Parity Violation in Deep Inelastic Scattering

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Representing the SoLID Collaboration

I. Parity Violation

II. PVDIS Physics Potential
   A. Electroweak Couplings
   B. Charge Symmetry
   C. Higher Twist
   D. Other Physics and Targets: \( d_\nu/u_\nu \);
      Isoscaler EMC effect

III. Experiments: JLab Hall A 6 GeV, JLab Hall C 12 GeV and JLab Hall A SOLID

IV. SIDIS w/SoLID@JLab

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Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.
Why measure of parity violation in electron scattering?

- Because it’s hard and physicists like challenges.
- PV gives access to the weak interaction at low energy (well below the mass of the $Z^0$).

\[
\sigma^l \propto \left| M_{\gamma} + M_{Z^0}^l \right|^2 \quad \sigma^r \propto \left| M_{\gamma} + M_{Z^0}^r \right|^2
\]

\[
A_{PV} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{M_{Z^0}^l - M_{Z^0}^r}{M_{\gamma}}
\]

Graphic from Ray Arnold
Abstract
We have measured parity violating asymmetries in the inelastic scattering of longitudinally polarized electrons from deuterium and hydrogen. For deuterium near $Q^2 = 1.6$ (GeV/c)$^2$ the asymmetry is $(-9.5 \times 10^{-5})Q^2$ with statistical and systematic uncertainties each about 10%
PVDIS variables

\[ A_{PV} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{M^l_{Z_0} - M^r_{Z_0}}{M_\gamma} \]

\[ \propto - \left( \frac{G_F Q^2}{4\pi\alpha} \right) \left( g^e_A g^T_V + \beta g^e_V g^T_A \right) \]

- The couplings \( g \) depend on electroweak physics as well as on the weak vector and axial-vector hadronic current.

- Both **new physics at high energy scales** as well as interesting **features of hadronic structure** come into play.

- A program with many targets and a broad kinematic range can reveal the physics.

Is the glass half full or half empty?
PVDIS variables

\[ A_{\text{iso}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \]
\[ = \left( \frac{3 G_F Q^2}{\pi \alpha 2 \sqrt{2}} \right) \left( 2 C_{1u} - C_{1d} (1 + R_s) + Y (2 C_{2u} - C_{2d}) \frac{R}{R + 1} \right) \]
\[ R(x, Q^2) = \frac{\sigma^l}{\sigma^r} \approx 0.2 \]
PVDIS variables

\[ A_{iso} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \]

\[ = -\left( \frac{3G_FQ^2}{\pi\alpha 2\sqrt{2}} \right) \frac{2C_{1u} - C_{1d} (1 + R_s) + Y (2C_{2u} - C_{2d}) R_v}{5 + R_s} \]

\[ Y = \frac{1 - (1 - y)^2}{1 + (1 - y)^2 - y^2 \frac{R}{R+1}} \]

\[ R(x, Q^2) = \frac{\sigma^l}{\sigma^r} \approx 0.2 \]

Z_{SoLID}? (See talk by J. Erler)

\[ C_{1u} = -\frac{1}{2} + \frac{4}{3} \sin^2 \theta_W \approx -0.19 \]
\[ C_{1d} = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \approx 0.35 \]
\[ C_{2u} = -\frac{1}{2} + 2 \sin^2 \theta_W \approx -0.04 \]
\[ C_{2d} = \frac{1}{2} - 2 \sin^2 \theta_W \approx 0.04 \]

Cahn and Gilman, PRD 17 1313 (1978) polarized electrons on deuterium
Recall: $\sin^2 \theta_W$ projects couplings onto Standard Model—measurements of couplings to elucidate extensions to the S.M.
Sensitivity: $C_1$ and $C_2$ Plots

World's data
Sensitivity: $C_1$ and $C_2$ Plots

World’s data
PVDIS variables

\[ A_{iso} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \]

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\[ R(x, Q^2) = \frac{\sigma^l}{\sigma^r} \approx 0.2 \]

\[ R_s(x) = \frac{2S(x)}{U(x) + D(x)} \quad \text{Large } x \to 0 \]

\[ R_v(x) = \frac{u_v(x) + d_v(x)}{U(x) + D(x)} \quad \text{Large } x \to 1 \]

QCD

- Parton distributions (u, d, s, c)
- Charge Symmetry (CSV)
- Higher Twist (HT)
- Nuclear Effects (EMC)
QCD: Charge Symmetry Violation

We already know CSV exists:

- u-d mass difference \( \delta m = m_d - m_u \approx 4 \text{ MeV} \)
  \( \delta M = M_n - M_p \approx 1.3 \text{ MeV} \)

- electromagnetic effects

- Direct observation of CSV—very exciting!
- Important implications for PDF’s
- *Could be a* partial explanation of the NuTeV anomaly

For \( A_{PV} \) in electron-\(^{2}\text{H DIS:} \)

MRST PDF global with fit of CSV
Martin, Roberts, Stirling, Thorne Eur Phys J C 35, 325 (04)
QCD: Charge Symmetry Violation

We already know CSV exists:

- u-d mass difference \[ \delta m = m_d - m_u \approx 4 \text{ MeV} \]
- d-m mass difference \[ \delta M = M_d - M_u \approx 1.3 \text{ MeV} \]
- electromagnetic effects

- Direct observation of CSV—very exciting!
- Important implications for PDF's
- *Could be a partial explanation of the NuTeV anomaly*

For \( A_{PV} \) in electron-\(^2\)H DIS:

MRST PDF global with fit of CSV
Martin, Roberts, Stirling, Thorne Eur Phys J C35, 325 (04)
QCD: Higher Twist

From the Quark Parton Model (QPM) to QCD

1. Add DGLAP evolution
2. Add higher order terms in the Operator Product Expansion (OPE) ↔ Higher Twist Terms

Parton Model—leading twist

Quark-gluon diagram

(a)  (b)  (c)

Di-quarks

What is a true quark-gluon operator?

FIG. 3. The only gluon operator that we keep is the operator $O^9$, which can be expressed as a four-quark operator using the equations of motion.

Quark-gluon operators correspond to transverse momentum

QCD equations of motion
QCD: Higher Twist--MRST Fits

\[ F_2(x,Q^2) = F_2(x)(1 + D(x)/Q^2) \]

\[ Q^2 = \frac{(W^2-M^2)}{(1/x-1)} \]

\[ Q_{\text{min}}^2 = Q^2(W=2) \]

<table>
<thead>
<tr>
<th>x</th>
<th>( Q^2_{\text{min}} )</th>
<th>D(x)</th>
<th>( D/Q^2_{\text{min}} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LO</td>
<td>N^3LO</td>
</tr>
<tr>
<td>0.1-0.2</td>
<td>0.5</td>
<td>-.007</td>
<td>0.001</td>
</tr>
<tr>
<td>0.2-0.3</td>
<td>1.0</td>
<td>-.11</td>
<td>0.003</td>
</tr>
<tr>
<td>0.3-0.4</td>
<td>1.7</td>
<td>-.06</td>
<td>-0.001</td>
</tr>
<tr>
<td>0.4-0.5</td>
<td>2.6</td>
<td>.22</td>
<td>0.11</td>
</tr>
<tr>
<td>0.5-0.6</td>
<td>3.8</td>
<td>.85</td>
<td>0.39</td>
</tr>
<tr>
<td>0.6-0.7</td>
<td>5.8</td>
<td>2.6</td>
<td>1.4</td>
</tr>
<tr>
<td>0.7-0.8</td>
<td>9.4</td>
<td>7.3</td>
<td>4.4</td>
</tr>
</tbody>
</table>

If \( C(x) \sim D(x) \), there is large sensitivity at large \( x \).

Order of DGLAP influences size of HT

Higher twist falls slowly compared to PDF’s at large \( x \).
Need Full Phenomenology

\[
\frac{d^2 \sigma}{dx dy}_{EM} \propto 2xy F_1^\gamma + \frac{2}{y} \left( 1 - y - \frac{xyM}{2E} \right) F_2^\gamma
\]

\[
F_1^\gamma = F_2^\gamma (1 + R) \rightarrow R = \frac{\sigma_L}{\sigma_T}
\]

\[
\frac{d^2 \sigma}{dx dy}_{yZ}^V \propto \frac{G}{2\sqrt{2\pi}\alpha} \left\{ - g_A \left[ 2xy F_1^{yZ} + \frac{2}{y} \left( 1 - y - \frac{xyM}{2E} \right) F_2^{yZ} \right] \right\}
\]

\[
\frac{d^2 \sigma}{dx dy}_{yZ}^A \propto \frac{G}{2\sqrt{2\pi}\alpha} \left[ - g_V x (2 - y) F_3^{yZ} \right]
\]

\[A_{PV}^{yZ} = \sigma_{yZ}^V + \sigma_{yZ}^A\]

There are 5 relevant structure functions

Isospin rotation of \(vd\) charge current

\[F_3^{yZ} = \frac{5}{18} F_3^\gamma\]

Small; use \(v\) data
(Higher twist workshop at Madison, Wisconsin)
Why HT in PVDIS is Special

Bjorken,
PRD 18, 3239 (78)
Wolfenstein,
NPB146, 477 (78)

\[
V_\mu = (\bar{u} \gamma_\mu u - \bar{d} \gamma_\mu d) \Leftrightarrow S_\mu = (\bar{u} \gamma_\mu u + \bar{d} \gamma_\mu d)
\]

Isospin decomposition before using PDF’s

\[
\frac{(C_{1u} - C_{1d}) \langle VV \rangle + \frac{1}{3}(C_{1u} + C_{1d}) \langle SS \rangle}{\langle VV \rangle + \frac{1}{3} \langle SS \rangle} \propto \int \langle D \mid j_\mu(x) J^\nu(0) + J^\mu_0(x) j^\nu(0) \mid D \rangle e^{iq \cdot x} d^4 x
\]

Zero in QPM

HT in $F_2$ may be dominated by quark-gluon correlations

Vector-hadronic piece only

Use $\nu$ data for small $b(x)$ term.
Future PVDIS Measurements at JLab

- JLab Hall A 6 GeV
  See talk by Xiaochao Zheng

- JLab Hall C Baseline Spectrometers (12 GeV)

- JLab Hall A SOLID Spectrometer (12 GeV)
**12 GeV Hall C**

*Baseline equipment*

- Measurement with baseline spectrometers
- Sensitive to both Hadronic effects and to Standard Model effects

### Approximate Kinematics

<table>
<thead>
<tr>
<th>$x_{Bj}$</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$E'$ (GeV)</th>
<th>$\Theta$ (deg)</th>
<th>$W^2$ (GeV)</th>
<th>$A_d$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35</td>
<td>3.3</td>
<td>6.0</td>
<td>13.5</td>
<td>7.1</td>
<td>-285</td>
</tr>
</tbody>
</table>

### Uncertainty ($\delta A_d/A_d \times 10^{-3}$)

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>5.0</td>
</tr>
<tr>
<td>Systematic</td>
<td></td>
</tr>
<tr>
<td>Polarimetry</td>
<td>5</td>
</tr>
<tr>
<td>$Q^2$</td>
<td>4</td>
</tr>
<tr>
<td>Rad. Corr.</td>
<td>4</td>
</tr>
<tr>
<td>Total Syst.</td>
<td>7.6</td>
</tr>
</tbody>
</table>

If there is something interesting (*Charge Symmetry Violation* or *Standard Model* deviation) the experiment may be able to see it—but baseline equipment expt. cannot tell the difference.
SoLID: A large acceptance apparatus for JLab Hall A

- Moderate running times
  - Large Acceptance
  - High Luminosity on LH2 & LD2
- Better than 1% errors for small bins
- Kinematics:
  - Large $Q^2$ coverage
  - $x$-range 0.25-0.75
  - $W^2 > 4$ GeV$^2$

- Spectrometer requirements:
  - Solenoid contains low energy backgrounds (Møller, pions, etc)
Search for a Solenoid

- There are a number of Solenoids available right around Rome
Search for a Solenoid

- There are a number of Solenoids available right around Rome
- And even period appropriate transportation schemes
Step 1: Find a solenoid—“The usual suspects”

- MEGA (Hall D)
- New Hall D design
- All could work within the constraints of our physics needs
- Present effort focused on CLEO Magnet
SoLID: A large acceptance apparatus

- **Moderate running times**
  - Large Acceptance
  - High Luminosity on LH2 & LD2
- **Better than 1% errors for small bins**
- **Kinematics:**
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  - $W^2 > 4$ GeV$^2$

- **Spectrometer requirements:**
  - Solenoid contains low energy backgrounds (Møller, pions, etc)
  - Polarized $e^-$ beam (M. Poelker, M. Pitt)
  - Trajectories measured after baffles
  - Fast tracking—GEM (E. Cisbani), particle ID, calorimetry, and pipeline electronics
  - Precision polarimetry (0.4%) (see talks by S. Glamazdin, E. Chudakov, K Aulenbacher A. Narayan, M. Friend)
Statistical Errors (%) vs. Kinematics

Statistical sensitivity for SOLID spectrometer

Error bar $\sigma_A/A(\%)$ shown at center of bins in $Q^2, x$

- 2 months at 6.6 GeV
- 4 months at 11 GeV
Coherent Program of PVDIS Study

Strategy: requires precise kinematics and broad range

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>Y</th>
<th>Q^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Physics</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>CSV</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Higher Twist</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

- Measure \( A_d \) in **narrow** bins of \( x, Q^2 \) with 0.5% precision
- Cover broad \( Q^2 \) range for \( x \) in \([0.3,0.6]\) to constrain HT
- Search for CSV with \( x \) dependence of \( A_d \) at high \( x \)
- Use \( x > 0.4 \), high \( Q^2 \) to measure a combination of the \( C_{i/q} \)'s

Fit data to: 

\[
A_{\text{Meas.}} = A_{\text{SM}} \left[ 1 + \frac{\beta_{\text{HT}}}{(1 - x)^3 Q^2} + \beta_{\text{CSV}} x^2 \right]
\]
Sensitivity: $C_1$ and $C_2$ Plots

World’s data
QCD: Charge Symmetry Violation

\[
\frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}
\]
PVDIS on the Proton: $d/u$ at High $x$

\[
\alpha^P(x) \approx \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}
\]

*Deuteron analysis has large nuclear corrections (Yellow)*

$A_{PV}$ for the proton has no such corrections (complementary to BONUS)
CSV in Heavy Nuclei: 
EMC Effect

Isovector EMC Effect and the NuTeV Anomaly

I. C. Cloët,¹ W. Bentz,² and A. W. Thomas³
PRL 102, 252301 (2009)

- Mean Field approach to estimate an EMC-like effect for $N \neq Z$ nuclei
- Possible explanation for NuTeV anomaly which used iron target.
CSV in Heavy Nuclei: EMC Effect

\[ Q^2 = 5.0 \text{ GeV}^2 \]
CSV in Heavy Nuclei: EMC Effect

\[ Q^2 = 5.0 \text{ GeV}^2 \]
What about NuTeV?

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p-n CSV and isoscaler CSV
Bentz, Cloet Londergan, Thomas PLB693 462 2010
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Flavor Dependent Shadowing Brodsky PRD70 (2004) 116003
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Other Models???
What about NuTeV?

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proton-neutron CSV:
- tested with $A_{PV}$ fit on deuterium
- Neutron Excess CSV
- tested with Lead target

Paul E. Reimer, PAVI 11

9 September 2010
SIDIS and Transverse Spin with the SoLID Spectrometer

From Jain-ping Chen

9 September 2010
E12-11-007: SIDIS using Longitudinally Pol. $^3$He and SoLID

*a study of spin-orbital correlation*

- **Semi-Inclusive DIS $\pi^\pm$ production**
  - Longitudinally Pol. $^3$He target effective pol. neutron target, achieved world-best performance
  - SoLID large symmetric acceptance detector, high statistics and better angular modulation separation

- **Extraction of novel TMDs**
  - $A_{UL}(\sin(2\phi_h)) \rightarrow h_{1L}^\perp$
  - $A_{LT}(\cos(\phi_h - \phi_S)) \rightarrow g_{1T}$
  - $A_{LL} \rightarrow g_{1L}$

- **Many predictions available**
  - First Lattice QCD calculation
  - Light-cone quark model and others

- **No GPD Correspondence**
  - Genuine sign of intrinsic transverse motion

- **Links to Collinear PDFs**

  \[ h_{1L}^{q(t)}(x) = -x^2 \int \frac{dy}{y^2} h_t^g(y) \]

  \[ g_{1T}^{q(t)}(x) = x \int \frac{dy}{y} g_t^q(y) \]

  hep-ph/0603194

- **Lattice QCD, arXiv:0908.1283**

- **Light-Cone CQM, arXiv:0806.2298**
Summary

- Measurements of Parity Violation in Deep Inelastic Scattering contain a wealth of information about:
  - The Standard Model
  - Charge Symmetry (CSV)
  - Higher Twist (HT)

- For the complete picture—to unravel the full richness of the physics reach of this process a dedicated—a large-acceptance spectrometer is needed.

- SoLID will also provide critical nuclear structure test (NuTeV $\sin^2 \theta_W$)

- Large additional program of SI-DIS planned for SoLID spectrometer