PVDIS: 12 GeV at JLab

For the SOLID Collaboration
OUTLINE

• PVDIS
• Physics Potential
  – Electroweak couplings
  – CSV
  – Higher Twist
• Apparatus
• Conclusions
First Electron Parity Experiment

It was realized independently in the mid 70s at SLAC:
$A_{PV}$ in Deep Inelastic Scattering off liquid Deuterium: $Q^2 \sim 1 \text{ (GeV)}^2$

$A_{PV} \sim 10^{-4} \cdot Q^2 \text{ (GeV}^2\text{)}$

This experiment convinced the world that the Z-boson violated parity
PV Asymmetries: Any Target

\[ \sigma \propto |A_{\gamma} + A_{\text{weak}}|^2 \]

\[-A_{LR} = A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{\text{weak}}}{A_{\gamma}} \sim \frac{G_F Q^2}{4 \pi \alpha} \left( g_A^e g_V^T + \beta g_V^e g_A^T \right) \]

• 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 untangle the physics

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Electron-Quark Phenomenology

\[ C_{1i} = 2g^e_A g^i_V \]
\[ C_{2i} = 2g^e_V g^i_A \]

\[ C_{1u} = -\frac{1}{2} + \frac{4}{3} \sin^2(\theta_W) + \delta C_{1u} \approx -0.19 \]
\[ C_{1d} = \frac{1}{2} - \frac{2}{3} \sin^2(\theta_W) + \delta C_{1d} \approx 0.35 \]
\[ C_{2u} = -\frac{1}{2} + 2 \sin^2(\theta_W) + \delta C_{2u} \approx -0.030 \]
\[ C_{2d} = \frac{1}{2} - 2 \sin^2(\theta_W) + \delta C_{2d} \approx 0.025 \]

Moller PV is insensitive to the C_{ij}

\( C_{1u} \) and \( C_{1d} \) will be determined to high precision by \( Q_{\text{weak}}, \text{APV Cs} \)

\( C_{2u} \) and \( C_{2d} \) are small and poorly known:
one combination can be accessed in PV DIS

New physics such as compositeness, leptoquarks:
\( \text{Deviations to } C_{2u} \) and \( C_{2d} \) might be fractionally large

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Deep Inelastic Scattering

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

\[ x \equiv x_{Bjorken} \]
\[ y \equiv 1 - E'/E \]
\[ f_i^\pm \equiv f_i \pm \bar{f}_i \]
\[ a(x) = \frac{\sum C_{2i} Q_i f_i^+(x)}{\sum Q_i^2 f_i^+(x)} \]
\[ b(x) = \frac{\sum C_{2i} Q_i f_i^-(x)}{\sum Q_i^2 f_i^+(x)} \]

For an isoscalar target like \(^2\text{H},\) structure functions largely cancel in the ratio at high \(x\)

At high \(x\), \(A_{PV}\) becomes independent of \(x, W\), with well-defined SM prediction for \(Q^2\) and \(y\)

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

\(C_{2q}\) inaccessible in elastic scattering
DIS at high x (Approved)

\[
\frac{2C_{2u} - C_{2d}}{2C_{1u} - C_{1d}} \sim 0.14
\]

0.5% fractional precision on the asymmetry is needed!

\[
\frac{\delta(A_{PV})}{A_{PV}} \sim 0.5% \\
\frac{\delta(2C_{2u} - C_{2d})}{(2C_{2u} - C_{2d})} \sim 5%
\]

Feasible (in narrow kinematics) with existing JLab spectrometers.

JLab 11 GeV proposal: Conditional approval
Paschke, Reimer, Zheng et al.

• Experimental systematic errors challenging
• Averaged over large Q^2, W, and x range
PVDIS with SOLID

• Solenoid (from BaBar, CDF or CLEO II) contains low energy backgrounds (Moller, pions, etc) trajectories measured after baffles
  • Fast tracking, particle ID, calorimetry,
  • and pipeline electronics
  • Precision polarimetry (0.4%)

• High Luminosity on LH$_2$ & LD$_2$
• Better than 1% errors for small bins
• $x$-range 0.25-0.75
• $W^2 > 4$ GeV$^2$
• $Q^2$ range a factor of 2 for each
• Moderate running times
Statistical Errors (%) vs Kinematics

For SOLID Spectrometer

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

4 months at 11 GeV
2 months at 6.6 GeV

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Why do we need so many data points?

• Possible new physics
  – New interactions
  – Charge symmetry violation (CSV)
  – Higher twist effects

Like neutron beta decay experiments: many diverse physics topics
Sensitivity: $C_1$ and $C_2$ Plots

World’s data

Precision Data

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Search for CSV in PV DIS

\[ u^p(x) = d^n(x) ? \]
\[ d^p(x) = u^n(x) ? \]

• u-d mass difference
• electromagnetic effects

\[ \delta u(x) = u^p(x) - d^n(x) \]
\[ \delta d(x) = d^p(x) - u^n(x) \]

• Direct observation of parton-level CSV would be very exciting!
• Important implications for high energy collider pdfs
• Could explain significant portion of the NuTeV anomaly

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

\[ \frac{\delta A_{PV}}{A_{PV}} = 0.28 \frac{\delta u - \delta d}{u + d} \]

Sensitivity will be further enhanced if \( u+d \) falls off more rapidly than \( \delta u-\delta d \) as \( x \to 1 \)

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CSV Theory and Data

Broad minimum (90% C.L.)

fully explains NuTeV

doubles NuTeV deviation

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

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Sensitivity with PVDIS

\[ R_{CSV} = \frac{\delta A_{PV}(x)}{A_{PV}(x)} = 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)} \]
Higher Twist

Subject of recent workshop at Madison, Wisconsin

- $A_{PV}$ sensitive to diquarks: ratio of weak to electromagnetic charge depends on amount of coherence (elastic He vs PVDIS)
- Do diquarks have twice the $x$ of single quarks?
- If Spin 0 diquarks dominate, likely only $1/Q^4$ effects
Need Full Phenomenology

\[
\left[ \frac{d^2 \sigma}{dx dy} \right]_{EM} \propto 2xyF_1^\gamma + \frac{2}{y} \left( 1 - y - \frac{xyM}{2E} \right)F_2^\gamma
\]

\[
\left[ \frac{d^2 \sigma}{dx dy} \right]_\gamma \propto \frac{G}{2 \sqrt{2 } \pi \alpha} \left[ -g_A \{ 2xyF_1^{\gamma Z} + \frac{2}{y} \left( 1 - y - \frac{xyM}{2E} \right)F_2^{\gamma Z} \} \right]
\]

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

\[
A_B^{PV} = \frac{\sigma^V_{\gamma Z} + \sigma^A_{\gamma Z}}{\sigma_{EM}}
\]

\[
a(x) = \frac{\sigma^V_{\gamma Z}}{\sigma_{EM}}
\]

\[
f(y)b(x) = \frac{\sigma^A_{\gamma Z}}{\sigma_{EM}}
\]

There are 5 relevant structure functions

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(Higher twist workshop at Madison, Wisconsin)
Best HT Data

$F_2$ dominates the cross section

Higher twist is clearly seen at the PVDIS kinematics. What can we add?

Analysis of Blumlein and Botcher

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# MRST Fits

\[ F_2(x, Q^2) = F_2(x)(1 + D(x)/Q^2) \quad Q^2 = (W^2 - M^2)/(1/x - 1) \quad Q^2_{\text{min}} = Q^2(W=2) \]

\[
| \begin{array}{|c|c|c|c|c|c|}
\hline
x & D(x) & D(x)/Q^2_{\text{min}} & D/Q^2_{\text{min}}(\%) & D/Q^2_{\text{min}}(\%) \\
\hline
& \text{LO} & \text{NNNLO} & \text{LO} & \text{NNNLO} \\
0.1-0.2 & -0.007 & 0.001 & 0.5 & -14 \\
0.2-0.3 & -0.11 & 0.003 & 1.0 & -11 \\
0.3-0.4 & -0.06 & -0.001 & 1.7 & -3.5 \\
0.4-0.5 & 0.22 & 0.11 & 2.6 & 8 \\
0.5-0.6 & 0.85 & 0.39 & 3.8 & 22 \\
0.6-0.7 & 2.6 & 1.4 & 5.8 & 45 \\
0.7-0.8 & 7.3 & 4.4 & 9.4 & 78 \\
\hline
\end{array}
\]

\[ A_{PV} = A_{PV}(1 + C(x)/Q^2) \]

---

MRST, PLB582, 222 (04)

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PVDIS at 12 GeV
F$_2$D(x): All x on Same Scale

Order of DGLAP influences size of HT

Higher twist falls slowly compared to PDF’s at large x.
D(x) versus x

If C(x)≈D(x), there is large sensitivity at large x.
Why HT in PVDIS is Special

Bjorken,
PRD 18, 3239 (78)

Wolfenstein,
NPB146, 477 (78)

\[
l_{\mu\nu} \int \langle D | j^\mu(x)J^\nu(0) + J^\mu(x)j^\nu(0) | D \rangle e^{iq\cdot x} d^4 x
\]

\[
l_{\mu\nu} \int \langle D | j^\mu(x)j^\nu(0) | D \rangle e^{iq\cdot x} d^4 x
\]

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

\[
\langle VV \rangle = l_{\mu\nu} \int \langle D | V^\mu(x)V^\nu(0) | D \rangle e^{iq\cdot x} d^4 x
\]

\[
A = \frac{(C_{iu} - C_{id}) \langle VV \rangle + \frac{1}{3} (C_{iu} + C_{id}) \langle SS \rangle}{\langle VV \rangle + \frac{1}{3} \langle SS \rangle}
\]

Isospin decomposition before using PDF's

\[
\langle VV \rangle - \langle SS \rangle = \langle (V - S)(V + S) \rangle \propto l_{\mu\nu} \int \langle D | \bar{u}(x)\gamma^\mu u(x)\bar{d}(0)\gamma^\nu d(0) | D \rangle e^{iq\cdot x} d^4 x
\]

HT in F_2 may be dominated by quark-gluon correlations

Vector-hadronic piece only

Use ν data for small b(x) term.

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Zero in QPM

Higher-Twist valance quark-quark correlations
What is a true quark-gluon operator?

Di-quarks correspond to transverse momentum.

Quark-gluon operators correspond to transverse momentum.

QCD equations of motion.
Test Questions

1. Which diagram is HT?
2. Is the HT diagram qq or qg?

Diagrams (a)-(c) cancel in $A_{PV}$
Coherent Program of PVDIS Study

Strategy: requires precise kinematics and broad range

Fit data to:
\[ A = A \left[ 1 + \beta_{HT} \frac{1}{(1-x)^3 Q^2} + \beta_{CSV} x^2 \right] \]

\[ C(x) = \frac{\beta_{HT}}{(1-x)^3} \]

- 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 \( Q^2 \), and \( \ldots \) to measure a combination of the \( C_{iq} \)'s

<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>

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Other Targets

• Hydrogen: d/u
• EMC effect
• N≠Z nuclei
PVDIS on the Proton: d/u at High X

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

Deuteron analysis has large nuclear corrections (Yellow)

\( A_{PV} \) for the proton has no such corrections (complementary to BONUS)

The challenge is to get statistical and systematic errors \( \sim 2\% \)

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PVDIS at 12 GeV
CSV in Heavy Nuclei: EMC Effect

Additional possible application of SoLID

Isovector-vector mean field. (Cloet, Bentz, and Thomas)
SoLID Spectrometer

Gas Cerenkov

Shashlyk

Baffles

GEM’s

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Collaboration


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PVDIS at 12 GeV
STATUS and PLANS

- Jan. 2009: Conditional approval
- Jan. 2010: Seek full approval
- Fall 2010: Director’s review
- Spring 2011: Seek CD0
Kinematics at large $x$
Baffles

Rates in detectors reduced by more than 10
Physics Resolution (%) vs Detector Resolution and Angle
Conclusions

• PVDIS addresses many physics topics
  – Electroweak couplings
  – CSV at the quark level
  – Di-quarks
  – d/u for the proton
  – Nuclear-induced CSV

• SOLID spectrometer can deliver the physics
Figure of Merit vs Scattering Angle

![Graph showing the relationship between Figure of Merit and Scattering Angle](image)

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Lots of Pions at Low Energies

Need gas Cerenkov plus shower counter with preradiator
Pion Rejection: Shashlik Detector

Total Pion Signal

$E_{\text{preshower}}/E_{\text{total}}$

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