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

J.H. Lee and F. Videbæk for the BRAHMS Collaboration *

Brookhaven National Laboratory - Physics Department
Upton, NY 11973 - U.S.A.

Measurements of cross-sections and transverse single spin asymmetries of identified charged hadrons at forward rapidities from transversely polarized proton collisions at $\sqrt{s} = 200$ GeV are presented. The results are discussed in the context of interplay between perturbative and non-perturbative QCD effects.

1 Introduction

Despite decades of experimental and theoretical efforts, the exact nature of spin structure of the nucleon still remains elusive. One of the puzzles is the origin of the large transverse Single Spin Asymmetries (SSAs) at large-$x_F(=2p_L/\sqrt{s})$ observed in a wide range of energies in $p^{\uparrow}+p$ ($\bar{p}^{\uparrow}+p$) collisions [2], whereas SSAs are expected to be suppressed and may rise only as an $\mathcal{O}(1/p_T)$ effect at leading-twist in massless perturbative QCD (pQCD) [3]. Recently, new measurements of SSAs have been available from semi-inclusive deep-inelastic scattering (SIDIS) [4, 5] and $p^{\uparrow}+p$ at RHIC [6, 7]. They provide more opportunities for stringent tests for the pQCD inspired theoretical models to get insight into the fundamental mechanisms of SSA as well as the relevant hadron structure. Main theoretical focuses to account for the recently observed SSAs at high energies in the context of pQCD have been on the role of partonic transverse momentum effects in the structure of the initial transversely polarized nucleon [8], and the fragmentation process of a polarized quark into hadrons [9]. Higher twist effects arising from quark-gluon correlations have also been considered as a possible origin of SSA [10]. These theoretical models have been successful in describing some aspects of SSAs, but there still remains challenges of characterizing all transverse spin phenomena in the context of pQCD, which is in good agreements with unpolarized or spin-averaged cross-sections at RHIC. In spite of the theoretical progresses and efforts, it is still conceivable that the spin degree of freedom even at the RHIC energy domain, where $\sqrt{s} \gg \Lambda_{QCD}$, is not dominated by pQCD phenomena and substantially driven by contribution from non-pQCD effects [11].

In these proceedings, we discuss the SSA measurements by BRAHMS at forward rapidities covering high-x_F where large SSAs have been observed in $p^{\uparrow}+p$ at $\sqrt{s} = 200$ GeV at RHIC. The discussion is focused on p_T, flavor, multiplicity, and energy dependence of SSAs in the context of possible signatures of non-pQCD effect of transverse spin phenomenon.

2 Validation of pQCD at RHIC: Spin-averaged cross-sections

The invariant identified charged hadron spectra in $p+p$ at $\sqrt{s}$=200 GeV are shown in Fig. 1. The spectra are normalized to $\approx$ 41mb of the total inelastic cross-section. The data have

*This work was supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

been corrected for the geometrical acceptance of the spectrometer, multiple scattering, loss of tracks due to weak decays, and absorption in the material along the path of the detected particles. The spectra are not corrected for feed-down from the weak decays of K_s^0, $\Lambda, \bar{\Lambda}$ and higher mass hyperons mainly due to unknown hyperon yields at forward rapidities. In Fig. 1, data are also compared with the QCD-inspired Monte-Carlo model, PYTHIA [12]. The data and PYTHIA descriptions for the mesons in the all measured rapidities are in a good agreement.

A significant disagreement in describing protons at forward rapidities calls for better theoretical understanding of the baryon production mechanism, in particular the transport mechanism since a significant fraction of the protons in the fragmentation region might still be related to the protons transported at the measured kinematic range. Comparisons to the other pQCD calculations, including next-to-leading-order pQCD calculations to the BRAHMS measurements have been made previously [13, 14]. The comparisons have shown that the calculations for the meson production are also in good agreements down to $p_T{\sim}1$ GeV/c to the data at mid- and forward rapidities. That confirms that in this energy regime pQCD is applicable for the un-polarized particle productions at RHIC in particular at high-rapidity region where large SSAs have been measured.

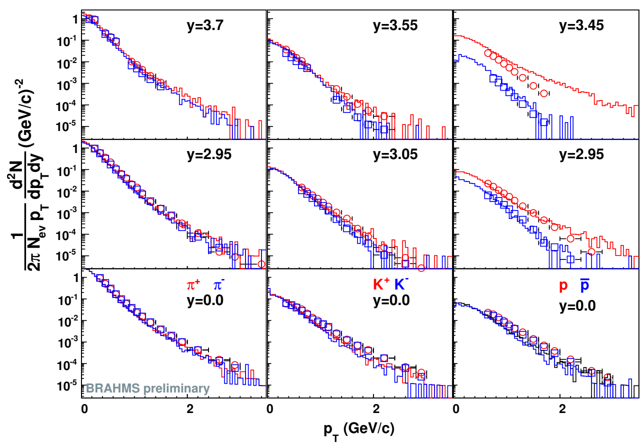


Figure 1: Invariant spectra for $\pi^{\pm}$ (left), $K^{\pm}$ (middle), and $p, \bar{p}$ (right) at 3 different rapidities indicated in each panel at $\sqrt{s} =$ 200 GeV. Positive and negative particles are displayed with circles and squares, respectively. The spectra are compared with PYTHIA calculations.

3 Single Spin Asymmetry Measurements at high-x_F

The SSA in $p + p$ collisions is defined as a “left-right” asymmetry of produced particles from the hadronic scattering of transversely polarized protons, and is customary defined as analyzing power A_N:

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

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 CNI measurements is about 50% for RHIC Run-5. The systematic error on the A_N measurements is estimated to be ~10% including uncertainties from the beam polarization (~6%). The systematic error represents mainly scaling uncertainties on the values of A_N. The data presented here were collected with the BRAHMS detector system [15] in polarized $p+p$ collisions from Run-5 with recorded integrated luminosity corresponding to 2.4 pb^{-1} at $\sqrt{s} = 200$ GeV. The kinematic coverage of the data taken with BRAHMS Forward Spectrometer at 2.3° and 4° for $\sqrt{s} = 200$ GeV as a function of p_T and x_F can be found in [16].

4 p_T-dependent Single Spin Asymmetries

One of the strong indications that SSAs are in accordance with pQCD description can be power-suppressed nature of A_N, which should be realized in the data as an decrease of SSAs with p_T. Fig. 2 shows $A_N(\pi^+)$ and $A_N(\pi^-)$ as a function of x_F for 5 different p_T regions from 0.5 to 2.5 GeV/c. The measurements exhibit no clear systematic p_T-dependence of SSAs in the measured kinematic range. The absence of consistent $1/p_T$-dependence in the data is similar to what was reported by STAR in $p+p \rightarrow \pi^0 + X$ [17] in the same reaction. It is possibly due to a non-trivial interplay between soft and hard processes in the measured kinematic region complicated by limited acceptance coverage of the experiment.

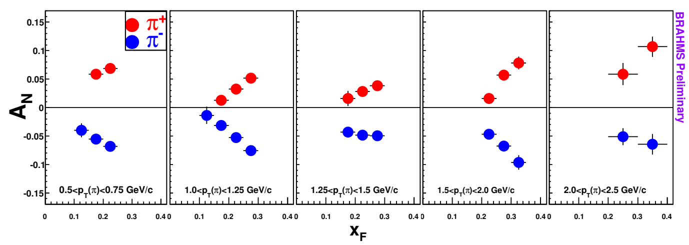


Figure 2: A_N vs. x_F for π^+ and π^- at $\sqrt{s} = 200$ GeV at fixed p_T values: $0.5 < p_T < 0.75$, $1. < p_T < 1.25$, $1.25 < p_T < 1.5$, $1.5 < p_T < 2.0$, and $2.0 < p_T < 2.5$ GeV/c, respectively.

5 Flavor-dependent Single Spin Asymmetries

Since partonic description of SSAs are expected to be sensitive mainly to the valence content of the particles measured, flavor dependence of asymmetries will provide strong constraints to the theoretical description of SSAs. The SSAs for $K^{\pm}$, and $p, \bar{p}$ as a function of x_F are shown in Fig. 3. The asymmetries for $K^+(u\bar{s})$ is positive as is the A_N of $\pi^+(u\bar{d})$, which is expected if the asymmetry is mainly carried by valence quarks, but the measured positive SSAs of $K^-(\bar{u}s)$ seem to contradict the näive expectations [18] of valence quark dominance in the SSA producing mechanism. In a valence-like model (no Sivers effect from sea-quarks and/or gluons), non-zero positive $A_N(K^-)$ implies large non-leading fragmentation functions ($D_u^{K^-}$,

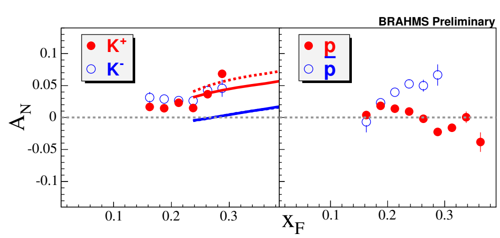
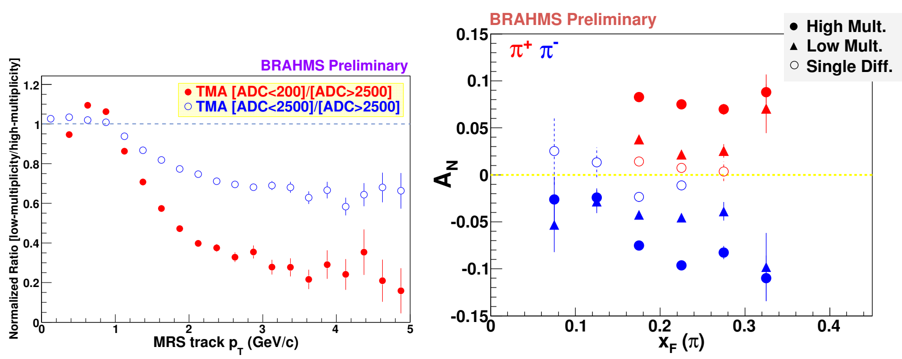


Figure 3: A_N vs. x_F for $K^{\pm}$ (left), and p and $\bar{p}$ (right) at $\sqrt{s} = 200$ GeV. The curves are from the twist-3 calculations with (solid line) and without (broken line) sea- and anti-quark contribution.

$D_d^{K^-}$) and insignificant contribution from strange quarks. Twist-3 calculations [19] shown in the figure also under-predict $A_N(K^-)$ due to the small contribution of sea and strange-quark contribution to A_N in the model. This non-vanishing SSAs for K^- is consistent with the measurements in $p+p$ at $\sqrt{s} = 62.4$ GeV [7], but not with the preliminary results by HERMES, where large SSAs for K^+ were observed while SSAs for K^- were consistent with zero in SIDIS [20]. In Fig. 3, anti-protons which carry no valence quark show also significant positive A_N as for K^-, but protons show no significant asymmetries in contrast to pions and kaons in the same kinematic region. The insignificant observed asymmetries of protons are consistent with the measurements at lower energies [21, 22].



(a) (b)

Figure 4: (a) Ratio of the p_T spectra for charged hadrons at y∼0. Spectra for the lowest-multiplicity (solid circles) and middle-multiplicity (circles) are divided by the spectrum for the highest-multiplicity. (b) Multiplicity-dependent $A_N(\pi^{\pm})$ for the highest-multiplicity (solid circle), lowest-multiplicity (solid triangles), and single diffractive events (circles).

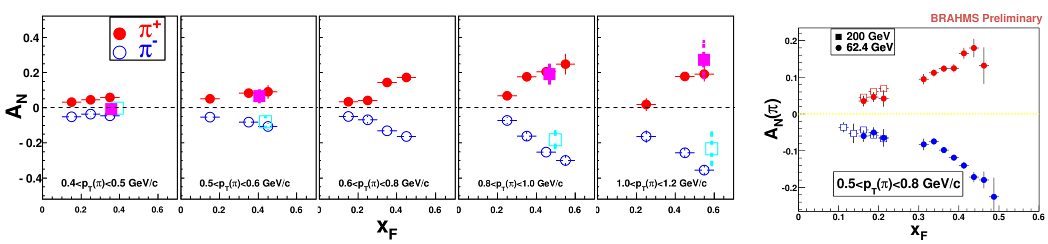
6 Multiplicity-dependent Single Spin Asymmetries

Particle multiplicity in $p+p$ carries information on the collision dynamics, and is expected to be sensitive to the impact parameter and "hardness" of the collisions. Since ∼10% [23] of $dN/d\eta$ near mid-rapidity estimated to be originated from hard processes in $p+p$ at $\sqrt{s} = 200GeV$, spectra for high multiplicity events are expected to be hard, i.e. have higher $\langle p_T \rangle$. Multiplicity of the event was selected utilizing the Tile Multiplicity Array (TMA) [24], which measured charged particles in $-2 < \eta < 2$. The data were divided into three multiplicity classes: lowest, middle, and highest multiplicity events. Fig. 4(a) shows the ratios of normalized yields of lowest- and middle-multiplicity class events divided by the highest-multiplicity events reconstructed by Mid-Rapidity Spectrometer (MRS) [15] at y∼0. The ratio of lowest/highest multiplicity as function of p_T is very similar as what has been observed by STAR [25] of 1-track/9-track events.

Figure 4(b) shows SSAs for the highest-multiplicity and the lowest-multiplicity events. The figure also shows SSAs for the highly single diffractive enriched process. Single diffractive events are from a process with a large rapidity gap between the backward beam rapidity and the forward rapidities characterized by excluding events with a hit(s) in backward "CC" detector [7] which measured charged particles in $-3.25 > \eta > -5.25$ and also no hits in TMA. The multiplicity dependent SSAs show that events with more produced particles give stronger asymmetries for pions. The strong dependence of pion SSAs on the multiplicity can imply that the asymmetries are likely originated from hard collisions, but also suggests that there might be significant non-pQCD effects in play such as the collision geometry and the energy conservation in the collision process.

7 Collision Energy-dependent Single Spin Asymmetries

As the collision energy increases, more pQCD applicable processes are expected to be dominating the mechanism responsible for generating transverse SSAs. Energy dependent asymmetry measurements are then expected to provide some insight on how the mechanism responsible for SSAs changes. Figure 5(a) shows comparison of charged pion asymmetries measured at $\sqrt{s} = 19.4$ [26] and 62.4 GeV [7] and Fig. 5(b) shows two measurements at 62.4 GeV [7] and 200 GeV where the two measurements kinematically overlaps at $0.5 < p_T(\pi) < 0.8$ GeV/c. The asymmetries and their x_F-dependence are qualitatively in agreement with the measurements from E704/FNAL [26]. It is noted that the p_T range for the comparison might be too low for applying pQCD. Contrary to the observation that there is no significant energy dependence in SSAs for pions in $p(\bar{p}) + p$ as shown in Fig. 5, significantly different SSAs have been measured depending on the energy in SIDIS by HERMES [4] and COMPASS [5]. The energy independence of SSAs in $p(\bar{p}) + p$ indicates that transverse SSAs are unlikely dominated by partonic processes at the measured kinematic region and not mainly driven by a process independent factorized process.



(a) (b)

Figure 5: (a) A_N vs. x_F for π^+ and π^- at $\sqrt{s} = 62.4$ GeV (circles) [7] at fixed p_T values of $0.4 < p_T < 0.5$, $0.5 < p_T < 0.6$, $0.6 < p_T < 0.8$, $0.8 < p_T < 1.0$, and $1.0 < p_T < 1.2$ GeV/c, and compared with A_N at $\sqrt{s} = 19.4$ GeV (squares) [27]. (b) Comparisons of $A_N(\pi^{\pm})$ at $\sqrt{s}$=62.4 and 200 GeV at $0.5<p_T<0.8$ GeV/c.

8 Summary

Transverse SSAs and cross-sections for inclusive identified charged hadron production at forward rapidities in $p^{\uparrow}+p$ at $\sqrt{s} = 200$ GeV have been measured in BRAHMS at RHIC. The cross-section measurements show that the energy regime is pQCD applicable as the spin-averaged cross-section data were described by the pQCD inspired models in a wide range of rapidity. The measured p_T, flavor, multiplicity and energy dependent SSAs of identified hadrons suggest the manifestation of non-pQCD phenomena in the mechanism driving SSAs. The differential SSA results allow more complete and stringent tests of theoretical models describing spin degree of freedom in the context of pQCD and non-pQCD in the RHIC energy regime.

References

[1] Slides: `http://indico.cern.ch/materialDisplay.py?contribId=322&sessionId=4&materialId=slides&confId=53294`

[2] For a review, see V. Barone, A. Drago, and P.G. Racliffe, Phys. Rept. 359 1 (2002), V. Barone and P.G. Ratcliffe "Transverse Spin Physics", World Scientific (2003).

[3] G.L. Kane, J. Pumplin and W. Repko, Phys. Rev. Lett. **41** 1689 (1978).

[4] A. Airapetian *et al.*, (HERMES Collaboration) Phys. Rev. Lett. **94** 012002 (2005).

[5] V.Y. Alexakhin *et al.*, (COMPASS Collaboration) Phys. Rev. Lett. **94** 202002 (2005).

[6] J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **92** 171801 (2004).

[7] I. Arsene *et al.*, Phys. Rev. Lett. **101**, 042001 (2008).

[8] D. Sivers, Phys. Rev. **D41** 83 (1990).

[9] J.C. Collins, Nucl. Phys. **B396** 161 (1993).

[10] J. Qiu and G. Sterman, Phys. Rev. **D59** 014004 (1999).

[11] A.E. Dorokhov, N.I. Kochelev, and W.-D. Nowak, arXiv:0902.3165 (2009), and references therein.

[12] PYTHIA Version 6.4. T. Sjöstrand, S. Mrenna, and P. Skands, JHEP **05** 026 (2006).

[13] I. Arsene *et al.*, Phys. Rev. Lett. **98**, 252001 (2007).

[14] D. de Florian, R. Sassot, and M. Stratmann, Phys. Rev. **D76** 074033 (2007).

[15] M. Adamczyk *et al.* (BRAHMS Collaboration), Nucl. Instr. Meth. **A499** 437 (2003).

[16] J.H. Lee and F. Videbæk, Proceedings of the 15th International Workshop on Deep-Inelastic Scattering and Related Subjects, April 2007, Munich, Germany.

[17] B.I. Abelev *et al.* (STAR Collaboration), Phys. Rev. Lett. **101** 222001 (2008).

[18] M. Anselmino *et al.*, Phys. Lett. **B442** 470 (1998).

[19] C. Kouvaris *et al.*, Phys. Rev. **D74** 1104013 (2006).

[20] M. Diefenthaler *et al.* (HERMES Collaboration), arXiv:0706.2242 (2007).

[21] S. Saroff *et al.*, Phys. Rev. Lett. **64** 995 (1990).

[22] V. Abramov *et al.*, Proc. of 16th International Spin Physics Symposium, SPIN2004, Oct. 2004, Trieste, Italy.

[23] B.I Abelev *et al.*, Phys. Rev. **C79**, 034909 (2009).

[24] Y.K. Lee *et al.*, Nucl. Instr. Meth. **A516**, 281 (2004).

[25] Z. Chajecki and M. Lisa, Phys. Rev. **C79**, 034908 (2009).

[26] D.L. Adams *et al.* (E704 Collaboration), Phys. Lett. **B264** 462 (1991).

[27] A. Bravar *et al.* (E704 Collaboration), Phys. Rev. Lett. **77** 2626 (1996).