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Parity Violation in DIS Region with SoLID at JLab 12 GeV

Ye Tian[a,*] for the SoLID Collaboration

[a] *Syracuse University, Crouse Dr, Syracuse, NY, USA*

E-mail: yetian@syr.edu

In this contribution, we will present an overview of future parity violation deep inelastic scattering (PVDIS) experiments, which will use the proposed Solenoidal Large Intensity Device (SoLID) at Jefferson Lab (JLab). The experiments aim to obtain data with high statistic by a polarized electron beam scattering on unpolarized deuteron and proton targets. The proposed measurements with the SoLID spectrometer will simultaneously cover a large kinematic range in both Bjorken x and the momentum transfer Q^2 ($0.25 < x < 0.75$ and $2\ \text{GeV}^2 < Q^2 < 10\ \text{GeV}^2$). A measurement of PVDIS in the deuteron aims to extract fundamental coupling constants C_{2q} with a high precision, providing an opportunity to probe physics beyond the Standard Model. This measurement can also access QCD physics of searching for charge symmetry violation (CSV) in PDF's and higher-twist effects due to quark-quark correlations. In addition, the proton target experiment can be a powerful probe of the d/u ratio in the valence quark region without any nuclear correction and provide new insight into nuclear effects at high x. The designed SoLID spectrometer with its unique feature of high luminosity and large acceptance will make precision measurements of PVDIS possible. Recent progress on the beam test with a full set of SoLID detector prototypes will be discussed as well.

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1. Introduction

Parity violating electron-scattering (PVES) experiments with longitudinally polarized electrons and unpolarized nucleon or nuclear targets measure the parity violating asymmetry, which arises from the interference between electromagnetic and weak neutral currents. In such PVES, by flipping the spin of the incident electrons, one measures:

$$A_{PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}\ , \tag{1}$$

where $R(L)$ refers to right-handed (left-handed) incident electrons. Measuring A_{PV} can take the advantages of the cancellation of many possible theoretical and experimental uncertainties. PVES has been used as a powerful probe to explore important features of nuclear structure and search for Beyond the Standard Model (BSM) physics. A large number of measurements of A_{PV} have been published or are in progress, which are shown in Fig. 1. Moreover, great progress has been made over the years in improving the precision of A_{PV} measurements. The SoLID program is designed to measure A_{PV} in the deep inelastic scattering region (PVDIS) with a precision of about 0.6% over the kinematic coverage $0.25 < x < 0.75$ and in the momentum transfer $2 < Q^2 < 10$ (GeV/c)^2 range to access the vector-axial coupling between electrons and quarks.

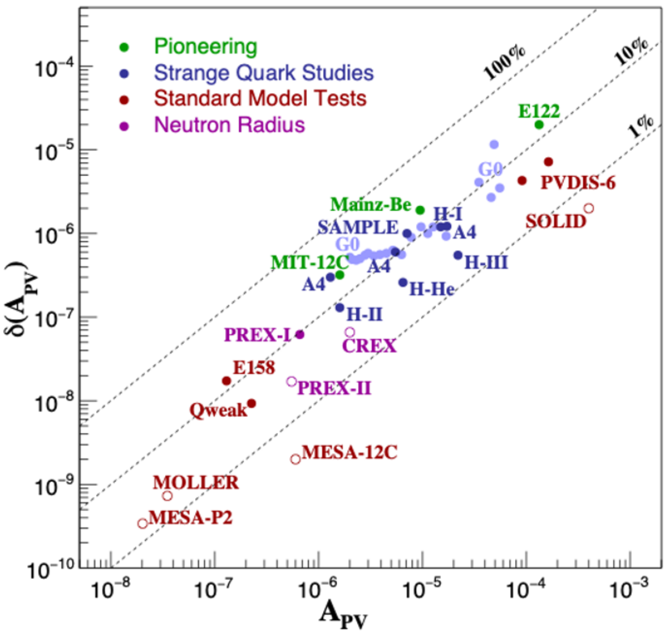


Figure 1: (Figure from Ref. [13]) The history of PVES measurements. The diagonal lines indicate the fractional error in the A_{PV} measurements. $\delta(A_{PV})$ presents total experimental error.

2. PVDIS Deuteron Target Measurement

In DIS region, a general expression for A_{PV} is

$$A_{PV}^{DIS} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + a_3(x)\frac{1-(1-y)^2}{1+(1-y)^2}\right]\ , \tag{2}$$

where $G_F = 1.166 \times 10^{-5}$ GeV^{-2} is the Fermi constant, α is the fine structure constant, $y = \nu/E$, and

$$a_1(x) = 2g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} \ , \ \ a_3(x) = g_V^e \frac{F_3^{\gamma Z}}{F_1^{\gamma}} \ . \tag{3}$$

The structure functions $F_{1,3}^{\gamma;\gamma Z}$ can be written in the parton model in terms of PDFs [12]. For an isoscalar target such as deuterium, the structure functions are canceled out and Eq. (3) can be written as:

$$a_1^D(x) = \frac{6}{5}(2C_{1u} - C_{1d})(1 + \frac{2S^+}{u^+ + d^+}) \ , \ \ a_3^D(x) = \frac{6}{5}(2C_{2u} - C_{2d})(\frac{u^+ - d^-}{u^+ + d^+}) + \ldots \tag{4}$$

In valence qark region, if one neglects sea quarks, then the Eq. (4) can be rewritten as:

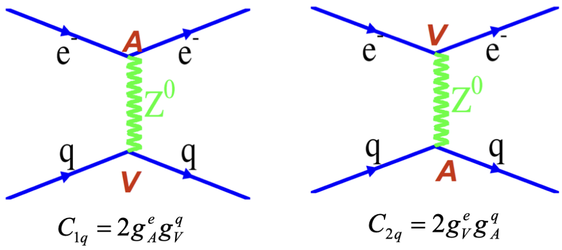


Figure 2: Electromagnetic weak neutral current interaction

$$a_1^D(x) = \frac{6}{5}(2C_{1u} - C_{1d}) \ , \ \ a_3^D(x) = \frac{6}{5}(2C_{2u} - C_{2d}) \tag{5}$$

where C_{1j} and C_{2j} give the axial- vector and vector-axial couplings to the jth quark, respectively (shown in Fig. 2). Those couplings are well defined at the tree level in the Standard Model, which are calculated as:

$$C_{1u} = 2g_A^e g_V^u \approx -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W \approx -0.19 \ , \tag{6}$$

$$C_{2u} = 2g_V^e g_A^u \approx -\frac{1}{2} + 2\sin^2\theta_W \approx -0.030 \ , \tag{7}$$

$$C_{1d} = 2g_A^e g_V^d \approx \frac{1}{2} - \frac{2}{3}\sin^2\theta_W \approx 0.34 \ , \tag{8}$$

$$C_{2d} = 2g_V^e g_A^d \approx \frac{1}{2} - 2\sin^2\theta_W \approx 0.025 \ . \tag{9}$$

It is very useful to measure each C_{ij} couplings as precisely as possible to search for BSM physics. Figure 3 shows the status of those coupling constant measurements. The SoLID PVDIS projection along with 6 GeV PVDIS measurements and the future P2 experiment is going to restrict the phase space for the measurements of the $[2g^{eu} - g^{ed}]_{VA}$ versus $[2g^{eu} - g^{ed}]_{AV}$ significantly, which is in terms of a mass been probed for BSM physics up to an energy scale that is comparable to the reach of the LHC. At large y, measured A_{PV}^{DIS} is sensitive to the C_{2q}, which cannot be studied in low energy reactions because of large and uncertain radiative corrections. The weak missing angle $sin^2\theta_W$ can be extracted by measuring the A_{PV}^{DIS} with isoscalar targets as well. The SoLID

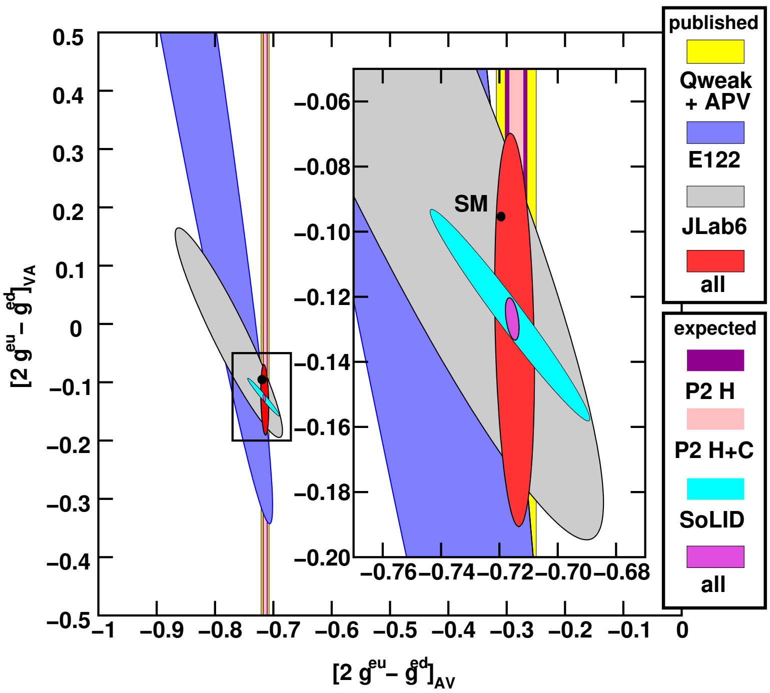


Figure 3: (Figure from Ref. [12]) The phase space of the linear combinations of vector-axial g^{eq}_{VA} and axial-vector g^{eq}_{AV} electron-quark effective coupling constants. By combining the 6 GeV Qweak [11] measurement on g^{eq}_{AV} (yellow vertical band) and the JLab 6 GeV PVDIS [9, 10] measurements (grey ellipse), the available world data constraint is shown as the red ellipse. The SoLID projection is shown as the cyan ellipse. The expected results from P2 are shown as purple and pink vertical bands). The magenta ellipse presents the combined projection by using SoLID, P2, and all existing world data.

Deuteron PVDIS program will provide a new measurement of the weak mixing angle $\sin^2\theta_W$ in the intermediate Q^2 region shown in Fig. 4. Along with the upcoming MOLLER experiment [8] at JLab and the P2 experiment [4] at the MESA facility in Mainz, it will help to distinguish the mass limit of a dark boson Z_d [12]. Regarding the BSM physics, there are a number of possibilities. An interesting one is leptophobic Z' [1]. Since it is vector-axial coupling, it only contributes to the C_2 coupling, which SoLID PVDIS measurement is sensitive for.

The remaining QCD effects: charge symmetry violation and higher-twist effects, which are of great interest in themselves, can be isolated by their kinematic dependence. The A^{DIS}_{PV} precision measurements over a broad kinematic range in both x and Q^2 (shown in Fig. 5) are essential to disentangle those QCD effects and electroweak physics. The A^{DIS}_{PV} projected data is fitted with the function:

$$A^{DIS}_{PV,(D)} = A^{\text{EM}}_{PV,(D)} \left(1 + \frac{\beta_{\text{HT}}}{(1-x)^3 Q^2} + \beta_{\text{CSV}} x^2\right), \qquad (10)$$

where $A^{\text{EM}}_{PV,(D)}$ is expressed in terms of $\sin^2\theta_W$ and the corresponding uncertainty projection is shown in Fig. 4. The fit parameter β_{HT} is related to higher twist effects with a kinematic dependence of $\frac{1}{(1-x)^3Q^2}$, and β_{CSV} is related CSV with a kinematic dependence of x^2. In particular, the new physics is supposed to have a variation with Y, which is a function of the scattered electron energy

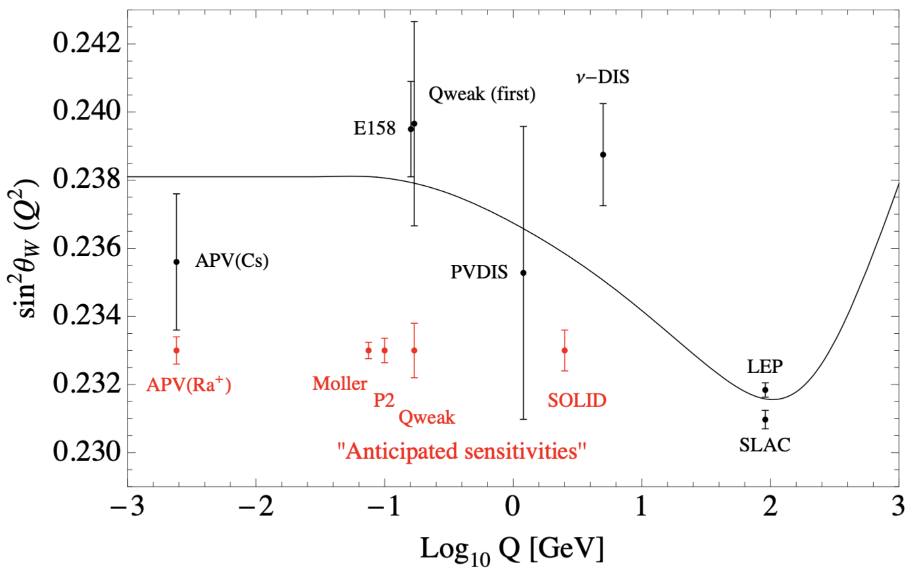


Figure 4: (Adapted from Ref. [3]) Current measurements of the weak mixing angle $sin^2\theta_W$ at various Q, which are shown as black points. The black curve represents the expected SM prediction for the running of $sin^2\theta_W$ with Q [3]. The SoLID projection along with expectations from the experiments under analysis and proposed is illustrated with the red point with possible uncertainties.

given approximately by

$$Y \quad = \quad \frac{1-(1-y)^2}{1+(1-y)^2} \, . \tag{11}$$

The charge symmetry violation is expected to have a variation with x while higher twist effects probably have a large variation with x and Q^2. By fitting the entire field of data that we can take to extract the CSV and higher-twist contributions, the measurement of A_{PV}^{DIS} can be interpreted in terms of the C_{1q} and C_{2q} coupling coefficients.

3. PVDIS Proton Target Measurement

Beside deuterium, hydrogen is another useful target. Since it is a non-isoscalar target, the structure functions do not cancel out in the expression of Eq. (3). The determination of PDF ratio $d(x)/u(x)$ at high x is a topic of considerable interest. The standard determination of the d/u ratio relies on fully inclusive DIS on a proton target compared to a deuteron target. In this way, the complicated nuclear physics effects at large x in Deuteron targets lead to large uncertainties in the d/u ratio. However, the d/u extraction made directly from PVDIS measurement on proton target can eliminate nuclear physics effects corrections. For a proton target, omitting sea quark distributions [14], the A_{PV}^{DIS} in the parton model is given by [12]:

$$A_{PV,(p)}^{DIS} = \frac{3G_F Q^2}{2\sqrt{2}\pi\alpha} \frac{(2g_{AV}^{eu} - \frac{d}{u}g_{AV}^{ed}) + Y[2g_{VA}^{eu} - \frac{d}{u}g_{VA}^{ed}]}{4+\frac{d}{u}} \, . \tag{12}$$

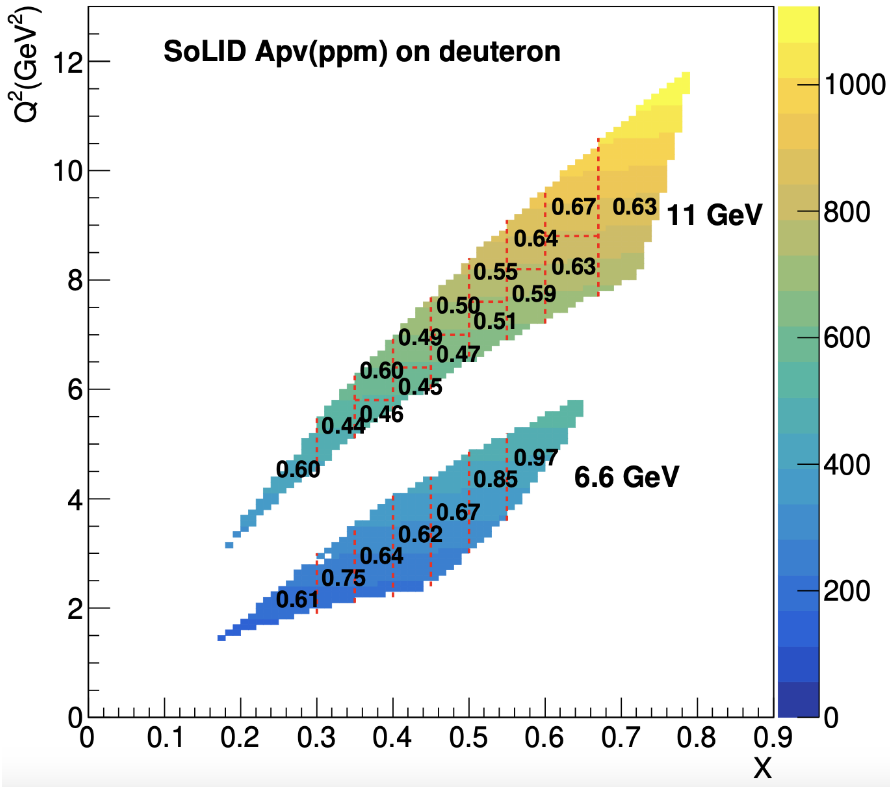


Figure 5: The expected statistical precision in PVDIS asymmetry on a deuteron target is shown on the (x, Q^2) plane for two runs of 120 days at 11GeV and 60 days at 6.6 GeV with a 50 μA beam and 85% polarization. The numbers in each bin indicate the statistical precision of the projected asymmetry.

SoLID PVDIS program is complementary to the rest of the JLab d/u programs, which are shown in Fig. 6. The precision PVDIS proton measurement, as a clean probe, will provide information on the d/u ratio at large x region and on nuclear physics models relevant for future inclusive scattering measurements involving the deuterium or heavier nuclear targets.

4. PVDIS Experimental Setup

To address the need of A_{PV}^{DIS} measurements for a large acceptance in both x and Q^2, a Solenoidal Large Intensity Device (SoLID), shown in Fig. 7, is proposed at Hall A of JLab to measure the A_{PV} in the DIS region (PVDIS) with different targets. SoLID has large acceptance and was designed to handle a very high luminosity up to $10^{39}/cm^2/s$ for the proposed PVDIS measurement. The PVDIS configuration uses five of Gas Electron Multipliers GEM planes for tracking, a light gas Čerenkov (LGC) for electron particle identification (PID) and pions background rejection, and Electromagnetic Calorimeter (ECal) for electron PID. The corresponding polar angle coverage is $22° < \theta < 35°$. Besides, a set of baffles is designed to reduce positive and neutral background particles while keeping a reasonable fraction of DIS electrons. Furthermore, the SoLID PVDIS configuration can observe a possible flavor dependent EMC effect by measuring A_{Pv} on a heavy

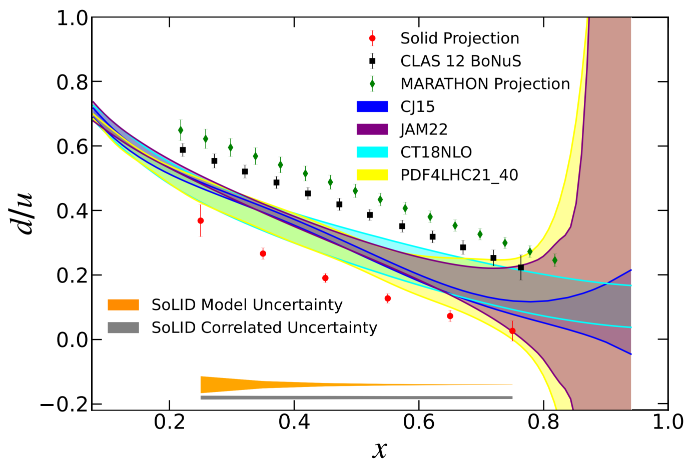


Figure 6: (Figure from Ref. [12]) The projections of d/u ratio from SoLID PVDIS proton measurement shown in red points are compared with the current world fits from a number of PDF groups and their uncertainties. The two horizontal shaded bands show the uncertainty in d/u ratio due to omitting sea quarks in Eq. (12). The black squares and green diamonds are the projections from the proposals [5, 7] of CLAS12 BoNuS and MARATHON experiments [6], respectively.

nuclei target, such as ^{48}Ca. (For further information on the proposed EMC PVDIS experiment with a ^{48}Ca target, see [2].)

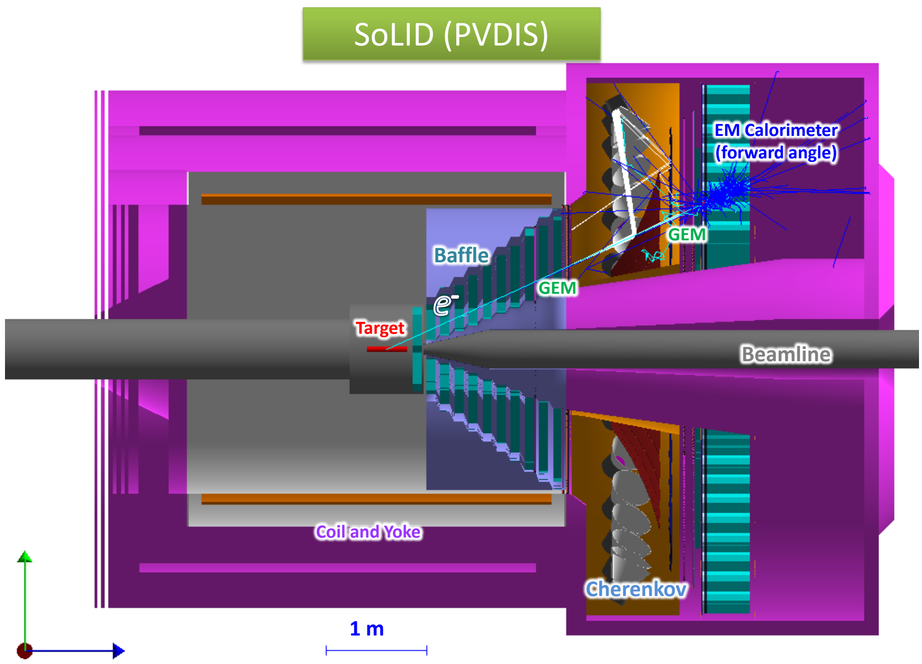
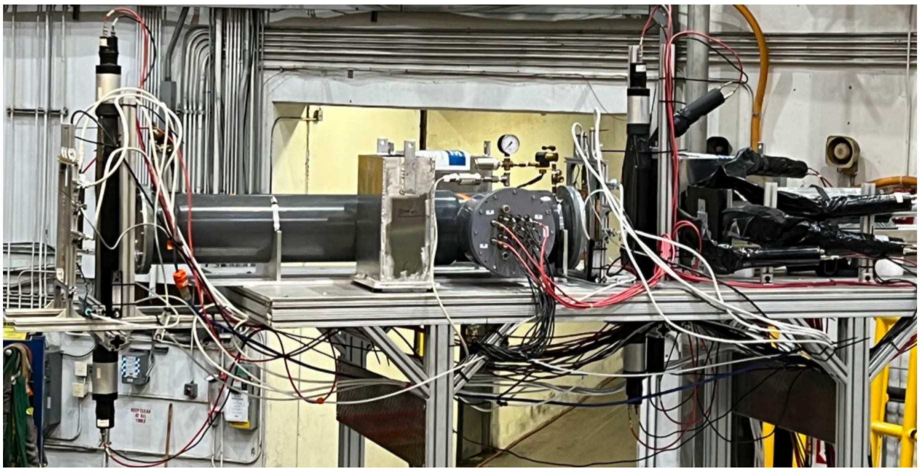


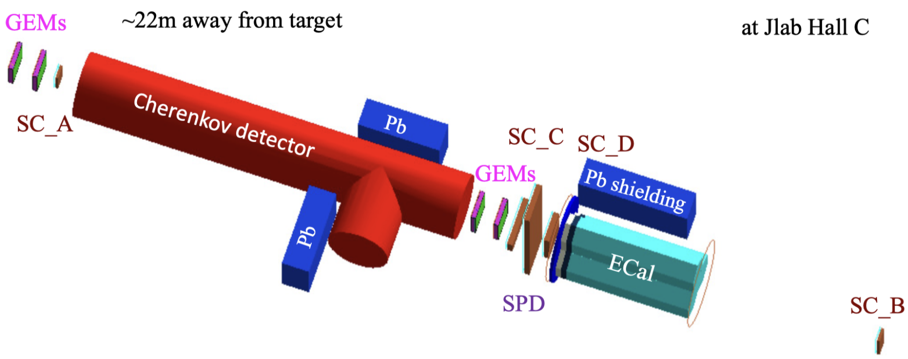
Figure 7: The configuration of SoLID PVDIS setup.

5. Beam Test at Hall C of JLab

A beam test of a full set of SoLID detector prototypes (shown in Fig. 8a and the corresponding simulation configuration is shown in Fig. 8b): GEMs, LGC, a Large Angle Scintillator Pad Detector (LASPD), ECal, DAQ and associated electronics was taken parasitically (without magnetic field) at Hall C of JLab from August 2022 to February 2023, which aims to benchmark simulation of rate and background. Meanwhile the beam test is design study ECal and LASPD performance under high rate, high radiation and high background condition, indeed to study ECal and LASPD particle identification (PID). The beam test stand, which is about 22 m away from the target, was placed at 18° right side of the beam line in where the majority of test data were taken. The beam test data analysis is still ongoing. A preliminary result with the 5 μA photon dominant data sample shows that the photon rejection factor for the prototype LASPD is 7 : 1 (shown in Fig. 9). The data sample used to extract the photon rejection factor contains high energy electrons, which can be further quantified based on the simulation. Thus, the photon rejection factor can be improved ultimately with a more purified photon dominant data sample.



(a)



(b)

Figure 8: (a) Picture of the beam test detectors mounted on the test stand. (b) The corresponding detectors in the simulation setup. From front (left) to back (right): GEM00, GEM01, SC_A, Cherenkov, GEM10, GEM11, SC_C, LASPD, SC_D, Preshower, Shower, and SC_B.

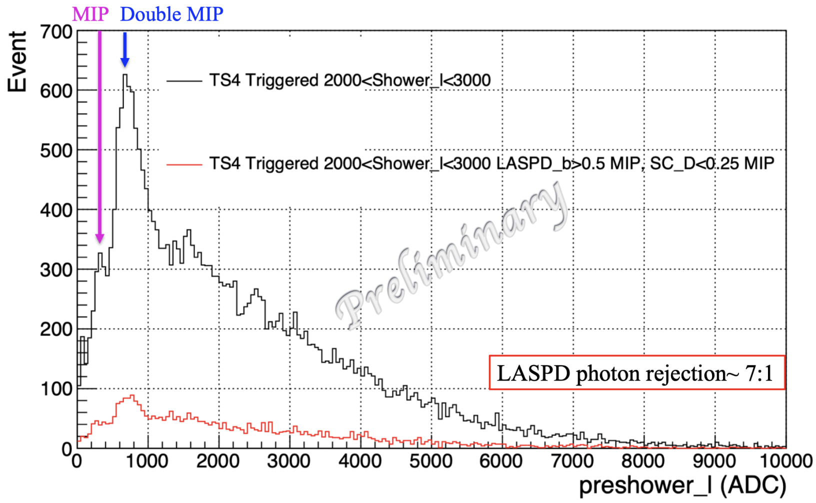


Figure 9: The black histogram shows measured preshower distributions with ShowerSum>0.5 MIP trigger and the shower cuts for selecting the photon dominant events, which contribute to the double MIP peak. The red histogram with additional cuts: LASPD>0.5 MIP and SC_D<0.25 MIP. The ratio of the black histogram and red histogram shows the LASPD photon rejection factor 7 : 1 at the double MIP peak region.

6. Summary

A precision PVDIS measurement on deuteron target is sensitive to C_{2q} weak couplings, which is a precision test of the Standard Model. This measurement can also help on searching charge symmetry violation at the quark level and higher-twist effects due to quark-quark correlations. While a PVDIS measurement on proton target is a clean way to determine the d/u ratio at high-x without any nuclear corrections. Pre-R&D activities on Čherenkov, GEM readout, and Ecal detector beam tests were completed recently. Technical risks were assessed and addressed in the pre-R&D activities.

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