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The JLab TMD Program at 6 GeV and 11 GeV

Andrew Puckett[*†]
University of Connecticut, Storrs, CT
E-mail: andrew.puckett@uconn.edu

The precise mapping of the nucleon's transverse momentum dependent parton distributions (TMDs) in the valence quark region has emerged as one of the flagship physics programs of the recently upgraded Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab (JLab). The TMDs describe the three-dimensional, spin-correlated densities of quarks and gluons in the nucleon in momentum space, and are accessible experimentally through detailed studies of the Semi-Inclusive Deep Inelastic Scattering (SIDIS) process, $N(e,e'h)X$. The already unrivaled intensity, polarization and duty factor performance of CEBAF will combine with the dramatic expansion of its kinematic reach embodied by the recent near-doubling of the maximum beam energy to enable the first fully differential precision measurements of SIDIS structure functions in the valence region. In this paper, I will review the existing and forthcoming SIDIS results from the 6 GeV era of CEBAF operations and present an overview of the planned JLab SIDIS program at 11 GeV beam energy.

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[*]Speaker.

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1. Introduction

New insight regarding the three-dimensional quark structure of the nucleon in momentum space has emerged from the study of lepton-nucleon Semi-Inclusive Deep Inelastic Scattering (SIDIS). The simplest and best studied process both experimentally and theoretically is the single inclusive hadron electroproduction reaction $N(l,l'h)X$, in which a hadron h is observed carrying a large fraction z of the energy of the quark recoiling from a "hard" collision with the lepton beam and a small to moderate transverse momentum p_T^h relative to the (large) momentum transfer.

In the domain of "hard scattering", corresponding to large values of the momentum transfer $Q^2 \gtrsim 1$ GeV^2, the virtual photon-nucleon invariant mass $W^2 \gtrsim 4$ GeV^2 and the "missing" mass of unobserved final state particles $M_X^2 \gtrsim 2.5$ GeV^2, the SIDIS cross section "factorizes" as the convolution of universal, transverse-momentum-dependent parton distribution functions (TMDs), perturbatively calculable elementary hard scattering cross sections, and universal parton-to-hadron fragmentation functions [1, 2, 3, 4]. The TMDs depend on the longitudinal momentum fraction x carried by the quark, the initial quark transverse momentum $\mathbf{k}_\perp$, and the scale Q^2 of the hard subprocess. The fragmentation functions depend on the hadron energy fraction z, the scale Q^2, and the transverse momentum $\mathbf{p}_\perp$ generated in the fragmentation process. Eight TMDs contribute to the SIDIS cross section at leading twist, when all combinations of beam and target polarization are considered, and each can be separately extracted by measuring the dependence of the cross section on the azimuthal angles ϕ_h and ϕ_S between the lepton scattering plane and, respectively, the hadron production plane and the target spin direction [5].

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab (JLab) consists of two antiparallel superconducting radio-frequency linear accelerators connected by five magnetic recirculation arcs. At the end of 6 GeV operations in 2012, CEBAF routinely delivered high duty-cycle electron beams with energy up to 6 GeV, polarization up to 90% and continuous-wave beam currents of up to 180 μA to three different experimental halls [6, 7]. In this document, I give an overview of published and forthcoming SIDIS results from the 6 GeV era of CEBAF operations and an overview of the planned SIDIS program using the upgraded CEBAF beam. Note that the review of results from the 6 GeV program in this work closely follows and borrows heavily from the discussion in Ref. [8].

2. Results from Hall A

During 6 GeV operations, CEBAF's Experimental Hall A was equipped with two High Resolution Spectrometers (HRSs) with small acceptance in solid angle (~ 6 msr) and momentum ($\Delta p/p \sim \pm 5\%$) and high resolution ($\sigma_p/p \sim 10^{-4}$) for precise measurements in well-defined kinematics with good control of systematic uncertainties at high luminosities [9]. Experiment E06-010 ran in Hall A from November 2008 to February 2009. 5.9 GeV polarized electrons were scattered on a transversely polarized ^{3}He target, which functions as an effective polarized neutron target. Positive and/or negative hadrons were detected in the left HRS at a central momentum of 2.35 GeV/c and a central scattering angle of 16 deg. Scattered electrons were detected in the BigBite spectrometer [10] at a central angle of 30° on the beam right at x values ranging from $0.1 < x < 0.45$. The primary physics goal of E06-010 was the measurement of the target single-spin asymmetries (SSAs) in SIDIS, but many other significant physics results were obtained from the data, as described below.

E06-010 extracted the azimuthal moments of the transverse target SSA corresponding to the Collins ($A_{UT}^{\sin(\phi_h+\phi_S)}$) and Sivers ($A_{UT}^{\sin(\phi_h-\phi_S)}$) effects in the $^3He(e,e'\pi^+)X$ and $^3He(e,e'\pi^-)X$ channels [11], and also the charged kaon channels $^3He(e,e'K^+)X$ and $^3He(e,e'K^-)X$ [12]. The charged pion results are currently the most precise measurements of the neutron Collins and Sivers asymmetries for $x > 0.2$ and are largely consistent with the existing data and theoretical predictions available at the time of publication. The charged kaon Collins and Sivers asymmetries from E06-010 are consistent with zero for the K^+ channel and negative for the K^- channel, albeit with large statistical uncertainties. The same experiment also produced the first measurement of the double-spin asymmetry $A_{LT}^{\cos(\phi_h-\phi_S)}$ in SIDIS with a longitudinally polarized electron beam on a ^{3}He target [13]. This asymmetry is sensitive to the TMD g_{1T} describing the distribution of longitudinally polarized quarks in a transversely polarized nucleon. A clear non-zero asymmetry was observed for the $^3He(e,e'\pi^-)X$ channel, providing the first experimental indication of a non-zero A_{LT} in SIDIS on a ^{3}He (neutron) target.

The target-normal SSA A_y in inclusive DIS was also extracted from the data of E06-010 [14]. This asymmetry is identically zero in the one-photon-exchange approximation, but can be nonzero in the presence of multi-photon-exchange effects. The measured A_y asymmetry is non-zero and negative at the 2.9σ level, and is compatible in sign and magnitude with the prediction of a model of two-photon-exchange based on quark-gluon-quark correlators with input from the Sivers function measured in SIDIS [15].

SSAs of inclusive hadron production $^3He(e,h)X$, with $h = \pi^+, \pi^-, K^+, K^-, p$ were also extracted from E06-010 data [16]. These asymmetries have been predicted assuming validity of TMD factorization for the inclusive hadron production process via the Sivers and/or Collins mechanisms [17]. However, this factorization is not expected to be valid at the low values of hadron transverse momentum p_T for which these asymmetries were measured in Hall A. The inclusive hadron SSA data from E06-010 are nonetheless interesting given their high precision; the asymmetries are significantly nonzero and strongly dependent on the hadron species, and await theoretical interpretation.

E06-010 also produced the first measurement of the $A_{UT}^{\sin(3\phi_h-\phi_S)}$ ("pretzelosity") asymmetry for charged pions [18] on a ^{3}He (neutron) target. In the TMD framework, this asymmetry is generated via the convolution of the TMD $h_{1T}^{\perp}$ and the chiral-odd Collins fragmentation function $H_1^{\perp}$, and is sensitive to the interference between quark wavefunction components differing by two units of orbital angular momentum [19].

3. Results from Hall B

The CEBAF Large Acceptance Spectrometer (CLAS) in Hall B [20] is a six-coil toroidal magnetic spectrometer with a predominantly azimuthal magnetic field orientation, which results in large acceptance and moderate resolution at forward scattering angles. During the 6 GeV era of CEBAF operations, CLAS was used to study multi-particle final states with broad kinematic coverage in inclusive, semi-inclusive and exclusive reactions induced by electron and (tagged) photon beams.

The CLAS collaboration published cross sections for semi-inclusive π^+ electroproduction on an unpolarized proton target from data collected during the October 2001-January 2002 run period at a beam energy of 5.75 GeV [21]. The ϕ_h-independent structure functions were found to be in rather good ($\sim$20%-level) agreement with NLO pQCD predictions assuming dominance of current fragmentation. The measured $\langle\cos(2\phi_h)\rangle$ moments of the cross section, sensitive to the Boer-Mulders TMD [2], were found to be small, except at low z values, where they were positive. At JLab energies, the low-z data from CLAS are outside the region where TMD factorization is expected to be valid. The measured $\langle\cos(\phi_h)\rangle$ moments of the cross section were found to be small and incompatible with predictions of a significantly larger $\langle\cos(\phi_h)\rangle$ moment due to the sum of the Cahn [22] and Berger [23] effects.

CLAS also discovered the first clear evidence of a non-zero beam spin asymmetry (BSA) $A_{LU}^{\sin\phi_h}$ in semi-inclusive π^+ production [24] on an unpolarized proton target at a beam energy of 4.3 GeV. The $A_{LU}^{\sin\phi_h}$ asymmetry is a twist-three observable sensitive to qgq correlations, and has contributions from several twist-2 and twist-3 TMDs and fragmentation functions. Higher-energy (and higher precision) data for the BSA in semi-inclusive π^0 production at a beam energy of 5.78 GeV were obtained from the CLAS e1-dvcs experiment [25]. Very recently, even higher-precision data at 5.5 GeV from the CLAS e1f data set were published for the BSA in semi-inclusive π^+, π^- and π^0 production at a beam energy of 5.5 GeV [26]. With the addition of the recent CLAS data, existing SIDIS BSA data have reached an impressive level of kinematic coverage and precision with significant discrimination power among model calculations of the higher-twist effects that produce this observable.

CLAS has also measured SIDIS on a longitudinally polarized ammonia target and extracted the beam target double-spin asymmetry A_1^h and the longitudinal target single-spin asymmetry $A_{UL}^{\sin(2\phi_h)}$ in semi-inclusive production of charged and neutral pions at a beam energy of 5.7 GeV [27]. The results for the A_1 asymmetries suggest a non-trivial transverse momentum dependence of quark helicity distributions in the proton. The SSA results showed the first evidence for a non-zero $A_{UL}^{\sin(2\phi_h)}$, indicating potentially significant quark spin-orbit correlations in the proton. It is worth noting that the relative sign of the observed $A_{UL}^{\sin(2\phi_h)}$ asymmetry in π^+ production measured by CLAS and the $A_{LT}^{\cos(\phi_h-\phi_S)}$ asymmetry in π^- production on the neutron reported by the Hall A collaboration [13] is compatible with quark-model predictions of relations among the TMDs to which these observables are sensitive [28].

4. Results from Hall C

During the 6 GeV era at CEBAF, experimental Hall C was equipped with two moderate-acceptance, high-resolution focusing magnetic spectrometers for precise cross section measurements with well-defined acceptance at high luminosities [29], similar to the HRS pair in Hall A. In contrast to Hall A, the Hall C spectrometers were not identical but were designed with complementary capabilities. The High Momentum Spectrometer (HMS) is a superconducting magnetic spectrometer with a 25-degree central vertical bend angle, and is capable of reaching a central momentum of up to $\sim$7.5 GeV at its maximum field setting. The Short-Orbit Spectrometer (SOS) was designed with a short flight path for the efficient detection of unstable particles.

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The first dedicated SIDIS experiment at Jefferson Lab was carried out in Hall C [30, 31]. Differential cross sections for semi-inclusive π^+ and π^- production from liquid hydrogen and deuterium targets were surveyed in targeted kinematics to test the validity of a partonic description of the process at the relatively modest energy of 5.5 GeV. First, the z dependence of the cross section was scanned at a fixed $(x, Q^2) = (0.32, 2.3\ \mathrm{GeV}^2)$ with $p_T \approx 0$. Then, the x dependence was scanned in the range $0.2 < x < 0.6 (1.5 < Q^2 < 4.6\ \mathrm{GeV}^2)$ at a fixed z of 0.55, again with $p_T \approx 0$. Finally, the p_T dependence was measured from $0 < p_T < 0.4$ GeV at fixed $(x, Q^2, z) = (0.32, 2.3\ \mathrm{GeV}^2, 0.55)$. All measurements were carried out at a fixed value of the energy transfer $\nu = 3.8$ GeV. The experiment found that the SIDIS cross section was in reasonable agreement with a naive, leading-order parton-model prediction using standard PDFs and fragmentation functions, provided the missing mass $M_X^2 \gtrsim 2.5\ \mathrm{GeV}^2$ remained above the nucleon resonance region. Moreover, ratios of cross section differences $\sigma^{\pi^+} - \sigma^{\pi^-}$ obtained from proton and deuteron targets, which depend only on the valence PDF ratio d_V/u_V in first approximation, were consistent with predictions of this ratio from the CTEQ6 LO PDFs for $z < 0.7$. The p_T dependence of the cross sections for π^+ and π^- production from proton and deuteron targets were compatible with a Gaussian p_T dependence. The p_T^2 widths were similar, but not identical, for different hadron/target combinations.

5. Forthcoming Results from 6 GeV CEBAF Data

The long shutdown of CEBAF for the construction of the 12 GeV upgrade has halted the flow of new SIDIS data for the last several years. However, a significant number of additional SIDIS results are expected from ongoing analyses of previously collected data, mainly but not exclusively from the CLAS detector. Anticipated results include, but are not limited to:

- Hadron multiplicity ratios of heavy nuclei over deuterium for studies of quark hadronization and propagation in cold nuclear matter. Data are from the CLAS-eg2 experiment and nuclear targets include carbon, iron and lead.
- Unpolarized SIDIS cross sections, including hadron multiplicities and azimuthal moments such as $\cos(\phi_h)$ and $\cos(2\phi_h)$ for charged and neutral pions from the CLAS-e1f data set.
- High-statistics SIDIS data on longitudinally polarized NH_3 and ND_3 targets, including A_1^h and $A_{UL}^{\sin(2\phi_h)}$ asymmetries, from the CLAS-eg1-dvcs experiment.

6. The JLab TMD program at 11 GeV

A coherent and comprehensive program of SIDIS measurements is planned using the upgraded 11 GeV CEBAF, that exploits the complementary capabilities of experimental Halls A, B and C.

6.1 Hall A SIDIS program

The unique contribution of Hall A to the JLab 11 GeV SIDIS program consists of several large-installation experiments. The common feature of these experiments is their ability to take full advantage of polarized target technologies whose luminosity capabilities exceed that of the large acceptance CLAS12 spectrometer in Hall B (see below) by an order of magnitude or more. All of the approved SIDIS experiments in Hall A make use of the recent Gas Electron Multiplier (GEM) technology [32] for high-rate charged-particle tracking.

The first such experiment, E12-09-018 [33], approved for 64 beam-days, will use the existing BigBite spectrometer and the new Super BigBite Spectrometer (SBS) to measure target single (and double) spin asymmetries in SIDIS on a high-luminosity transversely polarized ^{3}He target [34]. E12-09-018 increases the statistical figure-of-merit for target SSA measurements by roughly a factor of 1,000 compared to E06-010 [11] by using the moderate solid angle and large momentum acceptance of SBS in place of the small-acceptance HRSs, and by increasing the design luminosity of the polarized $^3\mathbf{He}$ target by roughly a factor of 5 compared to E06-010, to a total useful luminosity of about 1.8×10^{37} cm^{-2} s^{-1}.

The other currently approved SIDIS experiments in Hall A will use the planned Solenoidal Large Intensity Device (SoLiD), a major new large-acceptance detector embedded in a solenoidal magnetic field, designed to operate at the high luminosities characteristic of Hall A with large acceptance, approaching (but not equaling) that of CLAS12 in Hall B. There are currently three approved SIDIS experiments in the SoLiD program. Experiments E12-10-006 [35] (90 approved beam-days) and E12-11-007 [36] (35 approved beam-days) will measure SIDIS spin asymmetries on transversely and longitudinally polarized $^3\mathbf{He}$ targets, respectively. The SoLiD polarized $^3\mathbf{He}$ measurements are complementary to those of E12-09-018 in that their kinematic coverage is mainly at lower values of Q^2, but their statistical precision is significantly higher, due to both the larger solid-angle acceptance and the larger SIDIS cross section at lower Q^2 values. A third approved SIDIS experiment using SoLiD is E12-11-108 [37] (120 approved beam-days), which will measure SIDIS on a transversely polarized proton ($N\mathbf{H}_3$) target.

6.2 Hall B SIDIS program

The upgraded CLAS12 spectrometer in Hall B has a design similar to the CLAS detector from the 6 GeV era, but with more acceptance at forward scattering angles and an order-of-magnitude higher design luminosity (compared to CLAS) of 10^{35} cm^{-2} s^{-1}. CLAS12 is a large acceptance, general-purpose detector of charged and neutral particles with momenta above 1 GeV/c, scattering angles greater than 5 degrees, and nearly 2π azimuthal angular acceptance. CLAS12, more than any other existing or planned detector at CEBAF, is ideally suited for broad surveys of the entire kinematic phase space of the SIDIS reaction accessible with an 11 GeV beam including measurements on unpolarized targets and polarized targets whose luminosity capabilities are well-matched to the design luminosity of CLAS12, such as dynamically polarized ammonia ($N\mathbf{H}_3$ and $N\mathbf{D}_3$) and transversely polarized solid HD in the frozen-spin state ("HDice"). It is the optimal detector for precision, fully differential mapping of the unpolarized SIDIS cross sections, including hadron multiplicities and azimuthal moments, and also the twist-3 beam-spin asymmetry $A_{LU}^{\sin\phi}$. Unpolarized SIDIS data from CLAS12 will lay the foundation for the theoretical interpretation of JLab SIDIS data and the global extraction of TMDs in the valence region. CLAS12 large-acceptance data will establish the region of validity of the TMD formalism for all SIDIS measurements in the 11 GeV era of CEBAF. The core unpolarized SIDIS data set will be produced by CLAS12 run groups "A", consisting of 139 approved beam-days at full luminosity on a liquid hydrogen target, and "B", consisting of 90 approved beam-days at full luminosity on a liquid deuterium target. Approved physics proposals include experiments E12-06-112 [38], E12-09-007 [39], E12-09-008 [40] and E12-11-109a [41]. Several experiments on polarized targets are also planned using the CLAS12 detector. CLAS12 run group "C" includes 170 approved beam-days at CLAS12 design luminosity on longitudinally polarized $N\mathbf{H}_3$ and $N\mathbf{D}_3$ targets, allowing for fully differential mapping of the A_{LL} and $A_{UL}^{\sin(2\phi)}$ asymmetries [42, 43]. Conditionally approved run group "G" will measure SIDIS on a transversely polarized solid HD target in the frozen-spin state ("HDice") [44], which has a maximum projected luminosity capability of 10^{34} cm^{-2} s^{-1} in the CEBAF electron beam. The *HDice* concept [44] has two very significant advantages over the more proven ammonia technology for large-acceptance electron-scattering experiments, in that it has low dilution factors (all of the target nucleons are polarized, in principle) and its polarization can be preserved with a relatively small holding field, minimizing the deflection of the primary beam and associated large backgrounds in the detectors. On the other hand, the expected maximum luminosity for such a target in an electron beam is about an order of magnitude below the design luminosity of CLAS12.

6.3 Hall C SIDIS program

The main role of experimental Hall C in the JLab 11 GeV SIDIS program is to provide unpolarized cross section measurements of high accuracy and precision in well-defined, targeted kinematics. The standard equipment of Hall C in the 11 GeV era includes the pre-existing High Momentum Spectrometer (HMS) and the new Super High Momentum Spectrometer (SHMS), which is similar in design to the HMS, but is capable of reaching more forward scattering angles and has a maximum momentum of 11 GeV. These small-acceptance, focusing magnetic spectrometers have well-defined acceptances and excellent angular and momentum resolution. Their detector packages are located in well-shielded, field-free regions at the end of long flight paths in vacuum through the spectrometer magnetic fields. The HMS and SHMS are designed to perform absolute cross section measurements with percent-level control of systematic uncertainties. Currently approved measurements include longitudinal/transverse separation of the unpolarized SIDIS cross section [45], measurements of π^+/π^- ratios in SIDIS on a deuterium target to constrain charge symmetry violation in quark distributions [46], measurements of the transverse momentum dependence of SIDIS cross sections [47], and measurements of semi-inclusive π^0 production as a validation of factorization for the SIDIS process [48]. These measurements will provide detailed understanding of the reaction mechanism of the SIDIS process, and provide powerful cross checks of the anticipated large-acceptance data from CLAS12.

7. Summary

The exploratory measurements of SIDIS observables during the 6 GeV era of CEBAF operations have shown that the partonic interpretation of the SIDIS process appears to be accessible even at the modest energies of the JLab 6 GeV era, albeit in a very limited phase space. These initial studies appear to show that the interpretation of 11 GeV SIDIS data in the TMD framework is feasible within a much larger useful phase space. The capabilities of CEBAF make it uniquely suited to carry out precision fully differential mapping of the SIDIS structure functions in the valence region. Mapping these structure functions on the four-dimensional kinematic phase space of the

SIDIS process requires experiments with high statistical figure-of-merit, especially for novel polarization phenomena such as the Collins and Sivers effects that generate relatively small observable asymmetries. High statistical figure-of-merit in turn requires the high beam polarization, intensity and duty factor of CEBAF, highly polarized proton and "neutron" targets that can operate at high luminosities, and detectors with large solid-angle and momentum acceptance at forward scattering angles that can operate in an environment of high background counting rate with good resolution and excellent particle ID performance. The complementary target and detector capabilities of Halls A, B and C will facilitate a SIDIS program that maximizes the physics productivity of the upgraded CEBAF by producing the "gold standard" data set for the extraction of TMD's from SIDIS data in the valence region.

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