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FORWARD PHYSICS AT STAR STATUS OF ANALYSIS ON FORWARD AND MID RAPIDITY CORRELATION MEASUREMENTS IN P+P AND D+AU

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Measurements of the production of high energy π^0 mesons at large pseudorapidity, coincident with charged hadrons at mid-rapidity, for proton+proton and deuteron+gold collisions at $\sqrt{s_{NN}} = 200$ GeV are reported. The p+p cross section for inclusive π^0 production follows expectations from next-to-leading order perturbative QCD. Both the inclusive cross section and the di-hadron azimuthal correlations are consistent with a model where parton showers supplement leading-order pQCD. A suppression of the back-to-back azimuthal correlations was observed in d+Au, qualitatively consistent with the gluon saturation picture.

It has been established from deep inelastic scattering (DIS) experiments that parton distribution functions (PDFs) are modified for nucleons bound in heavy nuclei. When the partons carry only a small fraction of the bound nucleon's momentum (Bjorken $x < 0.1$), nuclear PDFs are found to be smaller than nucleon PDFs[1]. This phenomenon is known as shadowing. Establishing a quantitative understanding of nuclear PDFs is an essential step towards understanding the dynamics of relativistic heavy ion collisions to address whether such collisions form a quark gluon plasma. Knowledge of nuclear gluon distribution functions is particularly important and is, at present, limited because of the limited range in resolution scale (Q^2) spanned by the world data on nuclear DIS. Studies of proton+nucleus collisions at large center of mass energies ($\sqrt{s_{NN}}$=200 GeV) can provide constraints to the gluon density in heavy nuclei.

In the perturbative QCD explanation of large-rapidity particle production, a large-x parton, typically a quark, scatters from a low-x parton and then fragments into the observed particle(s). Forward charged particle production is found to be suppressed in d+Au collisions [2], consistent with the expectation of gluon saturation [3,4], indicating a different mechanism for particle production. Explanations of the suppression based on leading-twist perturbative QCD calculations employing a model of gluon shadowing have also been suggested [5]. Further tests of the possible role played by gluon saturation at RHIC energies could be provided by the study of particle correlations [6]. If the gluon density in the incident heavy ion is saturated, the large-x parton from the deuteron is expected to undergo multiple interactions through the dense gluon field resulting in multiple recoil partons instead of a single recoil parton. Hence, back-to-back di-hadron azimuthal correlations for d+Au collisions are expected to be smaller than those in p+p collisions. Coherent multiple parton scattering can also modify di-hadron azimuthal correlations [7] which may

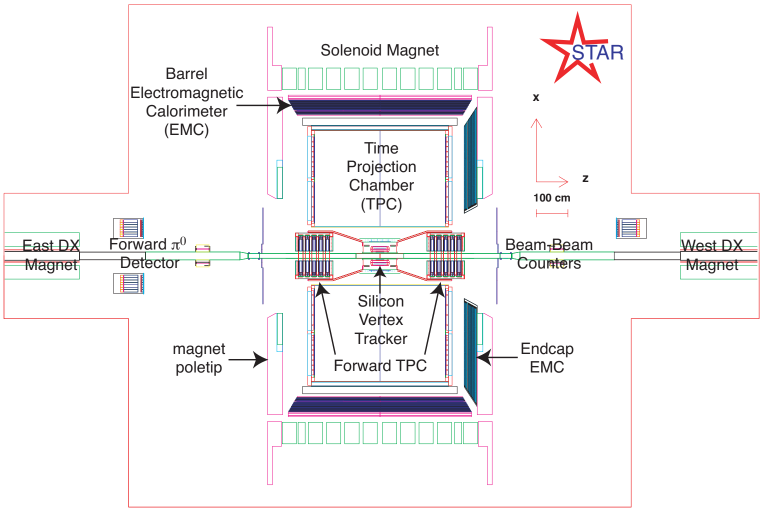

Figure 1. Top view of the STAR detector. The scale is such that displacements transverse to the beam (x) are two times larger than displacements along the beam (z).

be another approach to particle production in the presence of a saturated gluon distribution. Leading twist calculations of particle production including conventional shadowing do not result in modifications of di-hadron azimuthal correlations [8].

An important question to address is whether fixed-order pQCD is appropriate to describe forward particle production in p+p collisions at $\sqrt{s}$=200 GeV. For $\sqrt{s} \leq 62$ GeV, next-to-leading order pQCD severely underpredicts measured π^0 cross sections [9]. At $\sqrt{s}$=200 GeV and larger collision energies, there is quantitative agreement between NLO pQCD calculations and measured cross sections at mid-rapidity [10]. This agreement has been found to extend to π^0 production at $\langle\eta\rangle = 3.8$ [11]. Further tests of the underlying dynamics responsible for forward particle production can be obtained from the study of particle correlations. In particular, strong azimuthal correlations of hadron pairs are expected when particle production arises from $2 \rightarrow 2$ parton scattering, where in the hard scattering two initial-state partons scatter and result in two final-state partons. When a parton is scattered to fixed η, the pseudorapidity distribution of the recoil parton is quite broad and is given by the convolution of PDFs with the angular distribution for partonic scattering. Extending pQCD beyond leading order introduces $2 \rightarrow 3$ parton scattering that leads to a reduction of back-to-back azimuthal correlations of final-state hadron pairs. Similar effects are expected as the rapidity interval ($\Delta\eta$) between jet pairs increases [12].

This paper reports cross sections for forward inclusive π^0 production for p+p collisions at $\sqrt{s}$=200 GeV. The azimuthal correlations between a forward π^0 ($\langle\eta_\pi\rangle$=4.0) and mid-rapidity charged hadrons were studied. These measurements for p+p collisions allow us to test our understanding of the particle production mechanism. In addition, exploratory studies with d+Au collisions at $\sqrt{s_{NN}}$=200

GeV are reported, and azimuthal correlations of hadron pairs separated by large $\Delta\eta$ were compared to those for p+p collisions. Forward π^0 production in d+Au collisions refers to observation of the π^0 in the direction of the incident deuteron.

The Solenoidal Tracker At RHIC (STAR) is a multipurpose detector at Brookhaven National Laboratory. One of its principal components is a time projection chamber (TPC) embedded in a 0.5T solenoidal magnetic field used for tracking of charged particles produced at $|\eta| <1.2$. A forward π^0 detector was installed in STAR as shown in Fig. 1 to allow for the detection of high energy π^0 mesons at large rapidity. The FPD provides triggering and reconstruction of neutral pions produced with $3.3 < \eta < 4.1$. Data were collected over two years of RHIC operations. In the 2002 run, p+p collisions were studied with a prototype FPD. Details about triggering, event reconstruction and normalizations are available in Ref. [11]. In the 2003 run, p+p collisions were studied with the FPD and exploratory measurements were also performed for d+Au collisions.

The differential cross section for inclusive π^0 production for $30 < E_\pi < 55$ GeV at $\langle\eta\rangle = 3.8$ was previously reported [11]. The event reconstruction and normalization methods were extended to allow measurement of the differential cross section at $\langle\eta\rangle = 3.3$. The results are shown in Fig. 2 in comparison to NLO pQCD calculations evaluated at η=3.3 and 3.8 using CTEQ6M [13] parton distribution functions and equal renormalization and factorization scales of p_T. The NLO pQCD calculations are consistent with the data, in contrast to π^0 data at lower $\sqrt{s}$ [9]. The solid line was calculated using the "Kniehl-Kramer-Pötter" (KKP) set of fragmentation functions [14], while the dashed line uses the "Kretzer" set [15]. The difference between the two reflects the uncertainty in the fragmentation functions at these kinematics. At the chosen scale, the KKP fragmentation functions tend to agree with the data better than Kretzer, consistent with what has been observed for midrapidity π^0 data at $\sqrt{s} = 200$ GeV [10].

Correlations between a π^0 produced at large rapidity with large Feynman x ($x_F > 0.25$) and charged particles produced at $|\eta| < 0.75$ were also studied. The efficiency uncorrected average multiplicity of charged particles with $|\eta| <0.75$ and $p_T >0.2$ GeV/c for events coincident with a forward π^0 is 5.1 for p+p, and 14.4 for d+Au. This multiplicity is approximately 10% larger than what is observed for minimum-bias events. The leading charged particle (LCP) analysis selects the mid-rapidity track with the highest $p_T >0.5$ GeV/c in each event. The azimuthal angle difference $\Delta\phi = \phi_{\pi^0} - \phi_{LCP}$ is computed for each event. Distributions of $\Delta\phi$, normalized by the number of π^0 observed at $\langle\eta_\pi\rangle$=4.0, for two π^0 energy bins for p+p collisions are shown in Fig. 2. The left column of the figure shows simulations using PYTHIA 6.222 [16] that account for detector resolution and reconstruction efficiency for both the forward π^0 and the mid-rapidity charged particles. The right hand column are preliminary STAR data.

The normalized $\Delta\phi$ distributions were fitted by the sum of a constant and a Gaussian distribution centered at $\Delta\phi = \pi$. Correlations near $\Delta\phi = 0$ are not expected because of the large rapidity interval between the π^0 and the LCP. The fitted parameters are the area under the Gaussian distribution (S), representing the azimuthally correlated coincidence probability; the azimuthally uncorrelated coincidence probability (B); and the width of the Gaussian (σ), having contributions

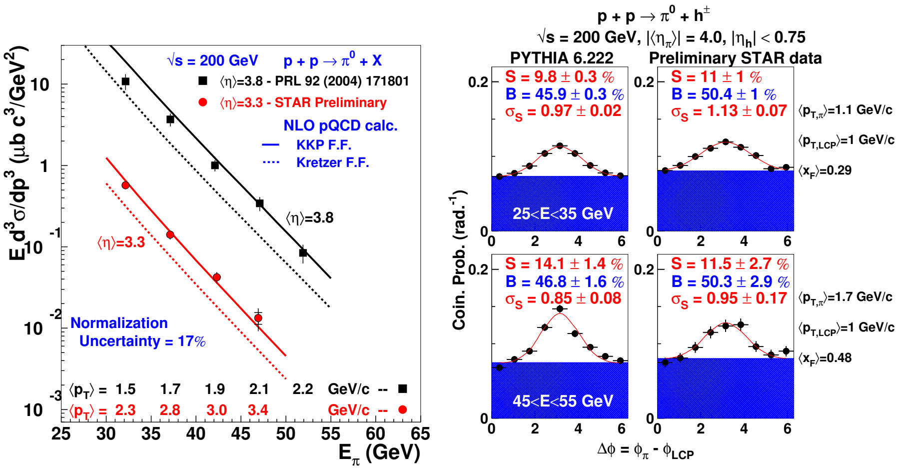

Figure 2. (*Left*) Inclusive π^0 production cross section versus leading π^0 energy (E_π) at average pseudorapidities ($\langle\eta\rangle$) 3.3 and 3.8. The average transverse momentum ($\langle p_T\rangle$) is correlated with E_π since the measurements were at a fixed η. The inner error bars are statistical, and are smaller than the symbols for most data points. The outer error bars combine these with E_π-dependent systematic errors added in quadrature. The curves are NLO pQCD calculations evaluated at $\eta =$ 3.3 and 3.8 using different fragmentation functions as described in the text. (*Right*) Coincidence probability as function of azimuthal angle difference between π^0 at forward rapidity ($\langle\eta\rangle$=4.0) and the leading charged particle at mid rapidity ($|\eta| < 0.75$, $p_T > 0.5$ GeV), in two different π^0 energy bins for p+p collisions at $\sqrt{s}$=200 GeV. The left column is for PYTHIA simulations and the right column is data. Fits to the data are described in the text. Error bars on the points represent only the statistical uncertainty.

from transverse momentum in the hadronization of the jets and the momentum imbalance between the pair of jets (k_T). The errors on the fitted parameters are based on the full error matrix.

The PYTHIA simulation reproduces most features of the p+p data. The azimuthally correlated di-hadron coincidence probability (S) can be identified in the PYTHIA simulation as arising from $2 \rightarrow 2$ parton scattering, resulting in a forward jet that fragments into the observed forward π^0 and a midrapidity recoil jet that fragments into the observed charged hadrons. The width of the correlation may be underestimated by PYTHIA indicating that the average k_T between the jet pair is too small. The azimuthally uncorrelated coincidence probability (B) primarily arises from $2 \rightarrow 3$ partonic processes, fully accounted for in NLO pQCD calculations, and approximately treated by initial- and final-state parton showers by PYTHIA. This interpretation is evident in the data when the azimuthal angle used in the correlation analysis is derived from the vector sum of the momenta of charged hadrons observed at midrapidity with p_T >0.2 GeV/c with a further condition that the magnitude of the vector sum exceeds 0.5 GeV/c. The azimuthally correlated coincidence probability is found to be $\sim$ 30% larger in such an analysis with a corresponding reduction in B.

An exploratory data set for forward π^0 production was obtained for d+Au

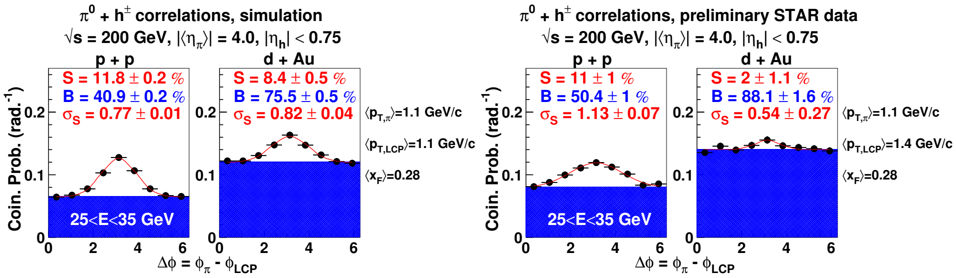

Figure 3. Coincidence probability as function of azimuthal angle difference between π^0 at forward rapidity ($\langle\eta\rangle = 4.0$) and leading charged particle at mid rapidity ($|\eta| < 0.75$, $p_T > 0.5$GeV). (*Left*) HIJING 1.381 simulations for p+p and d+Au collisions, including detector effects. HIJING has substantially smaller k_T compared to PYTHIA 6.222, and it gives smaller σ in p+p compared to PYTHIA (Fig. 2). (*Right*) STAR preliminary data for p+p and d+Au collisions.

collisions. For this data, the calibration of the FPD is, at present, known to only 10%. This prevents an accurate determination of the inclusive π^0 cross section for d+Au collisions. Work is underway to improve upon this calibration. The slow variation of the p+p$\rightarrow$ π^0 + $h^\pm$ correlations with π^0 energy suggests that similar observables in d+Au collisions should be relatively insensitive to calibration uncertainties. The normalized $\Delta\phi$ distribution for d+Au collisions, analyzed in the same way as the p+p data, is shown in comparison to p+p data in Fig. 3.

There is a large increase of $\mathrm{B_{dAu}}$ relative to $\mathrm{B_{pp}}$. This increase is also expected in default HIJING simulations [8], as shown in Fig. 3. HIJING models d+Au collisions using PYTHIA for inelastic nucleon-nucleon interactions and the Glauber model to account for multiple collisions. The growth in B arises when a nucleon from the deuteron beam interacts with multiple nucleons from the Au beam. The HIJING simulation does not predict a significant difference between the width $\sigma_{\rm dAu}$ relative to $\sigma_{\rm pp}$. For the data, the fitted $\sigma_{\rm dAu}$ is much smaller than $\sigma_{\rm pp}$, most likely reflecting the inadequacy of the functional form used to represent $\Delta\phi_{\rm dAu}$. The azimuthally correlated π^0 + $h^\pm$ coincidence probability is smaller in d+Au collisions than for p+p collisions. Part of the reduction is due to the fact that S is proportional to σ and the fit results in a width for $\Delta\phi_{\rm dAu}$ that is likely to be unphysically small. HIJING simulations, that include a model of shadowing for nuclear PDFs, predict a significant azimuthally correlated π^0 + $h^\pm$ coincidence probability. This is not observed in the preliminary STAR data.

The largest systematic uncertainty in the $\Delta\phi$ distribution is expected to be the present understanding of the calibration of the calorimeter. Simulation studies of the calorimeter response suggest that an improved understanding of the calibration can be obtained. The difference between $\mathrm{S_{pp}}$ and $\mathrm{S_{dAu}}$ is observed in several different methods of extracting an azimuthal angle from the charged particles observed with $|\eta|$ <0.75. The impact of the functional form used to represent the $\Delta\phi$ distribution is under investigation. Complete assessment of systematic errors is underway.

In summary, cross sections for the inclusive production of π^0 mesons in p+p collisions at $\sqrt{s}$=200 GeV, at $\langle\eta_\pi\rangle$=3.3 and 3.8 are found to be consistent with NLO pQCD calculations, in contrast to the situation at smaller $\sqrt{s}$. The azimuthal correlation between pairs of hadrons separated by large $\Delta\eta$ is described by a leading order pQCD calculation including parton showers [16] for p+p collisions. Agreement of these calculations with the inclusive cross sections and di-hadron correlations strongly suggest that forward π^0 production arises from partonic scattering at this collision energy. This agreement means that forward particle production can be exploited as a probe of low-x parton densities in p+Au or d+Au collisions at $\sqrt{s_{NN}}$=200 GeV. Within the conventional theoretical framework, the lowest x values can be reached when both hadrons are detected in the forward direction [17]. The possible existence of gluon saturation in the Au nucleus may modify the correlation between the recoil jet rapidity and the initial-state Bjorken x value. Exploratory studies of forward π^0 production in d+Au collisions suggest that the azimuthally correlated component of hadron pairs separated by large rapidity intervals is suppressed relative to what is observed for p+p collisions and from model calculations. This is qualitatively consistent with the 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 possible existence of a saturated gluon state in the Au nucleus. A quantitative theoretical understanding of the rapidity and p_T distribution of di-hadron correlations would facilitate experimental tests of a possible color glass condensate.

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