Parity-Violating Deep Inelastic Scattering (PVDIS) at JLab 6 and 12 GeV

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November 21, 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
Inclusive Electron Scattering Basics

Inclusive: only scattered electron is detected

\[ k' = (E', \mathbf{k}') \]

\[ q = (\nu, \mathbf{q}) \]

\[ Q^2 = -q^2 \]

\[ P = (M, 0) \]

\[ W^2 = p'^2 \]

"Elastic": \( W = M_p \) (form factors)

"Resonance": \( 1 < W < 2 \text{GeV} \) (structure functions)

"Deep Inelastic": \( W > 2 \text{ GeV} \), (structure functions, parton distribution functions)
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 $Z^0$. 
Unlike electric charge, need two charges (couplings) for weak interaction: $g_L, g_R$

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

\[ -i \frac{g_Z}{2} \gamma^\mu [g_V^e - g_A^e \gamma^5] \]
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 $V(e) \times A(targ)$ and $A(e) \times V(targ)$
Effective Couplings in the Standard Model

- 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:

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

“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:

\[ C_{1q} \equiv 2g_A^e g_V^q, \quad C_{2q} \equiv 2g_V^e g_A^q \]

“electron-quark effective couplings”
**Effective Couplings and New Contact Interactions**

- 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:

  \[
  C_{1q} \equiv 2 g_A^e g_V^q, \quad C_{2q} \equiv 2 g_V^e g_A^q
  \]

- “electron-quark effective couplings”

\[
C_{1q} = g_{AV}^e q, \quad C_{2q} = g_{VA}^e q
\]

**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

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

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

\[
a(x) = \frac{1}{2} g_A^e \frac{F^y_1 F^y_3}{F^y_1} = \frac{1}{2} \sum_i C_{1i} Q_i q_i^+(x) \]

\[
b(x) = g_V^e \frac{F^y_3}{F^y_1} = \frac{1}{2} \sum_i C_{2i} Q_i q_i^-(x)
\]

\[
x \equiv x_{Bjorken} = \frac{Q^2}{2 M \nu}
\]

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

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

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

\[
b(x) = \frac{3}{10} \left[ 2 C_{2u} - C_{2d} \right] \left( \frac{u^+_V + d^+_V}{u^+ + d^+} \right)
\]
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 \((^2H)\), structure functions largely simplifies:

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

If neglecting sea quarks, asymmetry is no longer sensitive to PDFs \(\rightarrow\) “static limit”

\[ x = x_{Bjorken} = \frac{Q^2}{2 M \nu} \]
\[ q_i^+(x) \equiv q_i(x) + \bar{q}_i(x) \]
\[ q_i^-(x) = q_i^V(x) \equiv q_i(x) - \bar{q}_i(x) \]
Still, $C_{2q}$ are more difficult to access than $C_{1q}$.

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

\[ y = \frac{E - E'}{E} = \frac{\nu}{E} \]

\[ r^2 = 1 + \frac{Q^2}{\nu^2} \]

\[ Y = \left[ \frac{r^2}{1 + R} \right] \frac{1 - (1 - y)^2}{1 + (1 - y)^2 - y^2 \left[ 1 - \frac{r^2}{1 + R} \right]} - xy \frac{M}{E} \]

- The term sensitive to the quark spin is kinematically suppressed due to angular momentum conservation.
- $C_{2q}$ are much smaller than $C_{1q}$:

\[ C_{1u} = -\frac{1}{2} + \frac{4}{3} \sin^2 \theta_W \]

\[ C_{1d} = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \]

\[ C_{2u} = -\frac{1}{2} + 2 \sin^2 \theta_W \]

\[ C_{2d} = \frac{1}{2} - 2 \sin^2 \theta_W \]
Best Data on $C_{1q}$ (eq AV couplings) from PVES+APV

Androic et al., PRL 111, 141803 (2013);

X. Zheng, HiX2014, Laboratori Nazionali di Frascati, November 2014
Projecting to $C_{1q}$ vs $C_{2q}$ (e-q AV vs. VA couplings)
Add E122 - the first PVES (1978)
and combine them
then zoom in
PVDIS at 6 GeV (JLab E08-011)
- Staff: ~700
- User community: ~1300
- Beam first delivered in 10/95
- In full operation since 11/97
- ~10^2 PhDs to date (~1/3 of US PhDs in Nuclear Physics)
- 6 GeV until 2012, 12 GeV - 2014
- "Continuous beam", provides the highest polarized luminosity of the world
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 GeV$^2$, and five resonance kinematics.
- Spokespersons: Robert Michaels, Paul Reimer, X. Z.
- Students: Xiaoyan Deng, Kai Pan, Diancheng Wang
- Postdoc: Ramesh Subedi
## E08-011 Kinematics

<table>
<thead>
<tr>
<th>Kin#</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>
DIS Asymmetry Results

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

\[ A_{Q^2=1.085, x=0.241}^{\text{SM}} = (1.156 \times 10^{-4}) \left[ (2 \, C_{1u} - C_{1d}) + 0.348 \left( 2 \, C_{2u} - C_{2d} \right) \right] = -87.7 \text{ ppm} \]

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

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

\[ A_{Q^2=1.901, x=0.295}^{\text{SM}} = (2.022 \times 10^{-4}) \left[ (2 \, C_{1u} - C_{1d}) + 0.594 \left( 2 \, C_{2u} - C_{2d} \right) \right] = -158.9 \text{ ppm} \]

uncertainty due to PDF: 0.5%  5%
uncertainty due to HT: 0.5%/Q^2, 1.2ppm
Previous data: Elastic PVES + APV

$2C_{2u} - C_{2d}$ vs. $2C_{1u} - C_{1d}$ graph.
Add JLab PVDIS
2C_{2u} - C_{2d}

best fit

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

X. Zheng, HiX2014, Laboratori Nazionali di Frascati, November 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 P67

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

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

X. Zheng, HiX2014, Laboratori Nazionali di Frascati, November 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)

Wang et al., PRL 111, 082501 (2013);
X. Zheng, HiX2014, Laboratori Nazionali di Frascati, November 2014
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 $^3$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, HiX2014, Laboratori Nazionali di Frascati, November 2014
Coherent PVDIS Program with SoLID @ 11 GeV
Coherent PVDIS Program with SoLID @ 11 GeV

$[2g^e - g^d]_{AV}$

$[2g^e - g^d]_{VA}$

SLAC–E122
JLab–Hall A
SoLID

10 TeV
20 TeV
30 TeV
40 TeV
50 TeV

X. Zheng, HiX2014, Laboratori Nazionali di Frascati, November 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 2σ 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-A724, 90 (2013); Wang et al., PRL111, 082501 (2013); Wang et al., Nature506, no.7486, 67 (2014); Want et al., arXiv:1411.3200 (nucl-ex)

X. Zheng, HiX2014, Laboratori Nazionali di Frascati, November 2014
It's not easy to count electrons! — Our customized fast counting DAQ with online particle identification

total cost: $200k
Data Quality

(pair-wise asymmetry pull plots):

\[
pull = \frac{A_i - \langle A \rangle}{\Delta A_i}
\]
From Measured to Physics Asymmetry

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

$$A_{\text{phys}} = \left( \frac{A_{\text{raw}}}{P_b} - \sum_i A_i f_i \right) \frac{1}{1-\sum_i f_i}$$

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

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

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

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_b )</td>
<td>88.18%</td>
</tr>
<tr>
<td>( \Delta P_b )</td>
<td>±1.76%</td>
</tr>
<tr>
<td>( 1 + f_{\text{depol}} ) ( \text{(syst.)} )</td>
<td>1.0010</td>
</tr>
<tr>
<td>( 1 + f_{Al} )</td>
<td>0.9999</td>
</tr>
<tr>
<td>( \text{(syst.)} )</td>
<td>±0.0024</td>
</tr>
<tr>
<td>( 1 + f_{dt} )</td>
<td>1.0147</td>
</tr>
<tr>
<td>( \text{(syst.)} )</td>
<td>±0.0009</td>
</tr>
<tr>
<td>( 1 + f_{rc} )</td>
<td>1.015</td>
</tr>
<tr>
<td>( \text{(syst.)} )</td>
<td>±0.020</td>
</tr>
<tr>
<td>( 1 + f_{\gamma\gamma,\gamma Z\text{boxes}} ) ( \text{(syst.)} )</td>
<td>0.998</td>
</tr>
<tr>
<td>( 1 + f_{\gamma\gamma} ) ( \text{(total)} )</td>
<td>±0.002</td>
</tr>
</tbody>
</table>

\[ \Delta f_{\pi^-} \quad \Delta f_{\text{pair}} \quad \Delta f_{A_n} \quad \Delta Q^2 \]

\[ \text{rescatt bg} \quad \text{target impurity} \]

\[ \Delta f_{\pi^-} \quad \pm 0.009\% \quad \pm 0.04\% \quad \pm 2.5\% \quad \pm 0.85\% \quad \ll 0.2\% \quad \pm 0.06\% \]

\[ A^\text{phys} \text{ (ppm)} \]

\[ \text{(stat.)} \quad -91.10 \quad ±3.11 \quad ±2.97 \quad ±4.30 \]

[Image]
From Measured to Physics Asymmetry

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

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

| \( P_b \) | 89.29 | 88.73% |
| \( \Delta P_b \) | 1.19% | ±1.50% |

| 1 + \( f_{\text{depol}} \) (syst.) | 1.0021 | < 10^{-4} |

| 1 + \( f_{\text{Al}} \) (syst.) | 0.9999 | 0.9999 |
| \( \pm 0.0024 \) | \( \pm 0.0024 \) |

| 1 + \( f_{\text{dt}} \) (syst.) | 1.0049 | 1.0093 |
| \( \pm 0.0004 \) | \( \pm 0.0013 \) |

| 1 + \( f_{\text{rc}} \) (syst.) | 1.019 | ±0.004 |

| 1 + \( f_{\gamma\gamma,\gamma\text{Z} \text{boxes}} \) (syst.) | 0.997 | – |
| \( \pm 0.003 \) | \( \pm 0.005 \) |

\[ \Delta f_{\pi^-} \]

\[ \Delta f_{\text{pair}} \]

\[ \Delta f_{A_n} \]

\[ \Delta Q^2 \]

rescatt bg

target impurity

Asymmetry

\[ A_{\text{phys (ppm)}} \]

(stat.)

(syst.)

(total)

| \( A_{\text{phys (ppm)}} \) | –160.80 | ±6.39 |
| \( \pm 3.12 \) | ±7.12 |
## Pion Asymmetries

<table>
<thead>
<tr>
<th>HRS, Kinematics</th>
<th>Left DIS#1</th>
<th>Left DIS#2</th>
<th>Right DIS#2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>narrow path</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[ A_{\pi}^{\text{meas}} \pm \Delta A_{\pi}^{\text{meas}} ] (total) (ppm)</td>
<td>(-48.8 \pm 14.0)</td>
<td>(-22.0 \pm 21.4)</td>
<td>(-20.3 \pm 6.0)</td>
</tr>
<tr>
<td>[ A_{e,\text{dit}}^{\text{bc, raw}} \pm A_{e,\text{dit}}^{\text{bc, raw}} ] (stat.) (ppm)</td>
<td>(-78.5 \pm 2.7)</td>
<td>(-140.3 \pm 10.4)</td>
<td>(-139.8 \pm 6.6)</td>
</tr>
<tr>
<td>[ f_{\pi/e} \pm \Delta f_{\pi/e} ] (total) ((\times 10^{-4}))</td>
<td>((1.07 \pm 0.24))</td>
<td>((1.97 \pm 0.18))</td>
<td>((1.30 \pm 0.10))</td>
</tr>
<tr>
<td>[ \left( \frac{\Delta A_{e}}{A_{e}} \right)_{\pi^-\nu} ]</td>
<td>(0.89 \times 10^{-4})</td>
<td>(0.63 \times 10^{-4})</td>
<td>(0.27 \times 10^{-4})</td>
</tr>
<tr>
<td></td>
<td>wide path</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[ A_{\pi}^{\text{meas}} \pm \Delta A_{\pi}^{\text{meas}} ] (total) (ppm)</td>
<td>(-41.3 \pm 12.8)</td>
<td>(-23.7 \pm 21.4)</td>
<td>(-20.3 \pm 6.0)</td>
</tr>
<tr>
<td>[ A_{e,\text{dit}}^{\text{bc, raw}} \pm A_{e,\text{dit}}^{\text{bc, raw}} ] (stat.) (ppm)</td>
<td>(-78.3 \pm 2.7)</td>
<td>(-140.2 \pm 10.4)</td>
<td>(-140.9 \pm 6.6)</td>
</tr>
<tr>
<td>[ f_{\pi/e} \pm \Delta f_{\pi/e} ] (total) ((\times 10^{-4}))</td>
<td>((0.72 \pm 0.22))</td>
<td>((1.64 \pm 0.17))</td>
<td>((0.92 \pm 0.13))</td>
</tr>
<tr>
<td>[ \left( \frac{\Delta A_{e}}{A_{e}} \right)_{\pi^-\nu} ]</td>
<td>(0.54 \times 10^{-4})</td>
<td>(0.55 \times 10^{-4})</td>
<td>(0.21 \times 10^{-4})</td>
</tr>
</tbody>
</table>
Pair Production Background

- Took reversed-polarity runs, mostly to determine e+/e- ratio. Positron asymmetry from those runs have very large error;
- Assumed positron asymmetry to be similar to $\pi^-$ asymmetry;
- Effect on the measurement is about 10 times larger than $\pi^-$ background.
### 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, independently</td>
<td>Counting DAQ using both GC and lead glass for PID 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 = (-9.5 \pm 1.6) \times 10^{-5} (GeV/c)^{-2} ]</td>
<td>±0.86 \times 10^{-5} (stat)±5% (Pb)±3.3% (beam) ±2% (π contamination) ±(3-4)% (stat) ±syst.</td>
<td></td>
</tr>
<tr>
<td>[ \sin^2 \theta_w = 0.20 \pm 0.03 ]</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Proton results</strong></td>
<td>[ A/Q^2 = (-9.7 \pm 2.7) \times 10^{-5} (GeV/c)^{-2} ]</td>
<td>±3% (radiative corrections)</td>
</tr>
</tbody>
</table>