FORWARD PION PRODUCTION IN p+p AND d+Au COLLISIONS AT STAR

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Measurements are reported of the production of high energy $\pi^0$ mesons from the STAR experiment in p+p and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and $\langle \eta \rangle = 4.00$ (d beam direction). The inclusive yield agrees with perturbative QCD calculations in p+p collisions, but is reduced in d+Au collisions. The azimuthal correlations of the forward $\pi^0$ with charged hadrons at midrapidity agree with PYTHIA in p+p collisions, but are suppressed in d+Au collisions. The results are consistent with the conjecture that the gluon density in nuclei is suppressed.

1 Introduction

In contrast to the nucleon, very little is known about the density of gluons in nuclei. For protons, the gluon parton distribution function (PDF) is constrained primarily by scaling violations in deeply-inelastic lepton scattering (DIS) measured at the HERA collider. The data are accurately described by QCD evolution equations that allow the determination of the gluon PDF. It is found that the gluon PDF increases as the momentum fraction of the parton ($x_{Bj}$) decreases. In nuclei, the density of gluons per unit transverse area is expected to be larger than in nucleons. The interplay between large gluon densities and unitarity requirements on cross sections makes the nucleus a natural environment in which to establish if, and under which conditions, gluon saturation occurs. Quantifying gluon saturation is important because of the expectation that the nuclear matter created in central collisions of Au-Au nuclei evolves from an initial state produced by the collisions of the low-$x_{Bj}$ fields in each nucleus. Fixed target nuclear DIS experiments have reported a suppression of the inclusive structure function normalized to proton DIS at low-$x_{Bj}$, but are limited in the kinematic range necessary to determine the nuclear gluon PDF.

Many models exist which attempt to describe nuclear effects at low-$x_{Bj}$. Saturation models include a QCD based theory called the Color Glass Condensate (CGC), where gluon splitting is

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balanced by gluon-gluon recombination to create dense macroscopic fields. Another approach models quarks scattering coherently from multiple nucleons, leading to an effective shift in the \( x_{Bj} \) probes.\(^{6}\) Shadowing models suppress the nuclear gluon PDF in a standard factorization framework.\(^{9}\) Parton recombination models modify the fragmentation of a quark passing through many gluons.\(^{7}\) Other descriptions include factorization breaking in heavy nuclei.\(^{10}\) With the data presently available, the mechanism by which low-\( x_{Bj} \) gluon suppression occurs is unconstrained.

Using factorization in a perturbative QCD (pQCD) framework, the PDFs and fragmentation functions (FFs) measured in electromagnetic processes can be used in the description of hadronic scattering processes. In p+p collisions at \( \sqrt{s} = 200 \text{ GeV} \), factorized leading twist pQCD calculations have been shown to quantitatively describe inclusive \( \pi^0 \) production over a broad rapidity window.\(^{11,12}\) In pQCD, forward \( \pi \) production in p+p collisions can be viewed as a probe of low-\( x_{Bj} \) gluons (g) in one proton with the valence quarks (q) of the other. Recently, the yield of forward negatively charged hadrons (\( h^- \)) in the d-beam direction of d+Au collisions was found to be reduced when normalized to p+p collisions.\(^{13}\) The reduction is especially significant since isospin effects are expected to reduce \( h^- \) production in p+p collisions, but not in d+Au collisions.\(^{14}\) The \( h^- \) suppression in d+Au has been interpreted as gluon suppression at low-\( x_{Bj} \).

Insight on the particle production mechanism can be gained by analyzing the angular correlations of the forward hadron with a coincident hadron at midrapidity.\(^{15}\) A pQCD calculation of the parton kinematics probed in inclusive forward hadroproduction reveals a broad distribution in \( x_{Bj} \).\(^{16}\) Assuming collinear elastic parton (2 → 2) scattering, the pseudorapidity \( (\eta = -\ln(\tan(\theta/2))) \) of the second particle is correlated with \( x_{Bj} \) of the probed gluon, and a strong back-to-back azimuthal correlation is expected. In a saturation picture, the quark is expected to undergo multiple interactions through the dense gluon field, resulting in multiple recoil partons instead of a single recoil parton.\(^{17,18}\)

2 Experimental Results

The Solenoidal Tracker At RHIC (STAR) is a multipurpose detector at BNL. One of its principal components is a time projection chamber used for tracking charged particles produced at \( |\eta| < 1.2 \). A forward \( \pi^0 \) detector (FPD) comprising 7 × 7 matrices of 3.8 × 3.8 × 45 cm\(^3\) Pb-glass detectors was installed to detect high energy \( \pi^0 \) mesons with 3.3 < \( \eta < 4.1 \). Data were collected over two years of RHIC operations at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). In the 2002 run, p+p collisions were studied with a prototype FPD.\(^{11}\) In the 2003 run, p+p collisions were studied and exploratory measurements were performed with d+Au collisions.

The cross sections for \( p+p \rightarrow \pi^0 + X \), where \( \langle \eta \rangle = 3.3 \) and \( \langle \eta \rangle = 3.8 \), were reported previously. Preliminary results at \( \langle \eta \rangle = 4.0 \) are compared with NLO pQCD calculations in Fig.\(^{1} \) (left).\(^{18}\) The largest \( E_{\text{T}} \)-dependent systematic error at \( \langle \eta \rangle = 4.0 \) is the energy calibration, resulting in 0.08 < \( \delta E_{\pi}/E_{\pi} \) < 0.12. The absolute angle uncertainty is the largest contribution to the normalization error.\(^{19}\) The two curves use two sets of FF’s, differing primarily in the gluon-to-\( \pi^0 \) production.\(^{20}\) As \( p_T \) decreases, the data make the transition from consistency with KKP to consistency with Kretzer. This trend is also observed at midrapidity.\(^{12}\) At low \( p_T \), the dominant contributions to \( \pi^0 \) production are \( qg \) and \( gg \) scatterings, making \( D_{\pi}^g \) the dominant FF.\(^{21}\)

Nuclear effects on particle production are quantified by \( R_{\text{dAu}}^{X} \), the ratio of the inclusive yield of \( X \) in d+Au compared to p+p collisions normalized by the number of nucleon-nucleon collisions. This same measure was used at midrapidity, where it was found \( R_{\text{dAu}}^{h^0} \gtrsim 1 \).\(^{21}\) The solid circles in Fig.\(^{1} \) (right) are STAR preliminary data for \( R_{\text{dAu}}^{\pi^0} \) at \( \langle \eta \rangle = 4.0 \). On average, 0.5 more photons per event are observed in d+Au collisions than in p+p collisions for events with > 30 GeV detected in the FPD. This leads to the largest \( p_T \)-dependent systematic error.
Figure 1: Inclusive $\pi^0$ yield for p+p (left) and d+Au collisions normalized by p+p (right). The pion energy ($E_\pi$) is correlated with the transverse momentum ($p_T$), as the FPD was at fixed values of pseudorapidity ($\eta$). The inner error bars are statistical, while the outer combine these with the $E_\pi$ ($p_T$) dependent systematic errors, and are often smaller than the points. The curves (left) are NLO pQCD calculations evaluated at fixed $\eta$, using different fragmentation functions. The x’s and stars (right) are BRAHMS data for $h^-$ production at smaller $\eta$.

which comes from the background correction to the d+Au yield. The ratio $R_{dAu}^{\pi^0}$ at $\langle \eta \rangle = 4.00$ is significantly smaller than $R_{dAu}^{h^-}$ at smaller $\eta$, consistent with the trend expected from models which suppress the nuclear gluon density. \(^{6}\) Linearly extrapolating $R_{dAu}^{h^-}$ to $\eta = 4$, $R_{dAu}^{\pi^0}$ is systematically smaller, consistent with expectations of isospin suppression of $p + p \rightarrow h^- + X$\(^{14}\).

Exploratory measurements of the azimuthal correlations between a forward $\pi^0$ and midrapidity $h^\pm$ were completed for p+p and d+Au collisions. The data analysis and detailed comparisons to simulations were presented earlier.\(^{13}\) The left two plots in Fig. 2 are simulations, using PYTHIA 6.222\(^{23}\) for p+p and HIJING 1.38\(^{24}\) for d+Au collisions. The right two plots in Fig. 2 are data. The leading charged particle (LCP) analysis selects the midrapidity track with the highest $p_T$ > 0.5 GeV/c, and computes the azimuthal angle difference $\Delta \phi = \phi_{\pi^0} - \phi_{LCP}$ for each event. The normalized distributions are fit with the sum of a constant and a Gaussian centered at $\pi$. Correlations near $\Delta \phi = 0$ are not expected because of the large $\eta$ separation between the $\pi^0$ and the LCP. The fit values are the areas under both the back-to-back peak (S) and the constant (B), and the width of the peak ($\sigma_S$).
PYTHIA reproduces most features of the p+p data. The back-to-back peak arises from $2 \rightarrow 2$ scattering, resulting in forward and midrapidity jets that fragment into the $\pi^0$ and LCP, respectively. The width of the peak is smaller in PYTHIA than in the data, indicating that the momentum imbalance between the jets is too small in PYTHIA. This was also seen for back-to-back jets at the Tevatron.$^{25}$

The back-to-back peak is significantly smaller in d+Au collisions than in p+p, qualitatively consistent with the coherent scattering$^7$ and CGC$^{16}$ models. HIJING includes a model of shadowing for nuclear PDF’s, and predicts a sizable back-to-back peak. This is not observed in the preliminary STAR data. Complete assessment of systematic errors is underway.

In summary, inclusive forward $\pi^0$ cross sections from p+p collisions at $\sqrt{s} = 200$ GeV are consistent with NLO pQCD calculations. Azimuthal correlations of the forward $\pi^0$ with midrapidity $h^\pm$ are described by PYTHIA, which uses leading order pQCD with parton showers. The success of both of these calculations implies that forward $\pi^0$ production arises from partonic scattering in p+p collisions at $\sqrt{s} = 200$ GeV. In d+Au collisions, the inclusive yield of forward $\pi^0$ mesons is found to be significantly reduced compared to p+p. The $\eta$ dependence of the reduction is consistent with models which suppress the gluon density in nuclei, in addition to exhibiting isospin effects at these kinematics. Exploratory studies suggest that the back-to-back peak of forward $\pi^0$ mesons with midrapidity $h^\pm$ is suppressed in d+Au relative to p+p collisions. This is qualitatively consistent with expectations that the particle production in a dense gluon medium differs from conventional leading-twist NLO pQCD expectations. More data for forward particle production and di-hadron correlations in d+Au collisions are required to reach a definitive conclusion about the existence of gluon saturation in the Au nucleus, or if an alternative description of the forward rapidity suppression is valid. A quantitative theoretical understanding of the rapidity and $p_T$ dependence of di-hadron correlations would facilitate experimental tests of a possible color glass condensate.

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