Weak form factors and standard model tests

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The $Z^0$ has shown itself to be an increasingly versatile probe over the past 2+ decades

- Establishing the standard model.
- Exploring the role of strange quarks in hadronic structure.
- Searching for physics beyond the standard model.

Weak amplitudes can be readily studied by measuring parity violating asymmetries that result from their interference with electromagnetic amplitudes.

$$\neg A_{LR} = A_{PV} = \frac{\sigma^\uparrow \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \sim \frac{A_{\text{weak}}}{A_{\gamma}} \sim \frac{G_F Q^2}{4\pi \alpha}$$
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Exciting and diverse new applications are coming. For example:
- PREx: Mapping out the neutron distribution in lead.
- Studying charge symmetry violation (CSV) in the parton distribution functions.

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The parity violating spin-asymmetry that results from elastic scattering off the proton is rich with diverse types of physics!

\[ A_{PV} = \left[ \frac{-G_F M_p^2 Q^2}{\pi \alpha \sqrt{2}} \right] \left[ (1 - 4 \sin^2 \theta_W) - \frac{\epsilon G_E^{p\gamma} (G_E^{m\gamma} + G_E^{s\gamma}) + \tau G_E^{p\gamma} (G_M^{m\gamma} + G_M^{s\gamma})}{\epsilon (G_E^{p\gamma})^2 + \tau (G_M^{p\gamma})^2} \right] - A_A \]
Parity violating spin-asymmetry in elastic scattering from the proton

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\[ A^{PV} = \left[ -\frac{G_F M_p^2 Q^2}{\pi \alpha \sqrt{2}} \right] \left[ (1 - 4 \sin^2 \theta_W) \right] \frac{\epsilon G_E^{p \gamma} (G_E^{m\gamma} + G_E^{s}) + \tau G_E^{p \gamma} (G_M^{m\gamma} + G_M^{s})}{\epsilon (G_E^{p \gamma})^2 + \tau (G_M^{p \gamma})^2} - A_A \]

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- This term is proportional to hadronic structure, including the strange-quark form factors.
- This term is proportional to the neutral weak axial form factor, and contains contributions from things such as the anapole moment.
In PV elastic $\bar{e}$-p scattering, different kinematics emphasizes different physics.

The relative contributions from the weak charge and hadronic structure change dramatically depending on the $Q^2$. 
experiments to measure strange form factors

HAPPEX
forward angle, integrating,
$G_E^s + 0.39 \ G_M^s$ at $Q^2=0.48 \ \text{GeV}^2$
$G_E^s + 0.08 \ G_M^s$ at $Q^2=0.1 \ \text{GeV}^2$
$G_E^s$ at $Q^2=0.1 \ \text{GeV}^2$ ($^4\text{He}$)

SAMPLE
Open geometry, backward angle, integrating,
$G_M^s$ and $G_A$ at $Q^2=0.1 \ \text{GeV}^2$

A4 (Mainz)
fast-counting calorimeter for background rejection
$G_E^s + 0.23 \ G_M^s$ at $Q^2=0.23 \ \text{GeV}^2$
$G_E^s + 0.1 \ G_M^s$ at $Q^2=0.1 \ \text{GeV}^2$
$G_M^s, G_A$ at $Q^2=0.1, 0.23, 0.5 \ \text{GeV}^2$

GO
fast counting, open geometry with ToF for background rejection
$G_E^s + \eta \ G_M^s$ over $Q^2=[0.12, 1.0] \ \text{GeV}^2$
$G_M^s, G_A$ at $Q^2=0.23, 0.63 \ \text{GeV}^2$
Experimental approach for Happex

• Polarized electrons are scattered off protons or $^4\text{He}$ nuclei in a 20 cm 400W transverse-flow LH$_2$ or high-pressure $^4\text{He}$ target.
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- Elastically scattered electrons are detected using a high-resolution spectrometer (septum + QQDQ) at 4°-8° and 5 mstr/spectrometer arm.
- High rates (120 MHz for H and 12 MHz for $^4$He) are handled using integrating Cherenkov detectors.
Data from Happex II proton run

Histogram of asymmetries associated with individual pulse pairs shows Gaussian behavior over six decades

Asymmetries associated with each slug - a group of runs taken for a given half-wave plate setting.

\[ Q^2 = 0.1089 \pm 0.0011 \text{ GeV}^2 \]

\[ A_{\text{raw}} = -1.418 \pm 0.105 \text{ ppm (stat)} \]
Overall, there has been tremendous progress on our understanding of $G_E^s$ and $G_M^s$. At $Q^2 = 0.1 \text{ GeV}^2$:

Pre-Happex II pre-G0 time period with only A4 (Mainz) and SAMPLE
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All results, including SAMPLE, A4, Happex II, and G0 extrapolated to 0.1 GeV$^2$
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Current and future data on $G_E^s + \eta G_M^s$ at forward angles at all $Q^2$.

Black line shows very simple naive fit.

Data are suggestive of positive values, but would be unlikely to convince a skeptic.
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More Happex data are forthcoming at $Q^2 = 0.6\text{ GeV}^2$, (centered at zero). Not shown are upcoming back-angle data from both G0 and A4.
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New data at $Q^2 = 0.6$ GeV$^2$ should strongly constrain the higher $Q^2$ region.
Two decades of effort has resulted in atomic-scale control over helicity-correlated beam parameter differences.

**Charge asymmetries** or “PITA” effect: Bates carbon experiment.

**Position differences from lensing:** steering from lensing-type phenomena: Bates carbon experiment.

**Position differences from intrinsic phase gradients:** due to phase gradients intrinsic to the Pockels cell or other optical components, SLAC E158.

**Position differences from induced phase gradients:** due to coupling of divergence to the Pockels cell tilt: Happex II.
Helicity-correlated beam parameters averaged over the Happex II runs

<table>
<thead>
<tr>
<th></th>
<th>Helium</th>
<th>Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_Q$</td>
<td>-0.377 ppm</td>
<td>0.406 ppm</td>
</tr>
<tr>
<td>$A_{\text{Energy}}$</td>
<td>3 ppb</td>
<td>0.2 ppb</td>
</tr>
<tr>
<td>$\Delta x$</td>
<td>-0.2 nm</td>
<td>0.5 nm</td>
</tr>
<tr>
<td>$\Delta x'$</td>
<td>4.4 nrad</td>
<td>-0.2 nrad</td>
</tr>
<tr>
<td>$\Delta y$</td>
<td>-26 nm</td>
<td>1.7 nm</td>
</tr>
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The control achieved during the hydrogen run was unprecedented. Control during the helium run, while more than sufficient, was limited due to electronic cross-talk problems.
Steady progress has made it possible to consider increasingly challenging parity experiments

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<tr>
<th>Experiment</th>
<th>physics asymmetry</th>
<th>stat. error</th>
<th>sys. error due to beam</th>
<th>limits on position differences</th>
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<tr>
<td>*HAPPEX I</td>
<td>-15,050 ppb</td>
<td>980 ppb</td>
<td>±20 ppb</td>
<td>&lt; 12 nm</td>
<td></td>
</tr>
<tr>
<td>*SLAC E158</td>
<td>-131 ppb</td>
<td>14 ppb</td>
<td>±3 ppb</td>
<td>&lt; 12 nm</td>
<td>0.4 nrad</td>
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<td>*HAPPEX II-p</td>
<td>-1,580 ppb</td>
<td>120 ppb</td>
<td>±17 ppb</td>
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</tr>
<tr>
<td>†PREX</td>
<td>510 ppb</td>
<td>15 ppb</td>
<td>±1.0 ppb</td>
<td>&lt; 1.0 nm</td>
<td>0.4 nrad</td>
</tr>
<tr>
<td>†HAPPEX III</td>
<td>-22,100 ppb</td>
<td>550</td>
<td>±66 ppb</td>
<td>&lt; 40 nm</td>
<td>0.2 nrad</td>
</tr>
<tr>
<td>†Qweak</td>
<td>-288 ppb</td>
<td>5 ppb</td>
<td>14 ± 1.4 ppb</td>
<td>&lt; 40 nm</td>
<td>100 nrad</td>
</tr>
<tr>
<td>†12 GeV Møller</td>
<td>40 ppb</td>
<td>0.6 ppb</td>
<td>±0.2 ppb</td>
<td>~ 1 nm</td>
<td>0.03 nrad</td>
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The long legacy of parity experiments positions our community to perform sensitive searches for physics beyond the SM.

- Control of helicity-correlated effects at ppb levels.
- Strong constraints on hadronic effects such as non-zero strange-quark matrix elements.
- Unprecedented figures of merit in terms of polarization$^2 \times$ luminosity.
- Sensitive searches for physics beyond the SM such as $Q_{\text{weak}}$ (scheduled), and perhaps an 11 GeV Møller experiment.
There are exciting hints indicating physics beyond Standard Model

- Measurements of $\sin^2 \theta_W$ agree fairly poorly.
- $g-2$ of the muon is 2-3 $\sigma$ off the SM.
- Dark matter is unexplained.
- There are good reasons to expect additional physics!
Consider an amplitude $A^X$ due to new physics at a mass scale $M_X^2 \gg Q^2$.

On the Z pole, $A_Z$ will be purely imaginary while $A_X$ will likely be real. Accordingly:

$$\sigma \sim |A^Z|^2 + |A^X|^2 \quad \text{and} \quad A_{RL} \sim \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim A^Z_{RL} \left(1 + \frac{|A^X|^2}{|A^Z|^2}\right)$$

Away from the Z pole, at higher and lower energies, both amplitudes are real and interferences can occur.

$$\sigma \sim |A^\gamma + A^Z + A^X|^2 \quad \text{and} \quad A_{RL} \sim \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{A^Z + A^X}{A^\gamma}$$
Electron scattering provides access to very high energy scales

\[
\frac{\delta A_Z}{A_Z} \propto \frac{\pi}{\Lambda^2} \frac{g}{G_f}
\]

Sensitivity to new contact interactions will extend to energy scales \( \Lambda \) on the order of roughly 10 TeV

Already E158 provides the most accurate measurement of \( \sin^2 \theta_W \) at low \( Q^2 \)

\[\sin^2 \theta_W(Q)\]

Qweak and a possible Møller experiment at 11 GeV provide sensitivity that would be tremendously valuable in the upcoming era of LHC
Marciano likes to point out that if either the SLD or the best CERN numbers were not there, we would have a very different picture right now.

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\[ Q_{\text{weak}} \pm 0.00070 \]

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An 11 GeV Møller experiment, the ONLY possibility of resolving outstanding issues here, could be equal to or better than the best single measurement existing.
Qweak will (and an 11 GeV Møller experiment could) provide powerful probes of SUSY theories.

Qweak, by itself, provides considerable sensitivity to RPV SUSY theories.

Kurylov, Ramsey-Mulsolf, Su
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An 11 GeV Møller experiment could provide important sensitivity to RPC SUSY theories that include stable particles that could contribute to dark matter.

Kurylov, Ramsey-Mulsolf, Su
Qweak apparatus

Region I: GEM
Gas Electron Multiplier

Region II: Horizontal drift chamber location

Region III: Vertical Drift chambers

Quadz Cherenkov Bars
(insensitive to non-relativistic particles)

Lumi Monitors

Trigger Scintillator

Collimator System

$E_{beam} = 1.165 \text{ GeV}$
$I_{beam} = 180 \text{ A}$
Polarization $\sim 85\%$
Target $= 2.5 \text{ kW}$

Mini-torus

e- beam
An important perspective on SM tests is to consider a model independent effective Lagrangian. Each parity violating asymmetry can then be interpreted to constrain the coefficients $C_{1u}, C_{1d}, C_{2u},$ and $C_{2d}$.

Qweak is seen to put excellent constraints on a linear combination of $C_{1u}$ and $C_{1d}$.
To learn about ALL the coefficients $C_{1u}, C_{1d}, C_{2u},$ and $C_{2d}$, we need additional types of parity violating semi-leptonic measurements:

**PV deep inelastic scattering (PVDIS)**

\[
A_{PV} = \frac{G_F Q^2}{\sqrt{2} \pi \alpha} \left[ a(x) + f(y) b(x) \right] \quad \quad \quad x \equiv x_{Bjorken} \\
y \equiv 1 - E'/E \\
n_i^{\pm} \equiv f_i \pm \overline{f_i}
\]

\[
a(x) = \sum_i \frac{C_{1i} Q_i f_i^{+}(x)}{\sum_i Q_i^2 f_i^{+}(x)} \quad \quad b(x) = \sum_i \frac{C_{2i} Q_i f_i^{-}(x)}{\sum_i Q_i^2 f_i^{+}(x)}
\]

Just as with parity violation in elastic scattering, PVDIS can be used to study of host of physics phenomena, from standard model tests, to charge symmetry violation, to higher twist effects, and even d/u.
Sensitivity of PV DIS experiments approved or being considered at JLab

The coefficients $C_{2u}$, and $C_{2d}$ are relatively small in the standard model.

This in fact makes them more sensitive to certain types of new physics.

\[
\begin{align*}
C_{1u} &= -\frac{1}{2} + \frac{4}{3} \sin^2(\theta_W) \approx -0.19 \\
C_{1d} &= \frac{1}{2} - \frac{2}{3} \sin^2(\theta_W) \approx 0.35 \\
C_{2u} &= -\frac{1}{2} + 2 \sin^2(\theta_W) \approx -0.04 \\
C_{2d} &= \frac{1}{2} - 2 \sin^2(\theta_W) \approx 0.04.
\end{align*}
\]
Looking toward the future
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• Parity violation in electron scattering will provide the ONLY means for accessing certain important questions in electroweak physics until the ILC is built.
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- Parity violation in electron scattering will provide the ONLY means for accessing certain important questions in electroweak physics until the ILC is built.
- Both Møller and PVDIS are critical if we are to understand semi-leptonic interactions.