A High Precision Measurement of the Deuteron Spin-Structure Function g_1^d/F_1^d

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We propose to make definitive measurements of the deuteron spin structure function g_1^d/F_1^d in the deep-inelastic kinematics accessible with a 6 GeV beam at JLab. The principal goal is to provide the low Q^2 anchor points for NLO pQCD plus higher twist fits to g_1^d/F_1^d, which is particularly sensitive to $\Delta G(x)$ (the polarized gluon density of the nucleon) and the sum of up and down quark polarizations. By spanning a factor of typically two in the Q^2-range at nine values of x, the new data will strongly constrain the higher twist contribution to the fits, with a corresponding reduction in the polarized PDF uncertainties. The proposed measurements, when combined with existing and planned world data at higher Q^2, will provide the theoretically cleanest determination of $\Delta G(x)$ in the moderate to high x region, and will provide a necessary complement to the low x program of RHIC-spin.

The experiment will use both ^{6}LiD and ND_3 in the standard Hall C/UVa polarized target assembly as a source of polarized deuterons, with approximately equal running times for both to constrain the nuclear effects in ^{6}LiD, the target used by the higher Q^2 experiments at SLAC and CERN. Both the target and low current (100 nA) 6 GeV electron beam will be longitudinally polarized. Electrons scattered at angles from 22° to 38° will be detected in the detector assembly (BETA) planned for the upcoming SANE, Semi-SANE, and polarized Real Compton experiments. Additional measurements at lower Q^2 will be made using a 4.8 GeV beam energy with both BETA and and the HMS spectrometer.

We request a total of 19 days of production running (14 days at 6 GeV, 5 days at 4.8 GeV). Additionally, we request 5 overhead days for calibrations, target anneals and material changes, and one energy pass change. We also request an upgrade to the Hall C DAQ system to handle trigger rates up to 5 kHz. Most of the experiment (12 days of production running, 4 days overhead) can be run concurrently with the approved Semi-SANE experiment. Therefore, the request for new beam time is 8 days.

Contents

I. INTRODUCTION AND MOTIVATION

A full understanding of the spin structure of the nucleon (and determination of the polarized gluon density $\Delta G(x)$ in particular) is one of the goals of hundreds of physicists worldwide, spanning many labs and both particle and nuclear physics. It is not possible to cover the full effort in this brief proposal, but in the following sections we will endeavor to show that Jefferson Lab can play a significant role in this effort, even with the present beam energy limit of 6 GeV. Precision measurements of the nucleon spin structure functions for $0.15 < x < 0.6$ and $1\ \mathrm{GeV}^2 < Q^2 < 5\ \mathrm{GeV}^2$ is one of the DOE 2011 milestones for JLab, and measurements on a deuteron target provide the best possible constraints on the isoscalar combination of structure functions. This combination is particularly sensitive to $\Delta G(x)$ due to the absence of the large non-singlet Δq^3 term that dominates the proton and neutron structure functions individually.

A. Historical perspective

Deep-inelastic lepton scattering from nucleons has proved over the years to be the cleanest tool to study the short distance structure of the nucleon. The pioneering experiments at SLAC, followed by several generations of experiments at FermiLab, SLAC, CERN, DESY, and elsewhere, have made great strides in determining the spin-averaged parton densities of the quarks and gluons in the proton and neutron. Starting in the 1970's, experiments using polarized targets have been making steady progress in determining the spin-dependent parton densities, although over a more restricted range in momentum fraction x and momentum transfer squared Q^2 due to the lower luminosity available with polarized targets. Initial studies from SLAC and CERN, borne out with increased precision with subsequent experiments at SLAC, CERN, DESY, JLab, and elsewhere, showed that the up and down quarks sum to only a small fraction of total spin of the nucleon, in the framework of the Standard Model and pQCD. This implies that the net contribution of polarized gluons, strange quarks, and parton angular momentum must be substantial. A large effort is ongoing to study these contributions at RHIC, CERN (COMPASS), DESY (HERMES), and JLab.

B. Polarized PDFs

Specifically concerning the gluon spin, there are two approaches that are being followed. The first is to try to isolate specific processes in which a polarized gluon is involved at leading order, for example photon-gluon fusion leading to a pair of charmed quarks (COMPASS), or quark-gluon scattering leading to a high energy photon (RHIC-spin). The interpretation of these interactions is complicated due both to background events (other tree-level process that can lead to the same final state) and higher order QCD corrections.

A theoretically cleaner approach is to examine the Q^2 dependence of the spin structure function g_1. Perturbative QCD allows a simple expression of g_1 in terms of the quark and gluon distributions Δq, $\Delta \overline{q}$ and ΔG, which evolve according to the DGLAP equations [1] due to gluon radiation:

$$g_1(x, Q^2)_{\mathrm{pQCD}} = \frac{1}{2} \sum e_q^2 \left[(\Delta q + \Delta \overline{q}) \otimes \left(1 + \frac{\alpha_s(Q^2)}{2\pi} \delta C_q \right) + \frac{\alpha_s(Q^2)}{2\pi} \Delta G \otimes \frac{\delta C_G}{N_f} \right]. \quad (1)$$

In practice, fits to data should include the effects of both kinematic and dynamic higher twist. In the spin-averaged case, pQCD evolution is the bench-mark approach to which reaction-specific determinations of the gluon density $G(x)$ are compared. This is possible due to the high accuracy of measurements of the spin-averaged structure function F_2 over many decades in both x and Q^2 (needed because the evolution due to gluon radiation is essentially logarithmic in nature). In the polarized case, the kinematic range of present precision data [2, 3, 4, 5] is considerably more limited. Nonetheless, the data are of sufficient quality to obtain a very good description of the valence up and down quark densities, and rough indications of the gluon and sea quark densities. Figure 1 compares four different pQCD fits [6, 7, 8, 9]. One can see that even though the groups make different assumptions (for example, LSS [9] explicitly includes power law higher twist corrections), the results for the polarized up quarks are very similar, with somewhat more variation in the polarized down quarks, and a huge variation in the polarized gluon distribution (even the sign is not reliably determined with present data).

C. Jefferson Lab spin program

The spin physics program at Jefferson Lab has already had an impact on global pQCD fitting of polarized parton densities [9]. Although much of the kinematic region accessible

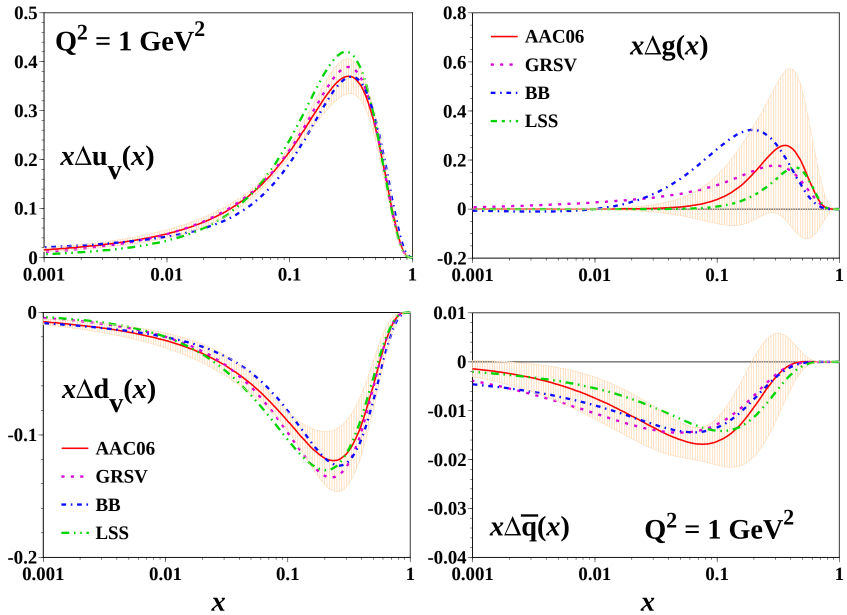

FIG. 1: Comparison of polarized parton distributions extracted by AAC [6], GRSV [7], BB [8], and LSS [9]. The shaded band indicates the uncertainty of the AAC06 parameterization.

with up to 6 GeV electrons is in the nucleon resonance region (missing mass $W < 2$) or at $Q^2 < 1$ GeV^2, where higher-twist contributions become dominant [10, 11], the region $0.15 < x < 0.6$ can be accessed with the cuts $W > 2$ GeV and $Q^2 > 1$ GeV^2 traditionally used to define the deep-inelastic region where DGLAP evolution equations (plus modest and tractable higher twist corrections) can be used to extract polarized parton density functions (PDFs) [9]. [In this proposal we maintain $Q^2 > 1$ GeV^2, but relax the cut on W somewhat (to 1.7 GeV), to access the transition region where higher twist effects become dominant, and thus constrain them empirically.] The high luminosity and duty factor of JLab, combined with advances in target technology and data handling ability, have made possible an ongoing program of precision measurements in the accessible DIS region for both polarized proton and neutron targets. The comparison of recent calculations of the polarization of the valence up and down quarks with the recent Hall B data in Fig. 2 highlights the impact of JLab's abilities, as does the reduction of the projected error in ΔG from the QCD fit of the LSS group [9] as shown in Fig. 3.

A careful review of the ongoing program shows that overall systematic errors will dominate over statistical uncertainties when including the JLab proton and neutron data in global QCD analyses. However, this is not yet the case for the deuteron (basically the average of

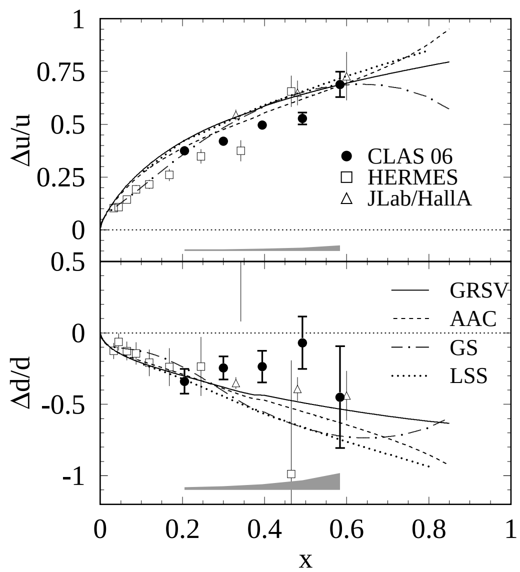

FIG. 2: Approximate polarization of the valence up and down quarks in the proton extracted from recent JLab experiments on the virtual photon asymmetry A_1 for the proton, deuteron and neutron (^{3}He).

the proton and neutron). The deuteron is of particular interest because it is more sensitive to the polarized gluon density $\Delta G(x)$ than the proton (at all x) or neutron (at low x) structure functions individually, due to the absence of the large non-singlet Δq^3 term. The Wilson coefficients for the gluon contribution (C_G in eq. 1) to both the proton and neutron are approximately equal in sign and magnitude. The polarized quark contributions to the proton are large and positive for the proton and small for the neutron. For the deuteron (equal mixture of u and d quarks), the positive u-quark polarization roughly cancels the negative d-quarks contributions, so that g_1^d is small compared to g_1^p (and indeed very close to zero for $x < 0.1$), resulting in a much larger *relative* significance of $\Delta G(x)$ than it has for the proton (or neutron at low x). The absence of a free polarized neutron target makes the situation more complicated. Although the use of polarized ^{3}He leads to relatively small statistical and experimental systematic errors, the interpretation error in extracting the free neutron structure functions is difficult to evaluate. For example, are higher twist contributions different for ^{3}He than for a free neutron? The much lower average density of the deuteron (characteristic Fermi momentum of 55 MeV, compared to 150 to 200 MeV in ^{3}He) greatly reduce the nuclear interpretation uncertainties. Thus is it is crucial to obtain high precision data on the deuteron over the full kinematic range accessible at JLab.

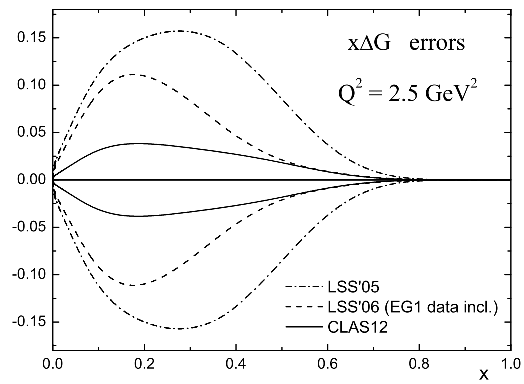

FIG. 3: Expected uncertainty for polarized gluon distribution ΔG from a NLO analysis of all world data. The outermost line shows the result from a recent analysis by Leader, Sidorov and Stamenov [9]. The second line is the updated result from these authors after inclusion of the new Eg1b data from CLAS at 5.7 GeV [12]. The innermost line shows the expected uncertainty after including the data set to be collected with the planned Eg12 experiment in the JLab 12 GeV era, including statistical and systematic errors.

D. Experimental Situation

We present all available higher precision g_1^d/F_1^d data in near-DIS kinematics ($Q^2 > 1$ GeV^2, $W > 1.7$ GeV) as a function of Q^2 in nine bins of x in Fig. 4. We include the recently published results from HERMES [4], COMPASS at CERN [5], and Eg1b [12] at JLab. The ongoing COMPASS experiment provides the high Q^2 leverage needed to determine $\Delta G(x)$ from the Q^2-dependence of g_1^d. For the Hall B Eg1b experiment, the final analysis will result in slightly smaller error bars and an extended Q^2 range when their 4.2 GeV data and some missing 5.7 GeV files are included. It can be seen that existing deuteron data are generally dominated by statistical errors (inner error bars on the plots). The relatively large systematic error for Eg1b is the result of low counting rates at 6 GeV beam energy for the quasi-elastic reaction used to determine the scale factor $P_b\, P_t$, the product of beam and target polarizations. There are no other JLab experiments on polarized deuterium for $W > 2$ GeV that have run or are planned in the 6 GeV era (other than Semi-SANE [13] with an inclusive electron trigger, the subject of the present proposal).

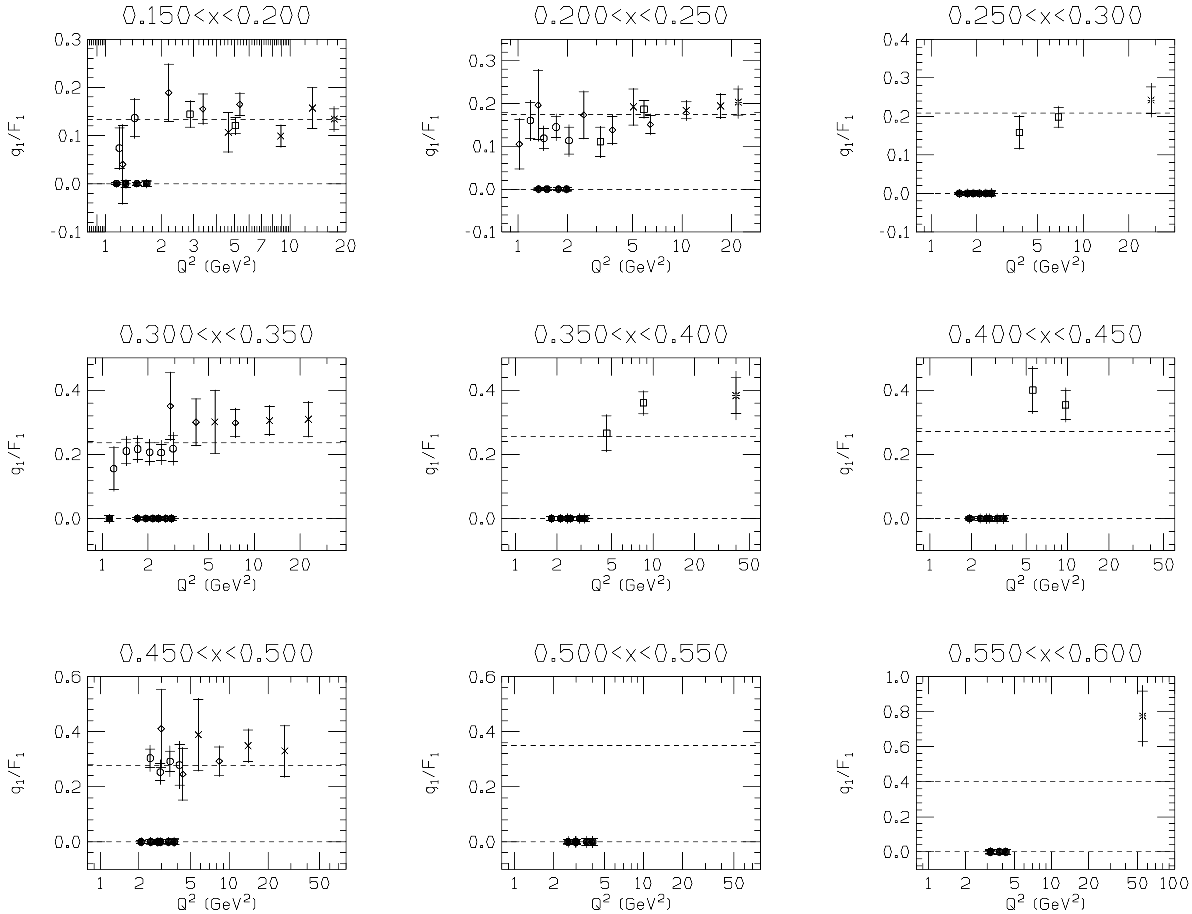

FIG. 4: Ratios g_1^d/F_1^d from Eg1b (open circles, 5.7 GeV data only), E143 (diamonds), E155 (crosses), HERMES (boxes), and COMPASS (stars). The projected data from this proposal are shown as the solid circles (ND_3 data only), plotted at zero (the statistical errors for our proposal are very small: in almost all cases smaller than the size of the symbol). The dashed line shows the E143 fit II model [2] used to estimate the scale factor systematic error for this proposal. In all cases, inner errors are statistical only, and outer are statistical and systematic added in quadrature.

E. This proposal

In this proposal, the goal is to reduce the total error on the low Q^2 points to the smallest possible value (typically 4% to 5% relative), as shown in Fig. 4. In addition, we will cover the largest possible Q^2 region in each x bin with point-to-point statistical and systematic errors at the few percent level, which will provide strong constraints on dynamic higher twist contributions. As data at high Q^2 improves, these data will provide the benchmark low-Q^2 values that will allow ever improving determinations of the polarized PDFs and

$\Delta G(x)$ in particular. Both AAC [6] and LSS [9] groups have indicated that the data from our proposed measurements will have a meaningful impact on their QCD calculations and intend to provide projections of this impact by January 2007.

II. FORMALISM

The experiment consists of measuring the yields ($N^{\pm}$) of longitudinally polarized electrons inclusively scattering from longitudinally polarized deuterons, where the $\pm$ index refers to parallel or anti-parallel polarization directions. The yield is then corrected for the helicity-dependent integrated beam charge ($Q^{\pm}$) and the lifetime of the DAQ system, $q^{\pm}_{LT}$. The asymmetry of the corrected yields is the raw asymmetry A_{raw}. Next, to go from A_{raw} to the physics asymmetry $A_{\parallel}$, five factors need to be taken into account: the beam polarization P_b, the target polarization P_t, the dilution factor f due to the unpolarized nuclei mixed with the polarized deuteron, and the nuclear correction terms C_1 and C_2:

$$A_{\parallel} = \frac{A_{raw}}{f\, P_b\, P_t\, C_1} + C_2 \tag{2}$$

The ratio of polarized to unpolarized structure functions will be determined from measured longitudinal asymmetries $A_{\parallel}$ using

$$\frac{g_1}{F_1} = \frac{A_{\parallel}}{d\, f_{RC}} + \frac{2Mx}{2E-\nu}\,\frac{g_2}{F_1} + A_{RC}, \tag{3}$$

where $d = [(1-\epsilon)(2-y)]/\{y[1+\epsilon R(x,Q^2)]\}$, $\epsilon^{-1} = 1 + 2[1+\gamma^{-2}]\tan^2(\theta/2)$, $y = \nu/E$, $\gamma^2 = Q^2/\nu^2$, and $\nu = E - E'$, with E representing the incident and E' the scattered electron energy in the lab frame, θ the electron scattering angle, M the nucleon mass, and f_{RC}, A_{RC} the radiative dilution and asymmetry corrections; $R(x,Q^2) = (1+\gamma^2)\, F_2(x,Q^2)/\,[2x\, F_1(x,Q^2)] - 1$ is typically 0.2 for the kinematics of this experiment [14]. For the contribution of the transverse spin structure function g_2 we can use the twist-two result of Wandzura and Wilczeck (g_2^{WW}) [15]

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(\xi,Q^2)d\xi/\xi, \tag{4}$$

evaluated using an empirical fit to g_1/F_1 [16]. Alternatively, we can use a fit for world data on g_2 directly (see below).

III. THE EXPERIMENT

The experiment consists of scattering longitudinally polarized electrons from longitudinally polarized deuterons, and detecting the scattered electrons in a large electromagnetic calorimeter array. The electron energy is determined from the energy deposited in a cluster of adjacent lead glass blocks, and the scattering angle is determined from the cluster position, with a small correction for the magnetic field of the polarized target. A gas Čerenkov counter is used to reject pions, and a front scintillator tracker is used to ensure that the electron originated from the 3-cm-long target cell. The asymmetry in normalized count rate A_{raw} is used to determine g_1^d/F_1^d, after correcting for beam polarization P_t, target polarization P_b, the fraction of polarizable nucleons (dilution factor) f, backgrounds, radiative effects, and using models for the L/T cross section ratio R and the spin structure function g_2^d (see above for details). Overall, the experimental setup is essentially identical to the planned experiments SANE [18] (E03-109, update presented at this PAC) and Semi-SANE [13] (E04-113, see Appendix A for abstract).

A. Beam

The beam will be longitudinally polarized and will be transported using the standard polarized target beam line. The beam polarization will be measured with the existing Møller system, and the position will be rastered over the target face with the existing raster system. Since the target field is parallel to the beam line in this experiment, the chicane magnets will only be weakly energized, if at all. The desired beam energy is nominally 6 GeV (in practice > 5.7 GeV) and 4.8 GeV (> 4.5 GeV), at a current of approximately 100 nA. The beam will be transported to the regular Hall C beam dump (since the longitudinal field of the polarized target does not deflect it significantly), resulting in less background than for the SANE experiment, which uses a transverse target field and therefore has to dump the beam inside the hall.

B. Target

We will use the UVa polarized target system, which uses Dynamic Nuclear Polarization to polarize materials in a 5 T magnetic field at a temperature of 1 K. The primary target for this experiment will be small pellets or sheets of ND_3 immersed in a liquid helium bath. The nominal dilution factor of 0.28 is decreased by a factor of 0.9 due the the liquid helium and the aluminum and Kapton target windows. We also plan to use ^{6}LiD for a substantial portion of the running. In this case, the nominal dilution factor of 0.23 is increased by a factor of 1.87 when one considers ^{6}Li as essentially consisting of an unpolarizable alpha accompanied by a deuteron that is polarized 87% as much as the free deuteron in the target. The net dilution factor of about 0.4 for ^{6}LiD is larger than the dilution factor of 0.25 for ND_3, but this is mostly compensated for by the higher average polarization of about 33% that we expect for ND_3, compared to to 22% for ^{6}LiD. Less overhead time for annealing the LiD target is required due to the much slower rate of depolarization from radiation damage. The high ^{6}LiD polarization obtained in the COMPASS experiment ($> 40\%$) cannot be acheived at JLab since beam heating precludes the use of a dilution refrigerator. A carbon target of known thickness will be used to determine the exact amount of polarizable material in the corresponding target cups. Data runs with and without liquid He in the target will be used to cross check the material thicknesses and densities.

C. The detector

The BETA detector package being assembled for SANE [18] and Semi-SANE [13] will also be used in the present experiment. It will be centered on a scattering angle of 30°. The heart of the system is BigCal, a fly's eye array of 1774 lead glass blocks, each with a front face area of 4 by 4 cm, located about 3.5 m from the target. The energy of electron candidates is determined by summing the energies in 9 adjacent blocks, with an expected resolution in energy of $5\%/\sqrt{E}$, and an angular resolution of about 1 mr. Calibration of the energy determination from the ADC readings of each block will be done initially using ep elastic scattering during the SANE experiment. As was discussed in the SANE proposal, we will monitor the gain calibrations using the copious sample of π^0 decays to $\gamma\gamma$ and γe^+e^-. In the latter case, the opening angle of m_π/P between the photon and the lepton pair, coupled with the splitting of the lepton pair caused by the magnetic field of the target, most events will produce three well-isolated clusters. The gain will also be monitored using periodic insertion of a known amount of laser light distributed by a Lucite panel in front of the array.

The most important detector element in particle identification is the gas Čerenkov counter. The index of refraction of the atmospheric nitrogen or CO_2 gas is low enough that essentially no pions or muons will produce significant Čerenkov light. Some pions will emit delta rays (soft electrons) in the front hodoscope, Čerenkov window, and in the gas, that will cause pions to be mis-identified as electrons. Hall background will also cause some mis-identification due to random coincidences with electrons in BigCal. Simulations show a pion rejection factor of between 200 and 1000, depending on what electron efficiency is desired and how much hall background there is.

A front tracker is being constructed to measure particle positions just in front of the Čerenkov counter, 50 cm from the target. Two arrays of 3 mm scintillator bars will measure the vertical coordinate with a resolution sufficient to separate positive and negative electrons at the low end of the energy spectrum (1.2 GeV). An additional plane measures the horizontal component, also using 3 mm wide scintillator bars. Combined with the BigCal cluster position, the tracker can localize events with a resolution of about 0.5 cm at the beam axis, providing a powerful rejection of background not originating from the 3-cm-long target cell (for example, the target can windows).

Finally, a Lucite detector array located between the Čerenkov counter and BigCal will provide additional position and timing redundancy.

Further details of the detector and electronics can be found in the SANE Jeopardy Update presented to this PAC.

D. Trigger and data acquisition

We will use the same single-arm triggers for BETA as the SANE experiment: basically a coincidence between the Čerenkov counter and a substantial energy deposition in the calorimeter. We will also pre-scale triggers that do not require the Čerenkov counter in order to obtain a good sample of $\pi \rightarrow \gamma\gamma$ events for calorimeter calibration. Due to the smaller scattering angle of 30° in the present proposal, compared to 40° in SANE, the trigger rate of good electrons will be increased to approximately 1.5 kHz and 1.2 kHz for the 6 and 4.8 GeV beam energies, respectively. We expect up to 2 kHz of additional triggers that will be rejected as background by off-line software analysis (better calorimeter energy determination, tighter Čerenkov-calorimeter timing cuts, matching to target cup using the front tracker, and matching of track to Čerenkov mirror). The π^0 trigger rate will be adjusted with a pre-scale factor to give about 500 Hz. Therefore the total trigger rate will be about 4 to 5 kHz, higher than the present Hall C capability, but well below the 9 kHz trigger rate recently achieved in Hall B. We propose straightforward upgrades to the Hall C system (software changes, spreading modules over more crates, possibly adding more TDC modules and only using half of the inputs to each) to allow trigger rates up to 5 kHz.

For some of the experiment, we will also use the HMS spectrometer in standard single arm electron mode. The highest rigger rate of about 1.5 kHz will be for the quasi-elastic setting ($E = 4.8$ GeV, $\theta = 11°$).

E. Kinematic Coverage

The kinematic coverage in x and Q^2 for this experiment is shown in Fig. 5, based on beam energies of 6 GeV and 4.8 GeV, and the angular range of BigCal centered at 30° ($22° < \theta < 38°$), as in the Semi-SANE experiment. The DIS cuts $W > 2$ GeV and $Q^2 > 1$ GeV^2 are indicated, as is the looser cut $W > 1.7$ GeV used for the higher twist analysis. A minimum scattered electron momentum of 1.2 GeV has been imposed to keep pion and pair-symmetric contamination to a manageable level (see below), and also to obtain a reasonable trigger rate. At low x, only a very limited range of Q^2 is accessible, but this grows with increasing x. The coverage is very similar to that obtained in the SANE experiment with two beam energies (4.8 and 6 GeV) at a fixed angle of 40°. We instead use an angle of 30° which maximizes the overlap in running time with Semi-SANE. A detailed summary of the expected kinematic bins is provided in Table I.

For dilution factor and target polarization studies, and to reduce the uncertainty of higher twist effects, we plan to measure quasi-elastically scattered electrons from 4.8 GeV beam in the HMS spectrometer for a portion of the running time: 2 days at 11° with a central momentum of 4.3 GeV (quasi-elastic setting), and 3 days at 16° and 2.8 GeV (inelastic setting). This will be simultaneous with ND_3 production data taking in BETA. The relative rates for the quasi-elastic setting are shown as a function of W in Fig. 6. The free deuteron quasi-elastic peak has a predicted width of about 0.05 GeV (1σ), while the width of the nitrogen peak is about 0.2 GeV, allowing a good separation of the free deuteron rates and asymmetries from those of nitrogen (and helium and aluminum target windows). The free deuteron peak is also well separated from inelastic pion production (3σ between peak and

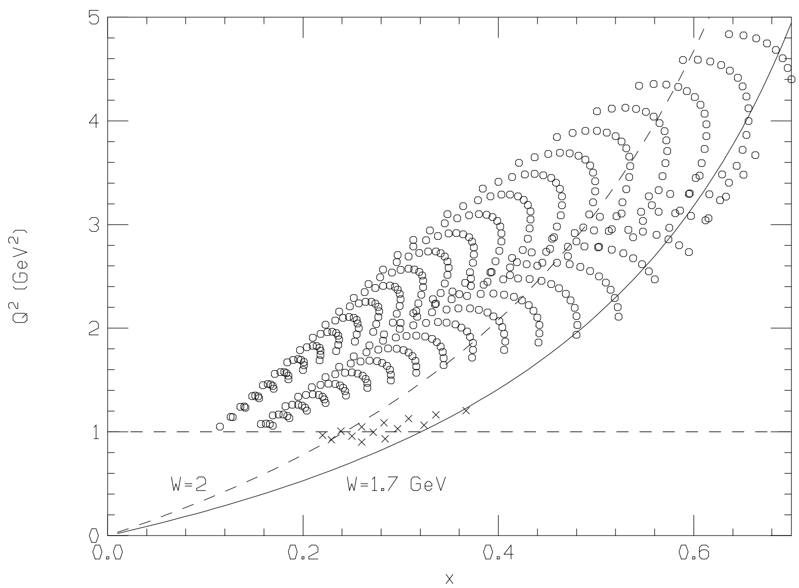

FIG. 5: Expected kinematic coverage. Open circles are for the BETA detector, while the crosses are for the HMS spectrometer (see run plan, Table IV). The dashed lines indicates the traditional DIS cuts at $W = 2$ GeV and $Q^2 > 1$ GeV^2, while the solid curve marks $W = 1.7$ GeV.

pion threshold from a free nucleon).

F. Statistical Uncertainties

The electron rates were calculated using a beam current of 100 nA, a total target thickness of 1.8 g/cm^2, and the NMC [17] parametrization of F_2 for the deuteron, and the R1998 model for R. The rates were integrated into the (x, Q^2) bins of this proposal in 1° steps in scattering angle and 0.1 GeV in scattered electron energy P to take into account the strong cross section variation across the acceptance of the BETA and HMS spectrometers.

The relative statistical error on g_1^d/F_1^d was calculated based on the kinematic bins in Table I, running times for the ND_3 target and BETA detector of 8 and 5 days for $E = 6$ and 4.8 GeV respectively (see Sec. VIII for additional details), an average dilution factor of 0.25, an average pion and pair-symmetric dilution factor of 0.8, a beam polarization of 80%, an average target polarization of 33%, and an average radiative dilution factor of 0.9. The results were cross-checked by scaling the published g_1^d relative errors from the Hall B Eg1b experiment [12]. The 5.7 GeV data set was used, and only the bins corresponding to $22° < \theta < 38°$ scattering angle were included. Because Eg1b only had 5 days of actual beam

$<x>$	$<Q^2>$ [GeV^2]	$<W>$ [GeV]	g_1/F_1	$\delta g_1/F_1$ (stat.)	$\delta g_1/g_1$ (syst.)
BigCal with $E_{\rm beam} = 6.0$ GeV					
0.13	1.19	3.04	0.0794	0.0032	0.0032
0.17	1.48	2.93	0.1030	0.0025	0.0041
0.22	1.77	2.77	0.1316	0.0030	0.0053
0.23	1.98	2.88	0.1350	0.0041	0.0054
0.27	2.07	2.62	0.1649	0.0032	0.0066
0.27	2.30	2.74	0.1648	0.0047	0.0066
0.28	2.48	2.82	0.1661	0.0063	0.0066
0.33	2.34	2.47	0.1983	0.0043	0.0079
0.33	2.62	2.61	0.1959	0.0054	0.0078
0.33	2.86	2.70	0.1969	0.0065	0.0079
0.38	2.51	2.34	0.2260	0.0052	0.0090
0.38	2.92	2.49	0.2262	0.0068	0.0090
0.38	3.19	2.59	0.2263	0.0082	0.0091
0.42	2.71	2.23	0.2545	0.0055	0.0102
0.42	3.09	2.37	0.2521	0.0077	0.0101
0.42	3.45	2.47	0.2543	0.0090	0.0102
0.47	2.93	2.13	0.2847	0.0067	0.0114
0.47	3.75	2.37	0.2824	0.0110	0.0113
0.48	3.39	2.25	0.2866	0.0075	0.0115
0.52	2.99	1.99	0.3147	0.0076	0.0126
0.52	4.03	2.26	0.3115	0.0117	0.0125
0.53	3.62	2.12	0.3194	0.0121	0.0128
0.57	3.19	1.90	0.3448	0.0094	0.0138
0.57	3.77	2.04	0.3423	0.0134	0.0137
0.57	4.25	2.14	0.3423	0.0141	0.0137
0.61	3.92	1.95	0.3666	0.0149	0.0147
0.62	3.36	1.81	0.3744	0.0100	0.0150
0.62	4.49	2.02	0.3736	0.0163	0.0149
0.66	4.15	1.84	0.3975	0.0150	0.0159

$<x>$	$<Q^2>$ [GeV^2]	$<W>$ [GeV]	g_1/F_1	$\delta g_1/F_1$ (stat.)	$\delta g_1/g_1$ (syst.)
BigCal with $E_{\rm beam} = 4.8$ GeV					
0.18	1.15	2.58	0.1063	0.0025	0.0043
0.22	1.34	2.43	0.1346	0.0026	0.0054
0.23	1.50	2.55	0.1353	0.0038	0.0054
0.27	1.73	2.43	0.1641	0.0042	0.0066
0.28	1.53	2.30	0.1653	0.0032	0.0066
0.28	1.89	2.49	0.1673	0.0061	0.0067
0.32	1.94	2.31	0.1938	0.0049	0.0078
0.33	1.70	2.17	0.1967	0.0035	0.0079
0.33	2.15	2.40	0.1964	0.0063	0.0079
0.37	1.83	2.07	0.2235	0.0054	0.0089
0.37	2.38	2.31	0.2233	0.0066	0.0089
0.38	2.13	2.19	0.2252	0.0054	0.0090
0.42	1.95	1.96	0.2533	0.0041	0.0101
0.42	2.59	2.20	0.2533	0.0077	0.0101
0.43	2.33	2.09	0.2551	0.0069	0.0102
0.47	2.46	2.00	0.2828	0.0075	0.0113
0.47	2.80	2.10	0.2829	0.0087	0.0113
0.48	2.08	1.85	0.2874	0.0064	0.0115
0.52	2.22	1.79	0.3123	0.0079	0.0125
0.52	2.60	1.89	0.3133	0.0082	0.0125
0.52	2.97	1.99	0.3146	0.0096	0.0126
0.57	2.74	1.80	0.3438	0.0100	0.0138
0.58	3.18	1.89	0.3473	0.0119	0.0139
0.62	3.36	1.81	0.3730	0.0164	0.0149
HMS with $E_{\rm beam} = 4.8$ GeV					
0.24	0.96	2.07	0.1410	0.0061	0.0056
0.28	0.98	1.92	0.1654	0.0051	0.0066
0.32	1.11	1.86	0.1936	0.0081	0.0077

TABLE I: Expected statistical and systematic error for each kinematic bin. Systematic errors do not include possible nuclear corrections for ^{6}Li (error will be in common with E155 and COMPASS).

on target, used a three times thinner target with a worse dilution factor, ran with 20 times lower beam current, and several other factors, the scale factor turns out to be close to 0.1 (equivalent to running Eg1b 100 times longer). The two methods of error estimation agree within 20%. The statistical uncertainties for the 6 day 6 GeV LiD running are expected to be very similar to those for ND_3.

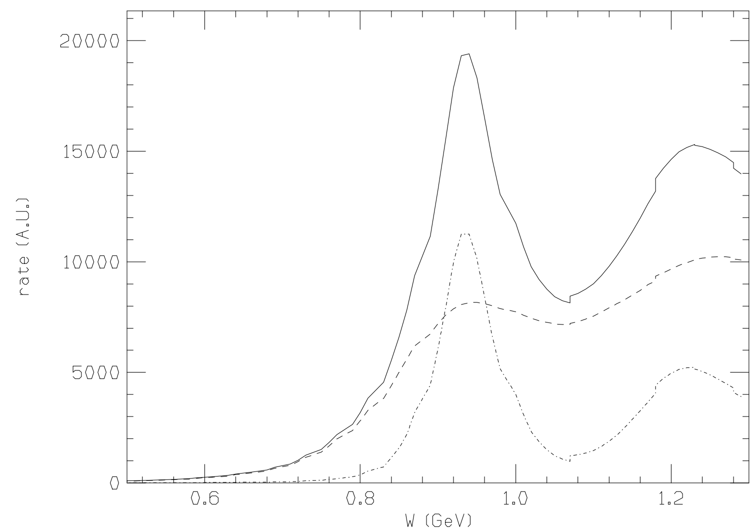

FIG. 6: Relative count rates vs. W as seen by HMS for $E = 4.8$ GeV and $\theta = 11°$ (quasi-elastic setting). The dotted line shows the ^{2}D values, the dashed line is for nitrogen, and the solid line is the sum of the two.

G. Systematic uncertainties

It is notoriously difficult to evaluate systematic errors, especially if there is no statistical process dominating a given uncertainty. In the following sections, we largely follow the same assumptions as made in previous DIS spin structure experiments, so at least we have a consistent basis for comparison. Our estimated experimental systematic errors are summarized in Table II.

1. Beam and target polarization

The largest systematic error in this experiment, as in most other g_1^d/F_1^d DIS experiments, is expected to be on the scale factor $P_b\,P_t$, the product of beam and target polarizations. In the Hall B Eg1b experiment [12], this error was over 10% (relative) at 5.7 GeV due to the limited statistical accuracy of the quasi-elastic asymmetry measurement used to determine $P_b\,P_t$. This method was chosen because the NMR coil design of the Hall B polarized target makes precise measurements of target polarization problematic. The UVa/SLAC polarized target to be used in this proposal has coils that are embedded in the cell, rather than surrounding the cells, and thus provide a good uniform sample of the polarized material. This

source	p-t-p	overall
$P_b\, P_t$	-	2.8%
dilution	1%	1.5%
pair-symmetric contribution	2%	-
pion contamination	2%	-
radiative corrections	1%	1.5%
^{7}LiD and ^{6}LiH	1%	2%
pile-up, dead time	1%	1%
Total		4.1%

TABLE II: Relative point-to-point (p-t-p) and overall experimental systematic errors expected from various sources for the ND_3 measurements.

will allow a direct measurement of the target polarization with a relative accuracy of $< 4\%$, as already established for ND_3 in E143 and LiD in the E155 [3] and E155x [19] experiments at SLAC using the same target materials. With careful, dedicated off-line studies of the NMR system, we may be able to reduce this error to 3%, but we are not depending on this option. We note that for ND_3, two methods can be used (area method and ratio of the two peak heights), providing an internal cross check for the NMR measurements. The Hall C Moller system will allow beam polarization measurements with a relative accuracy of 1.5%, so that the target polarization uncertainty will dominate the uncertainty in $P_b\, P_t$.

We propose to improve the determination of $P_b\, P_t$ for ND_3 by measuring the ed quasi-elastic asymmetry with the HMS spectrometer centered at 11° with a central momentum of 4.3 GeV, with a beam energy of 4.8 GeV. The deuteron quasi-elastic peak is four times narrower than those of the nitrogen, helium, and aluminum materials in the target, allowing a dilution factor of close to 0.6 at the quasi-elastic peak $W = M$ (see Fig. 6). In 2 days of running on, the deuteron asymmetry can be determined with a relative statistical accuracy of 2%. The error in the predicted asymmetry due to the uncertainty in nucleon form factors is less than 1%.

Corrections to the Plane Wave Impulse Approximation due to Final State Interactions (FSI) and Meson Exchange Currents (MEC) are of order $(5 \pm 2)\%$ according to the calculations of Arenhövel [20], with the uncertainty driven by modeling choices. A check on the MEC and FSI corrections is planned using the detailed model of J.M. Laget [21]. The RSS experiment [11] used the HMS spectrometer at similar kinematics and an ND_3 target and found good agreement (within their 5% statistical accuracy) with the Arenhövel calculation, using the target polarization as determined by the NMR system. We scaled the RSS results (which unfortunately had very low target polarization) to our conditions to verify that 2 days of running are sufficient to make a 2% relative accuracy measurement of the deuteron quasi-elastic peak.

Combining the two methods of determining $P_b P_t$ together, each with a essentially uncorrelated systematic errors of $< 4\%$, will results in a net systematic error on $P_b Pt$ of $< 2.8\%$. We note that the *relative* changes in target polarization will be monitored to better than 2% between target and energy changes, as the dominant systematic error in target polarization is an overall scale factor uncertainty.

2. Pair-symmetric background

The fraction of electrons originating from pair-symmetric processes is listed in Table III for representative kinematic points. At electron angles of 22° to 38°, more than 99% of these events come either from direct Dalitz decays of photoproduced $\pi^0 \rightarrow e^+e^-\gamma$, or from pair production ($\gamma \rightarrow e^+e^-$) of one of the two photons from a normal π^0 converting in the target, windows, or detectors upstream of the Čerenkov gas. We used a Monte Carlo by P. Bosted to simulate these processes. The results have been checked at identical kinematics in Hall B [22] and were found to agree within 20%. It can be seen that in the lowest x bins, the pair-symmetric background is significant. We may be able to reduce this by a factor of two if the front tracker performs well and is able to separate positively and negatively charged particles.

Even if the front tracker is too noisy for reliable separation, we will still be able to measure the fraction of pair-symmetric events in two ways: one is by positioning the HMS spectrometer at angles from 22° to 38° and momenta from 1.2 to 3 GeV, and directly measuring the positron to electron ratio in the particular geometry of this experiment. This can be done in just a few hours of running time. We will simulate the effects of the front tracker hodoscope and Čerenkov entrance window by making measurements with and without a sheet of plastic between target window and the spectrometer entrance window. A second way will be to measure the rate of 2-cluster and 3-cluster events in BigCal. The 3-cluster events coming from $\pi^0 \rightarrow e^+e^-\gamma$ will be kinematically very clear, as the reconstructed invariant mass will equal the pion mass, once the proper assignment of particle type is made to each cluster. We note that the average separation at BigCal between the electron and positron is 60 cm (due to the target magnetic field), large enough to have well-separated clusters, but small enough to have a reasonable chance for both to be detected in BigCal. A special feature of the electron/positron cluster pairs will be that they are vertically above and below each other. The average separation between the photon and the e^+e^- pair is 35 cm, again large enough to be well-separated, but small enough to have a good chance of detecting all three particles in BigCal. We will also record a fraction of the events with no Čerenkov signal to look for two clusters corresponding to $\pi^0 \rightarrow \gamma\gamma$ as another way of measuring the rate of neutral pion production. Combining all these measurements together, we will be able to determine the pair-symmetric dilution factor to better than 10% of itself, resulting in a point-to-point systematic error of $< 1.5\%$.

From measurements in SLAC E155 [23], we know that pion photoproduction can have a non-zero asymmetry. We will therefore correct the measured asymmetry according to:

$$A_{corr} = A_{meas}/(1 - f_b) - f_b A_{bknd},$$

where f_b is the background fraction, and A_{bknd} is the background asymmetry. Our simulations show that we will have approximately 10 times more $\pi^0 \rightarrow \gamma\gamma$ events in BigCal than electrons, where at least one of the photons has an energy above 1.2 GeV. We will prescale the events without a Čerenkov signal by approximately a factor of 10 in order to not saturate the DAQ capability, which will still leave us with more π^0 events (with 2 photons) than those with an electron or positron. Having measured the π^0 asymmetry accurately as a function of angle and momentum, we will use our simulation to evaluate the asymmetry for the pair-symmetric background with a relative accuracy of better than 10%. Thus, the total point to point systematic error from pair-symmetric background (dilution and background asymmetry) will be 2% on g_1^d/F_1^d in the worst case.

3. Dilution factor

In a pure ND_3 or ^{6}LiD target, the dilution factor is straightforward: there is exactly one free deuteron for every ^{6}Li nucleus, or 3 deuterons per nitrogen nucleus. We will consider the systematic error in treating ^{6}Li as the sum of a partially (87%) polarized deuteron plus an unpolarized alpha separately (see below). Considering here just the count rate dilution factor, the only consideration that enters for a pure target is the ratio of N/D or Li/D cross sections per nucleon. This "EMC" ratio is now known with an accuracy of better than 1.5% from recent high-statics measurements on d, He, and C carried out in Hall C at the the kinematics as the present proposal [24]. Since both the preliminary Hall C results and the published SLAC results [25] show there is a very small Q^2-dependence to the EMC ratio in our kinematic range, this dilution factor systematic error is in common with higher Q^2 measurements of g_1^d/F_1^d.

The main source of dilution factor uncertainty specific to the present experiment is therefore the exact amount of materials other than LiD or ND_3. This depends on the so-called packing fraction, i.e. the volume of the target cup occupied by chunks of LiD or ND_3. The typical value is 60%. This determines how much He is in the cup, filling the space around the chunks. We will measure this in three ways. First, we will use the traditional method of comparing count rates for the polarizable target with those in a cup with a known slab of carbon, and another with a slab of Li of known thickness. We will make these measurements both with and without helium in the target, using rates in both BETA and the HMS spectrometer. As a further check, we will make measurements of the LiD or ND_3 itself without helium, for a short period of time to avoid melting. A third check will be to measure the absolute cross section for quasi-elastic scattering with the HMS spectrometer at 11° (see above). The peak from the deuteron is much narrower than for the other target species, and can be used to measure the free deuteron fraction with an accuracy of about 4%, which leads to a dilution factor uncertainty of 1.5% since we already know that there is one ^{6}Li nucleus for every free deuteron, or 3 free deuterons for every nitrogen nucleus, and the only unknown is the exact amount of helium and target window material (we expect about 20%, by mass). Combining all this information, we are confident that we can determine the dilution factor to approximately 2% in this experiment.

A further improvement might be attained by using solid, thin disks of polarizable material instead of the randomly sized granules used to date. This will probably be easier to do for LiD than for ammonia. This would allow us to determine exactly the amount of ^{6}LiD in the beam's path, reducing the dilution factor determination to little more than an accurate thickness measurement. The technical implications of this approach as as yet unclear, however.

4. ^{7}Li, N, and ^{1}H Corrections

Based on E155 [16], we expect molar fractions of about 0.046 for ^{7}Li and 0.024 for ^{1}H in the LiD target sample, instead of the desired ^{6}Li and ^{2}D. Both of these contaminants are polarizable, with the ratio of ^{7}Li/^{6}Li polarization being about 3, and the ratio of ^{1}H/^{6}Li polarization being about 0.25. The overall relative correction to g_1^d/F_1^d is of order $(10 \pm 2)\%$, where the uncertainty is based on the accuracy of the relative polarization measurements and the nuclear corrections in ^{7}Li. The corrections for polarized nitrogen in ND_3 are relatively small and introduce a small and manageable systematic error. We have not decided yet whether to use ^{15}N or ^{14}N (there are pros and cons to each).

5. Dead time, pile-up, kinematic definition

The electron energy and scattering angle are primarily determined from the cluster energy and position in BigCal, with nominal uncertainties of $5\%/\sqrt{E'}$ and 1 mr, respectively. These resolutions give more than adequate definition of (x, Q^2) for the kinematic range of this experiment ($dQ^2/Q^2 < 0.05$, and $dx < 0.03$). However, systematic offsets caused by improper gain calibration, or extra or missing energy in clusters, can give systematic biases and non-Gaussian resolution effects. These issues have been studied extensively by the SANE collaboration for similar kinematics and rates as the present proposal, and are expected to cause less than 1% ptp and 1% overall systematic shifts in g_1^d/F_1^d. We note that backgrounds with the target field in the longitudinal configuration (this proposal) are expected to be much lower than for the transverse configuration (bulk of SANE running), in which the beam is dumped in the Hall. We will, however, periodically measure the BigCal energy spectrum at a variety of beam currents (using the HMS spectrometer for relative luminosity) to directly measure pile-up and dead time effects.

6. *Nuclear modeling*

About half of the world data set has been taken with an ND_3 (i.e. E143, JLab) or pure deuterium target (i.e. HERMES, Bates), and the other half (E155, COMPASS) with LiD. In particular, all of the highest Q^2 data have been taken (and will continue to be taken) with LiD. To first order, ^{6}Li can be treated as an unpolarized alpha plus a polarized deuteron (with 87% of the free deuteron polarization). Corrections to the spin-averaged total cross section (EMC effect) are under good control, but corrections to the effective polarization depend on a detailed understanding of the ^{6}Li wave function.

Furthermore, at the quark level, the polarized EMC effect for light nuclei has been recently predicted in a specific model [26] to differ as much as 10% from the spin-averaged ratio of structure functions. As experimentalists we think the best way to test the nuclear modeling, and hence open the opportunity to reliably combine data from all targets in global pQCD fitting, is to directly compare g_1^d/F_1^d extracted from the two target materials. The high luminosity available in Hall C makes this the ideal place to do the comparison. Therefore, we will run roughly equal times on each of LiD and ND_3 with the 6 GeV beam energy.

Using only the data with $W > 2$ GeV, we have plotted the projected statistical error in the ratio of extracted g_1^d values between the two nuclei in Fig. 7. The projected results are arbitrarily plotted at unity. The systematic error in the ratios will be dominated by the the errors in the average target polarization and the dilution factor, which we estimate to be between 3% and 5%, depending on how much of the NMR normaliztion errors are found to be in common. The point-to-point systematic errors in the ratio are relatively small, because the x-dependent corrections (such as pair-symmetric and pion backgrounds, radiative corrections, pile-up, dead time, and kinematic resolution effects) are in common for the two targets.

Also shown in Fig. 7, as the solid line, is the ratio calculated from R_{EMC} of Cloet et al. [26] (where R_{EMC} is the ratio of polarized to unpolarized EMC effects), naively assuming $R_{EMC}^{^6\mathrm{Li}} = R_{EMC}^{^7\mathrm{Li}}$ (calculations for ^6Li are planned but not yet available). It can be seen that the data from this proposal will be able to distinguish $R_{EMC} = 1$ from R_{EMC} of Ref. [26] (through their difference in x-dependence) with a significance of few standard deviations. Even more importantly, the data will rule out any unexpectedly large nuclear effects – or find them if they exist.

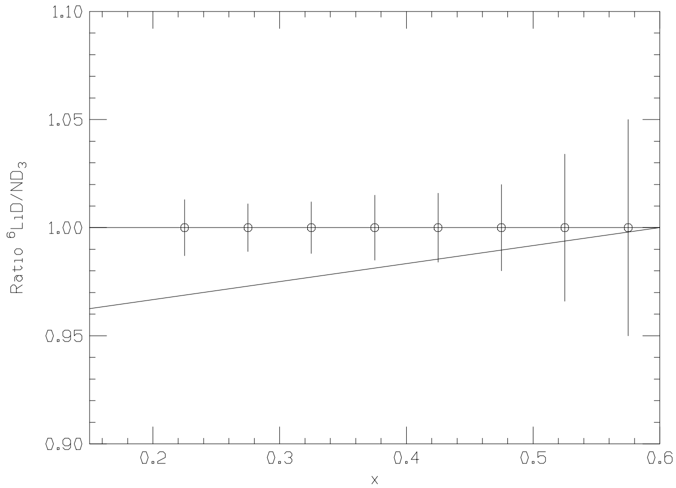

FIG. 7: Projected statistical error in the ratio of extracted g_1^d values between ND_3 and LiD, plotted arbitrarily at unity. Also shown (solid line) is a calculation based on [26] – see text for details.

The proposed comparison will provide an order-of-magnitude improvement over a comparison of ND_3 from SLAC E143 with LiD from SLAC E155. due to our much higher statistical precision.

7. *Charged pion background*

While there are approximately 50 times more pions than electrons with $P > 1.2$ GeV in the angular acceptance of BETA, only 0.2% to 0.5% of them will create a signal above threshold in the Čerenkov counter (from knock-ons and/or scintillation), depending on how well the detector performs. Further, most pions will deposit only a small fraction of their energy in the calorimeter, typically a few hundreds of MeV. We very conservatively estimate a pion rejection capability of 1:1000 to obtain the pion contamination listed in Table III for representative kinematic bins. The sum of negative and positive pions yields was calculated using a fit to the data of Wiser [27], which included beam energies of 5 and 7 GeV, and pion angles from 12° to 40°, thus directly spanning the coverage of the present experiment. The fit has been checked to be accurate to 20% at our kinematics. The pion rates will be measured accurately using the HMS spectrometer, with it's excellent particle ID and kinematic reconstruction capabilities, as well as counting prescaled triggers in BETA in which there is no Čerenkov signal and the BigCal energy deposition is that characteristic of pions. We will use the later events to measure the charged pion asymmetry with high statistical precision. We expect the systematic error from the pion correction to be at most 2%, in the lowest x bin, decreasing rapidly at higher x.

$<x>$	$< Q^2 >$	Pair symm.	π/e	f_{RC}	A_{RC}
0.175	1.4	15%	10%	0.90	-0.024
0.25	1.9	10%	8%	0.95	-0.019
0.35	2.5	6%	4%	0.97	-0.016
0.45	3.0	2%	1%	0.98	-0.012
0.55	3.7	1%	< 1%	0.99	-0.007

TABLE III: Fraction of triggers originating from pair-symmetric e^+e^- events (assuming no charge discrimination) and from mis-identified charged pions (also assuming no charge discrimination) in representative kinematic bins, including the extremes. The last two columns are the radiative dilution factor and the radiative offset correction to g_1^d/F_1^d.

8. Radiative Corrections

We have chosen kinematics where the radiative corrections are relatively small: values of the shift A_{RC} and the radiative dilution factor f_{RC} (from elastic and quasi-elastic tails) are listed in Table III, evaluated using the code RCSLACPOL [2, 28].

The systematic error from polarized radiative corrections to g_1^d/F_1^d has two principal components: modeling uncertainty, and uncertainty from higher-order (in $Z\alpha$) terms not included in the calculation. For deuterium, we estimate the second term to be less than 1.5%, and it is also likely the corrections have little Q^2-dependence, hence little effect on the extraction of higher twist terms and $\Delta G(x)$, as long as the same formalism is used to correct all the experiments being considered in a global fit. The modeling uncertainty is greatly reduced compared to only a few years ago, thanks to the wealth of high-precision data from JLab, Bates, and NIKHEF at lower Q^2 than the present experiment. We note that events radiating into a given (x, Q^2) bin essentially always come from lower Q^2, and usually from lower invariant mass W. We will perform a global fit to g_1^d/F_1^d including the first-pass results from the present experiment, and expect that the Q^2-dependence of g_1^d/F_1^d will be determined to better than 5% over most of the kinematic range of interest. Note that the absolute magnitude of g_1^d/F_1^d cancels in the radiative corrections: it is the (x, Q^2) dependence that matters. We estimate that in our kinematic region, the model dependence will introduce a relative p-t-p systematic error of about 1%, and an overall error of about 1.5%.

9. Knowledge of R and F_1

We have not included uncertainties in R and F_1 in our experimental systematic error table, because their uncertainties are time-dependent, and indeed are being reduced from year to year. Global analysis groups such as LSS [9] take this into account by fitting experimental data on g_1/F_1 with a consistent model for F_1 to extract g_1 from g_1/F_1, and a consistent model of R to correct the depolarization factor d (which has the term $1 + \epsilon R$).

In the near future, uncertainties in modeling R and F_1, and especially their dependence on Q^2 down to the low values of this proposal, will be dramatically improved thanks to the JLab experiment E06-009 (M. Christy and C. Keppel, spokespersons). This experiment is specifically designed to measure R and F_1 for the deuteron in the kinematic region of the present proposal, with the impact on g_1^d specifically mentioned as one of the motivations. The errors on R will be small enough to reduce the error on d to less than 2%, while the errors on F_1 (as reflected in a smooth parametrization of world data), will be on the order of 3%.

We note that if $R(x, Q^2)$ for nitrogen is different than that of deuterium, there could be a small but not negligible impact on the determination of the dilution factor in the ND_3 target. Fortunately, this issue will be addressed by the JLab experiment E04-001 (A. Bodek and C. Keppel, spokespersons), the main goal of which is the measurement of the nuclear dependence of $R(x, Q^2)$ and F_1. These measurements will reduce the error in the dilution factor f from uncertainty in R to less than 1%.

10. Correction from g_2

The relative contribution of g_2 to g_1^d/F_1^d is controlled by the scale factor $2Mx/(2E - \nu)$, which varies from 0.03 to about 0.15 over the x-range of this proposal. This factor scales the uncertainty in g_2 relative to the actual values of g_1. In the E155x [19] experiment, the uncertainty in xg_2^d in our kinematic range was approximately constant at 0.015, while xg_1^d increased from 0.1 to 0.2 for x from 0.15 to 0.6. Thus, based on the E155x measurements, the relative systematic uncertainty in g_1 due to the g_2 correction will vary from 1.5% at low x to 4% at high x. However, within the next two years, measurements of both g_2^p (SANE) and g_2^n (Hall A) will be conducted in the same kinematic region as our data. Taken together, these results can provide a significant constraint on the value of g_2^d, as is evident in Fig. 8. We therefore expect the systematic error due to g_2 to be $< 2\%$ in the highest x bin, with even smaller errors at lower x.

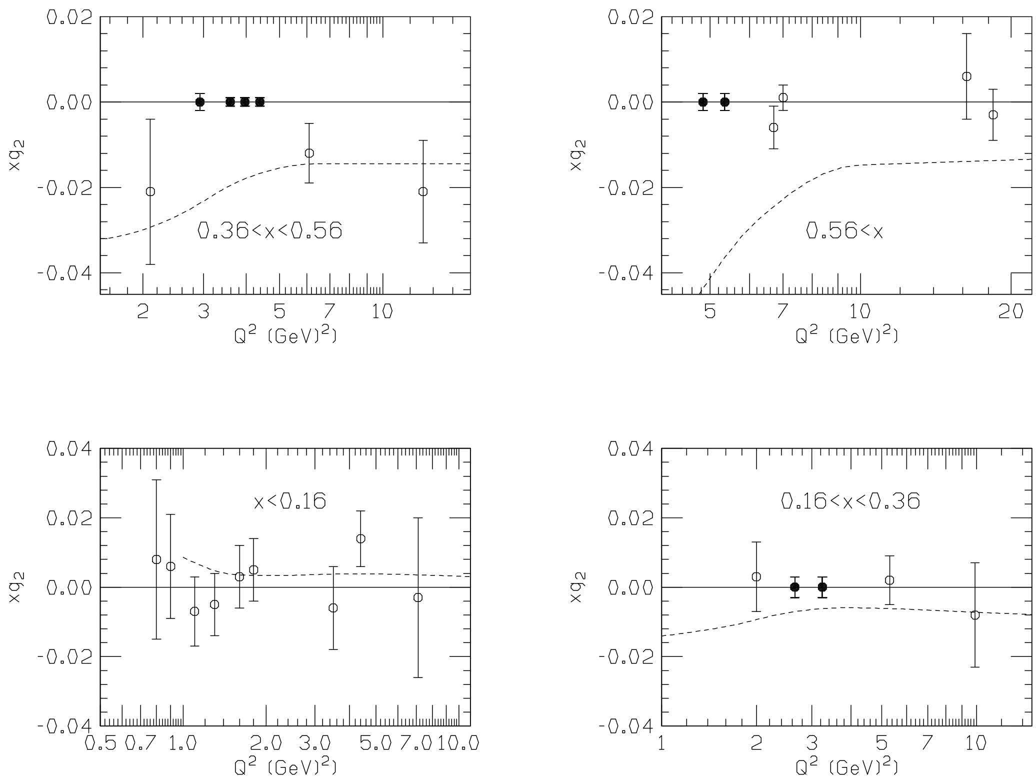

FIG. 8: g_2^d data at our kinematics. Shown are the E155x data [19] (hollow) and what we expect to obtain from combining the SANE measurements of g_2^p and the Hall A measurements of g_2^n (filled).

IV. PHYSICAL SIGNIFICANCE

From Fig. 4, it is clear that the small statistical and systematic errors of this proposal will greatly improve the world data base for g_1^d/F_1^d at the low Q^2 end of the traditional DIS kinematic region. The precise impact on extraction of polarized PDFs will of course depend on the number of assumptions made in global fitting, and future improvements in precision at higher values of Q^2 not presently accessible at JLab. It is absolutely clear, however, that the data from this proposal will greatly improve the constraints on possible higher dynamic twist contributions, which in turn allows an extended range of Q^2 to be used for the determination of $\Delta G(x)$ through logarithmic pQCD evolution.

The ideal approach, followed by the LSS group [9] is to include higher twist contributions directly in a global pQCD fit. In their notation, g_1 has contributions described as

$$g_1^{HT}(x,Q^2) = g_1^{TM}(x,Q^2) + \frac{h(x)}{Q^2}. \tag{5}$$

The $g_1^{TM}(x,Q^2)$ kinematic target mass corrections are calculable in QCD [29] (through relations than can be solved by iteration on models of g_1), with resulting uncertainties that are reasonably small and tractable for $4M^2x^2/Q^2 \ll 1$, which is the case for the present proposal. High-x resummation corrections [30] are also relatively small for our kinematics, but should not be ignored. What remains are dynamic higher twist contributions (related to quark-quark and quark-gluon correlations in the nucleon), described in lowest order by the function $h(x)$. Moments of higher twist can in principle be evaluated in models with some reliability, and experimental evaluations have found their net effect to be relatively small [10], partially due to cancellations between different orders of twist. However, there are no models that reliably predict the x-dependence of dynamic higher twist effects, so they must be determined from data. The LSS group [9] has found significantly non-zero values of $h(x)$ for both the proton and neutron. We display their results for the deuteron in Fig. 9 by averaging the values for the proton and neutron, under the assumption of negligible nuclear corrections to the neutron results (which come primarily from data using ^{3}He).

Also shown in Fig. 9 are the projected errors on $h(x)$ from the present proposal. Since most systematic errors are overall scale factors, the results are primarily determined by the statistical accuracy and the available range of Q^2. It can be seen that the error on $h(x)$ is reduced from the proton plus neutron analysis by up to a factor of five at the lowest values of x, where the gluon and sea quark distributions are dominant. Clearly, our improved determination of $h(x)$ will improve the accuracy with which these polarized distributions can be determined through simultaneous pQCD plus HT fits. Quantitative evaluations are presently under way by the LSS and AAC groups.

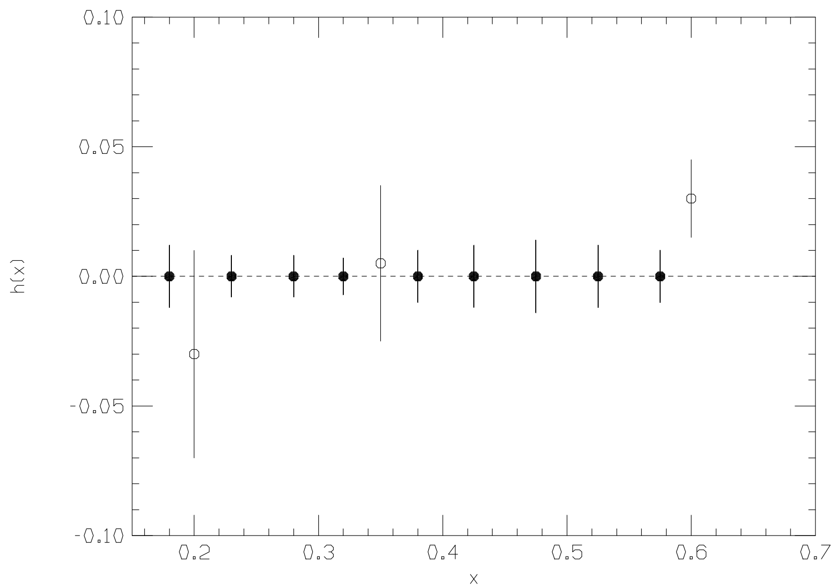

FIG. 9: Projected deuteron higher twist coefficients $h(x)$ from the present proposal (solid circles). Also shown are approximate values from the average of proton and neutron results from the analysis of LSS [9].

V. RELATION WITH OTHER EXPERIMENTS

There are no planned experiments to improve our knowledge of g_1^d/F_1^d in DIS kinematics in the JLab 6 GeV era. The final results from the Hall B Eg1b [12] experiment will have somewhat smaller errors than those shown in Fig. 3, due to the inclusion of 4.2 GeV beam energy results, although the highest Q^2 points will change less than 20%, as they are dominated by the inbending 5.7 GeV data, which has been pretty much fully analyzed. While it would be possible to obtain pseudo-deuteron results by combining the planned high-statistical accuracy g_1^p/F_1^p results that will be obtained parasitically from the approved Hall B experiment (E05-113), and by the longitudinal polarization portion of the SANE experiment in Hall C (E03-109), with the g_1^n/F_1^n results from the extensive program in Hall A using the^{3}He target, the resulting systematic errors would be larger than those of this proposal.

An experiment has been approved to make improved measurements of g_1^d/F_1^d in DIS kinematics in the 12 GeV era at JLab in Hall B (E12-06-109). The 11 GeV beam energy will allow measurements to lower x and higher Q^2, and the planned upgrades to the target and CLAS will allow good statistical precision. The results of the present proposal will still be of value, in the kinematic range of overlap, because both experiments will be systematic error limited, and the systematic errors will mostly be orthogonal between the two experiments.

VI. CHOICE OF HALL

The main reasons for choosing Hall C are: much of the data can be taken simultaneously with the already approved Semi-SANE experiment; higher figure-of-merit, so less running time needed; and potentially better target polarization measurements. To obtain the same statistical accuracy in Hall B for the high Q^2 points with a given target polarization requires twenty times longer running time (20 times lower beam current due to limitations on drift chamber occupancy, 3 times thinner target, 3 times larger solid angle for $\theta > 22°$, so a net factor of 20). Taking into account somewhat higher target polarization on average at lower beam current, and less overhead time for annealing, in practice about 10 times longer running time would be needed. Advantages in Hall B could be smaller errors on pair symmetric and pion backgrounds (sign measured reliably, E/P for extra pion rejection), smaller dead time and pile up effects, better kinematic definition (with tracking). These small advantages are not nearly big enough to offset the much longer running time needed.

VII. MANPOWER AND COLLABORATION

Since the collaboration includes most of the SANE and Semi-SANE collaborators, and the experiment would run in parallel with Semi-SANE, we do not anticipate any problems in preparing the detectors and acquiring the data. A small sub-group of the collaboration will focus on setting up the single arm trigger, planning the special runs needed to minimize systematic errors, and analyzing the data. Two of the spokespersons of this experiment have extensive previous experience in analyzing g_1^d/F_1^d from both SLAC and JLab experiments. We have been assured the full support of the UVa target group.

VIII. REQUEST

We request 5 days of 4.8 GeV beam, split between two HMS settings, and 8 (6) days for NH_3 (LiD) with 6 GeV beam, as summarized in Table IV. All data will be acquired with longitudinal polarization and BETA centered at 30°.

Well over half of this time, 12 days at 6 GeV, can be run concurrently with approved Semi-SANE experiment. The spokespersons of Semi-SANE have agreed to run about equal times with each of the two targets (rather than all LiD), if an extra two days is allocated for the presumed lower figure of merit with ND_3.

Approximately 3 days of overhead are needed for the 6 GeV beam energy running, essentially all of which would be in common with the Semi-SANE experiment. Thus, our total request is for 7 days of new PAC days for production running, and one 1 day of incremental overhead time, assuming interleaved/concurrent running with Semi-SANE.

E (GeV)	target	θ_{BETA}	θ_{HMS}	P_{HMS}	days
6.	ND_3	30.	10.8	±2.71	8
6.	^{6}LiD	30.	10.8	±2.71	6
4.8	ND_3	30.	12.	-4.3	2
4.8	ND_3	30.	16.	-2.8	3

TABLE IV: Summary of run plan. The first two points are in common with Semi-SANE, which uses HMS for approximately equal times in positive and negative polarity.

IX. SUMMARY

We propose to make definitive measurements of the deuteron spin structure function g_1^d/F_1^d in the deep-inelastic kinematics accessible with a 6 GeV beam at JLab. The principal goal is to provide the low Q^2 anchor points for NLO pQCD plus higher twist fits to g_1^d/F_1^d, which is particularly sensitive to $\Delta G(x)$ (the polarized gluon density of the nucleon) and the sum of up and down quark polarizations. By spanning a factor of typically two in the Q^2-range at nine values of x, the new data will strongly constrain the higher twist contribution to the fits, with a corresponding reduction in the polarized PDF uncertainties. The proposed measurements, when combined with existing and planned world data at higher Q^2, will provide the theoretically cleanest determination of $\Delta G(x)$ in the moderate to high x region, and will provide a necessary complement to the low x program of RHIC-spin.

The experiment will use both ^{6}LiD and ND_3 in the standard Hall C/UVa polarized target assembly as a source of polarized deuterons, with approximately equal running times for both to constrain the nuclear effects in ^{6}LiD, the target used by the higher Q^2 experiments at SLAC and CERN. Both the target and low current (100 nA) 6 GeV electron beam will be longitudinally polarized. Electrons scattered at angles from 22° to 38° will be detected in the detector assembly (BETA) planned for the upcoming SANE, Semi-SANE, and polarized Real Compton experiments. Additional measurements at lower Q^2 will be made using a 4.8 GeV beam energy with both BETA and and the HMS spectrometer.

We request a total of 19 days of production running (14 days at 6 GeV, 5 days at 4.8 GeV). Additionally, we request 5 overhead days for calibrations, target anneals and material changes, and one energy pass change. We also request an upgrade to the Hall C DAQ system to handle trigger rates up to 5 kHz. Most of the experiment (12 days of production running, 4 days overhead) can be run concurrently with the approved Semi-SANE experiment. Therefore, the request for new beam time is 8 days.

X. APPENDIX A: SEMI-SANE (E04-113) ABSTRACT

We propose to measure the spin asymmetries in semi-inclusive deep-inelastic $\vec{p}(e,e'h)X$ and $\vec{d}(e,e'h)X$ reactions ($h=\pi^+,\pi^-,K^+$ and K^-) on longitudinally polarized NH_3 and LiD targets. The large acceptance *BETA* detector, in the same configuration as in the approved "SANE" experiment, will be used to detect the scattered electrons. The HMS spectrometer will be used to detect the leading hadrons in coincidence ($z=0.5\sim0.7$). The high statistic data will allow a spin-flavor decomposition in the region of $x=0.12\sim0.41$ at $Q^2=1.21\sim3.14$ GeV^2. Four leading order methods and two next-to-leading order methods of flavor decomposition will be applied independently to provide consistency cross-checks. Especially, a next-to-leading order spin-flavor decomposition of Δu_v, Δd_v and $\Delta\bar{u}-\Delta\bar{d}$ will be extracted based on the measurement of the combined asymmetries $A_{1N}^{\pi^+-\pi^-}$. The possible flavor asymmetry of the polarized sea will be addressed in this experiment. The precision data from this experiment will significantly improve our knowledge of the flavor structure of the nucleon spin for both valence and sea quarks. The much improved knowledge on the moments of the polarized quark distributions will provide benchmark tests for theoretical models and lattice QCD calculations. In addition to the double-spin asymmetry A_{1N}^h, the target single-spin asymmetry A_{UL}^h will also be measured as by-products. Especially, the term $A_{UL}^{sin2\phi_h}$, which at the leading order is produced only through a non-vanishing T-odd Collins fragmentation function. Within the same data set, the deviation from the naive factorization assumption, which translates into the systematic uncertainties of the leading order flavor decomposition, will be clearly demonstrated by comparing the combined asymmetry $A_{1N}^{\pi^++\pi^-}$ with the inclusive asymmetry A_{1N}. A total of 25 days of new beam time at 6 GeV in Hall C is requested. In addition, permission is requested for parasitic data taking during the 6 GeV longitudinal target runs of the "SANE" experiment (2 days) to test spin-duality in $\vec{p}(\vec{e},e'\pi^+)X$ reaction through the resonance region.

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