New Letter of Intent to Jefferson Lab PAC 30

Semi-Inclusive Pion Production with a Longitudinally Polarized Target at 12 GeV

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Abstract

We propose to study single-spin and double-spin azimuthal asymmetries in semi-inclusive electroproduction of pions using the upgraded JLab 11 GeV polarized electron beam and the CLAS12 detector with a longitudinally polarized proton target.

The measurement of the $\sin 2\phi$ azimuthal moment of the target spin-dependent part of the cross section, in particular will provide information on the orbital momentum of quarks by measuring the leading twist transverse momentum dependent (TMD) parton distribution related to the interference between $L = 0$ and $L = 1$ light-cone wave functions. Combined with measurements of the Collins asymmetry with unpolarized target (the Boer-Mulders TMD) and transversely polarized target (transversity) this measurement will provide important information on the Collins polarized fragmentation function.

The P_T dependence of the double spin asymmetry will provide additional information on the flavor and polarization dependence of transverse momentum distributions of quarks. High statistics measurements of the double spin asymmetries in inclusive and 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.

The z and Q^2 dependences of the $\sin\phi$ to $\sin 2\phi$ moments will be studied to probe underlying T-odd distribution and fragmentation functions and also to verify the hypothesis that the former is twist-3, and the later twist-2.

Two-pion production will also be studied to help understand the diffractive ρ^0 and other 2-pion contributions to semi-inclusive DIS.

A total of 1000 hours is requested with luminosity of 10^{35} cm^{-2}s^{-1}, yielding an integrated luminosity of 5×10^8 nb^{-1}.

Contents

1 Introduction

Orbital momentum of partons has been of central interest since the EMC [1] measurements implied that the helicity of the constituent quarks account for only a fraction of the nucleon spin. Very little is known about quark-quark correlations, the quark distribution in transverse momentum and space, and contributions of correlated quark-antiquark pairs (mesons) to the nucleon wave function.

In recent years parton distribution functions have been generalized to contain information not only on the longitudinal but also on the transverse distributions of partons in a fast moving hadron. Two major sets of non-perturbative generalized parton distributions were introduced: the Generalized Parton Distributions (GPDs) [2, 3, 4] and Transverse Momentum Dependent (TMD) parton distributions. Eight independent TMD parton distributions have been identified [5, 6, 7, 8] at leading twist, all of which are accessible in Semi-Inclusive DIS (SIDIS). Furthermore, the phase-space Wigner distributions were introduced [9] which contain the most general one-body information on proton structure. After integration over the spatial coordinates, they reduce to TMDs (see Fig. 1), and after integration over the transverse momentum and a specific Fourier transform they recover the GPDs [2, 3, 4].

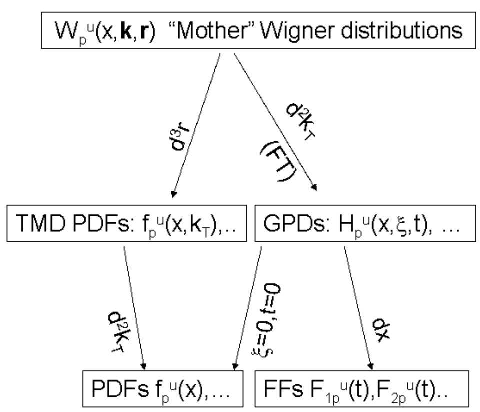

Figure 1: Wigner distributions. The f functions are the unpolarized PDFs, F_1 and F_2 are Dirac and Pauli elastic form factors and the kinematic variables ξ, t and k_T are the longitudinal and total momentum transfer and the transverse momentum of partons, respectively.

Single-Spin Asymmetries (SSAs) in azimuthal distributions of final state particles in semi-inclusive deep inelastic scattering play a crucial role in the study of transverse momentum distributions of quarks in the nucleon and provide access to the orbital angular momentum of quarks. Large SSAs, observed in hadronic reactions for decades [10, 11] have been among the most difficult phenomena to understand from first principles in QCD. Recently, significant SSAs were reported in semi-inclusive DIS (SIDIS) by the HERMES collaboration at HERA [12, 13, 14] for longitudinally and transversely polarized targets, and by the CLAS collaboration with a polarized beam [15]. HERMES measurement of the Collins effect indicate that unfavored polarized fragmentation function is large and has an opposite to favored fragmentation function sign. This finding is supported by the preliminary data from BELLE [16] indicating a significant Collins effect. CLAS target SSAs were measured using the 5.7 GeV data from the EG1 experiment using a polarized NH_3 target [17]. The large target SSA in semi-inclusive pion production measured at CLAS [18] and analyzed in terms of the Collins fragmentation [19], also indicate a significant Collins function. Measured $\sin 2\phi$ azimuthal moments of π^0 production at CLAS indeed indicate that favored an unfavored fragmentation functions are approximately equal.

This experiment is proposed to run with the DVCS experiment relying on the enhanced capabilities for detection of small angle photons making samples of all photons comparable which is important for the systematics of extraction of flavor dependences of the twist 2 TMD from x, z and $p_\perp$ dependences of the target SSA. These measurements are also essential for the study of polarized fragmentation process.

We propose a measurement of single and double spin asymmetries in SIDIS using the CLAS12 in Hall B at Jefferson Lab, a 11 GeV longitudinally polarized electron beam with a longitudinally polarized proton (NH_3) target. We propose to run with high luminosity, 10^{35} cm^{-2}s^{-1}, yielding an integrated luminosity of 5×10^8 nb^{-1}.

2 Theory and motivation

2.1 Phenomenology of the TMDs

As shown recently in Ref. [20, 22, 23, 24, 26], the interaction between the active parton in the hadron and the spectators leads to gauge-invariant TMDs. Furthermore, QCD factorization for semi-inclusive deep inelastic scattering at low transverse momentum in the current-fragmentation region has been established in Refs. [21, 25]. A detailed verification of factorization and calculations of the relevant factors in the factorization formulas have also been carried out in Ref. [21]. This new framework provides a rigorous basis to study the TMD parton distributions from SIDIS data using different spin-dependent and independent observables. TMD distributions (see Table 1) describe transitions of a nucleon with one polarization in the initial state to a quark with another polarization in the final state. The diagonal elements of the

Table 1: Leading twist transverse momentum dependent distribution functions. The U,L,T stand for transitions of unpolarized, longitudinally polarized and transversely polarized nucleons (rows) to corresponding quarks (columns).

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 are the momentum, longitudinal and transverse spin distributions of partons, and represent well-known PDFs related to the square of the leading-twist light-cone wave functions. 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 [27]. In particular, $f_{1T}^\perp$ and $h_1^\perp$, related to the imaginary part of the interference of wave functions for different orbital momentum states and known as the Sivers and Boer functions [28, 29, 30, 22, 23, 24], describe unpolarized quarks in the transversely polarized nucleon and transversely polarized quarks in the unpolarized nucleon respectively. They are *time-reversal odd* (T-odd) and can only be nonzero when initial or final state interactions cause an interference between different helicity states.

Another important quantity accessible in SSA measurements is the Mulders leading-twist distribution function $h_{1L}^\perp$. It is related to the real part of the interference of wave functions for different orbital momentum states, and describes transversely polarized quarks in the longitudinally polarized nucleon. In SIDIS the $h_{1L}^\perp$ appeares coupled to the Collins T-odd fragmentation function $H_1^\perp$ [31] which gives the probability of a transversely polarized quark fragmenting into unpolarized hadrons.

2.2 Factorization in SIDIS

For the longitudinally polarized target the SIDIS cross section at leading twist has four contributions [6, 21].

$$\begin{aligned}\frac{d\sigma}{dxdydz_h d^2\vec{P}_{h\perp}} &= \tfrac{4\pi\alpha_{\rm em}^2 s}{Q^4}(1-y+y^2/2)xF_{UU}^{(1)} - (1-y)x\cos(2\phi_h)F_{UU}^{(2)} \\ &+\lambda S_L y(1-y/2)xF_{LL} + S_L(1-y)x\sin(2\phi_h)F_{UL}\end{aligned} \tag{1}$$

The kinematic variables x, y are defined as: $x = Q^2/2(P_1q)$, and $y = (P_1q)/(P_1k_1)$. The variable $q = k_1 - k_2$ is the momentum of the virtual photon, $Q^2 = -q^2$, ϕ_h 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 (see Fig. 2), ϕ_S is the azimuthal angle of the transverse spin in the scattering plane. The subscripts in F_{UL}, F_{LL},etc., specify the beam (first index) and target(second index) polarizations, longitudinal (L), transverse (T), unpolarized (U),

Structure functions factorize into TMD parton distributions and fragmentation functions, and into soft and hard parts [21]

$$
\begin{aligned}
\sigma_{UU} \propto F_{UU} \propto & \quad f_1\left(x, k_\perp\right) D_1\left(z_h, p_\perp\right) S(\vec{\ell}_\perp) H_{UU}\left(Q^2\right) \\
\sigma_{LL} \propto F_{LL} \propto & \quad g_{1L}\left(x, k_\perp\right) D_1\left(z_h, p_\perp\right) S(\vec{\ell}_\perp) H_{LL}\left(Q^2\right) \\
\sigma_{UL} \propto F_{UL} \propto & \quad h_{1L}^\perp\left(x, k_\perp\right) H_1^\perp\left(z_h, p_\perp\right) S(\vec{\ell}_\perp) H_{UL}\left(Q^2\right),
\end{aligned} \tag{2}
$$

where $z = (P_1 P_h)/(P_1 q)$, $k_\perp$ and $p_\perp$ are quark transverse momenta before and after scattering, and P_1 and P_h are the four momenta of the initial nucleon and the observed final-state hadron respectively.

The unpolarized D_1 and polarized $H_1^\perp$ fragmentation functions depend in general on the transverse momentum of the fragmenting quark.

S_L is the longitudinal component of the target polarization with respect to the direction of the virtual photon. The different hard factors (H_{UU}, H_{LL},etc.), which are calculable in pQCD, in the SIDIS cross section are similar at one-loop order [21] and may cancel to a large extent in asymmetry observables. The soft factor $S(\vec{\ell}_\perp)$ comes from soft gluon radiation and is defined by a matrix element of Wilson lines in the QCD vacuum [21]. With a certain choice of factorization parameters, the soft factor could become unity. This may explain the success of existing phenomenology, based on the "naive" factorization assumption [7].

For a longitudinally polarized target the only azimuthal asymmetry arising in leading order is the $\sin 2\phi$ moment.

$$
\sigma_{UL}^{\sin 2\phi} \quad \propto \quad S_L 2(1-y) \sin 2\phi \sum_{q,\bar{q}} e_q^2 x h_{1L}^{\perp q}(x) H_1^{\perp q}(z), \tag{3}
$$

The physics of σ_{UL}, which involves the Collins fragmentation function $H_1^\perp$ and Mulders distribution function $h_{1L}^\perp$, was first discussed by Kotzinian and Mulders in 1996 [7, 6, 32]. The same distribution function is accessible in double polarized Drell-Yan, where it gives rise to the $\cos 2\phi$ azimuthal moment in the cross section [33].

Neglecting the contribution from the transverse component $A_\perp$, which is suppressed kinematically and therefore small [34], the double spin dependent contribution become a simple function of g_1:

$$
\frac{d^2\sigma_{LL}}{dx\, dQ^2} \quad = \quad \lambda S_L \frac{4\pi\alpha^2}{Q^4}\left(y(2-y) g_1(x, Q^2)\right), \tag{4}
$$

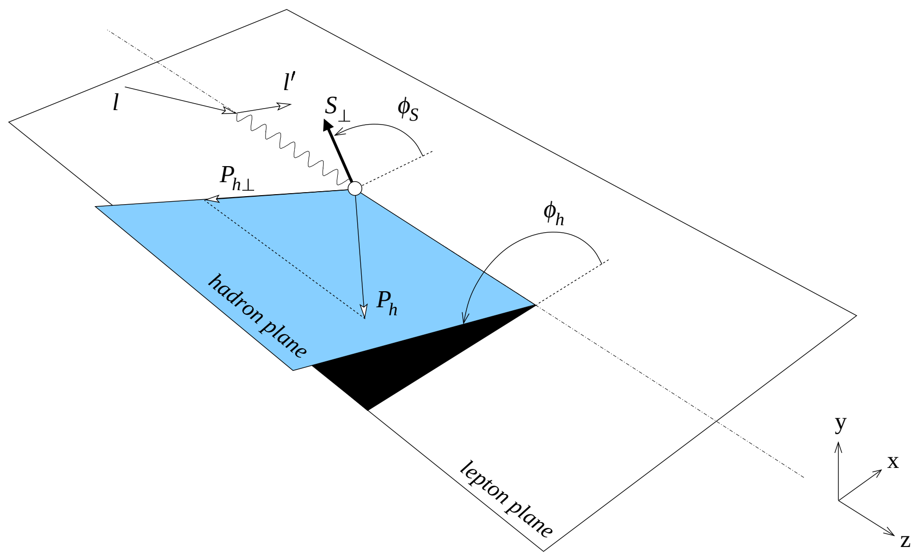

Figure 2: SIDIS kinematics. For a longitudinally polarized target, ϕ_S=0 or 180^o for negative and positive helicities of the proton, respectively.

The ratio of spin dependent and spin independent cross sections for the longitudinally polarized target is defined by the ratio of structure functions $g_1(x, Q^2)$ and $F_1(x, Q^2)$

$$A_{||} = \frac{g_1(x, Q^2)}{F_1(x, Q^2)} D'(y), \tag{5}$$

where the kinematic (depolarization) factor is given by

$$D'(y) = \frac{y(2-y)}{y^2 + 2\left(1 - y - \frac{y^2\gamma^2}{4}\right)\frac{(1+R)}{(1+\gamma^2)}}, \tag{6}$$

$R(x, Q^2)$ is the ratio of the longitudinal and transverse photo absorption cross sections and $\gamma^2 = 4M^2x^2/Q^2$.

3 Experimental situation

The validity of factorization of semi-inclusive electroproduction into a product of quark distribution functions and favored and unfavored fragmentation functions is crucial to the interpretation of target SSAs in terms of TMDs, which is the main goal of this proposal. Unpolarized data at 5.7 GeV, both from CLAS and Hall-C, support factorization, which predicts that the pion multiplicity (fraction of electron events with a pion observed at a given value of z) should be independent of x. It is also possible to examine factorization using double-spin SIDIS data. It is worthwhile to look at factorization with the additional spin degree of freedom, because the additional selectivity introduced by spin may delay the onset of factorization to higher values of Q^2 and W than for spin-averaged scattering. There are in fact preliminary indications that this may be the case in the related phenomenon of quark-hadron duality in inclusive scattering in the resonance region [35].

The double polarization asymmetry A_1 is measured by counting the sum and difference of events with anti-parallel ($\lambda = 1$,$S_L = 1$) and parallel ($\lambda = 1$,$S_L = -1$) spin states of beam and target:

$$A_1 = \frac{1}{fD'(y)P_eP_t}\frac{N^{+-} - N^{++}}{N^{+-} + N^{++}},$$

where f is the dilution factor, P_e and P_t are beam and target polarizations and $D'(y)$ is the depolarization factor (see Eq. 6).

A first factorization test comes from comparison of double spin asymmetries for all three pion flavors, as shown in the Fig. 3. The data cuts included $W > 2$ GeV and $Q^2 > 1.1$ GeV^2 to ensure DIS kinematics, and the average value of x is approximately 0.3.

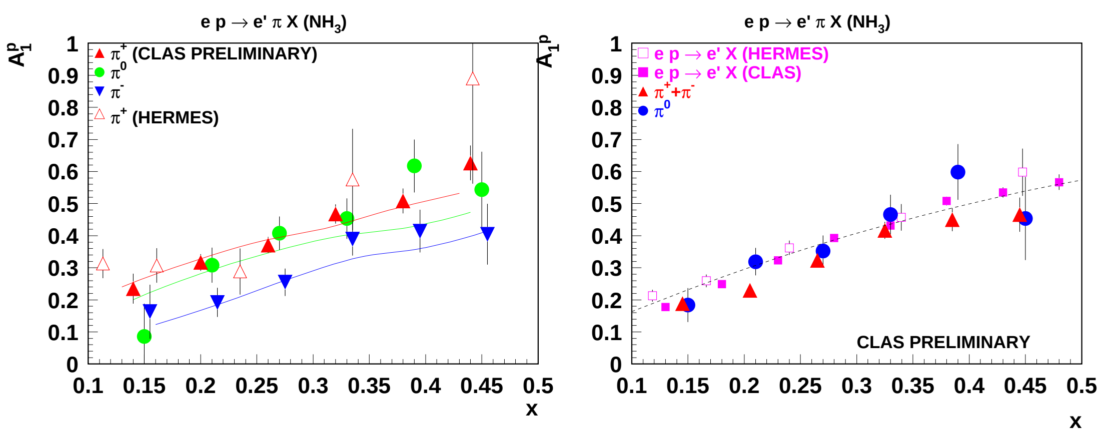

Figure 3: The double spin asymmetry as a function of x from an NH_3 target for different pion flavors. Open triangles correspond to the HERMES measurement of A_1^p for π^+ [36]. The right plot shows the comparison of inclusive A_1^p with the A_1^p for the sum of π^+ and π^- and A_1^p for π^0. The average beam polarization is 0.73 ± 0.03 and the average target polarization iss 0.72 ± 0.05. The curves present predictions from the LUND-MC for the same kinematic range and GRSV2000 PDFs.

The CLAS double polarized asymmetry A_1 is consistent with HERMES semi-inclusive data (Fig. 3) at fives times higher beam energy and three times higher Q^2, indicating no significant Q^2 dependence of the double polarized asymmetry A_1. An examination of the CLAS data on it's own indicates significant Q^2 dependence only for $Q^2 < 1$ GeV^2. The π^0 double spin asymmetry as well as A_1^p for the sum of charged pions are consistent with the inclusive A_1^p as expected in a simple partonic picture (see Fig. 3).

These studies suggest that factorization works for $W > 2$ GeV, $Q^2 > 1.1$ GeV^2, $0.15 < x < 0.5$, and $0.3 < z < 0.7$ for a 6 GeV electron energy. The improved statistical accuracy of this proposal for inclusive and SIDIS scattering for all three pion flavors will permit much more detailed and quantitative studies of factorization in spin-dependent electron scattering.

The $P_\perp$-dependence of the double-spin asymmetry was also studied for different bins in z and x to test the factorization hypothesis and possible transition to the perturbative limit, where at large P_T ($\Lambda_{QCD} << P_T << Q$) the asymmetry is expected to be independent of $P_\perp$ [21]. The measured double-spin asymmetry (see Fig. 4) at small P_T tends to increase for π^- and decrease for π^+. A possible interpretation of the P_T-dependence of the double spin asymmetry involve different widths of transverse momentum distributions of quarks with different flavor and polarization [37]. Required for this interpretation smaler width for d-quarks compared to u-quarks is consistent with observation from lattice QCD studies of a wider spread in transverse distances for d-quarks compared to u-quarks [38]. The same effect may be responsible for relatively large $\cos\phi$ moment of the double spin asymmetry (see Fig.4, right panel).

Detailed measurements of A_{LL} and its $\cos\phi$ moment as a function of P_T in different bins in x, z, Q^2 combined with measurements of azimuthal moments of the unpolarized cross section proposed for CLAS12 will allow to study the flavor dependence of transverse momentum distributions.

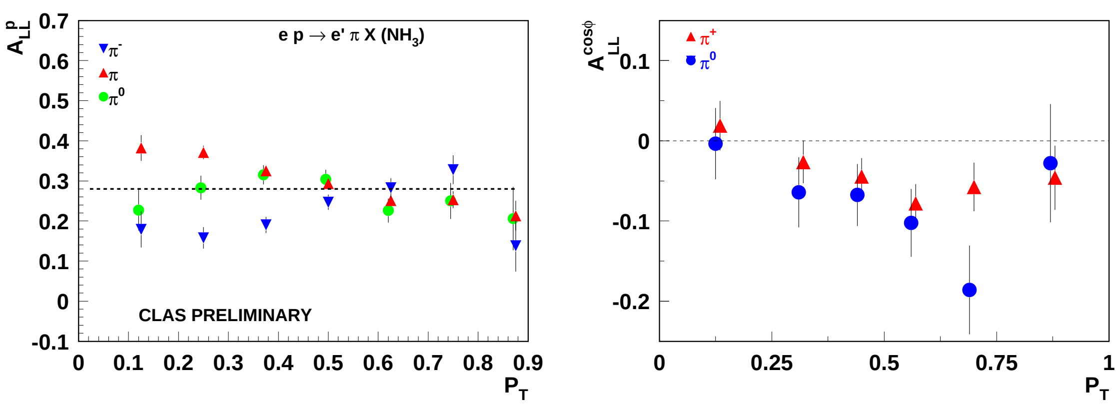

Figure 4: The double spin asymmetry A_{LL} (left) and its $\cos\phi$ moment (right) as a function of transverse momentum of hadrons, P_T, averaged in the $0.4 < z < 0.7$ range.

3.1 Leading twist SSA in SIDIS with polarized target and beam

Measurements of average moments $\langle W(\phi)\rangle_{UL} = \int \sigma_{UL}(\phi)W(\phi)d\phi / \int \sigma(\phi)\sin^2\phi d\phi$ ($W(\phi) = \sin\phi, \sin 2\phi$) of the cross section $\sigma_{UL}^{W(\phi)}$ will single out corresponding terms in the cross section. Thus the $\sin\phi$ SSA of the cross section for longitudinally polarized beam and unpolarized target is defined as:

$$A_{LU}^{\sin\phi} = \frac{\langle \sin\phi\rangle_{LU}}{\langle \sin^2\phi\rangle_{UU}} = \frac{1}{P^{\pm}N^{\pm}} \frac{\sum_{i=1}^{N^{\pm}} \sin\phi_i}{\sum_{i=1}^{N^{\pm}} \sin^2\phi_i}, \tag{7}$$

where $P^{\pm}$ and $N^{\pm}$ are the polarization and number of events for $\pm$ helicity state, respectively. For spin-dependent moments this is equivalent to the corresponding spin asymmetries A_{UL}^{W}. The final asymmetry is defined by the weighted average over two independent measurements for both helicity states or by fitting with corresponding azimuthal dependences ($\sin\phi, \sin 2\phi$) the spin asymmetries binned in the azimuthal angle.

A unique feature of the Collins mechanism is the presence of a leading twist $\sin 2\phi$ SSA for a longitudinally polarized target [32]. Measurements of the $\sin 2\phi$ SSA thus allow the study of the Collins effect with no contamination from other mechanisms. A recent measurement of $\sin 2\phi$ moment of σ_{UL} by HERMES [12] is consistent with zero. A measurably large asymmetry has been predicted only at large x ($x > 0.2$), a region well-covered by JLab [39]. The leading-twist distribution function $h_{1L}^{\perp}(x)$, accessible in this measurement, describes the transverse polarization of quarks in a longitudinally polarized proton.

The kinematic dependence of the SSA for π^+, measured from the Eg1 data set at 6 GeV are is consistent with predictions [40]. The π^+ SSA is dominated by the u-quarks; therefore with some assumption about the ratio of unfavored to favored Collins fragmentation functions, it can provide a first glimpse of the twist-2 Mulders TMD. The distribution function $h_{1L}^{\perp}$ was extracted using the π^+ target SSA [18], which is less sensitive to the unknown ratio of unfavored (d-quark fragmenting to π^+) to favored (u-quark fragmenting to π^+) polarized fragmentation functions (Fig. 6). The curve is the calculation by Efremov et al. [40], using $h_{1L}^{\perp}$ from the chiral quark soliton model evolved to Q^2=1.5 GeV^2. The extraction, however, suffers from low statistics and has a significant systematic error from the unknown ratio of the Collins favored and unfavored fragmentation functions, the unknown ratio of h_{1L}^{d}/h_{1L}^{u}, as well as from background from exclusive vector mesons. Current statistical errors for π^- and in particular π^0, which is relatively free of possible higher twist contributions [41], are large and do not allow strong conclusions from the measured SSAs. More data are required for a statistically significant measurement of the $\sin 2\phi$ moment.

It is important to note, that both π^+ and π^- SSAs may have significant contributions from exclusive vector meson production. The fraction of π^+ in the single pion sample, coming from exclusive ρ^0 decays is somewhat less, but still significant at

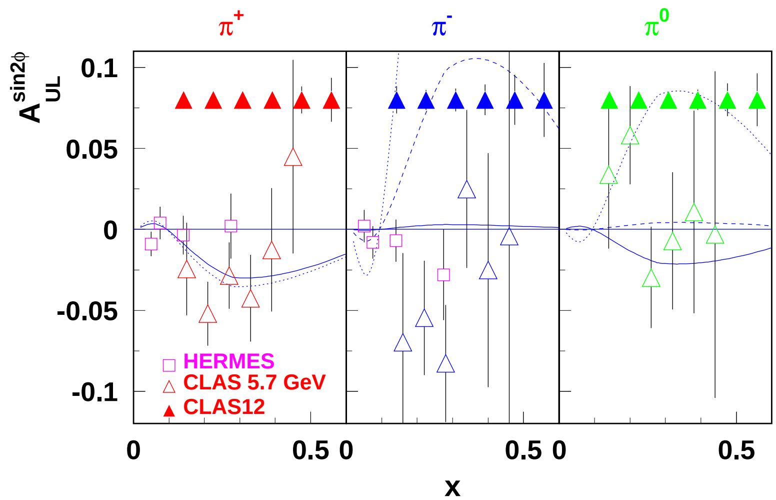

Figure 5: The projected x-dependence of the target SSA at 11 GeV. The triangles illustrate the expected statistical accuracy. The open squares and triangles show the existing measurement of the Mulders TMD from the HERMES and CLAS 5.7 GeV EG1 data sets respectively. The curves are calculated using [44].

large z and in particular for small x. The two pion data from CLAS12 would allow to extract exclusive two pion asymmetries and estimate their contribution to single pion SSA.

Projections for the resulting kinematic dependence of the leading twist SSA are shown in Fig. 5. Calculations were done using $h_{1L}^{\perp}$ from the chiral quark soliton model evolved to Q^2=1.5 GeV^2[40], f_1 from GRV95 [42], and D_1 from Kretzer, Leader and Christova[43]. Three different curves correspond to $H_1^{\perp u\to\pi^+}/H_1^{\perp u\to\pi^-} = 0, -1.2, -5$ [44]. Corresponding projected error bars for the Mulders TMD parton distribution is shown in Fig. 6.

The proposed measurement will pin down the TMD distribution and will constrain the ratio of favored and unfavored polarized fragmentation functions.

The new data will also allow a more precise test of the factorization ansatz and the investigation of the Q^2 dependence of both $\sin 2\phi$ and $\sin\phi$ asymmetries. This will enable us to study the leading-twist and higher-twist nature of both observables [45, 51, 46, 47, 48, 49, 50].

The g_1/F_1 for the sum of $\pi^{\pm}$ and π^0 final states as a function of x could serve an

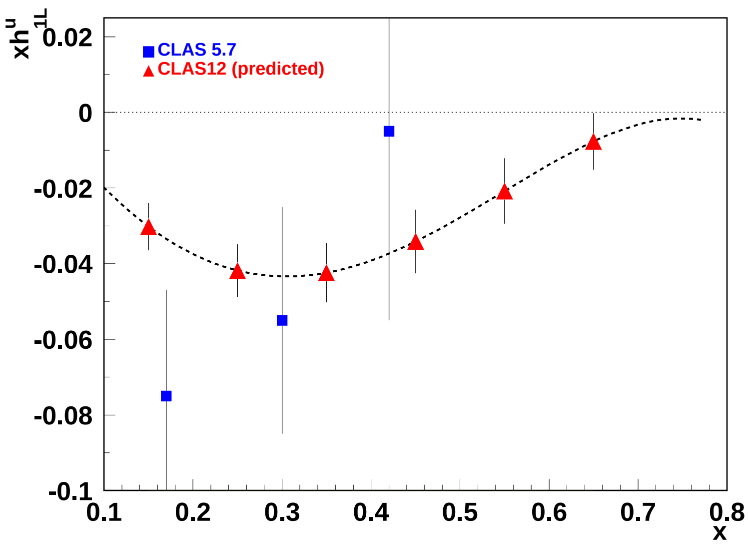

Figure 6: Mulders distribution function for u-quark from the π^+ SSA from CLAS12 (predicetd) compared with Eg1 data. The contribution from the unfavored production is included in the systematic error band. The variation for the ratio of unfavored to favored Collins functions is from -2.5 to 0.

important check for the applicability of partonic picture.

4 Summary

In this experiment we propose a study of TMD parton distributions using pion electroproduction in SIDIS with a 11 GeV electron beam, the CLAS12 detector in DVCS configuration (with Inner Calorimeter) and the polarized target. With the beam time of 1000 hours with highly polarized electrons at 11 GeV to access the large x and P_T region where the SSA due to Collins fragmentation is large.

Measured single and double spin asymmetries for all pions in a large range of kinematic variables (x_B, Q^2, z, $P_\perp$ and ϕ) combined with measurements with unpolarized target will provide detailed information on flavor and polarization dependence of transverse momentum distributions of quarks in valence region and in particular on the x_B and z and $P_\perp$ dependence of the twist-2 $h_{1L}^\perp$ parton distribution functions of u and d quraks.

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