

Studies of the Boer-Mulders Asymmetry in Kaon Electroproduction with Hydrogen and Deuterium Targets

Update of Experiment E12-09-008 (approved by PAC 34)

H. Avakian^{†*}, A. Bacchetta, V.D. Burkert, L.Elouadrhiri, V. Kubarovsky, S. Stepanyan, C. Weiss
Jefferson Lab, Newport News, VA 23606, USA

Z.-E. Meziani[†], B. Sawatzky, A. Lukhanin
Temple University 1900 N. 13th St. Philadelphia, PA 19122, 6082, USA

P.F. Dalpiaz, G. Ciullo, M. Contalbrigo[†], F. Giordano, P. Lenisa, L. Pappalardo
University of Ferrara, Via Paradiso, I-44100, Ferrara, Italy

K. Joo[†], P. Schweitzer, M. Ungaro
University of Connecticut, Storrs, CT 06269, USA

D. Ireland, R. Kaiser, K. Livingston, D. MacGregor, G. Rosner, B. Seitz[†]
Univ. of Glasgow, Glasgow G12 8QQ, UK

E. Cisbani, F. Cusanno, F. Garibaldi, S. Frullani
INFN Roma I and Istituto Superiore di Sanita', I-00161 Rome, Italy

P. Rossi, E. De Sanctis, L. Hovsepyan, M. Mirazita, and S. Anefalos Pereira
INFN, Laboratori Nazionali di Frascati, Via E. Fermi, I-00044 Frascati, Italy

M. Battaglieri, R. De Vita, V. Drozdov, M. Osipenko, M. Ripani, M. Taiuti
Dipartimento di Fisica and INFN, Sezione di Genova, Via Dodecaneso, 33 I-16146 Genova, Italy

V. Bellini, A. Giusa, F. Mammoliti, C. Randieri, G. Russo, M.L. Sperduto, C.M. Suter
INFN - Sezione di Catania and Universita' di Catania, I-95123 Catania, Italy

K. Hafidi, J. Arrington, R. Dupré, D. F. Geesaman, R. J. Holt
D. H. Potterveld, P. E. Reimer, P. Solvignon
Argonne National Lab, Argonne, IL 60439, USA

M. Aghasyan, S.E. Kuhn Old Dominion University, Norfolk, VA 23529, USA

K. Griffioen, Bo Zhao, College of William & Mary, VA 23187, USA

A. D'Angelo, C. Schaerf, V. Vegna
INFN Sezione di Roma Tor Vergata, Via della Ricerca Scientifica 1- I00133, Rome, Italy

R. De Leo, L. Lagamba, S. Marrone, G. Simonetti, E. Nappi, I. Vilardi
INFN Sezione di Bari and University of Bari, 70126 Bari, Italy

G.M. Urciuoli, INFN Roma I, I-00161 Rome, Italy

N. Kalantarians, D. Crabb, L.C. Smith, UVA, Charlottesville, VA 22904, USA

R. Avagyan, A. Avetisyan, R. Dallakyan, S. Taroyan
Yerevan Physics Institute, Alikhanian Br. 2, Yerevan, Armenia

F. Benmokhtar, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA

M. Anselmino, A. Kotzinian, B. Parsamyan, A. Prokudin
Università di Torino and INFN, Sezione di Torino, Via P. Giuria 1, I-10125 Torino
M. Burkardt New Mexico State University, PO Box 30001, Las Cruces, NM 88003, USA
B. Pasquini, Università degli Studi di Pavia, Pavia, Italy
Zhun Lu, Universidad Tecnica Federico Santa Maria, Casilla 110-V, Valparaiso, Chile
Bing Zhang, Bo-Qiang Ma, Peking University, Beijing 100871, China
L. Gamberg, Penn State Berks, Reading, PA 19610, USA
G.R. Goldstein, Tufts University, Medford, MA 02155, USA

A CLAS collaboration proposal

[†] Co-spokesperson * Contact: Harut Avakian, JLab, Newport News VA 23606. Email: avakian@jlab.org

Abstract

We are proposing a comprehensive program to study transverse momentum dependence of valence quark transverse spin distributions through measurements of spin-azimuthal asymmetries in semi-inclusive electroproduction of kaons using the upgraded JLab 11 GeV polarized electron beam and the CLAS12 detector with unpolarized proton and deuteron targets. The main objective is the study of correlations of the transverse spin of quarks with their transverse momentum, leading to observable spin and azimuthal asymmetries. The measurement of the $\cos 2\phi$ azimuthal moments of the semi-inclusive production of hadrons in DIS with unpolarized targets, in particular, will provide direct information on spin-orbit correlations by measuring the leading twist transverse momentum dependent (TMD) parton distributions related to the interference between states with different orbital momenta. Measurements with kaons are complementary to measurements with pions and will provide additional information on the Collins fragmentation mechanism. The x, z, P_T and Q^2 dependences of the $\cos 2\phi$ moment will be studied to probe the underlying T-odd distribution and fragmentation functions. The experiment will use the upgraded CLAS12 detector, 11 GeV highly polarized electron beam, unpolarized hydrogen and deuteron, targets. Kaon identification in the complete kinematic range will be done by the proposed CLAS12-RICH proximity-focusing detector. The large acceptance of CLAS12 would allow simultaneous detection of the scattered electrons and leading hadrons from the hadronization of the struck quark, providing information on its flavor and transverse momentum. We request 56 days of running on unpolarized hydrogen and deuterium. This measurement will simultaneously run with an already approved electroproduction experiment.

Contents

1	Introduction	3
1.1	Azimuthal Asymmetries in unpolarized SIDIS	4
2	Scientific Case and Recent Developements in the Kaon Sector	6
2.1	The flavor-dependence of Boer-Mulders and Collins functions	9
2.2	Transverse momentum dependence of partonic distributions	10
2.3	Vector meson contribution	11
3	Technical Progress Towards Realizing the Experiment	11
4	The Beam request and Expected Results	11
4.1	Statistical and systematic errors	11
4.2	Results	13
4.2.1	Projected results for unpolarized moments	13
4.3	Summary and Request	15

1 Introduction

Semi-inclusive deep inelastic scattering (SIDIS) has been used extensively in recent years as an important testing ground for QCD. Studies so far have concentrated on better determination of parton distribution functions, distinguishing between the quark and antiquark contributions, and understanding the fragmentation of quarks into hadrons. The use of polarization in leptonproduction provides an essential new dimension for testing QCD.

Azimuthal distributions of final state particles in semi-inclusive deep inelastic scattering are sensitive to the orbital motion of quarks and play an important role in the study of transverse momentum distributions of quarks in the nucleon. Correlations of spin and transverse momentum of quarks are by now universally recognized as essential ingredients of the structure of hadrons. They are described by a number of Transverse Momentum dependent Distribution functions (TMDs) [1, 2] which give rise to various observables in hard hadronic processes [3].

Large Single Spin Asymmetries (SSAs), have been among the most difficult phenomena to understand from first principles in QCD and can also be related to TMDs. Two fundamental mechanisms have been identified leading to SSAs in hard processes; the Sivers mechanism [4, 5, 6, 7, 8], which generates an asymmetry in the distribution of quarks due to orbital motion of partons, and the Collins mechanism [7, 1], which generates an asymmetry during the hadronization of quarks.

Significant progress has been made recently in understanding the role of partonic initial and final state interactions [6, 7, 8]. The interaction between the active parton in the hadron and the spectators was included in gauge-invariant TMD distributions [6, 7, 8, 9, 10]. Furthermore, QCD factorization for semi-inclusive deep inelastic scattering at low transverse momentum in the current-fragmentation region has been established in Refs. [11, 12]. This new framework provides a rigorous basis to study the TMD parton distributions from SIDIS data using different spin-dependent and independent observables.

TMD parton distribution and fragmentation functions in DIS, Drell-Yan, and electron-positron annihilation have different gauge links, which raised a question of the universality of those functions [12, 10, 13]. It has been found that all six T-even TMD parton distributions are the same in SIDIS and Drell-Yan. The violation of universality for T-odd distributions appeared to be just a sign reversal from DIS to Drell-Yan, an exciting prediction that has to be confirmed by future experiments. Universality of TMDs in processes with hadrons in both initial and final states is violated, at least in its standard form [14, 13, 15], with far-reaching consequences in hadron collider physics.

Similar correlations arise in the hadronization process. One particular case is the Collins T -odd fragmentation function H_1^\perp [16], describing fragmentation of transversely polarized quarks into unpolarized hadrons. The Collins function is one of the most fundamental quantities accessible in hard fragmentation processes. It is of essential importance for spin physics because it works as an analyzer of the spin of the quark, but it is also interesting on its own because it allows the exploration of spin and orbital degrees of freedom of the QCD vacuum. It is universal [17, 12, 18], once measured in e^+e^- , it can be used in SIDIS and pp collisions and vice versa. For kaons in particular, the u to kaons Collins fragmentation function allows for exploring the structure of the strange vacuum, while the s to kaons Collins function allows for study the spin structure of the strangeness in the nucleon.

In recent years, measurements of azimuthal moments of hadronic cross sections in hard processes have emerged as a powerful tool to probe nucleon structure through transverse single spin asymmetries. Many experiments worldwide are currently trying to pin down various TMD effects through semi-inclusive deep-inelastic scattering (in experiments such as HERMES at DESY [19, 20, 21, 22], COMPASS at CERN [23], CLAS and Hall-A at Jefferson Lab [24, 25]), polarized proton-proton collisions (PHENIX, STAR and BRAHMS at RHIC) [26, 27, 28], and electron-positron annihilation (BELLE at KEK) [29, 30]. 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 $P_T \sim k_\perp$.

1.1 Azimuthal Asymmetries in unpolarized SIDIS

Within the one photon exchange approximation, the cross section for unpolarized SIDIS processes, $\ell p \rightarrow \ell h X$, can have a dependence on the azimuthal angle ϕ of the final hadron already at leading order. The cross section (see for ex.[11, 2]) has contributions from several structure functions:

$$\begin{aligned} \frac{d\sigma}{dx dy d\psi dz d\phi dP_{h\perp}^2} = & \frac{\alpha^2}{xy Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi F_{UU}^{\cos\phi} \right. \\ & \left. + \varepsilon \cos(2\phi) F_{UU}^{\cos 2\phi} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi F_{LU}^{\sin\phi} \right\}, \end{aligned} \quad (1)$$

where α is the fine structure constant and ε the ratio of longitudinal and transverse photon flux. The kinematic variables x and y are defined as: $x = Q^2/2(P_1 \cdot q)$, and $y = (P_1 \cdot q)/(P_1 \cdot k_1)$, respectively. The variable $q = k_1 - k_2$ is the momentum of the virtual photon, $Q^2 = -q^2$, ϕ is the azimuthal angle between the scattering plane and the hadron production plane (see Fig. 1). The subscripts of the structure functions specify the beam (first index) and target (second index) polarizations, for longitudinal (L), transverse (T), and unpolarized (U) case.

In the limit of $P_{h\perp} \ll Q^2$, the structure functions factorize into TMD parton distributions and fragmentation functions.

For an unpolarized target the only azimuthal asymmetry arising in leading order is the $\cos 2\phi$ moment [31],

$$\sigma_{UU}^{\cos 2\phi} \propto 2(1-y) \cos 2\phi \sum_{q,\bar{q}} e_q^2 x h_1^{\perp q}(x) \otimes H_1^{\perp q}(z). \quad (2)$$

where $z = (P_1 \cdot P_h)/(P_1 \cdot q)$, 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 Boer-Mulders distribution function, h_1^\perp , giving rise to the asymmetry, is related to the imaginary part of the interference of wave functions for different

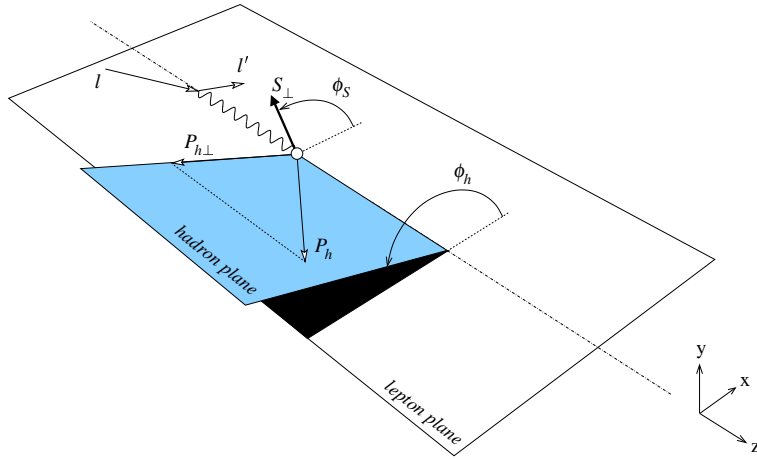


Figure 1: SIDIS kinematics. For an unpolarized target, only the angle ϕ enters the cross-section.

orbital momentum states, and describes transversely polarized quarks in the unpolarized nucleon. The same distribution function is accessible in the unpolarized Drell-Yan, where it gives rise to the $\cos 2\phi$ azimuthal moment in the cross section [32] and is a candidate to explain the violation of the Lam-Tung relation [33]. The study of this modulation is the target of many proposed Drell-Yan experiments, i.e. the planned E906 experiment at Fermilab [34]. The behavior of the Boer-Mulders distribution function was recently studied in large- x [35], large N_c [36], and large P_T [37] limits of QCD. There are Boer-Mulders asymmetry predictions for various models [38, 39, 40, 41], for all DIS and DY experiments.

At subleading order, a $\cos \phi$ azimuthal asymmetry arises in unpolarized SIDIS of pure kinematic origin (the so-called Cahn effect [42]). It accounts for the partons intrinsic transverse momenta in the target (\mathbf{k}_T) and the fact that produced hadrons may acquire transverse momenta from the fragmentation process (\mathbf{p}_T), so that final hadron transverse momentum $\mathbf{P}_{h\perp}$ is defined as their sum ($\mathbf{P}_{h\perp} = z\mathbf{k}_T + \mathbf{p}_T$). Within the same approach, kinematical corrections proportional to $(k_\perp/Q)^2$ lead to additional contributions in the $\cos 2\phi_h$ moment.

Data on azimuthal distribution in SIDIS are available from EMC experiments at CERN [43, 44], the E665 Fermilab experiment [45], and the ZEUS experiment at DESY [46, 47]. The data from ZEUS with average Q^2 value, $\langle Q^2 \rangle \simeq 750 \text{ GeV}^2$, is dominated by the perturbative contribution. In order to highlight the effect of the non perturbative contributions to the $\cos 2\phi$ moment (Boer-Mulders and higher twist), one has to probe the kinematical region corresponding to $P_T < 1 \text{ GeV}$ and Q^2 of order of few GeV^2 , such as HERMES, COMPASS, and JLab facilities, where the gluon emission is quite irrelevant. So far the azimuthal moments were measured only for pions and charged hadrons. Data for positive pions is available from CLAS [48] and in limited range of transverse momenta from Hall-C [49]. Both COMPASS[50] and HERMES [51] presented preliminary measurements of the $\cos 2\phi$ moments for positive and negative hadrons for hydrogen and deuterium targets, indicating that the Boer-Mulders effect may be more significant than anticipated.

The existing data on pions, however, are affected by large uncertainties and do not allow for drawing definite conclusions about the magnitude and the shape of the asymmetry and in particular, to the different contributing mechanisms. The CLAS12 approved experiment

E12-06-112 is designed to address this issue using a large-statistics pion sample.

The extraction of the Boer-Mulders transverse momentum dependent distributions is complicated by the presence of an essentially unknown Collins function. Recently a significant asymmetry was measured by BELLE [29, 30] in e^+e^- annihilation to pions, indicating that the Collins function is indeed large. Based on leading order, a procedure has been developed recently [52, 53] to extract the transversity distribution and Collins fragmentation functions, combining e^+e^- and semi-inclusive DIS data [21].

2 Scientific Case and Recent Developements in the Kaon Sector

A comprehensive study of the nucleon structure should consider the role of the quark flavor. The use of different targets in conjunction with the detection of various hadrons in the final state provide access to statistical information about the flavor of the struck quark. In particular, kaons provide enhanced sensitivity on strangeness in the matter (partonic sea of the nucleon) and in the vacuum (through fragmentation). Kaon detection is generally challenged by the about one order of magnitude larger flux of pions. Thus very little is known about the spin-orbit correlations related to the strange quark. Only recently dedicated measurements have become available and, despite the limited statistical accuracy, in most of the cases they show surprising results.

In high-energy hadron-hadron collisions, large single-spin asymmetries have been measured since the eighties at large rapidities (positive Feynman- x) which are opposite in sign for opposite charge pions, see Fig. 2. This is not the case for charged kaons, whose SSA are recently measured to be non zero and of the same sign up to 200 GeV in center-of-mass energy [28, 54]. In SIDIS, precise hadron identification has been exploited only by the second generation experiments. The Sivers effect, proposed as a possible explanation of the SSA in hadron-hadron collisions, generates SSA in SIDIS reactions for positive kaons which are found larger than for positive pions, see Fig. 3. The difference concentrate at low- Q , a possible indication of the presence of higher-twist effects in the kaon sector [55]. The results for negative kaons are not conclusive due to the limited statistics [56].

The Collins asymmetry has been measured to be non-zero and opposite in sign for opposite charge pions, see Fig. 4. This is an indication that favored and un-favored Collins FF are opposite but of similar magnitude, a result compatible with the fragmentation-function measurement at e^+e^- machines [29, 30]. The SSA for positive kaons is similar to that of positive pions in sign and magnitude, a result compatible with the dominance of the u -flavor in lepto-scattering over a proton target. However at HERMES, the signal for π^- and K^- are found to follow a different behavior, the former being large and negative, the latter being basically compatible with zero with a hint to be positive [57]. The result would be interesting since the K^- has no valence quarks in common with the target proton and sea quark transversity is expected to be small, thus K^- brings specific sensitivity on rank-2 Collins FF. Note that the knowledge of the Collins function has an impact on the extraction of all the chirally-odd TMD parton distributions. The result for K^- is still controversial, since COMPASS data [56] can not prove or disprove it, although seem to not support the same

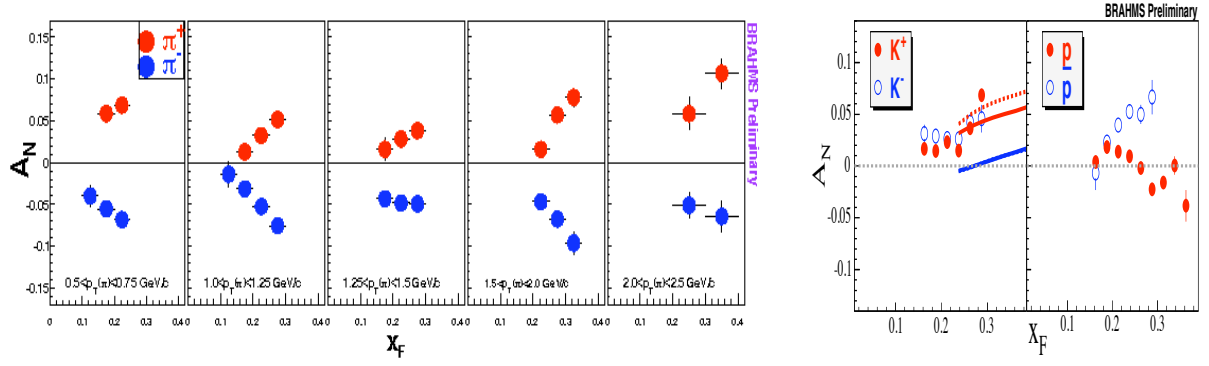


Figure 2: Single spin asymmetries for identified hadrons in proton-proton reactions at 200 GeV center-of-mass energy [54].

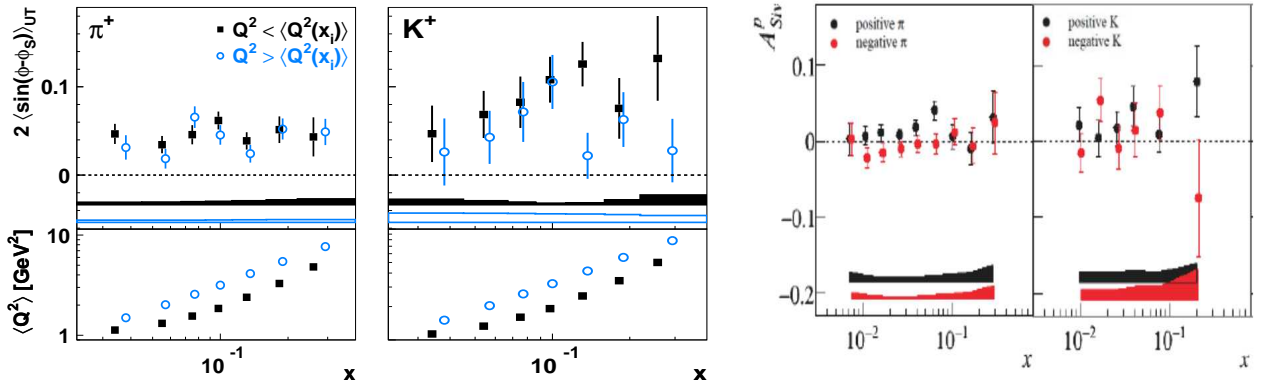


Figure 3: Sivers asymmetries measured for positive pions and kaons in two Q^2 ranges at HERMES [55] (Left) and measured for identified charged hadrons at COMPASS [56] (Right).

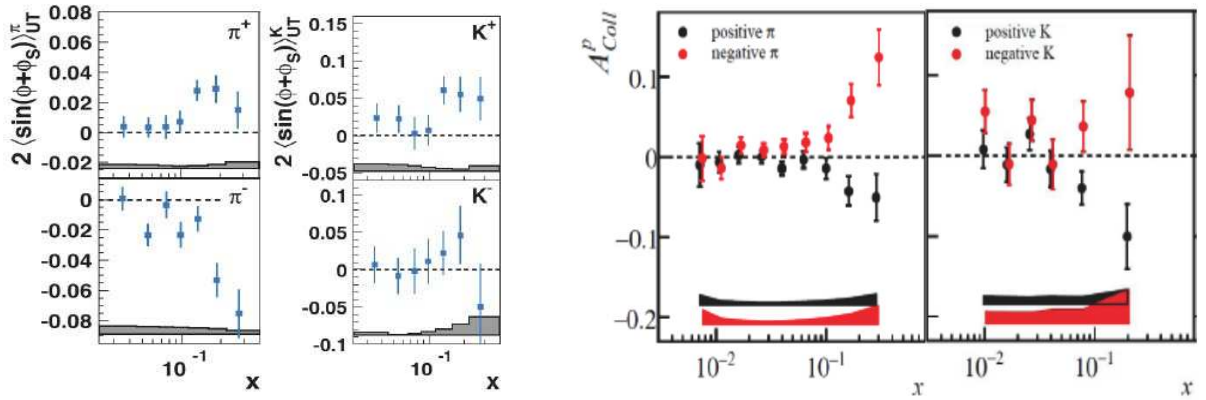


Figure 4: Collins asymmetries measured for identified charged hadrons at HERMES [57] (Left) and COMPASS [56] (Right).

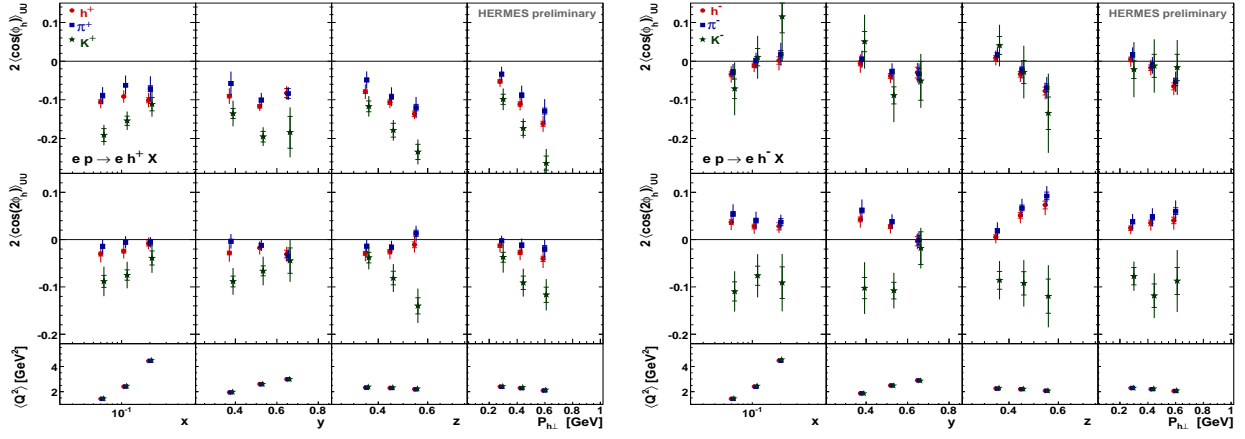


Figure 5: Azimuthal asymmetries in unpolarized SIDIS for identified hadrons [58].

finding, see Fig. 4. The issue can be solved only by novel high-precision experiments.

Azimuthal asymmetries in unpolarized SIDIS cross-section are generated by the Cahn and Boer-Mulders effects, but may get not-negligible contributions from quark-gluon-quark correlators (pure sub-leading twist terms). Only recently preliminary SIDIS results become available with hadron identification or charge separation. Opposite-charge pion signals show unexpected large differences which can be related to the peculiar flavor dependence of the Collins FF entering the Boer-Mulders term [51]. These reflect in analogous differences for opposite-charge unidentified hadrons, dominated by the pion subsample [59]. The kaon results are definitely surprising, showing $\cos 2\phi$ asymmetries much larger than pions but of the same sign for both charges [58], see Fig. 5. These asymmetries arise at leading-twist due to a convolution of Boer-Mulders with Collins functions, thus bring important piece of information on these two mechanisms. The sub-leading twist terms may also play a non-negligible role. The $\cos\phi$ asymmetry gets contributions only at sub-leading twist and can be used to constrain the related terms. It shows a K^+ signal larger than π^+ but a K^- signal compatible with π^- . The kaon signals are a challenge for the present understanding of the underlying physics processes. Any explanations is not possible without a disentanglement of the different contributions, possible only with high-precision mapping of the kinematical dependences.

The surprising and controversial pattern of TMDs results for kaons is an indication of a non trivial role of the sea quarks in the nucleon, or of a peculiar behaviour of the fragmentation mechanism in the presence of strange quark. Moreover a hint exists that kaons provide enhanced sensitivity on higher-twist effects [55]. The interpretation would become possible only in the presence of high-luminosity large-acceptance experiments able to explore the relevant kinematic dependences in conjunction with an efficient hadron identification. Examples of wanted informations are a precise Q -dependence to isolate higher-twist effect and an extended $P_{h\perp}$ -dependence to map the transient between perturbative and non-perturbative regime.

Nothing is known about polarization dependent FF (i.e. Collins) into kaons but an effort is being pursued to extract them from the large sample of data collected at B-

factories [30, 60]. Very precise information on the fragmentation process is anticipated in the next future thanks to the approval of Super B-factories. The detailed study can be completed only by SIDIS measurements which constrain FF at much lower center-of-mass energy with specific flavor sensitivity (not accessible in e^+e^- reactions). The detailed knowledge of the fragmentation process would reflect on the precise determination of parton distributions only at experiments with enough statistical precision and flavor sensitivity, like CLAS12 with a RICH detector dedicated to hadron identification.

The goal of our proposed experiment is to gather a data set on kaon SIDIS in the region $0.1 \leq x \leq 0.8$, $0 \leq P_T \leq 1.2$, and $0.2 \leq z \leq 0.8$. Global analysis of the data combined with the analogous measurement approved with pions and polarized target data [61] will provide access to the flavor-decomposition of TMDs.

2.1 The flavor-dependence of Boer-Mulders and Collins functions

So far no experimental information is available about the Collins fragmentation function for kaons. Recent direct calculations of kaon Collins function [62] indicated that it may be comparable with pion Collins function. HERMES measurements of the Collins asymmetry for pions and kaons, though, with large uncertainties, indicate that the differences may be significant [57].

Pions and kaons are both Goldstone bosons of chiral symmetry breaking. In the chiral limit one has

$$\lim_{m_K \rightarrow 0} \frac{H_1^{\perp(1/2)a/K}}{D_1^{a/K}} = \lim_{m_\pi \rightarrow 0} \frac{H_1^{\perp(1/2)a/\pi}}{D_1^{a/\pi}}, \quad (3)$$

where $H_1^{\perp(1/2)}$ means integration over the transverse momentum weighted with k_T .

Simultaneous measurements of the Boer-Mulders asymmetry for pions and kaons on proton and deuteron targets will provide an independent measurement of ratios of Collins functions of pions and kaons, providing complementary measurements to e^+e^- annihilation. Thanks to the different center-of-mass energy of fixed-target with respect collider experiments, the measurements can be used to test the evolution properties of the Collins function. That measurement will also provide a check of chiral limit prediction, where that ratio is expected to be at unity. With the knowledge of the Collins function, one can study all involved TMD distributions.

Measurement of the fraction coming from the Collins fragmentation of transversely polarized quarks in the unpolarized nucleon will require separation of other contributions, and in particular those due to the Cahn effect. Although, preliminary results from HERMES indicate that the Cahn contribution is not dominant in $\cos 2\phi$ as was expected before [63]. In order to extract the contribution related to the Collins fragmentation one needs a reliable calculation of the kinematical corrections. 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_T values below 1 (GeV/c) [63].

TMD	$\langle k_T \rangle$ in GeV	$\langle k_T^2 \rangle$ in GeV ²	$\frac{4\langle k_T \rangle^2}{\pi\langle k_T^2 \rangle}$	$\frac{\langle k_T^2 \rangle}{\langle k_{Tf_1}^2 \rangle}$
f_1	0.239	0.080	0.909	1.00
g_1	0.206	0.059	0.916	0.74
h_1	0.210	0.063	0.891	0.79
g_{1T}^\perp	0.373	0.176	1.007	2.20
h_{1L}^\perp	0.373	0.176	1.007	2.20
h_{1T}^\perp	0.190	0.050	0.919	0.63

Table 1: Predictions for the transverse momentum dependence of the T-even TMDs from the constituent quark model [65]. (Left) The mean transverse momenta and the mean square transverse momenta: if the transverse momenta in the TMDs were Gaussian, then the result for the ratio in the last row would be unity. (Right) Mean square transverse momenta of T-even TMDs in units of the mean square transverse momenta of f_1 , denoted as $\langle k_{Tf_1}^2 \rangle$. These ratios are considered to be a more robust model prediction.

2.2 Transverse momentum dependence of partonic distributions

The width for different partonic distributions can be different. For example values for different T-even partonic distributions, computed [64] in the constituent quark model [65], are listed in Table 1. Values normalized to the width of the unpolarized distribution function are listed in the same Table.

A common assumption is the Gaussian ansatz for the transverse momentum dependence of distribution and fragmentation functions with the average $P_{h\perp}$ of hadrons produced in SIDIS given by

$$\langle P_{h\perp}(z) \rangle = \frac{\sqrt{\pi}}{2} \sqrt{z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle}. \quad (4)$$

In the approximation of flavor and x or z -independent widths, a satisfactory description of HERMES deuteron data on average $P_{h\perp}$ [66] was obtained [67] with

$$\langle k_T^2 \rangle = 0.33 \text{ GeV}^2, \quad \langle p_T^2 \rangle = 0.16 \text{ GeV}^2. \quad (5)$$

Numerically very similar results were obtained in Ref. [63] from a study of EMC data [44] on the Cahn effect. Although the ansatz seems to describe the present available data sets [68], it has to be considered an approximation which is not necessarily valid and most of the models do not base on it.

The unpolarized azimuthal moment in kaon lepto-production will be studied as a function of $P_{h\perp}$, in different bins in x , z , and Q^2 , and complemented with the analogous measurements for pions. These measurements will provide access to widths in transverse momentum of different underlying partonic distributions, like the number density f_1 and the Boer-Mulders h_1 , and to their flavor dependence.

This measurements, in conjunction with the study of hadron multiplicities in a large range of kinematic variables (x_B , Q^2 , z , $P_{h\perp}$), will provide important input for the flavor decomposition of the transverse momentum dependence of all the others TMDs from polarized measurements.

2.3 Vector meson contribution

One of the main sources of uncertainties for pions is the fraction of pions coming from vector meson decays. Since the Collins asymmetry has a significant dependence on the type of a produced hadron, pions produced from rho decays will have very different moments compared to direct pions. This makes measurements with kaons, which have a much smaller contribution from vector meson production, very import in understanding the underlying dynamics of the part of measured asymmetries due to Collins fragmentation mechanism

3 Technical Progress Towards Realizing the Experiment

4 The Beam request and Expected Results

We propose a measurement of azimuthal moments of the single kaon cross section in SIDIS using the CLAS12 detector in Hall B at Jefferson Lab, a 6.6-11.0 GeV longitudinally polarized electron beam and unpolarized hydrogen and deuterium targets. The focus of our proposal is to study the $\cos 2\phi$ asymmetry, related to the correlation of intrinsic transverse momentum of quarks and their transverse spin. Competing mechanisms are also related to the transverse motion of quarks and are also relevant in the CLAS12 kinematic regime ($\langle Q^2 \rangle \sim 2 \text{ GeV}^2$).

The overall statistics of kaons is almost an order of magnitude less than for pions with most of the relevant sources of systematic errors being the same, so the main focus will be the new information we can access with kaon SIDIS measurements and in particular studies of the Collins fragmentation of kaons.

The JLab 12-GeV upgrade will provide the unique combination of wide kinematic coverage, high beam intensity (luminosity), high energy, high polarization, and advanced detection capabilities necessary to study the transverse momentum and spin correlations in semi-inclusive processes both in the target and current fragmentation regions for a variety of hadron species. In this proposal we focus on observables related to kaon production in DIS, accessible with unpolarized targets and new information on the structure of nucleon they can provide. Measurements of spin-orbital structure of hadrons with unpolarized hydrogen and deuterium targets will use the beam time of an already approved electroproduction experiment to study the Neutron Magnetic Form-Factor at High Q^2 [69].

4.1 Statistical and systematic errors

The proposed spin asymmetry measurement is rather insensitive to uncertainties in acceptances and charge normalization. The overall statistics of kaons is, though, an order of

magnitude less than for pions, with most of the relevant sources of systematic errors being the same. One of the main systematic errors affecting the extraction of the Collins moment is due to possible contamination of the single kaon sample with kaons from decays of exclusive K^* mesons. The fraction of indirect kaons, however, according to LUND studies, is significantly less than for pions (see Fig.6). The main difference from the pion production case for the background is the contribution from K^* production (e.g., $K^* \rightarrow K\pi$) and the radiative tail on exclusive Kaon production. The contributions to the systematic error from these backgrounds requires a detailed analysis once the requisite data are in hand, but experience with pion data from CLAS at 6 GeV show that one can avoid most of them by judicious choice of kinematic cuts.

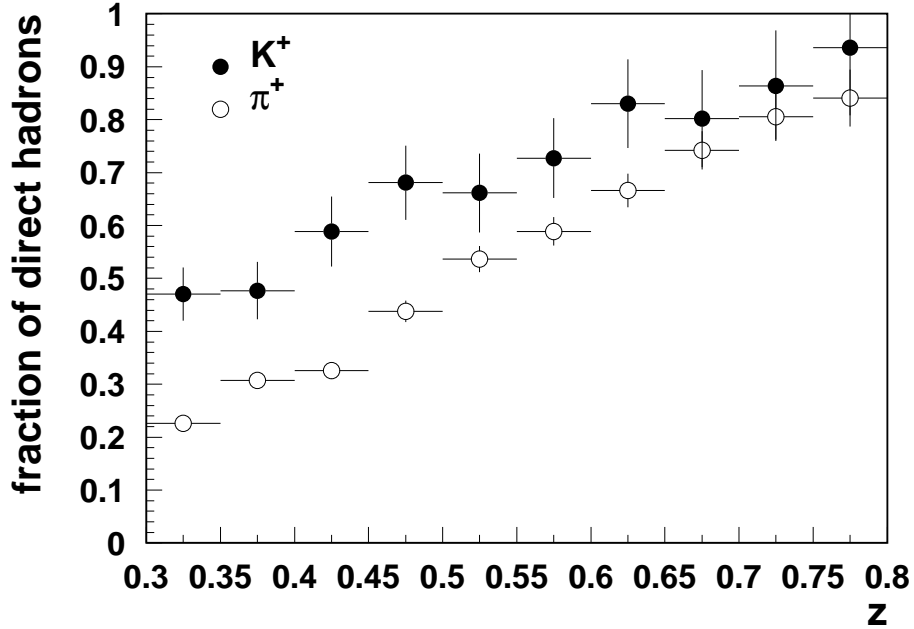


Figure 6: Fractions of direct (with a parent defined as "string") kaons and pions from PEPSI MC for ehX events.

Other sources of systematic errors include the longitudinal to transverse photo absorption cross section ratio, $R(x, Q^2)$ and the beam polarization (for $\sin \phi$). The main sources of systematic errors in measurements of azimuthal asymmetries are listed in the Table 2. These errors are all scale errors, so they are proportional to the size of the measured asymmetry.

Studies of other sources of systematics, related to physics background, including target fragmentation, semi-exclusive processes, exclusive vector meson contributions, and higher twist require the data of this measurement.

We based our predicted statistical errors in the following sections on the assumption of running 54 days on a hydrogen and deuterium [69]. For our estimate of the total systematic

Table 2: Uncertainties for asymmetry measurements.

Item	$A_{UU}^{\cos 2\phi}$	$A_{UU}^{\cos \phi}$	$A_{LU}^{\sin \phi}$
beam polarization	-	-	3%
acceptance corrections	4%	4%	2%
radiative corrections	3%	3%	3%
fitting procedure	4%	4%	3%

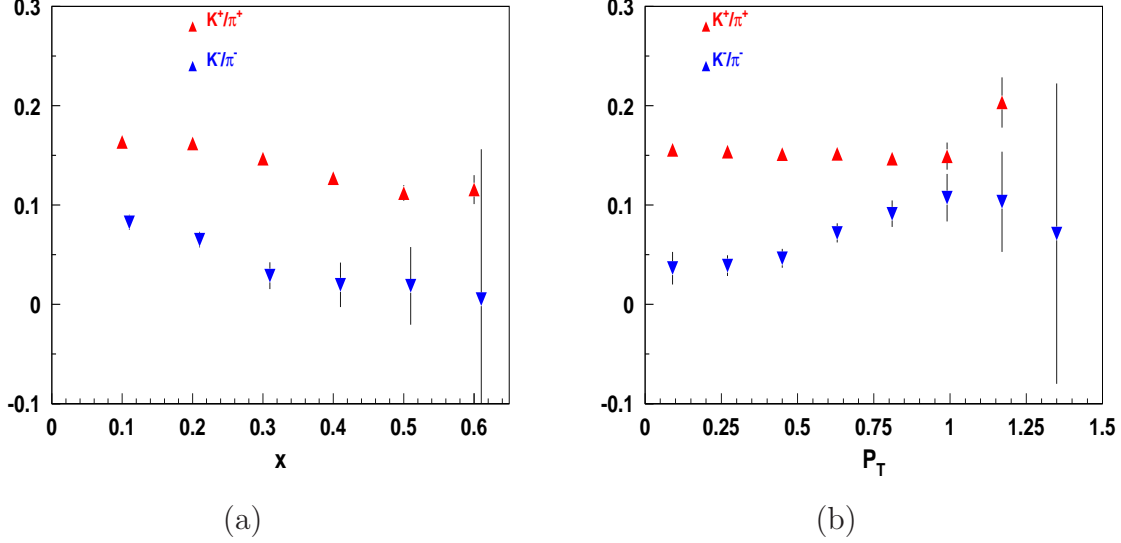


Figure 7: PEPSI-Lepto predictions for x -dependence (left) and P_T -dependence of kaon pion ratios.

error, we have added the systematic errors from the various contributions discussed in the previous Section in quadrature. They are listed in Table 2.

4.2 Results

The proposed experiment will simultaneously collect data on $p, d(\vec{e}, e'h)$, including kaons and pions. The charged kaons will be detected in the forward spectrometer and the central tracker of CLAS12 in coincidence with the scattered electrons and identified by the CLAS12-RICH detector. The following predicted results were obtained with a full simulation of the hadronization process [70] and the acceptance of CLAS12 for all particles.

The expected counts of kaons in different kinematic bins for the hydrogen and deuteron targets for each of the kaon charges were calculated using the PEPSI-MC kaon to pion ratios (Fig.7).

4.2.1 Projected results for unpolarized moments

The precision measurement of the Boer-Mulders asymmetry requires subtraction of all contributions to the $\cos 2\phi$ moment discussed above. All contributions, including the Cahn

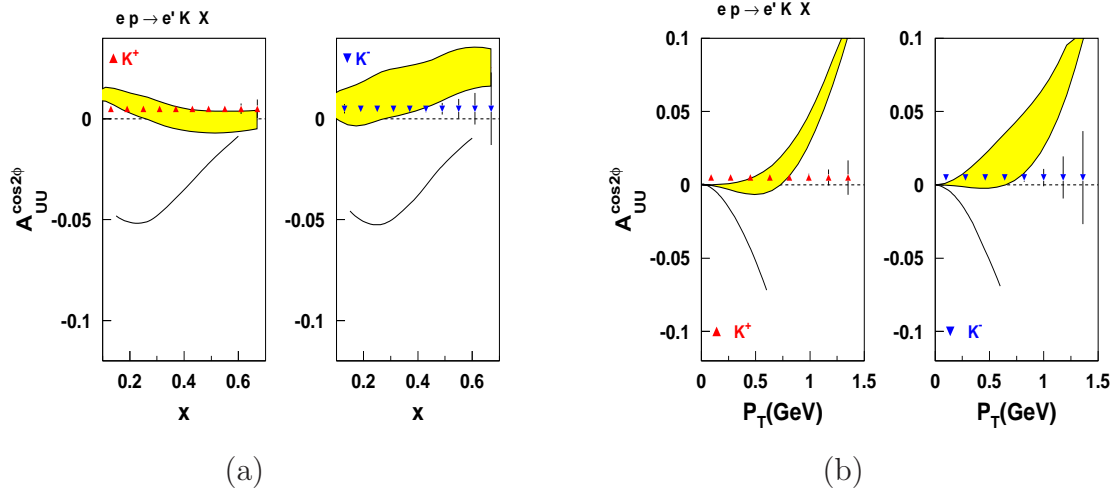


Figure 8: The $\cos 2\phi$ moment for kaons as a function of x (left) and P_T (right) for proton target at 11 GeV from 80 days of CLAS12 running. The band corresponds to set-I of Ref.[41] with Boer-Mulders function extracted [73] from the Drell-Yan data [74]. The Collins fragmentation function was approximated using the chiral limit. The black curve is from Ref. [40], with Collins function from parametrization [52] based on the e^+e^- and SIDIS data.

and Berger terms as well as the perturbative and radiative contributions to first order, are expected to be “flavor blind”, i.e. are the same for negative and positive kaons. The check performed with the $\cos \phi$ moment can serve as a test for that. 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 kaons will also provide additional to pion measurements [71], information on widths of k_T distributions, and their flavor dependence. The difference of the $\cos 2\phi$ moments for K^+ and K^- from π^+ and π^- will provide important information about sea orbital structure, described by corresponding Collins functions. Simultaneous measurement of the $\cos 2\phi$ and $\sin 2\phi$ moment of the cross section will provide independent measurements of the Collins effect, and provide complementary information to measurements of the Collins effect [16] with transversely polarized target [72] as well as direct measurements, which may be performed at BELLE [29].

Projections for some of the most important observables are shown on Figs. 8,9 for proton and deuteron targets, respectively. Measured $\cos 2\phi$ moment for charged kaons for two targets, combined with the measurements on pions [71], will allow the extraction of the Collins analyzing power ratios for pions and kaons, providing information on the polarized fragmentation function of kaons.

Proposed measurements of azimuthal asymmetries in SIDIS will measure the ratio of favored to unfavored polarized fragmentation functions for kaons provide independent to pion measurements constrains on the corresponding TMD distributions. The new data will also allow a more precise test of the factorization ansatz and the investigation of the Q^2 dependence of $\cos 2\phi$, $\cos \phi$, and $\sin \phi$ asymmetries. This will enable us to study the leading-twist and higher-twist nature of the corresponding observables [42, 75, 2].

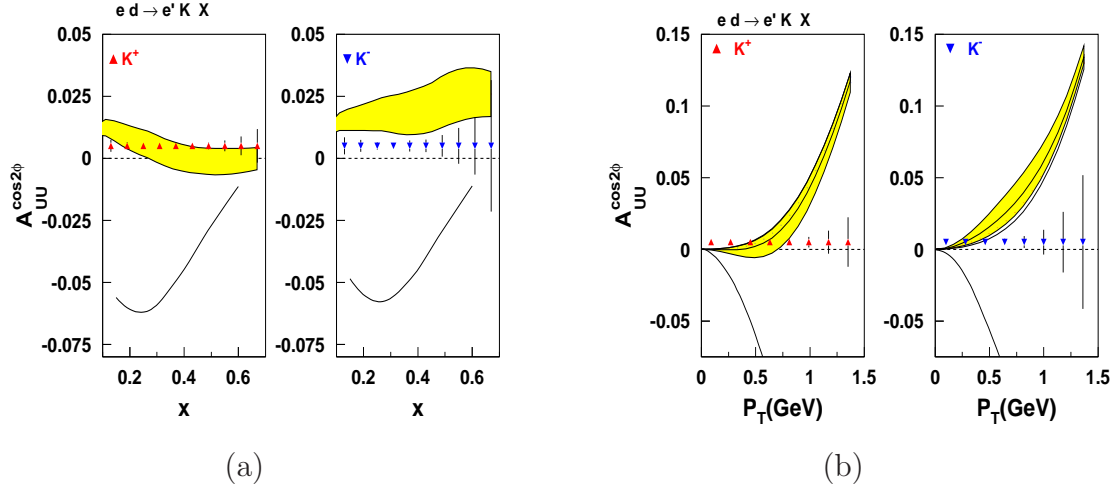


Figure 9: The $\cos 2\phi$ moment for kaons as a function of x (left) and P_T (right) for deuteron target at 11 GeV from 80 days of CLAS12 running. Curves are calculated using assumptions for Collins fragmentation function discussed above.

Measurement of the P_T dependence of the Boer-Mulders-asymmetry will also allow for checking of the high P_T predictions [11, 76, 37] to study the transition from a non-perturbative to a perturbative description. Both $\cos 2\phi$ and $\sin 2\phi$ asymmetries for semi-inclusive deep inelastic scattering in the kinematic regions of CLAS12 are predicted to be significant (a few percent on average) and tending to be larger in the large- x and large- z region.

The combined analysis of the future CLAS12 data on $\langle \cos 2\phi \rangle$ and of the previous HERMES measurements in the high- Q^2 domain (where higher-twist effects are less significant) will provide information on the Boer-Mulders function, shedding light on the correlations between transverse spin and transverse momenta of quarks.

At lower x , this very large data set allows us to further subdivide the data into bins in P_T and z . Once in hand, these data will be combined with CLAS12 data on pions and existing SIDIS data from HERMES, COMPASS and RHIC for a full NLO analysis.

Measured azimuthal asymmetries for kaons in a large range of kinematic variables (x_B , Q^2 , z , P_\perp and ϕ) combined with measurements with polarized target measurements and data for pions [61], 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 k_T dependence of leading TMD parton distribution functions. Measurements of spin and azimuthal asymmetries across a wide range of x , z , Q^2 , and P_T would allow to perform detailed tests of QCD dynamics in valence region.

4.3 Summary and Request

Understanding of spin-orbit correlations, together with independent measurements related to the spin and orbital angular momentum of the quarks, will help to construct a more complete picture of the nucleon in terms of elementary quarks and gluons going beyond the

Time	Activity
2 days	Commissioning: Empty target, interchange of targets
54 days	Production data taking on proton and deuterium (50% with reversed field)

Table 3: Requested beam time broken down by activity.

simple collinear partonic representation. The proposed set of measurements on unpolarized proton and deuteron targets will yield a comprehensive set of azimuthal moments in spin-dependent and independent SIDIS providing access to corresponding distribution and fragmentation functions in a wide range of x , Q^2 , z , and P_T . Our data, combined with the data from HERMES, COMPASS, and BELLE, will provide independent (complementary to e^+/e^-) measurement of polarized kaon Collins fragmentation function and will allow a study complementary to pion SIDIS study of leading twist TMD parton distribution $h_1^\perp(x, k_T)$.

In addition, the proposed experiment will yield data on single beam spin asymmetries in SIDIS, which can provide constraints on the higher-twist nucleon structure functions. As a by-product, the experiment will also provide interesting data on the exclusive cross section ratio $K * \Lambda/\rho^+ n$, which can be interpreted within the GPD formalism.

To achieve this goal, we request a total of 56 days of beam time with an 11 GeV electron beam in Hall B. We assume the same target configuration as an already approved experiment on measurement of the neutron magnetic form-factors [69]. The breakdown of this beam time is shown in Table 3. The number of days requested was chosen to allow a statistically significant measurement of the T-odd distribution and fragmentation functions.

We want to conclude by noting that while this proposed experiments requires a substantial commitment of beam time (56 days total), we will simultaneously take data with an already approved experiment to study the neutron magnetic form-factor [69].

References

- [1] P.J. Mulders and R.D. Tangerman, Nucl. Phys. B461 (1996) 197, hep-ph/9510301.
- [2] A. Bacchetta et al., JHEP 02 (2007) 093, hep-ph/0611265.
- [3] V. Barone, A. Drago and P.G. Ratcliffe, Phys. Rept. 359 (2002) 1, hep-ph/0104283.
- [4] D.W. Sivers, Phys. Rev. D43 (1991) 261.
- [5] M. Anselmino and F. Murgia, Phys. Lett. B442 (1998) 470, hep-ph/9808426.
- [6] S.J. Brodsky, D.S. Hwang and I. Schmidt, Phys. Lett. B530 (2002) 99, hep-ph/0201296.
- [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] D. Boer, P.J. Mulders and F. Pijlman, Nucl. Phys. B667 (2003) 201, hep-ph/0303034.
- [11] X. Ji, J. Ma and F. Yuan, Phys. Rev. D71 (2005) 034005, hep-ph/0404183.
- [12] J.C. Collins and A. Metz, Phys. Rev. Lett. 93 (2004) 252001, hep-ph/0408249.
- [13] C.J. Bomhof and P.J. Mulders, Nucl. Phys. B795 (2008) 409.
- [14] J. Collins and J.W. Qiu, Phys. Rev. D75 (2007) 114014, 0705.2141.
- [15] W. Vogelsang and F. Yuan, Phys. Rev. D76 (2007) 094013, 0708.4398.
- [16] J.C. Collins, Nucl. Phys. B396 (1993) 161, hep-ph/9208213.
- [17] A. Metz, Phys. Lett. B549 (2002) 139.
- [18] F. Yuan, Phys. Rev. D77 (2008) 074019, 0801.3441.
- [19] HERMES, A. Airapetian et al., Phys. Rev. Lett. 84 (2000) 4047, hep-ex/9910062.
- [20] HERMES, A. Airapetian et al., Phys. Rev. D64 (2001) 097101, hep-ex/0104005.
- [21] HERMES, A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002, hep-ex/0408013.
- [22] HERMES, A. Airapetian et al., Phys. Lett. B648 (2007) 164, hep-ex/0612059.
- [23] COMPASS, V.Y. Alexakhin et al., Phys. Rev. Lett. 94 (2005) 202002, hep-ex/0503002.
- [24] CLAS, H. Avakian et al., Phys. Rev. D69 (2004) 112004, hep-ex/0301005.
- [25] CLAS, H. Avakian et al., AIP Conf. Proc. 792 (2005) 945, nucl-ex/0509032.
- [26] STAR, J. Adams et al., Phys. Rev. Lett. 92 (2004) 171801, hep-ex/0310058.

- [27] PHENIX, M. Chiu, AIP Conf. Proc. 915 (2007) 539, nucl-ex/0701031.
- [28] BRAHMS, I. Arsene et al., Phys. Rev. Lett. 101 (2008) 042001, 0801.1078.
- [29] BELLE, K. Abe et al., Phys. Rev. Lett. 96 (2006) 232002, hep-ex/0507063.
- [30] BELLE Collaboration, R. Seidl et al., Phys.Rev. D78 (2008) 032011.
- [31] D. Boer and P.J. Mulders, Phys. Rev. D57 (1998) 5780, hep-ph/9711485.
- [32] R.D. Tangerman and P.J. Mulders, Phys. Rev. D51 (1995) 3357, hep-ph/9403227.
- [33] D. Boer, S.J. Brodsky and D.S. Hwang, Phys. Rev. D67 (2003) 054003, hep-ph/0211110.
- [34] P. Reimer et al., (DY measurements: Fermilab E906).
- [35] S.J. Brodsky and F. Yuan, Phys. Rev. D74 (2006) 094018, hep-ph/0610236.
- [36] P.V. Pobylitsa, hep-ph/0301236 (2003), hep-ph/0301236.
- [37] A. Bacchetta et al., JHEP 08 (2008) 023, 0803.0227.
- [38] V. Barone, Z. Lu and B.Q. Ma, Phys. Lett. B632 (2006) 277, hep-ph/0512145.
- [39] L.P. Gamberg, G.R. Goldstein and M. Schlegel, Phys. Rev. D77 (2008) 094016, 0708.0324.
- [40] V. Barone, A. Prokudin and B.Q. Ma, Phys. Rev. D78 (2008) 045022, 0804.3024.
- [41] B. Zhang et al., Phys. Rev. D78 (2008) 034035, 0807.0503.
- [42] R.N. Cahn, Phys. Lett. B78 (1978) 269.
- [43] European Muon, J.J. Aubert et al., Phys. Lett. B130 (1983) 118.
- [44] European Muon, M. Arneodo et al., Z. Phys. C34 (1987) 277.
- [45] E665, M.R. Adams et al., Phys. Rev. D48 (1993) 5057.
- [46] ZEUS, J. Breitweg et al., Phys. Lett. B481 (2000) 199, hep-ex/0003017.
- [47] ZEUS, S. Chekanov et al., Eur. Phys. J. C51 (2007) 289, hep-ex/0608053.
- [48] CLAS, M. Osipenko et al., Phys. Rev. D80 (2009) 032004, 0809.1153.
- [49] H. Mkrtchyan et al., Phys. Lett. B665 (2008) 20, 0709.3020.
- [50] COMPASS, W. Kafer, Transversity 2008 proceedings (2008), 0808.0114.
- [51] HERMES, G. F. and L. R., AIP Conf. Proc. 1149 (2009) 423, 0901.2438.
- [52] M. Anselmino et al., (2007), hep-ph/0701006.

- [53] M. Anselmino et al., Nucl. Phys. Proc. Suppl. 191 (2009) 98, 0812.4366.
- [54] BRAHMS, J. Lee et al.
- [55] HERMES, A. Airapetian et al., Phys. Rev. Lett. 103 (2009) 152002, 0906.3918.
- [56] C.S. for COMPASS, (2011), DIS 2011 Conference.
- [57] HERMES, A. Airapetian et al., Phys. Lett. B693 (2010) 11, 1006.4221.
- [58] G. F. and L. R., J. Phys. Conf. Ser. 295 (2011) 012092, 1011.5422.
- [59] G.S.f.t.C. Collaboration, (2010), 1012.4910.
- [60] I.G. for BaBar.
- [61] H. Avakian et al., JLab Experiment E12-07-015 (2008).
- [62] A. Bacchetta et al., Phys. Lett. B659 (2008) 234, 0707.3372.
- [63] M. Anselmino et al., Phys. Rev. D71 (2005) 074006, hep-ph/0501196.
- [64] S. Boffi et al., Phys. Rev. D79 (2009) 094012, 0903.1271.
- [65] B. Pasquini, S. Cazzaniga and S. Boffi, Phys. Rev. D78 (2008) 034025, 0806.2298.
- [66] HERMES, A. Airapetian et al., Phys. Lett. B562 (2003) 182, hep-ex/0212039.
- [67] J.C. Collins et al., Phys. Rev. D73 (2006) 014021, hep-ph/0509076.
- [68] P. Schweitzer, T. Teckentrup and A. Metz, Phys. Rev. D81 (2010) 094019, 1003.2190.
- [69] Jefferson Lab Hall B, G. Gilfoil et al., PAC32 Proposal (PR-12-07-104).
- [70] L. Mankiewicz, A. Schafer and M. Veltri, Comput. Phys. Commun. 71 (1992) 305.
- [71] H. Avakian et al., JLab Experiment E12-06-015 (2008).
- [72] Jefferson Lab Hall B, . H.Avakian et al., LOI to PAC34 (2008).
- [73] B. Zhang et al., Phys. Rev. D77 (2008) 054011, 0803.1692.
- [74] FNAL E866/NuSea, L.Y. Zhu et al., Phys. Rev. Lett. 100 (2008) 062301, 0710.2344.
- [75] A. Metz and M. Schlegel, Eur. Phys. J. A22 (2004) 489, hep-ph/0403182.
- [76] X. Ji et al., Phys. Rev. D73 (2006) 094017, hep-ph/0604023.