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The 6 GeV TMD Program at Jefferson Lab

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Résumé. The study of the transverse momentum dependent parton distributions (TMDs) of the nucleon in semi-inclusive deep-inelastic scattering (SIDIS) has emerged as one of the major physics motivations driving the experimental program using the upgraded 11 GeV electron beam at Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF). The accelerator construction phase of the CEBAF upgrade is essentially complete and commissioning of the accelerator has begun as of April, 2014. As the new era of CEBAF operations begins, it is appropriate to review the body of published and forthcoming results on TMDs from the 6 GeV era of CEBAF operations, discuss what has been learned, and discuss the key challenges and opportunities for the 11 GeV SIDIS program of CEBAF.

1 Introduction

New insight regarding the spin-dependent, three-dimensional momentum distributions of quarks in the nucleon has emerged from the study of lepton-nucleon Semi-Inclusive Deep Inelastic Scattering (SIDIS). The simplest and most well-studied SIDIS process from both the experimental and theoretical points of view is the single inclusive hadron electroproduction reaction $N(l, l'h)X$, in which a hadron h emerges at small to moderate transverse momentum p_T carrying a large fraction z of the energy of a quark recoiling after a "hard" deep inelastic collision with the lepton beam.

In the hard scattering regime, 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), elementary hard scattering cross sections calculable in perturbative QCD, and universal parton-to-hadron fragmentation functions [1–4]. 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. 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. In the leading-twist approximation, eight TMDs contribute to the SIDIS cross section 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].

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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. By 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, we review key results on SIDIS and TMDs from the 6 GeV era of CEBAF operations.

2 Results from Hall A

Experimental Hall A is 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 [8]. 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 angle of 16 deg. Scattered electrons were detected in the BigBite spectrometer [9] 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 numerous 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 and Sivers effects in the $^3He(e, e'\pi^+)X$ and $^3He(e, e'\pi^-)X$ channels [10]. The 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 same experiment also produced the first measurement of the double-spin asymmetry A_{LT} in SIDIS on a ^{3}He target [11]. 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.

The target-normal SSA A_y in inclusive DIS was also extracted from the data of E06-010 [12]. 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 [13].

SSAs of inclusive hadron production $^3He(e, h)X$, with $h = \pi^+, \pi^-, K^+, K^-, p$ were also extracted from E06-010 data [14]. These asymmetries have been predicted assuming validity of TMD factorization for the inclusive hadron production process via the Sivers and/or Collins mechanisms [15]. 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.

3 Results from Hall B

The CEBAF Large Acceptance Spectrometer (CLAS) in Hall B [16] 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 [17]. 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 [18] and Berger [19] 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 [20] 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 [21]. 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 [22]. 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 [23]. 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 [11] is compatible with quark-model predictions of relations among the TMDs to which these observables are sensitive [24].

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 [25], 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.

The first dedicated SIDIS experiment at Jefferson Lab was carried out in Hall C [26, 27]. 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 a relatively modest energy of 5.5 GeV. First, the z dependence of the cross section was scanned at a fixed $(x, Q^2) = (0.32, 2.3\ \text{GeV}^2)$ with $p_T \approx 0$. Then, the x dependence was scanned in the range $0.2 < x < 0.6(1.5 < Q^2 < 4.6\ \text{GeV}^2$ 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 $(x, Q^2, z) = (0.32, 2.3\ \text{GeV}^2, 0.55)$. 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 $M_X^2 \gtrsim 2.5\ \text{GeV}^2$ 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 data for the last two 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 the 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 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.

– Measurements of the $A_{UT}^{\sin(3\phi_h - \phi_S)}$ ("pretzelosity") asymmetry for charged pions from the Hall A polarized ^3He SIDIS data (E06-010 [28]). In the TMD framework, this asymmetry is the convolution of the $h_{1T}^{\perp}$ TMD with the Collins fragmentation function $H_1^{\perp}$, and is sensitive to the interference between quark wavefunction components differing by two units of orbital angular momentum [29].

– Collins and Sivers asymmetries in charged kaon production from the Hall A polarized ^3He SIDIS data (E06-010 [30]).

6 Outlook for 11 GeV CEBAF

The construction of the CEBAF upgrade is largely complete and commissioning of the upgraded accelerator has begun as of April 1, 2014. The 11 GeV maximum beam energy will significantly expand the volume of the kinematic phase space accessible in the SIDIS regime at JLab. The expanded kinematic reach of the upgraded CEBAF, when combined with its already unrivaled performance in terms of duty factor, intensity and polarization, will enable a comprehensive program of SIDIS studies of unprecedented precision. New polarized targets and detectors being constructed in Halls A, B and C will maximally exploit the potential of the upgraded CEBAF. High statistical figure-of-merit for polarized and unpolarized SIDIS observables will be reached using the complementary capabilities of the experimental halls. The large-acceptance CLAS12 detector in Hall B will perform broad-based surveys on polarized and unpolarized targets with the widest possible kinematic coverage at moderately high luminosities. Hall A will provide high-precision SIDIS data, especially on polarized neutron (^3He) targets, using a combination of moderately large acceptance and very high luminosity to reach high figure-of-merit at large Q^2 values. High-luminosity SIDIS studies in Hall A are facilitated by novel detection systems capable of high-rate charged particle tracking, such as the near-future Super BigBite Spectrometer, and the planned Solenoidal Large Intensity Device (SoLID) in the longer term. Hall C will provide precision cross section measurements with well-understood acceptance in well-defined kinematics using the existing High Momentum Spectrometer and the new Super High Momentum Spectrometer. The upgraded CEBAF will provide the first precision fully-differential 4D (x, Q^2, z, p_T) mapping of SIDIS observables in the valence region ($0.1 \lesssim x \lesssim 0.8$), and will lay the foundation for TMD studies at high energies and lower x values at a future electron-ion collider.

7 Summary and Conclusions

Much has been learned from the initial, exploratory studies of SIDIS at Jefferson Lab in the 6 GeV era. Perhaps the most significant outcome of these investigations is that the parton-model description of SIDIS appears to be accessible even at the relatively low energies of the 6 GeV era at CEBAF, albeit in a rather limited volume of the SIDIS phase space : $M_X^2 > 2.5\ \text{GeV}^2$, $W^2 > 4\ \text{GeV}^2$, $Q^2 > 1\ \text{GeV}^2$, $0.4 \leq z \leq 0.7$. Nonetheless, it certainly appears feasible to interpret SIDIS data at 11 GeV beam energy in the TMD framework. Given this reality, studies of SIDIS and TMDs have emerged as one of the main physics goals for the experimental program in the 12 GeV era of CEBAF. Nonetheless, significant challenges remain, including but not limited to the role of higher-twist and higher-order QCD effects, the model-independent extraction of TMDs from global analysis of observables of SIDIS and other reactions, the difficulties due to uncertain knowledge of fragmentation functions, and the contributions from target fragmentation. In addition, the expected data will pose new challenges in the control of experimental (and theoretical) systematic uncertainties to a level commensurate with the unprecedented statistical precision, and surprises are certaintly expected. In summary, the studies of SIDIS using CEBAF at 6 GeV have laid the foundation for the exciting, comprehensive, and highly-anticipated program of TMD studies that is about to begin with the upgraded CEBAF.

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