The JLab 6 GeV Parity Violation Deep Inelastic Scattering (PVDIS) Experiment

Xiaochao Zheng (Univ. of Virginia)

June 2nd, 2014

- PVDIS and electron-quark effective couplings
- The 6 GeV PVDIS experiment
- DIS results - electron-quark effective VA couplings
- Resonance results - duality in EW sector?
- Outlook for the 12 GeV Program - PVDIS with SoLID
Parity-Violating Electron Scattering

- To study nucleon structure not accessible in electromagnetic interaction:
  - elastic PVES: nucleon strange form factors; “neutron skin” in heavy nucleus

- To test the electroweak Standard Model:
  - Moller - E158
  - PVDIS
Parity Violation in the Standard Model

In weak interaction, all elementary fermions behave differently under parity transformation.

- They have a preferred chiral state when coupling to the $Z^0$. 

X. Zheng, JLab UGM 2014
Unlike electric charge, need two charges (couplings) for weak interaction: $g_L$, $g_R$

or “vector” and “axial” weak charges: $g_V \sim (g_L + g_R)$, $g_A \sim (g_L - g_R)$
Unlike electric charge, need two charges (couplings) for weak interaction: $g_L$, $g_R$

or “vector” and “axial” weak charges: $g_V \sim (g_L + g_R)$  
$g_A \sim (g_L - g_R)$

PVES asymmetry comes from $V(e) \times A(\text{targ})$ and $A(e) \times V(\text{targ})$
Unlike electric charge, need two charges (couplings) for weak interaction: $g_L, g_R$

or “vector” and “axial” weak charges: $g_V \sim (g_L + g_R), \quad g_A \sim (g_L - g_R)$

PVDIS asymmetry comes from:

$$C_{1q} \equiv 2g^e_A g^q_V, \quad C_{2q} \equiv 2g^e_V g^q_A$$

“electron-quark effective couplings”
Unlike electric charge, need two charges (couplings) for weak interaction: $g_L, g_R$

or “vector” and “axial” weak charges: $g_V \sim (g_L + g_R)$  $g_A \sim (g_L - g_R)$

PVDIS asymmetry comes from:

$C_{1q} \equiv 2 g_A^e g_V^q$,  $C_{2q} \equiv 2 g_V^e g_A^q$

“electron-quark effective couplings”
Unlike electric charge, need two charges (couplings) for weak interaction: $g_L$, $g_R$

or “vector” and “axial” weak charges: $g_V \sim (g_L + g_R)$, $g_A \sim (g_L - g_R)$

PVDIS asymmetry comes from:

$C_{1q} \equiv 2g_A^e g_V^q$, $C_{2q} \equiv 2g_V^e g_A^q$

“electron-quark effective couplings”

$C_{1q} = g_A^{e\,q}$, $C_{2q} = g_V^{e\,q}$

Accessing $C_{1q,2q}$

- Need electron beam on hadronic target
- In elastic PVES
  - directly probes $C_{1q}$, electrons' parity-violating property;
  - quarks' parity-violation is represented by the nucleon axial form factor $G_A$, and extracting $C_{2q}$ from $G_A$ is model-dependent
- Only in PVDIS, electron probes the quark and PVDIS asymmetry depends on $C_{2q}$ directly.
Formalism for Parity Violation in DIS

For an isoscalar target \(^2\text{H}\), structure functions largely simplifies:

\[
A_{PV} = \frac{G_F Q^2}{\sqrt{2 \pi \alpha}} [a(x) + Y(y) b(x)]
\]

\[
a(x) = \frac{1}{2} g_A^e \frac{F_{1}^{YZ}}{F_{1}^{Y}} = \frac{1}{2} \sum_i C_{1i} Q_i q^+_i (x) \]

\[
b(x) = g_V^e \frac{F_{3}^{YZ}}{F_{1}^{Y}} = \frac{1}{2} \sum_i C_{2i} Q_i q^-_i (x)
\]

\[
x \equiv x_{Bjorken} \quad y \equiv 1 - E'/E
\]

\[
q^+_i (x) \equiv q_i (x) + \bar{q}_i (x)
\]

\[
q^-_i (x) = q_i^V (x) \equiv q_i (x) - \bar{q}_i (x)
\]

\[
a(x) = \frac{3}{10} (2 C_{1u} - C_{1d}) \left(1 + \frac{0.6 s^+}{u^+ + d^+} \right)
\]

\[
b(x) = \frac{3}{10} (2 C_{2u} - C_{2d}) \left(\frac{u_v + d_v}{u^+ + d^+} \right)
\]
Formalism for Parity Violation in DIS

\[ A_{PV} = \frac{G_F Q^2}{\sqrt{2} \pi \alpha} \left[ a(x) + Y(y) b(x) \right] \]

For an isoscalar target (\(^2\text{H}\)), structure functions largely simplifies:

\[ a(x) = \frac{1}{2} g_A \frac{F_1^{yz}}{F_1^y} = \frac{1}{2} \sum_i C_{1i} Q_i q_i^+(x) \sum_i Q_i^2 q_i^+(x) \]

\[ b(x) = g_V \frac{F_3^{yz}}{F_1^y} = \frac{1}{2} \sum_i C_{2i} Q_i q_i^-(x) \sum_i Q_i^2 q_i^+(x) \]

If neglecting sea quarks, asymmetry is no longer sensitive to PDFs → “static limit”

\[ x \equiv x_{Bjorken} \quad y \equiv 1 - E'/E \]

\[ q_i^+(x) \equiv q_i(x) + \bar{q}_i(x) \]

\[ q_i^-(x) = q_i^V(x) \equiv q_i(x) - \bar{q}_i(x) \]
Best Data on $C_{1q}$ (eq AV couplings) from PVES+APV

Androic et al., PRL 111, 141803 (2013);
Projecting to $C_{1q}$ vs $C_{2q}$ (e-q AV vs. VA couplings)

$2C_{2u} - C_{2d}$ vs $2C_{1u} - C_{1d}$
Add E122

\[ 2C_{2u} - C_{2d} \]

\[ 2C_{1u} - C_{1d} \]

-1.50 \quad -1.25 \quad -1.0 \quad -0.75 \quad -0.50
and combine them
then zoom in
PVDIS at 6 GeV (JLab E08-011)
PVDIS at 6 GeV (JLab E08-011)

- Ran in Oct-Dec 2009, 100uA, 90% polarized electron beam, 20-cm liquid deuterium target
- Two High Resolution Spectrometers (HRS pair) detected electrons in the inclusive mode at DIS $Q^2=1.1$ and $1.9 \text{ GeV}^2$, and five resonance kinematics.
- Scaler-based fast counting DAQ specifically built for the 500kHz DIS rates w/ $10^4$ pion rejection.
### E08-011 Kinematics

<table>
<thead>
<tr>
<th>Kine#</th>
<th>HRS</th>
<th>$E_b$ (GeV)</th>
<th>$\theta_0$ (deg)</th>
<th>$E'_0$ (GeV)</th>
<th>$R_e$ (kHz)</th>
<th>$R_{\pi^-}/R_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIS#1</td>
<td>Left</td>
<td>6.067</td>
<td>12.9</td>
<td>3.66</td>
<td>$\approx 210$</td>
<td>$\approx 0.5$</td>
</tr>
<tr>
<td>DIS#2</td>
<td>Left &amp; Right</td>
<td>6.067</td>
<td>20.0</td>
<td>2.63</td>
<td>$\approx 18$</td>
<td>$\approx 3.3$</td>
</tr>
<tr>
<td>RES I</td>
<td>Left</td>
<td>4.867</td>
<td>12.9</td>
<td>4.0</td>
<td>$\approx 300$</td>
<td>$&lt; \approx 0.25$</td>
</tr>
<tr>
<td>RES II</td>
<td>Left</td>
<td>4.867</td>
<td>12.9</td>
<td>3.55</td>
<td>$\approx 600$</td>
<td>$&lt; \approx 0.25$</td>
</tr>
<tr>
<td>RES III</td>
<td>Right</td>
<td>4.867</td>
<td>12.9</td>
<td>3.1</td>
<td>$\approx 400$</td>
<td>$&lt; \approx 0.4$</td>
</tr>
<tr>
<td>RES IV</td>
<td>Left</td>
<td>6.067</td>
<td>15</td>
<td>3.66</td>
<td>$\approx 80$</td>
<td>$&lt; \approx 0.6$</td>
</tr>
<tr>
<td>RES V</td>
<td>Left</td>
<td>6.067</td>
<td>14</td>
<td>3.66</td>
<td>$\approx 130$</td>
<td>$&lt; \approx 0.7$</td>
</tr>
</tbody>
</table>
Scalier-Based Counting DAQ with online (hardware) PID

- DIS region, pions contaminate, can't use integrating DAQ.
- High event rate (~500KHz), exceeds Hall A regular DAQ's Limit (4kHz)

Scalier-Based Counting DAQ with online (hardware) PID

- DIS region, pions contaminate, can't use integrating DAQ.
- High event rate (~500KHz), exceeds Hall A regular DAQ's Limit (4kHz)
PID Performance - Single Run

Electron Detection Efficiency

Pion Rejection Factor

Affects measured asymmetry ($Q^2$) if it varies over the acceptance or if there are “holes”

Combined with Cherenkov, pion contamination $f < 2 \times 10^{-4}$.

Detector efficiencies extracted from VDC-on runs, taken daily
Data Quality

(pair-wise asymmetry pull plots):

\[ \text{pull} = \frac{A_i - \langle A \rangle}{\Delta A_i} \]

DIS I
- Entries: 1.02E7
- Mean: 4.09E-6
- RMS: 1.0017

DIS II
- Entries: 2.52E07
- Mean: -3.57E-6
- RMS: 0.99965
From Measured to Physics Asymmetry

correcting for background $f_i$ with asymmetry $A_i$:

$$A_{\text{phys}} = \frac{A_{\text{raw}}}{P_b} \left[ \sum_i A_i f_i \right]$$

$$1 - \sum_i f_i$$

$$A_{\text{phys}} \approx \frac{A_{\text{raw}}}{P_b} \prod_i (1 + \bar{f}_i)$$

$$\bar{f}_i \equiv f_i \left( 1 - \frac{A_i}{A_{\text{raw}} P_b} \right)$$
From Measured to Physics Asymmetry

\[ A_{Q^2=1.085, x=0.241}^{\text{raw}} = -78.45 \pm 2.68 \pm 0.07 \text{ ppm} \]

| \( P_b \) | 88.18\% |
| \( \Delta P_b \) | ±1.76\% |
| \( 1 + f_{\text{depol}} \) | 1.0010 |
| (syst.) | < 10^{-4} |
| \( 1 + f_{\text{Al}} \) | 0.9999 |
| (syst.) | ±0.0024 |
| \( 1 + f_{\text{dt}} \) | 1.0147 |
| (syst.) | ±0.0009 |
| \( 1 + f_{\text{rc}} \) | 1.015 |
| (syst.) | ±0.020 |
| \( 1 + f_{\gamma\gamma\text{box}} \) | 0.998 |
| \( 1 + \bar{f}_{\gamma\gamma,\gamma Z\text{box}} \) | ±0.002 |
| \( \Delta f_{\pi^-} \) | ±0.009\% |
| \( \Delta f_{\text{Pair}} \) | ±0.04\% |
| \( \Delta f_{A_n} \) | ±2.5\% |
| \( \Delta Q^2 \) | ±0.85\% |
| rescatt bg | \(< 0.2\% |
| target impurity | ±0.06\% |
| \( A_{\text{phys}} \) (ppm) | \(-91.10 \) |
| (stat.) | ±3.11 |
| (syst.) | ±2.97 |
| (total) | ±4.30 |
From Measured to Physics Asymmetry

\[
A_{Q^2=1.901, x=0.295}^{raw} = -140.30 \pm 10.43 \pm 0.16 \text{ ppm (LHRS)} \\
A_{Q^2=1.901, x=0.295}^{raw} = -139.84 \pm 6.58 \pm 0.46 \text{ ppm (RHRS)}
\]

| \( P_b \) | 89.29 | 88.73% | ±1.50% |
| \( \Delta P_b \) | 1.19% | < 10^{-4} |
| \( 1 + f_{\text{depol}} \) (syst.) | 1.0021 | ±0.0024 | ±0.0024 |
| \( 1 + f_{\text{Al}} \) (syst.) | 0.9999 | ±0.00024 | ±0.00024 |
| \( 1 + f_{\text{dt}} \) (syst.) | 1.0049 | ±0.0004 | ±0.0013 |
| \( 1 + f_{\text{rc}} \) (syst.) | 1.019 | ±0.004 |
| \( 1 + f_{\gamma\gamma \text{box}} \) | 0.997 | ±0.003 |
| \( 1 + f_{\gamma\gamma, \gamma Z \text{boxes}} \) (syst.) | ±1.005 | ±0.005 |

| \( \Delta f_{\pi^-} \) | ±0.006% | ±0.003% |
| \( \Delta f_{\text{pair}} \) | ±0.4% | ±0.2% |
| \( \Delta f_{\text{A}_n} \) | ±2.5% | ±2.5% |
| \( \Delta Q^2 \) rescatt bg | ±0.64% | ±0.65% |
| target impurity | ≪ 0.2% | ≪ 0.2% |
| Asymmetry \( A^{\text{phys}} \) (ppm) | \(-160.80\) ± 6.39 |
| (stat.) | ±3.12 |
| (syst.) | ±7.12 |
| (total) |
Compare to Standard Model?

\[ A_{Q^2 = 1.085, x = 0.241}^{phys} = -91.10 \pm 3.11 \pm 2.97 \text{ ppm} \]

\[ A^{SM} = \left( 1.156 \times 10^{-4} \right) \left[ 2 C_{1u} - C_{1d} + 0.348 \left( 2 C_{2u} - C_{2d} \right) \right] = -87.7 \text{ ppm} \]

uncertainty due to PDF: 0.5% 5%
uncertainty due to HT: 0.5%/\(Q^2\), 0.7ppm

\[ A_{Q^2 = 1.901, x = 0.295}^{phys} = -160.80 \pm 6.39 \pm 3.12 \text{ ppm} \]

\[ A^{SM} = \left( 2.022 \times 10^{-4} \right) \left[ 2 C_{1u} - C_{1d} + 0.594 \left( 2 C_{2u} - C_{2d} \right) \right] = -158.9 \text{ ppm} \]

uncertainty due to PDF: 0.5% 5%
uncertainty due to HT: 0.5%/\(Q^2\), 1.2ppm
Previous data: Elastic PVES + APV
Add JLab PVDIS

![Graph showing data with axes labeled as $2C_{2u} - C_{2d}$ on the y-axis and $2C_{1u} - C_{1d}$ on the x-axis.]
$2C_{2u} - C_{2d}$

Wang et al., Nature 506, no. 7486, 67 (2014);

X. Zheng, JLab UGM 2014
Quarks are not ambidextrous

By separately scattering right- and left-handed electrons off quarks in a deuterium target, researchers have improved, by about a factor of five, on a classic result of mirror-symmetry breaking from 35 years ago. See Letter p.67

Marciano., Nature 506, no. 7486, 43 (2014);
BSM Mass Limit on eq VA contact interaction

Wang et al., Nature 506, no. 7486, 67 (2014);
Four setting covered the full resonance region;
“Grouping” of lead glass blocks allowed a reasonable study of the $W$-dependence;
Resonance PV Asymmetry Results

A: Matsui, Sato, Lee, PRC72, 025204 (2005)
B: Gorchtein, Horowitz, Ramsey-Musolf, PRC84, 015502 (2011)
C: Hall, Blunden, Melnitchouk, Thomas, Young, PRD88, 013011 (2013)
Coherent PVDIS Program with SoLID @ 11 GeV

SoLID Physics topics:

- PVDIS deuteron (180 days) - $C_2$, $\sin^2 \theta_W$, CSV, diquarks,
- PVDIS proton (90 days) - d/u
- PV with $^3\text{He}$ (LOI)
- SIDIS
- $J/\psi$
Coherent PVDIS Program with SoLID @ 11 GeV

**Goal on $C_{2q}$:** one order of magnitude improvement over 6 GeV

X. Zheng, JLab UGM 2014
Summary and Perspectives

The 6 GeV PVDIS from JLab:

- Improved world data on the eq VA effective coupling term $2C_{2u}-C_{2d}$ by factor of five; agrees with the SM; and showed $2C_{2u}-C_{2d}$ is $2\sigma$ from zero - indicating a nonzero contribution to PVDIS asymmetry due to quark's chirality preference; BSM mass limits complimentary to collider experiments.

- Resonance PV asymmetries seem to indicate duality in the electroweak observables for the first time.

“New construction” experiments at JLab 12 GeV:

- PVDIS @ 11 GeV (SoLID) will improve $C_{2q}$ by another order of magnitude.

Subedi et al, NIM-A 724, 90 (2013); Wang et al., PRL 111, 082501 (2013); Wang et al., Nature 506, no. 7486, 67 (2014); long paper draft available.

X. Zheng, JLab UGM 2014
# SLAC E122 vs. JLab E08-011

<table>
<thead>
<tr>
<th></th>
<th>SLAC E122 (1978)</th>
<th>JLab E08-011 (2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam</strong></td>
<td>37%, 16.2-22.2 GeV</td>
<td>90%, 6.0674 GeV, 100uA</td>
</tr>
<tr>
<td><strong>Target</strong></td>
<td>30-cm LD2, LH2</td>
<td>20-cm LD2</td>
</tr>
<tr>
<td><strong>Spectrometer</strong></td>
<td>4°</td>
<td>12.9° and 20°</td>
</tr>
<tr>
<td><strong>Q^2</strong></td>
<td>1-1.9 GeV^2</td>
<td>1.1 and 1.9 GeV^2</td>
</tr>
<tr>
<td><strong>Data collection</strong></td>
<td>Integrating gas Cerenkov and lead glass detectors,</td>
<td>Counting DAQ using both GC and lead glass for PID</td>
</tr>
<tr>
<td></td>
<td>independently</td>
<td>at the hardware level</td>
</tr>
<tr>
<td><strong>Deuteron results</strong></td>
<td>(two highest energies only)</td>
<td></td>
</tr>
<tr>
<td>A/Q^2</td>
<td>(-9.5±1.6)x10^{-5} (GeV/c)^{-2}</td>
<td>(-9.7±2.7)x10^{-5} (GeV/c)^{-2}</td>
</tr>
<tr>
<td>±0.86x10^{-5}(stat)</td>
<td>±3% (radiative corrections)</td>
<td>±3%(stat)</td>
</tr>
<tr>
<td>±5%(Pb)</td>
<td>±2%(π contamination)</td>
<td>±(3-4)%(stat)</td>
</tr>
<tr>
<td>±3.3%(beam)</td>
<td></td>
<td>±syst.</td>
</tr>
<tr>
<td>sin^2θ_w</td>
<td>=0.20±0.03</td>
<td></td>
</tr>
<tr>
<td><strong>Proton results</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/Q^2</td>
<td>(-9.5±1.6)x10^{-5} (GeV/c)^{-2}</td>
<td></td>
</tr>
</tbody>
</table>

**sin^2θ_w = 0.20±0.03**
Some Older Plots

with recent PVES data and Qweak (projected)

all are 1σ limit

without JLab data

Qweak in Hall C (2010-May 2012): \( ^1 \text{H} + \vec{e} \rightarrow e' + p \) factor of 5 improvement in the proton weak (vector) charge \( Q^p_w = -2(2C_{1u} + C_{1d}) \)

X. Zheng, JLab UGM 2014
DAQ Deadtime Correction

(work of D. Wang)

Deadtime correction to asymmetry:

$$A_{\text{measured}} = A_{\text{phys}} (1 - \text{deadtime loss})$$

Deadtime Decomposition:

- **Group Deadtime**: proportional to group rate; narrow/wide.
- **Veto Deadtime**: T1/GC rate; the same for all groups.
- **Final OR**.
- **Overall Deadtime**: Veto DT + Group DT + Final OR DT

X. Zheng, JLab UGM 2014
We could use HT results on $F_3^{\gamma Z}$ from neutrino data in 0710.0124(hep-ph) to correct the $a_3$ term:

\[
F_{2,T,3}(x,Q^2) = F_{2,T,3}^{\tau=2}(x,Q^2) + \frac{H_{2,T,3}^{\tau=4}(x)}{Q^2} + \frac{H_{2,T,3}^{\tau=6}(x)}{Q^4} + \ldots
\]

for $F_2^\gamma$ and $F_2^1$

for any target

\[
F_3^\gamma = 2 \left[ d + s - \bar{u} - c \right]
\]

for deuteron

\[
F_3^\gamma = 2 \left[ u_V + d_V + 2s - 2\bar{c} \right]
\]