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

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


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## A CLAS collaboration proposal

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**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.

# 1 Introduction

The intrinsic transverse momentum of partons in the nucleon plays a 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]. 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.

Measurements of transverse momentum $P_T$ of final state hadrons in SIDIS with unpolarized nucleons provide access to leading twist momentum distribution $f_1(x, k_T)$. While the $x$-dependence of $f_1$ is known in details, the studies of its transverse momentum dependence in various experiments as well as lattice is just starting. Recent measurements of multiplicities and double spin asymmetries as a function of the final transverse momentum of pions in SIDIS at JLab [21, 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 [22, 23, 24, 25] and on lattice [26, 27] indicate that dependence of transverse momentum distributions on the quark polarization and flavor may be very significant.

Similar correlations arise in the hadronization process. One particular case is the Collins $T$-odd fragmentation function $H_1^\perp$ [2], 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 [28, 29, 30], 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.

Measurement of the azimuthal modulation of the cross section in unpolarized SIDIS provides access to the Boer-Mulders $h_1^\perp$ TMD [31], arising 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 Boer-Mulders 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 Boer-Mulders function would thus 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 [32].

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.

PAC34 approved Experiment E12-09-008, in which we proposed 56 days of measurements with polarized electron beam on unpolarized hydrogen and deuterium targets 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 beam polarization, and advanced detection capabilities to study the transverse momentum and spin correlations in semi-inclusive DIS.

# 2 Scientific Case and Recent Developments

Within the one photon exchange approximation, the double inclusive cross section for unpolarized SIDIS processes, $\ell\, p \to \ell\, h\, X$, can have a dependence on the azimuthal angle $\phi_h$ of the final hadron already at leading order. The cross section (see for ex.[33, 34]) has contributions from different structure functions:

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

where $\alpha$ is the fine structure constant, and $\varepsilon$ 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 $\phi_h$ ($\phi$) 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 [35]. The relevant kinematic variables are defined as:

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

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

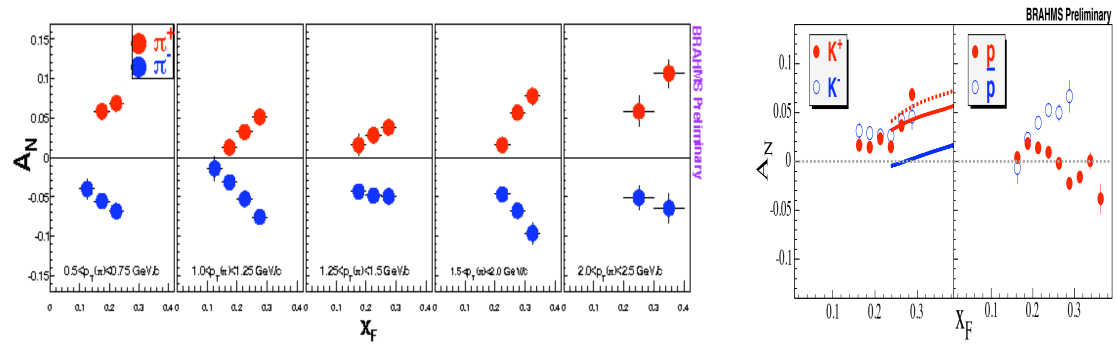



Figure 1: Single spin asymmetries for identified hadrons in proton-proton reactions at 200 GeV center-of-mass energy [43].

The transverse ($P_T$ or $P_{h\perp}$) and longitudinal ($P_L$) momentum of the pion are defined with respect to the virtual photon direction in the photon-nucleon center-of-mass system.

The structure functions on the r.h.s. depend on $x$, $Q^2$, $z$ 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 [33]. The $F_{UU}^{\cos 2\phi}$ structure function, first discussed by Boer and Mulders in 1998 [31], involves 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 a polarized fragmentation function. Significant asymmetry was measured recently by Belle [36, 37, 38], indicating that the Collins function is indeed large. The $F_{UU}^{\cos\phi}$ and $F_{LU}^{\sin 2\phi}$ structure functions get contributions only at sub-leading twist and can be used to constrain the related terms [34, 39, 40, 41].

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. 1. 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 [42, 43]. In SIDIS, precise hadron identification has been exploited only by the second generation experiments. The Sivers effect [44], 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. 2. The difference concentrate at low-Q, a possible indication of the presence of higher-twist effects in the kaon sector [45]. The results for negative kaons are not conclusive due to the limited statistics [46].

In SIDIS reactions with transversely polarized targets, the asymmetry involving transversity and Collins function has been measured to be non-zero and opposite in sign for opposite charge pions, see Fig. 3. This is an indication that favored and un-

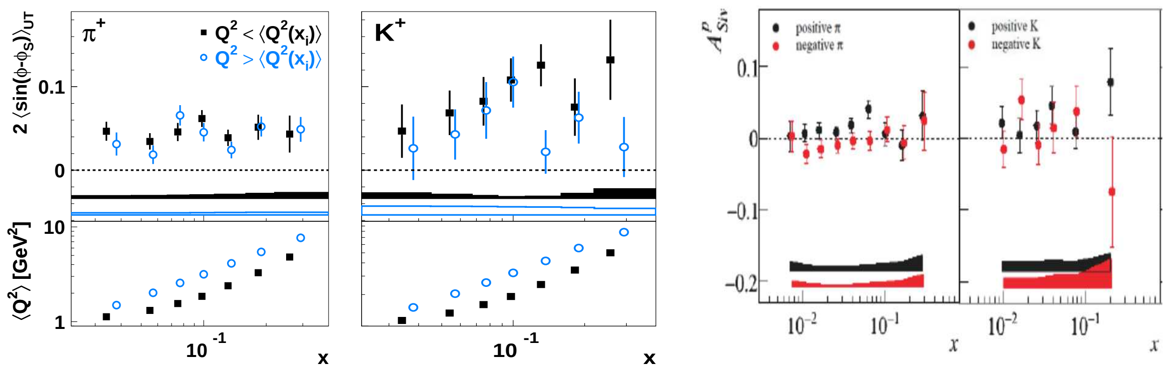


Figure 2: (Left) Sivers asymmetries measured at HERMES [45] for positive pions and kaons in two $Q^2$ ranges shown in the bottom panels. (Right) Sivers asymmetries measured for identified charged hadrons at COMPASS [46].

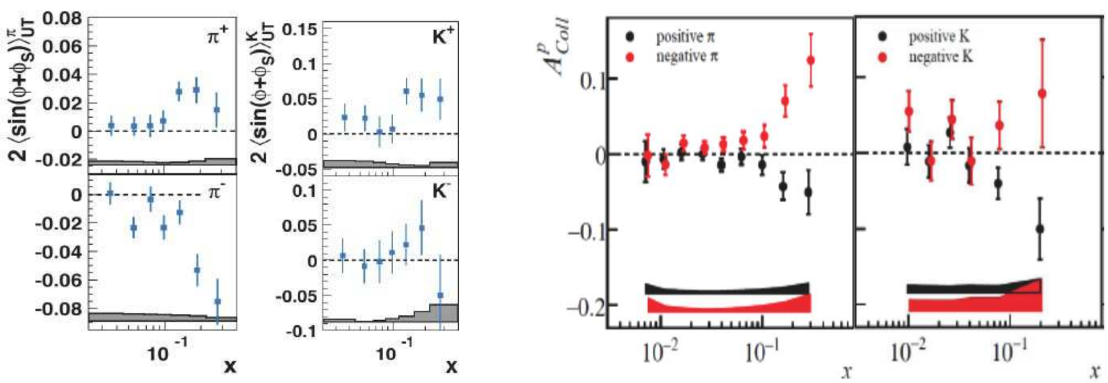


Figure 3: Collins asymmetries measured for identified charged hadrons at HERMES [16] (Left) and COMPASS [46] (Right).

favored Collins FF are opposite but of similar magnitude, a result compatible with the fragmentation-function measurement at $e^+e^-$ machines [36, 48]. 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 $\pi^-$ 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 [16]. 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 un-favored 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,

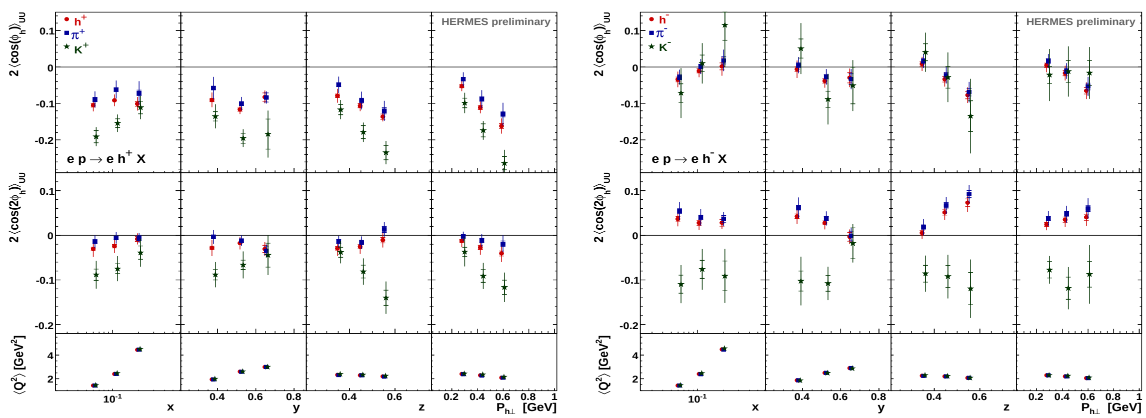



Figure 4: Azimuthal asymmetries in unpolarized SIDIS for identified hadrons [47].

since COMPASS data [46] can not prove or disprove it, although seem to not support the same finding, see Fig. 3. The issue can be solved only by novel high-precision experiments.

Only recently preliminary results on azimuthal asymmetries in unpolarized SIDIS cross-section 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 [49]. These reflect in analogous differences for opposite-charge unidentified hadrons, dominated by the pion subsample [50]. The kaon results are definitely surprising, showing $\cos 2\phi$ asymmetries much larger than pions but of the same sign for both charges [47] (see Fig. 4). Regarding the subleading $\cos\phi$ term, the measured $K^+$ signal is larger than $\pi^+$ but the $K^-$ signal is compatible with $\pi^-$. The kaon signals are a challenge for the present understanding of the underlying physics processes. Detailed studies require disentanglement of the different contributions, which is possible only with high-precision mapping of the kinematical dependences.

The surprising and controversial pattern of azimuthal asymmetries for kaons is an indication of a non trivial role of the sea quarks in the nucleon, or of a peculiar behavior of the fragmentation mechanism in the presence of strange quark. Moreover a hint exists that kaons provide enhanced sensitivity on higher-twist effects [45]. The interpretation would become possible only in the presence of high-luminosity large-acceptance experiments enabling the exploration of the relevant kinematic dependences in conjunction with an efficient hadron identification. Wide kinematical range is critical to allow precision measurements of $Q^2$-dependence of observables to isolate higher-twist effect, and an extended $P_{h\perp}$-dependence to access the $k_T$-distributions of quarks and map the transition between perturbative and non-perturbative regimes.

Extraction of polarization dependent FF (i.e. Collins) into kaons using the large sample of data collected at B-factories [48, 51] is underway. Very precise information on the fragmentation process is anticipated in the future, thanks to the approval of Super B-factories. The high precision SIDIS measurements with identified hadrons will constrain FF at much lower center-of-mass energy with specific flavor sensitivity (not accessible in $e^+e^-$ reactions), providing complementary information on evolution properties of polarized FFs.

The goal of our proposed experiment is to gather a high precision data set on kaon azimuthal asymmetries in SIDIS in the region $0.1 \leq x \leq 0.6$, $0 \leq P_T \leq 1.2$, and $0.3 \leq z \leq 0.7$ using the CLAS12 equipped with a RICH detector. Global analysis of the data combined with the analogous measurement approved with pions [52] and polarized target data [53] will provide access to the flavor-decomposition of TMDs and polarization effects in hadronization.

# 3 Technical Progress Towards Realizing the Experiment

The proposed experiment will use the upgraded CLAS12 spectrometer with the low threshold Cherenkov counter (LTCC) replaced by a RICH detector.

In the baseline design of CLAS12, particle identification (PID) in the forward detector is obtained by using the high threshold Cerenkov counter (HTCC), the low threshold Cerenkov counter (LTCC) and the Time-of-flight scintillator arrays (TOF) (see Fig. 5). In the $\sim 2.5 - 5$ GeV/c momentum region, the $\pi/K$ separation relies only on the LTCC performance. Moreover, in the $4.7 - 8$ GeV/c momentum region it is not possible to separate protons from kaons. In general, this PID system matches the requirements of the physics program at 12 GeV. However there are some physics reactions of high interest, such as the one covered by this proposal, that cannot be accessed without a better PID, especially for charged kaon detection. For semi-inclusive processes at 12 GeV beam energy, the $K/\pi$ ratio is of the order of $10 - 15\%$, thus the required rejection factor for pions is around 1 : 1000 (corresponding to $4.7\sigma$ pion-kaon separation). With the present configuration, assuming a realistic pion detection inefficiency for the LTCC of 10%, the $\pi/K$ contamination is 1 : 1. A RICH detector, to be installed in place of the low threshold Cerenkov counter, will significantly improve the CLAS12 particle identification overcoming the above limitations without having any impact on the baseline design of CLAS12.

In the momentum range of interest an aerogel RICH represents the best solution for the identification of $\pi/K/p$. This implies detecting Cherenkov light in the visible wavelength range and using photomultipliers (PMTs) as photon detectors. The use of aerogel as radiator and the detection of light in the visible wavelength range is however an expensive solution, in particular in the case of the CLAS12 RICH where, for each sector, the radiator area is of the order of 4 m$^2$ and the photon detection surface is of the order of 8 m$^2$. To limit the area of the photon detector to about 1 m$^2$ per sector the idea is to build a proximity focusing RICH with focusing mirrors. The

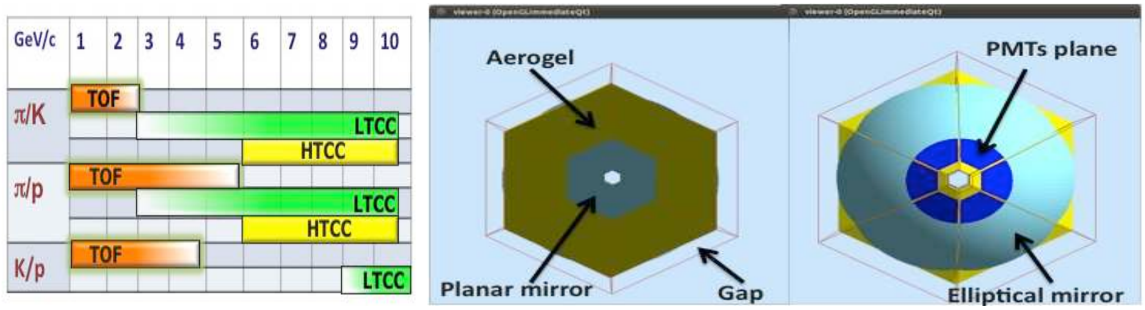



Figure 5: Hadron particle identification in CLAS12 (left) and the proximity focusing RICH with focusing mirrors (right)

approach is to instrument a limited area around the beam line to have direct detection of Cherenkov light for particles emitted in the forward region and at high momenta, while at large angles and lower momenta a system of focusing mirrors catches the light and reflect it toward the photon detector. A drawing of the proposed solution is illustrated in Fig. 5 where the main components of the system are shown: the planar mirror (positioned before the aerogel), the aerogel, the proximity gap, the PMTs plane covering the angular region between $3^\circ$ and $14^\circ$, and the elliptical mirror which reflects the light produced by the particles emitted at angles larger than $14^\circ$ towards the planar mirror.

Preliminary Monte Carlo studies based on GEANT4 with a realistic geometry of the CLAS12 detector and events generated with PYTHIA have been performed with the aim to optimize all the components of the detector. The dimensions of the radiator thickness and the gap length as well as the pad/pixel size of the photon detector have been varied in order to find the optimal combination which gives the smaller reconstruction error in the Cerenkov angle and the highest number of photoelectrons. An average number of 10 and 5 photoelectrons has been obtained for the direct and reflected light collection, respectively.

In order to have a precise information about the RICH performances in terms of pion/kaon separation a pattern recognition algorithm based on the event-wise Direct Ray Tracing (DRT) technique has been implemented. For each hypothesis of particle type(s), given the track(s) information, DRT realistically estimates the produced photon hits pattern to be compared with the measured one by means of a likelihood function. The most probable hypothesis of particle types(s) is assumed to be the true one. The results for particle momenta in the range 7-9 GeV/c, obtained using the RICH configuration shown in Fig. 5 with aerogel of increasing thickness from 2 to 6 cm, a gap length of $\sim$ 100 cm and a pad size of 0.6 cm, is shown in Fig. 6. In the figure the likelihood for the different particles hypothesis is shown. As it can be seen the contamination is widely smaller than 1%. For istance, the probability that a pion is misidentified as a kaon is 0.18% which corresponds to approximatively a greater than 4 $\sigma$ pion/kaon separation.

The preliminary Monte Carlo results on the performances of the proposed RICH are ecouraging; several potential improvements have been already identified and are under detailed investigation. Also test in realistic conditions of the proposed solution with a small prototype is underway.

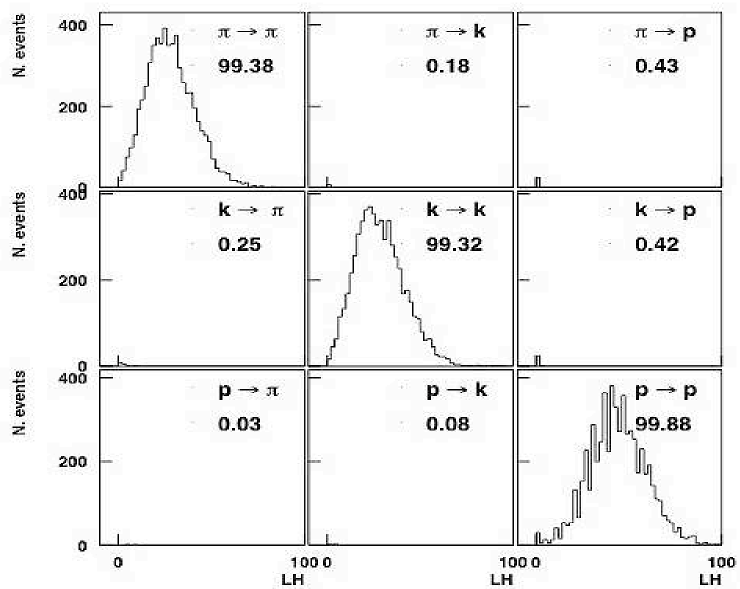



Figure 6: Likelihood distribution for the different particles hypothesis.

# 4 The Beam Request and Expected Results

In this proposal we focus on observables related to kaon production in DIS, accessible with unpolarized targets and the new information on the structure of nucleon they can provide. 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. 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 [52]. 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. Proposed measurements can be used to test the evolution properties of the Collins function. They will also provide a check of chiral limit prediction, where the ratio of pion and kaon fragmentation functions is expected to be at unity. With the knowledge of the Collins function, one can study all involved TMD distributions.

Table 1: 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% |

One of the main systematic errors affecting the extraction of the Collins moment is due to possible contamination of the single hadron sample with decay products of exclusive vector mesons. The fraction of indirect kaons, however, according to LUND studies, is significantly less than for pions. The main difference from the pion production case for the background is the contribution from $K^*$ production (e.g., $K^* \to K\pi$) 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.

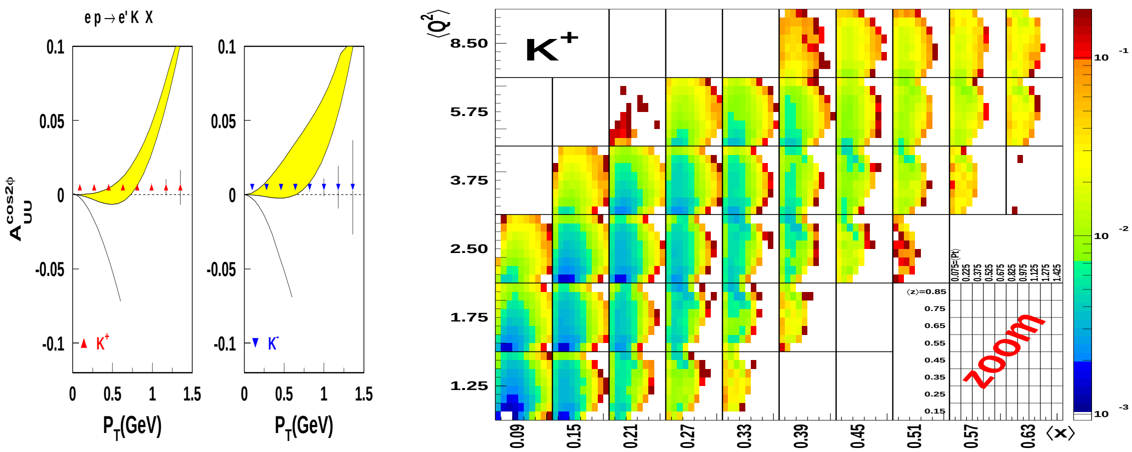
Other sources of systematic errors include the longitudinal to transverse photo absorption cross section ratio, $R(x, Q^2)$ and the beam polarization (for $\sin\phi$). The main sources of systematic errors in measurements of azimuthal asymmetries are listed in the Table 1. These errors are all scale 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 on the assumption of running 54 days on a hydrogen and deuterium [54]. For our estimate of the total systematic error (see Table 1), we have added the systematic errors from the various contributions in quadrature.

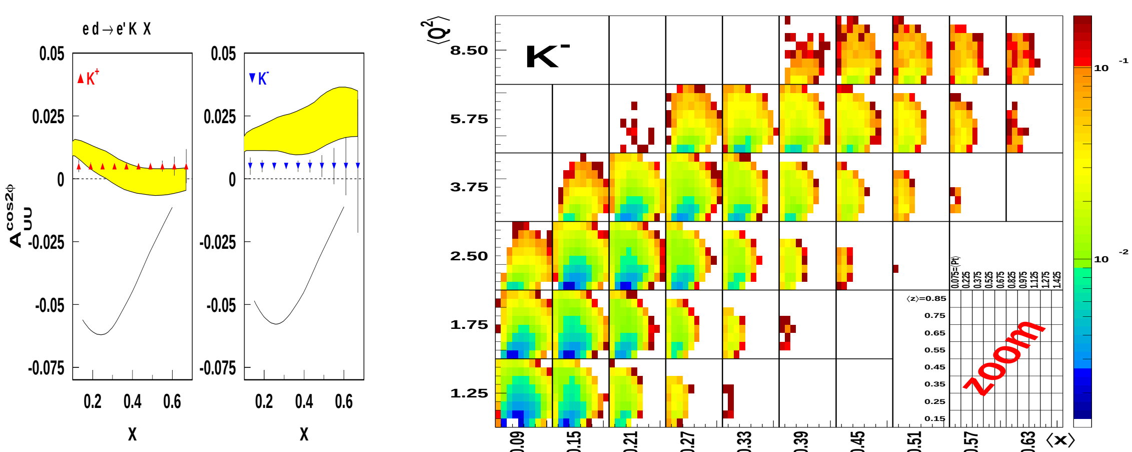
The following predicted results were obtained with a full simulation of the hadronization process [55] and the acceptance of CLAS12 for all particles, assuming kaons can be identified in the full kinematic range by the CLAS12-RICH detector replacing the LTCC. Projections for some of the most important observables are shown on Figs. 7,8 for proton and deuteron targets, respectively.

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 Measurement of the $\cos 2\phi$ for charged kaons for two targets in a wide range of $x$, $Q^2$, $z$, and $P_T$, will allow a complementary to pion SIDIS, study of leading twist TMD parton distribution $h_1^\perp(x, k_T)$. It will also provide complementary information to measurements of the Collins effect [2] with transversely polarized target [59, 60] as




(a) (b)

Figure 7: The $\cos 2\phi$ moment for kaons as a function of $P_T$ (left) for proton target at 11 GeV from 56 days of CLAS12 running. The band corresponds to theory predictions [56]. The black curve is from Ref. [57], with Collins function from parametrization [58]. The right plot shows 4D binning of the statistical uncertainties expected for $K^+$ measurements of the $\cos 2\phi$ moment.




(a) (b)

Figure 8: The $\cos 2\phi$ moment for kaons as a function of $x$ for deuteron target at 11 GeV from 56 days of CLAS12 running (left). Curves are calculated using assumptions for Collins fragmentation function discussed in Fig. 7. The right plot shows 4D binning with statistical errors on $K^-$ measurements.

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

Table 2: Requested beam time broken down by activity.

well as direct measurements, which may be performed at BELLE [36]. The difference of the $\cos 2\phi$ moments for $K^+$ and $K^-$ from $\pi^+$ and $\pi^-$ will provide important information about sea orbital structure, described by corresponding Collins functions. Measured $\cos 2\phi$ moment combined with the measurements on pions [61], will allow the extraction of the Collins analyzing power ratios for pions and kaons, providing independent information on the polarized fragmentation function of kaons.

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 [54]. The breakdown of this beam time is shown in Table 2. The number of days requested was chosen to allow a statistically significant measurement of the T-odd distribution and fragmentation functions.

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