrounding the TPC and projected to a distance of closest approach  $DCA < 1$  cm to the average beam trajectory. To avoid event selection multiplicity bias, an approximate event vertex position along the beam ( $z_{\text{vert}}$ ) was calculated by averaging  $z_{DCA}$  over all valid tracks. Accepted events were required to have  $|z_{\text{vert}}| < 75$  cm, corresponding to  $69\% \pm 4\%$  of all events. The track  $p_T$  fit did not include the event vertex. The CTB track-matching efficiency is  $94\% \pm 2\%$  and combinatorial background is  $2\% \pm 2\%$ . Other significant  $p + p$  tracking backgrounds result from weak decays and antinucleon annihilation in detector material, with corrections calculated using HIJING [23] and preliminary STAR measurements. Correction factors at high  $p_T$  are given in Table I. For  $p + p$  collisions relative to peripheral Au + Au, exclusion of the event vertex from the  $p_T$  fit results in poorer  $p_T$  resolution, while the CTB matching requirement results in lower tracking efficiency. The  $p + p$  inclusive spectrum was also analyzed for  $p_T < 3.5$  GeV/ $c$  by an independent method in which a primary vertex is found and incorporated into the track fit, with consistent results.

The  $p + p$  NSD differential cross section is the product of the measured per-event yield and the BBC NSD trigger cross section, and has a normalization uncertainty of  $\pm 14\%$ . The charged hadron invariant cross section has

been measured in  $\bar{p} + p$  collisions at  $\sqrt{s} = 200$  GeV [24]. The  $p + p$  cross section reported here is smaller by a factor of  $0.79 \pm 0.18$ , approximately independent of  $p_T$ , where the uncertainty includes the two spectrum normalizations and the correction for different acceptances [3]. The difference is due in large part to differing NSD cross section, which is  $35 \pm 1$  mb in [24] but is measured here to be  $30.0 \pm 3.5$  mb.

Figure 1 shows inclusive invariant  $p_T$  distributions of  $(h^+ + h^-)/2$  within  $|\eta| < 0.5$  for Au + Au and  $p + p$  collisions at  $\sqrt{s_{NN}} = 200$  GeV. The Au + Au spectra are shown for percentiles of  $\sigma_{\text{geom}}^{\text{AuAu}}$ , with 0%–5% indicating the most central (head-on) collisions. Error bars are the quadrature sum of the statistical and systematic uncertainties and are dominated by the latter except at the highest  $p_T$ .

Figure 2 shows  $R_{200/130}(p_T)$ , the ratio of charged hadron yields at  $\sqrt{s_{NN}} = 200$  and 130 GeV [3], for centrality-selected Au + Au collisions. Error bars are the quadrature sum of the statistical and systematic uncertainties, dominated for  $p_T > 4$  GeV/c by statistics at 130 GeV. In the absence of nuclear effects, the hard process inclusive yield in nuclear collisions is expected to scale as  $\langle N_{\text{bin}} \rangle$ , the average number of binary collisions for the respective centrality selection.  $R_{200/130}(p_T)$  has not been scaled by the ratio  $N_{\text{bin}}(200)/N_{\text{bin}}(130)$ , which Glauber model calculations [3,25] give as  $\sim 1.02$  for all centralities. Figure 2 also shows the saturation model calculation and pQCD-I calculations for  $p + p$  and centrality-selected Au + Au collisions (shadowing-only and full). Both models approximately reproduce the  $p_T$  dependence of the ratio for Au + Au for  $p_T > 2$  GeV/c,

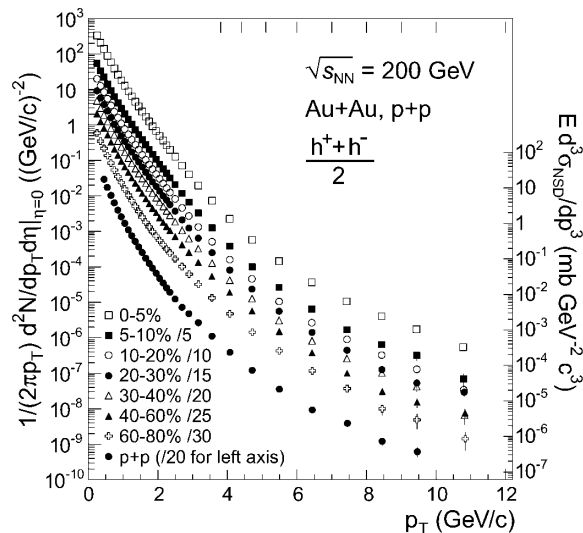


FIG. 1. Inclusive invariant  $p_T$  distributions of  $(h^+ + h^-)/2$  for centrality-selected Au + Au and  $p + p$  NSD interactions. Hash marks at the top indicate bin boundaries for  $p_T > 4$  GeV/c. The invariant cross section for  $p + p$  is indicated on the right vertical axis.

with pQCD-I slightly better for more peripheral collisions. The various pQCD-I calculations shown illustrate that in this model the reduction in  $R_{200/130}(p_T)$  for Au + Au relative to  $p + p$  is predominantly due to nuclear shadowing [15]. This sensitivity arises because the shadowing is  $x$  dependent and, at fixed  $p_T$ , different  $\sqrt{s}$  corresponds to different  $x_T = 2p_T/\sqrt{s}$ . The quantitative agreement of pQCD-I with the data improves for more peripheral collisions, suggesting that the prescription for the centrality dependence of shadowing in [15] may not be optimal. Alternatively, introduction of  $\sqrt{s}$ -dependent energy loss to the model in [15] may also improve the agreement.

Nuclear effects on the inclusive spectra are measured by comparison to a nucleon-nucleon (NN) reference via the nuclear modification factor:

$$R_{AA}(p_T) = \frac{d^2 N^{AA}/dp_T d\eta}{T_{AA} d^2 \sigma^{\text{NN}}/dp_T d\eta}, \quad (1)$$

where  $T_{AA} = \langle N_{\text{bin}} \rangle / \sigma_{\text{inel}}^{\text{NN}}$  from a Glauber calculation accounts for the nuclear collision geometry [3,25] and we adopt  $\sigma_{\text{inel}}^{\text{NN}} = 42$  mb.  $d^2 \sigma^{\text{NN}}/dp_T d\eta$  refers to inelastic collisions, whereas we have measured the  $p + p$  NSD differential cross section. However, singly diffractive interactions contribute predominantly to low  $p_T$  [26]. A multiplicative correction based on PYTHIA, applied to  $d^2 \sigma^{\text{NN}}/dp_T d\eta$  in Eq. (1), is 1.05 at  $p_T = 0.4$  GeV/c and unity above 1.2 GeV/c.

Figure 3 shows  $R_{AA}(p_T)$  at  $\sqrt{s_{NN}} = 200$  GeV for centrality-selected Au + Au spectra relative to the measured  $p + p$  spectrum. Horizontal dashed lines show Glauber model expectations [3,25] for scaling of the yield with  $\langle N_{\text{bin}} \rangle$  or mean number of participants  $\langle N_{\text{part}} \rangle$ , with grey bands showing their respective uncertainties summed in quadrature with the  $p + p$  normalization uncertainty. The error bars represent the quadrature sum of the Au + Au and remaining  $p + p$  spectrum

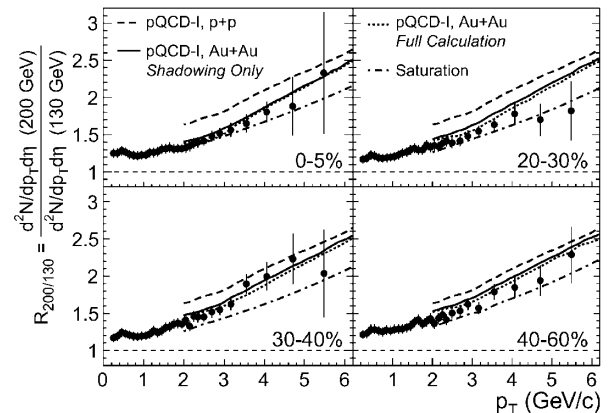


FIG. 2.  $R_{200/130}(p_T)$  vs  $p_T$  for  $(h^+ + h^-)/2$  for four different centrality bins. The overall normalization uncertainty is  ${}^{+6}_{-10}\%$  for the 40%–60% bin and is negligible for the other panels. Calculations are described in the text.

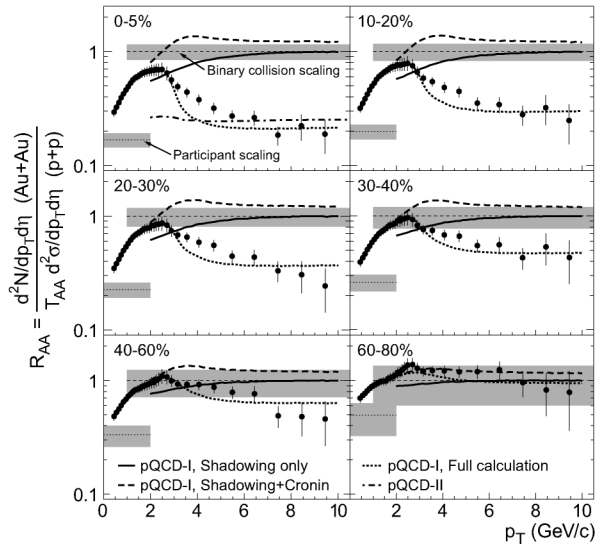


FIG. 3.  $R_{AA}(p_T)$  [Eq. (1)] for  $(h^+ + h^-)/2$  in  $|\eta| < 0.5$ , for centrality-selected Au + Au spectra relative to the measured  $p + p$  spectrum. The  $p + p$  spectrum is common to all panels. Calculations are described in the text.

uncertainties. For  $p_T < 6$  GeV/c,  $R_{AA}(p_T)$  is similar to that observed at  $\sqrt{s_{NN}} = 130$  GeV [3]. Hadron production for  $6 < p_T < 10$  GeV/c is suppressed by a factor of 4–5 in central Au + Au relative to  $p + p$  collisions.

Figure 3 also shows the full pQCD-I calculation and the influence of each nuclear effect. The energy loss for central collisions is a fit parameter, with the  $p_T$  and centrality dependence of the suppression constrained by theory. The Cronin enhancement and shadowing alone cannot account for the suppression, which is reproduced only if partonic energy loss in dense matter is included. The full calculation generally agrees with data for  $p_T > 5$  GeV/c if the initial parton density in central collisions is adjusted to be  $\sim 15$  times that of cold nuclear matter [27]. pQCD-II exhibits similar agreement for central collisions. In Ref. [9], the pQCD-II calculation was used to predict a  $p_T$ -independent suppression factor in this  $p_T$  range from the interplay between shadowing, the Cronin effect, and partonic energy loss.

Figure 4 shows  $R_{CP}(p_T)$ , the  $\langle N_{bin} \rangle$ -normalized ratio of central and peripheral Au + Au spectra.  $R_{CP}(p_T)$  extends to higher  $p_T$  than  $R_{AA}(p_T)$ , with smaller point-to-point uncertainties. The error bars show the quadrature sum of statistical and uncorrelated systematic uncertainties. Statistical errors dominate the uncertainties for  $p_T > 8$  GeV/c. Lines and grey bands are as in Fig. 3.  $R_{CP}(p_T)$  for  $p_T < 6$  GeV/c is similar to measurements at  $\sqrt{s_{NN}} = 130$  GeV [3], but is now seen to be approximately constant for  $5 < p_T < 12$  GeV/c. It is consistent with  $\langle N_{part} \rangle$  scaling at  $p_T \sim 4$  GeV/c as reported in [5], but is below  $\langle N_{part} \rangle$  scaling at higher  $p_T$ .

The  $p_T$  dependence of the suppression in Fig. 4 is well reproduced for  $p_T > 5$  GeV/c by the full pQCD-I

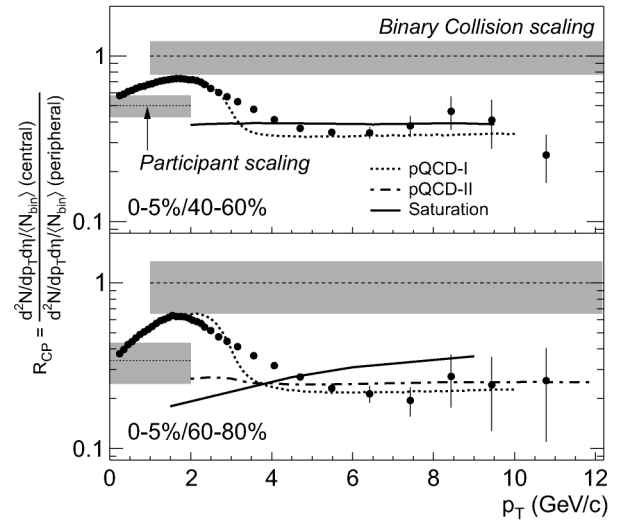


FIG. 4.  $R_{CP}(p_T)$  vs  $p_T$  for  $(h^+ + h^-)/2$ . Calculations are described in the text.

and pQCD-II calculations in both panels and the saturation calculation in the upper but not the lower panel. The magnitude of suppression is fitted to the central collision data in the pQCD models but is predicted in the saturation calculation. Attenuation of initial jet formation due to multiple nucleon interactions [13] generates an increase in partonic  $R_{AA}(p_T)$  for central collisions of a factor  $\sim 2$  in  $5 < E_T < 12$  GeV. A similar  $p_T$  dependence would be expected for high  $p_T$  hadrons, in contrast to observations. Suppression in the final-state due to in-medium scattering of fragmentation hadrons should also result in a rising  $R_{AA}(p_T)$  with increasing  $p_T$  due to the dependence of hadron formation time on the total jet energy [14], though detailed comparison of this model to data requires further theoretical development.

In summary, STAR has measured inclusive charged hadron yields from Au + Au and  $p + p$  collisions at  $\sqrt{s_{NN}} = 200$  GeV, at higher precision and over a much broader  $p_T$  range than previous measurements. Large, constant hadron suppression is observed in central nuclear collisions at high  $p_T$ . The systematic behavior of the suppression at high  $p_T$  is well described both by pQCD calculations incorporating final-state partonic energy loss in dense matter and a model of initial-state gluon saturation, though the latter model provides a poorer description of peripheral collision data. The isolation of initial-state effects on high  $p_T$  hadron production may be achieved through the study of  $d + Au$  collisions at RHIC, allowing a quantitative measurement of final-state effects from the data presented here.

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