Jefferson Lab PAC 44 Run-Group Proposal

The Transverse Nucleon, Single-Spin Asymmetry in Exclusive Pion Electroproduction

DRAFT v0.1: April 18, 2016

SoLID Collaboration

We propose to measure the transverse nucleon, single-spin asymmetry $A_{UT}^{sin(\phi-\phi_s)}$ in the exclusive pion production $\vec{n}(e, e'\pi^-)p$ reaction, during the transversely polarized ^{3}He target SIDIS experiment with SoLID. This polarization observable has been noted as being sensitive to the spin-flip generalized parton distribution (GPD) $\tilde{E}$, and factorization studies have indicated that precocious scaling is likely to set in at moderate $Q^2 \sim 2-4$ GeV^2, as opposed to the absolute cross section, where scaling is not expected until $Q^2 > 10$ GeV^2. Furthermore, this observable has been noted as being important for the reliable extraction of the charged pion form factor from pion electroproduction. The asymmetry data are projected to be of much higher quality than a pioneering measurement by HERMES [**?**].

This measurement is complementary to a proposal reviewed by PAC39 [**?**] for the SHMS+HMS in Hall C. The asymmetry that is most sensitive to $\tilde{E}$ is the longitudinal photon, transverse nucleon, single-spin asymmetry $A_L^{\perp}$ in exclusive charged pion electroproduction. The SHMS+HMS allow the L–T separation needed to reliably measure this quantity. However, the limited detector acceptance and the error-magnification inherent in an L–T separation necessitates the use of a next generation, externally polarized, continuous flow, high luminosity ^{3}He target based on a large volume polarizer and compressor being developed at the University of New Hampshire.

A wide $-t$ coverage is needed to obtain a good understanding of the asymmetry. Thus, it has always been intended to complement the SHMS+HMS $A_L^{\perp}$ measurement with an unseparated $A_{UT}^{sin(\phi-\phi_s)}$ measurement using a large solid angle detector. The high luminosity capabilities of SoLID make it well-suited for this measurement. Since an L–T separation is not possible with SoLID, the observed asymmetry is expected to be diluted by the ratio of the longitudinal cross section to the unseparated cross section. This was also true for the pioneering HERMES measurements, which provided a valuable constraint to models for the $\tilde{E}$ GPD.

I. SCIENTIFIC JUSTIFICATION

GH: This section is closely based on the Hall C proposal PR12-12-005. Suggestions for modification are welcome!

A. Generalized Parton Distributions and Contribution from the Pion Pole

In recent years, much progress has been made in the theory of generalized parton distributions (GPDs). Unifying the concepts of parton distributions and of hadronic form factors, they contain a wealth of information about how quarks and gluons make up hadrons. The key difference between the usual parton distributions and their generalized counterparts can be seen by representing them in terms of the quark and gluon wavefunctions of the hadron. While the usual parton distributions are obtained from the squared hadron wavefunction representing the probability to find a parton with specified polarization and longitudinal momentum fraction x in the fast moving hadron (Fig. 1a), GPDs represent the interference of different wavefunctions, one where the parton has momentum fraction $x + \xi$ and one where this fraction is $x - \xi$ (Fig. 1b). GPDs thus correlate different parton configurations in the hadron at the quantum mechanical level. A special kinematic regime is probed in deep exclusive meson production, where the initial hadron emits a quark-antiquark or gluon pair (Fig. 1c). This has no counterpart in the usual parton distributions and carries information about $q\bar{q}$ and gg-components in the hadron wavefunction.

Apart from the momentum fraction variables x and ξ, GPDs depend on the four momentum transfer t. This is an independent variable, because the momenta p and p' may differ in either their longitudinal or transverse components. GPDs thus interrelate the longitudinal and transverse momentum structure of partons within a fast moving hadron.

In order to access the physics contained within GPDs, one is restricted to the hard scattering regime. An important feature of hard scattering reactions is the possibility to separate clearly the perturbative and nonperturbative stages of the interaction. Qualitatively speaking, the presence of a hard probe allows one to create small size quark-antiquark and gluon configurations, whose interactions are described by perturbative QCD (pQCD). The non-perturbative stage of the reaction describes how the hadron reacts to this configuration, or how this probe is transformed into hadrons. This separation is the so-called factorization

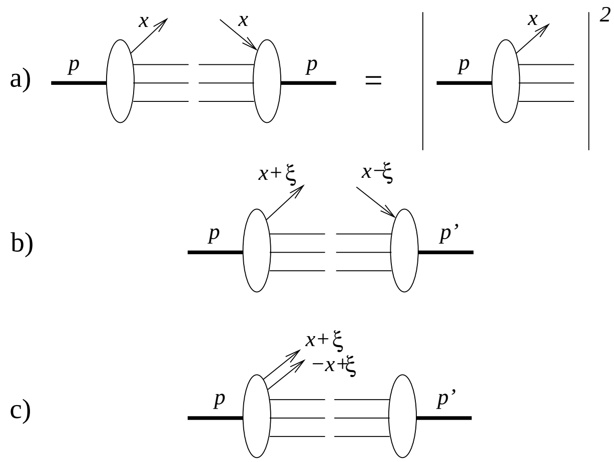

FIG. 1: (a) Usual parton distribution, representing the probability to find a parton with momentum fraction x in the nucleon. (b) GPD in the region where it represents the emission of a parton with momentum fraction $x + \xi$ and its reabsorption with momentum fraction $x - \xi$. (c) GPD in the region where it represents the emission of a quark-antiquark pair, and has no counterpart in the usual parton distributions. This figure has been adapted from Ref. [**?**].

property of hard reactions. Deep Exclusive Meson electro-Production (DEMP) was first shown to be factorizable in Ref. [**?**]. This factorization applies when the virtual photon is longitudinally polarized, which is more probable to produce a small size configuration compared to a transversely polarized photon.

GPDs are universal quantities and reflect the structure of the nucleon independently of the reaction which probes the nucleon. At leading twist-2 level, the nucleon structure information can be parameterized in terms of four quark chirality conserving GPDs, denoted H, E, $\tilde{H}$ and $\tilde{E}$. H and E are summed over quark helicity, while $\tilde{H}$ and $\tilde{E}$ involve the difference between left and right handed quarks. H and $\tilde{H}$ conserve the helicity of the proton, while E and $\tilde{E}$ allow for the possibility that the proton helicity is flipped. Because quark helicity is conserved in the hard scattering regime, the produced meson acts as a helicity filter. In particular, leading order QCD predicts that vector meson production is sensitive only to the unpolarized GPDs, H and E, whereas pseudoscalar meson production is sensitive only to the polarized GPDs, $\tilde{H}$ and $\tilde{E}$. In contrast, deeply virtual Compton scattering (DVCS) depends at the same time on both the polarized ($\tilde{H}$ and $\tilde{E}$) and the unpolarized (H and E) GPDs. This makes DEMP reactions complementary to the DVCS process, as it provides an additional tool to disentangle the different GPDs [**?**].

Besides coinciding with the parton distributions at vanishing momentum transfer ξ, the GPDs have interesting links with other nucleon structure quantities. Their first moments are related to the elastic form factors of the nucleon through model-independent sum rules [?]:

$$\sum_q e_q \int_{-1}^{+1} dx H^q(x,\xi,t) = F_1(t), \tag{1}$$

$$\sum_q e_q \int_{-1}^{+1} dx E^q(x,\xi,t) = F_2(t), \tag{2}$$

$$\sum_q e_q \int_{-1}^{+1} dx \tilde{H}^q(x,\xi,t) = G_A(t), \tag{3}$$

$$\sum_q e_q \int_{-1}^{+1} dx \tilde{E}^q(x,\xi,t) = G_P(t), \tag{4}$$

where e_q is the charge of the relevant quark, $F_1(t)$, $F_2(t)$ are the Dirac and Pauli elastic nucleon form factors, and $G_A(t)$, $G_P(t)$ are the isovector axial and pseudoscalar nucleon form factors. The t-dependence of $G_A(t)$ is poorly known, and although $G_P(t)$ is an important quantity, it remains highly uncertain because it is negligible at the momentum transfer of β-decay[?]. Because of partial conservation of the axial current (PCAC), $G_P(t)$ alone receives contributions from $J^{PG} = 0^{--}$ states[?], which are the quantum numbers of the pion, and so $\tilde{E}$ contains an important pion pole contribution (Fig. 2a).

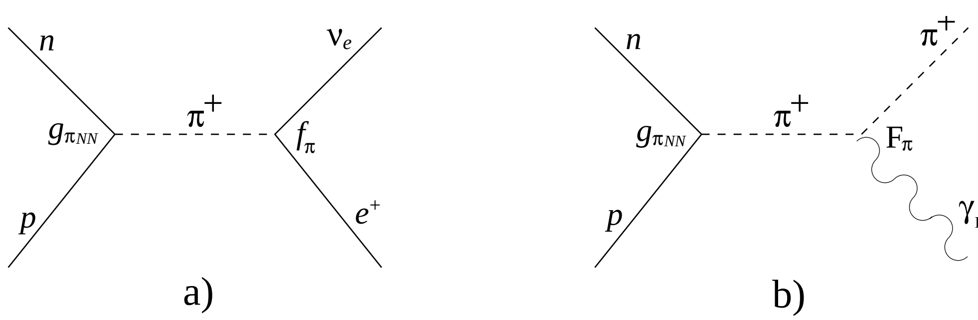

FIG. 2: (a) Pion pole contribution to $G_P(t)$, and hence to $\tilde{E}$. (b) Pion pole contribution to meson electroproduction at low $-t$.

Accordingly, Refs. [? ?] have adopted the pion pole-dominated ansatz

$$\tilde{E}^{ud}(x,\xi,t) = F_\pi(t) \frac{\theta(\xi > |x|)}{2\xi} \phi_\pi(\frac{x+\xi}{2\xi}), \tag{5}$$

where $F_\pi(t)$ is the pion electromagnetic form factor, and ϕ_π is the pion distribution amplitude.

$\tilde{E}$ cannot be related to already known parton distributions, and so experimental information about $\tilde{E}$ via DEMP can provide new information on nucleon structure which is unlikely to be available from any other source.

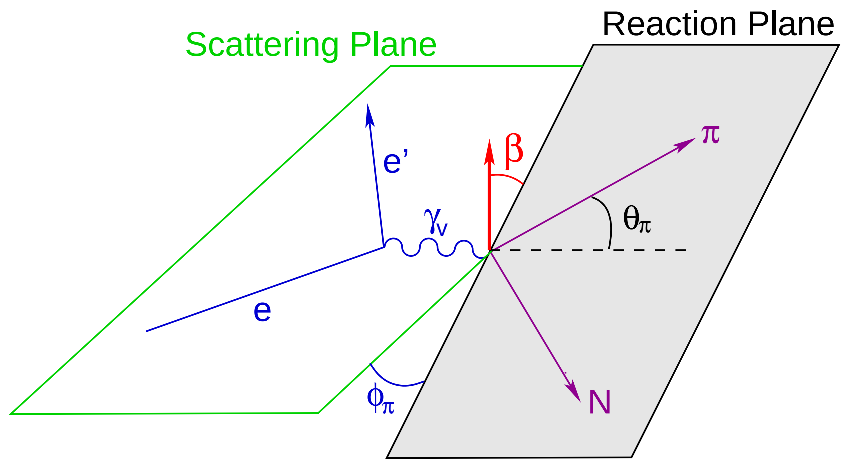

FIG. 3: Scattering and hadronic reaction planes for exclusive $\vec{N}(e, e'\pi)N'$. β is the angle between the target nucleon polarization vector and the reaction plane. Some works alternatively label this angle as $(\phi - \phi_s)$.

B. Single spin asymmetry in exclusive pion electroproduction

Frankfurt et al. [**?**] have considered a specific polarization observable which is the most sensitive observable to probe the spin-flip $\tilde{E}$. This variable is the single-spin asymmetry for exclusive charged pion production, $\vec{p}(e, e'\pi^+)n$ or $\vec{n}(e, e'\pi^-)p$, from a transversely polarized nucleon target, and is defined [**?**] as

$$A_L^{\perp} = (\int_0^{\pi} d\beta \frac{d\sigma_L^{\pi}}{d\beta} - \int_{\pi}^{2\pi} d\beta \frac{d\sigma_L^{\pi}}{d\beta})(\int_0^{2\pi} d\beta \frac{d\sigma_L^{\pi}}{d\beta})^{-1}, \tag{6}$$

where $d\sigma_L^{\pi}$ is the exclusive charged pion electroproduction cross section using longitudinally polarized photons and β is the angle between the nucleon polarization vector and the reaction plane (Fig. **??**). Frankfurt et al. [**?**] have shown that this asymmetry must vanish if $\tilde{E}$ is zero. If $\tilde{E}$ is not zero, the asymmetry will display a sinβ dependence. Their predicted asymmetry using the $\tilde{E}$ ansatz from Ref. [**?**] is shown in Fig. **??**. This calculation is Q^2-independent, depending only on how well the soft contributions cancel in the asymmetry.

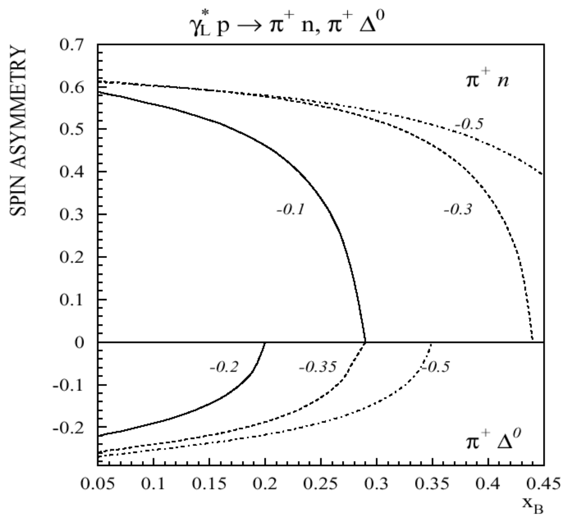

FIG. 4: Transverse single-spin asymmetry for the longitudinal electroproduction of $\pi^+ n$ and $\pi^+\Delta^0$ at different values of t [indicated on the curves in GeV^2]. The asymmetry drops to zero at the parallel kinematic limit, which is different for each t value, because the definition of β is ill-defined at this point. This figure is taken from Ref. [**?**].

It seems likely that a precocious factorization of the meson production amplitude into three parts – the overlap integral between the photon and pion wave functions, the hard interaction, and the GPD – will lead to a precocious scaling of $A_L^\perp$ as a function of Q^2 at moderate $Q^2 \sim 2-4$ GeV^2 [**?**]. This precocious scaling arises from the fact that higher order corrections, which are expected to be significant at low Q^2, will likely cancel when one examines the ratio of two longitudinal observables. In contrast, the onset of scaling for the absolute cross section is only expected for much larger values of $Q^2 > 10$ GeV^2.

This point is made clear in Fig. **??**. This figure shows renormalon model calculations [**?**] of both the asymmetry and the longitudinal cross section at $Q^2 = 4$ GeV^2. While the magnitude of the cross section changes significantly when taking into account the twist-four corrections, $A_L^\perp$ is essentially insensitive to them and displays the expected precocious scaling. The relatively low value of Q^2 for the expected onset of precocious scaling is important, because it will be experimentally accessible after the Jefferson Lab 12 GeV upgrade. This places $A_L^\perp$ among the most important GPD measurements that can be made in the meson scalar. If precocious scaling cannot be experimentally demonstrated in this ratio of two cross sections, then it may not be possible to determine GPDs from DEMP data.

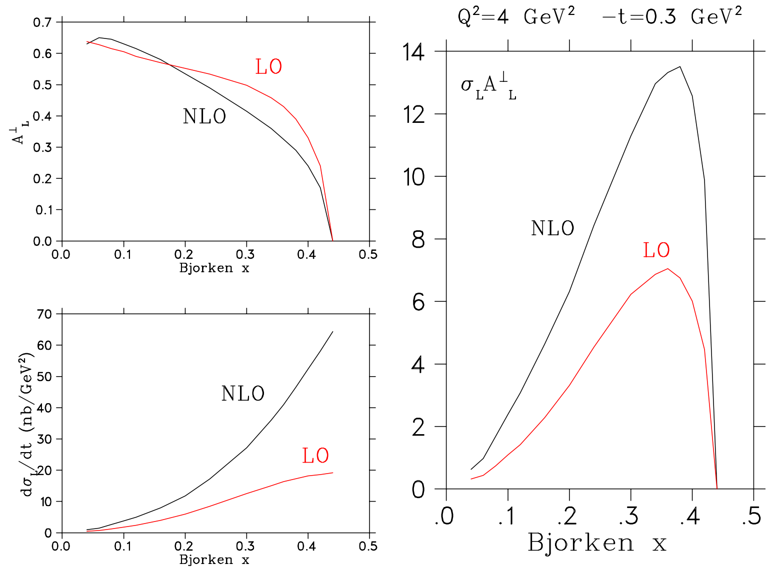

FIG. 5: Calculation of the longitudinal photon transverse nucleon spin asymmetry including twist-four corrections by A. Belitsky [?] at $-t = 0.3$ GeV^2, Q^2=4 GeV^2. The red curves are the leading order calculation, while the black curves have twist-four power effects taken into account. While the cross section is very sensitive to these corrections, the transverse spin asymmetry is stable. The figure of merit $\sigma_L A_L^\perp$ maximum at $x_B = 0.37$ corresponds to particle angles and momenta similar to those proposed here.

Refs. [?] and [?] also point out that the study of the transverse target single-spin asymmetry versus t is important for the reliable extraction of the pion form factor from electroproduction experiments (Fig. 2b). Investigations of hard exclusive π^+ electroproduction using a pQCD factorization model [? ?] find that at $x_B = 0.3$ and $-t = -t_{min}$, the pion pole contributes about 80% of the longitudinal cross section. Since the longitudinal photon transverse single-spin asymmetry is an interference between pseudoscalar and pseudovector contributions, its measurement would help constrain the non-pole pseudovector contribution, and so assist the more reliable extraction of the pion form factor. The upper $Q^2 = 6$ GeV^2 limit of the approved pion form factor measurements in the JLab 12 GeV program [?] is dictated primarily by the requirement $-t_{min} < 0.2$ GeV^2, to keep non-pion pole contributions to σ_L at an acceptable level [?]. Transverse target single-spin asymmetry studies versus t may eventually allow, with theoretical input, the use of somewhat larger $-t$ data for pion form factor measurements, ultimately extending the Q^2-reach of pion form factor data acquired with JLab 12 GeV beam. Thus, measurements of the transverse single-spin asymmetry are a logical step in the support of the pion form factor program.

C. The Complementarity of Separated and Unseparated Asymmetry Measurements

It has not yet been possible to perform an experiment to measure $A_L^{\perp}$. The conflicting experimental requirements of transversely polarized target, high luminosity, L–T separation, and closely controlled systematic uncertainty, make this an exceptionally challenging observable to measure. The SHMS+HMS is the only facility with the necessary resolution and systematic error control to allow a measurement of $A_L^{\perp}$. However, the beamtime required to do a good measurement with current polarized target technology is in the range of 10^3 days. To minimize the beamtime required, PR12-12-005 proposed the use of a next generation, externally polarized, continuous flow, high luminosity ^{3}He target based on a large volume polarizer and compressor developed at the University of New Hampshire [**?**]. The science case for this measurement was favorably reviewed by PAC39, and they encouraged the continued development of the target technology. Although the New Hampshire group is making continued progress on the development of the target, there is no timeline for its actual implementation at Jefferson Lab.

The most closely related measurement, of the transverse single-spin asymmetry in exclusive π^+ electroproduction without an L–T separation, was published by the HERMES Collaboration in 2010 [**?**]. Their data were obtained for average values of $\langle x_B \rangle = 0.13$, $\langle Q^2 \rangle = 2.38$ GeV^2 and $\langle t' \rangle = -0.46$ GeV^2, subject to the criterion $W^2 > 10$ GeV^2. The six Fourier amplitudes in terms of the azimuthal angles ϕ, ϕ_s of the pion-momentum and proton-polarization vectors relative to the lepton scattering plane were determined. Of these, at leading twist only the $\sin(\phi - \phi_s)_{UT}$ Fourier amplitude receives a contribution from longitudinal photons. If one assumes that longitudinal contributions dominate, these $A_{UT}^{sin(\phi-\phi_s)}$ values can be compared to GPD models for $\tilde{E}$, $\tilde{H}$.

Because transverse photon amplitudes are suppressed by $1/Q$, at very high Q^2 it is safe to assume that all observed meson production is due to longitudinal photons. At the lower Q^2 typical of the JLab and HERMES programs, however, this is not the case. Calculations by Goloskokov and Kroll [**?**] indicate much of the unseparated cross section measured by

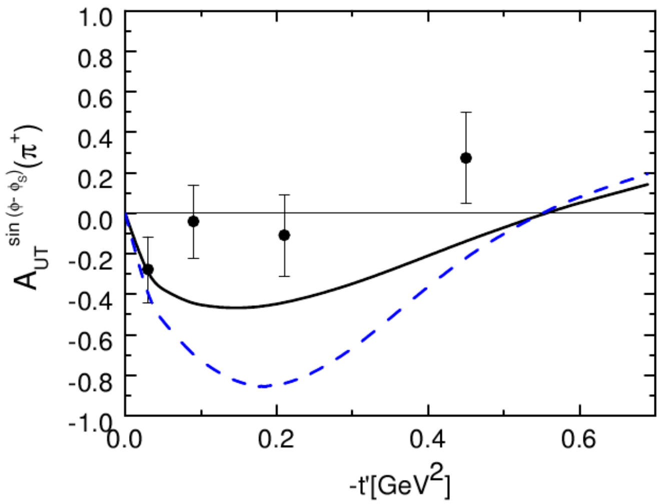

FIG. 6: Predictions by Goloskokov and Kroll for the $\sin(\phi - \phi_s)$ moment of A_{UT} in the handbag approach, in comparison to the data from HERMES at $Q^2 = 2.45$ GeV^2, $W = 3.99$ GeV. The independent variable is $-t' = |t - t_{min}|$. Dashed line: contribution from longitudinal photons only. Solid line: full calculation including both transverse and longitudinal photons. This figure is taken from Ref. [?].

HERMES [?] is due to contributions from transversely polarized photons. In addition, there are contributions to $A_{UT}^{sin(\phi-\phi_s)}$ from the interference between two amplitudes, both for longitudinal photons, as well as transverse photons [?]. As indicated in Fig. ??, the contribution from transverse photons tends to make the asymmetry smaller. At the HERMES kinematics, the dilution caused by transverse photons is about 50%.

A run-group proposal concurrent with the SoLID transversely polarized ^{3}He SIDIS experiment allows for an unseparated asymmetry measurement to be obtained on a sooner timescale than the Hall C measurement. In comparison to the HERMES measurement, the experiment proposed here will probe higher Q^2 and x_B, with much smaller statistical errors over a wider range of $-t$. SoLID will allow the first measurement for $Q^2 > 4$ GeV^2, where GPD-based calculations are expected to apply. Thus, the measurements should be more readily interpretable than those from HERMES. Similar measurements using CLAS-12 and a transversely polarized ^{1}H target have been discussed previously [?], but this measurement will allow for smaller statistical uncertainties, due to SoLID's higher luminosity capabilities.

Handbag model calculations by Goloskokov and Kroll [?] shed further light on the

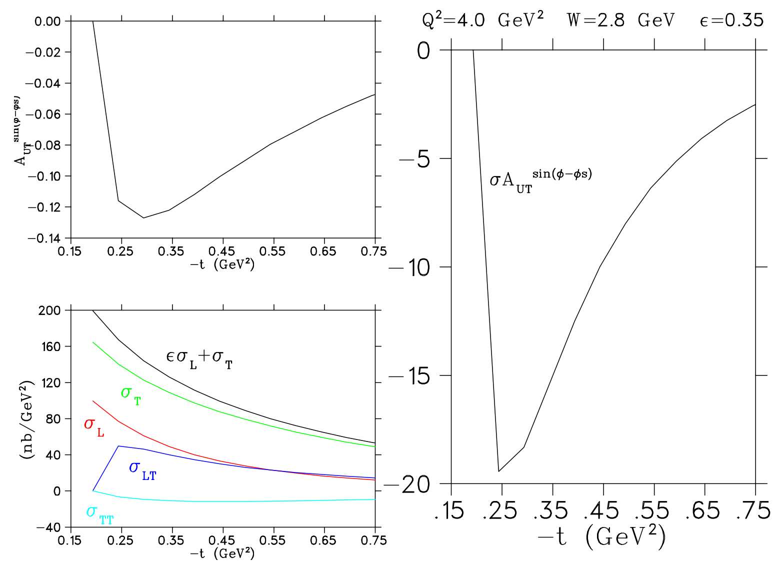

FIG. 7: Calculation of the cross section components and $\sin(\phi - \phi_s)$ moment of the transverse nucleon spin asymmetry A_{UT} in the handbag approach by Goloskokov and Kroll [?] for kinematics similar to those in Fig. ??. $x_B = 0.365$ for the kinematics in this figure.

expected asymmetry dilution. The lower left panel of Fig. ?? shows their predictions for the cross section components in exclusive charged pion production. Although their calculations tend to underestimate the σ_L values measured in the JLab $F_\pi - 2$ experiment [?], their model is in reasonable agreement with the unseparated cross sections [?]. They predict significant transverse contributions for JLab kinematics. A comparison of the unseparated asymmetry at $-t = 0.3$ GeV^2, $x_B = 0.365$ in Fig. ?? with the separated longitudinal asymmetry at the same values of x_B, $-t$ in Fig. ?? indicates a substantial dilution of the unseparated asymmetry due to transverse photon contributions, similar to that observed in Fig. ??.

In addition to allowing a measurement at $Q^2 > 4$ GeV^2, a measurement by SoLID of $A_{UT}^{sin(\phi-\phi_s)}$ will cover a fairly large range of $-t$, allowing the asymmetry to be mapped over its full range with good statistical uncertainties – from its required zero-value in parallel kinematics, through its maximum, and then back to near-zero as σ_T dominates σ_L at larger $-t$. The shape of the asymmetry curve versus $-t$, as well as its maximum value, are critical information for comparison to GPD-based models. At a later date, the New Hampshire polarized target might enable a measurement of $A_L^\perp$ in Hall C. Although undiluted, the error-magnification inherent in an L–T separation will make for larger uncertainties. The comparison of the maxima and t-dependences of both measurements will provide complementary data needed to extract $\tilde{E}$ information and better understand non-pole contributions complicating the extraction of the pion form factor from electroproduction data.

II. EXPERIMENTAL METHOD

GH: This section is a place-holder for new text that needs to be written.

Experimentally, the angle between the target polarization and the reaction plane, β, and the angle between the scattering and reaction planes, ϕ, are not independent. If the target polarization is at some angle, ϕ_s, relative to the scattering plane, then $\beta = \phi_s - \phi$. For the experimental set–up that will be discussed here, ϕ_s is relatively constant, so it will be useful to re–express the above cross sections in terms of β and ϕ_s. The polarized nucleon cross section then becomes:

$$
\begin{aligned}
\sigma_t = & -P_\perp \sin\beta\,[\sigma^y_{TT} + 2\epsilon\,\sigma^y_L] \\
& - P_\perp \sin\beta\,[\epsilon(\cos 2\phi_s \cos 2\beta + \sin 2\phi_s \sin 2\beta)\;\sigma^y_{TT'}] \\
& - P_\perp \sin\beta\left[\sqrt{2\epsilon(1+\epsilon)}(\cos\phi_s\cos\beta + \sin\phi_s\sin\beta)\;\sigma^y_{LT}\right] \\
& - P_\perp \cos\beta\left[\sqrt{2\epsilon(1+\epsilon)}(\sin\phi_s\sin\beta - \cos\phi_s\cos\beta)\;\sigma^x_{LT}\right] \\
& - P_\perp \cos\beta\,[\epsilon(\sin 2\phi_s \sin 2\beta - \cos 2\phi_s \cos 2\beta)\;\sigma^x_{TT}]\,. \qquad (7)
\end{aligned}
$$

A wide range of experiments have utilized polarized ^{3}He as an effective neutron target over a wide range of kinematics. And over the past decades several authors have calculated the effective neutron polarizations in ^{3}He using three-nucleon wave functions and various models of the $N-N$ interaction [**?**]. These are now well established, and the error introduced by uncertainty in the wave functions are small.

Other nuclear effects which can influence the experimental asymmetry for a neutron bound inside ^{3}He include, Fermi motion, off-shell effects, meson exchange currents, delta isobar contributions and π^- final state interactions. The exclusive nature of the process, the selected kinematics such as high Q^2, large recoil momentum and a complete coverage of the azimuthal angle ϕ ensures that corrections due to these nuclear effects will be small and can be modeled effectively. For example, the recoil momentum is >450 MeV/c for all settings proposed here, which minimizes Paul-blocking and π^- rescattering effects.

A. Set–up and Kinematics

The reaction of interest is $^3He(e, e'\pi^-)p + pp_{sp}$. The measurement of the transverse single-spin asymmetry requires the detection of the π^- in non-parallel kinematics. It is the component of the target polarization parallel to $\hat{q} \times \hat{p_\pi}$ that is important, and this direction is uniquely defined only in non-parallel kinematics.

As part of the program to minimize the sources of systematic errors, the target polarization will be reversed periodically by reversing the magnetic field direction.

B. Simulation of the Experiment - Acceptance

Ideally, one would like full coverage of the angle between the target polarization vector and the reaction plane, β over the full range of t.

C. Simulation of the Experiment - Missing Mass Resolution

D. Recoil Detection

E. Projected Real Event Rates

F. Anticipated Singles Rates

III. PROJECTED UNCERTAINTIES

IV. SUMMARY

The transverse single-spin asymmetry in the exclusive $\vec{n}(e, e'\pi^-)p$ reaction has been noted as being especially sensitive to the spin-flip generalized parton distribution (GPD) $\tilde{E}$. Factorization studies have indicated that precocious scaling is likely to set in at moderate $Q^2 \sim 2 - 4$ GeV^2, as opposed to the absolute cross section, where scaling is not expected until $Q^2 > 10$ GeV^2. Furthermore, this observable has been noted as being important for the reliable extraction of the charged pion form factor from pion electroproduction. Two crucial aspects of our experiment, which distinguish it from other previous or proposed measurements are the Rosenbluth L–T separation with controlled systematic uncertainties, and a new, externally polarized, continuous flow, high luminosity ^{3}He target based on a large volume polarizer and compressor developed at the University of New Hampshire. Unlike other ongoing or proposed experiments, where the dominance of the longitudinal contribution to the spin asymmetry at intermediate Q^2 is simply assumed, we intend to demonstrate whether this is in fact the case. Experimental data will be the final judege of whether soft physics contributions cancel sufficiently well in the asymmetry ratio to allow the GPD mechanism to be observable at JLab energies. We have designed our experiment to remove the contribution of competing physics backgrounds to the greatest extent possible, through the L–T separation, and the exclusive measurement. Thus, the magnitude of the observed asymmetry and its kinematic dependence should be a good test of whether the precocious scaling expectations of the GPD formalism will be ultimately realized at JLab energies. Our measurement will also help to constrain longitudinal backgrounds possibly complicating the extraction of the pion form factor from electroproduction experiment data, with the aim of eventually extending the kinematic range over which reliable data can be acquired from electroproduction data.

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