The $Q_{\text{weak}}$ Experiment at Jefferson Lab - A Search for New Physics at the TeV Scale

Mark Pitt* Virginia Tech
for the $Q_{\text{weak}}$ Collaboration

CIPANP 2009: 10th Conference on the Intersections of Particle and Nuclear Physics
La Jolla, CA May 26 – 31, 2009

- $Q^p_{\text{weak}}$ - How do we extract it from our measurements?
  - How is it computed in the Standard Model?
  - How does new physics affect it?

- Brief update on construction/installation/running status

* Work partially supported by the National Science Foundation
The Qweak Collaboration

D. Armstrong, A. Asaturyan, T. Averett, J. Benesch, J. Birchall, P. Bosted, A. Bruell, C. Capuano,
R. D. Carlini¹ (Principal Investigator), G. Cates, C. Carrigee, S. Chattopadhyay, S. Covrig, C. A. Davis,
K. Dow, J. Dunne, D. Dutta, R. Ent, J. Erler, W. Falk, H. Fenker, T. A. Forest, W. Franklin,
D. Gaskell, M. Gericke, J. Grames, K. Grimm, F.W. Hersman, D. Higinbotham, M. Holtrop,
J.R. Hoskins, K. Johnston, E. Ihloff, M. Jones, R. Jones, K. Joo, J. Kelsey, C. Keppel, M. Khol, P. King,
E. Korkmaz, S. Kowalski¹, J. Leacock, J.P. Leckey, L. Lee, A. Lung, D. Mack, S. Majewski, J. Mammei,
J. Martin, D. Meekins, A. Micherdzinska, A. Mkrtchyan, H. Mkrtchyan, N. Morgan, K. E. Myers, A. Narayan,
A. K. Opper, SA Page¹, J. Pan, K. Paschke, M. Pitt, M. Poelker, T. Porcelli, Y. Prok, W. D. Ramsay,
M. Ramsey-Musolf, J. Roche, N. Simicevic, G. Smith², T. Smith, P. Souder, D. Spayde, B. E. Stokes,
Yang, R. Young, H. Zhu, C. Zorn

¹Spokespersons  ²Project Manager

College of William and Mary, University of Connecticut, Instituto de Fisica, Universidad Nacional Autonoma de Mexico,
University of Wisconsin, Hendrex College, Louisiana Tech University, University of Manitoba, Massachusetts Institute of
Technology, Thomas Jefferson National Accelerator Facility, Virginia Polytechnic Institute & State University, TRIUMF,
University of New Hampshire, Yerevan Physics Institute, Mississippi State University, University of Northern British
Columbia, Cockroft Institute of Accelerator Science and Technology, Ohio University, Hampton University,
University of Winnipeg, University of Virginia, George Washington University, Syracuse University,
Idaho State University, University of Connecticut, Christopher Newport University
The $Q^p_{\text{weak}}$ Experiment: A Search for New TeV Scale Physics via a Measurement of the Proton’s Weak Charge

Measure: Parity-violating asymmetry in $e^+ p$ elastic scattering at $Q^2 \sim 0.03 \text{ GeV}^2$ to ~4% relative accuracy at JLab

Extract: Proton’s weak charge $Q^p_{\text{weak}} \sim 1 - 4 \sin^2 \theta_W$ to get ~0.3% on $\sin^2 \theta_W$ at $Q^2 \sim 0.03 \text{ GeV}^2$

tests “running of $\sin^2 \theta_W$” from $M^2_Z$ to low $Q^2$
sensitive to new TeV scale physics
“Running of $\sin^2 \theta_W$” in the Electroweak Standard Model

- Electroweak radiative corrections
  \[ \rightarrow \sin^2 \theta_W \text{ varies with } Q \]
Neutral Current Observable - Parity-Violating Asymmetry

\[ \sigma \propto \begin{vmatrix} \gamma \rightarrow Z \end{vmatrix}^2 + h_\gamma \begin{vmatrix} \gamma \rightarrow N \end{vmatrix}^2 + \begin{vmatrix} Z \rightarrow \gamma \end{vmatrix}^2 \]

\(\tilde{e} + N\) (elastic scattering)

\[ A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \begin{vmatrix} \gamma \rightarrow Z \end{vmatrix} \]

\[ = \left[ \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \right] \times F[\text{form factors, } \sin^2 \theta_W] \approx 3 \times 10^{-7} = 0.3 \text{ ppm} \]
**Q_p^{weak}: Extract from Parity-Violating Electron Scattering**

![Diagram](image)

As $Q^2 \to 0$

measures $Q_p$ - proton's electric charge

measures $Q_p^{weak}$ - proton's weak charge

\[
A = \frac{2 M^{NC}_{EM}}{M^{EM}} \quad \text{as } Q^2 \to 0, \theta \to 0
\]

\[
A = \left[ \frac{-G_F}{4\pi\alpha}\sqrt{2} \right][Q^2(1 - Q_p^{weak}) + F^p(Q^2, \theta)]
\]

\[
Q_p^{weak} = 1 - 4\sin^2 \theta_W \sim 0.072 \quad \text{(at tree level)}
\]

- $Q_p^{weak}$ is a well-defined experimental observable
- $Q_p^{weak}$ has a definite prediction in the electroweak Standard Model

Strange electric and magnetic form factors - measure contribution of strange quark sea to nucleon structure
Nucleon Structure Contributions to the Asymmetry

\[ A = A_{Q^2}^W + A_{\text{hadronic}} + A_{\text{axial}} \]
\[ = -0.19 \text{ ppm} - 0.09 \text{ ppm} - 0.01 \text{ ppm} \]

**hadronic:**
(31% of asymmetry)
- contains \( G_{E,M}^\gamma \), \( G_{E,M}^Z \)
- Constrained by HAPPEX, \( G^0 \), MAMI PVA4

**axial:**
(4% of asymmetry)
- contains \( G^e_A \)
- has large electroweak radiative corrections.
- Constrained by \( G^0 \) and SAMPLE

Constraints on \( A_{\text{hadronic}} \) from other Measurements

\[ A_{\text{hadronic}} = Q^4 B(Q^2) \]

Projected Hadronic Uncertainties from Planned Experiments

\[ B(Q^2, \theta) = A_{\text{had}}/Q^4 \]
Strange Form Factor Experiments – Now There’s Data!

See Nuclear and Nucleon Structure -9 tomorrow (Thomas, Souder, Beise)

SAMPLE:
Location: MIT-Bates
Targets: p, d
Kinematics: backward angle, \( Q^2 = 0.038, 0.10 \text{ GeV}^2 \)

HAPPEX I, II, III:
Location: Jefferson Lab Hall A
Targets: p, \(^4\text{He}\)
Kinematics: forward angle, \( Q^2 = 0.10, 0.48 \text{ GeV}^2 \)

Mainz PV-A4:
Location: Mainz MAMI microtron
Targets: p, d
Kinematics: forward & backward angles
\( Q^2 = 0.11, 0.23 \text{ GeV}^2 \)

HRS
Hall A

G0:
Location: Jefferson Lab Hall C
Targets: p, d
Kinematics: forward & backward angles
\( Q^2 = 0.1 - 1 \text{ GeV}^2 \)
Parity-Violating Asymmetry Extrapolated to $Q^2 = 0$
(R.D. Young, R.D. Carlini, A.W. Thomas, and J. Roche, PRL 99, 122003 (2007))

\[
\overline{A^p_{LR}} = A_s / (-G_F Q^2 / 4 \pi \alpha \sqrt{2}) = Q^p_{\text{weak}} + Q^2 B(Q^2)
\]

1\sigma bound from global fit to all PVES data (as/of 2007)
Anticipated $Q^p_{weak}$ Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta A_{phys}/A_{phys}$</th>
<th>$\Delta Q^p_{weak}/Q^p_{weak}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical (2200 hours production)</td>
<td>2.1%</td>
<td>3.2%</td>
</tr>
<tr>
<td>Systematic:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hadronic structure uncertainties</td>
<td>--</td>
<td>1.5%</td>
</tr>
<tr>
<td>Beam polarimetry</td>
<td>1.0%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Absolute $Q^2$ determination</td>
<td>0.5%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.5%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Helicity-correlated Beam Properties</td>
<td>0.5%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Total</td>
<td>2.5%</td>
<td>4.1%</td>
</tr>
</tbody>
</table>

4% error on $Q^p_{w}$ corresponds to ~0.3% precision on $\sin^2 \theta_w$ at $Q^2 \sim 0.03$ GeV$^2$

$$Q_{w}(p) = [\rho_{NC} + \Delta_e][1 - 4\sin^2 \hat{\theta}_w(0) + \Delta_e']$$

$$+ \Box_{ww} + \Box_{zz} + \Box_{\gamma Z}.$$

(Erler, Kurylov, Ramsey-Musolf, PRD 68, 016006 (2003))

$Q^p_{w} = 0.0713 \pm 0.0008$ theoretically

1.1% error comes from QCD uncertainties in box graphs, etc.
Electroweak Radiative Corrections

\[ Q_W(p) = \left[ \rho_{NC} + \Delta_e \right] \left[ 1 - 4 \sin^2 \hat{\theta}_W(0) + \Delta'_e \right] \]

\[ + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}. \]

<table>
<thead>
<tr>
<th>Source</th>
<th>( Q^p_{Weak} ) Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \sin \theta_W (M_Z) )</td>
<td>±0.0006</td>
</tr>
<tr>
<td>( Z\gamma ) box</td>
<td>±0.0005</td>
</tr>
<tr>
<td>( \Delta \sin \theta_W (Q)_{hadronic} )</td>
<td>±0.0003</td>
</tr>
<tr>
<td>( WW, ZZ ) box - 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>


Estimates of \( \gamma-Z \) box diagrams on \( A_{PV} \) at \( Q_{weak} \) Kinematics

TBE (Tjon, Blunden, Melnitchouk) 0.13% (hadronic: N and \( \Delta \))

arXiv:0903.2759

TBE (Gorchtein & Horowitz) \( \sim 6\% \) (dispersion relations; PVDIS FF)

Phys. Rev. Lett. 102, 091806 (2009)

Note: Perhaps \( \gamma-W \) box diagrams involved in \( V_{ud} \) extraction in nuclear beta decay can provide insight? (Erler, et al.)
Energy Scale of an “Indirect” Search for New Physics

- Parameterize **New Physics** contributions in electron-quark Lagrangian

\[
L_{e-q}^{PV} = L_{SM}^{PV} + L_{NEW}^{PV} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_{\mu} \gamma_5 e \sum_q C_{1q} \bar{q} \gamma^\mu q + \frac{g^2}{4\Lambda^2} \bar{e} \gamma_{\mu} \gamma_5 e \sum_q h_q \bar{q} \gamma^\mu q
\]

- A 4% Q^p_{Weak} measurement probes with 95% confidence level for new physics at energy scales to:

\[
\frac{\Lambda}{g} \sim \frac{1}{2\sqrt{2}G_F |\Delta Q^p_W|} \approx 2.3 \text{ TeV}
\]

- If LHC uncovers new physics, then precision low Q^2 measurements will be needed to determine charges, coupling constants, etc.

Some current and proposed mass scale \( \Lambda(\text{TeV}) \) lower limits

<table>
<thead>
<tr>
<th>Z' models</th>
<th>leptoquark (up)</th>
<th>leptoquark (down)</th>
<th>compositeness</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m(Z') )</td>
<td>( m_{LQ} )</td>
<td>( m_{LQ} )</td>
<td>( e-q )</td>
</tr>
<tr>
<td>Current direct search limits</td>
<td>Current electroweak fit</td>
<td>0.6% ( Q_W(Cs) )</td>
<td>13.1% ( Q_W(e) )</td>
</tr>
<tr>
<td>0.78</td>
<td>0.86</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>1.2</td>
<td>1.3</td>
<td>5.1</td>
<td>5.4</td>
</tr>
</tbody>
</table>

All Data & Fits Plotted at $1\,\sigma$

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

Young, Carlini, Thomas & Roche, PRL 99, 122003 (2007)
All Data & Fits Plotted at $1\sigma$

$$Q_{1w}^{I} = -2(2C_{1u} + C_{1d})$$

Standard Model Prediction

HAPPEX: H, He
G0: H,
PVA4: H
SAMPLE: H, D

Young, Carlini, Thomas & Roche, PRL 99, 122003 (2007)
New Physics Reach

\[ L_{PV}^{SM} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C_{1q}^{SM} \bar{q} \gamma^\mu q \]

\[ L_{NP}^{PV} = -\frac{g^2}{4\Lambda^2} \bar{e} \gamma_\mu \gamma_5 e \sum_q h_{Vq} \bar{q} \gamma^\mu q \]

Arbitrary quark flavour dependence of new physics:

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

Data sets limits on: \[ \frac{g^2}{\Lambda^2} \]
Lower Bound for “Parity Violating” New Physics

New PV physics scale > 0.9 TeV! (from 0.4 TeV)

Young, Carlini, Thomas & Roche, PRL 99, 122003 (2007)
Lower Bound for
“Parity Violating” New Physics

Qweak (4%) with PVES
Atomic only

95% CL

Qweak constrains new PV physics to beyond 2 TeV

Young, Carlini, Thomas & Roche, PRL 99, 122003 (2007)
**Q^p_{weak} & Q^{e}_{weak} - Complementary Diagnostics for New Physics**

**JLab Qweak**

- $Q^p_W = 0.0716$ (proposed)

- Experiment

- ±0.0029

- SUSY Loops

- $E_6 Z'$

- RPV SUSY

- Leptoquarks

**SLAC E158**

- $-Q^e_W = 0.0449$

- SM

- SM

---

- arrows show allowed “pull” of weak charges by new physics as constrained by previous experiments

- electron and proton weak charge experiments are complementary

Relative Shifts in Proton and Electron Weak Charges due to SUSY Effects

R parity (B-L conservation)

RPC SUSY occurs only at loop level

RPV SUSY occurs at tree level

Erler, Ramsey-Musolf, Su hep-ph/0303026

See K. Kumar talk, Precision Frontier-5, Sunday
Overview of the $Q^p_{\text{Weak}}$ Experiment at Jefferson Lab

$\bar{e}$-p elastic scattering

Elastically Scattered Electron

Experiment Parameters (integration mode)

- Incident beam energy: 1.165 GeV
- Beam Current: 180 $\mu$A
- Beam Polarization: 85%
- LH$_2$ target power: 2.5 KW

- Central scattering angle: $8.4^\circ \pm 3^\circ$
- Phi Acceptance: 53% of $2\pi$
- Average $Q^2$: 0.030 GeV$^2$
- Acceptance averaged asymmetry: $-0.29$ ppm
- Integrated Rate (all sectors): 6.4 GHz
- Integrated Rate (per detector): 800 MHz
Qweak overview

Čerenkov detectors

QTOR magnet

Lintels

Triple collimator system

35 cm LH$_2$ target

1.165 GeV 150 µA 85% pol.

e-

Tracking System for $Q^2$ measurements: (separate runs with <1nA)

- Trigger scintillator
- Vertical drift chambers
- Horizontal drift chambers
- Gas electron multiplier
$Q_p^{\text{Weak}}$ - Status of Production Mode Components

**QTOR: Toroidal Magnet**

**High Power Cryogenic Target**

- Target cell
- Beam
- Contours of Velocity Magnitude (m/s)
- Nov 17, 2008
- FLUENT 12.0 (3d pbns, rke)

**Main Quartz Detector and Electronics**

**Collimation System**
The $Q^2$ of the experiment is calibrated at low beam current with a tracking system.

Region 1: GEM
Region 2: HDC
Region 3: VDC
Schedule and Summary

$Q^p_{\text{weak}}$ experiment schedule

- Installation begins in October 2009
- Commissioning/Engineering run May 2010 – July 2010
- First production run: September 2010 – April 2011
- Second production run: November 2011 – May 2012
- Beamtime end = 12 GeV upgrade shutdown in May 2012
  (last experiment to run in Hall C before shutdown)

A successful $Q^p_{\text{weak}}$ experiment will provide:

- Precision measurement of the proton’s weak charge in the simplest system.
- Sensitive search for new physics with CL of 95% at the ~ 2.3 TeV scale.
- Fundamental $10 \sigma$ measurement of the running of $\sin^2 \theta_W$ at low energy.