(Run Group Addition Proposal to Jefferson Lab PAC 51)

Measurements of the Ratio $R = \sigma_L/\sigma_T$, p/d ratios, $P_{h\perp}$ dependence, and azimuthal asymmetries in Semi-Inclusive DIS π^0 production form proton and deuteron targets using the NPS in Hall C

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Executive Summary

We propose measurements of semi-inclusive deep-inelastic neutral pion electroproduction from both proton and deuteron targets in the kinematic region $0.2 < x < 0.6$ and $2 < Q^2 < 6$ GeV^2. The physics goals are: the ratio $R = \sigma_L/\sigma_T$ of longitudinal to transverse cross sections; the ratios of deuteron to proton cross sections; the transverse momentum dependence of the cross sections; the spin-independent $\cos(\phi_h)$ and $\cos(2\phi_h)$ modulations; and the beam-spin-dependant $\sin(\phi_h)$ modulations. All of these physics goals are driven by the need to more fully understand the production processes that enter into SIDIS. The processes include contributions from both dynamic and target higher-twist contributions. Other contributions come from deep-exclusive processes, pions originating from vector meson decay, and possible charge symmetry violation in fragmentation functions. The ultimate goal is a better understanding of the 3D structure on the nucleon.

Measurements will be made in Hall C using the HMS to detect electrons (and positrons) and using the Neutral Particle Spectrometer to detect neutral pions via their decay to two photons. The primary targets will be 10-cm-long liquid LH2 and LD2. Beam currents will be from 11 to 50 μA, and beam energies will be 6.5, 8.4, and 10.6 GeV. Most data will be collected simultaneously with the NPS electron-beam run group of approved DVCS, DVMP, and SIDIS experiments.

The range of z covered varies from z_{min} to the exclusive limit at $z = 1$, with $0.25 < z_{min} < 0.5$, depending on kinematic setting. The transverse momentum coverage extends to $P_{h\perp}^{max}$ values of 0.4 GeV to 0.5 GeV (at $z = 0.6$). We project that we will be able make high-precision measurements of R in at least 10 bins in $(z, P_{h\perp})$ at five values of (x, Q^2). We anticipate high-precision measurements of the three azimuthal modulations at least 20 bins in $(z, P_{h\perp})$ at nine values of (x, Q^2). We project very accurate measurements of the ratio of proton to deuteron cross sections at over 100 bins in $(z, P_{h\perp}, \phi_h)$ at each kinematic setting. Systematic errors are relatively small because the Hall C equipment has been specifically designed for precision cross section measurements.

We request seven additional PAC days to the 2023-2024 NPS run period: two days to add deuteron target running for two low-x settings, two days to make pair-symmetric background measurements where needed, and three days to provide a greatly increased range of ϵ for one (x, Q^2) setting.

I. INTRODUCTION

One of the principal goals of the physics program at Jefferson Lab is to improve our understanding of the 3D structure of the nucleon. The principal experimental tool in this endeavor is the process of semi-inclusive deep-inelastic scattering (SIDIS). While inclusive DIS has made great strides in elucidating the longitudinal distribution of quarks in the proton and neutron, SIDIS is a process that is sensitive to the transverse momentum and spin distribution, which are poorly known at present. To accomplish this goal, a full understanding of all the physics processes that contribute to SIDIS at JLab energies is needed. For this reason, it is important to have accurate measurements of the SIDIS structure functions with both proton and neutron targets, a range of final state particles (charged pions, neutral pions, kaons, vector mesons, and nucleons). Measurements with a range of beam energies are needed to separate the transverse and longitudinal structure functions. Polarized beam is needed to measure transverse-longitudinal interference structure functions. Polarized targets are needed to extract the spin structure functions.

An extensive program of SIDIS measurements is underway at Jefferson Lab. Much of the program can be accomplished with the CLAS12 experiments in Hall B. Experiments using spectrometers complement the CLAS12 program by providing higher luminosity for final-state particles close to the virtual photon direction, precise knowledge of the acceptance, precise knowledge of the detected electron and hadron momentum vectors, good particle identification capabilities at all momenta, the ability to precisely measure the ratio of rates from different targets, and precise measurements of the ratio of rates for oppositely charged particles (through reversal of the spectrometer magnetic fields). The equipment in Hall C has been specifically designed for precise measurements of absolute cross sections at different beam energies, allowing for accurate separation of transverse and longitudinal structure functions.

In Hall C, experiments E12-09-017 [1] and E12-09-002 [2] have made very precise measurements of SIDIS $\pi^{\pm}$, $K^{\pm}$, and p from both proton and deuteron targets with unpolarized 10.6 GeV electrons, which provide crucial anchor points to the wider kinematic coverage of CLAS. The A-rated experiment E12-06-104 [3] is scheduled (in 2024-5) to make precision measurements of the ratio of longitudinal and transverse cross sections ($R_{LT}^{SIDIS}$for $\pi^{\pm}$ for both proton and deuteron targets. Experiment E12-13-007 [4] is part of the currently-running Neutral

Particle Spectrometer run group, for which the experimental setup is primarily driven by the desire to make improved measurement of the deep exclusive π^0 electroproduction and Compton scattering [5], using 6.6, 8.8, and 11 GeV longitudinally polarized electron beams and an unpolarized proton target. E12-13-007 asked for concurrent measurements of π^0 SIDIS for the 11 GeV beam energy settings. After that proposal was made, the run group scope was expanded to include running at most kinematic settings with a deuteron target (experiment E12-22-006 [6]). With this Run Group Addition proposal, we would like to expand the π^0 SIDIS program to include concurrent data taking at all three beam energies (now reduced to 6.4, 8.5, and 10.6 GeV) and both proton and deuteron targets. The lower beam energy data will allow for separation of the transverse and longitudinal structure functions (R_{LT}^{SIDIS}). However, backgrounds from pair-symmetric processes are expected to be significant at lower beam energies, resulting in the need to request a small amount of additional beam time to measure them by reversing the polarity of the electron arm spectrometer. We also request time for a low energy kinematic setting, which will increase the kinematic range over which R_{LT}^{SIDIS}will be measured. We propose to include measurements on the deuteron at the lowest x setting, which were not included in E12-22-006 because of resolution issues. This will expand the kinematic range for which precision measurements of the proton/deuteron ratio is measured in π^0 SIDIS.

II. PHYSICS MOTIVATION

A. Formalism

The semi-inclusive scattering of longitudinally polarized electrons by unpolarized nucleons in the SIDIS kinematic region can be described formally [7] in terms of structure functions as

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

The five structure functions are all functions of $(x, Q^2, z, P_{h\perp})$, where (x, Q^2, y) are the standard DIS virtual photon variables, ϵ is the virtual photon polarization, and the detected hadron is characterized by its momentum fraction z, transverse momentum $P_{h\perp}$, and azimuthal angle ϕ_h about the virtual photon direction. The fine structure constant is represented by α, the kinematic factor $\gamma = 2Mx/Q$, and the electron beam helicty is λ_e. We define the SIDIS ratio of longitudinal to transverse structure functions as $R_{LT}^{SIDIS}(x, Q^2, z, P_{h\perp}) = F_{UU,L}(x, Q^2, z, P_{h\perp})/F_{UU,T}(x, Q^2, z, P_{h\perp})$. We also define $F_T(x, Q^2) = \int\int F_{UU,T}(x, Q^2, z, P_{h\perp})dzdP_{h\perp}^2$, $F_L(x, Q^2) = \int\int F_{UU,L}(x, Q^2, z, P_{h\perp})dzdP_{h\perp}^2$ and $R_{LT}^{DIS}(x, Q^2) = F_L(x, Q^2)/F_T(x, Q^2)$.

In the simple parton model picture at leading twist, integrated over transverse momentum, the leading structure function $F_{UU,T}(x, Q^2, z) = \sum q_i(x, Q^2)D_i^h(z, Q^2)$, where $q_i(x, Q^2)$ is the parton distribution function (PDF) for a quark of flavor i, and $D_i^h(z, Q^2)$ is the fragmentation function (FF) for the quark i to produce a hadron h.

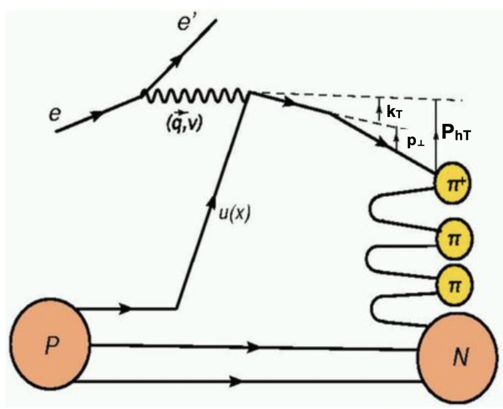

FIG. 1. Schematic of the pion SIDIS process showing that the final transverse momentum of the detected hadron $P_{h\perp}$ arises from the convolution of the struck quark transverse momentum k_T with the transverse momentum generated during the fragmentation $p_\perp$.

B. $P_{h\perp}$ dependence

SIDIS cross sections at fixed x, Q^2, z (averaged over ϕ_h) have been observed to be well-approximated by a Gaussian distribution for $0 < P_{h\perp} < 0.6$ GeV. As illustrated in Figure 1, both the quark transverse moment k_t and the fragmentation process transverse momentum $p_\perp$ width come into play to generate the observed hadron transverse momentum $P_{h\perp}$. Under the assumption that both the k_t and fragmentation function $p_\perp$ distributions are Gaussian, with widths $< k_t^2 >$ and $< p_\perp^2 >$ respectively, the $P_{h\perp}$ width $< P_{h\perp}^2 >$ could be expressed [8] as

$$< P_{h\perp}^2 > (z) = z^2 < k_t^2 > + < p_\perp^2 > (z).$$

Recent results using e^+e^- annihilation from the Belle Collaboration [10] indicate a modest, roughly linear increase of $< p_\perp^2 >$ with increasing z. Thus, a quadratic dependence in SIDIS could be an indication of the importance of quark inartistic transverse motion. Complicating matters, a z^2 dependence to $< p_\perp^2 >$ could be significant [24], so that $R_{LT}^{SIDIS}$and azimuthal modulations are crucial to any determinations of $< k_t^2 >$ (see below). By making measurements on both proton and neutron targets, one could hope to differentiate between the u quarks (which completely dominate SIDIS from a proton) and d quarks (which have relatively big contribution in SIDIS from a neutron), while a difference in the magnitude at low z could indicate a difference between "favored" FF ($D_u^{\pi^+}$, $D_d^{\pi^-}$) and "unfavored" FF ($D_d^{\pi^+}$, $D_u^{\pi^-}$). This simplified picture has been extended to high-order QCD analyses of world SIDIS and Drell-Yan data [13].

C. R-SIDIS

The $F_{UU,L}$ structure function is of great theoretical interest, because it is zero at leading twist, and therefore a sensitive way to measure higher twist contributions to SIDIS. This is essential to reliable extractions of PDFs and TMDs from SIDIS observables.

The principal twist-4 contributions to $F_{UU,L}$ [8, 9] are from: kinematic Wandzura-Wilczek (WW) type contributions that scale as k_t^2, mass corrections proportional to $(m_\pi/M)^2$, dynamic higher contributions, and factorization breaking terms. Calculations [8] of R_{LT}^{SIDIS}at JLab kinematics using just the WW contributions show little dependence on $P_{h\perp}$ at $z = 0.5$ (for $P_{h\perp} < 0.5$ GeV), a smooth fall-off with increasing Q^2, and magnitudes between 0.15 and 0.25, similar to the measured values of R_{LT}^{DIS}.

Another potentially big contribution to $R_{LT}^{SIDIS}$is from pions originating from exclusively or semi-exclusively produced vector mesons. Without a hermetic detector that can detect the full complement of final state particles, at any given values of z, it is not possible in Hall C experiments to distinguish between direct production of a leading pion in the fragmentation process, and a pion from ρ or ω produced near near $z = 1$. Measurements of exclusive ρ_0 electroproduction [11] are consistent with $R_{LT} = 0.5Q^2$, which results in substantial contributions to $R_{LT}^{SIDIS}$when the fraction of pions from vector meson decays is larger than 1%. Fortunately, planned analysis of data from CLAS12 Run Groups A and K will address this issue.

D. Studies of the deuteron/proton ratios

Measurements of the ratios of π^0 multiplicities from protons compared to deuterons are very sensitive to modifications of the factorization hypothesis. Ignoring sea quark contributions, assuming charge symmetry in quark distributions, and assuming isospin symmetry in fragmentation functions, the leading order multiplicity formulas are proton (p) and neutron (n) can be written as:

$$M_p^+ = (4uD_f + dD_u)/(4u + d)$$

$$M_p^0 = (4uD_0 + dD_0/(4u + d) = D_0$$

$$M_p^- = (4uD_u + dD_f)/(4u + d)$$

$$M_d^+ = (4(u + d)D_f + (u + d)D_u)/[4(d + u) + (u + d)] = (4D_f + D_u)/5$$

$$M_d^0 = (4(u + d)D_0 + (u + d)D_0/[4(u + d) + (u + d)] = D_0$$

$$M_d^- = (4(u + d)D_u + (u + d)D_f)/[4(u + d) + (u + d)] = (4D_u + D_f)/5$$

where D_f is the so-called favored fragmentation function describing the probability of a u quark fragmenting into a π^+ at momentum fraction z, assumed by isospin symmetry to be equal to that for $d \rightarrow \pi^-$. The "unfavored" D_u describes $u \rightarrow \pi^-$ and $d \rightarrow \pi^+$. The function $D_0 = (D_f + D_u)/2$ is the fragmentation for π^0 for either up or down quarks. The up (u) and down (d) quark distributions are functions only of (x, Q^2), while D_f and D_u depend only of (z, Q^2).

From the above, we can form several ratios and their predicted values:

$$R_\Sigma^\pm = (M_d^+ + M_d^-)/(M_p^+ + M_p^-) = 1$$

$$R_\Delta^\pm = (M_d^+ - M_d^-)/(M_p^+ - M_p^-) = (3/5)(4 + d/u)/(4 - d/u)$$

$$R_\Sigma^0 = M_d^0/M_p^0 = 1$$

All three ratios are independent of z, and $R_\Sigma^\pm$ and R_Σ^0 are unity at all values of (x, Q^2), while $R_\Delta^\pm$ depends only on the ratio of down to up quarks at a given value of (x, Q^2).

The previously published results [14] for $R_\Delta^\pm$ at $x = 0.3$, $Q^2 = 3$ GeV^2 show significant deviations from predictions using well-established PDFs for the u and d quark ratios. Preliminary results from Hall C experiments E12-09-007 and E12-009-002 for both $R_\Delta^\pm$ and $R_\Sigma\pm$ are shown in Fig. 2 for eight settings in (x, Q^2, W), where W is the total final-state invariant mass. Large deviations from the predictions given above are seen at the lower values of W, with the deviations seemingly decreasing with increasing W. Precision measurements of R_Σ^0 over a similar range in (x, Q^2), as a function of both z and transverse momentum $P_{h\perp}$, will be very useful in distinguishing among the factors contributing to the observed deviations from expectations, such as target and dynamic higher-twist contributions, violations of isospin symmetry in fragmentation functions, charge symmetry violations in quark distributions, and contributions from semi-exclusive and diffractive processes.

Experimentally, the deuteron/proton ratios have the advantage that most systematic errors cancel in the ratios, compared to measurements of the individual multiplicities. In Hall C deuteron and proton targets can be switched to the in-beam position within a few minutes.

E. Azimuthal Asymmetries

Already in the 1970's, theorists were attempting to understand the role of transverse quark momentum in the semi-inclusive process which could lead to a dependence of the cross section on the azimuthal angle of the detected hadron relative to the virtual photon direction. First observations shortly followed in the semi-inclusive measurements reported by the EMC. Fifty years later there is now a well-developed formulation in terms of the TMD structure functions in Eq. 1 which determine the $\cos\phi_h$. $\cos 2\phi_h$ and $\sin\phi_h$ modulations of the cross section. The $\cos\phi_h$ term was already predicted by R. Cahn[21] as a result of the interaction of the virtual photon with quarks in the nucleon with intrinsic transverse momentum. The $\cos 2\phi_h$ modulation results from the Boer-Mulders effect,[22] arising from correlation between quark intrinsic transverse momentum and the quark transverse spin coupled to the Collins fragmentation function [23] which preserves the correlation with fragmentation dependent on the struck quark transverse spin. In fact, the Boer-Mulders-Collins effect also contributes

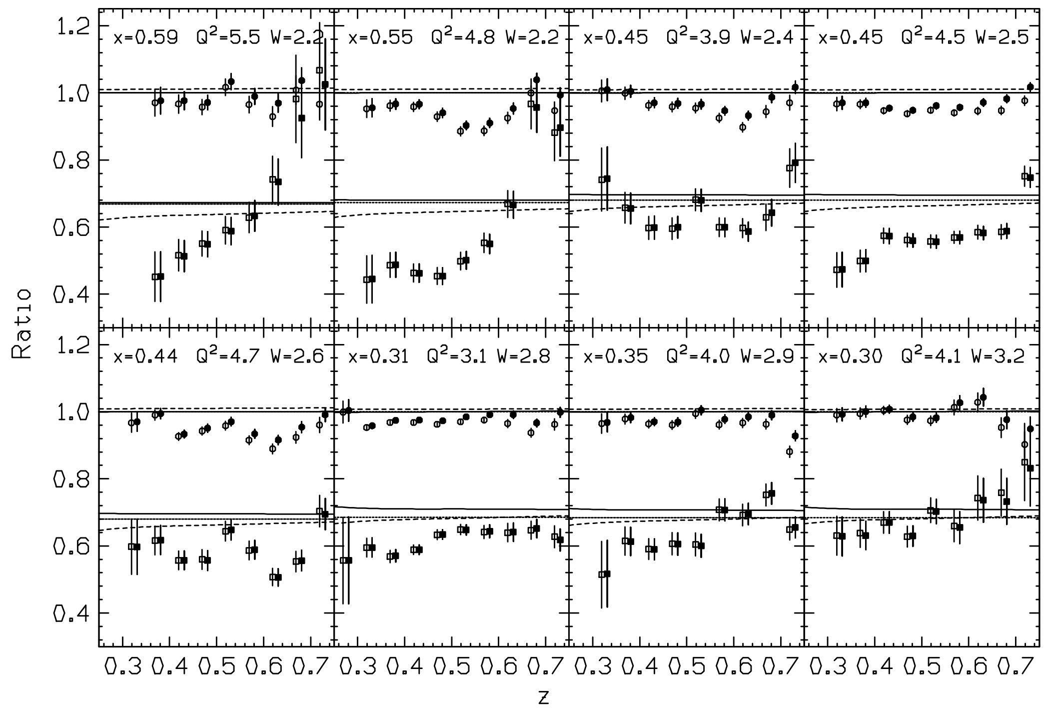

FIG. 2. Very preliminary results for $R^{\pm}_{\Sigma}$ (circles) and $R^{\pm}_{\Delta}$ (squares) from Hall C experiments E12-09-017 and E12-09-002. The open (solid) symbols are with (without) subtraction of diffraction ρ contributions. The values of x, Q^2 (in GeV^2) and W (in GeV) are indicated for each of the eight kinematic settings. The electron beam energy either 10.2 and 10.6 GeV. The upper set of curves (near unity) are predictions for $R^{\pm}_{\Sigma}$, while the lower set (near 0.6) are for $R^{\pm}_{\Delta}$. The solid cures use JAM2022[17] isospin-symmetric fragmentation functions, while the dashed cures use the non-symmetric fragmentation functions of DSS2006[16]. In both cases, quark distributions were taken from JAM2022[17].

to the $\cos\phi_h$ structure function. Phenomenological analyses of Barone et al. [24] stress that these structure functions are sensitive to higher twist contributions, hence the proposed measurements should provide important constraints.

The beam-spin asymmetry [25] results from the convolution of twist-3 PDFs with fragmentation functions and therefore is sensitive to quark-gluon correlations rather than a simple probabilistic density, for low values of $P_{h\perp}$. At higher $P_{h\perp}$, the transverse momentum dependence is dominated by QCD radiation rather than arising from the TMD. Results from CLAS and HERMES demonstrate a small but non-zero beam spin asymmetry that is consistent with estimates based on twist-3 distributions, specifically $g_\perp$, the higher twist version of the so-called Sivers TMD[26, 27]. Unfortunately there is still no complete theoretical treatment including all contributing terms at given twist.

As noted by Cahn, both the inclusive longitudinal cross section and the $\cos\phi_h$ modulation are dependent on k_t, with similar Q^2 falloff. Hence we expect that there may be an important implicit dependence between $R_{LT}^{SIDIS}$and the azimuthal asymmetries measured at the same kinematics with the same final-state hadron.

III. EXPERIMENT

A. Equipment

The experiment requires the use of 6.5, 8.5, and 10.6 polarized electrons with current ranging from 10 to 50 μA. The beam polarization with be measured with the standard Hall C equipment. Measurements will be made in Hall C using the HMS to detect electrons (and positrons) with the standard optics and detector configurations. The HMS angle settings range from 11 to 32 degrees, and the central momentum settings range from 1 to 7 GeV. The newly constructed Neutral Particle Spectrometer (NPS [15]) will be used to detect neutral pions via their decay to two photons. The NPS consists of 30 by 36 array of calorimeter crystals, placed on the SHMS spectrometer carriage to facilitate easy changes in the target-to-calorimeter distance (3 to 6 m) and angle with respect to the beam line (6 to 22 degrees). The primary targets will be the standard 10-cm-long liquid hydrogen and deuterium cells.

B. Kinematics

There are nine kinematic settings in (x, Q^2) covering the x-range of 0.2 to 0.6, and the Q^2 range of 3 to 6 GeV^2. The corresponding range of invariant final state mass W is 2.1 to 3.6 GeV. Beam energies of 10.6 GeV are used at all nine settings, while for five (x, Q^2) settings additional beam energies of 6.4 and/or 8.5 GeV will be used to provide a range of virtual photon polarization ϵ sufficient to perform Rosenbluth separations of the transverse and longitudinal structure functions. At each setting, the NPS will be placed along the virtual photon direction at a distance 3 m, 4 m, or 6 m from the target. The complete set of of kinematic settings is listed in Table I, along with the number of PAC days for the proton and deuteron targets. **Bolded** values are for additional days requested in this proposal.

The minimum π^0 energy that can be detected is 1.2 GeV, 1.5 GeV, and 2.4 GeV for target-calorimeter distances of 3 m, 4 m, and 6 m respectively. This is determined by the minimum opening angle between the two π^0 decay photons. The corresponding values of z_{min} are listed in Table II. The NPS granularity allows for good spacial separation of the two photos up to energies of 8 GeV, which corresponds to no kinematic limit on z_{max}. The range of pion transverse momentum varies with from 0 to $P_{h\perp}^{max}$, which increases approximately linearly with increasing z, as illustrated in Fig. 3. The values of $P_{h\perp}^{max}$ at $z = 0.6$ are listed in Table II. Due to the almost square configuration of the NPS, the azimuthal coverage in ϕ_h is fairly uniform at all π^0 energies and angles for which the NPS has good acceptance in $(z, P_{h\perp})$, as illustrated in Fig. 4.

C. Corrections

Corrections for contributions from the aluminum end-caps of the cryogenic targets will, as usual, be made be devoting a small percentage of the running time to measurements with the standard "aluminum dummy" target.

Radiative corrections will be performed, as for the previous Hall C SIDIS experiments, using the Hall C simulation code SIMC. Iterations will be made on the SIDIS cross section model until good convergence is obtained. Improvements to the exclusive πN and $\pi\Delta$ models will also be made, based on the results of the present experiment and data from CLAS.

A significant background process is $2\pi^0$ virtual photo-production, in which one π^0 is detected in the NPS, and the HMS detects the electron or positron from the Dalitz decay (γe^+e^-) of the other π^0. This background will be measured by taking data with reversed polarity in the HMS for a small percentage of the time used for electron running. From previous experience, we anticipate the pair-symmetric background to be negligible for settings where the π/e ratio is small, so we anticipate that pair-symmetric measurements will only be needed for a subset of the kinematic settings, as listed in Table III.

TABLE I. Kinematic settings for this proposal: beam energy E; DIS variables x, Q^2, final-state invariant mass W, virtual photon polarization ϵ, and virtual photon direction θ_π; HMS momentum E' and angle θ_e; The inclusive electron rate in the HMS is denoted by r_e, with the ratio of pions to electrons in the HMS denoted by π/e. The distance from the target to the NPS is labelled as d, the beam current by I, and the number of data collection PAC days are denoted by D_p and D_d for the proton and deuteron targets respectively. The **bold** values are for the additional time requested in this proposal (**5** PAC days). The total number of SIDIS electron-π^0 coincidences for the proton target is denoted by $C_{e\pi^0}$, in units of mega-counts.

Set	x	Q^2	W	E	ϵ	E'	θ_e	θ_π	r_e	π/e	d	I	$C_{e\pi^0}$	D_p	D_d
		GeV^2	GeV	GeV		GeV	deg	deg	KHz		m	μA	$\times 10^6$	day	day
Ia	0.20	2.0	3.0	6.4	0.29	1.07	31.3	5.8	0.1	267.	6	11	0.01	1	0
Ib	0.20	2.0	3.0	8.5	0.64	3.17	15.7	8.9	8.2	8.	4	50	6.45	1	**1**
Ic	0.20	2.0	3.0	10.6	0.78	5.27	10.9	10.4	31.8	1.	4	50	24.98	1	**1**
II	0.20	3.0	3.6	10.6	0.45	2.61	19.0	5.9	0.4	44.	6	11	0.25	1	0
IIIa	0.36	3.0	2.5	6.4	0.51	1.96	28.3	11.2	0.5	16.	3	28	0.75	1	1
IIIb	0.36	3.0	2.5	8.5	0.75	4.06	17.0	14.4	3.2	1.	3	28	9.19	2	2
IIIc	0.36	3.0	2.5	10.6	0.85	6.16	12.3	16.0	10.0	0.	3	28	14.47	1	1
IVb	0.36	4.0	2.8	8.5	0.52	2.58	24.7	9.9	0.8	11.	4	50	0.84	1	1
IVc	0.36	4.0	2.8	10.6	0.71	4.68	16.3	12.1	2.8	1.	3	38	28.78	3	3
V	0.36	5.5	3.3	10.6	0.41	2.46	26.6	7.5	0.3	27.	4	50	11.13	5	5
VIa	0.50	3.4	2.1	6.4	0.67	2.78	25.3	16.9	0.6	2.	3	28	0.6	**1.5**	**1.5**
VIb	0.50	3.4	2.1	8.5	0.83	4.88	16.5	19.9	2.9	0.	3	28	7.04	3	3
VIc	0.50	3.4	2.1	10.6	0.90	6.98	12.3	21.5	8.1	0.	3	28	14.60	2	2
VII	0.50	4.8	2.4	10.6	0.79	5.48	16.5	16.3	1.4	0.	3	28	16.51	5	5
VIIIa	0.60	5.1	2.1	6.4	0.46	1.87	38.1	13.2	0.1	11.	3	28	0.44	5	5
VIIIb	0.60	5.1	2.1	8.5	0.72	3.97	22.4	17.4	0.4	0.	3	28	0.61	1	1
VIIIc	0.60	5.1	2.1	10.6	0.83	6.07	16.2	19.5	1.1	0.	3	28	9.76	5	5
IX	0.60	6.0	2.2	10.6	0.76	5.27	18.9	16.9	0.5	0.	3	28	10.91	10	10

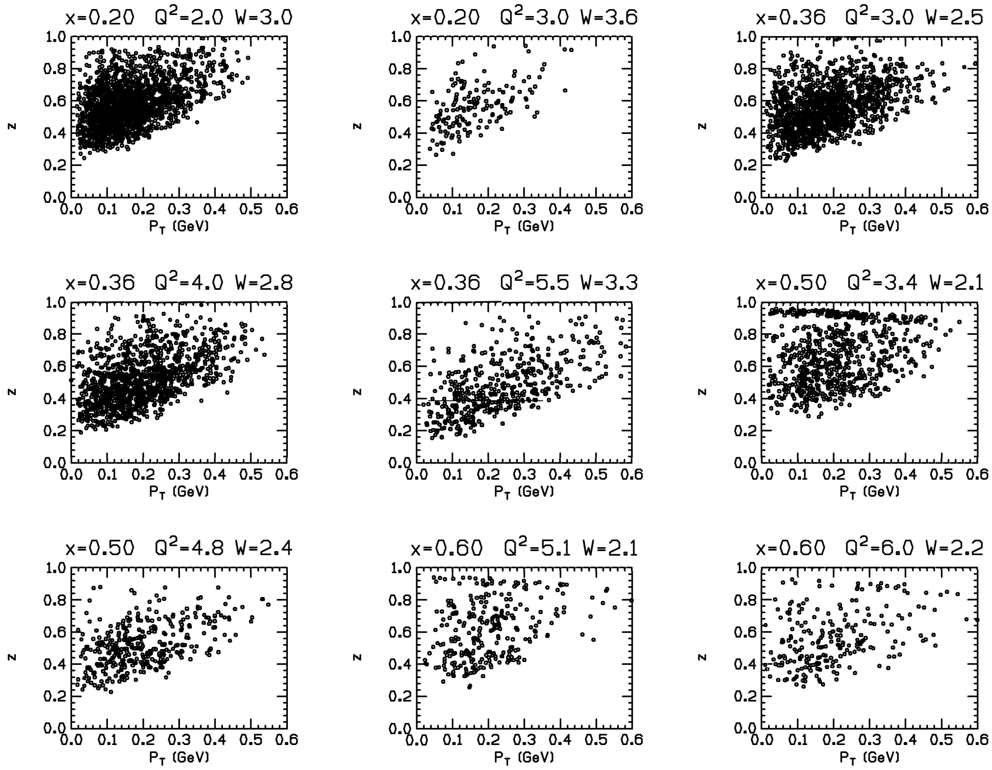

FIG. 3. Expected distribution of events in $(P_{h\perp}, z)$ for each kinematic setting.

The measured coincidence events will be diluted by accidental coincidences between the electron in the HMS and a photo-produced π^0 in the NPS. The coincidence time resolution is expected to be better than 2 nsec, so that accidentals can be measured in the side-band peaks, spaced at 4 nsec intervals by the beam time structure. We calculated the accidental to real coincidence ratio to be $A/R < 0.3$ for all of the kinematic settings except Ib and Ic, with $A/R \approx 0.6$, and Ia, for which $A/R = 3$. Coupled with the very low coincidence rate for setting Ia, it will not be used in the Rosenbluth separations.

D. Expected Results

The estimated total number of inelastic electron-π^0 coincidences at each setting for the proton target are listed in Table I. The count total will be about 50% larger on average for the deuteron target. For the settings with 10.6 GeV beam energy, the total ranges from 3 to 25 million events. This is one to two orders of magnitude higher than the totals (summed

TABLE II. Kinematic range of for π^0 detected in the NPS for each (x, Q^2) setting: $z_{min} < z < 1$ and $0 < P_{h\perp} < P_{h\perp}^{max}$ for $z = 0.6$. Also listed is the range in ϵ for the settings with more than one beam energy. Note that setting Ia is not included in the range for setting I, due to low count rates and high backgrounds at this setting. Also listed is the number (N_R) of $(z, P_{h\perp})$ bins for which measurements of R_{LT}^{SIDIS}can be made with a statistical error of < 0.04, and the number (N_ϕ) of $(z, P_{h\perp})$ bins for which the spin-independent $\cos(\phi_h)$ and $\cos(2\phi_h)$ and beam-spin-dependant $\sin(\phi_h)$ modulations can be measured with a statistical error of < 0.005.

set	x	Q^2	z_{min}	$P_{h\perp}^{max}$	$\delta\epsilon$	N_R	N_ϕ
I	0.2	2	0.3	0.3	0.14	20	20
II	0.2	3	0.4	0.2	0	0	1
III	0.36	3	0.45	0.2	0.34	20	20
IV	0.36	4	0.45	0.3	0.19	10	20
V	0.36	5.5	0.25	0.45	0	0	20
VI	0.5	3.4	0.40	0.15	0.23	10	20
VII	0.5	4.8	0.3	0.35	0	0	20
VIII	0.6	5.1	0.3	0.35	0.37	10	20
IX	0.6	6.0	0.3	0.35	0	0	20

TABLE III. Additional running time request (total 2 PAC days) for positron polarity in the HMS, needed to measure the pair-symmetric background to SIDIS. The format is the same as in Table I.

Set	x	Q^2	W	E	ϵ	E'	θ_e	θ_π	d	I	D_p	D_d
		GeV^2	GeV	GeV		GeV	deg	deg	m	μA	day	day
Ib	0.20	2.0	3.0	8.5	0.64	3.17	15.7	8.9	4	50	0.1	0.1
IIIa	0.36	3.0	2.5	6.4	0.51	1.96	28.3	11.2	3	28	0.1	0.1
IVb	0.36	4.0	2.8	8.5	0.52	2.58	24.7	9.9	4	40	0.1	0.1
V	0.36	5.5	3.3	10.6	0.41	2.46	26.6	7.5	4	40	0.3	0.3
VIIIa	0.60	5.1	2.1	6.4	0.46	1.87	38.1	13.2	3	28	0.3	0.3
VIa	0.50	3.4	2.1	6.4	0.67	2.78	25.3	16.9	6	28	0.1	0.1

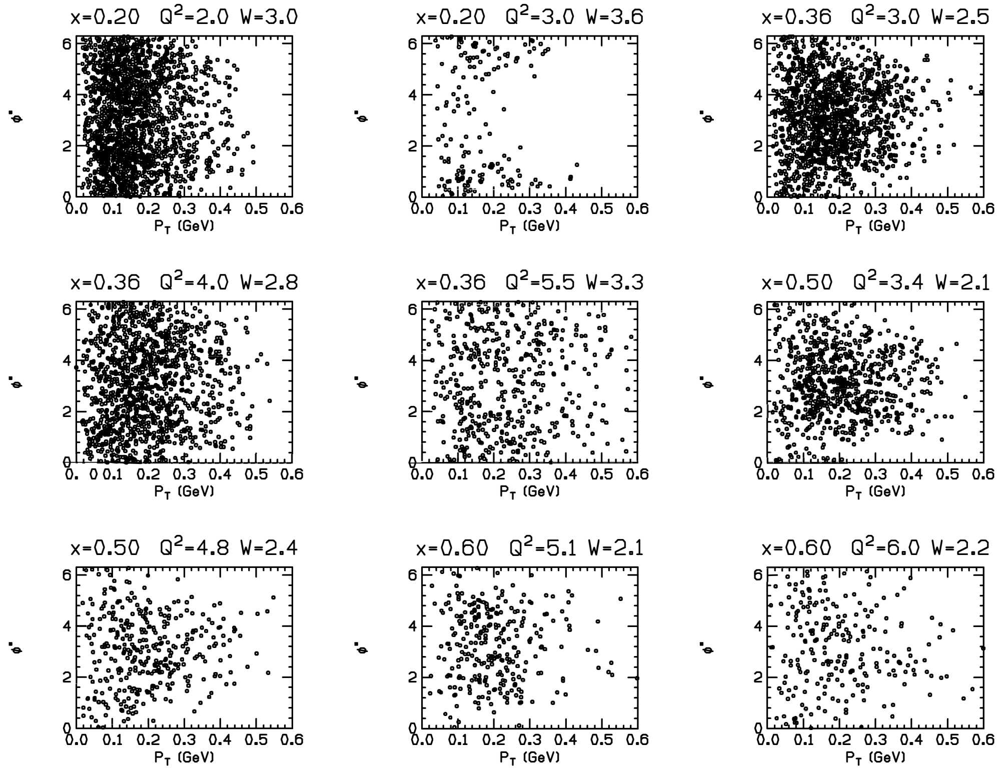

FIG. 4. Expected distribution of events in $(P_{h\perp}, \phi^*)$ for each kinematic setting.

over z) accumulated in the E12-09-017 and E12-09-002 experiments, which used the SHMS spectrometer to detect charged pions. Given that the integrated luminosity of this proposal and those experiments is comparable, this is the result of the approximately ten times larger solid angle of the NPS compared to the SHMS, the ability to cover the full range of z all at once, instead of needing typically five SHMS central momentum settings.

These large event numbers allow to divide the data into typically 300 bins in $(z, P_{h\perp}, \phi_h)$, each with over 10,000 events, resulting, resulting in statistical errors on the order of 1% (relative) on cross section measurements in each bin. This allows for the determination of the determination of the amplitude of the $\cos(\phi_h)$, $\cos(2\phi_h)$, and $\sin(\phi_h)$ modulations to better than 0.005 for of order 20 bins in $(z, P_{h\perp})$ at each (x, Q^2) setting, as listed in Table II. Models for these quantities are typically on the order of -0.1 to 0.1 at $P_{h\perp} = 0.2$ GeV, implying that this experiment will be very powerful in distinguishing between models. At each $(z, P_{h\perp})$ setting with 10.6 GeV beam energy, the ϕ_h-averaged cross section and the ratio of deuteron/proton cross sections will be determined with sub-percent precision in typically 20 bins as well. Relative systematic errors are difficult to quantify, but we expect relative errors of a few percent in overall normalization from in-common factors such as uncertainties in beam current, target thickness, beam energy, and radiative corrections. Because the ϕ_h modulations are near zero, these will be dominated by statistical errors. The ratio of deuteron/proton cross sections will be dominated by the overall normalization error in the ratio of target densities. Point-to-point systematic errors from radiative corrections, HMS spectrometer acceptance function, and variations in the NPS efficiency and calibrations are difficult to estimate accurately at this time, but are expected to be comparable or smaller than the statistical errors for most observables.

The expected results for $R_{LT}^{SIDIS}$are driven by the statistical accuracy of the lowest beam energy (lowest ϵ) used at each (x, Q^2) setting, divided by the range in ϵ, listed in Table II. The anticipated count totals at the lowest beam energy range from 0.2 to 2 million events, and the ϵ range varies from only 0.14 (for setting I) to 0.37 (for setting VIII). Combining these factors, we anticipate that we can divide measurements of R_{LT}^{SIDIS}into of order 10 bins in $(z, P_{h\perp})$ for each (x, Q^2) setting, each with a statistical error of less than 0.02 to 0.05, small compared to the range of model predictions which vary from 0 to 1. The overall systematic error at each (x, Q^2) setting will be of order $0.02/\delta\epsilon$, but the point-to-point systematic errors will be smaller. The systematic error on the proton-deuteron difference in R_{LT}^{SIDIS}will be even smaller, because most systematic effects are in common to both targets. Two examples of the possible results are shown in Figure 5

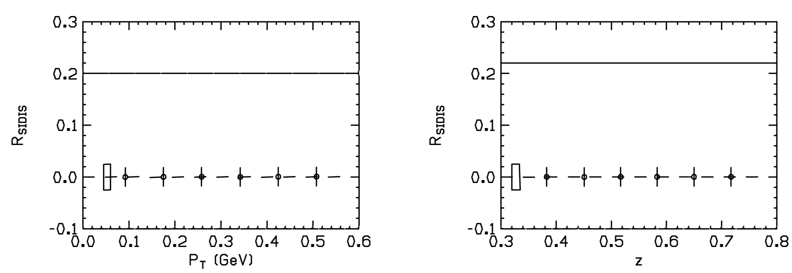

FIG. 5. Projected statistical errors on R_{LT}^{SIDIS}as a function of $P_{h\perp}$ (left) and z (right) for setting III. The rectangular boxes indicate the estimated point-to-point error in (R_{LT}^{SIDIS}- R_{LT}^{DIS}). The approximate value of $R_{LT}^{DIS}$from the SLAC parameterization [20] is indicated by the solid line.

The $P_{h\perp}$-dependence of SIDIS at small $P_{h\perp}$ is known to be well-described by a Gaussian in $P_{h\perp}$, equivalent to an exponential in $P_{h\perp}^2$, sometimes expressed as $e^{-bP_{h\perp}^2}$, with $4 < b < 5$ GeV^{-2} at JLab kinematics. We expect to measure b with a few percent relative statistical error for those setting in z where the $P_{h\perp}$ coverage extends to at least 0.3 GeV^2. As can be seen in Fig. 3, this corresponds to a z threshold of 0.4 to 0.6, depending on (x, Q^2). This will allow us to study the z-dependence of $< P_{h\perp}^2 >$ over a large enough range in z to look for the approximate quadratic dependence predicted for the $< k_t^2 >$ quark transverse momentum widths. The inclusion of the new data proposed here in more sophisticated analyses (such as the MAP collaboration[13]) will greatly improve TMD descriptions for $x > 0.2$, for which existing SIDIS data sets have very large statistical errors.

We expect to detect a relatively small number of η mesons, on the order of 0.1% to 1% of the pions, for momenta above 4 GeV. This could help to distinguish between different production mechanisms. For example, a big source of η is from the decay of the $S11(1520)$ baryon resonance.

E. Systematic errors

The standard experimental equipment in Hall C has been designed with specific attention to precision cross section measurements. Thus, we anticipate that systematic errors from knowledge of beam energy electron, kinematics, electron arm acceptance, beam current, target thickness, rate-dependant and HMS detector efficiency determinations will combine to yield normalization errors of about 1.5%. By placing the NPS on the SHMS carriage, the uncertainty in the π^0 angle will be negligible. Furthermore, the geometric acceptance is simply determined by the crystal array geometry, and will also make a relatively negligible contribution. The energy calibration of the individual crystals will be continuously monitored and calibrated using the well-known π^0 mass reconstructed from photon pairs. We expect a total systematic error of $\approx 2\%$ on raw cross section measurements. The systematic errors arsing from radiative corrections to the raw cross sections are difficult to quantify, and will vary with kinematics. We anticipate that they should contribute $< 2\%$ uncertainty to the corrected cross sections for most kinematic bins, after iteration on the models used to evaluate the radiative corrections. Larger errors could be expected at large z and large $P_{h\perp}$.

The systematic error on R_{LT}^{SIDIS} will be much smaller than $\approx 0.025/\delta\epsilon$ that would arise from uncorrelated systematic errors at the multiple beam energy measurements at a given value of (x, Q^2). This is because the virtual photon energy is kept constant, as is the distance from target to NPS, resulting in unvarying π^0 acceptance as a function of $(z, P_{h\perp}, \phi_h)$. The beam current in most cases is also kept constant, resulting in a cancellation of the luminosity systematic errors. The difference in NPS angles will be well controlled by its placement on the SHMS carriage. Finally, radiative correction factors have only a slight dependence of ϵ at fixed (x, Q^2) (except at large z and large $P_{h\perp}$). Combining all of these considerations, we expect a systematic error on R_{LT}^{SIDIS} on the order of 0.025 to 0.05 for most settings. Because all systematic errors related to the electron arm cancel, we estimate smaller errors on the difference (R_{LT}^{SIDIS}- R_{LT}^{DIS}), which is of particular interest.

An important check on systematic errors will be measurements of R_{LT}^{DIS} using the HMS single arm data only, and comparing with the world averages.

F. Complementary to other experiments

The HERMES collaboration [18] detected about 10^5 π^0 SIDIS events using 27 GeV positron beams on hydrogen targets, from which they extracted multiplicities as a function of z for $W > 3.3$ GeV. The present proposal aims to collect about 1000 times more events, on both proton and deuteron targets, which will allow for fine binning in $(x, Q^2, z, P_{h\perp}, \phi_h)$, albeit in a lower range of $2 < W < 3.6$ GeV.

The proton target azimuthal asymmetry measurements of this proposal have a strong overlap with CLAS12 Proposal E12-06-112[28] (Run Group A). Although covering a smaller range in $(z, P_{h\perp})$, the resolution in ϕ_h will be much better, providing a valuable cross check with the CLAS12 results at lower values of $P_{h\perp}$.

To the best of our knowledge, there are no published measurements of R_{LT}^{SIDIS} for π^0. For charged pions, the only published results for charged pions are from a 50-year-old series of measurements of semi-inclusive pion electroproduction carried out at Cornell with both hydrogen and deuterium targets [19]. This series of measurements covered a region $1 < Q^2 < 4$ GeV^2 and $0.1 < z < 0.9$. Within very large error bars, their results for R_{LT}^{SIDIS} are not inconsistent with R_{LT}^{DIS} [20]. In the near future, the A-rated Hall C experiment E12-06-104 [3] will measure R_{LT}^{SIDIS} for charged pions with similar statistical and systematic error as the present proposal for π^0, although with somewhat reduced kinematic coverage due to the limited out-of-plane acceptance of the SHMS spectrometer.

The present proposal is complementary to the CLAS SIDIS program in providing much smaller systematic errors on cross sections and ratios of cross sections from proton and deuteron targets, albeit over a kinematic region more focused close to the momentum-transfer direction. CLAS is ideally suited to study SIDIS reactions involving more than one hadron in the final state, such as vector meson production and di-pion production.

IV. BEAM TIME REQUEST

We request a total of seven PAC days beyond the approximately 90 PAC days approved for the NPS-electron run group. Our highest priority is two days to make pair-symmetric background measurements at the settings where these are expected to be significant. Our next priority is for three days to greatly increase the range of ϵ for the $x = 0.5$, $Q^2 = 3.4$ GeV^2 setting. The third priority is for two days to add deuteron target running to the 8.5 and 10.6 GeV beam energies used at the $x = 0.2$, $Q^2 = 2$ GeV^2 kinematic setting.

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[1] E12-09-017, "Transverse Momentum Dependence of Semi-Inclusive Pion Production" (spokespersons: R. Ent, P. Bosted, E. Kinney, H. Mkrtchyan)

[2] E12-09-002, "Precise Measurement of pi+/pi- Ratios in Semi-inclusive Deep Inelastic Scattering PartI: Charge Symmetry violating Quark Distributions" (spokespersons: K. Hafidi, W. Armstrong, D. Dutta, D. Gaskell)

[3] E12-06-104, "Measurement of the Ratio R=sigmaL/sigmaT in Semi-Inclusive Deep-Inelastic Scattering" (spokespersons: R. Ent, P. Bosted, E. Kinney, H. Mkrtchyan)

[4] E12-13-007, "Measurement of Semi-Inclusive π^0 Production as Validation of Factorization" (spokespersons: R. Ent, T. Horn, E. Kinney, H. Mkrtchyan, V. Tadevosyan)

[5] E12-10-010, "Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C" (spokespersons: C. Munoz Camacho, T. Horn, C. Hyde, R. Paremuzyan, J. Roche)

[6] E12-22-006, "Deeply Virtual Compton Scattering off the neutron with the Neutral Particle Spectrometer in Hall C" (spokespersons: C. Munoz Camacho, C. Hyde, M. Mazouz, J. Roche)

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[28] E12-06-112: Probing the Proton's Quark Dynamics in Semi-Inclusive Pion Production at 12 GeV. (spokespersons: H. Avakian, K. Joo, Z. Meziani, B. Seitz)

Appendix I: NPS Collaboration May 11, 2023

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