The Longitudinal Spin Structure of the Nucleon

Update of Experiment 12-06-109 (approved by PAC 30)

Moskov Amarian, Stephen Bültmann[†], Gail Dodge, Sebastian Kuhn[†*], Lawrence Weinstein
Old Dominion University

Harut Avakian, Peter Bosted, Volker Burkert, Alexandre Deur[†]
Jefferson Lab

Vipuli Dharmawardane[†]
New Mexico State University

Keith Griffioen[†]
The College of William and Mary

Hovanes Egiyan, Maurik Holtrop[†], Karl Slifer
University of New Hampshire

Yelena Prok[†]
Christopher Newport University

Don Crabb[†]
University of Virginia

Tony Forest[†]
Idaho State University

Angela Biselli
Fairfield University

Kyungseon Joo
University of Connecticut

Mahbub Khandaker
Norfolk State University

Elliot Leader
Imperial College, London, England

Aleksander V. Sidorov
Bogoliubov Theoretical Laboratory, JINR Dubna, Russia

Dimiter B. Stamenov
Inst. for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A CLAS collaboration proposal

[†] Co-spokesperson [*] Contact: Sebastian Kuhn, Department of Physics, Old Dominion University, Norfolk VA 23529. Email: skuhn@odu.edu

Abstract

We are proposing a comprehensive program to map out the x- and Q^2-dependence of the helicity structure of the nucleon in the region of moderate to very large x where presently the experimental uncertainties are still large. The experiment will use the CLAS12 detector, 11 GeV highly polarized electron beam, and longitudinally polarized solid ammonia targets (NH_3 and ND_3). Thanks to the large acceptance of CLAS12, we will cover a large kinematical region simultaneously. We will detect both the scattered electrons and leading hadrons from the hadronization of the struck quark, allowing us to gain information relevant for the flavor (and transverse momentum) dependence of polarized parton distributions. Using both inclusive and semi-inclusive data, we will separate the contribution from up and down valence and sea quarks in the region $0.1 \leq x \leq 0.8$. These results will unambiguously test various models of the helicity structure of the nucleon as $x \to 1$. A combined Next-to-Leading Order (NLO) pQCD analysis of our expected data together with the existing world data will significantly improve our knowledge of all polarized parton distribution functions, including for the gluons (through Q^2–evolution). High statistics data on the deuteron in the region of moderate x and with a fairly large range in Q^2 are crucial for this purpose. Finally, we will be able to improve significantly the precision of various moments of spin structure functions at moderate Q^2, which will allow us to study duality and higher-twist contributions. We request a total of 80 days of 11 GeV polarized beam in Hall B.

1 Introduction

One of the cornerstones of the physics program of Jefferson Lab after the 12 GeV upgrade is the investigation of the 3-dimensional valence structure of hadrons, and in particular the nucleon. Angular momentum plays a very important role in this structure, since the composition of the nucleon spin from its elementary constituents is still an open question. A large program is underway or in preparation at many laboratories world-wide to tackle this question. The energy-upgraded CEBAF at Jefferson Lab will play an important role in this context, because no other facility presently running or under construction will be able to probe, with comparable precision, those quarks that carry a large fraction of the nucleon momentum, x (valence quarks).

To fully elucidate the spin structure of the nucleon in the valence region, one has to combine information from many different experimental approaches. Both deeply virtual exclusive processes, which are sensitive to Generalized Parton Distributions (GPDs), and semi-inclusive processes (in particular those involving single spin asymmetries which are sensitive to Transverse Momentum-dependent Distributions - TMDs) will access some part of this puzzle. However, high precision measurements of structure functions (as well as of elastic form factors) remain indispensable, both to constrain the parameters of GPD and TMD fits, and as the most direct access to the longitudinal structure of the nucleon. In particular, spin structure functions of the nucleon in the valence region and at very large x are still poorly known, in spite of their fundamental significance for tests of pQCD and models of nucleon structure. Jefferson Lab with 11-12 GeV beams is the unique place where this gap can be finally closed. The accessible kinematics is also uniquely suited to study the transition from partonic degrees of freedom to hadronic ones, through detailed measurements of higher twist operator matrix elements and a complete investigation of the phenomenon of quark-hadron duality in spin structure functions. The importance of these experimental goals requires a complete set of measurements on both types of nucleons, protons and neutrons. In addition, since neutrons can only be accessed bound in nuclei, it is very important that both commonly used nuclear targets, ^{3}He and deuterium, be studied with high precision, since nuclear effects and their uncertainties are very different for these two cases. Furthermore, the deuteron is the best substitute for a purely isoscalar nucleon target, which is ideal for extracting information on gluon and sea quark helicity distributions through NLO analyses.

Presently, the only readily available and suitable targets for polarized protons and deuterons employ solid state compounds like ammonia, butanol or lithium deuteride at low (≈ 1 K) temperatures. These compounds are susceptible to radiation damage and beam heating, limiting severely the practically achievable luminosities. The upgraded CLAS12 detector will be a perfect match for these targets, since it

- is optimized for luminosities of 1-2$\cdot 10^{35}$ cm^{-2} s^{-1}, within a factor of 2-4 of the practical limit of cryogenic ammonia targets, and compensates for this relatively low luminosity with its very large acceptance

- already contains a solenoidal magnet which will provide the (typically 5 Tesla) field needed for dynamic nuclear polarization, thus minimizing the extra costs of a polarized target

- covers a large angular range, including backwards angles, which allows us to simultaneously measure inclusive, semi-inclusive and tagged structure functions (with backward-going target remnants) over the full kinematic range of interest (while also collecting data for deeply virtual exclusive processes and single spin asymmetries).

PAC30 approved Experiment E12-06-109, in which we proposed 80 days of measurements with polarized electron beam on a polarized hydrogen and deuterium target together with CLAS12 at its maximum luminosity. This experiment will take full advantage of the rich program laid out above and, among other topics, complete the measurement of spin structure functions of the nucleon in the valence region. In the following, we summarize recent developments and repeat our request for a total of 80 days of beam time at the highest priority.

2 Scientific Case and Recent Developments

Spin structure functions of the nucleon have been measured for three decades, beginning with the experiments at SLAC [1] and the discovery of the famous "spin puzzle" by the EMC [2]. Several experiments at SLAC, CERN and HERA followed, with the main goal to access the deep inelastic region down to (relatively) low x, which is necessary to test various sum rules [3] and to access information on the total fraction of the nucleon spin carried by quark helicities. The most recent data on inclusive spin structure functions in this (moderately) high Q^2, (moderately) low x region come from the COMPASS collaboration at CERN [4]. A comprehensive recent review of the status of spin structure function measurements (as well as theoretical developments) can be found in [5].

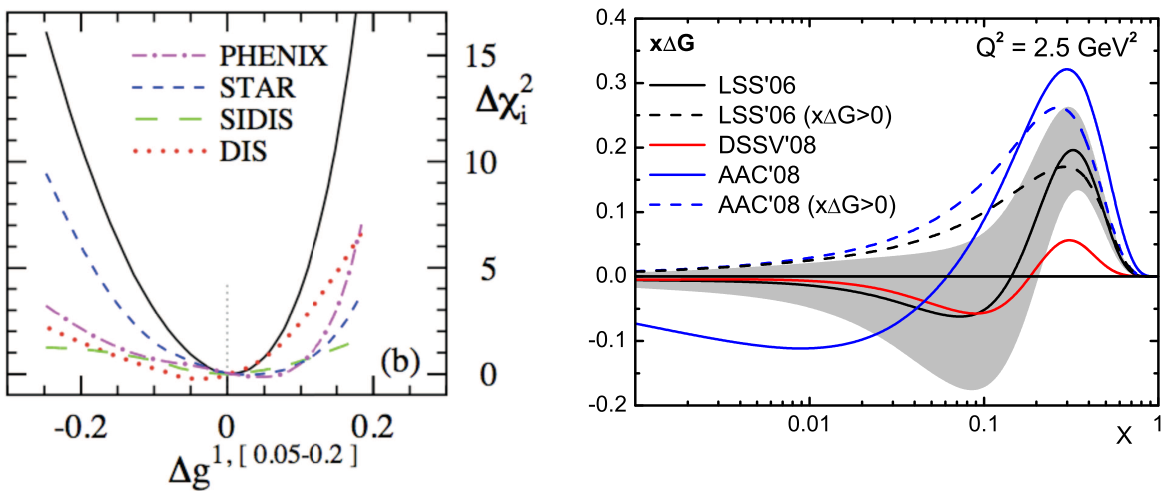

Figure 1: Combined NLO analyses of DIS, SIDIS and pp data to extract gluon helicity distributions. **Left:** The vertical axis shows the increase (relative to the best fit) in χ^2 of PDF fits to world data for different parameters for the distribution $\Delta G(x)$ while the horizontal axis shows the corresponding integral of ΔG over the range $0.05 < x < 0.2$ (from [17]). The curves show the individual contributions from various data sets to the total change in χ^2; note that on the positive side for the integral, DIS data (including those from Jefferson Lab) yield the strongest constraint. **Right:** The best fit (labeled "DSSV'08") together with parametrizations from other groups; note that the pp data from RHIC constrain ΔG to be around zero in the range $0.05 < x < 0.2$ while the functional form and absolute size of ΔG at larger x is still largely unknown.

Apart from contributing to the evaluation of moments that are related to nucleon axial current matrix elements, these data can also be used, via next-to-leading-order DGLAP analysis, to extract (within some model assumptions) the helicity-dependent distribution functions (PDFs) of valence and sea quarks as well as gluons (see, *e.g.*, [6, 7, 8, 9, 10]). The separation of the contributions from various quark and anti-quark flavors can be further advanced by including semi-inclusive scattering data into these analyses, since the leading hadron detected in coincidence with the scattered lepton retains some information on the flavor of the struck quark. The most recent data of this type come from HERMES [11] and COMPASS [12]. Finally, several new approaches have begun to yield more direct information on the helicity dependent gluon structure function $\Delta G(x)$. These experiments use either semi-inclusive high p_T [13] or charmed meson production [14] to access photon-gluon fusion amplitudes. An alternative approach uses polarized proton collisions at the RHIC facility at BNL. In this case, double spin asymmetries of pion [15] or jet [16] production at high p_T can be interpreted in terms of polarized gluon distributions. Ultimately, a combined analysis [17] of *all* of these different data in a rigorous NLO framework will yield the most precise information on the contribution from all parton helicities to the nucleon spin. However, it is instructive to examine the contribution of these various channels to our present knowledge (see Fig. 1): even in the x range 0.05 - 0.2, to which the RHIC data are most sensitive, existing DIS data alone provide about the same amount of information. In the future, data from COMPASS and especially RHIC will further reduce uncertainties in this region, and begin to constrain $\Delta G(x)$ at smaller x (using pp collisions at higher energies). However, it appears likely that the functional form of $\Delta G(x)$ is not simple and therefore a full mapping, over all accessible x, is needed before a final conclusion on the total fraction of the nucleon spin carried by gluon helicities can be drawn. The best option to reduce the present uncertainty at higher x lies with NLO analyses including DIS and SIDIS data.

Since such NLO analyses of DIS data use the logarithmic Q^2–dependence of PDFs to extract indirect information on the gluon, it is important to have high precision data at both the highest possible Q^2 (so far, COMPASS data) as well as the lowest Q^2 still consistent with the applicability of pQCD. Furthermore, since higher twist effects may become sizable at those lower Q^2, it is imperative that those latter data sets cover a relatively large Q^2 range in themselves, from below the customary DIS limit of $Q^2 = 1$ GeV^2 to at least several GeV^2. That way, higher twist corrections can be extracted from those same data with minimal statistical and systematical uncertainty. Finally, as explained above, good coverage at relatively large x is very important. This is where experiments at Jefferson Lab, both in the present 6 GeV era and especially with 11-12 GeV beam energy, can have a big impact, with no foreseeable competition elsewhere.

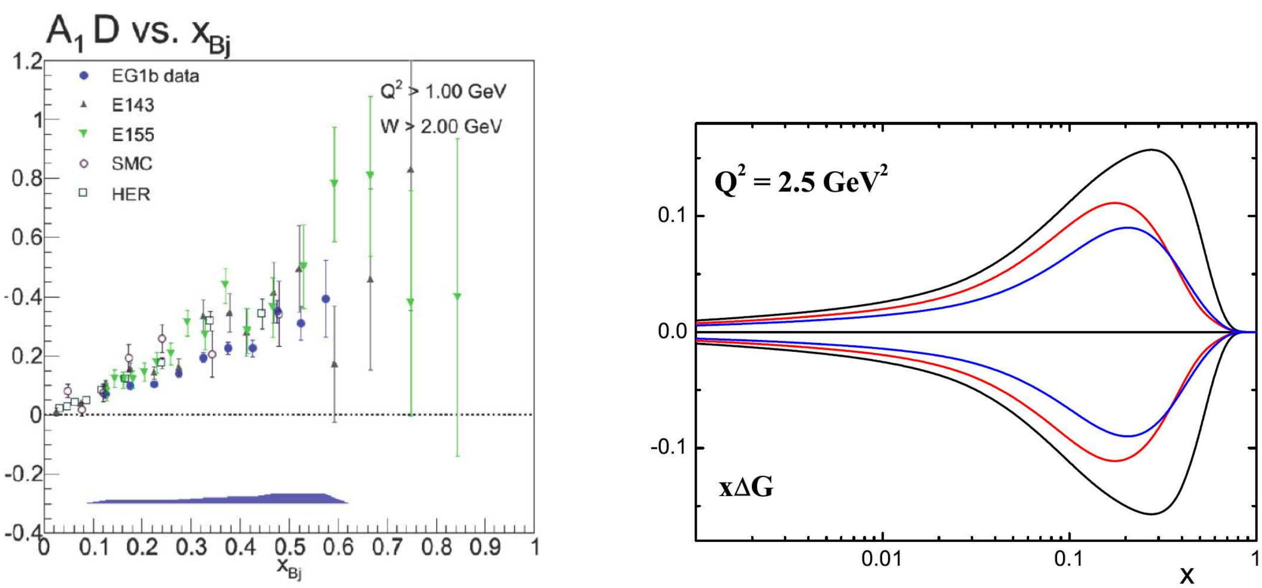

Figure 2: **Left:**Results for A_{1D} from the complete data set of EG1, together with other world data. **Right:** Effect of eg1 data (red, second-outermost curve) and COMPASS data (blue, innermost curve) on the uncertainty of the gluon distribution $\Delta G(x)$ (outermost black curve without inclusion of these data; from [10]).

Existing high precision DIS data in the moderate-to-high x region come mainly from Jefferson Lab experiments in Hall A (on ^{3}He) and the eg1 – eg1-DVCS program in Hall B (proton and deuteron). Hall C took data in the resonance region with the RSS experiment and, more recently in the DIS region on the proton with SANE (mostly in transverse target configuration). The EG1 data have been fully analyzed and mostly published [18, 19];

two final publications are underway. Figure 2 shows sample results from EG1 as well as the improvement in extracted PDF uncertainties due to inclusion of these data; once the remaining 6 GeV data set from CLAS and Hall C is analyzed, we expect about a factor 2 smaller statistical errors but no increase in kinematic coverage. This will result in only a modest further improvement of our knowledge of PDFs; to make substantial progress, we need both significantly better statistics and increased coverage. The experiment proposed here at 11 GeV will provide both, extending the useful x-range in the DIS region both to lower and higher x and to much higher Q^2, see Fig. 3.

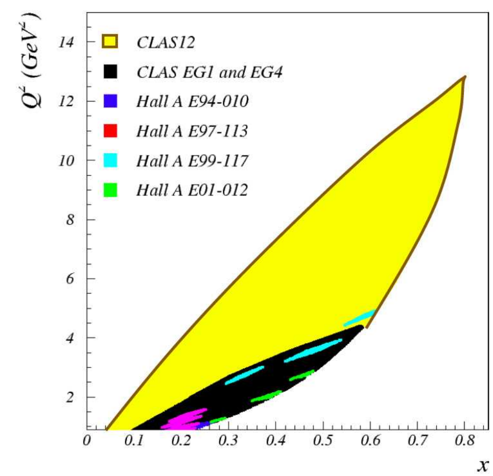

Figure 3: Kinematic coverage in the DIS region of existing 6 GeV JLab experiments and expected coverage for the proposed 12 GeV experiment.

Apart from the (indirect) constraints on gluon and sea quark distributions discussed above, measuring inclusive spin structure functions at high x has a very direct impact on our knowledge of the behavior of valence u and d quark distributions as $x \to 1$. This is presently an open question, since existing JLab data can only provide information up to $x \approx 0.6$, see Fig. 4. Simple $SU(6)$ symmetric quark models predict $A_{1p} = 5/9$ and $A_{1n} = 0$ in the valence region, which is already ruled out by the existing data. However, modified quark models including hyperfine interactions and relativistic effects [20] agree quite well with these data. These (and similar) models predict that while the ratio d/u goes to zero at large x, only the up quark polarization $\Delta u/u$ converges towards 1, while $\Delta d/d$ remains negative (see black solid curve from LSS [10] in Fig. 4). This is in stark contrast to expectations from pQCD, where helicity conservation dictates that both $\Delta u/u$ and $\Delta d/d$ go to +1 when $x \to 1$ (see dashed lines from [21] in Fig. 4). Recently, some modification of this approach due to quark orbital angular momentum [22] led to a more gradual increase of $\Delta d/d$, consistent with the data (solid curves in Fig. 4). Clearly, data at even higher x are sorely needed to resolve between these different predictions and to clarify the valence structure of the nucleon.

Finally, spin structure function data covering a large range in x at moderate Q^2 allow us to extract higher twist matrix elements from moments of these structure functions, using the OPE technique. An example of data on the twist-4 matrix element f_2 extracted from existing Jefferson Lab data [23] is shown in Fig. 5; as one can see, the precision achieved so far is limited. In particular, there are large systematic uncertainties because relatively low-

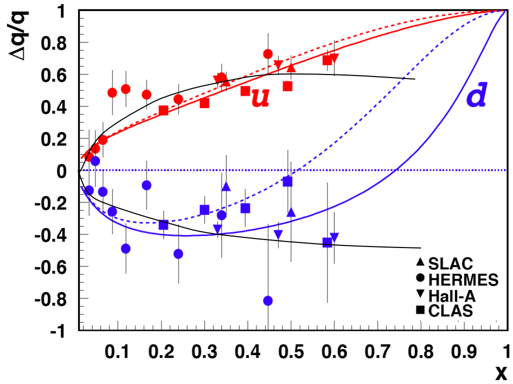

Figure 4: $\Delta u/u$ (upper half) and $\Delta d/d$ (lower half) results from Jefferson Lab Hall A and CLAS data (in leading order approximation), compared with other world data and three different predictions (see text).

Q^2 data had to be included to get enough lever arm in Q^2; this in turn necessitates including ad-hoc terms with higher powers of $1/Q^2$ in the fit. With the much larger kinematic coverage at 11-12 GeV, we will be able to exclude data below $Q^2 = 1$ GeV^2 in these fits and, at the same time, cover a much larger range in x with a single experiment, making extrapolations to $x = 0$ less uncertain than at present.

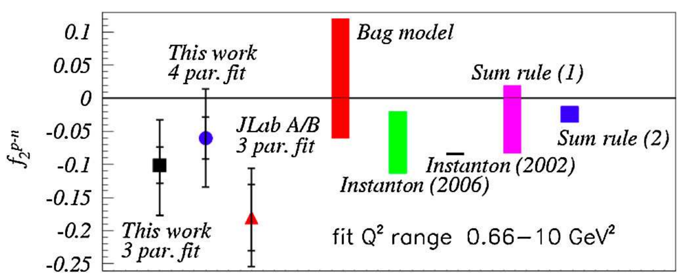

Figure 5: Values of the proton-neutron isovector matrix element f_2 from existing Jefferson Lab data, together with various theoretical predictions (from [23]).

3 Technical Progress Towards Realizing the Experiment

The proposed experiment will use the standard equipment of CLAS12 in addition to the polarized target. Many of the authors on this proposal are actively working on several of the detector components of CLAS12, including pre-shower calorimeter, high threshold cherenkov counter, and Region 1 and 2 forward tracking drift chambers, as well as data analysis software. All of these projects have made significant progress since the experiment was originally approved; for example, the first Region 2 drift chamber has been assembled and stringing has begun at JLab, with subsequent sectors to be strung in ODU's newly completed clean room.

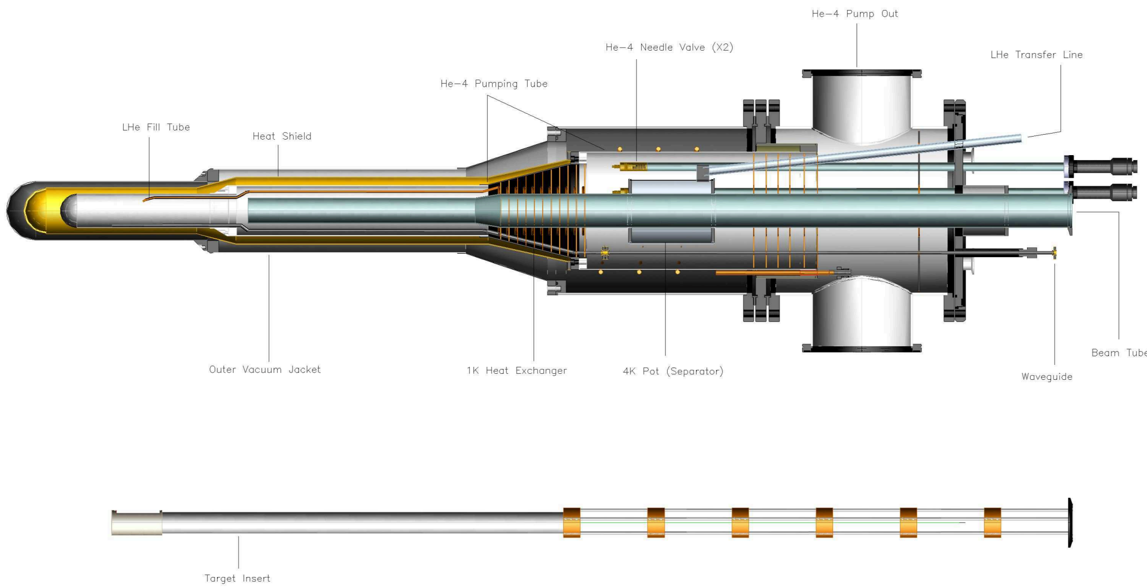

Figure 6: A schematic drawing of the polarized solid target cryostat and target insert for CLAS12. Note that the required 5 Tesla polarizing magnetic field will be provided "for free" by the solenoid of the CLAS12 central tracker, which was designed with this goal in mind. The target sits inside a horizontal ^{4}He evaporation refrigerator and will be dynamically polarized using a microwave system.

The major non-standard item required for successful execution of this program is the polarized target. A conceptual design was already completed at the time of the first PAC submission, see Fig. 6. Unfortunately, funding for this target had been subsequently removed from the base equipment budget for the Jefferson Lab 12 GeV upgrade, to cover required contingency costs in other parts of the project. In 2009, some of the spokespersons of this experiment (Kuhn, Bültmann, Prok, and Crabb) formed a consortium and submitted a successful MRI-R^2 proposal to NSF. The approved funding from this source will cover all costs of acquiring necessary hardware and prototyping, assembly, and testing of the polarized target. Subsequent to the availability of these funds, work has begun on the detailed design of all target components, in particular the in-beam cryostat and vacuum vessel. The design of the central Silicon Vertex Tracker for CLAS12 is now fully consistent with the required space to insert the polarized target into its center. Initial development work has also begun on the target insert and NMR system; several major components and measuring instruments have already been acquired. The total project, which also receives strong support from the JLab target group, is on track to be completed within 4 years, making the polarized target available as soon as the experimental program with CLAS12 can begin. In addition to the present experiment, this target also supports a large (PAC-approved) program of measurements of DVCS (E12-06-119), SIDIS (single target spin asymmetries; E12-07-107), and of the EMC effect in nuclear spin structure functions (LOI 10-005 to PAC35).

At PAC34, a series of SIDIS experiments (Proposals PR12-09-007, 008, 009) were approved for both unpolarized and longitudinally polarized target. All of these proposal require a RICH detector (in lieu of some sectors of the existing low-threshold cherenkov counter) to separate Kaons from pions and protons. Work on the design of such a RICH detector has begun in earnest, and first benchmark results have been presented at CLAS12 workshops. This development will clearly benefit the present experiment, as well, as it will allow us to access the full kinematic range of flavor-tagged spin structure functions in SIDIS, with separation of all three charge states of pions and kaons. This will lead to additional constraints of NLO analyses which will allow us to separate the contributions of valence and various sea quarks in the range $x > 0.1$, where existing data have relatively large uncertainties and one expects interesting effects to appear (e.g., a possible charge asymmetry in the polarized sea, analog to that seen in unpolarized PDFs). Several of the authors of this proposal update are working on this extension of the CLAS12 capabilities.

4 Beam Request and Expected Results

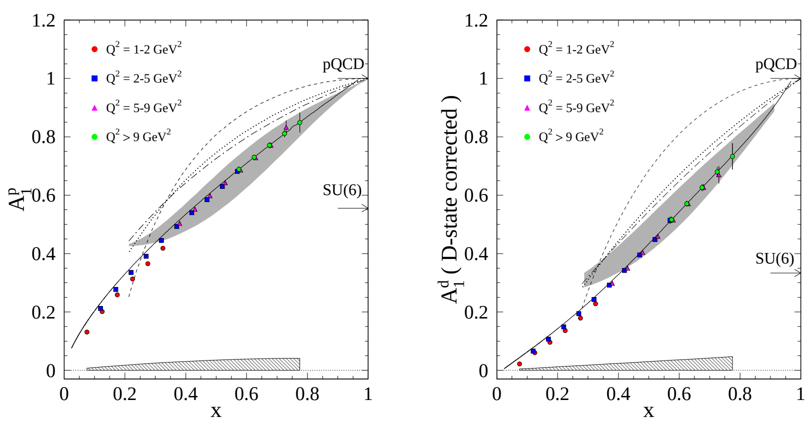

Figure 7: **Left:**Expected results for A_{1p}. **Right:** Expected results for A_{1d}.

We request 25 days of highly polarized (> 85%) electron beam (about 10-20 nA) on a 3 cm long NH_3 target (80 % polarization on average) and 45 days on a 3 cm long ND_3 target (40 % polarization on average). In addition, we request 10 days of beam on auxiliary targets (carbon - 8 days, and empty - 2 days). We also will need 5 additional days (without beam) for target changes, anneals (which will be needed about every other day), polarization reversals, and calibrations. The quoted parameters are fully consistent with recent operating experience during eg1-DVCS, which ran in 2009, including several days on an ND_3 target (which exhibited a slow drop of its polarization from about 43% to 33% during a 2-day period after it received its optimal radiation dose). The beam time requests are optimized so that statistical errors will be smaller or comparable to systematic ones in all kinematics of interest. In particular, the running time on deuterium is longer to partially compensate for the lower polarization and to maximize the impact on NLO extractions of polarized parton densities. In Figs. 7-9 we show a few representative results expected from this data set; these as well as additional plots (based on a full simulation of CLAS12) are contained in the original proposal.

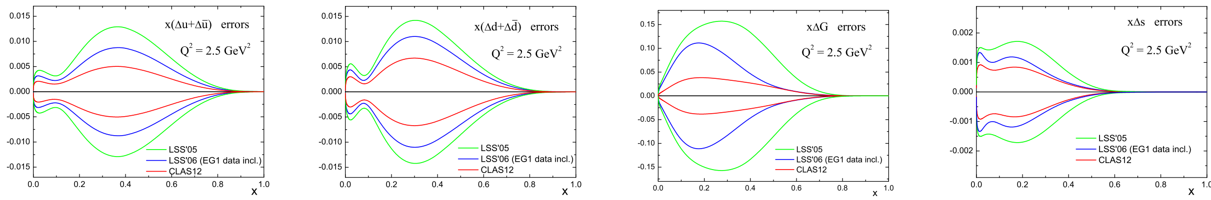

Figure 8: Expected uncertainties for polarized parton distributions Δu, Δd, ΔG and Δs from a NLO analysis of all world data. The two outermost lines show the result by Leader, Sidorov and Stamenov [10] discussed above. The innermost line shows the expected uncertainty after including the data set to be collected with this experiment, including statistical and systematic errors. Note that the x-range where these data will have the most impact depend on the functional form of the PDF parametrizations; nevertheless, the much smaller errors shown here are indicative of the statistical power in that x-range.

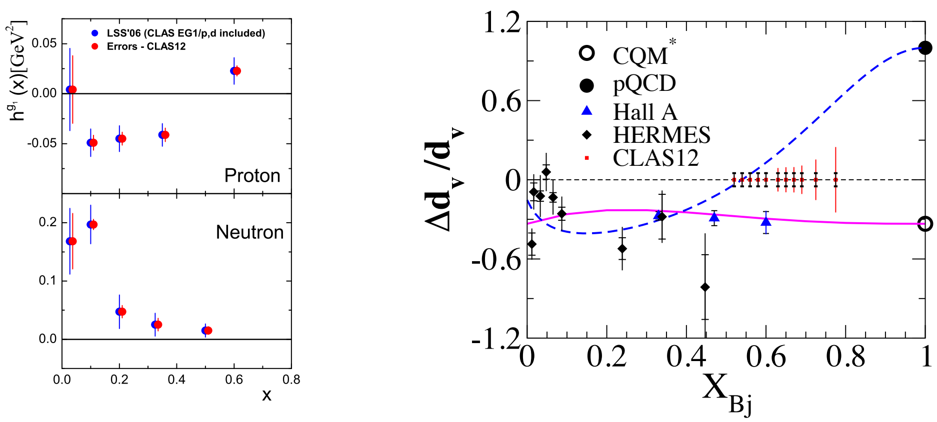

Figure 9: **Left:**Expected reduction in the error of higher-twist terms. **Right:** Expected results for the valence d quark polarization from semi-inclusive data with the proposed experiment (statistical and total error bars), as well as existing data. The dashed line represents a pQCD prediction [21] while the solid line represents the prediction from the hyperfine perturbed constituent quark model [20].

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