(Update for PR12-06-110)

Measurement of Neutron Spin Asymmetry A_1^n in the Valence Quark Region Using an 11 GeV Beam and a Polarized ^{3}He Target in Hall C

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Abstract

We present here an update to PR12-06-110 [2], precision measurements of the neutron spin asymmetry A_1^n in the kinematic region $0.3 < x < 0.77$ and $3 < Q^2 < 10$ (GeV/c)^2. The proposed measurement will be performed in Hall C using the upgraded 11 GeV beam, the HMS and the Super HMS (SHMS) spectrometers, and a polarized ^{3}He target. After updating on the recent theoretical development in section 1, we will present experimental updates: We plan to use the same target and cell design as the approved GEN-II experiment which has a factor of 8 improvement on the target luminosity compared to our original proposal. As a result, we are able to reduce the beam time request for DIS measurements by about 50% while matching approximately the statistical uncertainty of A_1^n at the highest x point ($x = 0.77$) to its systematic uncertainty, thus maximizing the physics outcome. Updated rate estimations are presented in section 2.3. In addition, in this update we have added two kinematic settings for measurements of A_1^n in the resonance region for radiative corrections, which will require 2 days of beam time and the results can be compared with DIS measurements to test the quark-hadron duality of polarized structure functions to higher precision than existing data. The procedure of DIS data analysis and systematic uncertainties remain the same as the original proposal and will be briefly repeated in section 3, along with systematic uncertainties of the resonance measurement.

The proposed measurements will provide the first precision data on A_1^n in the valence quark region above $x = 0.61$. If combined with existing world proton data and projected proton data from CLAS12, it will provide precision results on the polarized to unpolarized PDF ratios $\Delta u/u$ and $\Delta d/d$. These results will test various predictions including those from the relativistic constituent quark model, leading-order perturbative QCD (pQCD), and the latest pQCD calculations including the quark orbital angular momentum. The wide Q^2 span of the measurement will explore Q^2-dependence of A_1^n and improve our knowledge on the higher-twist effects. In sections 4.1 and 4.2 we present updates on the projected A_1^n results. While in section 4.3 of the original proposal we described the complementarity to the approved Hall A 11 GeV A_1^n experiment E12-06-122 using the BigBite spectrometer, in section 4.3 of this update we will specifically address the condition raised by PAC30. In section 4.4 we will provide projected $\Delta q/q$ results when the proposed DIS measurements are combined with the future CLAS12 proton experiment. The updated beam time request will be presented at the end in section 5.

[2] The original proposal from PAC30 will be submitted along with this update as the supporting document.

Contents

1 Physics Motivation and Theoretical Updates

1.1 The Physics of A_1^n and Existing Data

Although QCD has been recognized as the leading theory of strong interactions for almost 40 years, our work on QCD and understanding of the strong interaction are still in their elementary stage. Most of the difficulties we are facing now are on the theoretical side: We know that some aspects of high energy processes can be calculated using the well-established perturbation theory and the data can be used to test perturbative QCD (pQCD) calculations, however, so far we still do not have an efficient analytical tool to perform QCD calculations in the non-perturbative region, making it difficult to understand one of the most interesting phenomenon in strong interaction study: the quark confinement.

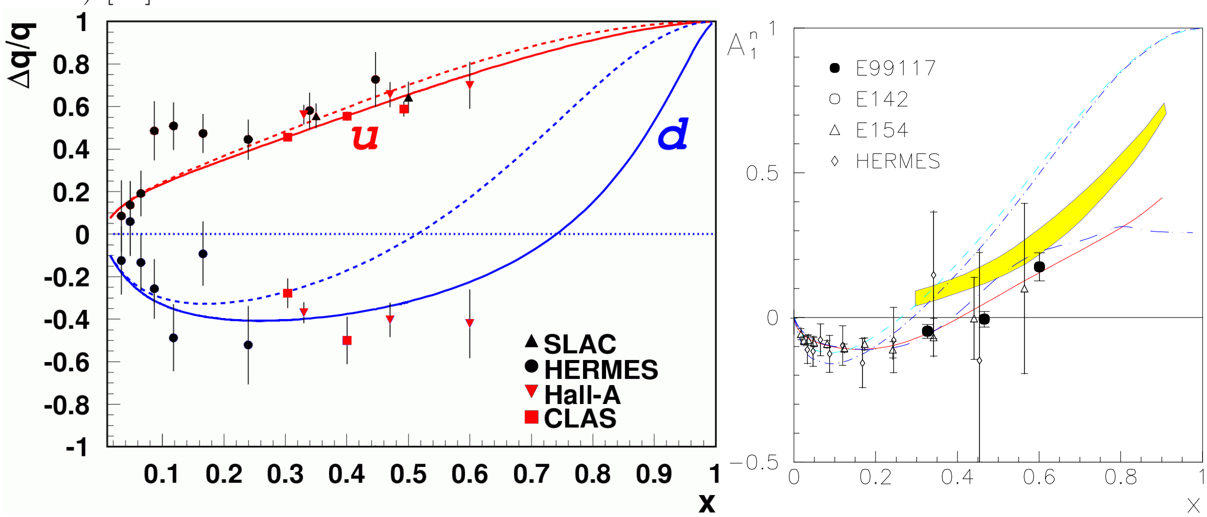
Even in the perturbative sector, we cannot yet use pQCD to predict all measured data: for most kinematic regions pQCD can only be used to calculate the Q^2-dependence of structure functions. Or if using sum rules, one can use symmetries and other first principles to predict the integrals of structure functions. For most cases the absolute values of structure functions themselves still cannot be predicted from the first principles of QCD, leaving a large amount of experimental information disconnected from theory. This is why in the latest NSAC Long Range Plan the first (out of three) current frontier of nuclear science was described to be: *"to understand QCD and its implications and predictions for the state of matter in the early universe, quark confinement, the role of gluons, and the structure of the proton and neutron"*.

The situation that QCD cannot make absolute predictions of structure functions, however, changes as we consider the valence quark region (the so-called large Bjorken x region): The valence quark region is so far one of the few places where pQCD can be used to predict the absolute values of certain structure functions or their ratios. Typical examples are the parton distribution function (PDF) ratio $d(x)/u(x)$, the spin asymmetries of the proton and the neutron A_1^p and A_1^n, and the polarized to unpolarized PDF ratios $\Delta u/u$ and $\Delta d/d$. In our original proposal, we presented a few leading theoretical predictions for $A_1^{p,n}$, $\Delta u/u$ and $\Delta d/d$ at large x, including SU(6)-based non-relativistic constituent quark model (CQM), hyperfine-perturbed relativistic CQM (RCQM), chiral soliton and instanton models, and leading-order pQCD with the constraint of hadron helicity conservation.

Among the observables mentioned above, the ratio $\Delta d/d$ is particularly interesting because their predicted values from theories are dramatically different from each other. Moreover, existing data on the ratio $\Delta d/d$ (the latest from JLab Hall A E99-117 [1, 2] using a polarized ^{3}He target and CLAS EG1b [3] using a polarized ND_3 target) still do not agree with the leading-order pQCD prediction that $\Delta d/d \to 1$ as $x \to 1$, see Fig. 1 (left panel). Because extractions of $\Delta q/q$ are typically done in the quark-parton model framework by combining data on A_1^p with A_1^n, with the uncertainties of $\Delta u/u$ ($\Delta d/d$) dominated by those of A_1^p (A_1^n), we show in Fig. 1 (right panel) existing world data on

A_1^n which were crucial in the $\Delta d/d$ extraction.

Figure 1: Existing data on $\Delta q/q$ [4] (left) and A_1^n [1, 2] (right). For $\Delta q/q$, predictions from the LSS(BBS) parameterizations (leading-order pQCD-based with hadron helicity conservation) [5] are shown as dashed curves. The solid curves are the updated pQCD-based parameterizations to be described in the next section. For A_1^n, two leading-order pQCD-based predictions with hadron helicity conservation are shown: BBS predictions (dashed curve in light blue) [6] and LSS(BBS) parameterization that fit to pre-JLab data (dash-dotted curve in dark blue) [5]. Other predictions for A_1^n include those from relativistic constituent quark model (yellow band) [7], statistical model (long-dashed curve in purple) [8, 9], and the LSS2001 parameterization of pre-JLab data (solid curve in red) [10].



One remarkable implication of the $\Delta d/d$ results is on our expectation of the quark orbital angular momentum (OAM): Before JLab data were published, it was known that the quark OAM contributes to the nucleon spin. However in the valence quark region it was expected from pQCD that its effect would decrease, if not completely disappear. The disagreement between the latest JLab data and the pQCD predictions indicates that the quark OAM plays a significant role in forming the nucleon spin even in the valence quark region up to $x = 0.61$. In fact, the JLab results on $\Delta d/d$ was quoted by the NSAC 2007 Long Range Plan as one of "the most important accomplishments since the 2002 Long Range Plan": *"Recent measurement further constrained the quark-gluon origin of the nucleon spin. JLAB and DESY experiments have found that the up quarks have their spin parallel to the nucleon polarization, while the down quarks have their spin antiparallel – and the sea quarks have very little polarization at all. Experiments at RHIC point to a relatively small gluon poalrization. These measurements indicate that the solution of the spin puzzle – how the various ingredients of nucleon structure contribute to its spin – still remains incomplete."*

In the next section we will present theoretical updates on pQCD calculations for $\Delta q/q$, focusing on the effect of incorporating quark OAM explicitly into the calculation. As one will see, to test the limit of pQCD and see if this latest calculation works, it is necessary to extend the measurement of $\Delta d/d$ to a higher x value than what has been measured with the 6 GeV beam. The measurement proposed here is an extension of the A_1^n measurement using the upgraded 11 GeV JLab beam in Hall C. Combined with the 11 GeV A_1^p measurement already proposed (and approved) in JLab Hall B/CLAS12 [11], we will extend this pQCD test up to $x = 0.77$ with high precision. The impact of the proposed measurement can perhaps be best described as the following (again, from the NSAC 2007 Long Range Plan): *"Experiments following the 12 GeV CEBAF Upgrade will indeed define the spin and flavor dependence of the valence quark distributions with high precision. . . . Measurements of the inclusive spin asymmetry for DIS from high-momentum valence quarks in the proton and the neutron will provide a precise determination of the polarized valence parton distributions Δu and Δd."*

1.2 Theoretical Updates

The solid curves in Fig. 1 (left) show the latest theoretical update on $\Delta q/q$ calculations [4] that included more than simply refitting to the JLab data. Compare to previous leading-order pQCD calculations where quark counting rules require $q^+(x) \propto (1-x)^3$ and $q^-(x) \propto (1-x)^5$ as $x \to 1$ and the valence quark OAM is assumed to be zero, the new calculation explicitly included a nonzero valence quark orbital angular momentum, resulting in a different analytic form that $q^-(x) \propto (1-x)^5 \log^2(1-x)$ as $x \to 1$. A direct result of this is that the turn-over of $\Delta d/d$ to the positive value happens at higher x than previous calculations and the slope at which this ratio approaches 1 as $x \to 1$ appears to be steeper. Since the existing world data up to $x = 0.61$ do not show any trend that $\Delta q/q$ is turning positive, it is important to have precision A_1 measurement of both the proton and the neutron to extract $\Delta q/q$ to $x = 0.75$ or higher in order to test the predictions of the pQCD models with or without quark orbital angular momentum.

1.3 Resonance Measurements

In order to perform radiative corrections to the DIS measurements, it is necessary to have data on A_1 also in the resonance region. This is the main reason why we added the resonance kinematics. In addition, these data will help to study quark-hadron duality as stated below.

Quark-hadron duality has become one of the focuses of hadronic physics study in the past decade. It describes a similarity between electron-nucleon scattering in the DIS, where the electrons scatter off asymptotically free quarks, and that in the nucleon resonance region where the electrons scatter off a highly correlated cluster of quarks and gluons. Quark-hadron duality was first observed in the unpolarized structure functions

F_1 and F_2, where it was observed experimentally that

$$\int_{x_1(W_1,Q^2)}^{x_2(W_2,Q^2)} dx F_2^{res}(x,Q^2) \;=\; \int_{x_1}^{x_2} dx F_2^{DIS}(x,Q^2)\ , \tag{1}$$

where $F_2^{res}(x,Q^2)$ is the structure function measured in the resonance region at low Q^2 and $F_2^{DIS}(x,Q^2)$ is the structure function measured in the DIS region and evolved down to the same Q^2. Duality can be further classified into global duality, where Eq. (1) holds when integrating over the entire resonance region, and local duality where it holds if integrated over a certain resonance. Data from JLab Hall C have demonstrated that global duality holds for unpolarized structure functions at the 10% level down to $Q^2 = 0.5$ (GeV/c)^2, while local duality holds for each of the three prominent resonance regions.

Tests of the quark-hadron duality in the polarized structure function g_1 were carried out at both JLab and DESY. It was shown the global duality holds for the proton and the deuteron down to $Q^2 = 1.7$ (GeV/c)^2 [3, 12], and for the neutron and the ^{3}He to at least $Q^2 = 1.8$ (GeV/c)^2 [13]. However, local duality appears to be violated for the proton and the deuteron in the Δ resonance region even for Q^2 values as high as 5.0 (GeV/c)^2, and similarly for the ^{3}He below $Q^2 = 2.2$ (GeV/c)^2. On the other hand, results on $A_1^{^3\mathrm{He},res}$ and $A_1^{n,res}$ above $Q^2 = 2.2$ (GeV/c)^2 do not show much resonance structure and agree with DIS results within current statistical uncertainties [13].

If quark-hadron duality holds for polarized structure functions, it would have practical values for the study of A_1: with the expected 11 GeV beam, it would cost too much beam time to place the spectrometer(s) at larger scattering angles than what are proposed here in order to extend the measure $A_1^{n,DIS}$ to x values much higher than 0.77. However, if duality holds then one could deduce the value of $A_1^{n,DIS}$ from resonance $A_1^{n,res}$ results above $x = 0.77$ which would cost much less beam time than DIS measurements. In this proposal we do not intend to extend the measurement this way, but rather try to study whether duality holds for A_1^n by measuring its value in the resonance region from $x = 0.45$ to $x = 0.77$. The precision will be comparable with the proposed DIS measurements at the corresponding x values, and at least a factor of three better than existing duality data on the neutron polarized structure functions. The extra beam time for the resonance measurement will be 2 days.

2 Experimental Updates

In this section we first focus on updates on the Super HMS spectrometer and the polarized ^{3}He target required by the proposed measurement. These provide updates to sections 2.2 and 2.3 of the original proposal. Then we present updates on the kinematics and expected event rates, including DIS, elastic, and the newly added resonance regions. These update sections 2.4 and 2.7 of the original proposal. Sections 2.1 (the electron beam), 2.5 and 2.6 (discussions about the pion and pair production background) of the original proposal do not need to be updated.

2.1 Update on the SHMS

The designed momentum and angle acceptances of the Super High-Momentum Spectrometer have changed slightly from the values we used in the original proposal in 2006. The table below shows the 2006 vs. current design values. The updated acceptances are used in the rate estimation of the following sections.

Table 1: Updates on the angle and momentum ranges and acceptances of SHMS.

Year	p range (GeV/c)	θ range	$\Delta p/p$	solid angle (msr)	y_{targ} (cm)
2006 design	2.0-10.4	$5.5° - 30°$	(-15.0%,25.0%)	3.8	30
2010 (current) design	2.0-11	$5.5° - 40°$	(-10.0%,22.0%)	5.0	30

2.2 Update on the Polarized ^{3}He Target

The most significant change in the instrument of the proposed measurement is on the polarized ^{3}He target design and performance. In our original proposal, we employed the typical target and cell design used by experiments in Hall A from 1997 to 2003: Namely, a beam current of 15 μA incident on a 40-cm long target cell with a density of 12 amg and a polarization of 50%. In the recent years, however, major studies have been done on the target design and its polarization mechanism, and a factor of 8 improvement is forseen in the polarized luminosity compared to our original proposal. A detailed explanation of these improvements was provided in the GEN-II proposal [14], and are briefly listed here:

1. The introduction of alkali-hybrid mixtures to greatly increase the efficiency with which the angular momentum of photons is transferred to ^{3}He nuclei. This technique has been used in a series of Hall A polarized ^{3}He experiments in 2009;

2. The advent of commercially available line-narrowed high-power diode-laser arrays. This has been employed in the series of Hall A polarized ^{3}He experiments in 2009 as well;

3. The introduction of greatly improved diagnostics that permit not just polarimetry of the ^{3}He, but also polarimetry of the alkali-metal vapors as well as the direct measurement of the alkali-vapor number densities. In addition, there has been the recognition of the presence of a poorly understood, but measurable, ^{3}He spin-relaxation mechanism that can be characterized by a so-called "X-factor". This factor has been studied extensively and its range appear to be predictable;

4. The demonstration of convection mixing in sealed target cells with no moving parts. The use of convection instead of conduction greatly improve the rate at which the ^{3}He polarization is transferred from the pumping to the target chamber, such that the ^{3}He nuclei in the target chamber can recover from the beam depolarization effect much faster than previous experiments, enabling the use of a higher beam current. The convection method requires a major change in the target cell design but has already been demonstrated to be feasible.

We plan to use the same target and cell design as the "high-luminosity GEN-II target cell": It consists of a 60-cm long target chamber, two transfer tubes to enable convection, and a pumping chamber that is similar to previous experiments. Besides the target chamber which will be made of gold-plated aluminum to avoid radiation damage and thus reduce the risk of explosion, the rest of the cell will be made of glass as usual. With all the improvements, the target can take up to 60 μA while maintaining a polarization of 60%. Compared to the target we used in the original proposal, the new design provides about a factor of 8 improvement in the polarization-square-weighted luminosity (or effective luminosity) for the SHMS, which results in an increase in both DIS and elastic rates to be described in the following sections. For the HMS the increase in the effective luminosity is not as high as the SHMS because of its limited y_{targ} acceptance (i.e. the HMS will not "see" the whole 60-cm scattering chamber for some of the kinematic settings), but is still significant due to the increase in the beam current and the polarization. With the increase in luminosity, if we used the same kinematic settings and beam time as in the original proposal, the statistical error bar would be 3 times smaller, and would be at least 50% smaller than the systematic uncertainty for all kinematic points proposed. To optimize the running condition while maximizing the physics outcome, we plan to reduce the beam time by 45% and approximately equalize the statistical and systematic uncertainties for the highest x point ($x = 0.77$). The total uncertainty on A_1^n for this point will be 40% smaller than the original proposal.

2.3 Update on Kinematics and Rates for DIS, Resonance, Elastic and $\Delta(1232)$ Measurements

The kinematic settings for DIS measurements stay the same as the original proposal and are shown in Table 2 below along with the updated rates. For rate estimation in the DIS region, we compare the cross section calculated from the NMC F_2, the CTEQ and the MRST parameterizations. We found that both CTEQ and MRST give slightly higher cross sections than NMC in the region $x < 0.4$, but much lower ones for large x, varying from 30% lower at $x = 0.6$ to 60% lower at $x = 0.77$. To be on the safe side, we take the smallest cross section among three parameterizations at all x. The projected uncertainties as well as the beam time have both reduced due to the improvement on the target luminosity. Also shown in Table 2 are the two newly added resonance kinematics (#5 for HMS and #D for SHMS). These resonance measurements will provide data needed for radiative corrections. For rate estimation in the resonance region we used the latest empirical fits [15, 16]. Part of these two settings provide overlap with DIS settings, as shown.

The pion to electron ratios are shown for each kinematics. The SHMS is designed to achieve a pion rejection factor of 1000 with the electron efficiency at or above 99% by using a gas cherenkov detector and lead-glass counters, and the HMS has routinely provided similar PID performance, both will be sufficient to limit the systematic uncertainty from the pion background to a negligible level compared to the expected statistical uncertainty. Details of the systematic uncertainties from the pion and pair production (positron) background were discussed in sections 2.5 and 2.6 of the original proposal and will not be repeated here.

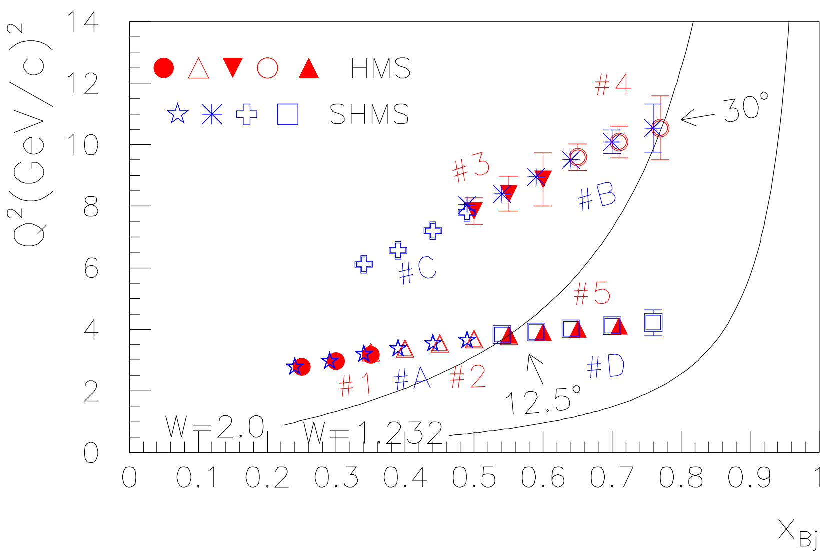
Figure 5 shows the updated projected uncertainties on A_1^n for the five settings on the HMS and the four settings on the SHMS, plotted at the corresponding x and Q^2 values.

Table 2: Kinematics for large x measurements of the A_1^n asymmetries at JLab 12 GeV Upgrade in Hall C. Both HMS and SHMS will be used at similar settings. For DIS kinematics, the π and e^+ background rates are estimations using the Wiser's fit [17]. Kinematics 5 for HMS and D for SHMS are newly added which focus on resonance production. These two settings also provide events in the DIS region, as shown.

	Kine	E_b GeV	E_p GeV	θ ($^\circ$)	(e, e') rate (Hz)	π^-/e	e^+/e^-	x (Q^2, in GeV^2) (W, in GeV) coverages
					DIS			
1	HMS	11.0	5.70	12.5	2300.75	< 0.5	$< 0.1\%$	0.25-0.35 (2.78- 3.17) (2.6- 3.0)
2	HMS	11.0	6.80	12.5	1768.35	< 0.1	$< 0.1\%$	0.35-0.55 (3.26- 3.78) (2.0- 2.6)
3	HMS	11.0	2.82	30.0	5.03	< 7.0	$< 0.9\%$	0.50-0.60 (7.84- 8.87) (2.6- 3.0)
4	HMS	11.0	3.50	30.0	0.94	< 1.6	$< 0.1\%$	0.65-0.77 (9.59-10.54) (2.0- 2.5)
5	HMS	11.0	7.50	12.5	598.43	< 0.1	$< 0.1\%$	0.45-0.55 (3.59- 3.78) (2.0- 2.3)
A	SHMS	11.0	5.80	12.5	2994.47	< 0.5	$< 0.1\%$	0.25-0.50 (2.79- 3.65) (2.1- 3.0)
B	SHMS	11.0	3.00	30.0	8.72	< 5.8	$< 0.7\%$	0.50-0.77 (8.04-10.54) (2.0- 3.0)
C	SHMS	11.0	2.25	30.0	28.35	< 36.0	$< 8.2\%$	0.35-0.50 (6.11- 7.81) (2.9- 3.5)
D	SHMS	11.0	7.50	12.5	581.08	< 0.1	$< 0.1\%$	0.45-0.55 (3.57- 3.78) (2.0- 2.3)
					Resonances			
5	HMS	11.0	7.50	12.5	666.78	–	–	0.55-0.83 (3.84- 4.26) (1.3- 2.0)
D	SHMS	11.0	7.50	12.5	579.92	–	–	0.55-0.89 (3.84- 4.36) (1.2- 2.0)

Table 3 shows the kinematic settings and the updated rate estimation for the elastic and the $\Delta(1232)$ measurements. These measurements will be used to check the product

Figure 2: Kinematic coverage of A_1^n measurement using HMS and SHMS with a 11 GeV beam. The higher (lower) Q^2 settings correspond to a scattering angle of 30° (12.5°). Kinematic points with overlapping x and Q^2 bins are shifted horizontally for clarity. The error bars are proportional to the expected statistical uncertainties on A_1^n. Here we try to match ΔA_1^n (stat.) at the two different Q^2 values. At highest x settings (30° angle), the smaller angle acceptance of the SHMS is compensated by its large y_{targ} acceptance, hence error bars from the SHMS is about the same as those from the HMS. The two solid curves show the separation between DIS and resonance kinematics ($W = 2.0$ GeV), and the location of the $\Delta(1232)$ resonance. Two resonance points at $x = 0.83$ and $x = 0.89$ are not shown because of too large error bars. Statistical uncertainties combining the two spectrometers and different kinematics are given in section 4.



of beam and target polarizations $P_b P_t$ to a 0.5% (statistical) level and to check the sign of transverse asymmetries. The kinematics stay the same as the original proposal, only rates and the beam time are different.

Table 3: Kinematics for elastic longitudinal and $\Delta(1232)$ transverse asymmetries. The HMS and SHMS will have the same momentum and angle settings.

Kine	E_b GeV	E_p GeV	θ (°)	elastic x-sec (nb/sr)	elastic rate (Hz)	Asymmetry	Time (hours)
Elastic	2.200	2.160	12.5	106.986	2840.3	$A_\parallel = 0.0589$	5.1
$\Delta(1232)$	2.200	1.815	12.5	-	-	$A_\perp \sim$ a few %	6

3 Updates on Systematic Uncertainties

The data analysis procedure and systematic uncertainties for DIS measurements were presented in section 3 of our original proposal and do not need to be updated. The data analysis procedure is outlined below in section 3.1, and in section 3.2 we discuss systematic uncertainties for the newly added resonance meausurement.

Among all the systematic uncertainties discussed in the original proposal, only one is from instrumentations (the beam and target polarizations $P_b P_t$), while all others are due to the prescription of the data analysis or the input structure functions used. The systematic uncertainties from event reconstruction and PID are negligible compared to the expected statistical uncertainties. We would like to point out (in section 3.3 below) that this is not a given, but rather a direct result of our choice of the spectrometers. The use of the HMS and the SHMS, both being small-acceptance spectrometers with excellent tracking and PID detectors, will ensure that the kinematics of the proposed measurement to be reconstructed correctly and the systematics from background particles to be under control. This advantage may not be true for open-geometry spectrometer systems of the 12 GeV upgrade.

3.1 Outline of the Data Analysis Procedure

The procedure for data analysis is as follows: first, the raw asymmetries obtained from longitudinally or transversely polarized targets ($A_{\parallel}^{raw,^3\mathrm{He}}$ and $A_{\perp}^{raw,^3\mathrm{He}}$) will be formed directly from data. Then corrections from target and beam polarizations, as well as dilution from unpolarized material inside the target will be made to extract the physics asymmetries $A_{\parallel}$ and $A_{\perp}$. The asymmetry $A_1^{^3\mathrm{He}}$ will then be formed from $A_{\parallel}$ and $A_{\perp}$. The systematic uncertainties on A_1^n include those from polarizations, dilution factor, kinematic variables, and nuclear corrections to extract A_1^n from $A_1^{^3\mathrm{He}}$ using [18]:

$$A_1^n = \frac{F_2^{^3\mathrm{He}}[A_1^{^3\mathrm{He}} - 2\frac{F_2^p}{F_2^{^3\mathrm{He}}} P_p A_1^p (1 - \frac{0.014}{2P_p})]}{P_n F_2^n (1 + \frac{0.056}{P_n})} . \quad (2)$$

Among these, the largest uncertainties comes from the effective proton polarization in the ^{3}He used in nuclear corrections: $P_p = -0.028 \pm 0.003$, which already includes the expected improvement on the ^{3}He wavefunctions from the completed experiment E05-102 [19]. A detailed break-down of systematic uncertainties for the proposed DIS measurements are shown in Fig. 4 in section 4.1.

3.2 Systematic Uncertainties for Resonance Measurements

For resonance measurement we will focus on comparison of the A_1^n or $A_1^{^3\mathrm{He}}$ in the resonance region to those from the DIS measurements between $x = 0.45$ and $x = 0.77$. We will follow the analysis procedure outlined in Ref. [13] for the extraction of $A_1^{^3\mathrm{He}}$ from data and its systematic uncertainty analysis. It is expected, however, that for $A_1^{^3\mathrm{He}}$ the systematic uncertainties should be all smaller than the expected statistical error.

Extraction of A_1^n from $A_1^{^3\mathrm{He}}$ in the resonance region in principle is more difficult than DIS data analysis because of the different resonance structures in F_2 for the proton, the neutron and the ^{3}He. This, however, is less of a problem for this proposal because of the relatively high Q^2 range. As shown in table 2, the Q^2 of the proposed resonance is above 3.84 (GeV/c)^2. In fact, at this Q^2 the unpolarized structure function F_2 no longer show resonance structure and its value agrees well with DIS parameterization. Therefore we will use Eq. (2) for extraction of A_1^n from $A_1^{^3\mathrm{He}}$ in the resonance region.

3.3 More Discussions on the Use of HMS and SHMS

In addition to the excellent PID performance expected from the HMS and the SHMS which reduces the systematic uncertainty from the pion and pair production background to negligible levels (see section 2.3 of this update and sections 2.5-2.6 of the original proposal), the use of these two small-acceptance spectrometers present many other advantages:

1. The small acceptance of these spectrometers will by themselves help to reduce background particles (as opposed to large-acceptance spectrometers);

2. These spectrometers have or are expected to have well-known optics (the optics can be well-calibrated) even at the edge of the acceptances where data for the highest x-bin are expected;

3. These spectrometers have excellent tracking detectors, which, when combined with the well-calibrated optics, will provide excellent reconstruction of the kinematic variables for the highest x-bin.

Overall, the HMS and the SHMS are expected to have the least instrumentational systematic uncertainties among all spectrometers of the 12 GeV upgrade that can accomodate high luminosities, and are ideal choices for the precision measurements proposed here.

4 Update on Expected Results and Complementarity with the Hall A Proposal

This section replaces section 4 of the original proposal, "Expected Results and Complementarity to the Hall A BigBite Proposal". We will provide projected results for the newly added resonance measurements along with updates for the DIS measurements. Then we will address the complementarity with the Hall A proposal PR06-12-122. In section 4.4 we present projected results for the ratio $\Delta q/q$.

4.1 Expected Results for A_1^n and Uncertainties

If the same amount of beam time as in the original proposal were used, the statistical uncertainties on A_1^n would be much smaller because of the improvement on the target luminosity, and in fact would be smaller than the expected systematic uncertainties for all kinematic points. In order to optimize the total uncertainties and the efficiency of utilizing the beam time, we have reduced the beam time request by 45% to match the statistical error of A_1^n at the highest x point ($x = 0.77$) to its systematic uncertainty.

Table 4 and Fig. 3 show the projected uncertainties on A_1^n. For rate estimation in the DIS region, we compare the cross section calculated from the NMC F_2, the CTEQ and the MRST parameterizations. To be on the safe side, we take the smallest cross section among three parametrizations at all x. For rate estimation in the resonance region we used the latest empirical fits [15, 16]. We use 85% and 60% for beam and target polarizations, respectively. The target length is 60 cm and the maximum beam current is 60 μA. See Fig. 3 caption for explanation of error bars and theoretical predictions.

Table 4: Projected statistical and systematic uncertainties for DIS data at different x and Q^2.

x	ΔA_1^n(stat.) low Q^2	ΔA_1^n(stat.) high Q^2	ΔA_1^n(stat.) two Q^2 combined	ΔA_1^n(syst.)	ΔA_1^n(total)
0.25	0.0022	–	0.0022	0.0054	0.0059
0.30	0.0020	–	0.0020	0.0063	0.0066
0.35	0.0025	0.0109	0.0024	0.0074	0.0078
0.40	0.0030	0.0084	0.0028	0.0089	0.0093
0.45	0.0029	0.0106	0.0028	0.0105	0.0109
0.50	0.0033	0.0081	0.0031	0.0124	0.0127
0.55	–	0.0069	0.0047	0.0145	0.0152
0.60	–	0.0092	0.0092	0.0168	0.0192
0.65	–	0.0105	0.0105	0.0197	0.0223
0.71	–	0.0143	0.0143	0.0246	0.0285
0.77	–	0.0288	0.0288	0.0340	0.0446

A breakdown of the total uncertainty for A_1^n for the DIS measurement is shown in Fig. 4. All systematic uncertainties are calculated in the same way as the original proposal. The dominating systematics comes from the uncertainty in the proton polarization inside ^{3}He (P_p). For the uncertainty from A_1^p in the nuclear correction, we used the projected A_1^p results of the approved CLAS12 experiment [11].

Figure 3: Projected data (red solid circles) for measurements of asymmetries A_1^n in the large-x region using a 11 GeV beam and HMS and SHMS in Hall C. Both DIS and resonance data are shown. The error bars show the expected statistical error and the error bands around the horizontal axis illustrate the expected systematic uncertainties. The horizontal axis shows the SU(6) prediction that $A_1^n = 0$. The curves illustrate (from top to bottom in the region $x > 0.6$): 1) the LSS(BBS) parametrization at $Q^2 = 4$ (GeV/c)^2 (light blue curve) [5]; 2) the BBS parameterization at $Q^2 = 4$ (GeV/c)^2 (dark blue curve) [6]; 3) the chiral soliton prediction by Weigel et al. (magenta curve above the yellow shaded band) [20, 21, 22]; 4) the RCQM (yellow shaded band) [7]; 5) the LSS2001 parameterization (black curve) [10, 23]; and 6) another chiral soliton prediction by Wakamatsu (magenta curve below horizontal axis) [24, 25]. Data shown are from SLAC E142 [26] and E154 [27, 28], HERMES [29], and JLab 6 GeV E99-117 [1].

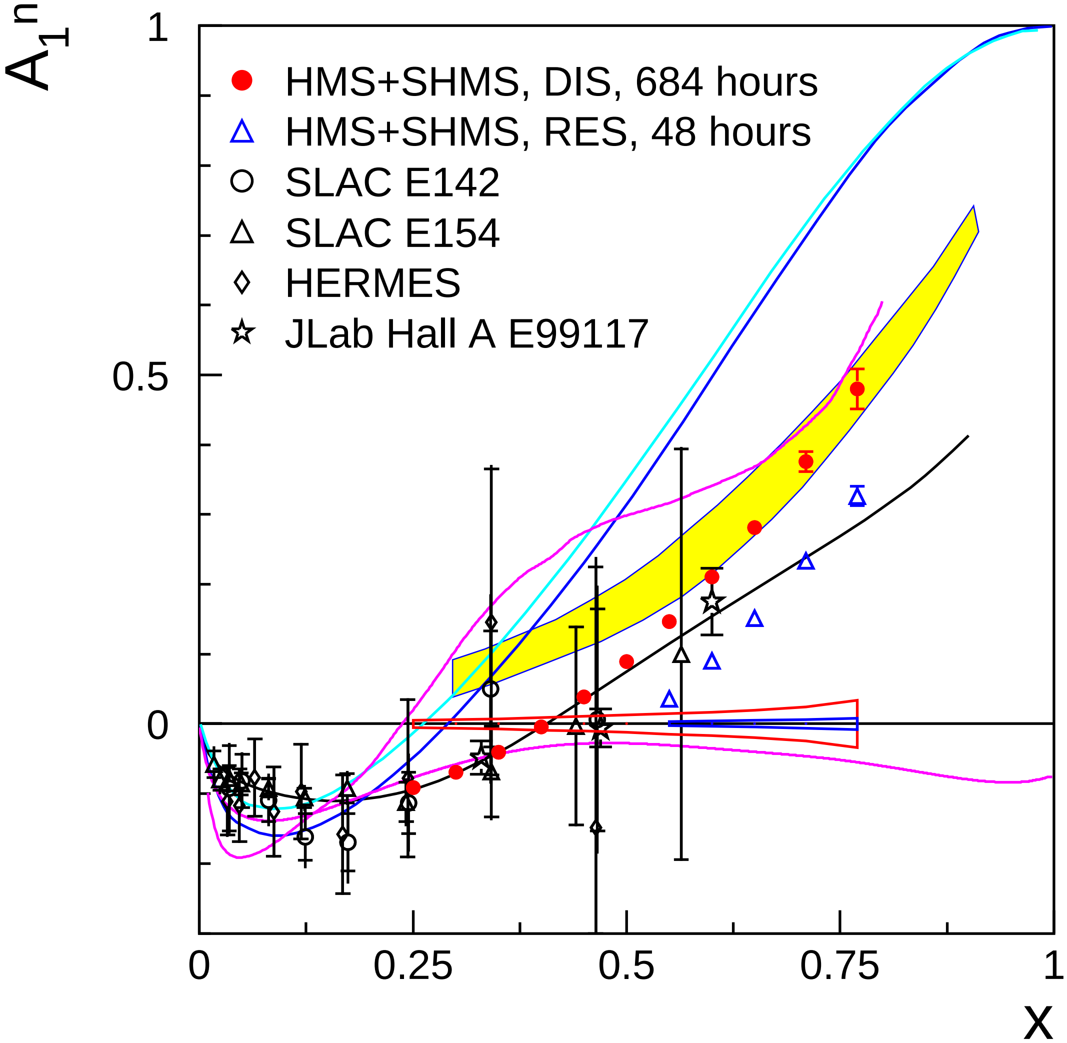
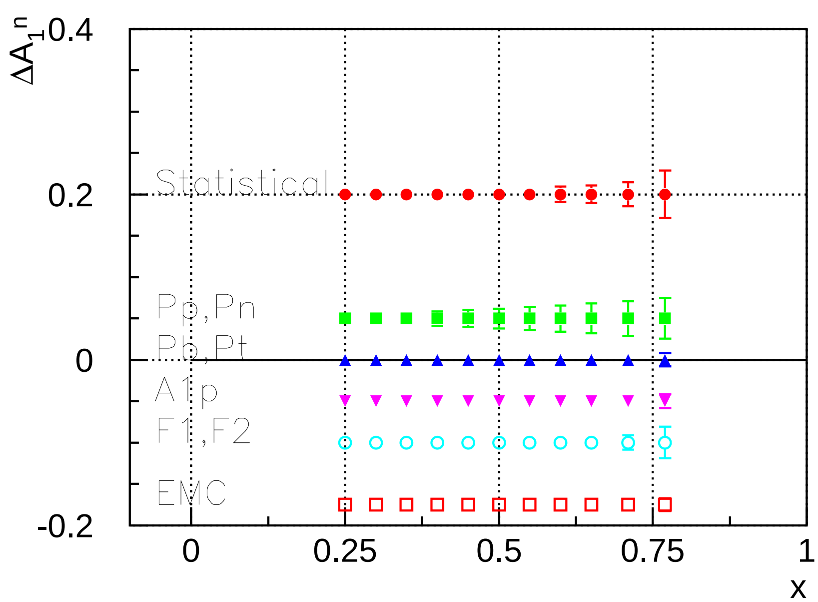


Table 5: Projected statistical and systematic uncertainties for resonance data at different x and Q^2. Resonance data will be taken at a scattering angle of 12.5° (same as the low Q^2 DIS data). The DIS fit for A_1 was used in the systematic uncertainty study.

x	ΔA_1^n(stat.)	ΔA_1^n(syst.)	ΔA_1^n(total)
0.55	0.0072	0.0145	0.0162
0.60	0.0061	0.0169	0.0180
0.65	0.0074	0.0197	0.0210
0.71	0.0095	0.0242	0.0260
0.77	0.0138	0.0323	0.0352
0.83	0.0302	0.0530	0.0610
0.89	0.0593	0.1003	0.1165

Figure 4: Statistical and systematic uncertainties for the proposed A_1^n measurement. Only DIS data are shown here. Systematic uncertainties shown here are mostly due to nuclear corrections in the data analysis. Uncertainties due to instrumentation and backgrounds (such as the detector's PID performance which determines the uncertainties from pion and pair production background) are not shown because they are expected to be negligible compared to the statistical error for the proposed measurements.



4.2 Expected Results for Neutron $h^{g_1}(x)$

Figure 5 shows the expected uncertainty on A_1^n at different Q^2 settings. This Q^2 leverage will allow a study of the Q^2-dependence of A_1^n, and further allow extraction of the higher-twist contribution to $g_1^n(x,Q^2)$ using [30]

$$\Big[\frac{g_1(x,Q^2)}{F_1(x,Q^2)}\Big]_{exp} = \frac{g_1(x,Q^2)_{LT} + h_1(x)/Q^2}{F_1(x,Q^2)_{exp}} \ . \tag{3}$$

A more detailed description of the formalism can be found in Section 1.4 of the original proposal. Existing data on h_1^{n,g_1} show its value to be consistent with zero above $x = 0.2$. Figure 6 shows projected global analysis results on h_1^{n,g_1} with the new data from this proposal included. Only DIS data will be included in this analysis.

Figure 5: Statistical uncertainty of A_1^n from HMS+SHMS at 30° (blue solid circles) and 12.5° (red solid triangles) plotted on a x-Q^2 plane. The scale of the error bars are given on the vertical axis on the right. Statistical uncertainties of previous world data (open markers) are also shown for comparison.

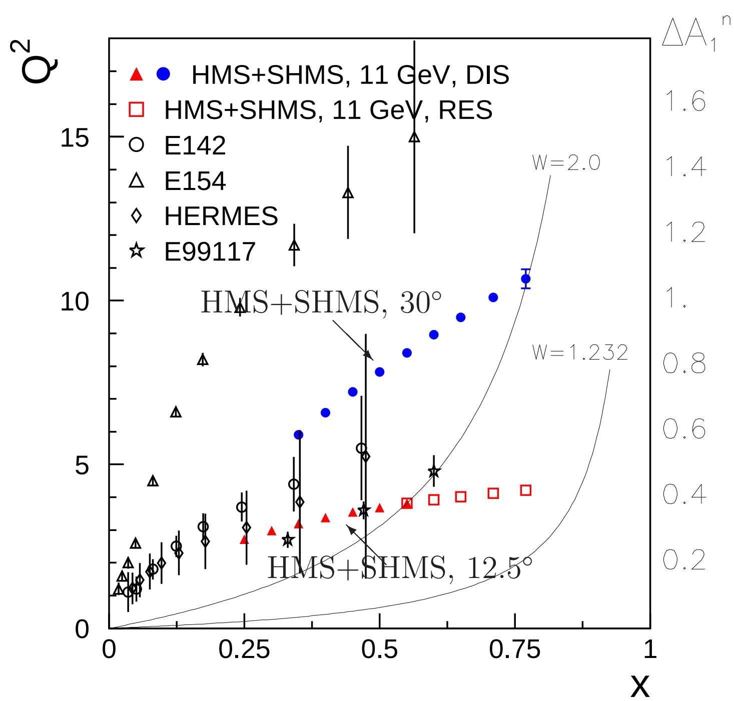
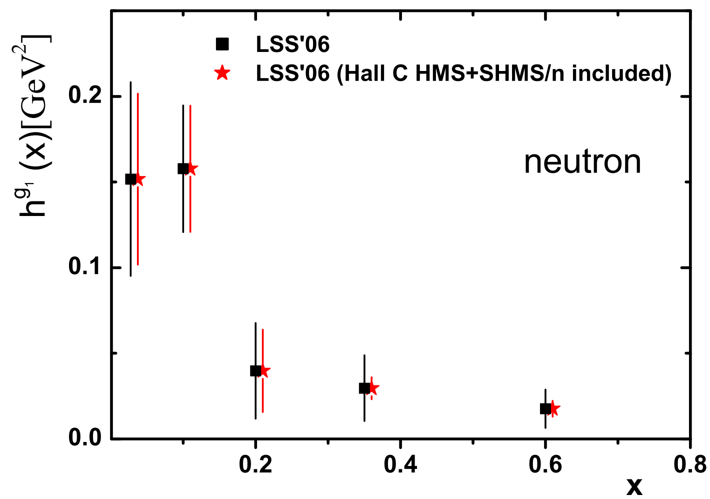


Figure 6: Expected uncertainties for the higher-twist contribution to $g_1^n(x, Q^2)$ extracted from a global analysis of DIS data. Current knowledge on this function is shown by black squares and the projected results are shown as red stars.



4.3 Complementarity with the Hall A Proposal PR12-06-122 and Our Answer to the PAC30 Condition

This proposal will perform a measurement of A_1^n at 11 GeV beam energy with two small acceptance spectrometers HMS and SHMS. The kinematic coverages are complementary to the Hall A proposal PR12-06-122 which will perform measurements at beam energies 6.6 and 8.8 GeV with the BigBite, an open geometry large acceptance spectrometer. The Hall A proposal will cover x up to 0.71 with a wide range of Q^2 to allow an extensive study of Q^2 dependence. This proposal will reach the highest x ($x = 0.77$) at large Q^2 with high precision: not only good statistics, but more importantly, excellent control of systematic uncertainties. As a "flagship" measurement driving the 12 GeV energy upgrade, the physics importance depends critically on reaching the highest x possible with the best precision and reliability in a reasonable beam time. The excellent control of the background with a small acceptance spectrometer ensures the reliability of the measurement. The excellent spectrometer properties of the HMS and SHMS make it possible to take the full advantage of the advancement in polarized ^{3}He target technology – near one order of magnitude improvement in luminosity – which compensates completely the disadvantage of small acceptance in the highest x bin.

In section 4.3 of the original proposal we emphasized that the kinematic coverage of this proposal, if combined with that of the Hall A proposal [31], will provide a better Q^2-coverage and thus allow a better study of the Q^2-dependence of A_1^n. This point remains true for this update: that if both experiments are performed, we will be able to study the Q^2-dependence up to $x = 0.71$ (the highest x point of the Hall A proposal) to greater details compared with if only one experiment is performed.

Then, we would like to also address the issue/condition raised by PAC-30: Currently the Hall A proposal is using only a 6.6 and a 8.8 GeV beam because it is unknown yet whether the BigBite spectrometer can handle the high background rate for the 11 GeV beam, in particular the high pion to electron ratio anticipated for that beam energy. So what if the Hall A measurement is done in the early stage of the 12 GeV upgrade, and the background is found to be not as severe as one expects, thus allow the use of the BigBite spectrometer with a 11 GeV beam to measure A_1^n up to $x = 0.77$? We answer this concern as follows:

- From the experience of running E05-015 [32], which performed a measurement of single spin asymmetry in inclusive DIS with the BigBite, and E06-014 [33], which performed a measurement of d_2^n with the BigBite, it is clear that it is extremely challenging to control background in an open spectrometer even at 6 GeV running conditions. The DIS event rate at high x is very low due to fast dropping in parton distributions, typically two to three orders of magnitude smaller compared to the low x events, while the background from π^- is two orders of magnitude higher in rates. In the BigBite, these events (low and high x, DIS electrons and background pions) will be collected at the same time and will be difficult to separate from each other without excellent tracking and PID detectors. In addition, we found from our data that much more severe background is from π^0 which decays to two photons and then produce e^+e^- pairs. The photon background is difficult to identify even when tracking information is required, and is the leading systematic uncertainty in the analysis of E05-015 and E06-014.

  With the careful planning and the expected advancement in detector technology, the Hall A proposal with the BigBite is expected to be able to take partial advantage of the increase in target luminosity (2×10^{36}) and still be able to make good measurements at 6.6 GeV and 8.8 GeV, however it is clear that this is already pushing to the level where systematic uncertainty from the background becomes a significant concern. To push further to the 11 GeV beam with the BigBite, while the statistical uncertainty will improve over this proposal, background control will be an extremely difficult challenge and the reliability of the measurement will probably become a major concern. The total uncertainty at the highest x bin will be likely worse than what we propose here because the uncertainty is already dominated by systematics in this proposal;

- Even though the BigBite spectrometer, being open-geometry, has the advantage of large acceptance and therefore requires less beam time to cover a wide range of kinematics, the use of the HMS and the SHMS spectrometers has several advantages: It can take full advantage of the high luminosity development in the polarized ^{3}He target and achieve full statistics in the highest x bin. In contrast to the BigBite, for HMS and SHMS there will be far better control in the background. The measurement will be much cleaner than that from the BigBite, therefore will allow a more reliable extraction of the physics results.

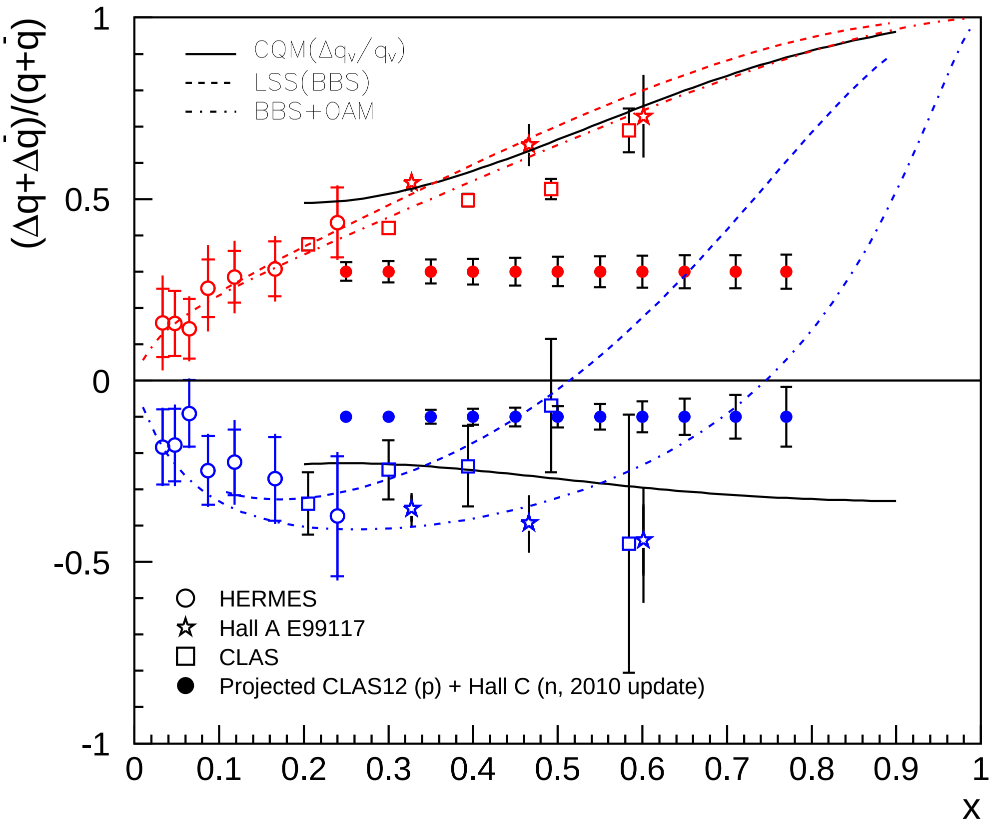
- As stated in earlier sections, the physics of A_1^n at large x is crucial for our understanding of the nucleon spin structure, the nucleon valence quark structure, and the strong interactions. The 6 GeV measurement was described as one of "the most important accomplishment of the past 5 years (2002-2007)", it should be extended to 11 GeV and this is one of the "flagship" experiments of the JLab 12 GeV upgrade. For a physics topic as important as this, performing two independent measurements with completely different instrument and thus systematic uncertainties could be worthwhile. Therefore, even if the BigBite spectrometer could be used with a 11 GeV beam and reach $x = 0.77$ for DIS measurement (with likely worse systematic uncertainties), carrying out both the Hall A measurement and this proposal could provide independent check of systematics, and thus improve the confidence we have in the physics outcome.

To summarize, the physics importance of the 12 GeV flagship measurement of A_1^n at large x critically depends on reaching the highest x with the best precision and reliability. It is experimentally challenging to control systematics due to background. The small acceptance spectrometers (HMS and SHMS) will provide excellent control of the background, thus will take full advantage of the high luminosity development in the polarized ^{3}He target, and will allow us to perform the measurement at the highest x point with the best precision and reliability in a reasonable amount of beam time.

4.4 Expected Results for $\Delta q/q$ if Combined with CLAS12

Neglecting sea quark contributions, the polarized to unpolarized PDF ratio $\Delta q/q$ can be extracted by combining data on A_1^p and A_1^n, or g_1^p/F_1^p and g_1^n/F_1^n. Although the approved CLAS12 experiment [11] will measure both the proton and the neutron spin structure functions, the best results on $\Delta d/d$ are expected from combining the CLAS proton results with the neutron results from a polarized ^{3}He target, either using the Hall A BigBite (up to $x = 0.71$) or this proposal (up to $x = 0.77$). Figure 7 shows the expected results if the A_1^n DIS measurements proposed here are combined with the CLAS12 projected proton results. The error bars include both statistical and systematic errors.

Figure 7: Expected results on $\Delta u/u$ (red) and $\Delta d/d$ (blue) extracted from the neutron results of this proposal and the proton results of CLAS12 [11]. Also shown are predictions from RCQM (solid curves) [7], the leading-order pQCD-based LSS(BBS) parameterization of pre-JLab data (dahsed curves) [5], and the latest pQCD-based parameterization which incorporates the effects of quark OAM in the fit (dash-dotted curves) [4] as described in section 1.2.



5 Update on Beam Time Request and Contributions to Hall C 12 GeV Equipment

This replaces section 5 of the original proposal.

5.1 Beam Time Request

The beam time allocation for production runs at each kinematics is shown in Table 6.

Table 6: Beam time for DIS (636 hours) and resonance (48 hours) measurements. We have reduced the beam time by 45% compared to our original proposal.

Kine	E_b (GeV)		θ (°)	E_p (GeV)	e^- production (hours)	e^+ prod. (hours)	Tot. Time (hours)
DIS							
1	11.0	HMS	12.5	5.70	12	0	12
2	11.0	HMS	12.5	6.80	24	0	24
3	11.0	HMS	30.0	2.82	59	1	60
4	11.0	HMS	30.0	3.50	539	1	540
A	11.0	SHMS	12.5	5.80	36	0	36
B	11.0	SHMS	30.0	3.00	496	4	500
C	11.0	SHMS	30.0	2.25	93	7	100
Resonances							
5	11.0	HMS	12.5	7.50	48	0	48
D	11.0	SHMS	12.5	7.50	48	0	48

Additional beam time include:

- Commissioning of the spectrometers, the beamline and the Compton polarimeter. Assuming this is not the first experiment in Hall C to use the newly-installed polarized ^{3}He target, the commissioning will likely take 4 calendar days (or 3 PAC days). The commissioning time will be longer if we also need to commission the target.

- To check the dilution factor due to unpolarized material in the target, we need to measure the nitrogen cross section using reference cells filled with nitrogen: 2 hours at the HMS (SHMS) kinematics 1 (A), 2 (A), and 4 hours at kinematics B, 3 (C) and 4 (C). This requires a total of 16 hours for DIS production settings; For resonance kinematics we request a total of 2 hours for the nitrogen measurement.

- To check the product of beam and target polarizations P_bP_t and to check the sign of transverse asymmetries, we need 8 hours to measure the longitudinal asymmetry of $\vec{e}-{}^3\vec{\mathrm{He}}$ elastic scattering (including 2 hours of N_2 reference cell runs) and 6 hours to measure the transverse asymmetry of $\Delta(1232)$ production. The beam energy for these two measurements will be 2.2 GeV and both SHMS and HMS will be set at 12.5°;

- optics runs: data will be taken on a multi-foil carbon target with the 2.2 GeV beam to study the optics of the HMS and the SHMS. This will take 8 hours total.
- beam pass change from 2.2 to 11 GeV, 8 hours;
- beam polarization measurements: non-invasive for Compton and 8 hours for 2 Moller measurements (one at each beam energy);
- configuration changes: 10 (angle or momentum) $\times$ 0.5 hours + 8 (polarity) = 13 hours;
- target polarization measurements, about 4% of production time (that's 60 minutes per day), or 28 hours.

The total beam time request is 853 hours, or 35.5 days.

5.2 Contributions to Hall C 12 GeV Equipment

As stated in the original proposal, we are planning to make the following contribution to the Hall C 12 GeV equipment: The polarized ^{3}He collaboration will install the polarized ^{3}He target in Hall C. In addition, the University of Virginia and the Temple University groups are committed to make at least 2 FTE-years contribution to Hall C beamline commissioning at the 12 GeV Upgrade, including the Compton and the Moller polarimetry, the ARC energy measurement and the raster system.

6 Summary

We request for 853 hours, or 35.5 days of beam time at 11 GeV to measure neutron spin asymmetry A_1^n in the deep inelastic scattering region $0.3 < x < 0.77$ and $3 < Q^2 < 10$ (GeV/c)^2. The proposed measurement will extend our present knowledge of A_1^n from $x = 0.61$ to $x = 0.77$ and its wide Q^2 coverage will explore Q^2-dependence of A_1^n. When combined with the proton data from CLAS12 experiments, the value of polarized parton distribution function ratios $\Delta u/u$ and $\Delta d/d$ can be extracted in the same x region. Results from this measurement will provide the first precision data in the unexplored "deep" valence quark region above $x = 0.61$ and test various predictions including those from the relativistic constituent quark model and perturbative QCD. In particular, the latest pQCD-based prediction which explicitly incorporated the effect of the quark orbital angular momentum shows that $\Delta d/d$ should cross zero around $x = 0.75$, and the proposed measurement will be able to test this and learn the importance of the quark orbital angular momentum.

This 11 GeV Hall C proposal with the HMS and the SHMS is complementary to the Hall A 6.6/8.8 GeV proposal using a large-acceptance BigBite spectrometer. With the use of small-acceptance spectrometers (HMS and SHMS) along with their excellent detectors, systematic uncertainties from background will be well under control, allowing us to take full advantages of the luminosity upgrade of the polarized ^{3}He target and to achieve high statistical precision in a reasonable amount of beam time. It will provide a very clean measurement and the most reliable physics results in the very large x region.

Acknowledgment

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