(E12-10-007 Update to Jefferson Lab PAC-50)

Precision Measurement of Parity-violation in Deep Inelastic Scattering Over a Broad Kinematic Range

May 14, 2022

Spokespeople: P. Souder [1], P.E. Reimer, X. Zheng
(JLab Hall A and SoLID Collaborations [2])

Executive Summary

We provide an update to the SoLID PVDIS experiment, E12-10-007, approved by PAC37 in 2010. The main goal of SoLID PVDIS is to test the Standard Model (SM) and search for beyond-the-SM (BSM) physics. Even though the SM is consistent with a large number of experimental tests, evidence that the SM is incomplete and that it belongs to a larger theoretical framework remains, such as the long-lasting dark matter and hierarchy problems. Testing of the SM and search for BSM physics will remain a long-term effort pursued by communities from low energy atomic physics to the high energy program at the LHC, and SoLID PVDIS belongs to this EW/BSM program yet remains unique given its unambiguous access to a specific combination of the electron-quark effective couplings. On the hadronic physics side, PVDIS on the proton provides access to the PDF ratio d/u at high x, free from nuclear effects that cloud even the latest experiments that utilized innovative experimental techniques. In short, the physics motivation of SoLID PVDIS remains strong.

Extensive progress has been made on the development of the SoLID spectrometer, from procurement and refurbishment of the magnet, to detector pre-R&D activities, to progress in data acquisition and simulation. Discussions with theory groups are also in progress on the interpretation of the data. The measurement described in our original proposal remains feasible and the budget for systematic uncertainties valid. In this document, we will review the physics motivation of PVDIS and updates to the landscape of EW/BSM physics and PDF ratio d/u study, and provide progress on the apparatus. In 2010, we requested 338 PAC days of beam time and were approved for 169 days. We request 338 PAC days of beam time, same as the original proposal.

[1] Contact person, email: souder@phy.syr.edu
[2] For full author list please see SoLID PVDIS Collaboration list and Hall A Collaboration list

1 Introduction

The Standard Model (SM) is a theoretical framework that successfully explains nearly all existing phenomenon of particle physics. However, there is long-standing evidence of new physics, such as dark matter and neutrino mass, that suggest many possibilities to extend the SM to higher energy scales. Thus it is useful to carry out as many high-precision measurements as possible to test the SM and to shed light on where beyond-the-standard model (BSM) physics might occur.

The Solenoid Large Intensity Device (SoLID), to be used in the measurement proposed here, is a general purpose spectrometer that will be used to realize a large physics program. The large acceptance, high intensity nature of SoLID will provide a unique opportunity to measure the parity violation asymmetry in electron deep inelastic scattering (PVDIS). The first PVDIS experiment, SLAC E122 [1, 2], provided a pivotal role in establish the SM. During the 6 GeV era of JLab, the PVDIS asymmetry was measured and a value of the effective vector electron axial-vector quark neutral current coupling combination $2g^{eu}_{VA} - g^{ed}_{VA}$ was extracted, showing for the first time this quantity is non-zero [3].

PVDIS is one of a number of PVES experiments performed in progress, see left panel of Fig. 1. Remarkable progress over time has been made in both how small an asymmetry can be measured and also how precise (relative uncertainty) the measurement can be made. It is in the context of this record that we are willing to tackle an experiment as challenging as the present one, where we are pushing the envelope in how precisely an asymmetry ($\delta A_{\rm PV}/A_{\rm PV} \sim 0.5\%$) can be measured, see right panel of Fig. 1.

The specific physics case for the SoLID PVDIS experiment is presented in PR-12-9-012 and PR-12-007, and was updated in Section 2.3 of the SoLID Pre-CDR [4]. The experimental details are also in the Pre-CDR. In this document, we will focus on new developments that have impact on the motivation for the experiment as well as new information on the design, much of which is contained in the recently-completed PRE-R&D reports.

2 Phenomenology of PVDIS

The fundamental parity-violating weak neutral current Lagrangian can be approximated as four fermion contact interactions at low energy scales, $Q^2 \ll M_Z^2$. Counting only parity-violating terms:

$$\mathcal{L}^{eq}_{\rm NC} = \frac{1}{2v^2}\left(\bar{e}\gamma^\mu\gamma^5 e \sum_{q=u,d} g^{eq}_{AV}\bar{q}\gamma_\mu q + \bar{e}\gamma^\mu e \sum_{q=u,d} g^{eq}_{VA}\bar{q}\gamma_\mu\gamma^5 q\right) \ , \tag{1}$$

where $v = (\sqrt{2}G_F)^{-1/2} = 246.22$ GeV is the Higgs vacuum expectation value setting the electroweak scale with G_F the Fermi constant. For the SM at the tree level, the electron-quark effective couplings are

$$g^{eu}_{AV} = C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W;\ \ g^{ed}_{AV} = C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W$$
$$g^{eu}_{VA} = C_{2u} = -\frac{1}{2} + 2\sin^2\theta_W;\ \ g^{ed}_{VA} = C_{2d} = \frac{1}{2} - 2\sin^2\theta_W.$$

In the previous proposal, the notations $C_{1q,2q}$ were used. The new notation g's [5] differ from the more familiar couplings C_{iq} in the detailed radiative corrections.

In this notation, the asymmetry for PVDIS for the deuteron can be written approximately as

$$A^{\rm DIS}_{RL,d} \approx \frac{3}{20\pi\alpha}\frac{Q^2}{v^2}\left[(2g^{eu}_{AV} - g^{ed}_{AV}) + (2g^{eu}_{VA} - g^{ed}_{VA})\frac{1-(1-y)^2}{1+(1-y)^2}\right] , \tag{2}$$

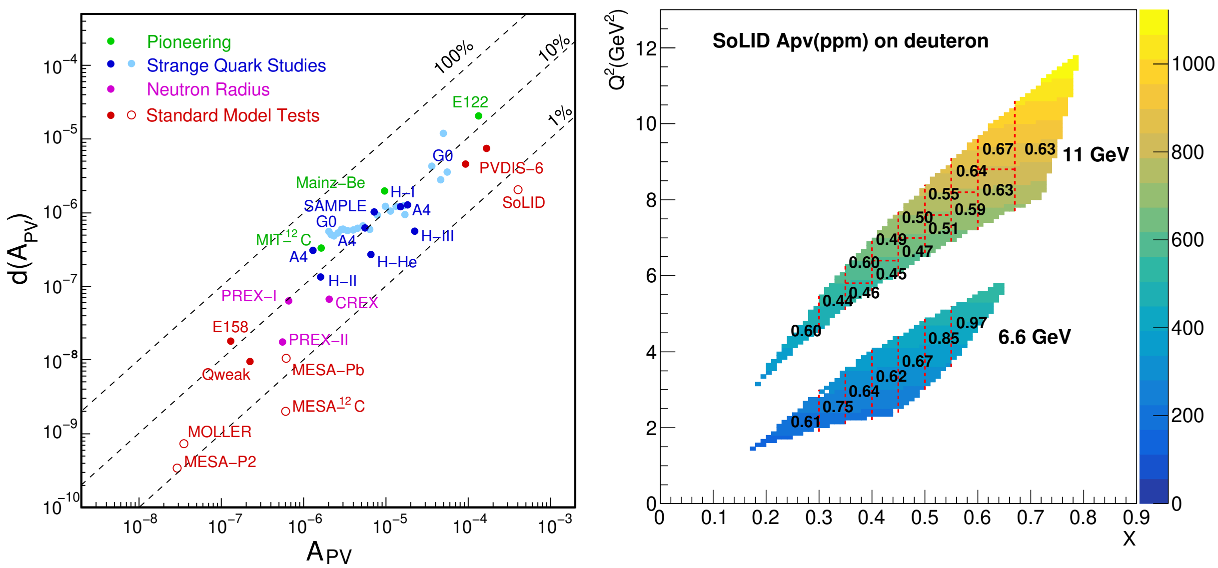

Figure 1: Left panel: History of PVES experiments in the size and precision of the asymmetry measured. Right panel: Anticipated kinematic coverage for SoLID in the PVDIS configuration. The top band is for a 11 GeV beam and the bottom band is for a 6.6 GeV beam. The number in each bin (with bin boundary shown by red dashed lines) represent the relative statistical precision in percent, while the color scale shows the size of A_{PV} for the deuteron in ppm.

where α is the fine structure constant and the PDF and many other possible corrections cancel to first order due to the isoscalar nature of the target. The SoLID spectrometer is designed to have large acceptance at large y, so that A_{PV} is very sensitive to the g_{VA}^{eq} couplings.

The main motivation for the experiment is that PVDIS is the only known experiment that can isolate one combination of the coupling constants, $2g_{VA}^{eu} - g_{VA}^{ed}$ with minimal theoretical errors. For processes at lower values of Q^2, large, uncertain radiative corrections involving hadrons limit the possible precision. The fundamental motivation for PVDIS is that it is important to measure as many of the couplings as possible, each to as high a precision as possible.

From Eq. 2, we see that PVDIS is also sensitive to the g_{AV}^{eq}, but presently these are well known from Atomic parity-violation and the recently-published Qweak experiment [6]. In the future, the P2 experiment [7] at MESA will further improve on the precision of these couplings. With the new data published by Qweak and anticipated from P2, the uncertainty on the g_{AV}^{eq} will essentially be completely negligible in extracting $2g_{VA}^{eu} - g_{VA}^{ed}$, an important development since the proposal was submitted. The projected uncertainties on the couplings from SoLID and P2 are shown in the left panel of Fig. 2. We note from Fig 1 that the the ^{12}C part of P2 proposes to measure an asymmetry at the 0.5% level.

3 Physics beyond the Standard Model

One possibility for BSM physics is new interactions that occur at the multi-TeV scale. At low energies, these interactions are manifest as contact interactions of the form of Eq. 1. In total, there are 86 possible operators for SM particles. The theoretical framework to model these heavy-particle new physics is called Standard Model Effective Field Theory (SMEFT), and global analyses can be done to identify regions of parameter space where new physics is not excluded. In this context, the goal of SoLID is to reduce the volume of this multi-dimensional parameter space by an order of magnitude by measuring one specific combination of the coupling constants.

One experiment at the LHC, the production of Drell-Yan e^+e^- pairs, has relevance for SoLID. Although the observables in the experiment are parity conserving, there are large interference terms with the parity-violating SM that give sensitivity to parity-violating couplings. The experiment thus measures linear combinations of 14 couplings. The SoLID measurement will provide an additional constraint. An SMEFT analysis of the both LHC Drell-Yan and PVES data has been published [8]. The analysis was limited to scenarios where many of the couplings were arbitrarily set to zero. We are awaiting a full model-independent analysis that can show the full impact of SoLID.

Another possibility for BSM physics is the existence of "dark light" in which there is a light boson that also couples to dark matter [9]. The resulting modification to PVES experiments is that $\sin^2\theta_W$ has an additional Q^2-dependence beyond that predicted by the SM. Here, PVDIS is unique in that its $Q^2 \sim 7(\text{GeV/c})^2$. In this scenario, the analysis process is different from the determination of the couplings. Instead of extracting $2g^{eu}_{VA} - g^{ed}_{VA}$, the SM values of the couplings are used and the asymmetry becomes a function of $\sin^2\theta_W$. The value of $\sin^2\theta_W$ can thus be extracted from the measured asymmetry and compared with other high-precision measurements at different Q^2 values.

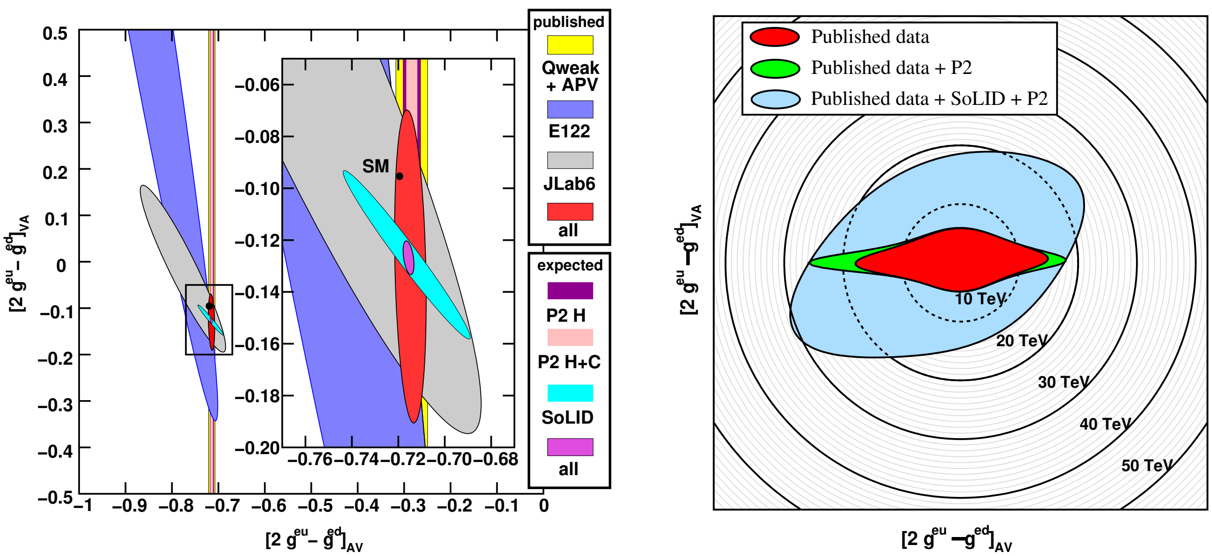

Figure 2: Left panel: Expected limits on the coupling constants from future experiments. Right panel: Projection limits on the scale of BSM physics for SoLID. Definitions are given in Ref.[3].

4 Measurement of the PDF d/u Independent of Nuclear Structure

A measurement of A^{DIS}_{RL} on a proton target is sensitive to the ratio of the d to u quark PDF. The standard determination of the d/u ratio relies on fully inclusive DIS on a proton target compared to a deuteron target. In the large x region, nuclear corrections in the deuteron target lead to large uncertainties in the d/u ratio. However, they can be completely eliminated if the d/u ratio is obtained from the proton target alone, such as from $A_{RL}^{\rm DIS}$ for a proton target, given approximately by

$$A_{RL,p}^{\rm DIS} \approx \frac{1}{4\pi\alpha}\frac{Q^2}{v^2}\left[\frac{12\,g_{AV}^{eu} - 6\,g_{AV}^{ed}\;d/u}{4+d/u}\right].$$

Precision measurements of $A_{RL}^{\rm DIS}$ on a proton target can thus be a powerful and unambiguous probe of the d/u ratio.

Since the proposal was submitted, there have been two important developments in the field on this topic. First, W production data from Fermilab have greatly improved the measurement of d/u at high Q^2 [10]. At low Q^2, the most important development is the publication of recent data from the MARATHON collaboration. The MARATHON data [11] have been interpreted in two different ways [11, 12], highlighting the importance of the proposed measurement of PVDIS asymmetry with a hydrogen target. It is important that the nuclear physics be understood and that the determinations of d/u be understood both from W production and light nuclei.

5 PVDIS at the Future EIC

The Electron Ion Collider (EIC) will be the first lepton-ion collider that polarizes both the electron and the proton (ion) beams, and the first collider with the capacity to flip its electron beam helicity at the source level. These unique design features will allow a direct measurement of A_{PV} at a collider setting for the first time.

The impact of EIC on the determination of the weak mixing angle and NC couplings is marginal [13] because of two reasons: First, while EIC is expected to reach a 10^{33} cm^{-1} s^{-1} luminosity, it is still four orders of magnitude below that of SoLID. Second, the electron beam polarimetry at the EIC is expected to reach 1% uncertainty, limiting the precision of the measurement. We note the larger uncertainty on $\sin^2\theta_W$ expected for the annual integrated luminosity of EIC than our proposed measurement using SoLID. In addition, as outlined in Section 2, only eD scattering will allow a direct access to the combination $2g_{VA}^{eu} - g_{VA}^{ed}$ with minimal ambiguity from PDFs, and it is unlikely that all beam time of EIC will be spent on eD collision. This further limits the impact of EIC on EW NC study in terms of a precision determination of the specific EW couplings $2g_{VA}^{eu} - g_{AV}^{ed}$. Finally, the EIC access, and thus tests the SM, in a different energy range from SoLID.

6 Progress on the SoLID Apparatus

Since the approval in 2010 of five SoLID experiments with high rating by the JLab PAC, the collaboration has developed a Pre-CDR [4] which gives the details for the SoLID apparatus as well as a cost estimate. In 2015, SoLID together with the approved experiments received a strong endorsement from the Nuclear Physics Long Range Plan. In September of 2019, the Pre-CDR successfully passed the second of two JLab Director's Reviews. The latter review covered a detailed cost estimate and detailed analysis that concluded that all critical items were low risk. The Pre-CDR was the basis of the SoLID MIE submitted to the DOE in February of 2020. In 2020, the DOE funded a Pre-R&D plan, which has demonstrated that there are no show-stoppers in the design of SoLID. In March of 2021, the DOE performed the Science Review of SoLID. We give a brief overview of the features of SoLID apparatus and pre-R&D progress below.

In the Pre-CDR, we have demonstrate that the apparatus can achieve the following goals:

1. High luminosity (10^{37} cm^{-2}s^{-1} for SIDIS and J/ψ, 10^{39} cm^{-2}s^{-1} for PVDIS with baffles)
2. Large acceptance: 2π in azimuthal angle ϕ; In polar angle θ: $8° - 24°$ for SIDIS and J/ψ, $22° - 35°$ for PVDIS: Momentum range: $1 - 7$ GeV/c
3. High rates (trigger rate limit 100 KHz for SIDIS and J/ψ, 600 KHz of the 30 sectors for PVDIS)
4. High background tolerance ($\sim$1 GHz, dominated by low energy photons/electrons)
5. High radiation environment tolerance (10^{2-3} krad)
6. Moderate resolutions ($1 - 2\%$ in momentum, $1 - 2$ mrad in θ, 6 mrad in ϕ)
7. Good electron PID; moderate pion PID (SIDIS), and demanding Kaon PID (SIDIS-Kaon, enhanced configuration)
8. High precision with low systematic effects

Since the SoLID experiments were approved, the CLEO magnet, located at Cornell University, was chosen. JLAB requested the magnet in 2012 and it was moved to JLAB in 2016, along with most of the required return iron. JLAB is currently performing minor refurbishment of the magnet and preparing for a cold test to establish the magnet's operational condition. The cold test is scheduled to be completed before the end of 2022.

The SoLID apparatus in its PVDIS configuration is shown in Fig. 3. Significant progress has been made in all subsystems, and many components have been tested and shown to meet specifications. The UVa group has built large GEM chambers with sizes what SoLID needs. They also successfully built and operated GEM detectors for the PRad experiment and SBS experiment. During our recent execution of the Pre-R&D plan, we have tested new VMM3 GEM readout chips, which we plan to use instead of the obsolete APV25 chips listed in the original proposals. We have demonstrated that with the VMM3 chips operated in a mode with a 25 ns shaping time, the readout can handle the high rates required for SoLID.

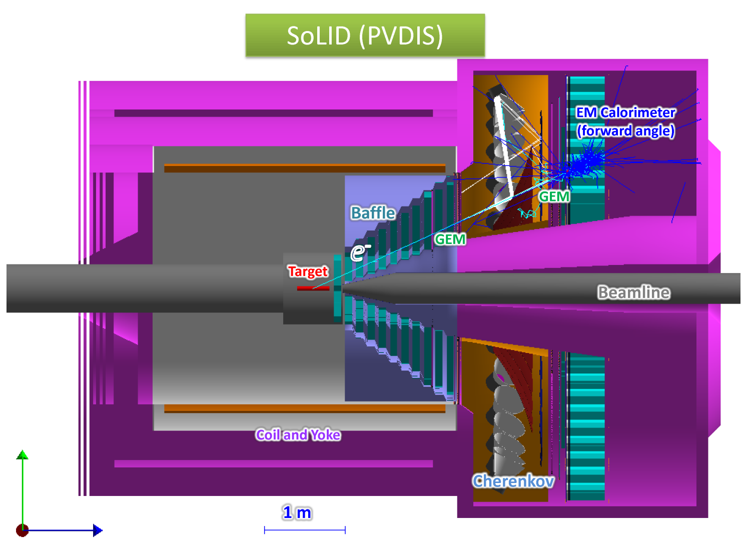

Figure 3: SoLID apparatus in its PVDIS configuration [4].

A prototype Cherenkov was tested with beam at JLab Hall C in 2020, both at low rates and also at high rates equal to those expected in the SoLID spectrometer. Photoelectrons were detected with MaMPT's as described in the proposal. In both the low and high rate configurations, clean signals could be identified and the overall electronics performed very well. In addition, an Incom LAPPD (or large-area micro-channel plate PMT), which can operate at higher magnetic fields, was tested. So far, this new technology appears to be a promising alternative of the Cherenkov readout.

The ECal prototype modules were successfully tested at the Fermilab Test Beam Facility in January of 2021. Data showed that the energy resolution of the 3-module setup reached the SoLID requirement of $\delta E/E = \sqrt{10\%}/\sqrt{E}$ and the position resolution exceeded the required 1 cm specification.

The SoLID DAQ system is based on JLab 12 GeV FADC base pipelined electronics, which now have been successfully used in Hall B and D. The system can meet the PVDIS deadtime requirement of 0.1%. Special features of the JLab FADC required for SoLID, which were built into the JLab design but never used in previous applications, have now been successfully tested for all systems as part of the SoLID Pre-R&D plan.

Currently, a beam test of a full set of SoLID detector prototypes – GEM, LGC, ECal, DAQ and associated electronics– is in preparation. The goal of the test is to fully characterize the functionality of the detector system under a high-rate, high radiation environment that are similar to SoLID operation.

The SoLID simulation software, based on GEMC/GEANT4, is a single package that is used to model all approved experiments and run-group experiments. It is being used to optimize the design and evaluate the impact of the results from the past and ongoing tests. A Kalman Filter based track finding and fitting algorithm was developed and tested with fully digitized GEM simulation data. Tracking resolutions with good tracking efficiency were obtained with background taken into account. We are actively working on assembling simulation, reconstruction, and analysis into one software framework.

Lastly, we anticipate that beam polarimetry will be one of the largest systematic errors. The recently completed CREx experiment achieved an uncertainty in the Compton polarimetry of 0.52% for a 2.18 GeV beam [14]. This is already close to the uncertainty budgeted in our original proposal, and is a promising progress towards the polarimetry precision required by the SoLID PVDIS measurement.

7 Update on Systematic Uncertainties

7.1 Contributions from PDFs

Our current estimate of the systematic uncertainties is given in Table 1. Compared with the original proposal, we have added uncertainty related to the use of PDFs in our analysis process following the recommendation from the March 2021 Science Review. To estimate the effect of PDF uncertainty, we calculated the value of A_{PV} using CT18NLO [15] (LHAPDF [16] ID 14400–14458) and MMHT2014nlo_68cl [17] (ID 25100–25150) PDF sets. Considering data points at $x = 0.4$ and above (which are most relevant for BSM and CSV search), the average relative uncertainty on the deuteron PVDIS asymmetry from CT18NLO is 0.18% (at 90% C.L.) and the values calculated using CT18NLO and MMHT14NLO are consistent within uncertainties. The uncertainty from MMHT14NLO is smaller. We thus use a conservative estimation of 0.2% as an overall uncertainty. The total systematic uncertainty increased from 0.53% in our original proposal to 0.57% and the total uncertainty from 0.61% to 0.64%.

Since the March 2021 Science Review, we have conducted extensive studies of the PDF effect on the extraction of electroweak parameters following the prescription described in Section IV of [13]. We found the effect from PDF uncertainty to be consistent with Table 1.

Polarimetry	0.4
Q^2	0.2
Radiative Corrections	0.2
Event reconstruction	0.2
Statistics	0.3
PDF uncertainty	0.2
Total systematic	0.57
Total statistic and systematic	0.64

Table 1: Updated error budget for the SoLID deuterium PVDIS asymmetry measurement in percent (%).

7.2 Progress on Radiative Corrections

Since 2010, and in particular prompted by the March 2021 Science Review, extensive discussions with theory groups have been made on how a high-precision radiative correction for the measurement can be carried out. First, progress has been made on the uncertainty estimation of external radiative corrections using data that will be collected in the low W region simultaneously with the measurement. For internal radiative correction, we have adapted the event generator `Djangoh` [18], originally developed for HERA cross section analysis, to fixed-target experiments and to nuclear targets. We have made modification to `Djangoh` such that it can be used to calculate parity violation asymmetry to high precision, immune from the statistical limit of a Monte-Carlo program. While there are still detailed work to be done, we anticipate that the 0.2% uncertainty projected on the radiative corrections as given in Table 1 can be reached.

8 Summary

Although the Standard Model has been successful, many experiments at the LHC, JLab, Mainz, Fermilab, etc. are searching for new physics by making precision measurements. One important type of experiments, PVES, includes Qweak, MOLLER and SoLID PVDIS with a deuterium target at JLab and P2 at Mainz. These PVES experiments have made many advances over the years that give them impressive reach for new physics. PVDIS with a hydrogen target can also make a significant contribution to the issues surrounding the measurement the PDF ratio d/u at large x.

The design of the SoLID spectrometer is well underway. The solenoid magnet from the CLEO experiment has arrived at JLab and is being tested. An MIE describing the spectrometer has been submitted to the DOE. The physics case was reviewed by the DOE in March 2021. Extensive simulations have shown that the design is capable of completing the physics goals. A successful Pre-R&D plan has demonstrated that the proposed novel apparatus is on track to meeting the specifications.

References

[1] C. Y. Prescott et al., *Parity Nonconservation in Inelastic Electron Scattering, Phys. Lett. B **77** (1978) 347–352.*

[2] C. Y. Prescott et al., *Further Measurements of Parity Nonconservation in Inelastic electron Scattering, Phys. Lett. B **84** (1979) 524–528.*

[3] PVDIS collaboration, D. Wang et al., *Measurement of parity violation in electron–quark scattering, Nature* ***506*** *(2014) 67–70*.

[4] SoLID collaboration, *Solid (solenoidal large intensity device), updated preliminary conceptual design report, .*

[5] J. Erler and S. Su, *The Weak Neutral Current, Prog. Part. Nucl. Phys.* ***71*** *(2013) 119–149*, [1303.5522].

[6] QWEAK collaboration, D. Androić et al., *Precision measurement of the weak charge of the proton, Nature* ***557*** *(2018) 207–211*, [1905.08283].

[7] D. Becker et al., *The P2 experiment, Eur. Phys. J. A* ***54*** *(2018) 208*, [1802.04759].

[8] R. Boughezal, F. Petriello and D. Wiegand, *Disentangling Standard Model EFT operators with future low-energy parity-violating electron scattering experiments, Phys. Rev. D* ***104*** *(2021) 016005*, [2104.03979].

[9] H. Davoudiasl, H.-S. Lee and W. J. Marciano, *Low Q^2 weak mixing angle measurements and rare Higgs decays, Phys. Rev. D* ***92*** *(2015) 055005*, [1507.00352].

[10] A. Accardi, L. T. Brady, W. Melnitchouk, J. F. Owens and N. Sato, *Constraints on large-x parton distributions from new weak boson production and deep-inelastic scattering data, Phys. Rev. D* ***93*** *(2016) 114017*, [1602.03154].

[11] JEFFERSON LAB HALL A TRITIUM collaboration, D. Abrams et al., *Measurement of the Nucleon F_2^n/F_2^p Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment, Phys. Rev. Lett.* ***128*** *(2022) 132003*, [2104.05850].

[12] JEFFERSON LAB ANGULAR MOMENTUM (JAM) collaboration, C. Cocuzza, C. E. Keppel, H. Liu, W. Melnitchouk, A. Metz, N. Sato et al., *Isovector EMC Effect from Global QCD Analysis with MARATHON Data, Phys. Rev. Lett.* ***127*** *(2021) 242001*, [2104.06946].

[13] R. Boughezal, A. Emmert, T. Kutz, S. Mantry, M. Nycz, F. Petriello et al., *Neutral-Current Electroweak Physics and SMEFT Studies at the EIC,* 2204.07557.

[14] A. Zec, “Compton Polarimetry for Neutral Weak Form Factor Measurements in ^{208}Pb and ^{48}Ca.” Ph.D. thesis, University of Virginia, 2022.

[15] T.-J. Hou et al., *Progress in the CTEQ-TEA NNLO global QCD analysis,* 1908.11394.

[16] A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht et al., *LHAPDF6: parton density access in the LHC precision era, Eur. Phys. J. C* ***75*** *(2015) 132*, [1412.7420].

[17] L. A. Harland-Lang, A. D. Martin, P. Motylinski and R. S. Thorne, *Parton distributions in the LHC era: MMHT 2014 PDFs, Eur. Phys. J. C* ***75*** *(2015) 204*, [1412.3989].

[18] K. Charchula, G. A. Schuler and H. Spiesberger, *Combined QED and QCD radiative effects in deep inelastic lepton - proton scattering: The Monte Carlo generator DJANGO6, Comput. Phys. Commun.* ***81*** *(1994) 381–402*.