Parity Violation in PVDIS
With SOlid

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Outline

• Physics potential
  – Standard Model Test
  – Charge Symmetry Violation (CSV)
  – Higher Twist
  – d/u for the Proton

• New Solenoidal Spectrometer (SoLID)

• Polarimetry
PV Asymmetries: Any Target and Any Scattering Angle

- $A_{LR} = A_{PV} = \frac{\sigma - \sigma}{\sigma + \sigma} \sim \frac{A_{weak}}{A_{\gamma}} \sim \frac{G_F Q^2}{4 \pi \alpha} \left( g_A e g_V^T + \beta g_V e g_A^T \right)$

The couplings $g^T$ depend on electroweak physics as well as on the weak vector and axial-vector hadronic current.

For PVDIS, both new physics at high energy scales as well as interesting features of hadronic structure come into play.

A program with a broad kinematic range can untangle the physics.
PVDIS: Electron-Quark Scattering

Many new physics models give rise to neutral ‘contact’ (4-Fermi) interactions:
Heavy Z’s, compositeness, extra dimensions…

Consider $f_1 f_\bar{1} \rightarrow f_2 f_\bar{2}$ or $f_1 f_\bar{2} \rightarrow f_1 f_2$

$$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{g_{ij}}{\Lambda} f_{1i} \gamma_\mu f_{2i} f_{\bar{2}j} \gamma^\mu f_{\bar{1}j}$$

g_{ij}’s for all $f_1 f_2$ combinations and $L,R$ combinations

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

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

$C_{1u} = -\frac{1}{2} + \frac{4}{3} \sin^2 (\theta_W) + \delta C_{1u} \approx -0.19$

$C_{1d} = \frac{1}{2} - \frac{2}{3} \sin^2 (\theta_W) + \delta C_{1d} \approx 0.35$

$C_{2u} = -\frac{1}{2} + 2 \sin^2 (\theta_W) + \delta C_{2u} \approx -0.030$

$C_{2d} = \frac{1}{2} - 2 \sin^2 (\theta_W) + \delta C_{2d} \approx 0.025$

Moller PV is insensitive to the $C_{ij}$

April 13, 2010
Deep Inelastic Scattering

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

where

- \( x \equiv x_{Bjorken} \)
- \( y \equiv 1 - E'/E \)
- \( f_i^\pm \equiv f_i \pm f_i' \)

\[ a(x) = \frac{\sum_i C_{1i} Q_i f_i^+(x)}{\sum_i Q_i^2 f_i^+(x)} \]
\[ b(x) = \frac{\sum_i C_{2i} Q_i f_i^-(x)}{\sum_i Q_i^2 f_i^+(x)} \]

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 \( y \)

New combination of:
- Vector quark couplings \( C_{1q} \)
- Also axial quark couplings \( C_{2q} \)

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

Sensitive to new physics at the TeV scale

Unknown radiative corrections for coherent processes

PVDIS: Only way to measure \( C_{2q} \)
Sensitivity: $C_1$ and $C_2$ Plots

World’s data

Precision Data

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Evidence for unexpected hadronic physics?

1. $s\neq \bar{s}$
2. Nucleon CSV
3. Nuclear CSV
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-\(^2\)H 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 \( x \to 1 \)
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 a 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
Why HT in PVDIS is Special

Start with Lorentz Invariance

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

\[ V_\mu = \left( u_\gamma \gamma^\mu u - \bar{d}_\gamma \gamma^\mu d \right) \Leftrightarrow S_\mu = \left( u_\gamma \gamma^\mu u + \bar{d}_\gamma \gamma^\mu d \right) \]

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

Next use CVC (deuteron only)

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

Zero in QPM

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

HT in $F_2$ is dominated by quark-gluon correlations

Vector-hadronic piece only

Higher-Twist valance quark-quark correlations

Wolfenstein,
NPB146, 477 (78)

Bjorken,
PRD 18, 3239 (78)
Quark-Quark vs Quark-Gluon

PVDIS is the only known way to isolate quark-quark correlations.

What is a true quark-gluon operator?

Quark-gluon operators correspond to transverse momentum.

QCD equations of motion.

Might be computed on the lattice.

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

Parton Model or leading twist

Quark-gluon diagram

Di-quarks
Higher Twist Fit to $\nu$ Data

**FIGURE 2.** Left figure: the 1σ error bands for the high-twist terms in the isospin-symmetric combinations of different structure functions (solid lines: $F_2$, dashes: $F_T$, dots: $F_L$) for charged leptons. Right figure: corresponding 1σ bands for neutrino scattering off an isoscalar target (upper panel: $F_2$, lower panel: $xF_2$). The predictions for $F_2$ from charged leptons rescaled by the corresponding leading twist terms are also shown for comparison.

Analysis of Alekhin, Kulagin, and Petti
Statistical Errors (%) vs Kinematics

**Strategy:** sub-1% precision over broad kinematic range for sensitive Standard Model test and detailed study of hadronic structure contributions

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

- 4 months at 11 GeV
- 2 months at 6.6 GeV
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)= \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  to measure a combination of the \( C_{iq} \)'s

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>y</th>
<th>Q²</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>
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 $\sim 2\%$
CSV in Heavy Nuclei: EMC Effect

Additional possible application of SoLID

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

International Collaborators:
- China (Gem’s)
- Italy (Gem’s)
- Germany (Moller pol.)

Babar Solenoid
Gas Cerenkov
Shashlyk Calorimeter
Baffles
GEM’s

ANL design

PVDIS with SOlid
JLab/UVA prototype
Atomic Hydrogen For Moller Target

Moller polarimetry from polarized atomic hydrogen gas, stored in an ultra-cold magnetic trap

- Tiny error on polarization
- Thin target (sufficient rates but no dead time)
- 100% electron polarization
- Non-invasive
- High beam currents allowed
- No Levchuk effect

10 cm, $\rho = 3 \times 10^{15}/\text{cm}^3$
in $B = 7 \text{ T}$ at $T=300 \text{ mK}$

$$\frac{n_+}{n_-} = e^{-2\mu_B/kT} \approx 10^{-14}$$

Brute force polarization

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High Precision Compton

At high energies, SLD achieved 0.5%. Why do we think we can do better?

- SLD polarimeter near interaction region - background heavy
- No photon calorimeter for production
- Hall A has “counting” mode (CW)
- Efficiency studies
- Tagged photon beam
- Greater electron detector resolution

So why haven’t we done better before?

- Small asymmetries
  - = long time to precision
  - = cross-checks are difficult
- Zero-crossing technique is new. (zero crossing gets hard near the beam)
- Photon calorimetry is harder at small $E_\gamma$

Its a major effort, but there is no obvious fundamental showstopper
## Error Budget in %

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Statistics</td>
<td>0.3</td>
</tr>
<tr>
<td>Polarimetry</td>
<td>0.4</td>
</tr>
<tr>
<td>Q2</td>
<td>0.2</td>
</tr>
<tr>
<td>Radiative Corrections</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.6</strong></td>
</tr>
</tbody>
</table>
PVDIS Collaboration

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Summary

• The physics is varied and exciting.
  – Excellent sensitivity to $C_{2u}$ and $C_{2d}$.
  – Test CSV at quark level.
  – Unique window on higher twists.

• We will build a novel apparatus (with many other possible applications, eg. SIDIS)
Layout of Spectrometer using CDF coil

- Coil mounting is well understood from CDF
  - Designed to be supported by end
  - Supports allow radial movement in both ends for thermal
  - One end fixed axially
- Will need to check for decentering forces due to field asymmetry (Lorentz forces)
## Error Projections for Moller Polarimetry

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hall C</th>
<th>Hall A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fe at 3T</td>
<td>H₁ gas</td>
</tr>
<tr>
<td>Target polarization</td>
<td>0.25%</td>
<td>0.50%</td>
</tr>
<tr>
<td>Target angle</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Analyzing power</td>
<td>0.24%</td>
<td>0.30%</td>
</tr>
<tr>
<td>Levchuk effect</td>
<td>0.30%</td>
<td>0.20%</td>
</tr>
<tr>
<td>Target temperature</td>
<td>0.05%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Dead time</td>
<td>-</td>
<td>0.30%</td>
</tr>
<tr>
<td>Background</td>
<td>-</td>
<td>0.30%</td>
</tr>
<tr>
<td>Others</td>
<td>0.10%</td>
<td>0.30%</td>
</tr>
<tr>
<td>Beam extrapolation</td>
<td>?</td>
<td>0.15%</td>
</tr>
<tr>
<td>Total</td>
<td>0.47%</td>
<td>0.82%</td>
</tr>
</tbody>
</table>

Table from MOLLER director’s review by E. Chudakov
Summary of Compton Uncertainties

<table>
<thead>
<tr>
<th>Relative Error (%)</th>
<th>electron</th>
<th>photon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{beam}$</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Laser Polarization</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Radiative Corrections</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>False Asymmetries</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Background</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Deadtime / Pileup</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Analyzing power</td>
<td>0.15</td>
<td>0.40</td>
</tr>
<tr>
<td>Total</td>
<td>0.34</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Independent detection of photons and electrons provides **two (nearly) independent polarization measurements**; each should be better than 0.5%.

This would represent a significant step beyond what has been done at JLab before, but there is no fundamental reason why it should not be achievable.

Participants from UVa, Syracuse, JLab, CMU, ANL, Miss. St.
Layout of Moller and PVDIS
Need Full Phenomenology

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

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

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

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

There are 5 relevant structure functions

\[ A_B^{PV} = \frac{\sigma_V^{\gamma Z} + \sigma_A^{\gamma Z}}{\sigma_{EM}} \]

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

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

Small; use $\nu$ data

(Higher twist workshop at Madison, Wisconsin)
SoLID Spectrometer
Access to the Detectors

• End Cap rolls backward along the beam line on Hilman Rollers
• 342 metric tons for both end caps with baffles installed
• Must allow for 5% rolling resistance
Baffle geometry and support
Elastic Radiative Tail