Forward Neutral Pion Production in $p + p$ and $d + \mathrm{Au}$ Collisions at $\sqrt{s_{NN}} = 200$ GeV

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Measurements of the production of forward π^0 mesons from $p + p$ and $d +$ Au collisions at $\sqrt{s_{NN}} = 200$ GeV are reported. The $p + p$ yield generally agrees with next-to-leading order perturbative QCD calculations. The $d +$ Au yield per binary collision is suppressed as η increases, decreasing to $\sim$30% of the $p + p$ yield at $\langle \eta \rangle = 4.00$, well below shadowing expectations. Exploratory measurements of azimuthal correlations of the forward π^0 with charged hadrons at $\eta \approx 0$ show a recoil peak in $p + p$

that is suppressed in $d + \mathrm{Au}$ at low pion energy. These observations are qualitatively consistent with a saturation picture of the low-x gluon structure of heavy nuclei.

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Little is known about the gluon structure of heavy nuclei [1]. For protons, the gluon parton distribution function (g-PDF) is constrained at small x (fraction of nucleon momentum) primarily by scaling violations observed in deep-inelastic lepton scattering (DIS) at the HERA collider [2]. The proton DIS data are accurately described by evolution equations of quantum chromodynamics (QCD) that allow the determination of the g-PDF [3]. As x decreases, the g-PDF is found to increase from gluon splitting as the partons evolve. At a sufficiently small value of x, yet to be determined by experiment, the splitting is expected to become balanced by recombination as the gluons overlap, resulting in gluon saturation [4]. At a given x, the density of gluons per unit transverse area is expected to be larger in nuclei than in nucleons; thus, nuclei provide a natural environment in which to search for gluon saturation. Fixed target nuclear DIS experiments are restricted in the kinematics available; they have determined the nuclear g-PDF only for $x \gtrsim 0.02$ [1].

Using factorization in a perturbative QCD (pQCD) framework, PDFs and fragmentation functions (FFs) measured in electromagnetic reactions are used to calculate hadronic processes. In $p + p$ collisions, next-to-leading order (NLO) pQCD calculations quantitatively describe inclusive π^0 production over a broad range of pseudorapidity ($\eta = -\ln[\tan(\theta/2)]$) at center-of-mass energy $\sqrt{s} = 200$ GeV [5,6], but not at lower $\sqrt{s}$ [7]. In pQCD, hadroproduction at large η from $p + p$ collisions at $\sqrt{s} = 200$ GeV probes gluons in one proton using the valence quarks of the other, covering a broad distribution of gluon x peaked around 0.02 [8]. Analogously, hadroproduction in the d-beam (forward) direction of $d + \mathrm{Au}$ collisions is sensitive to the gluon structure of the Au nucleus. Quantifying if saturation occurs at RHIC energies is important because the matter created in heavy-ion collisions comes predominantly from the collisions of low-x gluons [9]. Recently, the yield of forward negatively charged hadrons (h^-) in $d + \mathrm{Au}$ collisions was found to be suppressed relative to $p + p$ [10]. The suppression is especially significant since isospin effects should reduce h^- production in $p + p$ collisions, but not in $d + \mathrm{Au}$ [8].

Many models try to describe forward hadroproduction from heavy nuclei. In the color glass condensate (CGC) formulation, the low-x gluon density is saturated, resulting in dense color fields that scatter the partons from the deuteron beam [11]. The average gluon-x decreases rapidly with increasing η to $\approx 10^{-4}$ for pions produced at $\eta = 4$ [12]. Another approach scatters quarks coherently from multiple nucleons, leading to an effective shift in gluon-x [13]. Shadowing models modify the nuclear g-PDF in a standard factorization framework [8,14]. Other models include limiting fragmentation [15], parton recombination [16], and factorization breaking [17].

Additional insight into the particle production mechanism can be gained by analyzing the azimuthal correlations ($\Delta\phi$) of the forward π^0 with coincident hadrons. Assuming collinear elastic parton ($2 \rightarrow 2$) scattering, a back-to-back peak at $\Delta\phi = \pi$ is expected, with the rapidity of the recoil particle correlated with x of the struck gluon. In a saturation picture, the quark undergoes multiple interactions through the dense gluon field, resulting in multiple recoil partons instead of a single one [13,18], thereby modifying the $\Delta\phi$ distribution and possibly leading to the appearance of monojets [19].

We present the yields of high energy π^0 mesons at forward rapidities from $p + p$ (Fig. 1) and $d + \mathrm{Au}$ (Fig. 2) collisions at $\sqrt{s_{NN}} = 200$ GeV. The data are compared with models and with h^- data at smaller η. The $\Delta\phi$ distributions of the forward π^0 with midrapidity $h^\pm$ are presented.

Data were collected by the STAR experiment (Solenoid Tracker at RHIC) at the Brookhaven National Laboratory Relativistic Heavy-Ion Collider (RHIC). At midrapidity, a time projection chamber is used to detect charged particles, while a forward π^0 detector (FPD) is used at forward rapidities. In 2002, $p + p$ collisions were studied with a prototype FPD (PFPD) [5]. In 2003, $p + p$ collisions were studied with the complete FPD and exploratory measurements were made for $d + \mathrm{Au}$ collisions.

The luminosity was determined using the rate of coincidences on either side of the interaction region between beam-beam counters (BBC) for $p + p$ [5] and zero-degree calorimeters for $d + \mathrm{Au}$ [20]. For $p + p$, the transverse size of the colliding beams and the number of ions were measured, giving a coincidence cross section of $26.1 \pm 0.2(\mathrm{stat}) \pm 1.8(\mathrm{syst})$ mb [21]. For $d + \mathrm{Au}$, the cross section of coincidences was measured to be $(19.2 \pm 1.3)\%$ of the hadronic, $\sigma_{\mathrm{hadr}}^{d\mathrm{Au}}$ [20]. The integrated luminosity for these data was ≈ 350 nb^{-1} (200 μb^{-1}) for $p + p$ ($d + \mathrm{Au}$).

Events required more energy in the calorimeter than from a 15 GeV electron. A BBC coincidence reduces noncollision background but requires an E_π-independent 10% correction to the yields [5] to account for its efficiency. The energy is calibrated to $\approx 1\%$ from the centroid of the π^0 peak in the diphoton invariant mass, $M_{\gamma\gamma}$ [22]. Monte Carlo simulations with physics backgrounds and the full detector response describe $p + p$ and $d + \mathrm{Au}$ data for many variables, e.g., $M_{\gamma\gamma}$ in Fig. 2 (inset). Jet background is reduced in the FPD by requiring two recon-

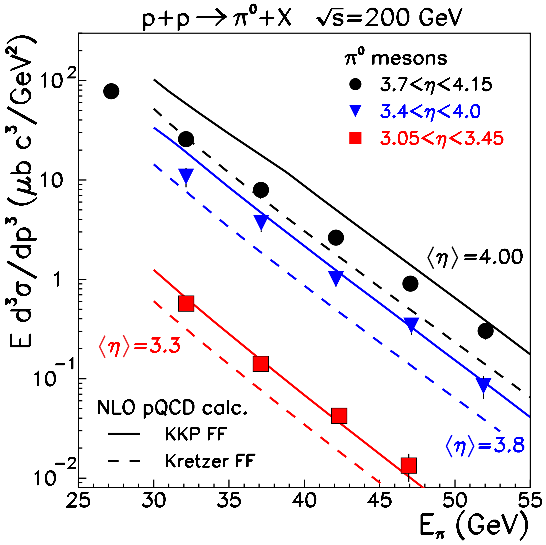

FIG. 1 (color online). Inclusive π^0 cross section for $p + p$ collisions vs the leading π^0 energy (E_π) averaged over 5 GeV bins at fixed pseudorapidity (η). The error bars combine statistical and point-to-point systematic errors. The curves are NLO pQCD calculations using two sets of fragmentation functions (FF).

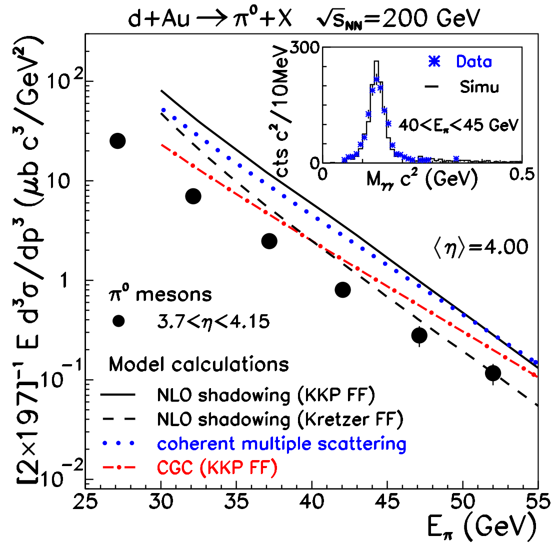

FIG. 2 (color online). Inclusive π^0 cross section per binary collision for $d + \mathrm{Au}$ collisions, as in Fig. 1. The curves are calculations described in the text. (Inset) Diphoton invariant mass spectrum for data (stars), normalized to simulation (histogram).

structed photons ($N_\gamma = 2$), selecting 78% (53%) of events with $E_\pi > 25$ GeV and $N_\gamma \geq 2$ in $p + p$ ($d + \mathrm{Au}$) data. The π^0 detection efficiency is determined in a matrix of E_π and η from background-corrected simulations. For $d + \mathrm{Au}$ it is dominated by the FPD geometrical acceptance and is within 8%–19% of the efficiency in $p + p$.

Inclusive π^0 cross sections for $p + p$ collisions at $\sqrt{s} = 200$ GeV are seen in Fig. 1 at $\langle\eta\rangle = 3.3$, 3.8 [5], and 4.00. Data are in 5 GeV bins, plotted at the average E_π. Data at $\langle\eta\rangle = 3.3$ and 3.8 were taken with the PFPD, where the systematic error increases with E_π from 10%–26%, dominated by the correction for the jet accompanying the π^0 [5]. Data at $\langle\eta\rangle = 4.00$ were taken with the FPD, where the systematic error is 8%–16%, dominated by the energy calibration [22]. The normalization error is 17% for both $p + p$ and $d + \mathrm{Au}$, dominated by the absolute η error [22]. The curves are NLO pQCD calculations [23] using CTEQ6M PDFs [24] and equal renormalization and factorization scales of $p_T = E_\pi/\cosh\eta$. Scale dependence is comparable at $\eta \approx 4$ and $\eta \approx 0$. Theoretical systematic errors, attributed to scale dependence at $\eta \approx 0$ [6], may require further study at large η. The solid and dashed curves use Kniehl-Kramer-Pötter (KKP) [25] and Kretzer [26] fragmentation functions (FFs), respectively. The primary difference between them is the g-to-π FF, which may occur at $p_T \lesssim 2$ GeV$/c$, where the dominant contribution to π^0 production becomes gg scattering [27]. At $\langle\eta\rangle = 3.3$ and 3.8, the data are consistent with KKP. At $\langle\eta\rangle = 4.00$, the data drop below KKP and approach Kretzer as p_T decreases, similar to the trend at $\eta \approx 0$ [6].

The study of effects from possible gluon saturation in a nucleus begins with the inclusive π^0 cross section for $d + \mathrm{Au}$ collisions (Fig. 2). No explicit constraint is placed on the collision centrality. The systematic error is 10%–22%, dominated by the background correction. The solid (dashed) curve is a NLO pQCD calculation using Au PDFs with shadowing [8] and KKP (Kretzer) FFs. The dotted curve is a LO calculation of multiple parton scattering [13], normalized to π^0 data at $\eta \approx 0$ [6]. The dot-dashed curve is a LO calculation convoluting CTEQ5 PDFs and KKP FFs, replacing the hard partonic scattering with a dipole-nucleus cross section to model parton scattering from a CGC in the nucleus [12], normalized to $d + \mathrm{Au} \to h^- + X$ data at $\eta = 3.2$ [10]. This model predicts the correct p_T dependence but overpredicts the π^0 data by a factor of 2, a factor that could approach unity with use of the Kretzer FF.

The nuclear modification factor is defined as:

$$R_{d\mathrm{Au}}^{Y} = \frac{\sigma_{\mathrm{inel}}^{pp}}{\langle N_{\mathrm{bin}}\rangle \sigma_{\mathrm{hadr}}^{d\mathrm{Au}}} \frac{E d^3\sigma/dp^3(d + \mathrm{Au} \to Y + X)}{E d^3\sigma/dp^3(p + p \to Y + X)}. \quad (1)$$

The inelastic $p + p$ cross section is $\sigma_{\mathrm{inel}}^{pp} = 42$ mb, while $\sigma_{\mathrm{hadr}}^{d\mathrm{Au}} = (2.21 \pm 0.09)$ b and the mean number of binary collisions, $\langle N_{\mathrm{bin}}\rangle = 7.5 \pm 0.4$, are from a Glauber model calculation [20]. The prefactor in $R_{d\mathrm{Au}}^{Y}$ is equal to the ratio of binary collisions in $p + p$ and $d + \mathrm{Au}$, $1/(2 \times 197)$. Figure 3 shows $R_{d\mathrm{Au}}^{\pi^0}$ versus p_T at $\langle\eta\rangle = 4.00$ with h^- data at smaller η [10]. Systematic errors from $p + p$ and $d + \mathrm{Au}$ are added in quadrature. The normalization error includes the $\langle N_{\mathrm{bin}}\rangle$ error but not the absolute η error, since the FPD position was the same for $d + \mathrm{Au}$ and $p + p$ data.

In the absence of nuclear effects, hard processes scale with the number of binary collisions and $R_{d\mathrm{Au}}^{Y} = 1$. At

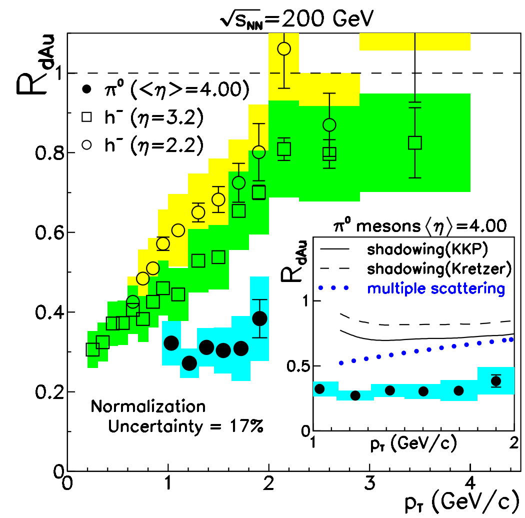

FIG. 3 (color online). Nuclear modification factor ($R_{d\mathrm{Au}}$) for minimum-bias d + Au collisions vs transverse momentum (p_T). The solid circles are for π^0 mesons. The open circles and boxes are for negative hadrons [10]. The error bars are statistical, while the shaded boxes are point-to-point systematic errors. (Inset) $R_{d\mathrm{Au}}$ for π^0 mesons with the ratio of curves in Figs. 1 and 2.

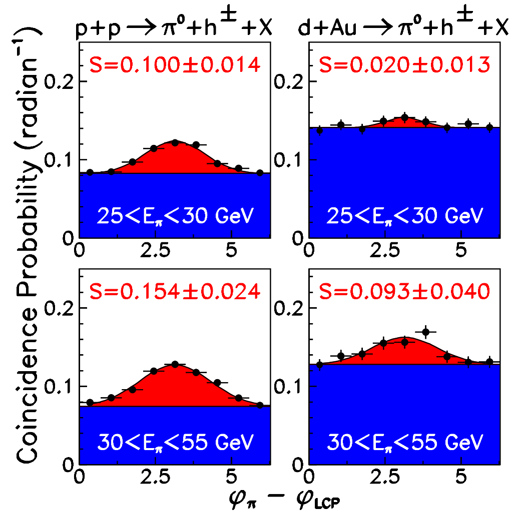

FIG. 4 (color online). Coincidence probability vs azimuthal angle difference between the forward π^0 and a leading charged particle at midrapidity with $p_T > 0.5$ GeV/c. The left (right) column are $p + p$ (d + Au) data. The curves are fits described in the text, including the area of the back-to-back peak (S).

midrapidity, $R^{h^\pm}_{d\mathrm{Au}} \gtrsim 1$, with a Cronin enhancement for $p_T \gtrsim 2$ GeV/c [10,20]. As η increases, $R^{Y}_{d\mathrm{Au}}$ becomes much less than 1. This decrease with η is qualitatively consistent with models that suppress the nuclear gluon density [11,13,14,16]. Scaling $R^{h^-}_{d\mathrm{Au}}$ by 2/3 to account for isospin effects on $p + p \to h^- + X$ [8], $R^{\pi^0}_{d\mathrm{Au}}$ is consistent with a linear extrapolation of the scaled $R^{h^-}_{d\mathrm{Au}}$ to $\eta = 4$. The curves in the inset are ratios of the calculations in Figs. 1 and 2. The data lie below all the predictions.

Exploratory measurements of the azimuthal correlations between the forward π^0 and midrapidity $h^\pm$ are seen in Fig. 4 for $p + p$ and d + Au collisions. The leading charged particle (LCP) analysis picks the track at $|\eta_h| < 0.75$ with the highest $p_T > 0.5$ GeV/c, and computes $\Delta\phi = \phi_{\pi^0} - \phi_{\mathrm{LCP}}$ for each event. The $\Delta\phi$ distributions are normalized by the number of π^0 seen at $\langle\eta\rangle = 4.00$. Correlations near $\Delta\phi = 0$ are not expected since $\eta_{\pi^0} - \eta_{\mathrm{LCP}} \approx 4$. The data are fit to a constant plus a Gaussian for the back-to-back peak centered at $\Delta\phi = \pi$. The fit parameters are highly correlated, and their errors are from the full error matrix. The values do not depend on N_γ. The area S under the back-to-back peak is the probability that a LCP is correlated with a forward π^0. The area B under the constant represents contributions from the underlying event. The total coincidence probability per trigger π^0 is $S + B \approx 0.62(0.90)$ for $p + p$ (d + Au), and is constant with E_π. The ratio S/B for $p + p$ does not depend on midrapidity track multiplicity. The peak width has contributions from transverse momentum in hadronization and from momentum imbalance between the scattered partons.

A PYTHIA simulation [28] including detector resolution and efficiencies predicts most features of the $p + p$ data [29]. PYTHIA expects $S \approx 0.12$ and $B \approx 0.46$, with the back-to-back peak arising from $2 \to 2$ scattering, resulting in forward and midrapidity partons that fragment into the π^0 and LCP, respectively. The width of the peak is smaller in PYTHIA than in the data, which may be in part because the predicted momentum imbalance between the partons is too small, as was seen for back-to-back jets at the Tevatron [30].

The back-to-back peak is significantly smaller in d + Au than in $p + p$, qualitatively consistent with the monojet picture in the coherent scattering [13] and CGC [18] models. HIJING [31] uses a model of shadowing for nuclear PDFs. It predicts that the back-to-back peak in d + Au should be similar to $p + p$, with $S \approx 0.08$. The data are not consistent with the HIJING expectation at low E_π.

In conclusion, the inclusive yields of forward π^0 mesons from $p + p$ collisions at $\sqrt{s} = 200$ GeV generally agree with NLO pQCD calculations. However, by $\langle\eta\rangle = 4.00$, the spectrum is found to be harder than NLO pQCD, becoming suppressed with decreasing p_T. In d + Au collisions, the yield per binary collision is suppressed with increasing η, decreasing to ~30% of the $p + p$ yield at $\langle\eta\rangle = 4.00$, well below shadowing and multiple scattering expectations, as well as exhibiting isospin effects at these kinematics. The p_T dependence of the d + Au yield is consistent with a model which treats the Au nucleus as a CGC. Exploratory measurements of azimuthal correlations of the forward π^0 with charged hadrons at midrapidity show a recoil peak in $p + p$ collisions that is suppressed in d + Au at low E_π, as would be expected for monojet production. These effects are qualitatively consistent with a gluon saturation picture of the Au nucleus, but cannot definitively rule out other interpretations. A systematic program of measurements, including direct photons and dihadron correlations over a broad range of $\Delta\eta$, p_T, and $\sqrt{s}$, is needed to explore the nuclear modifications to particle production. A quantitative theoretical understanding of the observables is needed to facilitate experimental tests of a possible color glass condensate.

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