DIS on Longitudinally Polarized Deuterium

Proposal to increase the beam time allocation for the ND_3 part of Experiment 12-06-109 (approved by PAC 30 and rated “A” by PAC 36.)

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A CLAS collaboration proposal

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Abstract

We are proposing to add 50 more days of running to the 50 days already approved for the portion of Experiment 12-06-109 with CLAS12 and 11 GeV polarized electrons on longitudinally polarized deuterons (ND_3). This additional beam time (plus 10-15 days overhead) will significantly reduce the uncertainty on polarized parton distributions, in particular for d quarks, in the limit of large x, as well as for gluons and the strange quark sea at moderate to large x. It will bring the deuteron data at least closer to parity with the already approved 120 days of data on the proton, thus maximizing the information that can be extracted from a single experiment, as well as making more significant comparisons with other experiments (e.g. on ^{3}He) possible. This will be important to assess the impact of nuclear effects on the extraction of Δd at high x, and to guarantee that the unique opportunity to finally map out the asymptotic behavior of all quark distribution provided by Jefferson Lab's 12 GeV beam will be optimally utilized. In this proposal, we are providing updated estimates of various quantities that can be extracted from these data under the assumption of a doubling for the integrated luminosity on the deuteron.

1 Introduction

Experiment 12-06-109 is 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. By collecting inclusive (DIS) and semi-inclusive (SIDIS) data over a wide kinematic range with CLAS12 and 11 GeV polarized electrons on both longitudinally polarized protons (NH_3) and deuterons (ND_3), this program aims to constrain global fits of polarized parton (quark and gluon) distributions, extract higher twist corrections to the DIS structure functions, and evaluate moments connected to local operators in the Operator Product Expansion (OPE). Experiment 12-06-109 was originally approved by PAC 30 (with a further review and scientific rating of "A" by PAC 36) for a total of 80 days, 30 days on NH_3 and 50 days on ND_3 (both including overhead).

In the meantime, additional experiments on longitudinally polarized *protons* have been approved, with high rating. These experiments have brought the total number of PAC-approved days for the NH_3 target to 120 (run group Ca with CLAS12). [REF] In the meantime, the total runtime for the ND_3 target (run group Cb) has been largely unchanged (at present 65 days including all overhead for auxiliary measurements, target operations etc.). This discrepancy is even more striking when taking into account that ND_3 targets tend to have polarizations of roughly a factor 1/2 lower than NH_3 targets, resulting in an overall figure of merit (FoM) eight times worse than for the proton. This means that any analysis that requires information from both targets (e.g., global fits to extract polarized parton distributions) would have uncertainties that are totally dominated by the statistical error from the deuteron.

While some of the goals of the original experiment 12-06-109 can be reached with reasonable precision even with 50 PAC days on the deuteron, there are some physics observables whose precision would be "statistics-starved" under this scenario. In particular, the asymptotic behavior of the PDF Δd at large x would be much less constrained than what is possible with a doubling of the integrated luminosity. Deuteron data are also crucial to determine the total contribution from quark helicities to the nucleon spin ($\Delta\Sigma$), as well as polarized gluon and strange quark PDFs at moderate to large x (see details in the following sections). Because of their smaller count rates, SIDIS channels will benefit significantly from additional statistics. As we lay out in detail in the following sections, a doubling of the actual run time on polarized ND_3 from 50 to 100 days (plus the necessary overhead) will optimize the overall physics output from Experiment 12-06-109 and maximize the return on the large investment in the spin physics program with Jefferson Lab at 12 GeV. No other facility presently running or under construction will be able to probe, with comparable precision, the kinematic region of moderate to large x and moderate Q^2 accessible here.

1.1 The Deuteron and CLAS12

A complete mapping of spin structure functions and the extraction, through global PDF fits, of polarized parton distributions require a complete set of measurements on both types of nucleons, protons and neutrons, over the widest possible range in x and Q^2. 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. For these reasons, a high-statistics measurement on polarized deuterium (ND_3) is obligatory.

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).

Our group is leading the development of an optimized longitudinally polarized proton and deuteron target for CLAS12, and coordinates the run group C using these targets. Significant investments in this program have already been made, partially through an NSF MRI grant. No other experiment with this particular type of targets has been planned with similar kinematics, at Jefferson Lab or elsewhere. We believe that adding 60–65 more days of running to the already established run group C (an overall increase by only 25%) will yield an optimal return on this investment.

2 Scientific Case and Recent Developments

Figure 1: Compilation of recent polarized PDF fits from various groups. This Figure is from the JAM15 paper [5] (Fig. 17) where all references for these fits can be found.

Inclusive and flavor-tagged spin structure functions of the nucleon have been measured for over three decades [1], beginning with the experiments at SLAC [2] and the discovery of the famous "spin puzzle" by the EMC [3]. The goal of these experiments is to determine, via next-to-leading-order DGLAP analyses, the helicity-dependent distribution functions (PDFs) of valence and sea quarks as well as gluons, see Fig. 1. Collinear spin structure functions can also be used to evaluate moments that are related to nucleon axial current matrix elements (e.g., the overall contribution of quark helicities to the nucleon spin), and to test fundamental sum rules like the Björken sum rule [4]. Finally, measuring their dependence on the photon virtuality Q^2 allows us to determine higher twist contributions, matrix elements in the framework of the operator product expansion (OPE), and the transition from partonic (high Q^2) to hadronic (low Q^2) degrees of freedom, including duality and tests of the Gerasimov-Drell-Hearn sum rule and its extensions in, e.g., Chiral perturbation theory (χPT). [REFS] In the new era of three-dimensional mapping of the nucleon parton distributions, collinear spin structure functions serve both as a crucial constraint on GPDs and TMDs, and provide two of the four ingredients to the celebrated nucleon spin sum rule.

Within recent years, data from high-energy polarized proton collisions at RHIC [6, 7, 8, 9, 10] have constrained the contribution of gluon and sea quark helicities at low to moderate $x \leq 0.2$ to the nucleon spin. Further information has come from measurements of open charm production [11]. The most recent inclusive data from COMPASS [12] extend our knowledge of spin structure functions to the lowest x and highest Q^2 yet. Meanwhile, the spin structure function program with Jefferson Lab's 6 GeV has been concluded and most results have been published. In particular, very precise data on proton, deuteron and ^{3}He targets [13, 14, 15, 16, 17, 18] have recently appeared that cover a large kinematic range, from low Q^2 to the DIS region. This program is being continued in the 12 GeV era, with several experiments in three halls approved with scientific rating of "A". The unique importance of these expected Jefferson Lab data is threefold:

Figure 2: Impact of recent Jefferson Lab data on the global NLO PDF fit by the Jefferson Lab Angular Momentum (JAM) collaboration. This Figure is from the recent JAM15 paper [5] (Fig. 15) where all relevant references can be found. The l.h.s. fits are for the leading twist distributions for three quark flavors and gluons, while the r.h.s. shows the results for various higher-twist terms.The yellow lines are from repeated Monte Carlo fits including all world data except those from Jefferson Lab; the red lines include the Jefferson Lab data and clearly have a much more narrow uncertainty band.

1. For a DGLAP determination of all individual parton distribution functions, but in particular those of the gluon, from DIS data, a large leverarm in Q^2 is required to

exploit scaling violations. The recent precise data from COMPASS [12] cover the high-Q^2 limit[1], while precise data at the lowest Q^2 consistent with DIS come from Jefferson Lab. The latter cover a large range in Q^2, which in itself allows us to reliably extract and control for higher-twist effects. Figure 2 demonstrates the significant improvement in our knowledge of *all* polarized PDFs enabled already by the existing Jefferson Lab data.

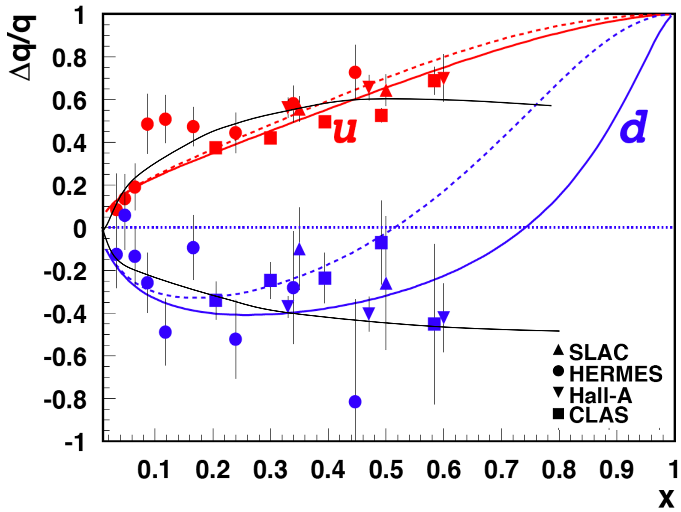

Figure 3: $\Delta u/u$ (upper half) and $\Delta d/d$ (lower half) results from Jefferson Lab Hall A and CLAS data (in leading order approximation), compared with other world data and three different predictions: a fit by Leader, Stamenov and Siderov [19] (black line), and two pQCD predictions without [20] (dashed) and with [21] (solid red and blue lines) inclusion of orbital angular momentum effects.

2. While the contribution from PDFs in the valence region $x > 0.3$ and, especially, in the limit $x \to 1$, to the overall nucleon spin is not very large, knowledge of PDFs in this regime is crucial to understand the valence structure of the nucleon and to test predictions from pQCD and various models. Only Jefferson Lab at 12 GeV can provide the necessary precision data in these kinematics for the foreseeable future. In particular, the asymptotic polarization of d quarks in the proton, $\Delta d/d$ at large x, is presently poorly known (see Fig. 3), and a reliable measurement requires high statistics data from both deuterons and ^{3}He.

3. Beyond the leading-order PDFs, higher twist structure functions are of high current interest in themselves, since they contain information about correlations and interactions between gluons and quarks in the nucleon. Again, only at Jefferson Lab, with its unique combination of high luminosity and moderate Q^2, can these structure functions be studied in detail (see the r.h.s. of Fig. 2 for examples).

[1]These will be greatly improved upon, both in kinematic reach and in precision, by data to be acquired with the future EIC; however, the low-Q^2 data fromJefferson Lab will likely not be matched in the foreseeable future.

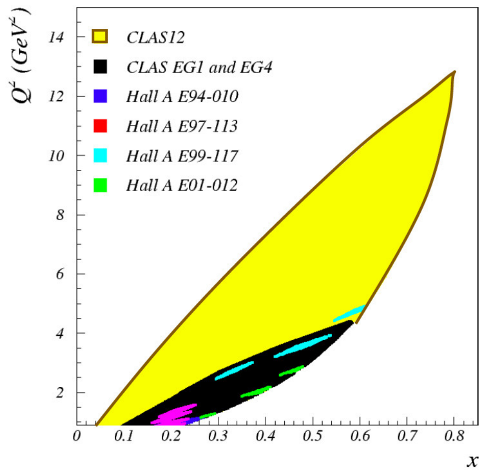

Figure 4: Kinematic coverage in the DIS region of existing 6 GeV JLab experiments and expected coverage for the proposed 12 GeV experiment.

Experiment 12-06-109 at 11 GeV will extend the useful x-range in the DIS region both to lower and higher x and to much higher Q^2, compared to the existing Jefferson Lab data; see Fig. 4. Especially at the upper end, the expected data will still be limited in statistics; a doubling of the integrated luminosity will yield significant improvements in the information we can extract from these data, as we will show below.

3 Expected Results

3.1 PDFs

The main goal of E12-06-109 is to determine the $x-$dependence of each individual parton (quark *or* gluon) distribution in the region of moderate to very high x, $0.06 \leq x \leq 0.8$. This is the region most relevant to the low-energy properties of the nucleon, where valence quarks and sea quarks confined in the "meson cloud" dominate. It is also the region where measurements at RHIC and charm production at COMPASS can contribute only little but which is important to our understanding of the dynamics that impart a net polarization to the "valence-like" sea quarks and gluons at high x.

Figure 5 shows the expected uncertainty on all these distributions from a NLO fit just to the DIS data, both for the presently allocated beam time (120 days on NH_3, 50 days on ND_3) as well as for the increased beam time on deuterium proposed here.

DISCUSSION WILL FOLLOW BASED ON WHAT THE JAM RESULTS SHOW... we are patiently awaiting the results from Monte Carlo runs presently under way. We will update this section as soon as we have those results.

It is important to clarify that the total uncertainty on the deuterium data points is nearly entirely driven by accumulated statistics. The by far most important systematic uncertainty will be the normalization of the data due to the product of beam and target polarization and due to the dilution factor. Both of these quantities will be determined experimentally

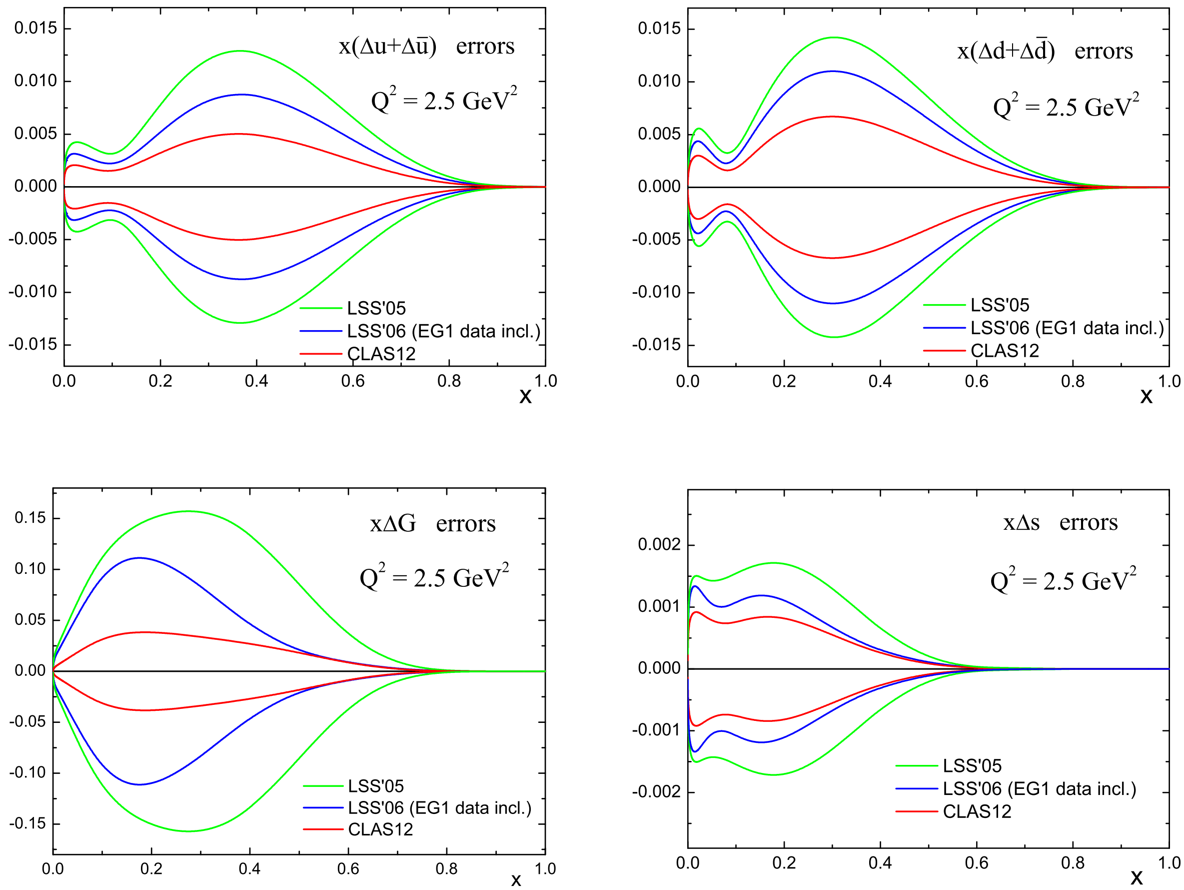

Figure 5: PLACEHOLDER: TO BE REPLACED BY UP-TO-DATE JAM RESULTS: Expected uncertainties for polarized parton distributions Δu, Δd, ΔG and Δs from a NLO analysis of all world data. The two outermost lines show the result by Leader, Sidorov and Stamenov [19] discussed above. The innermost line shows the 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.

(directly - for the polarization - or indirectly through auxiliary measurements). In particular, the polarization product P_bP_t will be extracted from a measurement of the exclusive D$(e, e'p)n$ reaction, for which the expected double-spin asymmetry is very well known and sophisticated models for final state interactions exist (which our group has tested experimentally []). Due to the somewhat small magnitude of this asymmetry (driven by the requirement of low Q^2 to get reasonable count rates), this measurement requires high statistics. Data will be taken simultaneously with DIS and other channels, meaning that the the uncertainty in P_bP_t will decrease proportional to that in the measured structure functions. Similarly, the dilution factor will be determined using sophisticated models of electron scattering from the various nuclear components of the target; however, some normalization factors (e.g., overall target density of the various species) have to be taken from precise measurements on auxiliary targets. These measurements will gain the same improvement in statistics as the main measurements on ND_3.

3.2 Quark polarization at high x

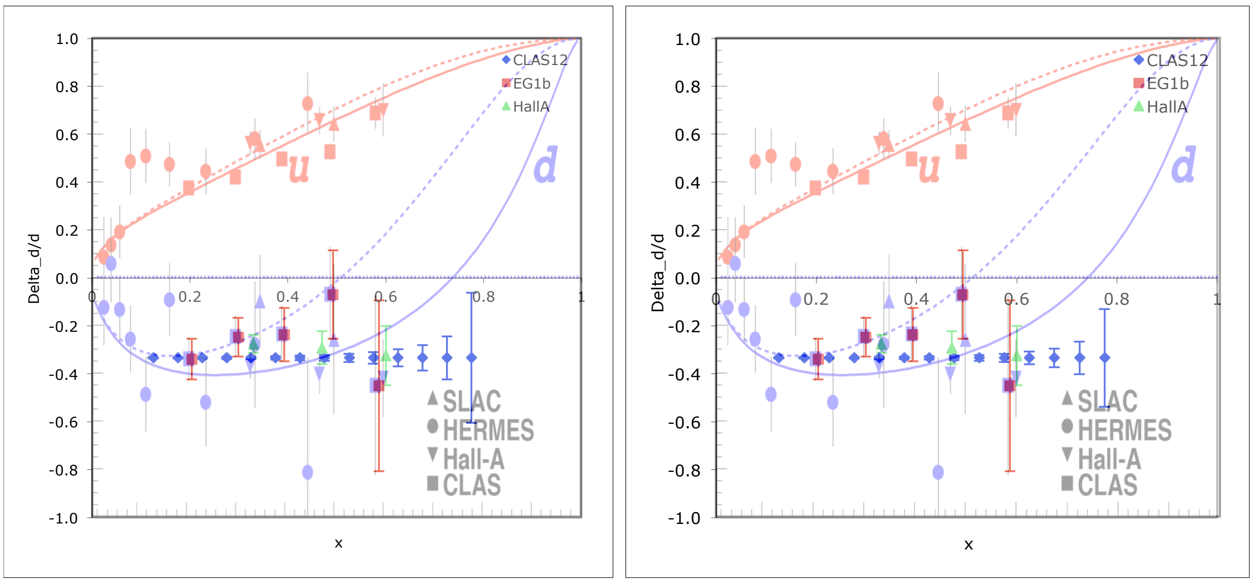

Figure 6: Expected precision for the polarization of d quarks, $\Delta d/d$, versus x, from E12-06-109 as approved (l.h.s.) and with an additional 50 days of beam time on the deuteron (r.h.s.). Existing data are shown lightly shaded (squares are from CLAS at 6 GeV) while the expected data are shown as blue diamonds. The two curves are the expectations from pQCD without [20] and with [21] inclusion of orbital angular momentum effects. The expected data are placed according to expectations from hyperfine-perturbed quark models [22] which, at least at present, cannot be ruled out.

In Figure 6, we focus on the impact our proposed data will have on the determination of the d-quark polarization at the highest x reachable with Jefferson Lab at 12 GeV. The "expected data points" are based on a detailed Monte Carlo simulation of the measured asymmetries on the proton and the deuteron, including both statistical and systematic uncertainties. While we used a simple-minded LO ("naïve parton model") calculation to extract the valence quark polarizations from these measurements, the expected uncertainty will not change much with a more sophisticated analysis like the JAM PDF fit described above. The obvious point from this figure is that, as presently scheduled, our expected data will have limited statistical power to definitely answer the question (by themselves) whether $\Delta d/d$ will remain negative for $x \to 1$ as expected from some NLO fits [19] and from hyperfine-perturbed quark models [22] or whether it will converge to $+1$ as expected by pQCD, as indicated in the solid curves in Fig. 6. In particular, the two last data points are only 3.7 and 1.2 standard deviations from zero, so with a statistical fluctuation of the actually measured data points by only one standard deviation, the solid curve in Fig. 6 would still be (nearly) compatible with those data, with a χ^2 of 4.9 for two degrees of freedom ($p = 8.7\%$).

With a doubling of the integrated luminosity on the deuteron, the statistical error bars on $\Delta d/d$ will go down nearly exactly by a factor of $1/\sqrt{2}$, since the proton results (that also enter the calculation) are already vastly more precise than the deuteron ones. As stated above, the systematic uncertainties will also go down, by nearly the same amount (and the uncertainties are statistics-dominated at high x). Repeating the same calculation, we find that the agreement with the "wrong" curve is now much worse, with a χ^2 of 11.3 for two degrees of freedom ($p = 0.35\%$). While it is true that more information on $\Delta d/d$ is expected from the approved experiments on ^{3}He, it is precisely at high x that smearing effects and uncertainties from nuclear binding become the largest, making an independent measurement on the most lightly bound nucleus, deuterium, mandatory. Our proposal for an additional 50 days on that target will strengthen this independent result significantly.

3.3 Further results from SIDIS

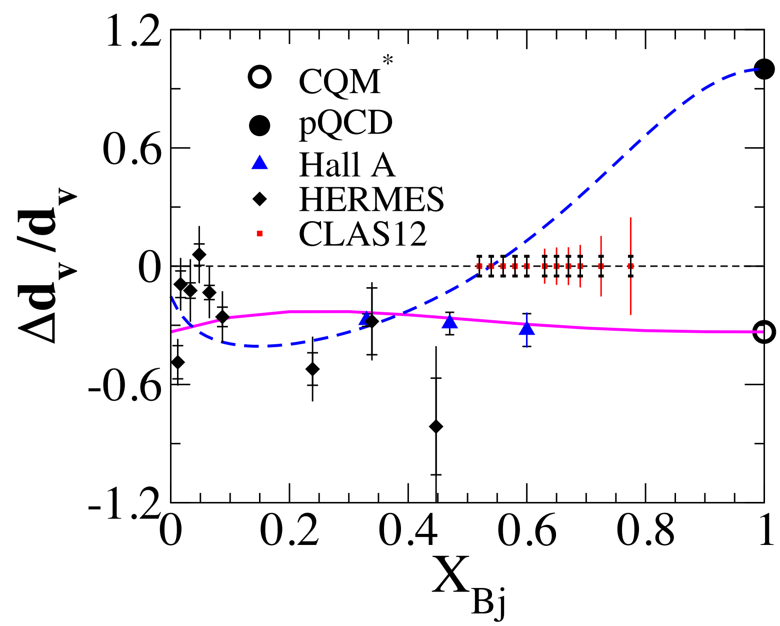

Figure 7: Expected results for the valence d quark polarization from semi-inclusive data with the proposed experiment, as well as existing data. The horizontal risers indicate the systematic uncertainties (!), while the length of the error bars indicates the statistical uncertainties. The dashed line represents a pQCD prediction [20] while the solid line represents the prediction from the hyperfine perturbed constituent quark model [22].

In addition to the determination of polarized PDFs from inclusive DIS measurements, run group C also supports a large number of approved measurements with semi-inclusive detection of pions and Kaons. For example, we show in Fig. 7 the expected results from a combination of SIDIS production of pions (π^+ and π^-) from both proton and deuteron targets that directly measures (in LO) the valence d-quark polarization. This figure is from the original proposal for E12-06-109 and hasn't been updated yet, but it is clear that similar arguments as for the previous subsection apply: A reduction of the statistical error bars (indicated by the *full* length of the vertical lines) by a factor $1/\sqrt{2}$ would turn this marginally significant measurement into a strong, independent confirmation for the trend observed in DIS.

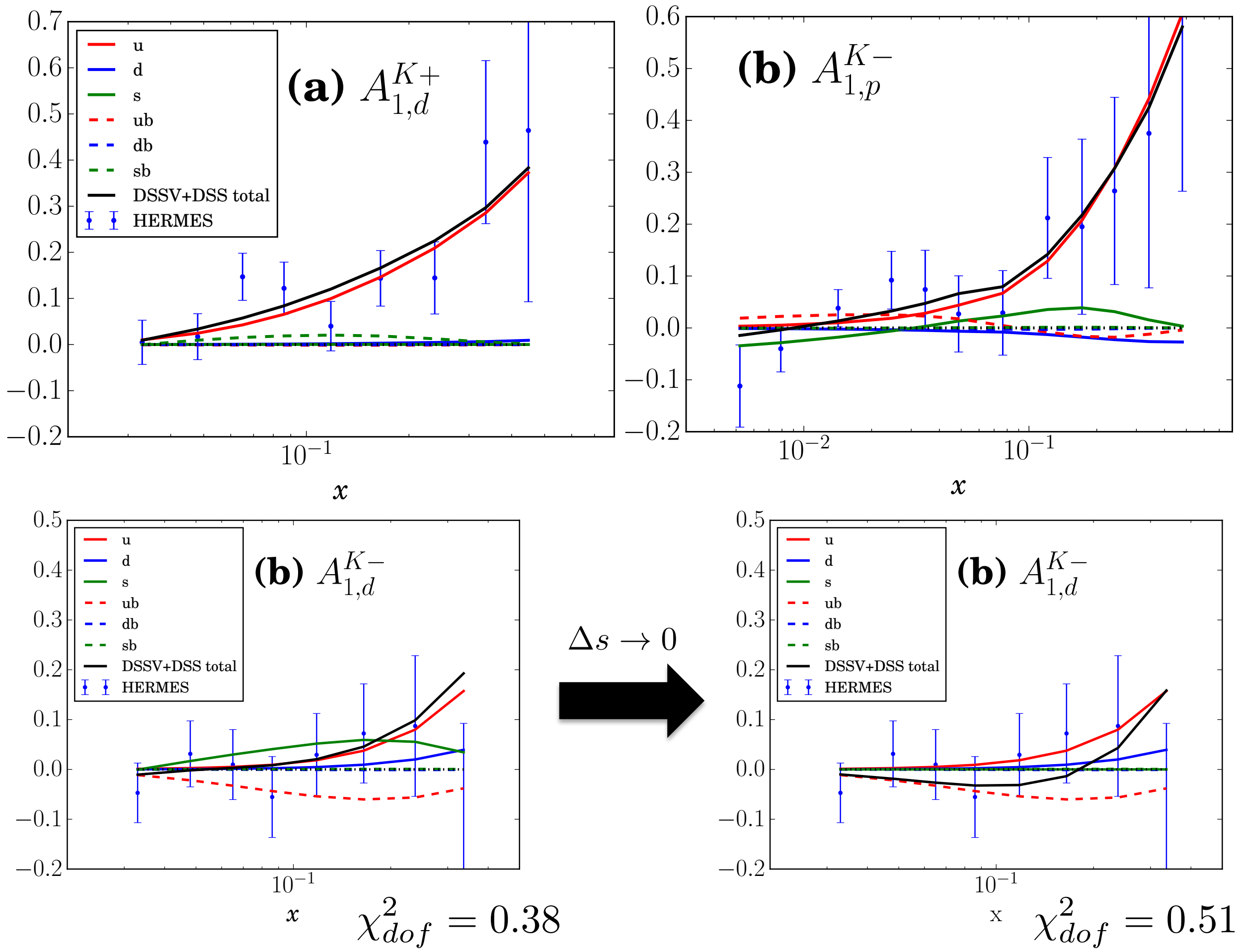

Figure 8: Contributions to the measured asymmetry in SIDIS Kaon production from various quark (solid lines) and anti-quark (dashed lines) flavors, according to a preliminary JAM analysis. The data points are from HERMES. The top row shows the K^+ asymmetry on the deuteron (l.h.s.) and the K^- asymmetry on the proton (r.h.s.). The bottom row shows two fits to the K^- asymmetry on the deuteron, either with the s-quark contribution allowed to vary freely for a minimized χ^2 (left) or with this contribution set to zero (right). Figure courtesy of J.J. Ethier.

More generally, a combined analysis of all inclusive and semi-inclusive measurements within the framework of NLO DGLAP analysis will further constrain the individual quark and gluon PDFs and allow a clear separation of quark and antiquark contributions of each flavor to the sea. The JAM collaboration is now gearing up to include this information in their fits, carefully assessing the impact of our (lack of) knowledge of the required fragmentation functions. While simulations are not yet available, it is clear again that higher precision will translate in additional knowledge. As an example we consider (in Fig. 8) the impact of various measurements on our knowledge of the strange quark sea in the nucleon, which is still a contentious topic without a clear consensus whether the contribution of this strange sea to the nucleon spin is positive, negative or negligible.

The top row of Fig. 8 shows that the K^+ asymmetry (on either target) and the K^- asymmetry on the proton are rather insensitive to the strange quark polarization, since in both cases u-quarks dominate because of their prevalence and larger charge. However, the K^- asymmetry on the deuteron is much more sensitive to strange quarks, since in the deuteron, u and d quark contributions to K^- production fortuitously cancel to a large extent. Hence, a precise measurement of this channel down to the lowest available $x \approx 0.06$ at Jefferson Lab has great promise to answer the question whether strange quarks in the nucleon carry positive helicity, negative helicity or whether there is a node in the distribution where their polarization transitions from plus to minus. Unfortunately, the only data existing so far (from HERMES) have large error bars, so that an alternative fit without any s-quark contribution only increases the χ^2 per degree of freedom from 0.38 to 0.51 (see bottom row of Fig. 8). With the vastly better statistics available from CLAS12, this situation should be much improved (note that CLAS12 will cover the same kinematic region as HERMES except for the two lowest data points). The importance of finally "nailing down" this least-known quark contribution to the nucleon spin is another strong justification to collect the highest statistics data set on the deuteron possible.

4 Beam Request

We request 50 additional days for a total of 100 days of 11 GeV longitudinally polarized ($>$ 85%) electrons on a longitudinally polarized ND_3 target in CLAS12 (total luminosity 2×10^{35} nucleons×electrons/cm^2/s), plus 15 additional days for a total of 30 days at various beam energies for calibration, in-situ irradiation of the target material, target changes, anneals and polarization reversals, as well as beam polarization (Møller) measurements.

(To be harmonized with the other RG proposals).

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