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 $p\uparrow + p$  at  $\sqrt{s} = 62.4$  and 200 GeV*

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# 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 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 Quantum Chromodynamical description of hadronic structure.

## 1 Introduction

Transverse spin dependence of hadron cross-sections in  $p^\uparrow p$  ( $\bar{p}^\uparrow p$ ) reactions at the energy regime where 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- $x$ ,  $x_F = 2p_L/\sqrt{s}$ . Main theoretical focuses to account for the observed SSAs in the framework of QCD have been on the role of transverse momentum dependent (TMD) partonic effects in the structure of the initial transversely polarized nucleon [4] and the fragmentation process of a polarized quark into hadrons [5]. 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 SSA [6, 7]. Recently, new measurements of SSAs have been available from semi-inclusive deep-inelastic scattering (SIDIS) [8, 9] and  $p^\uparrow + p$  at RHIC providing more insight into the fundamental mechanisms of SSA as well as the relevant hadron structure [10, 11].

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 [12] in a wide kinematic range will be a crucial test for partonic pQCD description. In particular, flavor dependent SSA measurements allow more complete and stringent tests of theoretical models due to flavor dependence in 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 customary defined as analyzing power  $A_N$ :

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

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 [13] in polarized  $p + p$  collisions from Run-5 with recorded integrated luminosity corresponding to  $2.4 \text{ pb}^{-1}$  at  $\sqrt{s} = 200 \text{ GeV}$  and from Run-6 with recorded integrated luminosity of  $0.21 \text{ pb}^{-1}$  at  $\sqrt{s} = 62.4 \text{ GeV}$ . The kinematic coverage of the data taken with BRAHMS-FS at  $2.3^\circ$  and  $4^\circ$  for  $\sqrt{s} = 200 \text{ GeV}$  and at  $2.3^\circ$  and  $3^\circ$  for  $\sqrt{s} = 62.4 \text{ GeV}$  as a function of  $p_T$  and  $x_F$  are shown in Fig. 1.

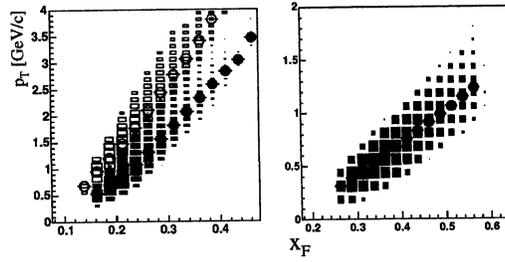


Figure 1:  $p_T$  vs.  $x_F$  for the data used in the SSA analysis at  $\sqrt{s} = 200 \text{ GeV}$  (left Panel). The open symbols are for FS at  $4^\circ$  and closed boxes are at  $2.3^\circ$  at full field setting. At  $\sqrt{s} = 62.4 \text{ GeV}$  (right panel), data from FS at  $2.3^\circ$  and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

### 3 Results

The analyzing power  $A_N$  for charged pions,  $A_N(\pi^+)$  and  $A_N(\pi^-)$  at  $\sqrt{s} = 200 \text{ GeV}$  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  $\pi^+$  and negative for  $\pi^-$  decreasing with  $p_T$ . The

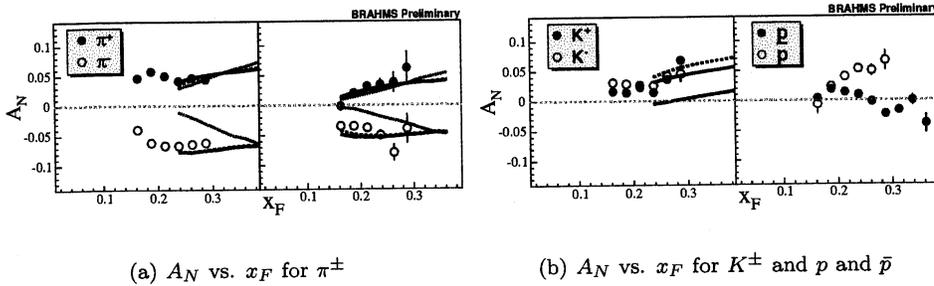


Figure 2:  $A_N$  vs.  $x_F$  for pions (a) and for  $K^\pm, p$  and  $\bar{p}$  (b) at  $\sqrt{s} = 200 \text{ GeV}$ . Pions are measured using FS at  $2.3^\circ$  (left panel) and  $4^\circ$  (right panel), and kaons and protons are measured at  $2.3^\circ$ . The curves are from the twist-3 calculations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

asymmetries and their  $x_F$ -dependence are qualitatively in agreement with the measurements from E704/FNAL [2] and also  $A_N(\pi^0)$  measurements at RHIC [10]. The  $1/p_T$  dependence might indicate that  $A_N$  is in accordance with the expected power-suppressed nature of  $A_N$  [14]. Figure 2 compares  $A_N(\pi)$  with a pQCD calculation in the range of  $p_T > 1 \text{ GeV}/c$

using “extended” twist-3 parton distributions [6] including the “non-derivative” contributions [14, 15]. In this framework, two calculations from the model are compared with the data: two valence densities ( $u_v, d_v$ ) in the ansatz with and without sea- an anti-quark contribution in the model fit. The calculations describe the data within the uncertainties. As the calculations shown in the figure, the dominant contribution to SSAs are from valence quarks and sea- and anti-quark contributions on SSAs are small that the current measurements are not able to quantitatively constrain the contribution. The data are also compared with Siverson mechanism which successfully describe FNAL/E704  $A_N$  data. The calculations compared with the data use valence-like Siverson functions [16, 17] for  $u$  and  $d$  quarks with opposite sign. The fragmentation functions used are from the KKP parameterization [18], but the Kretzer fragmentation function [19] 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 the energy. In valence-like model (no Siverson 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 under-predict  $A_N(K^-)$  due to the small contribution of sea and strange-quark contribution 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 the 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  $x_F$  are shown in Fig. 3 with  $p_T$  coverages as shown in Fig. 1. The measured  $A_N$  values show strong dependence in  $x_F$  reaching large asymmetries reaching up to  $\sim 40\%$  at  $x_F \sim 0.6$ . 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  $A_N$  in  $x_F < 0$ , where  $\hat{u} \rightarrow 0$ , indicate that  $A_N$  is dominated by the process where  $\hat{t}$  is small, and 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  $\pi^+$  and  $\pi^-$  are in agreement qualitatively while Siverson effect under-predicts especially for  $\pi^-$ . Similarly as for the 200 GeV data, strangeness asymmetries at 62.4 GeV,  $A_N(K^-)$  needs an extra or a different mechanism to account for positively non-zero  $A_N(K^-)$  at similar level of  $A_N(K^+)$  as shown in Fig. 3.

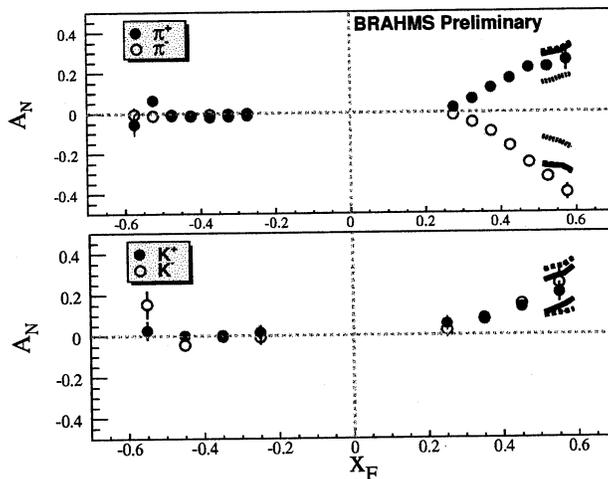


Figure 3:  $A_N$  vs.  $x_F$  for  $\pi^\pm$  and  $K^\pm$  at  $\sqrt{s} = 62.4$  GeV for positive and negative  $x_F$ . See Fig.2 for descriptions of the curves shown.

## 4 Summary

In summary, BRAHMS has measured SSAs for inclusive identified charged hadron production at forward rapidities in  $p^\dagger+p$  at  $\sqrt{s} = 200$  GeV and 62.4 GeV. A twist-3 pQCD model of  $A_N$  describes  $x_F$  dependent  $A_N(\pi)$  and their energy dependence at high  $p_T$  ( $p_T > 1$  GeV/ $c$ ) where the calculations are applicable, but it's challenging for pQCD models consistently describe spin-averaged cross section at lower energies. Measurements of  $A_N$  for kaons and protons suggest the manifestation of non-pQCD phenomena and/or a 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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