STUDIES OF TMDs WITH CLAS and CLAS12

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In recent years transverse momentum dependent parton distributions and fragmentation functions have been generalized to account for transverse degrees of freedom of quarks inside the nucleon. They offer novel views on QCD dynamics inside hadrons and help to increase our understanding of the intriguing transverse momentum and spin of hadrons. An overview of ongoing TMDs studies in Hall B at Jefferson Lab is given.

Keywords: Parton distributions, Transverse Momentum, Spin

1. Introduction

Modern developments in hadron physics emphasize the role of correlations between partonic transverse momentum and spin that are crucial for our understanding of the spin structure of the nucleon in terms of the quark and gluon degrees of freedom of QCD. Such spin-orbit correlations are described by transverse momentum dependent parton distribution and fragmentation functions (TMDs), which are currently under intense investigation both from the experimental and theoretical side. These functions give rise to interesting single-spin phenomena in semi-inclusive lepton- and hadron-induced processes. TMDs are probability densities for finding a polarized/unpolarized parton with a longitudinal momentum fraction x and transverse momentum $\vec{k}_T$ in a polarized/unpolarized nucleon, see Table 1, where U, L, and T stand for transitions of unpolarized, longitudinally polarized, and transversely polarized nucleons (rows), and correspondingly for quarks (columns). The diagonal elements of the table (f_1, g_1, h_1) are the partonic momentum, longitudinal spin and transverse spin distribution functions. Similar quantities arise in the hadronization process. Two fundamental mechanisms have been identified leading to single spin asymmetries

(SSAs) in hard processes: the Sivers mechanism [1–5], which generates an asymmetry in the distribution of quarks due to orbital motion of partons and the Collins mechanism [4,6], which generates an asymmetry during the hadronization of quarks.
Most of our information on TMDs is obtained from semi-inclusive deep inelastic scattering (SIDIS) experiments, $lN \to e'hX$ (with l = lepton, h = hadron). Here, one of the main players in the game is CLAS at JLab, where a broad experimental program is underway to access all TMDs listed in Table 1. Also new measurements of SSAs for both pions and kaons electroproduction have been approved by the JLab PAC for the 12 GeV beam using the CLAS12 detector.

Table 1. Leading-twist transverse momentum-dependent distribution functions.

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

2. TMDs studies at JLab with CLAS

2.1. *Longitudinally Polarized Target*

For a longitudinally polarized target the only azimuthal asymmetry arising at leading order is the $\sin 2\phi$ moment [7–9], involving the Collins fragmentation function $H_1^\perp$ and the Ralston-Soper-Mulders-Tangerman (RSMT) distribution function $h_{1L}^\perp$ [7,10], describing the transverse polarization of quarks in a longitudinally polarized proton [7–9,11].
Measurements of SSAs in SIDIS kinematics have been done at Jefferson Lab using a 5.7 GeV electron beam and the CEBAF Large Acceptance Spectrometer (CLAS) [12] (EG1 experiment). Scattering of longitudinally polarized electrons off a polarized NH_3 and ND_3 targets was studied over a wide range of kinematics. The average beam polarization was $\sim 73\%$ and the average target polarization for NH_3 (ND_3) was $\sim 70\%$ ($\sim 30\%$). The scattered electrons and pions were detected in CLAS. In the DIS kinematics ($Q^2 > 1$ GeV^2, $W^2 > 4$ GeV^2), ~ 8 millions π^+ have been detected in the $y < 0.85$, $z > 0.4$ range.

The $\sin 2\phi$ moment $A_{UL}^{\sin 2\phi}$ as a function of x is plotted in Fig. 1 (full triangles) [13]. Calculations [14,15] using $h_{1L}^{\perp}$ from the chiral quark soliton model [16] and the Collins function [17] extracted from HERMES [18] and Belle [19] data, are plotted as filled bands. In the plot $A_{UL}^{\sin 2\phi}$ measurements from HERMES [18] (open squares) are also plotted. The kinematic dependence of the SSA for π^+ from the CLAS data is roughly consistent with these predictions. The interpretation of the π^- data, which tend to have SSAs with a sign opposite to expectations, may require accounting for additional contributions. By the way, current statistical errors for π^-, and in particular for π^0, are large and do not allow strong conclusions from the measured SSAs. Data at 6 GeV with ten times higher statistics have been collected in 2009 (experiment E05-133). They will allow statistically significant measurement of the $\sin 2\phi$ moment. The projected sensitivity of results for this experiment are shown as full triangles in the upper part of Fig. 1.

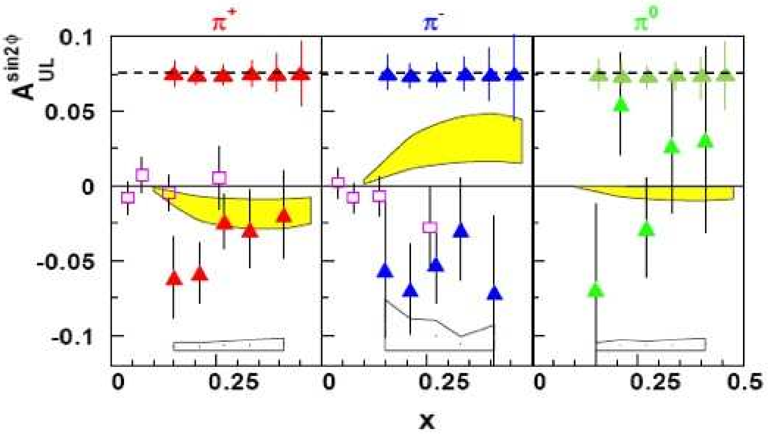

Fig. 1. The measured x-dependence of the longitudinal target SSA $A_{UL}^{\sin 2\phi}$ (full triangles). The squares show the existing $A_{UL}^{\sin 2\phi}$ measurement from HERMES [18]. The lower band shows the systematic uncertainty. The upper band shows the existing theory predictions with uncertainties due to the Collins function [14,15]. The full triangles in the upper part of the plots show the projected sensitivity of results for the experiment E05-133.

The data with longitudinally polarized beam and target provides important information input for the flavor decomposition through the measurement of double spin asymmetries, sensitive to the ratio of helicity and momentum distributions. The dependence of the double-spin asymmetry A_1 as a function of P_T and integrated over all x $(0.12 \div 0.48)$ for $Q^2 > 1$ GeV^2, $W^2 > 4$ GeV^2 and $y < 0.85$, is shown in Fig. 2.

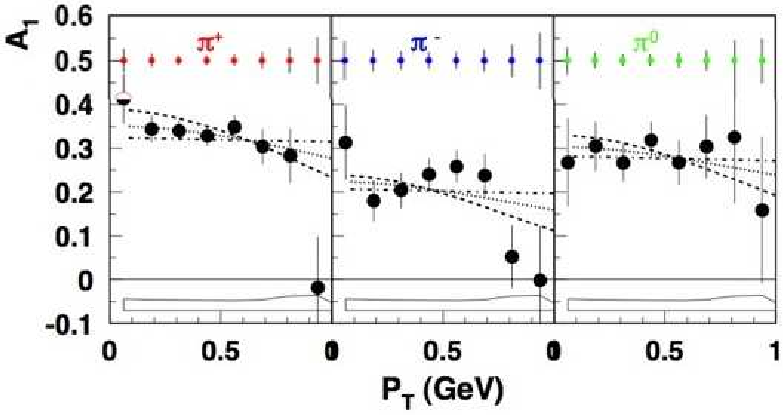

Fig. 2. The double spin asymmetry A_1 as a function of transverse momentum P_T, integrated over all kinematical variables. The open band corresponds to systematic uncertainties. The dashed, dotted and dash-dotted curves are calculations for different values of the ratio of the transverse momentum widths for g_1 and f_1 (0.40, 0.68, 1.0) for a fixed width for f_1 (0.25 GeV^2) [20].

Although these plots are consistent with flat distributions, $A_1(P_T)$ may decrease with P_T at moderately small P_T for π^+. The slope for π^- could be positive for moderate P_T (ignoring the first data point). A possible interpretation of the P_T-dependence of the double-spin asymmetry may involve different widths of the transverse momentum distributions of quarks with different flavor and polarizations [20] resulting from a different orbital structure of quarks polarized in the direction of the proton spin and opposite to it [21,22]. In Fig. 2 the measured A_1 is compared with calculations of the Torino group [20], which uses different values of the ratio of widths in k_T for partonic helicity, g_1, and momentum, f_1, distributions, assuming Gaussian k_T distributions with no flavor dependence.

2.2. *Transversely Polarized Target*

In the last few years, first results on transverse SSAs have become available [23,24]. HERMES measurements for the first time directly indicated significant azimuthal moments generated both by Collins and Sivers effects.

An experiment using a trasversely polarized target in a frozen-spin state, such as the HD-Ice target has been approved at JLab (CLAS experiment E08-015) and is planned to run late 2011. The advantages of an HD-Ice target compared to the solid state dynamically polarized NH_3 and ND_3 targets are manifold: it requires a small holding field and this potentially allows the target to be located even in the center of the detector, thus dramatically increasing the acceptance; in addition the HD-Ice target has almost no diluition; the polarization are expected to be very high: 75% for hydrogen and 40% for deuterium.

2.3. *Unpolarized Target*

Beam-spin asymmetries measurement in single neutral semi-inclusive pion electroproduction has been carried out using a 5.77 GeV electron beam and the CLAS detector. For this measurement scattering of longitudinally polarized electrons off a liquid-hydrogen target was studied over a wide kinematic region. The beam-spin asymmetries in single-pion production off the unpolarized target are higher-twist by their nature [25,26]. The higher twist observables are important for understanding the long-range quark-gluon dynamics. Different contributions to the beam SSAs, discussed so far, provide information on different leading and sub-leading parton distribution and fragmentation functions, related to both Collins and Sivers production mechanisms. At fixed and moderate values of the four momentum transfer Q^2 and at large values of x_B and z (where x_B is the fraction of the momentum of the nucleon carried by the struck quark and z is the fraction of the virtual photon energy carried by the detected π^0), the contribution of multiparton correlations or higher twist effects increases, eventually leading to a breakdown of the partonic description. Kinematical dependences of observables, will thus provide tests of the applicability of partonic descriptions.

In CLAS the kinematic dependences of the π^0 beam-spin asymmetry on x_B, z and P_T (where P_T is the transverse momentum of the π^0) have been measured. The asymmetry shows no significant x_B-dependence within the measured range. The $A_{UL}^{\sin\phi}$ moment as a function of P_T is shown in Fig. 3. It increases at low P_T and reaches a plateau at values of about 0.3 GeV, and there is an indication that its decrease at large P_T, expected from perturbative QCD, starts already at $P_T \sim 0.6$ GeV. In Fig. 3 the preliminary CLAS results are compared with HERMES data [27], where, for the comparison a kinematic factor has been applied to take into account the different kinematical ranges covered by the two experiments. The observed large beam spin asymmetry for π^0 indicates that the major contribution in pion SSAs may be due to the Sivers mechanism. The obtained results provide a very significant improvement in statistical errors compared with published HERMES data, providing important input for studies of higher twist effects.

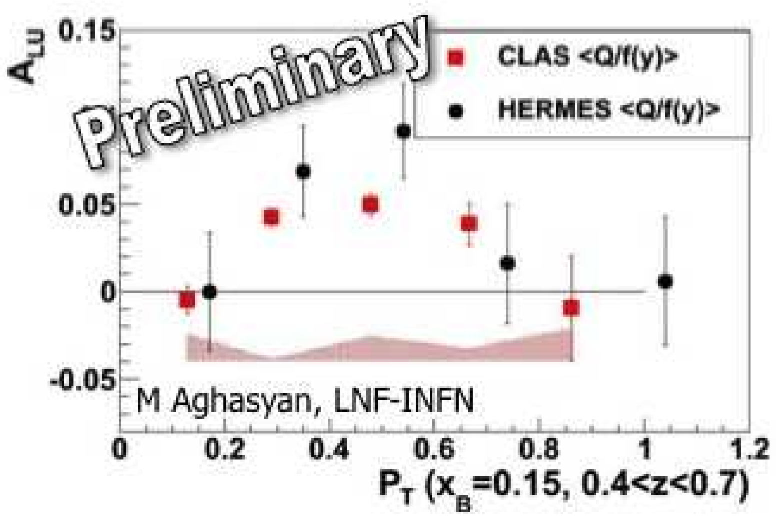

Fig. 3. The measured P_T-dependence of the $A_{UL}^{\sin\phi}$ for x_B=0.15 integrated over $0.4 < z < 0.7$. Error bars present the statistical and the bands the systematic uncertainties. The CLAS data are compared with the HERMES ones [27].

3. Future TMDs studies at JLab with CLAS12

The study of the transverse structure of the nucleon represents a key challenge of the present research in hadron physics and is one of the main scientific goals for the 12 GeV upgrade of the Jefferson Laboratory [28], which is expected to start to be operational in 2015. The complexity of the task of mapping out TMDs requires the interplay of different and complementary measurements of various observables over a wide kinematic range involving experiments with polarized beams and targets.

In Hall B the extended x and Q^2 range of the accessible kinematic plane, together with the expected luminosity of 10^{35} cm^{-2} s^{-1}, and a new large angle detector, CLAS12, will allow for the measurement of single- and double-spin asymmetries with at least an order of magnitude better accuracy than the present, or soon to come, experimental data.

One of the key points of the new detector should be the possibility to identify semi-inclusive kaons with high rejection power from proton and pion backgrounds. In fact, kaon measurements are of fundamental importance in order to achieve flavor separation in the extraction of the distribution functions from the measured asymmetries. For this, the construction of a RICH detector, allowing in particular kaon to pion separation with a rejection factor better than 1:100 in the whole range of kaon momenta above 1 GeV/c, has been proposed. The Sivers asymmetry for kaons as expected with CLAS12, compared with existing data from HERMES [29] is shown in Fig. 4.
The CLAS12 experimental program on the TMDs includes measurements of all the eight leading twist parton distribution functions with the proper choice of beam and/or target polarizations. A full list of the relevant observables and the expected accuracy can be found in the several proposals already approved by the Jefferson Laboratory Program Advisory Committee [30].

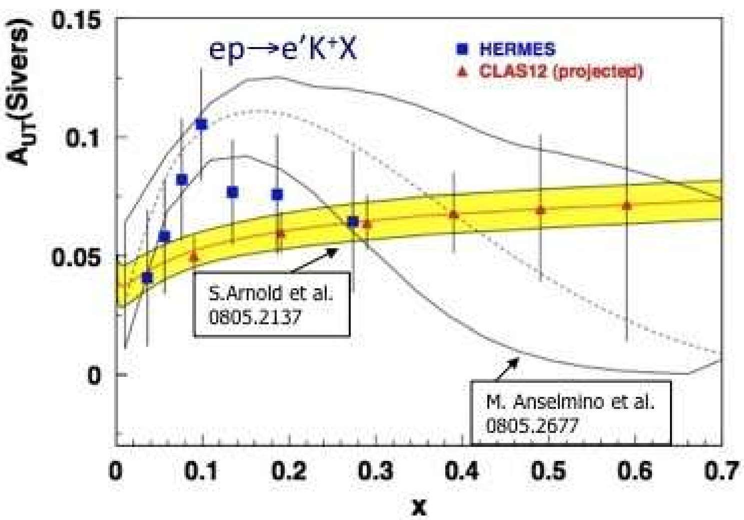

Fig. 4. Projected results for the kaon Sivers asymmetry for CLAS12 as a function of x compared with HERMES data [29] and theoretical predictions.

4. Conclusions and Outlook

Transverse momentum dependent distribution and fragmentation functions have been found to be one of the main tools to access spin-orbit correlations of the partons in the nucleon. TMDs can be accessed unambiguously in SIDIS with polarized/unpolarized leptons and nucleons by observing the azimuthal distributions of produced hadrons. CLAS in Hall B is playing a major role in these studies, which are also one of the main driving forces behind the upgrade of Jefferson Lab.

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