PROCEEDINGS OF SCIENCE

TMD Physics at 12-GeV Jefferson Lab with SoLID

Tianbo Liu[*][†]
Department of Physics, Duke University, Durham, NC 27708, U.S.A.
Duke Kunshan University, Kunshan, Jiangsu 215316, China
E-mail: `liutb@jlab.org`

The Solenoidal Large Intensity Device (SoLID) has been proposed in Hall A at Jefferson Lab, which will fully utilize the great physics potential of the 12-GeV energy upgrade by combining high luminosities and large acceptance. Three of five highly-rated approved experiments are the semi-inclusive deep inelastic scatterings (SIDIS) of 11 GeV and 8.8 GeV electron beams on transversely and longitudinally polarized ^{3}He targets and a transversely polarized proton target with detection of charged pions and electrons in coincidence to study the transverse momentum dependent parton distributions (TMDs). The SoLID SIDIS experiment will provide $4D$ (x, z, Q^2, P_T) mappings of Sivers, Collins, pretzelostiy and worm-gear asymmetries in the valence quark region with high precision. In this talk, we present the expected physics results from SoLID SIDIS measurements on TMD extractions, transversity distributions, and the tensor charge of u and d quarks. The constraint on quark electric dipole moments (EDMs) with the tensor charge measurement and neutron EDM experiments will also be discussed.

XXIV International Workshop on Deep-Inelastic Scattering and Related Subjects
11-15 April, 2016
DESY Hamburg, Germany

---

[*] Speaker.

[†] On behalf of SoLID collaboration

PoS(DIS2016)244

1. Overview of SoLID

The Solenoidal Large Intensity Device (SoLID) is designed for Hall A to fully exploit the capabilities of the CEBAF 12-GeV upgrade at Jefferson Lab. It is capable of handling high luminosity, $\sim 10^{37-39}\,\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$, and has large acceptance. For SIDIS configuration, it has 2π azimuthal angle coverage and 8° to 24° polar angle coverage. There are already five highly-rated approved experiments at SoLID with wide physics interests. Three of them are semi-inclusive deep inelastic scattering (SIDIS) experiments [1, 2, 3] aiming to unravel the nucleon structure, particularly the spin structure, in the valence quark region to have unprecedented precision measurements of quark three dimensional momentum distributions. The parity violating deep inelastic scattering (PVDIS) experiment [4] is focusing on the exploration of new physics beyond the standard model (SM) in $10 \sim 20$ TeV region, as a complementary to the reach of the LHC. The other experiment is to measure the cross section of J/ψ electroproduction near threshold [5], in order to probe the color field in the nucleon to access to QCD conformal anomaly, which is related to the proton mass budget.

2. SIDIS experiments

It has been more than 25 years since the discovery that the quark spin only contributes a small fraction, about 30% in recent analyses, to the proton spin [6, 7]. This invoked both theoretical and experimental investigations on nucleon spin structures. Nowadays, the remaining proton spin is usually attributed to the orbital angular momenta and the gluon spin, though there are still different decomposition versions [8]. Experimentally, the quark helicity term is well measured, and the gluon helicity term is also started being known [9]. In order to have full understanding of the "proton spin puzzle", one must have the orbital terms measured. Since the orbital angular momentum is essentially the correlation between the coordinate and the momentum, an ideal place to access them is the Wigner distributions [10], or equivalently the generalized transverse momentum dependent parton densities [11]. Unfortunately, no feasible process is currently known to measure it. However, the transverse momenta and the transverse coordinates distributions can be respectively measured through transverse momentum dependent parton distributions (TMDs) and generalized parton distributions (GPDs). Both of them are three dimensional descriptions of nucleon partonic structures, and are related to the orbital angular momentum [12, 13, 14].

Among the five approved experiments at SoLID, three are SIDIS experiments with 11 GeV and 8.8 GeV electron beam by coincident measurement of a charged pion and the scattered electron to have unprecedented precision measurements of TMDs in the valence quark region. In these experiments, transversely polarized helium-3 target [1], longitudinally polarized ^{3}He target [2], and transversely polarized NH_3 target [3] will be respectively utilized. Both the ^{3}He and the NH_3 targets were used in 6 GeV experiments, and high in-beam polarization was achieved. The ^{3}He target is used as an effective polarized neutron target because its spin is dominantly from the neutron spin.

With one-photon exchange approximation, the SIDIS differential cross section is expressed in terms of 18 structure functions of x, z, P_T, and Q^2 [15]. They can be measured by different combination of beam and target polarizations and the separation of different azimuthal modulations. Due to the high luminosity and the large acceptance, ultimately high statistics are expected at SoLID. This allows us to have $4D$ bins to investigate any kinematic correlation in the structure functions.

In total, there will be about 1400 neutron bins and about 650 proton bins. In the parton model, the structure functions are expressed as the convolution of a transverse momentum dependent distribution function and a fragmentation function. At leading twist, eight quark TMDs are defined for the nucleon, and all of them can be accessed with SoLID. The flavor separation will be obtained via the combination of the neutron and proton data, as well as the data in other experiments.

The single spin asymmetries are core measurements in these SIDIS experiments, including the Sivers, Collins, and pretzelosity asymmetries, to extract quark Sivers, transversity, and pretzelosity distributions. These terms are separated according to their different azimuthal angle dependence. The Sivers function is a naive time reversal odd TMD that arises from the nontrivial gauge link in the quark-quark correlation matrix. It reflects the correlation between quark transverse momentum and nucleon transverse spin. A non-vanishing Sivers function can be obtained from the final (or initial) state interaction, and thus a sign change is predicted for the Sivers functions measured from the SIDIS and Drell-Yan processes. This prediction is recently published by STAR [16] through the $W^{\pm}/Z$ meson production processes. The transversity is a chiral odd distribution that describing the transversely polarized quark density in the transversely polarized nucleon. Its chiral odd property results in simpler evolution effect without mixing with gluons, but makes the measurement from inclusive DIS process suppressed by m_q/Q. It needs to couple to another chiral odd function, such as the Collins fragmentation function in SIDIS process, or another chiral odd distribution in Drell-Yan process. The transversity distribution can also be extracted through the dihadron process in the framework of collinear factorization [17]. This is approved as a run-group experiment at SoLID [18]. The pretzelosity is another chiral odd distribution that is the interference of the wave functions differing by two units of orbital angular momentum. Its first transverse momentum weighted moment is related to quark orbital angular momentum in some models. These asymmetries have been explored in HERMES, COMPASS and JLab 6 GeV transversity experiment (E06-010) [19, 20, 21]. The data have been utilized to extract quark Siver, Collins, and pretzelosity distributions, but due to the low precision we still have large uncertainties in the global fits.

3. Physics impact

SoLID SIDIS program aims to have unprecedented precision measurements of TMDs in the valence quark region. The high statistics allows us to have four dimensional bins with small statistical uncertainties, which will significantly improve the accuracy of the measurements of the asymmetries. In addition, the 2π azimuthal angle coverage reduces much systematic uncertainties, and thus the nuclear effect becomes the dominant systematic uncertainty, which could reach 4∼5% as one recent estimation suggested [22]. Therefore, SoLID SIDIS data will have much improvement on the knowledge of quark TMDs. In Figure 1, we show the SoLID projection of Sivers functions compared with recent global fit. The statistical and systematic uncertainties are quadratically combined. The uncertainty bands are estimated in the same way as explained in [23] with the same functional form. Similar improvements on the determination of the other quark TMDs will also be obtained.

Among the core measurements of the TMD program at SoLID, the transversity is one that has collinear limit. It describes the transversely polarized quark density, which is a counter part of the helicity that represents the longitudinally polarized quark density. Due to the relativistic effect, they

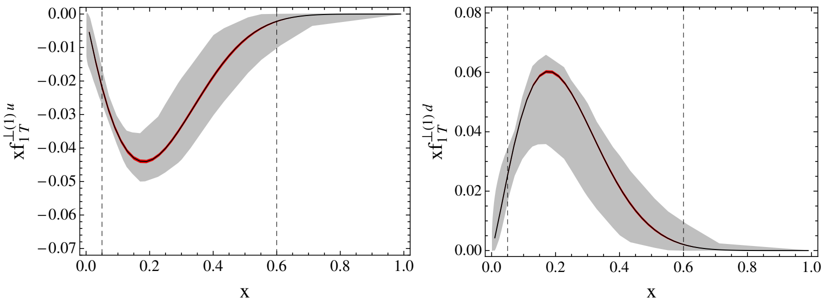

Figure 1: Sivers function. The left panel is the first transverse moment of *u* quark Sivers function, while the right panel is the one for *d* quark Sivers function. The gray bands are the uncertainties from a recent global fit [23], and the red bands are the SoLID projections based on the same parametrization functions. The region between the dashed lines indicate the kinematical covered region at SoLID, while the regions outside are from extrapolations.

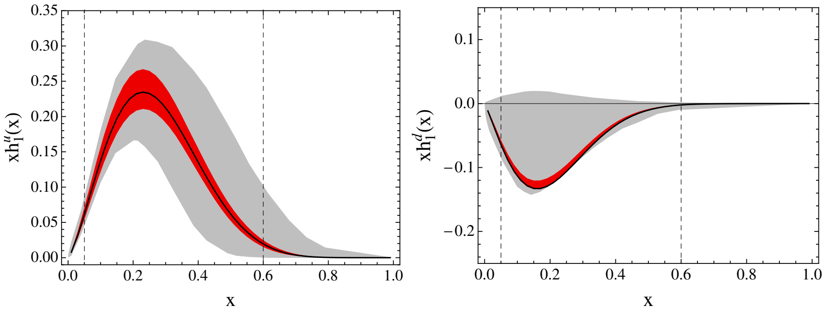

Figure 2: Transversity. The left panel is the *u* quark transversity distribution, while the right panel is the *d* quark transversity distribution. The gray bands are the uncertainties from the global fit [24], and the red bands are the SoLID projections based on the same parametrization. The region between the dashed lines can be directly measured at SoLID, while the regions outside are from extrapolations.

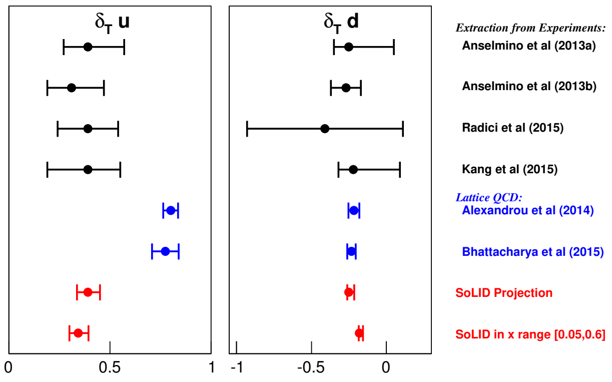

Figure 3: Tensor charge of *u* (left) and *d* (right) quarks. The black points are current global fits by different groups, the blue ones are lattice QCD calculations, and the red ones are the SoLID projections based on the global fit [24].

are not the same. Its chiral odd nature makes it a different evolution behavior from the other two leading twist collinear PDFs. The expected improvement on transversity distributions by SoLID is shown in Figure 2.

The moment of the transversity is the tensor charge, which is a fundamental quantity defined by the matrix element of local operators as

$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = \delta_T q\,\bar{u}(P,S)i\sigma^{\mu\nu}u(P,S), \tag{3.1}$$

to describe the coupling to a tensor current. The tensor charge is dominated by valence quark contribution which region is mostly covered by SoLID. Thus, SoLID data are expected to provide strict constraint on the tensor charge. In Figure 3, we compare the present extractions by global fits, lattice QCD calculations, and SoLID projections based on the "standard" parametrization in [24]. The contribution to the tensor charge from the transversity tails out of the region directly measured by SoLID is estimated by extrapolation. However, the uncertainty from the extrapolation is expected to be small, since the valence quark distributions will drop to zero at $x \to 1$.[1]

Together with the upper limit on neutron electric dipole moment (EDM), the determination of tensor change will put constraint on quark EDMs [27]. Nonzero EDM of a fermion is a signature of time-reversal violation, or CP-violation if CPT-invariance assumed. In the standard model, the CP-violation phase in the CKM matrix contributes to quark EDM from three-loop level, and hence results in extremely small value ($10^{-34} e \cdot \mathrm{cm}$) [28]. The strictest constraint on QCD θ-term is from the EDM limit. Therefore, the improvement on quark EDM limit will help us search for new physics, which usually has additional CP-violation terms and leads to larger quark EDM.

4. Summary

Lepton scattering is a powerful tool to probe the internal structure of the nucleon. The SoLID project at Jefferson Lab will maximize the science potential of the 12-GeV upgrade by combining high luminosities and large acceptance. SIDIS experiments at SoLID will have unprecedented precision measurements of three-dimensional momentum distributions of quarks in the valence region. The high statistics will allow to have four dimensional bins to measure all azimuthal asymmetries, in order to have accurate extraction of quark TMDs. The collinear transversity distribution is also a highlight measurement, and SoLID data will provide much improvement on the determination of its moment, the tensor charge. Together with world neutron EDM experiments, the precise extraction of tensor charge will put strict constraint on quark EDMs. Therefore, SoLID SIDIS experiments will not only have precise measurement of nucleon structures, but also help to search for new physics.

Acknowledgment

This work is supported in part by the US Department of Energy under contract numbers DE-FG02-03ER41231 and by the Duke Kunshan University.

---

[1] The TMD evolution effect is also taken into account in a recent study of SoLID impact on the tensor charge extraction. The improvements on the small-x, large-x, and SoLID acceptance regions are estimated separately [26].

References

[1] JLab Experiment E12-10-006, spokespersons: J.-P. Chen, H. Gao (contact), X.-D. Jiang, J.-C. Peng, and X. Qian, http://hallaweb.jlab.org/collab/PAC/PAC34/PR-09-014-transversity.pdf.

[2] JLab Experiment E12-11-007, spokespersons: J.-P. Chen, J. Huang (contact), Y. Qiang, W. B. Yan, https://www.jlab.org/exp_prog/PACpage/PAC37/proposals/Proposals/New%20Proposals/PR-11-007.pdf.

[3] JLab Experiment E12-11-008, spokespersons: K. Allada, J.-P. Chen, H. Gao (contact), X.-M. Li, and Z.-E. Meziani, https://www.jlab.org/exp_prog/proposals/11/PR12-11-108.pdf.

[4] JLab Experiment E12-10-007, spokespersons: P. A. Souder (contact), http://hallaweb.jlab.org/collab/PAC/PAC34/PR-09-012-pvdis.pdf.

[5] JLab Experiment E12-12-006, spokespersons: H. Hafidi, Z.-E. Meziani (contact), X. Qian, N. Sparveris, and Z. W. Zhao, https://www.jlab.org/exp_prog/proposals/12/PR12-12-006.pdf.

[6] J. Ashman *et al.*, Phys. Lett. B **206**, 364 (1988).

[7] J. Ashman *et al.*, Nucl. Phys. B **328**, 1 (1989).

[8] E. Leader and C. Lorcé, Phys. Rep. **541**, 163 (2014).

[9] N. Sato *et al.*, Phys. Rev. D **93**, 074005 (2016).

[10] C. Lorcé and B. Pasquini, Phys. Rev. D **84**, 014015 (2011).

[11] S. Meissner, A. Metz, and M. Schlegel, J. High Energe Phys. 08 (2009) 056.

[12] X. Ji, Phys. Rev. Lett. **78**, 610 (1997).

[13] J. She, J. Zhu, and B.-Q. Ma, Phys. Rev. D **79**, 054008 (2009).

[14] A. Bacchetta and M. Radici, Phys. Rev. Lett. **107**, 212001 (2011).

[15] A. Bacchetta *et al.*, J. High Energy Phys. 02 (2007) 093.

[16] L. Adamczyk *et al.*, Phys. Rev. Lett. **116**, 132301 (2016).

[17] A. Bacchetta, A. Courtoy, and M. Radici, Phys. Rev. Lett. **107**, 012001 (2011).

[18] JLab Experiment E12-10-006A, spokespersons: J.-P. Chen, A. Courtoy, H. Gao, A. W. Thomas, Z. Xiao, and J. Zhang (contact), https://www.jlab.org/exp_prog/proposals/14/E12-10-006A.pdf.

[19] X. Qian *et al.*, Phys. Rev. Lett. **107**, 072003 (2011).

[20] Y. Zhang *et al.*, Phys. Rev. C **90**, 055209 (2014).

[21] Y. X. Zhao *et al.*, Phys. Rev. C **90**, 055201 (2014).

[22] S. Scopetta, Phys. Rev. D **75**, 054005 (2007).

[23] M. Anselmino *et al.*, Eur. Phys. J. A **39**, 89 (2009).

[24] M. Anselmino *et al.*, Phys. Rev. D **87**, 094019 (2013).

[25] C. A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006).

[26] Z. Ye *et al.*, arXiv:1609.02449 [hep-ph].

[27] See *e.g.*, M. Pitschmann, C. Y. Seng, C. D. Roberts and S. M. Schmidt, Phys. Rev. D **91**, 074004 (2015).

[28] A. Czarnecki and B. Krause, Phys. Rev. Lett. **78**, 4339 (1997).