Looking for New Physics with the Weak Interaction: Recent Results from Qweak, and Future Perspectives

October 6, 2017

Kent Paschke
Outline

• Introduction to electron scattering
• Weak interaction, parity symmetry, and parity-violating electron scattering
• Peering beyond the SM at low energies
• The Qweak Experiment
• Results
• One more 3rd generation experiment: n-star in a terrestrial nucleus
• Next generation experiments
• Summary
Introduction to Electron Scattering
Introduction to electron scattering

Electron scattering: electromagnetic interaction, described as an exchange of a virtual photon.

If photon carries low momentum
-> long wavelength
-> low resolution

Increasing momentum transfer
-> shorter wavelength
-> higher resolution to observe smaller structures

$Q^2$: 4-momentum of the virtual photon
Elastic Form Factors and Extended Targets

The point-like scattering probability for elastic scattering is modified to account for finite target extent by introducing the “form factor”

Assuming spherically symmetric (spin-0) target

\[
\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} |F(q)|^2
\]

point-like target, electron spin

\[
F(q) = \int e^{iqr} \rho(r) d^3r
\]

Form factor is the Fourier transform of charge distribution

Figure from Particles and Nuclei, Povh et al.
Elastic Form Factors and Extended Targets

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Assuming spherically symmetric (spin-0) target

\[ \frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \left| F(q) \right|^2 \]

point-like target, electron spin

\[ F(q) = \int e^{iqr} \rho(r) d^3r \]

Form factor is the Fourier transform of charge distribution
Elastic Electron-Nucleon Scattering

For targets with spin, must also account for magnetic moment

Electric and Magnetic form factors $G_E(Q^2)$ and $G_M(Q^2)$

$$\frac{d\sigma}{d\Omega_{Rosenbluth}} = \frac{d\sigma}{d\Omega_{Mott}} \left\{ \frac{(G_E^2 + \tau G_M^2)}{1 + \tau} + 2\tau G_M^2 \tan^2(\theta/2) \right\}$$

With no structure

$G_E = 1$ (proton charge)

$G_M = 1$ (magnetic moment = $\mu_B$).

At $Q^2 = 0$, the probe does not resolve the target

$G_E(0) = 1$ (electric charge)

$G_M(0) = \mu$ (magnetic moment in units of $\mu_B$)

Proton (and neutron magnetic) form-factors follow dipole form
(exponential charge distribution)
Weak Interaction, Parity Symmetry, and Parity Violating Electron Scattering
Weak Interaction and parity

1930’s - The weak nuclear interaction was needed to explain nuclear beta decay

1950’s - Discovery of parity-violation by the weak interaction

Parity transformation

\[ x, y, z \rightarrow -x, -y, -z \]

\[ \vec{p} \rightarrow -\vec{p}, \quad \vec{L} \rightarrow -\vec{L}, \quad \vec{S} \rightarrow -\vec{S} \]

Parity transformation is analogous to reflection in a mirror:

. . . reverses momentum but preserves angular momentum

. . . takes right-handed (helicity = +1) to left-handed (helicity = -1).
Charge and Handedness

**Electric charge determines strength of electric force**

<table>
<thead>
<tr>
<th></th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ Charge</td>
<td>$q = 0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$</td>
<td>$q = 0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$</td>
</tr>
<tr>
<td>$W$ Charge</td>
<td>$T = \pm \frac{1}{2}$</td>
<td>zero</td>
</tr>
</tbody>
</table>

Neutrinos are “charge neutral”: do not feel the electric force

**Weak charge determines strength of weak force**

Left-handed particles
(Right-handed antiparticles)
have weak charge

Right-handed particles
(left-handed antiparticles)
are “weak charge neutral”

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$^{60}$Co</td>
<td>$W^-$</td>
<td>$^{60}$Ni</td>
</tr>
<tr>
<td>observed</td>
<td>$\ell_L$</td>
<td>$\ell_R$</td>
</tr>
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</table>

right-handed anti-neutrino
left-handed anti-neutrino
Weak neutral currents are proposed under electroweak unification (late ‘60s, Weinberg Salam Glashow, but others, also...) → The weak mixing angle $\theta_W$ introduced

Gargamelle bubble chamber uncovers $\nu_\mu$ e$^-$ events in 1973, more convincingly in 1976.

This demonstrated the existence of the neutral current ($Z^0$) but not its nature

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<tr>
<td>$Z$ Charge</td>
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</table>

• What is the gauge structure of the underlying theory?
• Is this the electroweak unification of GWS?
• Another EW unification?
• A new interaction?

Landmark experiment (late 1970s): parity-violating electron scattering
Electron Scattering and Parity-violation

- Incident beam is longitudinally polarized
- Change sign of longitudinal polarization
- Measure fractional rate difference

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{|M_Z^0|}{|M_\gamma|} \]

“Electroweak” models predicted
- interference of electromagnetic and weak amplitudes
- values for electron & quark weak neutral current coupling

Scattering cross-section
\[ \sigma = |M_\gamma + M_Z|^2 \]
**PVeS Verifies the “Standard Model” (1978)**

*Parity Non-Conservation in Inelastic Electron Scattering, C.Y. Prescott et. al, 1978*

\[ A_{PV} \sim 100 \pm 10 \text{ ppm} \]

Definitive answer on gauge structure of electroweak interaction

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</tr>
<tr>
<td>W Charge</td>
<td>( T = \pm \frac{1}{2} )</td>
<td>zero</td>
</tr>
<tr>
<td>Z Charge</td>
<td>( T - q \sin^2 \theta_W )</td>
<td>( -q \sin^2 \theta_W )</td>
</tr>
</tbody>
</table>

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current".
Progress in PVeS studies

Broad program studying the structure of protons and nuclei, and searching for new (beyond Standard Model) physics
Beyond the Standard Model with Precision at Low Energies
Direct vs Indirect Searches

(according to Hans Christian Andersen)
The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Markus J.G. Veltman "for elaborating the quantum structure of electroweak interactions in physics" circa 1994.

The EW Standard Model has only three parameters, fixed by $\alpha_{\text{EM}}$, $G_F$, and $M_Z$.

Global fit over large precision data set to constrain additional parameters appearing in 1-loop corrections (H mass, fermion masses and mixing, and $\alpha_{\text{strong}}$).

Ultraprecise (0.1%) measurements of "derived" parameters ($\sin^2 \theta_W$ and $M_W$) are the most sensitive consistency checks of the EW theory.
Amazing consistency of the Standard Model prediction, between directly measured $m_H$, $m_W$, $m_t$, $\sin^2\theta_W$.

(Courtesy: J. Erler)

early 2012
New Physics with Precision at Low Energies

Low $Q^2$ offers complementary probes of new physics at multi-TeV scales

$EDM, g_\mu -2, \beta$ decay, $0\nu\beta\beta$ decay, DM, LFV…

Parity-Violating Electron Scattering: Low energy weak neutral current couplings
(SLAC, Jefferson Lab, Mainz)

Many new physics models give rise to new neutral current interactions

$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{\text{new}}$

Heavy Z’s and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

Low energy NC interactions ($Q^2 \ll M_Z^2$)

Heavy mediators = contact interactions

for each fermion and handedness combination
reach, characterized by mass scale $\Lambda$, coupling $g$

$A_X \propto \frac{1}{Q^2 - M_X^2} \sim \frac{4\pi}{\Lambda^2}$

Contact interaction

Example:
Standard model $e-q$ or $e-e$
couplings

$C^{SM}_{1i} \equiv 2g_A^eg_V^i$

$C^{SM}_{2i} \equiv 2g_V^eg_A^i$
Renormalization scheme defines $\sin^2 \theta_W$ at the Z-pole.

$\gamma$-Z mixing and other diagrams are absorbed into the coupling constant

At the Z-pole - measuring properties of the SM $Z^0$ boson

Off the Z-pole, low-energy measurements are sensitive to (new) parity-violating interactions
The QWeak Experiment
Measuring APV

Goal: $10^{-7}$ asymmetry measurement at the few percent level

How do you pick a tiny signal out of a noisy environment?

Measure fractional rate difference between opposing helicity states

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$A_{measured} \sim -200 \text{ ppb with 4\% precision}$

$N \sim 1 \times 10^{16} \text{ electrons!}$

High rates to get statistical precision, but also:
- Control Noise - quiet electronics, luminosity stability
- Low backgrounds - must be known PV asymmetry
- Polarimetry - Can’t do better on $A_{PV}$ than on $P_{beam}$
- Kinematics - Interpretation requires $Q^2$ precision
- False Asymmetries - electronics, beam motion...?
Measuring $A_{PV}$

Elastic signal focused on detector

- Collimator
- Inelastics
- Ring of Integrating Quartz Cherenkov detectors
- Toroidal Magnet
- 35 cm Liquid Hydrogen Target

Rapid (1kHz) measurement over helicity reversals to cancel noise

Analog integration of detector current

- ~6 GHz total rate
- 1 GeV, 180 μA, 1.5 years

Detector Signal

<table>
<thead>
<tr>
<th>Helicity States</th>
<th>A_1</th>
<th>A_2</th>
<th>A_3</th>
<th>...</th>
<th>A_n</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>+</td>
<td>-</td>
<td>+</td>
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<td></td>
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<td></td>
<td>+</td>
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Counts

- 230 ppm at 240 Hz
- 1ppm precision in 4 minutes
CEBAF at JLab

Superconducting, continuous wave, recirculating linac

1500 MHz RF, with 3 interleaved 500 MHz beams

“Cold” RF is makes a clean, quiet beam... perfect for precision experiments

5x1.2 GeV = 6. GeV Maximum Energy

2013 Upgrade
The Qweak Spectrometer

Toroidal Spectrometer separates elastics into each of 8 detectors

Each detector:
• 2 meters long
• lead radiator, fused silica
• Cerenkov light from shower
• collected by phototube at each end
The Entire Accelerator Complex is our Apparatus

- **Polarized Source Laser** - rapid reversal, keep spin states the same intensity, position, shape...
- **Spin Manipulation** - crossed E and B fields, to rotate spin in low energy injector
- **Position/Energy Modulation** - for calibrating detector sensitivity
- **Polarimeters**
- **Precise monitors** for beam current and position
Qweak Experimental Target
World’s highest power and lowest noise cryogenic target
35 cm, 180 µA electron beam, 2.5 kW deposited power

- Designed with CFD simulation
- Flow rate
- Beam direction

Target Density noise. Boiling!

- Fast helicity reversal (1 ms) cancelled density fluctuations
- Density Variation: ~50 ppm over 4 ms at 180 µA
Polarimetry

**Møller:** $ee$ scattering off polarized iron foil
- 4T field, saturated iron
- experience with ~1% precision in Hall C
- modified spectrometer for 1 GeV
- invasive, low current only

**Compton:** $e\gamma$ scattering with polarized green laser light
- new polarimeter
- low $E_{\text{beam}}$: low analyzing power, low scattering energies
- diamond microstrip detector
- *per mille* control of laser polarization inside cavity

Result: ~0.6% precision on 89% polarization

Comparison of independent polarimeters

- **Møller**
- **Compton**

*Important milestone for high precision polarimetry needed for future program*

Physical Review X6 (2016) no.1, 011013

Don Jones

UVa-built Fabry-Perot optical cavity at 1.7kW
Polarized Electrons for Qweak

- High intensity, high polarization through photoemission from GaAs photocathode
- Rapid-flip of beam helicity by reversing laser polarization
- Pockels cell to flip laser polarization
- Beam must look the same for the two polarization states
- Photocathode has preferred axis: analyzing power for linear light

If on average linear polarization = 0, that doesn’t mean that it is everywhere zero

A non-zero 1st moment creates a position difference

A non-zero 2nd moment creates a spot-size difference

Average beam asymmetries were small over course of run

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>X</td>
<td>-2.7 nm</td>
</tr>
<tr>
<td>X'</td>
<td>-0.14 nrad</td>
</tr>
<tr>
<td>Y</td>
<td>-1.9 nm</td>
</tr>
<tr>
<td>Y'</td>
<td>-0.05 nrad</td>
</tr>
<tr>
<td>Energy</td>
<td>-0.6 ppb</td>
</tr>
</tbody>
</table>

Manolis Kargiantoulakis
Summary of Measurement

Various methods of polarization reversal
- Half-wave plate in source optics
- Injector spin manipulation
- Energy (g-2 precession)
Beam Corrections

Measurement of the sensitivity of the Main Detector elements to beam motion. The spectrometer provides a high degree of cancellation for beam motion effects.

\[ A_c = A_r - \sum \alpha_i \Delta x_i - \beta A_E \]

Effect of sinusoidal beam position modulation on main detector element

But, imperfect implementation led to inconsistent calibration information

In the end:
- gross inconsistencies removed from calibration
- small inconsistencies were shown to be harmless
- corrections were small, agreed between techniques

Net Correction: 3.5 ± 1.7 ppb

Don Jones
Scattering from the beampipe was recognized as a possible source of background.

- But collimation didn’t fully solve the problem.
- Radiators were added to the main detector to enhance hard scatters and cut soft backgrounds.

Studies (included blocking octants):
- beamline background \( f \approx 0.2\% \) in MD
- asymmetry due to beam halo
- asymmetry well measured by background detectors

Large asymmetries seen in both “small angle” and “background” monitors, were correlated with main detectors.

Scaling of backgrounds over the course of the run, and correlation with main detectors, were stable.

Net Correction: \(-1.2 \pm 1.7 \text{ ppb}\)
Detector Chirality?

Apparent polarization analyzing effect, so that PMTs on opposite ends of each detector bar see opposite sign asymmetry shifts.

Scattered electrons arrive at detector with significant radial polarization component.
Polarization Sensitive Detector

Mott scattering asymmetry: low energy phenomenon

\[ A_T = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \propto \vec{S}_e \cdot \frac{\vec{k}_e \times \vec{k}'_e}{|\vec{k}_e \times \vec{k}'_e|} \]

- The electron showering through lead radiator can become polarization-dependent via multiple scattering
- Only significant after is E<30 MeV or so, for large angles
- Cancellation between positive asymmetry for small angle scattering, negative for large angle scattering
- Electron ends up more likely to point toward one PMT, depending on its incident polarization
Estimated Residual Bias from Polarization Sensitive Detectors

- This should cancel: positive asymmetry in one PMT, negative in the other
- Quality of cancellation depends on imperfections in each bar optical properties and alignment
- Monte Carlo simulation of light collection used to estimate Abias for each bar, based on observed response and measured geometry

\[ A_{\text{bias}} = 4.3 \pm 3.0 \text{ ppb} \]
## Asymmetry and Net Corrections

Raw Asymmetry $\sim 175 \pm 6.4$ ppb

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Run 1</th>
<th>Run 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{raw}$</td>
<td>$-192.7 \pm 13.2$ ppb</td>
<td>$-170.7 \pm 7.3$ ppb</td>
</tr>
<tr>
<td>$A_T$</td>
<td>$0 \pm 1.1$ ppb</td>
<td>$0 \pm 0.7$ ppb</td>
</tr>
<tr>
<td>$A_L$</td>
<td>$1.3 \pm 1.0$ ppb</td>
<td>$1.2 \pm 0.9$ ppb</td>
</tr>
<tr>
<td>$A_{BCM}$</td>
<td>$0 \pm 4.4$ ppb</td>
<td>$0 \pm 2.1$ ppb</td>
</tr>
<tr>
<td>$A_{BB}$</td>
<td>$3.9 \pm 4.5$ ppb</td>
<td>$-2.4 \pm 1.1$ ppb</td>
</tr>
<tr>
<td>$A_{beam}$</td>
<td>$18.5 \pm 4.1$ ppb</td>
<td>$0.0 \pm 1.1$ ppb</td>
</tr>
<tr>
<td>$A_{bias}$</td>
<td>$4.3 \pm 3.0$ ppb</td>
<td>$4.3 \pm 3.0$ ppb</td>
</tr>
</tbody>
</table>

Aluminum windows, 2.5% background, but $A_{PV} = 1.5$ppm (-7X the proton $A_{PV}$) so about 20% correction
# Summary of Measurement

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>-223.5</td>
<td>15.0</td>
<td>10.1</td>
<td>18.0</td>
</tr>
<tr>
<td>Run 2</td>
<td>-227.2</td>
<td>8.3</td>
<td>5.6</td>
<td>10.0</td>
</tr>
<tr>
<td>Run 1 and 2 combined with correlations</td>
<td>-226.5</td>
<td>7.3</td>
<td>5.8</td>
<td>9.3</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: $A_{BCM}$</td>
<td>5.1</td>
<td>25%</td>
<td>2.3</td>
<td>17%</td>
</tr>
<tr>
<td>Beamline Background: $A_{BB}$</td>
<td>5.1</td>
<td>25%</td>
<td>1.2</td>
<td>5%</td>
</tr>
<tr>
<td>Beam Asymmetries: $A_{beam}$</td>
<td>4.7</td>
<td>22%</td>
<td>1.2</td>
<td>5%</td>
</tr>
<tr>
<td>Rescattering bias: $A_{bias}$</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: $A_{b1}$</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>
APV and Extracting Qweak

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[ -G_F Q^2 \right] \frac{\epsilon G_E^{pZ} G_M^{pZ} + \tau G_{E,M}^{pZ} - \frac{1}{2} (1 - 4 \sin^2 \theta_W) \epsilon' G_{M}^{pZ} \tilde{G}_A^p}{\epsilon (G_E^{pZ})^2 + \tau (G_{M}^{pZ})^2} \]

Assuming charge symmetry, the weak form-factors relate to electromagnetic form factors of the proton and neutron

\[ 4G_{E,M}^{pZ} = (1 - 4 \sin^2 \theta_W) G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - G_{E,M}^{s} \]

Results on strangeness is linked to which EMFF data you choose to believe (Ben Gilbert)
Extracting $Q_{\text{weak}}$ Results

Parameterization of electromagnetic form-factors
Fit for: weak charge, strangeness, axial form-factors
with usual convention for contact interactions

\[ g = \sqrt{4\pi} \]

the exclusion limits are

\[ \frac{\lambda}{g} \approx 7.5 \text{ TeV} \rightarrow \lambda \approx 27 \text{ TeV} \]
Weak Mixing Angle

\[
\sin^2 \theta_W = 0.2382 \pm 0.0011 \quad (~0.5\%)
\]

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

Dark photon, couples to Dark Sector massive particles but with small E&M couplings to known matter

511keV line in galactic core, Pamela high energy positron excess, (g-2)μ discrepancy

New model: a dark Zd0 with no coupling to the 3 known generations of matter, but mass mixing with the Z0

Davoudiasl, Lee, Marciano
Weak Charge Distribution of Heavy Nuclei

Nuclear theory predicts a neutron “skin” on heavy nuclei

<table>
<thead>
<tr>
<th></th>
<th>proton</th>
<th>neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric charge</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Weak charge</td>
<td>~0.08</td>
<td>1</td>
</tr>
</tbody>
</table>

Mean-field model predictions of $A_{PV}$ correlate with the neutron skin of a heavy nucleus

$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_W}{F_{ch}}$

- Neutron skin thickness is highly sensitive to the pressure in neutron-rich matter.
- The greater the pressure, the thicker the skin as neutrons are pushed out against surface tension.

Knowledge of $r_n$ highly model dependent, not well constrained by robust measurements

Rocal-Maza et al, PRL 106, 252501 (2011)
**R_n of $^{208}$Pb: Equation of state for neutron-rich nuclear matter**

**Density Dependence of Symmetry Energy**

Energy penalty for breaking n=Z symmetry

$$S = \frac{E}{N}$$

Slope at saturation density

$$L \propto \frac{\partial S(\rho)}{\partial \rho} \bigg|_{\rho_0}$$

B.A. Brown [PRL 85, 5296 (2000)]

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**APV from $^{208}$Pb provides a clean measure of L, testing the description of nuclear matter**

Isovector properties are not well measured.

Models informed mostly by measurements of properties sensitive to $p+n$.

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**Heavy nucleus vs Neutron Star**

- Stiffness vs core collapse
- Mass/radius
- Cooling mechanisms (URCA or not)
Measuring Neutron Skins at JLab

PREX (\(^{208}\text{Pb}\))
- important check on nuclear structure data set
- uniform nuclear matter
- terrestrial laboratory for n-star matter

CREX (\(^{48}\text{Ca}\))
- isovector probe in moderate size system
- finite size effects
- Within reach of microscopic calculations

Very clean separation of elastic events by HRS optics
no PID needed; detector sees only elastic events

Spring 2019:
PREX (3% APV, \(r_n\) to 0.06 fm)
CREX (2.5% APV, \(r_n\) to 0.02 fm)
Qweak: proton structure $F$ contributes ≈30% to asymmetry, ≈2% to $δ(\frac{Q^p_W}{Q^p_W})$

Negligible for significantly lower $Q^2$

• $E_{\text{Beam}} = 155$ MeV, 25-45°
• $Q^2 = 0.0048$ GeV$^2$
• 60 cm target, 150 uA, $10^4$ hours

• $A_{\text{PV}} = -29$ ppb to 1.5% (0.44 ppb)
• $δ(\sin^2θ_W) = 0.00031 (0.13%)$
MOLLER at 11 GeV JLab

\[ \delta(\sin^2 \theta_W) = \pm 0.00024 \text{ (stat.)} \pm 0.00013 \text{ (syst.)} \rightarrow \sim 0.1\% \]

Matches best collider (Z-pole) measurement!

**best contact interaction reach for leptons at low OR high energy**

To do better for a 4-lepton contact interaction would require:
- Giga-Z factory
- Linear collider
- Neutrino factory
- Muon collider

\[ A_{PV} = 35.6 \text{ ppb} \]
\[ \delta(A_{PV}) = 0.73 \text{ parts per billion} \]
\[ \delta(Q^e_W) = \pm 2.1 \% \text{ (stat)} \pm 1.0 \% \text{ (syst)} \]

Outlook:
- \(~25M\$ required\)
- CD0 approved
- (but project “paused”)
- 2-3 years construction
- 3-4 years running
PV-DIS: controlling hadronic contributions requires precise kinematics and broad range

Strategy: sub-1% precision over broad kinematic range: sensitive Standard Model test and detailed study of hadronic structure contributions

Requires 0.4% e- polarimetry

Spectrometer will also support a broad program of TMD studies

- high luminosity, large acceptance
- repurpose the CLEO solenoid

Additional nuclear and nucleon partonic structure

- nuclear targets: nuclear tensor fields
- proton: high-x d/u
PV-DIS at EIC

EIC can access interesting $Q^2$ region with PV-DIS - no past or planned measurements

Assumptions:
• Dedicated deuterium run
• This measure will average over $^2$H polarization
• 200 days of beam time
• Int. Lumi. ~267 fb$^{-1}$ (incl. eff.)

Simulated using “Day-1 EIC detector” described in ePHENIX LOI

• Polarimetry $\sim$0.5% for highest energy, luminosity
• Differential luminosity precision $\sim$5x10$^{-4}$

Simulations from Yuxiang Zhao, SBU
New Physics Complementarity

Best Collider $\delta(\sin^2\theta_W)$:
- $A_{l}(SLD): 0.00026$
- $A_{fb}(LEP): 0.00029$

Future projections, similar time scale:
- Final Tevatron: $\sim 0.00046$
- LHC 14 TeV, 300 fb$^{-1}$: $\sim 0.00036$

Note: pdf uncertainties
- MOLLER: $\sim 0.00028$
- Mainz P2: $\sim 0.00032$

$\Lambda > 5$ TeV
- Doubly-Charged Scalars
- Significant reach beyond LEP-200

$e^+e^- $ scattering
Lepton Number Violation
- $\Delta > 5$ TeV

Mass reach
assumptions on isospin structure, strong coupling
- E158 $\sim 17$ TeV
- PV-DIS-6 $\sim 8$ TeV
- Qweak $\sim 27$ TeV
- MOLLER $\sim 39$ TeV
- P2 $\sim 49$ TeV
- SOLID $\sim 22$ TeV

Future projections, similar time scale:
- Final Tevatron: $\sim 0.00046$
- LHC 14 TeV, 300 fb$^{-1}$: $\sim 0.00036$

Note: pdf uncertainties
- MOLLER: $\sim 0.00028$
- Mainz P2: $\sim 0.00032$

Davoudiasl, Lee, Marciano
PRD89 (2014), 095006
PRD92 (2015) 055005


Erler and Su, arXiv:1303.5522

Future constraints: MOLLER & P2

R-Parity-conserving Supersymmetry
SOLID: 100-200 GeV range
Buckley and Ramsey-Musolf
A measurement of the proton weak charge has been completed, providing a new tight constraint on possible new physics.

New challenges arise with increasing precision. The experiments are hard, but worth it.

Unprecedented precision enabled by technological advances, preparing for the next generation of PVES experiments.

Electroweak Physics with PVES is a powerful component of the low energy fundamental symmetries program:

- P2, SOLID, MOLLER: Future Flagship experiments for electron beam facilities
- Search for new interactions from 100 MeV to 10s of TeV

Neutron skin provides a crucial check on nuclear structure theory.

A rich experimental program is envisioned over the next 10 years at Jefferson Lab and Mainz MESA facility.