Measurement of the weak charge of the proton: Qweak at Jefferson Lab

Paul M. King (Ohio University)
for the Qweak Collaboration

* XVII International Conference on Hadron Spectroscopy and Structure*
26 September 2017, University of Salamanca
• Qweak ran in Hall C of Jefferson Lab with two 6-month run periods in 2010-2012
  • Commissioning data (~4% of data set) was published in PRL 111, 141803 (2013).
  • Full analysis is now complete
• Measured the parity-violating asymmetry of longitudinally polarized electrons scattering from a LH2 target at low \( Q^2 = 0.0248 \) (GeV/c)\(^2\)
  • Extract the weak charge of the proton, \( Q^p_W \), quark vector weak coupling constants, and \( \sin^2 \theta_W \) at low \( Q^2 \)
  • Deviations from SM predictions would be sensitive to PV semi-leptonic physics beyond the standard model
The Qweak Collaboration


Spokespersons   Project Manager   Grad Students   *deceased

Institutions:
1. University of Zagreb
2. College of William and Mary
3. A.I. Alikhanyan National Science Laboratory
4. Massachusetts Institute of Technology
5. Thomas Jefferson National Accelerator Facility
6. Ohio University
7. Christopher Newport University
8. University of Manitoba, 9. University of Virginia
10. TRIUMF
11. Hampton University
12. Mississippi State University
13. Virginia Polytechnic Institute & State Univ
14. Southern University at New Orleans
15. Idaho State University
16. Louisiana Tech University
17. University of Connecticut
18. University of Northern British Columbia
19. University of Winnipeg
20. George Washington University
21. University of New Hampshire
22. Hendrix College, Conway
23. University of Adelaide
24. Syracuse University
25. Duquesne University

101 collaborators 26 grad students
11 post docs 27 institutions
Standard Model and beyond

Standard model
→ Renormalizable gauge theory
  + spontaneous symmetry breaking
→ Believed to be incomplete!

“Energy frontier” - like LHC
→ Make new particles (“X”) directly in high energy collisions

“Precision frontier” – weak charge, g-2(μ), EDMs, etc.
→ Measure indirect effects of new particles (“X”) made virtually in low energy processes
Parity-violating electron scattering

Scattering of longitudinally polarized electrons

\[ \overline{e}^- + p \rightarrow e^- + p \]

SM neutral current e-p processes

\[ \sigma \propto |\mathcal{M}^{EM}|^2 + 2 \mathcal{M}^{EM} \mathcal{M}^{NC}_{PV} + |\mathcal{M}^{NC}_{PV}|^2 \]

Parity violated in the weak interaction yielding a scattering asymmetry:

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{\mathcal{M}^{EM} \mathcal{M}^{NC}_{PV}}{|\mathcal{M}^{EM}|^2} \propto \frac{G_F}{\alpha} \]
Weak charges

Electron-quark scattering, four-fermion contact interaction

\[ \mathcal{L}_{eq}^{PV} = -\frac{G_F}{\sqrt{2}} \sum_i \left[ C_{1i} \bar{e} \gamma_\mu \gamma_5 e \bar{q} \gamma^\mu q + C_{2q} \bar{e} \gamma_\mu e \bar{q} \gamma^\mu \gamma^5 q \right] + \mathcal{L}_{\text{new}}^{PV} \]

<table>
<thead>
<tr>
<th>Particle</th>
<th>Electric charge</th>
<th>Weak vector charge ((\sin^2 \theta_W \approx \frac{1}{4}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>-1</td>
<td>(Q^e_W = -1 + 4 \sin^2 \theta_W \approx 0)</td>
</tr>
<tr>
<td>u</td>
<td>+\frac{2}{3}</td>
<td>(-2C_{1u} = +1 - \frac{8}{3} \sin^2 \theta_W \approx +\frac{1}{3})</td>
</tr>
<tr>
<td>d</td>
<td>-\frac{1}{3}</td>
<td>(-2C_{1d} = -1 + \frac{4}{3} \sin^2 \theta_W \approx -\frac{2}{3})</td>
</tr>
<tr>
<td>p(uud)</td>
<td>+1</td>
<td>(Q^p_W = 1 - 4 \sin^2 \theta_W \approx 0.07)</td>
</tr>
<tr>
<td>n(udd)</td>
<td>0</td>
<td>(Q^n_W = -1)</td>
</tr>
</tbody>
</table>

Weak charge “triad” (M. Ramsey-Musolf)

- d-quark dominated
- u-quark dominated
- Semi-Leptonic
- Leptonic

\(Q^e_W\) and \(Q^p_W\) are suppressed in SM → increased sensitivity to new physics.

ie. 6% on \(Q^p_W=0.0708\) sensitive to new neutral current amplitudes as weak as \(\sim 4 \times 10^{-3} G_F\)
Parity violating electron scattering

\[ A_{PV} = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[ \varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1 - 4\sin^2\theta_W)\varepsilon G_M^\gamma G_A^e \right] \varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2 \]

At forward scattering angles and low 4-momentum transfer \((Q^2)\):

\[ A_{PV} = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[ Q_W^p + Q^2 B(Q^2, \theta) \right] \]

Proton's weak charge:

\[ Q_W^p = 1 - 4\sin^2\theta_W \] at tree level

“Form factor” term due to finite proton structure, including strange quark contributions – determined well by existing PVES high \(Q^2\) data. (About 30% for Qweak)
Qweak apparatus

**Production Mode:**
180 μA, Integrating

Acceptance-defining Pb collimator:
5.8° ≤ θ ≤ 11.6°

35 cm LH₂ target
3 kW cooling power at ~20 K

e- beam
E = 1.16 GeV
I = 180 μA
P = 89%

Quartz Cherenkov detectors with Pb preradiator
~800 MHz rate/bar

Toroidal Spectrometer

High-density concrete shielding wall
How we measure PV asymmetries

- Integrate the light signal in the Cerenkov detectors, sum them, and record the value every 1 msec

- "Normalize" the integrated signal (S) to the beam charge (Q)
  \[ Y = \frac{S}{Q} \]

- Flip the electron beam helicity and form a blinded asymmetry from four adjacent data samples (\( BF \in [-60,60] \) ppb):
  \[ A = \frac{Y^+ - Y^-}{Y^+ + Y^-} + BF \]

- Repeat 2 billion times! (2200 hours of data-taking) to get desired statistical error

\[ \sigma = 230 \text{ ppm per quartet} (= 4 \text{ msec}) \]

LH2 statistical width (per quartet):
- Counting statistics: 200 ppm
- Main detector resolution: 92 ppm
- Target noise/boiling: 55 ppm
- BCM Resolution: 43 ppm
- Electronic noise: 3 ppm
Multiple helicity reversals

Rapid pseudo-random reversal (960/sec): Rejects LH$_2$ target “boiling noise”.

IHWP at ~8-hour intervals: Mechanical action unable to induce electrical or magnetic induced false asymmetries.

Wien filter at monthly intervals: Rejection of beam size (or focus) modulation induced false asymmetry and suppression of slow drifts in apparatus linearity.

Also as check construct NULL: “out-of-phase” quantity from the two slow reversal techniques to bound unaccounted for false asymmetries.

Full experimental weighted NULL = $-1.75 \pm 6.51$ ppb
Correct raw asymmetry for measured false asymmetries

Correct measured asymmetry for polarization, backgrounds, acceptance, etc

\[ A_{\text{msr}} = A_{\text{raw}} + A_T + A_L + A_{\text{BCM}} + A_{\text{BB}} + A_{\text{beam}} + A_{\text{bias}} \]

\[ A_{\text{cp}} = R_{\text{tot}} \frac{A_{\text{msr}}/P - \sum_{i=1,3,4} f_i A_i}{1 - \sum_{i=1}^{4} f_i} \]

\[ R_{\text{tot}} = R_{\text{RC}} R_{\text{Det}} R_{\text{Acc}} R_{Q^2} \]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>15.0</td>
<td>10.1</td>
<td>18.0</td>
</tr>
<tr>
<td>Run 2</td>
<td>8.3</td>
<td>5.6</td>
<td>10.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Run 1 error (ppb)</th>
<th>Run 1 fractional</th>
<th>Run 2 error (ppb)</th>
<th>Run 2 fractional</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCM Normalization: ( A_{\text{BCM}} )</td>
<td>5.1</td>
<td>25%</td>
<td>2.3</td>
<td>17%</td>
</tr>
<tr>
<td>Beamline Background: ( A_{\text{BB}} )</td>
<td>5.1</td>
<td>25%</td>
<td>1.2</td>
<td>5%</td>
</tr>
<tr>
<td>Beam Asymmetries: ( A_{\text{beam}} )</td>
<td>4.7</td>
<td>22%</td>
<td>1.2</td>
<td>5%</td>
</tr>
<tr>
<td>Rescattering bias: ( A_{\text{bias}} )</td>
<td>3.4</td>
<td>11%</td>
<td>3.4</td>
<td>37%</td>
</tr>
<tr>
<td>Beam Polarization: ( P )</td>
<td>2.2</td>
<td>5%</td>
<td>1.2</td>
<td>4%</td>
</tr>
<tr>
<td>Target windows: ( A_{b_1} )</td>
<td>1.9</td>
<td>4%</td>
<td>1.9</td>
<td>12%</td>
</tr>
<tr>
<td>Kinematics: ( R_{Q^2} )</td>
<td>1.2</td>
<td>2%</td>
<td>1.3</td>
<td>5%</td>
</tr>
<tr>
<td>Total of others</td>
<td>2.5</td>
<td>6%</td>
<td>2.2</td>
<td>15%</td>
</tr>
<tr>
<td>Combined in quadrature</td>
<td>10.1</td>
<td></td>
<td>5.6</td>
<td></td>
</tr>
</tbody>
</table>

- Run 1 and 2 were both statistics limited
- Systematic error in Run 2 was significantly better than Run 1 due to known differences between the two periods
- Largest corrections were from the target windows (~38 ppb) and beam asymmetries (~18 ppb in Run 1)
Rescattering bias

- Parity-conserving rescattering in the Pb pre-radiators due to spin precession of scattered electron changed the light collected by the two PMTs in a helicity-dependent manner.
- As $A_{ep}$ is the average of the PMTs, the effect cancels to first order.
- The non-canceling $A_{bias}$ is dominated by variation in bar construction, not the details of the Pb analyzing power.
- GEANT simulations and models tied to our asymmetry and light yield data were used to determine $A_{bias}$.

Contributions to $A_{bias}$ Uncertainty
- Optical Model: ± 2.7 ppb
- Simulation cross checks: ± 2.3 ppb
- Glue Joints Effects: ± 1.5 ppb
- Effective Model: ± 1.5 ppb
- $A_{bias}$ Correction: 4.3 ± 3.0 ppb
Run 1 and 2 had different conditions and changes between runs that caused observable change in some of the beam-related systematic corrections. The good agreement between the fully corrected asymmetries gives confidence in the result.
Extracting the weak charge

Performed a global fit in $Q^2$ and $\theta$ to the reduced asymmetry (following PRL 99, 122003)

$$A_{ep}/A_0 = Q_W^p + Q^2 B(Q^2, \theta) \quad A_0 = -G_F Q^2/(4\pi\alpha\sqrt{2})$$

- Using all PVES data on $p$, $d$, & $^4$He targets up to $Q^2 = 0.63$ (GeV/c)$^2$. Forward and backward angle data, from SAMPLE, HAPPEX, G0, & PVA4
- Uses 5 free parameters: $C_{1u}$, $C_{1d}$, $\rho_s$, $\mu_s$, & $G_A^{Z(T=1)}$
  - EM form factors from Arrington & Sick, PRC 76, 035201 (2007).
  - $G_E^S$, $G_M^S$, and $G_A^Z$ use a dipole form: $(1-Q^2/\lambda^2)^{-2}$, with $\lambda = 1$ GeV/c
  - The isoscalar part of $G_A^Z$ is small and constrained by theory (Zhu, et al., PRD 62, 033008 (2000))
- All e-p data points were corrected for E & $Q^2$ dependence of $\gamma Z$-box contributions: for Qweak, this is a $6.4\%\pm0.6\%$ relative effect
e-p asymmetries with global fit result

Data Projected to the Forward-Angle Limit

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

- **Q**\(_W^p\) (this result) \(0.0719 \pm 0.0045\)
- **Q**\(_W^p\) (SM) \(0.0708 \pm 0.0003\)
### Variations of the global fit

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Error</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_W^p )</td>
<td>0.0719</td>
<td>0.0045</td>
<td>Qweak ( A_{ep} ) +</td>
</tr>
<tr>
<td>( \rho_s )</td>
<td>0.19</td>
<td>0.11</td>
<td>PVES data base</td>
</tr>
<tr>
<td>( \mu_s )</td>
<td>-0.18</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>( G_A Z(T=1) )</td>
<td>-0.67</td>
<td>0.33</td>
<td></td>
</tr>
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</table>

| \( Q_W^n \)    | -0.9808 | 0.0063 | Qweak \( A_{ep} \) +          |
| \( Q_W \)      | -0.9808 | 0.0063 | PVES data base +              |
| \( C_{1u} \)   | -0.1874 | 0.0022 | APV \(^{133}\text{Cs} \)      |
| \( C_{1d} \)   | 0.3389  | 0.0025 |                               |
| \( C_1 \)      | -0.9317 |        |                               |

| \( Q_W^p \)    | 0.0684  | 0.0039 | Qweak \( A_{ep} \) +          |
| \( Q_W \)      | 0.0684  | 0.0039 | PVES data base +              |
| \( Q_W \)      | 0.0706  | 0.0047 | LQCD (strange quarks)         |

Including cesium APV (PRL 109, 203003) allows extraction of neutron weak charge & separation of \( C_{1u} \), \( C_{1d} \) quark coupling constants.

Addition of Lattice QCD constraint on strange quarks (Green et al. PRD92, 031501 (2015); Sufian et al. PRL118, 042001 (2017).) further improves precision of \( Q_W^p \).

P.M. King; Qweak at Jefferson Lab
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<td>0.0718</td>
<td>0.0045</td>
<td></td>
</tr>
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<td>-0.1874</td>
<td>0.0022</td>
<td>PVES data base</td>
</tr>
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<td>$C_{1d}$</td>
<td>0.3389</td>
<td>0.0025</td>
<td>APV $^{133}$Cs</td>
</tr>
<tr>
<td>$C_1$ correlation</td>
<td>-0.9317</td>
<td></td>
<td></td>
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<td></td>
<td>PVES data base</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LQCD (strange quarks)</td>
</tr>
<tr>
<td>$Q_W^p$</td>
<td>0.0706</td>
<td>0.0047</td>
<td>Qweak $A_{ep}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EMFF’s &amp; theory axial</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LQCD (strange)</td>
</tr>
</tbody>
</table>

Precision of Qweak’s $A_{ep}$ dominates determination of $Q_W^p$

Alternate “Standalone” technique to extract $Q_W^p$ does NOT depend on other PV measurements

26 September 2017

P.M. King; Qweak at Jefferson Lab
Running of $\sin^2 \theta_W$

Solid Curve by: J. Erler, M. Ramsey-Musolf and P. Langacker

$Q_{\text{weak}}$ decreasing

$Q_{\text{weak}}$ increasing

$\sin^2 \theta_W(Q)$

$Q$ (GeV)

$Q_{\text{weak}}$ (+ LQCD strange)

$Q_{\text{weak}}$ (ep)

APV ($^{133}\text{Cs}$)

eDIS (ed)

Tevatron

LEP 1

SLC

LHC

NuTeV (ve)

E158 (ee)

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Sensitivity to new physics

\[ \mathcal{L}_{NC+NP}^{PV} = \frac{-G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma^5 e \sum_q \left( C_{1q} - \frac{\sqrt{2} g^2}{G_F \Lambda^2} h^q_V \right) \bar{q} \gamma^\mu q \]

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

\[ Q_w^p = -2(2C_{1u} + C_{1d}) \]

New PV Physics Ruled Out @95% CL Below Mass Scale of \( \Lambda/g \)

\[ \mathcal{L}_{NNNP} = \frac{-G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma^5 e \sum_q \left( C_{1q} - \frac{\sqrt{2} g^2}{G_F \Lambda^2} h^q_V \right) \bar{q} \gamma^\mu q \]

\[ h^u = \cos \theta_h \quad h^d = \sin \theta_h \]

\[ R = \frac{\sqrt{2} g^2}{G_F \Lambda^2} \]

SM values indicated by the red square. Dashed contours indicate value of \( \Lambda/g = 3, 5, \) and 8 TeV. (\(^{133}\)Cs APV, from PDG - Flambaum)

\[ \theta_h \] is “flavor mixing angle” in Lagrangian for new physics at value \( \Lambda/g \) mapped around boundary of experimental limits.
Summary

• Qweak has measured the proton weak charge in PVES, in good agreement with SM
  
  \[ A_{ep} = -226.5 \pm 7.3 \text{ (stat)} \pm 5.8 \text{ (syst)} \text{ ppb at } \langle Q^2 \rangle = 0.0248 \text{ (GeV/c)}^2 \]
  
  \[ Q_W^p \text{ (this exp.)} = 0.0719 \pm 0.0045 \quad Q_W^p \text{ (SM)} = 0.0708 \pm 0.0003 \]

• Bounds new neutral current semi-leptonic PV physics:
  • Amplitudes above \( \sim 8 \times 10^{-3} G_F \) ruled out at 95% CL
  • Mass/coupling scales of heavy new physics ruled out at \( \Lambda/g < 7.5 \text{ TeV at } \) 95% CL (following Erler, et al. arXiv:1401.6199 prescription)
  • Quark flavor dependent mass/coupling limits reach \( \Lambda/g \sim 20 \text{ TeV} \)
  • Will play a role in future analyses of bounds (or discoveries) of a variety of new physics

• Several ancillary measurements should also lead to additional physics results.

• Provides scientific and technical developments for next generation of measurements to build on
### Leptoquarks

- Analysis a bit dated (2003), but suggestive; included HERA, LEP, and APV data (missing more recent HERA data; see Aaron, et al. Phys. Lett. B **705**, 52 (2011).)

**New $Q_{weak}$ data (6.2% 1σ error) has sensitivity to distinguish among LQ types at 95% CL**

<table>
<thead>
<tr>
<th>Scalar Leptoquarks</th>
<th>Vector Leptoquarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>LQ</td>
<td>Consistency</td>
</tr>
<tr>
<td>$S_1^L$</td>
<td>0.57</td>
</tr>
<tr>
<td>$S_1^R$</td>
<td>0.01</td>
</tr>
<tr>
<td>$\bar{S}_1^R$</td>
<td>0.44</td>
</tr>
<tr>
<td>$S_3$</td>
<td>0.76</td>
</tr>
<tr>
<td>$R_2^L$</td>
<td>0.44</td>
</tr>
<tr>
<td>$R_2^R$</td>
<td>0.89</td>
</tr>
<tr>
<td>$\bar{R}_2^L$</td>
<td>0.13</td>
</tr>
</tbody>
</table>

- LHC limits currently at $\sim 1$ TeV for $g^2 = 4\pi \alpha$
- Similar limit from Qweak: $\sim 2.3$ TeV
- Low energy precision data continues to play important role in recent analyses including LHC data: see Phys. Rep. **641**, 1 (2016)
Dark Photon – Sensitivity to MeV scale Mediators

“Dark photon” – possible portal for new force to communicate with SM

“Dark parity violation”
(Davoudiasl, Lee, Marciano, Phys. Rev. D{89}, 095006 (2014))

• New source of low energy parity violation through mass mixing between $Z_0$ and $Z_d$
• Complementary to direct searches for heavy dark photons; observable even if direct decay modes are “invisible”
• Example: possible deviations of $\sin^2 \theta_W$ for dark photons respecting rare kaon decay constraints and muon g-2 is explained

• New $Q_{\text{weak}}$ point rules out some of the allowed region

In contrast to the lighter variety, these would show signatures both in low energy PV (shift of weak mixing angle) and in rare Higgs decays or direct Drell-Yan production at LHC:

$$H \rightarrow Z Z_d \text{ or } H \rightarrow Z_d Z_d \quad pp \rightarrow Z_d X$$

The specific bands were influenced by the NuTeV result, but the new $Q_{\text{weak}}$ data disfavors that region.

Dark Photon – Sensitivity to GeV scale Mediators

- $m_{\text{dark Z}} = 15$ GeV
- $m_{\text{dark Z}} = 25$ GeV

Log$_{10} Q$ [GeV] vs. $\sin^2 \theta_W (Q^2)$

"Anticipated sensitivities"
Beam parameter asymmetry correction

$$A_{beam} = - \sum_{i=1}^{5} \left( \frac{\partial A}{\partial \chi_i} \right) \Delta \chi_i$$

Run 1: $A_{beam} = 18.5 \pm 4.1$ ppb
Run 2: $A_{beam} = 0.0 \pm 1.1$ ppb
Aluminum target window background

- **Dilution fraction** ($f_1$): directly measured with empty target
- **Asymmetry** ($A_1$): directly measured with dedicated beam time on thick “dummy” target of identical alloy to hydrogen target windows
  - Corrections for effect of $\text{H}_2$ made using simulation and data-driven models of elastic and quasi-elastic scattering

$$f_1 \approx 2.5\%, \quad A_1 = 1515 \pm 77 \text{ ppb}, \quad \text{resulting in a } 38 \text{ ppb correction to } A_{ep}$$
Electroweak Radiative Corrections

\[ Q^p_W = [1 + \Delta \rho + \Delta e] \left[ (1 - 4 \sin^2 \theta_W(0)) + \Delta e' \right] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z} \]

<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>( \pm 0.0006 )</td>
</tr>
<tr>
<td>( Z\gamma ) box ( (6.4% \pm 0.6%) )</td>
<td>( 0.00459 \pm 0.00044 )</td>
</tr>
<tr>
<td>( \Delta \sin \theta_W (Q)_{\text{hadronic}} )</td>
<td>( \pm 0.0003 )</td>
</tr>
<tr>
<td>( WW, ZZ ) box - pQCD</td>
<td>( \pm 0.0001 )</td>
</tr>
<tr>
<td>Charge symmetry</td>
<td>( 0 )</td>
</tr>
<tr>
<td>Total</td>
<td>( \pm 0.0008 )</td>
</tr>
</tbody>
</table>


Calculations of Two Boson Exchange effects on \( Q^p_W \) at our Kinematics:

Recent theory calculations applied to entire data set of PV measurements as appropriate in global analysis.

Our \( \Delta A_{ep} \) precise enough that corrections to higher \( Q^2 \) points make little difference in extrapolation to zero \( Q^2 \).

**Energy Dependence \( \gamma Z \) correction:**

**Axial Vector \( \gamma Z \) correction:**
Peter Blunden, P.G., Melnitchouk, W., Thomas, A.W. New Formulation of \( \gamma Z \) Box Corrections to the Weak Charge of the Proton. Phys. Rev. Lett. 107, 081801 (2011).

**\( Q^2 \) Dependence \( \gamma Z \):**
Qweak’s ancillary measurements

Many ancillary measurements were performed to constrain background contributions; most will lead to additional physics results.

Parity-violating asymmetries
- Elastic $^{27}$Al
- $N\to\Delta$ asymmetry at $E=1.16$ GeV and 0.877 GeV
- Non-resonant inelastic near $W=2.5$ GeV (related to $\gamma$-Z box diagram)
- Pion photoproduction ($E=3.3$ GeV)

Parity-conserving transverse asymmetries (two-photon exchange process)
- Elastic $ep$
- Elastic $^{27}$Al, $^{12}$C
- $N\to\Delta$
- Non-resonant inelastic transverse asymmetry
- Pion photoproduction transverse asymmetries