# (A Proposal to Jefferson Lab 12 GeV - PAC38, Update to PR12-09-018, conditionally approved by PAC34 and PAC37) Target Single-Spin Asymmetries in Semi-Inclusive Pion and Kaon Electroproduction on a Transversely Polarized ${ }^{3} \mathrm{He}$ Target using Super BigBite and BigBite in Hall A 

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#### Abstract

An experiment is proposed to measure the Single Spin Asymmetries of the Semi-Inclusive Deep Inelastic Scattering (SIDIS) process $\vec{n}\left(e, e^{\prime} \pi^{ \pm, 0}\left(K^{ \pm}\right)\right.$), using the large-solid-angle Super Bigbite Spectrometer (SBS), the BigBite Spectrometer, and a novel polarized ${ }^{3} \mathrm{He}$ target that includes alkali-hybrid optical pumping and convection flow to achieve very high figure-of-merit. Both spectrometer arms will utilize GEM-based tracking to accommodate the high rates. The abundant statistics will allow the determination of the Collins and Sivers functions for the neutron roughly 10 times more accurately than obtained for the proton by the HERMES experiment, in a detailed grid of the kinematic variables $x, p_{T}$, and $z$. Furthermore, by performing measurements at two energies, 8.8 and 11 GeV , we will have data at two values of $Q^{2}$ for each $x$ value.

The azimuthal coverage of our experiment is chosen to optimize the figure of merit of the measured asymmetries for the proposed apparatus, and is facilitated by collecting data at a series of neutron polarization directions, always transverse to the beam direction. The SIDIS pions and kaons will be detected over a wide range of hadron momenta above 2 GeV , in a wide range of polar and azimuthal angles of the hadron momentum relative to the electron scattering plane and the momentum transfer. Between the large acceptances of the electron and hadron arms, an electron polarized-nucleon luminosity on the order of $4 \cdot 10^{36} \mathrm{~cm}^{-2} / \mathrm{s}$, and a target polarization of $65 \%$, we will obtain in a two-month run about 100 times more statistics (after accounting for differences in polarization and dilutions) than the HERMES experiment. The experiment has significant potential for the discovery of new effects in hadronic physics.


## Chapter 1

## Introduction

### 1.1 Outline of the Document: Summary of Updates Since PAC37

In this outline, we list the major new developments since conditional approval of this experiment by PAC37:

- Major Physics Developments

1. The final results of JLab E06-010 have been released and submitted for publication [1]. Virtually no more SIDIS SSA data is forthcoming between now and JLab 12 GeV , except an update from COMPASS with $\sim 2 X$ currently published statistics on a proton target.
2. A world-wide effort in polarized Drell-Yan measurements has emerged as a major direction in spin physics

- Transverse SSA measurements in pionic Drell Yan on transversely polarized protons at the COMPASS experiment. Production data collection expected 2013-2015
- Polarized Drell-Yan at RHIC: Andy fixed target program with RHIC polarized beam. 2013-2015 production data.
- DY SSA is a major goal of both the STAR and PHENIX decadal plans.
- Fermilab. E906 will collect data on unpolarized targets with a 120 GeV proton beam in 2011-2013. Serious proposals to install a polarized proton target and/or to polarize the FNAL main injector beam are under consideration.
- Additional Drell-Yan proposals are under consideration at J-PARC and FAIR using polarized anti-protons, and elsewhere.

3. The growing body of results expected from Drell-Yan SSA measurements in the near future underscores the urgency for precision SIDIS measurements to aid the combined interpretation of SIDIS and DY data, and to check the expected sign change of the Sivers function between SIDIS and DY. The proposed experiment presents one of the best opportunities in the near term future to keep the field moving forward.

- Technical Progress of This Experiment

1. Fully realistic Monte Carlo simulations of the GEM tracking in the full background conditions of the GEp-V experiment and this experiment, demonstrating highly efficient and accurate tracking performance for this experiment (see section 3.5.2).
2. Redesign of the BigBite Gas Cherenkov for the A1n experiment using highly segmented, small-area PMTs (see section 3.6).
3. Simplified BigBite trigger design based on the shower counter only (see section 3.6.1).
4. Detailed analysis of the DAQ rate demonstrating sufficient ( $\sim 90 \%$ ) livetime in the proposed detector configuration (see section 3.7).
5. Monte Carlo studies of the $\pi^{0}$ acceptance and reconstruction using HCAL, demonstrating the feasibility to extract $\pi^{0}$ SSAs with comparable precision to charged pions (see section 5.1.2).
6. Status of target development: see chapter 4.

- Progress in Development of the Physics Case and Data Analysis Framework For This Experiment

1. Updated Monte Carlo of acceptance, resolution, rates and asymmetries (see section 5.1).
2. Generation and analysis of large-statistics pseudo-data sets, validation of extraction method and statistical error estimation (see section 5.2.1).
3. Projected physics results in 1D (for comparison to HERMES/COMPASS) 2D, and 3D kinematic binning (and effective fully-differential 4D using the two beam energy settings). See section 5.2.2 and [2].
4. Thanks to A. Prokudin for providing parameter sets for Collins, transversity and Sivers functions for asymmetry modeling and uncertainty estimation in our Monte Carlo, and proper integration over our acceptance, and also for performing a pseudo-global fit to demonstrate the physics impact of these measurements.
5. Thanks to A. Del Dotto for updated calculations of the nuclear effects on the extraction of neutron information from ${ }^{3} \mathrm{He}$ and the systematic uncertainties resulting from the effective polarization approximation.
6. Examination of azimuthal coverage in a fully-differential kinematic space: appendix B.

- Comparison to competing experiments and discussion of the role of this experiment in the JLab 12 GeV SIDIS program. See section 6.1.
- Beam time request: section 6.2.2.
- Replies to the PAC37 Draft Report: appendix C
- Updated replies to the PAC34 Final Report: appendix D


### 1.2 Partonic Structure of the Nucleon

There are a large number of review articles which thoroughly document the status of the field, see e.g. [3] and [4]; in this section we provide a general overview and some details concerning
aspects of quark transverse degrees of freedom. The discovery and study of the partonic structure of hadrons present a great success story of particle physics. Experiments have obtained significant insights into QCD without the use of quark beams. Quark distributions and quark polarizations have been probed by virtual photons over a wide range of the momenta.

In the case of inclusive electron scattering $\left(e, e^{\prime}\right)$ there is a kinematic difference between studies of nuclei and studies of the nucleon due to difference in the ratio of the relevant constituent mass, $m$, and binding energy, $U$. In nuclei, with a constituent nucleon of 1 GeV mass and binding energy of 10 MeV , this ratio is 100 but in a nucleon, whose constituent is a quark of few MeV mass with a binding energy of a few hundreds MeV , the ratio is 0.01 . This large difference in the $m / U$ ratio necessitates a change from the non-relativistic shell model of the nuclei to the parton model of the nucleon described in the infinite momentum frame and explains the success of the collinear approximation for the leading twist QCD diagrams. There are also fundamental differences between nucleon-nucleon forces and parton interactions within the nucleon, the foremost being the realization of quark confinement.

Using the semi-inclusive process of nucleon knockout from nuclei, ( $e, e^{\prime} p(n)$ ), experiments provide insight into nucleon momentum distributions, final-state interactions, and subtle effects associated with nucleon binding; high quality studies of nucleon knockout from the nuclei have proved productive. In the same manner, the semi-inclusive process from a nucleon can provide unique information at the quark level. The electro-production of hadrons from nucleons involves the fragmentation of the struck quark and its interaction with the remnant nucleon. In spite of these complications, the key features of the struck quark characteristics can be investigated. Semi-inclusive deep inelastic scattering, SIDIS, provides access to the quark transverse momentum dependent distributions (TMDs), some of which result from the spin of the nucleon. The study of SIDIS contributes to our understanding of the origin of quark orbital angular momentum and flavor decomposition of PDFs.

The proposed experiment will study the reactions $\vec{n}\left(\vec{e}, e^{\prime} \pi^{ \pm, 0}\right)$ and $\vec{n}\left(\vec{e}, e^{\prime} K^{ \pm}\right)$simultaneously, focusing on high-statistics measurement of the azimuthal asymmetries of pion and kaon yields with respect to the virtual photon momentum and the direction of the nucleon polarization. The experimental setup is optimized for a measurement with the direction of nucleon polarization orthogonal to the electron scattering plane and the transverse momentum of the hadron below 1.5 GeV . In this chapter the basic formalism of deep inelastic scattering (DIS) and the semi-inclusive DIS are presented.

### 1.3 Deep Inelastic Scattering

In Deep Inelastic Scattering (DIS), a photon exchange is used to probe the structure of the nucleon. The plot in Fig. 1.1 is a representation of the DIS process and introduces kinematic quantities which are defined in Table 1.1. The deep inelastic electron scattering process is: $e(k)+$ $N(P) \rightarrow e^{\prime}\left(k^{\prime}\right)+X\left(P_{X}\right)$. The initial electron (e) with 4-momentum $k=(E, \mathbf{k})$ exchanges a photon of 4 -momentum $q$ with a target $(N)$ with 4 -momentum $P$. In an inclusive experiment the outgoing electron ( $e^{\prime}$ ) with 4-momentum $k^{\prime}=\left(E^{\prime}, \mathbf{k}^{\prime}\right)$ is detected. The DIS process is often modeled in the Bjorken limit in which $Q^{2}$ and photon energy $\nu$ both go to infinity while the ratio, $x_{B j}=Q^{2} /(2 M \nu)$, is held fixed. Another useful dimensionless variable is $y=\nu / E$, the fractional energy loss of the electron in the scattering process. The target's spin 4 -vector $\mathbf{S}$ describes the target polarization direction in the lab frame. This direction, $\mathbf{S}$, is often decomposed into $S_{L}$ and


Figure 1.1: Kinematics quantities for description of electron-nucleon scattering: $k$ and $k^{\prime}$ are the four-momenta of incoming and outgoing electrons.
the $\mathbf{S}_{\mathbf{T}}$, longitudinal and transverse projections with respect to the direction of the 3-momentum of the virtual photon.


Figure 1.2: Schematic notations for DIS and transverse momentum-independent structure functions.

Three parton distribution functions describe the structure of the nucleon at leading twist: the unpolarized distribution $f_{1}(x)$, the helicity distribution $g_{1}(x)$, and the transversity distribution $h_{1}(x)$ (also indicated by $\delta q(x)$ ). The function $f_{1}(x)$ is the quark density in the an unpolarized nucleon. The function $g_{1}(x)$ presents the distribution of longitudinally polarized quarks in a longitudinally polarized nucleon (with respect to the $\gamma^{*} 3$-momentum). The transversity distribution, $h_{1}(x)$, describes the distribution of transversely polarized quarks in a nucleon transversely polarized with respect to the $\gamma * 3$-momenta. The Figure 1.2 shows a schematic representation for the leading parton distributions.

## Inclusive DIS Cross Sections

The differential cross section of inclusive inelastic $e N$ scattering process is written in the usual notation as:

$$
\frac{d^{2} \sigma}{d E^{\prime} d \Omega_{e^{\prime}}}=\frac{\alpha^{2}}{4 E^{2} \sin ^{4}\left(\frac{\theta}{2}\right)}\left[W_{2}\left(q^{2}, \nu\right) \cos ^{2}\left(\frac{\theta}{2}\right)+2 W_{1}\left(q^{2}, \nu\right) \sin ^{2}\left(\frac{\theta}{2}\right)\right]
$$

In the approximation of $E, E^{\prime} \gg M$ and finite $q^{2}, \nu$ we will use

| $M$ |  |  | Mass of target nucleon |
| ---: | :--- | :--- | :--- |
| $k$ | $=(E, \mathbf{k})$ |  | 4-momenta of the initial state electron |
| $P$ | $\stackrel{l a b}{=}(M, 0)$ |  | 4-momentum of the initial target nucleon |
| $S_{T}$ |  | Target's spin 4-vector |  |
| $k^{\prime}$ | $=\left(E^{\prime}, \mathbf{k}^{\prime}\right)$ |  | 4-momenta of the final state electron |
| $\theta$ |  | Polar angle of the scattered electron |  |
| $q$ | $=\left(E-E^{\prime}, \mathbf{k}-\mathbf{k}^{\prime}\right)$ |  | $\gamma^{*}$ 4-momentum |
| $Q^{2}$ | $=-q^{2}$ |  | Negative squared 4-momentum transfer |
| $\nu$ | $=P \cdot q / M$ |  | $\gamma^{*}$ energy in the target rest frame |
| $\epsilon$ | $\stackrel{l a b}{=}\left[1+2 \frac{\nu^{2}+Q^{2}}{Q^{2}} \tan ^{2} \frac{e_{e}}{2}\right]^{-1}$ |  | $\gamma^{*}$ polarization parameter |
| $y$ | $=(P \cdot q) /(P \cdot k) \stackrel{l a b}{=} \nu / E$ |  | $\gamma^{*}$ fractional energy |
| $x$ | $=Q^{2} /(2 P \cdot q) \stackrel{l a b}{=} Q^{2} /(2 M \nu)$ |  | Bjorken scaling variable $x$ |
| $s$ | $=(k+P)^{2}=Q^{2} / x y+M^{2}$ |  | Square of the total 4-momentum |
| $z$ | $=E_{h} / \nu$ |  | Elasticity, fractional energy of the observed hadron |
| $W^{2}$ | $=(P+q)^{2}=$ |  | Squared invariant mass of the $\gamma^{*}$-nucleon system |
|  | $=M^{2}+2 M \nu-Q^{2}$ |  | 4-momentum of an observed hadron |
| $P_{h}$ | $=\left(E_{h}, \mathbf{P}_{h}\right)$ | Component of $\mathbf{P}_{h}$ perpendicular to $\mathbf{q}$ |  |
| $p_{T}$ |  | Polar angle between virtual photon and detected |  |
| $\theta_{q h}$ |  | hadron directions |  |
| $\phi$ |  | Angle between the electron scattering and hadron |  |
| $\phi_{S}$ |  | production planes |  |
| $\phi_{S}$ |  | Azimuthal angle of the nucleon spin with respect to $\mathbf{q}$ |  |
| $W^{\prime 2}$ | $=\left(M+\nu-E_{h}\right)^{2}-\left\|\mathbf{q}-\mathbf{P}_{h}\right\|^{2}$ | invariant mass of the hadron system |  |

Table 1.1: Kinematic variables of DIS and SIDIS (the definition of azimuthal angles follow the Trento convention [5]).

$$
\frac{d^{2} \sigma}{d E^{\prime} d \Omega_{e^{\prime}}} \approx \frac{\alpha^{2}}{4 E^{2} \sin ^{4}\left(\frac{\theta}{2}\right)} \frac{F_{2}\left(q^{2}, \nu\right)}{\nu}
$$

It also could be written as:

$$
\frac{d^{2} \sigma}{d x d y}=\frac{4 \pi \alpha^{2}\left(s-M^{2}\right)}{Q^{4}}\left[(1-y) F_{2}+y^{2} x F_{1}-\frac{M^{2}}{\left(s-M^{2}\right)} x y F_{2}\right]
$$

where $F_{1}, F_{2}$ are DIS structure functions.
The differential cross section for the electro-production of a hadron, $h$, for unpolarized beam and unpolarized target can be presented as:

$$
\frac{d^{3} \sigma}{d E^{\prime} d \Omega_{e^{\prime}} d \Omega_{h}}=\Gamma \frac{d \sigma_{\gamma^{*}, h}}{d \Omega_{h}}
$$

where $\Gamma$ is the virtual photon flux factor, given by:

$$
\Gamma=\frac{\alpha}{2 \pi^{2}} \frac{E^{\prime}}{E} \frac{s-M^{2}}{2 M Q^{2}} \frac{1}{1-\epsilon}
$$

and $d \sigma_{\gamma^{*}, h} / d \Omega_{h}$ is the cross section for hadron production by the virtual photon.

## Semi-Inclusive DIS Cross Sections

The SIDIS cross section for a polarized beam and a polarized target requires six terms schematically written as:

$$
\begin{aligned}
& \sigma_{\gamma *, h}\left(\phi, \phi_{S}\right)=\sigma_{U U}+\lambda_{e} \sigma_{L U}(\phi)+S_{L} \sigma_{U L}(\phi)+ \\
+ & \lambda_{e} S_{L} \sigma_{L L}(\phi)+S_{T} \sigma_{U T}\left(\phi, \phi_{S}\right)+\lambda_{e} S_{T} \sigma_{L T}\left(\phi, \phi_{S}\right)
\end{aligned}
$$

where $\lambda_{e}$ is the longitudinal polarization (helicity) of the beam while $S_{T}$ and $S_{L}$ describe the transverse and longitudinal polarization of the target relative to the direction of the exchanged photon.

There are three types of twist-2 transverse momentum independent quark distributions for the nucleon. These are:

1. the spin-independent distributions $q(x)$ for each flavor measured in the unpolarized structure functions $F_{1}$ and $F_{2}$,
2. the spin-dependent distributions $\Delta q(x)$ measured in $g 1$ and
3. the transversity distributions $\delta q(x)$ (or $h_{1}(x)$ ).

As soon as the transverse momentum of the parton relative to the nucleon is taken into account, at the leading order, 5 additional distribution functions for a total of 8 Transverse Momentum Dependent (TMD) functions (see Fig. 1.3) enter into the description of the nucleon; two of them, Sivers and the Pretzelosity will be introduced later in this chapter.


Figure 1.3: Pictorial view of the Transverse Momentum Dependent quark distribution functions, describing the nucleon at the leading twist.

In the parton model the DIS structure functions $F_{1}$ and $F_{2}$ are written as:

$$
F_{1}(x)=\frac{1}{2 x} F_{2}(x)=\frac{1}{2} \sum_{q} e_{q}^{2}\{q+\bar{q}\}(x)
$$

here the $\{q+\bar{q}\}(x)=\left(q^{\uparrow}+\bar{q}^{\uparrow}\right)(x)+\left(q^{\downarrow}+\bar{q}^{\downarrow}\right)(x)$
The polarized structure function, $g_{1}=\sigma_{L L} / \sigma_{U U}$, is written as:

$$
g_{1}(x)=\frac{1}{2} \sum_{q} e_{q}^{2} \Delta q(x)
$$

where $\Delta q(x)=\left(q^{\uparrow}+\bar{q}^{\uparrow}\right)(x)-\left(q^{\downarrow}+\bar{q}^{\downarrow}\right)(x)$.
The transversity distributions, $\delta q(x)$, describe the density of transversely polarized quarks inside a transversely polarized proton.

$$
\delta q(x)=q^{\uparrow}(x)-q^{\downarrow}(x)
$$

### 1.4 Transversity

Now we focus on the transversity physics and SIDIS cross section (equation 1.6) term $\sigma_{U T}$. This term involves a transversely polarized target and an unpolarized beam and introduces an azimuthal-dependent cross section. Using variables defined in Table 1.1, this cross section can be written as:

$$
\begin{equation*}
\frac{d \sigma_{\gamma *, h}}{d x d y d z d \phi}=d \sigma_{U U}+\left|S_{T}\right| d \sigma_{U T}\left(\phi, \phi_{S}\right) \tag{1.1}
\end{equation*}
$$

The cross section for the unpolarized beam and the unpolarized target could be presented as ${ }^{1}$ :

$$
\begin{equation*}
d \sigma_{U U}=\frac{4 \pi \alpha^{2} s}{Q^{4}}\left(1-y+\frac{y^{2}}{2}\right) \sum_{q} e_{q}^{2}\left[f_{1}^{q} \otimes D_{1}^{q}\right] \tag{1.2}
\end{equation*}
$$

The $\sigma_{U T}$, at the leading twist-2 order can be decomposed into the Collins, Sivers and Pretzelosity terms [6] (higher twists are suppressed by a factor of $1 / Q$ at least).

$$
\begin{align*}
d \sigma_{U T}^{\text {Collins }} & =\frac{4 \pi \alpha^{2} s}{Q^{4}}(1-y) \sin \left(\phi+\phi_{S}\right) \sum_{q} e_{q}^{2}\left[w_{C} \cdot h_{1}^{q} \otimes H_{1}^{\perp q}\right]  \tag{1.3}\\
d \sigma_{U T}^{\text {Sivers }} & =\frac{4 \pi \alpha^{2} s}{Q^{4}}\left(1-y+\frac{y^{2}}{2}\right) \sin \left(\phi-\phi_{S}\right) \sum_{q} e_{q}^{2}\left[w_{S} \cdot f_{1 T}^{\perp q} \otimes D_{1}^{q}\right]  \tag{1.4}\\
d \sigma_{U T}^{\text {Pretzelosity }} & =\frac{4 \pi \alpha^{2} s}{Q^{4}}(1-y) \sin \left(3 \phi-\phi_{S}\right) \sum_{q} e_{q}^{2}\left[w_{P} \cdot h_{1 T}^{q} \otimes H_{1}^{\perp q}\right] \tag{1.5}
\end{align*}
$$

where the convolution on the right hand side involves the integral on the initial $\left(\mathbf{k}_{T}\right)$ and final $\left(\mathbf{p}_{T}\right)$ transverse momenta of the parton with the corresponding weighting factors $w_{C, S, P}{ }^{2}$ :

$$
\begin{equation*}
\left[w_{j} f \otimes H\right]=x \int d^{2} \mathbf{p}_{T} d^{2} \mathbf{k}_{T} \delta^{(2)}\left(\mathbf{p}_{T}-\mathbf{P}_{\perp} / z-\mathbf{k}_{T}\right) \cdot w_{j}\left(\mathbf{P}_{\perp}, \mathbf{k}_{T}, \mathbf{p}_{T}\right) \cdot f\left(x, \mathbf{k}_{T}, Q^{2}\right) \cdot H\left(z, \mathbf{p}_{T}, Q^{2}\right) \tag{1.6}
\end{equation*}
$$

where $f$ and $H$ are respectively a TMD function (depending on the initial parton) and a fragmentation function (depending on the final, detected, hadron), and in particular:

[^0]$h_{1}^{q}$ is the chirally odd Transversity function [7], directly related to the above defined transversity, by an integration in $\mathbf{P}_{\perp}$.
$f_{1 T}^{\perp q}$ is the Sivers function [8], related to the correlation between nucleon transverse spin and parton transverse momentum. Its non zero value, predicted by a restricted application of the time reversal invariance of QCD, is actually a result of final state interaction between the scattered quark and the target remnant, before fragmentation [9]. In fact, time reversal, which reverses spin and momenta and transforms FSI into Initial State Interaction (ISI), is related to the generalized universality of the Sivers functions in SIDIS and Drell-Yan processes, where the sign of the Sivers function is expected to be opposite to that in SIDIS; the experimental verification of this QCD prediction is of fundamental importance.
$h_{1 T}^{\perp, q}$ is the Pretzelosity function [10], related to the interference of orbital angular momentum wave functions differing by 2 units, and therefore gives indication of the deviation of the "nucleon cloud" from a sphere. The Pretzelosity, in a model-dependent way, is the difference of the helicity and the transversity distributions. This term is suppressed respect to Collins and Sivers by two power in $P_{\perp}$ in $w_{P}$.
$H_{1}^{\perp q}$ is the Collins fragmentation function, which generates an asymmetry in the fragmentation of polarized quarks into unpolarized hadrons.
$D_{1}^{q}$ is the relatively well known (for pions) unpolarized fragmentation function.
In the following discussion we will omit the Pretzelosity term for simplification of notation; however it is our intention to include it in the extraction of the other functions, as discussed in section 5.3. From the cross sections, we can construct the single spin asymmetry, SSA, written as:
\[

$$
\begin{equation*}
A_{U T} \equiv \frac{1}{\left|S_{T}\right|} \frac{d \sigma\left(\phi, \phi_{S}\right)-d \sigma\left(\phi, \phi_{S}+\pi\right)}{d \sigma\left(\phi, \phi_{S}\right)+d \sigma\left(\phi, \phi_{S}+\pi\right)}=\frac{1}{\left|S_{T}\right|} \frac{d \sigma_{U T}}{d \sigma_{U U}} \tag{1.7}
\end{equation*}
$$

\]

This full SSA, in first approximation, contains the Collins and the Sivers parts modulated by the $\sin ()$ function of different combinations of the azimuthal angles.

$$
\begin{equation*}
A_{U T}=A_{U T}^{\text {Collins }} \sin \left(\phi+\phi_{S}\right)+A_{U T}^{\text {Sivers }} \sin \left(\phi-\phi_{S}\right) \tag{1.8}
\end{equation*}
$$

where the Collins and Sivers asymmetries are related to the above distribution and fragmentation function by corresponding (first order) moments:

$$
A_{U T}^{\text {Collins }}=2 \frac{\int d \phi_{S} d^{2} \mathbf{P}_{\perp} \sin \left(\phi+\phi_{s}\right) d \sigma_{U T}}{\int d \phi_{S} d^{2} \mathbf{P}_{\perp} d \sigma_{U U}}
$$

and

$$
A_{U T}^{\text {Sivers }}=2 \frac{\int d \phi_{S} d^{2} \mathbf{P}_{\perp} \sin \left(\phi-\phi_{s}\right) d \sigma_{U T}}{\int d \phi_{S} d^{2} \mathbf{P}_{\perp} d \sigma_{U U}}
$$

where the integration in $\mathbf{P}_{\perp}$ requires a specific prescription (assumption), for example in the form of dependence of the distribution and fragmentation functions from the corresponding quark transverse momenta (such as the Gaussian ansatz used in 5).

The Collins $[7,11]$ and Sivers [8] asymmetries have very different origin and reveal new features of the nucleon structure.

### 1.5 The Longitudinal-Transverse Term

In experiments with longitudinally polarized beam and transversely polarized target, the $\sigma_{L T}$ term of equation 1.6 can be accessed through the double spin asymmetry $A_{L T}$, given by a combination of a twist-2 term and $1 / Q$ suppressed higher twist terms with specific ( $\phi, \phi_{S}$ ) modulations; at leading twist, it can be written as

$$
d \sigma_{L T} \sim \cos \left(\phi-\phi_{S}\right) \sum_{q} e_{q}^{2}\left[w_{W G} \cdot g_{1 T}^{\perp q} \otimes D_{1}^{\perp q}\right]
$$

where $g_{1 T}^{\perp q}$ is the so called Worm-Gear LT TMD which is related to the probability to find longitudinally polarized quarks in a transversely polarized nucleon ${ }^{3}$. This is the only TMD not influenced by initial and final state interactions, being neither chiral-odd nor naive-T-odd. Moreover a signal in the Worm-Gear LT is related to the relativistic boosts.

### 1.6 Spin-orbit effects and the FSI in nuclear physics

In a non-relativistic model of an atom, the spin-orbit (LS) term of the Hamiltonian appears due to the electron's magnetic moment. This LS term is responsible for many phenomena, including the fine splitting in atomic level structure which allows high polarization of the CEBAF beam and also the Mott-based polarimetery used for the CEBAF beam. In the low-energy nucleon-nucleon and nucleon-nucleus interaction the role of spin-orbit interactions is even more pronounced; JLab experiments use it to determine the proton polarization at the level of accuracy required for the measurement of the electric form factor of proton.

The importance of spin-orbit effects in hadron physics was discovered many years ago. However, such effects obviously require quark transverse momentum, which was excluded by the collinear approximation, and was neglected for some time. The EMC discovery of the "spin crisis" brought attention to the issue of parton orbital angular momentum and transverse spin physics. In the absence of a free quark beam, the SIDIS process provides a good substitute since the parameters of a struck quark, after absorption of the virtual photon, can be calculated.

### 1.7 Transverse momentum physics and impact parameter distributions at large $\mathbf{Q}^{2}$

M. Burkardt has presented the phenomenology and applications of the impact parameter representation of the Generalized Parton Distributions to the SIDIS process in a number of articles [12, 13]. The impact parameter is defined as the distance from the point of interaction of the virtual photon with the struck quark to the transverse center of the longitudinal momentum, which in turn is defined by $\mathbf{r}_{\perp}=\sum_{q} x_{q} \cdot \mathbf{r}_{\perp, q}$ where the sum is over all quarks.

When a virtual photon is absorbed by a transversely polarized nucleon the quark density has some azimuthal variation [12]. The amplitude of such a variation is directly related to the experimentally observed form factors of elastic electron-nucleon scattering. This was first calculated in

[^1]Neutron charge and transverse densities


Figure 1.4: Charge density (black) and transverse density of the neutron.
$[14,15]$ (see Fig. 1.4). The connection between the impact-parameter dependent densities and the form factors follows from the results:

$$
\begin{gathered}
q\left(x, \mathbf{b}_{\perp}\right)=\int \frac{d^{2} q}{(2 \pi)^{2}} e^{i \mathbf{q} \cdot \mathbf{b}_{\perp}} H_{q}\left(x, t=-\mathbf{q}^{2}\right) \\
\rho_{0}\left(b_{\perp}\right) \equiv \sum_{q} e_{q} \int d x q\left(x, \mathbf{b}_{\perp}\right)=\int d^{2} q F_{1}\left(\mathbf{q}^{2}\right) e^{i \mathbf{q} \cdot \mathbf{b}_{\perp}} \\
\rho_{0}\left(b_{\perp}\right)=\int_{0}^{\infty} \frac{Q \cdot d Q}{2 \pi} J_{0}\left(Q b_{\perp}\right) F_{1}\left(Q^{2}\right) \\
\rho_{T}\left(\mathbf{b}_{\perp}\right)=\rho_{0}\left(b_{\perp}\right)-\sin \left(\phi_{b}-\phi_{S}\right) \int_{0}^{\infty} \frac{d Q}{2 \pi} \frac{Q^{2}}{2 M} J_{1}\left(Q b_{\perp}\right) F_{2}\left(Q^{2}\right)
\end{gathered}
$$

As suggested by M. Burkardt, in the process of struck-quark fragmentation the leading hadron obtains an azimuthal anisotropy due to attraction from the nucleon remnant. Such final state interactions correspond to the Sivers effect. Deformation of the quark distribution in a polarized nucleon also results in an orbital angular momentum of the quarks and is related to the quark anomalous magnetic moment. The effect of a flavor segregation naturally leads to the different sign of the SSA for positive and negative pions, which is in agreement with recent HERMES results.

### 1.8 Experimental and theoretical status

The first semi inclusive DIS measurements of the Collins and Sivers asymmetries with transversely polarized targets have been performed recently by the HERMES experiment [16] on the proton
and the COMPASS experiment [17] on the deuteron (and very recently on the proton [18]) ${ }^{4}$. Very recently, the first results on ${ }^{3} \mathrm{He}$ pion Collins and Sivers asymmetries from the Transversity experiment at JLab Hall A have been submitted for publication [1]. Table 1.2 summarizes the most recent references to the measurements of the twist-2 asymmetries accessible with unpolarized beam and transversely polarized target. The COMPASS and HERMES experiments overlap in $x$

Table 1.2: References to the most recents results from COMPASS, HERMES and JLab on Collins (C), Sivers (S) and Pretzelosity (P).

| Target | $\pi^{0}$ | $\pi^{ \pm}$ | $K^{0}$ | $K^{ \pm}$ | $h^{ \pm}$ | Reference |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| p | SCP | S |  | S | C, | HERMES [21] |
|  |  | C |  | C |  | HERMES [22] |
|  |  | P |  | P |  | HERMES (prel.) [23] |
|  |  | C,S |  |  |  | COMPASS [18] |
|  |  |  |  | C,S |  | COMPASS (prel.) [24] |
|  |  |  |  |  |  | COMPASS (prel.) [25] |
| d |  | C,S | C,S | C,S |  | COMPASS [26] |
|  |  |  |  |  | P | COMPASS (prel.) [25] |
| ${ }^{3} \mathrm{He}$ |  | C,S |  |  |  | JLab (prel.) [27] |

range (upper central value limit is $\sim 0.3$ ) but cover quite different $Q^{2}$ regions ( $Q_{\text {HERMES }}^{2}$ up to $\sim 10$ $\mathrm{GeV}^{2}, Q_{\text {COMPASS }}^{2}$ up to $\sim 100 \mathrm{GeV}^{2}$ ) and therefore direct comparison of their data requires careful analysis which is still incomplete. The JLab data overlap COMPASS and HERMES at $x \sim 0.1-0.3$ and its $Q^{2}$ and $W$ are slightly smaller thanHERMES.

The results from the above experiments clearly show:

1. Consolidated measurements exist for proton and deuteron targets only, with limited statistics for kaons; the first direct neutron asymmetries, with moderate statistics, were recently extracted from the JLab ${ }^{3} \mathrm{He}$ data.
2. Collins asymmetries on the proton:

- positive asymmetry (both HERMES and COMPASS ${ }^{5}$ ) for $\pi^{+}$and $K^{+}$; increasing with $x$.
- consistent with 0 for the $\pi^{0}$ observed in HERMES
- negative (both HERMES and COMPASS) for the $\pi^{-}$
- consistent with 0 for the $K^{-}$in both HERMES and COMPASS

3. Sivers asymmetries on the proton:
[^2]- clean positive seen in HERMES for $\pi^{+}$and $K^{+}$, rising with $z$, and rising from low $P_{T}$ toward a plateau at high $P_{T}$. The latest COMPASS results on $\pi^{+}$show a similar trend to HERMES but do not completely reproduce the strength and behaviour;
- HERMES observed a significant $K^{+}$Sivers asymmetry, even larger than $\pi^{+}$; the $K^{-}$ asymmetry seems to be slightly positive; the corresponding preliminary COMPASS asymmetries are compatible with zero;

4. Collins and Sivers asymmetries on the deuteron: small and compatible with zero for $\pi$ and $K$ (COMPASS)
5. $\pi^{ \pm}$Collins and Sivers asymmetries on ${ }^{3} \mathrm{He}$ : the results of the JLab experiment show small asymmetries ( $<5 \%$ magnitude), with a $\pi^{+}$Sivers asymmetry favoring negative values. The neutron results, the precision of which is statistics-limited, are basically compatible with the expected neutron asymmetries from combined analysis of the HERMES and COMPASS data on proton and deuteron targets.

The latest analysis from HERMES, presented for the first time at SPIN08 [28] has extracted the Collins and Sivers asymmetries in 2 dimensional grids of the three combinations of the relevant variables $x, z$ and $p_{T}$ (The $(x, z)$ results are reported in figures 1.5 and 1.6 ).

An intensive program on the Transverse Momentum Dependent distribution functions has been (and continues to be) carried out by the CLAS collaboration (which already measured a non-zero beam-spin azimuthal asymmetry coming from higher twist terms) and will be further expanded in the CLAS12 era, likely with a transversely polarized HD target [29] whose compatibility with a relatively high intensity electron beam is being tested. The above results from HERMES and COMPASS have motivated intense theoretical studies on the nucleon spin structure which have been reinforced by new conceptual frameworks such as the Generalized Parton Distribution functions. In 2007 Anselmino and collaborators have extracted, for the first time, the Transversity and Collins functions for the valence $u$ and $d$ quarks, based on a global analysis (fit) of the HERMES proton data, COMPASS deuteron results and BELLE $e^{+} e^{-}$data [30] at high $Q^{2} \sim 110 \mathrm{GeV}^{2}$. The extracted transversity distributions are reproduced in fig. 1.7; the main conclusions can be summarized by:

- The $u$ and $d$ transversity distributions show the same general features as the Helicity distributions: positive for $u$ and negative for $d$;
- Distributions are about half of the Soffer limit [31] and smaller than model predictions;
- The disfavoured ${ }^{6}$ Collins fragmentation functions are opposite in sign to the favoured ${ }^{7}$ FFs and larger in magnitude; this aspect tends to explain the observed large $\pi^{-}$Collins asymmetry on proton, but is not present in the unpolarized fragmentation functions;

In addition the same fit predicts quite well the latest results of the Collins asymmetry from COMPASS on proton as shown in [33].

The same group also extracted a new parametrization of the Sivers function published in Ref. [34] by fitting the HERMES and COMPASS proton and deuteron data respectively.

[^3]

Figure 1.5: The first (and unique) 2D grid proton Collins moments extracted by HERMES and presented in [28].

New fits have been presented recently and the extracted Sivers distributions are reported in Fig. 1.8:

- The $d$ and $u$ magnitudes are very similar;
- The $\bar{s}$ quark distribution is no longer sizeable as in the original fit;
- Overall, the sea quark distributions are relatively small.

This is the first evidence from SIDIS of a non-zero T-odd parton distribution function, wrongly assumed to be forbidden by time reversal invariance until, which is actually broken by Final State Interactions, until very recently. As claimed by the authors, high $x$ data is vital to get more accurate (and constrained) results.

Finally, it is worth mentioning the status of the Worm-Gear LT TMD and its corresponding $A_{L T}^{\cos \left(\phi-\phi_{S}\right)}$ asymmetry introduced above. Only preliminary results exist: HERMES has presented


Figure 1.6: The first (and unique) 2D grid proton Sivers moments extracted by HERMES and presented in [28].
subleading terms from $\sigma_{U T}$ on the proton related to the Worm-Gear (but also to transversity and Sivers) TMD showing a signal in $\pi^{-}$and $K^{+}$in the $\sin \left(\phi_{S}\right)$ modulated term (see Ref. [23]). The first HERMES extraction of the Worm-Gear TMD from the $\sigma_{L T}$ term was recently reported in Ref. [35], showing a slightly positive signal for negative pions and positive kaons. COMPASS extracted preliminary $\cos \left(\phi-\phi_{S}\right)$ asymmetries Ref. [25]. Preliminary ${ }^{3} \mathrm{He}$ asymmetries have also recently been presented by the JLab experiment [27], showing a positive signal for negative pions.

In summary, both the Sivers and Collins effects have been observed on the proton, although the statistics do not permit an effective multidimensional representation of the data. The same asymmetries are compatible with zero for the deuteron. Almost direct neutron measurements will be soon available [1], but with limited statistical precision. Therefore, additional high-statistics data on the neutron are highly desirable, for both $\pi$ and $K$. Finally, we point out that no data exist for $x>0.3$, where all the already measured non-zero asymmetries are expected to be even larger.


Figure 1.7: The first determination of the Transversity functions for $u$ and $d$ quarks (left) and favored and unfavored Collins fragmentation functions (right). Plots are from Ref. [30] (see text).


Figure 1.8: The Sivers functions for all 6 quarks flavors. Plots are from Ref. [32].

## Chapter 2

## Proposed Measurements

### 2.1 Overview

This section starts from a concept of the transversity SIDIS experiment, moves through the proposed detector configuration, and formulates the main elements of the experiment setup; the details are discussed in the next chapters. A study of the novel features of QCD dynamics in a nucleon is possible via Semi-Inclusive Deep Inelastic Scattering, which has already been investigated with high precision by the HERMES and COMPASS experiments [36, 37] as discussed in the previous chapter. Nevertheless, there remain very interesting questions which require a polarized target for investigation and much larger statistics than presently obtained. These include TMD distributions and the related functions $h_{\perp}, H_{\perp}$, which are accessible only with the transversely polarized target.

The spin observables allow access to the spin and orbital angular momenta of the nucleon constituents and provide powerful tests of the nucleon QCD models. Since the EMC experiment at CERN, a large body of data on the polarization observables has been accumulated. The significant role of quark orbital angular momentum has been established. The phenomenology of semi-inclusive processes, including models of GPDs and TMDs, is a central issue of hadron physics today. The high statistical and systematic accuracy which can be achieved by these measurements will open possibilities for decisive tests of theory and future discoveries in this field.

The upgrade of the CEBAF accelerator will make available a CW $11 \mathrm{GeV} 75 \mu \mathrm{~A}$ electron beam in Hall A, which could be used for the study of SIDIS processes. A large beam intensity will allow us to explore a wide range of kinematics needed for a complete SIDIS program with high $\mathrm{Q}^{2}$, high $x_{B j}$, and high $z$. The SIDIS experiments, in the most important cases, require just a two-arm experimental setup with an electron arm and a hadron arm. The electron arm is needed to tag the deep-inelastic events and determine the virtual-photon 4-momentum. The hadron arm apparatus is required for detection of a leading hadron, which takes a significant part of the virtual photon momentum. The use of a polarized target will allow access to the spin-observables, including measurements of single-spin asymmetries (SSA). Optimization of an SSA measurement must provide sufficient statistics and maximum coverage range in each of four variables: the Bjorken $x$, the hadron energy $z$, the hadron transverse momentum $P_{\perp}$, and the momentum transfer $\mathrm{Q}^{2}$.

For the measurement of the azimuthal variations, wide coverage of the phase space is needed for both $\phi$, the azimuthal angle between the hadron production and lepton scattering planes, and $\phi_{S}$, the azimuthal angle between the lepton plane and the component of the target polarization
transverse to $\vec{q}$ (refer to Tab. 1.1). Wide $\phi$ and $\phi_{s}$ coverage could be achieved, for example, by the use of several directions of the target polarization. In fact, a large out-of-plane acceptance of both arms allows complete coverage with just two target polarization directions - vertical and horizontal (both perpendicular to the electron beam). An even more complete and uniform coverage will be achieved in the proposed experiment by using two additional directions at $\pm 45^{\circ}$ relative to the vertical, also orthogonal to the beam direction. For an experiment utilizing the 11 GeV beam, the pion and kaon momentum would be between 2 and 7 GeV for $z$ between 0.2-0.7. As a result, an angular acceptance of $12^{\circ}$ in the hadron polar angle relative to the momentum transfer will allow acceptance of particles with $P_{\perp}$ up to $\sim 1 \mathrm{GeV}$.

The transverse single-spin asymmetry is equal to zero at $P_{\perp}=0$ (the meson momentum directed along the virtual photon), which makes collection of the statistics with small values of $P_{\perp}$ inefficient for measurements of these asymmetries. In contrast, the azimuthal asymmetry exhibits a wide maximum at $p_{\perp} \sim 0.3-0.7 \mathrm{GeV}$, where the data are most useful for the transversity measurement. In addition, focusing the experiment on the $P_{\perp}$ above 0.2 GeV simplifies the setup because with the $11-\mathrm{GeV}$ beam the direction of the virtual photon is often very close to the beam direction.

The design of an optimized experiment is always a compromise between performance, preparation time, and cost. The parameters of the polarized target have a significant impact. The polarized ${ }^{3} \mathrm{He}$ target offers a luminosity of up to $10^{38} \mathrm{~cm}^{-2} / \mathrm{s}$, while a very low temperature HD target could provide very small dilution and good polarization for luminosity around $10^{34} \mathrm{~cm}^{-2} / \mathrm{s}$ (parameters need to be confirmed because such a target was never used with any electron beam), so the two types of targets are suitable for different types of detector configurations: The polarized ${ }^{3} \mathrm{He}$ target is suited to the moderate solid angle setup with excellent PID of $e / \pi / K$ in full momentum range while the HD target is suited to a detector with very large (nearly $4 \pi$ ) acceptance. At the same time, it must be noted that for the study of the transverse single-spin asymmetries of the neutron, the proposed ${ }^{3} \mathrm{He}$ measurements allow a factor of 40 higher figure-of-merit than that of the HD target in CLAS12. In addition to these target-luminosity-PID experimental aspects, there is a very important difference in the final state systematics in measurements of the neutron transversity with the HD and ${ }^{3} \mathrm{He}$ targets. In the case of the HD target, the polarization of a bound proton is as high as that of a neutron one, so a correction due to re-scattering from the proton is large. In the case of the ${ }^{3} \mathrm{He}$ target, there are two protons, which doubles the probability of re-scattering, but their combined effect in asymmetry is still much smaller than in the HD case due to low polarization of the protons in ${ }^{3} \mathrm{He}$.

We propose to base the design of the hadron arm on the Super Bigbite Spectrometer [38]. The concept and design of this spectrometer were initiated by the GEp(5)experiment [39], which will measure the proton form factors ratio at very large momentum transfer. The acceptance of the SBS can cover the range of 1 to 2 radians in azimuthal angle (in the beam coordinate system), and $5^{\circ}$ to $10^{\circ}$ in polar angle, depending on the central scattering angle, $\theta_{\text {central }}$. At a polar angle of $14^{\circ}$, the solid angle of the SBS allows the capture of a significant part of the reaction products from semi-inclusive processes in one setting of the detector. The large solid angle, wide momentum acceptance from 1 GeV and up, resolution of $1 \%$, and the ability to detect particles of both polarities combine to make the SBS a very attractive hadron arm. The compact geometry of this hadron arm makes it easy to configure an optimized electron arm based on the existing BigBite spectrometer. Figure 2.1 shows a schematic representation of the combined angular acceptance of the hadron arm and the electron arm.


Figure 2.1: The schematic angular acceptance of the setup with SBS and BB viewed along the beam direction. The central angles are: $\theta_{e}=30^{\circ}$ for BB and $\theta_{h}=14^{\circ}$ for SBS. Azimuthal ranges with respect to the beam are: $\pm 24^{\circ}$ for BB and $\pm 30^{\circ}$ for SBS. The solid angle acceptance of the HRS, which was used as the hadron arm for experiment E06-010, is superimposed on the SBS for comparison.

### 2.2 Physics Goals

We propose to measure the $\pi^{ \pm, 0}$ and $\mathrm{K}^{ \pm}$Single-Spin Asymmetries on a transversely polarized nucleon target at a series of kinematic settings which corresponds to a grid covering the four variables; $x, z, P_{\perp}$, and $\mathrm{Q}^{2}$, with statistical and systematic accuracy better than $0.5 \%$ in twodimensional kinematic bins, and one-to-several percent precision in fully differential $x, z, P_{\perp}, Q^{2}$ bins. The physics goal is to investigate the nature of the $A_{U T}$ asymmetries by means of precision measurements with minimal assumptions about higher-twist role, $\mathrm{Q}^{2}$ evolution, and fragmentation functions.

In fact, we intend to:

- extract, with high statistics, the Sivers and Collins (and Pretzelosity) asymmetries from the measured $A_{U T}$ on both $\pi$ and K;
- provide the asymmetries within a grid: multi-dimensional binning on the relevant variables $\left(x, P_{\perp}\right.$ and $z$ for all five mesons $\left(\pi^{+}, \pi^{-}, \pi^{0}, K^{+}, K^{-}\right)$);
- provide the $Q^{2}$ dependence in the range detailed in chapter 5 ;
- explore for the first time the high $x$ valence region (with partial overlap to HERMES, COMPASS and JLab-6GeV data); and
- Realize a multi-parameter fitting of the asymmetries using unbinned experimental data.


### 2.3 Kinematics

The choice of kinematics is driven by a number of considerations, among them the intent to

- maximize $W$ - the hadronic system invariant mass,
- maximize $W^{\prime}$ - same as $W$, minus the detected hadron, and
- align the hadron spectrometer central angle close to the virtual photon.

Optimization of the main parameters determined that the electron arm will be at a fixed angle of $30^{\circ}$ and the hadron arm at $14^{\circ}$. The distributions of events are presented in the figures of Sec. 5. The kinematic binning in $x$ and the corresponding average $Q^{2}$ values are summarized in Table 2.1.

| Run | A | B |
| ---: | :---: | :---: |
| $E_{\text {beam }}(\mathrm{GeV})$ | 8.8 | 11 |
| $x$ range | $\left\langle Q^{2}\right\rangle\left(\mathrm{GeV}^{2}\right)$ | $\left\langle Q^{2}\right\rangle\left(\mathrm{GeV}^{2}\right)$ |
| $0.1<x<0.2$ | 2.4 | 3.2 |
| $0.2<x<0.3$ | 3.4 | 4.4 |
| $0.3<x<0.4$ | 4.4 | 5.8 |
| $0.4<x<0.5$ | 5.4 | 7.1 |
| $0.5<x<0.6$ | 6.3 | 8.4 |
| $0.6<x<0.7$ | 7.0 | 9.5 |

Table 2.1: The DIS kinematics of the proposed data points: approximate average $Q^{2}$ values for different $x$ bins.

The proposed kinematic grid has $6 x$ bins in $0.1<x<0.7$ for both beam energies, $5 z$ bins in $0.2(0.25)<z<0.7(0.75)$ for $E=11(8.8) \mathrm{GeV}$, and 6 (5) $P_{\perp}$ bins in $0<P_{\perp}<1.2 \mathrm{GeV}\left(0<P_{\perp}<1\right.$ $\mathrm{GeV})$ for $E=11(8.8) \mathrm{GeV}$. Rates and expected statistics will be discussed in section 5 .

### 2.4 Systematics

The small amplitudes of the Sivers and Collins asymmetries on ${ }^{3} \mathrm{He}$ and the high statistical precision of the proposed measurements require the development of methods to suppress systematic uncertainties. There are systematic uncertainties in the experimental data and systematic uncertainties in the extraction procedure for the nucleon data from the raw observables. The latter is of special concern for the neutron transversity experiment because the neutrons are always bound in nuclei.

Experimental systematics Changing the target polarization direction at regular intervals is a standard but important procedure for reducing systematics. For example, the polarization of the internal target was changed every $60-90$ seconds in the HERMES experiment. Changing the polarization direction for solid $\mathrm{NH}_{3}, \mathrm{ND}_{3}$, HD targets and high pressure ${ }^{3} \mathrm{He}$ targets is more complicated and requires much more time. For example, the E06-010 experiment [40] uses 20 minute intervals between changes. The new idea of the convection flow ${ }^{3} \mathrm{He}$ target, which was proposed and checked recently by our collaboration, allows a novel approach to the spin-direction change. We plan to rotate the direction of the target holding field without change of the field in the polarization pumping cell. Compensation coils will be used to provide a stable beam on the target. We
expect that spin-direction will be changed every 120 seconds with a new polarized target approach (see section 4) without any loss of polarization and without significant dead time for the transition period.

Another important source of systematic uncertainty is the effect of the finite acceptance on the extraction of target spin-dependent and -independent azimuthal modulations of the SIDIS cross section. A natural solution is to take a fraction of the data using an unpolarized target, which will help to disentangle the effects of acceptance and "unwanted" azimuthal modulations of the unpolarized cross section which could contaminate the extraction of the target spin-dependent Collins and Sivers moments. Additionally, we will reverse the polarity of the SBS magnet at regular intervals. In both magnet polarities, both $\pi^{ \pm}$and $K^{ \pm}$will be detected simultaneously, and since the detectors will be oriented vertically, the SBS acceptance will be symmetric and (nominally) the same for up- and down-bending particles. Reversal of the magnet polarity will cancel out any residual systematic differences in acceptance between positively and negatively charged particles, and will also increase the vertical angle acceptance of the hadron arm by taking data for each hadron charge in both upbending and downbending configurations, thereby increasing the effective $\phi$ coverage and further reducing the systematics on the extraction of azimuthal moments due to finite $\phi$ coverage. The beam helicity asymmetry (when the polarization of the target is in the horizontal plane) will also be used to monitor the stability of the apparatus.

Extraction procedure systematics The measurement of polarization asymmetries in the SIDIS process is complicated by several effects:

- scattering of the final hadron in the material of the target,
- charge exchange of the hadron in the material of the target,
- final state interaction of the hadron in the nucleus during the production process, and
- effect of the nucleon orbital momentum in the nucleus during the production process.

The first two effects could be taken into account using experimental data for the pion-nucleus right-left asymmetry. For the last two effects, there are a few calculations which are not consistent between themselves. The known estimate of the size of the polarized FSI effect in the neutron Sivers asymmetry extracted from ${ }^{3} \mathrm{He}\left(\mathrm{e}, \mathrm{e}^{\prime} \pi^{ \pm}\right.$) measurement is relatively large ( of order $1 \%$ according to Ref. [1]).

We expect that the effect could be calculated to a $10-20 \%$ fraction of its value [41]. In such a case the systematic uncertainty will be comparable to the projected statistical accuracy of the proposed experiment. In the present experiment we plan to measure the asymmetries for the charged as well as for the neutral pion channels, which will allow an independent test of the calculations.

## Chapter 3

## Experimental Setup

The experiment will be performed in the TJNAF Hall A using the Super Bigbite [42] and the BigBite magnetic spectrometers. An electron beam will pass through a $60-\mathrm{cm}$ long polarized ${ }^{3} \mathrm{He}$ target. The scattered electrons will be detected in the BigBite spectrometer and the SIDIS pions and kaons will be detected in the Super Bigbite spectrometer (SBS).

The total projected luminosity is of $2 \times 10^{37}$ electron-nucleon $\mathrm{Hz} / \mathrm{cm}^{2}$, which corresponds to about $4 \times 10^{36}$ electron-polarized neutron (see the beam and target parameters below). Such electron-polarized nucleon luminosity is about 400,000 times higher than the luminosity used in the HERMES experiment and about 3-4 times higher than any previous experiment involving a polarized ${ }^{3} \mathrm{He}$ target. There is only one element of the proposed experiment which needs to be added exclusively for this measurement. This element is a Ring Imaging CHerenkov counter in the SBS spectrometer for high quality hadron identification. As presented later, we plan to reuse the HERMES RICH, properly adapted for SBS.

The layout of the proposed experimental set-up is shown in Fig. 3.1. There are two detector arms: the electron arm and the hadron arm. They are located at $30^{\circ}$ and $14^{\circ}$ on opposite sides of the beam line.

The measurement of the target single-spin asymmetry presents a significant challenge for the control of the target and detector stability because of the relatively long time between target polarization changes. We have found a method (see the next chapter) to shorten this time to 120 seconds, which is 10 times shorter than was possible before. We plan to use a set of compensation coils located upstream and downstream of the target to nullify the beam position and direction changes when the direction of the holding field varies.

The data acquisition system for this experiment will include the FastBus TDCs 1877S and the custom VME electronics for GEM chambers. A simple trigger based on signals from two calorimeters will be used. The DAQ system with data sparsification will allow a trigger rate of 18 kHz with less than $10 \%$ dead time.

### 3.1 CEBAF polarized beam

We plan to use a $40 \mu \mathrm{~A}$ beam with $85 \%$ polarization. This value of polarization has already been obtained in many JLab experiments. The beam polarization will be measured with the Hall A Møller/Compton polarimeters to make sure that it is maintained at maximum level. The stability


Figure 3.1: Schematic view of the SIDIS two-arm setup.
of the beam polarization will be continuously monitored by the Compton polarimeter.

### 3.2 Novel polarized target

A full description of the polarized ${ }^{3} \mathrm{He}$ target is presented in Sec. 4. Here we list the key parameters:

- The target length is 60 cm .
- The gas pressure is 10 atm .
- The beam path outside the target is in a vacuum.
- The total thickness (weight) is $115 \mathrm{mg} / \mathrm{cm}^{2}$.
- The ${ }^{3} \mathrm{He}$ thickness (weight) is $75 \mathrm{mg} / \mathrm{cm}^{2}$.
- The Neutron thickness (weight) is $25 \mathrm{mg} / \mathrm{cm}^{2}$.


### 3.3 Online monitors

The stability of the product of the beam and the target polarizations will also be monitored. We plan to do this by using a stand-alone shower calorimeter located in the plane of the target polarization. As it was observed during the GEn experiment [43], the counting rate in such a counter has significant helicity dependence due to double spin asymmetry in the $\vec{\gamma} \vec{n} \rightarrow \pi^{\circ} X$ process. The large rate in such a counter allows very quick detection of problems. Because the beam polarization
is relatively stable, any change in the double spin asymmetry could indicate a change in the target polarization.

Additional monitoring of the beam stability will be done by using the HAPPEX system of the beam parameter monitoring and the Lumi monitors, which are located at a small angle with respect to the beam line downstream of the target $\left(1.5^{\circ}\right)$. The scalers, gated by the signals according to the beam helicity and the target polarization directions, will be used for the beam charge measurement, the triggers rates, and the counting rates of selected individual detectors.

### 3.4 Luminosity, Beam line, and Shielding considerations

The background rate in the detector is a key consideration which puts strong constraints on the performance of every experiment. The configuration of the present experiment is the most efficient because the detectors are located behind large dipole magnets with field integrals of 1 Tm in BigBite and 2 Tm in SBS. Behind such dipoles the detectors are relatively calm. For example, we found experimentally that the rate of BigBite MWDC drops by a factor of 15 when the magnet is ON. The design of the polarized targets used in all previous experiments in Hall A included a large amount of material on the beam line. For example, in E06-010 the total amount was $317 \mathrm{mg} / \mathrm{cm}^{2}$, of which only $49 \mathrm{mg} / \mathrm{cm}^{2}$ is $\mathrm{He}-3$, while glass windows of the cell and vacuum windows with air $/{ }^{4} \mathrm{He}$ constitute the rest.

The new design of the He-3 target developed by the UVa group will use a cell with Be windows in a vacuum with a total amount of material of about $115 \mathrm{mg} / \mathrm{cm}^{2}$ in spite of the larger amount of He-3 in a 60 cm long target. Such a reduction of the material budget will allow us to increase the beam current to $40 \mu \mathrm{~A}$ without a considerable increase in total luminosity.

Extensive Monte Carlo simulations were performed for the development of the SBS project. They included MCs of the previous experiments with BigBite and optimization of the SBS beam line structure [42]. Two main results from these studies are: The beam line diameter should be as large as possible, and the beam line should be shielded by at least 5 cm of lead from the beginning of the narrow part for at least 10 meters. In other words, the narrow pipe of the beam line after the target is a primary source of background, which produces a long shower requiring up to 20 radiation length for absorption. MC simulations performed for the SBS and later for BigBite confirmed that coverage of the beam line by a lead pipe of 5 cm thickness allows a factor of 3 reduction of the rate in detectors. Such shielding is a part of the present experimental proposal in which the detectors are located at relatively large angles behind dipoles.

### 3.5 Super Bigbite Spectrometer

The spectrometer was conceived of as a part of an approved experiment, E12-07-109, which will measure the proton form factor ratio at momentum transfers up to $12 \mathrm{GeV}^{2}$. The spectrometer, SBS, in the proposed experiment includes a dipole, a high resolution tracker, a Ring Imaging CHerenkov counter, and a segmented calorimeter as a trigger. The important feature of SBS, which could be placed at forward angles from $3.5^{\circ}$, is a beam path through a cut in the right yoke of the magnet. Such a configuration is known in the field of accelerator design as a Lamberson magnet, often used for the vertical injection into synchrotrons. Figure 3.2 presents a concept of the beam line arrangement and resulting field on the beam line. Another important feature of SBS



Figure 3.2: The concept of the beam path through a yoke of the 48D48 dipole.
is a high resolution tracker with a high rate capability based on Gas Electron Multiplier detectors invented by F. Sauli [44]. The E12-07-1009, GEp(5), experiment will require construction of three trackers: The first tracker, FT, for the momentum analysis of the recoil proton, the second tracker, ST, and the third one, TT, for two polarimeters (needed for the GEp(5)experiment). The FT tracker has an area of $40 \mathrm{~cm} \times 150 \mathrm{~cm}$ and consists of six chambers. The ST tracker has an area of $50 \mathrm{~cm} \times 200 \mathrm{~cm}$ and consists of four chambers. All chambers are built from 40 cm by 50 cm modules.

For the proposed SIDIS experiment, the magnet will be placed at a distance of 245 cm from the target to the return yoke, providing a solid angle of 40 msr , as shown in Figure 3.3. The magnet inter-pole gap has a width of 46 cm , so at $14^{\circ}$ central angle of SBS, the 60 cm long target will be seen with full solid angle. The magnet is followed by a tracker, a RICH counter, and a hadron calorimeter, HCAL. After the GEp(5) experiment, four planes of the FT tracker (and one large GEM chamber from ST) will be used behind the BigBite magnet (an electron arm of SIDIS), and $\mathrm{ST} / \mathrm{TT}$ will be placed closer to the SBS magnet to provide the full 50 cm by 200 cm area coverage with five chambers (with a nominal 0.4 mm pitch readout density). The tracker will be followed by a large area RICH counter. Figure 3.4 shows the configuration of SBS for the proposed SIDIS experiment.

A scintillator fiber detector will be placed behind the RICH mirror. The modules of this detector are under construction for the $\operatorname{GEp}(5)$ electron arm. It will use the $2 \times 2 \mathrm{~mm}^{2}$ cross section 800 mm long fibers and 16 -channel maPMTs for readout. In the proposed experiment the SciFi detector will cover the front face of the hadron calorimeter. The accurate measurement of the track vertical coordinate near the calorimeter will allow very simple and reliable data analysis.

Table 3.1 shows the parameters of SBS as it will be used in the proposed experiment. The vertex resolution of SBS is about 1.1 cm , allowing very effective suppression of background from the end-cap windows of the target cell as well as suppression of accidental events by using the correlation between the vertices reconstructed in the electron arm and in the hadron arm.


Figure 3.3: Solid angle acceptance of SBS at a central angle of $14^{\circ}$ and a distance of 245 cm , as a function of momentum (left panel) and vertex coordinate along the beamline (right panel). The average effective solid angle for $p \geq 2 \mathrm{GeV}$ is 40 msr .

| SBS parameter | Symbol | Unit | Value |
| :---: | :---: | :---: | :---: |
| Distance from the target to the first tracker plane |  | $(\mathrm{cm})$ | 345 |
| Central angle | $\theta_{c}$ | $($ degree $)$ | 14 |
| Horizontal angular range | $\Delta \theta_{h}$ | (degree) | $\pm 3.6$ |
| Vertical angular range | $\Delta \theta_{v}$ | (degree) | $\pm 12$ |
| Momentum resolution | $\delta_{p} / p$ | $(\%)$ | $0.03 p+0.29$ |
| Horizontal angular resolution | $\sigma_{\theta_{h}}$ | $(\mathrm{mrad})$ | $0.09+0.59 / p$ |
| Vertical angular resolution | $\sigma_{\theta_{v}}$ | $(\mathrm{mrad})$ | $0.14+1.34 / p$ |
| Vertex resolution (along beam) | $\sigma_{y}$ | $(\mathrm{~mm})$ | $(0.53+4.49 / p) / \sin \theta_{c}$ |

Table 3.1: The parameters of SBS in the SIDIS experiment with all detector acceptances taken into account.

### 3.5.1 RICH detector

One key aspect of the proposed experiment will be the extraction of the transverse asymmetry for both pions and kaons; since the population of kaons is expected to be about 1 order of magnitude less than that for pions, and of the same order as that of protons, a good hadron identification system is required (rejection better than 1:100). Such a system will consist of a RICH detector.

The concept of the RICH, the design and even most of the components are from the dual radiator HERMES experiment ${ }^{1}$, where the counter provided excellent PID over the required momentum range for the pions and the kaons [45].

Fig. 3.5 shows the arrangement of the components in the HERMES RICH counter, while fig.

[^4]

Figure 3.4: Schematic view of the SBS with the detector for the SIDIS experiment.
3.6 presents a schematic view of the working principle of the dual radiator RICH:

- Over threshold charged hadrons produce Cherenkov photons in a $5-\mathrm{cm}$ thick aerogel wall at the entrance of the detector and possibly along the gas filling the gap between the aerogel and mirrors.
- The generated photons are reflected by an array of focusing mirrors ${ }^{2}$ on a regular matrix of 3/4" diameter PMTs which sits approximately in the focal surface of the mirrors.
- The signal from the PMTs, with a characteristic rise time of $\approx 2 \mathrm{~ns}$ and duration on the order of 10 ns will be amplified, discriminated and read out by LeCroy 1877S Fastbus TDCs with 0.5 ns count resolution. In the offline analysis, the correlation between the RICH and HCAL timing signals with a width of the timing window of 10 ns will be used to achieve a very high signal-to-noise ratio for the RICH reconstruction.

The HERMES RICH has an entrance window of $187 \times 46 \mathrm{~cm}^{2}$, which fits quite well in the SBS acceptance. The orientation of the RICH longer side will be vertical (as shown in Fig. 3.7), rotated by 90 degrees with respect to the original horizontal setting in HERMES. The open geometry of SBS allows the required space for a relatively easy implementation and installation of the RICH.

Fig. 3.8 shows the performance of the HERMES counter, which has been very stable during the whole period of operation at HERMES (from 1997 to 2007) [46].

Even at the much higher proposed luminosity compared with the HERMES experiment, the small area of the ring images of charged pions and kaons, when combined with the track information and precise momentum reconstruction from the GEMs, will result in very clean and reliable event reconstruction, as detailed in sections 3.5.2 and 5 .

[^5]

Figure 3.5: The 3D CAD view of the HERMES RICH counter.


Figure 3.6: Schematic view of the HERMES RICH working principle.


Figure 3.7: Schematic 3D view of the HERMES RICH in the Super BigBite spectrometer.


Figure 3.8: PID results from the RICH counter in HERMES.

### 3.5.2 Counting Rates of the Super Bigbite Detectors

In this section we present the counting rate of the individual detectors in the SBS spectrometer and the considerations related to handling of the background rates.

## GEM tracker counting rates

The GEM tracker of the proposed experiment will be assembled from the GEp(5) polarimeter GEM chambers which will be constructed by the UVa group as a part of the SBS spectrometer project.

At the proposed luminosity, the hit rate in the GEM chamber was estimated at $40 \mathrm{kHz} / \mathrm{cm}^{2}$, which represents no difficulty for the operation of GEMs, which can tolerate rates up to $50 \mathrm{MHz} / \mathrm{cm}^{2}$. The key parameter of interest is the effective time resolution of the GEM chamber, which defines the chamber raw occupancy for the track search procedure. We found that for background conditions of the $\mathrm{GEp}(5)$ experiment, such an occupancy is about $11 \%$, and effective memory time of the system (the chamber with the electronics) is less than 75 ns . The occupancy in SIDIS will be below $0.5 \%$ because of much lower luminosity and a larger distance between the detector and target.

The total counting rate in a whole GEM chamber is expected to be of $300-400 \mathrm{MHz}$. The number of accidental hits per event per chamber after the time cut is applied will be 20-30. The reconstruction of the particle track in SIDIS experiment from the GEM tracker data was evaluated using a complete MC simulation and reconstruction analysis package developed for the GEp(5) configuration [47]. We used the MC data produced with the $10 \% \mathrm{GEp}(5)$ luminosity, which is four times higher than the SIDIS luminosity. In the SIDIS case we consider tracks with arbitrary direction in contrast to $\operatorname{GEp}(5)$, where the proton track has a strong correlation with the electron scattering angle. We found the efficiency of track finding is above $95 \%$, and the probability of extra (false) tracks is below $2 \%$ per event even before use of a coordinate and timing information from the Hadron Calorimeter. A further step in analysis will use a time-of-flight (time between signals of the Hadron Calorimeter in SBS and the Shower Calorimeter in BigBite) whose resolution is of 0.5 ns . This will allow a 5 ns wide time window in off-line analysis and a reduction of the false track probability by a factor of 6 compared with the online 30 ns time window.

The significant counting rate of the charged pions $(2 / 3$ of the total rate in SBS) leads to the accidental tracks. With 2 MHz of such tracks and better than 75 ns resolution time of the GEM chamber, the expected fraction of events with one accidental track is below $15 \%$. For each track, a corresponding hit in HCal will be identified, the accurate time information of which will allow us to put a ToF cut of 5 ns and reduce the accidental track fraction to $1 \%$.

The next powerful cut is based on the vertex-vertex correlation between the two arms, which has a rejection capability factor of 10 or more.

## RICH detector counting rates

The particle identification requirements of this experiment demand the use of aerogel in the RICH detector. The refraction index of the aerogel in the HERMES RICH is 1.03 and the thickness is 5.65 cm , resulting in a total weight of $\approx 0.8 \mathrm{~g} / \mathrm{cm}^{2}$. The electron Cherenkov threshold energy in this aerogel is 2.1 MeV . While the magnet of the SBS shields the RICH detector from low-energy charged particles originating in the target, low energy photons produced by the interaction of the beam with the target can reach the detector. These photons produce secondary electrons in the aerogel primarily via Compton scattering and pair production. Some of the secondary electrons


Figure 3.9: Left: the layout of important components of the SBS in GEANT for estimation of the RICH background rate. "PMT window glass" includes both the PMT windows and the quartz gas seal window. Right: the same experimental setup, with added illustrative lead shielding of the beamline and the PMTs. The additional shielding illustrated on the right panel reduced the estimated background rates in the detectors by roughly a factor of two. See text for details.
can produce Cherenkov light in the aerogel, which can reach the photon detector of the RICH and lead to a large counding rate.

The effect of this background on the RICH counting rates was calculated using Pavel Degtiarenko's GEANT3.21-based MCWORKS package, which is widely used throughout JLab for radiation budget and background rate calculations, and has been benchmarked against experimental data in many different configurations. The software contains a detailed layout of the beamline, beam dump and other aspects of the geometry of Hall A. We modified this code to include essential components of this experiment relevant to the calculation of the RICH background counting rate. These include a $60-\mathrm{cm}{ }^{3} \mathrm{He}$ target at 10 atm , enclosed in a standard glass cell (the simulation could be modified for different cell geometries and materials as described in section 4), the SBS magnet with a simplified magnetic field description consisting of a uniform 16.4 kG field in the magnet gap (resulting in a field integral of 2.0 Tm ), a realistic implementation of the hadronic calorimeter HCAL, the aerogel wall as described above, the borosilicate glass windows of the PMTs of the RICH detector ${ }^{3}$ (approximately 3 mm thick at a density of $2.2 \mathrm{~g} / \mathrm{cm}^{3}$ ), and the 2 mm -thick quartz window that provides the gas seal isolating the detector active area from the sensitive $C_{4} F_{10}$ gas volume [45]. The layout of elements of the SBS setup in JLab Hall A relevant to the RICH background rate estimation is shown in figure 3.9.

[^6]For a given number of incident beam electrons at 11 GeV , the energies, trajectories and coordinates of all primary and secondary electrons and positrons produced in the aerogel and the PMT and quartz windows, regardless of origin or production mechanism, were recorded in an ntuple once per event. This ntuple was then analyzed by a second, stand-alone Monte Carlo simulation which was used to calculate the Cherenkov photon yield. The average number of Cherenkov photons emitted by an electron or positron $\left(z^{2}=1\right)$ above threshold in a path length $d x$ and wavelength interval $d \lambda$ is given by
bibitemwiser D.E. Wiser, Ph.D. Thesis, University of Wisconsin-Madison (1977) (unpublished).

$$
\begin{equation*}
\frac{d^{2} N}{d x d \lambda}=\frac{2 \pi \alpha z^{2}}{\lambda^{2}}\left(1-\frac{1}{\beta^{2} n^{2}}\right) \tag{3.1}
\end{equation*}
$$

where $n$ is the index of refraction of the medium. Making the simplifying assumption that the index of refraction is wavelength-independent, the number of Cherenkov photons emitted per unit path length is calculated by integrating (3.1) in the range $\lambda_{1}=250 \mathrm{~nm}$ to $\lambda_{2}=700 \mathrm{~nm}^{4}$ :

$$
\begin{align*}
\frac{d N}{d x} & =\frac{\pi \alpha\left(\lambda_{2}-\lambda_{1}\right)}{\lambda_{2} \lambda_{1}}\left(1-\frac{1}{\beta^{2} n^{2}}\right) \\
& \approx 590\left(1-\frac{1}{1.06 \beta^{2}}\right) \mathrm{cm}^{-1} \tag{3.2}
\end{align*}
$$

For a high-energy $(\beta \rightarrow 1)$ electron, the number of photons emitted per cm of aerogel is 33 .
The total rate of electrons and positrons produced above threshold in the aerogel for a beam current of $40 \mu \mathrm{~A}$ is about 240 MHz . To calculate the rate of PMT hits due to this background, a simple Monte Carlo calculation of the photon yield was performed. First, the path length of each electron in the aerogel was estimated as the lesser of the distance to the aerogel boundary along the electron trajectory or the NIST "ESTAR" range for electrons in aerogel obtained from a lookup table as a function of the electron kinetic energy. The simplifying assumption was made that the electrons emit Cherenkov light as if they were traveling at a constant velocity equal to their initial velocity along their whole path length. Since in reality the electrons are slowing down appreciably within the aerogel as they lose energy through radiation and ionization, our calculation represents an upper limit on the number of photons emitted.

For each electron track, the number of emitted photons was sampled from a Poisson distribution about the average number calculated using equation (3.2). The emission angle $\cos \theta_{C}=1 / n \beta$ was determined from the electron velocity, and the azimuthal angle of emission was generated randomly in $0 \leq \phi_{C} \leq 2 \pi$. Finally, the emission vertex for each photon was generated randomly along the path of the electron in aerogel. The Monte-Carlo generated Cherenkov photons were then projected to the (spherical) mirror, where the reflection probability was assumed to be $100 \%$ if the photon hit the mirror and $0 \%$ otherwise. The reflected photon trajectories were finally projected to the detector plane, where geometrical cuts were applied to determine whether the photons hit the detector. The assumed geometries of the mirror and detector, which were reasonably accurate idealized versions of their true geometries in the HERMES RICH counter, were validated by calculating the photon yield and collection efficiency for high-energy muon tracks propagating along the central axis of the detector. For these tracks, the geometric collection efficiency of the idealized geometry is $100 \%$. However, the packing fraction of the PMT photocathodes on the surface of the detector is not 1 .

[^7]As a first approximation, we multiply the average number of photons per event by the number of PMTs times the area of one PMT $\left(=\pi R^{2}=2.85 \mathrm{~cm}^{2}\right)$ and divide by the total area of the detector surface. This results in an average of 115 photons per high-energy charged track, given all the assumptions made in our calculation.

The distribution of the counting rate across the detector plane is shown in figure 3.10. Our results are summarized in Table 3.2.

| Beamline+detector Pb shielding? | No | Yes |
| :---: | :---: | :---: |
| Total rate of $n \beta>1$ electrons in aerogel $(\mathrm{MHz})$ | 244 | 73 |
| Area of PMT $\left(\mathrm{cm}^{2}\right)$ | 2.85 | 2.85 |
| Total detector area $\left(\mathrm{cm}^{2}\right)$ | 9257 | 9257 |
| Number of PMTs | 1934 | 1934 |
| Packing fraction $(\%)$ | 60 | 60 |
| Monte Carlo $N_{\text {Cherenkov }}(\beta=1)$ | 115 | 115 |
| HERMES $N_{P M T \text { erogel }}^{\text {ali }}(\beta=1)$ | 10 | 10 |
| Normalization factor | 0.087 | 0.087 |
| $<d N / d t>_{\text {background }}$, Aerogel $(\mathrm{kHz} / \mathrm{PMT})$ | 111 | 65 |
| $<d N / d t>$ background, Glass + Quartz $(\mathrm{kHz} / \mathrm{PMT})$ | 28 | 17 |
| Average total rate $(\mathrm{kHz} / \mathrm{PMT})$ | 139 | 82 |
| Average PMT occupancy $(\Delta t=10 \mathrm{~ns})(\%)$ | 0.139 | 0.082 |

Table 3.2: Summary of GEANT simulation results for RICH background counting rates, $E_{\text {beam }}=$ $11 \mathrm{GeV} / \mathrm{c}$. The left (right) column corresponds to the beamline shielding configuration left (right) panel of Figure 3.9. See text for details.

To normalize the results of our calculation of the photon yield to a detector counting rate, we use the experimentally observed fact that the average number of hit PMTs per high-energy charged track in the HERMES RICH counter is about 10 [45]. Since our estimate of the number of photons emitted by a high-energy charged track moving along the axis of the aerogel, collected by the mirror and reflected to the detector plane, normalized to the fraction of the detector area that is active is 115 , the proper conversion factor from photon yield to counting rate in our simulation is approximately $8.7 \%$. Under this assumption, the average rate of background hits is about 111 (65) kHz per PMT without (with) the additional lead shielding of the beamline and detectors illustrated in the right panel of figure 3.9.

The next most important contribution to the background counting rate in the SBS RICH detector is the direct interaction of the background with the borosilicate "UV glass" windows of the PMTs and the quartz window providing the gas seal for the detector volume. This material was described in GEANT with an assumed thickness of 3 mm and using the mass fraction data for Pyrex Corning borosilicate glass obtained from the Particle Data Group [48]. Because the PMT matrix does not have direct line-of-sight to the target, the production rates are generally much lower, but they must still be estimated, because a large fraction of electrons that enter or are produced in the PMT windows will produce a signal.

Tests using one of the HERMES RICH PMTs with a radioactive source and a scintillation detector also instrumented by a PMT (see section 3.6.1) determined that the average probability of a PMT hit when an electron interacts with the glass of the PMT window is approximately 0.39 .


Figure 3.10: Results of GEANT simulation of the RICH counting rate due to the interaction of soft photon backgrounds with the aerogel wall. Left(right): Counting rate per PMT as a function of the $x(y)$ (horizontal(vertical)) coordinate at the detector plane. The black points show the results with no added shielding of the beamline, while the red points show the result with added lead shielding of the beamline, illustrating the reduction in background rate and the better uniformity of the distribution of said rate from added shielding, with the remaining background coming predominantly from the target (The $+x$ direction in the detector coordinate system is closest to the beamline.)

Assuming that this probability holds (on average) for the background, we estimated the hit rate on the PMTs due to direct interaction of the background with the PMT windows as roughly 28 (17) kHz per PMT without (with) additional beamline and detector shielding, about one-fourth of the background counting rate from aerogel. In contrast to the aerogel, the PMT glass and quartz windows are not located directly in view of the target. However, the Cherenkov threshold in the PMT window glass ( $\mathrm{n}=1.48$ ) is much lower than the threshold in aerogel; therefore, lowerenergy backgrounds reaching the glass indirectly from the beamline after one or more "bounces" have a higher signal probability than the electrons produced in aerogel: Hence, the $39 \%$ empirical probability of a signal for electrons produced directly in the glass compared to about $9 \%$ for aerogel. Combining the aerogel and "direct" PMT glass interaction rates due to low energy neutral (photon) backgrounds gives a total rate of 139 (82) kHz/PMT background counting rate which, in combination with the TDC readout and tight timing window which we will implement, results in a very low occupancy on the order of $10^{-3}$ for the proposed experimental configuration.

While additional, more detailed simulations of the RICH performance in the proposed configuration are ongoing, including a full GEANT4 description of the RICH geometry for studies of detector response and event reconstruction, the basic results obtained here already demonstrate that the counting rates under the proposed luminosity will be manageable, with a considerable "safety margin" of at least an order of magnitude, assuming the implementation of a TDC readout for the PMT signals ${ }^{5}$.

## HCAL counting rates and the SBS trigger



Figure 3.11: The counting rate in the hadron calorimeter of SBS.
The calorimeter counting rate vs. the threshold energy is presented in Fig. 3.11 obtained from

[^8]

Figure 3.12: Effective solid angle of BigBite as a function of the vertex position along the $60-\mathrm{cm}$ target.
the "Wiser" code [49]. The counting rate for the threshold of 1.5 GeV is about 3 MHz , which means the probability of a second hit in a 30 ns time window relative to the electron time signal will be $9 \%$. The corresponding false tracks will be rejected using the time coincidence between the hadronic calorimeter and the electron arm calorimeter and the correlation of its vertex position at the target with that of the electron arm.

### 3.6 BigBite Spectrometer

The spectrometer has a 96 msr solid angle when it is used with a short target at a nominal position with 110 cm from the target to the magnet yoke. Figure 3.13 shows the side view of BigBite as it was used during the GEN1 experiment. However, when the BigBite magnet is placed at $30^{\circ}$, the distance between the target and the magnet yoke must be 155 cm due to geometry constraints. The electron detector package includes a tracker, a Gas Cherenkov counter, a twolayer electromagnetic calorimeter, and a scintillator hodoscope. The average value of the solid angle for a 60 cm long target was found to be on the order of 60 msr , see Fig. 3.12.

The BigBite detector package will be upgraded with the four GEM chambers ( 40 cm by 150 cm ), a new segmented Gas Cherenkov Counter (under construction for the A1n experiment), a large 50 cm by 200 cm GEM chamber (from the package of the GEp(5) experiment), followed by an existing two-layer lead-glass calorimeter made of 243 blocks of $8.5 \times 8.5 \times 35 \mathrm{~cm}^{3}$ dimensions. We plan also to use a new highly segmented scintillator hodoscope of 90 two-PMT counters between the two layers of the calorimeter (also under construction for the A1n experiment).

The Monte Carlo simulations of the transversity experiment (already performed using the BigBite spectrometer) were made [50]. The calculated counting rate of the wire chambers was found to be of $95 \%$ of the experimental value, which is a very good agreement. For the proposed experiment, the counting rate of the GEM tracking package was calculated using the same Monte Carlo package
with full structure of the GEM. The obtained counting rate is below 90 MHz in the whole active area for the projected luminosity of the proposed experiment. At such a rate in a full chamber the number of hits per event per plane is 7 . The projected probability of one or more false track in an event is below $1 \%$. Even if all triggers are due to charged particles (trigger rate is 200 kHz ), the probability of an accidental track is $1.5 \%$. It was observed in all recent experiments with BigBite that only $10 \%$ of triggers have a corresponding track and the other $90 \%$ are due to photon induced signals in the calorimeter, so the actual probability of an accidental track is $0.2 \%$.


Figure 3.13: The side view of the BigBite spectrometer.

### 3.6.1 Counting Rates of the BigBite Detectors

Tracker At the projected luminosity of this experiment, the expected hit rate in the BigBite tracker will be less than $20 \mathrm{kHz} / \mathrm{cm}^{2}$. Such a rate is comfortable for GEM trackers which can operate at rates up to $50 \mathrm{MHz} / \mathrm{cm}^{2}$. Track reconstruction efficiency expected to be above $95 \%$ base on the discussed above considerations for the Super BigBite tracker and experimental results for the MWDC tracker in BgBite.

## Lead-glass calorimeter

In a large solid-angle open geometry spectrometer such as BigBite the requirements of the trigger detector are very different than in a small solid-angle large bend-angle spectrometer such as the HRS. Instead of a pair of thin scintillator counters as the trigger is made in the HRS [51], the BigBite trigger uses the full energy of the scattered electrons. The energy is measured by the
segmented shower calorimeter, see Fig. 3.13. The operation of the shower detector of BigBite is also well understood from our previous experiments [43, 40]. The expected counting rate of the lead-glass calorimeter in the proposed experiment is shown in Fig. 3.14 as a function of the threshold. The threshold level of 1 GeV , which is required in this experiment for the lowest $x$ bin,


Figure 3.14: The counting rate of the BigBite calorimeter vs threshold.
will result in a 200 kHz counting rate. Such a high rate presents a major problem for the single arm DAQ; however, with help from the SBS trigger we can use a coincidence and reach a modest rate of DAQ ( 18 kHz ). Because of the Cherenkov nature of the signal in the lead-glass calorimeter and its relatively small thickness of one nuclear interaction length, the dominant source of observed rate is due to neutral pions, which decay to photons efficiently detectable in the lead-glass calorimeter. In the GEn experiment, it was observed that up to $90 \%$ of triggers are due to the photon induced signals in the calorimeter.

## Gas Cherenkov counter

An efficient instrument for pion rejection is a Gas Cherenkov counter. For example, in the Hall A HRS spectrometer, the 10-PMT counter provides reliable pion rejection and can be used on the trigger level. However, in the large angular and momentum acceptance BigBite spectrometer, the optics of Cherenkov rays requires a large area of PMTs. The optics for such a counter was designed [52] with the location of all PMTs at the large angle side (relative to the beam line). According to a study during the d2n experiment [53], the rate of PMTs on the large angle side was of $12 \mathrm{kHz} / \mathrm{cm}^{2}$ of PMT photocathode area at a total luminosity of $1.34 \times 10^{37} \mathrm{~Hz} / \mathrm{cm}^{2}$. In the proposed experiment, projected total luminosity is higher by a factor of 1.5 than it was during the d2n experiment. We plan to use an array of 5501.25 " diameter PMTs for the Cherenkov counter, which will lead to a rate of 95 kHz per PMT. The total rate in the array will be 52 MHz . Such a
rate is too high for direct use in the BigBite trigger. As a result, we plan to use the Gas Cherenkov data for off-line analysis only. When only 20 PMTs of relevant area of array are used with a 10 ns time window, the number of accidental hits per event is expected to be just 0.02 .

The detailed MC simulation of the counting rate in the PMTs for conditions of the d2n experiment, which is very successful in prediction of the MWDC rate, underpredicted the PMT rate by a factor of four. For conditions of the SIDIS proposal, the same MC predicted a counting rate of 56 kHz per PMT. We used a more conservative value ( 95 kHz ) based on interpolation from the d2n data.

### 3.7 Logic of the Experiment Trigger and DAQ rate

The trigger of the hadron arm will use the signal from the hadron calorimeter with a threshold of 1.5 GeV to guarantee efficient detection of hadrons with momenta above 2 GeV . The corresponding trigger rate is about 3 MHz , mainly due to high-energy pions. We will use the trigger of the electron arm, with an expected rate of 200 kHz , as a DAQ trigger in coincidence with that of the hadron arm. Requiring a 30 ns coincidence time window between the trigger signals of the two arms reduces the online DAQ rate to 18 kHz .

The concept of the trigger and data analysis is shown in Fig. 3.15. The DAQ rate of 18 kHz is defined by accidental coincidences between the triggers of the two arms. As illustarted in the figure the off-line analysis will reduce the fraction of accidental events in the event sample below $1 \%$. In such calculation we didn't applied the BigBite preshower/shower PID which allows additonal rejection of pion in the BigBite by a factor of 10 .

Such a DAQ rate will lead to less than $10 \%$ dead time according to our calculations and experimental checks with the FastBus modules. In the SIDIS experiment, the DAQ system of each spectrometer has VME electronics for GEM chambers and HCal, which are pipe line type and essentially dead-time free, and FastBus electronics (LeCroy 1877S TDC), which have the buffering capabilities and the programmable time window for data sparsification. The FastBus will be used for multi PMT Cherenkov counters and BigBite timing hodoscope (total of 6100 channels). The 1877 S TDC allows a very effective reduction of the data volume such that the projected total rate of data readout from the FastBus is $7 \mathrm{Mb} / \mathrm{s}$ or just $15 \%$ of the known capability of a single FastBus crate. The data conversion time in the TDC, which sometimes could be a limiting factor, will be reduced by using a large number of modules and several FastBus crates.

### 3.7.1 Trigger considerations

The BigBite trigger is based on an electromagnetic calorimeter of 243 PMTs. Due to significant variation of the HV on the PMTs, the signal propagation time could vary for individual PMTs by about 10 ns . We plan to measure these variations for each PMT using a correlation between the module, identified by its large signal, and the time between the shower trigger and the signal from a plastic scintillator counter. Delay lines will be inserted between PMTs and summing modules to minimize the time variations. The Hadron calorimeter, which will be used in SBS, has 250 PMTs whose signals will be digitized by FADCs with a 4 ns time step. These signals will be summed in digital form (after proper time corrections) in groups of 16 . The sum- 16 contains the whole hadron shower. The sum- 16 signal corresponding to the energy deposition above 1.5 GeV will be directed to coincidence with the BigBite trigger signal.


Signal $85 \mathrm{~Hz} /$ Acc. 0.15 Hz
Figure 3.15: Concept of the trigger and data analysis.

### 3.7.2 BigBite detector and DAQ

The particle detector for the proposed experiment includes the following subsystems:

1. Gas Cherenkov counter: 550 phototubes;
2. Scintillator hodoscope: $90 \times 2=180$ phototubes;
3. Lead Glass Calorimeter: $(2+7) \times 27=243$ phototubes;
4. Front GEMs : 4 layers $\times 3$ sections $\times(1000+1250)$ strips $=27000$ channels;
5. Rear GEMs : 1 layer $\times 5$ sections $\times(1000+1250)$ strips $=11250$ channels.

The signals from the first three subsystems are going to be digitized by LeCroy FastBus TDCs and ADCs, while the GEM readout is based on the ASIC APV25-S1 and custom-made VME modules [54].

The data rate will be 65 words $\times 4$ byte $\times 0.018 \mathrm{MHz}=4.7 \mathrm{Mb} / \mathrm{sec}$. The FastBus data read rate in the Block Transfer mode achieves $40 \mathrm{Mb} / \mathrm{sec}$. Therefore, with properly arranged event buffering, the dead time in the described case will be defined purely by conversion time in TDC, which does not exceed $6 \mu \mathrm{sec}$. However, to provide such a performance of the DAQ, one must enable the pedestal suppression in ADCs and set a minimal width of the timing gates of TDCs. More details of DAQ setup are provided in technical note [55].

### 3.7.3 Super Bigbite detector and DAQ

The particle detector for the proposed experiment includes the following subsystems:

1. RICH counter: 1934 phototubes;
2. Hadron Calorimeter: $10 \times 25=250$ phototubes;
3. SciFi plane : $2 \times 1650$ fibers $=3300$ PMT channels;
4. Tracker GEMs : 5 layers $\times 5$ sections $\times(1000+1250)$ strips $=56250$ channels.

The signals from the first three subsystems are going to be digitized by LeCroy FastBus TDCs, while GEM readout, as in the BigBite detector, is based on the ASIC APV25-S1 and custom-made VME modules [54].

The data rate will be 48 words $\times 4$ byte $\times 0.018 \mathrm{MHz}=2.6 \mathrm{Mb} / \mathrm{sec}$. As it was in case of BigBite, such a data flux is much lower than the FastBus readout speed capability.

## Chapter 4

## The Polarized ${ }^{3} \mathrm{He}$ Target

This section presents the description of the polarized ${ }^{3} \mathrm{He}$ target which is based on the technique of spin-exchange optical pumping. We note that the target is similar in many respects to the targets that will be used for E12-06-122 (an experiment to measure the DIS neutron spin asymmetry $A_{1}^{n}$ ) and E12-09-016 (an experiment that will measure the electric form factor of the neutron, $G_{E}^{n}$, up to $Q^{2}=10 \mathrm{GeV}^{2}$ ). Both E12-06-122 and E12-09-016 (which we will refer to herein as $A_{1}^{n}$ and GEN-II respectively) are fully approved and have been allocated beam time.

The polarized ${ }^{3} \mathrm{He}$ targets used at JLab have undergone dramatic improvements in performance during the past decade. This is illustrated in Fig. 4.1, in which we show a particular figure-of-merit for ${ }^{3} \mathrm{He}$ targets built for each of four experiments. The figure-of-merit, representing the total number of spins polarized per second, weighted by the polarization squared, has increased dramatically by nearly an order of magnitude. We note that this is an updated version of a figure that appeared in a recent DOE publication that collected together highlights from the various subfields of nuclear physics.


Figure 4.1: Illustrated is the dramatic increase in a particular figure-of-merit, described in the text, for the polarized ${ }^{3} \mathrm{He}$ targets that were utilized in the indicated JLab experiments.

There are two technologies that are largely responsible for the large jumps in performance associated with the experiments shown on Fig. 4.1 that are labeled GEN-I and Transversity. As indicated, GEN-I was the first JLab experiment to utilize "alkali-hybrid" technology. In spinexchange optical pumping, an alkali vapor is optically pumped, and the ${ }^{3} \mathrm{He}$ nuclei are subsequently polarized through spin-exchange collisions. Historically, rubidium ( Rb ) has been used as the alkali
metal. For GEN-I, however, a mixture of Rb and potassium (K) was used which resulted in a large (5-10) increase in the efficiency with which the angular momentum of the polarized alkalimetal atoms was transferred to the ${ }^{3} \mathrm{He}$ nuclei. This made it possible to polarize the gas much more quickly, and to achieve higher saturation polarizations. The technology that made possible the jump in performance associated with the Transversity experiment was the use of spectrallynarrowed lasers. All of the experiments shown utilize high-power diode-laser arrays. The spectral widths of the lasers used for the Transversity experiment, however, were roughly 10 times narrower than had been the case previously. This resulted in nearly a ten-fold increase in the optical pumping rate, something that made it possible to achieve much higher alkali-metal polarizations, and hence, higher ${ }^{3} \mathrm{He}$ polarizations.

While both the GEN-I and Transversity targets benefited from unprecedented performance, it is nevertheless the case that they were limited by a phenomenon we refer to herein as polarization gradients. The design of what is now a typical polarized ${ }^{3} \mathrm{He}$ target cell at JLab is shown in Fig. 4.2. The upper chamber, known as the "pumping chamber", is where spin-exchange optical pumping takes place. The lower chamber, known as the "target chamber", is the region through which the electron beam passes. The tube connecting the two chambers is known as the "transfer tube". The mechanism by which polarized ${ }^{3} \mathrm{He}$ makes its way from the pumping chamber to the target chamber in this design is diffusion. In the past, the timescales characterizing diffusion were quite fast compared to the time scales with which the ${ }^{3} \mathrm{He}$ was polarized, and the time scales associated with spin relaxation due to the electron beam. It is now the case, however, that the transfer tube represents a serious bottleneck. In short, the gas in the target chamber is not being replenished quickly enough. We have developed and tested a new target-cell design, however, in which gas is moved between the pumping chamber and the target chamber quite quickly using convection. This new cell design allows us to fully exploit the dramatic improvements in performance that are illustrated in 4.1.


Figure 4.2: Shown is one of the glass polarized ${ }^{3} \mathrm{He}$ target cells used during GEN-I (E02-013). These were the first polarized ${ }^{3} \mathrm{He}$ target cells used in electron scattering to incorporate alkalihybrid technology.

Despite what would appear to be ambitious design goals for the SBS SIDIS target, the technical milestones required have already been largely demonstrated. The Transversity experiment typically
ran with with $12 \mu \mathrm{~A}$ of beam current and a ${ }^{3} \mathrm{He}$ polarization that averaged $60.4 \%$ and was often well over $65 \%$ in the pumping chamber. Because of polarization gradients, however, the ${ }^{3} \mathrm{He}$ polarization in the target chamber averaged about $55 \%$. The Transversity target polarization was also somewhat suppressed because the experiment used the NMR technique of AFP to flip the nuclear spins roughly every 20 minutes. For the SBS SIDIS experiment, we plan to build a target with roughly three times the volume of the Transversity experiment, and around twice the volume of the GEN-I experiment. The larger target will make make the target less sensitive to beam current. Also, target spin flipping will be accomplished using "adiabatic rotation", a technique with significantly less spin loss than AFP. Polarization gradients will be virtually absent by using our new convection-based cell design. With these changes, it should be straightforward to run at $40 \mu \mathrm{~A}$ while maintaining $65 \%$ polarization. The target will also have metal end windows through which the electron beam will pass, and the pumping chamber will be further from the beam line, allowing radiation shielding. The target will thus be far more resistant to rupturing than in past experiments.

### 4.1 The principles behind the GEN-II target

It is useful to review some of the polarization dynamics that occur in our target cells. If the diffusion time between the pumping chamber and the target chamber is fast enough that it can be neglected, the time dependence of the ${ }^{3} \mathrm{He}$ polarization has a particularly simple form:

$$
\begin{equation*}
P_{\mathrm{He}}(t)=P_{\mathrm{Alk}} \frac{\gamma_{s e}}{\gamma_{s e}(1+X)+\Gamma}\left(1-e^{-t\left(\gamma_{s e}+\Gamma\right)}\right) \tag{4.1}
\end{equation*}
$$

where $P_{\mathrm{He}}$ is the nuclear polarization of the ${ }^{3} \mathrm{He}, P_{\mathrm{Alk}}$ is the polarization of the alkali-metal vapor, $\gamma_{s e}$ is the rate of spin-exchange rate between the ${ }^{3} \mathrm{He}$ and the Rb , and $\Gamma$ is the spin-relaxation rate of the ${ }^{3} \mathrm{He}$ nuclei due to all other processes. The factor $(1+X)$ accounts for what is now a well-established additional relaxation mechanism whose presence has been empirically established but whose origin is unknown[56]. The factor $(1+X)$ has the form given because the additional relaxation mechanism has been seen to be roughly proportional to the alkali-metal number density. We note that the factor " $X$ " can be measured for any particular cell, and is one of the quantities that we have begun to measure for the various target cells that we produce.

The spin exchange rate can be written

$$
\begin{equation*}
\gamma_{s e}=f_{p c}\left(k_{s e}^{\mathrm{K}}[\mathrm{~K}]+k_{s e}^{\mathrm{Rb}}[\mathrm{Rb}]\right) \tag{4.2}
\end{equation*}
$$

where $f_{p c}$ is the fraction of ${ }^{3} \mathrm{He}$ atoms that are located within the pumping chamber, $k_{s e}^{\mathrm{K}}\left(k_{s e}^{\mathrm{Rb}}\right)$ is the constant characterizing spin exchange between ${ }^{3} \mathrm{He}$ and $\mathrm{K}(\mathrm{Rb})$, and $[\mathrm{K}]([\mathrm{Rb}])$ is the number density of $\mathrm{K}(\mathrm{Rb})$ atoms within the pumping chamber. It can be seen that in order to achieve high polarizations, we must have the relaxation rate $\Gamma \ll \gamma_{s e}$. In principal, if the alkali-metal number density can be made arbitrarily high, the ${ }^{3} \mathrm{He}$ polarization can approach the limiting value of $P_{\mathrm{Alk}} /(1+X)$. In the past, the highest alkali-metal number density that could be maintained at something approaching $100 \%$ was strongly limited by the available laser power. By using alkalihybrid mixtures and line-narrowed lasers, however, it is now possible to use very high alkali number densities.

The spin relaxation rate $\Gamma$ contains several contributions and can be written

$$
\begin{equation*}
\Gamma=\Gamma_{\text {wall }}+\Gamma_{\text {bulk }}+\Gamma_{\text {beam }} \tag{4.3}
\end{equation*}
$$

where $\Gamma_{\text {wall }}$ is spin relaxation due to collisions between the ${ }^{3} \mathrm{He}$ atoms and the container walls, $\Gamma_{\text {bulk }}$ is spin relaxation due to ${ }^{3} \mathrm{He}-{ }^{3} \mathrm{He}$ collisions, and $\Gamma_{\text {beam }}$ is spin relaxation due to the electron beam. For our target cells, the time constant associated with spin relaxation due to wall collisions and bulk effects, $\left(\Gamma_{\text {wall }}+\Gamma_{\text {bulk }}\right)^{-1}$, is usually in the range of $20-40$ hours. The beam depolarization rate has been studied both theoretically[57] and experimentally[58] and is given by

$$
\begin{equation*}
\Gamma_{\text {beam }}=\left(76,292 \mathrm{~cm}^{2} / \mathrm{g}\right) \rho_{\mathrm{He}} L_{t c} J_{\text {beam }} / N_{H e} \tag{4.4}
\end{equation*}
$$

where $\rho_{\mathrm{He}}$ is the mass density of ${ }^{3} \mathrm{He}$ in the target chamber, $L_{t c}$ is the length of the target chamber, $J_{\text {beam }}$ is the beam current in particles per unit time, and $N_{H e}$ is the total number of ${ }^{3} \mathrm{He}$ atoms in the target.

The time constant associated with beam depolarization, $\left(\Gamma_{\text {beam }}\right)^{-1}$ was on the order of 30 hours during Transversity with beam currents of roughly $12 \mu \mathrm{~A}$. For SIDIS, for our proposed target configuration, we need to offset the effects of higher beam current $(40 \mu \mathrm{~A})$, and a longer target ( 60 cm instead of 40 cm ). This is accomplished largely by increasing the volume of the SIDIS target by roughly a factor of three compared to Transversity (a factor of two compared to GENI). The net result is that $\left(\Gamma_{\text {beam }}\right)^{-1}$ will be about 25 hours. As mentioned earlier, however, this small difference will be more than compensated by a lower loss rate during reversals of the target polarization. Thus, it is possible to predict the improved capability of the SBS SIDIS target using no more than scaling arguments.

### 4.2 Recent ${ }^{3} \mathrm{He}$ target performance metrics.

With the implementation of the alkali-hybrid technology, and the adoption of spectrally-narrowed high-power diode-laser arrays, we began achieving unprecedented levels of polarization in our lab at UVa. In Fig. 4.3, we show one of the first measurements of polarization versus time during which we broke the $70 \%$ mark. In fact, prior to this period, we had not exceeded $60 \%$. This emboldened us to move forward on the path at JLab of adopting spectrally-narrowed lasers, and laid the groundwork for the unprecedented performance seen during Transversity.

With the target improvements described earlier, the effective luminosity for the recently completed 6 GeV Transversity experiment was the highest ever for a polarized ${ }^{3} \mathrm{He}$ target used in an electron scattering experiment. While running beam (typically $12 \mu \mathrm{~A}$ ), the polarization in the pumping chamber averaged $60.4 \%$ and was often well over $65 \%$, despite doing AFP (for spin flips) every 20 minutes. During GEN-I, which ran a few years earlier, the effective luminosity was also precendent setting, with polarizations over $50 \%$ in the pumping chamber with around $8 \mu \mathrm{~A}$ of current. As discussed earlier, these dramatic increases in performance were due the implementation of alkali-hybrid technology, a move to spectrally narrowed lasers (which were not previously commercially available), and a painstaking program of optimization.

Despite the excellent and unprecedented performance achieved during Transversity, as discussed previously, the target was actually limited in its performance by the fact that the mixing of the gas between the pumping and target chambers was limited by the relatively slow process of diffusion. The ratio of the equilibrium polarizations in the target chamber, $P_{t c}^{\infty}$, and the pumping chamber, $P_{p c}^{\infty}$ is well approximated by

$$
\begin{equation*}
\frac{P_{t c}^{\infty}}{P_{p c}^{\infty}}=\frac{1}{1+\Gamma_{t c} / d_{t c}} \tag{4.5}
\end{equation*}
$$



Figure 4.3: Shown is one of the first measurements by our target collaboration during which a polarization of $70 \%$ or greater was achieved. The high polarization and fast "spinup times" opened the door to greatly improved target performance. Highly optimized target cells, alkalihybrid technology and spectrally-narrowed high-power laser-diode arrays were all critical to this achievement.
where $\Gamma_{t c}$ is the spin relaxation rate in the target chamber due to the electron beam and all other processes, and $d_{t c}$ is the diffusion rate out of the target chamber. For the Transversity cells $d_{t c} \sim 0.9 \mathrm{hrs}^{-1}$, and under operating conditions with beam, $\Gamma_{t c} \sim 1 / 12 \mathrm{hrs}$, yielding $P_{t c}^{\infty} / P_{p c}^{\infty} \sim 0.92$. Thus, while the ${ }^{3} \mathrm{He}$ polarization in the pumping chamber while taking beam was often over $65 \%$, the polarization in the target chamber was around $10 \%$ lower. The issue of polarization gradients, however, is one that we have solved.

### 4.3 Convection Tests in a Prototype GEN-II Target Cell

As has already been emphasized, the success of the GEN-II/SIDIS target relies critically on our ability to circulate the polarized gas between the pumping chamber and the target chamber using convection. Indeed, this is the enabling technology for the target, because it allows us to circulate gas using a sealed cell with no moving parts. We thus felt that demonstrating our ability to drive convection would remove important uncertainties regarding our target design, so we constructed an all-glass sealed cell that approximates the basic geometry that we are planning. The dimensions were chosen not to correspond to what we will ultimately build, but rather to a cell could be readily fabricated and tested using our existing apparatus. An annotated photograph of our test cell is shown in the left-hand panel of Fig. 4.4.

To drive convection, a small hot-air driven heater was attached to the right-hand transfer tube leading out of the pumping chamber. To detect and characterize the convection, a small slug of gas was "tagged" by depolarizing it using a short pulse of resonant RF delivered by a small "zapper coil" that was wrapped around the left-hand transfer tube. The movement of the tagged slug of gas was then tracked using a set of four "pick-up coils" that were spaced equally along the length of the target chamber. The heater, the zapper coil, and the four pick-up coils are all shown schematically in the left-hand panel of Fig. 4.4.

Representative data from our tests are shown in the right-hand panel of in Fig. 4.4. At $t=0$, a pulse of RF was delivered by the zapper coil, creating a depolarized slug of gas. The polarization of the gas passing through the four pick-up coils was monitored by making an NMR measurement


Figure 4.4: In the left-hand panel we show our prototype convection cell, along with a schematic representation of the heater used to drive convection, and the coils used to track the gas flow using an NMR technique. In the right-hand panel we show NMR signals as a function of time for our four pick-up coils. Transients corresponding to the passage of a tagged (depolarized) slug of gas are clearly apparent.
every 5 seconds using the technique of adiabatic past passage. Each of the four coils clearly shows the passage of the depolarized gas as evidenced by a transient dip in the measured polarization. The first transient of reduced polarization appears in coil \#1, the most upstream coil. Transients subsequently appear in each of coils \#2-\#4. It is interesting to note that the transient is relatively narrow as observed by coil $\# 1$, but broadens when observed by each successive coil. This is because of classic Hagen-Pouiselle flow of a (not very) viscous fluid as well as diffusion, both of which cause the slug of depolarized gas to spread out. The data were of sufficient quality that we can compute the speed of the gas, which in the case shown was, was around $20 \mathrm{~cm} / \mathrm{min}$. By varying the temperature of the heater on the transfer tube, were were able to vary the speed of the gas flow from (low speed) diffusion-limited flow to around $80 \mathrm{~cm} / \mathrm{min}$ in a stable and reproducible manner.

The implications of using convection-driven polarized ${ }^{3} \mathrm{He}$ targets are quite profound. First, we are no longer limited in the speed with which we can replenish gas that has been depolarized by the electron beam. In addition, we are for the first time in a position to physically separate the region in which the ${ }^{3} \mathrm{He}$ is polarized from the region in which the ${ }^{3} \mathrm{He}$ serves as a target. Among other things, this provides considerable flexibility in the manner in which we generate magnetic holding fields, a matter that we will return to shortly.

### 4.4 The GEN-II/SIDIS High-Luminosity Target

Several lessons should be taken away from the discussion in the previous sections. First and foremost, we are now polarizing ${ }^{3} \mathrm{He}$ spins at such a fast rate, and to such high polarization, that it is possible to build a new generation of targets capable of greatly increased luminosity. With this said, it is also clear that the target-cell design illustrated in Fig. 4.2 is not suitable for some of the upcoming polarized ${ }^{3} \mathrm{He}$ experiments. If one were to simply take the Transversity target, for example, and irradiate it with the proposed luminosity for SIDIS, the previous arguments suggest that polarizations would be well below $50 \%$. This is due to two factors: 1 ) the total rate at which
${ }^{3}$ He spins were polarized for Transversity is a bit low for the anticipated beam depolarization, and 2) the polarization gradient between the pumping and target chambers would be unacceptably large. The GEN-II/SIDIS target, however, will implement several changes to resolve these issues.

There are three changes that will insure that the GEN-II/SIDIS target will operate with polarizations in the $65 \%$ + range despite higher beam currents:

- The size of the target will be substantially larger (more than three times the volume of the Transversity target),
- the gas mixing will be by convection instead of diffusion and
- metal windows for the electron beam and radiation shielding for the pumping chamber will insure robustness despite the high beam currents.

On the first point, we note that the GEN-I targets contained roughly 3 STP liters of ${ }^{3} \mathrm{He}$, and the Transversity targets contained roughly 2 STP liters of ${ }^{3} \mathrm{He}$. The GEN-II/SIDIS target will contain roughly 7 STP liters, and we will scale the number of lasers typically used during operation from 4 to 10 . We note that we have run in the past with as many as 7 lasers in our target system, and because of the fiber-optic technology we currently use, 10 lasers will actually represent a considerably simpler system than was the case when we had 7 lasers in our system. Using the same 5 -to- 1 optical-fiber combiners that we currently use, we will have four optics lines in the GEN-II/SIDIS system. During earlier JLab polarized ${ }^{3} \mathrm{He}$ experiments, we actually ran with 14 optics lines. Since scaling up the size of the target means little more than scaling up the laser system, this change is straightforward.

On the second point, as discussed earlier, we have already constructed a prototype target cell in which gas mixing is based on convection instead of diffusion. The concept works extremely well, and we have fine control over the velocity with which the gas moves through the target chamber. We will discuss this more shortly.

The third feature that distinguishes the SBS SIDIS cell from its predecessors is the use of a metal end windows for the target chamber, and the use of radiation shielding for the pumping chamber. We have undertaken a series of studies aimed at fabricating cells that incorporate both glass and metal parts. While this work is still in progress, we have already established a technique for making gold-plated metal cell components in which the spin-relaxation time constants are at least 6 hours. What this means is that cells with limited amounts of metal (such as windows for the electron beam) will be only minimally impacted by faster spin-relaxation on metal walls. In fact, we believe that our tests were limited by factors other than our gold coatings, so we suspect that we can do even better. We note that published experiments from Ernst Otten's group at Mainz suggest that gold can provide spin-relaxation time constants of 20 hours [59]. For the purpose of this update, however, we see no reason to base our target on future progress. With have already achieved sufficient control of the spin-relaxation rate due to metal components to begin incorporating limited amounts of metal, and the beam windows are the highest priority.

Most of the time a polarized ${ }^{3} \mathrm{He}$ target cell ruptures, it is the pumping chamber that explodes. This is probably because the walls in the large-diameter spheres have the highest stresses in the whole target. With convection-driven gas flow, there is no need to minimize the distance between the pumping chamber and the target chamber. For the SBS SIDIS target, we will place radiation shielding between the two parts of the cell, thus greatly reducing the radiation damage incurred by the pumping chamber.


Figure 4.5: A straw-man sketch of the SBS SIDIS target cell. Two transfers tubes connect the pumping chambers to the target chamber to make it possible to drive convection between the two chambers. Also, the upper portion of the target is made of glass, whereas the lower portion is made of glass with gold-coated metal end windows for the electron beam. We note that the exact placement of the pumping chamber with respect to the target chamber can be chosen fairly arbitrarily since the gas is transported so quickly.

With all this in mind, we present a straw-man version of the SBS SIDIS target in Fig. 4.5. Our plan is to have the target in vacuum. We note that the original large-volume ${ }^{3} \mathrm{He}$ targets developed by some of us that were used at SLAC for E142 and E154 were also run in vacuum, so there are no new technical challenges there. We show two pumping chambers because the cell needs to have three times the volume of the Transversity targets, and equivalently slightly over twice the volume of the GEN-I target. Since we already believe that stress in the large spherical pumping chamber is an issue, we prefer to use two spheres of roughly the diameter of GEN-I targets. Again, we note that such flexibility is only possible because of the convection-driven gas flow. Using two pumping chambers also insures that the laser intensity (Watts per $\mathrm{cm}^{2}$ ) will be the same as what we have done in the past. There is some anecdotal evidence that excessive laser intensity can lead to cell deterioration.

Next, we comment on the magnetic holding fields. Historically, the magnetic field homogeneity requirements for the JLab polarized ${ }^{3} \mathrm{He}$ targets have been driven by the need to minimize polarization losses during NMR measurements, which were performed using the technique of Adiabatic Fast Passage (AFP). During AFP, all of the spins of the target are flipped simultaneously, and for a holding field of roughly 20 Gauss, the homogeneity requirement is thus $5-10 \mathrm{mG} / \mathrm{cm}$. For the SBS SIDIS target, however, we will perform polarimetry using pulse NMR. We will only be sampling the polarization in a small region of the target, the homogeneity requirement of $5-10 \mathrm{mG} / \mathrm{cm}$ only needs to be maintained in a small region. When looking at the average over the entire target, we will require only $50 \mathrm{mG} / \mathrm{cm}$. This relaxed requirement provides very convenient flexibility on how the magnetic fields are produced. The pumping chambers will be kept in a vertical magnetic field
generated using an iron box driven by current coils. This is the approach we already successfully implemented during GEN-I, and has the added advantage that it provides shielding from other magnetic fields. The target chamber, in contrast, will be kept in a field generated by at least two pairs of Helmholtz coils. The field on the target chamber will be able to be rotated to any arbitrary angle to provide full azimuthal coverage for the experiment. The requirement that the average gradient experienced by the gas in the cell be $50 \mathrm{mG} / \mathrm{cm}$ is easy to achieve assuming that the transfer tubes carrying gas between the two regions have a length of roughly a half meter. Again, this is only possible because of the convection driven design.

Reversal of the target polarization will be accomplished by adiabatically rotating the holding field of the target chamber (while leaving undisturbed the holding field of the pumping chamber). We will probably flow the target gas at a rate such that it will take around 10 minutes for gas to travel from the pumping chamber, down through the target chamber, and back into the pumping chamber. This is more than enough time for the spins to adiabatically follow the magnetic field through an arbitrary change in direction with negligible loss of polarization. Similarly, when the target-chamber holding field is rotated, even if done in ten seconds or less, the adiabaticity of the rotation is well within the limits for negligible spin loss. One of us (Cates) used essentially this technique in an experiment at Los Alamos in which polarized muonic ${ }^{3} \mathrm{He}$ was produced by stopping muons in polarized ${ }^{3} \mathrm{He}$ gas $[60]$. The holding field for the ${ }^{3} \mathrm{He}$ was adiabatically rotated once every two minutes by $180^{\circ}$, and no measurable loss of polarization was detected. If, for the SIDIS experiment, we also rotate the spins once every two minutes, and we take around 10 seconds for the rotation, the loss in data-taking time should be no more than $10 \%$.

We conclude by noting that we are already actively designing the target for the Hall A $A_{1}^{n}$ experiment, and it will incorporate many of the features described above. The GEN-II experiment will also use a very similar target. Indeed we have designed each of the three targets so that they successively represent a staged approach to the SBS SIDIS experiment, something that will make the design and building effort more efficient.

## Chapter 5

## Experiment Plan, Data Analysis and Expected Results

The proposed experiment has basically 4 free parameters: the beam energy, the two spectrometer angles and the target polarization orientation. We intend to acquire data at 2 different beam energies, 8.8 and 11 GeV , in order to extract asymmetries at significantly different values of $Q^{2}$ for the same values of $x$ and $z$. The choice of central electron and hadron angles is driven by several competing factors and is subject to several constraints, chief among which is the space constraint due to the physical size of the spectrometer magnets and the beamline downstream of the target. The electron arm angle of $30^{\circ}$ is chosen to focus the DIS kinematic coverage in the valence region at large $Q^{2}$ values. After fixing the electron arm angle, the hadron arm angle is chosen to optimize the SIDIS phase space coverage for the study of transverse spin phenomena, which requires coverage at finite transverse momentum $p_{T}$.

For the central electron kinematics at $x \approx 0.4$, the three-momentum transfer vector $\mathbf{q}$ makes an angle of approximately $7^{\circ}$ with the beamline. Centering the hadron arm along the central direction of $\mathbf{q}$ has the advantage of providing full $\phi$ coverage (see Table 1.1), but at the cost of significantly reduced solid angle and $p_{T}$ coverage. Since the transverse SSAs representing the primary physics goals of this proposal vanish as $p_{T} \rightarrow 0$, and since large solid angle for both the electron and hadron arms is essential to extracting the azimuthal modulations of the SSAs with small statistical and systematic uncertainties, the optimal position of the hadron arm for this experiment is not directly along $\mathbf{q}$, but at a small angle to the central direction of $\mathbf{q}$. Therefore, our chosen hadron arm angle of $14^{\circ}$ represents the best compromise among competing constraints.

The target magnetic field will be periodically rotated to eight different spin orientations perpendicular to the beamline, equally spaced in $(0,2 \pi)$, to cover the entire azimuthal phase space in $\phi_{S}$. Asymmetries will be sampled in 2-dimensional space in the relevant kinematic variables ( $x, z$ ), $\left(x, p_{T}\right)$ and $\left(z, p_{T}\right)$ and, at somewhat lower precision, in three-dimensional $\left(x, z, p_{T}\right)$ space. Due to the $5 / 1$ vertical/horizontal aspect ratio of the BigBite angular acceptance, $x$ and $Q^{2}$ are almost one-to-one correlated for a given beam energy. Data at two beam energies will allow studies of the $Q^{2}$ dependence of the asymmetries at fixed $x$, providing fully differential asymmetry information, which will serve as a powerful constraint on global TMD analysis. The quality of the data will be assured by an experimental design that provides excellent target performance, high luminosity, simplicity of acceptance and event reconstruction, and excellent particle identification. In the following sections, we describe the expected physics output of the experiment in detail.

### 5.1 Monte Carlo Simulation: Phase Space, Cross Sections, Rates and Asymmetries

Electrons are detected in the BigBite spectrometer, whose trigger will accept momenta from 1.0 GeV. Hadrons are detected by the SBS, which includes the adapted HERMES RICH detector for hadron PID. For both beam energies, BigBite will be fixed at a central angle of $30^{\circ}$ on beam right at a distance of 1.55 m from the target to the entrance of the BigBite dipole. The SBS will be located at a central angle of 14 degrees on beam left at a distance of 2.45 m from the target to the SBS dipole. The SBS trigger threshold will be set at roughly 1.5 GeV for the efficient detection of hadrons with momenta exceeding $2.0 \mathrm{GeV} / \mathrm{c}$. The magnetic field settings of the spectrometers will be fixed. The SBS detector package will be arranged vertically behind the dipole, such that the acceptance will be symmetric between positive and negative charged particles, which will be detected simultaneously. The polarity of the SBS magnet will be reversed periodically to minimize systematics resulting from residual acceptance/efficiency differences between positive and negative particles. Moreover, dividing the data equally between opposite SBS polarities will increase the vertical angle coverage of the hadron arm by approximately $14 \%$ by reversing the direction of the vertical bend, thereby increasing the effective $\phi$ coverage of the data, an important feature for reducing systematic uncertainties.

### 5.1.1 Phase Space

The phase space distributions of accepted particles have been determined from a Monte Carlo simulation including realistic angular and momentum acceptance for BigBite and a "box" acceptance for SBS (the solid-angle acceptance of SBS is limited by the tracker area). The BigBite model has been tuned to optics calibration data taken during the Hall A neutron transversity experiment [40]. Reconstructed kinematics were smeared by realistic estimates of detector resolution. Figure 5.1 shows the kinematic coverage of the proposed measurements in $Q^{2}, z$ and $p_{T}$ versus $x$, while figure 5.2 shows $W, W^{\prime}$ and $y$ versus $x$. Figure 5.3 shows the one-dimensional distributions of $x, Q^{2}, z$, and $p_{T}$, with events distributed according to the SIDIS cross section model used in the simulation, described below.

### 5.1.2 Resolution

## Charged Hadrons

The momentum, angular and vertex resolution of both the electron and hadron arms is excellent and more than adequate to address the physics goals of this proposal. The resolution of the SBS-BB combination in the relevant kinematic variables $x, z, p_{T}$, and $Q^{2}$ for charged hadrons is shown in figure 5.4. These resolutions are smaller than the planned kinematic bin width by a factor of at least ten. A more significant issue is the resolution of the azimuthal angles needed to extract the azimuthal moments of the SSAs sensitive to different TMD contributions.

Figure 5.5 shows the $p_{T}$-dependent resolution of $\sin \phi, \sin \left(\phi+\phi_{S}\right)$ and $\sin \left(\phi-\phi_{S}\right)$, which diverge approximately as $1 / \sin \theta_{h q}=p_{h} / p_{T}$ as $p_{T} \rightarrow 0$. The resolution of the sine and/or cosine of the relevant combinations of azimuthal angles is below 0.05 for $p_{T}>0.1 \mathrm{GeV}$, again for charged hadrons. The resolutions of the same angle combinations are also shown in Figure 5.6, but expressed as the resolution of the angles themselves rather than as sines and cosines. The results are similar.


Figure 5.1: Kinematic coverage of the proposed measurements. Left to right: $Q^{2}, z$, and $p_{T}$ coverage correlated with $x$, and $p_{T}$ vs. $z$, for $E_{\text {beam }}=11 \mathrm{GeV}$ (top row) and $E_{\text {beam }}=8.8 \mathrm{GeV}$ (bottom row). SIDIS cuts $Q^{2}>1 \mathrm{GeV}^{2}, W>2 \mathrm{GeV}, W^{\prime}>1.5 \mathrm{GeV}$ and $y<0.9$ have been applied. The electron (hadron) momentum is restricted to $p_{e}>1 \mathrm{GeV} / \mathrm{c}\left(p_{h}>2 \mathrm{GeV} / \mathrm{c}\right)$.

As discussed in section 5.2.2, these azimuthal resolutions are perfectly adequate for the extraction of the relevant asymmetry moments, and a cut at $p_{T}>0.05$ or 0.1 GeV can be applied if necessary to suppress events with very poor angular resolution, without affecting the physics goals of this experiment in the least.

## Neutral Pion Detection and Reconstruction

The hadronic-calorimeter (HCAL) based trigger for the SBS will also efficiently detect the decay photons from high-energy $\pi^{0}$ production. The planned assembly of HCAL for this experiment consists of a 10 (horizontal) $\times 25$ (vertical) cell arrangement of $15 \times 15 \mathrm{~cm}^{2}$ cells of iron-scintillator sandwich. The energy resolution of such an arrangement for electromagnetic showers is expected to be $\sigma_{E} / E \approx 14 \% / \sqrt{E}$, where $E$ is the $\gamma$ energy in GeV . The $15 \times 15 \mathrm{~cm}^{2}$ cell size is rather large compared to the transverse shower size, meaning that most photons will leave large signals in one or at most two cells, except when they impact the surface of HCAL near the boundaries between cells. Therefore, the shower coordinate reconstruction can be approximated by simply assigning the shower coordinates to the center of the cell with the maximum energy deposition. The $1 \sigma$ resolution of the coordinate measurement will thus be $15 / \sqrt{12} \approx 4.3 \mathrm{~cm}$. This energy and coordinate resolution turns out to be more than adequate for the efficient identification and accurate kinematic reconstruction for $\pi^{0}$, adding significantly to the physics output of the proposed experiment.

In the offline analysis, the identification of $\pi^{0}$ events proceeds by searching for two large-energy hits in HCAL with a clear spatial separation and a good time coincidence with each other and


Figure 5.2: Kinematic coverage of the proposed measurements. Left to right: $W, W^{\prime}$ and $y$ coverage versus $x$, for $E_{\text {beam }}=11 \mathrm{GeV}$ (top) and $E_{\text {beam }}=8.8 \mathrm{GeV}$ (bottom). SIDIS cuts $Q^{2}>1 \mathrm{GeV}^{2}$, $W>2 \mathrm{GeV}, W^{\prime}>1.5 \mathrm{GeV}$ and $y<0.9$ have been applied. The electron (hadron) momentum is restricted to $p_{e}>1 \mathrm{GeV} / \mathrm{c}\left(p_{h}>2 \mathrm{GeV} / \mathrm{c}\right)$.


Figure 5.3: One-dimensional kinematic distributions of the proposed experiment. From left to right: $x, Q^{2}, z$ and $p_{T}$, for $E_{\text {beam }}=11 \mathrm{GeV}($ top $)$ and $E_{\text {beam }}=8.8 \mathrm{GeV}$ (bottom). SIDIS cuts $Q^{2}>1 \mathrm{GeV}^{2}, W>2 \mathrm{GeV}, W^{\prime}>1.5 \mathrm{GeV}$ and $y<0.9$ have been applied. The electron (hadron) momentum is restricted to $p_{e}>1 \mathrm{GeV} / \mathrm{c}\left(p_{h}>2 \mathrm{GeV} / \mathrm{c}\right)$. Events are distributed according to the SIDIS cross section. See text for details.


Figure 5.4: Resolution of kinematic variables $x, z, p_{T}$ and $Q^{2}$ in the proposed experiment.


Figure 5.5: Azimuthal angle resolution as a function of $p_{T}$ in GeV , expressed as the difference between the sine of the generated angle and the sine of the reconstructed angle, for the hadron angle $\phi$ (a), the Collins angle $\phi+\phi_{S}(\mathrm{~b})$, and the Sivers angle $\phi-\phi_{S}(\mathrm{c})$.


Figure 5.6: Azimuthal angle resolution as a function of $p_{T}$ in GeV , expressed as the difference between the generated angle and the reconstructed angle, for the hadron angle $\phi$ (a), the Collins angle $\phi+\phi_{S}(\mathrm{~b})$, and the Sivers angle $\phi-\phi_{S}(\mathrm{c})$.
with the electron arm. The absence of correlated tracks in the GEMs and RICH rings will also be required. Then, combined with the interaction vertex reconstructed by BigBite (the electron arm), the coordinates and energy of the two $\gamma \mathrm{s}$ will be used to reconstruct their angles and momenta. The four-momenta of the two photons thus defined will be used to reconstruct the $2 \gamma$ invariant mass and the $\pi^{0}$ momenta and scattering angles. Figure 5.7 shows the expected resolution for the $\pi^{0}$ invariant mass, the hadron SIDIS variables $z$ and $p_{T}$ and the $p_{T}$-dependent azimuthal angle resolution, expressed in terms of $\sin \phi$ (bottom right). The surface of HCAL in its planned configuration will be approximately 623 cm from the center of the target. Its useful active area will be about 345 cm (vertical) $\times 120 \mathrm{~cm}$ (horizontal). A SIDIS simulation of $\pi^{0} \rightarrow 2 \gamma$ in our experimental setup has been used to determine the phase space for $\pi^{0} \mathrm{~S}$ and their relative acceptance compared to charged hadrons. The need to detect both photons in order to identify $\pi^{0} \mathrm{~s}$ and the angular distribution of the decay reduces the acceptance for neutral pions relative to charged pions; however, in the 2-7 GeV momentum range for SIDIS, the acceptance of the setup for $\pi^{0}$ is adequate. Figure 5.8 shows the momentum-dependent distance between the two photons at the surface of HCAL. The larger opening distance reduces the acceptance at lower momenta.

Figure 5.9 shows the results for the $\pi^{0}$ acceptance relative to $\pi^{+}$. The relative $\pi^{0}$ acceptance was obtained from the Monte Carlo-generated sample of $\pi^{+}$events by treating each individual $\pi^{+}$event as if it were a $\pi^{0}$ leaving the target with the same momentum, generating the back-to-back decay photons isotropically in the $\pi^{0}$ rest frame, boosting to the lab frame and projecting to the surface of HCAL. Then, if both photons fell within the HCAL active area, their energies were smeared by an assumed resolution of $\sigma_{E} / E=14 \% / \sqrt{E}(E$ in GeV$)$ and their reconstructed coordinates were assigned to the center of the $15 \times 15 \mathrm{~cm}^{2}$ cell in which they impacted HCAL (the same method was used to estimate the kinematic and angular resolution shown in Figure 5.7). The main result of the study is that the average acceptance of the proposed experiment for $\pi^{0} \mathrm{~S}$ is about $53 \%$ relative to charged pions, but increases with pion momentum (and therefore with $z$ ). At high $z$ values where the cross section is relatively low, the relative $\pi^{0}$ acceptance approaches $80 \%$.

### 5.1.3 Cross Sections, SIDIS Event Selection, and Rates

The unpolarized cross section in the Monte Carlo was calculated using the CTEQ6 PDFs [61] and the DSS2007 FFs [62]. The unpolarized differential cross section for semi-inclusive $N\left(e, e^{\prime} h\right) X$


Figure 5.7: Particle ID and kinematic reconstruction for $\pi^{0} \rightarrow 2 \gamma$ reconstruction using HCAL. The invariant mass resolution (top left) is approximately 19 MeV . The resolution in $z$ (top right) and $p_{T}$ (bottom left) is significantly worse than for charged hadrons, but still roughly a factor of 4 below the planned kinematic bin width (of course we are free to bin the data differently for $\pi^{0} \mathrm{~S}$ if needed). Finally, the azimuthal angle resolution (bottom right) appears to be adequate at least down to $p_{T} \sim 0.1 \mathrm{GeV}$.


Figure 5.8: Momentum-dependent distance between the two photons detected at the surface of HCAL from $\pi^{0} \rightarrow 2 \gamma$ decay.
scattering is calculated according to

$$
\begin{equation*}
\frac{d \sigma}{d E_{e}^{\prime} d \Omega_{e} d z d p_{T}^{2} d \phi_{h}}=\frac{4 \alpha^{2} E_{e}^{\prime 2}}{Q^{4}}\left[\frac{2 H_{1}}{M} \sin ^{2} \frac{\theta_{e}}{2}+\frac{H_{2}}{\nu} \cos ^{2} \frac{\theta_{e}}{2}\right], \tag{5.1}
\end{equation*}
$$

where the SIDIS structure function $H_{2}$ at leading order is given by

$$
\begin{equation*}
H_{2}\left(x, Q^{2}, z, p_{T}^{2}\right)=x \sum_{q} e_{q}^{2} q\left(x, Q^{2}\right) D_{q}^{h}\left(z, Q^{2}\right) \frac{b_{q}^{h}}{2 \pi} e^{-b_{q}^{h} p_{T}^{2}}, \tag{5.2}
\end{equation*}
$$

where the sum runs over six light quark flavors $q=u, d, s, \bar{u}, \bar{d}, \bar{s}, q\left(x, Q^{2}\right)$ is the unpolarized PDF for quark flavor $q, D_{q}^{h}\left(z, Q^{2}\right)$ is the unpolarized FF for quark flavor $q$ to hadron $h$, and a factorized Gaussian transverse momentum dependence is assumed. The Callan-Gross relation $H_{2}=2 x H_{1}$ is assumed for the $H_{1}$ structure function, which corresponds to neglecting the longitudinal cross section. The transverse momentum width of the quark distribution and fragmentation functions is contained in the factors $b e^{-b p_{T}^{2}} / 2 \pi$ in Eqn. (5.2). The inverse Gaussian widths $b_{q}^{h}$ are given by

$$
\begin{equation*}
b_{q}^{h}=\frac{1}{z^{2}\left\langle k_{\perp}^{2}\right\rangle_{q}+\left\langle p_{\perp}^{2}\right\rangle_{q}^{h}}, \tag{5.3}
\end{equation*}
$$

where $\left\langle k_{\perp}^{2}\right\rangle$ is the characteristic width of the intrinsic quark transverse motion in the nucleon and $\left\langle p_{\perp}^{2}\right\rangle$ is the characteristic transverse-momentum width in the fragmentation process. In the absence of better knowledge of the quark flavor and hadron-species dependence of the distribution and fragmentation widths, constant values $\left\langle k_{\perp}^{2}\right\rangle=0.25 \mathrm{GeV}^{2}$ and $\left\langle p_{\perp}^{2}\right\rangle=0.20 \mathrm{GeV}^{2}$ are assumed, as in Ref. [63]. As mentioned above, the distribution of events in the phase space plots shown in Figs. 5.1-5.3 corresponds to the cross section model of Eqn. (5.1) convoluted with the combined acceptance function of the two-spectrometer arrangement.


Figure 5.9: Acceptance for $\pi^{0}$ relative to $\pi^{+}$. Top left (right): $z\left(p_{T}\right)$ distribution for $\pi^{+}$(black solid) and $\pi^{0}$ (red dot-dashed), obtained by treating each accepted $\pi^{+}$as if it were $\pi^{0}$, generating the decay photons isotropically in the $\pi^{0}$ rest frame, projecting to HCAL in the lab frame, and smearing for detector resolution (see text for details). Bottom left (right): Fraction of $\pi^{0}$ events accepted (relative to $\pi^{+}$) as a function of $z\left(p_{T}\right)$.

| $E_{\text {beam }}, \mathrm{GeV}$ | 11.0 | 8.8 |
| :---: | :---: | :---: |
| ${ }^{3} \mathrm{He}\left(e, e^{\prime} \pi^{+}\right) X$ rate Hz | 35.5 | 49.3 |
| ${ }^{3} \mathrm{He}\left(e, e^{\prime} \pi^{-}\right) X$ rate, Hz | 23.8 | 30.8 |
| ${ }^{3} \mathrm{He}\left(e, e^{\prime} K^{+}\right) X$ rate, Hz | 13.1 | 21.4 |
| ${ }^{3} \mathrm{He}\left(e, e^{\prime} K^{-}\right) X$ rate, Hz | 8.5 | 9.7 |

Table 5.1: Total event rates for charged pion and kaon electroproduction for $40 \mu \mathrm{~A}$ beam current $\left(3.9 \times 10^{36} \mathrm{~cm}^{-2} \mathrm{~s}^{-1} e \vec{n}\right.$ luminosity), after applying all SIDIS event selection cuts.

The following cuts were applied in the analysis of the simulated data to select SIDIS events, for both beam energies:

- $Q^{2}>1 \mathrm{GeV}^{2}$ : Standard low- $Q^{2}$ cutoff for DIS data.
- $W>2 \mathrm{GeV}$ : Minimum invariant mass to avoid the resonance region for inclusive DIS
- $W^{\prime}>1.5 \mathrm{GeV}$ : Minimum "missing" mass to avoid the resonance region for SIDIS.
- $y<0.9$ : Suppress higher-order QED effects.
- $p_{e}>1.0 \mathrm{GeV}:$ Minimum electron momentum corresponding to the trigger threshold of the BigBite shower calorimeter.
- $p_{h}>2.0 \mathrm{GeV}:$ Minimum hadron momentum for the analysis of SIDIS data. Corresponds to $z>0.2$ for $E=11 \mathrm{GeV}$. Suppresses the target fragmentation region.

SIDIS counting rates were estimated using the cross section and spectrometer models described above combined with the following assumptions on luminosity:

- A $60-\mathrm{cm}$ long ${ }^{3} \mathrm{He}$ gas target with a thickness of $0.078 \mathrm{~g} \mathrm{~cm}^{-2}$, corresponding to a density of $1.3 \times 10^{-3} \mathrm{~g} \mathrm{~cm}^{-3}$ (roughly speaking, the assumed ${ }^{3} \mathrm{He}$ density corresponds to a pressure of 10.6 atm at "room" temperature of 300 K ).
- $40 \mu A$ beam current (see Chapter 4 for detailed justifications.)
- Combining the first two assumptions, the assumed $e \vec{n}$ luminosity is $3.9 \times 10^{36} \mathrm{~cm}^{-2} \mathrm{~s}^{-1}$.

Large-statistics pseudo-data sets were generated for $\pi^{ \pm}$and $K^{ \pm}$production on ${ }^{3} \mathrm{He}$. The proposed experiment will also measure the asymmetries for $n\left(e, e^{\prime} \pi^{0}\right) X$. Isospin symmetry for the $\pi^{0}$ fragmentation functions implies $\sigma_{\pi^{0}}=\left(\sigma_{\pi^{+}}+\sigma_{\pi^{-}}\right) / 2$. For the purposes of this proposal, the SIDIS cross section on ${ }^{3} \mathrm{He}$ was assumed to be a simple sum over free protons and neutrons. Rejection sampling was used to produce pseudo-data distributed according to the acceptance-convoluted cross section. Table 5.1 shows the total SIDIS counting rates for $\pi^{ \pm}$and $K^{ \pm}$electroproduction, calculated using the cross section model described above.

Note that because the unpolarized fragmentation functions for kaons are relatively poorly known, and since standard fragmentation function codes, such as the DSS2007 FFs used in our simulation, tend to overestimate the charged kaon yields at the conditions of our experiment compared to the kaon multiplicities measured at HERMES [64], we expect the true kaon event rates
to be somewhat lower than the estimates shown in table 5.1. The average $K / \pi$ production ratio measured by HERMES on a proton target is $\sim 20 \%$ ( $13 \%$ ) for $K^{+}\left(K^{-}\right)$, compared to the $30-$ $40 \%$ ratios predicted by our simulation in Table 5.1. Therefore, we have conservatively scaled our asymmetry uncertainty projections for kaons such that the $K / \pi$ ratios match those of the HERMES experiment. In addition, the momentum-dependent decay probabilities for charged pions and kaons were taken into account in the simulation. The survival probabilities for kaons (pions) to reach the HCAL detector of SBS range from $67 \%(92 \%)$ at 2 GeV to $89 \%(98 \%)$ at 7 GeV .

### 5.1.4 Asymmetries

Intrinsic single-spin asymmetries in the SIDIS cross section were generated in the Monte Carlo simulation for each event following the empirical parametrizations of Anselmino et al., including the fit of Ref. [30] for the transversity distribution and the Collins fragmentation function and Ref. [32] for the Sivers functions. The asymmetry moments $A_{U T}^{\text {Collins }}$ and $A_{U T}^{\text {Sivers }}$ were used to calculate the angular modulation of the SIDIS cross section according to

$$
\begin{equation*}
d \sigma_{U T}=d \sigma_{U U}\left[1+P_{T} \sin \left(\theta_{S}\right)\left(A_{U T}^{\text {Collins }} \sin \left(\phi+\phi_{S}\right)+A_{U T}^{\text {Sivers }} \sin \left(\phi-\phi_{S}\right)\right)\right] \tag{5.4}
\end{equation*}
$$

where $d \sigma_{U U}$ and the $A_{U T}$ moments are functions of $x, y, z, Q^{2}$, and $p_{T}, P_{T}$ is the target polarization, assumed to be $65 \%$, and $\theta_{S}$ is the polar angle of the target spin orientation relative to the $\mathbf{q}$-vector. The $\sin \left(\theta_{S}\right)$ factor accounts for the fact that longitudinal and transverse target polarization are defined relative to the momentum transfer $\mathbf{q}$, while the target polarization is transverse to the beam direction, which does not exactly coincide with the direction of $\mathbf{q}$. The third allowed leading-twist azimuthal modulation, "pretzelosity" $\left(\sin \left(3 \phi-\phi_{S}\right)\right)$, which results from the TMD $h_{1 T}^{\perp}$, was assumed to be zero in generating asymmetries in the Monte Carlo, but was extracted in the fitting procedure described below to test the impact of the simultaneous extraction of three angular modulation terms on the statistical and systematic error compared to fitting only the Collins and Sivers moments.

Monte Carlo statistics corresponding to equal integrated luminosities were generated for each of eight target spin directions, always perpendicular to the beam direction, and equally spaced at $45^{\circ}$ intervals relative to the vertical direction, leading to a full and nearly uniform coverage in the Collins $\left(\phi+\phi_{S}\right)$ and Sivers $\left(\phi-\phi_{S}\right)$ angles. Along with the unpolarized cross section, the calculated asymmetries were included as part of the event probability, which is the convolution of the cross section with the experimental acceptance/efficiency. Events were sampled according to this probability, resulting in a complete pseudo-data set with "built-in" asymmetries which could be analyzed to extract the Collins and Sivers moments, providing a rigorous demonstration of the validity of the chosen extraction procedure and statistical error calculation.

Figures 5.10 and 5.11 illustrate the correlated $p_{T}$ and $\phi$ azimuthal coverage for the two beam energies, integrated over $x$ and $z$, in polar and Cartesian representations, respectively. Though relatively non-uniform, coverage of the hadron azimuthal angle $\phi$ is very good, reaching nearly half of $2 \pi$ at $p_{T}=1 \mathrm{GeV}$, and even larger at low $p_{T}$. By taking a small fraction of our data with an unpolarized target, our excellent $\phi$ coverage will allow us to constrain the $A_{U U}^{\cos \phi}$ (Cahn effect) and $A_{U U}^{\cos 2 \phi}$ (Boer-Mulders effect) modulations of the unpolarized cross sections, which can induce small corrections to $A_{U T}$, minimizing the associated systematic uncertainty in the extraction of the Collins and Sivers moments. By taking equal fractions of our data in each of eight target spin orientations, which should not be a large technical challenge for the planned target design, we


Figure 5.10: Polar plots of $p_{T}$ vs. $\phi$ coverage, integrated in $x$ and $z$. From left to right: $\phi, \phi_{S}$, $\phi+\phi_{S}$ (Collins), and $\phi-\phi_{S}$ (Sivers) for $E=11 \mathrm{GeV}$ (top row) and $E=8.8 \mathrm{GeV}$ (bottom row). Ellipses at constant radial coordinate correspond to constant $p_{T}=0.5 \mathrm{GeV}$ (inner) and $p_{T}=1.0$ GeV (outer).


Figure 5.11: Cartesian plots of $\phi$ vs. $p_{T}$ coverage, integrated in $x$ and $z$. From left to right: $\phi, \phi_{S}$, $\phi+\phi_{S}$ (Collins), and $\phi-\phi_{S}$ (Sivers) for $E=11 \mathrm{GeV}$ (top row) and $E=8.8 \mathrm{GeV}$ (bottom row).
achieve complete coverage of the target spin azimuthal angle $\phi_{S}$ over our full $p_{T}$ range. Furthermore, our coverage of the Collins $\left(\phi+\phi_{S}\right)$ and Sivers ( $\phi-\phi_{S}$ ) angles is complete and quite nearly uniform. For a discussion and presentation of the $p_{T}$-dependent azimuthal coverage in our planned kinematic binning of $x$ and $z$, see Appendix B.

The ${ }^{3} \mathrm{He}$ asymmetry moments were calculated from the model proton and neutron asymmetries, assuming a ${ }^{3} \mathrm{He}$ polarization of $65 \%$, using the effective polarization approximation [67, 68], given by

$$
\begin{equation*}
A_{U T}^{3 H e}=P_{p} f_{p} A_{U T}^{p}+P_{n}\left(1-f_{p}\right) A_{U T}^{n}, \tag{5.5}
\end{equation*}
$$

where $P_{p}=-0.028_{-0.004}^{+0.009}$ and $P_{n}=0.86_{-0.02}^{+0.036}$ are the proton and neutron effective polarizations in ${ }^{3} \mathrm{He}$, respectively, and $f_{p}=2 \sigma_{p} / \sigma_{3} \mathrm{He}$ is the "proton dilution", defined as the fraction of the ${ }^{3} \mathrm{He}$ SIDIS cross section carried by the (almost) unpolarized protons. This approximation was also used in the extraction of neutron asymmetry moments from the simulated data.

### 5.2 Projected Physics Results and Impacts

In this section, we present the expected physics results of the experiment in detail. Section 5.2.1 explains the data analysis procedure and the maximum likelihood method used to extract the Collins and Sivers SSA moments and calculate the statistical uncertainties. Section 5.2.2 provides comprehensive documentation of our expected physics results.

### 5.2.1 Asymmetry Extraction and Statistical Error Calculation

The azimuthal moments of the single-spin asymmetry can be extracted using a linearized, unbinned maximum likelihood method. The measured normalized yield is given by

$$
\begin{equation*}
N\left(\phi, \phi_{S}\right)=N_{0} \frac{\epsilon\left(\phi, \phi_{S}\right)}{4 \pi^{2}}\left[1+P_{T} \sin \theta_{S}\left(A_{C} \sin \left(\phi+\phi_{S}\right)+A_{S} \sin \left(\phi-\phi_{S}\right)\right)\right] \tag{5.6}
\end{equation*}
$$

where $N_{0} \equiv N_{0}\left(x, Q^{2}, z, p_{T}^{2}\right)$ is the azimuthally integrated yield in a given fully-differential 4D kinematic bin, determined by the product of the cross section, acceptance and integrated luminosity, $A_{C} \equiv A_{U T}^{\text {Collins }}, A_{S} \equiv A_{U T}^{\text {Sivers }}, P_{T}$ is the target polarization and $\epsilon\left(\phi, \phi_{S}\right)$ is the azimuthal dependence of the acceptance/efficiency. The normalized azimuthal distribution of events is $f\left(\phi, \phi_{S}\right) \equiv \frac{N\left(\phi, \phi_{S}\right)}{\varepsilon N_{0}}$, where $\varepsilon \equiv \int_{0}^{2 \pi} d \phi \int_{0}^{2 \pi} d \phi_{S} N\left(\phi, \phi_{S}\right) / N_{0}$ is a normalization constant defined so that $f\left(\phi, \phi_{S}\right)$ is a probability distribution. Under these definitions, a likelihood function for the azimuthal asymmetry moments can be defined as

$$
\begin{align*}
\mathcal{L}\left(A_{C}, A_{S}\right) & =\prod_{i=1}^{N_{\text {event }}} f^{i}\left(\phi^{i}, \phi_{S}^{i}\right) \\
& =\prod_{i=1}^{N_{\text {event }}} \frac{\epsilon\left(\phi^{i}, \phi_{S}^{i}\right)}{4 \pi^{2} \varepsilon}\left[1+P_{T} \sin \theta_{S}^{i}\left(A_{C} \sin \left(\phi^{i}+\phi_{S}^{i}\right)+A_{S} \sin \left(\phi^{i}-\phi_{S}^{i}\right)\right)\right] \tag{5.7}
\end{align*}
$$



Figure 5.12: Distribution of $\sin \theta_{S}$ at 11 GeV (a) and 8.8 GeV (b).

Converting the product into a sum by taking the logarithm, we obtain

$$
\begin{align*}
\ln \mathcal{L}\left(A_{C}, A_{S}\right)= & \sum_{i=1}^{N_{\text {event }}}\left\{\ln \epsilon-\ln \left(4 \pi^{2} \varepsilon\right)+\right. \\
& \left.\ln \left[1+P_{T} \sin \theta_{S}^{i}\left(A_{C} \sin \left(\phi^{i}+\phi_{S}^{i}\right)+A_{S} \sin \left(\phi^{i}-\phi_{S}^{i}\right)\right)\right]\right\} \tag{5.8}
\end{align*}
$$

The maximum-likelihood estimators for the parameters $A_{C}$ and $A_{S}$ can be obtained by solving the coupled, nonlinear partial differential equations $\partial \ln \mathcal{L} / \partial A_{C}=\partial \ln \mathcal{L} / \partial A_{S}=0$. However, assuming the asymmetries are "small", we can simplify the calculation by Taylor-expanding the logarithm in the third term on the right-hand side as $\ln (1+x)=x-x^{2} / 2+\mathcal{O} x^{3}$, resulting in a system of linear algebraic equations for the asymmetries:

$$
\sum_{i=1}^{N_{\text {event }}}\left(\begin{array}{cc}
\lambda_{C}^{(i)^{2}} & \lambda_{C}^{(i)} \lambda_{S}^{(i)}  \tag{5.9}\\
\lambda_{C}^{(i)} \lambda_{S}^{(i)} & \lambda_{S}^{(i)^{2}}
\end{array}\right)\binom{A_{C}}{A_{S}}=\sum_{i=1}^{N_{\text {event }}}\binom{\lambda_{C}^{(i)}}{\lambda_{S}^{(i)}},
$$

where the coefficients $\lambda_{C}$ and $\lambda_{S}$ are defined as

$$
\begin{align*}
\lambda_{C} & \equiv P_{T} \sin \theta_{S} \sin \left(\phi+\phi_{S}\right)  \tag{5.10}\\
\lambda_{S} & \equiv P_{T} \sin \theta_{S} \sin \left(\phi-\phi_{S}\right) . \tag{5.11}
\end{align*}
$$

The $\sin \theta_{S}$ factor represents the transverse component of the target polarization relative to the momentum transfer, and its deviation from unity, which causes a relative change in the asymmetry magnitude as a function of the angle of $\mathbf{q}$ with respect to the beamline, is quite small in the proposed experiment, as shown in figure 5.12. Equation (5.9) can be written in a compact form as a matrix equation $M \mathbf{A}=\mathbf{b}$, where $M$ is the $2 \times 2$ matrix of weighted sums on the left-hand side, $\mathbf{A}$ is the column vector of the asymmetry moments we intend to extract, and $\mathbf{b}$ is the column vector of weighted sums appearing on the right-hand side of (5.9). $M$ and $\mathbf{b}$ are directly calculated from
the normalized yields measured in the experiment, and the asymmetry moments are subsequently obtained from $\mathbf{A}=M^{-1} \mathbf{b}$. The standard errors in the asymmetry moments are obtained from the diagonal elements of the covariance matrix $M^{-1}$ :

$$
\begin{equation*}
\delta \mathbf{A}_{i}=\sqrt{\left|M_{i i}^{-1}\right|} \tag{5.12}
\end{equation*}
$$

Notice that in the partial derivatives $\partial \ln \mathcal{L} / \partial A_{C / S}$, the acceptance functions do not contribute. Under the assumptions of $180^{\circ}$ symmetric $\phi_{S}$ acceptance, achieved by flipping the target spin, and equal effective integrated luminosity in each target spin state, achieved by flipping the target spin very frequently, it can be shown that these maximum-likelihood estimators are unbiased [69]; i.e., that acceptance effects cancel. Furthermore, this formalism can be expanded straightforwardly to an arbitrary number of azimuthal moments, although more complicated situations can arise, for example when we allow for azimuthal dependence of the unpolarized cross section causing the denominator of $f\left(\phi, \phi_{S}\right)$ to assume a non-trivial $\phi$-dependence. The effects of other allowed azimuthal modulations of the SIDIS cross section on the extraction of the Collins and Sivers SSA moments will be discussed in section 5.3.4. The preceding discussion pertains to the extraction of the raw asymmetry on ${ }^{3} \mathrm{He}$. After extracting the ${ }^{3} \mathrm{He}$ asymmetries using the maximum likelihood method, the corresponding neutron asymmetries were extracted using Eqn. (5.5). The dilution factor $f_{p}$ and the proton asymmetries $A_{U T}^{p}$ were calculated from the cross section and asymmetry models discussed in sections 5.1.3 and 5.1.4, respectively.

### 5.2.2 Expected Results

In this section, we present the expected experimental results in detail. First, we demonstrate the validity of our extraction method by comparing the asymmetries extracted from the Monte Carlo data to the input model asymmetries.

Figures 5.13 and 5.14 show illustrative examples confirming the validity of the maximum likelihood method presented in section 5.2.1. In Figure 5.13 (5.14), the Sivers (Collins) moments in the $n\left(e, e^{\prime} \pi^{+}\right) X$ reaction were extracted from the simulated data in two-dimensional kinematic bins in $x$ and $z$, with six $x$ bins from $0.1<x<0.7$ and $5 z$ bins from $0.2<z<0.7$. In the simulation, asymmetries were calculated for each event as a function of the fully-differential kinematics of the event, namely, $x, Q^{2}, z$ and $p_{T}$ (and also $y$, which was calculated from $x, Q^{2}$ and $E_{b e a m}$ for each event). The calculated asymmetry was then included in the overall sampling probability for each event. In the data analysis, we are free to bin the data using any dimensionality and granularity we choose, and extract the asymmetries in each bin using equations (5.9). In the two-dimensional kinematic binning shown in Figs. 5.13 and 5.14, the extracted asymmetries (data points) in each $z$ bin as a function of $x$ are compared to the input asymmetries plotted as a function of $x$ using a fine-grained binning, but averaged over all events in the $z$ bin in question, which amounts to integrating the input asymmetry from the model over the coarse $z$ range of the bin, and also over the unbinned variables $p_{T}$ and $Q^{2}$, properly folded with our experimental acceptance. In the bottom right panel of both figures, we show the $x$ dependence of the extracted and model input asymmetries integrated over the full $z$ range of the analysis.

Figure 5.15(a) shows the results of extracting the Collins and Sivers moments from our simulated data in fully differential $x, z$ and $p_{T}$ bins (with $Q^{2}$ and $x$ strongly correlated), in terms of the distribution of "residuals"; i.e., the difference between extracted and input asymmetries in units of the statistical error. The residual distributions for both the Collins and Sivers moments are


Figure 5.13: Comparison of extracted Sivers moments for $n\left(e, e^{\prime} \pi^{+}\right) X$ at $E=11 \mathrm{GeV}$ to the model asymmetries used in the Monte Carlo, as a function of $x$, for 5 bins in $z$ from $0.2<z<0.7$ (top left to bottom center) and $z$-integrated (bottom right). Asymmetry uncertainties were calculated from the Monte Carlo data for comparison to the input asymmetry in order to validate the extraction procedure, and are not scaled to the full statistics, which are expected to be roughly twice the statistics generated for the Monte Carlo study. See text for details.


Figure 5.14: Comparison of extracted Collins moments for $n\left(e, e^{\prime} \pi^{+}\right) X$ at $E=11 \mathrm{GeV}$ to the model asymmetries used in the Monte Carlo, as a function of $x$, for 5 bins in $z$ from $0.2<z<0.7$ (top left to bottom center) and $z$-integrated (bottom right). Asymmetry uncertainties were calculated from the Monte Carlo data for comparison to the input asymmetry in order to validate the extraction procedure, and are not scaled to the full statistics, which are expected to be roughly twice the statistics generated for the Monte Carlo study. See text for details.

(a) "Residuals" of extracted asymmetry moments, in units of standard deviation, for the three-dimensional $x, z, p_{T}$ bins shown in Figures 5.27 and 5.29, for $n\left(e, e^{\prime} \pi^{+}\right) X$ at 11 GeV , for Collins (left) and Sivers (right) moments.

(b) Distribution of statistical error in Collins (left) and Sivers (right) moments for the three-dimensional kinematic bins shown in Figures 5.27 and 5.29, for $n\left(e, e^{\prime} \pi^{+}\right) X$ at 11 GeV .

Figure 5.15: (a) Difference between extracted and input Collins (left) and Sivers (right) moments in units of standard deviation, for $n\left(e, e^{\prime} \pi^{+}\right) X$ at 11 GeV , in fully differential kinematic binning ( 6 bins in $0.1<x<0.7,5$ bins in $0.2<z<0.7$ and 6 bins in $0<p_{T}(\mathrm{GeV})<1.2$, and $Q^{2}$ strongly correlated with $x$ ). These residuals are Gaussian-distributed with a mean $(\sigma)$ compatible with 0 (1), thus confirming the validity of the maximum-likelihood extraction and statistical error calculation from our simulated data. (b) Distribution of absolute statistical errors in the Collins (left) and Sivers (right) moments for the same kinematic binning as in (a). This choice of binning results in 123 bins with an average separated neutron asymmetry uncertainty of $\sim 4 \%$ and a most probable asymmetry uncertainty of $\sim 1.5 \%$.
compatible with Gaussians of $\mu=0$ and $\sigma=1$, providing a strong validation of the maximumlikelihood extraction and statistical error estimation for the proposed experiment. Figure 5.15(b) shows the distribution of the absolute statistical error in the extracted Collins and Sivers moments for $n\left(e, e^{\prime} \pi^{+}\right) X$, scaled to the requested 40 production beam days at 11 GeV , for 6 bins in $0.1<x<$ $0.7,5$ bins in $0.2<z<0.7$, and 6 bins in $0<p_{T}(G e V)<1.2$. The average statistical uncertainty of about $4 \%$ is skewed by the long tails of the distribution due to large uncertainties in bins at the periphery of the acceptance. The most probable uncertainty is $1.5 \%$, and the vast majority of bins (83\%) have statistical uncertainties below $5 \%$.

The purpose of Figs. 5.13, 5.14 and 5.15 is to demonstrate that in our experimental configuration, the maximum-likelihood extraction of the Collins and Sivers moments is reliable and robust. In each figure, most of the extracted data points are within $1 \sigma$ of the input asymmetries, properly integrated over "unbinned" dimensions, for one-, two- and three-dimensional binning. It is worth noting that the negative correlation between $p_{T}$ and $x$ in our acceptance implies that at high $x$, the distribution of events is concentrated mostly at lower $p_{T}$ values. In our analysis, no minimum $p_{T}$ cut was applied. Since the azimuthal angle resolution diverges as $p_{T} \rightarrow 0$ (as shown in figure 5.5), some of the observed fluctuations of the extracted asymmetry with respect to the input asymmetry at high $x$ could be attributed to the divergence of the azimuthal angular resolution, which in the final data analysis could be suppressed with a reasonable low- $p_{T}$ cutoff.

## Projected Results in One Dimension: Comparison to Existing Data

An important gauge of the physics impact of this experiment is the improvement in knowledge of the Collins and Sivers effects in SIDIS on a neutron target relative to the best current knowledge extracted from existing measurements on proton and deuterium targets by the HERMES and COMPASS collaborations. The HERMES experiment published results on the Collins [22] and Sivers [21] asymmetries in SIDIS on transversely polarized protons for both pions and kaons. The COMPASS experiment published results for pions and kaons in SIDIS on transversely polarized deuterons [26]. In addition, COMPASS also published measurements on a proton target [18], and very recently, JLab experiment E06-010 has submitted the first results for Collins and Sivers moments on ${ }^{3} \mathrm{He}$ for publication [1].

A common feature of all of these pioneering, first-generation measurements is that their precision is statistics-limited, and each experiment could only meaningfully extract the kinematic dependence of the asymmetries in one dimension, while integrating over other dimensions (see, however, Figures 1.5 and 1.6 for a preliminary 2D extraction by the HERMES experiment). Figures 5.16 and 5.17 show the expected statistical precision of the neutron Collins and Sivers moments, respectively, for charged pions and kaons, as a function of $x$ for 40 days of production running at $E=11 \mathrm{GeV}$. Asymmetries for neutral pions will be measured with similar precision to those of the charged pions, providing a crucial test of isospin symmetry. Furthermore, the neutral pions are immune to the background from the decays of diffractively produced vector mesons that can contaminate the charged pion sample. Although such backgrounds are expected to be small (see section 5.3.5), the neutral pion data will be extremely helpful in understanding the effects of different reaction mechanisms on the interpretation of the measured asymmetries.

Several beneficial aspects of the proposed kinematic coverage and precision deserve explicit mention here.

- High precision at large $x$ and high $Q^{2}$, and overlap with existing data. The high- $x$ coverage of


Figure 5.16: Projected uncertainties in extracted Collins moments for $n\left(e, e^{\prime} h\right) X$ with 40 days at $E=11 \mathrm{GeV}$, in one-dimensional $x$ binning, for $h=\pi^{+}, \pi^{-}, K^{+}$and $K^{-}$from top left to bottom right. Absolute uncertainties in the separated neutron asymmetries range from 0.2-1.1\% $\left(\pi^{+}\right), 0.2-$ $0.7 \%\left(\pi^{-}\right), 0.4-2.6 \%\left(K^{+}\right)$and $0.6-3.3 \%\left(K^{-}\right)$. Projected data are compared to HERMES proton data [22], COMPASS deuteron data [26], and predictions based on the latest global fitting of the transversity and Collins functions [30], with uncertainty band. No predictions are shown for the kaon asymmetries due to insufficient information to constrain the transversity and Collins functions for strange quarks in the global fit procedure.


Figure 5.17: Projected uncertainties in extracted Sivers moments for $n\left(e, e^{\prime} h\right) X$ with 40 days at $E=11 \mathrm{GeV}$, in one-dimensional $x$ binning, for $h=\pi^{+}, \pi^{-}, K^{+}$and $K^{-}$from top left to bottom right. Absolute uncertainties in the separated neutron asymmetries range from 0.2-1.1\% $\left(\pi^{+}\right)$, $0.2-0.7 \%\left(\pi^{-}\right), 0.4-2.6 \%\left(K^{+}\right)$and $0.6-3.3 \%\left(K^{-}\right)$. Projected data are compared to HERMES proton data [22], COMPASS deuteron data [26], and predictions based on the latest six-flavor decomposition of the Sivers functions [32], with uncertainty band. Note that the vertical scale is twice as large compared to Fig. 5.16 in order to accommodate the wider range of predicted Sivers asymmetries cf. Collins.
the proposed measurements is at least equal to that of the SOLID experiment E12-10-006[70], with (complementary) coverage at higher $Q^{2}$ values at the same $x$ (see Figure 5.1).

- The model predictions shown in the figures give a qualitative sense for the current knowledge of neutron asymmetries for an assumed $x$ dependence; but in reality, the Sivers function in particular is completely unknown in the high- $x$ region, with only loose theoretical guidance.
- The model for the Collins asymmetry assumes the validity of the Soffer bound [31], a modelindependent limit on the size of the transversity distribution significantly more restrictive than positivity, and is enforced in the fit parametrization, which therefore predicts a narrow range of generally small neutron asymmetries. However, current data and fitting favor a $d$ quark transversity distribution close to the Soffer bound, and the E06-010 results [1] are suggestive of a large negative Collins asymmetry in $n\left(e, e^{\prime} \pi^{+}\right) X$ at high $x$, albeit with marginal statistical significance. If confirmed by future precision measurements, such an asymmetry would indicate a violation of the Soffer bound for the $d$ quark transversity distribution. This experiment will have sufficient precision to establish such a violation conclusively, which would present a major challenge to current understanding of the application of QCD to nucleon spin physics [71].
- Although the $\pi^{+}$production rates are about $50 \%$ higher than $\pi^{-}$, the proton dilution in ${ }^{3} \mathrm{He}$ is more favorable for $\pi^{-}$production ( $1-f_{p} \sim 0.27$ at $x \sim 0.35$ ) than for $\pi^{+}$production ( $1-f_{p} \sim 0.2$ at $x \sim 0.35$ ), leading to comparable uncertainties in neutron asymmetries.

Figures 5.18 and 5.19 show the projected uncertainties as a function of $x$, integrated over $z$ and $p_{T}$ within the experimental acceptance, for 20 days of production running at $E=8.8 \mathrm{GeV}$. Although the overall rates are higher at $E=8.8 \mathrm{GeV}$, the precision in the highest $x$ bin $(0.6<x<0.7)$ is significantly reduced at 8.8 GeV compared to 11 GeV , largely as a result of the $W>2 \mathrm{GeV}$ and $W^{\prime}>1.5 \mathrm{GeV}$ thresholds setting in at lower $x$ values for a given $Q^{2}$. The expected precision in the lower $x$ bins is essentially equal to the precision at $E=11 \mathrm{GeV}$.

Figure 5.20 illustrates the power of the proposed measurements to improve our knowledge of the Sivers functions in the valence region. In Fig. 5.20(a), pseudo-data for $A_{U T}^{\text {Sivers }}$ in $n\left(e, e^{\prime} \pi^{+}\right) X$, with uncertainties corresponding to half of our expected statistics with 40 days of production at $E=11 \mathrm{GeV}$, are shown together with the latest prediction of an updated 2010 global fit based on the model of Anselmino et al. [32]. Fig. 5.20(b) shows the expected uncertainty corridor after including the pseudo-data in the fit. The allowed range of Sivers moments shrinks by at least a factor of 5 .

## Results in Two Dimensions

The high statistics of the proposed measurements will enable the first precision multi-dimensional studies of the kinematic dependence of the Collins and Sivers (and Pretzelosity) asymmetries on a neutron target, in kinematics focused on the high- $x$ region at high $Q^{2}$, which is dominated by valence quarks. The proposed experiment will also provide the first precision neutron measurements at $x>0.3$, at $Q^{2}$ values between those of the HERMES and COMPASS experiments ${ }^{1}$ and well

[^9]

Figure 5.18: Projected uncertainties in extracted Collins moments for $n\left(e, e^{\prime} h\right) X$ with 20 days at $E=8.8 \mathrm{GeV}$, in one-dimensional $x$ binning, for $h=\pi^{+}, \pi^{-}, K^{+}$and $K^{-}$from top left to bottom right. Absolute uncertainties in the separated neutron asymmetries range from 0.2-2.1\% $\left(\pi^{+}\right), 0.2-1.2 \%\left(\pi^{-}\right), 0.5-5.8 \%\left(K^{+}\right)$and $0.6-6.9 \%\left(K^{-}\right)$. Projected data are compared to HERMES proton data [22], COMPASS deuteron data [26], and predictions based on the latest global fitting of the transversity and Collins functions [30], with uncertainty band. No predictions are shown for the kaon asymmetries due to insufficient information to constrain the transversity and Collins functions for strange quarks in the global fit procedure.


Figure 5.19: Projected uncertainties in extracted Sivers moments for $n\left(e, e^{\prime} h\right) X$ with 20 days at $E=8.8 \mathrm{GeV}$, in one-dimensional $x$ binning, for $h=\pi^{+}, \pi^{-}, K^{+}$and $K^{-}$from top left to bottom right. Absolute uncertainties in the separated neutron asymmetries range from 0.2-2.1\% $\left(\pi^{+}\right)$, $0.2-1.2 \%\left(\pi^{-}\right), 0.5-5.8 \%\left(K^{+}\right)$and $0.6-6.9 \%\left(K^{-}\right)$. Projected data are compared to HERMES proton data [22], COMPASS deuteron data [26], and predictions based on the latest six-flavor decomposition of the Sivers functions [32], with uncertainty band. Note that the vertical scale is twice as large compared to Fig. 5.18 in order to accommodate the wider range of predicted Sivers asymmetries cf. Collins.


Figure 5.20: Example impact of the proposed measurements of $A_{U T}^{\text {Sivers }}$ in $n\left(e, e^{\prime} \pi^{+}\right) X$, using only half of the expected statistics and one-dimensional $x$-binning. In (a), pseudo-data based on half of our expected statistics are compared to the current (2010) uncertainty corridor for the neutron Sivers moment based on the model of [32]. In (b), the expected uncertainty corridor obtained by including the pseudo-data in the fit is shown. Note that only the $\pi^{+}$data at $E=11 \mathrm{GeV}$, at half of projected statistics, have been included in the fit so far. The experiment will also produce results for $\pi^{-}, \pi^{0}$ and $K^{ \pm}$at both $E=11 \mathrm{GeV}$ and $E=8.8 \mathrm{GeV}$.
above the $Q^{2}$ range probed by JLab E06-010[1], accomplished using a lower beam energy than the HERMES and COMPASS experiments by detecting large-angle scattering at high luminosity.

For charged and neutral pions, the typical neutron asymmetry precision of a few tenths of a percent (when binned in one dimension) permits detailed multi-dimensional studies that were difficult to impossible in previous lower-precision experiments. In an experiment with infinite statistics and kinematic coverage, the asymmetries would be studied in a fully-differential phase space consisting of all variables on which they depend. In the SIDIS reaction in the current fragmentation regime, as in the proposed experiment, the quantities of interest are the azimuthal moments of the nucleon spin-dependent cross section, described in terms of structure functions that depend on $x, Q^{2}, z$ and $p_{T}$. However, significant physics insight can be gained through studies of asymmetries integrated over one or more dimensions of this phase space. In the case of the Collins and Sivers effects, it is important to keep in mind the different nature of the underlying structure functions. The Sivers TMD $f_{1 T}^{\perp}\left(x, \mathbf{k}_{\perp}\right)$ describes the correlation between the nucleon spin and the transverse motion of unpolarized quarks with longitudinal momentum fraction $x$ and transverse momentum $\mathbf{k}_{\perp}$. Since the initial quark is unpolarized, the measured Sivers $A_{U T}$ asymmetry in SIDIS involves the convolution of $f_{1 T}^{\perp}$ with the unpolarized fragmentation function $D_{1}(z)$. Therefore, to first order, $A_{U T}^{\text {Sivers }}$ should only depend on $x$ and $p_{T}$ and should not depend on $z$. However, an indirect $z$ dependence can be introduced due to the $z$ dependence of the fraction of the initial quark $\mathbf{k}_{\perp}$ carried by the observed hadron which is assumed to be a fragmentation product of the struck quark.

For the Collins asymmetry, the situation is more complicated since polarization of the initial quark is also involved, so that $A_{U T}^{\text {Collins }}$ depends in principle on $x, z$ and $p_{T}$ through both the transversity distribution $h_{1}^{q}\left(x, \mathbf{k}_{\perp}\right)$ and the spin-dependent Collins fragmentation function $H_{1}^{\perp}\left(z, \mathbf{p}_{\perp}\right)$. Moreover, the extraction of $h_{1}$ from SIDIS is complicated by the relatively poor knowledge of $H_{1}^{\perp}$ [30]. The ability to vary $x$ and $z$ independently over large ranges in the proposed experiment, with high statistical precision, will be especially helpful in the deconvolution of the effects of distribution and fragmentation functions from the measured asymmetries.

Figures 5.21 and 5.22 compare the expected statistical precision of our experiment with 40 days of production data at 11 GeV , in two-dimensional $x$ ( 6 bins $0.1<x<0.7$ ) and $z(5$ bins $0.2<z<$ 0.7 ) bins, to the allowed range of neutron Sivers moments for $\pi^{+}$and $\pi^{-}$production, respectively, where the theoretical predictions and estimated uncertainty corridors were obtained from the fit to HERMES and COMPASS data in [32]. The model predicts large, negative asymmetries on the neutron, particularly for $\pi^{+}$production, which is dominated by the nucleon's down quark distribution, with strong $x$ and $z$ dependence. In the two-dimensional binning shown, most of the $z$ dependence reflects the positive correlation between $z$ and $p_{T}$ within our acceptance, and predicted asymmetries which increase as a function of $p_{T}$. The typical neutron asymmetry uncertainty in $6 \times 5$ kinematic binning is at the $0.5-1 \%$ level. Multi-dimensional studies of such precision will vastly improve our understanding of the Sivers effect in SIDIS on a neutron target, and therefore for down quarks in the nucleon.

Figures 5.23 and 5.24 show the expected uncertainties in the Collins moments for $\pi^{+}$and $\pi^{-}$ production on the neutron at 11 GeV . The uncertainties in the Collins moments as a function of $x$ and $z$ are virtually identical to those of the Sivers moments. However, relative to the size and range of the predicted asymmetries, the expected precision in the Collins moments is somewhat worse, reflecting the enforcement of the Soffer bound in the model for the transversity distribution. The asymmetries could be significantly larger in the event of a Soffer bound violation. Even relative


Figure 5.21: Results binned in $x$ and $z$ for the Sivers asymmetry in $n\left(e, e^{\prime} \pi^{+}\right) X$ at $E=11 \mathrm{GeV}$, with predictions from the global fit [32] with central value and uncertainty corridor.


Figure 5.22: Results binned in $x$ and $z$ for the Sivers asymmetry in $n\left(e, e^{\prime} \pi^{-}\right) X$ at $E=11 \mathrm{GeV}$, with predictions from the global fit [32] with central value and uncertainty corridor.


Figure 5.23: Results binned in $x$ and $z$ for the Collins asymmetry in $n\left(e, e^{\prime} \pi^{+}\right) X$ at $E=11 \mathrm{GeV}$, with predictions from the global fit [30] with central value and uncertainty corridor.


Figure 5.24: Results binned in $x$ and $z$ for the Collins asymmetry in $n\left(e, e^{\prime} \pi^{-}\right) X$ at $E=11 \mathrm{GeV}$, with predictions from the global fit [30] with central value and uncertainty corridor.


Figure 5.25: Results binned in $x$ and $z$ for the Sivers asymmetry in $n\left(e, e^{\prime} K^{+}\right) X$ at $E=11 \mathrm{GeV}$, with predictions from the global fit [32] with central value and uncertainty corridor.
to the small asymmetries predicted in this model, the relative asymmetry precision will be at the $10-20 \%$ level, and far superior to that of previous experiments.

Figures 5.25 and 5.26 show the expected precision for $K^{+}$and $K^{-}$neutron Sivers asymmetries, respectively, binned in $x$ and $z$, compared to the model prediction with uncertainty corridors. The precision of the Collins moments is virtually identical; however, no predictions for the Collins moments in kaon production are shown since the existing fit [30] only focused on $u$ and $d$ quarks using charged pion data, and therefore the predictions for kaons and their uncertainties can be misleading. Precision SSA measurements in SIDIS kaon production are a unique advantage of the proposed experiment in the overall JLab 11 GeV SIDIS program. See the discussion in section 6.1.

## Results in Fully-Differential $x, z$, and $p_{T}$ Bins

The phase space coverage of this experiment, shown in Figure 5.1, spans a large, independent range of $x, z$ and $p_{T}$. For a single beam energy, $Q^{2}$ is strongly correlated with $x$. With our requested production data taking at $E=8.8 \mathrm{GeV}$, data will be obtained at $Q^{2}$ values from $1-2 \mathrm{GeV}^{2}$ lower at the same $x$ than at $E=11 \mathrm{GeV}$. Combined with a $\phi$ coverage of roughly half of $2 \pi$ and full $\phi_{S}$ coverage obtained by rotating the target spin orientation, the azimuthal moments of the SSAs in SIDIS on the neutron can be extracted rigorously in a fully-differential grid of $x, z$ and $p_{T}$, with minimal range of integration in $Q^{2}$ for a given $x$, and two values of $Q^{2}$ at each $x$ to help quantify the importance of higher-twist and higher-order QCD effects. As shown in Figure 5.15, a uniformly binned $6 \times 5 \times 6$ grid of $\left(x, z, p_{T}\right)$ results in approximately 120 SSA measurements in independent kinematics at each beam energy, $80 \%$ of which result in absolute separated neutron asymmetry uncertainties below $5 \%$ for charged pions, with a most probable (average) uncertainty of $1.5 \%$


Figure 5.26: Results binned in $x$ and $z$ for the Sivers asymmetry in $n\left(e, e^{\prime} K^{-}\right) X$ at $E=11 \mathrm{GeV}$, with predictions from the global fit [32] with central value and uncertainty corridor.
(4\%). Of course, the data can be reorganized into variable-width bins of equal statistical precision, but the projections presented in this proposal use fixed-width bins for simplicity of analysis and presentation.

Figures 5.27 and 5.28 show the expected neutron $\pi^{+}$and $\pi^{-}$Sivers results at 11 GeV , respectively. Asymmetries are plotted at the values predicted by the model of [32] with projected statistical uncertainties, as a function of $x$, with $z$ increasing from left to right and $p_{T}$ increasing from top to bottom. The strong combined $x, z$ and $p_{T}$ dependences of the Sivers moments in $n\left(e, e^{\prime} \pi^{+}\right) X$ are of particular interest, as this channel is dominated by the $d$ quark Sivers function of the nucleon, and the model predicts very large asymmetries. At large $z$ and $p_{T}$, even though the expected asymmetry precision is only at the $3-4 \%$ level, this corresponds to a relative precision of $10 \%$ given the large predicted asymmetry. In the $\pi^{+}$channel, the benefits of fully-differential mapping of the asymmetries are quite clear and the precision of the proposed experiment is sufficient to confirm or falsify the expected $x, z$ and $p_{T}$ dependence. In the $\pi^{-}$channel, on the other hand, the expected precision relative to the expected three-dimensional variations of $A_{U T}^{S i v e r s}$ is less impressive, but still sufficient to identify any large dependencies not predicted by this or other models. If, on the other hand, the dependence on one or more of the allowed dimensions is weak, the data can be combined/integrated over those dimensions to increase the precision in the remaining "interesting" dimensions. Even without integration, the 1 -few\% level precision with which the asymmetries will be mapped in the fully differential phase space will tightly constrain the allowed parameter space of available models, helping the theory and phenomenology of transverse nucleon spin structure to advance far beyond the current level of understanding and predictive power.

Figures 5.29 and 5.30 show the projected uncertainties for the Collins moments in $\pi^{+}$and $\pi^{-}$ production at 11 GeV , which are identical to those of the Sivers moments in each kinematic bin, but are instead plotted at the predictions for $A_{U T}^{\text {Collins }}$ from the model of [30]. For brevity's sake, we


Figure 5.27: Results binned in $x, z$ and $p_{T}$ for the Sivers asymmetry in $n\left(e, e^{\prime} \pi^{+}\right) X$ at $E=11 \mathrm{GeV}$. Data points are plotted at the values predicted by the model of [32], with error bars corresponding to the requested 40 days of production at 11 GeV .


Figure 5.28: Results binned in $x, z$ and $p_{T}$ for the Sivers asymmetry in $n\left(e, e^{\prime} \pi^{-}\right) X$ at $E=11 \mathrm{GeV}$. Data points are plotted at the values predicted by the model of [32], with error bars corresponding to the requested 40 days of production at 11 GeV .


Figure 5.29: Results binned in $x, z$ and $p_{T}$ for the Collins asymmetry in $n\left(e, e^{\prime} \pi^{+}\right) X$ at $E=11 \mathrm{GeV}$. Data points are plotted at the values predicted by the model of [30], with error bars corresponding to the requested 40 days of production at 11 GeV .


Figure 5.30: Results binned in $x, z$ and $p_{T}$ for the Collins asymmetry in $n\left(e, e^{\prime} \pi^{-}\right) X$ at $E=11 \mathrm{GeV}$. Data points are plotted at the values predicted by the model of [30], with error bars corresponding to the requested 40 days of production at 11 GeV .
do not show all of the projections for 1D, 2D and 3D kinematic binning for the Collins and Sivers moments for all hadron species $\pi^{ \pm, 0}$ and $K^{ \pm}$in this proposal. Detailed kinematic tables for two and three-dimensional binning can be found at the URL given in Ref. [2].

### 5.3 Systematic Uncertainties

Several possible sources of systematic error may affect the accuracy of the measured asymmetries. The analysis of the proposed experiment will benefit greatly from the experience gained by the HERMES experiment and the recent E06-010 Hall A Transversity experiment [1, 72].

In fact, the proposed experiment intends to use an apparatus that can be considered a hybrid of HERMES and E06-010:

- Two-spectrometer, open-geometry configuration similar to HERMES;
- One of the spectrometers already used in the 6 GeV experiment at JLab (with reconfigured tracking and trigger);
- Nearly identical hadron identification to that of HERMES;
- Similar or better momentum and angular resolution compared to HERMES;
- Similar spin flip period to HERMES ( 100 s ), which suppresses systematics.

A large fraction of the lessons learned from the recently completed 6 GeV experiment can be applied to the current experiment. Moreover, many of the achievements of the HERMES analysis in extracting the asymmetries can easily be adapted.

In general, the extraction of the SSAs defined in Eqn. (5.4) is affected by multiple sources of systematic error including

1. The accuracy of the luminosity and target polarization ;
2. The accuracy of the reconstructed kinematics
3. The purity of particle identification.
4. Fluctuations and drift of the experimental conditions (e.g. detector efficiency);
5. Random background events entering the coincidence;
6. The approximations inherent to eqn. (5.4) such as:

- Nuclear effects (the neutron is not free) and the uncertainty in the knowledge of the polarization of the protons and their SSAs.
- QED radiative effects, which in the case of SSA extraction consist primarily of kinematic bin migration.
- Higher twist effects, higher-order QCD corrections, lepton-photon non-collinearity and additional allowed azimuthal modulations of the cross section
- Non-SIDIS processes entering into the cuts (such as Vector Meson production, target fragmentation, etc.);
- The charge-symmetric pair production background in identified DIS electrons, which was the dominant background in the analysis of the E06-010 experiment [1], will be measured and corrected by reversing the polarity of BigBite. The asymmetry of the pair production background can be measured during the reverse polarity runs, but also will be monitored parasitically during the production runs due to the large acceptance of BigBite, which can measure downbending ( $e^{+} h$ ) coincidence events during the production data taking of upbending ( $e^{-} h$ ) events, albeit with different acceptance.

7. The detector acceptance, which does not affect the SSA extraction in the case that the product of the effective integrated luminosity and the acceptance is $180^{\circ}$ symmetric in $\phi_{S}$.

The systematic errors in reconstructed kinematics and the fluctuations of the experimental conditions tend to cancel out in yield ratios used to form the raw asymmetry measurements. Residual effects due to target polarization drift and detector efficiency are minimized by frequent target spin flips. The high luminosity enables daily analysis of acquired subsets of data to monitor the stability of experimental conditions. The effects of target polarization drift on the asymmetries can easily be corrected using frequent target polarization measurements as discussed in [1].

Single-arm DIS events will be used as a precise luminosity monitor and as a cross check of the beam luminosity monitor. Other effects of the experimental apparatus will be investigated using the standard method of the "fake asymmetry" extracted from randomly assigning the target spin state to the data (both from production and calibration runs). Finally, an upper limit can be placed on any unaccounted-for residual false asymmetries by measuring the so-called "witness channel" single-arm asymmetries in inclusive production of $e^{-}, \pi^{ \pm}$, etc, with the target polarization orientation parallel to the scattering plane (horizontal), which vanish as a consequence of parity conservation [1].

### 5.3.1 Target-related Effects

The phenomenological scheme currently adopted for extracting neutron SSAs is based on the approach proposed by S. Scopetta in [68]. In such an approach, the calculations are performed in the Bjorken limit using the Plane Wave Impulse Approximation (PWIA) which includes three crucial assumptions:

1. The virtual photon interacts with a single nucleon;
2. The internal structure of the bound nucleon is the same as the free one. Therefore, the nuclear dynamics determine only the momentum, binding energy and polarization of the struck nucleon. In PWIA the nuclear effects are contained in the so-called nuclear spectral function (see, e.g. [73]) describing the probability density to find a nucleon with a given momentum, removal energy and polarization in the nucleus.
3. The main final state considered is composed of a light pseudoscalar meson and a three-nucleon state, both in the two- and three-body break-up channels. The final state interaction is retained only in the spectator two-nucleon system. It is worth noting that the jet originating from the nucleon that absorbs the virtual photon can generate multiple light hadrons in addition to the final nucleon. In the present theoretical approach only one light hadron is taken into account.

The nuclear effects can affect the extraction of the neutron SSAs by up to $7 \%$ (relative), when comparing the neutron SSAs extracted from the corresponding ${ }^{3} \mathrm{He}$ SSAs using the effective polarization approximation of eqn. (5.5) to the model neutron SSAs used as input to the full calculation of the ${ }^{3} \mathrm{He} \mathrm{SSAs}$ by folding the free neutron structure with the nuclear spectral function. Within this framework, one can also extend the proposed extraction scheme to other leading-twist TMDs.

More refined theoretical analysis is also under way [74]. In particular, work is in progress on two items:

- A fully Poincaré-covariant Light-front description of the ${ }^{3} \mathrm{He}$ tensor, at finite $Q^{2}$, has been obtained. This allows one to carefully take into account the actual kinematics in the theoretical calculations of the nuclear effects, matching the kinematical cuts of the experiment;
- The possible role of final state interactions (FSI) in the extraction of the neutron SSAs from the corresponding ${ }^{3} \mathrm{He} \mathrm{SSAs}$ is under investigation.

The small effective proton polarization in ${ }^{3} \mathrm{He}\left(p_{p}=-2.8 \%\right)$ results in a small offset in the asymmetries $\left(A_{n}=\frac{A_{H e}-P_{p} f_{p} A_{p}}{P_{n}\left(1-f_{p}\right)}\right.$ ) that can be controlled using the data from HERMES and COMPASS on the proton ${ }^{2}$. The nuclear effects were estimated for the E06-010 JLab Transversity experiment and the relative effects were found to be at the few-percent level or less. The same calculations have been kindly performed by the author for the present kinematics and results are summarized in figures 5.32 and 5.31 for Collins and Sivers asymmetries respectively.

According to these results, in the above mentioned assumptions, the extraction of the asymmetries (both Collins and Sivers) is affected only by a few percent relative to the input model. At higher hadron momenta, the situation is even better. However, Final State Interactions (FSI) of the outgoing hadron are not included in this approach; their effects are expected to be reasonably modest, due to the large momentum of the observed hadrons. In the analysis of experiment E06010, the uncertainties introduced by FSI of the outgoing pion with the spectator nucleons were twofold. First, the proton dilution $f_{p}$, which was obtained by measuring the yield ratios between unpolarized $\mathrm{H}_{2}$ and ${ }^{3} \mathrm{He}$ targets, can be affected by unpolarized FSI as follows: The deviation of the ${ }^{3} \mathrm{He}$ SIDIS cross section from $2 \sigma_{p}+\sigma_{n}$ due to initial-state nuclear effects is well-characterized by EMC effect measurements on ${ }^{3} \mathrm{He}$ [75]. However, in SIDIS the produced hadron may rescatter or be absorbed by the spectator nuclear remnant, reducing the measured yield on ${ }^{3} \mathrm{He}$ relative to the sum over free nucleons, causing an extraction of $f_{p}$ from measured yield ratios to overestimate the proton dilution $f_{p}$. Secondly, spin-dependent FSI effects can occur in the rescattering of hadrons by the polarized neutron (and, to a lesser extent by the protons with small polarization) due to large spin-orbit effects such as those observed in $\pi \vec{N}$ scattering. In the E06-010 analysis, such effects were estimated using a simple Glauber rescattering model and found to be smaller than $1 \%$ [1]. Since the precision of the results of experiment E06-010 was statistics-limited, a fully realistic treatment of FSI effects at the $1 \%$ (absolute) level was relatively unimportant; however, for this and other future precision ${ }^{3} \mathrm{He}$ SIDIS experiments such as [70], the treatment of nuclear wavefunction and FSI effects will undoubtedly be an important, if not dominant component of the systematic uncertainty in the extracted neutron information.

The inclusion of FSI in the PWIA framework is a work in progress, which was recently combined with a new relativistic approach for few-nucleon systems that has already been applied to the

[^10]

Figure 5.31: Collins asymmetry model used for the production of $\pi^{-}$(full), and the one extracted from the full calculation in [68] (dashed) and a naive approximation where the proton contribution is neglected (dotted); refer to fig. 2 of [68]. Two hadron momenta are reported ( $z \sim 0.45$ ), for both beam energies


Figure 5.32: Sivers asymmetry model used for the production of $\pi^{-}$(full), and the one extracted from the full calculation in [68] (dashed) and a naive approximation where the proton contribution is neglected (dotted); refer to fig. 2 of [68]. Two hadron momenta are reported ( $z \sim 0.45$ ), for both beam energies.
prediction of the electromagnetic form-factors of a trinucleon system [76]. Interesting results are expected in the coming months, which also will exploit the latest results from HERMES and COMPASS as well as from the 6 GeV transversity experiment from JLab. The authors of the above articles have joined the present experiment and are willing to contribute to the theoretical framework for the extraction of the neutron asymmetries. In summary, the total uncertainty from the target effects is expected to be at the level of $7 \%$ relative to the measured asymmetry.

### 5.3.2 Random Coincidences

Random events entering the coincidence time window and vertex correlation cut represent an additional source of dilution; in fact the background corrected asymmetry $\left(A_{C}\right)$ can be expressed by[66]:

$$
A_{C}=\frac{N_{T}}{N_{S}} A_{M}-\frac{N_{B}}{N_{S}} A_{B}=\frac{1}{1-f_{B}} A_{M}-\frac{f_{B}}{1-f_{B}} A_{B}
$$

where $N_{T}, N_{S}$ and $N_{B}$ are the total, signal and background events, $A_{M}$ and $A_{B}$ are the measured (not background corrected) and background asymmetries and $f_{B}=N_{B} / N_{T}$ is the background dilution factor ${ }^{3}$. Starting from the single arm random rates of 200 kHz and 3 MHz for the BB and SBS (see section 3.7) due mainly to positive and negative pions, $f_{B}$ is suppressed by

- Track reconstruction in BigBite, which eliminates the $\pi^{0}$ background
- Offline identification of electrons in BigBite using the preshower/shower and Gas Cherenkov detector, which reduces the single-arm rate of the electron arm to the $\sim 1 \mathrm{kHz}$ level.
- The small ( $\sim 4 \mathrm{~ns}$ ) coincidence time window between the BigBite calorimeter and scintillator time signals and the SBS HCAL time signal, which reduces the random coincidence to 12 Hz ;
- The precise cut on the vertex correlation between the electron and hadron arms of $\pm 2.0 \mathrm{~cm}$ $\approx 3 \sigma$, which decreases the random coincidence rate by a factor of $4.0 / 60=0.067$, obtaining a coincidence rate of 0.8 Hz ;
- Momentum reconstruction in Super BigBite and rejection of events below 2 GeV reduces the accidentals by another factor of roughly 2 to $\sim 0.4 \mathrm{~Hz}$.

In the worst-case condition of the proposed experiment $(11 \mathrm{GeV})$ the above rate must be compared to a total SIDIS charged pion rate of about 59 Hz (see table 5.1), which corresponds to a dilution factor $f_{B} \sim 0.7 \%\left(\sigma_{f_{B}} \sim 0.08 / \sqrt{N_{T}}\right)$.

In the pessimistic case of a background asymmetry opposite to the measured asymmetry, the expected upper limit of the error due to the background coincidence is therefore: $\sim \sqrt{2} \sigma_{f_{B}}$, that is below $10 \%$ of the typical statistical error presented in section 5.2.2. Fig. 5.33 shows the accidental background (line) and the corresponding signal as a function of the hadron transverse momentum; at $P_{\perp}=1 \mathrm{GeV}$ the background is $1 \%$ of the signal, making the asymmetry extraction clearly feasible.

[^11]

Figure 5.33: Signal and accidental background versus the hadron transverse momentum $P_{\perp}$. The accidental background has been approximated by a linear function of $p_{T}$ (motivated by assuming a random distribution of accidentals and a $\sin \theta_{h q} d \theta_{h q}$ phase space factor). The linear background is multiplied by 10 in the plot to make it visible.

### 5.3.3 Hadron Identification

The performance of the HERMES RICH detector that will be adapted to the SBS spectrometer has been deeply investigated in HERMES. Two reconstruction techniques have been used in the rather clean HERMES ring reconstruction: Inverse and Direct raytracing [45]. The latter, based on a mixture of analytic approximations and Monte Carlo simulations, is expected to work better in the higher-background-rate environment of the proposed experiment, owing to its ability to straightforwardly handle multi-track events. Hadron misidentification (especially for kaons due to the unfavored production ratio) can be represented as an additional (polarized) background (see section 5.3.2). The systematic uncertainties in the RICH identification can be characterized and understood in depth using dedicated low luminosity runs which produce a clean pattern on the RICH.

### 5.3.4 Acceptance Effects: Other Allowed Azimuthal Modulations

In addition to the leading-twist Collins, Sivers and Pretzelosity asymmetries, the extraction of $A_{U T}$ is affected by other allowed azimuthal modulations of the SIDIS cross section, at both leading and subleading twist. The general expression for the cross section was given in [65]. The additional terms affecting the target SSA are described below and summarized (up to twist 3) in table 5.2:

- Higher twist terms of the above asymmetries (twist 4) with the same azimuthal modulations. Their relatively strong $\left(1 /\left(Q^{2}\right)^{2}\right)$ dependence on $Q^{2}$ will be investigated; this is one purpose of the two beam energies.
- Higher twist $A_{U T}$ terms (twist 3$)$ with different characteristic azimuthal modulations $(\sin (2 \phi-$ $\left.\phi_{S}\right)$ and $\left.\sin \left(\phi_{S}\right)\right)$ which can be included in the fit to constrain their contributions.
- $A_{U L}$ terms due to the fact that the photon is not collinear with the lepton beam. The small longitudinal target spin component leads to a $\sin 2 \phi$ modulation at twist 2 , and a $\sin \phi$ term

Table 5.2: Azimuthal modulations other than the Collins and Sivers asymmetries involved in the target SSA.

| Modulation | Beam/Target Pol. | Twist | Comment |
| :---: | :---: | :---: | :---: |
| $\sin \left(3 \phi-\phi_{S}\right)$ | $\mathrm{U} / \mathrm{T}$ | 2 | Pretzelosity amplitude |
| $\sin \left(2 \phi-\phi_{S}\right)$ | $\mathrm{U} / \mathrm{T}$ | 3 |  |
| $\sin \left(\phi_{S}\right)$ | $\mathrm{U} / \mathrm{T}$ | 3 |  |
| $\sin (2 \phi)$ | $\mathrm{U} / \mathrm{L}$ | 2 | Small long. target component wrt virtual photon |
| $\sin (\phi)$ | $\mathrm{U} / \mathrm{L}$ | 3 | Small long. target component wrt virtual photon |
| $\cos (2 \phi)$ | $\mathrm{U} / \mathrm{U}$ | 2 | Boer-Mulders on the denominator of $A_{U T}$ |
| $\cos (\phi)$ | $\mathrm{U} / \mathrm{U}$ | 2 | Cahn Effect on the denominator of $A_{U T}$ |

at twist 3. These terms can be accounted for by small (few percent) corrections as in the HERMES analysis[36];

- Residual asymmetries ${ }^{4}$ from $\sigma_{U U}$ can in principle produce some systematic effects. They present $\cos 2 \phi$ and $\cos \phi$ modulations and their effects (expected to be negligible as in HERMES, [66]) can be estimated by including them in the fit for the extraction of the other asymmetries.

Finally, although the primary physics focus of this proposal is on the leading-twist target singlespin asymmetries, we request polarized beam, which will allow the extraction of the leading-twist $A_{L T}^{\cos \left(\phi-\phi_{S}\right)}$ asymmetry which probes the $g_{1 T}$ "worm-gear" TMD describing the longitudinal polarization of quarks in a transversely polarized nucleon. Unpolarized beam will be formed by summing over beam helicity states, flipped rapidly to cancel out slow fluctuations in experimental conditions.

The extraction of the asymmetries using the maximum likelihood method discussed in section 5.2.1 included only Collins and Sivers moments as a first approximation, but can be straightforwardly expanded to include an arbitrary number of different modulations simultaneously. As mentioned above, the first three terms of Table 5.2 enter in $A_{U T}$ as do the Collins and Sivers effects. The U/L terms come from the fact that the electron beam and the virtual photon are not collinear and the target is transversely polarized with respect to the electron beam. The last two terms are present in the unpolarized cross section which enters the denominator of $A_{U T}$. Unfortunately these terms combine with $\sin \left(\phi_{S}\right)$ to mimic the Sivers and Collins amplitudes. Moreover, their presence imposes the use of a non-linear fit method. In order to estimate the effects of the various terms one proceeds as in the HERMES, COMPASS, and JLab Transversity experiments, performing the fit with an increasing number of parameters and/or modulation terms. Thanks to the much higher statistics and azimuthal coverage compared to previous experiments, one can increase the number of terms included in the fit without significantly increasing the statistical error, giving more stable results.

According to the HERMES (binned Least Square and unbinned Maximum Likelihood methods c7:pap08 and [78]) and E06-010 analyses, the $\sin \left(\phi_{S}\right)$ and $\sin \left(2 \phi-\phi_{S}\right)$ terms produce the most sizeable effects on the Collins and Sivers extraction. Furthermore, it has been found that a

[^12]6 -parameter fit including the first 3 terms of table 5.2 (in addition to Collins, Sivers and constant terms) produces stable fit results, without noticeably affecting the statistics of the extracted amplitudes. Therefore, we do not expect that the inclusion of the additional terms in the extraction of the Collins and Sivers asymmetries significantly degrades the statistical error; while it certainly reduces the systematic error. The Cahn and Boer-Mulders modulations in the denominator will be extracted by a fit of the unpolarized cross section, taking into account the radiative and acceptance effects using a Monte Carlo such as PYTHIA (or other near future stable physics generators such as GMC_TRANS). Detailed Monte Carlo studies will be used for the estimation of the systematic effects due to acceptance and detector smearing. The studies already done for this proposal indicate that such effects will be easily controlled. It is important to note that the proposed apparatus (SBS and BigBite) is relatively simple. Both spectrometers consist of detectors behind large dipole magnets with very simple geometry, simple magnetic field configurations and acceptance and simple, reliable event reconstruction based on straight-line tracking in field-free regions, total absorption of the particle energy in calorimeters, and clean PID using Cherenkov detectors. Such simplicity will enable rapid and reliable data analysis, and represents a significant advantage of the proposed experiment relative to similar planned experiments such as SOLID [70].

The Monte Carlo studies of asymmetry extraction presented in section 5.2 have already demonstrated that the asymmetry extraction will be reliable and robust in the proposed experimental acceptance. Further reduction of the acceptance effects can be achieved with a new extraction method [79, 66] based on an unbinned Maximum Likelihood fit of the measured data with a probability density function (PDF), the fitted parameters of which are the coefficients of a Taylor expansion of the asymmetries in the relevant kinematic variables. The extracted asymmetry moments should correspond to those extracted from an ideal $4 \pi$ detector.

### 5.3.5 Physics Backgrounds

The fluctuation of a virtual photon into its hadronic components and the subsequent interaction of these components with the nucleon may generate hadrons in the final state that represent an additional background to the SIDIS hadrons (see previous section 5.3.2). Such a background can be described by the Vector Meson Dominance model in terms of the interaction of vector mesons ( $\rho^{0}, \omega$ and $\phi$ ) with the nucleon.

The contamination of the SIDIS pion sample by vector meson decays has been estimated using the PYTHIA generator tuned to the HERMES data [80] and is presented as a function of $x$ in figure 5.34. Detailed analysis [78] of the HERMES data (which suffers from higher contamination) has shown that the VM effect on the Collins and Sivers extraction is negligible. Moreover, its influence can be investigated during the analysis by looking at higher- $z$ data in which the VM events are expected to be relevant.


Figure 5.34: Pion contamination from Vector Meson processes

## Chapter 6

## Summary

In this section, we discuss the role of this experiment in the overall JLab 11 GeV SIDIS program, including a comparison to proposals with similar physics goals.

### 6.1 The Role of C12-09-018 in the Context of the JLab 11 GeV SIDIS Program

The primary physics goal of this experiment is a precision survey of the single spin asymmetries in SIDIS on a transversely polarized neutron ( $\left.{ }^{3} \mathrm{He}\right)$ target in a wide, multi-dimensional kinematic coverage, for charged and neutral pions and charged kaons. Since this proposal was first conditionally approved by PAC34, a SIDIS proposal based on the SOLID apparatus [70], originally conceived to measure the parity-violating asymmetries in DIS, deferred with regret by PAC34, was fully approved by PAC35. The SOLID experiment, whose physics goals are similar to this experiment, proposed to measure the SSAs for charged pion electro-production in a dense 4D grid of $Q^{2}, x, z$ and $p_{T}$, by using a detector with essentially $2 \pi$ azimuthal angle acceptance around the beamline and polar angle coverage focused in the forward angle region, with $6.6^{\circ}<\theta_{e}<22^{\circ}$ polar angle coverage for electrons and $6.6^{\circ}<\theta_{h}<12^{\circ}$ for hadrons. In approximately 70 days of production data taking on ${ }^{3} \mathrm{He}$, the SOLID SIDIS experiment will measure approximately 1400 bins covering a complementary kinematic phase space to this experiment. By focusing on the forward-angle, low- $Q^{2}$ region and emphasizing "complete" azimuthal coverage, the SIDIS event rates in SOLID are substantially higher than in this proposal, leading to the collection of extremely high statistics, thus allowing for an "ultimate" precision 4D kinematic mapping of the asymmetries. Such high statistical precision and fully differential binning will be extremely useful for global TMD analysis.

While there is a large overlap between the collaborations of SOLID and this proposal, and we fully support the SOLID experiment (indeed, all of the spokespersons of this proposal are members of the SOLID SIDIS collaboration), in this document we must necessarily emphasize the specific advantages of this experiment and the complementary aspects of the two experiments as part of the overall JLab SIDIS program. None of what follows should be read as an attempt to disparage the SOLID experiment, but rather as an argument for why the two experiments are complementary and why both should be supported.

The figure-of-merit for SSA measurements using polarized ${ }^{3} \mathrm{He}$ has a handful of ingredients. It is defined as the reciprocal of the relative statistical asymmetry uncertainty squared, which can
be expressed as $F O M=N A^{2}$, where $N$ is the total number of events and $A$ is the measured asymmetry. $N$ is determined by the product of solid angle, momentum acceptance, and integrated luminosity folded with the reaction cross section. $A$ is the physics asymmetry, which is diluted by the target polarization, the effective polarization in ${ }^{3} \mathrm{He}$, and the proton dilution. A naive comparison of the figure of merit of the SOLID experiment and this experiment is discussed below.

The solid angle of the SOLID experiment can be approximated by $\Delta \Omega_{e, h}=2 \pi \Delta \cos \theta_{e, h}$, giving $\Delta \Omega_{e, h}=0.416,0.0955$ and $\Delta \Omega_{e} \Delta \Omega_{h}=0.040 \mathrm{sr}^{2}$, while for this experiment, the same product is $\Delta \Omega_{e} \times \Delta \Omega_{h}=0.064 \times 0.04=2.6 \times 10^{-3} \mathrm{sr}^{2}$. The product of total electron and hadron solid angles for SOLID is therefore 15 times higher than SBS+BB. On the other hand, the luminosity of the $\mathrm{SBS}+\mathrm{BB}$ experiment is higher, by a factor of $(60 \mathrm{~cm} \times 40 \mu A) /(40 \mathrm{~cm} \times 15 \mu A)=4$. Therefore, the product of total solid angle and luminosity of the SOLID experiment is only a factor of 3.75 higher than the SBS +BB configuration, before taking into account the cross section weighting. Because the SIDIS hadrons are predominantly found in a narrow cone around the direction of the momentum transfer, an arguably more appropriate comparison is based on the ratio of electron solid angles alone, since after the electron kinematics are fixed, the interesting range of hadron angles is rather narrowly focused. Such a consideration reduces the ratio of the product of luminosity and solid angle between SOLID and SBS + BB to about 1.6, assuming complete coverage of the hadron phase space for $p_{T}<1 \mathrm{GeV}$ in both experiments. In reality, the ratio in question lies somewhere between 1.6 and $3.7 \tilde{5}$ in a kinematics-dependent way.

Neither experiment is significantly limited by momentum acceptance. It should be quite obvious based on these considerations that the superior statistical precision of the SOLID experiment compared to the proposed SBS + BB configuration derives not from a much larger solid angle acceptance, but primarily from higher rates at forward angles. The electron (hadron) polar angle range for BB (SBS) is approximately $24^{\circ}<\theta_{e}<36^{\circ}\left(10^{\circ}<\theta_{h}<18^{\circ}\right)$, which is completely (mostly) orthogonal to that of the SOLID experiment, making the kinematics of the two experiments entirely complementary. It is quite generally true that for a given $x$, the proposed $\mathrm{SBS}+\mathrm{BB}$ experiment covers higher $Q^{2}$ values. Therefore, the role of higher-twist effects, target and hadron mass corrections, and other $1 / Q^{2}$ suppressed effects that impact the physics interpretation, will be less important in the proposed experiment than in the SOLID experiment. Indeed, such concerns are part of the reason that the SOLID experiment requested significant additional beam time on unpolarized hydrogen and deuterium targets in order to check factorization in identical kinematics. The high- $Q^{2}$ data from this experiment will significantly enhance the eventual physics interpretation of the lower- $Q^{2}$, higher-precision data from SOLID and provide complementary kinematics that will greatly enhance global TMD analysis.

In light of these considerations, it is our view that the two experiments should not be viewed as having overlapping physics output due to the lack of overlap in kinematic coverage. However, we list several more clear advantages of the proposed experiment below for the PAC's consideration:

- Asymmetry measurements for additional hadron species, including $K^{ \pm}$and $\pi^{0}$, will aid the flavor decomposition of the underlying TMDs related to transverse SSAs and provide a check of isospin symmetry and an independent constraint on reaction-mechanism effects.
- Simplicity of acceptance: Both SBS and BB consist of detector packages located in fieldfree regions behind open-geometry dipole magnets, providing shielding of low-energy charged particles and sufficient vertical bend for percent-level momentum resolution with extremely simple optics.
- Simplicity of reconstruction: In a high-background-rate environment, straight-line tracking in field-free regions, constrained by total absorption shower calorimeters and highly-segmented Cherenkov detectors for PID makes the reconstruction of the kinematics, the PID analysis and the suppression of backgrounds extremely simple and reliable.
- The proposed experiment largely uses apparatus that either already exists or has been approved for other experiments. For BigBite, we will use a configuration and kinematic settings virtually identical to the approved A1n experiment, while for Super BigBite, the only additional hardware required for SIDIS compared to the GEp-5 experiment is the RICH detector, for which we will reuse the HERMES RICH, since its geometry and performance characteristics are extremely well suited for the SBS detector package.
- As part of the broad and highly productive physics program of the SBS, the proposed experiment can run in the first few years after the 12 GeV upgrade, providing urgently needed precise SSA data to advance the field (see the discussion on the urgency in the introduction). In contrast, the SOLID SIDIS experiment requires a longer timeline, since it represents a more ambitious hardware project, and since it is most likely to run after the completion of the SBS form factor experiments and the 12 GeV Möller experiment. In other words, in addition to having complementary kinematic coverage, the timeliness of the data from the proposed experiment will be extremely important to make progress in this increasingly active field as a stepping stone to the "ultimate" experiment with high enough precision to map the asymmetries in the fully-differential kinematic phase space.

Apart from the SOLID ${ }^{3}$ He SIDIS experiment, no other currently approved SIDIS proposal has similar physics goals to this experiment. However, we note that two new proposals for SIDIS SSA measurements will also be submitted to PAC38. First, there is a proposal to use a DNP-polarized $\mathrm{NH}_{3}$ target combined with the SOLID detector to measure the proton transversity. Given the planned program of high-precision neutron SIDIS measurements, precise proton measurements are very important, both in their own right and to reduce the systematic uncertainties in the neutron measurements. Therefore, these $\mathrm{NH}_{3}$ measurements are complementary to the proposed ${ }^{3} \mathrm{He}$ measurements. Also, the CLAS12 collaboration will submit a proposal to use a transversely polarized frozen-spin HD target to measure proton and deuteron transverse SSA measurements. The low dilution factors of the proposed target and the very large acceptance of CLAS12, which comes closest to an ideal $4 \pi$ detector out of all the proposed experiments, make such measurements very attractive. It is worth noting, however, that the expected luminosity capability of such a target is $\sim 400$ times lower than the proposed ${ }^{3} \mathrm{He}$ target, such that the figure of merit for neutron measurements is roughly 40 times higher using SBS+BB than with HD in CLAS12. Furthermore, the performance of the polarized HDice target in a high-intensity electron beam has yet to be conclusively demonstrated, although a test run is planned for fall 2011. We therefore also consider the CLAS12 HD proposal to be complementary to the Hall A ${ }^{3} \mathrm{He}$ program including SBS+BB and SOLID.

### 6.2 Conclusions

### 6.2.1 Summary of Physics Output

We have developed a SIDIS proposal with the Super Bigbite spectrometer (SBS) as the hadron arm, the BigBite spectrometer as the electron arm, and a high-luminosity polarized ${ }^{3} \mathrm{He}$ target. A measurement of the proton form factor ratio using SBS was approved by PAC32, which underlined in its report the interest in further proposals that would use SBS, especially in SIDIS physics.

The design approach in our experiment uses a scheme that has worked very well in previous fixed-target experiments with a high-energy beam: HERMES and COMPASS. Specifically, we use an open-geometry dipole spectrometer at a small angle with respect to the beam. The key difference in our proposed experiment is a very high luminosity, made possible in part by major advances in polarized ${ }^{3} \mathrm{He}$ target technology, some of which were specifically aimed at facilitating the SBS physics program. Also critical to making use of this luminosity is the use of GEM technology for high-rate high-resolution tracking, and advanced RICH technology for particle ID.

The experimental results will include:

- Improved knowledge of the Collins and Sivers neutron asymmetries (by a factor of 10 with respect to the best data on the proton) for $\pi^{+}, \pi^{-}$and $\pi^{0}$ electro-production in the DIS regime.
- Extraction of the Collins and Sivers neutron asymmetries in a 2-dimensional grid for $\mathrm{K}^{+}$and $\mathrm{K}^{-}$electro-production in the DIS regime.
- Accurate values of pion asymmetries up to $x=0.7$ and $z=0.7$.
- The first accurate evaluation of $\mathrm{Q}^{2}$ dependence of the Collins and Sivers asymmetries, including reasonably fine binning in Bjorken $x$.

Data taking will occur at two electron beam energies, 8.8 and 11 GeV , which will facilitate studying the $Q^{2}$ dependence of the SIDIS asymmetries. We will have excellent azimuthal coverage through the use of multiple target polarization directions, all of which will be transverse to the beam direction.

The responsibility for the construction of most major elements of the SBS spectrometer has already been assumed by various members of the form-factor collaboration. The only element of the SBS that will be added specially for the SIDIS experiment is a RICH detector, for which we will adapt the HERMES RICH detector (presently in the storage at UVA). Since the polarized ${ }^{3} \mathrm{He}$ target is virtually identical to the target that will be used for the proposed 12 GeV Hall A GEN experiment, this proposal does not represent a huge incremental increase to the SBS program in terms of equipment.

### 6.2.2 Summary of Beam Time Request

The next table summarizes our beam time requests.

|  | Time (day) |
| :--- | :---: |
| Production run at $E=11 \mathrm{GeV}$ | 40 |
| Production run at $E=8.8 \mathrm{GeV}$ | 20 |
| Calibration Runs | 2 |
| Target maintenance and configuration changes | 2 |
| Total | 64 |

Productions runs have been presented in the previous sections. Calibration runs include measurements with reference cells filled with (unpolarized) ${ }^{3} \mathrm{He}, \mathrm{H}_{2}$ and $\mathrm{N}_{2}$, and optics calibration targets. We expect that the new polarized target will require similar (or smaller) maintenance then the current polarized ${ }^{3} \mathrm{He}$. As long as possible, non production operations will be performed during the scheduled beam down time.

## Appendix A

## Collaboration Responsibilities

The following is a list of personnel from the institutions and their intended contributions to the proposed experiment:

- The UVa group will take responsibility for the construction and operation of the highpolarization high-luminosity ${ }^{3} \mathrm{He}$ target, which is also a major part of an approved GEN experiment. The UVa group will also take responsibility for the construction of the GEMbased tracker in the Super Bigbite Spectrometer and its operation.
- The CMU group will use their expertise in calorimeters to implement the hadron calorimeter and the beam line magnetic shielding, both of which are also required in the GEP5 experiment E12-07-109. The CMU group also plays a lead role in the approved $G_{M}^{n}$ experiment using the SBS.
- The INFN group is committed to the realization of the approved $G_{E p}$ experiment and to providing a GEM tracker for BigBite, as well as taking the lead in its operation and support. They will also have a significant role in the implementation of the RICH detector. The source of funding for this group is INFN.
- The Hall A collaborators will take responsibility for the infrastructure associated with the 48D48 magnet, which will be used in both this and the three approved SBS-related FormFactor experiments.
- The Los Alamos group has played a lead role in transverse nucleon spin structure experiments through the JLab Hall A transversity experiment E06-010. The Los Alamos group has played a lead role in the development of the physics simulations and data analysis framework for the proposed measurements, helping to optimize the experiment design and collaborating with leading theorists in the field to characterize the physics impact of the proposed measurements in depth. The Los Alamos group plans to assume a significant share of the responsibility for the implementation of the HERMES RICH detector in the SBS.

The UVa group has played a leading role in advancing polarized ${ }^{3} \mathrm{He}$ target technology, and has recently focused on demonstrating the necessary steps that will enable the implementation of a very-high-luminosity target. In addition to alkali-hybrid technology and the use of spectrally narrowed lasers, which have already delivered major improvements in performance in running experiments,
the UVa group has recently demonstrated the use of "convection-driven" cells that make it possible to tolerate high beam currents without excessive loss of polarization. The UVa group has also recently developed a major new tracker system for the BigBite spectrometer.

The CMU group has made major contributions to JLab parity experiments in both Halls A and C, the Hall A GEN experiment (E02-013), and many experiments in Hall B. CMU has take responsibility to prepare much of the hadron calorimeter elements and their implementation.

The INFN groups at JLab have recently merged into a single, stronger Italian collaboration. The collaboration has also gained additional members, doubling its original size to a total of about 30 researchers. One of the 3 main physics objectives of the collaboration program is devoted to the study of the spin structure of the nucleon. The source of research funding for this group is the INFN. Members of the INFN group had a leading role in the design, construction and operation of the HERMES RICH and of the Hall A RICH. About $1 / 3$ of the members are directly involved in the development of the SBS project. In fact, the program of experiments with the SBS spectrometer got a strong support of INFN, which already approved the development of the First Tracker of SBS.

The Glasgow group is working on design and construction of the front-end electronics for the large arrays of PMT (BigBite Gas Cherenkov counters and Super BigBite RICH), effectively contributing several FTE's.

The Florida International University also intends to contribute to the development of a GEMbased tracker at least 1 FTE and put a graduate PhD thesis student in this experiment.

## Appendix B

## Fully Differential Azimuthal Coverage

Figure B. 1 shows the $p_{T}$ dependent $\phi$ coverage for $E=11 \mathrm{GeV}$ for our planned kinematic binning in $x$ and $z$, which consists of dividing the data in $6 x$ bins in the interval $0.1<x<0.7$ and $5 z$ bins in $0.2<z<0.7$. The variations in $p_{T}$ and $\phi$ coverage reflect the negative correlation between $p_{T}$ and $x$ and the positive correlation between $p_{T}$ and $z$ within our acceptance. These correlations can be understood by considering the nature of the apparatus. First, the electron arm, BigBite, has a large momentum acceptance and a large out-of-plane angular acceptance, but a relatively smaller in-plane angle acceptance. To first order, the electron scattering angle $\theta_{e}$ can be regarded as fixed (though the actual in-plane angle acceptance of $\sim \pm 6^{\circ}$ is rather large), such that $x$ and $Q^{2}$, which vary according to the scattered electron momentum, are one-to-one correlated. In this approximation, the direction of $\mathbf{q}$ is also strongly correlated with $x$. Furthermore, the hadron arm is located at a fixed angle, with a $4 / 1$ vertical/horizontal aspect ratio for its angular acceptance, so that the polar angle of the observed hadron with respect to $\mathbf{q}$ is confined within a small range corresponding to the solid angle acceptance of the SBS. To first order, both particle scattering angles are fixed, and the kinematics $x, Q^{2}, z$ and $p_{T}$ are varied by changing particle momenta. At large $x$, the momentum transfer $\mathbf{q}$ makes a larger angle $\theta_{q}$ relative to the beamline, implying smaller angles $\theta_{h q}$ between observed hadrons and the momentum transfer, hence, the negative correlation between $p_{T}$ and $x$, clearly visible in Figure B.1, in which $x$ increases from top to bottom. Similarly, at fixed $\theta_{h q}, p_{T}$ is varied by varying the hadron momentum, implying a positive correlation between $p_{T}$ and $z$, also visible in Figure B.1, in which $z$ increases from left to right.

Figure B. 2 shows the $x$ and $z$ dependence of the $p_{T}$-correlated target spin-angle $\phi_{S}$ coverage. Unlike the asymmetric $\phi$ coverage resulting from the positioning of the hadron arm at a larger angle than the central direction of $\mathbf{q}$, the $\phi_{S}$ coverage is essentially complete for all $x$ and $z$, a result of our plan to orient the target spin in eight directions around the beamline at angles equally spaced in a $2 \pi$ interval about the vertical direction. The correlations between $p_{T}, x$ and $z$ are still reflected, however. The $p_{T}$-correlated coverage in $\phi \pm \phi_{S}$ at 11 GeV is shown in Figure B. 3 (Collins angle $\phi+\phi_{S}$ ) and Figure B. 4 (Sivers angle $\phi-\phi_{S}$ ).


Figure B.1: Polar $p_{T}$ vs. $\phi$ coverage for $E=11 \mathrm{GeV}$ as a function of $x$ and $z$. Data are divided into 6 equal-width $x$ bins in $0.1<x<0.7$ and $5 z$ bins in $0.2<z<0.7$. Rows from top to bottom represent increasing $x$ bins, while columns from left to right represent increasing $z$ bins.


Figure B.2: Polar $p_{T}$ vs. $\phi_{S}$ coverage for $E=11 \mathrm{GeV}$ as a function of $x$ and $z$. Data are divided into 6 equal-width $x$ bins in $0.1<x<0.7$ and $5 z$ bins in $0.2<z<0.7$. Rows from top to bottom represent increasing $x$ bins, while columns from left to right represent increasing $z$ bins.


Figure B.3: Polar $p_{T}$ vs. $\phi+\phi_{S}$ (Collins angle) coverage for $E=11 \mathrm{GeV}$ as a function of $x$ and $z$. Data are divided into 6 equal-width $x$ bins in $0.1<x<0.7$ and $5 z$ bins in $0.2<z<0.7$. Rows from top to bottom represent increasing $x$ bins, while columns from left to right represent increasing $z$ bins.


Figure B.4: Polar $p_{T}$ vs. $\phi-\phi_{S}$ (Sivers angle) coverage for $E=11 \mathrm{GeV}$ as a function of $x$ and $z$. Data are divided into 6 equal-width $x$ bins in $0.1<x<0.7$ and $5 z$ bins in $0.2<z<0.7$. Rows from top to bottom represent increasing $x$ bins, while columns from left to right represent increasing $z$ bins.

## Appendix C

## Replies to Issues Raised by PAC37

In this appendix, we address the comments of the draft PAC37 report. The draft report of PAC37 is attached below for reference.

The PAC is keen to see a full comparison of this proposal with other competing SIDIS proposals with respect to the projected results as it will have to ultimately rank them within a single category. The PAC urges the proponents to provide their projections with a three dimensional binning $\left(x, z, P_{t}\right)$ for a given $Q^{2}$.

1. A detailed comparison and discussion of the unique role and complementarity of this experiment in the context of the JLab 11 GeV SIDIS program is given in section 6.1.
2. Projections in three-dimensional $\left(x, z, p_{T}\right)$ bins are plotted and discussed in section 5.2.2 for charged pions. Full details of projected results in three-dimensional binning including kinematic tables are given at [2]. Here we summarize the projections: in a 3D grid of $6(x) \times$ $5(z) \times 6\left(p_{T}\right)$ bins equally spaced in $0.1<x<0.7,0.2<z<0.7$ and $0<p_{T}(\mathrm{GeV})<1.2$, our experimental acceptance yields $\sim 120$ measurements at each beam energy for charged and neutral pions, more than $80 \%$ of which have absolute separated (Collins/Sivers) neutron asymmetry uncertainties less than $5 \%$, with a most probable uncertainty of $1.5 \%$ and an average uncertainty of $4 \%$, skewed higher by large-uncertainty bins at the periphery of the acceptance. Though the number of bins is about an order of magnitude lower than the approved SOLID experiment, which has similar physics goals, the kinematic coverage of this proposal is practically complementary to that of the SOLID experiment. At 11 GeV , our apparatus covers the range of electron polar scattering angles from $24-36^{\circ}$, while the SOLID apparatus covers electron angles from about 6.6-22 ${ }^{\circ}$. The proposed hadron polar angle coverage is from $10.4-17.6^{\circ}$, compared to $6.6-12^{\circ}$ for SOLID. Since the beam energy is the same in the two experiments, and a similar range of scattered electron momenta is probed, experiment C12-09-018 quite generally covers higher $Q^{2}$ values than the SOLID apparatus at similar $x$, thus making the phase space of the two experiments entirely complementary. For kaons, we do not present our projections in three-dimensional binning, as the nearly one order-of-magnitude lower statistics for kaons do not permit a meaningful fully differential binned extraction of the asymmetries. However, we plan to extract the kaon asymmetries in all three combinations of two-dimensional projections from the three-dimensional ( $x, z, p_{T}$ ) phase space, and in the more limited regions where the kaon statistics are higher we will have some ability to further bin the data along the remaining "integrated" dimension. Since other

SIDIS proposals with polarised neutron (e.g. SOLID or HD with CLAS12) are not able to measure kaon asymmetries or have much lower statistics, we consider the kaon ID capabilities of this proposal to be unique among large-acceptance/high-luminosity SIDIS proposals for JLab 12 GeV .

In light of the considerations above, we wish to emphasize our view that the importance of multi-dimensional kinematic binning has been overemphasized in the consideration of the merits of planned SIDIS experiments, when in fact the more important question is whether a given experiment provides enough multi-dimensional kinematic coverage and statistics to accomplish multi-dimensional fitting of the relevant physics observables, be they asymmetries, structure functions, cross sections, etc. To further clarify this point, in addition to extracting the relevant asymmetries using kinematic bins of varying dimensionality and granularity, we plan to analyze the entire data set at the individual event level using the novel approach of a completely unbinned likelihood fit to extract the parameters of a flexible model which includes the fully-differential kinematic dependences of the asymmetries. Such a model consists of a multi-dimensional Taylor expansion of the asymmetries in $x, z, p_{T}$ and $Q^{2}$, the number of terms in which will be determined by the amount of flexibility needed to describe the data. Such an approach is identical in philosophy and in practice to the approach used to extract the proton electric and magnetic form factors from a large number of cross section measurements at Mainz [77], and to the fitting of the optics tensors used for angle, momentum and vertex reconstruction in the magnetic spectrometers in Halls A and C such as the HRS, HMS and also BigBite and (will be used for) SuperBigBite. The advantage of this kind of analysis is that polynomial expansions are a) sufficiently flexible to describe arbitrary functions and b) are linear functions of their coefficients, which are the parameters to be determined, such that numerically and mathematically speaking, the fit procedure is extremely simple and efficient. In such an analysis the result of the experiment will be the parameters of the flexible model and their uncertainties and correlations.
Returning to the question of how we will extract and present the kaon asymmetries, our expected results for 1D and 2D kinematic binning have been presented in 5.2.2 and tabulated at [2]. Though we have not yet fully developed and tested the aforementioned unbinned likelihood approach, we wish to reiterate that the proposed asymmetry precision for kaons is far superior to previously published SIDIS data and, to our knowledge, will provide the best kaon SSA measurements of any existing proposal for JLab 12 GeV .

The PAC recognizes that clear progress was made in the study of backgrounds at 6 GeV by the proponents but it was short of fully demonstrating the feasibility of this experiment at the proposed luminosity, thus have not responded satisfactorily to item 1) of the previous PAC report. While the PAC endorses the physics goals of the experiment it was not fully convinced that the simulations of the background are realistic enough at 6 GeV to warrant a confident extrapolation of the rates at the proposed luminosity.

The GEANT calculation of the background rates in the proposed experiment uses the same underlying description of the Hall A beamline and target geometry, and the same description of BigBite used to calculate background rates in the completed $d_{2}^{n}$ and transversity experiments, for which we have data from which we can make a direct comparison to our GEANT calculations. In fact, the rates are not "extrapolated" to the proposed luminosity, but are predicted at the proposed
luminosity and beam energy. The studies of backgrounds at 6 GeV were used as a benchmark to validate the code in a configuration in which a direct comparison to experimental data is possible. As described in section 3.6, an extremely detailed description of the BigBite, beamline and target geometry of the 6 GeV transversity and $d_{2}^{n}$ experiments was developed in order to compare the various detector counting rates. The agreement between the GEANT-predicted background rates and the observed MWDC counting rates for the 6 GeV transversity experiment was at the $5 \%$ level, an extremely good level of agreement for this kind of study. The GEANT prediction of the PMT counting rates on the small-angle (closest to the beam) side of the BigBite Gas Cherenkov (GC) detector in the transversity experiment, in which BigBite was at the same location as in the proposed experiment, was too low by roughly a factor of 8 , and on the large-angle (farthest from the beam) side by a factor of four. We plan to take advantage of the recent redesign of the BigBite GC for the approved $A_{1}^{n}$ experiment, in which all PMTs will be located on the large-angle side of BigBite. In order to be conservative in our estimates, the factor of four ratio between data and MC for the GC PMT counting rates is included in our rate calculations for the proposed experiment. Since we no longer plan to use the GC in the electron arm trigger, but only in the offline analysis, the consideration of the GC counting rate with respect to the BigBite trigger is rendered moot. The background rate calculations for the HERMES RICH in SBS using the same GEANT code demonstrated beyond a reasonable doubt that its operation is feasible with a large safety margin, thanks to its high segmentation and the planned implementation of a TDC readout for each PMT using available to our collaboration LeCroy 1877S Fastbus TDC modules, which allows the application of a $\sim 10 \mathrm{~ns}$ offline time window for the RICH PMT signals. Based on the results of our calculations, even if GEANT underestimated the RICH background counting rates by a factor of 50, which is rather unlikely, its operation would still be feasible. Regarding this discussion of feasibility, we wish to stress that the background counting rate environment of the proposed experiment, from the point of view of reconstruction and trigger/DAQ issues, is substantially less demanding (or at least not more demanding) than many other fully approved experiments using the same or similar apparatus, including the GEp(5) experiment [39], the $A_{1}^{n}$ experiment [82], and the SOLID experiment [70]. Moreover, the solutions to the feasibility issues raised by PAC34 have been clearly identified. See chapter 3 for details.

Title: "Measurement of the Semi-Inclusive $\pi$ and $K$ electro-production in DIS regime from transversely polarized ${ }^{3} \mathrm{He}$ target with the SBS \& BB spectrometers in Hall A"

Spokespersons: G. Cates, E. Cisbani, G. Franklin, B. Wojtsekhowski
Motivation: The motivation is to study the transverse spin structure of the neutron. By measuring the azimuthal dependence of semi-inclusive DIS with respect to the nucleon spin direction, different functions such as the Collins and Sivers asymmetries can be studied, which have sensitivity to initial state and final state quark interactions, respectively. This will lead to a better understanding of the role or orbital motion of quarks in the nucleon and quark-gluon interactions.

Measurement and Feasibility: In this experiment an electron beam of 8.8 and 11 GeV scatters off a highly transversely polarized ${ }^{3} \mathrm{He}$ gas target. The relevant physics is accessed through a full azimuthal coverage achieved by the rotation of the target transverse spin direction with respect to the leading final hadron detection plane. A range of $\mathrm{Q}^{2}$ will be used to study higher twist effects. Several design improvements over the existing target would be made to allow the use of higher beam currents (of the order of $50 \mu \mathrm{~A}$ ) than is presently possible. The scattered electrons would be detected in the existing BigBite spectrometer, and semi-inclusive charged pions and kaons would be detected in a new Super BigBite spectrometer. GEM detectors would be used to perform tracking in the very high singles rate environment of each spectrometer. Pions and kaons would be identified using a large dual RICH detector taken from the HERMES experiment.

Issues: The PAC is keen to see a full comparison of this proposal with other competing SIDIS proposals with respect to the projected results as it will have to ultimately rank them within a single category. The PAC urges the proponents to provide their projections with a three dimensional binning $\left(x, z, P_{t}\right)$ for a given $\mathrm{Q}^{2}$

The PAC recognizes that clear progress was made in the study of backgrounds at 6 GeV by the proponents but it was short of fully demonstrating the feasibility of this experiment at the proposed luminosity, thus have not responded satisfactorily to item 1) of the previous PAC report. While the PAC endorses the physics goals of the experiment it was not fully convinced that the simulations of the background are realistic enough at 6 GeV to warrant a confident extrapolation of the rates at the proposed luminosity.

## Appendix D

## Replies to Issues Raised by PAC34

Update: These replies, submitted with the version of this proposal evaluated by PAC37, are superseded by the replies to PAC37 given in C. Updates for PAC38 are shown in bold italics. In this appendix, we address the comments of the PAC34 report. The full report of PAC34 is attached below for reference.

The tracking and particle identification of pions and kaons at forward angles at several times $10^{37} \mathrm{~cm}^{2} \mathrm{~s}^{-1}$ luminosity, with only a very large opening dipole magnet between the target and the detectors, is likely to be a huge technical challenge. In particular, the HERMES RICH detector was previously used in a similar setup (behind a large dipole magnet) at luminosities of up to $10^{32} \mathrm{~cm}^{2} \mathrm{~s}^{-1}$, five orders of magnitude lower than the proposed use.

Since this proposal was evaluated by PAC34, realistic calculations of the rates due to the dominant background from secondary electrons produced in aerogel and the PMT windows due to the interaction of soft photons produced in the target and along the beamline indicate that the average occupancy per PMT of the RICH, at the few $10^{-3}$ level, will be significantly lower than previously estimated, and the reconstruction and particle identification will be reliable and efficient (see section 3.5.2 for details of the simulations). Because the charged track information will be involved in the reconstruction of events in the RICH detector, only a small fraction of PMTs in the active area of the RICH are relevant in the analysis of any given track/event. In the absolute worst case of aerogel rings for $\beta=1$ particles, the characteristic ring size is on the order of ten times the PMT radius, resulting in approximately 100 PMTs being located on the ring. In this case, the average number of PMTs on the expected ring firing due to the uncorrelated background rate would be 0.1. From Poisson statistics, such rings would have one or more background hits in $9.5 \%$ of events, with exactly one background hit in $9 \%$ of events, two hits in $0.45 \%$ of events, and three or more hits in less than $.05 \%$ of events. Since the average number of hits on $\beta=1$ aerogel rings is approximately 10 , the average signal-to-noise ratio for such events would be approximately $100: 1$, and at least $10: 1$ in the roughly $10 \%$ of events with only one background hit. The resulting loss in efficiency and purity of hadron identification would therefore be minimal even for very high momentum hadrons, and in the momentum range of interest for SIDIS, which is $2-7 \mathrm{GeV} / \mathrm{c}$, the signal-to-noise ratio will be even better due to smaller ring sizes. The fine segmentation of the RICH detector and the few-ns level time window for the PMT hits in the offline analysis lead us to state with high confidence that the particle identification in the proposed experiment will perform as expected.

The tracking problem is much more difficult than for exclusive reactions using the same apparatus, since the coincident hadrons can be found anywhere within the acceptance.

The tracking difficulties faced by the GEp(5)experiment, which will be overcome using the twobody kinematic correlations in elastic ep scattering, do not apply to the same extent in the proposed experiment for two simple but important reasons. First, this experiment proposes to run at a factor of 20 lower luminosity than the $\operatorname{GEp}(5)$ experiment. Therefore, the issue of soft background hits in the GEMs reducing the tracking efficiency is substantially less important. Secondly, by covering the face of the HCAL detector with GEMs, and correlating precisely the measured coordinates of the track with the high-energy hadronic shower measured in the HCAL with $<5 \mathrm{~cm}$ coordinate resolution, the acceptance for track reconstruction will be reduced by roughly a factor of 100 in the offline analysis compared to the full acceptance. Update: Since the evaluation by PAC37, the results of a fully realistic Monte Carlo of the tracking reconstruction including background conditions at four times higher rate than expected in the proposed experiment, has found that the GEM tracking in SBS will be highly efficient and accurate (i.e., low false positives). See section 3.5.2 for details.

Can a combination of beam tests and fully realistic simulations demonstrate the feasibility of running the experiment at the proposed luminosity?

After the first consideration of this proposal by PAC34, many more experimental studies have been performed relevant to this proposal. Such studies include, but were not limited to the following:

- The successful completion of experiment E06-010[40], in which BigBite was operated under similar conditions to the proposed experiment, and the tracking efficiency using MWDCs with much lower rate capability than the planned GEM trackers exceeded $92 \%$. Furthermore, the performance of the lead-glass shower and preshower calorimeter of BigBite was excellent and is well understood. Additionally, the dominant background counting rate in the shower trigger from $\pi^{0}$ photoproduction and subsequent decay was well characterized, supporting our background rate estimates for the proposed experiment.
- Successful testing of GEM detectors during the PREX experiment in Hall A.
- Bench tests of the PMT response to low energy backgrounds for both the SBS RICH and BigBite Gas Cherenkov detectors using a radioactive source.

Furthermore, the more detailed, realistic studies of the low-energy photon backgrounds in the detectors since PAC34 lead us to expect an even lower occupancy for the PMTs of the HERMES RICH detector than estimated in the original proposal when running at the proposed luminosity. Our plan to use existing TDC channels for the readout electronics of the RICH detector with ns level resolution will allow further suppression of the background rate by an order of magnitude (compared to HERMES) by correlating the PMT signals in time with the calorimeter time signals. It is the highly segmented nature of the RICH detector that makes possible its operation in the high-luminosity, high-background rate environment of the proposed experiment.

On the BigBite side, the biggest concern for the detector counting rates comes from the Gas Cherenkov (GC) detector, which uses larger-area, 5 " diameter PMTs. At the high luminosity of the proposed experiment, a radical series of upgrades to the readout electronics using flash ADCs with FPGAs (but for only 20 channels, resulting in minimal cost) relative to the completed $d_{2}^{n}$ and 6 GeV transversity experiments and carefully designed shielding of the beamline and an evacuated
target enclosure with a reduced amount of non ${ }^{3} \mathrm{He}$ material on the beamline will reduce the background counting rates of the BigBite GC to a manageable level for online triggering and offline pion rejection (see details in sections 3.6 and 3.7.). The previous paragraph is obsolete in light of the new plan not to use the $B B G C$ in the trigger and to exploit the A1n redesign of the BB GC for offline pion rejection.

Will the very high rates affect the ability to extract relatively small spin asymmetries accurately?

Our expectation from simulations, anchored by operational experience with the relevant detectors at similar luminosities to what is proposed, is that the ratio of true to accidental coincidences in our SIDIS event sample will be at least 200:1. For details, see section 3.7. At this level of contamination from random coincidences, the resulting error in the asymmetry will be less than $10 \%$ of the projected statistical uncertainty on the asymmetry, as detailed in section 5.3.2. Additionally, the single-spin asymmetry of the random background will be measured and corrected for, further reducing the systematic uncertainty due to the small random backgrounds.

Would a better coverage at smaller hadron angles, perhaps combined with running at lower luminosity, give a better overall result (due to better coverage in $p_{T}, \theta_{p q}$, and $\left.\phi^{*}\right)$ ?

In short, no, because the parameters of the experiment for the proposed apparatus are optimized for the study of transversity. Of course, a more complete multidimensional coverage in $p_{T}$ and $\phi^{*}$ would always be welcome. But it is worth noting that at the proposed settings, the SBS acceptance covers at least half of the $2 \pi$ azimuthal phase space already, providing enough angular range to separately extract all the relevant Fourier moments of the $\left(\phi, \phi_{S}\right)$ azimuthal distribution. In the proposed experiment, the hadron arm is centered at an angle of $14^{\circ}$ relative to the beam line. By moving the SBS to approximately $7^{\circ}$, the hadron acceptance would be centered along $\vec{q}$ for the central kinematics of $x \approx 0.4$, giving full azimuthal coverage at small $p_{T}$. However, this would come at the expense of smaller overall solid angle and smaller $p_{T}$ coverage at generally smaller values of $p_{T}$. For the study of transversity, it is much better to have coverage at finite $p_{T}$ since the Collins and Sivers asymmetries are expected to vanish as $p_{T} \rightarrow 0$. Finally, from the point of view of statistics and rates, the centering of the SBS at finite $p_{T}$ does not result in a large reduction in figure-of-merit because of the relatively soft Gaussian $p_{T}$ dependence of the unpolarized cross section for a given $x$ and $z$.

The proposed experiment covers a large range in $\theta_{\vec{q} h}$, corresponding to excellent $p_{T}$ coverage. In the high- $x(x \approx 0.6)$ region of the proposed experiment, the experiment covers the range $0 \leq$ $p_{T} \leq 0.8 \mathrm{GeV} / \mathrm{c}$, while in the low- $x$ region $(x \approx 0.2)$, the coverage is roughly $0.2 \leq p_{T} \leq 1.6$ $\mathrm{GeV} / \mathrm{c}$. As detailed in section 5 , by varying the target spin orientation in at eight directions around the beamline, our coverage in the relevant target spin-dependent azimuthal angles, such as $\phi_{S}, \phi \pm \phi_{S}$ and $3 \phi-\phi_{S}$ will be full $2 \pi$ and $180^{\circ}$ symmetric about $\vec{q}$, which minimizes the acceptance effects on the extraction. As mentioned above, the only relevant azimuthal angle for which our experiment does not have nearly full or symmetric coverage is $\phi_{\bar{q} h}$. Our coverage in $\cos \phi_{p q}$ and $\cos 2 \phi_{p q}$ is centered at $|\cos (\phi(2 \phi))|=1$ with a sufficient range of variation that the azimuthal modulations of the unpolarized cross section will be constrained in the analysis and, with the proposed large statistics, their potential systematic effects on the extraction of transverse target spin-related asymmetries will be under excellent control. Additionally, calibration measurements with an unpolarized target will characterize these azimuthal modulations of the cross section and help disentangle them from the experimental acceptance.

Is it possible to add some (limited) $\pi^{0}$ detection to enhance the physics output of the proposal?

We agree that a measurement of the Collins and Sivers effects in ${ }^{3} \overrightarrow{H e}\left(e, e^{\prime} \pi^{0}\right) X$ would be of great value to the overall SIDIS program of the JLab 12 GeV upgrade, as the $\pi^{0}$ channel would provide an important test of isospin symmetry in the relevant asymmetries, and is immune to backgrounds from different reaction mechanisms such as diffractive vector meson production that are important for charged pions. In fact, the proposed experiment will already be capable of detecting $\pi^{0}$ s in a limited capacity using the hadronic calorimeter HCAL, which is also sensitive to the decay photons from $\pi^{0}$. However, we are also interested in performing a dedicated measurement of the asymmetries for $\pi^{0}$ production by replacing the HCAL and other detectors with the lead-glass calorimeter BigCal, which is ideal for the detection and reconstruction of $\pi^{0} \rightarrow 2 \gamma$, behind the magnet of SBS. To this end, we have already begun investigating the $\pi^{0}$ acceptance and mass resolution from the reconstruction of $\pi^{0} \rightarrow 2 \gamma$ events using HCAL. Preliminary estimates suggest the acceptance for $\pi^{0}$ will be on the order of $70 \%$ relative to that of $\pi^{ \pm} / K^{ \pm}$. However, the estimation of backgrounds in this channel is a non-trivial problem requiring further investigations which we will pursue. Update: Since PAC37, we have performed detailed simulation studies of the $\pi^{0}$ acceptance and resolution using HCAL, which have clearly demonstrated our ability to identify $\pi^{0}$ s and reconstruct their kinematics. The average relative acceptance for $\pi^{0}$ s is $53 \%$, and is higher at high $z$ and high $p_{T}$ where rates are low.

Is a $z$ cut of 0.2 too low for JLab kinematics?
The $z$ coverage of our experiment derives from the large momentum acceptance of the SBS spectrometer, and a cut at larger $z$, e.g. $z>0.3$ would not significantly affect the coverage of the other kinematic variables. We agree that the data at lower $z$ may present additional challenges in terms of physics analysis and interpretation, but since the collection of the data for $0.2<z<0.3$ does not significantly affect the technical difficulty of the proposed measurements, the data will be provided "for free" in addition to the region $0.3<z<0.7$ which is thought to be more clearly interpretable in the factorized partonic framework of current fragmentation.

What will the effect of diffractive vector meson production be on the extraction of SIDIS structure functions?

According to the analysis done using the PYTHIA generator (figure 5.34 of this proposal), the expected contamination from exclusive vector meson production is below $3 \%$ and its influence on the asymmetry extraction according to the HERMES analysis, in which the contamination is higher, is expected to be negligible. Furthermore, given the large angular and momentum acceptance in the SBS, and the symmetry of the SBS acceptance for positive and negative (upbending and downbending) particles, we expect to have some ability to detect and reconstruct $\rho \rightarrow \pi^{+} \pi^{-}$events in which both charged tracks are detected in the same event, giving us an additional handle on the contribution from such processes. Exclusive meson production is expected to become important for $z>0.7$, above the $z$ range of this proposal. Furthermore, we expect to closely collaborate with experiments in CLAS12 which will provide complementary information on $\rho$ production and decay.

What is the impact of radiative tails from exclusive and resonance region scattering on the structure function extraction? (In particular, will the cross sections and spin asymmetries of these regions by sufficiently well known?)

By comparing our kinematics to those of experiment E00-108 in Jefferson Lab Hall C[81], for which preliminary estimates have been made of the contamination of SIDIS events from radiative tails of exclusive and resonant scattering, and noting that where our experiment overlaps the

Hall C data in $z$, the values of $W, W^{\prime}$ and $Q^{2}$ are generally larger in comparison, we expect the contamination from these radiative tails to be on the order of several \% or less. Furthermore, we will directly constrain the relative contribution and spin asymmetries of these processes in our SIDIS sample using the data from our experiment, which will cover up to $z=1$. This is because the SBS acceptance in the proposed detector and magnet configuration is not limited at high momentum, and will accept particles up to the full beam energy. Therefore, our control over the radiative tails from exclusive and resonance region scattering will not only be informed by all previously existing data and models, but also directly by our data, which will provide both the yields and asymmetries of the exclusive channels, and we therefore do not anticipate any difficulty in the extraction of SIDIS structure functions as a result of such effects. Update: In the final analysis of the E06-010 experiment, the contamination from exclusive radiative tails was estimated at less than $3 \%$ for charged pions, with minimal impact on the asymmetry extraction.

Can the possibility of polarized proton and deuteron targets to obtain neutron structure functions be considered and integrated into a comprehensive program at JLab?

We agree that a measurement of the transverse target single-spin asymmetries in SIDIS using polarized proton and deuteron targets with the BigBite+SBS combination in the same configuration would be highly desirable and promising. Indeed, the technical and practical challenges of such an experiment are being actively investigated. However, compared to the use of polarized ${ }^{3} \mathrm{He}$, such experiments using solid-state DNP-polarized $N H_{3} / N D_{3}$ and/or ${ }^{6} \mathrm{LiD}$ targets present substantial additional technical challenges, including the large holding fields required to maintain the target polarization and orientation, the lower frequency with which the target spin direction can be changed and its effect on the systematic uncertainties in the asymmetry extraction due to both drifts in effective luminosity and reduced acceptance, the constraints on the size of the apertures for scattered particles due to the coils of the holding magnet, and the generally lower overall luminosity capability of such targets. Presently, a significant amount of effort is being directed toward overcoming these challenges. For the time being, as mentioned above, we consider such measurements highly desirable, but given the large differences in technical requirements between these kinds of targets and measurements using polarized ${ }^{3} H e$, we think that the use of these targets is more appropriately considered as a separate proposal. Additionally, since one of the primary advantages of this proposal compared to other SIDIS experiments for the 12 GeV upgrade, such as CLAS12, is the much higher luminosity capability of this proposal, which may be limited by the target in the case of polarized protons and deuterons, we plan to consider whether a polarized proton/deuteron proposal using $\mathrm{BB}+\mathrm{SBS}$ in Hall A is appropriate in the context of the overall JLab SIDIS program before developing a full proposal.

The unique capabilities and contributions of the proposed ${ }^{3} \mathrm{He}$ experiment when considered in the context of the overall SIDIS program for the JLab 12 GeV upgrade are manyfold, but the primary advantages are

- The high luminosity capability of the ${ }^{3} H e$ target.
- The fact that ${ }^{3} \mathrm{He}$ is close to an effective polarized neutron target, in the sense that the nuclear polarization of ${ }^{3} \mathrm{He}$ resides almost entirely on the neutron
- Large acceptance
- Good momentum, angle and vertex resolution of both arms through the use of high-resolution GEM trackers and magnetic analysis of the scattered particles
- Outstanding particle identification capability using the HERMES RICH detector in the hadron arm, and the combination of gas Cherenkov, pre-shower and shower detectors on the electron arm. No other large-acceptance experiment at JLab (SoLiD, CLAS12) in the 12 GeV era can provide hadron identification of this quality without substantial additional funds, at least 10X higher than the expected cost of implementation of the existing HERMES RICH detector in the SBS.

In addition the PAC feels that a strong theoretical effort to determine the nuclear effects in extracting neutron structure functions from ${ }^{3} \mathrm{He}$ measurements is highly desirable.

We agree with this recommendation of the PAC. Since this proposal was first submitted, the theoretical advancement of the field of TMDs and single-spin asymmetries has progressed from pure classification, first measurements and the discovery of non-zero signals, to the first TMD extraction based on a global analysis. The understanding of the nuclear effects in the extraction of SIDIS structure functions is also rapidly progressing. Recently, Scopetta [68] has estimated the initial-state nuclear effects on the Collins and Sivers asymmetries in the proposed kinematics, while studies of the effect of hadron final-state interactions are ongoing. For details of the calculations, see section 5.3. See updated discussion of nuclear effects in Chapter 5.3

## Individual Proposal Report

Proposal: PR12-09-018
Scientific Rating: N/A
Title: Measurement of the Semi-Inclusive $\pi$ and $K$ electro-production in DIS regime from transversely polarized ${ }^{3} \mathrm{He}$ target with the SBS \& BB spectrometers in Hall A

Spokespersons: G. Cates, E. Cisbani, G. Franklin, B. Wojtsekhowski

## Motivation:

The motivation is to study the transverse spin structure of the neutron. By measuring the azimuthal dependence of semi-inclusive DIS with respect to the nucleon spin direction, different functions such as the Collins and Sivers asymmetries can be studied, which have sensitivity to initial state and final state quark interactions, respectively. This will lead to a better understanding of the role or orbital motion of quarks in the nucleon.

## Measurement and Feasibility:

The experiment would use 8.8 and 11 GeV electron beams in Hall A, scattering off a highly polarized, transversely polarized ${ }^{3} \mathrm{He}$ gas target. A range of $\mathrm{Q}^{2}$ will be used to study higher twist effects. Several design improvements over the existing target would be made to allow the use of higher beam currents (of the order of $50 \mu \mathrm{~A}$ ) than is presently possible. The scattered electrons would be detected in the existing BigBite spectrometer, and semi-inclusive charged pions and kaons would be detected in a new Super BigBite spectrometer. GEM detectors would be used to perform tracking in the very high singles rate environment of each spectrometer. Pions and kaons would be identified using a large dual RICH detector taken from the HERMES experiment.

The proposed target upgrades are ambitious, but plausible. The factor of ten faster spin reversal rate requested in this proposal is likely to be a challenging goal if this I to be met without loss of target polarization. The tracking and particle identification of pions and kaons at forward angles at several times $10^{37} \mathrm{~cm}^{2} \mathrm{~s}^{-1}$ luminosity, with only a very large opening dipole magnet between the target and the detectors, is likely to be a huge technical challenge. In particular, the HERMES RICH detector was previously used in a similar setup (behind a large dipole magnet) at luminosities of up to $10^{32} \mathrm{~cm}^{2} \mathrm{~s}^{-1}$, five orders of magnitude lower than the proposed use. The tracking problem is much more difficult than for exclusive reactions using the same apparatus, since the coincident hadrons can be found anywhere within the acceptance. The experimental setup is not fundamentally different from CLAS12, which also has a magnetic field between the target and most detectors, but the proposal aims to run at 100 times the luminosity of CLAS12. Another possible feasibility issue is the ageing of the thousands of phototubes used in the RICH detector, which will be of order of fifteen to twenty years old by the time this experiment runs. The operation of BigBite at the proposed luminosity will also be challenging, but seems much more likely to be feasible than the operation of the hadron arm.

## Issues:

First, see the "Comments to all SIDIS Proposals" in the overall report.
Some of the additional issues raised by this proposal include:

1) Can a combination of beam tests and fully realistic simulations demonstrate the feasibility of running the experiment at the proposed luminosity?
2) Will the very high rates affect the ability to extract relatively small spin asymmetries accurately?
3) Would a better coverage at smaller hadron angles, perhaps combined with running at lower luminosity, give a better overall result (due to better coverage in $\mathrm{p}_{\mathrm{t}}, \theta_{\mathrm{pq}}$ and $\phi^{*}$ ).
4) Is it possible to add some (limited) $\pi^{0}$ detection to enhance the physics output of the proposal?
5) Is a $z$ cut of 0.2 too low for JLab kinematics?
6) What will the effect of diffractive vector meson production be on the extraction of SIDIS structure functions?
7) What is the impact of radiative tails from exclusive and resonance region scattering on the structure function extraction? (In particular, will the cross sections and spin asymmetries of these regions be sufficiently well known?)
8) Can the possibility of polarized proton and deuteron targets to obtain neutron structure functions be considered and integrated into a comprehensive program at JLab?

In addition the PAC feels that a strong theoretical effort to determine the nuclear effects in extracting neutron structure functions from ${ }^{3} \mathrm{He}$ measurements is highly desirable.

Despite the questions of feasibility raised above, the PAC strongly endorses the physics goals of the experiment and the collaboration is encouraged to submit a new proposal that addresses the technical concerns in some detail, as the somewhat ambitious experimental setup and proposed high luminosity requires a more thorough justification than more modest proposals. These necessary simulation studies will be required by any subsequent technical review in any case.

Recommendation: Conditional Approval

## Bibliography

[1] X. Qian et al., "Single Spin Asymmetries in Charged Pion Production from Semi-Inclusive Deep Inelastic Scattering on a Transversely Polarized ${ }^{3}$ He Target", arxiv:1106.0363 (2011).
[2] Complete 2D and 3D kinematic tables for this proposal can be found at http://www.jlab.org/~puckett/PR1209018/KineTables/
[3] S.D. Bass, Reviews of Modern Physics, 77, 2005.
[4] M. Burkardt et al., "Spin-polarized high-energy scattering of charged leptons on nucleons", Rep. Prog. Phys. 73 (2010) 016201
[5] A. Bacchetta et al., Phys. Rev. D 70, 117504 (2004).
[6] L.L. Pappalardo, "Transverse spin effects in polarized semi inclusive deep inelastic scattering", PHD Thesis, Ferrara 2008, available at http://www.fe.infn.it/u/pappalardo/thesis.pdf
[7] J.C. Collins, Nucl. Phys. B 396, 161 (1993).
[8] D.W. Sivers, Phys. Rev. D 41, 83 (1990); 43, 261 (1991).
[9] J.C. Collins, Phys. Lett. B536 (2002) 43.
[10] H. Avakian et al., "Pretzelosity distribution function", arXiv/hep-ph:0808.3982, 2008.
[11] J.C. Collins and A. Metz, Phys. Rev. Lett. D 93, 252001 (2004).
[12] M. Burkardt, Phys. Rev. 66, 1140052002.
[13] M. Burkardt, arXiv:0709.2966v3 [hep-ph] (2008).
[14] G.A. Miller, Phys. Rev. Lett. 99, 112001 (2007).
[15] C.E. Carlson and M. Vanderhaeghen, Phys. Rev. Lett. 100, 032004 (2008).
[16] L. Pappalardo, "Measurement of Collins and Sivers asymmetries at HERMES", talk given at the 20008 Transversity Workshop, Ferrara, available at http://www.fe.infn.it/transversity2008/
[17] COMPASS Collaboration, "Collins and Sivers Transverse Spin Asymmetries for Pions and Kaons in Deuterons", CERN.PH-EP/2008-002.
[18] M.G. Alekseev et al, "Measurement of the Collins and Sivers asymmetries on transversely polarized protons", PLB 692 (2010) 240-246.
[19] D.L. Adams et al, Phys. Lett. B264 (1991) 462-466.
[20] A. Airapetian et al, Phys. Rev. Lett. 84 (2000) 4047-4051.
[21] A. Airapetian et al., "Observation of the Naive-T-Odd Sivers Effect in Deep-Inelastic Scattering", PRL 103, 152002 (2009).
[22] A. Airapetian et al., "Effects of transversity in deep-inelastic scattering by polarized protons", PLB 693 (2010) 11-16.
[23] L. Pappalardo, "TMDs studies at HERMES", GPD2010 Workshop, ECT - Trento, October 11-15, 2010.
[24] A. Bressan, "Recent Results from COMPASS", SPIN2010 and G. Pesaro: "Single spin asymmetries on identified hadrons at COMPASS", SPIN2010.
[25] H. Wollny, "Studies of TMDs at COMPASS", GPD2010 Workshop, ECT - Trento, October 10-15, 2010.
[26] M. Alekseev et al., "Collins and Sivers asymmetries for pions and kaons in muon-deuteron DIS", PLB 673 (2009) 127-135
[27] X. Jiang, "Neutron Transversity Experiment at JLab", TMD2010, ECT - Trenoto, June 21-25, 2010.
[28] M. Contalbrigo, "Transverse Spin Physics at HERMES", presented at SPIN 2008, available at http://www.faculty.virginia.edu/spin2008/scientific_program.html
[29] H. Avakian, "TMD measurements at CLAS6 and CLAS12", talk presented at the TRANSVERSITY 2008 workshop, 2008, available at http://www.fe.infn.it/transversity2008/
[30] M. Anselmino et al., "Transversity and Collins functions from SIDIS and e+e- data", Phys. Rev. D 75, 054032 (2007), arXiv:hep-ph/0701006 and arXiv:hep-ph/0807.0173v1 (2008).
[31] J. Soffer, Phys. Rev. Lett. 74 (1995) 1292-1294.
[32] M. Anselmino et al, "Sivers Effect for Pion and Kaon Production in Semi-Inclusive Deep Inelastic Scattering", EPJ A 39, 89 (2009), arXiv/hep-ph:0805.2677.
[33] A. Martin, "COMPASS Results on Transverse Spin and Transverse Momentum Effects", DIS2010, Florence, April 2010.
[34] M. Anselmino et al., EPJA 39, 89 (2009).
[35] M. Diefenthaler, "Signals for transversity and transverse-momentum-dependent quark distribution functions studied at the HERMES experiment", PhD Thesis, Friedrich-AlexanderUniversit at Erlangen-N urnberg, 2010.
[36] A. Airapetian et al., Phys. Rev. Lett. 94, 012002 (2005).
[37] V.Y. Alexakhin et al., Phys. Rev. Lett. 94, 202002 (2005).
[38] http://hallaweb.jlab.org/12GeV/SuperBigBite/
[39] E. Brash, E. Cisbani, M. Jones, M. Khandaker, L. Pentchev, C.F. Perdrisat, V. Punjabi, B. Wojtsekhowski (spokespeople), Large Acceptance Proton Form Factor Ratio Measurements at 13 and $15(\mathrm{GeV} / c)^{2}$ Using Recoil Polarization Method, JLab experiment E12-07-109.
[40] J-P. Chen, X. Jiang, J-C. Peng, JLab Hall A experiment E06-010, E. Cisbani, H. Gao, X. Jiang, Hall A experiment E06-011.
[41] M. Sargsian, provite communication, 2011.
[42] SBS Conceptual Design Report. http://www.jlab.org/ bogdanw/SBS-CDR/SBS-CDR.pdf
[43] G. Cates, N. Liyanage, B. Wojtsekhowski (spokespeople), Measurement of the Neutron Electric Form Factor $G_{E n}$ at High $Q^{2}$, JLab experiment E02-013.
[44] F. Sauli, Nucl. Instr. Meth. A386 (1997) 531.
[45] N. Akopov et al, Nucl. Instr. Meth. A479 511 (2002).
[46] R. De Leo, "Long-term operational experience with the HERMES RICH detector", talk presented at RICH 2007, Trieste, Italy; available at: http://rich2007.ts.infn.it/
[47] Progress report on the SuperBigbite Project (Response to the recommendations from the second Technical Review). http://www.jlab.org/ bogdanw/SBS-CDR/TR2 Response.pdf
[48] K. Nakamura et al, JPG 37, 075021 (2010) (Particle Data Group: http://pdg.lbl.gov)
[49] D.E. Wiser, Ph.D. Thesis, University of Wisconsin-Madison (1977) (unpublished).
[50] V. Nelyubin, report "A GEANT Simulation of Backround Rate in Quartz Window of PMT XP4508 in Cherenkov Detector of BigBite", 2010.
[51] J. Alcorn et al. Nucl. Inst. Meth. A 522, 294 (2004).
[52] T. Averett, B. Wojtsekhowski, Bo Zhao, "Design of the BigBite Gas Cherenkov optics with large array of PMTs", Hall A Tech. Report, 2011.
[53] B. Sawatzky, "Hall A Technical Note for the BigBite Cerenkov Detector", Hall A Tech. Report draft, June 2010.
[54] E. Cisbani, private communications (2011).
[55] I. Rachek and B. Wojtsekhowski, JLab technical note TN 11-017: availbale at https://jlabdoc.jlab.org/docushare/dsweb/View/Collection-12749
[56] E. Babcock et al, Phys. Rev. Lett. 96, 083003 (2006).
[57] K.D. Bonin, T.G. Walker and W. Happer, Phys. Rev. A 37, 3270 (1988).
[58] K.P. Coulter et al, Nuc. Inst. and Meth. in Phys. Res. A276, 29 (1989).
[59] A. Deninger et al, Eur. Phys. J. D 38, 439 (2006).
[60] N.R. Newbury et al, Phys. Rev. Lett. 67, 3219 (1991).
[61] H.L. Lai et al, hep-ph/9903282.
[62] deFlorian et al, Phys. Rep. D 75114010 (2007) and hep-ph/0703242v1, 22 Mar 2007
[63] M. Anselmino et al, Phys. Rev. D 71, 074006 (2005).
[64] A. Airapetian et al, Phys. Rev. D 75 (2007) 011103(R), hep-ex/0605108; B. Maiheu, "Hadronization in electron - proton scattering at HERMES", PHD Thesis, Universiteit Gent, March 2006.
[65] A. Bacchetta et al, "Semi-inclusive deep inelastic scattering at small transverse momentum", JHEP02 (2007) 093.
[66] L.L. Pappalardo, "Transverse spin effects in polarized semi inclusive deep inelastic scattering", PHD Thesis, Ferrara 2008, available at http://www.fe.infn.it/u/pappalardo/thesis.pdf.
[67] X. Zheng et al. Phys. Rev. C 70, 065207 (2004)
[68] S. Scopetta, "Sivers function an Constituent Quark Model", talk given at the 20008 Transversity Workshop, Ferrara, available at http://www.fe.infn.it/transversity2008/ S. Scopetta, Phys. Rev. D 75054005 (2007).
[69] J. Huang and Y. Qiang, http://www.jlab.org/~jinhuang/Transversity/MLE.pdf (2010)
[70] JLab proposal PR-12-10-006 http://www.jlab.org/exp_prog/proposals/10/PR12-10-006.pdf
[71] J.P. Ralston, arxiv:0810.0871 (2008).
[72] K.C. Allada, "Measurement of Single Spin Asymmetries in Semi-Inclusive Deep Inelastic Scattering Reaction $n^{\uparrow}\left(e, e^{\prime} \pi^{+}\right) X$ at Jefferson Lab", PhD Thesis, University of Kentucky, 2010 X. Qian, "Measurement of Single Spin Asymmetry in $n^{\uparrow}\left(e, e^{\prime} \pi^{ \pm}\right) X$ in Transversely Polarized ${ }^{3} \mathrm{He} ", \mathrm{PhD}$ Thesis, Duke University, 2010.
[73] C. Ciofi degli Atti, E. Pace, G. Salmè, Phys. Rev. C 46, 1591, (1992); Phys. Rev. C 51, 1108 (1995).
[74] A. Del Dotto, G. Salmè, S. Scopetta, private communication.
[75] J. Seely et al. Phys. Rev. Lett. 103, 202301 (2009).
[76] F.A. Baronicini et al, "Trinucleon Electromagnetic Form Factors and the Light-Front Hamiltonian Dynamics", Intl. Conf. on "Perspectives in Hadronic Physics", Trieste, May 2008. AIP - AIPConf.Proc.1056:272-279,2008
F.A. Baroncini et al, "Relativistic Hamiltonian Dynamics and Few-Nucleon Systems, Few Body Syst.43:173-178,2008.
[77] J.C. Bernauer et al. Phys. Rev. Lett. 105, 242001 (2010).
[78] U. Elschenbroich, "Transverse Spin Structure of the Proton Studied in Semi-Inclusive DIS", DESY-THESIS-2006-004, (2006).
[79] A. Miller, "Extracting azimuthal Fourier moments from sparse data", presented at the HERMES Transversity Week, Gent, (2006)
[80] L.L. Pappalardo and M. Contalbrigo, private communication.
[81] JLab Hall C Experiment E00-108; T. Navasardyan etal. Phys. Rev. Lett. 98, 022001 (2007).
[82] J. Annand, T. Averett, G. Cates, G. Franklin, N. Liyanage, G. Rosner, B. Wojtsekhowski, X. Zheng (spokespeople), JLab experiment E12-06-122.


[^0]:    ${ }^{1}$ At the leading twist 2 an additional $\cos 2 \phi$ term is present, and will be considered in the analysis section.
    ${ }^{2}$ The weight $w$ is function of combination of scalar products of the transverse momenta of the parton and final hadron.

[^1]:    ${ }^{3} g_{1 T}^{\perp q}$ also enter in subleading twist terms of the $\sigma_{U T}$ but in combination with higher twist fragmentation functions

[^2]:    ${ }^{4}$ First SSA evidence were observed in polarized protons and anti-protons pion production[19] at FNAL while more recently the first SSA on SIDIS of longitudinally polarized proton target has been observed by HERMES [20]. In both cases, interpretation in terms of Sivers and Collins effects were proposed, however they cannot be disentangled.
    ${ }^{5}$ The definition of the asymmetries in COMPASS has opposite sign respect to HERMES.

[^3]:    ${ }^{6}$ Fragmenting quark flavour is not a valence flavour in the produced hadron.
    ${ }^{7}$ Fragmenting quark flavour is one of the valence flavour in the produced hadron.

[^4]:    ${ }^{1}$ One of the two HERMES RICH has been preserved and transported to UVA together with the aerogel wall of the other RICH. All components are in a controlled environment at UVA.

[^5]:    ${ }^{2}$ Parallel photons coming from the radiators are reflected toward a single point on the focal surface.

[^6]:    ${ }^{3}$ The aerogel of the RICH and the glass windows of the PMTs are the thickest Cherenkov radiators in the SBS detector package.

[^7]:    ${ }^{4}$ This range corresponds to the wavelength sensitivity of the XP1911UV PMTs

[^8]:    ${ }^{5}$ The STAR RICH detector has performed with largely undiminished PID quality at occupancies of up to $5 \%$.

[^9]:    ${ }^{1}$ The average $Q^{2}$ of the HERMES experiment was $<Q^{2}>\sim 2.4 \mathrm{GeV}^{2}$, while the average $Q^{2}$ of the proposed experiment is $<Q^{2}>\sim 5.5 \mathrm{GeV}^{2}$. However, when making $Q^{2}$ comparisons at similar $x$, the average $Q^{2}$ of the HERMES experiment is $6.2 \mathrm{GeV}^{2}$ at $x \sim 0.28$, compared to $4.8 \mathrm{GeV}^{2}$ at the same $x$ in the proposed experiment.

[^10]:    ${ }^{2}$ With $f_{p} \sim 2 f_{n}$, the offset corresponds to about $4 \%$ of the measured asymmetry and its relative uncertainty is $\sim 2 \cdot 0.028 \cdot 0.32 / .86=0.02$ (with 0.32 being the maximum uncertainty on $p_{p}$ ).

[^11]:    ${ }^{3}$ The statistical error on the dilution factor is $\sigma_{f_{B}} \sim \sqrt{f_{B}} / \sqrt{N_{T}}$

[^12]:    ${ }^{4}$ due to the Boer-Mulders distribution function convoluted to the Collins dragmentation function and to the higher-twist Cahn effect related to the transverse motion of the quark in the nucleon.

