Qweak
Analysis Update

- Qweak overview
- First determination of $Q_w^p$
- Current analysis status
- Summary, outlook

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Qweak Overview

Qweak was completed in May 2012 after 2 years of data taking and is currently in the analysis stage.

Measurement of the parity-violating asymmetry $A_{PV}$ on elastic e-p scattering, at forward angles and low $Q^2$, between electron states of opposite helicity

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

- **180uA e⁻ beam, 1.165 GeV, 89% polarization**
- **R helicity**
- **L helicity**

LH2 target

Main detector: Azimuthally symmetric array of 8 Cerenkov bars
Motivation

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{2 M_{weak}^{PV}}{M_{EM}}$$

The parity-violating weak amplitude can be accessed through the asymmetry

⇒ Allows first determination of the neutral-weak charge of the proton, $Q_w^p$

Asymmetry predicted to be tiny in the SM: ~ -216 ppb (parts per billion)

Qweak proposes a 3% measurement of $A_{PV}$

⇒ Precision test of the Standard Model

Very challenging to achieve this level of precision; Required:

➢ High statistics (high beam current, high polarization, high power cryotarget)
➢ Careful control of systematics (false asymmetries, backgrounds, polarization, $Q^2$)
First result released on a small subset of the data, the “Commissioning” or “Run 0” data set.

Qweak periods:
Run 0 (Jan – Feb 2011), Commissioning  
Run 1 (Feb – May 2011)  
Run 2 (Nov 2011 – May 2012)

- Taken between Jan. 31 2011 and Feb. 8 2011, constitutes only 4% of the full data set
- Separate blinding factor allows early unblinding
- Some subsystems were still being commissioned and were only available during Run 1 and 2: beam modulation, Compton polarimeter, injector spin manipulation

The result presented over the next slides is from the Run 0 period only.
Measured asymmetry must be first corrected and normalized.

- $R_{\text{tot}}$: Radiative corrections, kinematics normalization
- $P$: Polarization
- $f_i$: Fraction of bkgd in signal (aka “dilution”)
- $A_i$: Asymmetry of bkgd

\[
A_{ep} = R_{\text{tot}} \frac{A_{msr}/P - \sum_{i=1}^{4} f_i A_i}{1 - \sum f_i}
\]

\[
A_{msr} = -204 \pm 34 \text{ ppb} \quad (16.5\% \text{ rel})
\]

\[
A_{ep} = -279 \pm 35 \text{ (stat)} \pm 31 \text{ (syst) ppb} \quad (16.8\% \text{ rel})
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Smallest asymmetry and smallest absolute error bar ever measured in e-p scattering
First determination of the neutral-weak charge of the proton, $Q_w^p$

$Q_w^p$ can be extracted from the PV asymmetry:

$$\overline{A}_{LR}^p = A_{LR}^p / A_0 = Q_w^p + Q^2 B(Q^2), \quad A_0 = \frac{-G_F Q^2}{4 \pi \alpha \sqrt{2}}$$

(Forward angles, low $Q^2$)

Hadronic structure enters here. Sufficiently constrained from world PVES data and suppressed at Qweak kinematics.

Because $Q_w^p$ is suppressed in the SM, a 4% determination will allow a 0.3% extraction of $\sin^2 \theta_w$:

At tree level:

$$Q_w^p = 1 - 4 \sin^2 \theta_w$$

→ Sensitivity to new physics at the few TeV scale
**First determination of the neutral-weak charge of the proton, \( Q_w^p \)**

\[
\frac{A}{A_0} = Q_w^p + Q^2 B(Q^2)
\]

Global fit:
\[
Q_w^p = 0.064 \pm 0.012
\]

The Qweak point significantly shifts the result of the global fit and reduces the uncertainty.

Increased consistency with SM value:
\[
Q_w^p(SM) = 0.0710 \pm 0.0007
\]
First determination of the neutral-weak charge of the proton, $Q_w^p$

$$Q_w^p = 0.064 \pm 0.012$$

Even with only 4% of the full data set, Qweak significantly constrains new physics scenarios.

Model independent mass reach (95% CL) comparable to LHC limits:

Mass scale over coupling of new physics

$$\frac{\Lambda}{g} \approx \frac{1}{2} \frac{1}{\sqrt{2} G_F |\Delta Q_w^p|} \sim 1.1 \text{ TeV}$$

Strongly coupled theories have $g^2 \sim 4\pi$.
Separate limits can be quoted for models that interfere constructively and destructively with the Standard Model.
Constraints on $C_{1q}$ couplings

$C_{1q}$: Vector quark couplings

$$Q_w^p = -2 \left( 2C_{1u} + C_{1d} \right)$$

PVES has sensitivity to a $C_{1u}, C_{1d}$ combination that is orthogonal to APV
**Constraints on $C_{1q}$ couplings**

Combining APV + PVES, global constraints on $C_{1q}$:

\[
C_{1u} = -0.184 \pm 0.005 \\
C_{1d} = 0.335 \pm 0.005
\]

From these the weak charge of the neutron is extracted for the first time:

\[
Q_w^n = -2 \left( 2C_{1d} + C_{1u} \right) \\
\Rightarrow Q_w^n = -0.975 \pm 0.010
\]

In agreement with SM value:

\[
Q_w^n (SM) = -0.9890 \pm 0.0007
\]
Current Qweak analysis status

Paper with Run 0 results submitted for publication
Analysis for full measurement ongoing

- Aluminum target window dilution
- Aluminum target window asymmetry
- Beamline backgrounds
- Beam corrections
- Polarization
- $Q^2$ (Simulation and tracking)

Ancillary measurements: transverse asymmetry leakage, $N \rightarrow \Delta$ inelastic asymmetry, constrain of the $\square_{yz}$ diagram contribution

<table>
<thead>
<tr>
<th>Correction Value (ppb)</th>
<th>Contribution to $\Delta A_{\text{cp}}$ (ppb)</th>
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</thead>
<tbody>
<tr>
<td><strong>Normalization Factors Applied to $A_{\text{Raw}}$</strong></td>
<td></td>
</tr>
<tr>
<td>Beam Polarization $1/P$</td>
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<tr>
<td>Kinematics $R_{\text{tot}}$</td>
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<tr>
<td>Bckgrnd Dilution $1/(1 - f_{\text{tot}})$</td>
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<td><strong>Asymmetry corrections</strong></td>
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<tr>
<td>Beam Asymmetries $\kappa A_{\text{reg}}$</td>
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<td>Transverse Polarization $\kappa A_T$</td>
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<td>Detector Linearity $\kappa A_L$</td>
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<tr>
<td>Backgrounds $\kappa P f_i A_i$</td>
<td>$\delta(f_i)$</td>
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<td>Target Windows $(b_1)$</td>
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<td>Beamline Scattering $(b_2)$</td>
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<tr>
<td>Other Neutral bkg $(b_3)$</td>
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<tr>
<td>Inelastics $(b_4)$</td>
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</tr>
</tbody>
</table>
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Ancillary measurements: transverse asymmetry leakage, $N \rightarrow \Delta$ inelastic asymmetry, constrain of the $\square_{yz}$ diagram contribution

With 25x more data in hand the statistical uncertainty will shrink by a factor of 5. Systematic uncertainty contributions must also be constrained for the full measurement.

Relatively large statistical errors for Run 0 allowed for conservative systematic uncertainties. As analysis matures and all subsystems become available we can do a lot better.
Aluminum target window background correction

Largest correction to the measured asymmetry (~30%)

At Qweak kinematics:

\[ A_{PV}^{(27\text{Al})} \approx -\frac{G_F Q^2}{4\pi \alpha \sqrt{2}} \left[ Q_w^p + Q_w^n \left( \frac{N}{Z} \right) \right] \]

Order of magnitude higher asymmetry than H

Aluminum signal fraction (Run 0 value)

\[ f_{Al} = 3.2 \pm 0.2 \, \% \]

Goal: Reduce uncertainty of this fraction by factor of 4

Average \( Q^2 \) of \( e^- \) scattered from the US window is lower due to kinematic acceptance.

Signal fractions from the US and DS windows are different and radiative corrections applied separately.
Aluminum target window dilution
Measurement driven, compared with simulation.

Rate from Al windows measured directly with empty target.

Profile of US window shifted due to ionization energy loss with LH2 present. Model dependence of the radiative corrections is the largest uncertainty contribution to the Aluminum rate.

Independent determination from cold gas density study (not used for Run 0 value):
Dilution Factor: Dependence on Gas Density

Radiative corrections will be studied on “dummy” Al targets of different thicknesses (not used for Run 0). Parallel efforts on simulation and track reconstruction to constrain the model uncertainty from the profile shift.

Simulation: Aluminum quasi-elastic and inelastic generators; nuclear inelastic rates.
Target window thickness precision measurement.

Aug 20, 2013
Aluminum target window asymmetry

\[ A_{PV}(^{27}\text{Al}) \approx \frac{-G_F Q^2}{4\pi \alpha \sqrt{2}} \left[ Q_w^p + Q_w^n \left( \frac{N}{Z} \right) \right] \]

Run 0 value: \( A_{\text{Al}} = 1.76 \pm 0.26 \text{ ppm} \)

Goal: Reduce uncertainty by factor of 3-4

- 7x more Aluminum data in hand will reduce the statistical uncertainty of \( A_{\text{Al}} \)

- Systematic uncertainties will benefit from studies on H asymmetry: beamline backgrounds, beam corrections, polarization, \( Q^2 \)
**Beamline Background asymmetry correction**

Soft background from interactions with the W beam collimator and the beamline.

Run0 correction: \[ C_{BB} = 11 \pm 23 \text{ ppb} \]

Largest Run 0 uncertainty contribution

Goal: Reduce uncertainty by an order of magnitude

Error bar artificially inflated in Run 0 to account for non-zero “null” IHWP In+Out asymmetry, believed to be connected to this background.

Here the **weight** is the correlation of the Main Detector to the background detector asymmetry. This “convoluted” background asymmetry gives the (naively) implied effect on the Main Detector.

Note: The average “null” asymmetry over the full run is consistent with zero.
Beamline Background asymmetry correction

Bkgd fraction in the MD was measured directly by blocking primary events in two of the octants:

\[ f_{BB} = 0.2 \pm 0.1 \% \]

Conservative error bar accounts for a wide range of beam conditions. Analysis effort to utilize the MD-to-US Lumi asymmetry correlation to track changes with beam conditions.

The background signal fraction of the bkgd detectors was extracted from the same study.

Parallel simulation efforts to fully understand the signal of these detectors.
Beamline Background asymmetry correction

Background detectors provide continuous monitoring. They see large and highly correlated asymmetries, roughly proportional to their background signal fraction.

The correlation of these asymmetries to the Main Detector dominates the systematic uncertainty of this correction.

**Asymmetry of different background detectors**

**Major challenge in understanding this correlation:**

Cleanly separate the effect of helicity correlated beam differences ("false asymmetries") from the Beamline Background asymmetry.

Especially challenging when the background asymmetries are correlated to beam differences through beam jitter.
Beam corrections

Run0 correction: \[ C_{beam} = -40 \pm 13 \text{ ppb} \]

Goal: Reduce uncertainty by an order of magnitude

Helicity correlated (HC) differences on beam parameters shift the measured asymmetry:

\[ A_{\text{meas}} = A_{\text{phys}} \sum_{i=1}^{N} \frac{\partial A}{\partial P_i} \delta P_i, \]

where \( P_i = x, y, \theta_x, \theta_y, E \)

The asymmetry sensitivities are extracted through linear regression on natural beam motion.

But regression slopes are dominated by beam jitter, which eventually averages away like \( \sigma/\sqrt{N} \).
These slopes may not be appropriate to describe the systematic effect of HC differences.

It will be very difficult to extract “clean” sensitivities from natural beam motion.

Regression does what it is supposed to and removes correlation to HC differences, but may also sweep things under the rug.
**Beam corrections**

The good news:

The modulation subsystem was available after Run 0.

Driven modulation from a pair of air-core dipoles (for position and angle) or a superconducting RF cavity (for energy modulation) gives clear detector responses. This was always considered the preferred method to extract sensitivities.

Modulation should give the “true” detector sensitivities to trajectory and energy. They have been seen to be more stable than regression sensitivities.

Correcting the background detectors with the true sensitivities is also a necessary step for the Beamline Background correction.

Aug 20, 2013
Polarimetry

The Hall C Møller polarimeter provided the polarization for Run 0:

\[ P = 89.0 \pm 1.8 \% \] (Run 0 value)

Main systematic uncertainties: High current extrapolation, beam position;

**Goal: Reduce uncertainty down to \( \sim 1\% \)**

The Compton polarimeter was available after April 2011. Non-invasive continuous monitoring of the polarization from two independent detectors: electron and photon
Polarimetry

The Compton e\(^{-}\) detector performed admirably!
Provided continuous polarization measurements in very good agreement with Møller.

Run 1:
Different combinations of Møller and Compton may be used. Møller Q3 issues, Compton unavailable before April.

Run 2:
“Default” polarization value from Compton e\(^{-}\) detector with input from Møller and Compton γ.
The Polarimetry group will likely achieve \(<1\%\) precision, better than our proposal.

Ongoing analysis:
- Understand small differences between Compton e\(^{-}\) and Møller results
- Compton e\(^{-}\): Finalize background subtraction and fitting technique for polarization extraction
- Møller: Simulations to understand “bad quad” period in Run 1
Summary

- Qweak released its first result from the commissioning part of the experiment:

\[ A_{PV} = -279 \pm 35 \text{ (stat)} \pm 31 \text{ (syst)} \text{ ppb} \quad (16.8\% \text{ relative}) \]

- Combining with world PVES data we make the first determination of the neutral-weak charge of the proton:

\[ Q_w^p = 0.064 \pm 0.012 \quad (18.7\% \text{ relative}) \]

- 25x more data in hand for the full measurement

- Analysis has matured and important subsystems are available for the rest of the run. Significant progress is being made towards the uncertainty goals.

- Full Qweak result expected in 2014
Outlook

Run 0 result, 17% uncertainty
Outlook

The full Qweak result has the potential to place very tight constraints on possible SM extensions.