Probing the Proton's Quark Dynamics in Semi-Inclusive Pion Production at 12 GeV

Update of Experiment E12-06-112 (approved by PAC 30)

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A CLAS collaboration proposal

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Abstract

We propose to study azimuthal asymmetries in semi-inclusive electroproduction of pions using the JLab 12 GeV polarized electron beam and the CLAS12 detector with an unpolarized hydrogen target.

The measurement of the $\cos 2\phi$ azimuthal moment of the cross section, in particular, will probe the Collins fragmentation function and will also provide information on the orbital motion of quarks by determining the leading-twist Boer-Mulders transverse-momentum-dependent (TMD) parton distribution, related to the interference between $L = 0$ and $L = 1$ light-cone wave functions.

The $\sin\phi$ and $\cos\phi$ moments will also be analyzed, further probing the transverse momentum distributions of partons and allowing the study of the higher-twist contributions. The P_T and Q^2-dependences of the $\cos 2\phi$, $\sin\phi$, and $\cos\phi$ moments will be studied to test the transition from a non perturbative description of the process at low P_T to its perturbative description at high P_T. High-statistics measurements of semi-inclusive pion production will be used to study the $(Q^2, W, x, P_\perp, z)$ phase space, where factorization of PDFs and fragmentation functions holds. Two-pion production will also be studied to help understand the diffractive ρ^0 and other two-pion contributions to semi-inclusive deep inelastic scattering.

A total of 2000 beam hours is requested. The experiment makes use of the base equipment in Hall B, including the CLAS12 and ancillary beamline instrumentation.

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}	$\mathbf{h_1}$ $h_{1T}^\perp$

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).

1 Introduction

Inclusive deep inelastic scattering processes probe the longitudinal momentum distribution of the nucleon. In the last few years it became clear that hard exclusive and semi-inclusive processes can provide information on transverse momentum of quarks and transverse distance of a quark from the center of mass of the nucleon, enabling the so-called " nucleon tomography", or scanning the nucleon in transverse slices.

In perturbative QCD, which applies when the transverse momentum $P_\perp$ of the detected hadron is large compared to Λ_{QCD}, asymmetries vanish at leading twist level. The observed spin-dependent and spin-independent azimuthal asymmetries occur at $P_\perp$ below 1-2 GeV, which is not much larger than Λ_{QCD} or the typical parton transverse momenta of the order of 0.5 GeV. Thus the asymmetries could arise from non-collinear parton configurations or from multi-parton correlations ("higher twist" effects, which are suppressed at large $P_\perp$). The intrinsic transverse momentum of partons in the nucleon plays the crucial role in most explanations [1, 2, 3, 4, 5, 6, 7, 8, 9, 10] of non-zero azimuthal asymmetries in semi-inclusive DIS [11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. In contrast to inclusive deep inelastic lepton-nucleon scattering where transverse momentum is integrated out, these processes are sensitive to transverse momentum scales on the order of the intrinsic quark momentum $P_T \sim k_\perp$. Azimuthal distributions of final state particles in semi-inclusive deep inelastic scattering provide access to the orbital motion of quarks and play an important role in the study of transverse momentum distributions (TMDs) of quarks in the nucleon. TMD distributions (see Table 1) describe different spin-spin and spin-orbit correlations in momentum space [21, 22, 23, 24].

Measurements of transverse momentum P_T of final state hadrons in SIDIS with unpolarized nucleons provide access to the leading twist momentum distribution $f_1(x, k_T)$. While the x-dependence of f_1 is known in details, studies of its transverse momentum dependence in various experiments as well as lattice are just starting. Recent measurements of multiplicities and double spin asymmetries as a function of the final transverse momentum of pions in SIDIS at JLab [25, 18] 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 [26, 27, 28, 29] and on lattice [30, 31] indicate that dependence of transverse momentum distributions on the quark polarization and flavor may be very significant. Measurements of transverse momentum dependence of f_1 will be also important for interpretation of ongoing studies of high P_T hadrons at different facilities[32, 33, 34, 35].

A measurement of the azimuthal modulation of the cross section in unpolarized SIDIS provides acces to the Boer-Mulders $h_1^\perp$ TMD [36] which arises from an interference between final state interaction phases from states that differ by one unit of orbital angular momentum. The most simple mechanism that can lead to a BM function is a correlation between the spin of the quarks and their orbital angular momentum. In combination with a final state interaction that is on average attractive, already a measurement of the sign of the BM function would already reveal the correlation between orbital angular momentum and spin of the quarks. The same distribution function is also accessible in Drell-Yan production, where it gives rise to the $\cos 2\phi$ azimuthal moment in the cross section [37].

PAC30 approved Experiment E12-06-112, in which we proposed 2000 hours of measurements with polarized electron beam on a unpolarzied hydrogen with CLAS12 at its maximum luminosity. This experiment will take full advantage of the unique combination of wide kinematic coverage, high beam intensity (luminosity), high energy, high polarization, and advanced detection capabilities to study the transverse momentum and spin correlations in semi-inclusive DIS both in the target and current fragmentation regions.

2 Scientific Case and Recent Developments

Within the one photon exchange approximation, the double inclusive cross section for unpolarized SIDIS processes, $\ell\, p \to \ell\, h\, X$, has a dependence on the azimuthal angle ϕ_h of the final hadron already at leading order. The cross section (see for ex.[38, 22]) has contributions from two structure functions:

$$\begin{aligned}
&\frac{d\sigma}{dx_{\scriptscriptstyle B}\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \\
&\quad \frac{\alpha^2}{x_{\scriptscriptstyle B} y Q^2}\, \frac{y^2}{2\,(1-\varepsilon)} \left(1+\frac{\gamma^2}{2x_{\scriptscriptstyle B}}\right) \Bigg\{ F_{UU,T} + \varepsilon\, F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{UU}^{\cos\phi_h} \\
&\qquad + \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e\, \sqrt{2\,\varepsilon(1-\varepsilon)}\, \sin\phi_h\, F_{LU}^{\sin\phi_h} \Bigg\},
\end{aligned} \tag{1}$$

where α is the fine structure constant, and ε is ratio of longitudinal and transverse photon flux. The incoming (l) and outgoing (l') lepton lines, along with the virtual photon (q) direction define the lepton scattering plane. The angle ϕ_h (ϕ) is the azimuthal angle between the scattering plane formed by the initial and final momenta of the electron and the production plane formed by the transverse momentum of the observed hadron and the virtual photon [39]. The relevant kinematic variables are defined as:

$$-Q^2 = (l - l^{'})^2, \quad \nu = \frac{p \cdot q}{M} = E - E^{'}, \quad W^2 = 2M\nu + M^2 - Q^2,$$

$$x_B = \frac{Q^2}{2pq}, \quad y = \frac{\nu}{E}, \quad z = \frac{E_\pi}{\nu}, \quad x_F = \frac{2P_L}{W},$$

The transverse (P_T) and longitudinal (P_L) momenta of the pion are defined with respect to the virtual photon direction (CMS)

The structure functions on the r.h.s. depend on $x_{_B}$, Q^2, z and $P_{h\perp}^2$. According to the transverse momentum dependent factorization the structure functions factorize into TMD parton distributions and fragmentation functions (FFs), and into soft and hard parts [38]. The $F_{UU}^{\cos 2\phi}$, first discussed by Boer and Mulders in 1998 [36], depends on the Boer-Mulders function, $h_1^\perp(x, k_T)$, and the Collins fragmentation function $H_1^\perp(z, p_T)$ ($k_\perp$ and $p_\perp$ are quark transverse momenta before and after scattering). The measurement of transverse spin dependent distribution is, thus, complicated by the presence of an additional polarized fragmentation function. Significant asymmetry was measured recently by Belle [40, 41, 42], indicating that the Collins function is indeed large.

Within the leading order (zero-th order in α_s) parton model with twist-two distribution and fragmentation functions, the simplest azimuthal asymmetry, a $\cos\phi_h$ dependence, arises in unpolarized SIDIS (the so-called Cahn effect [43]). It is related to the quark intrinsic transverse motion, $\boldsymbol{k}_\perp$, and gives a kinematical correction to the usual cross-section, computed in collinear configuration, proportional to $k_\perp/Q$. The study of the cross-section dependence on $\cos\varphi_h$ and on P_{hT} allows to extract the parameters describing the unpolarized TMD DFs, $f_1^q(x, \boldsymbol{k}_\perp^2)$, and FFs, $D_q^h(x, \boldsymbol{p}_\perp^2)$ (for a recent analysis see [44], where the Sivers asymmetry was also analyzed).

Within the same approach, kinematical corrections proportional to $(k_\perp/Q)^2$ lead to additional contributions in the $\cos 2\phi_h$ moment. In order to extract the contribution of the Boer-Mulders $\otimes$ Collins part one needs a reliable calculation of the kinematical corrections. Additional contribution to $\cos\phi_h$ and $\cos 2\phi_h$ moments coming from processes when the final meson is produced at short distances via hard-gluon exchange [45] may also be significant in the kinematic regime where the ejected meson carries most of the virtual photon momentum (large z). Perturbative QCD contributions (at order α_s and possibly α_s^2) to the kinematical $\cos\phi_h$ and $\cos 2\phi_h$ asymmetries also have to be evaluated. Such a study shows that the parton model with TMD DFs and FFs dominates at P_{hT} values below 1 (GeV/c) [44].

The $h_1^\perp$ distribution function has been studied in various QCD inspired models, mainly using a one-gluon exchange[5, 46, 47, 23, 48, 49, 50, 51, 52, 53, 54]. The results in the light-cone quark model [54] for the densities with transversely polarized

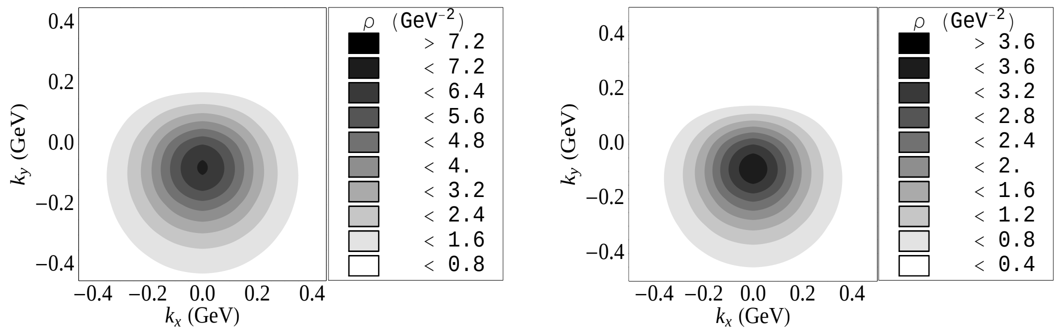

Figure 1: Quark densities in the $\boldsymbol{k}_T$ plane for transversely polarized quarks in an upolarized proton for up (left panel) and down (right panel) quark from Pasquini and Yuan [54]

quarks in an unpolarized proton shown in Fig. 1 are in good agreement with recent lattice calculation[31]. The Boer-Mulders function is negative for both up and down quarks and the sideway shift is always in the positive $\hat{y}$ direction. Even though the Boer-Mulders function is smaller in magnitude for down quark than for up quark, the average sideways distortion for down quark ($\langle \boldsymbol{k}_x^d \rangle = -215$ MeV) was predicted to be stronger than for up quarks ($\langle \boldsymbol{k}_x^u \rangle = -159$ MeV). $\langle \boldsymbol{k}_x^u \rangle = -159$ MeV, and $\langle \boldsymbol{k}_x^d \rangle = -215$ MeV.

Proposed studies include the dependence of the unpolarized SIDIS cross-section on 1) P_{hT}, 2) $\cos\phi_h$, 3) $\cos 2\phi_h$. A careful analysis of the data from points 1) and 2), in particular at small P_{hT} values, will lead to a consistency check of the overall scheme and to a better extraction of the parameters describing the $\boldsymbol{k}_\perp$ and $\boldsymbol{p}_\perp$ dependence of the DFs and FFs, respectively. Having achieved that, one has a full control on the kinematical azimuthal asymmetries and can therefore exploit the data from point 3) to extract the parameters of the Boer-Mulders DFs and Collins FFs. This should be done by using, in addition, the combined data from HERMES, COMPASS and BELLE[40, 41, 42].

In order to extract k_T-dependence of, both f_1 and $h_1^\perp$, it is advantageous to project the differential cross section onto Fourier modes [55]. At leading twist and tree-level, the weighted integral of cross section can be related to a product of TMDs and fragmentation functions in Fourier space.

$$\int_0^{2\pi} \frac{d\phi_S}{2\pi} \int_0^{2\pi} d\phi_h \int_0^\infty d|\boldsymbol{P}_{h\perp}|\, |\boldsymbol{P}_{h\perp}|\, J_0(|\boldsymbol{P}_{h\perp}||\boldsymbol{b}_T|) \left[\frac{d\sigma}{dx_{_B}\, dy\, d\phi_S\, dz_h\, d\phi_h\, |\boldsymbol{P}_{h\perp}| d|\boldsymbol{P}_{h\perp}|}\right]$$
$$= \frac{\alpha^2}{y Q^2} \frac{y^2}{(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x_{_B}}\right) \sum_a e_a^2\, \tilde{f}_1^a(x, z^2 \boldsymbol{b}_T^2) \tilde{D}_1^a(z, \boldsymbol{b}_T^2)\,,$$

where Fourier transform of a generic TMD f (or a generic fragmentation function D)

is defined as

$$\tilde{f}(x, \boldsymbol{b}_T^2) \equiv \int d^2\boldsymbol{k}_T\, e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_T}\; f(x, \boldsymbol{k}_T^2) = 2\pi \int d|\boldsymbol{k}_T||\boldsymbol{k}_T|\; J_0(|\boldsymbol{b}_T||\boldsymbol{k}_T|)\; f^a(x, \boldsymbol{k}_T^2)\;, \quad (2)$$

where J_0 is a Bessel function. The formalism in $\boldsymbol{b}_T$-space avoids convolutions, making it easier to perform a model independent analysis. The fundamental objects in this formalism are the (derivatives of) Fourier transformed TMDs $\tilde{f}_1$, $\tilde{h}_1^{\perp(1)}$ [2] and fragmentation functions $\tilde{D}_1$, $\tilde{H}_1^{\perp(1)}$. Theoretically, these $|\boldsymbol{b}_T|$-dependent distributions contain the same information as their conventional, momentum dependent counterparts. In practice, however, only a limited range in $|\boldsymbol{b}_T|$ is accessible with sufficient accuracy from experiments. Thus, to carry out the Fourier transformation back to conventional TMDs, model assumptions must be made in order to supplement information over the whole range of $|\boldsymbol{b}_T|$.

The $|\boldsymbol{b}_T|$-dependent distributions are also the objects that appear in the evolution equations that describe the scale dependence beyond tree level, see, e.g., Ref. [56]. Lattice calculations of TMDs are performed in b-space rather than momentum space as well [30, 31]. This suggests that it is the $|\boldsymbol{b}_T|$-dependent quantities that are most suitable for a model independent analysis and comparison with lattice data.

The main questions to address, when applying this procedure to CLAS12 data, are the limited range in hadron transverse momenta and the low Q^2, as Fourier-transformed quantities receive (through the Fourier integral) contributions from the entire range of P_T, while the whole factorization formalism requires $P_T << Q$. The studies of effects of the cut on the maximum value of P_T are in progress. The above transformation depends on the external parameter $\mathcal{B}_T \equiv |\boldsymbol{b}_T|$. Choosing different values of this parameter allows us to scan the transverse momentum dependence of the distributions in Fourier space.

3 Technical Progress Towards Realizing the Experiment

The proposed experiment will use the upgraded CLAS12 spectrometer in its standard configuration. We will run at the maximum magnetic field and maximum luminosity of $10^{35}/\mathrm{cm}^2\mathrm{s}$. The total event rate in the DIS region for this experiment is expected to be around 2000 Hz above $Q^2 = 1$ GeV^2. Estimates of the total trigger rate are around 20 kHz. A data acquisition rate of 10 kHz has already been achieved with today's technology for the present CLAS DAQ, so that the required data acquisition rate for this experiment is a rather modest extrapolation.

At PAC34, several SIDIS experiments (Proposals E12-09-007, 008, 009) were approved for both unpolarized and longitudinally polarized target. All of these proposal

[2] 1 indicates first derivative over $\boldsymbol{b}_T^2$, also includes J_2 [55]

require a RICH detector to separate Kaons from pions and protons. Work on the design of such a RICH detector has begun, and first benchmark results have been presented at CLAS12 workshops. That will extend all proposed measurements, allowing separation of all three charge states of pions and kaons and studies of fragmentation process of hadrons.

4 The Beam Request and Expected Results

We propose a measurement of azimuthal moments of the single pion cross section in SIDIS using the CLAS12 [57] in Hall B at Jefferson Lab, a 6.6-11.0 GeV longitudinally polarized electron beam and an unpolarized hydrogen target. Although the focus of the proposed experiment is the study of azimuthal moments of π^+ and π^-, π^0's will be measured as well, and used as a cross check. The goal of the proposed experiment is to measure the kinematic dependence of azimuthal moments in pion production in SIDIS and in particular the $\cos 2\phi$ moment of the target spin-independent cross section. This will be the first statistically significant measurement of kinematic dependences for the Boer-Mulders TMD distribution in the valence region. The $\cos\phi$ and $\sin\phi$ moments will also be studied to establish their twist-3 nature from their Q^2 and P_T dependences.

The expected number of counts and corresponding statistical errors are based on a full simulation of inclusive and semi-inclusive inelastic scattering with the CLAS12 acceptance folded in. Events were generated with the clas12DIS generator [58]. This generator is basically an implementation of the LUND Monte Carlo package called PEPSI (Polarized Electron-Proton Scattering Interactions) [59]. It is based on polarized and unpolarized parton distribution functions and the LUND string model for hadronization, and has been tested successfully against several low-Q^2 experiments with 5.7 GeV beam at Jefferson Lab.

A fast Monte Carlo simulation program has been used to define the acceptance and resolution of the CLAS12 detector with all of the standard (base) equipment in place. Realistic MC simulations are crucial for separation of different contributions to $\cos\phi$ and $\cos 2\phi$ azimuthal moments arising from higher twists, radiative corrections [60] and in particular from the detector acceptance. The CLAS12 FAST-MC program was used to simulate the physics events and study the extraction of azimuthal moments and acceptance corrections.

In the cross section measurements (P_T, and ϕ-dependences) the overall systematic error is estimated to be $\sim 6-7\%$ including $\sim$4.0% due to acceptance and $\sim$3.0% due to radiative corrections. The systematic uncertainties for different moments are listed in the Table 2.

We propose to run 2000 hours on hydrogen target with luminosity $\sim 10^{35}$ cm^{-2}s^{-1}. The number of days was chosen to achieve a statistical error that is not significantly larger than the systematical error at the highest x and P_T points.

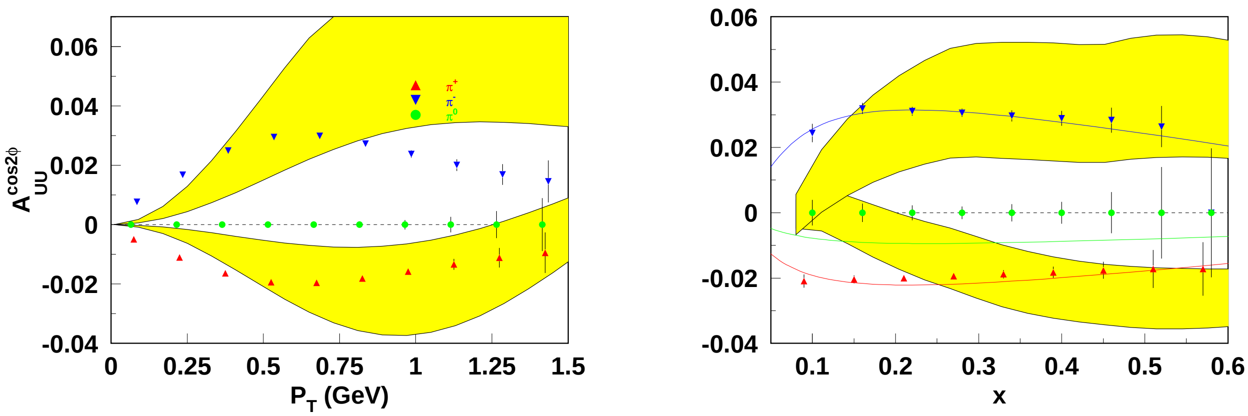

Figure 2: The $\cos 2\phi$ moment as a function of P_T for $4. < Q^2 < 5.$ (left) and as a function of x for $0.8 < P_T < 0.9, 0.5 < z < 0.55$ (right) at 11 GeV for pions from 2000h of CLAS12. The red curve is calculation in the light-cone constituebt quak model [61] and the band for two models from [62, 63].

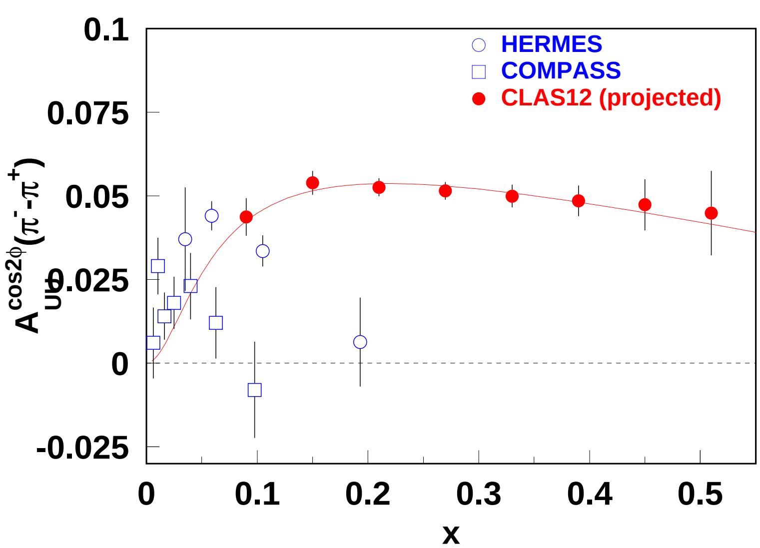

Figure 3: The difference of azimuthal asymmetries $A_{UU}^{\cos(2\phi_h)}$ for negative and positive pions or hadrons, as function of x. The experimental points were obtained taking the differences of preliminary π^- and π^+ HERMES data [64], and preliminary h^- and h^+ COMPASS data [65]. The projected CLAS12 (filled circles) error bars show the propagation of statistical errors, corrected for dilution from HT contributions (assuming equal magnitudes). The theoretical curve is obtained using $h_1^{\perp(1)q}(x)$ from the LCCQM [54].

Table 2: Expected systematic uncertainties for azimuthal moments

Source	$\Delta A^{cos\phi}$	$\Delta A^{cos2\phi}$	$\Delta A^{sin\phi}$
Beam polarization			2%
ϕ acceptance	3%	1%	1%
other moments	1%	2%	1%
Radiative corrections	2%	1%	1%
Total	$< 4\%$	$< 3\%$	$< 3\%$

Projections for the kinematical dependence of the $\cos 2\phi$ for 2000 hours of running with the proposed configuration in a typical three dimensional bin is shown on Fig. 2. A very large data set (in particular at lower x) allows us to further subdivide the data into bins in P_T and z. The precision measurement of the Boer-Mulders asymmetry requires subtraction of all higher twist and radiative contributions to the $\cos 2\phi$ moment. High-precision measurement will define whether the asymmetry stays constant at large Q^2, as predicted by pQCD [38]. The new data will allow more precise tests of the factorization ansatz and the investigation of the Q^2 dependence of both $\cos 2\phi$ and $\cos\phi$ asymmetries. This will enable us to study the leading-twist and higher-twist nature of both observables.

Competing mechanisms, which may be also relevant in the CLAS12 kinematic regime ($\langle Q^2 \rangle \sim 2$ GeV^2), including the Cahn [43] and Berger [45] terms as well as the perturbative and radiative contributions to first order are expected to be “flavor blind”[66, 67], i.e. are the same for negative and positive pions. In the calculations one can expect, in the first approximation, those effects to cancel in the difference of the asymmetries for π^- and π^+. The projection for the difference of $\cos 2\phi$ moments for positive and negative pions are shown in Fig. 3.

Contributions to $\cos\phi$ moment are also related to contributions to $\cos 2\phi$ and their extraction will provide an additional check for the background contributions to $\cos 2\phi$ being under control. Extraction of $\cos\phi$ and $\cos 2\phi$ moments for all 3 pions will provide additional information on widths of k_T distributions and their flavor dependence.

The difference of the $\cos 2\phi$ moments for π^+ and π^- combined with measurement of the $\sin 2\phi$ moment of the cross section, or the Kotzinian-Mulders asymmetry with longitudinally polarized target[68, 69] and the Collins effect with transversely polarized target, also planned with CLAS12, will provide independent information on the Collins function. This data compared with measurements of Collins function performed at BELLE [41] will check our understanding of its evolution properties.

The proposed measurements, in addition, will allow the extraction of the transverse momentum, P_T and Q^2-dependence of the beam SSAs at fixed x_B and z (Fig.4). The beam SSAs in single-pion production combined with the measurements of higher

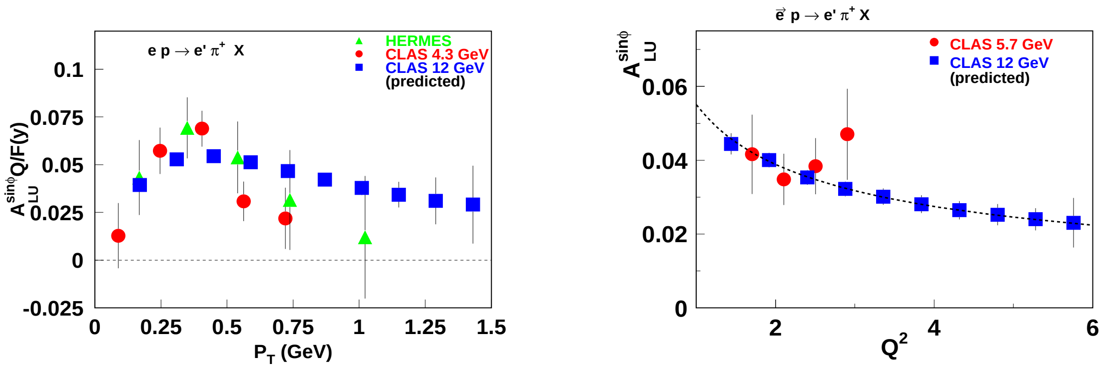

Figure 4: Beam SSA measured as a function of the transverse momentum of the π^+ (left) and momentum transfered Q^2 (right). The P_T-dependent SSA is corrected for the kinematic factor $F(y)$ accounting different average y in two experiments.

twist asymmetries in dihadron production [70] will enable us to further examine the factorization hypothesis and to study the higher-twist nature of the process and probe the transition from non-perturbative (low P_T) to perturbative (high P_T) regimes of QCD.

4.1 Summary and Request

In this proposal we outline a study of transverse momentum distributions of quarks and in particular the Boer-Mulders TMD parton distribution function using pion electroproduction in SIDIS for $1 < Q^2 < 11$ GeV^2, an 11 GeV electron beam, and the CLAS12 detector.

For this proposal, we assumed beam time of 2000 hours with polarized electrons at 11 GeV to access the large x, Q^2, and P_T region where the effects related to transverse momentum and spin of quarks are large. With the increased beam energy and luminosity we expect an increase of the statistics by a factor of ~ 100 compared to existing HERMES and CLAS data.

In addition, the large kinematic and geometric acceptance of CLAS12 will let us study hadronic distributions in the target fragmentation region and in particular Λ production, and also accumulate a significant sample of two-pion final states [70]. Interesting in their own right [71, 72, 73], these distributions are also important in studies of the background to SIDIS pions from exclusive two pions and ρ in particular.

The measurements we intend to carry out are important for the future development of the formalism of TMD parton distributions. This study involves a simultaneous scan of various variables (x_B, Q^2, z, $P_\perp$ and ϕ) and for that a large acceptance detector such as CLAS12 is most suitable. Analysis of already existing electroproduction data from the CLAS E16 experiment and studies based on simulations have shown that the proposed measurements are feasible.

The major improvement in the projected error bars for pions for the dedicated measurement results from the increased acceptance for SIDIS pions (large M_X, Q^2, P_T) and the higher luminosity. This will allow us to map out the x_B and z and $P_\perp$ dependence of azimuthal moments of pions in smaller bins. The proposed measurement with CLAS12 will produce precision data on the azimuthal asymmetries in SIDIS, and will provide the measurement of a twist 2 TMD parton distribution in the valence region and a wide range in P_T, which will unlikely be superseded by any ongoing or planned experiments.

Beam Request

This experiment can be carried out with 2000 hours. It does not require a polarized target and can run during the first year of operation.

The measurements involve the standard CLAS12 configuration also proposed for DVCS studies. Therefore these experiments can run simultaneously. Precise data for SIDIS asymmetries from CLAS12 will provide new and deeper insight into the nucleon structure and in particular distributions of transverse momentum and spin of quarks.

References

[1] D.W. Sivers, Phys. Rev. D43 (1991) 261.

[2] J.C. Collins, Nucl. Phys. B396 (1993) 161, hep-ph/9208213.

[3] P.J. Mulders and R.D. Tangerman, Nucl. Phys. B461 (1996) 197, hep-ph/9510301.

[4] A.M. Kotzinian and P.J. Mulders, Phys. Rev. D54 (1996) 1229, hep-ph/9511420.

[5] S.J. Brodsky, D.S. Hwang and I. Schmidt, Phys. Lett. B530 (2002) 99, hep-ph/0201296.

[6] S.J. Brodsky, D.S. Hwang and I. Schmidt, Nucl. Phys. B642 (2002) 344, hep-ph/0206259.

[7] J.C. Collins, Phys. Lett. B536 (2002) 43, hep-ph/0204004.

[8] X. Ji and F. Yuan, Phys. Lett. B543 (2002) 66, hep-ph/0206057.

[9] A.V. Belitsky, X. Ji and F. Yuan, Nucl. Phys. B656 (2003) 165, hep-ph/0208038.

[10] Z.B. Kang and J.W. Qiu, Phys. Rev. Lett. 103 (2009) 172001, 0903.3629.

[11] HERMES, A. Airapetian et al., Phys. Rev. Lett. 84 (2000) 4047, hep-ex/9910062.

[12] CLAS, H. Avakian et al., Phys. Rev. D69 (2004) 112004, hep-ex/0301005.

[13] HERMES, A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002, hep-ex/0408013.

[14] COMPASS, V.Y. Alexakhin et al., Phys. Rev. Lett. 94 (2005) 202002, hep-ex/0503002.

[15] COMPASS, E.S. Ageev et al., Nucl. Phys. B765 (2007) 31, hep-ex/0610068.

[16] HERMES, A. Airapetian et al., Phys. Lett. B693 (2010) 11, 1006.4221.

[17] The COMPASS, M.G. Alekseev et al., Phys. Lett. B692 (2010) 240, 1005.5609.

[18] The CLAS, H. Avakian et al., Phys. Rev. Lett. 105 (2010) 262002, hep-ex/1003.4549.

[19] M.G. Alekseev et al., Eur. Phys. J. C70 (2010) 39, 1007.1562.

[20] X. Qian et al., (2011), nucl-ex/1106.0363.

[21] K. Goeke, A. Metz and M. Schlegel, Phys. Lett. B618 (2005) 90, hep-ph/0504130.

[22] A. Bacchetta et al., JHEP 02 (2007) 093, hep-ph/0611265.

[23] S. Meissner, A. Metz and K. Goeke, Phys. Rev. D76 (2007) 034002, hep-ph/0703176.

[24] C. Lorce and B. Pasquini, (2011), 1104.5651.

[25] H. Mkrtchyan et al., Phys. Lett. B665 (2008) 20, hep-ph/0709.3020.

[26] Z. Lu and B.Q. Ma, Nucl. Phys. A741 (2004) 200, hep-ph/0406171.

[27] M. Anselmino et al., Phys. Rev. D74 (2006) 074015, hep-ph/0608048.

[28] B. Pasquini, S. Cazzaniga and S. Boffi, Phys. Rev. D78 (2008) 034025, hep-ph/0806.2298.

[29] C. Bourrely, F. Buccella and J. Soffer, (2010), 1008.5322.

[30] P. Hagler et al., Europhys. Lett. 88 (2009) 61001, hep-lat/0908.1283.

[31] B.U. Musch et al., (2010), 1011.1213.

[32] HERMES, A. Airapetian et al., Phys. Rev. Lett. 84 (2000) 2584, hep-ex/9907020.

[33] Spin Muon (SMC), B. Adeva et al., Phys. Rev. D70 (2004) 012002, hep-ex/0402010.

[34] COMPASS, E.S. Ageev et al., Phys. Lett. B633 (2006) 25, hep-ex/0511028.

[35] PHENIX, A. Adare, (2007), arXiv:0704.3599 [hep-ex].

[36] D. Boer and P.J. Mulders, Phys. Rev. D57 (1998) 5780, hep-ph/9711485.

[37] R.D. Tangerman and P.J. Mulders, Phys. Rev. D51 (1995) 3357, hep-ph/9403227.

[38] X. Ji, J. Ma and F. Yuan, Phys. Rev. D71 (2005) 034005, hep-ph/0404183.

[39] A. Bacchetta et al., Phys. Rev. D70 (2004) 117504, hep-ph/0410050.

[40] Belle, K. Abe et al., Phys. Rev. Lett. 96 (2006) 232002, hep-ex/0507063.

[41] Belle, A. Ogawa et al., AIP Conf. Proc. 915 (2007) 575.

[42] Belle, R. Seidl et al., Phys. Rev. D78 (2008) 032011, 0805.2975.

[43] R.N. Cahn, Phys. Rev. D40 (1989) 3107.

[44] M. Anselmino et al., Phys. Rev. D71 (2005) 074006, hep-ph/0501196.

[45] E.L. Berger, Z. Phys. C4 (1980) 289.

[46] F. Yuan, Phys. Lett. B575 (2003) 45, hep-ph/0308157.

[47] L.P. Gamberg, G.R. Goldstein and K.A. Oganessyan, Phys. Rev. D67 (2003) 071504, hep-ph/0301018.

[48] L.P. Gamberg, G.R. Goldstein and M. Schlegel, Phys. Rev. D77 (2008) 094016, hep-ph/0708.0324.

[49] A. Courtoy et al., Phys. Rev. D78 (2008) 034002, 0801.4347.

[50] A. Bacchetta et al., (2008), hep-ph/0807.0323.

[51] A. Kotzinian, (2008), 0806.3804.

[52] J.R. Ellis, D.S. Hwang and A. Kotzinian, Phys. Rev. D80 (2009) 074033, 0808.1567.

[53] L. Gamberg and M. Schlegel, Phys. Lett. B685 (2010) 95, 0911.1964.

[54] B. Pasquini and F. Yuan, Phys. Rev. D81 (2010) 114013, 1001.5398.

[55] D. Boer et al., (2011), in preparation.

[56] A. Idilbi et al., Phys. Rev. D70 (2004) 074021, hep-ph/0406302.

[57] L.e.a. Elouadrhiri, The CLAS12 Spectrometer: Components and Performance. .

[58] H. Avakian and P. Bosted., (2006).

[59] L. Mankiewicz, A. Schafer and M. Veltri, Comput. Phys. Commun. 71 (1992) 305.

[60] I. Akushevich, N. Shumeiko and A. Soroko, Eur. Phys. J. C10 (1999) 681, hep-ph/9903325.

[61] B. Pasquini and P. Schweitzer, (2011), 1103.5977.

[62] B. Zhang et al., Phys. Rev. D77 (2008) 054011, hep-ph/0803.1692.

[63] Z. Lu and I. Schmidt, Phys. Rev. D81 (2010) 034023, 0912.2031.

[64] F. Giordano and R. Lamb, J. Phys. Conf. Ser. 295 (2011) 012092, hep-ex/1011.5422.

[65] G.f.t.C. Sbrizzai, (2010), 1012.4910.

[66] V. Barone, S. Melis and A. Prokudin, Phys. Rev. D81 (2010) 114026, 0912.5194.

[67] P. Schweitzer, T. Teckentrup and A. Metz, Phys. Rev. D81 (2010) 094019, 1003.2190.

[68] H. Avakian et al., JLab Experiment E12-07-107 (2007).

[69] H. Avakian et al., JLab Experiment E12-09-009 (2009).

[70] Jefferson Lab Hall B, H. Avakian et al., PAC38 Proposal .

[71] HERMES, P.B. van der Nat and K. Griffioen, (2005), hep-ex/0501009.

[72] R.L. Jaffe, X.m. Jin and J. Tang, Phys. Rev. Lett. 80 (1998) 1166, hep-ph/9709322.

[73] A. Bacchetta and M. Radici, Phys. Rev. D67 (2003) 094002, hep-ph/0212300.