Measurement of the weak charge of the proton with $Q_{\text{weak}}$

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University of Virginia
The Qweak Collaboration


Spokespersons  Project Manager  Grad Students  *deceased

101 collaborators  26 grad students
11 post docs  27 institutions

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
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
The path to discovery

- In order to reveal the way nature works a multi-pronged approach is needed

- From astronomical observations (cosmic frontier) to direct measurements (energy frontier) to indirect measurements (intensity frontier)

- Some of our most tantalizing results have come from indirect searches where we get hints at what could lie ahead

- Each of these paths comes with their own pros and cons

Particle physicists’ intro to PVES

- uses longitudinally polarized electron beams
- measures asymmetries that are generally on the level of ppm or less

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{Z^0}{\gamma} \propto \left| \frac{M_Z}{M_\gamma} \right| \]
Particle physicists’ intro to PVES

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Kinematic cuts are already made when the experiment starts:
Particle physicists’ intro to PVES

- uses longitudinally polarized electron beams
- measures asymmetries that are generally on the level of ppm or less

Kinematic cuts are already made when the experiment starts:

Allows for the collection of large amounts of data (100s of MHz) needed to resolve small asymmetries:

$$A_{PV} = (-131 \pm 14 \pm 10) \text{ ppb}$$
History of PVES

- PVES has a long history of pushing the limits of precision and discovery
  - E122: ($\Delta A = 10$ ppm)
  - G0, A4, HAPPEX ($\Delta A = 0.25$ to 2 ppm)
  - E158 ($\Delta A = 17$ ppb)
  - Qweak ($\Delta A = 9$ ppb)
  - Moller ($\Delta A = 0.8$ ppb)
  - P2 ($\Delta A = 0.34$ ppb)
Electroweak measurements

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

- In the early 2000s E158 made the first measurement of electron weak charge $Q_e^W$
- Atomic Parity Violation measurements on $^{133}\text{Cs}$ gave unique insights into d-quark weak vector charge
- Finally $Q_{weak}$ directly measures the proton weak vector charge $Q_p^W$

- Weak charge is the analog to the electric charge:
  - also defined as $Q^2 \rightarrow 0$ (intrinsic property of particle)
  - proton and electron have nearly 0 weak charge
  - combined with the very well defined SM prediction makes it a good place to look for deviations (and new physics)

<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>$-2C_{1u} = +1 - \frac{3}{4} \sin^2 \theta_W \approx +\frac{1}{3}$</td>
</tr>
<tr>
<td>d</td>
<td>$-\frac{1}{3}$</td>
<td>$-2C_{1d} = -1 + \frac{3}{4} \sin^2 \theta_W \approx -\frac{1}{3}$</td>
</tr>
<tr>
<td>p(uud)</td>
<td>$+1$</td>
<td>$Q_p^W = 1 - 4 \sin^2 \theta_W \approx 0$</td>
</tr>
<tr>
<td>n(udd)</td>
<td>$0$</td>
<td>$Q_n^W = -1$</td>
</tr>
</tbody>
</table>
Quark Vector couplings $\sim$ contact interaction

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

- At low $Q^2$ ($Q^2 \ll M_Z$) the SM Lagrangian is effectively a 4-fermion contact interaction
- $Q_{\text{weak}}$ is sensitive to quark vector couplings $C_{1u}$ and $C_{1d}$
Tree-level Qweak asymmetry

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

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

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

- Unlike measurements on Q^e_W, Qweak asymmetry needs to take care of the hadronic part of the interaction
  - small Q^2 makes the contributions smaller compared to previous experiments (proton looks like a point particle)
  - The hadronic contributions can be determined from the previous PVES experiments
Qweak experimental setup

- Ran in three periods between 2010 and 2012 at the Continuous Electron Beam Accelerating facility at DOE’s Jefferson Lab

- Commissioning data published in PRL 111, 141803 (2013)

\[
Q_{w}^{p}(SM) = 0.0708 \pm 0.0003
\]

Initial result: \[
Q_{w}^{p}(PVES) = 0.064 \pm 0.012
\]

Final result: \[
Q_{w}^{p}(PVES) = \pm 0.0045
\]
Qweak experimental setup

- Careful preparation of the entire machine (from injector all the way to the experiment) has to be made
  - The injector was setup to have a fast helicity reversal at 1kHz
  - High polarization of the electron beam had to be maintained
  - Special care was taken to avoid helicity correlated beam asymmetries (intensity, beam positions)
  - Checks were done throughout the machine until the target to make sure beam quality was maintained
Qweak experimental setup

**Toroidal Spectrometer**

- 35 cm LH$_2$ target
- 3 kW cooling power at ~20 K
- e- beam
  - $E = 1.16$ GeV
  - $I = 180$ µA
  - $P = 89\%$

Acceptance defining
- Pb collimator
  - $5.8^\circ \leq \theta \leq 11.6^\circ$
Qweak experimental setup

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

- **35 cm LH$_2$ target**

- **3 kW cooling power at $\sim 20$ K**

- **Toroidal Spectrometer**

- **Acceptance defining Pb collimator**
  - $5.8^\circ \leq \theta \leq 11.6^\circ$

- **select elastic peak**
Qweak experimental setup

35 cm LH$_2$ target
3 kW cooling power at ~20 K

e- beam
E = 1.16 GeV
I = 180 $\mu$A
P = 89%

Acceptance defining Pb collimator
$5.8^\circ \leq \theta \leq 11.6^\circ$

select elastic peak

integrate for ~1msec

calculate asymmetry from 4 windows
Null asymmetry from Wiens: $A_{\text{Null}} = -1.8 \pm 6.5 \text{ ppb}$

- Insertable laser optics flip the polarization of the laser and electron beam
- Magnetic spin manipulation (Wein filter) allowed for direct electron beam polarization flip
- Energy variation through the accelerator (g-2 flip)

The physics asymmetry was consistent through these slow spin reversals
Corrections and systematics

- Correct the raw asymmetry for measured experimental factors (detector non-linearity, beam asymmetries)

- Apply additional corrections (polarization, acceptance, backgrounds)

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

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

The polarization measurement used both Compton and MOLLER measurements to reach $\sigma P$ of 1.05/0.73% (Run1/Run2).

- Target Al windows caused the largest correction (~38 ppb).
- Using vertical drift chambers we benchmarked detailed $Q^2$ simulations with data.
Corrections and systematics

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

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

- Cross checks between redundant sets of high precision beam monitoring systems allowed us to obtain a small uncertainty for our determination of beam properties (charge, position)

- Using these monitors we could determine remaining asymmetry in beam properties under the fast helicity flip

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<th>Run 2 fractional</th>
</tr>
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<tr>
<td>BCM Normalization: ( A_{\text{BCM}} )</td>
<td>2.3</td>
<td>17%</td>
</tr>
<tr>
<td>Beamline Background: ( A_{\text{BB}} )</td>
<td>1.2</td>
<td>5%</td>
</tr>
<tr>
<td>Beam Asymmetries: ( A_{\text{beam}} )</td>
<td>1.2</td>
<td>5%</td>
</tr>
<tr>
<td>Rescattering bias: ( A_{\text{bias}} )</td>
<td>3.4</td>
<td>37%</td>
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<td>Beam Polarization: ( P )</td>
<td>1.2</td>
<td>4%</td>
</tr>
<tr>
<td>Target windows: ( A_{b1} )</td>
<td>1.9</td>
<td>12%</td>
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<td>Kinematics: ( R_{Q^2} )</td>
<td>1.3</td>
<td>5%</td>
</tr>
<tr>
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Corrections and systematics

In the early stages of the experiment we observed a large amount of background coming from beam line elements

- We introduced a tungsten plug to reduce this background (not fully taken care of)

- A small contribution to the total signal (0.19%) remained after the introduction of the W-plug

- Further studies were done to determine and correct this background contribution

  - background detectors were used to account for possible helicity correlated asymmetries from this background

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

\[
A_{ep} = \frac{A_{\text{msr}}/P - \sum_{i=1,3,4} f_i A_i}{1 - \sum_{i=1}^{4} f_i}
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Corrections and systematics

During the analysis we observed a systematic difference between the asymmetries measured with the positive and negative PMTs.

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

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

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<td>Beam Asymmetries: ( A_{beam} )</td>
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\( A_{-} \sim -20 \text{ ppb} \)
\( A_{+} \sim -320 \text{ ppb} \)
Polarized scattering in preradiator

electron spins pressed when passing through Qtor resulting in ~50% transverse polarization at the Pb preradiator

produced significant asymmetry difference between + and - PMTs

\[ A_{PMTDD} = A_- - A_+ \]

this effect cancels at first order for our measurement

\[ A_{PV} = (A_- + A_+) / 2 \]

Corrected asymmetries were due to imperfections in quartz bar construction

Effect was evaluated using several MCs implementing low energy (few MeV) Mott Scattering and optical properties of the Quartz bars.
Corrections and systematics

<table>
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<tr>
<td>Run 1</td>
<td>-223.5</td>
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<td>18.0</td>
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<td>5.6</td>
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<td>-226.5</td>
<td>7.3</td>
<td>5.8</td>
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- Our final result is still statistically limited and dominated by the results from our second running period.
Determining $Q^p_w$

- Global fit:
  - 5 parameters: $C_{1u}$, $C_{1d}$, $\rho_s$, $\mu_s$ and $G^Z_A$
  - Using all PVES data up to $Q^2 = 0.63$ GeV$^2$

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

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- $Q^p_w$ is determined from a global fit of PVES data
  - our measurement is the closest to the extrapolation point and anchors the fit while the rest of the data determine the hadronic contributions

\[
Q^p_w (SM) = 0.0708 \pm 0.0003 \\
Q^p_w (PVES) = 0.0719 \pm 0.0045
\]
• E158 and Qweak are sensitive to different types of new physics

• strong consistency with SM for Qweak should put a stronger limit on scalar lepto-quarks (E158 insensitive)
• Some models point to a heavy dark photon \( (Z_d) \) could be detected at low \( Q \) through it’s mixing with between \( Z_0 \) and \( Z_d \)

• Complementary with direct searches
  
  • in this scenario the \( Z_d \) would not have any coupling with SM
Semi-leptonic PV Physics

Following prescription for new physics from contact interactions in *PhysRevD.68.016006*:

\[
\mathcal{L} = \mathcal{L}_{\text{SM}}^{PV} + \mathcal{L}_{\text{NEW}}^{PV}
\]

\[
\mathcal{L}_{\text{SM}}^{PV} = -\frac{G_F}{\sqrt{2}} e \gamma_\mu \gamma_5 e \sum_q C_1 q \bar{q} \gamma^\mu q,
\]

\[
\mathcal{L}_{\text{NEW}}^{PV} = \frac{g^2}{4 \Lambda^2} e \gamma_\mu \gamma_5 e \sum_f h_f \bar{q} \gamma^\mu q,
\]

- Our measurement of vector-proton weak neutral current charge constraints new physics which are comparable with current limits from LHC

\[g^2 = 4\pi\] limit is 26.3 TeV
Future PVES experiments

MESA/P2 at Mainz

- P2 will improve on the weak charge of the proton
- MOLLER will improve on the weak charge of the electron
- SOLID will make measurement over a wide kinematic range that will include test SM prediction for the axial proton weak charge

PVDIS SOLID at JLab
Future PVES experiments

MESA/P2 at Mainz

MOLLER at JLab

- P2 and MOLLER will have weak mixing angle determinations as precise as Z-pole measurement but at very low $Q^2$
Future PVES experiments

Currently published constraints (6GeV PVDIS, Qweak, APV)

Constraints after SOLID comparable with future LHC running.

$g^2 = 4\pi$

PVDIS SOLID at JLab
Summary

• Qweak has obtained the most precise determination of a PVES asymmetry and extracted the vector weak charge of the proton $Q_{pw}$

• Sensitive measurement of weak mixing angle limits the phase space of dark Zs

• Consistency with SM further constrains semi-leptonic PV physics above 26.3 TeV

• Future PVES experiments will bring us even closer to the answers we all seek
Backup
Qweak ~2.5 kW LH₂ Target

Target density fluctuations must be small compared to statistical uncertainty

This was achieved by:

- First use of fluid dynamics simulation in design to minimize "density changes", in liquid or at windows.
- Fast helicity reversal – up to ~1 ms flip rate allows common mode rejection "boiling" noise, line noise and undesired helicity correlated beam properties.
- Additional safeguards: large raster size ~(3mm x 3mm), faster pump speed, and more cooling directed onto windows...

The highest power cryo-target ever built! 35 cm long liquid hydrogen (LH₂)

*courtesy of R. Carlini

Ciprian Gal

University of Virginia
Corrections and systematics

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

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

- Our final result is still statistically limited

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</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>
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<td>4.7</td>
<td>22%</td>
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<td>3.4</td>
<td>11%</td>
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<tr>
<td>Target windows: ( A_{b1} )</td>
<td>1.9</td>
<td>4%</td>
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<td>12%</td>
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<tr>
<td>Kinematics: ( R_{Q^2} )</td>
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<td>2%</td>
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<td>Total of others</td>
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Result stability

- Including the APV data gives discrimination power for $C_{1u}$ and $C_{1d}$ which leads to $Q_{W}^{n}$

- The addition of LQCD data add additional constraints on the $Q_{W}^{p}$ determination

- A determination without the rest of the PVES data (but with some ansatz for the form factors) shows the power of the Qweak experiment

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Error</th>
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<tr>
<td>$Q_{W}^{p}$</td>
<td>0.0719</td>
<td>0.0045</td>
<td>Qweak $A_{ep}$</td>
</tr>
<tr>
<td>$Q_{W}^{n}$</td>
<td>-0.9808</td>
<td>0.0063</td>
<td>Qweak $A_{ep}$</td>
</tr>
<tr>
<td>$C_{1u}$</td>
<td>-0.1874</td>
<td>0.0022</td>
<td>PVES data base +</td>
</tr>
<tr>
<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>
</tr>
</tbody>
</table>

| $Q_{W}^{p}$    | 0.0684  | 0.0039 | Qweak $A_{ep}$ +            |
|                |         |        | PVES data base +           |
|                |         |        | LQCD (strange quarks)      |

| $Q_{W}^{p}$    | 0.0706  | 0.0047 | Qweak $A_{ep}$ +            |
|                |         |        | EMFF’s & theory axial +     |
|                |         |        | LQCD (strange)              |

$Q_{W}^{p}$ (this result) $0.0719 \pm 0.0045$

$Q_{W}^{p}$ (SM) $0.0708 \pm 0.0003$
PV Measurement

- Integrate light signal for ~1 msec
- Calculate asymmetry for 4 adjacent data samples and add a blinding factor
- Analyzed ~10^9 quartets which is equivalent to ~10^{17} detected electrons

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

σ = 230 ppm per quartet (= 4 msec)
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_{\text{Weak}} )</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 \( \Delta A_{\text{pv}} \) 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 \( \gamma Z \):

*courtesy of R. Carlini

Ciprian Gal
Inner error bars statistical, outer error bars point-to-point systematic uncertainties added in quadrature with statistical uncertainties.

Yellow band incorporates overall normalization uncertainties determining by weighted average and total uncertainty.

Time dependence of reported polarization driven by continuous Compton measurements, with small scale correction (0.21%) determined from uncertainty-weighted global comparison of Compton and Møller polarimeters.

*courtesy of R. Carlini