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SoLID-SIDIS: Future Measurements of Transversity, TMDs and more

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Over the past few decades, investigations of the nucleon structure mainly focused on the one dimensional study of parton distributions and structure functions. New theoretical developments, including both transverse momentum distributions (TMDs) [1, 2] and generalized parton distributions (GPDs) [3, 4], provide a new way to understand the 3 dimensional structure of the nucleon. TMDs give access to the nucleon tomography in the momentum space and also provide an opportunity to evaluate the contribution of quarks' and gluons' orbital angular momenta to the nucleon spin.

The experimental study of TMDs requires a device with high luminosity, large kinematic coverage and great detection resolutions. With the Jefferson Lab (JLab) 12 GeV electron beam, we have proposed a Solenoidal Large Intensity Device (SoLID) [5] in Hall A which is capable of performing such measurements. Several newly approved experiments[6, 7, 8] will perform measurements of both the single and double spin asymmetries via semi-inclusive deep inelastic scattering (SIDIS) from polarized ^{3}He ("neutron") and proton targets [9]. The new data will provide important information to extract TMDs with unprecedented precision.

Besides, we are also able to use SoLID to explore many more important physics topics. Several experiments for the measurements of PVDIS [10] and J/ψ production [11] have been approved and new proposals are under development. For example, with the similar SIDIS configuration, we are actively developing new measurements to study GPDs via deep virtual Compton scattering (DVCS) with polarized targets, doubly-DVCS, deep virtual meson production, time-like Compton scattering [12], and so on.

Our collaboration has submitted the pre-conceptual design report [5] to JLab and successfully passed the Director's Review in early 2015. Our collaborators are focusing on optimizing the detector system, finalizing the detector designs and proceeding on the detector R&D. We are looking forward to having the DOE Science Review in the near future.

XXIII International Workshop on Deep-Inelastic Scattering
27 April - May 1 2015
Dallas, Texas

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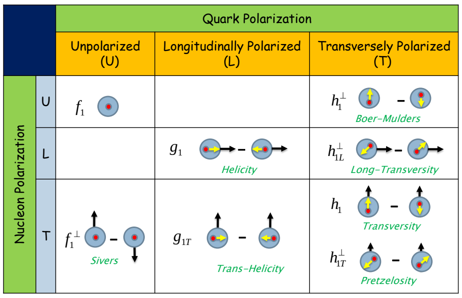
PoS(DIS2015)242

1. Transversity and Transverse Momentum Distributions

At the leading twist, there are eight TMDs [1, 2], encoding the correlations of quarks and nucleons with various polarization directions, as tabulated in Fig. 1. Only three TMDs on the diagonal survive the integration over the transverse momenta of the quarks, and reduce to the one-dimensional parton distribution functions (PDFs). Compared with the first two PDFs, the transversity function, h_1, is least known and can only be accessed by SIDIS processes [13] or Drell-Yan processes [14]. Its lowest moment defines the quark tensor charge, a fundamental quantity related to the nucleon spin, and can be calculated by lattice QCD. A precise determination of the tensor charge will play an essential role of testing the standard model.



Nucleon Polarization	Quark Polarization: Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1		$h_1^\perp$ Boer–Mulders
L		g_1 Helicity	$h_{1L}^\perp$ Long–Transversity
T	$f_{1T}^\perp$ Sivers	g_{1T} Trans–Helicity	h_1 Transversity $h_{1T}^\perp$ Pretzelosity

Figure 1: A table to illustrate the correlations of eight leading twist TMD functions among different nucleon and quark polarization states.

Other five TMDs explicitly depend, in addition to the longitudinal momentum fraction x, on the transverse momentum of quark, $\vec{k}_T$, and hence provide quantitative information about the quark's orbital angular momentum (OAM) inside the nucleon. Among them, the Sivers function [15], $f_1^\perp$, describes the distribution of unpolarized quarks inside a transversely polarized nucleon. The Boer-Mulders function [1, 2], $h_1^\perp$, gets access to the information of the correlations between quark's spin and its OAM. A non-zero distribution for either of these functions provides the information of the quark's OAM and its contribution to the nucleon spin [16, 17]. Both the Sivers function and the Boer-Mulders function are naive T-odd functions which depend on the state of the active quark during the interaction. Since in the SIDIS process the virtual photon interacts with the final state quark and the Drell-Yan process probes the quark in its initial state, one expects to observe different signs of these functions obtained by two processes. An investigation of such sign-change effect will help us to validate the QCD factorization theorem [18]. Two Worm-Gear functions [19], $h_{1L}^\perp$ and g_{1T}, describe the probabilities of finding a quark with its polarization perpendicular to the nucleon's polarization. They give the unique information of the quark spin-orbit correlations and probe the interference between nucleon wave functions that differ by one unit of OAM (mainly the $L=0$ and $L=1$ interference) [20, 21]. Finally, the Pretzelosity function, $h_{1T}^\perp$, requires the interference between two wave function components with two units of OAM difference [20], e.g., $\Delta L = 2$. It directly probes the quark relativistic effect and can quantitatively get access to the quark's OAM.

Exploring the wealth of information from all these TMDs reveals evidences of a rich 3D structure of the nucleon in the full momentum space and provides important information of the nucleon/parton spin-orbit correlations [16, 17].

2. Semi-Inclusive Deep Inelastic Scattering

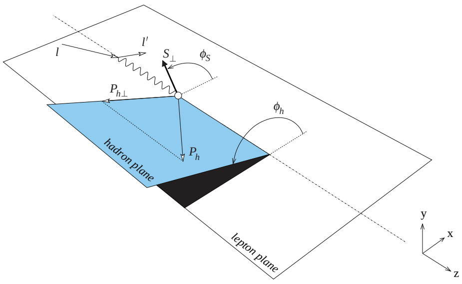


Figure 2: A scheme of the SIDIS process. The definitions of all quantities follow the Trento Convention.

All these TMDs can be accessed in the SIDIS processes. As illustrated in Fig. 2, an incoming electron is scattered by a quark in a nucleon and emits a virtual photon. The struck quark fragments into a hadron which is detected together with the scattered electron. The transverse momentum of the generated hadron ($p_h^\perp$) naturally couples to the quark spin and its initial orbital angular momentum. The SIDIS cross section is a convolutions of TMDs and Fragmentation Functions (FFs) [13]. While the FFs describe the hadronization process of the struck quark, TMDs get access to the correlations between the quark and the nucleon before the reaction. TMDs are embedded in different modulations depending on the beam and target polarization. Each modulation is as a function of the azimuthal hadron angle ϕ_h and quark transverse spin ϕ_S. Given the fact that these modulations are orthogonal, one is able to isolate each TMD, which is always convoluted by a particular FF, from the total cross section. The FFs can be separately obtained from other measurements, such as e^+e^- collider experiments [22]. To extract TMDs, a global analysis with the combination of the SIDIS data and the e^+e^- data is required to fully decouple the TMDs and FFs.

The common experimental approach to isolate individual TMD terms is to measure different azimuthal asymmetries with unpolarized or polarized SIDIS. For instance, by polarizing the target transversely in two opposite direction, one obtains a single target-spin asymmetry which is mainly composed of the Collins, Sivers and Pretzelosity asymmetries:

$$\begin{aligned} A_{UT}(\phi_h,\phi_S) &= \frac{1}{S_T}\frac{d\sigma(\phi_h,\phi_S - d\sigma(\phi_h,\phi_{S+\pi})}{d\sigma(\phi_h,\phi_S + d\sigma(\phi_h,\phi_{S+\pi})} \\ &= A_{UT}^{Collins} sin(\phi_h+\phi_S) + A_{UT}^{Sivers} sin(\phi_h-\phi_S) \\ &+ A_{UT}^{Pretzelosity} sin(3\phi_h-\phi_S) + \ldots, \end{aligned}$$

where $A_{UT}^{Collins} = \frac{2}{\pi}\int_0^\pi sin(\phi_h+\phi_S) d sin(\phi_h+\phi_S)\cdot A_{UT}(\phi_h,\phi_S)$. Analogously to the other two terms. These asymmetries are proportional to Sivers, Transversity and Pretzelosity TMDs associated with the FFs:

$$A_{UT}^{Collins} \propto \frac{h_1 \otimes H_1^\perp}{f_1 \otimes D_1}, A_{UT}^{Sivers} \propto \frac{f_{1T}^\perp \otimes D_1}{f_1 \otimes D_1}, A_{UT}^{Pretzelosity} \propto \frac{h_{1T}^\perp \otimes H_1^\perp}{f_1 \otimes D_1}, \tag{2.1}$$

where f_1 is the unpolarized PDF. $H_1^\perp$ and D_1 are the polarized and unpolarized FFs, respectively.

Utilizing the azimuthal moments of asymmetries in SIDIS to disentangle TMDs has been carried out by the HERMERS Collaboration [23] and the COMPASS Collaboration [24]. The JLab E06-110 Collaboration also successfully measured the SIDIS with longitudinally polarized electron beam and transversely polarized ^{3}He ("neutron") target. The single target-spin asymmetry results [25] showed sizable π^+ Collins asymmetry near $x = 0.34$, and negative Sivers π^+ asymmetry which is consistent with the measurements from HERMES and COMPASS. With the polarized beam and target, the collaboration also extracted the first ever asymmetries of g_{1T} [26], in which the π^- result gives a positive asymmetry while the π^+ one remains at zero. However, existing data is limited by the statistics as well as the kinematic coverage. A model-independent determination of these TMDs requires future data in a wider kinematic range with higher precision that allows a multiple dimensional analysis.

3. Precision Study of TMDs with SoLID

With the upgrade of the 12 GeV electron beam at JLab, we are developing an advanced solenoidal large intensity device (SoLID) [5] in Hall A to explore multiple physics topics, such as Parity Violation Deep Inelastic Scattering (PVDIS) [10], J/ψ production near the threshold [11], and the SIDIS as discussed here. The new device will provide unique features of large acceptance and high luminosity, which will open up a golden opportunity to study TMDs precisely by measuring both the single and double spin asymmetries in SIDIS processes with transversely and longitudinally polarized ^{3}He and proton targets [9]. We will be able to perform multi-dimensional binning on the new data in four kinematic quantities (Q^2, z, P_T and x), and fully map out TMDs in the valence quark region with unprecedented precision. We also can proceed a flavor separation with the combination of neutron and proton data taken within one detector system. Three highly rated experiments have been approved to perform these measurements:

- SIDIS with transversely polarized ^{3}He (E12-10-006) [6], approved 90 days, rated A
- SIDIS with longitudinally polarized ^{3}He (E12-11-007) [7], approved 35 days, rated A
- SIDIS with transversely polarized Proton (E12-11-108) [8], approved 120 days, rated A

Two run-group experiments [27, 28] were also approved, and more are coming to explore more interesting physics topics with these existing approved programs.

Fig. 3 illustrates the layout of the SoLID detector configuration dedicated to the SIDIS measurements. The system basically includes two detecting regions. The large-angle region, which is only for detecting electrons, is composed of four GEM trackers, one plane of scintillator pad detectors (SPD) for time-measurement and photon rejection, and a Shashlyk-type electromagnetic calorimeter (EC) for particle identification. The forward-angle region will detect both the electron and hadrons (e.g. $\pi^\pm$). It has two more GEMs in addition to the four GEMs shared by the large-angle region. A light-gas Čerenkov detector and a heavy-gas Čerenkov detector are used to perform e/π and π/K separations, respectively. A second SPD plane together with a Multi-gap Resistive Plate Chamber (MRPC) will provide precise timing information while rejecting most of high-energy photons. In the end, another EC plane is included. The entire detector system can cover the polar angle from 8° to 25°, and have a complete 2π coverage on the azimuthal angle. The momentum range goes from 1 GeV up to 7 GeV for both electrons and hadrons.

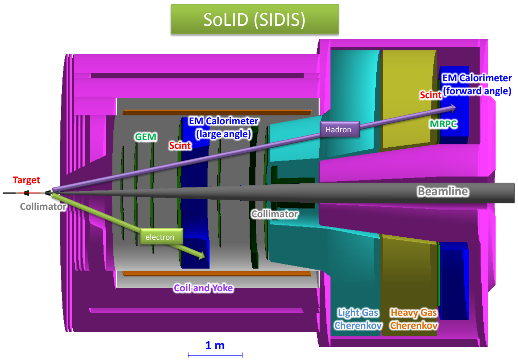


Figure 3: SoLID detector layout for the SIDIS measurements.

The design goal of this detector system is to maximize the detection capability and meanwhile, minimize the systematic uncertainties. The 2π azimuthal coverage, together with a nice feature of flipping target polarization in different directions, will help us to further reduce the systematic errors during the asymmetry extraction. We believe that with the high statistics and well controlled systematic uncertainties, the SoLID device will be an ideal detector for SIDIS and many other physics topics which have high demand on the experimental performance. For example, our collaborators are currently developing new GPD measurements with this detector configuration.

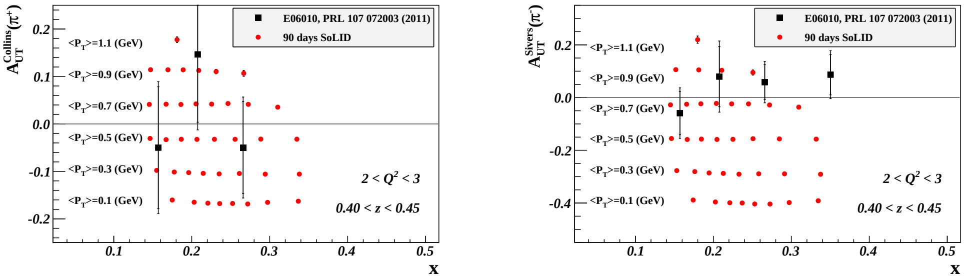


Figure 4: The projected JLab 12-GeV SoLID measurement of the π^+ Collins asymmetry and the π^- Sivers asymmetry from a transversely polarized ^{3}He target for a z bin of 0.4 to 0.45, and a Q^2 bin of 2 to 3 (GeV/c)^2 as a function of transverse momentum, and Björken x. The published result from the 6 GeV experiment is shown by black points [25].

As a demonstration, the 4D projected results of the π^+ Collins asymmetry and the π^- Sivers asymmetry in one typical (Q^2, z) bin are shown in Fig. 4. Such high statistical precision can be obtained within 90 days using a transversely polarized ^{3}He target. For the entire kinematic range, we have 48 similar bins which give totally 1400 data points. The data will enable us to individually isolate each TMD, provide quantitative information about the quark OAM inside the nucleon, and uncover crucial information about the dynamics of QCD.

Fig. 5 (right panel) reveals the current knowledge of the u and d quark tensor charge extracted, model-dependently, from analysis of existing data, and their predictions based on lattice QCD and

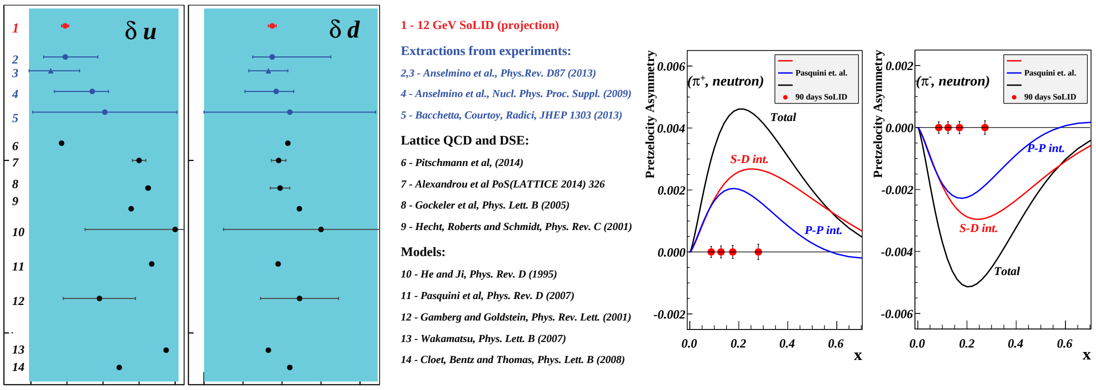


Figure 5: Left Panel: The projected precision of the tensor charge of u and d quark (red points) that SoLID data can achieve [29], together with model dependent extractions of these quantities based on the existing data (blue points). Predictions from lattice QCD calculations and various models are also given here (black points). Right Panel: The projected Pretzelosity asymmetry measurement from a transversely polarized ^{3}He target ("neutron") together with predictions from Boffi and Pasquini *et al.* [20] at the Q^2 value of 2.5 GeV^2.

various models. While the results from data consistent with each other but with large uncertainties, the values predicted by different models tend to fluctuate within a broad range. The future SoLID data, shown as the red point [29], should be able to pin down the uncertainty dramatically and provide important input for verifying various models and beyond the standard model search.

As the last example shown here, the figure on the left panel of Fig. 5 shows the projected measurements of the pretzelosity asymmetry on the neutron for both π^+ and π^-. The curves denote the model calculations from Ref. [20] and predict the contributions from interference of the S-D, and P-P orbital angular momenta together with the total. It is clear that at current stage, only the future high precision SoLID data will be able to isolate different contributions from such a small asymmetry, and hence provide quantitative information about the quark OAM.

4. Summary

We have given a brief discussion on the study of TMDs which can give access to the 3D structure of the nucleon, as well as the information of the quark OAM and its correlations with the nucleon spin. The SIDIS process serves as a powerful tool to probe individual TMDs by performing measurements of beam and/or target spin asymmetries. At 12 GeV era, by utilizing the high luminosity and large acceptance SoLID device together with polarized neutron and proton targets, the approved SIDIS programs in Hall A at JLab aim to uncover the full dependence of asymmetries in four-dimension bins (Q^2, z, p_T, x_B) and allow a model independent extraction of all TMD functions.

This work is supported in part by the U.S. Department of Energy under Contacts No. DE-FG02-03ER41231.

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