Highlights of Electroweak Tests of the SM at Low Energy

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Present & Past:
JLab Qweak
JLab PVDIS
SLAC E122
SLAC E158
BABAR/g-2

Future Tests:
Mainz P2
JLab SOLID
JLab Moller
The Search for New Physics

Two complementary approaches to searching for “New Physics”

“Energy frontier”
- like LHC – Large Hadron Collider

→ Make new particles (“X”) directly in high energy collisions

“Precision frontier”
- Examples: Qweak at JLab, μ(g-2), EDM, ββ decay, n β decay, etc.

→ Look for indirect effect of new particles (“X”) made virtually in low energy processes
The Standard Model prescribes the couplings of the fundamental fermions to the Z boson:

<table>
<thead>
<tr>
<th>fermions</th>
<th>$g_A^f = I_3$</th>
<th>$g_V^f = I_3 - 2Q \sin^2 \theta_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e, \nu_\mu$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>$e^-, \mu^-$</td>
<td>$-\frac{1}{2}$</td>
<td>$-\frac{1}{2} + 2 \sin^2 \theta_W$</td>
</tr>
<tr>
<td>$u, c$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2} - \frac{4}{3} \sin^2 \theta_W$</td>
</tr>
<tr>
<td>$d, s$</td>
<td>$-\frac{1}{2}$</td>
<td>$-\frac{1}{2} + \frac{2}{3} \sin^2 \theta_W$</td>
</tr>
</tbody>
</table>

For electroweak tests at JLAB ($Q^2 \ll M_Z^2$), restrict to parity-violating e-q and e-e interactions with four-fermion $u,d,e$ with four-fermion interaction:

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}} [\bar{e} \gamma^\mu \gamma_5 e (C_{1u} \bar{u} \gamma_\mu u + C_{1d} \bar{d} \gamma_\mu d) + \bar{e} \gamma^\mu e (C_{2u} \bar{u} \gamma_\mu \gamma_5 u + C_{2d} \bar{d} \gamma_\mu \gamma_5 d) + C_{ee} \bar{e} \gamma^\mu \gamma_5 e (\bar{e} \gamma_\mu e)]$$

The current/proposed programs will significantly improve the precision of all these couplings:

- quark vector: $C_{1u}, C_{1d}$
- quark axial-vector: $C_{2u}, C_{2d}$
- electron: $C_{ee}$
Charles Prescott and collaborators:
\[ e^- + d \rightarrow e^- + X, \quad Q^2 \sim 1.6 \text{ GeV}^2 \]

PV deep inelastic scattering at SLAC first result in 1978:

\[ A = - (152 \pm 26) \times 10^{-6} \]
\[ \sin^2 \theta_W = 0.224 \pm 0.020 \]

→ first measurement of parity-violation in the neutral weak current

"Finally, parity-violation in the neutral currents was discovered at the expected level in electron-nucleon scattering at SLAC in 1978, and after that most physicists took it for granted that the electroweak theory is essentially correct."

“Weak Charges” Via Low Energy Neutral Current Tests

“Weak Charges”: neutral current analog to the electric charges. $Q^e_W$ and $Q^p_W$ are suppressed in Standard Model → increased sensitivity to new physics.

Electron’s weak charge: $Q^e_W \equiv -2C_{ee} = -(1 - 4\sin^2\theta_W)$
- Parity-violating Moller scattering $\bar{e} + e \rightarrow e + e$
- Published: SLAC E158 ~ 13% on $Q^e_W$
- Planned: JLab MOLLER ~ 2.3% on $Q^e_W$

Neutron’s weak charge: $Q^A_W(Z,N) \equiv -2[C_{1u}(2Z + N) + C_{1d}(Z + 2N)]$
- $\approx Z(1 - 4\sin^2\theta_W) - N \approx -N$
- Atomic parity violation:
  - Published: Cesium ~ 0.5% on $Q^A_W$
  - Planned: KVI Ra ~ 0.2% on $Q^A_W$

Proton’s weak charge: $Q^p_W \equiv -2[2C_{1u} + C_{1d}] = (1 - 4\sin^2\theta_W)$
- Parity-violating elastic ep scattering $\bar{e} + p \rightarrow e + p$
- Running Complete: Qweak ~ 4.5% on $Q^p_W$
- Published: Qweak 14% (commissioning data)
- Planned: Mainz/MESA P2 ~ 2.5% on $Q^p_W$
Examples of Complementarity Between Weak Charges of Proton & Electron

Weak charge of the proton

Weak Charge of the electron

- SUSY-Loops
- $E_6 Z'$
- RPV SUSY
- Leptoquarks

(Jens Erié, Ramsey-Musolf, 2003)
"Running" of the weak mixing angle due to electroweak radiative corrections → key prediction of the Standard Model.

Any disagreement with SM prediction could be a signature of "New Physics".

Ref: Erler, et al., PDG 2012 update
Parity-Violating Asymmetry for the $Q_{\text{weak}}^p$ Experiment

The Jlab $Q_{\text{weak}}$ experiment determines the proton’s weak charge by measuring the parity-violating asymmetry in elastic scattering of longitudinally polarized electrons on unpolarized protons.

$$A_{\text{PV}} = \frac{2M_{\text{NC}}}{M_{\text{EM}}} = \left[ \frac{-G_F Q^2}{4\sqrt{2}\pi\alpha} \right] \begin{bmatrix} \varepsilon G_E^\gamma G_Z^E + \tau G_M^\gamma G_Z^M & -(1 - 4\sin^2\theta_W) \varepsilon' G_M^\gamma G_A^Z \end{bmatrix}$$

At forward scattering angles and low 4-momentum transfer:

$$A \equiv \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} \quad \begin{array}{c} \text{as} \quad Q^2 \rightarrow 0 \\ \theta \rightarrow 0 \end{array} \quad \left[ \frac{-G_F}{4\pi\alpha\sqrt{2}} \right] \begin{bmatrix} Q^2 \quad Q_{\text{weak}}^p \\ Q^4 B\left(Q^2\right) \end{bmatrix}$$

proton’s weak charge:

$$Q_{\text{weak}}^p = 1 - 4\sin^2\theta_W \quad \text{at tree level}$$

“Form factor” term due to finite proton size – hadronic structure ($\sim 30\%$ for $Q_{\text{weak}}$)

By running at a small value of $Q^2$ (small beam energy, small scattering angle) sensitivity to the effects of the proton’s detailed spatial structure is minimized.
Qweak Experimental Apparatus

Parameters:

- $E_{\text{beam}} = 1.165$ GeV
- $\langle Q^2 \rangle = 0.025$ GeV$^2$
- $\langle \theta \rangle = 7.9^\circ \pm 3^\circ$
- $\phi$ coverage = 50% of $2\pi$
- $I_{\text{beam}} = 180$ $\mu$A
- Integrated rate = 6.4 GHz
- Beam Polarization = 88%
- Target = 35 cm LH$_2$
- Cryopower = 3 kW
Combined Analysis
Extract: $C_{1u}$, $C_{1d}$, $Q_n^W$

$Q^n_W = -2 (C_{1u} + 2 C_{1d})$
$= -0.975 \pm 0.010$

$C_{1u} = -0.184 \pm 0.005$
$C_{1d} = 0.336 \pm 0.005$

$Q^p_W = -2 (2C_{1u} + C_{1d})$
$= 0.064 \pm 0.012$
SM prediction = 0.0710(7)

25x more production data still being analyzed, final result 2015
About 70% of the Qweak Run 2 Data (plot for NIM paper)
(Not corrected for Al target windows & a number of smaller corrections)

Run2 measured asymmetry

What's shown on this plot?

Natural – “False” asymmetries Corrected using “apparatus sensitivities” determined from natural beam noise.

Driven – “False” asymmetries Corrected using “apparatus sensitivities” determined from actively modulating beam properties.

What we learn from this plot

Corrections are small, but real.

Final regression “Model” appears linear and complete (absolutely essential to have a valid measurement)
$Q^p_W$ : Future P2 Experiment at Mainz/Mesa (200 MeV)

(Figures & table from: Frank Maas, Dark Forces at accelerators, INFN Frascati, Oct 17, 2012)

The 5x lower beam energy means the exp is free of the hadronic $\gamma Z$ Box diagram, but at the price of a much smaller asymmetry.

$\Delta A_{PV} \sim 0.34$ ppb

$\Delta Q^p_W / Q^p_W \sim 2\%$

Requires $\Delta A_{PV}$ be measured $\sim 10x$ more precisely than Jlab Qweak for an improvement of $\sim 2x$ in the $Q^p_W$
SLAC E158 “Moller” Experiment
(scattered polarized electrons off atomic electrons)

- High beam polarization and current.
- 1.5 m high-power LH$_2$ target.
- Quadrupole based spectrometer optimized for Moller kinematics.
- Stringent control of helicity-dependent systematics.
- Ancillary passive asymmetry reversals for controls.
- Principal backgrounds elastic & inelastic ep.
- Main systematics: polarization, helicity correlated beam effects.

Achieved:

$\Delta A_{PV} \sim 17$ ppb

$\Delta \sin^2 \theta_w \sim 0.0013$
Next Generation: The Jlab MOLLER Experiment

- Elastic $\bar{e} + e \rightarrow e' + e'$ scattering: 75 $\mu$A 11 GeV electron beam incident on liquid hydrogen target in JLab Hall A.

- Two normal conducting toroidal magnets in series. Double detector system gives $\sim$100% acceptance focusing of forward scattered ($\sim 0.7^\circ$) Moller electrons – others (e-p elastic, inelastic, etc.) are detected in different radial segments.

- High power cryogenic LH$_2$ target (150 cm long, 5.0 kW power deposit)

- $Q^2 \sim 0.0056 \ (\text{GeV/c})^2$ & $A_{PV} \sim 35 \times 10^{-9} = 35 \text{ ppb}$ planned precision $\sim 0.73 \text{ ppb}$ → very challenging measurement, state-of-art in all systematics. This would improve precision of by factor of 5 over previous measurement SLAC E158: PRL 95 081601 (2005).

- Competitive $\sin^2 \theta_W (\sim 0.1\%)$ determination with the most precise Z pole measurements

Status:

- Approved by JLAB PAC in January 2009

- Positive endorsement from JLAB Director’s Review in January 2010

- MIE funding request submitted by JLAB to DOE Nuclear Physics
Two most precise values of $\sin^2 \theta_W$ at Z pole ($A_{LR}^{b}$ from SLC and $A_{fb}^{b}$ from LEP) disagree by 3σ.

MOLLER goal is $\sin^2 \theta_W$ with comparable sensitivity to these two ($\pm 0.00029$); precise enough that result will have an impact on the central value of the world average.

MOLLER is the only method available in the next decade to directly address this issue at the same level of precision and interpretability.
Recent JLab PVDIS Measurement at 6 GeV

JLAB Experiment E08-011: PVDIS on deuterium using HRS (high resolution spectrometers) in JLab Hall A

- $E = 6.067 \text{ GeV}$
- 20 cm liquid deuterium (LD$_2$) target
- 100 $\mu$A polarized beam with 90% beam polarization

- Two kinematic points:
  - $Q^2 = 1.1 \text{ GeV}^2$, $x_B = 0.24$, $\theta = 12.90^\circ$
  - $Q^2 = 1.9 \text{ GeV}^2$, $x_B = 0.30$, $\theta = 20.00^\circ$

Goals:
- Improve the precision on the axial-vector neutral current quark couplings – $C_{2u}$, $C_{2d}$
- Provide first significant constraint on higher twist effects (HT) in PVDIS

Status:
- Published:
  Nature 506, 67–70 (06 February 2014)
Experimtally Determined Coupling Combinations Compared to SM Prediction


$[2 g_{eu} - g_{ed}]_{AV}$

APV constraint is Cs and TI and forms strongly elongated ellipse.


"Qweak" refers to "commissioning" result: PRL 111,141803 (2013)
Summary: Measurements of the Running of $\sin^2 \theta_W$

“Running” due to electroweak radiative corrections → key prediction of the Standard Model

Any disagreement with SM prediction could be a signature of “New Physics”
Next Generation: PVDIS using Proposed SoLID at 12 GeV JLab

- **Strategy:** Study PVDIS on both deuterium and hydrogen. Measure the PV asymmetry in narrow bins of $x, Q^2$ with 0.5% precision. Separates the SM and QCD (CSV, HT) pieces.

- **Extremely challenging effort:** Higher order twists (HT), CSV issues, parton distribution function uncertainties, high precision polarimetry requirements, …

- Requires spectrometer optimized to precise measurements at high luminosity over a broad range of $x$ and $Q^2$

**SOLID:**

- High luminosity from H and D, <1% precision in fine bins
- $x_b$ range 0.25-0.75, $W^2 > 4 \text{ GeV}^2$, large $Q^2$ range
- Baffling to cut backgrounds
- Fast tracking—GEM, particle ID, calorimetry, and pipeline electronics
- Precision polarimetry (0.4%) Compton and atomic hydrogen Moller

**Status:**

- Approved by JLAB PAC in January 2010
- Obtained approval to use CLEO superconducting solenoidal magnet
- Seeking funding
Kinematic Range and Strategy of SoLID PVDIS Experiment

Fit asymmetries to functional form to isolate Standard Model (SM), higher twist (HT), and charge symmetry violation (CSV) pieces.
SoLID: Anticipated Improvement on Neutral Current Quark Couplings

![Diagram of quark couplings with equations: $C_{1i} = 2g_A^e g_V^i$ and $C_{2i} = 2g_V^e g_A^i$.]

- This box matches the scale of the $C_{1q}$ plot.

**Graphs:**

1. **Left Graph:**
   - Variables: $C_{1u} + C_{1d}$ vs. $C_{1u} - C_{1d}$.
   - Regions marked: Qweak, PDG, 11 GeV PVDIS.

2. **Right Graph:**
   - Variables: $C_{2u} + C_{2d}$ vs. $C_{2u} - C_{2d}$.
   - Regions marked: SAMPLE, E122, PV-DIS-6.

- Red ellipses are PDG fits.
- Blue bands represent expected data: Qweak (left) and PV-DIS-6GeV (right).
- Green bands are the proposed measurement of PV-DIS.
Summary: Measurements of $\sin^2 \theta_W^{(\text{effective})}$

- **LEP and SLD Average**
  - $0.23153 \pm 0.00016$

- **Proposed: Precision of MOLLER EXP**

- **Proposed: Precision of PVDIS/SoLID**

- **Anticipated Final Precision**
  - JLab Qweak Result
  - $0.2299 \pm 0.0043$

- **$A_{fb}^{0, l}$**
  - $0.23099 \pm 0.00053$

- **$A_{l}(P_{T})$**
  - $0.23159 \pm 0.00041$

- **$A_{lr}$ (SLD)**
  - $0.23098 \pm 0.00026$

- **$A_{fb}^{0, b}$**
  - $0.23221 \pm 0.00029$

- **$A_{fb}^{0, c}$**
  - $0.23220 \pm 0.00081$

- **$Q_{fb}^{\text{had}}$**
  - $0.2324 \pm 0.0012$

- **$A_{FB}^{ee}$ (CDF), 2.0 fb$^{-1}$**
  - $0.2328 \pm 0.0011$

- **$A_{FB}^{l\mu}$ (CDF), 9 fb$^{-1}$**
  - $0.2315 \pm 0.0010$

- **$A_{FB}^{ee}$ (DØ), 9.7 fb$^{-1}$ Preliminary**
  - $0.23106 \pm 0.00053$
## Summary of Past & Future Precision Low Energy Parity Violation Measurements

\( \Lambda /g_{\text{new physics}} \) for 95% CL using formalism of Erler, et.al.- arXiv:1401.6199v1 [hep-ph] 23 Jan 2014

<table>
<thead>
<tr>
<th>Experiment</th>
<th>% Precision</th>
<th>( \Delta \sin^2 \theta_w )</th>
<th>( \Lambda /g ) [TeV]</th>
<th>( \theta )</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC-E122</td>
<td>8.3</td>
<td>0.011</td>
<td>1.5/g</td>
<td>9.4°</td>
<td>published</td>
</tr>
<tr>
<td>SLAC-E122</td>
<td>110</td>
<td>0.44</td>
<td>0.25/g</td>
<td>99.4°</td>
<td>published</td>
</tr>
<tr>
<td>APV ((^{205})Ti)</td>
<td>3.2</td>
<td>0.011</td>
<td>3.8/g</td>
<td>75.6°</td>
<td>published</td>
</tr>
<tr>
<td>APV ((^{133})Cs)</td>
<td>0.58</td>
<td>0.0019</td>
<td>9.1/g</td>
<td>74.9°</td>
<td>published</td>
</tr>
<tr>
<td>SLAC-E158</td>
<td>14</td>
<td>0.0013</td>
<td>4.8/g</td>
<td>-</td>
<td>published</td>
</tr>
<tr>
<td>Jlab-Hall A</td>
<td>4.1</td>
<td>0.0051</td>
<td>2.2/g</td>
<td>26.2°</td>
<td>published</td>
</tr>
<tr>
<td>Jlab-Hall A</td>
<td>61</td>
<td>0.051</td>
<td>0.82/g</td>
<td>116.2°</td>
<td>published</td>
</tr>
<tr>
<td>JLab-Qweak (~3 days)</td>
<td>19</td>
<td>0.0030</td>
<td>4.8/g</td>
<td>53.1°</td>
<td>published</td>
</tr>
<tr>
<td>JLab-Qweak (goal)</td>
<td>4.5</td>
<td>0.0008</td>
<td>9.3/g</td>
<td>53.1°</td>
<td>~spring 2015</td>
</tr>
<tr>
<td>JLab-SoLID</td>
<td>0.6</td>
<td>0.00057</td>
<td>6.2/g</td>
<td>53.1°</td>
<td>not yet funded</td>
</tr>
<tr>
<td>JLab-MOLLER</td>
<td>2.3</td>
<td>0.00026</td>
<td>11.0/g</td>
<td>-</td>
<td>not yet funded</td>
</tr>
<tr>
<td>Mainz-P2</td>
<td>2.0</td>
<td>0.00036</td>
<td>13.8/g</td>
<td>53.1°</td>
<td>funded (&gt;2020)</td>
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<tr>
<td>APV ((^{225})Ra(^+))</td>
<td>0.5</td>
<td>0.0018</td>
<td>9.6/g</td>
<td>75.7°</td>
<td></td>
</tr>
<tr>
<td>APV ((^{213})Ra(^+) / (^{225})Ra(^+))</td>
<td>0.1</td>
<td>0.0037</td>
<td>4.5/g</td>
<td>55.5°</td>
<td></td>
</tr>
<tr>
<td>PVES ((^{12})C)</td>
<td>0.3</td>
<td>0.0007</td>
<td>14/g</td>
<td>71.6°</td>
<td>“speculative”</td>
</tr>
</tbody>
</table>
Contact Interactions - $\Lambda/g$ [TeV] Reach from Parity Violation Measurements

- Green areas indicate 95% CL exclusion limits from published data
- Straight lines indicate primary pull of current and future measurements

(Figures below derived from a composite plot in the paper by:

(assuming $g_{\text{new physics}} = (4\pi)^{1/2}$ allows approximate comparison to HE collider limits)
New Physics Scenarios – A Recent Example

“Dark photon” – possible portal for new force to communicate with SM

- Astrophysical motivation: observed excess in positron data.
- Could explain muon g-2 anomaly?

“Dark parity violation” (Davoudiasl, Lee, Marciano, arXiv 1402.3620)

- Introduces a new source of low energy parity violation through mass mixing between $Z$ and $Z_d$ with observable consequences.
- Complementary to direct searches for heavy dark photons.
Parity-Violating Electron Scattering – Brief History & Relative Experimental Difficulty

Caveat Emptor: Trend line extrapolations may hit unforeseen limits!

Pioneering PVDIS (1978)
- early SM test – Prescott et al.
  - SLAC E122: $\Delta A_{PV} = \pm 10$ ppm

Strange FF Searches (98 – 09)
- SAMPLE, G0, A4, HAPPEX
  - $\Delta A_{PV} \sim 0.25$ ppm – 2 ppm
  - Note: Change of scale to ppb

Standard Model Tests (2003 – present)
- SLAC E158: $\Delta A_{PV} \sim 17$ ppb
- JLAB Qweak: $\Delta A_{PV} \sim 6$ ppb
- Jlab MOLLER: $\Delta A_{PV} \sim 0.8$ ppb
- Mainz P2: $\Delta A_{PV} \sim 0.34$ ppb
Search for a light Higgs Boson expected in extensions to the Standard Model such as non-Minimal Supersymmetry

- NMSSM predicts 7 Higgs bosons
  - CP-odd $A^0$, $A^1$
  - CP-even $H^0$, $H^1$, $H^2$
  - Charged $H^+$, $H^-$

- The lightest Higgs ($A^0$), a combination of a singlet and a non-singlet, is lighter than 2 bottom quarks

- The Higgs discovered at the LHC can be one of the heavier Higgs bosons
Search for a light Higgs Boson expected in extensions to the Standard Model such as non-Minimal Supersymmetry

The BABAR Collaboration searched for: \( \Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow gg, s\bar{s}, \mu^+\mu^-, \tau^+\tau^- \)

No significant signal has been seen
The Anomalous Magnetic Moment of the Muon $a_\mu$

$$a_\mu^{SM} = \left( \frac{g - 2}{2} \right)_\mu = a_\mu^{QED} + a_\mu^{had} + a_\mu^{weak}$$

$a_\mu$ precisely measured at BNL E821:

$$a_\mu^{exp} - a_\mu^{SM} = (28.7 \pm 8.0) \times 10^{-10} \sim 3.4\sigma$$

- Dominant uncertainty from hadronic vacuum polarization.
- Cannot be calculated by QCD "first principles"

Determine it via dispersion relations, by measuring the total hadronic cross section

$$a_\mu^{had} = \frac{\alpha^2}{3\pi^2} \int_0^\infty \frac{K(s)}{s} R(s) \, ds$$

Very ambitious program in BABAR:
- Precisely measure all relevant channels using events with Initial State Radiation.
- Syst. uncertainties <1% for $\sqrt{s} < 1$ GeV, and ~2-3% for $\sqrt{s} < 2$ GeV.
- Light quark spectroscopy up to $\sqrt{s}=5$ GeV

All BABAR measurements

PRL 103, 231801(2009)
\( a_{\mu}^{\text{had}} : \) Recent Measurements

- \( \sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-) \) 
  - Uncertainty of 2% in the peak region

- \( \sigma(e^+e^- \rightarrow K^+K^-) \) 
  - In all cases the most precise measurements.

- Some channel still missing, or measured with low statistics, going to be measured with full statistics.

- BABAR is the only experiment to measure low energy cross section from threshold up to \( \sim 4-5 \text{ GeV} \).

Previous average:

\[
\begin{align*}
  a_{\mu}^{\text{had}}(\pi^+\pi^-\pi^+\pi^-) &= (133.5 \pm 5.2) \times 10^{-11} \\
  a_{\mu}^{\text{had}}(K^+K^-) &= (216.3 \pm 7.3) \times 10^{-11}
\end{align*}
\]

Current measurement:

\[
\begin{align*}
  a_{\mu}^{\text{had}}(\pi^+\pi^-\pi^+\pi^-) &= (136.4 \pm 0.3 \pm 3.6) \times 10^{-11} \text{ BABAR only} \\
  a_{\mu}^{\text{had}}(K^+K^-) &= (229.5 \pm 1.4 \pm 2.2) \times 10^{-11}
\end{align*}
\]
Summary

- Low energy precision electroweak tests of the SM are complementary to direct searches for new physics.
- If a direct observation is made – the precision measurements may be essential in quantifying the properties of any new particles.
- However – there are no guarantees!