Abstract

Transverse Momentum Dependent parton distribution functions were introduced to describe both longitudinal and transverse momentum distributions of partons inside a nucleon. Great progress has been made in recent years in understanding these distributions measuring different spin asymmetries in semi-inclusive processes. Here we present an overview of the ongoing studies at CLAS and programs planned for the 6 and 12 GeV activity.

1 Introduction

The spin structure of the nucleon has been of particular interest since the EMC [1] measurements, subsequently confirmed by a number of other experiments [2–7], showed that the helicity of the constituent quarks account for only a fraction of the nucleon spin. Possible interpretations of this result include significant polarization of either the strange sea (negatively polarized) or gluons (positively polarized) and the contribution of the orbital momentum of quarks. The semi-inclusive deep inelastic scattering (SIDIS) experiments, when a hadron is detected in coincidence with the scattered lepton provide access to spin-orbit correlations. Observables are spin azimuthal asymmetries, and in particular single spin azimuthal asymmetries (SSAs), of the detected hadron, which are due to the correlation between the quark transverse momentum and the spin of the quark/nucleon.

2 Transverse Momentum Distributions

Significant progress has been made recently in understanding the role of partonic initial and final state interactions [8–10, 2]. The interaction between the active parton in the hadron and the spectators leads to gauge-invariant transverse momentum dependent (TMD) parton distributions [8,10–13]. Furthermore, QCD factorization for semi-inclusive deep inelastic scattering at low transverse momentum in the current-fragmentation region has been established in Refs. [14,15]. This new framework provides a rigorous basis to study the TMD parton distributions from SIDIS data using different spin-dependent and independent observables. TMDs are probability densities for finding a (polarized) parton with a longitudinal momentum fraction $x$ and transverse momentum $k_T$ in a (polarized) nucleon (see Tab. 1). The diagonal elements of the table are the partonic momentum, longitudinal and transverse spin distribution functions, and are the only ones surviving after
Table 1: Leading-twist transverse momentum-dependent distribution functions. \( U, L, \) and \( T \) stand for transitions of unpolarized, longitudinally polarized, and transversely polarized nucleons (rows) to corresponding quarks (columns).

<table>
<thead>
<tr>
<th>N/q</th>
<th>U</th>
<th>L</th>
<th>T</th>
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<tbody>
<tr>
<td>( f_1 )</td>
<td>( h_{1L}^- )</td>
<td>( h_{1T}^- )</td>
<td>( g_1 )</td>
</tr>
<tr>
<td>( g_1 )</td>
<td>( h_{1L}^+ )</td>
<td>( h_{1T}^+ )</td>
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\( \vec{k}_T \)-integration. Off-diagonal elements require non-zero orbital angular momentum and are related to the wave function overlap of \( L=0 \) and \( L=1 \) Fock states of the nucleon [16].

Similar quantities arise in the hadronization process, where a set of fragmentation functions can be introduced, describing the probability that a (polarized) parton fragment into a (polarized) hadron. For unpolarized hadrons, like for example pions and kaons, only two leading twist fragmentation functions are accessible: the usual unpolarized fragmentation function \( D_1 \) and the Collins \( T \)-odd fragmentation function \( H_{1\perp} \) [9] describing fragmentation of transversely polarized quarks into unpolarized hadrons.

3 TMDs measurements with CLAS at 6 GeV

Measurements of SSAs in SIDIS kinematics have been performed with CLAS at the Jefferson Laboratory using a 5.7 GeV energy electron beam. Scattering of unpolarized or longitudinally polarized electron beams off an unpolarized \( H_2 \) or longitudinally polarized \( NH_3 \) target has been studied in a wide range of kinematics. The average beam polarization was \( \approx 75\% \) and the average target polarization was \( \approx 70\% \). The scattered electron and charged or neutral pions were detected in the CLAS with DIS cuts \( Q^2 > 1 \text{ GeV}^2 \) and \( W > 2 \text{ GeV} \).

3.1 Single Spin Asymmetry with longitudinally polarized target

As was first discussed by Kotzinian and Mulders in 1996 [17], the spin-orbit correlation in a longitudinally polarized nucleon gives rise to a Single Spin Asymmetry which involves the leading twist distribution function \( h_{1L}^- \) and the Collins fragmentation function \( H_{1\perp}^+ \)

\[
\sigma_{UL}^{\sin 2\phi} \propto S_L(1 - y) \sin 2\phi \sum_{q, \bar{q}} e_q^2 h_{1L}^+(x) H_{1\perp}^+(z)
\]

(1)

where \( \phi \) is the azimuthal angle of the hadron with respect to the lepton plane and \( x, y, z \) are the fraction of the nucleon momentum carried by the struck quark, the fraction of the electron energy carried by the virtual photon and the fraction of the virtual photon momentum carried by the detected hadron, respectively. A recent measurement of the \( \sin 2\phi \) asymmetry for charged pions has been performed by Hermes [18] and is consistent with zero, as shown by the empty squares in Fig. 1. Non-zero asymmetries are predicted at large \( x \) (\( x > 0.2 \)), a region well covered by CLAS. Indeed, the preliminary CLAS results at 6 GeV for charged pions, reported with full triangles in Fig. 1, show significant negative SSAs, while the results for neutral pions are consistent with zero.
The yellow band in Fig. 1 is the result of a calculation by Efremov et al. [19], using the Kotzinian-Mulders distribution function \( h_{1L}^\perp \) from the chiral soliton model evolved at \( Q^2 = 1.5 GeV^2 \). With the current statistical errors on the \( \pi^+ \) and \( \pi^0 \) measurements, the experimental data seem to be in agreement with the calculation, while for the \( \pi^- \) the model predicts positive asymmetry while the measured SSA is negative.

Higher twist contributions are expected to generate \( \sin \phi \) asymmetries in the cross section. Preliminary CLAS results of the \( \sin \phi \) contributions to \( \sigma_{UL} \) are shown in Fig. 2 as a function of the transverse momentum \( P_T \) with full squares, together with the leading twist \( \sin 2\phi \) contributions (full circles).

These results indicate non-negligible higher twist contributions, of the same sign and comparable in size for \( \pi^+ \) and \( \pi^0 \) and with opposite sign for \( \pi^- \).

New 6 GeV data have been taken in 2009, with the expected statistical accuracy on the measured SSA shown by the projected data points in the top part of Fig. 1. They will allow to draw much more statistically significant conclusions on the size of the asymmetry and on the possible agreement with theoretical calculations.

### 3.2 Beam Single Spin Asymmetry with unpolarized target

Beam single spin asymmetries with an unpolarized target are zero at leading twist. Higher order terms involve either the leading twist distribution functions \( f_1 \) and \( h_{1L}^\perp \) convoluted with higher twist fragmentation functions or the leading twist unpolarized \( D_1 \) and Collins \( H_1 \) distribution functions convoluted with higher twist fragmentation functions. The resulting asymmetry contains the \( \sin \phi \) modulation

\[
\sigma_{LU}^{\sin 2\phi} \propto \frac{M_p}{Q^2} \sin \phi F_{LU}
\]

where \( M_p \) is the proton mass and the structure function \( F_{LU} \) encodes all the relevant distribution and fragmentation functions. The preliminary CLAS results obtained at 6 GeV in three different run periods are shown in Fig. 3 as a function of \( x \). As can be seen, positive and neutral pions have positive and comparable asymmetry. Since the \( \pi^0 \) Collins distribution function is expected to be small, these results seems to indicate that the Collins-type contribution to the beam SSA could be small.
3.3 Single spin asymmetry with a transversely polarized target

With unpolarized beam and a transversely polarized target, at leading twist the cross section contains several single spin asymmetry terms. The Sivers asymmetry

\[
\sigma_{UT}^{\sin(\phi - \phi_S)} \propto S_T \sin(\phi - \phi_S) \sum_{q,\bar{q}} e_q^2 f_{1T}^1(x) D_1^1(z) \quad (3)
\]

where \(\phi_S\) is the azimuthal angle of the target spin with respect to the lepton plane and \(S_T\) is the target polarization, contains the Sivers function \(f_{1T}^1\), describing unpolarized quarks in a transversely polarized target. It arises from the correlations between the transverse momentum of quarks and the transverse spin of the target and requires both orbital angular momentum, as well as non-trivial phases from the final state interaction.

The Collins asymmetry

\[
\sigma_{UT}^{\sin(\phi + \phi_S)} \propto S_T (1 - y) \sin(\phi + \phi_S) \sum_{q,\bar{q}} e_q^2 h_1(x) H_1^1(z) \quad (4)
\]

contains the transversity distribution function \(h_1\). This distribution function, describing transversely polarized quarks in a transversely polarized nucleon, is as fundamental as \(f_1\) and \(g_1\), but it is presently much less known than the other two. In fact, being charge conjugation-odd, the transversity can appear in the cross section only convoluted with another charge conjugation-odd distribution function, like the Collins function \(H_1\), making its extraction impossible in DIS. It does not mix with gluons, and in the non relativistic limit it is equal to \(g_1\). Thus it probes the relativistic nature of quarks and it has very different \(Q^2\) evolution than \(g_1\).

First measurements of the Sivers and Collins effects for pions have been obtained by Hermes [20]. The results for charged and neutral pions are shown in Fig. 4 (for Sivers) and in Fig. 5 (for Collins) by the empty squares. The measured asymmetries are in general large, however the limited range in \(x\) explored by Hermes does not allow to fully discriminate between the models. In fact, the various models ([21], [22], [23] for the Sivers effect and [21], [24] for the Collins effect) tend to give comparable results at small \(x\) and tend to diverge only for \(x > 0.2\). This region can be well explored by the new CLAS experiment [25] planned for 2011 to run with a polarized \(HD\)-ice target at 6 GeV. The data points on top of each plot of Fig. 4 and 5 show the expected statistical accuracy after about two months of data taking.
At leading twist, a third asymmetry

$$\sigma_{UT}^{\sin(3\phi - \phi_S)} \propto S_T \sin(3\phi - \phi_S) \sum_{q,\bar{q}} e_q^2 h_{1T}^\perp(x) H_{1}^\perp(z)$$

contains the distribution function \(h_{1T}^\perp\), which is responsible for the nonspherical shape of the nucleon [26]. In certain class of models, like the bag model and the spectator model [27], this distribution function is related to \(g_1\) and \(h_1\) through the relation

$$g_1(x) - h_1(x) = h_{1T}^\perp(x)$$

thus giving information on the relativistic nature of the quarks in the nucleon. A first look at this new function could be obtained by the new CLAS measurements at 6 GeV, as well as for the double spin asymmetry \(A_{LT}\) with longitudinally polarized beam. The latter contains the distribution function \(g_{1T}\), describing longitudinally polarized quarks in a transversely polarized nucleon.

4 TMDs measurements with CLAS at 12 GeV

The measurement of the transverse momentum distributions is one of the main scientific goals driving the 12 GeV upgrade of the Jefferson Laboratory [28], which is expected to start to be operational in 2015. 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 the measurement of single and double spin asymmetries with at least an order of magnitude better accuracy than the present, or near to come, experimental data.

One of the key point of the new detector should be the possibility to identify semi-inclusive kaons with high rejection power from proton and pion background. 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 has been proposed [29]. Such kind of detector would greatly improve the CLAS12 capability in terms of particle identification, 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.

The CLAS12 experimental program on the TMDs includes measurements of all the eight leading twist parton distribution functions in Tab.1 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 PAC [29,30].
5 Conclusions

Transverse Momentum Dependent distribution and fragmentation functions have been found as one of the main tool to access spin-orbit correlations of the partons in the nucleon. Measurements of Single (and Double) Spin Asymmetry have shown that the transverse degrees of freedom are crucial in understanding of the nucleon structure. In the last years, a significant amount of experimental data from several Laboratories has begun to come out. In this scenario, CLAS play an important role, being the only experiment having access to the large-x region, where model predictions have the biggest differences among each other.

With the foreseen large step forward in terms of luminosity and detection capability, the measurements planned to start in 2015 at the Jefferson Laboratory with the CLAS12 detector will provide information on the internal structure of the nucleon with unprecedented quality.

References

[28] http://www.jlab.org/12GeV/
[29] H. Avakian et al., CLAS proposal PR-09-009; K. Hafidi et al., CLAS proposal PR-09-007.