The Qweak Experiment
First Determination of the Proton’s Weak Charge

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for the Qweak Collaboration
May 29th, 2013

• Introduction & background
  • The electroweak sector and PVES
  • Electroweak/model corrections

• Instrumentation & methodology
  • Experimental setup
  • Subsystem overview

• Initial results
  • Measured $A_{phys}^{PV}$
  • Implications and “new” physics
Qweak Collaboration

~24 institutions
~23 grad students
~10 post docs


¹Spokespersons ²Project Manager Grad Students
The Standard Model

The SM is believed to be the effective low-energy theory of some “new” fundamental physics.

Finding new physics - two complementary approaches:

Energy frontier: Tevatron, LHC

Precision frontier:

• $\mu(g-2)$, EDM, $0\nu\beta\beta$ decay, etc
• $\nu$-oscillations
• Atomic parity violation (APV)
• Parity-violating electron scattering (PVES)

Should direct measurements find new physics, precision measurements provide important information, such as strength of couplings

Hallmark of precision frontier: choose observables that are zero or “highly suppressed”

One such observable is the proton’s weak charge ($Q^p_w$)
The weak charges

What exactly is the proton’s weak charge ($Q_W^p$)?

Neutral-weak analog of the proton’s electric charge
Dirac form factor of the neutral-weak interaction

The Standard Model makes a firm prediction of $Q_W^p$

<table>
<thead>
<tr>
<th></th>
<th>EM Charge</th>
<th>Weak Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>2/3</td>
<td>$1 - \frac{8}{3} \sin^2(\theta_w) \approx 0.38$</td>
</tr>
<tr>
<td>d</td>
<td>-1/3</td>
<td>$-1 + \frac{4}{3} \sin^2(\theta_w) \approx -0.69$</td>
</tr>
<tr>
<td>P (uud)</td>
<td>+1</td>
<td>$1 - 4 \sin^2(\theta_w) \approx 0.07$</td>
</tr>
<tr>
<td>N (udd)</td>
<td>0</td>
<td>-1</td>
</tr>
</tbody>
</table>

“Accidental suppression”$
\rightarrow$ sensitivity to new physics

Note: $Q_W^n = -1$

Q-weak is particularly sensitive to the quark vector couplings ($C_{1u}$ and $C_{1d}$).

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

$Q_W^n = -2(C_{1u} + 2C_{1d})$
The Running of the Weak Mixing Angle

The measurements at the Z-pole pin down the scale; they don’t describe the evolution in the low $Q^2$ regime.

Each experiment is sensitive to different potential new physics.

SM electroweak fit. Uncertainty is line width.

Vertical position arbitrarily placed
Error bar is proposed goal

Q-weak will make the most precise measurement of $\sin^2(\theta_W)$ at low-$Q^2$

$$\delta(\sin^2 \theta_W) \approx \pm 0.3\%$$

Probing the Weak Charge

The weak force is *unique*: it violates parity

To extract $Q_W^p$: measure the parity violating asymmetry in electron-proton scattering

$$\hat{e} + p \rightarrow e + p$$

35 cm LH2 target

Beam helicity change is equivalent to parity transformation

Rapid helicity reversal pattern (960 Hz) “quartets”
Probing the Weak Charge

The weak force is *unique*: it violates parity

To extract $Q^p_W$: measure the parity violating asymmetry in electron-proton scattering

Typically the photon exchange dominates, but interference with EM amplitude makes the neutral current accessible

$$ A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{|M_{PV}^{NC}|}{|M_{EM}|} $$

The SM prediction is

$\sim$ -216 parts per billion (ppb)

Tiny ($\sim 10^{-6}$) cross section asymmetry isolates weak interaction

For $Q^2 \ll (M_Z)^2$, $A \approx \frac{Q^2}{(M_Z)^2}$
Energy Dependence

In the Standard Model, the weak charge is *defined* at \( Q^2 = 0, E = 0 \).

\[
Q_W^p = [\rho_{NC} + \Delta_e][1 - 4 \sin^2 \hat{\theta}_W(0) + \Delta_e'] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}
\]

Full expression for \( Q_W^p \) has energy dependent corrections – need precise calculations.

The \( \Box_{WW} \) and \( \Box_{ZZ} \) are well determined from pQCD \( \propto \frac{1}{q^2-M^2_{W(Z)}+i\epsilon} \).

The \( \Box_{\gamma Z} \) isn’t pQCD friendly due to the photon leg \( \propto \frac{1}{q^2+i\epsilon} \)
Energy Dependence

In the Standard Model, the weak charge is defined at $Q^2 = 0, E = 0$.

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

Uncertainty from these corrections on current results is irrelevant.

Previously the uncertainty on this calculation was believed to be problematic for final result
Energy Dependence

In the Standard Model, the weak charge is *defined* at $Q^2 = 0, E = 0$.

$$Q_W^p = [\rho_{NC} + \Delta_e][1 - 4\sin^2 \hat{\theta}_W (0) + \Delta'_e] + \square_{WW} + \square_{ZZ} + \square_{\gamma Z}$$

Uncertainty from these corrections on *current* results is irrelevant.

$$\square_{\gamma Z} \text{ contribution to } Q_W^p \text{ (Qweak kinematics)}$$

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gorchtein &amp; Horowitz</td>
<td>$0.0026 \pm 0.0026$</td>
</tr>
<tr>
<td>Sibirtsev, Blunden &amp; Melnitchouk, Thomas</td>
<td>$0.0047^{+0.0011}_{-0.0004}$</td>
</tr>
<tr>
<td>Rislow &amp; Carlson</td>
<td>$0.0057 \pm 0.0009$</td>
</tr>
<tr>
<td>Gorchtein, Horowitz &amp; Ramsey-Muslof</td>
<td>$0.0054 \pm 0.0020$</td>
</tr>
<tr>
<td>Hall, Blunden, Melnitchouk, Thomas &amp; Young</td>
<td>$0.0052 \pm 0.00043$</td>
</tr>
</tbody>
</table>

Calculations are primarily dispersion theory type error estimates can be firmed up with data!

Qweak: inelastic asymmetry data taken at $W \sim 2.3 \text{ GeV}, \; Q^2 = 0.09 \text{ GeV}^2$
Extracting the weak charge

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

Reduced asymmetry more convenient
\[ A_{red} = \frac{A_{PV}}{A_0} \quad A_0 = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \]

One must extrapolate to \( Q^2 = 0 \).
We measure \( A_{PV} \) at \( Q^2 = 0.025 \text{ GeV}^2 \).

Consequences of low \( Q^2 \) measurement:
- Relatively insensitive to proton’s internal structure
- Short extrapolation distance → First determination: proton’s weak charge

Previous experiments explored hadronic structure more directly; help constrain our hadronic contribution

Data rotated to \( \theta_{lab} = 0 \)

Qweak kinematics

Hadronic term extracted from fit

SM
PVES Challenges

Qweak is the most precise (relative and absolute) PVES result to date, and will use past results to bound theoretical backgrounds

PVES challenges:

- Statistics
  - High rates required
  - High polarization, current
  - High powered targets with large acceptance

- Low noise
  - Electronics, target density fluctuations
  - Detector resolution

- Systematics
  - Helicity-correlated beam parameters
  - Backgrounds (target windows)
  - Polarimetry
  - Parity conserving processes

Small absolute and relative uncertainty (5ppb on $A_{PV}$)

- $\delta A_{PV} \approx \pm 2.1\%$
- $\delta Q^p_W \approx \pm 4\%$
- $\delta (\sin^2 \theta_W) \approx \pm 0.3\%$

PVEsS Experiment Summary
**Q-weak Apparatus**

- **Horizontal drift chambers**
- **Quartz Cerenkov Bars**
- **Toroidal Magnet Spectrometer**
- **Vertical Drift Chambers**
- **Trigger Scintillator**
- **Collimators**

**Electron beam**

**Target**

\[ E_{\text{beam}} = 1.165 \text{ GeV} \]
\[ Q^2 \approx 0.025 \text{ GeV}^2 \]
\[ \theta \sim 7-11^\circ \]

Current = 180 \( \mu \)A
Polarization = 85%
Target = 35 cm LH2
Cryopower = 2.5 kW

Red = low-current tracking mode
Blue = production (“integrating”) mode
**Q-weak Apparatus**

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**Parameters:**

- $E_{\text{beam}} = 1.165$ GeV
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**Color Codes:**

- Red = low-current tracking mode
- Blue = production (“integrating”) mode
Qweak Target

35 cm, 2.5 kW liquid hydrogen target

World’s highest powered cryotarget

- Temperature ~20 K
- Pressure: 30-35 psia
- Beam at 150 – 180uA

Target boiling might have been problematic!

LH2 statistical width (per quartet):

- Counting statistics: 200 ppm
- Main detector width: 92 ppm
- BCM width: 50 ppm
- Target noise/boiling: 37 ppm

Total: 228 ppm resolution per quartet

→ 50 ppb per perfect day!*

*perfect day: 100% efficiency
Main Detectors

• Main detectors
The toroidal magnet focuses elastically scattered electrons onto each bar
  – 8 Quartz Cerenkov bars
  – Azimuthal symmetry maximizes rates and reduces systematic uncertainties
  – 2 cm lead pre-radiators reduce background
  – Each electron produces ~100 photoelectrons

Close up of one detector in situ
**$Q^2$ determination**

To determine $Q^2$, we go to “tracking” mode:

- Currents ~ 50 pA
- Use Vertical + Horizontal Drift Chambers
- Re-construct individual scattering events

$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \{Q_w^p + B(\theta, Q^2)Q^2\}$$

Ultimately need to match data with Geant 3 and 4 simulations

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Simulation blue
Data red
Hall C Beam Polarimetry

Polarization is our largest systematic uncertainty (1%)
This is a challenging goal; so we built a second, independent measurement device.

Møller polarimeter
- First of its kind 15 years ago
- Thin, pure iron target
- Brute force polarization
- Limited to low current

Compton polarimeter
- Installed for Q-weak
- Run continuously at high currents
- Statistical precision: 1% per hour

We can detect both recoil electron and photon.
Beam Polarimetry

Preliminary Run 2 Polarization – For Illustrative Purposes Only

Note the wonderful agreement between both polarimeters!
In addition to the ~4% measurement of the proton’s weak charge, Q-weak conducted numerous other ancillary measurements:

• Elastic transverse asymmetry (proton)*
• Elastic transverse asymmetry (Aluminum)
• PV asymmetry in the $N \rightarrow \Delta$ region
• Transverse asymmetry in the $N \rightarrow \Delta$ region
• PV non-resonant inelastic scattering $\gamma Z$ box diagram constraining
• Transverse asymmetry in the PV inelastic scattering region (3.3 GeV)
• PV asymmetries in pion photoproduction
• Transverse asymmetries in pion photoproduction
• Measurements of elastic PV asymmetry on aluminum (alloys) / carbon

*Beam normal single spin asymmetry

Plenty of projects, plenty of results, 20+ theses....

Due to time constraints, highlight only the Transverse Elastic $\vec{e}p$
Normal production running: 89% longitudinal beam polarization
Small amount of transverse polarization
  • Large parity conserving asymmetry (~5ppm)
  • Leaks into the experimental asymmetry through broken azimuthal symmetry
Measurements of the Beam Normal Single Spin Asymmetry (BNSSA) provide:
  • Direct access to imaginary part of two-photon exchange
We need to correct for this!

Horizontal and vertical components measured separately

\[
A_{BNSS}(\phi_{det}) = B_n |P_T| \sin(\phi_{det} - \phi_s)
\]
Transverse Asymmetry Measurement

Normal production running: 89% longitudinal beam polarization
Small amount of transverse polarization

- Large parity conserving asymmetry (≈5ppm)
-Leaks into the experimental asymmetry through broken azimuthal symmetry

\[ B_n = -5.30 \pm 0.07\text{(stat)} \pm 0.15\text{(sys)} \text{ ppm} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>Preliminary</th>
<th>Anticipated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarization</td>
<td>2.2%</td>
<td>≈1.0%</td>
</tr>
<tr>
<td>Statistics</td>
<td>1.3%</td>
<td>≈1.3%</td>
</tr>
<tr>
<td>(Q^2)</td>
<td>1.2%</td>
<td>≈0.5%</td>
</tr>
<tr>
<td>Non-linearity</td>
<td>1.0%</td>
<td>≈0.2%</td>
</tr>
<tr>
<td>Regression</td>
<td>0.9%</td>
<td>≈0.9%</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.3%</td>
<td>≈0.3%</td>
</tr>
</tbody>
</table>

This is the most precise measurement of Beam Normal Single Spin Asymmetry to date.

Private communication with Buddhini Waidyawansa
Run periods

Q-weak ran from Fall 2010 – May 2012 in four distinct running periods

- Hardware checkout (Fall 2010-January 2011)
- Run 0 (Jan-Feb 2011)
- Run 1 (Feb – May 2011)
- Run 2 (Nov 2011 – May 2012)

This talk focuses only on the Run 0 period (about 1/25th of our total dataset).

This small bit already enables us to constrain possible “new” physics and is competitive with previous experiments.
$A_{PV} = - \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} [Q_W^p + B(\theta, Q^2)Q^2]$ 

Data rotated to $\theta_{lab} = 0$

$\overline{A}_{LR}^P$ is the reduced asymmetry.

Note the initial agreement with the standard model.

Our uncertainty band will eventually shrink by $\sim 5$.

The fit takes into account the $\theta, Q^2$ of each point. To plot: rotated data to forward angle, and corrected for the $Q^2$ and E dependence of the $\Box_{\gamma Z}$. 

Q$^p_W$ extraction
\[ Q^p_W \text{ extraction} \]

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

Data rotated to \( \theta_{lab} = 0 \)

The fit takes into account the \( \theta, Q^2 \) of each point. To plot: rotated data to forward angle, and corrected for the \( Q^2 \) and \( E \) dependence of the \( \Box_{\gamma Z} \).

Green line is fit without Q-weak. Note: already significant measurement; we “anchor” the fit.

\( A^P_{LR} \) is the reduced asymmetry.

Note the initial agreement with the standard model.

Our uncertainty band will eventually shrink by \( \sim 5 \).
Individual weak vector-couplings to the quarks are given by the $C_1$'s. The final result will form a tight band, providing the most precise measurement to date.

Black dot is SM value
PVES includes Q-weak and world data
APV is more sensitive to isoscalar combinations due to large neutron contribution
Red is combined fit

\[
C_{1u} = -0.1849 \pm 0.0053 \\
C_{1d} = 0.3370 \pm 0.0050
\]
Conclusions and Future

Our initial Run 0 measurement (only $1/25^{th}$ of our data):

- Our current measurement:
  \[ A_{PV}^p = -279 \pm 35\,(stat) \pm 29\,(sys) \ \text{ppb} \quad \langle Q^2 \rangle = 0.0250 \pm 0.0006 \ \text{GeV}^2 \]
  \[ \langle E_{beam} \rangle = 1155 \ \text{MeV} \quad \theta_{eff} = 7.90^\circ \]
  \[ Q_W^p = 0.064 \pm 0.012 \quad Q_W^p (SM) = 0.0710 \]
  \[ Q_W^n = -0.975 \pm 0.010 \quad Q_W^n (SM) = -0.9890 \]

These results are being submitted for publication. Analysis of full dataset underway, final results expected next year. Perhaps, some ancillary measurement results sooner.
Data Rotated to the Forward-Angle Limit
Thank you for your support JLab!


¹Spokespersons ²Project Manager Grad Students