A Measurement of the Weak Charge of the Proton through Parity Violating Electron Scattering using the Qweak Apparatus

By
Rakitha S. Beminiwattha
For
Qweak Collaboration
Outline

• Physics Motivation
• Qweak Apparatus
• Qweak Performance
• Experimental Methodology
• Results and Discussion
The SM is the most successful elementary particle theory developed so far. But missing phenomena like gravity and dark matter suggest it is a “Low energy” effective theory.
Testing the Standard Model

High energy frontier

Precision (intensity) frontier

Cosmological frontier

AMS 02
Parity Violating Electron Scattering

Due to PV nature of the neutral current, the differential cross section is dependent on the helicity of the electron.

The difference in helicity correlated scattering cross section is known as the PV asymmetry,

\[ A_{LR} = \frac{d\sigma^R}{d\Omega} - \frac{d\sigma^L}{d\Omega} \propto \frac{M^{EM} \cdot M^{NC}}{|M^{EM}|^2} \]
Parity Violating Electron Scattering

PV asymmetry expressed in terms of Sachs form factors of the proton and neutron, strange quark form factors, and axial-vector weak form factor

\[ A_{LR}(\vec{e}p) = -\frac{1}{2} A_{LR}^0 \left[ Q_{W}^{p} + \right. \]

\[ Q_{W}^{n} \cdot \frac{[\varepsilon G_{E}^{p}(\tau) G_{E}^{n}(\tau) + \tau G_{M}^{p}(\tau) G_{M}^{n}(\tau)]}{\varepsilon G_{E}^{p}(\tau)^{2} + \tau G_{M}^{p}(\tau)^{2}} \left. + \xi_{V}^{(0)} \cdot \frac{[\varepsilon G_{E}^{p}(\tau) G_{E}^{(s)}(\tau) + \tau G_{M}^{p}(\tau) G_{M}^{(s)}(\tau)]}{\varepsilon G_{E}^{p}(\tau)^{2} + \tau G_{M}^{p}(\tau)^{2}} \right. \]

\[ Q_{W}^{e} \cdot \sqrt{1 - \varepsilon^{2}} \sqrt{\tau(1 + \tau)} G_{M}^{P}(\tau) \tilde{G}_{A}^{P}(\tau) \varepsilon G_{E}^{p}(\tau)^{2} + \tau G_{M}^{p}(\tau)^{2} \]

At \( Q^2 \) of 0.025 GeV\(^2 \) \( F(Q^2, \theta) \) is about 25%

At tree level:

\[ Q_{W}^{p} = -2(2C_{1u} + C_{1d}) = 1 - 4 \cdot \sin^{2} \theta_{W} \]

Q\( \)\(_{\text{weak}} \) measurement is sensitive to the quark vector couplings

\[
\begin{align*}
C_{1u} &= -\frac{1}{2} + \frac{4}{3} \sin^{2} \theta_{W} \approx -0.19 \\
C_{1d} &= \frac{1}{2} - \frac{2}{3} \sin^{2} \theta_{W} \approx 0.35 \\
C_{2u} &= -\frac{1}{2} + 2 \sin^{2} \theta_{W} \approx -0.04 \\
C_{2d} &= \frac{1}{2} - 2 \sin^{2} \theta_{W} \approx 0.04
\end{align*}
\]
1. Extract the weak charge of the proton ($Q_{WP}$) by measuring the PV asymmetry. At tree-level weak charges are given by,

<table>
<thead>
<tr>
<th></th>
<th>EM Charge</th>
<th>Weak Charge ($g_V^l = -2C_{1f}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>-1</td>
<td>$-1 + 4\sin^2\theta_W \approx -0.07$</td>
</tr>
<tr>
<td>u quark</td>
<td>+2/3</td>
<td>$1 - (8/3)\sin^2\theta_W \approx 1/3$</td>
</tr>
<tr>
<td>d quark</td>
<td>-1/3</td>
<td>$-1 + (4/3)\sin^2\theta_W \approx -2/3$</td>
</tr>
<tr>
<td>Proton (2u+d)</td>
<td>+1</td>
<td>$1 - 4\sin^2\theta_W \approx 0.07$</td>
</tr>
<tr>
<td>Neutron (u+2d)</td>
<td>0</td>
<td>-1</td>
</tr>
</tbody>
</table>

$Q_{WP}$ is suppressed in the SM, making percent level measurements sensitive to TeV-scale **New PV Physics**

2. From $Q_{WP}$, the weak mixing angle ($\sin^2\theta_W$) is extracted.

In SM weak mixing angle at low energies is predicted from the “running of weak mixing angle” using the Z-pole measurement
Qweak Goals

• The Qweak experiment will provide a 4% direct measurement of the weak charge of the proton \( Q_w^p \) and a 0.3% measurement of the weak mixing angle \( \sin^2\theta_w \)

  • A test of Standard Model and new PV Physics beyond SM at TeV scale

• This talk is based on limited statistics data set: Run0

  • A proof of concept analysis which tested the analysis procedures and tools to be used for the final full data analysis

  • Only 1/25\(^{th}\) of the whole data set

  • A 19% measurement of \( Q_w^p \)

  • Quark vector couplings and weak charge of the neutron
Qweak Experiment

CEBAF @ Jefferson Lab
The Experiment: Apparatus

Cleanup collimators
Defining collimator
Cerenkov detector setup
Magnetic Spectrometer
Qweak target setup (out of frame)
Shield wall: under construction
The Experiment: Apparatus

\[
A_{\text{raw}} = \frac{N_R - N_L}{N_R + N_L}, \quad \text{and} \quad A_{\text{raw}} = \frac{\sum_{j=1}^{16} A_{\text{raw,pmt,j}}}{16}
\]

**Incident beam energy:** 1.16 GeV

**Beam Current:** up to 180 μA

**Target:** 35 cm LH2

**Luminosity:** 1 x 10^{39} s^{-1} cm^{-2}

**Beam Polarization:** 88%

**LH2 target power:** 3 kW

**Helicity is flipped at 960 Hz**

**Polarized electron beam**

**Horizontal Drift Chambers**

**Quartz Cerenkov Bars**

**LH2 Target**

**Collimators**

**Trigger Scintillator**

**Vertical Drift Chambers**

**Toroidal Magnet Spectrometer (QTOR)**
Outline

- Physics Motivation ✓
- Qweak Apparatus ✓
- **Qweak Performance**
- Experimental Methodology
- Results and Discussion
Precision Polarimetry

- Primary beam polarimetry during Run0 provided by Møller polarimeter
- For the final data set, use two independent polarimeters
- Existing Møller polarimeter
  - Low beam current and invasive
- New Compton polarimeter
  - Continuous and non-invasive

Run0 beam polarization, $P_e = 88.95 \pm 1.83\%$
Target Design

- World’s highest power cryogenic target ~3 kW
- Designed with computational fluid dynamics (CFD) to reduce density fluctuations

- Centrifugal pump (15 l/s, 7.6 kPa)
- 3 kW Heater
- 3 kW HX utilizing 4K & 14K He coolant
- 35 cm cell (beam interaction volume)
- Solid Tgts
Main Cerenkov Detectors

- Azimuthal symmetry maximizes rate and decreases sensitivity to false asymmetries from beam motion, transverse asymmetry

- Eight bars, each 2 m long, 1.25 cm thick
  - Spectrosil 2000: Rad-hard, Non-scintillating, and low-luminescence quartz

Simulation of MD

Radial direction

Azimuthal direction

Measured

Radial direction

Azimuthal direction
Qweak Performance

PVeS Experiment Summary

\[ \sigma_A = 230-260 \text{ ppm} \]
\[ A_{\text{Phys}} = -0.200 \text{ ppm} \]
\[ \delta A_{\text{Phys}} = 0.006 \text{ ppm} \]

Contribution | Expected width (ppm)
--- | ---
Pure statistics | 201
Detector resolution | 92
Current monitor resolution | 50
Target boiling | 57
Total | 233.7

Sample asymmetry at beam current of 178 \( \mu \text{A} \)
Outline

- Physics Motivation ✓
- Qweak Apparatus ✓
- Qweak Performance ✓
- **Experimental Methodology**
- Results and Discussion
The Experiment: Methodology

- Calculate the experimental asymmetry by measuring the yield from longitudinally polarized electrons scattering from unpolarized protons

\[ A_{\text{pmt}}^{\text{raw}} = \frac{N_R - N_L}{N_R + N_L}, \text{ and } A^{\text{raw}} = \frac{\sum_{j=1}^{16} A_{\text{pmt},j}^{\text{raw}}}{16} \]

- Extract ep PV asymmetry by:
  - Removing false asymmetries \( (A_{\text{False}}^i) \)
  - Correcting for the beam polarization \( (P_e) \)
  - Removing background contaminations \( (f_{bi}, A_{bi}) \)

\[ A^{\text{raw}} - \sum_{i} A_{\text{False}}^i \frac{1}{P_e} = (1 - f_{\text{Total}}) \cdot A^{\bar{e}p} + \sum_{i=1}^{4} f_{bi} \cdot A_{bi} \]
Background Corrections

• Measured yield consists of scattered elastic electrons (96.4%)

• Rest contains,
  • Scattered electrons from aluminum target window (3.2%), photons (0.4%), inelastic (0.02%)

• How backgrounds are corrected,

\[ Y_{\text{total}} = Y_{\tilde{e}p} + \sum_{i=1}^{N} Y_{bi} \]

\[ Y_{bi}, f_{bi} = \frac{Y_{bi}}{Y_{\text{total}}}, A_{bi} \]

From auxiliary measurements
• Aluminum target window
• Inelastic electrons
• Photons
Asymmetry Error: Run0 Summary

The Breakdown of $A_{ep}$ errors.

<table>
<thead>
<tr>
<th>Source</th>
<th>Contribution to $dA_{ep}$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{msr}$ statistical (Scaled)</td>
<td>0.0348</td>
</tr>
<tr>
<td>$A_{msr}$ systematic (Scaled)</td>
<td>0.0140</td>
</tr>
<tr>
<td>Polarization</td>
<td>0.0048</td>
</tr>
<tr>
<td>Al window asymmetry (b1)</td>
<td>0.0085</td>
</tr>
<tr>
<td>Al window dilution (b1)</td>
<td>0.0044</td>
</tr>
<tr>
<td>QTOR transport neutral asymmetry (b2)</td>
<td>0.0004</td>
</tr>
<tr>
<td>QTOR transport neutral dilution (b2)</td>
<td>0.0005</td>
</tr>
<tr>
<td>Beamline neutral asymmetry (b3)</td>
<td>0.0225</td>
</tr>
<tr>
<td>Beamline neutral dilution (b3)</td>
<td>0.0034</td>
</tr>
<tr>
<td>$N \rightarrow \Delta$ asymmetry (b4)</td>
<td>0.0002</td>
</tr>
<tr>
<td>$N \rightarrow \Delta$ dilution (b4)</td>
<td>0.0006</td>
</tr>
<tr>
<td>Det. bias correction</td>
<td>0.0018</td>
</tr>
<tr>
<td>EM radiative correction</td>
<td>0.0014</td>
</tr>
<tr>
<td>Acceptance correction</td>
<td>0.0028</td>
</tr>
<tr>
<td><strong>Total Systematic error</strong></td>
<td><strong>0.0290</strong></td>
</tr>
<tr>
<td><strong>Total Error</strong></td>
<td><strong>0.0453 (16%)</strong></td>
</tr>
</tbody>
</table>
PV ep Asymmetry Results (Unblinded)

The measured ep elastic scattering asymmetry from Wien0 data set,

$$A_{ep}(<Q^2>_{eff}) = -0.279 \pm 0.035 \text{ (stat.) } \pm 0.031 \text{ (syst.) ppm}$$

and Qweak kinematics at which this measurement was done,

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy at vertex, $&lt;E_{eff}&gt;$</td>
<td>$1.155 \pm 0.003$ GeV</td>
</tr>
<tr>
<td>Momentum transfer, $&lt;Q^2_{eff}&gt;$</td>
<td>$0.0250 \pm 0.0006$ (GeV)$^2$</td>
</tr>
<tr>
<td>Effective scattering angle, $&lt;\theta_{eff}&gt;$</td>
<td>$7.90 \pm 0.30^\circ$</td>
</tr>
</tbody>
</table>

*Kinematics are acceptance averaged

The kinematics parameters and measured ep elastic asymmetry are corrected for EM radiative corrections.
Electroweak Corrections

\[ Q_{W}^{P} = [\rho_{NC} + \Delta_{e}][1 - 4\sin^{2}\hat{\theta}_{W}(0) + \Delta_{e}'] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z} \]

A 7% correction to the weak charge from \( \Box_{\gamma Z} \)

The \( \Box_{\gamma Z} \) correction is primarily dispersion theory type calculation

- Error estimate can be improved by data
- Qweak took inelastic asymmetry data
Run0 Results and Discussion
Weak Charge of the Proton

PV ep asymmetry in SM,

\[ A_{\text{ep}} = -\frac{1}{2} A_{\text{LR}}^0 \left[ Q_{\text{W}}^P + F(Q^2, \theta) \right] \]

where \( F(Q^2) \) contains hadronic contributions (form factors) and an energy dependent electroweak radiative correction.

Weak charge can be extracted using two methods,

1. Hadronic contribution is calculated using EM Sach's form factors and weak axial form factors
   - Strange form factors are assumed to be zero based on current Parity Violating Electron Scattering (PVES) global data analysis

2. For final results, the weak charge is extracted by PV electron scattering (PVES) global data analysis
Global Analysis Summary

- Employs all PVES data up to $Q^2=0.63\ \text{GeV}^2$
- Forward and backward angle scattering asymmetries from proton, deuterium, and helium targets
- All data are corrected for energy and $Q^2$ dependence electroweak radiative corrections
- The analysis is based on the global analysis by Young et. al. PRL 99 122003 (2007)
Weak Charge Extraction

The global analysis with PV asymmetry from Qweak experiment

\[ A_{LR}^P = (Q_{w}^P + Q^2 B(Q^2)) \]

Since Qweak asymmetry measured at about 0.025 GeV^2, It is less sensitive to hadronic structure.
Constraints on $C_{1u}$ and $C_{1d}$

- Hadronic vector currents are built using only lightest quarks (u,d, and s).
- The weak charge of the proton is used to constrain the couplings for weak neutral hadronic vector currents in the SM.
- Combination Atomic PV and PVES results are used to extract $C_{1u}$ and $C_{1d}$. 

![Graph showing constraints on $C_{1u}$ and $C_{1d}$]
Agreement of the weak charge of the proton result with the Standard Model sets the model independent new PV interaction mass scale to 1.1 TeV at 95% C.L.
Summary: Run0 Results

- Run0 result is based on a statistically limited data set
  - Proof of concept analysis for final data set
  - Final results will be 5-6 times more accurate
  - First determination of weak charge of the proton
    - Manuscript is publication ready
    - One for the PDG
- Final results will be a test of the Standard Model and PV physics beyond SM at TeV scale
Thank You!


¹Spokespersons; ²Project Manager; Grad Students;
Supplementary
Electroweak Theory of SM

- The neutral current interaction between the fermions and gauge bosons is given by,

\[ \mathcal{L}_N = e J^\text{em}_\mu A^\mu + \frac{g}{\cos \theta_W} (J^3_\mu - \sin^2 \theta_W J^\text{em}_\mu) Z^\mu \]

- Parity Violation Electron Scattering (PVES) confirmed the electroweak structure
  - Confirmation of the model from the first PV electron scattering (PVES) experiment at SLAC
  - Found the weak mixing angle to be around $1/4$
  - A small axial vector $e$ X vector $f$ weak neutral interaction.
  - Further demonstrated by low energy APV/PV and high energy Z-pole precision measurements.
Electroweak Theory of SM

- The neutral current interaction between the fermions and gauge bosons is given by,
  \[ \mathcal{L}_N = e J^e_{\mu} A^\mu + \frac{g}{\cos \theta_W} (J^3_{\mu} - \sin^2 \theta_W J^{em}_{\mu}) Z^\mu \]

- Parity Violation Electron Scattering (PVES) confirmed the electroweak structure
  - Confirmation of the model from the first PV electron scattering (PVES) experiment at SLAC
  - Found the weak mixing angle to be around 1/4
    - a small axial vector(e) X vector(f) weak neutral interaction.
  - Further demonstrated by low energy APV/PV and high energy Z-pole precision measurements.

C. Prescott Phys. Lett. ,B77,347
The weak mixing (Weinberg) angle is a fundamental constant in electroweak interaction. The mixing angle is related to the $SU(2)_L$ and $U(1)_Y$ coupling constants, $g$ and $g'$, respectively.

\[
\sin^2 \theta_W = \frac{g'^2}{g'^2 + g^2} = 1 - \frac{M_W^2}{M_Z^2}
\]
Parity Violating Electron Scattering

PV asymmetry expressed in terms of Sachs form factors of the proton and neutron, strange quark form factors, and axial-vector weak form factor with the contributions from weak charges of proton, neutron, and electron separated,

\[ A_{LR}(\vec{e}p) = -\frac{1}{2} A^0_{LR} \left[ Q^p_W + \right. \]

\[ Q^n_W \cdot \frac{[\varepsilon G^p_E(\tau)G^n_E(\tau) + \tau G^p_M(\tau)G^n_M(\tau)]}{\varepsilon G^p_E(\tau)^2 + \tau G^p_M(\tau)^2} + \xi^{(0)}_V \cdot \frac{[\varepsilon G^p_E(\tau)G^{(s)}_E(\tau) + \tau G^p_M(\tau)G^{(s)}_M(\tau)]}{\varepsilon G^p_E(\tau)^2 + \tau G^p_M(\tau)^2} + \]

\[ Q^e_W \cdot \frac{\sqrt{1 - \varepsilon^2} \sqrt{\tau(1 + \tau)} G^p_M(\tau)\tilde{G}^p_A(\tau)}{\varepsilon G^p_E(\tau)^2 + \tau G^p_M(\tau)^2} \]

\[ = -\frac{1}{2} A^0_{LR} \left[ Q^p_W + F(Q^2, \theta) \right] \text{ At } Q^2 \text{ of } 0.025 \text{ GeV}^2 \text{ F}(Q^2) \text{ is about } 25\% \]

where, \[ A^0_{LR} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}, \varepsilon = \frac{1}{1 + 2(1 + \tau)\tan^2\frac{\theta}{2}}, \text{ and } \tau = \frac{Q^2}{4M^2} \]

At tree level: \[ Q^p_W = 2g^u_V + g^d_V, \quad Q^n_W = 2g^d_V + g^u_V, \quad Q^e_W = g^e_V \]
Parity Violating Electron Scattering

Main contribution to the PV asymmetry is from weak charge of proton rest is related to hadronic structure of the proton and energy dependent electroweak corrections

\[ A_{LR}(\bar{e}p) = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \left[ Q^p_W + F(Q^2, \theta) \right] = A_{Q^p_W} + A_{\text{Had}} \]

At \( Q^2 \) of 0.025 GeV\(^2 \) \( F(Q^2, \theta) \) is about 25%

At tree level:
\[ Q^p_W = 2g^u_V + g^d_V = 1 - 4 \cdot \sin^2 \theta_W \]

Q\(_\text{weak}\) measurement is sensitive to the quark vector couplings

\[
\begin{align*}
C_{1u} & = -\frac{1}{2} + \frac{4}{3} \sin^2 \theta_W & \approx & -0.19 \\
C_{1d} & = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W & \approx & 0.35 \\
C_{2u} & = -\frac{1}{2} + 2 \sin^2 \theta_W & \approx & -0.04 \\
C_{2d} & = \frac{1}{2} - 2 \sin^2 \theta_W & \approx & 0.04
\end{align*}
\]
Weak Charge of the Proton

Weak charge of the proton in SM with electroweak radiative corrections,

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

\[ Q_W^P (SM) = 0.0705 \pm 0.0008 \]

\[ \sin^2 \hat{\theta}_W(0) = 0.2387 \pm 0.0002 \]

The values of electroweak radiative corrections

<table>
<thead>
<tr>
<th>Correction</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho_{NC})</td>
<td>1.047</td>
</tr>
<tr>
<td>(\Delta_e)</td>
<td>-0.001</td>
</tr>
<tr>
<td>(\Delta_e')</td>
<td>-0.001</td>
</tr>
<tr>
<td>(\Box_{WW})</td>
<td>0.019</td>
</tr>
<tr>
<td>(\Box_{ZZ})</td>
<td>0.002</td>
</tr>
<tr>
<td>(\Box_{\gamma Z})</td>
<td>0.004</td>
</tr>
</tbody>
</table>

These values will be compared with Qweak results
Physics Motivation

The $Q_W^p$ measurement will provide additional constraints on the SU(3) isovector ($C_{1u} - C_{1d}$) and isoscalar ($C_{1u} + C_{1d}$) hadronic currents effective couplings.

The constraints on $C_{1u} - C_{1d}$ and $C_{1u} + C_{1d}$ from parity violating electron scattering and APV experiments done so far.

The Standard Model prediction

$$C_{1u} = \rho_e \left( -\frac{1}{2} + \frac{4}{3} \rho_e \frac{s^2}{2} \right) + \lambda'$$

$$C_{1d} = \rho_e \left( \frac{1}{2} - \frac{2}{3} \rho_e \frac{s^2}{2} \right) - 2 \lambda'$$
Coupling Constants

- The weak charge of the proton is used to constrain the couplings for weak neutral hadronic currents in the SM, which are build on the SU(3) octet and singlet currents using only lightest quarks (u,d, and s).

\[
\begin{align*}
\xi_V^{T=0} &= -2 \cdot \sqrt{3} (C_{1u} + C_{1d}) \\
\xi_V^{T=1} &= -2 \cdot (C_{1u} - C_{1d}) \\
g_V^f &= -2C_{1f} \quad \text{and} \quad g_A^f = -2C_{2f}
\end{align*}
\]

- Where couplings for leptons and quarks are defined below,

<table>
<thead>
<tr>
<th>Particle (f)</th>
<th>$g_V^f$</th>
<th>$g_A^f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>$1$</td>
<td>$-1$</td>
</tr>
<tr>
<td>$e^-$</td>
<td>$-1 + 4\sin^2 \theta_W$</td>
<td>$1$</td>
</tr>
<tr>
<td>u-quark</td>
<td>$1 - \frac{8}{3} \sin^2 \theta_W$</td>
<td>$-1$</td>
</tr>
<tr>
<td>d,s-quark</td>
<td>$-1 + \frac{4}{3} \sin^2 \theta_W$</td>
<td>$1$</td>
</tr>
</tbody>
</table>
New PV Physics: Model Independent Constraints

\[ L^{PV}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \cdot \sum_q C_{1q} \bar{q} \gamma^\mu q + \frac{g^2}{4\Lambda^2} \bar{e} \gamma_\mu \gamma_5 e \sum_q h^q V \bar{q} \gamma^\mu q \]

\[ L^{PV}_{\text{SM}} \]

\[ L^{PV}_{\text{new}} \]

\[ \Delta Q^P_W \]

\[ \frac{\Delta Q^P_W}{Q^P_W} \]

**g** is the new physics coupling while \( \Lambda \) is the new PV physics mass scale
New Physics: Model Independent Constraints

- The bounds on new quark-lepton PV physics scale
- New physics is ruled out below the curve at 95% C.L.

\[
\begin{align*}
L_{\text{new}}^{PV} & = \frac{g^2}{4\Lambda^2} \bar{e} \gamma_{\mu} \gamma_5 e \sum_q h^q_V \bar{q} \gamma^\mu q \\
h^u_V & = \cos \theta_h \\
h^d_V & = \sin \theta_h
\end{align*}
\]
New PV Physics Beyond SM

- New neutral gauge bosons (Z')
- SUSY: MSSM
  - SUSY loop effects
  - R-Parity status
- Leptoquarks

Weak charge of the proton and electron are complementary measurements for new physics. Effect of new physics at 95% C.L.

Model Dependent New Physics: Collider Example

- CDF and D0 results of the $t\bar{t}$ forward backward asymmetry $A_{FB}$
  - Results favored $t$ production in the incoming proton direction and $\bar{t}$ in the anti-proton direction
  - Observed $A_{FB} = 0.475 \pm 0.114$ a 3.4σ deviation from SM NLO prediction of $0.088 \pm 0.013$

- New physics models could account for the excess
A_{FB} New PV Physics Constraints

Models discussed feature a scalar or vector mediator


Plot shows how PV constraints could exclude certain models as the source of excess A_{FB}
A_{FB} New PV Physics Constraints

Models discussed feature a scalar or vector mediator


Plot show how PV constraints could exclude certain models as the source of excess A_{FB}
From the Measured to PV ep Asymmetry

\[
A_{ep} = R_{\text{exp}} \times \left\{ \frac{A_{\text{msr}}}{P_e} - f_{b1} \cdot A_{b1} - f_{b2} \cdot A_{b2} - f_{b3} \cdot A_{b3} - f_{b4} \cdot A_{b4} \right\} \\
(1 - f_{\text{Total}})
\]

- \( A_{\text{msr}} \) is the measured asymmetry
- Electron beam polarization: \( P_e \)
- Backgrounds (dilutions and asymmetries)
  - Al window background: \( b_1 \)
  - QTOR transport channel: \( b_2 \) (neutral particles)
  - Beam-line: \( b_3 \) (neutral particles)
  - \( N \rightarrow \Delta \) electrons: \( b_4 \) (inelastic electrons)
# Qweak Specifications (Run0)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average beam energy at vertex</td>
<td>1.155 GeV</td>
</tr>
<tr>
<td>Beam Polarization</td>
<td>88%</td>
</tr>
<tr>
<td>Beam Current (integrating Mode)</td>
<td>100-150 µA</td>
</tr>
<tr>
<td>Target</td>
<td>liquid hydrogen at 20 K</td>
</tr>
<tr>
<td>Target thickness</td>
<td>35 cm</td>
</tr>
<tr>
<td>Beam Luminosity</td>
<td>$1.0 - 1.5 \times 10^{39} \text{cm}^{-2} \text{s}^{-1}$</td>
</tr>
<tr>
<td>Beam Luminosity (counting Mode)</td>
<td>less than 1 nA</td>
</tr>
<tr>
<td>Nominal electron scattering angle</td>
<td>7.9°</td>
</tr>
<tr>
<td>Angular acceptance</td>
<td>±3°</td>
</tr>
<tr>
<td>Total azimuthal ($\phi$) acceptance</td>
<td>49% of $2\pi$</td>
</tr>
<tr>
<td>Solid angle, $\Delta\Omega$</td>
<td>37 msr</td>
</tr>
<tr>
<td>Integrated cross section</td>
<td>4.0µb</td>
</tr>
<tr>
<td>Integrated scattering rate</td>
<td>5 GHz (0.6 GHz per detector)</td>
</tr>
<tr>
<td>Acceptance averaged $Q^2$</td>
<td>0.025 GeV</td>
</tr>
<tr>
<td>physics asymmetry</td>
<td>-0.200 ppm</td>
</tr>
</tbody>
</table>
Experimental Bias Corrections

- EM radiative effects result in modification of the measured asymmetry and momentum transfer ($R_{RC}$)
  - depolarization of the incident electron
  - energy loss and angle change

![Diagram showing electron scattering and radiative effects](image)

virtual photons and loop effects

Bremsstrahlung photon emission
$A_{LR}^P \propto (Q_W^P + Q^2B(Q^2))$
The Experiment: Apparatus CAD View

Defining Collimator

Magnetic spectrometer (QTOR)

Čerenkov detector system

Target setup

Electron Beam
Outline

- Physics Motivation ✓
- Qweak Apparatus ✓
- **Data Acquisition and Software**
- **Electron Beam Polarization**
- Data Analysis
- Results and Discussion
Qweak Data Acquisition and Software System

Total of over 260 detector and monitor channels

We also used an independent DAQ for low beam current auxiliary studies (backgrounds, kinematics and etc.)
The scattered electron yield is integrated during each polarization (Helicity) state. The helicity is flipped pseudo-randomly at 960Hz. A 27 bit word is generated.
Non-Linearity and Charge Asymmetry

- Required to minimize the false asymmetry from non-linearity
- Minimized the charge asymmetry by using an active feedback system

\[ A_{\text{Raw}} = A_{\text{Phys}} + A_{\text{False}} + \text{Non-lin} \cdot A_{\text{Charge}} + \cdots \]
Data Quality Checks

The data quality cuts framework is integrated into the data analysis system which provides,

- Customizable quality checks for many different detector signals
- Diagnostic information on detectors during data taking and final data analysis

![Graph showing beam excursions and data quality cuts](image)
Target Performance

Measured helicity correlated target noise.

At 960 Hz reversal rate, the target noise (< 50 ppm) is very small compared to our measured helicity quartet ( ) asymmetry width (~230 ppm). (statistical power ~ \( \Delta A_{\text{quartet}} / \sqrt{N_{\text{quartets}}} \)).

Need fast reversal!

FFT of noise spectrum

Raster Scan @ 182 \( \mu \text{A} \)

46 ppm at 182 \( \mu \text{A}, 4\times4 \text{ mm}^2 \) raster!

Pump Scan @ 169 \( \mu \text{A} \), 4x4 mm Raster

42 ppm at 169 \( \mu \text{A}, 4\times4 \text{ mm}^2 \) raster!

s_p = 1.3 + (19.4/x)^2.399

s_p = 2.8 + (659/x)^1.168

assumes 1/f
Example: Neutral Background Dilution

- Two sources of neutral backgrounds were not 100% contained by collimators and magnetic spectrometer
  - Scattered electron interactions with collimators and beam-line: *beam-line background*
  - Elastic electrons scraping in the collimators and shield wall: *QTOR transport channel background*
- Took auxiliary data to determine these neutral background dilutions

### Origin of elastic photons that reach main detector

![Image of elastic photons origin](chart1.png)

- Photons from the collimator and shield wall
- Photons from Bremsstrahlung

### MD 1-5 Total Neutral Dilution

![Graph of neutral dilution vs. current](chart2.png)

- 0.4% dilution reached at certain QTOR current (A)