Overview of the recent results from CLAS

Marco Mirazita
I.N.F.N - Laboratori Nazionali di Frascati
E-mail: marco.mirazita@lnf.infn.it

Abstract.
An overview of the recent results obtained at the Thomas Jefferson Laboratory on the study of the nucleon internal structure is presented, with main focus on the CLAS measurements of the Transverse Momentum Dependent partonic functions.

1. The Jefferson Laboratory facility and CLAS
The Thomas Jefferson National Accelerator Facility (TJNAF or JLab) is located at Newport News, in Virginia (USA). It houses the Continuous Electron Beam Accelerator Facility (CEBAF), a high-current, high-duty electron beam machine with three experimental halls. A schematic of the accelerators is shown in Fig. 1.

The CEBAF is basically composed by two linear accelerator, each delivering to the electrons up to 0.4 GeV per pass, and two recirculating arcs. The electron beam can be circulated up to five times in the accelerator, so that the maximum achievable energy is about 6 GeV. The primary beam can then be split and sent to the three experimental halls (Hall A, B and C), with different energies and intensities. The polarization of the electron beam can be as high as 85% and, in order to minimize systematic effects, it is pseudo-randomly flipped between positive and negative values every about 30 ms.

The Hall A and C are both instrumented with two small acceptance, high precision spectrometers and routinely runs with beam currents sufficient to achieve a luminosity of the order of several times $10^{38} cm^{-2}s^{-1}$.

The Hall B is instrumented with the CEBAF Large Acceptance Spectrometer (CLAS), shown schematically in Fig. 2. The CLAS design is based on a toroidal field, generated by six superconducting coils arranged around the beam line, so that the field is pointing primarily in the azimuthal direction. The six coils divide the detector in six independent spectrometers, each of them containing:

- three regions of drift chambers, the second of which is immersed in the magnetic field, for particle’s track and momentum measurement;
- an array of scintillator counters for time of flight measurement and particle identification;
- a gas Cerenkov counter, for electron/pion separation;
- a forward electromagnetic calorimeter (EC), for neutral particles detection and used also to improve electron identification;
- a large angle calorimeter (in two sectors only), to extend neutral particle detection.
The geometry of the detector close to the beam line allows the installation of polarized as well as unpolarized targets. The Hall B instrumentation is completed by a tagger system, installed upstream of the CLAS detector, allowing the production of a real photon beam with intensity of up to several times $10^7$ photons per second.

For charged particles, CLAS covers all the polar angles $\theta$ between $8^\circ$ and $142^\circ$ in the laboratory frame and between 60 and 80% of the azimuthal angles $\phi$. The momentum resolution is between 0.5% (forward) and 1.5% (backward), with angular resolution of about 1 mrad in $\theta$ and about 4 mrad in $\phi$.

![Figure 1. Layout of the CEBAF accelerator.](image)

2. The CLAS physics program

The high intensity electron and photon beams, together with the availability of three experimental halls with different and complementary detectors, offer the unique opportunity to study the QCD from the non-perturbative regime to the microscopic partonic structure of the hadrons and nuclei, making of JLab a laboratory for the hadronic physics. In fact, the JLab physics program, started in 1996, covers many aspects of the hadronic physics, namely:

- measurement of the charge and magnetization distributions in the nucleons and in the nuclei;
- two-body correlations in nuclei;
- meson and baryon excitation spectrum;
- production of exotic hadrons;
- strangeness in nuclei;
- structure functions in the deeply inelastic regime;
- parity violation in electron-proton scattering;

Some of those physics items were present in the JLab program since the beginning of its operation, but others have emerged as exciting new developments only in the last years. In particular, the combination of high polarization electron beam with highly polarized targets have
open the possibility to study the internal structure of the nucleon not only in the inclusive regime, but also in the semi-inclusive and exclusive final states, giving access to new elementary functions like the Transverse Momentum Dependent (TMD) partonic distributions and the Generalized Parton Distribution (GPD) functions. In the following, a review of the recent results obtained at JLab on the TMD measurements will be presented.

3. Structure functions in Deeply Inelastic Scattering

The existence of point-like quarks inside the nucleon was inferred for the first time from the study of the Deeply Inelastic Scattering (DIS) performed at SLAC in the late 1960’s [1]. The DIS reaction, in which high energy electrons scatter off a proton target and the emerging electron is detected, is described by two kinematic variables: the virtuality of the exchanged photon $Q^2 = -q^2$ (where $q = p - p'$ is the 4-momentum of the virtual photon and $p$ and $p'$ are the initial and final electron 4-momenta), and the Bjorken variable $x_B = Q^2/2Pq$ (where $P$ is the target nucleon 4-momentum). The parity-conserving electromagnetic part of the DIS cross section is described by four structure functions, usually denoted by $F_1$, $F_2$, $g_1$ and $g_2$. The first two contribute when both the electron and the target nucleon are unpolarized, while the last two arise when the beam and the target are polarized. Although they depend on the two variables $Q^2$ and $x_B$, in the Bjorken limit, i.e. for $\nu, Q^2 \to \infty$ (where $\nu$ is the virtual photon energy) but with $x_B$ fixed, the structure functions are expected to scale approximately; that is, to depend only on $x_B$.

In the parton model the nucleon is composed by elementary constituents moving collinearly and in the DIS reaction the virtual photon is assumed to scatter incoherently off these constituents, so that the structure functions can be decomposed in a sum over the contributions coming from its partons. For the unpolarized structure function one gets

$$F_2 = \sum_q e_q^2 x (q + \bar{q}) = \frac{4}{9} x (u + \bar{u}) + \frac{1}{9} x (d + \bar{d}) + \frac{1}{9} x (s + \bar{s}) + \cdots$$

(1)

and the so-called Callan-Gross relation $F_2(x) = 2xF_1(x)$. Here $q$ and $\bar{q}$ are the quark and
antiquark Parton Distribution Functions (PDFs), expressed as a function of the fraction \( x = x_B \) of the nucleon longitudinal momentum carried by the parton.

Measurements of the unpolarized structure function have been performed over the last decades at SLAC, CERN, DESY and Fermilab over a kinematic range that spans several orders of magnitudes in \( Q^2 \) and \( x_B \). A summary of these experimental data is shown in Fig. 3. We see that the Bjorken scaling is well satisfied for the larger values of \( x_B \), that is in the region where valence quark contribution dominates the structure function. As \( x_B \) goes down, sea quark contributions start to be relevant and logarithmic scaling violation are observed. It was a great success of the QCD that these scaling violations could be correctly calculated perturbatively.

The parton model expansion of the polarized structure function \( g_1 \) is given by

\[
g_1 = \sum_q c_q^2 (\Delta q + \Delta \bar{q}) = \frac{1}{2} \left[ \frac{4}{9} x (\Delta u + \Delta \bar{u}) + \frac{1}{9} x (\Delta d + \Delta \bar{d}) + \frac{1}{9} x (\Delta s + \Delta \bar{s}) + \cdots \right] \tag{2}
\]

where \( \Delta q \) and \( \Delta \bar{q} \) are the polarized quark and antiquark PDFs. They represent the difference between the probabilities to find a parton with helicity aligned minus that with helicity antialigned to the nucleon momentum.
The second spin structure function \( g_2 \), related to the transverse spin structure, has no simple probabilistic interpretation, nevertheless it carries important information on the quark-gluon correlations. Its contribution to the cross section is generally small and only in the last years its measurement became possible.

Double spin experiments on the proton in the DIS domain have been performed at CERN, SLAC, DESY and in the last years also with COMPASS [2] and CLAS at JLab [3] and the results are shown in Fig. 4. Although not at the same level of the unpolarized data, those data provide a good knowledge of \( g_1 \). We also see that in the high-\( x_B \) region information comes almost exclusively from CLAS data.

![Figure 4. World data on \( g_1 \) for the proton as a function of \( Q^2 \) for fixed values of \( x_B \). The solid line is the conventional DIS frontier (\( Q^2 = 1 \text{ GeV}^2 \) and \( W = 2 \text{ GeV} \)). Note that Compass data [2] are not shown.](image)

4. Orbital angular momentum in DIS

The four structure functions \( F_1, F_2, g_1 \) and \( g_2 \) are the observables that can be directly measured in DIS experiments. However, physics information is enclosed in the PDFs and the extraction of those information from the data requires complicated fit procedures that involve some \textit{a priori} assumption. Extractions of the polarized PDFs from the experimental data of polarized structure function on the proton and on the neutron have been performed by SLAC [4], Hermes [5], Compass [2] and by CLAS [3] and Hall A [6]. Global fits of the data[5, 2], including valence and sea quark contributions, have revealed surprising results, as for example the sizeable breaking of the isospin symmetry in the light quark sector and the difference between the strange quark and antiquark distributions.

Extractions of the helicity distributions for \( u \) and \( d \) quarks are shown in Fig. 5. While \( \Delta u / u \) seems to approach the unity at high \( x \) as predicted by a variety of models (see for example [9]),
\( \Delta d/d \) remains negative over the whole explored region and shows no tendency to turn toward one.

In Fig. 5, the data are compared with a leading order pQCD [9] (dashed curve) and a pQCD fit including quark orbital angular momentum corrections [10] (solid curve). While both calculations are in agreement with the data for \( \Delta u/u \), the leading order pQCD model assuming quark helicity conservation is not reproducing the \( \Delta d/d \) data. Better agreement is found with the fit including quark angular momentum, suggesting that it may play an important role in this kinematic regime. Still this fit predicts \( \Delta d/d \to 1 \) for \( x \) approaching unity. In contrast, different models [8], [7] predict \( \Delta d/d \to -1/3 \) at high \( x \), in agreement with the trend that the experimental data seem to show. It is clear that new data at high \( x \) are needed to disentangle between the various models.

![Figure 5](image_url)

**Figure 5.** Extraction of \( \Delta u/u \) and \( \Delta d/d \) from SLAC [4], Hermes [5] and from CLAS [3] and Hall A [6] at JLab, compared with theoretical predictions.

The doubly polarized experiments in the DIS domain are the cornerstone of our understanding of the nucleon spin. Naively, in the parton model one can write down the sum rule for the nucleon spin \( S_N = 1/2 = 1/2 \Delta \Sigma \), where \( \Delta \Sigma \) is the quark spin contribution and is obtained by integrating the structure function \( g_1(x) \). From the experimental data a value \( \Delta \Sigma \approx 0.3 \) is estimated, thus more contributions must considered in the spin sum rule:

\[
S_N = \frac{1}{2} \Delta \Sigma + L_q + \Delta G + L_G
\]

with \( L_q \) being the quark orbital angular momentum and \( \Delta G \) and \( L_G \) the gluon spin and orbital momentum. Measurement of the polarized gluon distribution \( \Delta G/G \) at \( x \approx 0.1 \) are small, compatible with zero [11]. Large contributions might come from the low \( x \) region, which is not yet explored experimentally, but in any case it is clear that orbital angular momenta play an important role in solving the spin puzzle.

At the parton model level, introduction of the orbital angular momentum requires that quarks have non zero transverse momentum, thus the PDF definition should be extended beyond the collinear approximation used to parametrize the DIS structure functions.

5. Transverse Momentum Dependent PDFs

In the approximation of partons moving collinearly with the nucleon, three PDFs can be defined: the two measured in DIS experiments, \( f_1 \) (using now the SIDIS notation of the DIS \( F_1 \)) and \( g_1 \), plus a third one, \( h_1 \), describing transversely polarized quarks in a transversely polarized nucleon.
Table 1. Leading-twist transverse TMD functions: $U$, $L$, and $T$ stand for transitions of unpolarized, longitudinally polarized, and transversely polarized nucleons (rows) and quarks (columns).

The latter is not accessible in inclusive measurements and very little is known so far about this function.

When the partons are allowed to have also a transverse momentum, the PDFs acquire a more rich and complicated structure [12, 13]. At leading twist, there are eight independent Transverse Momentum Dependent (TMD) parton distribution functions, as shown in Tab. 1, where each row (column) refers to unpolarized ($U$), longitudinally ($L$) or transversely ($T$) polarized nucleon (quark). Each TMD depends not only on the fraction of longitudinal nucleon momentum $x$ carried by the quark, but also on the quark transverse momentum $k_{\perp}$. Along the diagonal of Tab. 1, we find $f_1(x, k_{\perp})$, $g_1(x, k_{\perp})$ and $h_1(x, k_{\perp})$ that, after integrating over the transverse momentum, reduce to the corresponding collinear PDFs. The remaining five TMDs are new objects, describing all the possible correlations between the momentum and the spin of the quark with those of the nucleon and originate from interference between wave functions with different angular momentum. They vanish after integration over $k_{\perp}$, thus their measurement requires the tagging of the transverse momentum of the struck quark.

6. Experimental access to TMDs

Because of the need to tag the quark transverse momentum, experimental access to TMDs requires the presence of more than one hadron in the initial or final state. In electron-proton scattering, this can be achieved by studying Semi-Inclusive Deeply Inelastic Scattering (SIDIS) reactions $e p \rightarrow e' h X$, in which the struck quark fragments into a final hadron $h$ with transverse momentum $P_T$. In a well defined kinematic regime, a factorization theorem for SIDIS processes has been proved [15], showing that the cross section of the reaction in Fig. 6 can be decomposed as

$$\sigma_{\text{SIDIS}} = \sum_q DF^q \otimes \sigma^{e q \rightarrow e' q'} \otimes FF^{q'}$$

where $DF^q$ is a TMD distribution function and $\sigma^{e q \rightarrow e' q'}$ is the elemental cross section for electron-quark scattering. A new object appears in this expression, the Fragmentation Function $FF^q$, describing amplitudes that a quark $q$ fragments into the final observed hadron. The FFs depend on the energy fraction $z$ of the final hadron and on the transverse momentum $P_{\perp}$ of the fragmenting quark. Restricting to spinless mesons, two of such FF are relevant in SIDIS processes: the unpolarized $D_1(z, P_{\perp})$ and the Collins $H_1^T(z, P_{\perp})$, the latter parametrizing the fragmentation of a transversely polarized quark into an unpolarized hadron.

Being a convolution of two functions, the SIDIS process allows the extraction of information on the TMD distribution functions only if the FFs are known from other measurements. This is in fact possible because of the general universality of the TMDs, which ensures that the same functions entering in the SIDIS cross section can be measured also in a large variety of experiments, namely:

- Drell-Yan (DY) processes $HH \rightarrow l^+l^- X$, involving two distribution functions for the initial hadrons;
Figure 6. SIDIS reaction $ep \rightarrow e'hX$.

- hadron production in collider experiment $l^+l^- \rightarrow h_1h_2X$, involving two fragmentation functions for the final hadrons;
- hadron production in proton-proton scattering $pp \rightarrow hX$, involving two distribution functions for the initial hadrons and one fragmentation function for the final hadron.

It must be noted that for some of these processes, the factorization has not been proved yet but it is simply assumed to analyze the data.

It is clear that a full comprehension of the internal nucleon structures in terms of TMDs requires the combined efforts of many laboratories and results from many different experiments. Also, disentangling between PDFs and FFs in the data calls for new analysis techniques [14] fully differential in the relevant kinematic variables.

A crucial test of the universality of the TMDs involves the so-called Sivers and Boer-Mulders functions. The Sivers function $f_{1T}^\perp$ describes unpolarized quarks inside a transversely polarized nucleon and it arises from correlation between the quark transverse momentum and the nucleon spin. Conversely, the Boer-Mulders function $h_{1T}^\perp$ describes unpolarized quarks inside a transversely polarized nucleon and it is produced by correlation between the quark transverse spin and the nucleon momentum. Both functions are non-zero because of initial or final state interaction and, because of that, they must change sign between SIDIS and DY processes, namely:

$$f_{1T}^\perp(SIDIS) = -f_{1T}^\perp(DY)$$
\[5\]

and

$$h_{1T}^\perp(SIDIS) = -h_{1T}^\perp(DY)$$
\[6\]

7. Measuring TMDs in SIDIS at JLab and CLAS

The SIDIS cross section contains 18 structure functions, each appearing as modulation in the azimuthal angle $\phi$ [16] of the final hadron. Decomposition of the structure functions in terms of TMDs distribution and fragmentation functions have been derived at leading order (twist-2, involving the eight PDFs at Tab. 1 and the unpolarized and Collins FFs) and next-to-leading order (twist-3, that is suppressed by one power of $M_p/Q$) [13, 12], although for the latter the factorization has not been completely proven. Contributions of the various structure functions can be isolated by computing azimuthal asymmetries or, equivalently, $\phi$ moments of the cross section.

Pion SIDIS measurements have been performed at JLab using the CLAS detector and in Hall A and C. Having different equipments, the three experiments provided different and
complementary data sets. In particular, CLAS measured asymmetries over a large kinematic range, while Hall A and C measured asymmetries and total cross sections in a limited kinematic range but with high statistical precision.

7.1. Results from CLAS
In the collinear limit, the helicity distribution $g_1$ is well known (see Fig. 4). The dependence of $g_1$ on the transverse momentum has been studied by CLAS [17] by measuring the double spin asymmetry $A_{LL}$ in the scattering of longitudinally polarized electron beam on a longitudinally polarized proton target and with a pion in the final state. Results for charged and neutral pions are shown in Fig. 7 as a function of the pion transverse momentum $P_T$. Although the data are consistent with flat $P_T$ dependence, the asymmetry moderately decreases with $P_T$ for charged pions. A possible interpretation of these results may involve different widths of the transverse momentum distribution of $g_1$ and $f_1$, arising from different orbital motion of quarks polarized in the direction of the proton spin or in the opposite one. Assuming a gaussian shape of the transverse momentum dependence, the convolution integrals over the involved transverse momenta can be analytically performed and the structure functions reduce to a product of the collinear DFs and FFs. In Fig. 7, the full, dashed and dotted curves are calculations [18] with three different values for the ratio of the transverse momentum widths for $g_1$ and $f_1$ (with fixed $f_1$ width of 0.25 GeV$^2$).

Figure 7. Double spin asymmetry as a function of the transverse momentum $P_T$ measured by CLAS [17] for the three pions. The full, dashed and dotted curves are calculations for different values for the ratio of the transverse momentum widths for $g_1$ and $f_1$ [18].

Single target spin asymmetries $A_{UL}$ have also been measured by CLAS [17] in SIDIS production of pions. The relevant structure function presents a leading twist contribution with a $\sin 2\phi$ modulation and a higher twist term with a $\sin \phi$ modulation. The leading twist term involves the Collins fragmentation function $H_{1L}^\perp$ and the $h_{1L}^\perp$ DF, describing the transverse polarization of quarks in a longitudinally polarized nucleon. The measured $P_T$ dependence of the amplitude of the two azimuthal modulations are shown in Fig. 8. The data have a significant $\sin 2\phi$ modulation for the two charged pions with opposite sign, and a relatively small one for $\pi^0$, in agreement with the expectation that the Collins function for $\pi^0$ may be suppressed, as already showed by Hermes data [19]. While $\pi^+$ data are roughly consistent with calculation of $h_{1L}^\perp$ [20, 21] and the Collins [22] function extracted from Hermes [19] and Belle [23] data, the interpretation of the $\pi^-$ is less straightforward. It may require accounting for additional
contribution as for example interference effects from exclusive $\rho\pi^0$ and $\pi^-\Delta^{++}$ channels. The CLAS data [17] also show a non-zero $\sin \phi$ modulation for all pions, which indicates that higher twist term can be relevant at the JLab energies.

Figure 8. The amplitude of the $\sin 2\phi$ (circles) and $\sin \phi$ (squares) modulations of the target single spin asymmetry as a function of the transverse momentum $P_T$ measured by CLAS [17] for the three pions.

CLAS measured also single beam asymmetry $A_{LU}$ in pion SIDIS production [24, 25]. The relevant structure function is modulated by a $\sin \phi$ dependence and presents four terms, involving higher twist distribution or fragmentation functions. The $P_T$ dependence of the asymmetry for $\pi^0$ is shown in Fig. 9 in four $x_B$ bins. It increases at low $P_T$ and reaches a plateau at about $P_T \approx 0.3$ GeV. There is also an indication of a possible decrease at large $P_T$, as expected from perturbative QCD.

The $x_B$ dependence of $A_{LU}$ for $\pi^+$ and $\pi^0$ is compared in Fig. 10. It is of the same order of magnitude for both pions over the whole measured range. This may suggest that the Collins term in the structure function may be negligible, because Collins function for $\pi^+$ is non-zero while it is small for $\pi^0$. Thus contributions related to spin-orbit correlations in the PDFs can be studied without a significant background from Collins mechanism.

Figure 9. The single beam spin asymmetry measured by CLAS [24, 25] for $\pi^0$ as a function of $P_T$ in four $x_B$ bins.
Figure 10. The single beam spin asymmetry measured by CLAS [24, 25] for $\pi^+$ (circles) and $\pi^0$ (triangles) as a function of $x_B$.

7.2. Results from Hall A and C
The Hall C accurately measured the unpolarized cross section for SIDIS production of charged pions on hydrogen and deuterium target [26]. The $P_T^2$ dependence of the cross section is shown in Fig. 11 with the full circle. These four data sets have been fitted by assuming different widths of the transverse momentum dependencies (assumed to be gaussians) of $u$ and $d$ quarks in both PDFs and FFs and neglecting the sea quarks (typical global fits give less than 10% sea contributions at $x_B \approx 0.3$). The fit results are shown in Fig. 11 by the full lines. They provide larger widths for $u$ quark than for $d$ in both distributions and fragmentation functions. They also seems to indicate a preference for larger widths in the fragmentation than in the distributions functions.

In Hall A, the first measurement of transverse target spin asymmetry $A_{UT}$ on the neutron has been performed [27]. The CEBAF unpolarized electron beam is scattered off a $^3$He transversely polarized target and charged pions are detected in the final state. The asymmetry $A_{UT}$ has contributions from Collins and Sivers effects. The Collins effect involves convolution of the transversity DF $h_1$ and the Collins FF $H_{1T}$ and presents a $\sin(\phi + \phi_S)$ modulation (here $\phi_S$ is the azimuthal angle of the target spin). The Sivers effect involves the convolution of the Sivers DF $f_{1T}$ and the unpolarized FF $D_1$, with a $\sin(\phi - \phi_S)$ modulation. The two contributions can be separated by calculating the Collins $A_C = 2 < \sin(\phi + \phi_S) >$ and Sivers $A_S = 2 < \sin(\phi - \phi_S) >$ moments of the cross section. Moreover, the neutron asymmetry is obtained from the measured data on the $^3$He target by deconvolving the proton contribution [28] and taking into account final state interaction corrections [29]. The results are shown in Fig. 12 as a function of $x_B$ and compared with several models [30, 31, 32, 33]. The Collins moments are small, compatible with zero (in agreement with theoretical expectations) except for the highest $x_B$ data point for $\pi^+$, showing a non-zero value at the $2\sigma$ level. The data also favor a negative Sivers moment for $\pi^+$, while the $\pi^-$ one is close to zero. This behaviour supports a negative Sivers function for $d$ quark, as already suggested by fenomenological fits [30, 34] to Hermes [36] and Compass data.

7.3. Experimental results: summary and open isues
TMDs studies have been performed in recent years or are underway not only at JLab but also in many other Laboratories, in SIDIS processes (EMC, Hermes, Compass) as well as in polarized proton-proton collisions (PHENIX, STAR, BRAHMS) and electron-proton annihilation (Belle,
Figure 11. The $P_T^2$ dependence of the unpolarized cross section for charged pion SIDIS production on proton (upper plots) and deuteron (lower plots) target measured at Hall C. The curves are phenomenological fits of the data, as explained in the text.

Figure 12. The $x_B$ dependence of the Collins (upper plots) and Sivers (lower plots) moments for charged pions SIDIS production measured by Hall A.

BaBar). All these data have demonstrated that measurements of polarized hadronic cross sections in hard processes are a powerful tool to probe the nucleon structure.

Many of the DFs in Tab. 1 have been measured to be non-zero. In particular, the recent Belle data [35] on two pion pairs production together with the Collins moment measurements
in double pion SIDIS done at Hermes [36] have allowed the first extraction of the transversity [37] in the framework of collinear factorization, the less known of the three PDFs surviving after transverse momentum integration.

Higher order (twist-3) contributions have been also measured at JLab, Hermes and Compass. They are not only important to correctly extract the twist-2 terms from the data, but they also carry important information on the largely unknown quark-gluon correlations.

Besides the need for more accurate experimental data to better understand the dynamics of quarks inside the nucleon, a number of problems remains still unclear. Extraction of the strange unpolarized quark distribution have been performed using DIS data under the assumption that it is proportional to the average of the non-strange quarks [38]. However, relaxing the proportionality requirement and including in the fit semi-inclusive data [39] showed that the shape of the $s$ quark is very different from the average of non-strange sea quarks.

The helicity distribution $\Delta s$ has also been extracted from DIS data, yielding to negative polarization. However, from more recent SIDIS data the strange sea polarization resulted, within statistic and systematic uncertainties, consisten with zero. It is important to independently verify this result with higher accuracy.

Hermes measurements of the Collins asymmetry for pions and kaons [36] have indicated that the differences between pions and kaons may be very significant. The asymmetry for $K^+$ is about double in magnitude than the $\pi^+$, while from $u$-quark dominance very similar amplitudes are expected. This indicates possible significant role of sea quarks. Similar behaviour can be seen also in the Collins measurements from Compass [40, 41] and from the Hermes data on the $\cos 2\phi$ moment of the unpolarized cross section [42], which involves the Boer-Mulders function $h_1^\perp$ and the Collins FF.

It is clear that the strange sector of TMD requires a strong effort and dedicated measurements in order to fully address these open issues.

8. The JLab upgrade at 12 GeV

The 6 GeV physics program of JLab will end in May 2012, when the accelerator complex will be shut down to undergo to an upgrade that will bring the maximum available energy of the electron beam to 12 GeV. The luminosity will also be increased by an order of magnitude. All the three experimental Hall equipments will be upgraded (Hall A and C) or completely renewed (Hall B), in order to better match the increased energy and a new experimental Hall D will be built. The start up of the new facility is expected in may 2013 with the commissioning of the new accelerator, followed by the commissioning of the experimental halls.

The physics program of the upgraded JLab will represent the natural continuation of the 6 GeV program, with the benefit of the increased beam energy and luminosity. In particular, for the nucleon structure study, the higher energy implies a better insight into the Deeply Inelastic Scattering region, allowing to reach higher values of $Q^2$ (where the factorization is in more solid grounds) and $x_B$ (i.e., extending the valence quark explored region).

In Hall B, the new CLAS12 detector, shown in Fig. 13, will be built. It is divided in a forward part to detect leading particles and a central part for recoil particles detection. The central detector will cover the angles between 40° and 135° and will be housed in a compact superconducting solenoidal magnet, wich will serve for particle track measurement and as shielding of the detectors from electromagnetic backgrounds as well.

The general structure of the forward part of CLAS12 is similar to that of the CLAS, being based on a toroidal field and azimuthally segmented in six independent spectrometers. It will detect charged and neutral particles with polar angles between 5° and 40°. Charged particle identification will rely on a time of flight system and on two Cerenkov counters with different thresholds. These system are well suited for electron/pion separation and for proton identification over the whole accessible momentum range, but, taking into account the relative
population of pions and kaons, it is not sufficient for good kaon identification above 3 GeV/c.

As discussed in the previous sections, the more recent experimental results have pointed out as many of the open issues in the TMD studies are connected to strange channels and in fact a relevant part of the CLAS12 physics program will involve kaon detection. For this reason, a project to replace part of the low threshold Cerenkov counter with a RICH detector is under development. The current project (still under discussion) foresees a first phase when only one RICH sector will be instrumented and in which unpolarized and longitudinal polarization measurements will be performed. In the next stage, a second (or possibly more) RICH sector will be installed, allowing to perform measurements that require either more statistics or a symmetric coverage (as for Collins and Sivers asymmetries).

9. Conclusions

The JLab with its CEBAF accelerator and the three experimental halls is a Laboratory dedicated to the study of the hadronic physics with electromagnetic probes in a large variety of aspects. The physics program extends from typical nuclear effects like long range correlations in nuclei to the study of the short distance vacuum structure in parity violating experiments.

In recent years, a big part of the physics program was devoted to the study of the Transverse Momentum Dependent distribution functions, new functions introduced to describe the internal structure of the nucleon. Studies of TMDs at JLab and in other laboratories have shown sizeable effects due to transverse motion of the quarks inside the nucleon, but also have open questions. These questions need to be addressed in a new generation of experiments, providing higher precision experimental data, and with new analysis techniques, necessary to unfold fundamental properties from the measured observables.
The 6 GeV era of JLab, started in 1996, will end in spring 2012, and after about one year of shut down, the 12 GeV operations of JLab will begin. The physics program of the 12 GeV JLab will be the natural continuation of the studies performed at the laboratory in the last 15 years. In particular, the increased beam energy will allow to extend the TMD studies at higher $Q^2$ and $x_B$ and the luminosity increased by about an order of magnitude will provide experimental data with an unprecedented statistical precision.

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