Studies of Spin-Orbit Correlations in Kaon Electroproduction in DIS with Longitudinally Polarized Hydrogen and Deuterium Targets

Update of Experiment E12-09-009 (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 and longitudinal 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 longitudinally polarized proton and deuteron targets. Main objectives include studies of correlations of the transverse spin of quarks with their transverse momentum, leading to observable spin and azimuthal asymmetries. The measurement of the $\sin 2\phi$ azimuthal moment of the semi-inclusive production of hadrons in DIS with longitudinally polarized 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 P_T dependence of the double spin asymmetry will provide additional information on the flavor and polarization dependence of transverse momentum dependence of helicity distributions of quarks, providing complementary to SSA measurements access to spin-orbit correlations. The x, z, P_T and Q^2 dependences of the $\sin 2\phi$ and $\sin \phi$ moments 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 and longitudinally polarized solid ammonia targets (NH_3 and ND_3). 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 30 days of running on NH_3 and 50 days of running on ND_3 (or possibly ^{6}Li D or HD), including about 20% overhead for target anneals, polarization reversal, and auxiliary measurements. This measurement will simultaneously run with already approved measurements using pion electroproduction.

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 longitudinally polarized leptons and nucleons provide access to leading twist helicity $g_{1L}(x, k_T)$ TMD. 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. Orbital momentum of quarks changes significantly the helicity distribution of quarks in the valence quark region, in particular the distributions of quarks anti-aligned, with proton spin [28]. Simple model calculations also indicate that quark distributions aligned, q^+, and anti-aligned, q^-, with proton spin will have also very different transverse momentum distributions [29]. That may lead to observable effects in transverse momentum, P_T, dependences of double-spin longitudinal asymmetries [23]. The latest results on TMDs from the Lattice QCD calculations [26, 30, 27], indicate that spin-orbit correlations could change the transverse momentum distributions of partons. Measurements of transverse momentum dependence of helicity distributions will be also important for interpretation of ongoing studies at different facilities worldwide of gluon polarization using high P_T hadrons [31, 32, 33, 34].

Measurement of the azimuthal modulation of the cross section in double polarized SIDIS, in addition provides access to the "worm gear" $h_{1L}^{\perp}$ TMD, describing transversely polarized quarks in the longitudinally polarized nucleon. The $h_{1L}^{\perp}$ distribution function has been studied in various QCD inspired models [35, 36, 24, 37, 38, 39], including large-x [40] and large N_c [41] limits of QCD. Calculations for $h_{1L}^{\perp}(x, k_T)$ have recently been performed in the perturbative limit [42], and first measurements have been performed using lattice methods [26]. A measurably large asymmetry has been predicted only at large x ($x > 0.2$), a region well-covered by JLab.

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 E12-09-009, in which we proposed a total of 103 days of beam time with an 11 GeV, 10 nA highly polarized electron beam in Hall B with CLAS12 at its maximum luminosity. This experiment will take full advantage of the unique combination of wide kinematic coverage, high beam intensity (luminosity), high energy, high polarization, and advanced detection capabilities to study the transverse momentum and spin correlations in semi-inclusive DIS.

2 Scientific Case and Recent Developments

Spin-orbit correlations are accessible in SIDIS with longitudinally polarized target in measurements of double and single-spin asymmetries. The structure functions defining the SIDIS cross section factorize into convolution of TMD parton distributions and fragmentation functions, and hard parts [43] . For longitudinally polarized leptons and nucleons they involve distribution functions g_1 and $h_{1L}^{\perp}$:

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

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 $H_1^{\perp}$ [2] fragmentation functions depend in general on the transverse momentum of the fragmenting quark.

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

$$F_{UL}^{\sin 2\phi_h} = \mathcal{F}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T) - \boldsymbol{p}_T\cdot\boldsymbol{k}_T}{M_N M_h} h_{1L}^{\perp} H_1^{\perp} \right], \tag{2}$$

where $\hat{\boldsymbol{h}} \equiv \boldsymbol{P}_{h\perp}/P_{h\perp}$ and $\mathcal{F}[fD] = x\sum_a e_a^2 \int d\boldsymbol{k}_T\, d\boldsymbol{p}_T\, \delta^{(2)}(\boldsymbol{k}_T - \boldsymbol{p}_T - \boldsymbol{P}_{h\perp}/z) f^a(x,k_T^2) D^a(z,p_T^2)]$, and e_a is the electric charge of a quark of flavor a.

The physics of σ_{UL}, which involves the Collins fragmentation function $H_1^{\perp}$ and "worm gear" distribution function $h_{1L}^{\perp}$, was first discussed by Kotzinian and Mulders in 1996 [3, 44, 4]. The same distribution function is also accessible in double-polarized Drell-Yan production, where it gives rise to the $\cos 2\phi$ and $\sin 2\phi$ azimuthal moment in the cross section [45, 46]. The measurement of transverse spin dependent distribution is complicated by the presence of the Collins fragmentation function. Significant asymmetry was measured recently by Belle [47, 48, 49], indicating that the Collins function is indeed large.

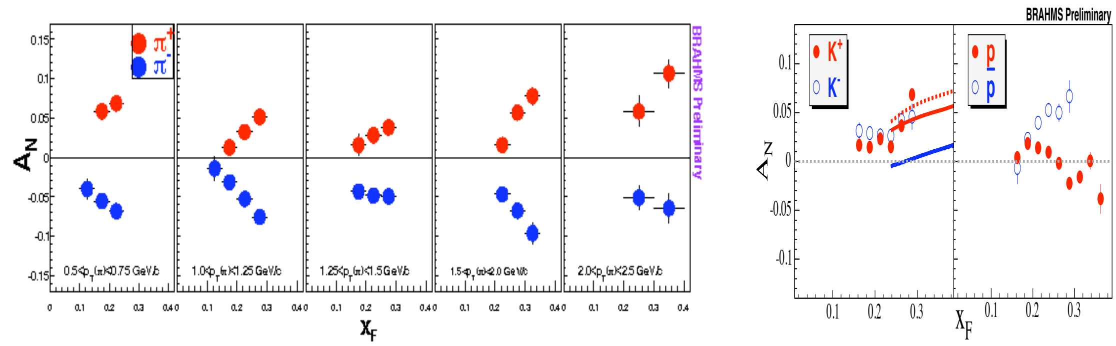


Figure 1: Single spin asymmetries for identified hadrons in proton-proton reactions at 200 GeV center-of-mass energy [51].

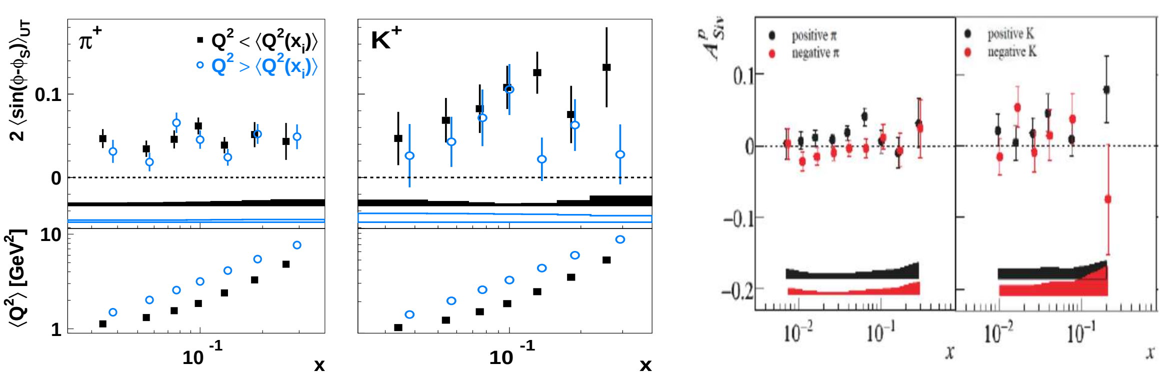


Figure 2: Sivers asymmetries measured for positive pions and kaons in two Q^2 ranges at HERMES [52] (Left) and measured for identified charged hadrons at COMPASS [53] (Right).

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 [50, 51]. 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. 2. The difference concentrate at low-Q, a possible indication of the presence of higher-twist effects in the kaon sector [52]. The results for negative kaons are not conclusive due to the limited statistics [53].

The Collins asymmetry has been measured to be non-zero and opposite in sign

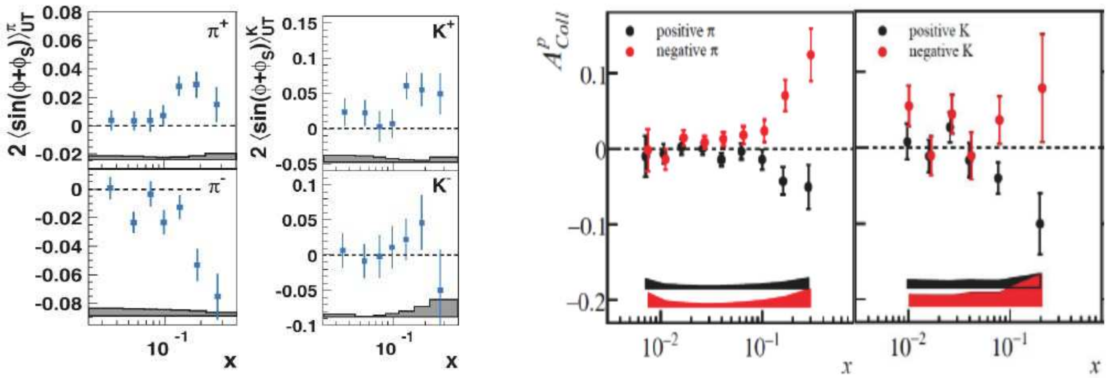


Figure 3: Collins asymmetries measured for identified charged hadrons at HERMES [16] (Left) and COMPASS [53] (Right).

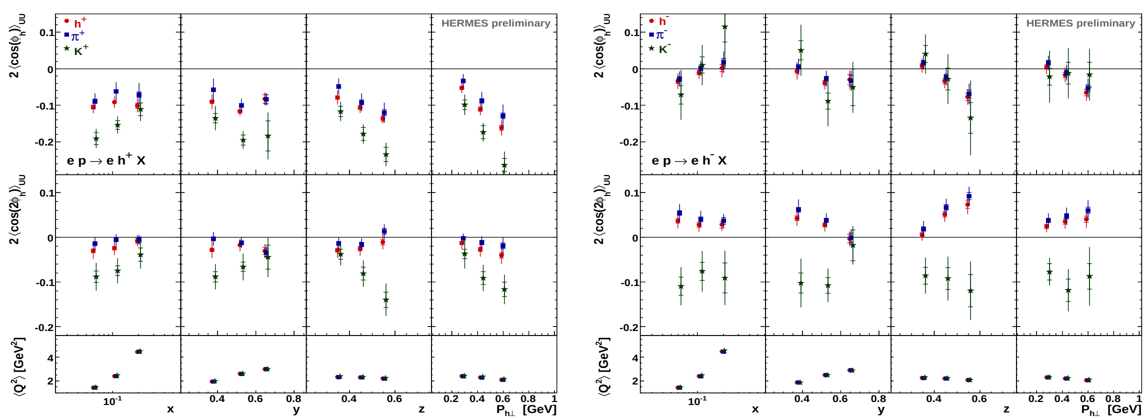


Figure 4: Azimuthal asymmetries in unpolarized SIDIS for identified hadrons [54].

for opposite charge pions, see Fig. 3. This is an indication that favored and unfavored Collins FF are opposite but of similar magnitude, a result compatible with the fragmentation-function measurement at e^+e^- machines [47, 55]. 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 [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, since COMPASS data [53] 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 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 [56]. These reflect in analogous differences for opposite-charge unidentified hadrons, dominated by the pion subsample [57]. The kaon results are definitely surprising, showing $\cos 2\phi$ asymmetries much larger than pions but of the same sign for both charges [54] (see Fig. 4). The measured K^+ signal is 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. 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 behaviour of the fragmentation mechanism in the presence of strange quark. Moreover a hint exists that kaons provide enhanced sensitivity on higher-twist effects [52]. 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 [55, 58] 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 with polarized hydrogen and deuterium targets in the region $0.1 \leq x \leq 0.8$, $0 \leq P_T \leq 1.5$, and $0.2 \leq z \leq 0.8$ using the CLAS12 equipped with a RICH detector. Global analysis of the data combined with the analogous measurement approved with pions [59] and unpolarized target data [60] 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 LTCC and the Time-of-flight scintillator arrays (TOF) (see Fig. 5). In the $\sim 2.5 - 5\ GeV/c$ momentum region, the π/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. At 12 GeV for semi-inclusive processes, the K/π ratio is of the order of $10-15\%$ thus the required rejection factor for pions is around 1 : 1000 (corresponding to 4.7σ pion-kaon separation) while with the present configuration, assuming a pion detection inefficiency for the LTCC of 10%, the π/K contamination is 1 : 1. A RICH detector, to be installed in place of the LTCC, will significantly improve the CLAS12 PID overcoming the above limitations.

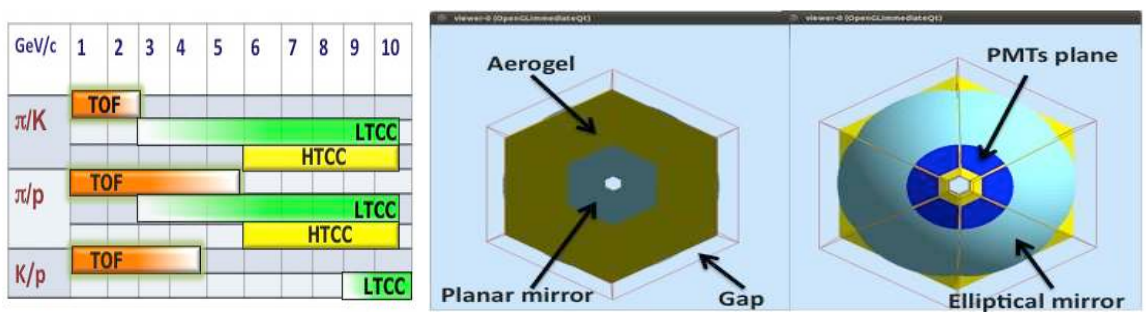


Figure 5: Hadron particle identification in CLAS12 (left) and the proximity focusing RICH with focusing mirrors (right)

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 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° and 14°, and the elliptical mirror which reflects the light produced by the particles emitted at angles larger than 14° 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 component 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; DRT combines the track(s) information with all feasible hypotheses on the tracking particle(s) and realistically estimates, for each hypothesis, the produced photon hits patters, which are combined to the simulated/measured one by means of a likelihood function. The most probable particle(s) hypothesis is assumed as the true one. The results obtained using the RICH configuration shown in Fig. 5 with aerogel of increasing thickness from 2 to 6 cm, a gap length of ~ 100 cm and a pad size of 0.6 cm and for particle momenta in the range 7-9 GeV/c 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 means approximatively a 4-5 σ pion/kaon separation.
The preliminary results of the ongoing Monte Carlo analysis are encouraging about the performances of the proposed RICH; 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.

4 The Beam Request and Expected Results

In this proposal we focus on observables related to kaon production in DIS, accessible with longitudinally polarized targets and the new information on the structure of nucleon they can provide. Simultaneous measurements of the Kotzinian-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 azimuthal moments in kaon lepto-production will be studied as a function of $P_{h\perp}$, in different bins in x, z, and

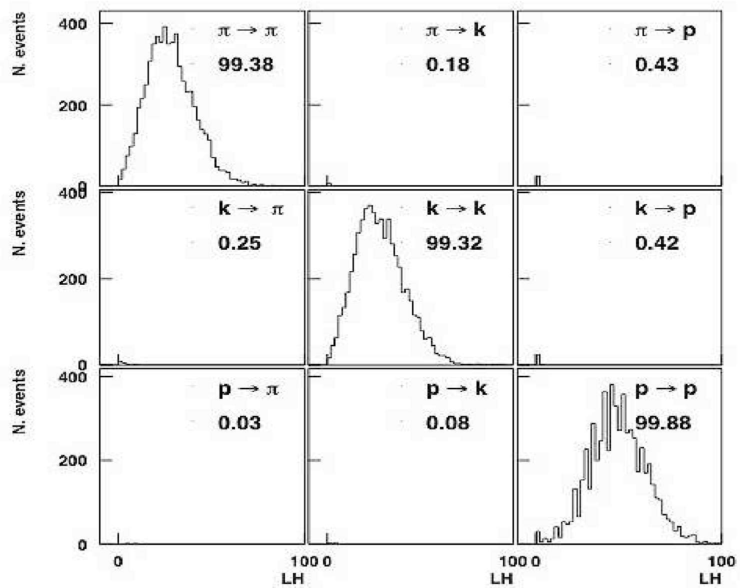


Figure 6: Likelihood distribution for the different particles hypothesis.

Q^2. These measurements combined with the analogous measurements for pions [59] will provide access to widths in transverse momentum of different underlying partonic distributions, like the number density g_1 and the $h_{1L}^{\perp}$ TMD, 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.

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

Table 1: Uncertainties for asymmetry measurements.

Item	A_1^p	$A_{UL}^{\sin\phi}$	$A_{UL}^{\sin 2\phi}$
beam x target polarization	2%	-	-
target polarization	-	3%	3%
depolarization and R	4%	-	-
dilution factor	3%	3%	3%
radiative corrections	3%	3%	3%
fitting procedure	-	4%	5%
transverse (to γ^*) spin effects	3%	3%	-%

target fragmentation, semi-exclusive processes, exclusive vector meson contributions, and higher twist require the data of this measurement.

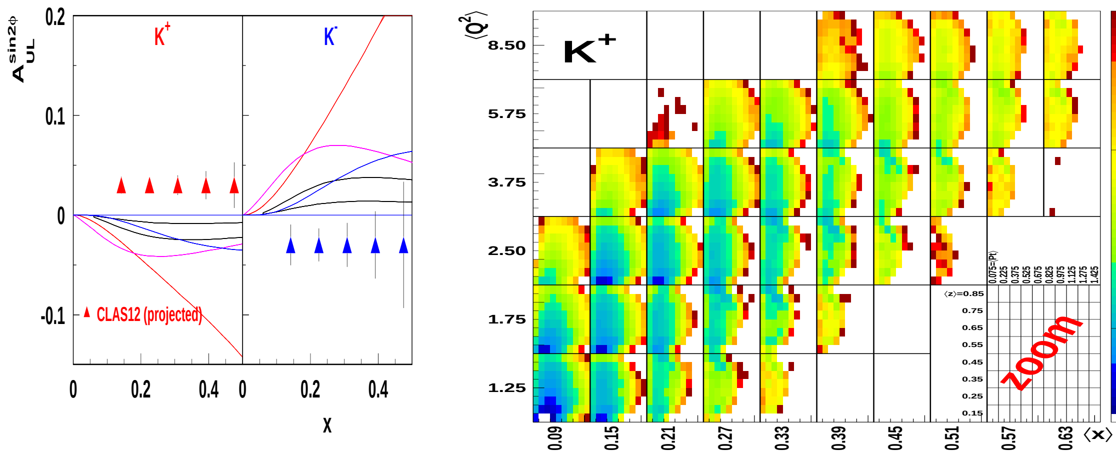
We based our predicted statistical errors in on the assumption of running 30 days on NH_3 and 50 days on ND_3. The number of days was chosen to achieve a statistical error that is not significantly larger than the systematical error at the highest x and P_T points. More days on deuterium than the proton ensures that both have the same statistical error at large P_T and optimizes the error on extracted quantities like $h_{1L}^{\perp u,d}$ and $H_1^{\perp u/K^+}$.

The following predicted results were obtained with a full simulation of the hadronization process [61] 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 read and blue curves are calculations in constituent quark model [24] using Schlumpf's wave function [62] and the hypercentral wave function for the momentum dependence of the light-cone wave function [63]. Both wave functions were used assuming no evolution of $h_{1L}^{\perp}$ and by evolving $h_{1L}^{\perp}$ in the same way as the transversity In both cases, in the denominator the unpolarized PDF f_1 from GRV98 was used, evolved at $Q^2 = 2.5GeV^2$.

Measurement of the $\sin 2\phi$ 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 $h_{1L}^{\perp}(x, k_T)$. It will also provide complementary information to measurements of the Collins effect [2] with transversely polarized target [64, 65] as well as direct measurements, which may be performed at BELLE [47]. The difference of the $\sin 2\phi$ moments for K^+ and K^- from π^+ and π^- will provide important information about sea orbital structure, described by corresponding Collins functions. Measured $\sin 2\phi$ moment combined with the measurements on pions [66], 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 103 days of beam time with an 11 GeV,



(a) (b)

Figure 7: The projected x-dependence of the target SSA at 11 GeV for proton (left). The triangles illustrate the expected statistical accuracy. The black curves show the bounds for calculations based on the relations between transversity and $h_{1L}^{\perp}$ [36]. Color curves correspond to calculations in constituent quark model [24] using different wave functions. The right plot shows 4D binning of the statistical uncertainties expected for K^+ measurements of the $\sin 2\phi$ moment.

10 nA highly polarized electron beam in Hall B. The breakdown of this beam time is shown in Table 2.

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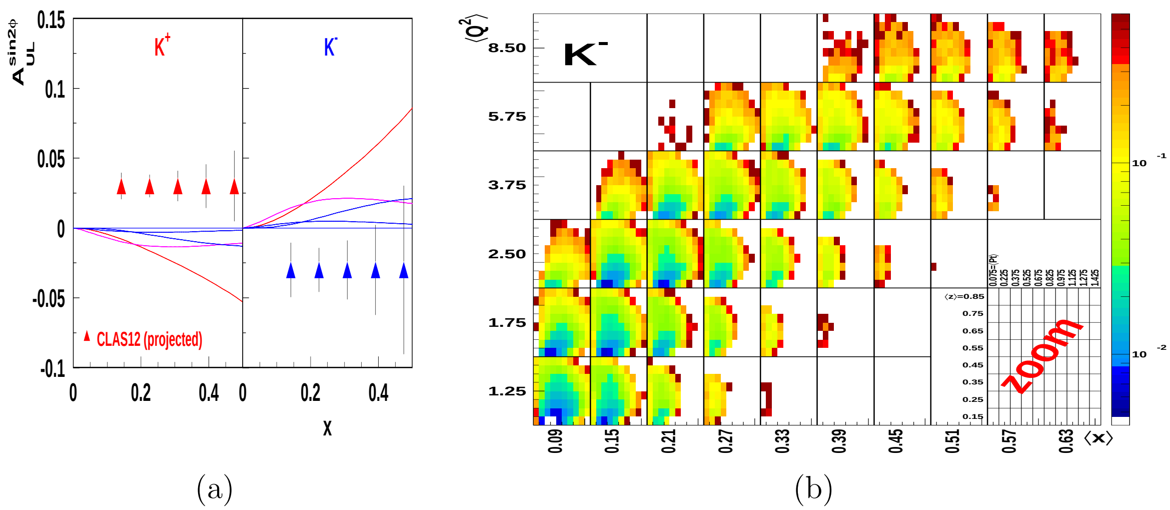

Figure 8: The projected x-dependence of the target SSA at 11 GeV for deuteron target (left). The triangles illustrate the expected statistical accuracy. The black curves show the bounds for calculations based on the relations between transversity and $h_{1L}^{\perp}$ [36]. Color curves correspond to calculations in constituent quark model [24] using different wave functions. The right plot shows 4D binning with statistical errors on K^- measurements.

Time	Activity
3 days	Commissioning: Beam raster set up, trigger optimization, low energy calibration runs
30 days	Production data taking on NH_3
50 days	Production data taking on ND_3
3 days (1 1/2 hours every other day)	Target anneals and/or target changes
10 days (intermittent with production data)	Calibration runs on ^{12}C and empty target
5 days	Production runs on ^{15}N
2 day (1 hour every other day – concurrent with anneals)	Möller polarimeter runs

Table 2: Requested beam time broken down by activity.

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