METHODS

The experiment was carried out in Hall A of the Thomas Jefferson National Accelerator Facility (JLab). A 100-μA polarized electron beam was incident on a 20-cm-long liquid deuterium target and scattered events were detected by the Hall A high resolution spectrometer (HRS) pair [1] in inclusive mode. Data were collected at two deep inelastic scattering (DIS) kinematics using a 6.067-GeV beam. Additionally, data were taken at four kinematics in the nucleon resonance region [2] for the purpose of radiative corrections. In the following we will review the formalism of parity-violating electron scattering (PVES) asymmetries, describe in detail the experimental setup and the analysis, and present the asymmetry results along with all corrections applied and the related systematic uncertainties. In the end we present calculations of the expected asymmetry values in the Standard Model.

Formalism

For electron scattering processes, the parity-violating (PV) asymmetry describes the relative difference between scattering cross sections with right-handed electrons σ_R and that with left-handed electrons σ_L:

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

For electron deep inelastic scattering off a nucleon or nuclear target, it can be written as [3]

$$\begin{aligned} A_{\rm PV} &= \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x,Q^2)Y_1(x,y,Q^2)\right. \\ &\quad \left. + a_3(x,Q^2)Y_3(x,y,Q^2)\right], \end{aligned} \tag{2}$$

where G_F is the Fermi constant, α is the fine structure constant, and $Q^2 \equiv -q^2$ is the negative of the four-momentum transferred from the electron to the target. For scatterings with fixed targets, $Q^2 = 2EE'(1-\cos\theta)$, where θ is the electron scattering angle, E and E' are the energies of the incident and the scattered electrons, respectively. The kinematic factors $Y_{1,3}$ are

$$Y_1 = \left[\frac{1+R^{\gamma Z}}{1+R^{\gamma}}\right] \frac{1+(1-y)^2 - y^2\left[1-\frac{r^2}{1+R^{\gamma Z}}\right] - xy\frac{M}{E}}{1+(1-y)^2 - y^2\left[1-\frac{r^2}{1+R^{\gamma}}\right] - xy\frac{M}{E}} \tag{3}$$

and

$$Y_3 = \left[\frac{r^2}{1+R^{\gamma}}\right] \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\left[1-\frac{r^2}{1+R^{\gamma}}\right] - xy\frac{M}{E}} \ , \tag{4}$$

where x is the Bjorken scaling variable $x \equiv Q^2/(2M\nu)$ with M the proton mass and $\nu = E - E'$ the energy transfer from the electron to the target; $y = \nu/E = (E - E')/E$ is the fractional energy loss of the electron, $r^2 = 1 + \frac{Q^2}{\nu^2}$, and $R^{\gamma(\gamma Z)}(x,Q^2)$ is the ratio of the longitudinal to transverse virtual photon electromagnetic absorption cross sections ($\gamma - Z^0$ interference cross sections). To a good approximation one has $R^{\gamma} \approx R^{\gamma Z}$ and $Y_1(y) \approx 1$.

In the simplest process where the electron exchanges a single photon or a single Z^0 boson with quarks inside the target, the measured parity violation can be decomposed into two terms: one from the product of the vector $e-Z^0$ coupling g_V^e and the axial-vector $q-Z^0$ coupling g_A^q, and the other from the product of the axial-vector $e-Z^0$ coupling g_A^e and the vector $q-Z^0$ coupling g_V^q. In this case, the $a_{1,3}$ terms are

$$a_1(x,Q^2) = 2g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}}, \quad a_3(x,Q^2) = g_V^e \frac{F_3^{\gamma Z}}{F_1^{\gamma}} \ . \tag{5}$$

The structure functions of the target, $F_{1,3}^{\gamma,\gamma Z}$, can be interpreted in the quark-parton model (QPM) as being related to the quark couplings and the parton distribution functions (PDF) $q_i(x,Q^2)$ and $\bar{q}_i(x,Q^2)$:

$$F_1^{\gamma}(x,Q^2) = \frac{1}{2}\sum e_{q_i}^2 \left[q_i(x,Q^2) + \bar{q}_i(x,Q^2)\right] , \tag{6}$$

$$F_1^{\gamma Z}(x,Q^2) = \sum e_{q_i} g_V^i \left[q(x,Q^2) + \bar{q}_i(x,Q^2)\right] , \tag{7}$$

$$F_3^{\gamma Z}(x,Q^2) = 2\sum e_{q_i} g_A^i \left[q_i(x,Q^2) - \bar{q}_i(x,Q^2)\right] . \tag{8}$$

Here the summation is over the quark flavor $i = u, d, s \cdots$ and e_{q_i} is the corresponding quark electric charge. In this formalism, relevant to testing of the electroweak Standard Model are the electron's and the quark's axial and the vector weak coupling constants $g_{V,A}^e$ and $g_{V,A}^i$ in Eqs. (5-8). In the Standard Model, the weak axial coupling g_A equals the particle's weak isospin T_3: $g_A = T_3 = 1/2$ for up, charm and top quarks and $-1/2$ for down, strange and bottom quarks and electrons. The weak vector coupling g_V is related to the particle's T_3 and electric charge Q: $g_V = T_3 - 2Q\sin^2\theta_W$ with θ_W the weak mixing angle.

It is also possible to describe the PVES asymmetry using the effective weak coupling constants $C_{1q,2q}$. In the above one-boson exchange picture of the Standard Model:

$$C_{1u} = 2g_A^e g_V^u = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W \ , \tag{9}$$

$$C_{2u} = 2g_V^e g_A^u = -\frac{1}{2} + 2\sin^2\theta_W \ , \tag{10}$$

$$C_{1d} = 2g_A^e g_V^d = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W \ , \tag{11}$$

$$C_{2d} = 2g_V^e g_A^d = \frac{1}{2} - 2\sin^2\theta_W \ . \tag{12}$$

When one considers interactions beyond the Standard Model, however, the factorization of the interaction into a $e - Z^0$ and a $q - Z^0$ vertex is no longer possible. In this case, the couplings $C_{1q,2q}$ could describe not only the photon and the Z^0 exchanges of the Standard Model, but also new $e - q$ contact interactions, electron and quark compositeness, and leptoquarks.

To obtain an intuitive picture of the PVES asymmetry and its decomposition in the Standard Model, more simplifications of Eqs. (5-8) are necessary. Defining $q_i^{\pm}(x,Q^2) \equiv q_i(x,Q^2) \pm \bar{q}_i(x,Q^2)$, one has in the QPM

$$a_1(x,Q^2) = 2\frac{\sum C_{1i} e_{q_i} q_i^+(x,Q^2)}{\sum e_{q_i}^2 q_i^+(x,Q^2)} , \tag{13}$$

$$a_3(x,Q^2) = 2\frac{\sum C_{2i} e_{q_i} q_i^-(x,Q^2)}{\sum e_{q_i}^2 q_i^+(x,Q^2)} . \tag{14}$$

For an isoscalar target such as the deuteron, neglecting effects from heavier quark flavors and assuming the isospin symmetry that $u^p = d^n$, $d^p = u^n$ [$u, d^{p(n)}$ are the up and down quark PDF in the proton (neutron)], $s = \bar{s}$, and $c = \bar{c}$, the functions $a_{1,3}(x,Q^2)$ simplify to

$$a_1(x,Q^2) = \frac{6\left[2C_{1u}(1+R_C) - C_{1d}(1+R_S)\right]}{5+R_S+4R_C} , \tag{15}$$

$$a_3(x,Q^2) = \frac{6\left(2C_{2u}-C_{2d}\right)R_V}{5+R_S+4R_C} , \tag{16}$$

where $R_c \equiv [2(c+\bar{c})]/(u+\bar{u}+d+\bar{d})$, $R_s \equiv [2(s+\bar{s})]/(u+\bar{u}+d+\bar{d})$ and $R_V \equiv (u-\bar{u}+d-\bar{d})/(u+\bar{u}+d+\bar{d})$. The asymmetry then becomes

$$A_{\rm PV} = \left(\frac{3G_F Q^2}{2\sqrt{2}\pi\alpha}\right)\frac{2C_{1u}[1+R_C(x,Q^2)] - C_{1d}[1+R_S(x,Q^2)] + Y_3(2C_{2u}-C_{2d})R_V(x,Q^2)}{5+R_S(x,Q^2)+4R_C(x,Q^2)} . \tag{17}$$

In addition, if one neglects sea quarks completely [4], $R_C = R_S = 0$, $R_V = 1$, no PDF is involved (i.e. neglecting nucleon structure) and

$$a_1(x,Q^2) = \frac{6}{5}\left(2C_{1u}-C_{1d}\right) , \quad a_3(x,Q^2) = \frac{6}{5}\left(2C_{2u}-C_{2d}\right) , \tag{18}$$

which leads to

$$A_{\rm PV} = \left(\frac{3G_F Q^2}{10\sqrt{2}\pi\alpha}\right)\left[(2C_{1u}-C_{1d}) + Y_3(2C_{2u}-C_{2d})\right] . \tag{19}$$

The asymmetry is of the order of magnitude of 10^{-4}, or 10^2 parts per million (ppm) at $Q^2 = 1$ (GeV/c)^2. Comparisons between Eq. (2) and Eq. (19) provides information on how much the input parton distribution functions affect the evaluation of the asymmetry.

Experimental Setup and Analysis Overview

The polarized electron beam was produced by illuminating a strained GaAs photocathode with circularly polarized laser light. The helicity of the electron beam was controlled by a helicity signal, which followed a quartet structure of either "RLLR" or "LRRL", with each state lasting 33 ms and the first state of each quartet selected from a pseudorandom sequence [5–8]. The helicity signal was sent to data acquisition system after being delayed by eight helicity states (two quartets). This delayed helicity sequence controlled the data collection, and periods of beam instability due to helicity reversal were rejected from the data stream. To reduce possible systematic errors, a half-wave plate (HWP) was inserted intermittently into the path of the polarized laser, which resulted in a reversal of the actual beam helicity while keeping the helicity signal sequence unchanged. The expected sign flips in the measured asymmetries between the two beam HWP configurations were observed. The laser optics of the polarized source were carefully configured to minimize changes to the electron-beam parameters under polarization reversal [9, 10]. A feedback system [11] was used to maintain the helicity-correlated intensity asymmetry of the beam below 0.1 parts per million (ppm) averaged over the whole experiment. The target was a 20-cm long liquid deuterium cell, with up- and downstream windows made of 0.10- and 0.13-mm thick aluminum, respectively.

The two DIS kinematics were: DIS#1 was taken at $\langle x\rangle = 0.241$, $Y_1 = 1.0$, $Y_3 = 0.44$ and $\langle Q^2\rangle = 1.085$ (GeV/c)^2, and DIS#2 at $\langle x\rangle = 0.295$, $Y_1 = 1.0$, $Y_3 = 0.69$, $\langle Q^2\rangle = 1.901$ (GeV/c)^2. Due to limitations in the HRS, DIS#1 was taken on the left HRS (the HRS on the left side of the beamline when viewing downstream), and DIS#2 was taken on both left and right HRSs. In order to count electrons up to 600 kHz and reject the pion photo- and electro-production backgrounds, a data acquisition (DAQ) and electronic system was specially designed for this experiment, which formed both electron and pion triggers. A CO_2 gas Čerenkov detector and a double-layered lead-glass shower counter were used to separate electrons from the pion background. The design of the DAQ, along with its particle identification (PID) performance and the deadtime corrections to the measured asymmetries, was reported elsewhere [12]. The overall charged pion π^- contamination was found to contribute less than 4×10^{-4} of the detected electron rate, with an electron detection efficiency of 92% and 95% for DIS#1 and DIS#2, respectively. Using the measured asymmetries from the pion triggers, the relative uncertainty on the measured electron asymmetries $\Delta A/A$ due to the π^- background was evaluated to be less than 2×10^{-4}. Relative corrections on the asymmetry due to DAQ deadtime were $(0.5-1.6)\%$ with uncertainties $\Delta A/A < 0.1\%$. The standard HRS DAQ [1] was used at low beam currents to precisely determine the kinematics of the experiment. This was realized through dedicated measurements on a carbon multi-foil target which provided data to determine the transport function of the HRSs.

The number of scattered particles in each helicity window was normalized to the integrated charge from the beam current monitors, from which the raw asymmetries $A_{\rm raw}$ were formed. The raw asymmetries were then corrected for helicity-dependent fluctuations in the beam parameters, following $A^{\rm bc}_{\rm raw} = A_{\rm raw} - \sum c_i \Delta x_i$, where Δx_i are the measured helicity window differences in the beam position, angle and energy. The values of the correction coefficients c_i could be extracted either from natural movement of the beam (called the "regression" method), or from calibration data collected during the experiment, in which the beam was modulated several times per hour using steering coils and an accelerating cavity (the "dithering" method). The largest of the corrections was approximately 0.6 ppm, and the difference between the two methods, in the range 0.07-0.16 ppm, was used as the systematic uncertainty in the beam corrections.

The beam-corrected asymmetries $A^{\rm bc}_{\rm raw}$ were then corrected for the beam polarization. The longitudinal polarization of the electron beam was measured intermittently during the experiment by a Møller polarimeter [1]. For DIS#1 it measured a polarization of $(88.18\pm1.76)\%$ averaged over the whole run period. The uncertainty was dominated by the knowledge of the Møller target polarization. A Compton polarimeter [13, 14] was used continuously for DIS#2, but was not available for DIS#1. The uncertainty of the Compton measurement came primarily from the limit in understanding the analyzing power. The Møller and Compton measurements for DIS#2 agreed well and were combined to give $(88.89\pm1.51)\%$. The passage of the beam through material before scattering causes a small depolarization effect that was corrected. This was calculated based on Ref. [15] and the beam depolarization was found to be less than 2.1×10^{-4} for all resonance kinematics.

Next, the asymmetries were corrected for various backgrounds. The pair-production background, which results from π^0 decays, was measured at the two DIS kinematics of this experiment by reversing the polarity of the HRS magnets and was found to contribute less than 5×10^{-3} of the detected rate. Since pions come from decay of nucleon resonances, which are produced at lower Q^2 than electrons of the same momentum and hence typically have smaller PV asymmetries, the relative uncertainty on the measured asymmetries due to this background was estimated to be no more than 3×10^{-3}. Background from the aluminum target windows was estimated using Eq. (2), with structure functions $F^{\gamma Z}_{1,3}$ for aluminum constructed from the MSTW2008 DIS PDF [16] and the latest world fit of the ratio of longitudinal to transverse virtual photon electromagnetic absorption cross sections $R\equiv\sigma_L/\sigma_T$ [17]. The relative correction to the asymmetry is at the 1×10^{-4} level with an uncertainty of $\Delta A/A = 0.24\%$ for both DIS#1 and #2. Here the uncertainty is estimated using the observed nuclear effect on the structure function F_1^γ [18–20], which is estimated to be no more than 10% for our two DIS kinematics. Target impurity adds about 0.06% of relative uncertainty to the measured asymmetry due to the presence of a small amount of hydrogen deuteride. Background from particles rescattering off the inner walls of the HRS was estimated using the probability of such rescattering, measured during earlier HAPPEX experiments [5–8]. The rescattering background adds no more than 0.2% relative uncertainty to the measured asymmetry.

Corrections from the beam polarization in the direction perpendicular to the scattering plane can be described as $\delta A = A_n\left[-S_H\sin\theta_{tr} + S_V\cos\theta_{tr}\right]$ where A_n is the beam-normal asymmetry, $S_{V,H,L}$ are respectively the electron polarization components in the vertical, horizontal and longitudinal directions, and θ_{tr} is the vertical angle of the scattered electrons. During the experiment the beam spin components were controlled to $|S_H/S_L| \leqslant 27.4\%$ and $|S_V/S_L| \leqslant 2.5\%$ and the value of θ_{tr} was found to be less than 0.01 rad. Therefore the beam vertical spin dominates this background: $\delta A \approx A_n S_V \cos\theta_{tr} \leqslant (2.5\%)P_b A_n$ where $P_b = S_L$ is the beam longitudinal polarization described earlier. The values of A_n were measured at DIS kinematics and, based on which it was estimated that the uncertainty due to A_n was no more than 2.5% of the measured asymmetries.

Radiative corrections were performed for both internal and external bremsstrahlung as well as ionization loss. External radiative corrections were performed based on the procedure first described by Mo and Tsai [21]. As inputs to the radiative corrections, PV asymmetries of elastic scattering from the deuteron were estimated using Ref. [22–24] and those from quasi-elastic scattering were based on Ref. [5]. PV asymmetries in the nucleon resonance region were based on our own resonance asymmetry results [2] and three theoretical models [25–27]. The simulation used to calculate the radiative corrections also takes into account the effect of HRS acceptance and particle identification efficiency variation across the acceptance.

Box-diagram corrections refer to effects that arise when the electron simultaneously exchanges two bosons ($\gamma\gamma$, γZ, or ZZ box) with the target, and they are dominated by the $\gamma\gamma$ and the γZ box diagrams. For PVES asymmetries, the box diagram effects include those from the interference between γ-exchange and the γZ box, the interference between Z-exchange and the $\gamma\gamma$ box, and the effect of the $\gamma\gamma$ box on the electromagnetic cross sections. Correction from the latter two was estimated to be -0.2% and -0.3% for DIS#1 and #2, respectively [28]. The uncertainty was estimated conservatively to be $\pm 0.2\%$ and $\pm 0.3\%$ respectively, i.e., a relative 100% uncertainty. The effect from the γZ box was taken into account as part of the electroweak radiative corrections and no $\gamma - Z$ correction was applied to the measured asymmetry.

Results for the measured physics asymmetry $A_{\rm exp}$ were formed from the beam-corrected asymmetry $A^{\rm bc}_{\rm raw}$ by correcting for the beam polarization P_b and backgrounds described above, with asymmetry A_i and fraction f_i, using the equation

$$A_{\rm exp} = \frac{\left(\frac{A^{\rm bc}_{\rm raw}}{P_b} - \sum_i A_i f_i\right)}{1 - \sum_i f_i} \ . \tag{20}$$

When all f_i are small with A_i comparable to or smaller than $A^{\rm bc}_{\rm raw}$, one can define $\bar{f}_i = f_i(1 - \frac{A_i}{A^{\rm bc}_{\rm raw}} P_b)$ and approximate

$$A_{\rm exp} \approx \frac{A^{\rm bc}_{\rm raw}}{P_b} \Pi_i \left(1 + \bar{f}_i\right) \ , \tag{21}$$

i.e., all corrections can be treated as multiplicative.

Table I of Supplementary Information presents the measured asymmetries along with all corrections and the final physics asymmetry results for the two DIS kinematics. The dithering-corrected asymmetries measured by the DAQ were used as $A^{\rm bc}_{\rm raw}$ and the difference between dithering and regression methods were used as the systematic uncertainty of $A^{\rm bc}_{\rm raw}$.

Calculation of Standard Model Expectations

In this section we explain how the Standard Model expectations of the parity-violating DIS (PVDIS) asymmetries were obtained. Based on these calculations, the asymmetries were expressed in terms of $2C_{1u} - C_{1d}$ and $2C_{2u} - C_{2d}$, allowing a simultaneous fit to these quantities that led to the main results presented for this experiment. At the end we address the higher twist effect due to quark-quark correlations inside the nucleon.

Electroweak radiative corrections were applied to all couplings used in the calculation of the asymmetry. The electromagnetic fine structure constant α was evolved to the measured Q^2 values from $\alpha_{EM}|_{Q^2=0} = 1/137.036$ [4]. The evaluation takes into account purely electromagnetic vacuum polarization. The Fermi constant is $G_F = 1.1663787(6) \times 10^{-5}$ GeV^{-2} [4]. The $C_{1q,2q}$ were evaluated using Table 7 and Eq. (114-115) of Ref. [29] at our measured Q^2 values in the $\overline{MS}$ scheme using a fixed Higgs mass $M_H = 125.5$ GeV, and the uncertainty is negligible. This calculation includes the "charge radius effect" and an estimate of the interference between γ-exchange and the γZ box, but not the effect from the $\gamma\gamma$ box. The effect from the $\gamma\gamma$ box was applied as a correction to the measured asymmetry as described in previous sections.

To express the measured asymmetries in terms of $2C_{1u} - C_{1d}$ and $2C_{2u} - C_{2d}$, we calculated all $F^{\gamma;\gamma Z}_{1,3}$ structure functions in Eqs. (2,5) based on parameterizations of parton distribution functions (PDFs). If calculations of the structure functions from PDFs are not available, the quark-parton model Eqs. (6-8) were used. In this case, leading-order (LO) PDFs were used whenever possible. The most suitable calculation for our kinematics is from the CTEQ/JLab ("CJ") fit [30] which provides structure functions at the next-to-leading order (NLO). However, the CJ fit does not apply to Q^2 values below 1.7 (GeV/c)^2. To utilize the $Q^2 = 1.085$ (GeV/c)^2 asymmetry result, it was necessary to compare the CJ calculation to other PDF fits at $Q^2 = 1.901$ (GeV/c)^2 and decide on the best PDF to use for Q^2 values below 1.7 (GeV/c)^2. This comparison was done among CJ, CT10 [31] and MSTW2008 [16]. For both CT10 and MSTW2008, the quark-parton model was used to calculate the structure functions PDFs. It was found that the leading-order MSTW2008 fit gives the closest results to CJ. The variation among all three fits was found to be small, at the level of relative 0.5% for the a_1 term and relative 5% for the a_3 term of the asymmetry. These variations were used as estimates of the uncertainty due to PDF and structure-function calculations. Values of the $a_{1,3}$ terms of the asymmetries are presented in Table II of Supplementary Information.

As can be seen from Eq. (13,14), the $a_{1,3}$ terms of the asymmetry are proportional to the $C_{1,2}$ couplings respectively. This proportionality, i.e. the coefficient for $2C_{1u} - C_{1d}$ or $2C_{2u} - C_{2d}$ in the asymmetry, describe quantatively the sensitivity to these couplings. This sensitivity is also shown in Table II of Supplementary Information.

The effect of possible differences between $R^{\gamma Z}$ and R^{γ} were studied [32]: To account for a shift of 1 ppm in the asymmetry, 7.7% and 4.5% differences between $R^{\gamma Z}$ and R^{γ} are needed, for $Q^2 = 1.085$ and 1.901 (GeV/c^2), respectively. Such large differences were considered highly unlikely and the uncertainty in the asymmetry due to the possible difference between $R^{\gamma Z}$ and R^{γ} was considered to be negligible compared to statistical uncertainties of the measurement.

The higher-twist (HT) effects refer to the interaction between quarks inside the nucleon at low Q^2, where renormalization of the QCD coupling breaks down. At a relative low Q^2 but not low enough for the effective QCD coupling to diverge, the HT effects introduce a $1/Q^2$-dependence to the structure functions in addition to the $\ln Q^2$ perturbative QCD evolution. The HT effects modify the PVDIS asymmetry through a change in the absorption cross section ratio R^γ in Eqs. (3,4), or through changes in the structure function ratios a_1 and a_3 of Eq. (5). The effect on R^γ was estimated in Ref. [33] and was found to be negligible. Studies of the HT effects on the PVDIS asymmetry through changes in the structure functions dates back to the SLAC E122 experiment [34, 35], where it was argued that the HT effects on the a_1 term of the asymmetry is very small. Latest discussions on HT effects of the PVDIS asymmetry, represented by work in Refs.[36–38], indicated that the HT contribution to the a_1 term is below or at the order of $0.5\%/Q^2$ for the x range of this experiment, where Q^2 is in units of GeV^2.

There is no theoretical estimation of the HT effects on the a_3 term of the asymmetry. However this term is bound by data on the neutrino structure function H_3^ν [33], which has the same quark content as $F_3^{\gamma Z}$. If applying the observed H_3^ν higher-twist Q^2 dependence to $F_3^{\gamma Z}$ alone, one expects the asymmetry to shift by +0.7 ppm and +1.2 ppm for the lower and the higher Q^2 results. We used these values as the uncertainty in the a_3 term due to HT effects.

Overall, a combination of theoretical and experimental bounds on the HT effects indicate that they do not exceed 1% of our measured asymmetry. The uncertainties in the a_1 and the a_3 terms were evaluated separately and the corresponding uncertainty in in C_{2q} due to the HT effects is in the order 0.01 and is negligible compared to the experimental uncertainties.

On the other hand, the HT effects represent non-perturbative correlations among quarks inside the nucleon and is worth studying on their own. For PVDIS asymmetries, the HT effects can be investigated through a fit

$$A_{\rm exp} \;=\; A_{\rm PV}^{EW}\left(1+\frac{\beta_{HT}}{(1-x)^3Q^2}\right)\,, \qquad (22)$$

where β_{HT} is the HT coefficient, $A_{\rm PV}^{EW}$ is the value calculated based on the Standard Model, the $1/Q^2$ factor is based on the expected Q^2-dependence of the HT term as mentioned earlier, and the $(1-x)^3$ term corresponds to the correlation probability among spectator quarks. Fitting to both E122 results and our measurement gives $\beta_{HT} = 0.034 \pm 0.043$ (GeV)^2, which is consistent with the expectation that our measurements are not sensitive to the HT effects at current precisions.

[1] Alcorn, J. *et al.*, Basic Instrumentation for Hall A at Jefferson Lab, Nucl. Instrum. Meth. A **522**, 294 (2004).

[2] Wang, D. *et al.* [Jefferson Lab Hall A Collaboration], Measurement of the Parity-Violating Asymmetry in Electron-Deuteron Scattering in the Nucleon Resonance Region, Phys. Rev. Lett. **111**, 082501 (2013).

[3] Cahn, R.N. and Gilman, F.J., Polarized electron-Nucleon Scattering in Gauge Theories of Weak and Electromagnetic Interactions, Phys. Rev. D **17**, 1313 (1978).

[4] Beringer, J. *et al.* [Particle Data Group Collaboration], Review of Particle Physics (RPP), Phys. Rev. D **86**, 010001 (2012).

[5] Aniol, K.A. *et al.* [HAPPEX Collaboration], Parity violating electroweak asymmetry in polarized-e p scattering, Phys. Rev. C **69**, 065501 (2004).

[6] Aniol, K.A. *et al.* [HAPPEX Collaboration], Parity-violating electron scattering from ^{4}He and the strange electric form-factor of the nucleon, Phys. Rev. Lett. **96**, 022003 (2006).

[7] Aniol, K.A. *et al.* [HAPPEX Collaboration], Constraints on the nucleon strange form-factors at $Q^2 = 0.1$ (GeV)^2, Phys. Lett. B **635**, 275 (2006).

[8] Acha, A. *et al.* [HAPPEX Collaboration], Precision Measurements of the Nucleon Strange Form Factors at $Q^2 \sim 0.1$ GeV^2, Phys. Rev. Lett. **98**, 032301 (2007);

[9] Sinclair, C.K. *et al.*, Development of a high average current polarized electron source with long cathode operational lifetime, Phys. Rev. ST Accel. Beams **10**, 023501 (2007);

[10] Adderley, P.A. *et al.*, Load-locked dc high voltage GaAs photogun with an inverted-geometry ceramic insulator, Phys. Rev. ST Accel. Beams **13**, 010101 (2010).

[11] Paschke, K.P., Controlling helicity-correlated beam asymmetries in a polarized electron source, Eur. Phys. J. A **32**, 549 (2007).

[12] Subedi, R. *et al.* A Scaler-Based Data Acquisition System for Measuring Parity Violation Asymmetry in Deep Inelastic Scattering, Nucl. Instrum. Meth. A. **724**, 90 (2013).

[13] M. Friend *et al.*, Upgraded photon calorimeter with integrating readout for Hall A Compton Polarimeter at Jefferson Lab, Nucl. Instrum. Meth. A **676**, 96 (2012);

[14] Escoffier, S. *et al.*, Accurate measurement of the electron beam polarization in JLab Hall a using Compton polarimetry, Nucl. Instrum. Meth. A **551**, 563 (2005).

[15] Olsen, H. and Maximon, L.C., Photon and Electron Polarization in High-Energy Bremsstrahlung and Pair Production with Screening, Phys. Rev. **114**, 887 (1959).

[16] Martin, A.D., Stirling, W.J., Thorne, R.S. and Watt, G., Parton distributions for the LHC, Eur. Phys. J. C **63**, 189 (2009).

[17] Bosted, P.E. and Christy, M.E., Empirical fit to inelastic electron-deuteron and electron-neutron resonance region transverse cross-sections, Phys. Rev. C **77**, 065206 (2008).

[18] Gomez, J. *et al.*, Measurement of the A-dependence of deep inelastic electron scattering, Phys. Rev. D **49**, 4348 (1994).

[19] Stein, S. *et al.*, Phys. Rev. D **12**, 1884 (1975).

[20] Rock, S. and Bosted, P.E., Ratio of electron scattering from nuclei to deuterium at low x and low momentum transfer, Phys. Lett. B **518**, 34 (2001).

[21] Mo, L.W. and Tsai, Y.S., Radiative Corrections to Elastic and Inelastic e p and mu p Scattering, Rev. Mod. Phys. **41**, 205 (1969).

[22] Beise, E.J., Pitt, M.L. and Spayde, D.T., The SAMPLE experiment and weak nucleon structure, Prog. Part. Nucl. Phys. **54**, 289 (2005);

[23] Abbott, D. *et al.*, [JLAB t20 Collaboration], Phenomenology of the deuteron electromagnetic formfactors, Eur. Phys. J. A **7**, 421 (2000);

[24] Pollock, S.J., Strange quarks in the deuteron, Phys. Rev. D **42**, 3010 (1990), [Erratum-ibid. D **43**, 2447 (1991)].

[25] Matsui, K., Sato, T. and Lee, T.-S.H., Phys. Rev. C **72**, 025204 (2005).

[26] Gorchtein, M., Horowitz, C.J., and Ramsey-Musolf, M.J., Model-dependence of the γZ dispersion correction to the parity-violating asymmetry in elastic *ep* scattering, Phys. Rev. C **84**, 015502 (2011); Gorchtein, M. private communication.

[27] Hall, N.L., Blunden, P.G., Melnitchouk, W., Thomas, A.W. and Young, R.D., Constrained gamma-Z interference corrections to parity-violating electron scattering, Phys. Rev. D **88**, 013011 (2013).

[28] Blunden, P., private communication.

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

[30] Owens, J.F., Accardi, A. and Melnitchouk, W., Global parton distributions with nuclear and finite-Q^2 corrections, Phys. Rev. D **87**, 094012 (2013).

[31] Lai, H.L. *et al.*, New parton distributions for collider physics, Phys. Rev. D **82**, 074024 (2010).

[32] Hobbs, T. and Melnitchouk, W., Finite-Q^2 corrections to parity-violating DIS, Phys. Rev. D **77**, 114023 (2008).

[33] Alekhin, S., Kulagin, S.A. and Petti, R., Modeling lepton-nucleon inelastic scattering from high to low momentum transfer, AIP Conf. Proc. **967**, 215 (2007).

[34] Bjorken, J.D., Model Independent Remarks On Electron - Quark Parity Violating Neutral - Current Couplings, Phys. Rev. D **18**, 3239 (1978).

[35] Wolfenstein, L., Testing the Weinberg-Salam Model in Polarized *ed* and *ep* Deep Inelastic Scattering, Nucl. Phys. B **146**, 477 (1978).

[36] Mantry S., Ramsey-Musolf M.J. and Sacco G.F., Examination of higher-order twist contributions in parity-violating deep-inelastic electron-deuteron scattering, Phys. Rev. C **82**, 065205 (2010).

[37] Belitsky, A.V, Manashov, A. and Schafer, A., Twist-four Corrections to Parity-Violating Electron-Deuteron Scattering, Phys. Rev. D **84**, 014010 (2011).

[38] Seng, C.-Y. and Ramsey-Musolf, M.J., Parity Violating Deep Inelastic Electron-Deuteron Scattering: Higher Twist and Parton Angular Momentum, Phys. Rev. C **88**, 015202 (2013).