Future of low-x forward physics at RHIC

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Abstract. Comparisons of particle production from high-energy ion collisions with next-to-leading order perturbative QCD calculations show good agreement down to moderate transverse momentum values. Distributions of azimuthal angle differences between coincident hadrons in these collisions support a partonic origin to the particle production, again down to moderate transverse momentum values. The rapidity dependence of inclusive and coincident particle production can therefore be used to probe parton distribution functions down to small momentum fractions where theory anticipates that parton saturation could be present. This paper describes how such experiments could be completed.

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1 Introduction

Comprehensive measurements of pp, d+Au and Au+Au interactions at $\sqrt{s_{NN}}=200$ GeV by the RHIC experiments strongly suggest that the central collisions of two gold nuclei lead to a new form of matter that appears opaque to high transverse momentum ($p_T$) hadrons [1]. This dense matter evolves from an initial state produced by the collisions of the low-$x$ gluon fields of each nucleus [2]. Understanding this initial state is the first topic mentioned in a recent report on scientific opportunities in heavy-ion physics. “Upgraded forward instrumentation” was identified as needed to elucidate the properties of the initial state [3]. Nucleon gluon density distributions are determined by global fits to data [4,5], but the low-$x$ nuclear gluon distribution is not yet known [6,7]. The nuclear gluon field distribution might be naively expected to result from a convolution of the gluon density distributions of all the individual nucleons. However, there is indirect experimental evidence from RHIC [8] that the low-$x$ gluon distribution in a large nucleus like gold is reduced, or shadowed, from the nominal superposition of the distributions of the included protons and neutrons, a phenomenon described as saturation.

In this document we describe a possible measurement of the gluon distribution in a large nucleus by detecting pairs of particles, at least one of which is produced at large pseudorapidity ($\eta = -\ln \tan \theta/2$, where $\theta$ is the polar angle of the produced particle), created in d(p)+Au collisions at $\sqrt{s_{NN}}=200$ GeV. Such rapidity correlations are possible by supplementing an existing RHIC experiment with a forward detector. Space, resolution and cost considerations imply that electromagnetic calorimetry, capable of accurate reconstruction of particle 4-momenta (i.e., identified $\gamma$, $\pi^0$ or other mesons decaying to all photon final states) is the optimal approach to such experiments. It has also been proposed to instrument another interaction region at RHIC with a large acceptance detector [9]. Such an addition would also allow the study of rapidity correlations.

In the early runs at RHIC, we have demonstrated that forward electromagnetic calorimeters (Fig. 1), the Forward $\pi^0$ Detector (FPD), can be used to measure $\pi^0$ produced at large $\eta$ in pp and d+Au collisions at $\sqrt{s_{NN}}=200$ GeV at STAR [11]. We have recently proposed to assemble a Forward Meson Spectrometer (FMS) that will be operated during future RHIC running periods by the STAR collaboration to enable measurement of the gluon distribution, $xg(x)$, in nuclei in the range 0.001 $< x < 0.1$. The function $g(x)$ gives the differential probability to find gluons with a fraction $x$ of the longitudinal momentum of the parent nucleon (Fig. 2). The FMS will cover the range 2.5 $< \eta < 4.0$ and give STAR nearly hermetic electromag-
Measurements with transversely polarized protons that are expected to resolve the origin of the large transverse spin asymmetries in $p_T^+ + p \rightarrow \pi^0 + X$ reactions for forward $\pi^0$ production.

In $d+Au$ collisions, the FMS will face the deuteron beam and will see neutral pions produced by large-$x$ quarks in the deuteron interacting with the low-$x$ gluons in the Au nucleus. The key to this analysis is the detection of a second particle in coincidence with a triggering particle in the FMS. The coincident signal might be a high-$p_T$ track or jet detected in the TPCs or it might be a $\gamma$ or $\pi^0$ detected in the BEMC or EEMC. For $x < 0.01$, the coincident particle will be a second $\gamma/\pi^0$ detected in the FMS, whose large acceptance makes this coincidence measurement possible. The spatial dependence of the nuclear gluon density [14, 15] will be investigated by analyzing two-particle correlations as a function of particle multiplicity in the Au beam direction with the existing STAR subsystems.

Analysis of the kinematics of the relative momentum between the trigger particle and the coincident particle allows us to determine $g(x)$ in the gold nucleus under the simple assumption of elastic scattering of collinear initial-state partons. This measurement of the gluon density provides the essential input to the simulation codes that attempt to determine the energy density achieved when heavy nuclei collide, in the state which could expand to become the quark gluon plasma.

The same correlated particle analysis will allow us to study the physics of the parton saturation region, if it exists for $Q^2 < 4$ GeV$^2$. This physics is associated with the transformation from a parton-dominated picture of the nuclear gluon distribution to a picture for which macroscopic QCD fields might play a role or provide the most appropriate physics description. The FMS granularity will enable the measurement of the azimuthal angle ($\phi$) of the trigger pion and a coincident pion. The peak in the $\Delta\phi = \phi_{\pi_1} - \phi_{\pi_2}$ distribution at $180^\circ$, the classic signature of the trigger pion and a coincident pion. The peak in the $\Delta\phi = \phi_{\pi_1} - \phi_{\pi_2}$ distribution at $180^\circ$, the classic signature of the trigger pion and a coincident pion. The peak in the $\Delta\phi = \phi_{\pi_1} - \phi_{\pi_2}$ distribution at $180^\circ$, the classic signature of the trigger pion and a coincident pion.

The analysis of FMS-triggered events at STAR will also be used in polarized proton running where the extended calorimeter acceptance will greatly enhance our ability to determine how quark and gluon fields conspire to share the proton’s $\frac{1}{2}$ unit of spin. Polarized deep inelastic scattering (DIS) experiments found that the intrinsic spin of quarks and antiquarks contribute only $\approx 20\%$ to the nucleon spin, contrary to early theoretical expectations of $> 60\%$. A prime objective of the RHIC spin program is to understand how gluon and parton orbital angular momentum play a role in this “missing spin puzzle”. The correlated pion analysis of the FMS and the analysis channels it opens will play a crucial role in answering these questions and could lead to the resolution of the long-standing question about the origin of the large transverse single spin asymmetry in forward pion production.
2 Nuclear gluon densities

A central objective in high energy physics has been the systematic characterization of parton (quark and gluon) density distributions [4,5]. As a consequence of factorization theorems we know that there is a class of high-p_T two-parton (leading twist) experiments that can be understood in terms of an initial state of independent partons within a proton. Within this framework, the part of the cross section due to a particular sub-process is equal to the product of a calculable parton-level cross section and the two universal initial state parton probability densities

$$\sigma(x_n, x_m) \propto \sigma_{nm} f_n(x_n) f_m(x_m).$$

The parton densities $f(x)$ are universal properties of the proton, applicable in all hard scattering processes, and in most cases (but not all) refer to the positive definite probability density to find a parton “$n$” ($n = q$ for quark, $\bar{q}$ for antiquark and $g$ for gluon, with $f_{g}(x)$ referred to as $g(x)$) carrying a fraction “$x$” of the parent nucleon longitudinal momentum; $x$ is a kinematic variable in DIS. We combine contributions from all partonic sub-processes that lead to the same final state and account for contributions that come from all possible $x$ values by adding the partial cross sections.

The nucleon gluon distribution $xg(x)$ is known in the region $0.001 < x < 0.01$ (Fig. 2) but the nuclear distributions are not. Our present understanding of how parton distribution functions (PDFs) are changed when nucleons are bound in a nucleus is primarily derived from DIS of charged leptons from nuclear targets. The charged leptons used in DIS interact with the electrically charged quarks, not with the electrically neutral gluons, and provide measurements of structure functions, $F_1$. In the parton model, $F_2(x, Q^2) = x \sum_n e_n^2 g_n(x, Q^2) + \eta_g(x, Q^2)$, where $e_n^2$ is the squared electric charge of the quark of type $n$ and $Q^2$ is the squared four momentum transfer of the scattered lepton, equated to the square of the scale at which the parton substructures are observed. Gluon densities are determined from the QCD evolution equations [18] applied to scaling violations of $F_2$ measured for the nucleon over an extremely large $x$ and $Q^2$ range at the HERA collider [12,13]. Sensitivity to $g(x)$ in DIS is approximately given by the $Q^2$ variation of $F_2$ at half that $x$ value, $g(2x) \propto \partial F_2(x, Q^2)/\partial (\ln Q^2)$ [19]. The kinematic range of the world data for the gluon distribution in nuclear targets is shown in the right panel of Fig. 2 as used in a recent global analysis of nuclear modifications to PDFs [6,7]. Such input to the nuclear gluon density is available only for $x > 0.02$ because nuclear DIS has been restricted to fixed target experiments. As will be discussed below, the study of $d(p)+Au$ collisions at $\sqrt{s}_{NN}$=200 GeV can provide direct sensitivity to the nuclear modification of the gluon density for $x$ values on the order of $x \sim 0.001$ and can test the universality of the nuclear gluon density in the range $0.02 < x < 0.1$. Comparable sensitivity in DIS to such low $x$ would require an electron-ion collider [20]. Measuring the PDF with quark and gluon probes allows us to get to $x$ and $Q^2$ values where saturation phenomena might be present.

3 Tests of parton saturation

Factorization theorems allow us to add cross sections rather than quantum amplitudes, with partons considered quantum mechanically independent of each other. Within this picture, we are tempted to imagine that the gluon distribution of a nucleus might be obtained by adding the gluon distributions for each nucleon, with some accounting for the relative motion of the nucleons in the nucleus. While perhaps true for large $x$ processes, at small $x$ the uncertainty principle tells us that the partons will all overlap in the longitudinal direction, so the partons do not interact independently. The front surface partons will interfere or shadow the back surface partons of the nucleus. For more than 20 years it has been recognized [21] that the quantum independence of partons cannot extend to very small $x$ where the gluon density is very large.

To determine the scale at which collective behavior might become evident, the uncertainty principle suggests that a scattering process at fixed $p_T$ will probe a transverse area approximately given by $S(p_T) = \pi (\hbar/p_T)^2$. For example, at $p_T = 2$ GeV/$c$, this corresponds to about 0.3 mb, small in comparison to the proton cross sectional area of about 30 mb. The number of gluons that are present and that could shadow one another above $x$ is nominally given by $n_{\text{gluons}}(x) = \int_0^x g(x')dx'$. At $x=0.01$, $n_{\text{gluons}} \approx 7$, increasing by 7–8 for each order of magnitude decrease in the lower limit of $x$. At $x=0.001$, the product of cross section times number of gluons is $S(2\text{GeV}/c) \times n_{\text{gluons}}(0.001) \approx 5$ mb. This estimate suggests that for events with these kinematics, the chances of finding more than one gluon within the transverse resolution of the scattering probe is less than 20%. However, in a nucleus of mass number $A$, the area of the nucleus grows roughly as $A^{2/3}$ while the number of gluons would nominally grow proportionally to $A$. Thus, the transverse density of nucleons should grow by a factor like $A^{1/3}$. For Au, this factor of 6 in transverse density suggests that shadowing could be substantial. By $x=0.0001$, it could become dominant. Of course, at lower $p_T$, the effects would show up at a larger value of $x$. Real predictions for the onset of shadowing vary with the model used [24], but whether shadowing modifies the gluon interactions at RHIC is an experimental question which must be answered with data.

For pp collisions at $\sqrt{s}=200$ GeV, unlike at lower $\sqrt{s}$ [25], next-to-leading order (NLO) pQCD calculations [27] quantitatively describe inclusive $\pi^0$ production at midrapidity [26] down to $p_T \sim 2$ GeV/$c$ using PDFs [4, 5] and fragmentation functions [28,29] that describe the hadronization of the scattered partons. Furthermore, dihadron azimuthal correlations have the same structure at these moderate $p_T$ as they do at the highest possible $p_T$ values, consistent with the idea that elastic scattering of quarks and gluons is responsible for the particle production [30].

Recent measurements at STAR using the prototype FPD already indicate that the factorized leading twist pQCD calculations work quite well to predict the $p+p \rightarrow \pi^0 + X$ cross section in the $3 < \eta < 4$ region [11]. This gives confidence in the interpretation that at $\sqrt{s}=200$ GeV the
The onset of this phase can be probed by measurements at small $x$ and at small $Q$ (related to the produced parton mass and the $p_T$ associated with the scattering). Mapping out the boundaries (Fig. 4) for saturation signatures for back-to-back jet correlations as a function of $x$ and $p_T$ is a primary mission of the FMS.

**Fig. 3.** Left: pQCD calculation of $\pi^0 - \pi^0$ production at large $\eta$ in pp and d+Au collisions at $\sqrt{s_{NN}}=200$ GeV [35]. The distributions integrate to $d\sigma/dp_T$ in units of $\text{nb}/\text{GeV}$. The smallest $x$ values are probed when $\pi^0 - \pi^0$ pairs are detected at large $\eta$. Middle: PYTHIA [36] simulation for $\pi^0 - \pi^0$ production at large $\eta$ in pp collisions at $\sqrt{s}=200$ GeV. The $\eta$ of the associated $\pi^0$ is strongly correlated with the $x$ value of the soft parton involved in the partonic scattering. Right: HIJING simulation for $\pi^0 - \pi^0$ production at large $\eta$ in d+Au collisions at $\sqrt{s}=200$ GeV. Compared to the pp simulations, the peaks in $\Delta \phi = \phi_{\pi_1} - \phi_{\pi_2}$ corresponding to elastic parton scattering, sit atop a background from other mechanisms for particle production.

**Fig. 4.** Diagram showing the boundary between possible “phase” regions in the $\tau = \ln(1/x)$ versus $\ln(Q^2)$ plane [22]. BFKL evolution [23] results in expected exponential growth of the gluon density at fixed $Q^2$ and increasing $\tau$. DGLAP evolution is discussed in the text.
collisions, midrapidity particle production was found to have a small enhancement, consistent with the Cronin effect [40], and back-to-back correlations [41] more closely resembled results from pp collisions than from Au+Au collisions. Hence, the suppression of back-to-back correlations in Au+Au collisions was attributed to the strongly interacting matter formed in those collisions, matter that was formed by interactions of the low-\(x\) gluons.

Measurements made by the BRAHMS collaboration for d+Au collisions [8] showed that inclusive particle production was suppressed as the rapidity of the observed particles increased. This provided a hint that the gluon distribution in the Au nucleus may be depleted at low-\(x\).

It is easy to understand how this suppression can occur within the standard pQCD picture of particle production. In that picture, the quarks and gluons each carry a fraction of their parent hadron momentum given by \(x\). They elastically scatter and then fragment to the final state hadrons observed with a given \(p_T\) and at a given \(\eta\). For collinear parton pairs, it is easily shown that

\[
x_+ \approx \frac{p_T}{\sqrt{s}}(e^{+\eta_1} + e^{+\eta_2}) \rightarrow x_F
\]

where the Feynman-\(x\) variable is \(x_F = 2p_T/\sqrt{s}\), relevant in the limit \(\eta_1 >> \eta_2\), and \(p_T\) is the longitudinal momentum component of the large \(\eta\) particle. For inclusive particle production, one of the two jets, or its hadronic surrogates, is observed at \(\eta_1\) and the second jet has a broad \(\eta_2\) distribution and \(\Delta \phi \approx 180^\circ\). By detecting a high energy hadron at large \(\eta_1\), initial states with a large-\(x\) parton (most probably a quark) and a low-\(x\) parton (most probably a gluon) are selected. For each unit rapidity increase, the average \(x\) of the gluon from the initial state parent hadron is decreased by \(e\). A similar decrease in \(x\) is a consequence of studying particle production in collisions at higher \(\sqrt{s}\). Hence, the observed suppression of particle production at increasing rapidity can be interpreted as a reduction in the probability of finding gluons in the nucleus at small \(x\).

The BRAHMS results [8] were confirmed in measurements by PHENIX [42]. The STAR collaboration also made measurements of large rapidity particle production and produced a limited data sample for two-particle correlations involving a large rapidity \(\pi^0\) [30], measured with the FPD. The topology of the energy deposition in the FPD allows for robust measurements of the energy and direction of neutral pions. Since the \(\pi^0\) is a pseudoscalar particle, kinematic distributions of its diphoton decay are exactly calculable in any frame of reference. Hence, calibrations of the FPD response can be obtained at the level of \(~1\%) simply by requiring a fully consistent response of all cells of the calorimeter to the photons produced by the \(\pi^0 \rightarrow \gamma \gamma\) decay. This same technique will be used for the FMS. Figure 5 shows that the simulation code PYTHIA [36] is able to reproduce the absolute cross section of the produced \(\pi^0\) from pp collisions. In addition, nearly all features of the \(\Delta \phi\) distributions for charged hadrons with \(|\eta| < 0.75\) coincident with forward \(\pi^0\) are reproduced by PYTHIA. This gives us a tool to guide the design of the FMS and the interpretation of the data.

5 Proton spin with the FMS

Our understanding of the two-particle correlations involving large rapidity particles, and our ability to use these correlations to measure nuclear gluon distributions, is a direct result of the methodology developed to understand the first spin asymmetry measurements at RHIC. It is no surprise that the FMS will also be a powerful tool in studying the spin structure of the proton.

An early prediction of pQCD was that, at leading twist and with collinear factorization, the chiral properties of the theory would make the transverse single spin asymmetry (SSA) small for particles produced with transversely polarized proton beams [44]. The SSA is the product of the beam polarization and the analyzing power \((A_N)\), and is measured from the azimuthal asymmetry of particle yields from a transversely polarized beam incident on an unpolarized target. However, from AGS energies [45] to Fermi Lab energies [46] and most recently at STAR [11] (Fig. 5), a large SSA has been observed. The consistent trend is that the SSA in \(p_T + p \rightarrow \pi^0 + X\) increases rapidly for \(x_F \approx 0.3\). Transverse single spin asymmetries have also been observed in semi-inclusive DIS from polarized targets [47] and experimental studies of these spin effects is an active area of research. The FMS is ideally suited to extend these studies.

There are multiple phenomenological effects that have been identified as possible sources for the large SSA, but only two are expected to be significant. One is the Sivers effect [49,50], which is an initial state correlation between the parton intrinsic transverse momentum, \(k_T\), and the transverse spin of the nucleon, \(S \propto S_T \cdot (P \times k_T)\), where \(P\) is the beam momentum and \(S_T\) is the transverse proton spin. In the Sivers framework, the SSA is sensitive to the contribution of quark orbital angular momentum to the nucleon spin. A large SSA is the result of a spin dependent \(p_T\) trigger bias favoring events where \(k_T\) is in the same direction as \(p_T\). The dynamics within the Sivers model or of twist-3 contributions [48] responsible for the observed SSA may be more clearly understood via semi-classical gluon fields in the polarized nucleon [58].

If the Sivers effect is present, we can further characterize it with a measurement of the away side jet. The \(k_T\) of the initial-state parton can be measured when final-state jet pairs are not exactly back to back \((\Delta \phi = 180^\circ)\) [57]. The spin dependence of this \(k_T\) measurement is exactly what the Sivers model predicts.

While the Sivers effect connects the SSA to the orbital angular momentum of quarks, a second effect, called the Collins effect [51,52], is directly sensitive to the transversity distribution function [53,54], related to the transverse polarization of quarks (and antiquarks) in a transversely polarized proton [55]. Here the quark scatters, preserving its transverse spin, and then fragments into pions and other hadrons. The fragmentation function reveals the polarization of the fragmenting quark and thus the initial
quark state. In this example, the asymmetry does not appear in the jet production directly, but only in the fragmentation. The jet axis would not show the transverse asymmetry, but a pion fragment would. Recent calculations that include the full $k_T$ dependence in the convolution integrals provide some indication that the Collins effect may be small [56].

The FMS will be able to distinguish between these mechanisms. By looking at pairs of same-side neutral pions, we can measure the SSA as a function of the two pion kinematics. With the FMS we will separately measure the contribution to the SSA that comes from the jet axis versus that which comes from the jet structure. Many theory papers have studied this problem: however, the need for data is great. The FMS STAR experiments on transverse polarization will provide to theorists the necessary input to determine the relative contributions from the Sivers effect and the Collins effect.

### 6 FMS configuration

The STAR FPD now taking data acts as the prototype for the proposed FMS. Our results with the FPD demonstrate the feasibility of large rapidity measurements with electromagnetic calorimetry in both pp and d+Au collisions at $\sqrt{s_{NN}}=200$ GeV at RHIC. Each FPD calorimeter is a $7 \times 7$ matrix of 3.8 cm $\times$ 3.8 cm $\times$ 45 cm lead-glass cells that can be positioned in the range $3.3 < \eta < 4.0$. These are identical to the 684 small cells to be used in the FMS and the techniques we have developed for FPD tuning and analysis are directly applicable to the FMS. By implementing the FMS in STAR, the study of $\gamma - \pi^0$ and $\pi^0 - \pi^0$ correlations in both rapidity and azimuthal angles is enabled over $-1 < \eta < 4$. The FMS also allows inclusive measurements of $\pi^0$, $\gamma$ and the production of heavy mesons that decay to all $\eta$ final states over a broad range of $\eta$ and $p_T$. A schematic of the proposed FMS detector is shown in Fig. 6, along with examples of the mass resolution from a topological analysis [59] of the energy deposition for data obtained with the current FPD.

We expect to achieve 1% accuracy in the calibration of the FMS, just as we have done for the FPD. Energy resolution of $< 15\%/\sqrt{E}$ has been demonstrated. Simulation studies compare well to FPD data and show that we can expect to locate the $\pi^0$ to better than 0.5 cm (RMS). Our expected $\pi^0$ mass resolution is $\sim 23$ MeV/c$^2$ based on experience with the FPD. For neutral pions with $20 < E < 60$ GeV the reconstruction efficiency of the FPD is just given by geometry. To predict event yields, we used a very conservative estimate of 35% for reconstruction and geometric efficiency. The FMS will provide complete azimuthal coverage for the pseudorapidity interval $2.5 < \eta < 4.0$ and will be built from existing lead-glass cells.

### 7 Plan for measurements

We will concentrate on measurements directed at our three immediate physics goals for d+Au and for pp running. In a future d+Au run at $\sqrt{s}=200$ GeV we will determine the gluon distribution in the gold nucleus. The large acceptance of the FMS will provide good statistics for comparisons of identified $\pi^0$ yields in pp and d+Au collisions over a very broad range in $p_T$ and pseudorapidity. We will measure the correlations between a trigger particle in the FMS (either a $\pi^0$ or a $\gamma$) and a second particle (jet surrogate) in the TPC, BEMC, EEMC or FMS. The threshold $p_T$ for the trigger and coincident particles will be investigated over the range $1 < p_T < 4$ GeV/c. The large size and high granularity of the FMS allow us to identify neutral pions at energies down to $\sim 10$ GeV, where hadronic energy deposition becomes a significant background. At maximum rapidity, this determines our lowest observable $p_T$ threshold. As seen in Fig. 3, the $\eta$ of the coincident particle correlates with the gluon $x$ value. The $\Delta\phi$ distribution reveals the scattering history. To develop the full picture of the gluon distributions, we will investigate the dependence of $\pi^0 - \pi^0$ correlations on $Q^2$. To determine the dynamical origin (Sivers or Collins) of the observed transverse single spin asymmetry for forward $\pi^0$ produc-

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**Fig. 5.** Left: Invariant cross sections for inclusive $\pi^0$ production at large rapidity in pp collisions at $\sqrt{s}=200$ GeV [11,43] compared to NLO pQCD calculations [27–29]. Middle: The data are compared with predictions from PYTHIA [36]. Right: The analyzing power for $\pi^0$ production at $(\eta)=3.8$ in pp collisions at $\sqrt{s}=200$ GeV [11]. The curves are predictions from pQCD models [48,50,52] evaluated at $p_T=1.5$ GeV/c.
-produced at large rapidity. Both when both jets from the elastic parton scattering are pro-
over inelastic scattering [30] although both contributions
that the lowest \( x \) values for the gluon density are probed
out shadowing and \( \sim 1.8 \times 10^5 \) events in the peak for simulations done with shadowing. We can expect that a 10-week d+Au run will allow us to sample \( 6 \times 10^6 \) minimum-bias interactions, based on RHIC performance for d+Au collisions achieved in the last weeks of run 3. Accounting for detector efficiencies for the FMS and end-cap EMC, the simulations suggest we will observe at least \( 8 \times 10^4 \) events in the \( \Delta \phi \) peak without shadowing. This is enough to investigate the spatial dependence of the nuclear gluon density [14,15] using particle multiplicity measurements in the Au beam direction made by other STAR subsystems to determine the sensitivity to the impact parameter of the collision. Broadening or disappearance of the away-side correlation could signal the transition to a macroscopic gluon field at sufficiently low \( x \).

For the polarized proton running, we base estimates of the rate of near-side \( \pi^0 - \pi^0 \) pairs on PYTHIA [36]. The STAR measurements (Fig. 5) show that the SSA is small below \( x_F \sim 0.4 \), and increases monotonically as \( x_F \) of the forward \( \pi^0 \) increases. In the Sivers picture, the SSA should be associated with the forward jet and should be present for \( \pi^0 - \pi^0 \) pairs from the same jet. We would expect a large SSA when \( x_{F1} + x_{F2} > 0.4 \). When one \( \pi^0 \) is observed at \( 3 < \eta < 4 \) with \( x_{F1} > 0.25 \) and a second \( \pi^0 \) is observed with \( \eta < 4 \) and \( x_{F2} > 0.15 \) and the \( 0 - 0 \) pair has \( |\eta_1 - \eta_2| < 0.5 \), the simulated \( \Delta \phi \) correlation shows a jet-like near-side correlation peak sitting atop a uniform background attributed to the underlying event. We expect \( 1.5 \times 10^4 \) \( \pi^0 - \pi^0 \) events in the near-side jet-like peak for 1 \( \text{pb}^{-1} \) of integrated luminosity for polarized pp collisions at \( \sqrt{s} = 200 \text{ GeV} \) with the FMS. For a beam polarization of 50% this would result in a statistical error on the analyzing power of \( \Delta A_N \sim 0.01 \). The Collins mechanism attributes the SSA to the correlation between the momenta of two hadrons from the same jet and the proton spin vector. The transverse momentum associated with jet fragmentation producing a \( \pi^0 \) with \( x_{F1} > 0.4 \) and \( 3 < \eta < 4 \) can be measured by detecting a second \( \pi^0 \) with \( \eta < 4 \) and \( x_{F2} > 0.15 \) and requiring that the \( 0 - 0 \) pair has \( |\eta_1 - \eta_2| < 0.5 \). Again, the \( \Delta \phi \) correlation shows a jet-like near-side correlation peak sitting atop a uniform background. For these kinematics, we expect \( 2 \times 10^3 \) \( \pi^0 - \pi^0 \) pairs in the jet-like near-side \( \Delta \phi \) peak.
for 1 pb\(^{-1}\) of integrated luminosity. If a non-zero Collins effect is observed, then larger integrated luminosity samples would be required to map out the \(x\) dependence of the transversity structure function.

8 Summary

Early experimental results from RHIC, coupled with theoretical developments that demonstrate the robustness of NLO pQCD calculations at collider energies down to moderate \(p_T\) values, suggest that a quantitative determination of the gluon density in a heavy nucleus can be obtained at an order of magnitude lower \(x\) than available from DIS on nuclear targets. Such studies require improved instrumentation in the forward direction at RHIC. In addition to providing crucial information to understand the initial state of heavy-ion collisions that may lead to a quark-gluon plasma, future low-\(x\) studies at RHIC may establish the existence of a macroscopic gluon field. Improved forward instrumentation can also disentangle the dynamical origin of transverse single spin asymmetries.

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