Few Body Syst (2007) 41: 43–52
DOI 10.1007/s00601-007-0186-2
Printed in The Netherlands

Few-Body Systems

Neutron transversity measurement at Jefferson Lab with a polarized ^{3}He target

H. Gao[1,*], J. P. Chen[2], E. Cisbani[3], X. Jiang[4], J. C. Peng[5], X. Qian[1], L. Y. Zhu[5]

[1] Department of Physics and the Triangle Universities Nuclear Laboratory, Duke University, Durham, NC, USA
[2] Jefferson Lab, Newport News, VA, USA
[3] INFN, Sezione di Roma Gruppo Collegato Sanità, Rome, Italy
[4] Rutgers University, Piscataway, NJ, USA
[5] University of Illinois at Urbana-Champaign, Urbana, IL, USA

Received 31 August 2007; Accepted 19 September 2007; Published online 26 November 2007
© Springer-Verlag 2007

Abstract A first measurement of single target spin asymmetry (SSA) from semi-inclusive electroproduction of charged pions from a transversely polarized ^{3}He target in deep-inelastic-scattering kinematics will take data in Hall A at Jefferson Lab in 2008. Such SSA will allow for an extraction of the much desired information on the Collins and Sivers asymmetry from the "neutron" in order to probe the quark transversity distributions. The experiment will be a coincidence measurement with the BigBite spectrometer detecting the scattered electrons and the left-arm HRS spectrometer detecting the charged pions. The prospect of future 11 GeV measurements at Jefferson Lab in Hall A using a solenoid magnetic detector system is also discussed in this talk.

1 Introduction

Understanding the structure of the nucleon from the underlying theory of strong interaction in terms of quark and gluon degrees of freedom of quantum chromodynamics (QCD) is a fundamental and challenging task in physics. The investigation of the nucleon structure experimentally and theoretically has been more than ever intense in the last two decades or so, largely due to progress and breakthrough achieved both in experiment and theory. With the development in polarized beam,

*E-mail address: gao@phy.duke.edu

Correspondence: H. Gao, Department of Physics and the Triangle Universities Nuclear Laboratory, Duke University, Durham, NC 27708, USA

recoil polarimetry, and polarized target technologies, polarization experiments have provided more precise data on quantities ranging from electromagnetic form factors of the nucleon [1, 2] from elastic electron-nucleon scattering to spin structure functions [3] probed in deep inelastic lepton-nucleon scattering. At the same time, significant theoretical progress in areas ranging from effective field theories to lattice QCD calculations has been made in describing these data and in providing new insight in understanding the structure of the nucleon.

Deep-inelastic scattering has been proven since the 1960s as a powerful probe of the internal quark structure of the nucleon by studying the quark distribution functions. At leading twist after integrating over the transverse momenta of quarks, three quark distribution functions describe the internal dynamics of the hadrons completely: the unpolarized parton distribution f_1, the longitudinal polarized parton distribution g_1, and the quark transversity distribution, h_1. The f_1 has been extracted with excellent precision over a large range of x and Q^2 after several decades of experimental and theoretical efforts. The comparison of the f_1 structure functions in a large Q^2 range with QCD evolution equations has provided one of the best tests of QCD. The g_1 function has been determined with reasonable precision over a smaller region of x and Q^2 from polarized DIS experiments carried out at CERN, SLAC, DESY in the last two decades, and most recently at JLab and at RHIC from polarized proton-proton scattering. What remains elusive is the transversity function, h_1, a chirally odd quark distribution function. It probes the relativistic nature of the quarks inside the nucleon and the lowest moment of h_1 measures a simple local operator, known as the ''tensor charge'', which is analogous to the axial charge, and can be calculated from lattice QCD.

Because of its chiral-odd nature, the experimental determination of the transversity function requires an additional chiral-odd function, for example, double-polarized Drell-Yan processes, single target spin azimuthal asymmetries from semi-inclusive DIS pion electroproduction, double spin asymmetries in Λ production from *e-p* and *p-p* reactions and other processes, and single-spin asymmetries from double pion production from *e-p* scattering. The single (target) spin azimuthal asymmetry can arise from the following mechanisms: the so-called Collins mechanism and the Sivers mechanism for semi-inclusive DIS electroproduction of pions. The quark transversity function in combination with the chiral-odd Collins fragmentation function [4] gives rise to an azimuthal (Collins) asymmetry in $\sin(\phi_h + \phi_S)$, where ϕ_h and ϕ_S are the azimuthal angles of the hadron (pion) and the target spin axis with respect to the virtual photon axis and relative to the lepton scattering plane, respectively. The Sivers asymmetry [5–7] refers to the azimuthal asymmetry in $\sin(\phi_h - \phi_S)$ due to the correlation between the transverse target polarization of the nucleon and the transverse momentum of the quarks, which involves the orbital angular momentum of the unpolarized quark [8, 9].

The first single target spin azimuthal asymmetry measurement by the HERMES collaboration [10] from semi-inclusive DIS pion electroproduction using a longitudinally polarized proton target showed significant non-zero asymmetries, which generated a lot of theoretical [11–21] and experimental interest. Recently, the HERMES SSA results [22] were obtained from a transversely polarized proton target from semi-inclusive electroproduction of pions in DIS kinematics. Signals due to the unknown Collins fragmentation function in conjunction with the

previously unmeasured quark transversity distribution have been seen in the extracted moment of $\langle \sin(\phi_h + \phi_S) \rangle$ from the data for both the positive pions and the negative pions. The Sivers asymmetry due to the correlation between the nucleon transverse polarization and quark transverse momentum was also extracted for the first time from the moment of the azimuthal $\langle \sin(\phi_h - \phi_S) \rangle$ distribution. The HERMES data show rather larger negative π^- Collins moments. This surprising feature might be explained by the possibility that disfavored fragmentation could be of unexpected importance and may enter with a sign opposite to that of the favored case. A very interesting observation from the HERMES data is that the Sivers moment extracted from the positively charged pion is positive over the entire x and z range of the experiment, while the Sivers moment from the negatively charged pion seems to be consistent with zero.

The COMPASS collaboration reported measurements [23, 24] of the Collins and Sivers asymmetries of charged hadrons on the deuteron. Both the Collins and the Sivers asymmetries are consistent with zero within experimental uncertainties. Some cancellation between the proton and the neutron in single-spin asymmetries may exist in measurements using a transversely polarized deuteron target, which may explain the smallness of the COMPASS Collins and Sivers asymmetries.

Jefferson Lab is in a unique place to make important contribution to the study of the quark transversity distributions, a fundamental and timely subject. The polarized inclusive DIS program at Jefferson Lab has made important, well-recognized contributions already in the field, particularly in the study of the nucleon longitudinal polarization distributions in the large x region. Recently, the Jefferson Lab CLAS collaboration reported [25] the first evidence for a non-zero beam-spin azimuthal asymmetry in the semi-inclusive production of positive pions in the deep inelastic scattering region. Whether factorization is valid or not for Jefferson Lab kinematics had been a major concern for all semi-inclusive DIS experiments at Jefferson Lab. The CLAS study [25] of the pion multiplicities as a function of x has been carried out and no x dependence has been observed, and this finding is consistent with the assumption of factorization.

The separate determination of the Collins and Sivers asymmetries from a transversely polarized ''neutron'' target employing a polarized ^{3}He target is very important. While both the π^+ and π^- Collins asymmetries for the neutron are predicted to be small based on the HERMES results and isospin symmetry, larger than expected Collins asymmetry in the case of the neutron will challenge the models of the transversity and the physics associated with these models. The predicted Sivers asymmetries for the π^+ in the case of the neutron can be as large as 40–50%, though the situation is very complicated and predictions vary over a large range.

The combined measurements of π^+ and π^- will allow for a study of the surprising feature suggested by the comparison between the HERMES π^+ and π^- results that the fragmentation in the case of the disfavored quark flavor seems to play an important role and may enter with an opposite sign as that of the favored case for the Collins moment. The HERMES experiment was carried out with a transversely polarized proton target. Therefore, measurements of charged pion from semi-inclusive electroproduction in the DIS region in an x-range comparable to that of the HERMES from a transversely polarized ''neutron'' target will be very

important. Further, the combination of the data from proton and ‘‘neutron’’ will allow for a flavor separation of quark transversity distributions, especially in the case of the Sivers asymmetries. Most recently, Anselmino [26] and collaborators carried out a global analysis of the semi-inclusive data from HERMES and COMPASS and the BELLE $e^+e^- \to h_1 h_2 X$ in terms of Collins fragmentation function and the quark transversity distribution. The Collins function was extracted for the first time by these authors and predictions for future Jefferson Lab experiments have been made. Therefore, our upcoming 6 GeV SIDIS single spin asymmetry measurements from electroproduction of charged pions are extremely timely.

2 The transversity study with 6 GeV at JLab

The 6 GeV neutron transversity experiment [27] ($n^\uparrow(e, e'\pi^\pm)$ reaction) employing a high-pressure polarized ^{3}He target will take place in Hall A at Jefferson Lab in 2008. The experiment will use the Hall A left-side high resolution spectrometer (HRS_L) situated at 16° as the hadron arm, and use the BigBite spectrometer at 30° beam-right as the electron arm. The HRS_L spectrometer magnet polarity will be reversed from positively charged hadron detection to negatively charged hadron detection and vice versa. Since this experiment is a coincidence experiment with the HRS_L at a relatively low rate, the HRS spectrometer can be used for interaction vertex reconstruction such that most of the complications associated with the BigBite wire chamber track reconstruction can be eliminated. In addition, when a tight coincidence timing cut is further required we expect that the majority of the background tracks and random hits in the BigBite wire chambers can be easily eliminated.

The Hall A polarized ^{3}He target [34] was successfully used in a number of experiments [28–33] in Hall A since 1998 in the standard configuration. The standard polarized ^{3}He target used optically pumped rubidium vapor to polarize ^{3}He nuclei via spin-exchange. Two sets of Helmholtz coils provided a 25 Gauss holding field for any direction in the scattering (horizontal) plane. Target cells were up to 40 cm long with density of about 10 amgs. Beam currents on target ranged from 10 to 15 μA to keep the beam depolarization effect small and the cell in-beam life time reasonably long (>3 weeks). The luminosity was about 10^{36} nuclei/s/cm^2. The in-beam average target polarization achieved was typically over 40%. Two polarimetries, NMR and EPR (electron-paramagnetic-resonance), were used to measure the polarization of the target. The uncertainty achieved for each method was less than 4% relative and the methods agreed well within errors. The recent development of Rb-K hybrid [35] ^{3}He target cells resulted in much improved target polarization and less demand on the target cell relaxation time due to much faster pump-up times associated with the hybrid cells. The hybrid cells were used successfully in the recently completed neutron electric form factor experiment [36] in Hall A. We will use 40-cm long hybrid ^{3}He target cells for our experiment. Further, the Helmholtz coils and laser optics are being modified to provide a target polarization along two specific orientations: the vertical direction and the transverse direction in the electron scattering plane relative to the beam direction. The experimental arrangement is illustrated in Fig. 1 and a close-up view near the pivot is shown in Fig. 2.

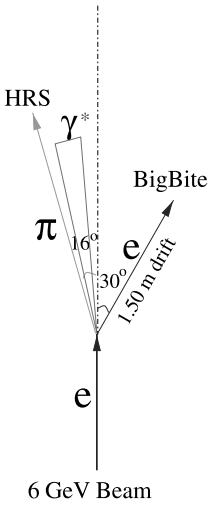

Fig. 1 The experimental arrangement: the target polarization is in the plane that is perpendicular to the plane of $\boldsymbol{q} \wedge (\boldsymbol{q} \times \boldsymbol{p}_\pi)$

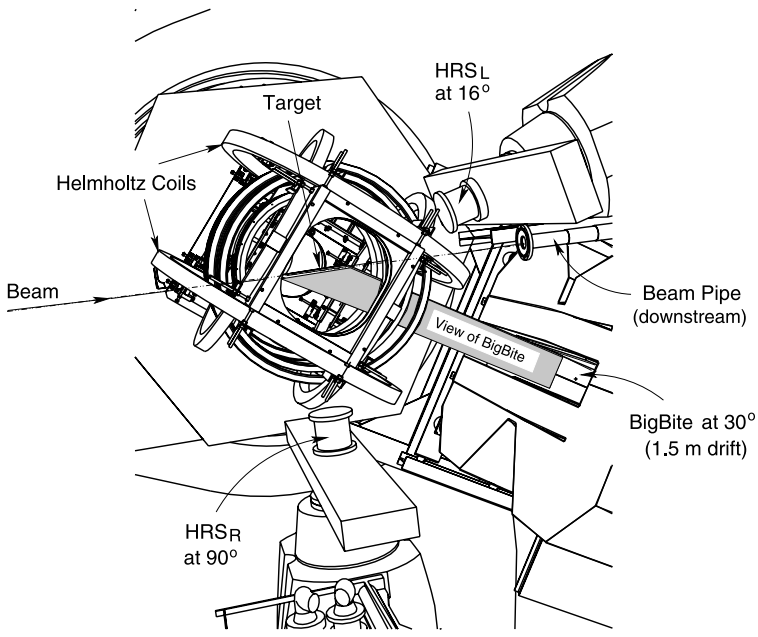

Fig. 2 A top view near the pivot. The left HRS is shown at 16°, the BigBite dipole magnet is shown at 30° beam right and at a drift distance of 1.5 m. The right HRS is at 90° as a luminosity monitor. The target coils are arranged to avoid interference with the beam line and the spectrometers

The experiment will reach the highest possible W with a 6 GeV beam ($2.33 < W < 3.05$ GeV), corresponding to $0.135 < x < 0.405$ and $1.31 < Q^2 < 3.10$ $(\mathrm{GeV}/c)^2$. The experiment will also detect the leading fragmentation pion which carries $z \approx 0.5$ of the energy transfer to favor the current fragmentation, where $z = E_h/\nu$ is the fraction of the virtual photon energy carried by the hadron. The value of W' is also chosen to be as high as possible with a cut of $W' > 1.5$ GeV to avoid contributions from resonance production channels. The W is the invariant

Table 1 Nominal kinematics of each x-bin (central value) for beam energy of $E = 6.0\,\text{GeV}$. One BigBite setting will cover all the kinematics listed. E' and θ_e are the electron arm momentum and angle. θ_q indicates the direction of the three-momentum vector of the virtual photon, $\boldsymbol{q}$. The hadron arm angle is fixed at 16°

E' (GeV)	θ_e (deg.)	$\langle x \rangle$	W (GeV)	Q^2 (GeV^2)	θ_q (deg.)	z_π	p_π (GeV/c)	W' (GeV)
						$\theta_\pi = 16.0°$		
0.815	30.0	0.135	3.050	1.310	4.40	0.46	2.40	2.20
1.246	30.0	0.225	2.793	2.003	7.22	0.51	2.40	1.99
1.612	30.0	0.315	2.554	2.592	9.93	0.55	2.40	1.80
1.925	30.0	0.405	2.331	3.095	12.52	0.59	2.40	1.62

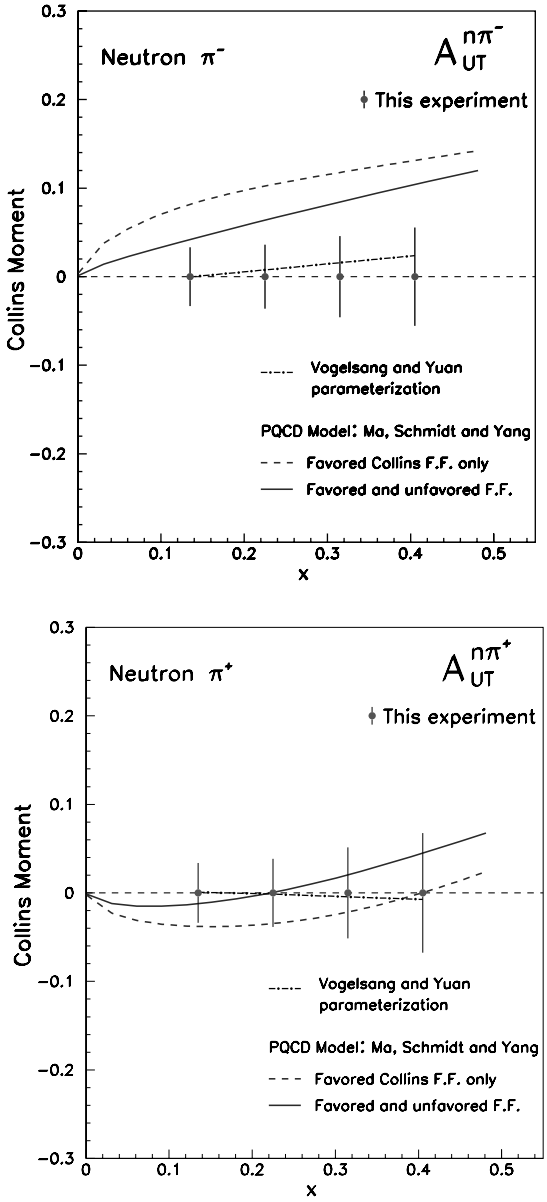

Fig. 3 The projected 6 GeV JLab measurements on Collins moment from the $n^\uparrow(e, e'\pi^-)$ and $n^\uparrow(e, e'\pi^+)$ reaction together with theoretical predictions

mass of the whole hadronic system and W' is the invariant mass of the hadronic system without the detected hadron. Because of the large momentum acceptance of the BigBite spectrometer, only one BigBite momentum setting is needed to cover all the kinematics of the experiment. A hadron arm momentum setting of $p_\pi = 2.4\,\mathrm{GeV}/c$ is chosen for the entire experiment. The kinematics for the entire experiment is listed in Table 1.

Figs. 3 and 4 show the projected 6 GeV measurements of the Collins moment and the Sivers moment from the $n^\uparrow(e, e'\pi^-)$ and $n^\uparrow(e, e'\pi^+)$ reaction, respectively. Also shown are the theoretical predictions from Vogelsang and Yuan [41], and Ma, Schmidt and Yang [14] in the case of the Collins moment; Anselmino et al. [42] and Vogelsang and Yuan [41] for the Sivers moment – both models describe the

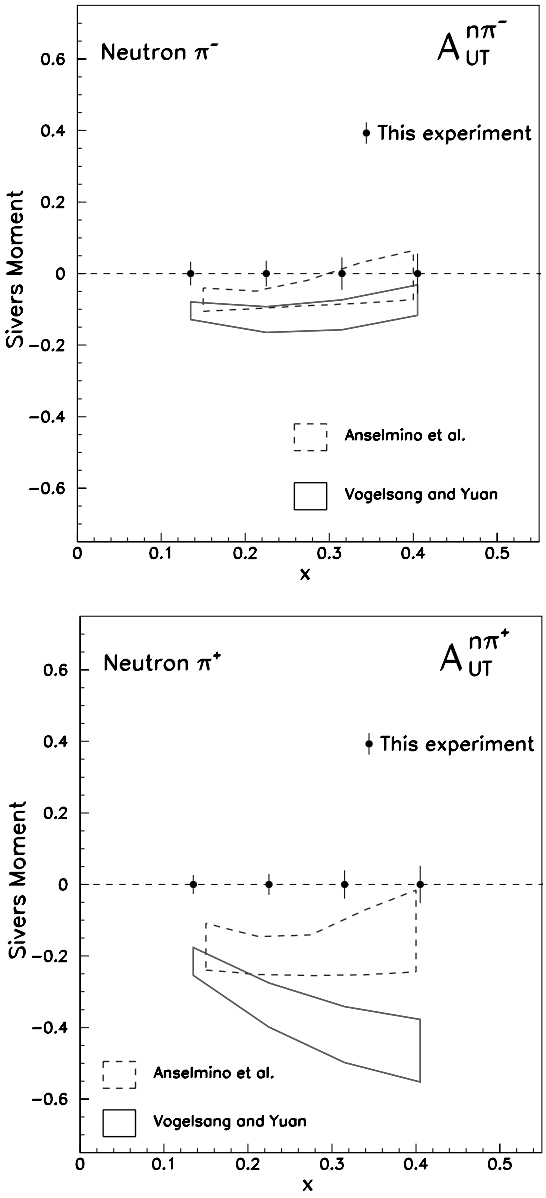

Fig. 4 The projected 6 GeV JLab measurements on Sivers moment from the $n^\uparrow(e, e'\pi^-)$ and $n^\uparrow(e, e'\pi^+)$ reaction together with theoretical predictions

HERMES transverse proton data [22] very well. With the projected precision of our 6 GeV measurement, one can test different theoretical approaches towards the Sivers moment.

3 The transversity study with 11 GeV at JLab

As mentioned before, Jefferson Lab is in a unique position with a 6 GeV beam already to make important contributions to the study of the quark transversity distributions. With a 12 GeV energy upgraded CEBAF at JLab, a new large acceptance solenoid detection system [37] proposed in Hall A will provide a unique opportunity [38] to have precision measurements of the Collins and Sivers asymmetry through the SIDIS pion (kaon) productions over a wide kinematics range. The large acceptance of this new device will provide high statistics measurements allowing for a 3D mapping in (x, z, P_T) of the Collins asymmetry and Sivers distribution function, where P_T is the transverse momentum of the detected hadron in the final state.

Fig. 5 shows a layout of the experimental setup. Fig. 6 shows a sample plot of the projection of the Sivers and the Collins asymmetry measurement for $z = 0.5-0.6$ as a function of P_T and x-bin for a 60 days of running with a transversely polarized ^{3}He target in detecting π^+ in coincidence with the scattered electrons. For the projections, we assume a 45% target polarization with spin-flip every 20 min, a 15 μA beam on a 10 amagats, 40 cm long ^{3}He target. The detector acceptance has been studied using a GEANT3 based Monte-Carlo simulation [37] assuming an overall 50% of azimuthal angular acceptance. The physical cross sections are calculated using CTEQ6 [39] parton distribution parameterizations

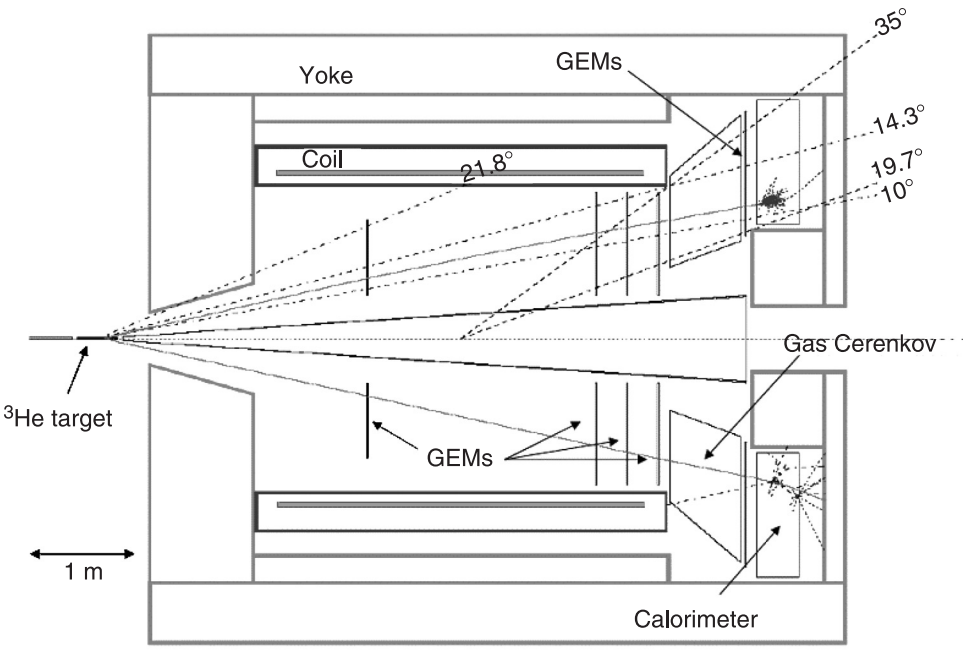

Fig. 5 The schematics of the experimental setup at 11 GeV

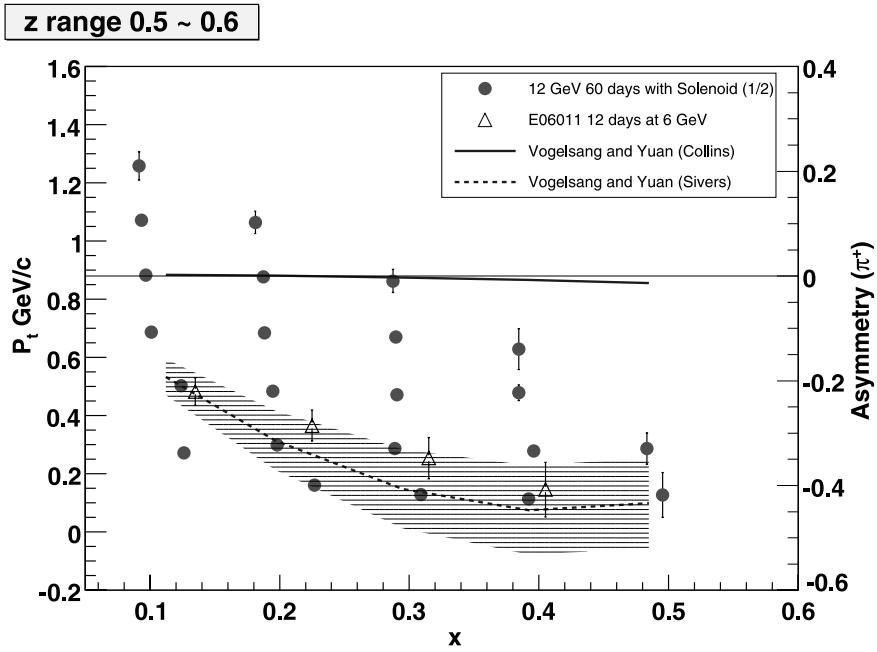

Fig. 6 The projection of the Sivers and the Collins asymmetry measurement for the π^+ case for $z = 0.5-0.6$ as a function of P_T and x-bin. The size of the error bar follows the axis on the right while the left axis shows the P_T range. The solid line shows the prediction of the Collins asymmetry from Vogelsang and Yuan, while the dashed line shows the prediction of the Sivers asymmetry by the same group. The gray band shows the theoretical uncertainties of the model

and AKK [40] fragmentation function parameterizations. To select events in the DIS region, the following cuts are used: $W > 2.3\,\text{GeV}$, $Q^2 > 1.0\,\text{GeV}^2/c^2$, $W' > 1.6\,\text{GeV}$ and $0.3 < z < 0.7$, where the W' is the missing mass of the final particle system except the scattered electron and the detected leading-hadron. Also shown in the figure are theoretical predictions from Vogelsang and Yuan [41] which fit the HERMES data and describe the COMPASS data.

This new precision measurement together with the CLAS12 measurement in Hall B from a transversely polarized proton target and the world data will allow for the first time to extract the Sivers distribution function, the transversity distribution function as well as the Collins fragmentation function. The Collins function can be cross-checked with the e^+e^- annihilation measurement [26]. The kaon data collected simultaneously with a kaon particle identification detector can provide additional information of transversity and Sivers distribution functions of sea quarks. Combining with the hydrogen data at similar kinematic region, a flavor decomposition of the transversity and the Sivers distribution functions for both the valence and the sea quark can be carried out.

Acknowledgment We thank A. Afanasev, M. Anselmino, H. Avagyan, E. Chudakov, L. Gamberg, P. J. Mulders, M. Schlegel, W. Vogelsang, and F. Yuan for helpful discussions. This work is supported in part by the U.S. Department of Energy under contract number DE-FG02-03ER41231. H.G. also acknowledges the support of the National Science Foundation of China (No. 10528510).

References

1. Gao H (2003) Int J Mod Phys E 12:1; Erratum (2003) Int J Mod Phys E 12:567
2. Hyde-Wright CE, de Jager K (2004) Ann Rev Nucl Part Sci 54:217
3. Filippone BW, Ji XD (2001) Adv Nucl Phys 26:1
4. Collins JC (1993) Nucl Phys B 396:61
5. Meng T, Pan J, Xie Q, Zhu W (1989) Phys Rev D 40:769
6. Sivers DW (1990) Phys Rev D 41:83
7. Anselmino M, Boglione M, Murgia F (1999) Phys Rev D 60:054027
8. Brodsky SJ, Hwang DS, Schmidt I (2002) Phys Lett B 530:99
9. Burkardt M (2004) Phys Rev D 69:057501
10. Airapetian A, et al. (HERMES) (2002) Phys Rev Lett 84:4047; (2001) Phys Rev D 64:097101; (2003) Phys Lett B 562:182
11. Boglione M, Mulders PJ (2000) Phys Lett B 478:114
12. Anselmino M, Murgia F (2000) Phys Lett B 483:74
13. Efremov AV, Goeke K, Schweitzer P (2002) Eur Phys J C 24:407
14. Ma B-Q, Schmidt I, Yang J-J (2002) Phys Rev D 66:094001
15. Efremov AV, Goeke K, Schweitzer P (2003) Eur Phys J C 32:337
16. Schweitzer P, Bacchetta A (2004) Nucl Phys A 732:106
17. Bacchetta A, Metz A, Yang J-J (2003) Phys Lett B 574:225
18. Gamberg LP, Goldstein GR, Oganessyan KA (2003) Phys Rev D 68:051501
19. Brodsky SJ, Hwang DS, Schmidt I (2002) Phys Lett B 530:99
20. Ji X, Yuan F (2002) Phys Lett B 543:66
21. Collins JC (2002) Phys Lett B 536:43
22. Airapetian A, et al. (HERMES) (2005) Phys Rev Lett 94:012002
23. Ageev ES, et al. (COMPASS Collaboration) (2005) Phys Rev Lett 94:202002
24. Ageev ES, et al. (COMPASS Collaboration) [hep-exp/0610068]; (2007) Nucl Phys B 765:31
25. Avakian H, et al. [hep-ex/0301005]; (2004) Phys Rev D 69:112004
26. Anselmino M, et al. [hep-ph/0701006]
27. JLab E06-010/E06-011: Jiang X, Chen JP, Cisbani E, Gao H, Peng JC (spokespersons)
28. Amarian M, et al. (2002) Phys Rev Lett 89:242301; (2004) 92:022301; (2004) 93:152301; Meziani Z, et al. (2005) Phys Lett B 613:148
29. Xu W, et al. (2000) Phys Rev Lett 85:2900; Xiong F, et al. (2001) Phys Rev Lett 87:242501; Xu W, et al. (2003) Phys Rev C 67:012201 (R)
30. Zheng X, et al. (2004) Phys Rev Lett 92:012004; (2004) Phys Rev C 70:065207
31. Kramer K, et al. (2005) Phys Rev Lett 95:142002
32. JLab E01-012: Chen JP, Choi S, Liyanage N (spokespersons)
33. JLab E97-110: Chen JP, Deur A, Garibaldi F (spokespersons)
34. http://hallaweb.jlab.org/targets/polhe3/polhe3_tgt.html; and tech notes in http://www.jlab.org/e94010/
35. Babcock E, et al. (2003) Phys Rev Lett 91:123003; Kramer K, et al. (to appear) NIMA
36. JLab E02-013: Cates G, McCormick K, Reitz B, Wojtsekhowski B (spokespersons)
37. Chudakov E (2006) Presentation at the JLab Spin Workshop
38. Afanasev A, et al. [hep-ph/0703288]
39. Pumplin J, et al. (2002) JHEP 0207:012; [hep-ph/0201195]
40. Albino S, Kniehl BA, Kramer G (2005) Nucl Phys B 725:181; (2006) Nucl Phys B 734:50
41. Vogelsang W, Yuan F (private communication)
42. Anselmino M (private communication)