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Studies of the 3D Structure of the Nucleon at JLab

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Abstract Studies of the 3D structure of the nucleon encoded in Transverse Momentum Dependent distribution and fragmentation functions of partons and Generalized Parton Distributions are among the key objectives of the JLab 12 GeV upgrade and the Electron Ion Collider. Main challenges in extracting 3D partonic distributions from precision measurements of hard scattering processes include clear understanding of leading twist QCD fundamentals, higher twist effects, and also correlations of hadron production in target and current fragmentation regions. In this contribution we discuss some ongoing studies and future measurements of spin-orbit correlations at Jefferson Lab.

Keywords spin · nucleon structure · parton distributions

1 Introduction

The quark-gluon dynamics manifests itself in a set of non-perturbative functions describing all possible spin-spin and spin-orbit correlations, in particular, describing transverse momentum dependent distributions of partons (TMDs), transverse space distributions of partons or Generalized Parton Distributions (GPDs), and Fracture Functions (FFs), defined as conditional probabilities to produce a hadron in the target fragmentation for a given flavor of a struck quark (see Table 1). In recent years, measurements of azimuthal moments of polarized hadronic cross sections in hard processes have emerged as a powerful tool to probe nucleon structure in general and access the TMDs and GPDs, in particular. Many experiments worldwide are currently trying to pin down various effects related to the nucleon structure through semi-inclusive deep-inelastic scattering (HERMES at DESY [1; 2; 3; 4], COMPASS at CERN [5; 6; 7; 8; 9], Jefferson Lab [10; 11; 12; 13; 25; 14; 15]) polarized proton-proton collisions (PHENIX, STAR and BRAHMS at RHIC) [16; 17; 18], and electron-positron annihilation (Belle and BaBar) [19; 20; 21].

Azimuthal distributions of final state particles in semi-inclusive deep inelastic scattering, in particular, are sensitive to the orbital motion of quarks and play an important role in the study of TMDs in the nucleon. The first results on transverse Single Spin Asymmetries (SSAs) in azimuthal distributions of final state hadrons have been reported by the HERMES and COMPASS [3; 5; 6; 22; 8; 7; 9] collaborations, indicating significant azimuthal moments generated both by the Collins [23] and the Sivers [24] effects, describing spin orbit correlations in the final hadronization and initial distribution processes, respectively.

Measurements of SSAs at JLab, performed with longitudinally polarized NH_3 [13] and transversely polarized ^3He [25; 26; 15; 14], indicate that spin orbit correlations may be significant for certain

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N/q	U	L	T		U	L	T		U	L	T
U	$\mathbf{f}_1$		$h_1^\perp$	U	$\mathcal{H}$		$\mathcal{E}_T$	U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L		$\mathbf{g}_{1L}$	$h_{1L}^\perp$	L		$\tilde{\mathcal{H}}$	$\tilde{\mathcal{E}}_T$	L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}^\perp$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1, h_{1T}^\perp$	T	$\mathcal{E}$	$\tilde{\mathcal{E}}$	$\mathcal{H}_T, \tilde{\mathcal{H}}_T$	T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^h, \hat{t}_{1T}^\perp, \hat{t}_{1T}^{\perp\perp}$

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

Fig. 1 The Kotzinian-Mulders asymmetry from CLAS (left plot). The open squares and triangles show the existing measurement from HERMES and the preliminary results from CLAS 5.7 GeV CLAS data sets [13], respectively. The curves are calculated using Ref. [27]. The left panel shows the SSA from Hall-A [26].

combinations of spins of quarks and nucleons and transverse momentum of scattered quarks. Single spin asymmetries measured by CLAS with longitudinally polarized protons (NH_3 target) related to the TMD $h_{1L}^\perp$, describing transversely polarized quarks in the longitudinally polarized nucleon, and the one measured by Hall-A with the transversely polarized neutron (polarized ^3He target) related to the TMD $g_{1T}^\perp$, describing longitudinally polarized quarks in the transversely polarized nucleon (see Fig. 1), are consistent with the light-cone quark model predictions [28], as well as lattice calculation [29] for corresponding TMDs, for the expected relative sign of SSAs $A_{UL}^{\sin 2\phi}$ in $e\pi^+X$ and $A_{LT}^{\cos(\phi - \phi_S)}$ in $e\pi^-X$.

Significant azimuthal moments in leptonproduction ($A_{UU}^{\cos \phi}$), which have been measured in SIDIS already by EMC collaboration [30; 31], were reproduced by latest measurements at CERN, HERMES and JLab [11; 12; 32; 33; 34]. The first unambiguously measured single spin phenomena in SIDIS, which triggered important theoretical developments, were the sizable longitudinal target ($A_{UL}^{\sin \phi}$) and beam ($A_{LU}^{\sin \phi}$) spin asymmetries observed at HERMES and JLab [1; 2; 10; 4]. They could be interpreted in terms of higher twist distribution functions.

Recent measurements of multiplicities and double spin asymmetries as a function of the final transverse momentum of pions in SIDIS at JLab and HERMES [11; 13; 47] suggest that transverse momentum distributions may depend on the polarization of quarks and possibly also on their flavor. Calculations of transverse momentum dependence of TMDs in different models [35; 36; 28; 37] and on lattice [29; 38] indicate that the dependence of the transverse momentum distributions on the quark polarization and flavor may be very significant. Combination of measurements in a large Q^2 range from HERMES, COMPASS and JLab would allow studies of evolution effects and control possible higher twist contributions in the measurements of TMD observables in general, and of the Sivers asymmetry in particular. Comparison of JLab12 data with HERMES, COMPASS, and future Electron Ion Collider (EIC) (Fig.2) will pin down the non-trivial Q^2 evolution of Sivers asymmetry.

Much higher Q^2 range accessible at JLab12 would allow for studies of Q^2 -dependence of different higher twist spin-azimuthal asymmetries (Fig 3), which, apart from providing important information on quark-gluon correlations are needed for understanding of possible corrections from higher twists

Fig. 2 Comparing CLAS12 and EIC [39] projected data with HERMES [46] and COMPASS [8] results on the Sivers asymmetry.

Fig. 3 Projections for higher-twist lepton spin asymmetry $A_{LU}^{\sin\phi}$ for positive pion production as a function of Q^2 (right) compared to published data from CLAS [10] and projected CLAS12 [40] in one x, z bin ($0.2 < x < 0.3$, $0.5 < z < 0.55$). The right panel shows projections for x -dependence of the SSA measurements with CLAS12 using two hadron production [41]. Lines correspond to model predictions based on bag [58] and spectator [42] models.

to leading twist observables. An important process, which can provide independent information on twist-3 TMDs, is the di-hadron production in SIDIS [49]. The projections for corresponding CLAS12 measurements [41] of the SSA in dihadron production as a function of Bjorken- x are shown in Fig.3.

2 Target fragmentation and back-to-back hadron production

Although the Target Fragmentation Region (TFR) of DIS, when the hadrons are created from the target remnant, carries important information about the spin and flavor structure of the nucleon, it has not been studied systematically in experiments due to lack of theory fundamentals. The main physical question in the TFR is how the diquark-like remnant system after the DIS process dresses itself up to become a full-fledged hadron, i.e., by which mechanism the quark-antiquark pairs restoring color neutrality are produced, and how this process is correlated with the spin of the target or/and the produced particles. Recently the leading twist formalism for spin and transverse-momentum dependent fracture functions (FFs) has been developed [48]. The structure functions defining the cross section for hadron production in TFR for different polarization states involve unpolarized, longitudinally and transversely polarized quark FFs (see Tab. 1). With hadrons detected in the TFR, the beam SSAs appear already at leading order. With two hadrons detected in the final state, structure functions may depend also on the relative azimuthal angle of the two hadrons, generating a long range correlation between hadrons produced in CFR and TFR. The kinematic plane for back-to-back hadron production is shown on Fig. 4.

Fig. 4 Kinematic plane for back-to-back (b2b) hadron production in SIDIS (left) and measured SSA in back-to-back proton and π^+ production as a function of the product of their transverse momenta $P_{T1}P_{T2}$.

Choosing as independent azimuthal angles $\Delta\phi = \phi_2 - \phi_1$ and ϕ_2 , the beam spin asymmetry could be defined as

$$A_{LU}(x, z, P_{T1}^2, P_{T2}^2, \Delta\phi, \dots) = \frac{\int d\phi_2 \sigma_{LU}}{\int d\phi_2 \sigma_{UU}} = \frac{-\frac{P_{T1}P_{T2}}{m_2 m_N} F_{k1}^{\hat{u} \cdot D_1} \sin(\Delta\phi)}{F_0^{\hat{u} \cdot D_1}}, \quad (1)$$

where z is the fraction of the virtual photon energy carried by the forward pion, P_{T1}, P_{T2} are transverse momenta of the final state hadrons, and structure functions $F_0^{\hat{u} \cdot D_1}$ and $F_{k1}^{\hat{u} \cdot D_1}$ are convolutions of unpolarized and polarized FFs with the standard unpolarized fragmentation function D_1 . First measurements of single spin asymmetry defined by Eq.1 in semi-inclusive production of protons and charged pions in coincidence with the scattered electron in hard scattering kinematics ($Q^2 > 1 \text{ GeV}^2$, $W^2 > 4 \text{ GeV}^2$) have been performed by the CLAS collaboration using 5.5 GeV and 5.7 GeV longitudinally polarized electron beams scattering off a 5-cm-long liquid-hydrogen target (CLAS e1f and e16 experiments). The beam spin asymmetry, $A_{LU}^{\sin \Delta\phi}$, has been calculated as a sinusoidal modulation of the difference of azimuthal angles of proton and π^+ with respect to the lepton scattering plane, for different electron helicity states. The modulation was extracted for different bins in x, z of the pion and the product of transverse momenta of final state proton and pion with respect to the virtual photon in the CM frame. Target and current fragmentation regions were selected by cuts on the x_F variables of protons ($x_F < 0$) and pions ($x_F > 0$).

Significant asymmetries in b2b production of protons and pions have been observed for all 3 pions in the final state. The z -dependence of the SSA shows a trend for asymmetry (see Fig.4) to change the sign at large z , indicating opposite sign in the exclusive limit. With a cut on the missing mass of the e/π^+X system, $M_X > 1.4$ we have almost no data at $z > 0.7$.

The x -dependence of the $A_{LU}^{\sin \phi}$ is consistent with asymmetry being large in the large- x region, where the valence quark presence is very significant. Similar behavior has been observed also for events with neutral and negative pions in the final state, detected in coincidence with scattered electron and proton in the target fragmentation region.

3 Hard Exclusive Processes and GPDs

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 [50]. The different nucleon spin components of the GPDs [44; 43] describing unpolarized and longitudinally polarized quarks (Table 1) 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. The latest measurements of DVCS cross sections from unpolarized proton target from JLab Halls A&B [59; 52] are consistent with theory predictions for a rapid change of the cross section with azimuthal angle, due to Bethe-Heitler propagators, pushing the DVCS to smaller bins in the azimuthal angle ϕ for separation of different azimuthal moments. Further separation of contributions from unpolarized GPDs, and in particular polarized GPDs, require measurements with longitudinally and transversely polarized targets. Latest measurements of target spin

Fig. 5 Spin asymmetries using the Hall-B polarized NH_3 target for exclusive photons [61] and neutral pions [60] for $\langle Q^2 \rangle = 1.94 \text{ (GeV/c)}^2$, $\langle x \rangle = 0.25$

asymmetries in DVCS from CLAS collaboration (see Fig. 5) suggests that t -dependence of polarized quark GPDs may be significantly different than for the unpolarized GPDs, indicating that transverse space distributions of quarks may depend on their spin.

Additional information about the spin/flavor separation can come from meson production data. In particular pseudoscalar meson electroproduction provides access to transversely polarized quark GPDs, H_T^q , E_T^q , $\tilde{H}_T^q$, $\tilde{E}_T^q$, corresponding to parton helicity-flip (chiral-odd) processes [53], not accessible in DVCS studies [56]. For example, the chiral-odd GPD H_T encode unique information on the transverse spin structure of the proton and on the tensor charge since it is defined as a generalization of the quarks transversity distribution, $h_1(x)$. Exclusive pseudoscalar meson electroproduction provides a unique possibility to access the “transversity” or chiral-odd GPDs through polarized scattering measurements [45]. Other important observables accessible in hard exclusive production of pseudoscalar mesons include the GPD $\bar{E}_T$ describing the transverse space distributions of transversely polarized quarks in the unpolarized nucleon and the longitudinal-transverse (LT) correlation provided by $\tilde{E}_T$, which may be relevant for interpretation of orbital angular momentum [51].

Measurements of different final state mesons, π^0 , η and K will provide important complementary information for flavor decomposition of the various GPDs [55; 54], and in particular, help to further improve the precision of the tensor charge. The measurements for π^0 and η SSAs over a large kinematic range are challenging, since their cross sections are small (compared to charged pions). In addition the clean detection of π^0 s and η s requires the measurement of their two decay photons. Since the precision attainable in charge particle detection is typically much higher, charged kaons provide a very attractive alternative to neutral mesons channels in studies of transversity GPDs. It has been argued that the H_T effects are essential in the $K^+\Lambda$ channel while in the $K^+\Sigma^0$ leptonproduction the $\bar{E}_T$ contribution is mostly important [57]. Predictions for the cross section of the $K^+\Lambda$ and $K^+\Sigma^0$ leptonproduction [57] has been used to justify future measurements with CLAS12 [62].

The future measurements with the 12GeV upgrade of Jefferson Lab will be essential for the study of the transverse momentum and transverse space dependent distributions in the valence region. At JLab there are several closely-related proposals approved to measure spin and azimuthal asymmetries in all three Halls, providing complementary studies of different aspects of the complex structure of the nucleon in terms of flavor, momentum and spin.

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