

Target and beam-target spin asymmetries in exclusive pion electroproduction for $Q^2 > 1 \text{ GeV}^2$. I. $e p \rightarrow e \pi^+ n$

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(Received 9 August 2016; revised manuscript received 10 October 2016; published 20 March 2017)

Beam-target double-spin asymmetries and target single-spin asymmetries were measured for the exclusive π^+ electroproduction reaction $\gamma^* p \rightarrow n\pi^+$. The results were obtained from scattering of 6-GeV longitudinally polarized electrons off longitudinally polarized protons using the CEBAF Large Acceptance Spectrometer at Jefferson Laboratory. The kinematic range covered is $1.1 < W < 3$ GeV and $1 < Q^2 < 6$ GeV². Results were obtained for about 6000 bins in W , Q^2 , $\cos(\theta^*)$, and ϕ^* . Except at forward angles, very large target-spin asymmetries are observed over the entire W region. Reasonable agreement is found with phenomenological fits to previous data for $W < 1.6$ GeV, but very large differences are seen at higher values of W . A generalized parton distributions (GPD)-based model is in poor agreement with the data. When combined with cross-sectional measurements, the present results provide powerful constraints on nucleon resonance amplitudes at moderate and large values of Q^2 , for resonances with masses as high as 2.4 GeV.

DOI: [10.1103/PhysRevC.95.035206](https://doi.org/10.1103/PhysRevC.95.035206)

I. INTRODUCTION

A. Physics motivation

The detailed internal structure of the nucleon has long been studied using exclusive electroproduction of pseudoscalar mesons, a process that is sensitive to contributions from individual nucleon resonance states. Photoproduction and electroproduction at very low four-momentum transfer squared (Q^2) help to determine resonance properties such as mass, width, parity, spin, and decay branching ratios. Larger values of Q^2 are needed to study transition form factors, and also reveal the existence of resonances that are suppressed in photoproduction [1]. Initial large- Q^2 measurements of spin-averaged cross sections for exclusive π^+ electroproduction from Cornell [2,3] had limited statistical accuracy. Recent measurements from Jefferson Laboratory (JLab) [1,4–8] have greatly improved the situation.

Experiments using polarized nucleon targets and polarized electron beams are particularly useful in distinguishing among resonances of different spin, isospin, and parity, because all single-spin asymmetries vanish in the absence of interference terms. This is particularly true at larger values of final-state invariant mass W , where many resonances overlap [9].

Nucleon resonance contributions are most important in the central center-of-mass region ($\cos(\theta^*) = 0$, or equivalently $t = u = s/2$). At forward angles and large W , nonresonant t -channel contributions dominate, and the description of pion electroproduction is more appropriately made using phenomenological Regge-pole models [10]. More recently, the nuclear physics community has begun to evaluate exclusive electroproduction reactions in terms of generalized parton distributions (GPD) [11,12]. In such GPD models, spin asymmetries vanish in leading twist and are therefore sensitive to higher-twist operators.

Beam asymmetries at large Q^2 for π^+n electroproduction from a proton target were published from JLab for

$W < 1.7$ GeV [7] and are also the subject of an early investigation for $W > 2$ GeV [13]. Beam-target asymmetries and target single-spin asymmetries for positive and negative pions were reported from the eg1a and eg1b experiments at Jefferson Lab [14,15] using 1.7- to 5.7-GeV electrons and a polarized ammonia target. The present experiment used 6-GeV electrons only and greatly improves the statistical precision of exclusive positive pion electroproduction asymmetries for $Q^2 > 1$ GeV². The present analysis closely follows that presented in Ref. [15]. After a summary of the formalism, details of the experimental setup, analysis, and results are presented in the following sections.

II. FORMALISM

We express the pion electroproduction cross section by

$$\sigma = \sigma_0(1 + P_B A_{LU} + P_T A_{UL} + P_B P_T A_{LL}), \quad (1)$$

where P_B and P_T are the longitudinal beam and target polarizations, respectively, σ_0 is the spin-averaged cross section, and A_{LU} , A_{UL} , and A_{LL} are the beam, target, and beam-target asymmetries, respectively. The cross sections and asymmetries are all functions of five independent variables. For this analysis, the variables (W , Q^2 , $\cos(\theta^*)$, ϕ^* , E) are used, where θ^* , ϕ^* are the center-of-mass decay angles of the final state with invariant mass W into a meson and a nucleon, Q^2 is the squared virtual photon four-momentum, and E is the incident electron beam energy. The conventions used for θ^* and ϕ^* are given in Ref. [15]. The relationship between the present A_{LL} and A_{UL} observables and the cross-sectional components used by the MAID group [9] are also given in Ref. [15].

III. EXPERIMENT

The eg1-dvcs experiment [16,17] took data in 2009, and had many similarities to an earlier experiment [15] which took data in 2000–2001. While the latter experiment was designed as a broad survey in W and Q^2 , using beam energies from 1.6 to 5.7 GeV, the present experiment was focused on a wide range of spin-dependent electroproduction reactions at large values of Q^2 , using the highest available beam energy

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at JLab. Improvements in the beam parameters, target design, detector configuration, and data acquisition all combined to result in factors of four to five smaller statistical uncertainties for $Q^2 > 1 \text{ GeV}^2$ compared to the earlier experiment [15]. A brief summary of the experimental setup is presented below: For more details, see Refs. [16,17].

The present experiment used 6-GeV longitudinally polarized electrons from CEBAF at JLab impinging on a 0.025-radiation-length longitudinally polarized solid ammonia target immersed in liquid helium [18]. The target polarization direction was along the incident electron direction, *not* the direction of the momentum transfer vector. Scattered electrons and charged pions were detected in the CEBAF Large Acceptance Spectrometer (CLAS) [19]. The typical beam current was 7 nA, with a total of approximately 2×10^{17} electrons traversing the ammonia target over the course of the experiment. The beam polarization, as periodically measured using Møller scattering in an upstream polarimeter, averaged 85%.

About 90% of the running time was on polarized protons (NH_3 target), 10% on a reference unpolarized carbon target, and 1% on an empty cell. The 1.5-cm-diameter target cups contained 1 g/cm^2 of material immersed in a 2-cm-long liquid helium bath. The sub-millimeter-diameter beam was slowly deflected to uniformly cover the 1.5-cm-diameter front face of the target. The beam position, averaged over a few minutes or longer, was kept stable at the 0.1-mm level, using feedback from a set of beam position monitors. A split superconducting solenoid magnet provided a highly uniform 5-T magnetic field surrounding the target ($\delta B/B \approx 10^{-5}$).

Particles were detected in CLAS for polar angles from 15 to 48 deg. CLAS comprises six azimuthally symmetric detector arrays embedded in a toroidal magnetic field. Charged particle momenta and scattering angles were measured with the drift chamber tracking system. Electrons were separated from a significantly larger flux of charged pions using segmented gas Cherenkov detectors (CC, pion threshold 2.6 GeV) and a sampling electromagnetic calorimeter (EC) (see Refs. [16,19] for more details). A layer of time-of-flight scintillator counters (SC) between the CC and EC was used for hadron identification. The hardware trigger system was designed to have high efficiency for events with a scattered electron with an energy greater than 0.3 GeV, while rejecting other events. The hardware Cherenkov and calorimeter thresholds were adjusted to give a trigger rate of about 3000 Hz, with a dead time of about 10%.

The standard CLAS detector set was augmented for this experiment with an inner calorimeter (IC), used for forward-angle photon detection. This calorimeter consists of an array of small lead-tungstate crystals, each 15 cm long and roughly 2 cm squared. The IC was not used in the present analysis because no photons are involved, but it blocked part of the acceptance at small angle.

The data taking relevant to the present analysis was divided into two parts: Part A (early 2009) used targets centered at 58 cm upstream of the CLAS center ($z_0 = -58 \text{ cm}$); part B (mid-2009) used targets shifted an additional 10 cm upstream to $z_0 = -68 \text{ cm}$. This provided a larger acceptance for charged particles. Combined with a higher integrated luminosity, the

TABLE I. Run period names, nominal beam energy, $P_B P_T$, and P_B , where P_B (P_T) is the beam (target) polarization, for the two running periods of the experiment.

Run Period	Beam energy	$P_B P_T$	P_B
Part A	5.887 GeV	0.637 ± 0.011	0.85 ± 0.04
Part B	5.954 GeV	0.645 ± 0.007	0.85 ± 0.04

bulk of the present results come from part B. The CLAS torus polarity was set to bend electrons inwards for almost all of the running time, and the torus current was 2250 A. A summary of running conditions is given in Table I. Additional information about the experimental setup can be found in Refs. [16,17].

IV. ANALYSIS

A. Data processing

A subset of the data was used to calibrate the response of all of the CLAS detectors and instruments used to measure beam position and current. The alignment of the detectors, as well as the target magnet, was also determined.

The raw data were passed through a standard CLAS analysis package that transformed raw timing and pulse-height signals into a set of so-called particles for each trigger event. Direction cosines at the target for charged particles, as well as their momenta, were determined from their tracks as measured by the drift chambers (DC). Constraints were placed that the track should originate from a line segment within the 1.5-cm-long target, with the line defined by the rastered beam position for each trigger. For neutron candidates, direction cosines were determined from their hit positions in the EC, assuming the same vertex position as the corresponding scattered electron. Charged-particle tracks were associated with the corresponding CC signals, EC energy deposition, and timing from the SC using geometrical matching. Additional details can be found in the two archival papers describing the eg1b inclusive analysis [20,21].

A subset of the recorded events was subsequently written to skimmed data files for further processing. These data files only contained events that had a reasonable chance of passing the event selection cuts of the present analysis.

B. Particle identification

Exclusive π^+ electroproduction was analyzed using two topologies: $ep \rightarrow e\pi^+n$ and $ep \rightarrow e\pi^+(n)$. Both topologies require detection of the scattered electron and a pion. The $ep \rightarrow e\pi^+n$ topology also requires the detection of a neutron. The total numbers of events passing the cuts of topology $ep \rightarrow e\pi^+n$ were 32 438 for part A and 96 215 for part B. The total numbers of events passing the cuts of topology $ep \rightarrow e\pi^+(n)$ were 208 835 for part A and 684 981 for part B.

1. Electron identification

Electrons were identified by requiring a signal of at least one photoelectron in the Cherenkov detector, at least two thirds of the most probable electron energy to be deposited in the EC, and a vertex position reconstructed within 4 cm of the nominal

target center. The electron scattering angle was required to be between 15.5 and 38 deg. These cuts are not as restrictive as those placed on electrons for the inclusive electron scattering analysis [16] of the present experiment, because the exclusivity cuts discussed below remove essentially all of the events where another type of particle might be misidentified as an electron.

2. Charged pion identification

Charged pions were identified by requiring that the time of arrival at the scintillator counters be within 0.7 ns of that predicted from the time of arrival of the electron in the event. This timing cut removed all protons from the sample, but allowed between 10% to 100% of K^+ , depending on kaon momentum. These events were removed by the missing mass cut discussed below. Positrons were removed from the sample by requiring small (or no) signal in the Cherenkov detector and a small deposited energy in the electromagnetic calorimeter. Also required were a vertex position reconstructed within 4 cm of the nominal target center and a polar scattering angle between 15 and 48 deg.

3. Neutron identification

Neutrons were identified by requiring a deposited energy of at least 0.3 GeV in the EC (set by the time window of the hardware trigger), with a time of arrival at the EC corresponding to $\beta < 0.95$ to separate neutrons and photons. The direction cosines of the neutron were determined from the EC hit coordinates and the vertex position defined by the electron. For those rare events with a very forward-angle neutron, the neutrons passed through the inner calorimeter on the way to the EC. Generally, this had no effect on the neutrons, because the number of interaction lengths in the IC was relatively small. In the case where the neutron interacted in the IC, making a hadronic shower, the exclusivity cuts on direction cosines removed most of these events, effectively further lowering the already low neutron-detection efficiency. The neutron momentum could not be determined from time of flight with sufficient accuracy to be useful.

C. Exclusivity kinematic cuts

For both topologies, kinematic cuts were placed to improve the signal-to-background ratio. The value of kinematic cuts is twofold. First, most of the kinematic quantities have a wider distribution for bound nucleons (in target materials with $A > 2$) than for free protons. Kinematic cuts therefore reduce the dilution of the signal of interest (scattering from polarized free protons) compared to the background from unpolarized nucleons in materials with $A > 2$ (i.e., the nitrogen in the ammonia molecules, the liquid helium bath, and the Kapton and aluminum target windows). Second, kinematic cuts are needed to isolate single-meson production from multimeson production and from single-kaon production. Final cut values were chosen empirically in an iterative procedure to minimize the uncertainties on the final results.

For the $ep \rightarrow e\pi^+(n)$ topology, the only kinematic cut available is on the missing mass. For the $ep \rightarrow e\pi^+n$ topology,

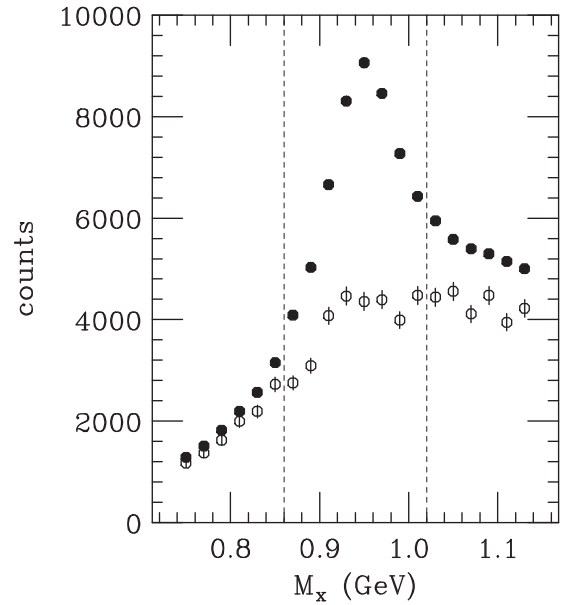


FIG. 1. Sample electron-pion missing mass distribution for the topology $ep \rightarrow e\pi^+(n)$, averaged over the full kinematic range of the experiment. Counts from the ammonia target are shown as the solid circles and counts from the carbon target (scaled by the ratio of integrated luminosities on bound nucleons) are shown as the open circles. The vertical dashed lines indicate the cuts used in the analysis.

cuts on the cone angles of the detected neutron further reduce nuclear backgrounds.

1. Electron-pion missing mass cut

For both topologies, the electron-pion missing mass $M_x^{e\pi}$ should be equal to the neutron mass of 0.939 GeV. In general, one would like the upper cut on $M_x^{e\pi}$ to be well below $M + m_\pi = 1.08$ GeV, to avoid contributions from multipion production. Placing tighter cuts helps to reduce the nuclear background.

The distribution in $M_x^{e\pi}$ is shown for topology $ep \rightarrow e\pi^+(n)$ in Fig. 1 averaged over the full kinematic range of the experiment. The solid circles correspond to counts from the ammonia target, while the open circles correspond to counts from the carbon target, scaled by the ratio of luminosities for $A > 2$ nucleons. A clear peak is seen near the nucleon mass from the ammonia target, with a smaller but wider distribution from the carbon target, that matches the wings on the ammonia distributions on the low-mass side of the peak. On the high side of the peak, the ammonia rates are higher, due to the radiative tail of the single-pion production, and the gradual turn-on of multipion production. The vertical dashed lines show the cuts used: $0.86 < M_x^{e\pi} < 1.02$ GeV. Within the cut region, approximately half of the events come from nucleons in nuclei with $A > 2$ and half from free protons.

The distribution in $M_x^{e\pi}$ is shown for topology $ep \rightarrow e\pi^+n$ in Fig. 2. The nuclear background is greatly reduced in this case, because additional cuts can be placed on the direction cosines of the detected neutron.

The spectra were examined to see if the optimal cut value depends on W , Q^2 , $\cos(\theta^*)$, or ϕ^* . Although the peak widths

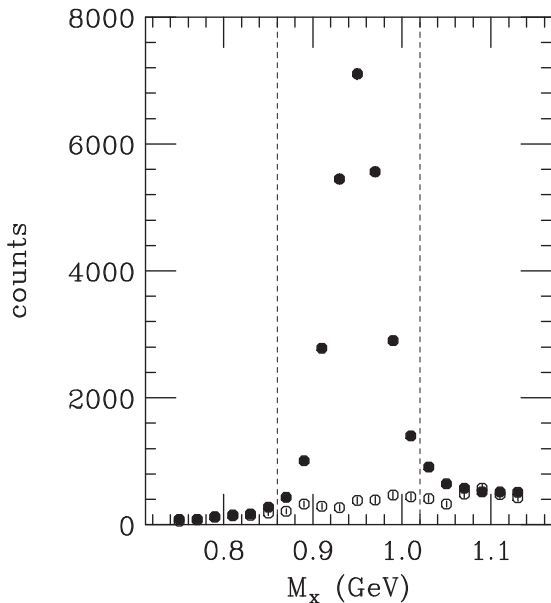


FIG. 2. Same as Fig. 1, but for the topology $ep \rightarrow e\pi^+n$. Cuts on the neutron angle have been applied.

vary somewhat with kinematic variables, a constant cut value did not degrade the signal-to-noise ratios by more than a few percent.

2. Neutron angular cuts

For the topology $ep \rightarrow e\pi^+n$, cuts on the cone angles of the neutron are very useful in rejecting background from $A > 2$ materials in the target. From the kinematics of the detected electron and pion, the direction cosines of the recoil neutron are calculated and compared with the observed angles. We denote the difference in predicted and observed angles as $\delta\theta_N$ in the in-plane direction and $\delta\phi_N$ in the out-of-plane direction (which tends to have worse experimental resolution). Distributions of these two quantities are shown in Figs. 3 and 4, respectively. It can be seen that with cuts on M_x and the complementary angle, the nuclear background is relatively small and flat compared to the peaks from the free proton. We used the cuts $|\delta\theta_N| < 3^\circ$ and $|\delta\phi_N| < 6^\circ$ for all kinematic bins. Events that failed either one of these cuts were not moved over to the $ep \rightarrow e\pi^+(n)$ topology event sample.

D. Kinematic binning

The kinematic range of the experiment is $1.1 < W < 3$ GeV and $1 < Q^2 < 6$ GeV². As shown in Fig. 5, the range in Q^2 changes with W . We therefore made four bins in Q^2 , where the limits correspond to electron scattering angles of 15.5, 18, 21, 26, and 38 deg. In order to study possible resonance structure, we used fixed W bins of width 0.05 GeV for $W < 1.9$ GeV, which is comparable to the experimental resolution. For $W > 1.9$ GeV, the bin widths gradually increase, to achieve roughly equal counting rates, with bin boundaries at 1.90, 1.96, 2.03, 2.11, 2.20, 2.31, 2.43, 2.56, 2.70, 2.85, and 3 GeV. The bin limits are shown in Fig. 5.

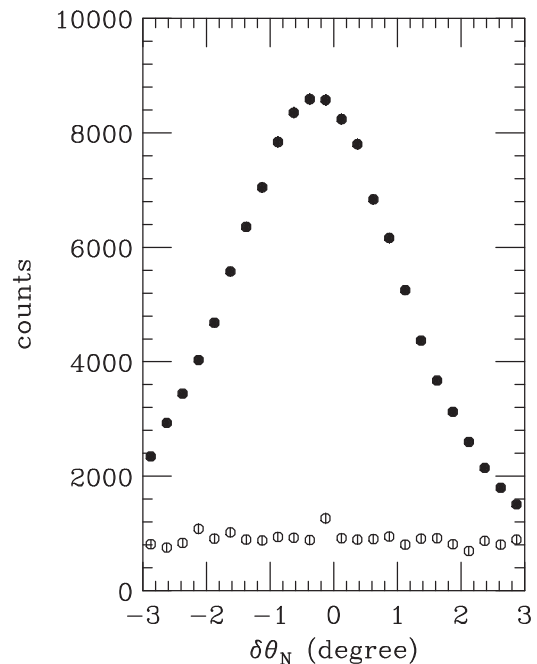


FIG. 3. Distribution of the in-plane angular difference in predicted and observed nucleon direction cosines for the topology $ep \rightarrow e\pi^+n$. The black points are for the ammonia target, while the open circles are from the carbon target, scaled by integrated luminosity. The analysis cuts correspond to the edge of the histogram. All other relevant exclusivity cuts (i.e., on $M_x^{e\pi}$ and $\delta\phi_N$) have been applied.

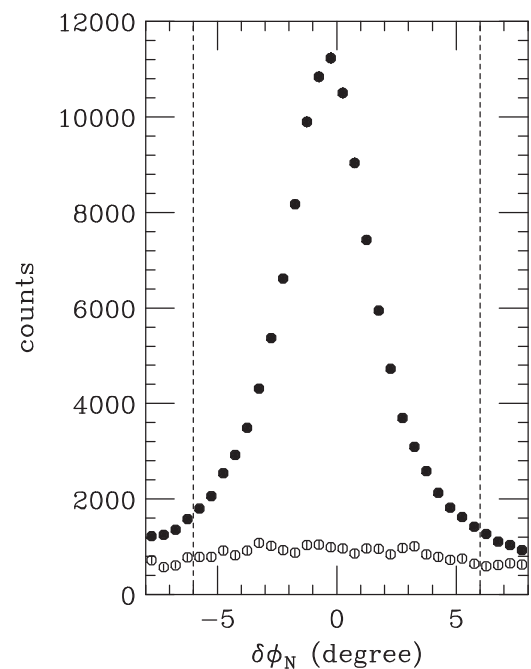


FIG. 4. Same as Fig. 3, except now for the out-of-plane angular difference (after application of cuts on $M_x^{e\pi}$ and $\delta\theta_N$). The vertical dashed lines indicate the cuts used in the analysis.

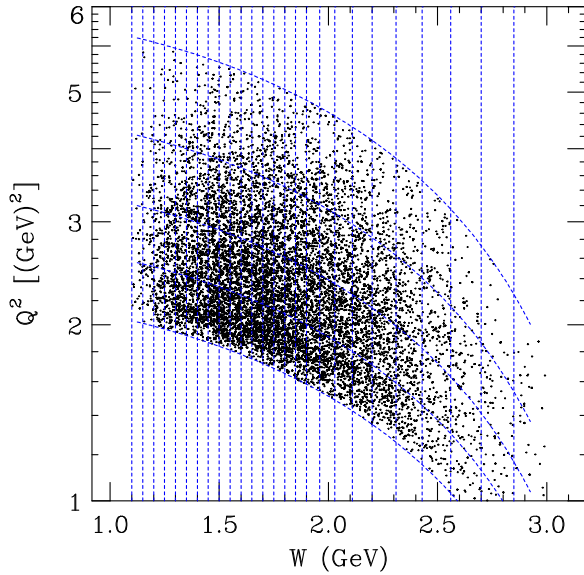


FIG. 5. Distribution in (W, Q^2) of events for the $ep \rightarrow e\pi^+(n)$ topology passing all exclusivity cuts. The vertical dashed lines show the limits of the W bins used in the analysis, while the left-to-right curves show the bin limits in Q^2 , defined by fixed bins in θ_e of 15.5, 18, 21, 26, and 38 deg (from bottom to top).

An examination of event rates showed a strong enhancement at forward values of $\cos(\theta^*)$ for both topologies studied, roughly independent of (W, Q^2) . There are essentially no events with $\cos(\theta^*) < -0.2$. We decided to use six bins in $\cos(\theta^*)$, with boundaries at $-0.2, 0.2, 0.44, 0.63, 0.78, 0.9$, and 0.995 . The uppermost boundary of 0.995 was chosen to maintain a ϕ^* resolution [which is approximately given by $0.04/\sin(\theta^*)$] smaller than the width of the ϕ^* bins. We used 12 bins in ϕ^* , equally spaced between 0 and 2π .

A strong consideration in choosing the bin sizes was that we required at least ten counts in a given bin in order to have approximately Gaussian statistical uncertainties. The total number of bins is 7488, of which about 6000 had enough events to be included in the final results.

V. ASYMMETRIES

Spin asymmetries were formed as follows:

$$A_{LL} = \frac{N^{\uparrow\downarrow} + N^{\downarrow\uparrow} - N^{\uparrow\uparrow} - N^{\downarrow\downarrow}}{N_{\text{tot}} f P_B P_T}, \quad (2)$$

$$A_{UL} = \frac{N^{\uparrow\uparrow} + N^{\downarrow\downarrow} - N^{\uparrow\downarrow} - N^{\downarrow\uparrow}}{N_{\text{tot}} f P_T}, \quad (3)$$

where the symbols N represent the number of events in a given helicity configuration, divided by the corresponding integrated beam current. The first superscript refers to the beam polarization direction and the second indicates the target polarization direction. In both cases, the symbol \uparrow refers to helicity pointing in the down-beamline direction, and vice versa. The total number of counts is denoted by $N_{\text{tot}} = N^{\uparrow\uparrow} + N^{\downarrow\downarrow} + N^{\uparrow\downarrow} + N^{\downarrow\uparrow}$ and f is the dilution factor,

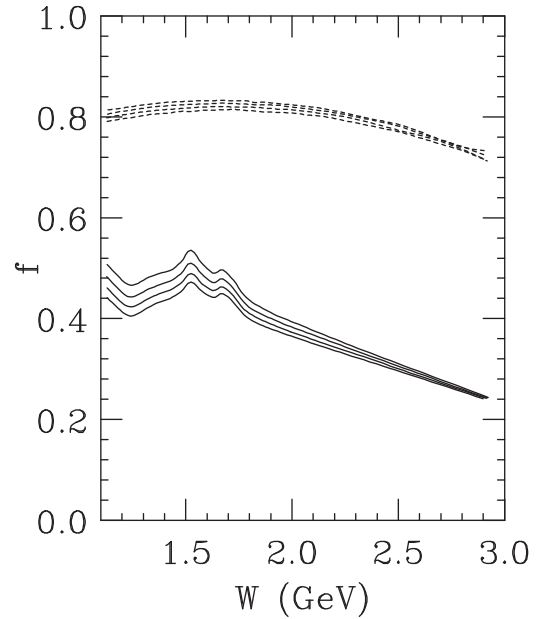


FIG. 6. Dilution factors f as a function of W for the $ep \rightarrow e\pi^+(n)$ topology (dashed curves) and the $ep \rightarrow e\pi^+(n)$ topology (solid curves) for the four Q^2 bins of this experiment and the middle bin in $\cos(\theta^*)$. The values of f decrease weakly with increasing Q^2 .

defined as the fraction of events originating from polarized free protons, compared to the total number of events.

A. Beam and target polarization

Both the beam and target polarization directions are along the direction of the incident electron. The product of beam polarization (P_B) and target polarization (P_T) was determined using the well-understood beam-target spin asymmetry in elastic ep scattering. The results are listed in Table I. The beam polarization was measured once every few days using Møller scattering, and it is also listed in the table. The proton target polarization was determined by dividing $P_B P_T$ by P_B . This proved to be more accurate than using direct NMR measurements of the target polarization, which were relatively accurate from run to run but had a large overall normalization uncertainty. Within the uncertainties, the two approaches to determining P_T are consistent.

B. Dilution factor

The dilution factor f is defined as the ratio of scattering rate from free nucleons to the scattering rate from all nucleons in the target. With the assumption that the cross section per nucleon is the same for bound protons in all of the nuclear materials (with $A > 2$) in a given target, and also that the effective detection efficiency is the same for the ammonia and carbon targets, then

$$f = 1 - R_{A>2} \frac{N_C}{N_{NH_3}}, \quad (4)$$

where N_C and N_{NH_3} are the number of counts from the carbon and ammonia targets respectively, measured in a

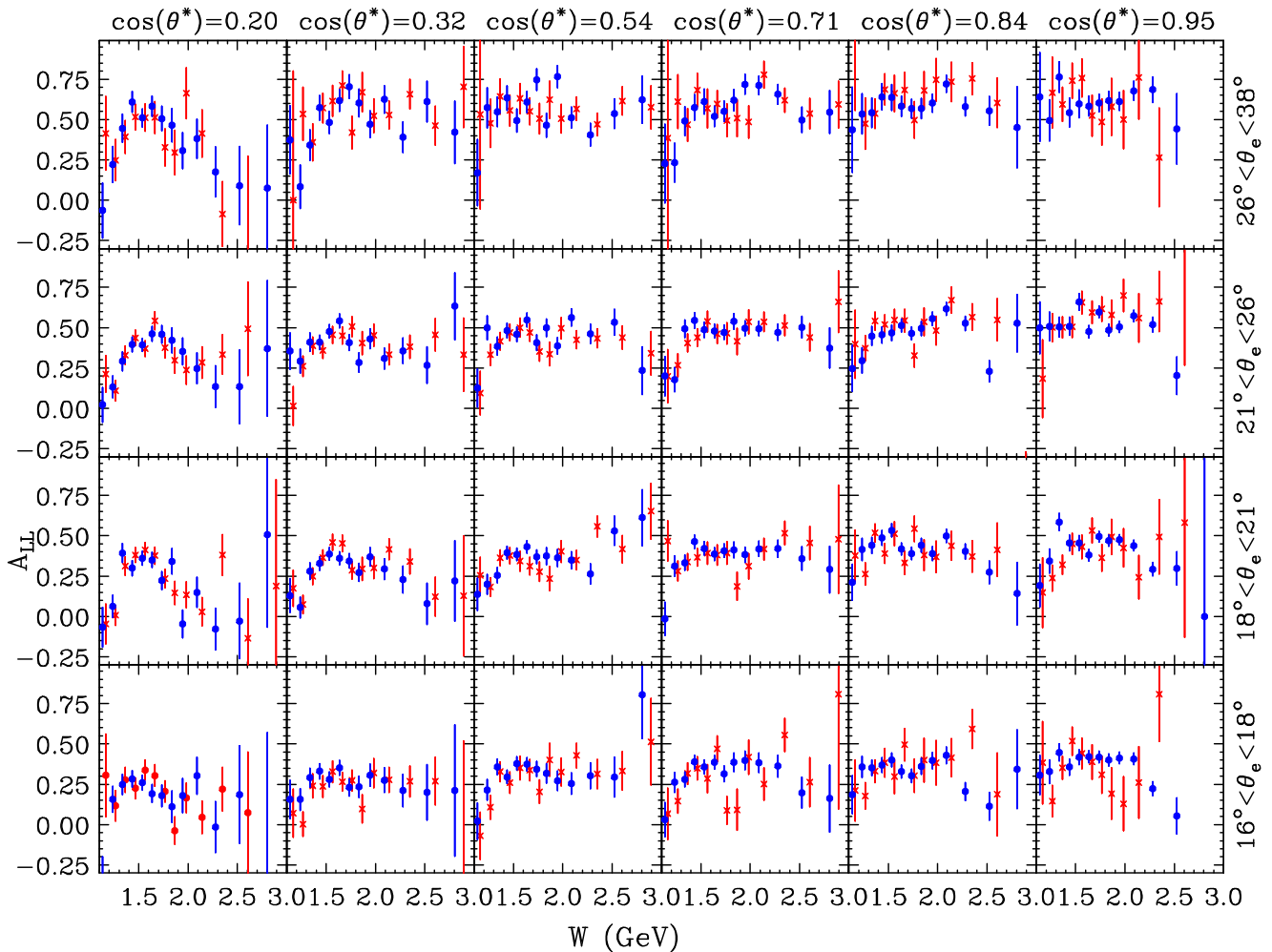


FIG. 7. Beam-target double-spin asymmetry A_{LL} for the $ep \rightarrow e\pi^+n$ topology (red crosses) compared to the $ep \rightarrow e\pi^+(n)$ topology (blue circles), averaged over ϕ^* , as a function of W , in the six $\cos(\theta^*)$ bins of this analysis and the four Q^2 (θ_e) bins used.

given kinematic bin for a given topology, normalized by the corresponding integrated beam charge. The symbol $R_{A>2}$ denotes the ratio of the number of bound nucleons in the ammonia target to the number of bound nucleons in the carbon target. Bound nucleons are defined to be in materials with atomic number $A > 2$. The latter was determined from a detailed analysis of the target composition using inclusive electron scattering rates from ammonia, carbon, and empty targets, yielding $R_{A>2} = 0.71$ for part A and $R_{A>2} = 0.72$ for part B.

Because the integrated luminosity on the carbon target was about ten times lower than on the ammonia target, there is a large amplification of the uncertainty on the ratio of carbon to ammonia counts, $\frac{N_C}{N_{NH_3}}$. We therefore took advantage of the fact that f is a very slowly varying function of kinematic variables and did a global fit to $\frac{N_C}{N_{NH_3}}$. The fit values were then used to evaluate f in each kinematic bin.

As in Ref. [15], the functional forms for the fit contained 21 terms of the form $p_i \cos^{N_c}(\theta^*) W^{N_w} (Q^2)^{N_Q}$, where p_i is a free parameter, and the exponents $N_C N_W N_Q$ are 000, 100, 010, 001, 020, 011, 110, 002, 101, 200, 120, 210, 201, 300, 220, 211, 202, 310, 301, 320, and 311. An additional eight terms were

included to account for the influence of the three prominent nucleon resonances centered at 1.23, 1.53, and 1.69 GeV, with widths 0.220, 0.120, and 0.120 GeV. The reason that these resonance terms are needed is that the nucleon resonances are effectively broadened in the target materials with $A > 2$ by Fermi motion. This generates resonant-like structures in the ratio of carbon to ammonia count rates. Tests were made to see if any ϕ^* -dependent terms would improve the fits. No significant improvements were found.

The dilution factors for part B for the two topologies are shown in Fig. 6 as a function of W for the four Q^2 bins of this analysis and the middle bin in $\cos(\theta^*)$. The results are similar for the other bins in $\cos(\theta^*)$. For the fully exclusive topology, $ep \rightarrow e\pi^+n$, the dilution factor is large, about 0.8 on average, corresponding to the good rejection of background that is possible with the exclusivity cuts when the recoil neutron is detected. For the topology $ep \rightarrow e\pi^+(n)$, the dilution factor is reasonably good for $W < 2$ GeV, averaging about 0.45, with significant resonant structure visible. For $W > 2$ GeV, there is a trend for f to decrease, dropping to values as low as 0.25 at the highest values of W . This is because Fermi broadening results in an increasing amount of multipion production from

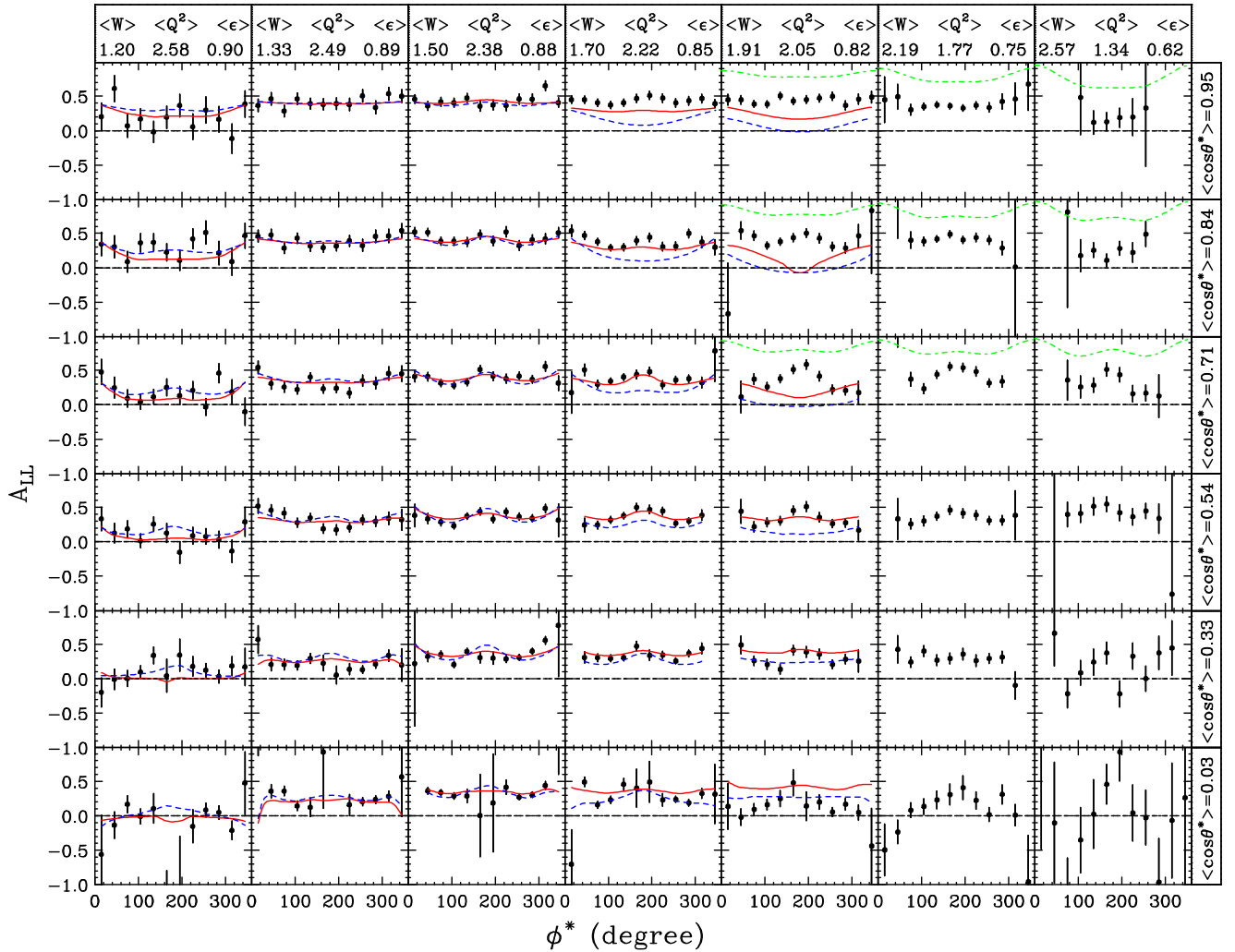


FIG. 8. Beam-target double spin asymmetry A_{LL} for the reaction $ep \rightarrow e\pi^+n$ as a function of ϕ^* in seven bins in W (columns) and six $\cos(\theta^*)$ bins (rows). The results are from the two lower Q^2 bins of this analysis. The error bars reflect statistical uncertainties only. The solid red curves are from the MAID 2007 fit [9], the blue long-dashed curves are from a JANR fit [25], and the green short-dashed curves are for the GPD-inspired model from Goloskokov and Kroll [12].

the nuclear target materials. The Q^2 dependence is relatively weak for both topologies. Because part A had much lower statistical accuracy than part B, we used the part B fit shape for part A, after first checking for consistency.

C. Combining data sets

The entire asymmetry analysis was performed separately for parts A and B. The results were combined by averaging asymmetries, weighted by their respective statistical uncertainties, for each of the four-dimensional bins. Since the two configurations differ only in the acceptance function, which should cancel in forming the asymmetries, the expectation is that they should be fully compatible statistically. This expectation was verified for both asymmetries for both topologies.

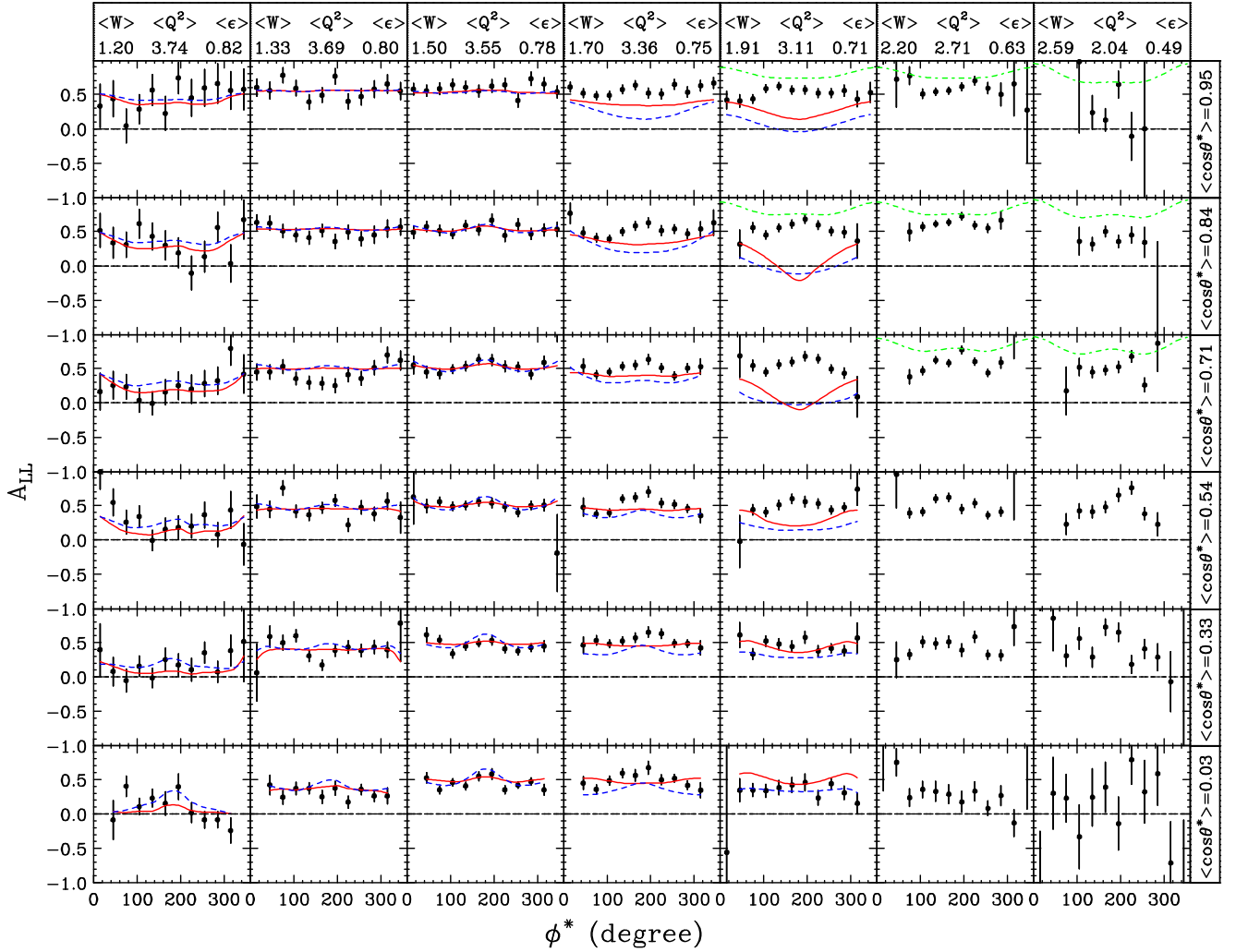
D. Combining topologies

The next step was to combine the fully exclusive topology with the one with a missing neutron. For both asymmetries,

the topologies were found to be statistically compatible ($\chi^2 = 4610$ for A_{LL} and $\chi^2 = 4720$ for A_{UL} , for 4607 degrees of freedom). This good agreement between topologies can be observed by visual examination of plots in which both topologies are plotted together, such as Fig. 7, which show A_{LL} for the two π^+ topologies as a function of W in a grid over θ_e (i.e., Q^2) and $\cos(\theta^*)$. In this figure, adjacent bins in W were averaged together and a straight average over ϕ^* was performed.

E. Radiative corrections

Radiative corrections take into account that the incident beam energy, scattered electron energy, or the electron scattering angle at the vertex can all be different from those measured in the detector, due to electrons radiating photons in the field of a nucleon or nucleus. Although the corrections are significant for spin-averaged exclusive cross sections, they are negligible for spin asymmetries, due to the facts that bremsstrahlung is largely spin-independent, and the cross-sectional variation is


 FIG. 9. Same as Fig. 8, except for the two larger Q^2 bins of this analysis.

small within the exclusivity cuts used for a given kinematic bin. This was verified by explicit calculations using the Mo-Tsai formalism [22] with the equivalent radiator approximation (internal radiation equivalent to external radiation) and the angle peaking approximation (photon emitted along the incident or scattered electron direction only). In these calculations, we used the MAID fit [9] to describe the cross-sectional and asymmetry variations within each kinematic bin. The calculations were performed using a Monte Carlo simulation technique. Within the statistical uncertainty of the calculation (typically $\delta A = 0.005$ for a given kinematic bin), no significant deviations from zero were observed. The average depolarization of the electron from bremsstrahlung was also evaluated and found to be much less than 1%.

F. Polarized nitrogen correction

As is discussed in Ref. [16], the nitrogen in the ammonia targets is slightly polarized, and in the case of inclusive electron scattering, a correction of about 1.8% to the beam-target asymmetry is needed. In the present exclusive analysis, the correction is reduced to about 0.5% for $ep \rightarrow e\pi^+(n)$ and less than 0.2% for $ep \rightarrow e\pi^+n$, because most of the events from

nitrogen are removed by the exclusivity cuts. No corrections were applied in the present analysis, and this omission is accounted for in the systematic uncertainty budget.

G. Systematic uncertainties

The dominant systematic uncertainty on all the asymmetry results is an overall scale uncertainty from the beam and target polarizations. The uncertainty in A_{LL} is relatively small (1.4%) because $P_B P_T$ was well-measured using ep elastic scattering. The relative uncertainty in A_{UL} is larger (4%) due to the uncertainty in P_B , from which we obtained P_T by dividing $P_B P_T$ by P_B .

The other source of normalization uncertainty is the dilution factor. As discussed in more detail in Ref. [16], the uncertainties in the target composition correspond to about a 2.5% relative uncertainty in the amount of background subtraction, which corresponds to 1% to 1.5% in the asymmetry results, for the missing neutron topology, and less than 0.5% for the fully exclusive topology.

Another source of systematic uncertainty is in the factor $R_{A>2}$. We compared three methods of determining this factor:

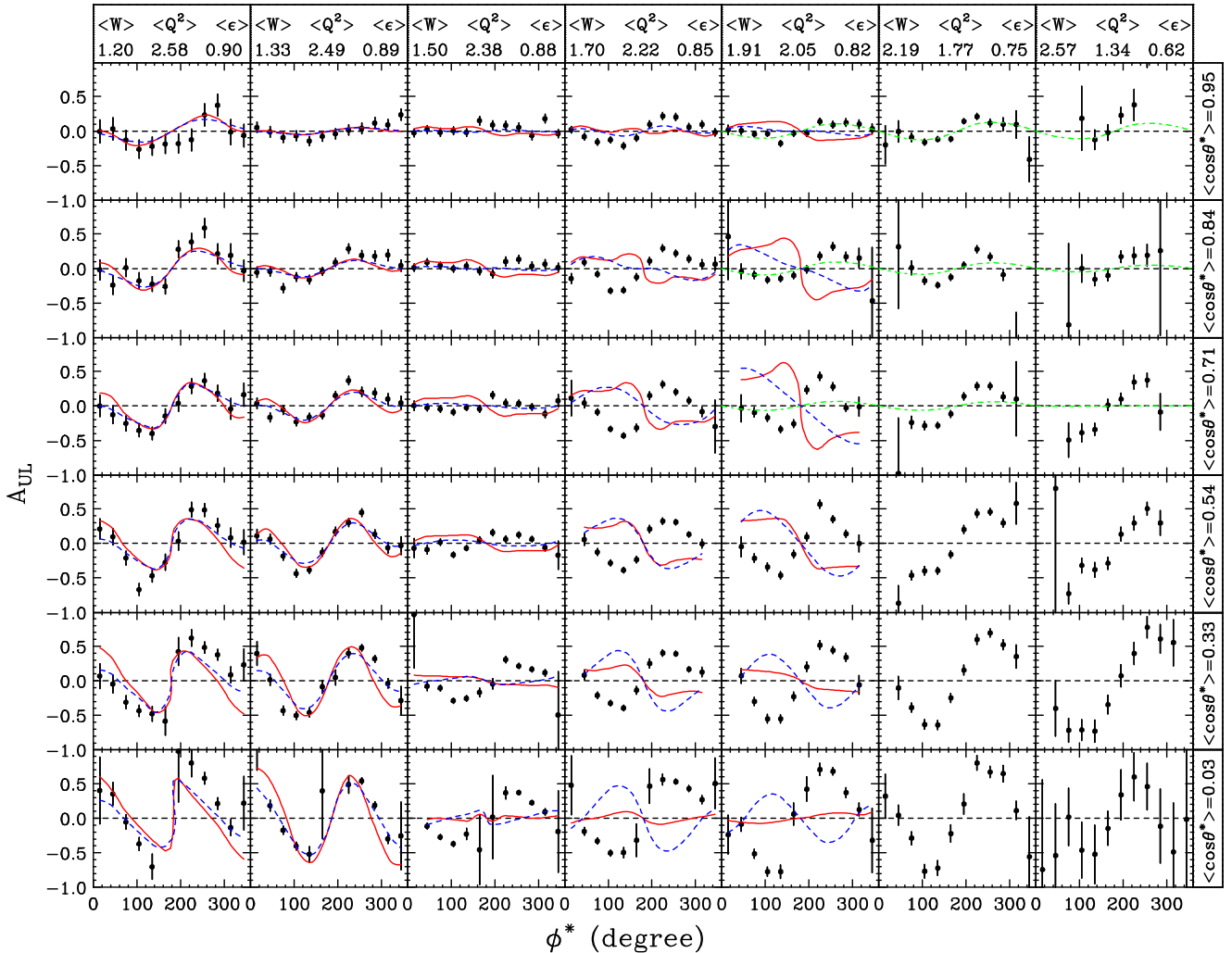


FIG. 10. Target single-spin asymmetry A_{UL} for the reaction $ep \rightarrow e\pi^+n$ as a function of ϕ^* in seven bins in W (columns) and six $\cos(\theta^*)$ bins (rows). The results are from the two lower Q^2 bins of this analysis. The error bars reflect statistical uncertainties only. The solid red curves are from the MAID 2007 fit [9], the blue long-dashed curves are from a JANR fit [25], and the green short-dashed curves are for the GPD-inspired model from Goloskokov and Kroll [12].

a study of inclusive electron scattering rates; fits to the low electron-pion missing mass spectra; and the value that gives the best agreement for A_{LL} between the fully exclusive topology and the topology where the recoil nucleon is not detected. This last technique relies on the fact that the fully exclusive topology has much less nuclear background. From these comparisons, we estimate a systematic uncertainty of about 2% (relative) for $R_{A>2}$. This translates into approximately 1.5% (at low W) to 2.5% (at high W) overall normalization uncertainties on both A_{LL} and A_{UL} .

It is also possible for assumptions made in the dilution factor fitting, such as the lack of ϕ^* dependence, to result in point-to-point systematic uncertainties. Based on trying out several different functional forms to the fit, these were found to be much smaller than the point-to-point statistical uncertainties.

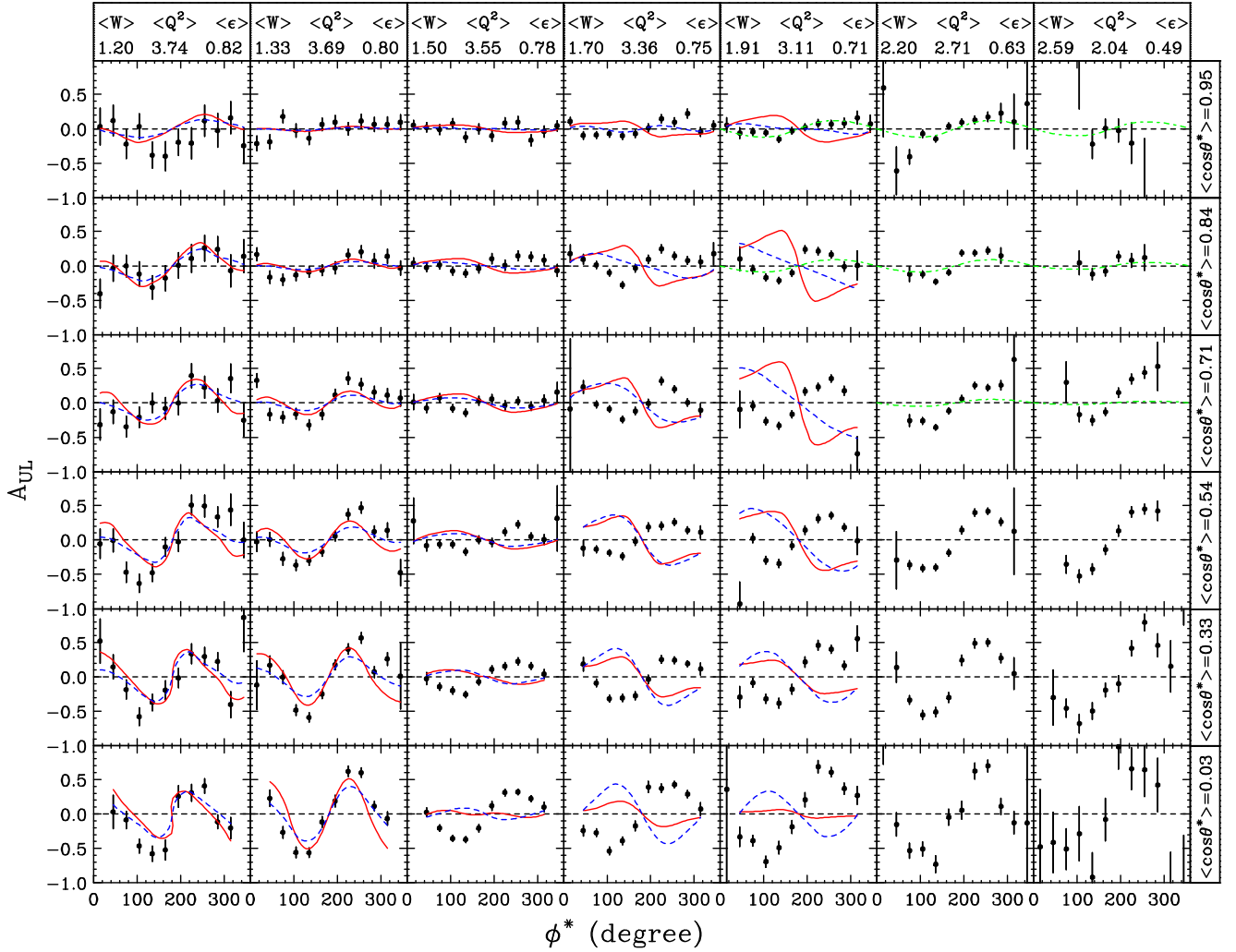
Finally, it is clear from Fig. 1 that the cut on electron-pion missing mass is not 100% effective at removing multipion production for the topology with one missing nucleon. Since the contamination is larger for $M_x^{e\pi} > M$ than for $M_x^{e\pi} < M$,

we divided the data into two distinct sets, based on the above criteria, and compared both A_{LL} and A_{UL} asymmetries. We obtained $\chi^2/\text{d.f.} = 0.98$ ($\chi^2/\text{d.f.} = 1.02$) for agreement of the two A_{LL} (A_{UL}) data sets, where d.f. indicates degrees of freedom, indicating that the admixture of some multipion events into the single-pion samples does not affect the final asymmetry results significantly.

Adding the above sources of uncertainty in quadrature, we obtain an overall normalization uncertainty of 3% for A_{LL} and 5% for A_{UL} .

VI. RESULTS

With over 6000 kinematic points, each with relatively large uncertainties, it is a challenge to portray the entire data set in a meaningful way. For plotting purposes, we therefore averaged together adjacent bin triplets or quartets in W and adjacent bin pairs in Q^2 . The complete set of results is available in the CLAS physics database [23] and in the Supplemental Material associated with this article [24]. All results are for the fully


 FIG. 11. Same as Fig. 10, except for the two larger Q^2 bins of this analysis.

exclusive topology and the topology with a missing neutron combined together, as explained above.

A. A_{LL}

The results for the beam-target spin asymmetry A_{LL} are plotted as a function of ϕ^* in seven bins in W and six bins in $\cos(\theta^*)$ in Fig. 8 for the lower Q^2 data and in Fig. 9 for the higher Q^2 data. There is very little difference between these plots, indicating a weak dependence on Q^2 for a given kinematic bin.

The main feature of the data is a relatively large and positive asymmetry (averaging about 0.4) for most kinematic bins. The major exception is for the lowest W bin, centered on the $\Delta(1232)$ resonance, where the values of A_{LL} are closer to zero. This feature is expected because the $\Delta(1232)$ transition is dominated by spin-1/2 to spin-3/2, which gives a negative value of A_{LL} , balancing the positive contribution from the Born terms. Of particular interest are the bins centered on $W = 1.70$, $W = 1.91$, and $W = 2.19$ GeV. Here, A_{LL} is roughly 0.4, independent of ϕ^* , at forward angles where t -channel processes dominate. At lower values of $\cos(\theta^*)$, an increasingly large ϕ^* dependence can be seen, with a

noticeable enhancement near $\phi^* = 180^\circ$. This suggests the importance of s -channel resonance excitations.

Also shown on the plots are the results of two representative fits to previous data (limited to $W < 2$ GeV): the 2007 version of the MAID unitary isobar fit [9] and the unitary isobar version of the JLab analysis of nucleon resonances (JANR) fit [25], averaged with the same weighting as the data points. Formally, these two fits are rather similar in nature, but they differ in the data sets used and in the functional forms used for the Q^2 dependence of the resonance form factors. By and large, both the MAID 2007 and the JANR fits describe the data reasonably well up to $W = 1.6$ GeV, with large differences in the ϕ^* dependence appearing at larger W . Also shown on the plots are the GPD-based model of Goloskokov and Kroll [12], which has no explicit s -channel resonance structure included. This model generally predicts larger values of A_{LL} than observed. A refinement of the higher-twist terms in this model might well lead to better agreement.

B. A_{UL}

The results for the target spin asymmetry A_{UL} are plotted as a function of ϕ^* in seven bins in W and six bins in $\cos(\theta^*)$

in Fig. 10 for the lower Q^2 data and in Fig. 11 for the higher Q^2 data. It can be seen that the Q^2 dependence of the results is weak. The main feature of the data is a positive $\sin(\phi^*)$ modulation that is small at forward angles and grows to nearly maximal values at central angles, even at the largest values of W .

The sign and magnitude of this modulation is well reproduced by the MAID and JANR fits for $W < 1.4$ GeV, where the $\Delta(1232)$ resonance dominates. At larger values of W , both fits predict a sign change in the $\sin(\phi^*)$ modulation, which is not observed in the data. The magnitude of the modulation is also much larger in the data than in the previous fits near $\cos(\theta^*) = 0$. The GPD-inspired model from Goloskokov and Kroll [12] agrees well with the small asymmetries observed at very forward angles, but does not predict the large asymmetries observed at smaller values of $\cos(\theta^*)$.

Combined with the results for A_{LL} , the results for A_{UL} strongly suggest that there are important nucleon resonance contributions to exclusive pion electroproduction for $W > 1.6$ GeV and $Q^2 > 1$ GeV². For example, the Particle Data Group [26] lists four 3-star and 4-star N^* resonances with masses above 2 GeV (at 2190, 2220, 2250, and 2600 MeV) and a 4-star Δ resonance with mass 2420 MeV.

VII. SUMMARY

Beam-target double-spin asymmetries and target single-spin asymmetries were measured for the exclusive π^+ electroproduction reaction $\gamma^* p \rightarrow n\pi^+$. The results were obtained from scattering of 6-GeV longitudinally polarized electrons off longitudinally polarized protons using the CEBAF Large Acceptance Spectrometer at Jefferson Lab. The kinematic range covered is $1.1 < W < 3$ GeV and $1 < Q^2 < 6$ GeV². Results

were obtained for about 6000 bins in W , Q^2 , $\cos(\theta^*)$, and ϕ^* . Except at forward angles, very large target-spin asymmetries are observed over the entire W region. Reasonable agreement is found with the phenomenological MAID 2007 fit [9] and the 2009 JANR fit [25] to previous data for $W < 1.5$ GeV, but very large differences are seen at higher values of W , where no large- Q^2 data were available when the fits were made. The large target-spin asymmetries are also not accounted for by a GPD model. We anticipate that the present target and beam-target asymmetry data, when combined with beam-spin asymmetry and spin-averaged cross-sectional data in new global analyses, will yield major insights into the structure of the proton and its many excited states.

ACKNOWLEDGMENTS

We thank I. Aznauryan for providing the JANR source code and L. Tiator for providing the MAID 2007 source code. We thank X. Zheng for suggesting the functional form of the dilution factor fit. We acknowledge the outstanding efforts of the staff of the Accelerator and the Physics Divisions at Jefferson Lab that made this experiment possible. This work was supported by the US Department of Energy (DOE), the National Science Foundation, the Scottish Universities Physics Alliance (SUPA), the United Kingdom's Science and Technology Facilities Council, the National Research Foundation of Korea, the Italian Istituto Nazionale di Fisica Nucleare, the French Centre National de la Recherche Scientifique, and the French Commissariat à l'Énergie Atomique. This material is based upon work supported by the US Department of Energy, Office of Science, Office of Nuclear Physics, under Contract No. DE-AC05-84ER-40150.

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- [1] K. Park *et al.* (CLAS Collaboration), *Phys. Rev. C* **91**, 045203 (2015).
- [2] C. J. Bebek *et al.*, *Phys. Rev. D* **13**, 25 (1976).
- [3] C. J. Bebek *et al.*, *Phys. Rev. D* **17**, 1693 (1978).
- [4] T. Horn *et al.*, *Phys. Rev. C* **78**, 058201 (2008).
- [5] H. P. Blok *et al.*, *Phys. Rev. C* **78**, 045202 (2008).
- [6] X. Qian *et al.*, *Phys. Rev. C* **81**, 055209 (2010).
- [7] H. Egiyan *et al.* (CLAS Collaboration), *Phys. Rev. C* **73**, 025204 (2006); K. Park *et al.* (CLAS Collaboration), *ibid.* **77**, 015208 (2008).
- [8] K. Park *et al.* (CLAS Collaboration), *Eur. Phys. J. A* **49**, 16 (2013).
- [9] [www.portal.kph.uni-mainz.de/MAID/]; D. Drechsel, O. Hanstein, S. S. Kamalov, and L. Tiator, *Nucl. Phys. A* **645**, 145 (1999).
- [10] M. Vanderhaeghen, M. Guidal, and J. M. Laget, *Phys. Rev. C* **57**, 1454 (1998).
- [11] J. C. Collins, L. Frankfurt, and M. Strikman, *Phys. Rev. D* **56**, 2982 (1997).
- [12] S. V. Goloskokov and P. Kroll, *Eur. Phys. J. C* **65**, 137 (2010); **47**, 112 (2011).
- [13] H. Avakian *et al.* (CLAS Collaboration), *Phys. Rev. D* **69**, 112004 (2004).
- [14] R. De Vita *et al.* (CLAS Collaboration), *Phys. Rev. Lett.* **88**, 082001 (2002).
- [15] P. E. Bosted *et al.* (CLAS Collaboration), *Phys. Rev. C* **94**, 055201 (2016).
- [16] Y. Prok *et al.* (CLAS Collaboration), *Phys. Rev. C* **90**, 025212 (2014).
- [17] E. Seder *et al.* (CLAS Collaboration), *Phys. Rev. Lett.* **114**, 032001 (2015); S. Pisano *et al.* (CLAS Collaboration), *Phys. Rev. D* **91**, 052014 (2015).
- [18] C. D. Keith *et al.*, *Nucl. Instrum. Methods* **501**, 327 (2003).
- [19] B. A. Mecking *et al.*, *Nucl. Instrum. Methods* **503**, 513 (2003).
- [20] R. G. Fersch *et al.* (CLAS Collaboration) (unpublished).
- [21] N. Guler *et al.* (CLAS Collaboration), *Phys. Rev. C* **92**, 055201 (2015).
- [22] Y. S. Tsai, Report No. SLAC-PUB-848 (1971); *Rev. Mod. Phys.* **46**, 815 (1974).
- [23] CLAS database [clasweb.jlab.org/physicsdb/]
- [24] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevC.95.035206> for plain-text tables of asymmetry results for this experiment.
- [25] I. G. Aznauryan, *Phys. Rev. C* **67**, 015209 (2003); I. G. Aznauryan *et al.* (CLAS Collaboration), *ibid.* **80**, 055203 (2009).
- [26] C. Patrignani *et al.* (Particle Data Group), *Chin. Phys. C* **40**, 100001 (2016).