Studies of the 3D structure of the proton at Jlab

H. Avakian[†]

[†] *Jefferson Lab, 12000 Jefferson Ave., Newport News, VA 23606*

Abstract

In recent years parton distributions, describing longitudinal momentum, helicity and transversity distributions of quarks and gluons, have been generalized to account also for transverse degrees of freedom. Two new sets of more general distributions, Transverse Momentum Distributions (TMDs) and Generalized Parton Distributions (GPDs) were introduced to describe transverse momentum and spatial distributions of partons. Great progress has been made since then in measurements of different Single Spin Asymmetries (SSAs) in semi-inclusive and hard exclusive processes, providing access to TMDs and GPDs, respectively. Studies of TMDs and GPDs are also among the main driving forces of the JLab 12 GeV upgrade project.

1 Introduction

The orbital momentum of partons has been of central interest since the SLAC and EMC measurements implied that the helicity of the constituent quarks account for only a fraction of the nucleon spin. Single-spin asymmetries (SSA) in azimuthal distributions of final-state particles in semi-inclusive deep inelastic scattering (DIS) play a crucial role in the study of transverse momentum distributions of quarks in the nucleon and provide access to the orbital angular momentum of quarks. In recent years, measurements of azimuthal moments of polarized hadronic cross sections in hard processes, and in particular the SSAs, have emerged as powerful tools to probe nucleon structure through their sensitivity to Generalized Parton Distributions (GPDs) and Transverse Momentum Dependent parton distribution functions (TMDs) in hard exclusive and semi-inclusive production of final states particles, respectively (see Table 1). The first unambiguous measurements of single spin phenomena in SIDIS, which triggered important theoretical developments, were the sizable longitudinal target spin asymmetries ($A_{UL}^{\sin\phi}$) observed at HERMES [1, 2]. Measurements of non-zero SSAs in electroproduction attracted a huge amount of theoretical and experimental interest, and many experiments worldwide are currently trying to pin down various effects related to nucleon structure through semi-inclusive deep-inelastic scattering (HERMES

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^{\perp}$
L		$\mathbf{g_{1L}}$	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 , $h_{1T}^{\perp}$

	U	L	T
U	$\mathcal{H}$		$\mathcal{E}_T$
L		$\widetilde{\mathcal{H}}$	$\widetilde{\mathcal{E}}_T$
T	$\mathcal{E}$	$\widetilde{\mathcal{E}}$	$\mathcal{H}_T$,$\widetilde{\mathcal{H}}_T$

Table 1: Leading twist TMD distribution functions (left) and GPDs[10] (right). The U,L,T correspond to unpolarized, longitudinally polarized and transversely polarized nucleons (rows) and quarks (columns).

at DESY, COMPASS at CERN, Jefferson Lab), polarized proton-proton collisions (PHENIX, STAR and BRAHMS at RHIC), and electron-positron annihilation (Belle at KEK). Two fundamental QCD mechanisms giving rise to single spin asymmetries were identified. First, the Collins mechanism [3, 4, 5], where the asymmetry is generated in the fragmentation of transversely polarized quarks, and second, the Sivers mechanism [6, 7, 8, 9], where the asymmetry is generated by final state interactions at the distribution-function level. Studies of SSAs are currently driving the upgrades of several existing facilities (JLab and RHIC) and the design and construction of new facilities worldwide (EIC, GSI, and JPARC).

All TMD parton distributions are accessible in spin and azimuthal asymmetry measurements in SIDIS with polarized beams and targets, where the TMDs appear convoluted with corresponding fragmentation functions. So far QCD factorization for semi-inclusive deep inelastic scattering at low transverse momentum in the current fragmentation region has been established in Refs. [8, 9] only for leading-twist contributions. Structure functions factorize into TMD parton distributions, fragmentation functions, and hard scattering terms $(H_{UU}, ...)$[8]

$$
\begin{aligned}
\sigma_{UU} &\propto F_{UU} \propto && f_1\left(x, k_T\right) D_1\left(z_h, p_T\right) H_{UU}\left(Q^2\right), \\
\sigma_{LL} &\propto F_{LL} \propto && g_1\left(x, k_T\right) D_1\left(z_h, p_T\right) H_{LL}\left(Q^2\right), \\
\sigma_{UL} &\propto F_{UL} \propto && h_{1L}^{\perp}\left(x, k_T\right) H_1^{\perp}\left(z_h, p_T\right) H_{UL}\left(Q^2\right),
\end{aligned}
$$

where k_T and p_T are quark transverse momenta before and after scattering, z_h is the fractional energy of the detected hadron, and the hadron's transverse momentum is $P_T = zk_T + p_T$. Distribution functions f_1,g_1 and $h_{1L}^{\perp}$ describe unpolarized quarks in an unpolarized nucleon, longitudinally polarized quarks in a longitudinally polarized nucleon, and transversely polarized quarks in a longitudinally polarized nucleon, respectively. Unpolarized (D_1) and polarized ($H_1^{\perp}$ Collins) fragmentation functions also depend on the transverse momentum of the fragmenting quark.

2 Future measurements of 3D PDFs with CLAS12

Recent measurements of multiplicities and double spin asymmetries as a function of the final transverse momentum of pions in SIDIS at JLab [11, 12] suggest that transverse momentum distributions may depend on the polarization of quarks and possibly also on their flavor. Kinematic dependencies of single and double spin asymmetries have been measured in a wide range in x and P_T with CLAS using a longitudinally polarized proton target. Measurements of the P_T-dependence of the double spin asymmetry, performed for the first time, indicate the possibility of different average transverse momenta for quarks aligned or anti-aligned with the nucleon spin [12].

Precision measurements using the upgraded CLAS detector (CLAS12) with polarized NH_3 and ND_3 targets will allow access to the k_T-distributions of u and d-quarks aligned and anti-aligned with the spin of the nucleon. Projections for the resulting P_T-dependence of the double spin asymmetries for all three pions are shown in Fig. 1 for an NH_3 target [13, 14]. Integrated over transverse momentum, the data will also be used to extract the k_T-integrated standard PDFs.

A wider range in Q^2 provided by the CLAS12 detector at JLab would also allow studies of Q^2-evolution, important for understanding and controlling possible higher-twist contributions. By using QCD evolved TMDs one can explain observed discrepancies between HERMES [15] and COMPASS [16, 17] data, and predictions have been made for the non-trivial behavior of the Sivers asymmetry as a function of Q^2 [18]. Measuring the Q^2-dependence of the Sivers function is one of the main goals of the upgraded CLAS12 experiment using a transversely polarized HD target [19]. The projected Q^2-dependence of the Sivers function, as expected from CLAS12 is shown in Fig. 1.

At large x ($x > 0.2$), a region well-covered by JLab [13, 14], a large $\sin 2\phi$ target SSA has been predicted (see Fig.2), which is sensitive to the distribution function $h_{1L}^{\perp}$ [21, 22, 23, 24, 25]. The same distribution function is also accessible in double-polarized Drell-Yan production, where it gives rise to a $\cos 2\phi$ azimuthal moment in the cross section [4].

The $\sin\phi$ moment of the spin-dependent cross section for the longitudinally polarized target, first measured by the HERMES Collaboration [1], is dominated by higher-twist contributions [26] which are suppressed by $1/Q$ at large momentum transfer. Higher-twist observables, such as longitudinally polarized beam or target SSAs, are important for understanding long-range quark-gluon dynamics. Recently, higher-twist effects in SIDIS were inter-

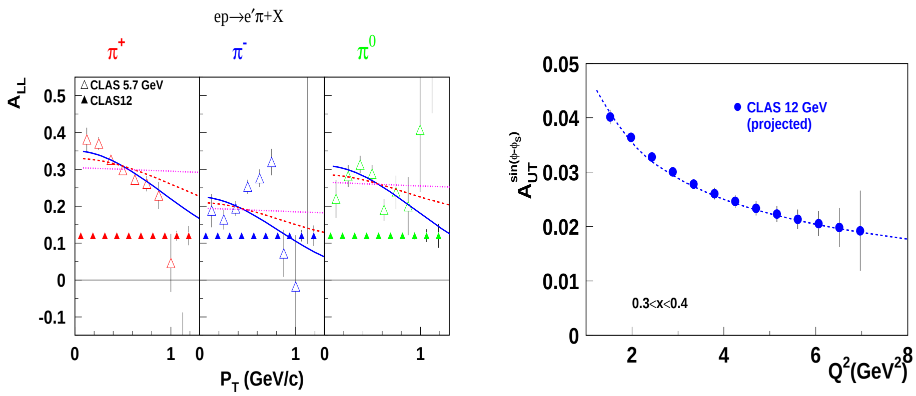

Figure 1: Projected double spin asymmetry A_{LL} (left) for the NH_3-target as a function of the transverse momentum of hadrons, P_T, averaged over $0.4 < z_h < 0.7$ range. Curves are calculated using different k_T widths for helicity distributions [20] and the Q^2-dependence of the Sivers asymmetry (right) for a given bin in x. The curve corresponds to predictions based on the evolution of the Sivers function [18]

preted in terms of an average transverse force acting on the active quarks at the instant after being struck by the virtual photon [27].

Only three functions at twist-3 (from 16) survive integration over transverse momentum (collinear functions): e, h_L and g_T. Together with the twist-2 PDFs (f_1, g_1, h_1), they give a detailed picture of the nucleon in longitudinal momentum space. Higher twist (HT) functions are of interest for several reasons. Most importantly, they offer insights into the physics of the largely unexplored quark-gluon correlations, which provide direct and unique insights into the dynamics inside hadrons [28]. They describe multiparton distributions corresponding to the interference of higher Fock components in the hadron wave functions, and, as such, have no probabilistic partonic interpretations. Yet they offer fascinating doorways into the study of the structure of the nucleon.

The comparison of beam SSAs for all 3 pions [29, 30, 31, 32], with contributions from only the Collins effect, indicate that Sivers-type contributions ($g^{\perp} \otimes D_1$)[33] may be significant for π^+ and π^0 but small for π^-. This is consistent with the latest observations by HERMES and COMPASS [15, 16, 17], where a large Collins effect was observed for charged pions, while the Sivers effect was found to be significant only for π^+.

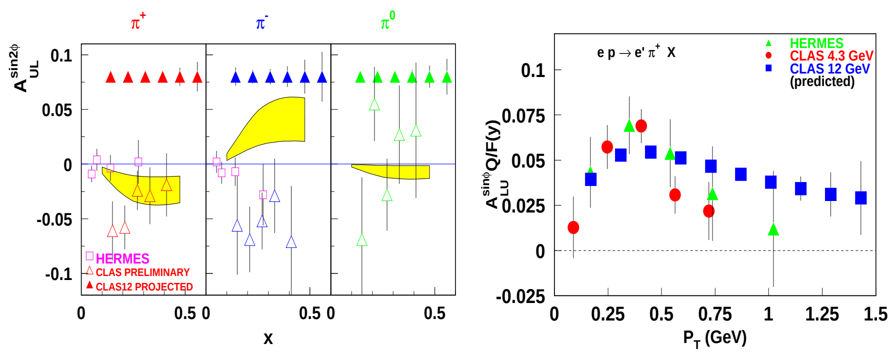

Figure 2: The projected x-dependence of the target SSA at 11 GeV. The triangles illustrate the expected statistical accuracy. The open squares and triangles show the existing measurement of the Kotzinian-Mulders asymmetry from HERMES and the results from 5.7 GeV CLAS data sets, respectively. The curves are calculated using Ref. [34]. The projected beam-spin analyzing power (blue squares) is shown in the right panel for the $\sin\phi$ moment as a function of transverse momentum of the π^+. The P_T-dependent SSA from HERMES is corrected for the kinematic factor accounting for different average y in two experiments.

Measurements of various observables in hard exclusive production versus the momentum transfer to the nucleon, t, on other hand, provide the information necessary for transverse nucleon imaging [37]. The different nucleon spin components of the GPDs[35, 36] can be extracted by measuring spin asymmetries in Deeply Virtual Compton Scattering (DVCS) with polarized targets. Information about the flavor decomposition requires measurements with both protons and neutrons. Additional information about the spin/flavor separation can come from meson production data. The DVCS single spin asymmetry for a transversely polarized target is the most sensitive observable to the elusive GPD E, providing access to the orbital angular momentum. Comparison of theoretical predictions to data on DVCS spin azimuthal asymmetries from the HERMES Collaboration for a transversely polarized target [38] indicate a great sensitivity to the angular momentum of u-quarks.

A full program to extract GPDs from measurements requires coverage over a large kinematic range in x_B, t, and Q^2, along with measurements of several final states, using a polarized beam and a polarized target (both longitudinal and transverse). Results that yield Compton Form Factors (CFFs) using the fitting code of Ref. [39] provide access to the corresponding GPDs. Projected data from all approved CLAS12 DVCS measurements with a longitudinally polarized beam will be analyzed together. Combinations of CLAS12 experiments with unpolarized, longitudinally polarized and transversely polarized targets will allow the extraction of seven CFFs for essentially all (x_B, Q^2, t) bins with quite good precision. In particular, the measurement of the transverse target spin observables is crucial for reconstructing the E CFFs (see Fig. 3).

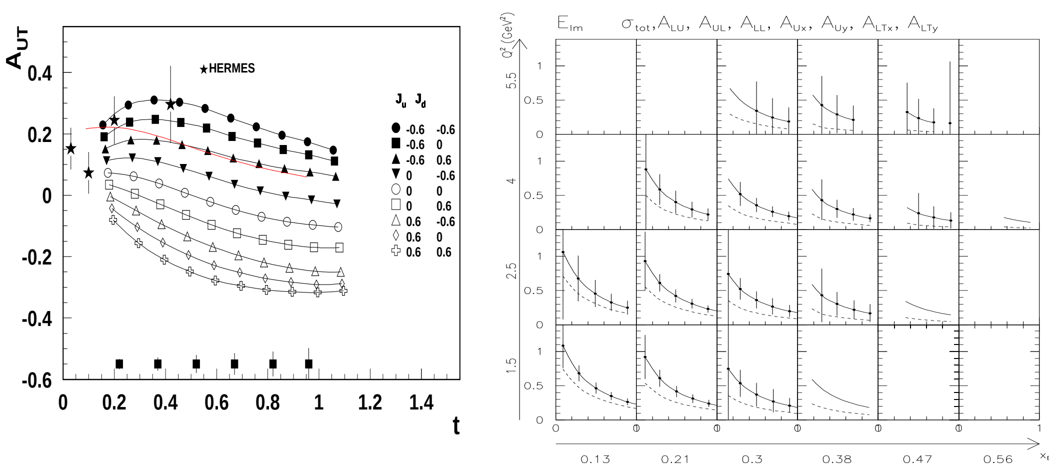

Figure 3: Expected $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ amplitudes as a function of t, (left) as predicted by the dual parametrization for GPDs H and E [40] ($\widetilde{\mathcal{H}} = \widetilde{\mathcal{E}} = 0$). The projected statistical errors on A_{UT} correspond to 100 days of running with hydrogen at a polarization of 60% for average values of $x = 0.2$ and Q^2=2.5 GeV^2. The red curve shows the VGG model prediction using the valence approximation for GPD-E. HERMES [41] points are shown for comparison. The systematic error is expected to be smaller than the statistical one. The right panel shows projected CFFs from the simultaneous fit to A_{LU}, A_{UL}, A_{LL}, A_{Ux}, A_{Uy}, A_{Lx}, A_{Ly} and of the unpolarized cross section. For each (x_B, Q^2, t) bin the $Im\{\mathcal{E}\}$ CFF is displayed as a function of t.

A combined analysis of CLAS12 data sets from unpolarized, longitudinally polarized, and transversely polarized targets will allow to extract all relevant TMDs and GPDs, which describe the 3D structure of the nucleon.

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