Parity Violating Electron Scattering: Recent Results and Future Prospects

(Expanded version of CIPANP06 Plenary Talk)

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J. Piekerewicz, M. Pitt, P. Souder

June 12, 2006
Jefferson Lab Users Meeting
Weak Neutral Current (WNC) Interactions

Low energy WNC interactions \( (Q^2 \ll M_Z^2) \)

**Historical Context:**

- **1960s:** An Electroweak Model of Leptons (and quarks)
  - \( SU(2)_L \times U(1)_Y \) gauge theory predicted the Z boson
- **1973:** antineutrino-electron scattering
  - First weak neutral current observation
    - Gargamelle observes one \( \nu \mu e^- \) event
    - First measurement of weak mixing angle
- **Mid-70s:** Does the Weak Neutral Current interfere with the Electromagnetic Current?
  - Central to establishing \( SU(2)_L \times U(1)_Y \)

\[
\begin{pmatrix}
\nu \\
\langle e \rangle_l \\
(\bar{e}^0)
\end{pmatrix} \quad \begin{pmatrix}
\nu \\
(\bar{e}^0) \\
\langle e \rangle_r
\end{pmatrix}
\]

- Parity is conserved
- Consider fixed target electron scattering
- Parity is violated

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Parity-Violating (PV) Electron Scattering

\[ \sigma \propto |A_\gamma + A_{\text{weak}}|^2 \sim |A_{\text{EM}}|^2 + 2 A_{\text{EM}} A_{\text{weak}}^* + ... \]

\[ -A_{LR} = A_{PV} = \frac{\sigma - \sigma}{\sigma + \sigma} \sim \frac{A_{\text{weak}}}{A_\gamma} \sim \frac{G_F Q^2}{4 \pi \alpha} g \]

- \( g \) and \( g_A \) are function of \( \sin^2 \theta_W \)
- \( \beta \) is a kinematic factor
- \( Q^2 \) is the 4-momentum transfer
- \( g_T \) affected by QCD physics

**Established experimental technique:** \( \delta(A_{PV}) < 10 \, \text{ppm} \)

**Cleanly observed weak-electromagnetic interference**

**Parity Violation in Weak Neutral Current Interactions**

**\( \sin^2 \theta_W = 0.224 \pm 0.020 \): same as in neutrino scattering**

\( A_{PV} \) in Deep Inelastic Scattering off liquid Deuterium: \( Q^2 \sim 1 \, (\text{GeV})^2 \)

E122 at the Stanford Linear Accelerator Center (SLAC)

20 GeV polarized electron beam on a 30 cm LD\(_2\) target
Parity-violating electron scattering has become a precision tool

Combined with judicious choices of kinematics and targets:

- Many-Body Nuclear Physics
- Nucleon Structure Physics
- Valence Quark Physics
- Search for New TeV Physics

Address fundamental physics issues over a range of energy scales
Outline

• Strangeness in Nucleons
  – New Results from HAPPEX at Jefferson Lab
  – Status and Plans for further measurements
• The Neutron Skin of a Heavy Spinless Nucleus
  – A planned measurement of elastic WNC amplitude off $^{208}$Pb
• Low Energy Weak Mixing Angle Measurements
  – Final Result from the E158 Experiment at SLAC
  – Possible New Measurements at Jefferson Lab and an LC
• PV Deep Inelastic Scattering at JLab at 11 GeV
  – Potential of precision studies of nucleon structure at high $x$
• Summary
Nucleon Structure & Strangeness

**QCD is intractable at low $Q^2$; what is its relationship to hadron structure?**

Why don’t sea quarks destroy Quark Model predictions?

Strange quarks are relatively light;
What can we say about its role?

**Spin dependent deep inelastic scattering**

$$S = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \Delta L$$

$$A_{\parallel} = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\downarrow\uparrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\downarrow}}$$

**Proton Spin**

Experiments: \[ \Delta \Sigma \sim 0.25 \]

**SU(3)_f symmetry-breaking introduces uncertainties**

**Semi-inclusive DIS (HERMES)**
(Needs fragmentation functions)

"$\Delta s$" = $\int \Delta s(x) \, dx = +0.03 \pm 0.03 \text{(stat)} \pm 0.01 \text{(syst)}$

Neutrino deep inelastic scattering

πN scattering:
Strange mass: 0–20%

What about the nucleon’s charge and magnetization distributions?
Elastic Electron Scattering 101

Measure $\sigma$ as a function of $Q^2$

Neglecting recoil and spin:
Obtain Fourier transform of charge distribution

Nucleon charge and magnetization distributions:
$G_E(Q^2), G_M(Q^2)$
electric and magnetic form factors
$G_E^p(0) = 1$ \quad $G_E^n(0) = 0$
$G_M^p(0) = +2.79 \equiv \mu_p$
$G_M^n(0) = -1.91 \equiv \mu_n$

Nuclear charge distribution

Is this a valid picture?
Need flavor-separation of $G_E, G_M$
Elastic Electroweak Scattering

$A_{PV}$ for elastic e-p scattering:

$$A_E = \mathcal{E} \ G_E^p \ G_E^Z, \quad A_M = \tau \ G_M^p \ G_M^Z, \quad A_A = -(1 - 4 \sin^2 \theta_W) \mathcal{E} \ G_M^p \ G_A^e$$

Kaplan & Manohar (1988)
McKeown (1989)

Helium: Unique $G_E$ sensitivity
Deuterium: Enhanced $G_A$ sensitivity
How Big Are $G_E^s$, $G_M^s$?

Experimental determination of non-zero $G^s$ is unambiguous

Various theoretical estimates:
- Vector Meson Dominance Models
- Quark models
- Dispersion Theory
- Lattice Gauge theory
- Chiral-Quark Soliton Model

Theoretical predictions for strange magnetic moment

$\mu_s \equiv G^s_M (Q^2 = 0)$

Little theoretical guidance on $Q^2$ dependence

$Q^2 \sim 0.1 \text{ GeV}^2$
Overview of Experiments

**SAMPLE**
- Open geometry, integrating
  - $G_M$ $^s$, $(G_A)$ at $Q^2 = 0.1$ GeV$^2$

**HAPPEX**
- $G_E^s + 0.39$ $G_M^s$ at $Q^2 = 0.48$ GeV$^2$
- $G_E^s + 0.08$ $G_M^s$ at $Q^2 = 0.1$ GeV$^2$
- $G_E^s$ at $Q^2 = 0.1$ GeV$^2$ ($^4$He)

**A4**
- Open geometry
- Fast counting calorimeter for background rejection
  - $G_E^s + 0.23$ $G_M^s$ at $Q^2 = 0.23$ GeV$^2$
  - $G_E^s + 0.10$ $G_M^s$ at $Q^2 = 0.1$ GeV$^2$
  - $G_M^s$, $G_A^e$ at $Q^2 = 0.1$, 0.23, 0.5 GeV$^2$

**GO**
- Open geometry
- Fast counting with magnetic spectrometer + TOF for background rejection
  - $G_E^s + \eta$ $G_M^s$ over $Q^2 = [0.12, 1.0]$ GeV$^2$
  - $G_M^s$, $G_A^e$ at $Q^2 = 0.23$, 0.62 GeV$^2$
Status as of 2005

Over the past three years:
New data from A4, G0 and HAPPEX

\[ Q^2 \sim 0.1 \text{ GeV}^2 \]

- Add SAMPLE & HAPPEX-He
- Multiple constraints at \[ Q^2 \sim 0.1 \text{ GeV}^2 \]
- Would imply 5-10% contribution to magnetic moment from strange quarks (50-100% of isoscalar magnetic moment)
Experimental Technique

"strain" boosts polarization, but introduces anisotropy in response.

100 x 600 mm

12 m dispersion sweeps away inelastic events

Polarimeters

Compton 1.5-3% syst
Continuous

Møller 2-3% syst

Target
400 W transverse flow
20 cm, LH2
20 cm, 200 psi 4He

High Resolution Spectrometer
S+QQDQ 5 mstr over 4°-8°

Elastic Rate:
1H: 120 MHz
4He: 12 MHz

100 kV

Accelerator

polarized source
GaAs

laser

pockels cell

half-wave plate

polarized electrons

Cherenkov cones

PMT

Transverse axis (mm)

Dispersive axis (mm)
New Preliminary HAPPEX Results

**Helicity Window Pair Asymmetry**

<table>
<thead>
<tr>
<th>HV Window</th>
<th>R</th>
<th>L</th>
<th>R</th>
<th>L</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>15 Hz</td>
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</table>

**Hydrogen**

Systematic control $\sim 10^{-8}$

$A_{PV} = -1.60 \pm 0.12 \text{ (stat)} \pm 0.05 \text{ (syst)} \text{ ppm}$

$A(G^s=0) = -1.640 \text{ ppm} \pm 0.041 \text{ ppm}$

**Helium**

Normalization control $\sim 2\%$

$A_{PV} = +6.43 \pm 0.23 \text{ (stat)} \pm 0.22 \text{ (syst)} \text{ ppm}$

$A(G^s=0) = +6.37 \text{ ppm}$

$A_{raw \text{ correction}} \sim 11 \text{ ppb}$

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Implications and Outlook

- Rapid variation at low $Q^2$ unlikely
- Await backward angle measurements from A4, G0
- Deuterium running will provide constraints on $G_A$
- One high precision point at $Q^2 \sim 0.6$

$Q^2 \sim 0.1 GeV^2$

G0 Status report
by D. Gaskell
(Parallel Session I)

$G_M^s = 0.28 +/- 0.20$
$G_E^s = -0.006 +/- 0.016$

~3% +/- 2.3% of proton magnetic moment
(same as 20% of isoscalar magnetic moment)

$0.2 +/- 0.5%$ of electric distribution

HAPPEX-only fit suggests something even smaller:

$G_M^s = 0.12 +/- 0.24$
$G_E^s = -0.002 +/- 0.017$

- Approved program well-matched to ultimate sensitivity of the technique
- Models dealing with "sea" properties are extremely challenging
- Experimentally, a 20-year old quest nearing completion
- Ultimate insight: unquenched Lattice QCD calculations with light chiral quarks
An Alternate Fit to Data $Q^2 \sim 0.1 \text{ GeV}^2$


Young et al, nucl-ex/0604010
- Fit to all proton data up to $Q^2 \sim 0.3 \text{ GeV}^2$
- Specific choices of $Q^2$ dependence
- Simultaneously fit axial form factor

Parallel Session I

R. Young
- Central value and error of calculation
- Details of fit

Zhu et al.

D. Toublan
- Heavy vs light sea quark contribution to the magnetic moment

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**Probing Neutron-Rich Matter**

- The proton distribution of heavy nucleus: mapped via electron scattering
- The neutron distribution:
  - probed with hadrons
  - highly model-dependent
  - neutron “skin” ~ 0.1 - 0.3 fm?
- Neutron density a fundamental observable:
  - Impacts a variety of physics

- $^{208}\text{Pb}$ neutron skin and neutron star crust made of similar material
- At what radius does transition from liquid to non-uniform matter take place?
- Mean Field theory predicts correlation between neutron star transition density and $^{208}\text{Pb}$ neutron skin

$^{208}\text{Pb}$ neutron skin and neutron star crust made of similar material. At what radius does transition from liquid to non-uniform matter take place? Mean Field theory predicts correlation between neutron star transition density and $^{208}\text{Pb}$ neutron skin.
PReX at Jefferson Lab

\[ \delta(A_{PV}) \sim 3\% \quad \rightarrow \quad \delta(R_p - R_n) \sim 1\% \]

\[ Q^p_{EM} \sim 1 \quad Q^n_{EM} \sim 0 \]

\[ Q^n_W \sim 1 \quad Q^p_W \sim 1 - 4\sin^2\theta_W \]

**Constrain neutron halo for Atomic Parity Violation Expts**

A technically demanding measurement:

- Rate \sim 2 \text{ GHz}
- Separate excited state at 2.6 MeV
- Stat. Error \sim 15 \text{ ppb}
- Syst. Error \sim 1 \text{ to } 2 \%

Tentatively scheduled to run in 2008

- Tight control of beam properties
- New “warm” septum
- High power Lead target
- New 18-bit ADC
- New radiation-hard detector
- Polarimetry upgrade
Beyond Standard Model @ Low $Q^2$

- Precise predictions @ 0.1%
- Indirect access to TeV scale

- World electroweak data has marginal $\chi^2$, but no discernable pattern
- Data used to put limits on energy scale of new physics effects

- Parity-conserving contact interactions probed at 10-20 TeV level
- Parity-violating contact interactions probed at few TeV level

$Q^2 \sim M_Z^2$

\[ \frac{\delta A_Z}{A_Z} \alpha \frac{\pi/\Lambda^2}{g G_F} \quad \Rightarrow \quad \frac{\delta(g)/g}{\sin^2 \theta_W} \lesssim 0.01 \]

\[ \Lambda \sim 10 \text{ TeV} \]

\[ A_Z^2 \left[ 1 + \frac{A_X^2}{A_Z^2} \right] \quad \text{no interference!} \]
The SLAC E158 Experiment

'-'Violating Left-Right Asymmetry In Fixed Target Møller Scatt

Goal: error small enough to probe TeV scale physics

\[ A_{PV} \propto m_e E_{lab} (1 - 4 \sin^2 \vartheta_W) \]
\[ A_{PV} \approx -4 \times 10^{-9} \times E_{beam} \times P_{beam} \]

E158 Collaboration

- Berkeley
- Caltech
- Jefferson Lab
- Princeton
- Saclay
- SLAC
- Smith
- Syracuse
- UMass
- Virginia

8 Ph.D. Students
60 physicists

2001: Engineering run
2002-2003: Physics runs
2004: First PRL
2005: Final result

End Station A at SLAC

BEAM

45 GeV, 48 GeV
85% longitudinal polarization

Precision beam monitoring

TARGET

154 cm target
\[ L \sim 10^{38} \text{ cm}^{-2}\text{s}^{-1} \]

DETECTOR

2 GHz scattered Møller rate

N+,N-

4-7 mrad

Novel small-angle spectrometer
Radiation-hard, ultra-quiet detector
SLAC E158 Main Result

Parity Violating Electron Scattering: Recent Results and Future Prospects

\[ \frac{I}{2} - q \sin^2 \theta_w \]

\[ \sin^2 \theta_{\text{eff}} = 0.2397 \pm 0.0010 \pm 0.0008 \]

- Limit on $\Lambda_{LL} \sim 7 \text{ or } 16 \text{ TeV}$
- Limit on SO(10) $Z'$ ~ 1.0 TeV
- Limit on lepton flavor violating coupling ~ $0.01G_F$

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Weak Mixing Angle at HIGH $Q^2$

The Average: $\sin^2 \theta_w = 0.23122(17)$

$\Rightarrow m_H = 89^{+38}_{-28}$ GeV

$\Rightarrow S = -0.13 \pm 0.10$

$3\sigma$ apart

W. Marciano, CIPANP06
EW & BSM Session

$A_{LR}$
(also APV in Cs)

$\sin^2 \theta_w = 0.2310(3)$

$\downarrow$

$m_H = 35^{+26}_{-17}$ GeV

$S= -0.11 \pm 17$

Rules out the SM!

$A_{FB}$ (Z→ bb)
(also Moller @ E15)

$\sin^2 \theta_w = 0.2322(3)$

$\downarrow$

$m_H = 480^{+350}_{-230}$ GeV

Rules out SUSY!
Favors Technicolor

• Tevatron & LHC will make some improvements on $M_W$
• $\sin^2 \theta_W$ improvements at hadron colliders very challenging
• Must wait for “Giga-Z” option of ILC or Neutrino Factory

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Future Possibilities (Purely Leptonic)

ν-e in reactor can test neutrino coupling: \( \sin^2 \theta_W \) to ± 0.002

Møller at 11 GeV at Jlab

\( \sin^2 \theta_W \) to ± 0.00025! e.g. \( Z' \) reach

\( \Lambda_{ee} \sim 25 \) TeV reach!

Higher luminosity and acceptance

• Comparable to single Z pole measurement: shed light on disagreement
• Best low energy measurement until ILC or ν-Factory
• Could be launched ~ 2012

Does Supersymmetry (SUSY) provide a candidate for dark matter?

• Neutralino is stable if baryon (B) and lepton (L) numbers are conserved
• B and L need not be conserved (RPV): neutralino decay

JLab e²e @ 12 GeV

Kurylov, Ramsey-Musolf, Su

95% C.L.
JLab 12 GeV
Møller

\[ \Lambda_{ee} \sim 25 \text{ TeV reach!} \]

Higher luminosity and acceptance

\( \sin^2 \theta_W \) to ± 0.00025!

\[ \sin^2 \theta_W \text{ to } \pm 0.00025! \]

\[ \text{e.g. } Z' \text{ reach } \sim 2.5 \text{ TeV} \]
Ultrahigh Precision at ILC

Measure contribution from scalars to oblique corrections

\[
\frac{\delta m_H}{m_H} \approx 10\% \text{ for } \delta \sin^2 \theta_W \approx 0.00004
\]

(world average ~0.00016)

Critical crosscheck

\[\sigma \propto \frac{1}{E_{\text{lab}}}\] Figure of Merit rises linearly with \(E_{\text{lab}}\)

\[A_{\text{LR}} \text{ and } M_e \text{ at future colliders:} \]
Systematics extremely challenging!

Energy scale to \(10^{-4}\), polarimetry to 0.15%

Møller scattering at the ILC

<table>
<thead>
<tr>
<th>K.K, Snowmass 96</th>
<th>E158</th>
<th>LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>48</td>
<td>250-500</td>
</tr>
<tr>
<td>Intensity/pulse</td>
<td>(4.5 \times 10^{11})</td>
<td>(14 \times 10^{11})</td>
</tr>
<tr>
<td>Pulse Rate (Hz)</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>(P_e)</td>
<td>85%</td>
<td>90%</td>
</tr>
<tr>
<td>Time (s)</td>
<td>(4 \times 10^6)</td>
<td>(2 \times 10^7)</td>
</tr>
<tr>
<td>(A_{\text{LR}}) (ppm)</td>
<td>0.15</td>
<td>1-2</td>
</tr>
<tr>
<td>(\delta A_{\text{LR}}) (ppm)</td>
<td>0.015</td>
<td>0.008</td>
</tr>
<tr>
<td>(\delta \sin^2(\theta_W))</td>
<td>0.001</td>
<td>0.00008</td>
</tr>
</tbody>
</table>

- Fixed target has advantages for systematics
- Could work with ILC “exhaust” beam
Qweak at JLab

Physics Asymmetry: \[ A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}} \left[ Q^2 Q_{weak}^p + Q^4 B(Q^2) \right] \]

Region 1: GEM
Gas Electron Multiplier

Region 2: Horizontal drift chamber location

Region 3: Vertical Drift chambers

- \( \delta(A_{PV}) \sim 3\% \)
- \( \delta(\sin^2\theta_W) \sim \pm 0.0007 \)
- Design under way
- Data \( \sim 2009 \)
Future Measurements (Semi-leptonic)

- NuTeV motivates closer look at lepton-quark WNC couplings
- 4 model-independent e-q couplings to nail down
- Implications for models of new TeV scale physics

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

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

- \( C_{2i} \)'s small & poorly known: difficult to measure in elastic scattering
- PV Deep inelastic scattering experiment with high luminosity 11 GeV beam
PV DIS at 11 GeV with an LD$_2$ target

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

\[ y \equiv 1 - \frac{E'}{E} \]

For an isoscalar target like $^2$H, structure functions largely cancel in the ratio:

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

\((Q^2 \gg 1 \text{ GeV}^2, W^2 \gg 4 \text{ GeV}^2, x \sim 0.3-0.5)\)

• Must measure $A_{PV}$ to 0.5% fractional accuracy!
• Luminosity and beam quality available at JLab

• 6 GeV experiment launches PV DIS measurements at JLab
• 11 GeV experiment requires tight control of normalization errors
• Important constraint should LHC see anomaly
• Need to characterize nucleon structure at high-$x$ to high precision

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Precision High-x Physics with PV DIS

Charge Symmetry Violation (CSV) at High $x$: clean observation possible?

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

$\frac{\delta A_{PV}(x)}{A_{PV}(x)} = 0.3 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$

- Direct observation of parton-level CSV: exciting!
- Implications for high energy collider pdfs
- Could explain significant portion of the NuTeV anomaly

Need 1% $A_{PV}$ measurement at $x \sim 0.75$

For hydrogen $^1H$:

$$a(x) = \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$

Longstanding issue: $d/u$ as $x \rightarrow 1$

- Allows $d/u$ measurement on a single proton!
- Vector quark current! (electron is axial-vector)
A Vision for Precision PV DIS Physics

- Hydrogen and Deuterium targets
- Better than 2% errors
  - It is unlikely that any effects are larger than 10%
- $x$-range 0.25–0.75
- $W^2$ well over 4 GeV$^2$
- $Q^2$ range a factor of 2 for each
  - (Except $x \sim 0.75$)
- Moderate running times

- solid angle $> 200$ msr
- Count at 100 kHz
- online pion rejection of $10^2$ to $10^3$

Goal: Form a collaboration, start real design and simulations, and make pitch to US community at the next nuclear physics long range plan (2007)
Summary

• New HAPPEX results on nucleon neutral weak form factors:
  • Helium: $G_E^s = +0.004 \pm 0.014_{\text{stat}} \pm 0.013_{\text{syst}} (Q^2 = 0.077 \text{ GeV}^2)$
  • Hydrogen: $G_E^s + 0.088G_M^s = +0.004 \pm 0.011_{\text{stat}} \pm 0.005_{\text{syst}} \pm 0.004_{\text{FF}}$
  • Final measurements to be completed within two years

• A clean measurement of the neutron’s skin in $^{208}\text{Pb}$: implications for neutron star formation and properties

• E158 has carried out a precision measurement of $\sin^2\theta_W$
  • $A_{PV}: -131 \pm 14 \pm 10 \text{ ppb}$
  • Running of weak mixing angle established at $6\sigma$
  • $\sin^2\theta_{\text{eff}} = 0.2397 \pm 0.0010 \pm 0.0008$
  • New constraints on TeV scale physics

• Future experiments could improve sensitivity by ~ 2 to 6
• An “ultimate” measurement could be done at an LC

• New era of PV DIS measurements with JLab 12 GeV upgrade
Search for CSV in PV DIS

\[ u^p(x) = d^n(x) \] \ • u-d mass difference
\[ d^p(x) = u^n(x) \] \ • 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:

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

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

Strategy:

• measure or constrain higher twist effects at \( x \sim 0.5-0.6 \)
• precision measurement of \( A_{PV} \) at \( x \sim 0.7 \) to search for CSV
\[ d(x)/u(x) \text{ as } x \to 1 \]

Proton Wavefunction (Spin and Flavor Symmetric)

\[
| p \uparrow \rangle = \frac{1}{\sqrt{2}} u \uparrow (ud)_{S=0} \rangle + \frac{1}{\sqrt{18}} u \uparrow (ud)_{S=1} \rangle - \frac{1}{3} u \downarrow (ud)_{S=1} \rangle
\]

\[
- \frac{1}{3} d \uparrow (uu)_{S=1} \rangle - \frac{\sqrt{2}}{3} d \downarrow (uu)_{S=1} \rangle
\]

SU(6): 
\[ d/u \sim 1/2 \]

Valence Quark: 
\[ d/u \sim 0 \]

Perturbative QCD: 
\[ d/u \sim 1/5 \]

Longstanding issue in proton structure

PV-DIS off hydrogen

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

\[ a(x) = \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)} \]

- Allows \( d/u \) measurement on a single proton!
- Vector quark current! (electron is axial-vector)
PV DIS and Nucleon Structure

• Analysis assumed control of QCD uncertainties
  - Higher twist effects
  - Charge Symmetry Violation (CSV)
  - $d/u$ at high $x$
• NuTeV provides perspective
  - Result is $3\sigma$ from theory prediction
  - Generated a lively theoretical debate
  - Raised very interesting nucleon structure issues: cannot be addressed by NuTeV
• JLab at 11 GeV offers new opportunities
  - PV DIS can address issues directly
    • Luminosity and kinematic coverage
    • Outstanding opportunities for new discoveries
    • Provide confidence in electroweak measurement
**E158 Analysis**

**Basic Idea:**
- Quartz
- Copper
- Light guide
- PMT
- Shielding

**Radial and azimuthal segmentation**

**Observed left-right asymmetry distribution**

- Raw asymmetry distribution in one PMT: RMS ~ 3460 ppm
- Charge normalized distribution in one PMT: RMS ~ 1108 ppm

- Distribution regressed for energy, position, angle in one PMT:
  - ~ 1.8 Million electrons/pulse
  - $\sigma = 527$ ppm

- Grand width:
  - ~ 15 Million electrons/pulse
  - $\sigma = 194$ ppm

- Corrections for beam fluctuations
- Average over runs
- Statistical tests
- Beam polarization and other PMT normalization
Physics Runs

Run 1: Apr 23 12:00 – May 28 00:00, 2002
Run 2: Oct 10 08:00 – Nov 13 16:00, 2002
Run 3: July 10 08:00 – Sep 10 08:00, 2003

Data divided into 75 “slugs”:
- Wave plate flipped ~ few hours
- Beam energy changed ~ few days

$A_{PV}$ Sign Flips

45 GeV: 14.0 revs
48 GeV: 14.5 revs
Raw Asymmetry Statistics

\[ A_i - \langle \bar{A} \rangle \]

\[ \sigma_i \approx 200 \text{ ppm} \]

\[ N = 85 \text{ Million} \]

\[ A_i - \langle \bar{A} \rangle \]

\[ \sigma_i \approx 600 \text{ ppb} \]

\[ N = 818 \]
Final Analysis of All 3 Runs

\[ A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9} \]

\[ g-2 \text{ spin precession} \]

\[ A_{PV} \approx -1 \times 10^7 \text{ GeV: 14.0 revs} \times (1 - 4 \sin^2 \theta_W) \]

\[ 48 \text{ GeV: 14.5 revs} \]

\[ \approx 250 \text{ ppb} \]

\[ \chi^2/df = 78.5/74 \]

Electroweak Physics

\[
\sin^2 \theta_W = \frac{e^2}{g^2} \rightarrow \text{test gauge structure of SU}(2) \times \text{U}(1)
\]

- Czarnecki and Marciano
- Erler and Ramsey-Musolf
- Sirlin et. al.
- Zykonov

Future Prospects
Backgrounds & Normalization

Integrating calorimeter:
background dilutions and asymmetries must be separately measured or bounded.

- Elastic and inelastic e-p scattering and radiative tail
- High energy pions
- High and low energy photons
- Neutrons
- Synchrotron radiation

Total dilution: 9.3% in Run I, 7.6% in Run II & II

- Beam polarization measured using polarized foil target
  - Same spectrometer used with dedicated movable detector
- Energy scale and spectrometer alignment to determine $\langle Q^2 \rangle$
- Linearity of PMTs

Largest systematic errors:
- Inelastic ep: $-22 \pm 4$ ppb
- Beam polarization: $0.89 \pm 0.04$
## Summary of Corrections

<table>
<thead>
<tr>
<th>Correction</th>
<th>(f_{\text{bkg}})</th>
<th>(\sigma(f_{\text{bkg}}))</th>
<th>(A_{\text{corr}}) (ppb)</th>
<th>(\sigma(A_{\text{corr}})) (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam first order</td>
<td>-</td>
<td>-</td>
<td>-10</td>
<td>1</td>
</tr>
<tr>
<td>Beam higher orders</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Beam spotsize</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Transverse asymmetry</td>
<td>-</td>
<td>-</td>
<td>-4</td>
<td>2</td>
</tr>
<tr>
<td>High energy photons</td>
<td>0.004</td>
<td>0.002</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Synchrotron photons</td>
<td>0.002</td>
<td>0.001</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Neutrons</td>
<td>0.003</td>
<td>0.001</td>
<td>-1</td>
<td>1</td>
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<tr>
<td>ep elastic</td>
<td>0.056</td>
<td>0.007</td>
<td>-7</td>
<td>1</td>
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<tr>
<td>ep inelastic</td>
<td>0.009</td>
<td>0.001</td>
<td>-22</td>
<td>4</td>
</tr>
<tr>
<td>Pions</td>
<td>0.001</td>
<td>0.001</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.075</td>
<td>0.008</td>
<td>-40</td>
<td>6</td>
</tr>
</tbody>
</table>

- Scale factors:
  - Average Polarization 89 ± 4% ⇔ New “NLC” cathode !
  - Linearity 99 ± 1%
  - Radiative corrections: 1.01 ± 0.01
“ep” Detector Data

- Radiative tail of elastic ep scattering is dominant background
- 8% under Moller peak
- Additional 1% from inelastic e-p scattering
- Coupling is large: similar to 3 incoherent quarks: $0.8 \times 10^{-4} \times Q^2$
- Background reduced in Run II & III with additional collimation

At low $Q^2$: $A_{LR} \sim 10^{-4} \times Q^2$
Transverse Asymmetry

Two-photon exchange QED effect

for Møller scattering at 46 GeV

\[ A_T \propto \frac{\alpha m_e}{\sqrt{s}} = -3.5 \text{ ppm} \cdot \sin \phi \]

Observe ~ 2.5 ppm up-down asymmetry w/ horizontal polarization
First measurement of single-spin transverse asymmetry in e-e scattering.

Theory References:
1. A. O. Barut and C. Fronsdal, (1960)
2. L. L. DeRaad, Jr. and Y. J. Ng (1975)
Form Factors

\[ J_{\mu}^{EM} = \sum_{q} Q_{q} \langle \bar{N} | \bar{u}_{q} \gamma_{\mu} u_{q} | N \rangle = \bar{N} \left[ \gamma_{\mu} F_{1}^{\gamma} + \frac{i \sigma_{\mu\nu} q^{\nu}}{2M_{N}} F_{2}^{\gamma} \right] N \]

Adopt the Sachs FF: \( G_{E}^{\gamma} = F_{1}^{\gamma} + \pi F_{2}^{\gamma} \quad G_{M}^{\gamma} = F_{1}^{\gamma} + F_{2}^{\gamma} \)

(Roughly: Fourier transforms of charge and magnetization)

NC probes same hadronic flavor structure, with different couplings:

\[ G_{E/M}^{\gamma} = \frac{2}{3} G_{E/M}^{u} - \frac{1}{3} G_{E/M}^{d} - \frac{1}{3} G_{E/M}^{s} \]

\[ G_{E/M}^{Z} = \left( 1 - \frac{8}{3} \sin^{2} \theta_{W} \right) G_{E/M}^{u} - \left( 1 - \frac{4}{3} \sin^{2} \theta_{W} \right) G_{E/M}^{d} - \left( 1 - \frac{4}{3} \sin^{2} \theta_{W} \right) G_{E/M}^{s} \]

\( G_{E/M}^{Z} \) provide an important new benchmark for testing non-perturbative QCD structure of the nucleon
Charge Symmetry

One expects the neutron to be an isospin rotation of the proton*:

\[ G_{E/M}^{p,u} = G_{E/M}^{n,d} , \quad G_{E/M}^{p,d} = G_{E/M}^{n,u} , \quad G_{E/M}^{p,s} = G_{E/M}^{n,s} \]

\[ G_{E/M}^{\gamma,p} = \frac{2}{3} G_{E/M}^{u} - \frac{1}{3} G_{E/M}^{d} - \frac{1}{3} G_{E/M}^{s} \]

\[ G_{E/M}^{\gamma,n} = \frac{2}{3} G_{E/M}^{d} - \frac{1}{3} G_{E/M}^{u} - \frac{1}{3} G_{E/M}^{s} \]

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{M_Z M_{\gamma}}{M_{\gamma}^2} = -\frac{G_F Q^2}{\sqrt{2\pi\alpha}} F(G_{E/M}^{p}, G_{E/M}^{n}, G_{E/M}^{s}, G_A) \]

* See B. Kubis & R. Lewis, nucl-th/0605006 & Randy Lewis’ talk at this meeting
Beam Asymmetries
Energy: -3 ppb
X Target: -5 nm
X Angle: -28 nm
Y Target: -21 nm
Y Angle: 1 nm

Total Corrections:
Left: -370 ppb
Right: 80 ppb
All: 120 ppb
Beam Position Corrections, Hydrogen

Surpassed Beam Asymmetry Goals for Hydrogen Run

Energy: -0.25 ppb
X Target: 1 nm
X Angle: 2 nm
Y Target: 1 nm
Y Angle: <1 nm

Corrected and Raw, Left arm alone, Superimposed!

Total correction for beam position asymmetry on Left, Right, or ALL detector: 10 ppb
Compton Polarimetry

**Hydrogen:** 86.7% ± 2%

Compton Polarimetry

**Helium:** 84.0% ± 2.5%

Continuous, non-invasive
Here: Electron Detector analysis
Cross-checked with Møller, Mott polarimeters
also: independent electron analysis

Helium ran with lower beam energy, making the analysis significantly more challenging.

New developments in both photon and electron analyses in preparation: anticipate <2% systematic uncertainty
Miscellany

• **Backgrounds:**
  - Dilutions: 2.2% (\(^4\)He) 0.8% (\(^1\)H)
  - Systematic: 60 ppb (\(^4\)He) 16 ppb (\(^1\)H)

• **\(Q^2\) & effective kinematics:**  \(Q^2 < 1.0\%\)

• **Two-photon exchange corrections:**
  - Small  Marc Vanderhaeghan’s talk
  - (no explicit correction made)

• **Transverse asymmetry:**
  - Measured directly in dedicated runs, cancels in left-right sum;
  - Systematic: 4 ppb (\(^1\)H) 8 ppb (\(^4\)He)

• **Electromagnetic Form Factors:**

• **Axial Form Factor:**
  - Highly suppressed for \(^1\)H  (not present for \(^4\)He)

• **Vector Electroweak Radiative Corrections:**
  - Particle Data Group

• **Blinded Analysis**
4He: Nuclear Effects

O⁺  O⁺  T=0 transition

• Any one-body electroweak operator \( O \):
  \[
  <J,T|O|J,T> = J,T \left( | \begin{array}{c} \alpha \, \beta \end{array} \right) <J'|O|J'>
  \]
  one-body density matrix element (nuclear structure)
  single-particle matrix element (nucleon structure)

• Asymmetry involves ratio of weak/EM matrix elements (\( G_F^e \) and \( G_E^{T=0} \));
  Single term in \( J,T \) in transition; \( O \) same in weak and EM except for couplings
  same one-body density matrix elements in numerator/denominator
  nuclear structure cancels, only nucleon form factors remain

This result is EXACT, if:

– 4He g.s. pure isospin state: Ramavataram, Hadjimichael, Donnelly PRC 50(1994)1174
– Meson exchange corrections small: Musolf, Schiavilla, Donnelly PRC 50(1994)2173

• Nuclear effects all \(< 1\%\), no explicit correction made.
### Error Budget - Helium

<table>
<thead>
<tr>
<th></th>
<th>2005</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>False Asymmetries</td>
<td>48 ppb</td>
<td>103 ppb</td>
</tr>
<tr>
<td>Polarization</td>
<td>192 ppb</td>
<td>115 ppb</td>
</tr>
<tr>
<td>Linearity</td>
<td>58 ppb</td>
<td>78 ppb</td>
</tr>
<tr>
<td>Radiative Corrections</td>
<td>6 ppb</td>
<td>7 ppb</td>
</tr>
<tr>
<td>$Q^2$ Uncertainty</td>
<td>58 ppb</td>
<td>66 ppb</td>
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<tr>
<td>Al background</td>
<td>32 ppb</td>
<td>14 ppb</td>
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<td>Helium quasi-elastic</td>
<td>24 ppb</td>
<td>86 ppb</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>216 ppb</strong></td>
<td><strong>205 ppb</strong></td>
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</table>

### Error Budget - Hydrogen

<table>
<thead>
<tr>
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<tbody>
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<td>Polarization</td>
<td>37 ppb</td>
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<td>Linearity</td>
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<td>15 ppb</td>
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<tr>
<td>Radiative Corrections</td>
<td>3 ppb</td>
<td>7 ppb</td>
</tr>
<tr>
<td>$Q^2$ Uncertainty</td>
<td>16 ppb</td>
<td>12 ppb</td>
</tr>
<tr>
<td>Al background</td>
<td>15 ppb</td>
<td>16 ppb</td>
</tr>
<tr>
<td>Rescattering Background</td>
<td>4 ppb</td>
<td>32 ppb</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>49 ppb</strong></td>
<td><strong>63 ppb</strong></td>
</tr>
</tbody>
</table>
HAPPEX-II 2005 Preliminary Results

**HAPPEX-\(^4\)He:**

\[
Q^2 = 0.0772 \pm 0.0007 \text{ (GeV/c)}^2 \\
A_{PV} = +6.43 \pm 0.23 \text{ (stat) } \pm 0.22 \text{ (syst) ppm}
\]

\[
A(G_s=0) = +6.37 \text{ ppm}
\]

\[
G^s_E = 0.004 \pm 0.014 \text{(stat)} \pm 0.013 \text{(syst)}
\]

**HAPPEX-H:**

\[
Q^2 = 0.1089 \pm 0.0011 \text{ (GeV/c)}^2 \\
A_{PV} = -1.60 \pm 0.12 \text{ (stat) } \pm 0.05 \text{ (syst) ppm}
\]

\[
A(G_s=0) = -1.640 \text{ ppm} \pm 0.041 \text{ ppm}
\]

\[
G^s_E + 0.088 G^s_M = 0.004 \pm 0.011 \text{(stat)} \pm 0.005 \text{(syst)} \pm 0.004 \text{(FF)}
\]
EM Form Factors

Electromagnetic form factors parameterized as by:

<table>
<thead>
<tr>
<th>FF</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_E^p$</td>
<td>2.5%</td>
</tr>
<tr>
<td>$G_M^p$</td>
<td>1.5%</td>
</tr>
<tr>
<td>$G_E^n$</td>
<td>10%</td>
</tr>
<tr>
<td>$G_M^n$</td>
<td>1.5%</td>
</tr>
<tr>
<td>$G_A^{(3)}$</td>
<td>–</td>
</tr>
<tr>
<td>$G_A^{(8)}$</td>
<td>–</td>
</tr>
</tbody>
</table>

GE$n$ from BLAST:
Claimed uncertainty at 7-8%
Background
Dedicated runs at very low current using track reconstruction of the HRS

Dipole field scan to measure the probability of rescattering inside the spectrometer

Helium
- Helium QE in detector: 0.15 +/- 0.15%
- Helium QE rescatter: 0.25 +/- 0.15%
- Al fraction: 1.8 +/- 0.2%

Hydrogen:
- Al fraction: 0.75 +/- 25%
- Hydrogen Tail + Delta rescatter: <0.1%

Total systematic uncertainty contribution ~40 ppb (Helium), ~15ppb (Hydrogen)
Determining $Q^2$

Asymmetry explicitly depends on $Q^2$:

$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left\{ \left(1 - 4\sin^2 \theta_W \right) - \frac{\varepsilon G_E^p (G_E^n + G_E^s) + \tau G_M^p (G_M^n + G_M^s)}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2} \right\}$$

$$Q^2 = 2EE' (1 - \cos \theta)$$

**Goal:** $\delta Q^2 < 1\%$

$Q^2$ measured using standard HRS tracking package, with reduced beam current

- Central scattering angle must be measured to $\delta \theta < 0.5\%$
- Asymmetry distribution must be averaged over finite acceptance

12 June 2006  Parity Violating Electron Scattering: Recent Results and Future Prospects
A Simple Fit (for a simple point)

Simple fit:
GEs = r_s^* \tau
GMs = \mu_s
Includes only data Q^2 < 0.3 GeV^2
Includes SAMPLE constrained with G_A theory and HAPPEX-He 2004, 2005
G0 Global error allowed to float with unit constraint
Nothing intelligent done with form factors, correlated errors, etc.

Quantitative values should NOT be taken very seriously, but some clear, basic points:

- The world data are consistent.
- Rapid Q^2 dependence of strange form-factors is not required.
- Sizeable contributions at higher Q^2 are not definitively ruled out. (To be tested by HAPPEX-III, G0 and A4 backangle.)