Parity-Violating and Parity-Conserving Asymmetries in ep and eN Scattering in the Qweak Experiment

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September 29, 2017
Electroweak Box Workshop, Amherst Center for Fundamental Interactions
Parity-Violating Asymmetries are Typically Small

Asymmetry between $+$ and $-$ incoming electron helicity

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \quad \text{with} \quad \sigma = \left| \begin{array}{c} e \quad e' \quad \gamma \\ q \quad q' \\ e \quad e' \quad Z \\ q \quad q' \end{array} \right| + \ldots$$

Interference of photon and weak boson exchange

$$M^{EM} \propto \frac{1}{Q^2} \quad M^{NC} \propto \frac{1}{M_Z^2 + Q^2}$$

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \propto \frac{\mathcal{M}^{NC}_{PV}}{\mathcal{M}^{EM}} \propto \frac{Q^2}{M_Z^2} \propto G_F Q^2 \approx \mathcal{O}(\text{ppm, ppb}) \quad \text{when} \quad Q^2 \ll M_Z^2$$
Parity-Violating Asymmetry to Access Electroweak Parameters

Electroweak Box

The Qweak Experiment
Strategy to Measure Parts-Per-Billion: Integration

Event or counting mode

- Each event individually detected, digitized and read-out
- Selection or rejection possible based on event characteristics
- 100 ns pulse separation limits rate to 10 MHz per detector segment; at least 1 day for 1 ppm precision

Integrating or current mode

- Very high event rates possible, as long as detectors are linear
- But no rejection of background events possible after the fact
- $Q_{Weak}$ segment rates 800 MHz; MOLLER segment rates up to 2.5 GHz; P2 up to 0.5 THz
Parity-Violating Asymmetry to Access Electroweak Parameters

Electroweak measurements with protons (elastic scattering)

\[ A_{PV}(p) = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[ \frac{\epsilon G_E G_Z + \tau G_M G_Z^* - (1 - 4\sin^2\theta_W)\epsilon' G_M G_A^*}{\epsilon(G_E)^2 + \tau(G_M)^2} \right] \]

In the forward elastic limit \( Q^2 \rightarrow 0, \theta \rightarrow 0 \) (plane wave):

\[ A_{PV}(p) \xrightarrow{Q^2\rightarrow0} -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left[ Q_W^p + Q^2 \cdot B(Q^2) \right] \propto Q_W^p \text{ when } Q^2 \text{ small} \]

Precision electroweak Standard Model test of \( \sin^2\theta_W \):

\[ A_{PV}(p) \propto -1 + 4\sin^2\theta_W \]
Determination of the Weak Charge of the Proton

Pushing the envelope of intensity (more detected electrons)
- Higher beam current (180 µA versus usually < 100 µA)
- Longer cryo-target (35 cm versus 20 cm, 2.5 kW in 20 K LH2)
- Higher event rates up to 800 MHz (integrating mode)
- Typical luminosity of $1.7 \times 10^{39} \text{ cm}^{-2} \text{s}^{-1}$, $\int \mathcal{L} dt = 1 \text{ ab}^{-1}$

Pushing the envelope of precision (better measurements)
- Electron beam polarimetry precision of 1% at 1 GeV
- Helicity-correlated asymmetries at ppb level (beam position at nm level)
- Determination of $Q^2$ since $A_{PV} \propto Q^2$
- Isolate elastic scattering from background processes ($f_i, A_i$)
Determination of the Weak Charge of the Proton

1 The Qweak Apparatus, NIM A 781, 105 (2015)
Determination of the Weak Charge of the Proton

Determination of the Weak Charge of the Proton

\[1 \text{ The Qweak Apparatus, NIM A 781, 105 (2015)}\]
Determination of the Weak Charge of the Proton

Azimuthal array of Čerenkov detector

- 8 fused silica radiators, 2 m long × 18 cm × 1.25 cm
- Pb preradiator tiles to suppress low-energy/neutral yield
- 5 inch PMTs with gain of 2000, low dark current
- 800 MHz electron rate per bar, defines counting noise
Determination of the Weak Charge of the Proton

First experiment with direct access to proton’s weak charge

- Experiment collected data between 2010 and 2012 with toroidal spectrometer and integrating quartz detectors
- Preliminary results were published in 2013 based on commissioning data\(^1\) (4% compared to the independent full data set)

Long awaited final results are now here

- Unblinding on March 31, 2017
- Release of unblinded result at PANIC’17 in Beijing:
  - Sunday September 3, 2017, at PANIC in plenary session
  - Friday September 8, 2017, at Jefferson Lab
- Publication to be submitted in October 2017

\(^1\) First Determination of the Weak Charge of the Proton, Phys. Rev. Lett. 111, 141803 (2013)
Determination of the Weak Charge of the Proton

Background treatment in integrating experiments

- Measured asymmetry $A_{msr}$ corrected for all background contributions
  - with their own parity-violating asymmetry $A_i$ (ppm-level)
  - and their dilution in the measured asymmetry $f_i$ (%-level)

$$A_{PV} = R_{total} \frac{A_{msr}}{P} - \sum f_i A_i$$

Unprecedented precision comes with inevitable surprises

- Discovered qualitatively new “beamline background”
  - Generated by scattering of helicity-dependent beam halo on clean-up collimator downstream of target and into detector acceptance
- Discovered qualitatively new “rescattering bias”
  - Spin precession of scattered electrons in spectrometer, followed by nuclear transverse spin azimuthal asymmetry when scattering in lead pre-radiators
## Determination of the Weak Charge of the Proton

All uncertainties in ppb

<table>
<thead>
<tr>
<th></th>
<th>Run 1</th>
<th>Run 2</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Normalization: $A_{BCM}$</td>
<td>5.1</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Beamline Background: $A_{BB}$</td>
<td>5.1</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Beam Asymmetries: $A_{beam}$</td>
<td>4.7</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Rescattering bias: $A_{bias}$</td>
<td>3.4</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>Beam Polarization: $P$</td>
<td>2.2</td>
<td>(1.2)</td>
<td></td>
</tr>
<tr>
<td>Al target windows: $A_{b1}$</td>
<td>(1.9)</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>Kinematics: $R_{Q^2}$</td>
<td>(1.2)</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Total of others &lt; 5%, incl ()</td>
<td>3.4</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>10.1</td>
<td>5.6</td>
<td>5.8</td>
</tr>
<tr>
<td>Total statistical uncertainty</td>
<td>15.0</td>
<td>8.3</td>
<td>7.3</td>
</tr>
<tr>
<td>Total combined uncertainty</td>
<td>18.0</td>
<td>10.0</td>
<td>9.3 (p = 86%)</td>
</tr>
</tbody>
</table>

$A_{PV}(4\%) = -279 \pm 31(\text{syst}) \pm 35(\text{stat}) = -279 \pm 47(\text{total})$

$A_{PV}(\text{full}) = -226.5 \pm 5.8(\text{syst}) \pm 7.3(\text{stat}) = -226.5 \pm 9.3(\text{total})$
### Q\textsubscript{Weak}: Largest Uncertainties in Precision Q\textsubscript{Weak} Result

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>Run 1 ((\delta(A_{PV}))</th>
<th>Run 2 ((\delta(A_{PV}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>All uncertainties in ppb</td>
<td>(\delta(A_{PV})) fraction</td>
<td>(\delta(A_{PV})) fraction</td>
</tr>
<tr>
<td>Charge Normalization: (A_{BCM})</td>
<td>5.1 25%</td>
<td>2.3 17%</td>
</tr>
<tr>
<td>Beamline Background: (A_{BB})</td>
<td>5.1 25%</td>
<td>1.2 5%</td>
</tr>
<tr>
<td>Beam Asymmetries: (A_{beam})</td>
<td>4.7 22%</td>
<td>1.2 5%</td>
</tr>
<tr>
<td>Rescattering bias: (A_{bias})</td>
<td>3.4 11%</td>
<td>3.4 37%</td>
</tr>
<tr>
<td>Beam Polarization: (P)</td>
<td>2.2 5%</td>
<td>&lt; 5%</td>
</tr>
<tr>
<td>Al target windows: (A_{b1})</td>
<td>&lt; 5%</td>
<td>1.9 12%</td>
</tr>
<tr>
<td>Kinematics: (R_{Q^2})</td>
<td>&lt; 5%</td>
<td>1.3 5%</td>
</tr>
<tr>
<td>Total of others</td>
<td>3.4 11%</td>
<td>2.5 20%</td>
</tr>
<tr>
<td>Combined in quadrature</td>
<td>10.1</td>
<td>5.6</td>
</tr>
</tbody>
</table>
Intercept of $A_{PV}$ at $Q^2 \rightarrow 0$ gives weak charge ($Q^2 = 0.025 \text{ GeV}^2$)

$$
\overline{A}_{PV} = \frac{A_{PV}}{A_0} = Q_p^W + Q^2 \cdot B(Q^2, \theta = 0) \quad \text{with} \quad A_0 = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}
$$

Global fit$^1$ of all parity-violating electron scattering with 4% data$^2$

- Fit of parity-violating asymmetry data on H, D, $^4$He, $Q^2 < 0.63 \text{ GeV}^2$
- Free parameters are $C_{1u}$, $C_{1d}$, strange charge radius $\rho_s$ and magnetic moment $\mu_s$ ($G^s_{E,M} \propto G_D$), and isovector axial form factor $G^Z_A$,$^1$,$^T=1$
  - $Q^p_W(SM) = 0.0710 \pm 0.0007$ (theoretical expectation)
  - $Q^p_W(PVES) = 0.064 \pm 0.012$ (global fit of 4% data$^2$)
  - After combination with atomic parity-violation on Cs:
    - $C_{1u} = -0.1835 \pm 0.0054$
    - $C_{1d} = 0.3355 \pm 0.0050$


Determination of the Weak Vector Charge of the Proton

New global fit of all parity-violating electron scattering with full data set

- Fit of parity-violating asymmetry data on H, D, $^4$He, $Q^2 < 0.63$ GeV$^2$
- Free parameters were $C_{1u}$, $C_{1d}$, strange charge radius $\rho_s$ and magnetic moment $\mu_s$ ($G^s_E, M \propto G_D$), and isovector axial form factor $G^{Z, T=1}_A$

\[ Q^p_W(PVES)) = 0.0719 \pm 0.0045 \]
\[ \sin^2 \theta_W = 0.2382 \pm 0.0011 \]
\[ \rho_s = 0.19 \pm 0.11 \]
\[ \mu_s = -0.18 \pm 0.15 \]
\[ G^{Z, T=1}_A = -0.67 \pm 0.33 \]

- After combination with atomic parity-violation on Cs:
  - $C_{1u} = -0.1874 \pm 0.0022$
  - $C_{1d} = 0.3389 \pm 0.0025$
Determination of the Weak Vector Charge of the Proton

Data Projected to the Forward-Angle Limit

\[ A_{ep} / A_0 = Q_W^p + Q^2 B(Q^2, \theta = 0) \]

- **Qweak 2017**
- **Qweak 2013**
- **HAPPEX**
- **SAMPLE**
- **PVA4**
- **G0**
- **SM (prediction)**

\[ Q^2 [\text{GeV/c}^2] \]
Determination of the Weak Vector Charge of the Proton

Electroweak Box

The Qweak Experiment
Determination of the Weak Vector Charge of the Proton

Using lattice QCD in the extraction

- It is possible to add the lattice strangeness form factor to the global fit.
- \( Q^p_W(LQCD) = 0.0684 \pm 0.0039 \)

\[ Q^2 (\text{GeV}^2) \]

lattice QCD (this work, \( m_\pi = 317 \text{ MeV} \))

lattice QCD (this work, physical point)

lattice QCD [17]

connected LQCD + octet \( \mu \) from expt. [16]

...same, with quenched lattice QCD [29]

finite-range-regularized chiral model [30]

light-front model + deep inelastic scattering data [31]

perturbative chiral quark model [32]

dispersion analysis [33]

parity-violating elastic scattering [34]

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\(^1\) J. Green et al, Phys. Rev. D92, 031501 (2015)
Electroweak Radiative Corrections

Procedure per Erler et al.\textsuperscript{1}

\[ Q^p_W = (\rho_{NC} + \Delta_e)(1 - 4 \sin^2 \theta_W(0) + \Delta'_e) + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z} \]

<table>
<thead>
<tr>
<th>Correction to ( Q^p_W )</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \sin \theta_W(M_Z) )</td>
<td>±0.0006</td>
</tr>
<tr>
<td>( \Box_{\gamma Z}(6.4 \pm 0.6)% )</td>
<td>±0.00044</td>
</tr>
<tr>
<td>( \Delta \sin \theta_W(Q))had</td>
<td>±0.0003</td>
</tr>
<tr>
<td>( \Box_{WW}, \Box_{ZZ} ) (pQCD)</td>
<td>±0.0001</td>
</tr>
<tr>
<td>Charge symmetry</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>±0.0008</td>
</tr>
</tbody>
</table>

Electroweak Radiative Corrections

Discussion of $\Box_{\gamma Z}$

- We use the most recent available treatment by Hall et al.\(^1\) (which is the same treatment we used in the publication of the commissioning run in 2013)
- $\Box_{\gamma Z}^V = (5.4 \pm 0.4) \times 10^{-3}$ using \(^1\)
- $\Box_{\gamma Z}^A = (-0.7 \pm 0.2) \times 10^{-3}$ using \(^2\)
- $Q^2$ dependence using \(^3\)

What if?

- If we use an uncertainty on $\Box_{\gamma Z}$ of $\pm 0.0020$ as per Gorchtein et al.\(^1\)
- $Q^P_W(PVES)$ changes from $0.0719 \pm 0.0045$ to $0.0716 \pm 0.0048$

\(^1\)Hall, Blunden, Melnitchouk, Thomas, Young, Phys. Lett. B753 (2016) 221-226
\(^2\)Blunden, Melnitchouk, Thomas, Phys. Rev. Lett. 107, 081801 (2011)
Sensitivity to New Physics

Effective four-point interactions of some higher mass scale\(^1\)

\[
\mathcal{L}_{e-q}^{PV} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C_{1q} \bar{q} \gamma^\mu q + \frac{g^2}{\Lambda^2} \bar{e} \gamma_\mu \gamma_5 e \sum_q h_q^V \bar{q} \gamma^\mu q
\]

Limits on new physics energy scale if uncertainty \(\Delta Q^p_W\)

\[
\frac{\Lambda}{g} = \frac{1}{2} \left( \sqrt{2} G_F \Delta Q^p_W \right)^{-1/2}
\]

Assuming that we have an arbitrary flavor dependence of the new physics:

\[
h^u_V = \cos \theta_h \quad h^d_V = \sin \theta_h
\]

Sensitivity to New Physics
Sensitivity to New Physics

Leptoquarks

- Impact explored in Erler, Kurylov, Ramsey-Musolf, Phys. Rev. D 68, 016006
- Some other data has since been released (HERA), which may affect the opportunities for the $Q_{Weak}$ result to distinguish

Dark parity-violation

- $Q_{Weak}$ result rules out some of the allowed region
Ancillary Measurements: Borne of Paranoia

Whatever could affect $A_{PV}$ was measured and corrected for

- Each background has asymmetry $A_i$ and dilution $f_i$
- Non-hydrogen scattering: aluminum alloy of target windows
- Non-elastic contributions besides elastic $ep$: $N \rightarrow \Delta$, Møller
- Non-longitudinal polarization: horizontal, vertical transverse
- Non-electron particles reaching detector: $\pi$ production
- Particles not originating from target: blocked octants
- Particles not reaching main detectors: superelastic region,

Priorities driven by weak charge needs until recently

- First: corrections on $A_{PV}(p)$ due to $A_{PV}$(Al alloy), $B_n$(H + Al alloy)
- Then: extract $B_n$(H), turn Al alloy into $^{27}$Al for $A_{PV}(^{27}$Al)
- Then: corrections due to $B_n$(Al alloy), extract $B_n(^{27}$Al)
Ancillary Measurements: Transverse Asymmetry

Transverse single spin asymmetries

- Some transverse polarization, slightly broken azimuthal symmetry
- Measure with transversely polarized beam (H or V)
- Parity-conserving T-odd transverse asymmetry of order ppm

$$B_n = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = \frac{2\Im(T^{1\gamma*} \cdot \text{Abs}T^{2\gamma})}{|T^{1\gamma}|^2} \approx \mathcal{O}(\frac{m}{E}) \approx \text{ppm}$$

- $T^{1\gamma}_{fi} = \mathcal{O}(\alpha_{em})$
- $T^{2\gamma}_{fi} = \mathcal{O}(\alpha_{em}^2)$
- $+ \ldots$
Ancillary Measurements: Transverse Asymmetry

Azimuthal asymmetries

\[
A_T(\phi) = \frac{N^\uparrow(\phi) - N^\downarrow(\phi)}{N^\uparrow(\phi) + N^\downarrow(\phi)} = B_n S \sin(\phi - \phi_S) = B_n (P_V \cos \phi + P_H \sin \phi)
\]

with \( P_V = S \sin \phi_S \) and \( P_H = S \cos \phi_S \)

Available transverse single spin asymmetries

- Elastic \( \bar{e}p \) in H, C, Al at \( E = 1.165 \) GeV
- Inelastic \( \bar{e}p \rightarrow \Delta \) in H, C, Al at \( E = 0.877 \) GeV and 1.165 GeV
- Elastic \( \bar{e}e \) in H at \( E = 0.877 \) GeV
- Deep inelastic \( \bar{e}p \) in H at \( W = 2.5 \) GeV
- Pion photoproduction in H at \( E = 3.3 \) GeV
Ancillary Measurements: Transverse Asymmetry on H

Two hours of data taking in \( H \): \( A_T(\text{oct}) = A \sin \phi \)

![Vertical Transverse Asymmetry](image)

| \( \chi^2 \) / ndf | 5.19 / 5 |
| Prob               | 0.39     |
| \( A_{\text{reg}} \) | -4.61 ± 0.20 |

Two hours of data taking in \( V \): \( A_T(\text{oct}) = A \cos \phi \)

![Horizontal Transverse Asymmetry](image)

| \( \chi^2 \) / ndf | 4.87 / 5 |
| Prob               | 0.43     |
| \( A_{\text{reg}} \) | -4.76 ± 0.20 |

Electroweak Box

The Qweak Experiment
Ancillary Measurements: Transverse Asymmetry on H

Cancellation with slow helicity reversal for $H$

Cancellation with slow helicity reversal for $H$
Ancillary Measurements: Transverse Asymmetry on H

- 90 degrees phase difference between $H$ and $V$ as expected
- Not corrected for polarization, backgrounds, acceptance, ...
Ancillary Measurements: Transverse Asymmetry on $H$

- Background corrections (as for main experiment):

$$B_n = R_{total} \frac{A}{P} - \sum f_i A_i$$

- Measured corrections $f_i$ and $A_i$ for aluminum windows, $N \rightarrow \Delta$

- $R_{total}$ includes radiative corrections, acceptance averaging, $Q^2$ variation with $\phi$ in each octant

- Most precise transverse asymmetry in $ep$ in hydrogen (50 hours of data):
  $$B_n = -5.35 \pm 0.07\text{(stat)} \pm 0.15\text{(syst)} \text{ ppm}$$

- $\langle E \rangle = 1.155 \pm 0.003$ GeV, $\langle \theta \rangle = 7.9 \pm 0.3$ degrees
Ancillary Measurements: Transverse Asymmetry on H

Theoretical models:

Ancillary Measurements: Transverse Asymmetry on Al, C

$Q_{\text{Weak}}$ wasn’t made for this

- Large energy acceptance of spectrometer (150 MeV at 1.165 GeV)
- Nuclei are hardly ideal with low-lying levels

$B_n \approx -11$ ppm in elastic scattering off C

- Analysis complete but no result released yet by collaboration
- Dissertation of Martin McHugh (GWU) is available on UMI and consistent with PREX at 1σ
- Target is 99% $^{12}$C, no significant contaminations
- Correction for contribution from quasi-elastic scattering
- No attempts at separation of nuclear excited states and GDR from elastic scattering
- $B_n(C)$ is a quantity that does not correspond to a purely elastic state
$B_n \approx [-11, -14]$ ppm in elastic scattering off $^{27}$Al

- Some figures released by collaboration, no numbers, analysis nearing completion
- Alloy is a mixture with up to 10% other elements
- Attempts to treat quasi-elastic nuclear excited states and GDR more appropriately
- $B_n(^{27}\text{Al})$ will be interpretable as referring to a purely elastic state
- Results to be shown at Fall 2017 DNP meeting by Kurtis Bartlett (W&M)
Ancillary Measurements: Transverse Asymmetry on Al

Aluminum azimuthal asymmetry is non-zero (uncorrected data)

- Aluminum alloy with $\approx 10\%$ contaminations
- Corrections needed for quasielastic, $N \rightarrow \Delta$, nuclear excited states
Ancillary Measurements: Transverse Asymmetry on Al

Contaminants

- Working with Chuck Horowitz on distorted wave $\sigma$ and $A_{PV}$
- Implementation into $Q_{Weak}$ Monte Carlo simulations to determine their contributions

<table>
<thead>
<tr>
<th>Element</th>
<th>% by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>88.70</td>
</tr>
<tr>
<td>Zn</td>
<td>6.3</td>
</tr>
<tr>
<td>Mg</td>
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<tr>
<td>Cu</td>
<td>1.8</td>
</tr>
<tr>
<td>Cr</td>
<td>0.21</td>
</tr>
<tr>
<td>Fe</td>
<td>0.12</td>
</tr>
<tr>
<td>Si</td>
<td>0.10</td>
</tr>
<tr>
<td>Total</td>
<td>99.93</td>
</tr>
</tbody>
</table>
Ancillary Measurements: Transverse Asymmetry on Al

Quasi-elastic scattering

- Free nucleon approximation and some heuristics related to isoscalar/isovector impact on sign of asymmetry
- However, free nucleon approximation may not be sufficient per E. Hadjimichael, G. I. Poulis, T. W. Donnelly, Phys. Rev. C 45, 2666 (1992)
- More detailed quasi-elastic implementation per Horowitz, Phys. Rev. C 47, 826 (1992), which his grad student Zidu Lin has adapted to $^{27}\text{Al}$
Ancillary Measurements: Transverse Asymmetry on Al

Nuclear excited states

- Fitting nuclear excited state form factors using MIT Bates data
- Implementation into $Q_{Weak}$ Monte Carlo simulations to determine their contributions
Ancillary Measurements: Transverse Asymmetry on C, Al

Projected uncertainties for $B_n$ for C and Al

- HAPPEX, PREX: Abrahamyan et al., PRL 109, 192501 (2012)
Ancillary Measurements: Transverse Asymmetry in $N \rightarrow \Delta$

Access to the $\gamma \ast \Delta \Delta$ form factor

- Large asymmetries in the forward region
- Several possible intermediate states $N$, $\Delta$
Ancillary Measurements: Transverse Asymmetry in $\mathcal{N} \rightarrow \Delta$

Before any background corrections

![Graph showing asymmetry vs octant before background corrections]

- Large radiative tail from elastic scattering as dilution with small asymmetry
- $B_n(\mathcal{N} \rightarrow \Delta) = 43 \pm 16$ at $\langle \theta \rangle = 8.3$ degrees
- Nuruzzaman, CIPANP2015, arXiv:1510.00449 [nucl-ex]

After background corrections

- $\chi^2 / \text{ndf} = 8.8 / 7$, $\text{Prob} = 0.3$
  - $\varepsilon_{\text{reg}} = 5.3 \pm 0.5$
- $\chi^2 / \text{ndf} = 6.1 / 7$, $\text{Prob} = 0.5$
  - $\varepsilon_{\text{reg}} = 4.4 \pm 0.8$
Ancillary Measurements: Transverse Asymmetry in $N \rightarrow \Delta$

- Includes $N$, and $\Delta(1232)$
Ancillary Measurements: Transverse Asymmetry in $N \rightarrow \Delta$

- Includes $N$, $\Delta(1232)$, $S11(1535)$, and $D13(1520)$
Ancillary Measurements: Transverse Asymmetry in Møller

Summary

Determination of the Weak Charge of the Proton

- Most precise parity-violating asymmetry measurement:
  \[ A_{PV} = -226.5 \pm 7.3\text{(stat)} \pm 5.8\text{(syst)} \text{ ppb at } \langle Q^2 \rangle = 0.0249 \text{ GeV}^2 \]
- Weak charge \( Q^p_W(PVES) = 0.0719 \pm 0.0045 \) in excellent agreement with \( Q^p_W(SM) = 0.0708 \pm 0.0003 \)
- Amplitudes above \( 8 \cdot 10^{-3} \cdot G_F \) ruled out
- Heavy new physics with \( \Lambda/g < 7.5 \text{ TeV} \) ruled out
- Triad of high precision low energy weak charge measurements now complete
Summary

Many ancillary measurements for which data is available:

$A_{PV}$ helicity asymmetries:
- Elastic $^{27}\text{Al}$
- $N \rightarrow \Delta (E \text{ of } 1.16 \text{ GeV, 0.877 GeV})$
- Near $W = 2.5 \text{ GeV}$ (for $\Box_{\gamma Z}$)
- Pion photoproduction ($E \text{ of } 3.3 \text{ GeV}$)

$B_n$ transverse asymmetries:
- Elastic $ep$, $^{27}\text{Al, C}$
- $N \rightarrow \Delta$
- Near $W = 2.5 \text{ GeV}$
- Pion photoproduction ($E \text{ of } 3.3 \text{ GeV}$)
- Møller
Topics for Discussion

Prioritization of ancillary analysis

- Currently in progress (or preliminary results):
  - $B_n$ for $ep$
  - $A_{PV}$ for $N \rightarrow \Delta$
  - $A_{PV}$ for $^{27}$Al
  - $B_n$ for $^{27}$Al, C

Ask a theorist

- Preference for $g^2/\Lambda^2$ over $g^2/4\Lambda^2$?
- Limits on leptoquarks?
Additional Material
Uncertainties

Parity-Violating and Parity-Conserving Nuclear Asymmetries
  Tracking Detectors
  Beam Polarimetry
  Helicity-Correlated Beam Properties
  Data Quality

Precision Polarimetry
  Atomic Hydrogen Polarimetry

Radiative Corrections
The $Q_{\text{Weak}}$ Experiment: Kinematics in Event Mode

Reasons for a tracking system?

- Determine $Q^2$, note: $A_{\text{meas}} \propto Q^2 \cdot (Q_P^W + Q^2 \cdot B(Q^2))$
- Main detector light output and $Q^2$ position dependence
- Contributions from inelastic background events

Instrumentation of only two octants

- Horizontal drift chambers for front region (Va Tech)
- Vertical drift chambers for back region (W&M)
- Rotation allows measurements in all eight octants

Track reconstruction

- Straight tracks reconstructed in front and back regions
- Front and back partial tracks bridged through magnetic field
Requirements on beam polarimetry

- Largest experimental uncertainty in $Q_{Weak}$ experiment
- Systematic uncertainty of 1% (on absolute measurements)

Upgrade existing Møller polarimeter ($\vec{e} + \vec{e} \rightarrow e + e$)

- Scattering off atomic electrons in magnetized iron foil
- Limited to separate, low current runs ($I \approx 1 \mu A$)

Construction new Compton polarimeter ($\vec{e} + \vec{\gamma} \rightarrow e + \gamma$)

- Compton scattering of electrons on polarized laser beam
- Continuous, non-destructive, high precision measurements
The Q\text{Weak} Experiment: Improved Beam Polarimetry

Compton polarimeter

- **Beam**: 150 $\mu$A at 1.165 GeV
- **Chicane**: interaction region 57 cm below straight beam line
- **Laser system**: 532 nm green laser
  - 10 W CW laser with low-gain cavity
- **Photons**: PbWO$_4$ scintillator in integrating mode
- **Electrons**: Diamond strips with 200 $\mu$m pitch
Data Quality: Slow Helicity Reversal

\(\lambda/2\)-plate and Wien filter changes

- Insertable \(\lambda/2\)-plate (IHWP) in injector allows ‘analog’ flipping helicity frequently
- Wien filter: another way of flipping helicity (several weeks)
- Each ‘slug’ of 8 hours consists of same helicity conditions
Helicity-Correlated Beam Properties Are Understood

Measured asymmetry depends on beam position, angle, energy

- Well-known and expected effect for PVES experiments
- “Driven” beam to check sensitivities from “natural” jitter

---

Run 11781: Main Detector Barsum X-Sensitivities (ppm/mm) for Qweak Target: LH2, 164.7 uA, 4.0x4.0 mm

---

Electroweak Box

The Qweak Experiment
However, Some Beamline Background Correlations Remain

After regression, correlation with background detectors
- Luminosity monitors & spare detector in super-elastic region
- Background asymmetries of up to 20 ppm (that’s huge!)
Beamline Background Correlations Remain

Hard work by grad students: now understood, under control

- Partially cancels with slow helicity reversal (half-wave plate)
- Likely caused by large asymmetry in small beam halo or tails
- Scattering off the beamline and/or “tungsten plug”

Qualitatively new background for PVES experiments at JLab

- Second regression using asymmetry in background detectors
- Measurements with blocked octants to determine dilution factor $(f_{b_2}^{MD} = 0.19\%)$
Data Quality: Understanding the Asymmetry Width

Asymmetry width

- 240 Hz helicity quartets (+ − − + or − + + −)
- Uncertainty = \( \text{RMS}/\sqrt{N} \)
- 200 ppm in 4 milliseconds
- < 1 ppm in 5 minutes

Measurement

Battery width

- Pure counting statistics ≈ 200 ppm
- + detector resolution ≈ 90 ppm
- + current monitor ≈ 50 ppm
- + target boiling ≈ 57 ppm
- = observed width ≈ 233 ppm

Asymmetry width
Data Quality: Helicity-Correlated Beam Properties

Natural beam motion
- Measured asymmetry correlated with beam position and angles
- Linear regression:
  \[ A_c = \sum_i \frac{\partial A}{\partial x_i} \Delta x_i \]
  \[ i = x, y, x', y', E \]
Data Quality: Helicity-Correlated Beam Properties

Natural beam motion

- Measured asymmetry correlated with beam position and angles
- Linear regression:
  \[ A_c = \sum_i \frac{\partial A}{\partial x_i} \Delta x_i \]
  \[ i = x, y, x', y', E \]

Driven beam motion

- Deliberate motion
Excellent agreement between natural and driven beam motion

- Figure includes about 50% of total dataset for $Q_{\text{Weak}}$ experiment
- No other corrections applied to this data
Sensitivity to New Physics

Lower bound on new physics (95% CL)

- Constraints from
  - Atomic PV: \( \Lambda g > 0.4 \text{ TeV} \)
  - PV electron scattering: \( \Lambda g > 0.9 \text{ TeV} \)
  - Projection \( Q_{\text{Weak}} \): \( \Lambda > 2 \text{ TeV} \)
  - 4% precision
Lower bound on new physics (95% CL)

Constraints from

- Atomic PV: \( \frac{\Lambda}{g} > 0.4 \text{ TeV} \)
- PV electron scattering: \( \frac{\Lambda}{g} > 0.9 \text{ TeV} \)
Sensitivity to New Physics

Lower bound on new physics (95% CL)

Constraints from
- Atomic PV: \( \frac{\Lambda}{g} > 0.4 \text{ TeV} \)
- PV electron scattering: \( \frac{\Lambda}{g} > 0.9 \text{ TeV} \)

Projection \( Q_{\text{Weak}} \)
- \( \frac{\Lambda}{g} > 2 \text{ TeV} \)
- 4\% precision
Sensitivity to New Physics

Different experiments sensitive to different extensions

**JLab $Q_{weak}$**

$q^p_w = 0.0716$

*Experiment*  
*SUSY Loops*  
*E$_6$ Z’*  
*RPV SUSY*  
*Leptoquarks*

**SLAC E158 (complete)**

$-Q^e_w = 0.0449$

*Experiment*  

In the diagram:

- **RPC SUSY**
- **Generic Z’**
- **RPV SUSY**
- **Leptoquarks**

**The Qweak Experiment**
Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge $uud$

$$Q^p_W = -2(2C_{1u} + C_{1d})$$

Early experiments

- SLAC and APV
Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge $uud$

$$ Q_W^p = -2(2C_{1u} + C_{1d}) $$

Early experiments
- SLAC and APV

Electron scattering
- HAPPEX, G0
- PVA4/Mainz
- SAMPLE/Bates
Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge $uud$

$$Q^P_W = -2(2C_{1u} + C_{1d})$$

Early experiments
- SLAC and APV

Electron scattering
- HAPPEX, G0
- PVA4/Mainz
- SAMPLE/Bates

$Q_{Weak}$ experiment
## Precision Electroweak Experiments: JLab 12 GeV

### MOLLER Experiment

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta A_{PV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mom. transfer $Q^2$</td>
<td>0.5%</td>
</tr>
<tr>
<td>Beam polarization</td>
<td>0.4%</td>
</tr>
<tr>
<td>2$^{nd}$ order beam</td>
<td>0.4%</td>
</tr>
<tr>
<td>Inelastic $ep$</td>
<td>0.4%</td>
</tr>
<tr>
<td>Elastic $ep$</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

### SoLID PV-DIS Experiment

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta A_{PV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam polarization</td>
<td>0.4%</td>
</tr>
<tr>
<td>Rad. corrections</td>
<td>0.3%</td>
</tr>
<tr>
<td>Mom. transfer $Q^2$</td>
<td>0.5%</td>
</tr>
<tr>
<td>Inelastic $ep$</td>
<td>0.2%</td>
</tr>
<tr>
<td>Statistics</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

Precision beam polarimetry is crucial to these experiments.
Precision Electroweak Experiments: Polarimetry

Compton Polarimetry
- $\vec{e}\vec{\gamma} \rightarrow e\gamma$ (polarized laser)
- Detection $e$ and/or $\gamma$
- Only when beam energy above few hundred MeV
- High photon polarization but low asymmetry
- Total systematics $\sim 1\%$
  - laser polarization
  - detector linearity

Møller Polarimetry
- $\vec{e}\vec{e} \rightarrow ee$ (magnetized Fe)
- Low current because temperature induces demagnetization
- High asymmetry but low target polarization
- Levchuk effect: scattering off internal shell electrons
- Intermittent measurements at different beam conditions
- Total systematics $\sim 1\%$
Atomic Hydrogen Polarimetry

New polarimetry concept\(^1\)
- 300 mK cold atomic H
- 8 T solenoid trap
- \(3 \cdot 10^{16}\) atoms/cm\(^2\)
- \(3 \cdot 10^{15}-17\) atoms/cm\(^3\)
- 100% polarization of e

Advantages
- High beam currents
- No Levchuk effect
- Non-invasive, continuous

Atomic Hydrogen Polarimetry: 100% Polarization of $e$

Hyperfine Splitting in Magnetic Field

- Energy splitting of $\Delta E = 2\mu B$:
  \[ \uparrow / \downarrow = \exp(-\Delta E / kT) \approx 10^{-14} \]
- Low energy states with $|s_es_p\rangle$:
  \[ |d\rangle = |\uparrow\uparrow\rangle \]
  \[ |c\rangle = \cos \theta |\uparrow\downarrow\rangle + \sin \theta |\downarrow\uparrow\rangle \]
  \[ |b\rangle = |\downarrow\downarrow\rangle \]
  \[ |a\rangle = \cos \theta |\downarrow\uparrow\rangle - \sin \theta |\uparrow\downarrow\rangle \]
  with $\sin \theta \approx 0.00035$
- $P_e(\downarrow) \approx 1$ with only $10^5$ dilution from $|\uparrow\downarrow\rangle$ in $|a\rangle$ at $B = 8$ T
- $P_p(\uparrow) \approx 0.06$ because 53% $|a\rangle$ and 47% $|b\rangle$}

Force $\vec{V}(-\vec{\mu} \cdot \vec{B})$ will pull $|a\rangle$ and $|b\rangle$ into field
Atomic Hydrogen Polarimetry: Expected Contaminations

Without beam
- Recombined molecular hydrogen suppressed by coating of cell with superfluid He, $\sim 10^{-5}$
- Residual gasses, can be measured with beam to $< 0.1\%$

With 100 $\mu$A beam
- 497 MHz RF depolarization for 200 GHz $|a\rangle \rightarrow |c\rangle$ transition, tuning of field to avoid resonances, uncertainty $\sim 2 \cdot 10^{-4}$
- Ion-electron contamination: builds up at 20%/s in beam region, cleaning with $\vec{E}$ field of $\sim 1$ V/cm, uncertainty $\sim 10^{-5}$
Projected Systematic Uncertainties $\Delta P_e$ in Møller polarimetry

<table>
<thead>
<tr>
<th>Source</th>
<th>Fe-foil</th>
<th>Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target polarization</td>
<td>0.63%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Analyzing power</td>
<td>0.30%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Levchuk effect</td>
<td>0.50%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Deadtime</td>
<td>0.30%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Background</td>
<td>0.30%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Other</td>
<td>0.30%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Unknown unknowns</td>
<td>0.00%</td>
<td>0.30% (?)</td>
</tr>
<tr>
<td>Total</td>
<td>1.0%</td>
<td>0.35%</td>
</tr>
</tbody>
</table>
P2 Experiment in Mainz: Weak Charge of the Proton

- "Q_{Weak} experiment" with improved statistical precision
- Dedicated 200 MeV accelerator MESA under construction
- Required precision of electron beam polarimetry < 0.5%
- Strong motivation for collaboration on a short timescale (installation in 2017)
Parity-Violating Electron Scattering: Running of Weak Mixing Angle

Running of $\sin^2 \theta_W$ ($Q_W^p = 1 - 4 \sin^2 \theta_W$)

- Higher order loop diagrams
- $\sin^2 \theta_W$ varies with $Q^2$

Electroweak Box
The Qweak Experiment
**$\gamma Z$ Box Corrections near 1.16 GeV**

In 2009, Gorchtein and Horowitz showed the vector hadronic contribution to be significant and energy dependent.

This soon led to more refined calculations with corrections of $\sim 8\%$ and error bars ranging from $\pm 1.1\%$ to $\pm 2.8\%$.

It will probably also spark a refit of the global PVES database used to constrain $G_L^e, G_L^e, G_A$.

### PV Amplitude

<table>
<thead>
<tr>
<th>PV Amplitude</th>
<th>Authors</th>
<th>Correction* @ E=1.165 (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A^e_x V^p$</td>
<td>GH</td>
<td>0.0026±0.0026**</td>
</tr>
<tr>
<td>(vanishes as E→0)</td>
<td>SBMT</td>
<td>0.0047 ±0.0011 -0.0004</td>
</tr>
<tr>
<td>$A^p_x A^p$</td>
<td>RC</td>
<td>0.0057±0.0009</td>
</tr>
<tr>
<td>(finite as E→0)</td>
<td>GHR-M</td>
<td>0.0054±0.0020</td>
</tr>
<tr>
<td></td>
<td>MS (as updated by EKR-M)</td>
<td>0.0052±0.0005***</td>
</tr>
<tr>
<td></td>
<td>BMT</td>
<td>0.0037±0.0004</td>
</tr>
</tbody>
</table>

\* Does not include a small contribution from the elastic.
** 5.7\%×$Q_w^p$(LO) = 0.0026. $Q_w^p$(LO) = 0.04532.
*** Included in $Q_w^p$. For reference, $Q_w^p = 0.0713(8)$.

Forthcoming axial results for $Q_w^a$ have the potential to impact the interpretation of Cs APV.
### γZ Box Corrections near 1.16 GeV

A Partial Bibliography

<table>
<thead>
<tr>
<th>PV Amplitude</th>
<th>Authors</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>$A_{XX}V_{XP}$ (vanishes as $E \to 0$)</td>
<td>GH</td>
<td>Gorchtein &amp; Horowitz, PRL 102, 091806 (2009)</td>
</tr>
<tr>
<td>SBMT</td>
<td></td>
<td>Sibirtsev, Blunden, Melnitchouk, and Thomas, PRD 82, 013011 (2010)</td>
</tr>
<tr>
<td>RC</td>
<td></td>
<td>Rislow &amp; Carlson, PRD 83, 113007 (2011)</td>
</tr>
<tr>
<td>GHR-M</td>
<td></td>
<td>Gorchtein, Horowitz, and Ramsey-Musolf, PRC 84, 015502 (2011)</td>
</tr>
<tr>
<td>$V_{XX}A_{XP}$ (finite as $E \to 0$)</td>
<td>MS</td>
<td>Marciano and Sirlin, PRD 27, 552 (1983), PRD 29, 75 (1984)</td>
</tr>
<tr>
<td>BMT</td>
<td></td>
<td>Blunden, Melnitchouk, and Thomas, PRL 107, 081801 (2011)</td>
</tr>
</tbody>
</table>
The *Q*Weak Experiment: Main Detector

Low noise electronics
- Event rate: 800 MHz/PMT
- Asymmetry of only 0.2 ppm
- Low noise electronics (TRIUMF)

I-V Preamplifier

18-bit 500 kHz sampling ADC
Reminder: weak vector charges
- Proton weak charge $Q_W^p \approx -0.072$
- Neutron weak charge $Q_W^n = -1$

Sources of neutron scattering
- Al target windows
- Secondary collimator events
- Small number of events, but huge false PV asymmetry
Atomic parity-violation on $^{133}$Cs

- Porsev, Beloy, Derevianko\(^1\): Updated calculations in many-body atomic theory
- Experiment: \( Q_W(^{133}\text{Cs}) = -73.25 \pm 0.29 \pm 0.20 \)
- Standard Model: \( Q_W(^{133}\text{Cs}) = -73.16 \pm 0.03 \)

NuTeV anomaly

- Reported 3 \( \sigma \) deviation from Standard Model
- Erler, Langacker: strange quark PDFs
- Londergan, Thomas\(^2\): charge symmetry violation, \( m_u \neq m_d \)
- Cloet, Bentz, Thomas\(^3\): in-medium modifications to PDFs, isovector EMC-type effect

\(^1\)Phys. Rev. Lett. 102 (2009) 181601
Isovector EMC effect\(^1\) affects NuTeV point\(^2\)

\[ 0.225 \leq \sin^2 \theta_{W} \leq 0.250 \]

\[ Q \ (\text{GeV}) \]

\[ 0.001 \leq Q \leq 10000 \]

\[ Q_{\text{weak}} \ [\text{JLab}] \]

\[ \nu\text{-DIS} \]

\[ Z\text{-pole} \]

\[ CDF \]

\[ D0 \]

\[ \text{SLAC E158} \]

\[ \text{APV(Cs)} \]

\[ \text{Møller [JLab]} \]

\[ \text{PV-DIS [JLab]} \]

\[ Q_{\text{weak}} \ [\text{JLab}] \]

\[ 1^1 I. \ Cloët, \ W. \ Bentz, \ A. \ M. \ Thomas, \ Phys. \ Rev. \ Lett. \ 102, \ 252301 \ (2009) \]

\[ 2^2 W. \ Bentz, \ Phys. \ Lett. \ B693, \ 462-466 \ (2010) \]
Isovector EMC effect\textsuperscript{1} affects NuTeV point\textsuperscript{2}

\begin{align*}
\sin^2 \theta_{\text{MS}} & \quad Q \ (\text{GeV}) \\
\end{align*}

\begin{itemize}
\item Standard Model
\item Completed Experiments
\item Future Experiments
\end{itemize}

\textsuperscript{1} I. Cloët, W. Bentz, A. M. Thomas, Phys. Rev. Lett. 102, 252301 (2009)

\textsuperscript{2} W. Bentz, Phys. Lett. B693, 462-466 (2010)