Single Spin Asymmetries of Identified Hadrons in $p^{\uparrow}+p$ at $\sqrt{s} = 62.4$ and 200 GeV

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Measurements of x_F-dependent single spin asymmetries (SSA) of identified charged hadrons, $\pi^{\pm}$, $K^{\pm}$, p, and $\bar{p}$, from transversely polarized proton collisions at $\sqrt{s} = 200$ and 62.4 GeV at RHIC are presented. The energy and flavor dependent asymmetry measurements bring new insight into the fundamental mechanisms of transverse spin asymmetries and the description of hadronic structure by Quantum Chromodynamics (QCD).

1 Introduction

Transverse spin dependence of hadron cross-setions in $p^{\uparrow}p$ ($\bar{p}^{\uparrow}p$) reactions at the energy regime where perturbative QCD (pQCD) is applicable are expected to be negligibly small in the lowest-order QCD approximation, whereas experimentally large asymmetries have been observed for large Feynman-x, $x_F = 2p_L/\sqrt{s}$. The main theoretical focus in accounting for the observed SSAs in the framework of QCD has been on the role of transverse momentum dependent (TMD) partonic effects in the structure of the initial transversely polarized nucleon [5] and on the fragmentation process of a polarized quark into hadrons [6]. Higher twist effects ("twist-3") arising from quark-gluon correlation effects beyond the conventional twist-2 distribution have been also considered as a possible origin of SSAs [7, 8]. Recently, new measurements of SSAs have been available from semi-inclusive deep-inelastic scattering (SIDIS) [9, 10] and $p^{\uparrow}+p$ at RHIC, providing more insight into the fundamental mechanisms of SSA as well as the relevant hadron structure [11, 12].

We present measurements of SSAs for $\pi^{\pm}$, $K^{\pm}$, p, and $\bar{p}$ at forward rapidities covering high-x_F at $\sqrt{s} = 62.4$ GeV and also at $\sqrt{s} = 200$ GeV. A simultaneous description of SSAs and the unpolarized cross-sections [13] in a wide kinematic range will be a crucial test for a partonic pQCD description. In particular, flavor dependent SSA measurements allow more complete and stringent tests of theoretical models due to the flavor dependence of parton distribution functions and fragmentation processes.

2 SSA Measurements at high-x_F

The SSA is defined as a "left-right" asymmetry of produced particles from the hadronic scattering of transversely polarized protons off unpolarized protons. Experimentally the asymmetry can be obtained by flipping the spins of polarized protons, and is customaryly defined as the analyzing power A_N:

$$A_N = \frac{1}{\mathcal{P}} \frac{(N^+ - \mathcal{L}N^-)}{(N^+ + \mathcal{L}N^-)}, \tag{1}$$

where $\mathcal{P}$ is the polarization of the beam, $\mathcal{L}$ is the spin dependent relative luminosity ($\mathcal{L} = \mathcal{L}_+/\mathcal{L}_-$) and $N^{+(-)}$ is the number of detected particles with beam spin vector oriented up (down).

The average polarization of the beam $\mathcal{P}$ as determined from the on-line CNI measurements is about 50% for RHIC Run-5 (200 GeV) and about 60% for Run-6 (62.4 GeV). The systematic error on the A_N measurements is estimated to be 20% including uncertainties from the beam polarization ($\sim$18%). The systematic error represents mainly scaling uncertainties on the values of A_N. The data presented here were collected with the BRAHMS detector system [14] in polarized $p+p$ collisions from Run-5 with a recorded integrated luminosity corresponding to 2.4 pb^{-1} at $\sqrt{s}$ = 200 GeV and from Run-6 with a recorded integrated luminosity of 0.21 pb^{-1} at $\sqrt{s}$ = 62.4 GeV. The kinematic coverage of the data taken with BRAHMS-FS at 2.3° and 4° for $\sqrt{s}$ = 200 GeV and at 2.3° and 3° for $\sqrt{s}$ = 62.4 GeV as a function of p_T and x_F are shown in Fig. 1.

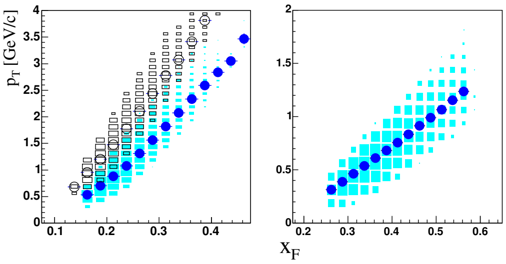
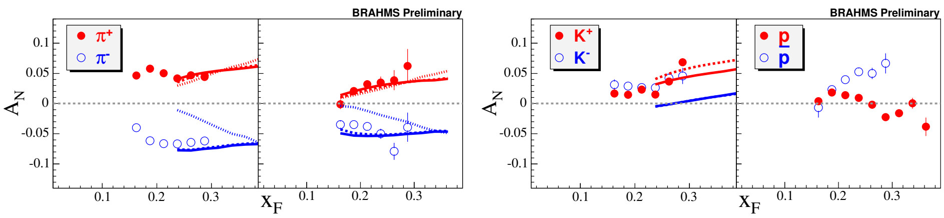


Figure 1: p_T vs. x_F for the data used in the SSA analysis at $\sqrt{s}$ = 200 GeV (left Panel). The open symbols are for FS at 4° and closed boxes are at 2.3° at full field setting. At $\sqrt{s}$ = 62.4 GeV (right panel), data from FS at 2.3° and 3° are combined. Mean values of p_T at a given x_F value are displayed as circles.

3 Results

The analyzing power A_N for charged pions, $A_N(\pi^+)$ and $A_N(\pi^-)$ at $\sqrt{s}$ = 200 GeV as a function of x_F are shown in Fig. 2 for the two FS angle settings with p_T coverages shown in Fig. 1. The A_N values are positive for π^+ and negative for π^- decreasing with p_T. The asymmetries and their x_F-dependence are qualitatively in agreement with the measurements from E704/FNAL [3] and also the $A_N(\pi^0)$ measurements at RHIC [11]. The $1/p_T$ dependence might indicate that A_N is in accordance with the expected power-suppressed nature of A_N [15]. Figure 2 compares $A_N(\pi)$ with a pQCD calculation in the range of



(a) A_N vs. x_F for $\pi^{\pm}$

(b) A_N vs. x_F for $K^{\pm}$, p and $\bar{p}$

Figure 2: A_N vs. x_F for pions (a) and for $K^{\pm}$, p and $\bar{p}$ (b) at $\sqrt{s}$ = 200 GeV. Pions are measured using the FS at 2.3° (left panel) and 4° (right panel), and kaons and protons are measured at 2.3°. The curves are from the twist-3 calculations with (line) and without (broken) sea- and anti-quark contributions. The predictions from the Sivers effect are shown as dotted lines. Errors are statistical only.

$p_T > 1$ GeV/c using "extended" twist-3 parton distributions [7] including "non-derivative" contributions [15, 16]. In this framework, two calculations are compared with the data: two valence densities (u_v,d_v) in the ansatz with and without sea- and anti-quark contribution in the model fit. The calculations describe the data within the uncertainties. The dominant contribution to SSAs are from valence quarks and sea- and anti-quark contributions are small that the current measurements are not able to quantitatively constrain the contribution. The data are also compared with the Sivers mechanism, which successfully describes FNAL/E704 A_N data. The calculations compared with the data use valence-like Sivers functions [17, 18] for u and d quarks with opposite sign. The fragmentation functions used are from the KKP parameterization [19], but the Kretzer fragmentation functions [20] gives similar results. The calculations shown with dotted lines in the figure underestimate A_N for both p_T ranges, which indicates that TMD parton distributions are not sufficient to describe the SSA data at this energy. In valence-like models (no Sivers effect from sea-quarks and/or gluons), non-zero positive $A_N(K^-)$ implies large non-leading fragmentation functions (D_u^{K-}, D_d^{K-}) and insignificant contribution from strange quarks. Twist-3 calculations also undershoot $A_N(K^-)$ due to the small contribution of sea and strange-quark contributions to A_N in the model. In Fig. 2, protons show no significant asymmetries compared to anti-protons, but require more understanding of their production mechanism to theoretically describe their behavior, because a significant fraction of the protons might still be related to the polarized beam fragments under the constraint of baryon conservation at this kinematic range.

The analyzing power A_N for charged pions in $p^\uparrow+p$ collisions at $\sqrt{s} = 62.4$ GeV as a function of x_F is shown in Fig. 3 with p_T coverages as shown in Fig. 1. For positive x_F the measured A_N values show strong dependence on x_F reaching large asymmetries up to $\approx 40\%$ at $x_F \approx 0.6$. In $p^\uparrow + p$ collisions, SSAs at $x_F < 0$ probe the kinematics of the sea (gluon) region of $p^\uparrow$ at small-x and the valence region of p. The measured insignificant A_N for $x_F < 0$, where $\hat{u} \to 0$, indicates that A_N is dominated by processes where $\hat{t}$ is small, and it shows no significant contribution to A_N from processes where gq scattering is enhanced. Compared with twist-3 calculations for $p_T > 1$ GeV/c, A_N for π^+ and π^- are in agreement qualitatively, while predictions based on the Sivers effect especially undershoot the π^- data. Similarly as for the 200 GeV data, strangeness asymmetries at 62.4 GeV, $A_N(K^-)$, need an extra or a different mechanism to account for positively non-zero $A_N(K^-)$ at a similar level of $A_N(K^+)$ as shown in Fig. 3.

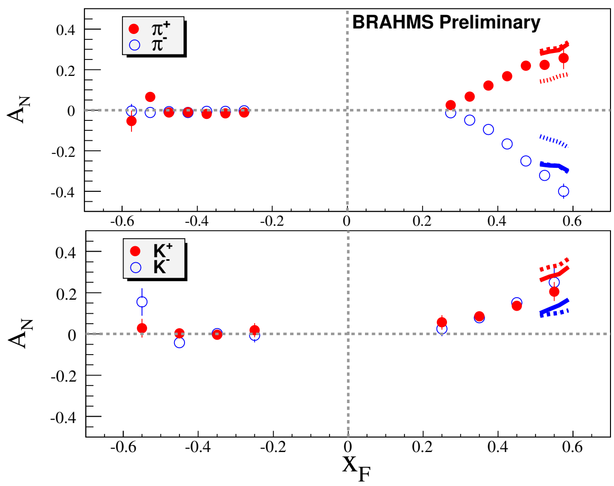


Figure 3: A_N vs. x_F for $\pi^\pm$ and $K^\pm$ at $\sqrt{s}$ = 62.4 GeV for positive and negative x_F. See Fig.2 for descriptions of the curves shown.

4 Summary

In summary, BRAHMS has measured SSAs for inclusive identified charged hadron production at forward rapidities in $p^{\uparrow}+p$ at $\sqrt{s} = 200$ GeV and 62.4 GeV. A twist-3 pQCD model of A_N describes the x_F dependence of $A_N(\pi)$ and the energy dependence for $p_T > 1$ GeV/c where the calculations are applicable. However, it is a challenge for pQCD models to consistently describe spin-averaged cross sections at lower energies. Measurements of A_N for kaons and protons suggest the manifestation of non-pQCD phenomena and/or call for more theoretical modeling with good understanding of the fragmentation processes. The energy and flavor dependent SSA measurements of identified hadrons allow more complete and stringent tests of theoretical models of partonic dynamics in the RHIC energy regime.

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