(Update to E12-06-121)

A Path to "Color Polarizabilities" in the Neutron: A Precision Measurement of the Neutron g_2 and d_2 at High Q^2 in Hall C

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1 Preface

This document is an addendum to the material in the full E12-06-121 proposal titled: *A Path to "Color Polarizabilities" in the Neutron: A Precision Measurement of the Neutron g_2 and d_2 at High Q^2 in Hall C*, approved in PAC30. We shall briefly reintroduce the physics at hand, summarize recent experimental activity since the proposal was written, and update our beamtime request to accommodate proposed upgrades and modifications to the polarized ^{3}He target and SHMS designs.

We feel that this experiment would be an excellent candidate for early running in Hall C. The demands on the new SHMS system are modest, and the collaboration has strong Hall C support with many detector system experts. The polarized ^{3}He target is, of course, not "baseline" equipment, but it is widely acknowledged that such a system will be required to fully realize the potential of the 12 GeV program in both Hall C and Hall A. As discussed in Section 5, we feel this measurement could serve as an ideal proving ground at moderate luminosities, and with high-impact physics, for the high-luminosity target design proposed for GEN-II in Hall A (approved, PAC34), and A_1^n in Hall C (conditionally approved in PAC30, resubmitted to PAC36).

2 Introduction

We propose a precision measurement of the neutron spin structure function $g_2(x,Q^2)$ over the kinematic region $0.2 < x < 0.95$ and $2.5 < Q^2 < 7\,\mathrm{GeV}^2/c^2$. In addition to mapping out the x and Q^2 evolution of g_2^n which (in contrast to g_1) is poorly understood at high x, we will extract the higher twist piece of the spin structure function $\bar{g}_2$ and evaluate the quantity $d_2^n = \int_0^1 \bar{g}_2\, dx = \int_0^1 x^2(2g_1 + 3g_2)\, dx$ at *constant* Q^2 for the very first time for $Q^2 > 1\,\mathrm{GeV}^2/c^2$. All previous measurements of d_2^n at higher Q^2 have required data taken over a broad range of Q^2 values to be evolved to some common Q^2 prior to evaluating the d_2 integral. At higher x, this evolution has required the transform from Q^2's of as much as $15\,\mathrm{GeV}^2/c^2$ down to a nominal $5\,\mathrm{GeV}^2/c^2$.

d_2 is related to the twist three matrix element in the Operator Product Expansion (OPE) framework and is connected to the quark-gluon correlations within the nucleon. Earlier work by Ji *et al.* related this quantity to a measure of how the *color* electric and magnetic fields responded to the polarization of the nucleon (alignment of its spin along one direction)—what he called the "color polarizabilities" [1, 2]. More recent analysis by Burkardt suggests that categorization may be too broad (*i.e.* by similar analogy, too many other observables would also become "polarizabilities"). He identifies d_2 as a measure of the *color Lorentz force* acting on the struck quark the instant after it was hit by the virtual photon [3]. That interpretation also connects the average transverse momentum of an ejected quark $\langle k_\perp \rangle$ in SIDIS with the transverse impulse generated by the same color Lorentz force acting on the struck quark, chromodynamic lensing, and the average transverse momentum arising from the Sivers effect[4, 5]. This quantity has also seen thorough study in Lattice QCD and is one of the cleanest observables with which to test the theory.

We plan to extract the spin structure functions g_1^n and g_2^n by measuring parallel and perpendicular asymmetries using the SHMS and upgraded HMS in Hall C. We will use the longitudinally polarized ($P_b = 0.80$) CEBAF electron beam at 11 GeV and the proposed 60 cm-long high pressure polarized ^{3}He target. Both the SHMS and the HMS will be operated in "single-arm" mode (*vs.* coincidence mode) to measure two different kinematic bites for each of four 125 hour floor configurations. The target polarization orientation will be set transverse or longitudinal to the beam with a value of $P_t = 0.55$ while the beam helicity will be reversed at a rate of 30 Hz. A beam current of $30\,\mu$A combined with a 60 cm long target of density 10 amg[*] provides a luminosity of roughly 10^{36} cm^{-2}s^{-1}. With the inclusion of

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[*] Amagat Number (amg) is the ratio of density in the target (ρ) over the gas density at STP (ρ_0).

an additional 200 hours for overhead and calibration, the total beam request is 700 hours, or roughly 29 days of beam. This total time is unchanged from the original beam request.

The upgraded SHMS/HMS combination in Hall C at Jefferson Lab provides an ideal facility for this measurement. The large momentum acceptance of the SHMS allows a very broad x region to be measured over nearly constant Q^2 in a single kinematic setting. The HMS can then be used to simultaneously fill in gaps in the low-x region, resulting in nearly contiguous x coverage over a broad Q^2 band—something that has never before been accomplished. The combined data will allow the extraction of $d_2^n(Q^2)$ at truly constant Q^2's of 3, 4, 5 and 6 GeV^2/c^2. The precision with which these values may be measured, combined with explicit information on the Q^2 evolution of d_2 provide a strict test of Lattice QCD.

3 Update on World Data and Related Experiments

The last few years have seen a number of interesting data presented for $Q^2 < 3\,\mathrm{GeV}^2/c^2$ [6, 7, 8]. These data continue to support the trend that d_n^2 is running to a value near zero, in marked contrast to the existing world average for d_n^2 quoted at $5\,\mathrm{GeV}^2/c^2$ (Fig. 3). It should be noted that the data for all of these recent results were taken in the resonance region (most, explicitly so), and seem to support the quark-hadron duality hypothesis [9]

In the first quarter of 2009, E06-014 "d_n^2 at 6 GeV" was successfully completed in Hall A[10]. That measurement utilized the BigBite spectrometer in conjunction with the LHRS and a polarized ^{3}He target to make an explicit measurement of d_n^2 at an average Q^2 of $3\,\mathrm{GeV}^2/c^2$. The 2009 Hall A approach used BigBite to measure parallel and transverse asymmetry data ($A_{\parallel}$ and $A\perp$), which will be combined with simultaneous cross section data collected in LHRS to directly extract d_n^2. Systematic effects associated with evolving the BigBite data, which have a modest kinematic coupling between x and a Q^2 range of 2–6 GeV^2/c^2, to the nominal $3\,\mathrm{GeV}^2/c^2$ at which the d_n^2 integral is computed were hedged against by measuring the integrand at two different Q^2 points for each x value. These data are still in the early stages of analysis.

4 Updated SHMS Parameters

The SHMS design has been tweaked slightly since the original proposal was approved at PAC30. Table 1 lists the 2006 and current design parameters:

Table 1: SHMS Design Parameters

	p_0 [GeV/c]	θ_{Lab}	$\Delta p/p$	Vertex Length [cm] @ 90°
2006 Baseline Design	2–11	5.5°–30°	$(-15\%, +25\%)$	30
2009 (Current) Design	2–11	5.5°–40°	$(-10\%, +22\%)$	30

5 Updated Polarized ^{3}He Target

The kinematic coverage and beam time requirements have been positively impacted by rather dramatic improvements realized by the polarized ^{3}He target group in the last few years. That group has also begun active development on the "next generation" polarized ^{3}He target that promises an eventual factor of 10 improvement in the polarized figure of merit.

In our original proposal, we assumed 10 μA on a 40 cm long target cell with an average ^{3}He polarization of 50%, and a density of 10 amg.† During the 2009 E06-014 run, the present design was able to provide an average ^{3}He polarization of 55% at 15 μA using the conventional 40 cm long glass target cells. The upgraded design is detailed in the approved GEN-II proposal [11], but the critical aspects include the following improvements.

- The addition of an alkali-hybrid gas mixture which significantly improves the polarization rate of the ^{3}He nuclei via a two step transfer process. This is a proven technique demonstrated during the 2008–9 polarized ^{3}He experiments in Hall A.
- The recent commercial availability of high-power, narrow line-width diode laser arrays. The efficacy of these new laser systems over the older hardware was also proven during the 2008–9 Hall A experiments.
- The development and demonstration of enhanced convective mixing using a new "dual transfer tube" target cell design. A prototype of this system has been successfully tested in the University of Virginia target lab. This allows the gas in the target chamber to be actively driven back into the upper chamber to be repolarized, significantly improving the system's ability to compensate for beam depolarization at higher currents.
- Improved polarimetry diagnostics developed (primarily) in the UVa target lab. This allows direct measurements of the ^{3}He *and* alkali-metal vapor polarization, as well as a direct measure of the alkali-vapor number densities.

In the updated beam request section (Sect. 6), we will assume the target design follows the physical specifications laid out in [11] for the "high-luminosity GEN-II" target cell. This includes a 60 cm long target chamber with the dual-transfer tube design to allow active convective circulation of the polarized gas. The proposed target cell itself will be metal (gold-plated Al, or similar) instead of glass to improve its ability to withstand increased current and radiation doses. The upper pumping chamber will remain glass, as in the present design. This design will also be shared with the update to the conditionally approved Hall C A_1^n proposal (PR12-06-110) also submitted to PAC36. The goal for the *GEN-II* target cell is to achieve 60% polarization with a beam current of 60 μA.

Note that our measurement does *not* require the aggressive projected luminosities needed by *GEN-II*, nor by the 12 GeV A_1^n proposal. We therefore propose our experiment be positioned as a "middle ground" in which the new techniques needed to achieve the ultimate luminosity goals may be refined. To this end, we elect to share mechanical design of the high-luminosity target, but will assume a more conservative beam current of only 30 μA, and 55% ^{3}He polarization, values that should be a fairly easy reach from presently demonstrated technology. As has been demonstrated time and again, new technologies inevitably experience teething pains, and rarely reach their ultimate goal in the first attempt.

We will also assume a 10 amg target density. Filling the cells is an inherently imprecise procedure, and has significant "slop." The 10 amg number seems a reasonable middle ground between the 12 amg design value and the somewhat lower number density ultimately realized for the 2008–9 cells used in Transversity and d_n^2 at 6 GeV.

With those assumptions, the proposed target should achieve a improvement in the polarized figure of merit over our original proposal of roughly 5.4× for the SHMS and 3.6× for the HMS (which can not

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† The proposal mentions 12 amg in two places—those are typos, the luminosities and rates were computed based on the 10 amg assumption.

Table 2: Parameters used for the SHMS and HMS rate estimates

	SHMS				HMS			
kinematic setting	I	II	III	IV	I	II	III	IV
beam energy	11 GeV							
beam current	30 μA							
beam polarization	0.8							
scattering angle	11.0°	13.3°	15.5°	18.0°	13.5°	16.4°	20.0°	25.0°
momentum range	-10% → +22%				-10% → +10%			
z-acceptance (at 90°)	30 cm				10 cm			
solid angle	5 msr				6 msr			
efficiency	0.80							
target length	60 cm							
target polarization	0.55							
eff. target density	10 amg							

take advantage of the increased target cell length). We elected to maintain our original 700 hour (29 day) beam time request, but take advantage of the increased luminosity by extending our kinematic coverage by 25%, and allocating additional time to improve our coverage of the high-Q^2, lower-x region. If the target, accelerator, and SHMS runs perfectly, then we would achieve a rough 2× improvement in the original statistical error estimates for each spectrometer setting. Should that be accomplished, we would exploit the improved statistics by increasing the number of bins per SHMS (HMS) and improving the sample resolution for g_2 *v.s.* x in each Q^2 band.

6 Updated Kinematics & Beam Request

As in the original proposal, we request 700 hours (29 days) of beam to measure the spin-polarized parallel $\sigma^3 He_{\parallel}$ and perpendicular $A_{\perp}^{^3He}$ cross sections. We will take advantage of the increased polarized luminosity of the improved ^{3}He target design to reduce the beam time allocated to the original kinematics, and then add new pair of SHMS and HMS settings. The new SHMS setting significantly boosts the coverage in the high-Q^2 region—following the suggestion from PAC30 to merge the coverage from the deferred 12 GeV Hall A g_2^n measurement into the Hall C experiment. As before, the HMS is used to fill in gaps in the $x < 0.5$ domain.

The updated request assigns 125 hours each for four groups of SHMS/HMS kinematics plus an additional 200 hours for calibration and overhead. This includes running the spectrometers with positive polarity to measure π backgrounds that may dilute the asymmetry (as discussed in the original proposal). Detailed settings and rate estimates are presented in Table 3. These calculations were performed using the same tools and techniques described in the original proposal, updated with the new target, beam, and SHMS parameters (see Tables 1 and 2). The estimated systematic uncertainties do not change significantly from those presented in the proposal.

Those data will be used to extract the g_2^n structure function on the neutron over the extensive kinematic region $0.2 < x < 0.95$ and $2.5 < Q^2 < 7\,\mathrm{GeV}^2/c^2$. In addition to mapping out the x and Q^2 evolution of g_2^n which (in contrast to g_1) is poorly understood at high x, we will extract the higher twist piece of the spin structure function $\bar{g}_2$ and evaluate the quantity $d_2^n = \int_0^1 \bar{g}_2 \; dx = \int_0^1 x^2(2g_1 + 3g_2) \; dx$

Table 3: Kinematic bins and expected rates for the SHMS. The uncertainties for $A_{\|}$ and $A_{\perp}$ are *statistical* only. **NOTE:** Estimates for the ‘—-’ entries are forthcoming.

SHMS Setting	E'_{bin} [GeV]	Q^2 [GeV^2]	x	W [GeV]	e^- rate [Hz]	π^- rate [Hz]	$t_{\|}$ [hrs]	$t_{\perp}$ [hrs]	$\Delta A_{\|}$ [$\cdot 10^{-4}$]	$\Delta A_{\perp}$ [$\cdot 10^{-4}$]
$\theta_0 = 11°$	6.772	2.737	0.345	2.468	853.2	19.6	10	115	2.0	0.5
	7.511	3.036	0.463	2.098	645.2	4.0	10	115	2.2	0.6
$E'_{cent} = 7.5$	8.251	3.335	0.646	1.648	259.2	0.84	10	115	3.4	0.1
GeV	8.990	3.634	0.963	1.013	0.68	0.15	10	115	63.2	19.0
$\theta_0 = 13.3°$	6.193	3.654	0.405	2.502	266	8.4	12	113	3.4	0.9
	6.867	4.052	0.522	2.144	171.2	1.52	12	113	4.0	1.2
$E'_{cent} = 7.0$	7.541	4.450	0.685	1.713	59.2	0.25	12	113	7.0	2.1
GeV	8.215	4.847	0.927	1.127	0.48	0.038	12	113	76	23.4
$\theta_0 = 15.5°$	5.749	4.600	0.466	2.480	96	3.32	13	112	5.3	1.6
	6.372	5.098	0.587	2.117	51.2	0.6	13	112	7.0	2.2
$E'_{cent} = 6.3$	6.996	5.597	0.744	1.676	13.2	0.1	13	112	14	4.4
GeV	7.619	6.096	0.960	1.067	0.06	0.015	13	112	202	70
$\theta_0 = 18.0°$	5.04	5.43	0.485	2.576	—	—	—	—	—	—
	5.60	6.03	0.595	2.232	—	—	—	—	—	—
$E'_{cent} = 5.6$	6.16	6.63	0.730	1.825	—	—	—	—	—	—
GeV	6.72	7.24	0.901	1.295	—	—	—	—	—	—

Table 4: Expected rates for the three HMS settings. The uncertainties for $A_{\|}$ and $A_{\perp}$ are *statistical* only. **NOTE:** Estimates for the ‘—-’ entries are forthcoming.

θ_0 [∘]	E'_{cent} [GeV]	Q^2 [GeV^2]	x	W [GeV]	e^- rate [Hz]	π^- rate [Hz]	$t_{\|}$ [hrs]	$t_{\perp}$ [hrs]	$\Delta A_{\|}$ [$\cdot 10^{-4}$]	$\Delta A_{\perp}$ [$\cdot 10^{-4}$]
13.5	4.305	2.617	0.208	3.293	885.2	1128	8	117	2.0	0.5
16.4	5.088	4.555	0.410	2.727	259.6	25.6	12	113	3.3	1.0
20.0	4.000	5.31	0.404	2.951	—	—	—	—	—	—
25.0	2.500	5.15	0.323	3.417	—	—	—	—	—	—

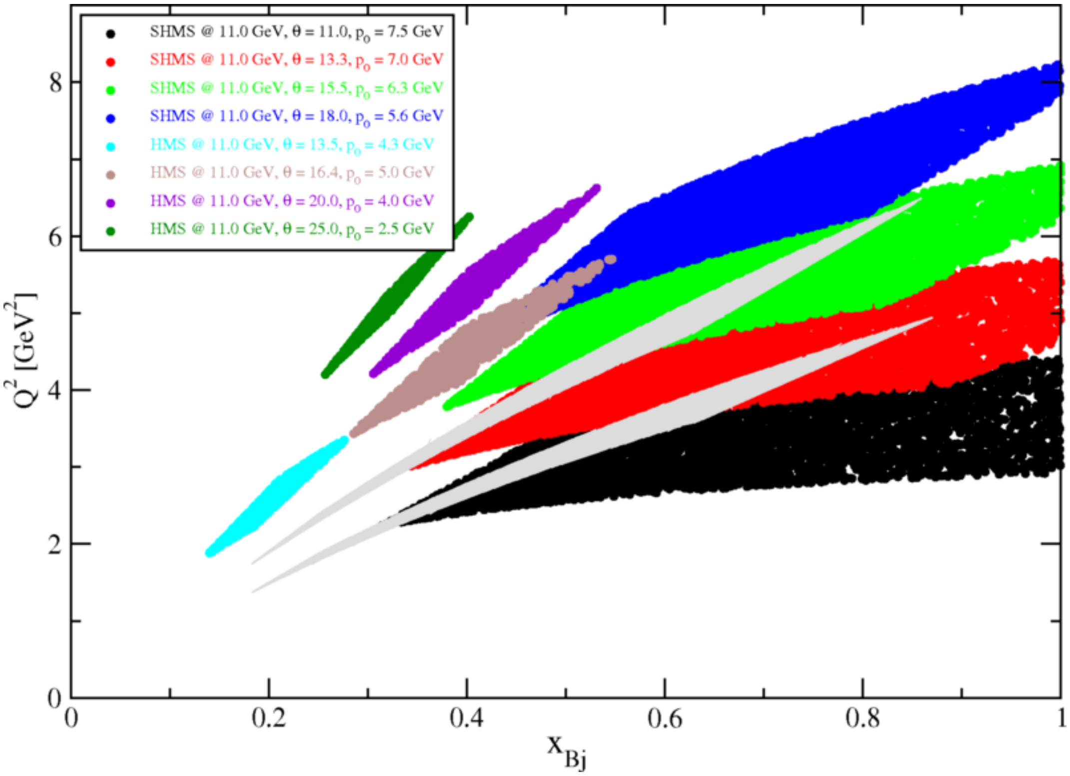

Figure 1: Kinematic coverage for the eight kinematic settings for the proposed experiment. The four SHMS bands will be subdivided into four or more bins (depending on the final statistics) during offline analysis. The lower grey bands reflect the coverage from the 6 GeV measurement E06-014.

at *constant* Q^2 for the very first time for $Q^2 > 1\ \mathrm{GeV}^2/c^2$. All previous measurements of d_2^n at higher Q^2 have required data taken over a broad range of Q^2 values to be evolved to some common Q^2 prior to evaluating the d_2 integral. For the dominant, higher x data, this evolution has required the transform from Q^2's of as much as $15\,\mathrm{GeV}^2/c^2$ down to $5\,\mathrm{GeV}^2/c^2$. Figure 1 shows the (x, Q^2) coverage for the updated beam-time request. Figure 2 presents the estimated statistical errors associated with the extracted $x^2 g_2^n$ values against the present world data.

The upgraded SHMS/HMS combination in Hall C at Jefferson Lab provides an ideal environment for this measurement. The large momentum acceptance of the SHMS allows a very broad x region to be measured over nearly constant Q^2 in a single kinematic setting. The HMS can then be used to simultaneously fill in gaps in the low-x region, resulting in nearly contiguous x coverage over a broad Q^2 band – something that has never before been accomplished. The combined data will allow the extraction of $d_2^n(Q^2)$ at truly constant Q^2's of 3, 4, 5, and $6\,\mathrm{GeV}^2/c^2$. The precision with which these values may be measured, combined with explicit information on the Q^2 evolution of d_2 provide a strict test of Lattice QCD.

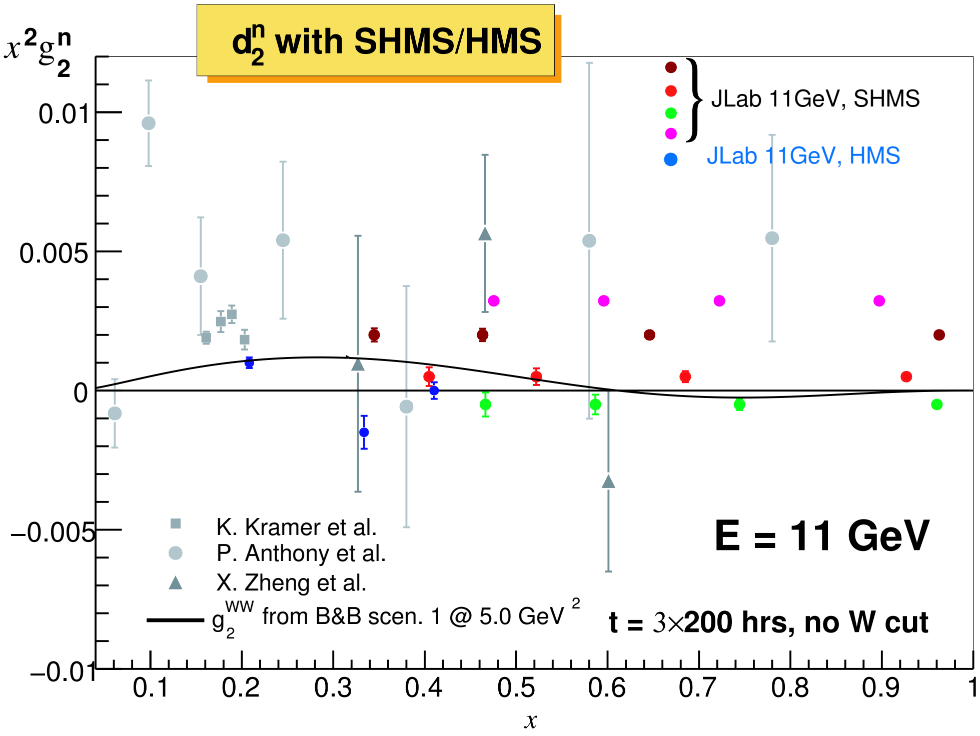

Figure 2: $x^2 g_2^n(x)$ *vs.* x presenting the statistical errors expected from the proposed measurement (colored circles). Existing world data are also shown. **Note:** The points associated with the present measurement are distributed along different horizontal lines, each representing a common $< Q^2 >$ value. This is in marked contrast to the existing world data for g_2^n for $Q^2 > 1\,\mathrm{GeV}^2/c^2$ which were measured over Q^2 values ranging from 1—15 GeV^2/c^2 and were "evolved" to a common Q^2 prior to computing d_2.

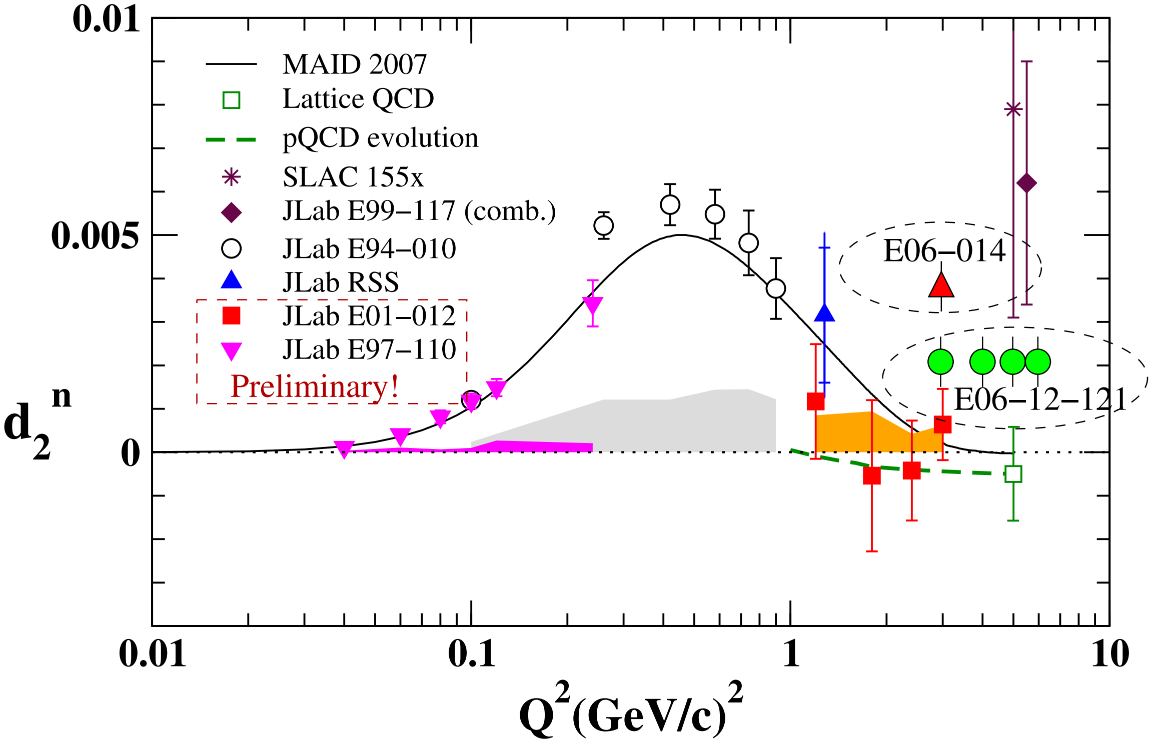

Figure 3: $\bar{d}_2(Q^2)$ without the nucleon elastic contribution are presented with estimated statistical errors for the proposed measurement. The anticipated statistical error from the 6 GeV E06-014 measurement is also shown. The SLAC E155 [12] neutron result is also shown here (open square). The solid line is the MAID calculation[13] while the dashed line is a perturbative QCD evolution. The lattice prediction [14] at $Q^2 = 5$ GeV^2 for the neutron d_2 reduced matrix element is negative but consistent with zero. We note that all models shown in Fig. 4 predict a negative value or zero at large Q^2 where the elastic contribution is negligible. At moderate Q^2 the data show a positive $\bar{d}_2^n$, and indicate a slow decrease with Q^2. Recent resonance results are also plotted. The combined SLAC+JLab datum shows a positive d_2^n value but with still a large error bar. [Figure adapted from a plot by P. Solvignon.]

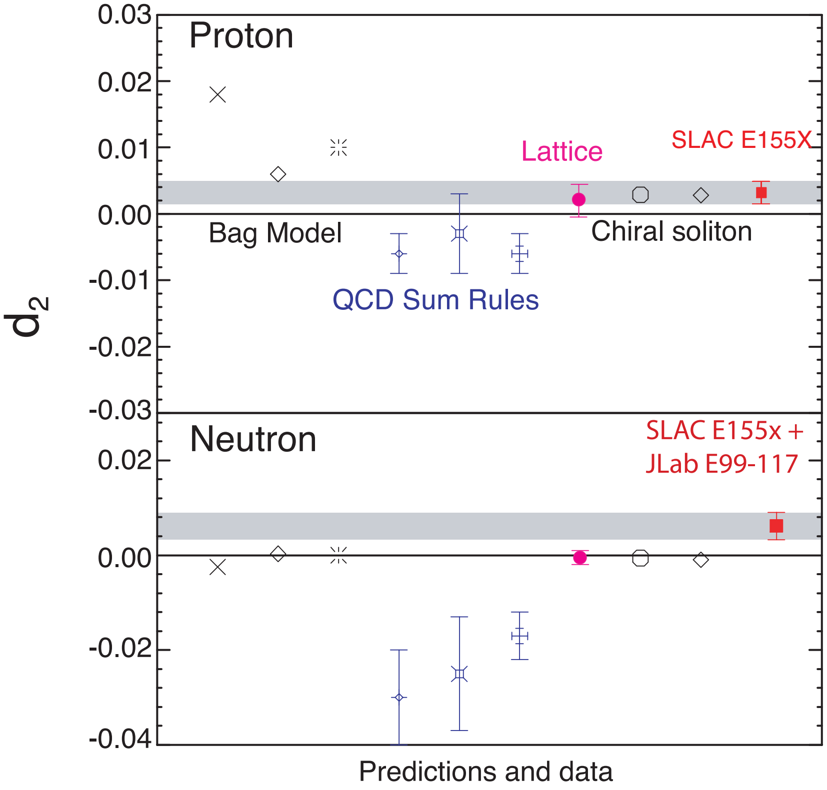

Figure 4: d_2 SLAC E155X results of the proton and SLAC E155x combined with JLab E99-117 results of the neutron results compared to several theoretical calculations including lattice QCD (see text). Upper panel is for the proton and lower panel is for the neutron.

7 Comments on *Issues* Section from PAC30 Final Report

The PAC30 reviewers made two comments in their final report that we would like to address.

The first refers to the fact that there is an inevitable significant contribution to the d_n^2 integral from the resonance region ($W \leq 2\,\mathrm{GeV/c}$), particularly at low-Q^2. While this has been a long-standing concern, one of the strengths of this measurement is the focus on directly measuring the evolution of d_n^2 over a relatively broad range of Q^2 (and with different resonance contributions). At some level, we must always trade between the uncertainties associated with evolving d_2 integrand points at high Q^2 (in the pure-DIS region) down to some nominal constant Q^2, or fixing the Q^2 and accepting some resonance "contamination." It is hoped that the large x and Q^2 coverage of this experiment will allow us to try multiple approaches to computing d_n^2 and perhaps disentangle some of these issues. The success of the quark-hadron duality in the JLab E01-012 experiment [15] suggests that nature may also work in our favor here.

The second comment mentions that large systematic uncertainties appear from ^{3}He to neutron and QED radiative corrections. The ^{3}He to neutron correction is critical to multiple experiments completed over the last several years and has received significant attention. The basic techniques are by now well established. Remaining uncertainties (particularly at higher-x) are under active study by both theoretical and experimental groups.

Lastly, we believe the radiative corrections are well under control. Much of the needed data will be measured as an intrinsic part of this experiment itself, limiting the dependence on models or other external data. The uncertainties in the corrections have been cross checked against the E01-012 (Spin-Duality) results—their worst-case uncertainty was 4.4%, consistent with our previous estimate.

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