

**Forward Neutral-Pion Transverse Single-Spin Asymmetries in  $p + p$  Collisions at  $\sqrt{s} = 200$  GeV**

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We report precision measurements of the Feynman  $x$  ( $x_F$ ) dependence, and first measurements of the transverse momentum ( $p_T$ ) dependence, of transverse single-spin asymmetries for the production of  $\pi^0$  mesons from polarized proton collisions at  $\sqrt{s} = 200$  GeV. The  $x_F$  dependence of the results is in fair

agreement with perturbative QCD model calculations that identify orbital motion of quarks and gluons within the proton as the origin of the spin effects. Results for the  $p_T$  dependence at fixed  $x_F$  are not consistent with these same perturbative QCD-based calculations.

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The production of particles with high transverse momentum from polarized proton collisions at high energies is sensitive to the quark ( $q$ ) and gluon ( $g$ ) spin structure of the proton. Perturbative QCD (pQCD) calculations are used to interpret spin observables when they can explain measured cross sections. The goal of measuring spin observables is to understand how the proton gets its spin from its  $q, g$  constituents.

One challenge to theory has been to understand the azimuthal asymmetry of particles produced in collisions of transversely polarized protons, known as analyzing power ( $A_N$ ) or transverse single-spin asymmetry. With vertical polarization, nonzero  $A_N$  corresponds to a left-right asymmetry of the produced particles. Sizable  $A_N$  are not expected in collinear pQCD at leading twist due to the chiral properties of the theory [1]. Nonetheless, large  $A_N$  are observed for inclusive pion production in  $p_1 + p$  collisions over a broad range of collision energies ( $\sqrt{s}$ ) [2–6] and in semi-inclusive deep inelastic scattering (SIDIS) from transversely polarized proton targets [7]. These observations have prompted extensions to pQCD that introduce transverse momentum dependence (TMD) correlated with the spin degree of freedom. For example,  $A_N$  could be generated by spin-correlated TMD fragmentation if there is transverse  $q$  polarization in a transversely polarized proton (“Collins effect”) [8]. This mechanism was considered to be suppressed for  $p_1 + p \rightarrow \pi + X$  until recently [9,10]. Spin-correlated TMD distribution functions (“Sivers functions”) [11,12] can explain large  $A_N$  [13]. These functions describe parton orbital motion within the proton, and thus are important for understanding the structure of the proton.

Although Sivers functions are extracted from SIDIS results, there is no proof [14] that they factorize in pQCD calculations of  $p_1 + p \rightarrow \pi + X$ . A factorized framework involving twist-3  $qg$  correlators has been introduced [15] and has successfully described [16] previous  $A_N$  results [4,6] for  $p_1 + p \rightarrow \pi + X$ . Of relevance to both approaches is a transverse momentum ( $k_T$ ) that is integrated over in inclusive processes. This  $k_T$  is intrinsic parton motion in the Sivers functions and its average is related to the inverse proton radius. Large  $k_T$  is where  $qg$  correlators are expected to provide a robust framework. Small  $k_T$  is where Sivers functions are expected to be applicable. Intermediate  $k_T$  values yield the same results in the two approaches, because moments of the Sivers functions are found to be related to the  $qg$  correlators [17,18].

Both theoretical frameworks [13,16] predict that  $A_N$  will increase as the longitudinal momentum ( $p_L$ ) of the pion increases, usually given by the Feynman  $x$ ,  $x_F = 2p_L/\sqrt{s}$ .

Both frameworks predict that, at fixed  $x_F$ ,  $A_N$  will decrease with increasing transverse momentum ( $p_T$ ), for  $p_T > 1.2 \text{ GeV}/c$ .

Analyzing powers in the hadroproduction of pions have been measured before, and typically show a strong increase as  $x_F$  increases [2–6]. Virtually no previous experimental results exist for the dependence of  $A_N$  on  $p_T$  at fixed  $x_F$ . For  $\sqrt{s} \leq 20 \text{ GeV}$ , the cross sections are at least 10 times larger than pQCD calculations for  $x_F$  values where  $A_N$  is sizable [19]. This led to the suggestion that beam fragmentation, the dissociation of the polarized proton by the unpolarized target, was responsible for the spin effects, and the expectation that at sufficiently large  $p_T$  these spin effects would vanish. At  $\sqrt{s} = 200 \text{ GeV}$ , inclusive  $\pi$  cross sections at central and forward rapidity are found to be in agreement with pQCD calculations above  $p_T \sim 2 \text{ GeV}/c$ , and are included with world data for  $\pi$  production from  $e^+e^-$  collisions, SIDIS, and other  $p + p$  collider results in a global analysis of fragmentation functions [20].  $A_N$  that increase with  $x_F$  are found at  $\sqrt{s} = 200 \text{ GeV}$  [6,21,22], but both precision measurements and the determination of the dependence on  $p_T$  have, until now, been missing.

In this Letter, we report precision measurements of the  $x_F$  dependence and first measurements of the  $p_T$  dependence of  $A_N$  at fixed  $x_F$  for  $p_1 + p \rightarrow \pi^0 + X$  at  $\sqrt{s} = 200 \text{ GeV}$ . The experiment has been performed at the Solenoidal Tracker at RHIC (STAR) [23] at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. The experiment was performed using vertically polarized colliding beams. Asymmetries are formed from yields measured with left-right symmetrical detectors, tagged by the polarization direction of one beam and summing over the polarization of the other beam. Positive  $x_F$  is probed by considering polarization of the beam heading towards the detectors and negative  $x_F$  is probed by considering polarization of the beam heading away from the detectors.

Measurements were carried out with a modular electromagnetic calorimeter, known as the forward pion detector (FPD), positioned at large pseudorapidity [ $\eta = -\ln(\tan\theta/2)$ ]. The  $\langle\eta\rangle = 4.0$  results, and some  $\langle\eta\rangle = 3.7$  results, reported here were obtained in the 2003 (2005) run having integrated luminosity  $L_{\text{int}} = 0.25 \text{ pb}^{-1}$  ( $0.1 \text{ pb}^{-1}$ ) and average beam polarization  $P_b \sim 35\%$  ( $50\%$ ).  $\langle\eta\rangle = 3.3$  and most of the  $\langle\eta\rangle = 3.7$  measurements were performed in the 2006 run, which resulted in  $L_{\text{int}} = 6.8 \text{ pb}^{-1}$  with  $P_b \sim 55\%$ . In the 2006 run, 111 of the 120 possible bunches of both RHIC rings, called “Blue” and “Yellow,” were filled with protons having predetermined

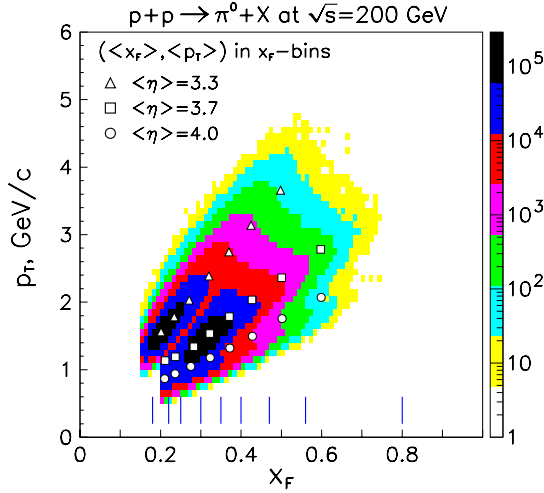


FIG. 1 (color online). Correlation between pion longitudinal momentum scaled by  $\sqrt{s}/2$  ( $x_F$ ) and transverse momentum ( $p_T$ ) for all events. Bins in  $x_F$  used in Figs. 2 and 4 are indicated by the vertical lines. There is a strong correlation between  $x_F$  and  $p_T$  at a single pseudorapidity ( $\langle\eta\rangle$ ).

patterns of polarization signs. The unfilled 9 bunches are sequential and correspond to the abort gap needed to eject the stored beams.  $P_b$  was measured every 3 h during RHIC stores by a polarimeter that detected recoil carbon ions produced in elastic scattering of protons from carbon ribbon targets inserted into the beams. The effective  $A_N$  of this polarimeter was determined from  $p_{\uparrow} + p_{\downarrow}$  elastic scattering from a polarized gas jet target [24] thereby determining  $P_b = 55.0 \pm 2.6\%$  ( $56.0 \pm 2.6\%$ ) for the Blue (Yellow) beam in the 2006 run [25].

The FPD comprises four modules, each containing a matrix of lead glass (PbGl) cells of dimension  $3.8 \text{ cm} \times 3.8 \text{ cm} \times 18$  radiation lengths. Pairs of modules were positioned symmetrically left ( $L$ ) and right ( $R$ ) of the beam line in both directions, at a distance of  $\sim 750 \text{ cm}$  from the interaction point [21]. The modules facing the Yellow (Blue) beam are square matrices of  $7 \times 7$  ( $6 \times 6$ ) PbGl cells. Data from all FPD cells were encoded for each bunch crossing, but only recorded when the summed energy from any module crossed a preset threshold.

Neutral pions are reconstructed via the decay  $\pi^0 \rightarrow \gamma\gamma$ . The offline event analysis included conversion of the data to energy for each cell, formation of clusters and reconstruction of photons using a fit with the function that parametrizes the average transverse profile of electromagnetic showers. Collision events were identified by requiring a coincidence between the east and west STAR beam-beam counters, as used for cross section measurements [26]. Events were selected when two reconstructed photons were contained in a fiducial volume, whose boundary excludes a region of width  $1/2$  cell at the module edges. Detector calibration was determined from the  $\pi^0$  peak position in diphoton invariant mass ( $M_{\gamma\gamma}$ ) distributions.

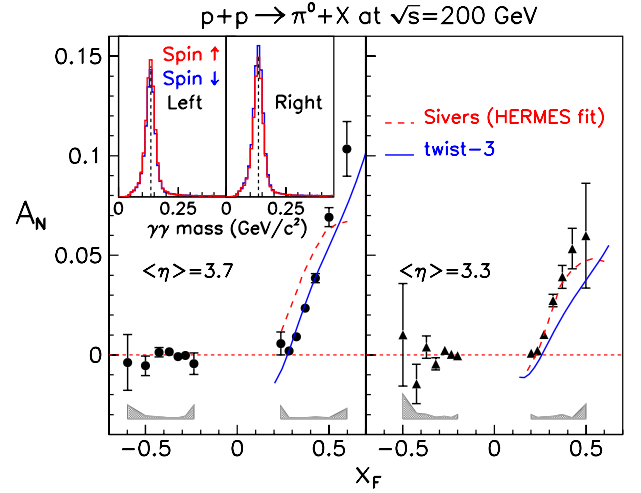


FIG. 2 (color online). Analyzing powers in  $x_F$  bins (see Fig. 1) at two different  $\langle\eta\rangle$ . Statistical errors are indicated for each point. Systematic errors are given by the shaded band, excluding normalization uncertainty. The calculations are described in the text. The inset shows examples of the spin-sorted invariant mass distributions. The vertical lines mark the  $\pi^0$  mass.

The estimated calibration accuracy is 2%. The analysis was validated by checking against full PYTHIA/GEANT simulations [27]. The reconstructed  $\pi^0$  energy resolution is given by  $\delta E_{\pi}/E_{\pi} \approx 0.16/\sqrt{E_{\pi}}$ .

Because of the limited acceptance there is a strong correlation between  $x_F$  and  $p_T$  for reconstructed  $\pi^0$  (Fig. 1). Spin effects in the  $x_F$ - $p_T$  plane are studied by positioning the calorimeters at different transverse distances from the beam, maintaining  $L/R$  symmetry for pairs of modules. Figure 1 shows loci from  $\langle\eta\rangle = 3.3, 3.7$ , and  $4.0$ . There is overlap between the loci, providing cross-checks between the measurements. Because the measurements were made at a colliding beam facility, both  $x_F > 0$  and  $x_F < 0$  results are obtained concurrently.

Events with  $0.08 < M_{\gamma\gamma} < 0.19 \text{ GeV}/c^2$  were counted separately by spin state from one or the other beam, with no condition on the spin state of the second beam, in the  $x_F$  bins shown in Fig. 1. For each run  $i$ ,  $A_{N,i}$  for each bin was then determined by forming a cross ratio

$$A_{N,i} = \frac{1}{P_b} \frac{\sqrt{N_{L\uparrow,i}N_{R\downarrow,i}} - \sqrt{N_{L\downarrow,i}N_{R\uparrow,i}}}{\sqrt{N_{L\uparrow,i}N_{R\downarrow,i}} + \sqrt{N_{L\downarrow,i}N_{R\uparrow,i}}}, \quad (1)$$

where  $N_{L(R)\uparrow(\downarrow),i}$  is the number of events in the  $L$  ( $R$ ) module when the beam polarization was up (down). Equation (1) cancels spin dependent luminosity differences through second order. Statistical errors were approximated by  $\Delta A_{N,i} = [P_b \sqrt{N_{L\uparrow,i} + N_{L\downarrow,i} + N_{R\uparrow,i} + N_{R\downarrow,i}}]^{-1}$ , valid for small asymmetries. All measurements of  $P_b$  for a store were averaged and applied to get  $A_{N,i}$  for each bin. The run-averaged  $A_N \pm \Delta A_N$  values are shown in Fig. 2.

Systematic errors potentially arise from several sources. The bunch counter, used for the spin directions, identifies events in the abort gaps arising from single-beam backgrounds. They account for  $<5 \times 10^{-4}$  of the observed yield. Systematic effects from gain variations with time are controlled by polarization reversals of the stored beam bunches, as demonstrated by examples of spin-sorted  $M_{\gamma\gamma}$  for  $L, R$  modules in the inset of Fig. 2. Distributions of the significance,  $S_i = (A_{N,i} - A_N)/\Delta A_{N,i}$ , are well described by zero mean value Gaussian distributions with  $\sigma$  equal to unity, as expected if the uncertainties are dominated by statistics, except near the trigger threshold where larger  $\sigma$  is observed. Systematic errors are estimated from  $\sigma \times \Delta A_N$  and differences in  $A_N$  associated with  $\pi^0$  identification, with the largest value chosen. The upper limit on a correlated systematic error, common to all points, arising from instrumental effects is  $\delta A_N \approx 4 \times 10^{-4}$ .

The same pair of modules concurrently measure  $A_N$  values consistent with zero for  $x_F < 0$  and  $A_N$  that increases with  $x_F$  for  $x_F > 0$ , depending on which beam spin is chosen. Null results at  $x_F < 0$  are natural since a possible gluon Sivens function is probed where the unpolarized gluon distribution is large. For  $x_F > 0$ , a calculation [13,28] using quark Sivens functions fit [29] to SIDIS data [7] best describes our results at  $\langle\eta\rangle = 3.3$ . Twist-3 calculations [16] that fit  $p_1 + p \rightarrow \pi + X$  data at  $\sqrt{s} = 20$  GeV [4] and preliminary RHIC results from the 2003 and 2005 runs at  $\sqrt{s} = 200$  GeV [21,22] best describe the data at  $\langle\eta\rangle = 3.7$ . Both calculations are in fair agreement with the variation of  $A_N$  with  $x_F$ . Neither calculation describes data at both  $\langle\eta\rangle$ .

Events from modules at different  $\langle\eta\rangle$  that overlap in the  $x_F$ - $p_T$  plane (Fig. 1) provide consistent results. Hence, it is possible to further bin the results not only by  $x_F$  but also by  $p_T$ . For this analysis,  $p_T$  is determined from the measured energy, the fitted position of the  $\pi^0$  within an FPD module, and the measured position of the module relative to the beam pipe and to the collision vertex. The  $z$  component of the event vertex uses a coarse time difference between the east and west beam-beam counters, and is determined to  $\sim 20$  cm resulting in  $\Delta p_T/p_T = 0.04$ , where  $\Delta p_T$  is the uncertainty in  $p_T$ . One method of determining the  $p_T$  dependence (Fig. 3) was to select events with  $|x_F| > 0.4$ .  $A_N$  is consistent with zero for  $x_F < -0.4$ . For  $x_F > 0.4$ , there is a hint of an initial decrease of  $A_N$  with  $p_T$ , although the statistical errors are large, since  $\langle\eta\rangle = 4.0$  data were only obtained in the 2003 and 2005 runs with limited integrated luminosity and polarization. For  $p_T > 1.7$  GeV/c,  $A_N$  tends to increase with  $p_T$  for  $x_F > 0.4$ . This is contrary to the theoretical expectation that  $A_N$  decreases with  $p_T$ .

The results in Fig. 3 may still reflect small correlations between  $x_F$  and  $p_T$  for each point, rather than the dependence of  $A_N$  on  $p_T$  at fixed  $x_F$ . To eliminate this correlation, event selection from Fig. 1 was made in bins of  $x_F$ ,

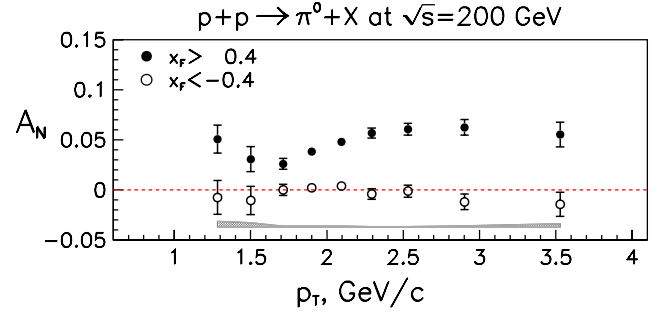


FIG. 3 (color online). Analyzing powers versus  $\pi^0$  transverse momentum ( $p_T$ ) for events with scaled  $\pi^0$  longitudinal momentum  $|x_F| > 0.4$ . Errors are as described for Fig. 2.

followed by bins in  $p_T$ . The resulting variation of  $A_N$  with  $p_T$  is shown in Fig. 4, compared to calculations [13] using a Sivens function fit to  $p_1 + p \rightarrow \pi + X$  data [4] and twist-3 calculations [16]. For each point, the variation of  $\langle x_F \rangle$  is smaller than 0.01. There is a clear tendency for  $A_N$  to increase with  $p_T$ , and no significant evidence over the measured range for  $A_N$  to decrease with increasing  $p_T$ , as expected by the calculations. This discrepancy may arise from unexpected TMD fragmentation contributions,  $x_F$ ,  $p_T$  dependence of the requisite color-charge interactions, evolution of the Sivens functions, or from process dependence not accounted for by the theory.

In summary, we have measured the  $x_F$  and  $p_T$  dependence of the analyzing power for forward  $\pi^0$  production in  $p_1 + p$  collisions at  $\sqrt{s} = 200$  GeV in kinematics ( $0.3 < x_F < 0.6$  and  $1.2 < p_T < 4.0$  GeV/c) that straddle the region where cross sections are found in agreement with pQCD calculations. The  $x_F$  dependence of the  $\pi^0$   $A_N$  is in

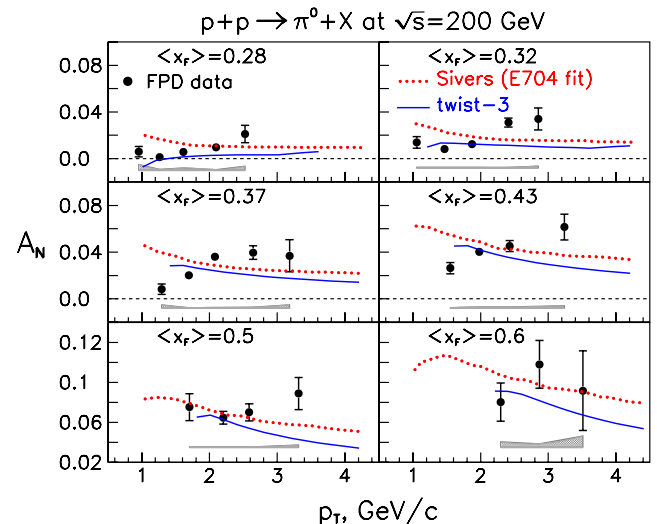


FIG. 4 (color online). Analyzing powers versus  $\pi^0$  transverse momentum ( $p_T$ ) in fixed  $x_F$  bins (see Fig. 1). Errors are as described for Fig. 2. The calculations are described in the text.

fair agreement with both a collinear twist-3 calculation and a calculation assuming factorization that attributes the spin effects to spin-correlated intrinsic transverse momentum of the quarks within the proton. Recent theoretical work interrelates these descriptions. Both calculations expect the spin effects to monotonically decrease with increasing  $p_T$  for  $p_T > 1.2$  GeV/ $c$ . Measurements of the  $p_T$  dependence at fixed  $x_F$  of  $A_N$  are not consistent with these expectations. This may reflect the presence of additional mechanisms for these spin effects. Future measurements capable of disentangling TMD fragmentation and distribution function contributions to  $\pi^0$  spin effects, and measurements of  $A_N$  for real and virtual photon production sensitive to only Sivers contributions, are required to definitively establish if partonic orbital motion is the correct explanation of these effects.

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