A New Proposal to Jefferson Lab PAC-35

A Detailed Study of the Reaction Mechanism in Semi-Inclusive DIS with the CLAS12 Detector

A CLAS Collaboration Proposal

L. Guo, X. Jiang [a](Co-Spokesperson), A. Klein, M.-X. Liu, A. Puckett(Co-Spokesperson)

Los Alamos National Laboratory, Los Alamos, New Mexico.

K. Joo(Co-Spokesperson), M. Ungaro

University of Connecticut, Storrs, Connecticut.

H. Avakian(Co-Spokesperson), V. Burkert, L. Elouadrhiri, M. K. Jones, B. Sawatzky

Jefferson Lab, Newport News, Virginia.

G. Dodge, S. Kuhn, L. Weinstein

Old Dominion University, Norfolk, Virginia.

H. Gao, M. Huang, G. Laskaris, X. Qian, Y. Qiang, Q.J. Ye

Duke University, Durham, North Carolina.

L. Zhu

Hampton University, Hampton, Virginia

A. Kim, W. Kim, V. Kuznetsov, S.S. Stepanyan

Kyungpook National University, Daegu 702-201, Republic of Korea

[a]Contact person, email: jiang@jlab.org

Abstract: We propose a detailed study of the reaction mechanism in semi-inclusive deep-inelastic $N(e, e'h)$ ($h = \pi^+, \pi^-, \pi^0$) reactions. Measurements will include: differential cross sections, hadron multiplicities and their relative ratios. Electron beams with energies of 11 GeV, 8.8 GeV, and 6.6 GeV will be scattered from unpolarized proton and deuteron targets, and the large acceptance CLAS12 detector in its baseline configuration will be used to detect the scattered electron and the final hadrons in coincidence. The goal of this experiment is to clearly answer the question: do we understand the reaction mechanism and thus the fundamental cross sections in SIDIS reactions at JLab-12 GeV? The high statistics cross section data from this experiment, spanning a dense 3D-grid of (x, Q^2, z), will be confronted with the predictions of state-of-the-art next-to-leading-order QCD global analysis. Once demonstrated, a detailed agreement between data and NLO-QCD predictions will allow us to firmly establish a kinematic region for which JLab-12 GeV SIDIS reactions can be reliably interpreted in terms of parton distributions and fragmentation functions to the next-to-leading-order and at leading twist. In addition, these high precision data will be used as inputs to the next generation NLO global analysis, which will include data from upcoming JLab-12 GeV unpolarized and polarized SIDIS, as well as data from e^+e^- and pp reactions, to strongly constrain quark fragmentation functions, parton densities and helicity distributions. The overwhelming majority of the beamtime requested for the proposed measurement *will be shared with other approved CLAS12 experiments*, including 1000 hours each at 11 GeV on unpolarized proton and deuteron targets, and 250 hours each at 8.8 and 6.6 GeV on an unpolarized proton target. **This experiment requests an additional 250 hours each for beam energies of 8.8 and 6.6 GeV on an unpolarized deuterium target.**

Contents

This proposal is based on an earlier Letter-Of-Intent submitted to JLab PAC-32 (LOI12-07-103). In its final report, PAC-32 recommended: **"... the committee recognizes the fundamental value of the proposed study and encourages the proponents to submit a full proposal."** The complete PAC-32 report on LOI12-07-103 is attached in Appendix-A.

1 Collaboration and Commitments

The core group of this experiment and their commitments are:

Los Alamos group: The group at Los Alamos National Laboratory has been heavily involved in spin physics and semi-inclusive DIS at JLab-6 GeV, including the Neutron Transversity experiment in Hall A , and the polarized deuteron target runs in Hall B during eg1-DVCS data taking. The group's funding is from DOE and from Los Alamos National Lab's Directed Research and Development Fund (LDRD). The group plans to be heavily involved in JLab-12 GeV physics, especially in SIDIS, transversity and transverse momentum dependent parton distributions.

Once this proposal is approved, the Los Alamos group will continue to commit one full time LANL Director's Postdoc Fellow (Puckett) on this project. One research staff (Jiang) will work part time on this project. Two other staff members (Liu, on RHIC spin and Klein, formerly of ODU and longtime CLAS collaboration member) and another postdoc (Guo, a former Hall B postdoc) are likely to join the project on a part time basis when other physics topics, especially high momentum Kaon detection, start to mature. Within the CLAS12 collaboration, the LANL group plans to take responsibility for SIDIS physics simulations, and detector and background rate simulations. The group will also be involved in RICH detector design and development efforts, and pursue internal and external funding to build at least one sector of the RICH detector for CLAS12. Several other members of the LANL group are currently leading the Forward Vertex Silicon Detector project for the PHENIX experiment at RHIC. At a later stage, as funding permits, the LANL group will bring this expertise to bear to contribute to the CLAS12 Silicon Vertex Detector's hardware, readout electronics, reconstruction software and commissioning. In addition, a LANL staff (Klein) has expressed interest and is currently engaged in discussion toward building/upgrading part of the CLAS12 wirechamber readout electronics.

UConn group:

The University of Connecticut (UConn) group is actively involved in this proposal using CLAS12 baseline equipment. Among the CLAS12 baseline equipment projects, the UConn group has taken responsibility for (1) the development of the CLAS12 detector simulation program (GEMC) based on Geant4-software-toolkit, and (2) the design, prototyping, construction and testing of the high threshold Cerenkov counter (HTCC). One faculty member (K. Joo), one research associate (M. Ungaro), six graduate students are already or will be working at least part time on the CLAS12 project for the next few years. The group is currently funded by the U.S Department of Energy (DOE) and the University of Connecticut Research Foundation (UCRF). Additional sources of funding will be sought as appropriate.

ODU group: Among CLAS12 baseline equipment, the ODU group has taken on the responsibility for the design, prototyping, construction and testing of the Region 2 Drift Chamber. Five faculty and one technician are working on this project now and over the next few years. Funding for the group is from DOE and from the university (50% salary of the technician and computer support). The university has also provided 6000 square feet of high bay laboratory space with has been equipped as a large clean room for our use. In addition to the DC project, we also pursue funding and will make a major contribution to the construction of the CLAS12 longitudinally polarized target.

KNU group: Kyungpook National University is fully committed to support the JLab 12 GeV upgrade. The group is dedicated to develop a frontier nuclear physics program and to take the leadership in important software and hardware projects commensurate with the group's physics goals and capabilities. We are currently in charge of designing, constructing, testing and commissioning the 12 GeV central TOF detector.

2 Introduction

2.1 Semi-inclusive deep inelastic scattering

Our knowledge of parton densities $q_f(x)$ and polarization distributions $\Delta q_f(x)$ has become increasingly precise as a result of two decades of a wide variety of high precision measurements. The most precise and clearly interpreted data are from inclusive deep-inelastic lepton scattering (DIS) experiments at CERN, SLAC and DESY. However, the information available from the inclusive DIS process has inherent limitations. As the cross sections are only sensitive to e_q^2, the quark charge squared, an inclusive experiment probes quarks and anti-quarks on an equal footing, and it is only possible to directly determine combinations of $q_f(x)+\bar{q}_f(x)$, but never $q_f(x)$ and $\bar{q}_f(x)$ separately.

Sensitivity to each individual quark flavor is realized in semi-inclusive deep inelastic scattering (SIDIS) in which one of the leading hadrons is also detected [2]. Since the leading hadrons from current fragmentation are most likely to be correlated with the struck quark, detection of the leading hadron effectively "tags" the

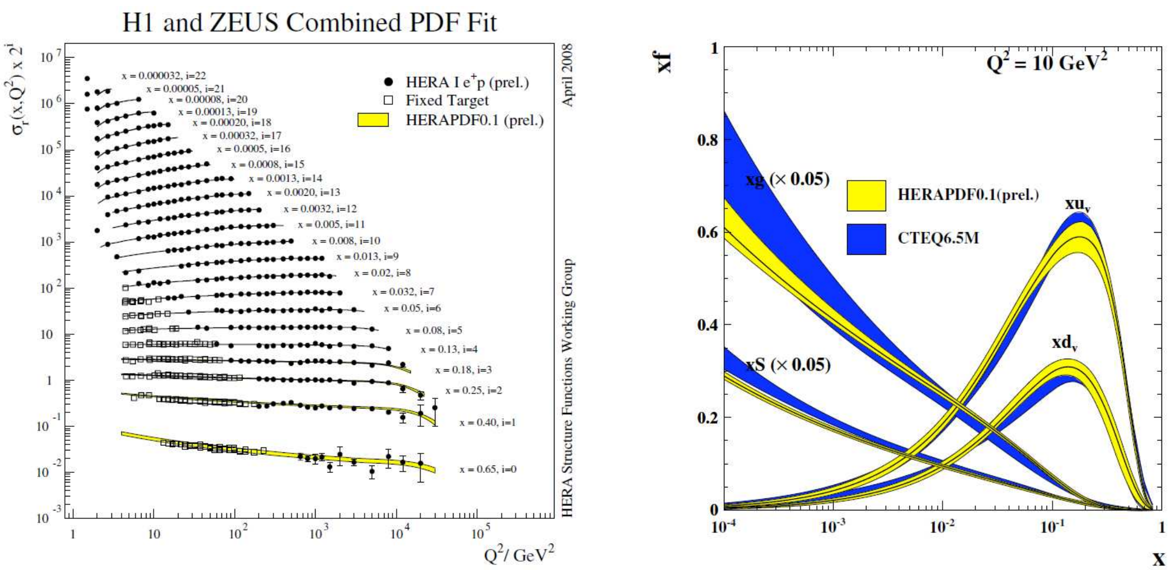

Figure 1: A combined PDF fit to HERA H1 and ZEUS inclusive DIS scattering data [1]. LEFT: combined neutral current DIS reduced cross section σ_r as a function of Q^2 at different x values, with HERA pdf fit superimposed. RIGHT: HERA PDFs at $Q^2 = 10$ GeV^2 compared to the PDFs from CTEQ6.5M.

struck quark. Therefore, SIDIS offers an unique opportunity for determining the spin, flavor, valence and sea structure of the nucleon, thereby significantly enriching our understanding of QCD and the nucleon structure [2]. Several years ago, Ji, Ma and Yuan explicitly proved [3] that QCD factorization is valid for SIDIS with hadrons emitted in the current fragmentation region with low transverse momentum $P_{h\perp} \ll Q$. QCD factorization of spin-dependent cross sections in SIDIS and Drell-Yan has also been proven for the low $P_{h\perp}$ case [4].

On the experimental side, the SMC experiment at CERN [5] first extracted leading order quark spin-flavor information through SIDIS at $\langle Q^2 \rangle = 10$ GeV^2. The HERMES experiment at DESY published the results of a leading order spin-flavor decomposition at $\langle Q^2 \rangle = 2.5$ GeV^2, and for the first time extracted the sea quark polarizations [7]. The COMPASS experiment at CERN recently has also extracted similar leading order polarized parton distributions [6]. Over the last five years, the HERMES and COMPASS measurements [8,9] of single-spin asymmetries on transversely polarized proton and deuteron targets have generated rapid new theoretical developments in the study and understanding of the SIDIS process. In addition to model calculations of the transversity distributions and lattice calculations of the tensor charges, increasingly large efforts have been devoted to understanding the reaction mechanisms of the single-spin asymmetry from the fundamental theory of the strong interaction, QCD. In particular, the rapid progress in the study of the Sivers effect and related mechanisms has brought our understanding to a new level. The link of the SSA in SIDIS with other areas of hadronic physics, such as the Drell-Yan and $p\bar{p}$ reactions and multi-hadron production processes, has not only raised great interest in theoretical efforts, but also in experimental efforts. Studies of TMDs and transversity physics have quickly become a major goal dominating the physics programs at a number of new facilities, including RHIC-spin and RHIC-II upgrade at BNL, J-PARC in Japan, FAIR at GSI in Germany, the JLab-12GeV upgrade, and the planned polarized electron-ion collider (EIC) in the U.S.

The next US nuclear physics long range plan highlighted the study of quark distributions, transversity and TMDs through SIDIS. The JLab 12 GeV upgrade will provide many of these unique opportunities, including:

- Transverse target single spin asymmetry measurements A_{UT} (on polarized proton, deuteron and ^{3}He targets) and extraction of Collins and Sivers moments to constrain quark transversity, the T-odd Collins fragmentation functions and the Sivers distributions for u and d-quarks.

- Longitudinal beam-target double-spin asymmetry measurements A_{LL} (on polarized proton, deuteron and ^{3}He) to constrain quark helicity distributions for each flavor separately and to access the polarized sea asymmetry $\Delta\bar{u} - \Delta\bar{d}$ (Approved proposal 12-07-107).

- Measurements of hadron azimuthal distributions (such as $cos(2\phi)$) on unpolarized targets to access information on quark spin-orbit correlations by extracting the so-called Boer-Mulders functions (Approved proposal PR12-06-112).

- Extraction of other azimuthal moments in single and double spin asymmetry measurements to extract TMDs and access quark spin-orbit correlations, for example: $\cos(\phi_h - \phi_S)$ in A_{LT} and $\sin(2\phi_h)$ in A_{UL} etc. (PR12-07-107).

- Measurements of unpolarized SIDIS cross sections to access the unpolarized sea asymmetry $\bar{u} - \bar{d}$.

2.2 Interpretations of SIDIS data at JLab-12 GeV

An important component toward realizing this ambitious SIDIS program at JLab 12 GeV is to provide evidence that SIDIS reactions at JLab-12 GeV kinematics can be reliably interpreted in terms of parton distributions and fragmentation functions.

Within the statistical precision of the HERMES and COMPASS experiments, SIDIS data have been interpreted in a self-consistent manner at the leading order, i.e. $\sigma^h(x, Q^2, z) = \sum_f q_f(x, Q^2) \cdot D_q^h(z, Q^2)$. Recent JLab E00-108 data[10], on unpolarized SIDIS cross section ratios, indicated that leading order naive x-z separation is not too far away from reality. As shown in Fig. 2, ratios of combined SIDIS multiplicities of proton over deuteron are almost z-independent in the region of $0.3 < z < 0.7$. This apparent "precocious scaling" or "quark-hadron duality" suggests that at modest beam energy and Q^2, information on the quark distribution is reasonably well-preserved in semi-inclusive reactions.

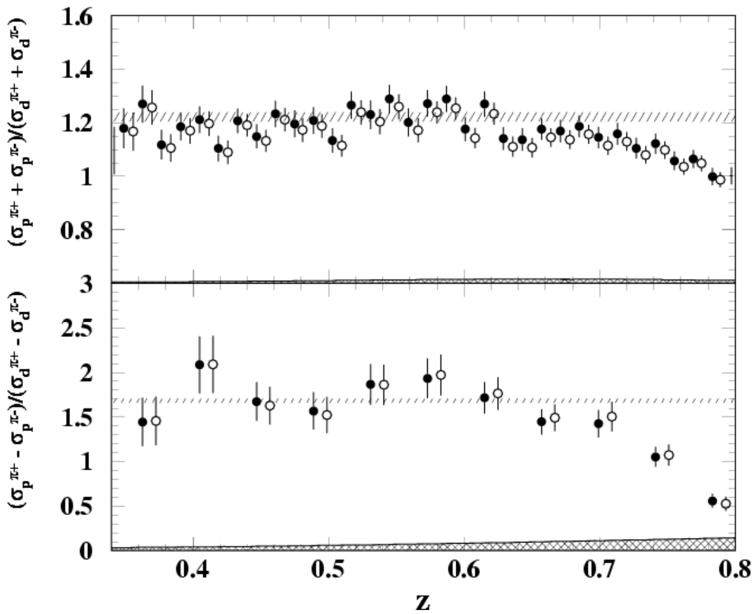

Figure 2: JLab Hall C SIDIS data at $E_0 = 5.5$ GeV, $x = 0.32$, $Q^2 = 2.3$ GeV^2. Ratios of combined SIDIS multiplicities of proton over deuteron.

At the next-to-leading order, following the well established formalism [12,13], tools of NLO global fits, including data sets from e^+e^-, SIDIS and pp reactions, have become available very recently [14]. Similar to the NLO fits of parton densities, these global fits provide "uncertainties" in fragmentation functions such that SIDIS cross sections can be predicted with a theoretical "error band".

2.3 The goal of this experiment

This experiment will provide precision data of charged and neutral pion multiplicities and their relative ratios in Semi-Inclusive Deep Inelastic Scattering (SIDIS) kinematics. By using the large-acceptance CLAS12 detector to integrate over the transverse $(P_{h\perp}, \phi_h)$ phase space of the observed hadrons, these data will be used to confront the predictions of NLO pQCD global fragmentation function fits in the collinear approximation at leading twist for JLab 12 GeV SIDIS kinematics, in order to:

- Test the assumption of universal/independent fragmentation for JLab 12 GeV SIDIS kinematics.
- Establish the region for which this NLO QCD picture of the SIDIS reaction mechanism is reliable.
- Quantify remaining effects beyond our state-of-the-art NLO comprehension, including possible higher-twist effects.

3 Physics motivations and definitions

3.1 Cross sections and hadron multiplicities in semi-inclusive DIS

The kinematics and the coordinate definitions in SIDIS are illustrated in Fig. 3. We define E$'$ as the energy of the scattered electron and θ_e as the scattering angle. $\nu = E - E'$ is the energy transfer in the lab frame. The Bjorken-x variable, which indicates the fractional momentum carried by the struck quark, is defined as: $x = Q^2/(2\nu M_N)$, where M_N is the nucleon mass. The momentum of the outgoing hadron is p_h and the fraction of the virtual photon energy carried by the hadron is: $z = E_h/\nu$. The hadron transverse momentum relative to $\vec{q}$ is labeled as $P_{h\perp}$ as shown in Fig. 3.

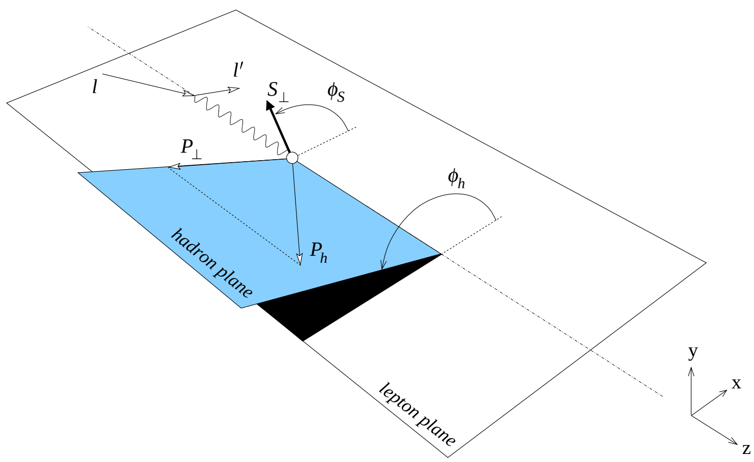

Figure 3: The definition of SIDIS kinematics, according to the Trento conventions.

3.2 Spin-independent cross sections at the Next-to-Leading-Order

The naive $x - z$ separation is not valid at the next-to-leading order when the one-gluon diagrams in Fig. 4 are considered. However, the exact form of these terms is well-known [16]. At NLO, additional terms with double convolutions of the type $q \otimes \mathcal{C} \otimes D$ arise in which $\mathcal{C}$ are well-known Wilson coefficients [17]:

$$[q \otimes C \otimes D](x,z) = \int_x^1 \frac{dx'}{x'} \int_z^1 \frac{dz'}{z'} q\left(\frac{x}{x'}\right) C(x',z') D\left(\frac{z}{z'}\right). \tag{1}$$

Not only are x and z mixed through the double convolutions at the next-to-leading order, the unpolarized cross section σ^h also depends on the virtual photon variable $y = (E_0 - E')/E_0$ due to the longitudinal component of the virtual photon.

We define the short-hand notation:

$$qD + \frac{\alpha_s}{2\pi} q \otimes C \otimes D = q\left[1 + \otimes \frac{\alpha_s}{2\pi} C \otimes\right] D, \tag{2}$$

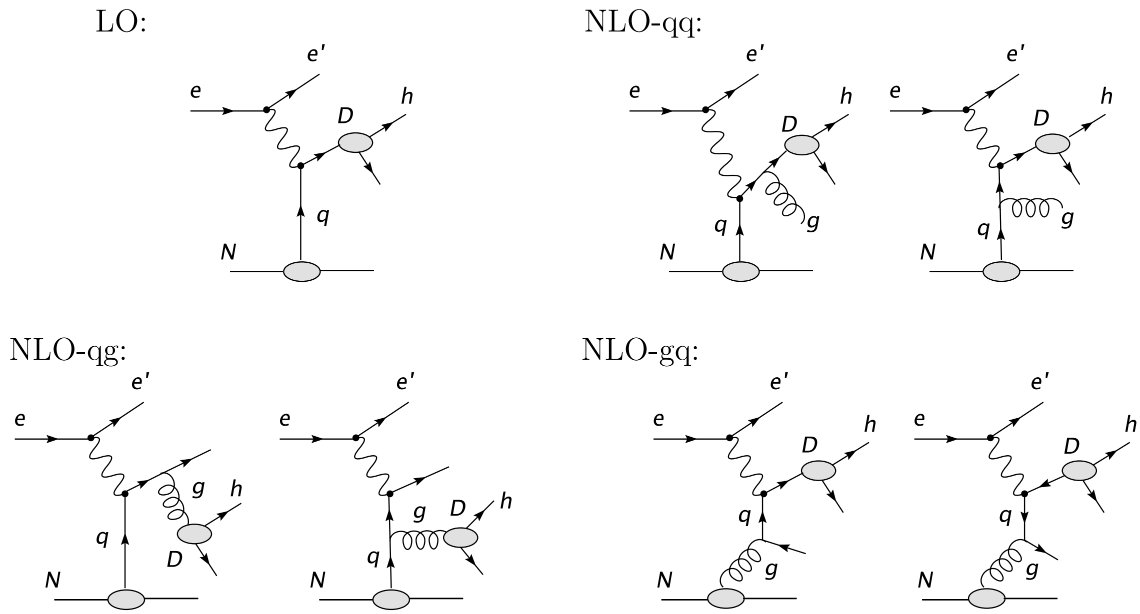

Figure 4: Semi-inclusive deep inelastic scattering diagrams at leading order (LO) and the next-to-leading order (NLO).

At NLO, we have:

$$\sigma^h(x,z) = \sum_f e_f^2 q_f \left[1 + \otimes \frac{\alpha_s}{2\pi}\mathcal{C}_{qq}\otimes\right] D^h_{q_f} + \left(\sum_f e_f^2 q_f\right) \otimes \frac{\alpha_s}{2\pi}\mathcal{C}_{qg} \otimes D^h_G + G \otimes \frac{\alpha_s}{2\pi}\mathcal{C}_{gq} \otimes \left(\sum_f e_f^2 D^h_{q_f}\right), \tag{3}$$

where $q_f(x)$ is the quark distribution function for flavor f. The functions $D^h_{q_f}(z)$ represent the probability that a quark f fragments into a hadron h. For any given set of PDFs, SIDIS cross sections can be calculated numerically [14] according to Eq. 3. It is also well-known that in Mellin-n space, the double-convolutions factorize into simple products under moments, and the parton distributions can be recovered by an inverse Mellin transformation, for which all moments of Wilson coefficients are already calculated [18].

3.3 NLO global fit of fragmentation functions.

Our knowledge of parton fragmentation functions has traditionally come from fits of existing e^+e^- annihilation data [20,21]. In a recent work [14], the first attempt was made to include data sets of e^+e^- as well as SIDIS and pp reactions in a NLO global fit. As shown in Fig. 5, the new fit reproduced HERMES SIDIS charged pion multiplicity data reasonably well. Following the NLO global fit [14], SIDIS cross sections at JLab 12 GeV kinematics are predicted for this experiment.

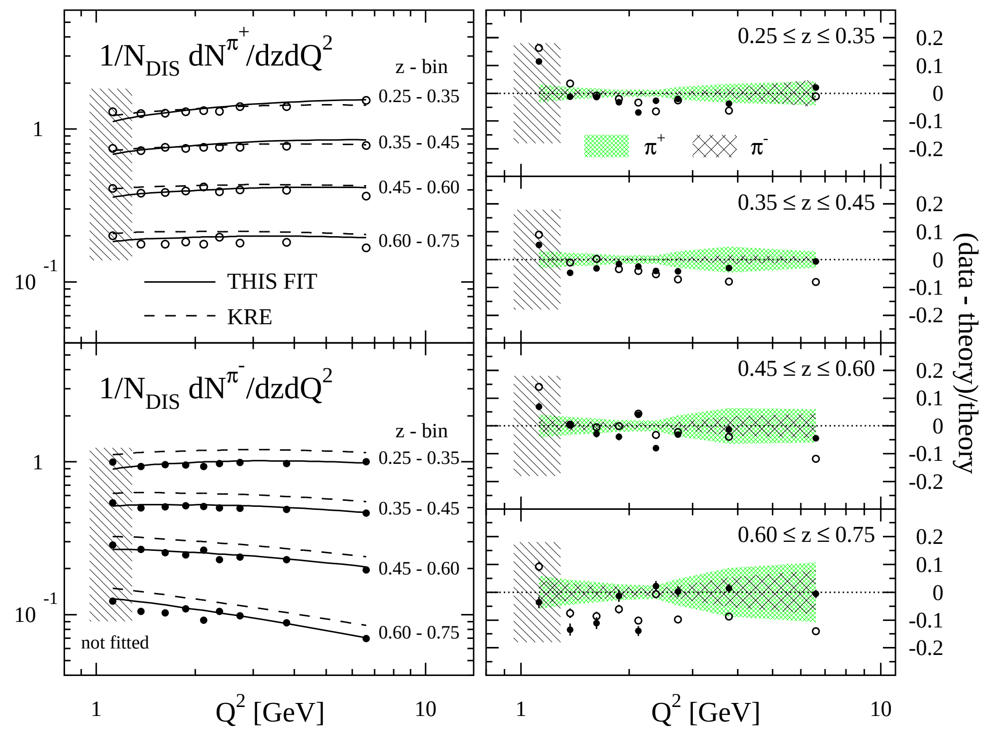

Figure 5: HERMES charged pion multiplicity data compared with the NLO global fit of de Florian, Sassot and Stratmann (solid line).

3.4 Observables of this experiment

In this experiment, the following observables will be measured:

Differential cross sections of SIDIS reaction

When care is taken in determining the absolute luminosity and the acceptance and detection efficiency for the scattered electron, absolute cross sections of SIDIS hadron production can be extracted from this experiment. Although this experiment will focus on measuring ratios of cross sections, extensive calibration runs, following well-established procedures for the 6 GeV CLAS detector[19] will be taken such that the absolute cross sections can be determined as by-products to better than $\pm 6\%$ in normalization uncertainties.

Hadron multiplicities

The multiplicity of hadron h produced at a fixed momentum fraction z in the SIDIS reaction is defined as the ratio of SIDIS cross section over inclusive DIS cross section, integrated over the hadron's transverse momentum and direction:

$$\frac{\sigma^h(x,z,Q^2)}{\sigma_{DIS}} = \frac{1}{\sigma_{DIS}} \int \frac{d\sigma^h}{d\Omega_h d^2 P_{h\perp}} \, d\Omega_h \; d^2 P^h_{h\perp} \tag{4}$$

Notice that in practice, the scattered electron's solid angle and detection efficiency, and the overall luminosity, do not enter into the measurements of hadron multiplicity, since they are canceled in the cross section ratio.

Ratios of charged pion multiplicities

We define the observable r as the ratio of π^- and π^+ multiplicities:

$$r(x,z,Q^2) = \frac{\sigma^{\pi^-}}{\sigma^{\pi^+}} \tag{5}$$

This ratio, when measured from the deuterium target, is sensitive to the ratio of "favored" to "unfavored" fragmentation functions D^+/D^-.

Combined charged pion multiplicity

The combined charged pion multiplicity is defined as:

$$\frac{\sigma^{\pi^+ + \pi^-}}{\sigma_{DIS}}(x,z,Q^2) = \frac{1}{\sigma_{DIS}} \left(\sigma^{\pi^+} + \sigma^{\pi^-} \right). \tag{6}$$

This combination of fragmentation functions is particularly interesting for comparison to e^+e^- annihilation data, for which the most reliably determined combination of fragmentation functions is $D^{\pi^+ + \pi^-}_{q+\bar{q}}$.

Ratios of combined multiplicities between proton and deuteron targets

We define the observables r^+ and r^- as the ratios of combined multiplicities between proton and deuteron targets:

$$r^+(x,z,Q^2) = \frac{\sigma_p^{\pi^+} + \sigma_p^{\pi^-}}{\sigma_d^{\pi^+} + \sigma_d^{\pi^-}} \tag{7}$$

$$r^-(x,z,Q^2) = \frac{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}}{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}}. \tag{8}$$

These ratios of multiplicities from proton and deuteron targets have the advantage that they are largely insensitive to fragmentation functions and depend mainly on combinations of PDFs. Furthermore, these observables experience partial cancellations of systematic uncertainties associated with pion acceptance and detection efficiency and should therefore be measured with significantly smaller systematic uncertainties compared to the multiplicities themselves. Precise measurements of the z-dependence of this ratio provide a powerful test of $x - z$ separation of the SIDIS cross section at the leading-order (LO) and next-to-leading order in pQCD (in the collinear, leading twist approximation).

4 This Experiment

4.1 CLAS12 forward detector

This experiment will use the forward CLAS12 spectrometer in its standard configuration, as illustrated in Fig: 6. The standard cryogenic hydrogen and deuterium targets will be used with electron beam energies of 11.0, 8.8, and 6.6 GeV at a nominal luminosity of 10^{35} cm^{-2}s^{-1}.

Details of the CLAS12 magnet and detector design can be found in the CLAS12 technical design report [22]. The technical design specifications of CLAS12 relevant to this experiment are as follows:

- Angular acceptance: $5^\circ < \theta < 40^\circ$.
- Electron detection and particle identification: Cherenkov to 5 GeV/c and calorimeter beyond 5 GeV/c. The planned High Threshold Cerenkov Counter (HTCC) for CLAS12 has a pion detection threshold of ≈ 5 GeV/c, providing for high pion rejection factors (> 300) over the entire momentum range below threshold. Above the threshold for pion detection, the existing electromagnetic calorimeter will provide the needed e/π separation.
- π^+/p separation: $p_h < 6.0$ GeV/c based on the timing resolution of the Forward Time-of-Flight (FTOF) system and the low-threshold Cerenkov counter (LTCC) for momenta above the pion threshold.

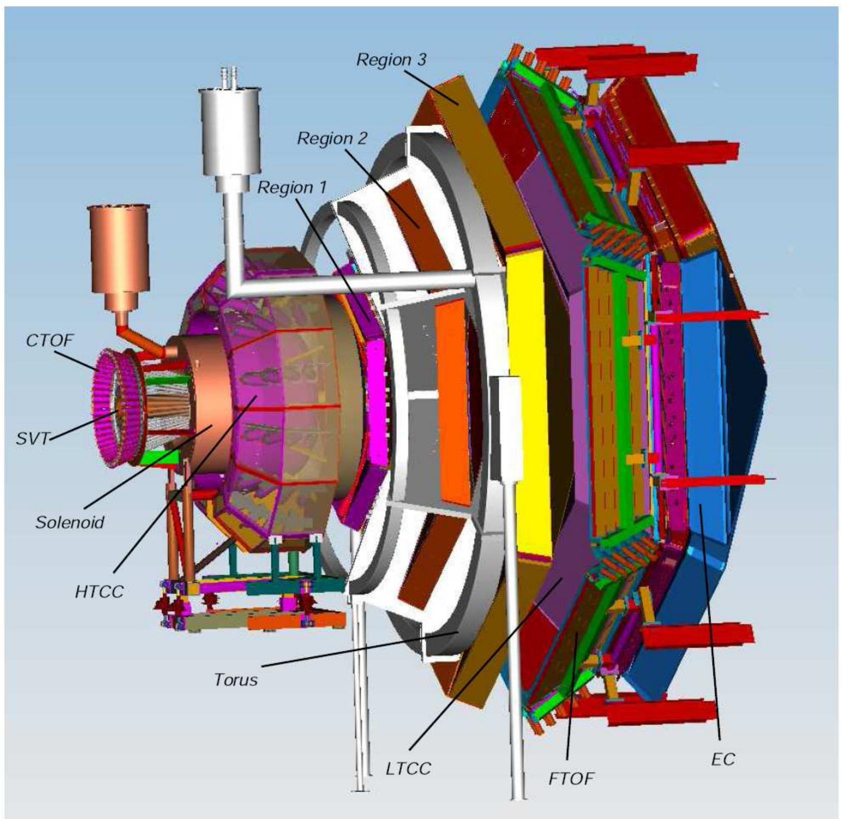

Figure 6: The standard configuration of the CLAS12 detector. Only the forward detector is used in this experiment.

- π/K separation: $p_K < 3.0$ GeV/c. The pion threshold in the LTCC is approximately 2.6 GeV/c. Below threshold, the FTOF system will provide sufficient resolution for charged kaon identification. For momenta above 3 GeV/c, π/K separation relies on the LTCC alone, and under reasonable assumptions on the pion detection efficiency and the ratio of pion to kaon production rates, the π/K ratio for particles identified as kaons is approximately 1:1. In other words, the baseline CLAS12 equipment cannot reliably separate kaons from pions above 3 GeV/c.

- π^0 ID from 2γ reconstruction: up to 11 GeV/c, mass resolution ~ 20 MeV.

4.2 Monte Carlo simulation

A detailed Monte Carlo simulation has been developed based on the LEPTO[24] program with modifications corresponding to the CLAS12 detector. The simulation was performed in two steps. First, for each beam energy and target, the LEPTO-based event generator was used to simulate SIDIS events using realistic PDFs for the DIS process and hadronization using the Lund string model. Then, the events were read back by the CLAS12 fast Monte Carlo (FASTMC), which simulates the CLAS12 acceptance and resolution in angles and momentum and produces histograms for each hadron species.

4.3 Kinematic coverage

The invariant mass W of the whole hadronic final state and the "missing mass" W' of the hadronic state not including the detected pion are given by:

$$\begin{aligned} W^2 &= M_N^2 + Q^2\left(\frac{1}{x} - 1\right), \\ W'^2 &= (M_N + \nu - E_\pi)^2 - |\vec{q} - \vec{p_\pi}|^2. \end{aligned} \tag{9}$$

The Feynman-x (x_F) variable, which is commonly used to separate the current fragmentation region from the target fragmentation region, is defined as

$$x_F \equiv \frac{2p_L^*}{W} \tag{10}$$

where p_L^* is the longitudinal component of the hadron momentum in the virtual photon-nucleon center-of-momentum frame. The SIDIS cuts are taken to be $Q^2 > 1$ GeV^2, $W > 2$ GeV and $x_F > 0$. Hadron momenta are required to be at least 1.0 GeV/c. For the invariant mass of the undetected system, $W' > 1.5$ GeV is required.

The inclusive DIS/SIDIS kinematic coverage of this experiment corresponding to beam energies of 11, 8.8 and 6.6 GeV is shown in Fig. 7 for (Q^2, x_{bj}) for detected DIS electrons, and in Fig. 8 for (W', x_{bj}) for events with a detected DIS electron and at least one detected charged and/or neutral pion. Fig. 9 compares the (z_π,

x) coverage of accepted and generated events in the simulation for π^+, π^-, and π^0. Similar comparisons are shown for ($p_\perp^\pi$, x_{bj}) and ($p_\perp^\pi$, ϕ_π) in Figs. 10 and 11, respectively. For all three beam energies, the CLAS12 acceptance covers the full range in ϕ and p_T. Although the acceptance in e.g., ϕ is highly non-uniform, the full ϕ coverage of CLAS12 should minimize the systematic uncertainty due to integration over ϕ.

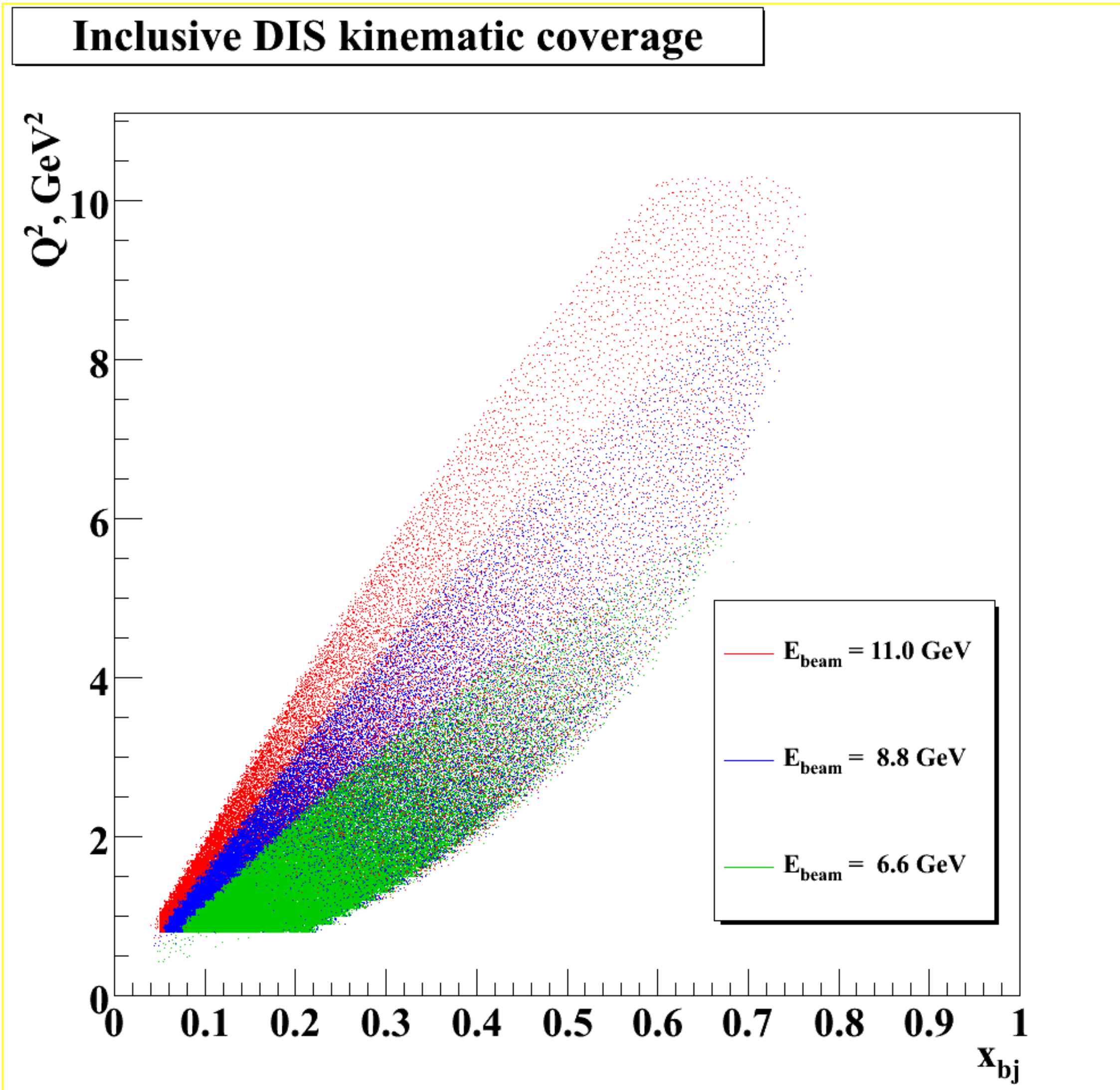

Figure 7: SIDIS phase space coverage of (Q^2, x_{bj}) for E_0=11, 8.8 and 6.6 GeV. The total number of events is not to scale.

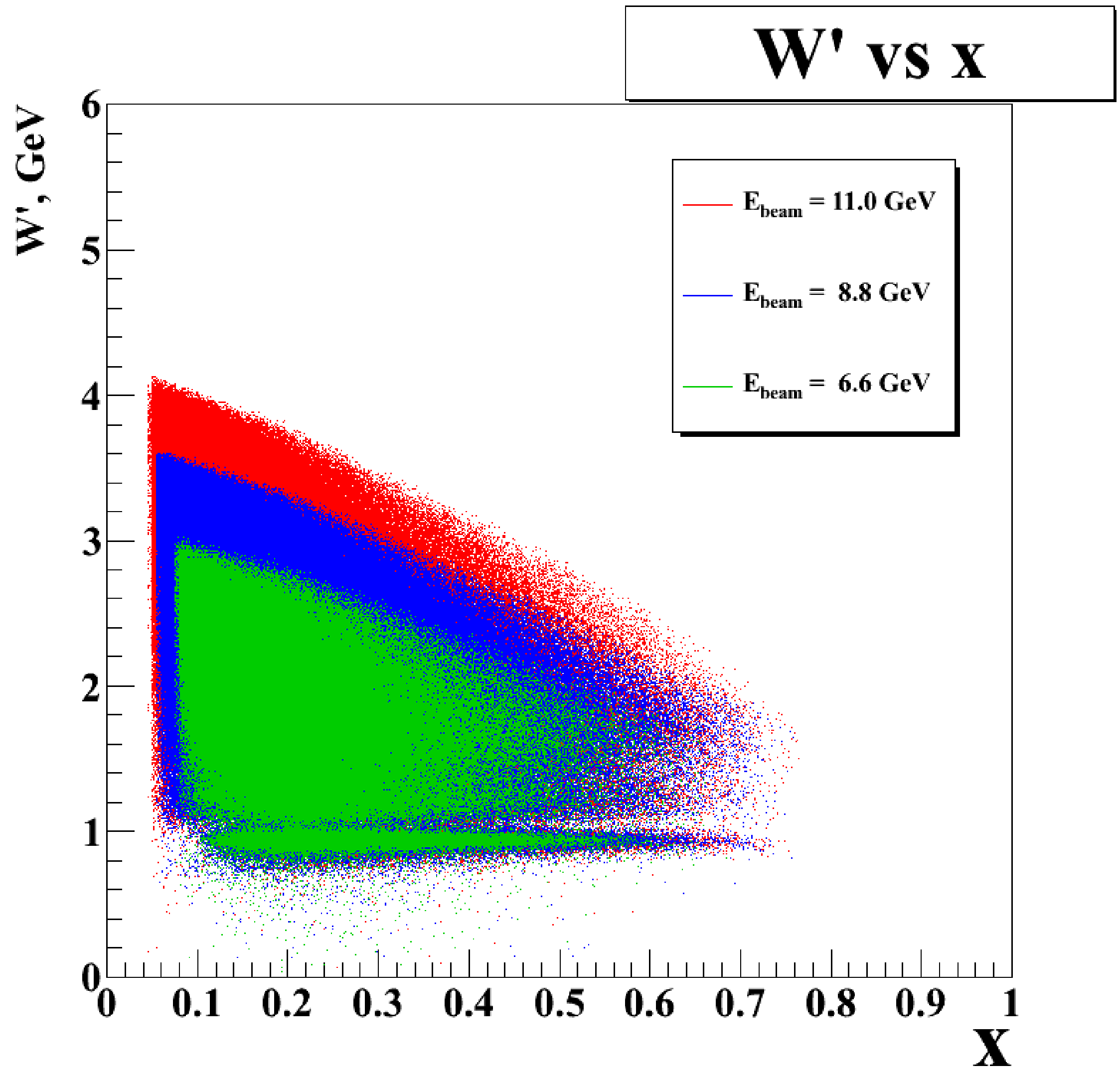

Figure 8: SIDIS phase space coverage of (W', x_{bj}), before W' and x_F cuts, for E_0=11, 8.8 and 6.6 GeV. The total number of events is not to scale. Standard inclusive DIS cuts $Q^2 > 1$ GeV^2, $W > 2$ GeV have been applied.

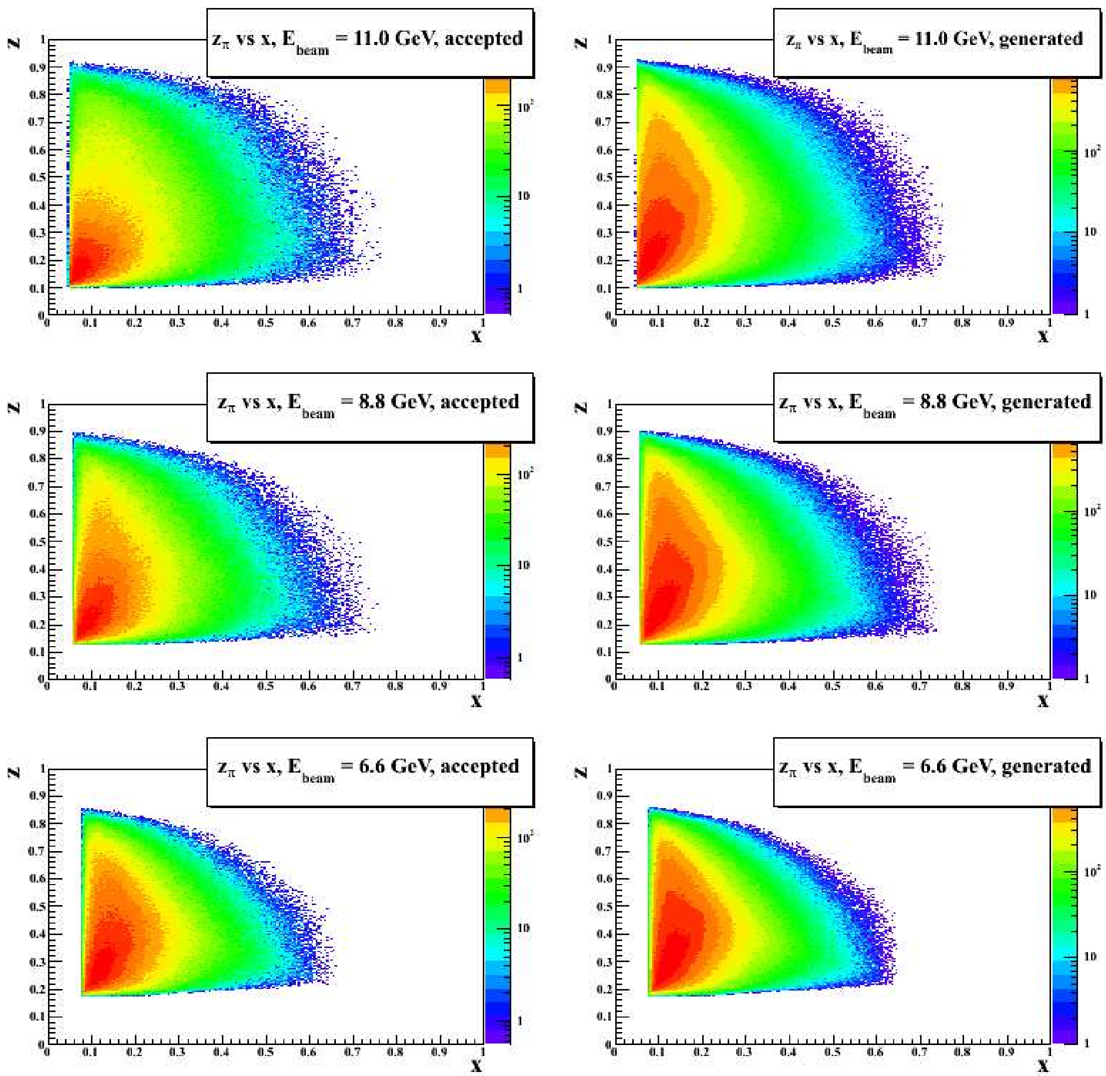

Figure 9: SIDIS phase space coverage of (z_π, x_{bj}) for E_0=11, 8.8 and 6.6 GeV, after applying W' and x_F cuts, for accepted events in the CLAS12 FASTMC (left) and generated events in the LEPTO-based Monte Carlo (right). The total number of events is not to scale.

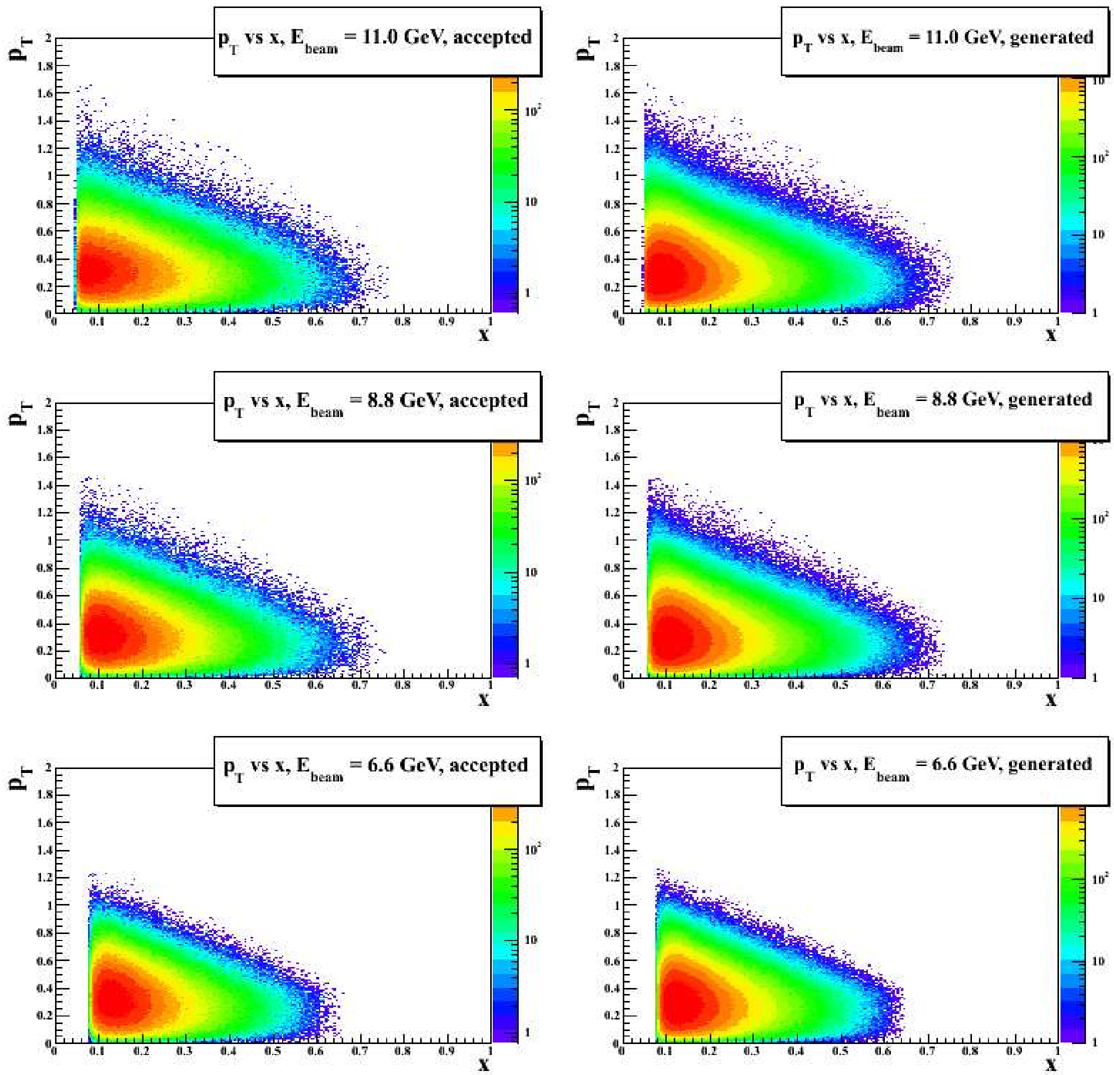

Figure 10: SIDIS phase space coverage of ($p_\perp^\pi$, x_{bj}) for E_0=11, 8.8 and 6.6 GeV, after applying W' and x_F cuts, for accepted events (left) and generated events (right).

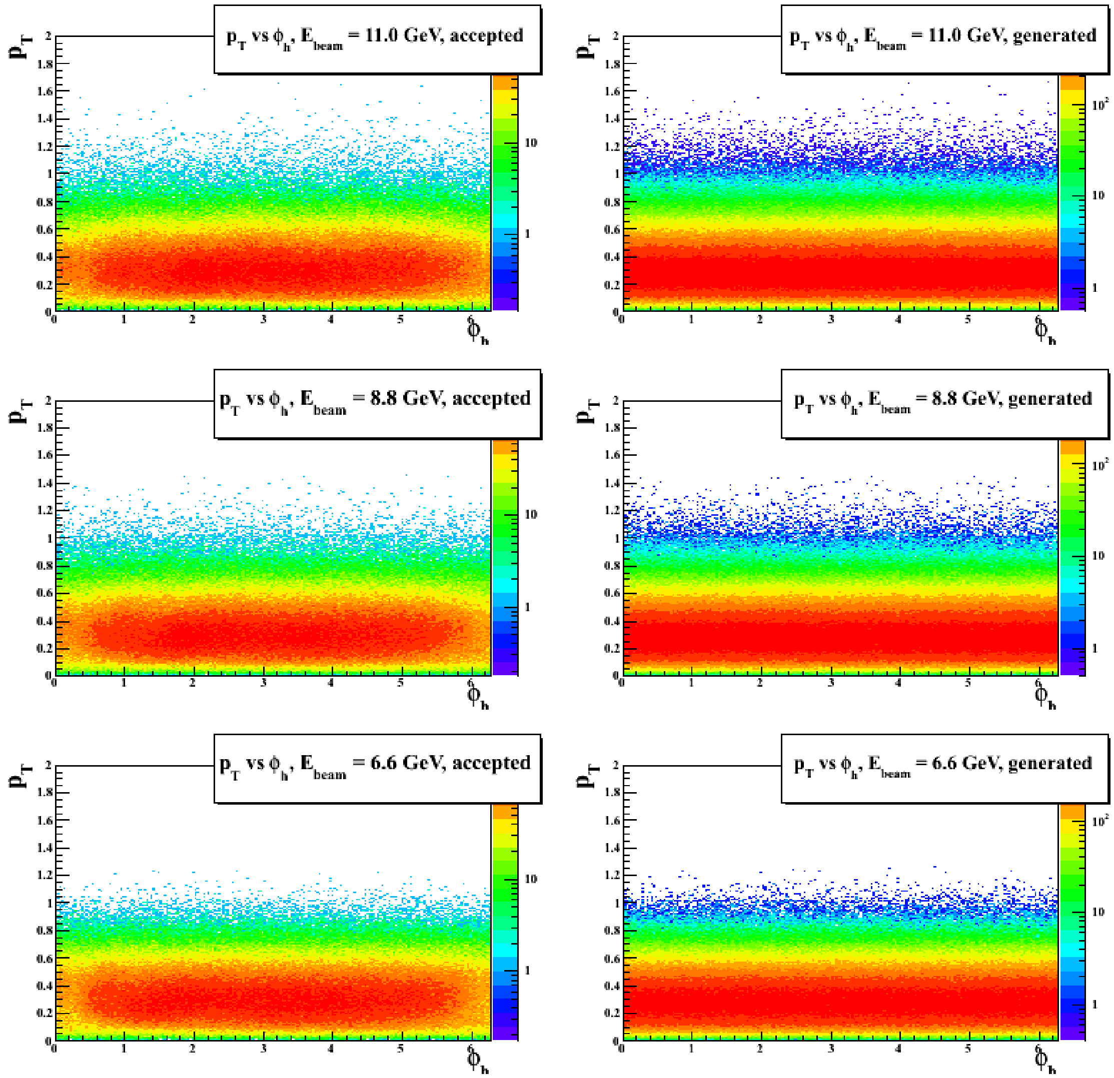

Figure 11: SIDIS phase space coverage of $(p_\perp^\pi,\ \phi_\pi)$ for E_0=11, 8.8 and 6.6 GeV, after applying W' and x_F cuts, for accepted (left) and generated (right) events.

4.4 Systematic uncertainties

Since SIDIS multiplicities are cross section ratios of coincidence vs inclusive channels, many common systematics, such as the luminosity and the acceptance and detection efficiency for the scattered electron, do not contribute to the systematics of multiplicities.

Major systematic uncertainties for hadron multiplicities :

Hadron phase space and integration:	$\pm 3.0\%$ relative
Hadron detection efficiency:	$\pm 3.0\%$ relative
Radiative corrections as in ratios:	$\pm 1.0\%$ relative

Total systematic uncertainty on hadron multiplicity: $\pm 4.0\%$ **relative**

For the determination of absolute cross sections, we assume additional $\pm 6\%$ combined systematic uncertainties from luminosity and normalization.

Systematic uncertainties for ratios r, r^+ and r^-:

Relative phase space difference:	$< 1.0\%$ relative
Relative hadron detection efficiency difference:	$< 1.0\%$ relative
Radiative correction difference:	$< 0.5\%$ relative

Total systematic uncertainty on multiplicity ratios r, r^+ and r^-: $< 1.5\%$ **relative**

4.5 Luminosity and beam time assumptions

Following the details outlined in the CLAS12 technical design report, we have assumed a nominal luminosity of 10^{35} cm^{-2}s^{-1} in our event rate estimation. The beam time allocations requested for this experiment are listed in Table 1. For the highest beam energy of 11 GeV, we assume 1000 hours of physics production running on both unpolarized liquid hydrogen and deuterium targets. These nominal 11 GeV production beam allocations will be shared between several physics programs including DVCS, deeply-virtual meson production, beam SSA in SIDIS, azimuthal asymmetries in SIDIS, and others using the same targets. These beam time allocations will not be driven by this proposal.

In addition, we assume a nominal 250 hours on both hydrogen and deuterium targets for beam energies of 8.8 and 6.6 GeV. Again, these beam time allocations will be driven by the needs of other low rate physics programs using the same targets. **All beam time allocations requested by this experiment can be shared with existing approved CLAS12 experiments, except for 250 hours each on an unpolarized deuterium target for beam energies of 8.8 and 6.6 GeV, as shown in table 1.**

	E_0=11 GeV	E_0=8.8 GeV	E_0=6.6 GeV
Beam on LH_2	1000 hours	250 hours	250 hours
Beam on LD_2	1000 hours	**250 hours**	**250 hours**

Table 1: Nominal beam time assumptions. Beam time requests in **bold** indicate new beam-time/target requests. All other beam time allocations can be shared with existing approved CLAS12 experiments.

5 Expected Results

The expected statistical accuracies from this experiment for a few selected kinematic bins are shown in this section, as examples, together with the predictions of the NLO QCD calculation [14]. In the examples in figures 12, 13, and 15, "$x = 0.2$" means the bin centered at 0.2 with a full width of $\Delta x = 0.05$. Similarly, "$Q^2 = 3.5$ GeV^2" means the bin centered at $Q^2 = 3.5$ GeV^2 with a full width of $\Delta Q^2 = 0.5$ GeV^2 and "$z = 0.5$" means the bin centered at 0.5 with a full width of $\Delta z = 0.1$.

5.1 SIDIS pion multiplicities and their z-dependencies

In Fig. 12, pion multiplicities off proton and deuteron targets for one Q^2 bin, $Q^2 = 3.5$ GeV^2, are shown as functions of z for four x-bins corresponding to $E_0 = 11$ GeV, with statistical uncertainties corresponding to 1,000 hours of CLAS12 running at the nominal luminosity of $10^{35} cm^{-2} s^{-1}$. The statistical uncertainties are smaller than the symbol sizes when plotted on the same vertical scale as the expected multiplicities, which are strongly z-dependent. The decreases along z are caused by the z-dependence of fragmentation functions. The changes between different x-bins are small but noticeable. The differences between π^- and π^+ multiplicities become smaller in the deuteron target compared to the proton target, an effect caused by averaging of u and d-quark contributions. π^0 production, which ends up exactly in the middle of π^- and π^+ for both targets, can be used to check the assumption of isospin symmetry and charge conjugation.

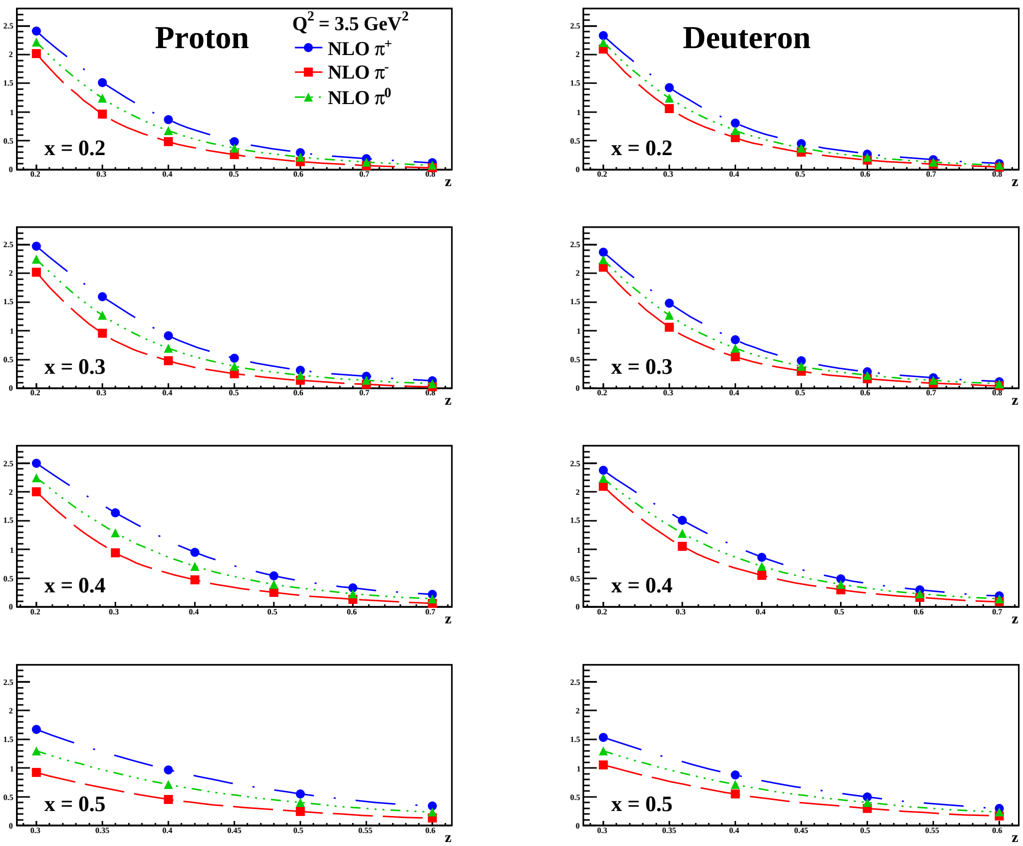

Figure 12: One example of the z-dependence of pion multiplicities for bin $Q^2 = 3.5$ GeV^2, E_0=11 GeV, with projected statistical uncertainties corresponding to the full beamtime request. Statistical error bars are smaller than the symbol size.

5.2 Q^2 dependence of pion multiplicities

In Fig. 13, pion multiplicities off proton and deuteron targets for one z-bin, $z = 0.5$, are shown as functions of Q^2 for four x-bins corresponding to $E_0 = 11$ GeV. The Q^2-dependences, which can be clearly identified by this experiment, are a clear feature of the NLO QCD effect caused by the evolution of PDFs and fragmentation functions. Zooming into one of the panels on Fig. 13, we show the $x = 0.4$ bin in Fig. 14 with data points from $E_0 = 11, 8.8$ and 6.6 GeV. Data from the overlapping region at the same x, z and Q^2 will be extremely powerful in identifying effects beyond the NLO contributions, thus quantifying the "unexplained" parts of the SIDIS cross sections at JLab kinematics. Additionally, the data in the overlapping Q^2 region will provide data on the ϵ-dependence of the SIDIS multiplicities, providing a rough check (but not necessarily a precise measurement) of the ratio $R = \sigma_L/\sigma_T$ in SIDIS and limiting the possible systematic uncertainty and/or complication of the physical interpretation of the data arising from our (lack of) knowledge of R. Even a rough determination of R in the large kinematic range accessible to CLAS12 would be an important complement to the approved Hall C experiment E12-06-104, which will perform much more precise L/T separation measurements in SIDIS, albeit in a more limited kinematic range.

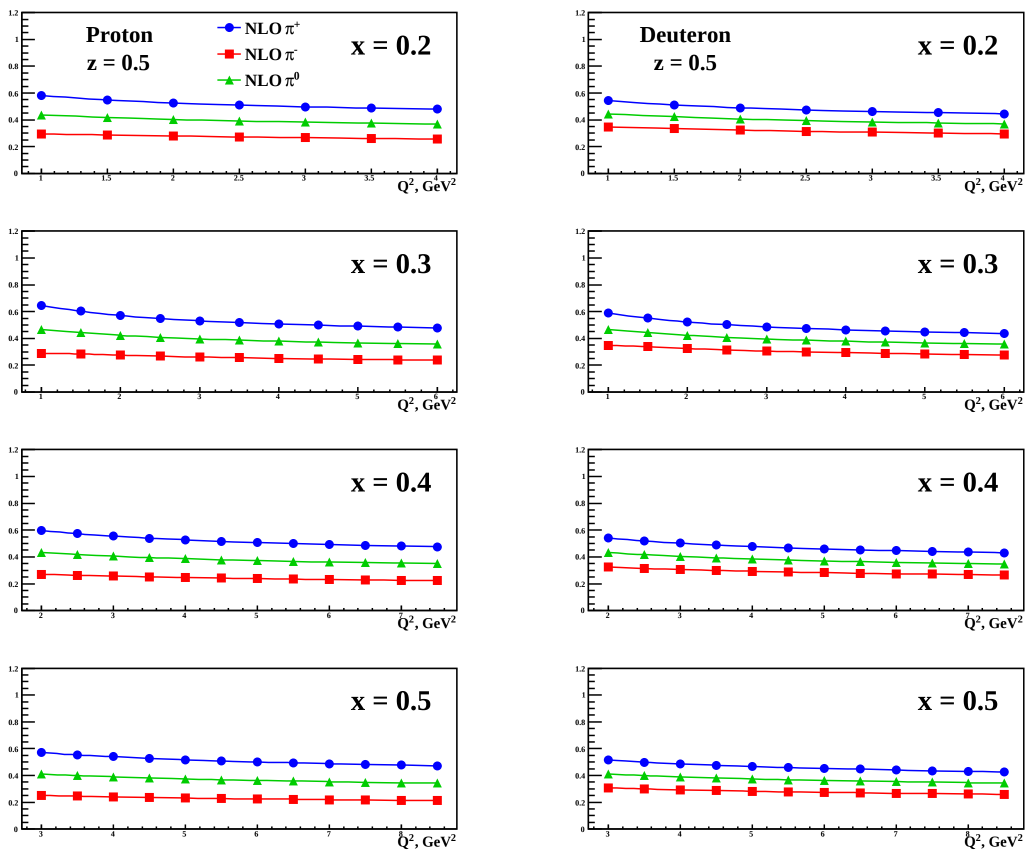

Figure 13: One example of Q^2 dependence of pion multiplicities for bin $z = 0.5$, E_0=11 GeV for the full integrated luminosity of this proposal. Error bars are smaller than the symbol size for most bins.

5.3 Ratios of combined charged pion multiplicities

Although the multiplicities of each hadron species are strongly z-dependent, the combined ratios r^+ and r^- of proton over deuteron are almost z-independent and

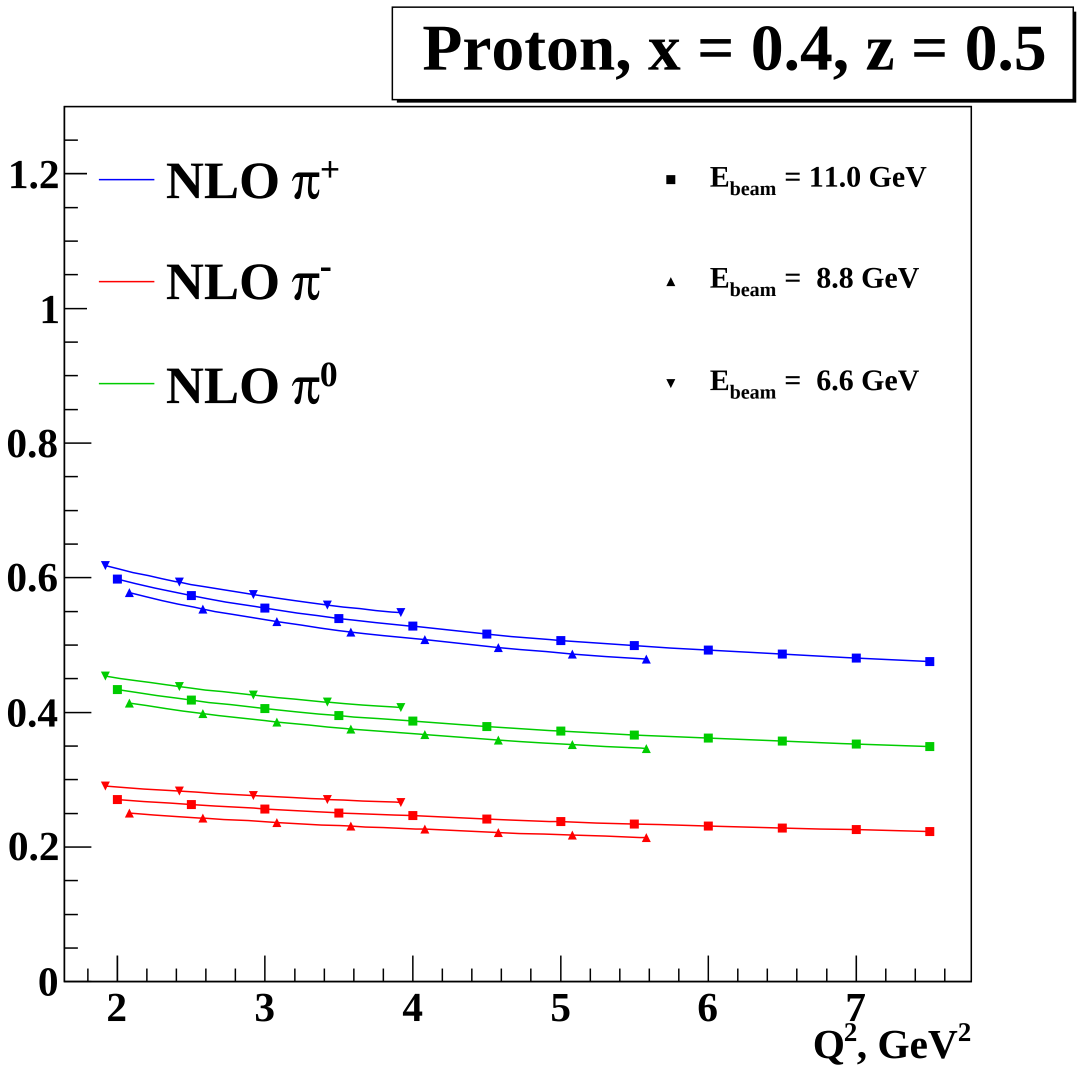

Figure 14: A zoomed-in view of the Q^2 dependence of pion multiplicities for bin $z = 0.5$ and $x = 0.4$, for E_0=11, 8.8 and 6.6 GeV, with uncertainties corresponding to the proposed integrated luminosities. The data points from the two lower beam energies are displayed with artificial offsets in Q^2 and in multiplicity from the NLO prediction for ease of viewing, and do not reflect any assumptions concerning the value of σ_L/σ_T.

only depend on PDFs. As shown in the solid lines in Fig. 15, this unique feature reflects the fact that the NLO terms, although not negligible, follow a common scaling trend such that their effects are mostly canceled in the ratios. As demonstrated by JLab Hall C data [10] in Fig. 2, at a very moderate beam energy of 5.5 GeV, scaling in the ratios r^+ and r^- appears to be rather obvious. With high statistics, this experiment will measure r^+ and r^- as functions of z in many bins of x and Q^2. The remaining z-dependence will again quantitatively define the remaining "unexplained" parts of the SIDIS cross sections beyond the next-to-leading order, leading twist pQCD picture, including possible higher-twist contributions. Figure 16 shows a zoomed-in view of the z dependence of the combined ratio r^+ predicted by the NLO fit[14] together with projected statistical uncertainties for an example bin centered at $Q^2 = 3.5$ GeV^2, $x = 0.3$.

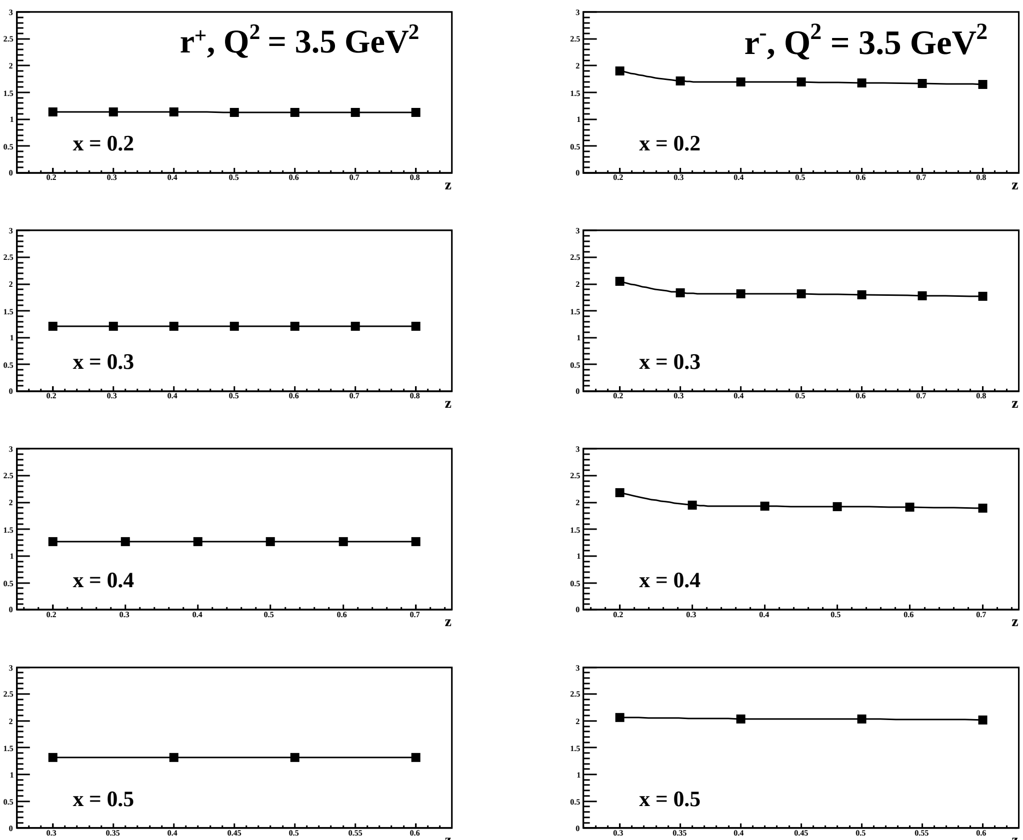

Figure 15: One example of the z-dependence of ratios of combined charged-pion multiplicities for bin $Q^2 = 3.5$ GeV^2, for E_0=11 GeV, with projected uncertainties corresponding to the proposed integrated luminosity.

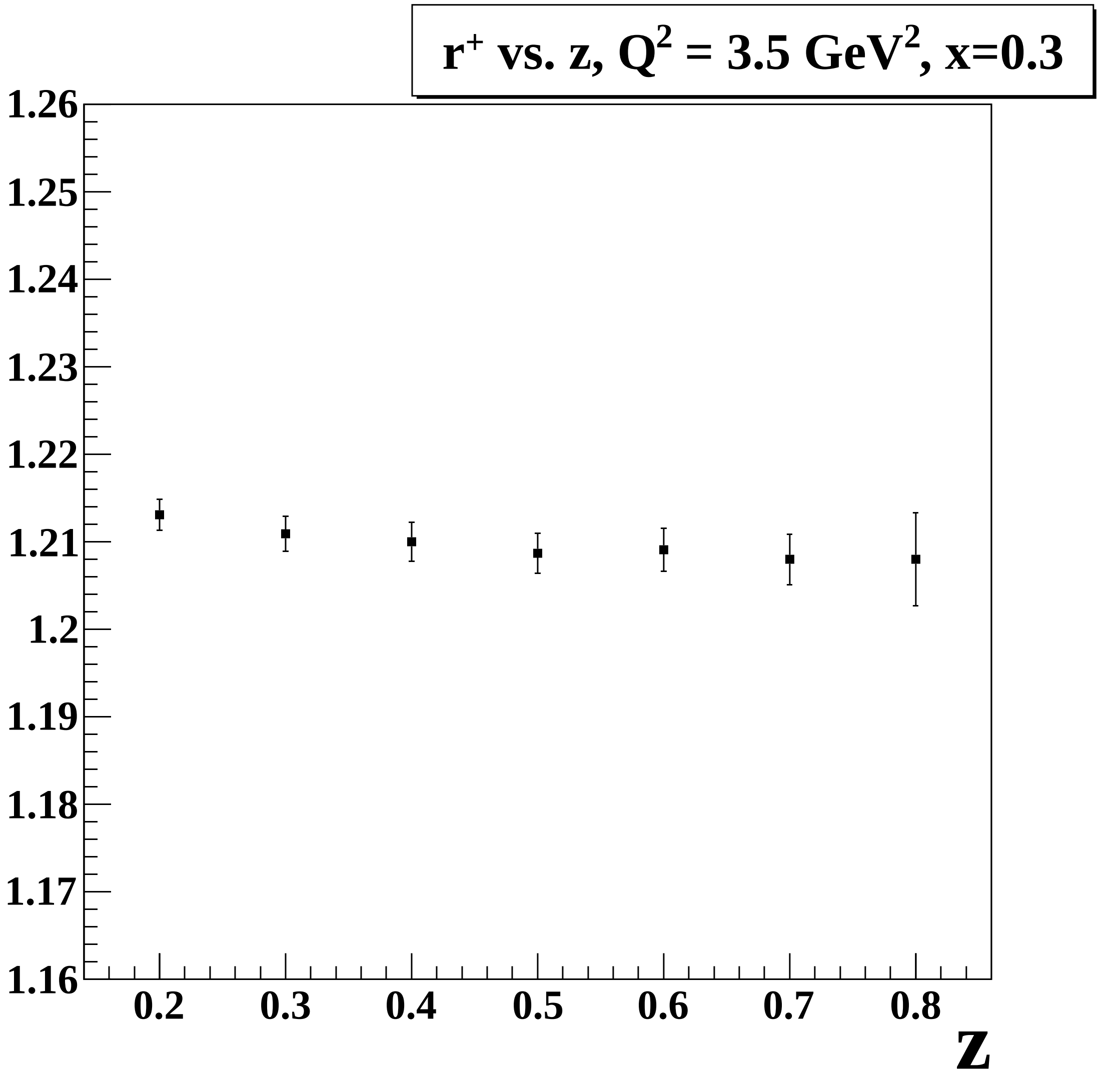

Figure 16: Zoomed-in example of z dependence of the ratio r^+ for $Q^2 = 3.5$ GeV^2, $x = 0.3$, with projected statistical errors for the proposed integrated luminosity. The typical statistical uncertainty for the combined ratios is $\approx \pm 0.2\%$ (relative).

Additional remark on statistical uncertainties and beam time request Considering the small statistical uncertainties shown in e.g. figure 15, many kinematic bins will be systematics-dominated given the full beam time request and the chosen granularity of the bins, suggesting the use of a finer binning, particularly in z, and a certain degree of flexibility in the amount of beam time needed to achieve the goals of the experiment. As a typical example, the relative statistical uncertainty in the combined ratio r^+ for the bin centered at $x = 0.3$, $Q^2 = 3.5$ GeV^2, and $z = 0.5$ for 1,000 hours of 11 GeV beam is $\frac{\Delta r^+}{r^+} \approx 0.2\%$. If the kinematic bins are instead chosen to be a factor of two smaller in x, Q^2 and z, reducing the statistics per bin by roughly a factor of eight, then this uncertainty would increase to $\approx 0.6\%$, which is competitive with the assumed systematic uncertainty for the combined ratio of multiplicities. On the other hand, since the SIDIS pion production rates drop for large x, Q^2, and z, many other bins will have comparable statistical and systematic uncertainties even given the full beam time request. Additionally, since the integration over the transverse momentum and azimuthal angle requires one to correct for the experimental acceptance, which is a complicated function of ϕ_h and $P_{h\perp}$ in addition to (x, Q^2, z), a reasonable statistical precision on the data binned in five dimensions $(x, Q^2, z, P_{h\perp}, \phi_h)$ will be helpful to keep systematic uncertainties associated with the integration over these variables at an acceptable level. Finally, while this proposal focuses on hadron multiplicities, which are integrated over ϕ_h and p_T, and their relative relations, related proposals using the same beam energy, target, and detector to study the azimuthal and transverse-momentum dependence of the unpolarized SIDIS reaction, and to extend the measurements beyond pions to include kaons, lack similar flexibility in beam time requirements to achieve the desired statistical precision and will require, at a minimum, beam allocations comparable to the nominal requests of this proposal.

In addition to the large number of already approved proposals to use the CLAS12 baseline equipment with unpolarized proton/deuterium targets with 11 GeV beam, the approved experiment E12-06-108 to measure L/T separated cross sections for exclusive π^0 and η production uses the two lower beam energies of this proposal on an unpolarized proton target. Therefore, the only *new* beamtime requested for the proposed experiment that has not already been approved is for 250 hours on an unpolarized deuterium target for each of the two lower beam energies.

6 Relation with other experiments

6.1 An overall strategy of SIDIS for JLab-12 GeV

In the final PAC34 report, an overall strategy of the SIDIS physics program for JLab-12 GeV was outlined. Each of halls A/B/C has the capability of carrying out SIDIS measurements. Here we summarize each hall's specific advantages:

- Hall A: High luminosity hall for large installation experiments(10^{38} cm^{-2}s^{-1}).

Large installation experiments beyond the 12 GeV baseline equipment will be carried out. Such experiments provide flexibility in spectrometer/detector and target arrangements and allow for high luminosities such as BigBite+Super BigBite, and the Large Solenoid Detector (SoLID). SIDIS measurements can be performed for example with an unpolarized Tritium target, a high density and high polarization ^{3}He target, longitudinal and transversely polarized proton and deuteron targets (NH_3, ND_3, etc.), with well focused kinematic coverage, especially in p_t and ϕ.

- Hall B with CLAS12. Large acceptance hall to run at a somewhat lower luminosity (10^{35} cm^{-2}s^{-1}).
  Large acceptance experiments will form the core of the SIDIS program, as PAC34 pointed out. CLAS12 is ideally suited for a more complete p_T and ϕ coverage, and large kinematic coverage. One can integrate over p_T and ϕ, and/or carry out detailed studies of p_T and ϕ dependence. With CLAS12, one can study detailed multi-dimensional variations of the properties of the SIDIS reaction. CLAS12 will easily accommodate longitudinally polarized targets, and can also accommodate transversely polarized targets given carefully designed shielding to reduce background rates.

- Hall C. High luminosity hall with a pair of high resolution magnetic spectrometers. Although the HMS-SHMS system can not cover the full range of p_T and ϕ simultaneously, with well defined, well focused kinematic coverage Hall C is the ideal laboratory for absolute cross section measurements (at low-p_T, for example). With well controlled systematic uncertainties, Hall C is perfect for Rosenbluth separation type experiments, such as $R = \sigma_L/\sigma_T$ in SIDIS to access higher-order and higher-twist parts of the SIDIS cross section.

6.2 The merit of this proposal within JLab's SIDIS program

With the large acceptance CLAS12 detector, this experiment will cover a broad range of SIDIS kinematics, allowing the NLO global fragmentation function fit to run its maximal course for the JLab 12 GeV SIDIS program. Specifically, we highlight the merit of this proposal within the framework of JLab 12GeV's SIDIS physics program:

- The capability to study Q^2 dependence with other kinematic variables fixed.

- The capability to vary x and z independently, at fixed Q^2.

- Full p_T coverage up to the maximum allowed at JLab12 GeV, allowing integration over p_T while minimizing model dependence due to extrapolation in p_T.

- The ability to cover a full range in ϕ, allowing detailed studies of the ϕ-dependence of both the CLAS12 acceptance and the fundamental cross sections, minimizing model-dependence of the integration over ϕ in the extraction of hadron multiplicities for fragmentation function analysis.

As PAC34 suggested, broad-based studies of the SIDIS reaction mechanism covering a large kinematic acceptance, including the proposed experiment, will provide much needed guidance for future high precision measurements with small-acceptance spectrometers, when the results are provided in a timely fashion.

7 Summary

This experiment will help answer the following questions: How well do we understand the fundamental cross sections in SIDIS at JLab-12 GeV, and what fraction of the cross section remains unexplained beyond the NLO pQCD, leading-twist collinear picture?

The success of this experiment will determine whether the onset of “naive” x-z factorization in the SIDIS reaction occurs at the moderate beam energies and finite values of Q^2 in JLab-12 GeV kinematics and provide precise data as input to the next generation of NLO global analysis of fragmentation functions.

8 Acknowledgment

We thank D. de Florian, R. Sassot and M. Stratmann for providing their NLO calculations.

9 Appendix-A. PAC-32 report on LOI12-07-103

Individual Proposal Report

Proposal: LOI12-07-103

Title: A Detailed Study of Semi-Inclusive Deep-Inelastic Pion Productions on Unpolarized Proton and Deuteron Targets with the CLAS12 Detector.

Spokespersons: X. Jiang and H. Lu

Motivation: The authors propose a detailed study of event multiplicity, azimuthal angle and transverse momentum dependence of semi-inclusive pion production with 11 GeV (and 8.8, 6.6 GeV) electron beam scattering off unpolarized proton and deuteron targets using the large acceptance CLAS12 detector. Measurements will span a dense three-dimensional grid of x, Q^2 and z and a wide p_T range. These survey data will be inputs to the next generation NLO global analysis of the polarized and unpolarized SIDIS as well as e^+e^- and pp data, to constrain the parton fragmentation functions, densities and helicity distributions. The proposed study will thus be of great importance for understanding the (deep) inelastic electroproduction and will belong to the mainstream of the scientific program of the Laboratory.

Measurement and Feasibility: This experiment will be entirely parasitic to any physics program involving CLAS12. However extracting the interesting events from the collected data as well as their analysis will be a major effort for which a large group with clearly defined commitments will be necessary.

Issues: The submitted document does not meet the criteria of a standard letter-of-intent. It lacks details of the experiment and simulation, data analysis, expected uncertainties as well as discussion of the relation of this experiment to other experiments and detailed information concerning the analysis commitments of the group.

Recommendation: In spite of the drawbacks listed above, the committee recognizes the fundamental value of the proposed study and encourages the proponents to submit a full proposal.

References

1. M. Wlasenko (H1 and ZEUS collaborations), Nucl. Phys. A **827**, 276c (2009).
2. L. L. Frankfurt, M. I. Strikman, L. Mankiewicz, A. Schafer, E. Rondio, A. Sandacz and V. Papavassiliou, Phys. Lett. B **230**, 141 (1989); F. E. Close and R. G. Milner, Phys. Rev. D **44**, 3691 (1991).
3. X. D. Ji, J. P. Ma and F. Yuan, Phys. Rev. D **71**, 034005 (2005),
4. Xiangdong Ji, Jian-Ping Ma and Feng Yuan, Phys. Lett. B **597**, 299 (2004).
5. The Spin Muon Collaboration, *Phys. Lett.* B **420**, 180 (1998).
6. The COMPASS Collaboration, Sept. 2009. arXiv:0909.3729.
7. HERMES collaboration, *Phys. Rev. Lett.* **92**, 012005 (2004), and *Phys. Rev.* D **71**, 012003 (2005).
8. A. Airapetian *et al.*, Phys. Rev. Lett. **94**, 012002 (2005).
9. V. Y. Alexakhin *et al.*, Phys. Rev. Lett. **94**, 202002 (2005).
10. T. Navasardyan, *et al. Phys. Rev. Lett.* **98**, 022001 (2007)
11. P. Mulders and R. D. Tangerman *Nucl. Phys.* B **461**, 197 (1996)
12. D. de Florian and R. Sassot, *Phys. Rev.* D **62**, 094025 (2000), and D. de Florian, O. A. Sampayo and R. Sassot, *Phys. Rev.* D **57**, 5803 (1998)
13. D. de Florian, G. A. Navarro and R. Sassot, *Phys. Rev.* D **71**, 094018 (2005).
14. D. de Florian, R. Sassot and M. Stratmann, *Phys. Rev.* D **75**, 114010 (2007), *Phys. Rev.* D **76**, 074033 (2007) and private communications.
15. A. Accardi, T. Hobbs and W. Melnitchouk. arXie:0907.2395.
16. D. Graudenz, *Nucl. Phys.* B **432**, 351 (1994).
17. D. de Florian, C. A. Garcia Canal, R. Sassot, *Nucl. Phys.* B **470**, 195 (1996).
18. Marco Stratmann and Werner Vogelsang, *Phys. Rev.* D **64**, 114007 (2001)
19. K. Joo *et al.*, Phys. Rev. Lett. **88**, 122001 (2002).
20. S. Kretzer, Phys. Rev. D **62**, 054001 (2000).
21. B. A. Kniehl, G. Kramer, and B. Potter, *Nucl. Phys.* B **582**, 514 (2000).
22. L. Elouadrhiri *et al.*, "An overview of the CLAS12 spectrometer", 2006.
23. Lai, H.L. *et al.*, *Eur. Phys. J.* **C12**, 375 (2000).
24. Ingelman, G. and Edin, A. and Rathsman, J., Computer Physics Communications, **101**, 108 (1997).