

Parity-Violating and Parity-Conserving Asymmetries in the Qweak Experiment

Wouter Deconinck, for the Qweak Collaboration

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XIIIth Quark Confinement and the Hadron Spectrum



WILLIAM & MARY

CHARTERED 1693

Supported by the National Science Foundation under Grant Nos. PHY-1405857, PHY-1714792.

There are Two Main Classes of Standard Model Tests

Energy frontier

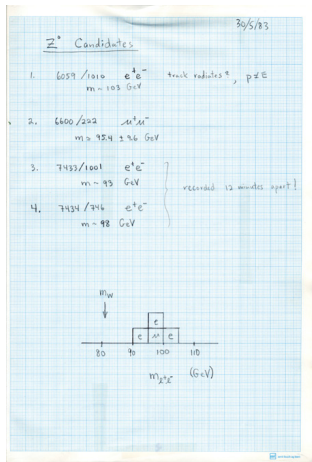
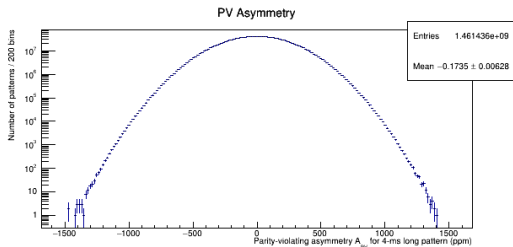


Image credit: James Rohlf, UA1/UA2

Intensity frontier

- Asymmetry uncertainty $\delta A \propto 1/\sqrt{N}$
- Q_{Weak} experiment: $\delta A \approx 6.3$ ppb
- 2.5×10^{16} scattered electrons detected
- Luminosity of about $1.7 \cdot 10^{39} \text{ cm}^{-2} \text{ s}^{-1}$, accumulating 40 fb^{-1} in 20 seconds



(Every entry in this histogram is 3 million electrons.)

Electroweak Interaction

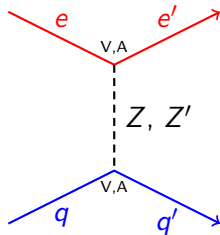
Parity symmetry is violated by $SU(2)_L$

- Weak interaction violates parity
- Electromagnetism conserves parity

Parity-violation neutral current ($g_V - \gamma_5 g_A$)



$$\begin{aligned}\mathcal{L}_{PV}^{NC} &= -\frac{G_F}{\sqrt{2}} \left[g_A^e (\bar{e} \gamma_\mu \gamma_5 e) \cdot \sum_q g_V^q (\bar{q} \gamma^\mu q) \right. \\ &\quad \left. + g_V^e (\bar{e} \gamma_\mu e) \cdot \sum_q g_A^q (\bar{q} \gamma^\mu \gamma_5 q) \right] \\ &= -\frac{G_F}{2\sqrt{2}} \left[\sum_q C_{1q} (\bar{e} \gamma_\mu \gamma_5 e) \cdot (\bar{q} \gamma^\mu q) \right. \\ &\quad \left. + \sum_q C_{2q} (\bar{e} \gamma_\mu e) \cdot (\bar{q} \gamma^\mu \gamma_5 q) \right]\end{aligned}$$



Several Electroweak Charges are Suppressed

Parity-violating electron scattering couplings

- Weak **vector** quark coupling: $C_{1q} = 2g_A^e g_V^q$ ($\gamma^\mu \gamma^5$ on **e** vertex)
- Weak **axial** quark coupling: $C_{2q} = 2g_V^e g_A^q$ ($\gamma^\mu \gamma^5$ on **q** vertex)

Particle	Electric charge	Weak vector charge ($\sin^2 \theta_W \approx \frac{1}{4}$)
u	$+\frac{2}{3}$	$-2C_{1u} = +1 - \frac{8}{3} \sin^2 \theta_W \approx +\frac{1}{3}$
d	$-\frac{1}{3}$	$-2C_{1d} = -1 + \frac{4}{3} \sin^2 \theta_W \approx -\frac{2}{3}$
p(uud)	+1	$Q_W^p = 1 - 4 \sin^2 \theta_W \approx 0$
n(udd)	0	$Q_W^n = -1$
e	-1	$Q_W^e = -2g_A^e g_V^e = -1 + 4 \sin^2 \theta_W \approx 0$

Weak **vector** charges of the **proton** and **electron** approximately zero

Accidental suppression of the weak vector charges in Standard Model makes them relatively more sensitive to new physics

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Weak **vector** charge of the **neutron** is large

Dominance of neutron over proton weak charge means that parity-violating scattering is sensitive to neutron distributions

Several Electroweak Charges are Suppressed

Parity-violating electron scattering couplings

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- Weak **axial** quark coupling: $C_{2q} = 2g_V^e g_A^q$ ($\gamma^\mu \gamma^5$ on **q** vertex)

Particle	Electric charge	Weak axial charge ($\sin^2 \theta_W \approx \frac{1}{4}$)
u	$+\frac{2}{3}$	$-2C_{2u} = -1 + 4\sin^2 \theta_W \approx 0$
d	$-\frac{1}{3}$	$-2C_{2d} = +1 - 4\sin^2 \theta_W \approx 0$

Weak **axial** charges of **quarks** approximately zero

Accidental suppression of the weak axial charges in deep-inelastic scattering of quarks

$$\frac{\Delta \sin^2 \theta_W}{\sin^2 \theta_W} = \frac{1 - 4 \sin^2 \theta_W}{4 \sin^2 \theta_W} \frac{\Delta \text{observable}}{\text{observable}}$$

Parity-Violating Asymmetries are Typically Small

Asymmetry between + and - incoming electron helicity

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \quad \text{with} \quad \sigma = \left| \begin{array}{c} e \quad e' \\ \diagdown \quad \diagup \\ \gamma \\ \diagup \quad \diagdown \\ q \quad q' \end{array} + \begin{array}{c} e \quad e' \\ \diagdown \quad \diagup \\ Z \\ \diagup \quad \diagdown \\ q \quad q' \end{array} + \dots \right|^2$$

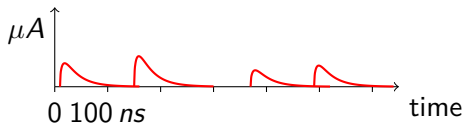
Interference of exchange of photon (\mathcal{P} -even) and weak boson (\mathcal{P} -odd)

$$\mathcal{M}^{EM} \propto \frac{1}{Q^2} \quad \mathcal{M}_{PV}^{NC} \propto \frac{1}{M_Z^2 + Q^2}$$

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \propto \frac{\mathcal{M}_{PV}^{NC}}{\mathcal{M}^{EM}} \propto \frac{Q^2}{M_Z^2} \propto G_F Q^2 \approx \mathcal{O}(\text{ppm, ppb}) \text{ when } Q^2 \ll M_Z^2$$

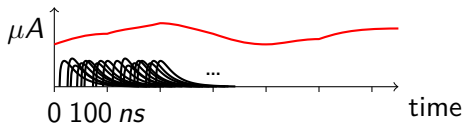
Strategy to Measure Parts-Per-Billion: Integration

Event or counting mode



- Each event individually detected, digitized and read-out
- Selection or rejection possible based on event characteristics
- 100 ns pulse separation limits rate to 10 MHz per detector segment; at least 1 day for 1 ppm precision

Integrating or current mode



- Very high event rates possible, as long as detectors are linear
- But no rejection of background events possible after the fact
- Q_{Weak} segment rates 800 MHz; MOLLER segment rates up to 2.5 GHz; P2 up to 0.5 THz

Parity-Violating Asymmetry to Access Electroweak Parameters

Electroweak measurements with protons (elastic scattering)

- Access to weak vector quark charges, measurements of $\sin^2 \theta_W$

Electroweak measurements with electrons (Møller scattering)

- Access to weak electron charge, measurements of $\sin^2 \theta_W$

Electroweak measurements with quarks (deep-inelastic scattering)

- Access to weak axial quark charges, measurements of $\sin^2 \theta_W$, measurements of weak structure functions

Electroweak measurements with nuclei (elastic scattering)

- Access to neutron distributions, measurements of neutron skin thickness

Determination of the Weak Charge of the Proton

Electroweak measurements with protons (elastic scattering)

$$A_{PV}(p) = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[\frac{\epsilon G_E G_E^Z + \tau G_M G_M^Z - (1 - 4\sin^2 \theta_W) \epsilon' G_M G_A^Z}{\epsilon (G_E)^2 + \tau (G_M)^2} \right]$$

In the forward elastic limit $Q^2 \rightarrow 0$, $\theta \rightarrow 0$ (plane wave):

$$A_{PV}(p) \xrightarrow{Q^2 \rightarrow 0} \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[Q_W^p + Q^2 \cdot B(Q^2) \right] \propto Q_W^p \text{ when } Q^2 \text{ small}$$

Weak charge is intercept at $Q^2 \rightarrow 0$ of normalized asymmetry $A_{PV}(p)/A_0$

$$A_{PV}(p) \xrightarrow{Q^2 \rightarrow 0} Q_W^p \xrightarrow{LO} -1 + 4\sin^2 \theta_W$$

Determination of the Weak Charge of the Proton

Qweak Experiment

- First experiment with **direct access** to proton's weak charge
- Experiment collected data between 2010 and 2012 with toroidal spectrometer and integrating quartz detectors

First determination based on subset of data

- First measurement was published in 2013 based on commissioning data¹ (4% compared to the independent full data set)

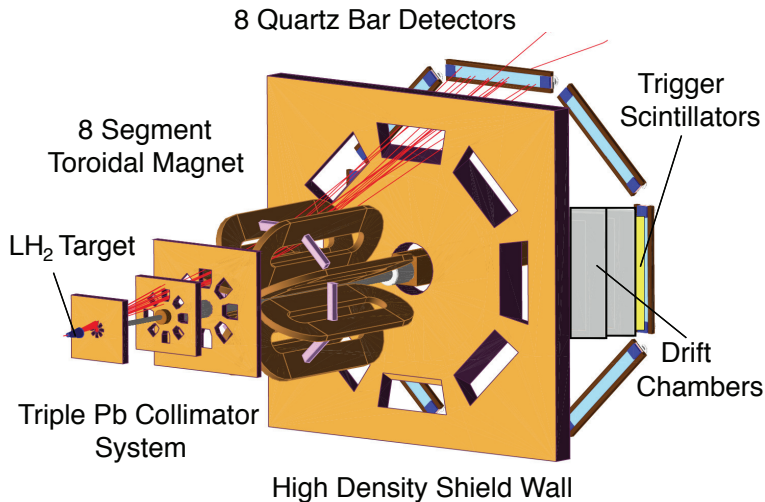
Precision final results are now published

- Precision measurement of weak charge in Nature²
- No disagreement with Standard Model; exclusion limits for BTSM

¹First Determination of the Weak Charge of the Proton, *Phys. Rev. Lett.* 111, 141803 (2013)

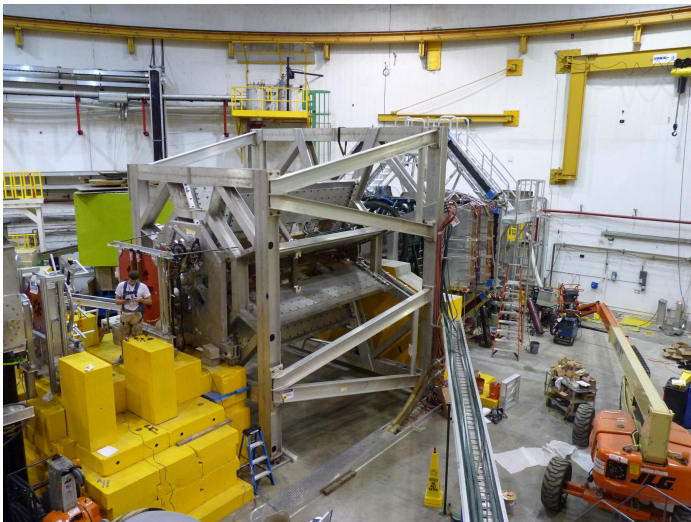
²Precision Measurement of the Weak Charge of the Proton, *Nature* 557, p207-211 (2018)

Determination of the Weak Charge of the Proton



¹ *The Qweak Apparatus, NIM A 781, 105 (2015)*

Determination of the Weak Charge of the Proton



¹ *The Qweak Apparatus, NIM A 781, 105 (2015)*

Determination of the Weak Charge of the Proton

Pushing the envelope of **intensity** (more detected electrons)

- Higher beam current ($180\ \mu\text{A}$ versus usually $< 100\ \mu\text{A}$)
- Longer cryo-target (35 cm versus 20 cm, 2.5 kW in 20 K LH2)
- Higher event rates up to 800 MHz (integrating mode)
- Typical luminosity of $1.7 \times 10^{39}\ \text{cm}^{-2}\ \text{s}^{-1}$, $\int \mathcal{L} dt = 1\ \text{ab}^{-1}$

Pushing the envelope of **precision** (better measurements)

- Electron beam polarimetry precision of 1% at 1 GeV
- Helicity-correlated asymmetries at ppb level (beam position at nm level)
- Precise determination of Q^2 since $A_{PV} \propto Q^2$
- Isolate elastic scattering from background processes (f_i , A_i)
 - This is why we must measure various background asymmetries

Determination of the Weak Charge of the Proton

Background treatment in integrating experiments

- Measured asymmetry A_{msr} corrected for all background contributions
 - with their own parity-violating asymmetry A_i (ppm-level)
 - and their dilution in the measured asymmetry f_i (%-level)

$$A_{PV} = R_{total} \frac{\frac{A_{msr}}{P} - \sum f_i A_i}{1 - \sum f_i}$$

Unprecedented precision comes with inevitable surprises

- Discovered qualitatively new “beamline background”
 - Generated by scattering of helicity-dependent beam halo on clean-up collimator downstream of target and into detector acceptance
- Discovered qualitatively new “rescattering bias”
 - Spin precession of scattered electrons in spectrometer, followed by nuclear transverse spin azimuthal asymmetry when scattering in lead pre-radiators

Determination of the Weak Charge of the Proton

All uncertainties in ppb	Run 1	Run 2	Combined
Charge Normalization: A_{BCM}	5.1	2.3	Note: correlations between factors
Beamline Background: A_{BB}	5.1	1.2	
Beam Asymmetries: A_{beam}	4.7	1.2	
Rescattering bias: A_{bias}	3.4	3.4	
Beam Polarization: P	2.2	(1.2)	
Al target windows: A_{b1}	(1.9)	1.9	
Kinematics: R_{Q^2}	(1.2)	1.3	
Total of others < 5%, incl ()	3.4	2.5	
Total systematic uncertainty	10.1	5.6	5.8
Total statistical uncertainty	15.0	8.3	7.3
Total combined uncertainty	18.0	10.0	9.3 (p = 86%)

$$A_{PV}(4\%) = -279 \pm 31(\text{syst}) \pm 35(\text{stat}) \text{ ppb} = -279 \pm 47 \text{ ppb}$$

$$A_{PV}(\text{full}) = -226.5 \pm 5.8(\text{syst}) \pm 7.3(\text{stat}) \text{ ppb} = -226.5 \pm 9.3 \text{ ppb}$$

Determination of the Weak Charge of the Proton

Intercept of A_{PV} at $Q^2 \rightarrow 0$ gives weak charge ($Q^2 = 0.025 \text{ GeV}^2$)

$$\overline{A_{PV}} = \frac{A_{PV}}{A_0} = Q_W^p + Q^2 \cdot B(Q^2, \theta = 0) \quad \text{with} \quad A_0 = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}$$

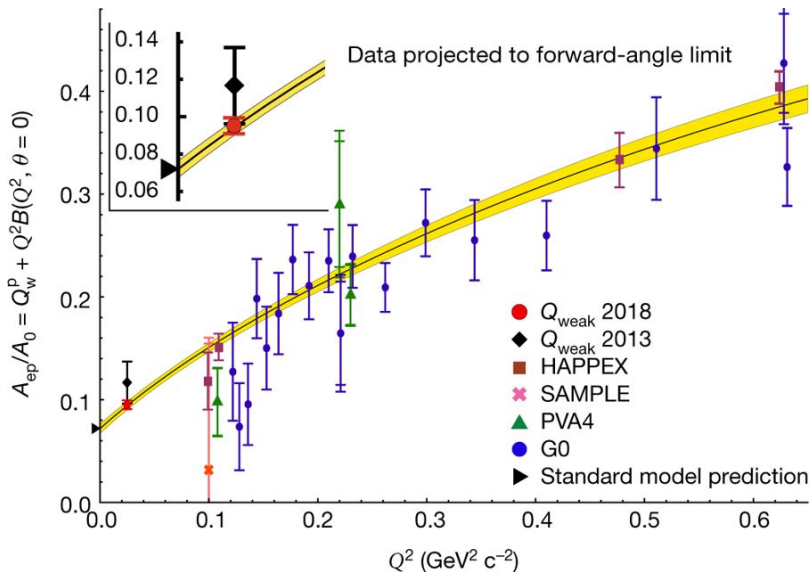
Global fit¹ of all parity-violating electron scattering with full data set²

- Fit of parity-violating asymmetry data on H, D, ^4He , $Q^2 < 0.63 \text{ GeV}^2$
- Free parameters were C_{1u} , C_{1d} , strange charge radius ρ_s and magnetic moment μ_s ($G_{E,M}^s \propto G_D$), and isovector axial form factor $G_A^{Z,T=1}$
- $Q_W^p(\text{PVES}) = 0.0719 \pm 0.0045$, $\sin^2 \theta_W(Q^2) = 0.2382 \pm 0.0011$
- $\rho_s = 0.19 \pm 0.11$, $\mu_s = -0.18 \pm 0.15$, $G_A^{Z,T=1} = -0.67 \pm 0.33$
- After combination with atomic parity-violation on Cs:
 - $C_{1u} = -0.1874 \pm 0.0022$
 - $C_{1d} = 0.3389 \pm 0.0025$

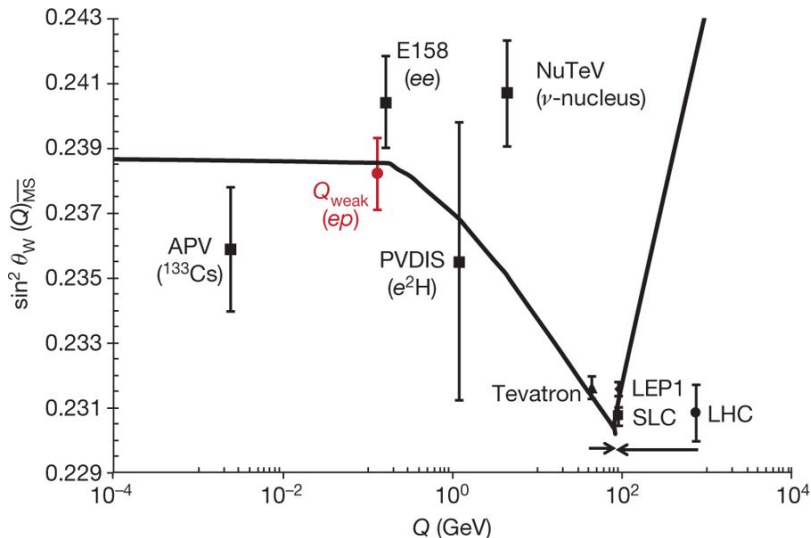
¹R. Young, R. Carlini, A.W. Thomas, J. Roche, *Phys. Rev. Lett.* 99, 122003 (2007)

²Precision Measurement of the Weak Charge of the Proton, *Nature* 558 (2018)

Determination of the Weak Vector Charge of the Proton



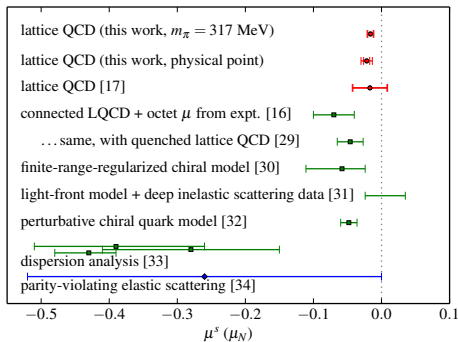
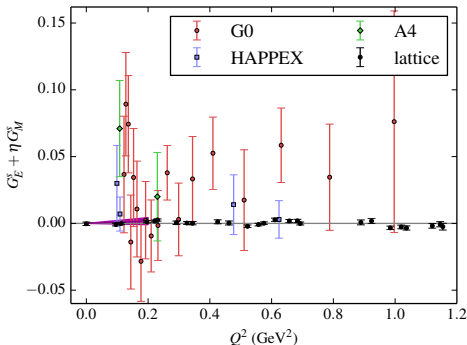
Determination of the Weak Vector Charge of the Proton



Determination of the Weak Vector Charge of the Proton

Can we use lattice QCD in the global fit?

- It is possible to add the lattice strangeness form factor to the global fit
- $Q_W^p(LQCD) = 0.0684 \pm 0.0039$ cf. $Q_W^p(PVES)) = 0.0719 \pm 0.0045$
- If, at some point, the community prefers using LQCD over PVES data...



¹J. Green et al, *Phys. Rev. D*92, 031501 (2015)

Sensitivity to New Physics

Effective four-point interactions of some higher mass scale¹

$$\mathcal{L}_{e-q}^{PV} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C_{1q} \bar{q} \gamma^\mu q + \frac{g^2}{\Lambda^2} \bar{e} \gamma_\mu \gamma_5 e \sum_q h_q^V \bar{q} \gamma^\mu q$$

Limits on new physics energy scale when uncertainty ΔQ_W^p

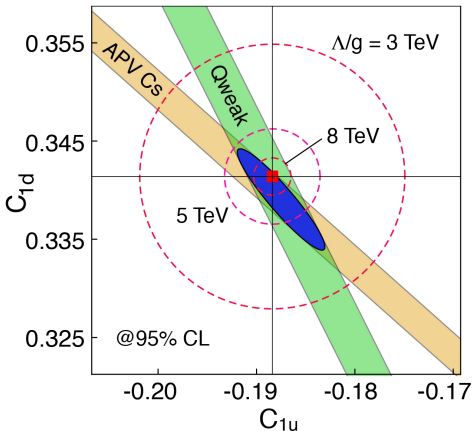
$$\frac{\Lambda}{g} = \frac{1}{2} \left(\sqrt{2} G_F \Delta Q_W^p \right)^{-1/2}$$

Assuming that we have an arbitrary flavor dependence of the new physics:

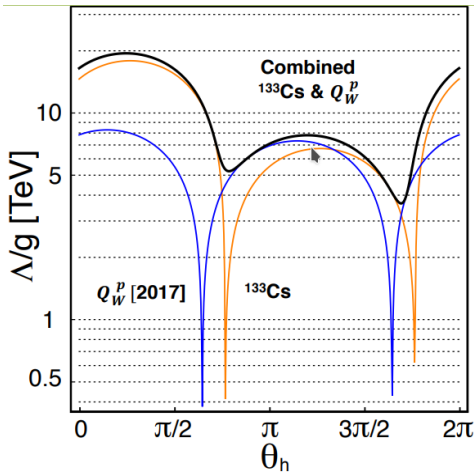
$$h_V^u = \cos \theta_h \quad h_V^d = \sin \theta_h$$

¹J. Erler, A. Kurylov, M. Ramsey-Musolf, PRD 68, 016006 (2003)

Sensitivity to New Physics



$$\Lambda_-/g = 8.4 \text{ TeV and } \Lambda_+/g = 7.4 \text{ TeV}$$



Ancillary Measurements: Borne of Paranoia

Whatever could affect A_{PV} was measured and corrected for:

- Each background has asymmetry A_i and dilution f_i
- Non-hydrogen scattering: aluminum alloy of target windows
- Non-elastic contributions besides elastic ep : $N \rightarrow \Delta$, Møller
- Non-longitudinal polarization: horizontal, vertical transverse
- Non-electron particles reaching detector: π production
- Particles not originating from target: blocked octants
- Particles not reaching main detectors: superelastic region

Priorities driven by weak charge needs until final publication

- First: corrections on $A_{PV}(p)$ due to $A_{PV}(\text{Al alloy})$, $B_n(\text{H} + \text{Al alloy})$
- Then: turn Al alloy into ^{27}Al for $A_{PV}(^{27}\text{Al})$, extract $B_n(\text{H})$
- Then: corrections due to $B_n(\text{Al alloy})$, extract $B_n(^{27}\text{Al})$

Ancillary Measurements: PV Asymmetry on Aluminum

A_{PV} on Aluminum measures neutron distribution R_n

- According to Horowitz a 4% measurement of the A_{PV} of pure ^{27}Al is sensitive to 2% changes in R_n .
- ^{27}Al 's R_n (neutron distribution radius) helps benchmark theory that is important for other nuclei and astrophysics.

Predicted Q_{weak} ^{27}Al results compared to PREx and CREx:

Exp.	Target	$R_p[\text{fm}]$	$R_n[\text{fm}]$	$R_{ch}[\text{fm}]$	$R_n - R_p[\text{fm}]$	Ref
Q_{weak}	^{27}Al	2.904	2.913	3.013	0.009 est.	1
PREx	^{208}Pb	5.45	$5.78^{+0.16}_{-0.18}$	5.50	0.33 $^{+0.16}_{-0.18}$	2
CREx	^{48}Ca	3.438	3.594	3.526	0.156 est.	3

¹Phys. Rev. C89, 045503 (2014)

²PRL 108, 112502 (2012)

³CC Calculations [CREx Proposal (2013)]

Ancillary Measurements: PV Asymmetry on Aluminum

Extraction of $A_{PV}(^{27}\text{Al})$

- Measurement/apparatus false asymmetry corrections typically on the order few ppb to 10s of ppb.
- Measurement/apparatus false asymmetry uncertainties of order few ppb.

$$A_{msr} = A_{raw} + A_{BCM} + A_{beam} + A_{BB} + A_L + A_T + A_{bias}$$

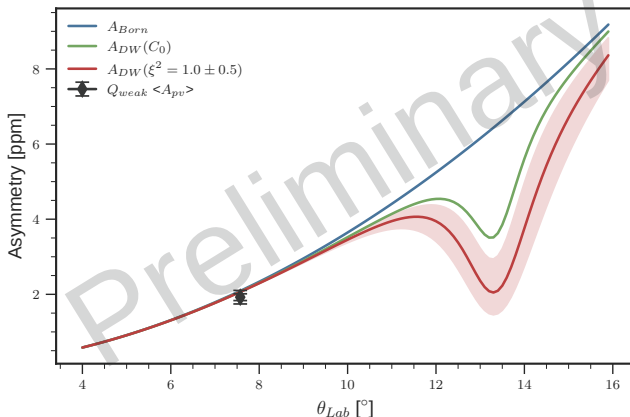
- Largest uncertainties come from background asymmetries that dilute the elastic aluminum asymmetry.
 - Examples: quasi-elastic, inelastic ($N \rightarrow \Delta$), alloy elements (Zn, Mg,...), discrete excitations,...

$$A_{PV} = R_{tot} \frac{\frac{A_{msr}}{P} - \sum_i f_i A_i}{1 - \sum_i f_i}$$

- Background corrected asymmetry requires additional small corrections for acceptance, radiative energy loss, and light collection bias.

Ancillary Measurements: PV Asymmetry on Aluminum

Preliminary Result of $A_{PV}(\text{Al})$



$$A_{PV} = 1.924 \pm 0.180(\text{tot.})[0.090(\text{stat.}) \pm 0.156(\text{sys.})]\text{ppm} \quad \partial A/A = 9.4\%(\text{tot.})$$

Ancillary Measurements: PV Asymmetry on Aluminum

Extraction of R_n

- Horowitz *et al.* calculated the correlation between R_n and $A_{p\nu}$. Using "ten distinct relativistic mean-field interactions." At a $Q^2 = 0.0235$ or $\approx 7.6^\circ$, assuming $E = 1.160$ GeV.

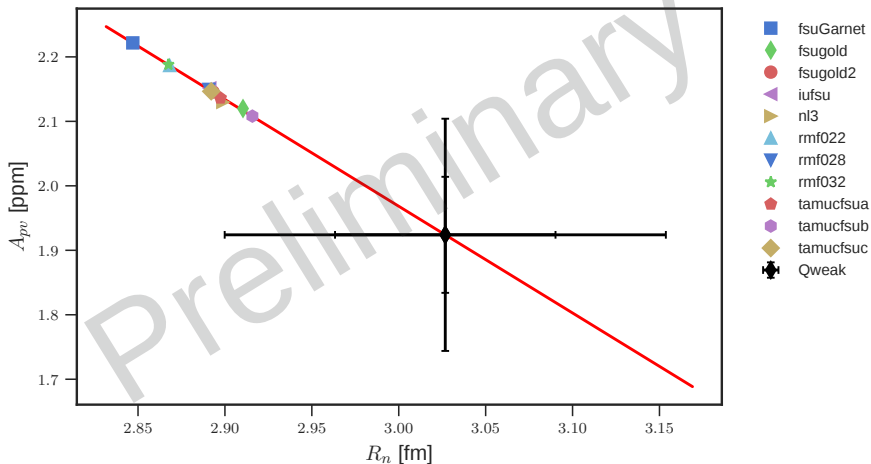
$$A_{p\nu} = -1.6555R_n + 6.9347$$

- Extract R_n by inverting equation then use our $A_{p\nu}$ as input.
- Relative uncertainty on R_n extracted with ln derivative.

$$\frac{\partial R_n}{R_n} = \frac{\partial A_{p\nu}}{A_{p\nu}} \div \frac{\partial \ln A_{p\nu}}{\partial \ln R_n} \quad \text{where} \quad \frac{\partial \ln A_{p\nu}}{\partial \ln R_n} = 2.23252$$

$$R_n = 3.027 \pm 0.127 \text{ fm} \quad \frac{\partial R_n}{R_n} = 4.2 \text{ [\%]}$$

Ancillary Measurements: PV Asymmetry on Aluminum



Note: models very sensitive to kinematics (Q^2).

Ancillary Measurements: PV Asymmetry on Aluminum

Skin Thickness, $R_n - R_p$

- Using a value of $R_p = 2.932$ fm from the set of relativistic mean field models.

$$\begin{aligned} R_n - R_p &= (3.027 \pm 0.127) - (2.932) \\ &= 0.095 \pm 0.127 \text{ [fm]} \end{aligned}$$

- Consistent with zero, which physically makes sense. Aluminum ($Z = 13$, $N = 14$) doesn't have a tremendous neutron excess.
- $A_{inelastic}$ contribution to A_{pv} is the reason for the large uncertainty in R_n and thus the skin thickness.
- Models predict a range of skin thicknesses: 0.004 fm – 0.024 fm.

Rich Future for Parity-Violating Electron Scattering!

Q_{Weak} and P2 Experiments

- Measurement of Q_W^p in $\vec{e}p \rightarrow e'p$ on protons in hydrogen

MOLLER Experiment

- Measurement of Q_W^e in $\vec{e}e \rightarrow ee$ on electrons in hydrogen

PV-DIS and SoLID Experiments

- Measurement of $C_{1,2q}$ in $\vec{e}q \rightarrow e'X$ on hydrogen, deuterium

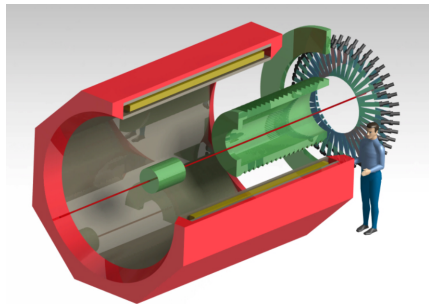
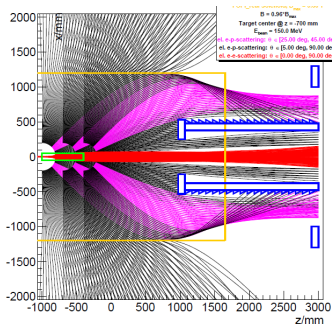
PREX and CREX Experiments

- Measurement of R_n in $\vec{e}A \rightarrow e'X$ on lead-208, calcium-40

P2: High Precision Measurement of Proton's Weak Charge

New Experiment: P2 Experiment in Mainz¹

- 155 MeV energy-recovery superconducting accelerator MESA
- Projected precision of $\sin^2 \theta_W$ to ± 0.0003 at $Q^2 = 0.0045 \text{ GeV}^2$
- Accelerator commissioning in 2018, experiment data taking in 2020
- Electron polarimetry at 0.5% precision with atomic hydrogen Møller



¹J. Univ. Sci. Tech. China 46 (2016) no.6, 481-487

Parity-Violating Asymmetry to Access Electroweak Parameters

Electroweak measurements with electrons (Møller scattering)

$$A_{PV}(e) = \frac{G_F Q^2}{\pi \alpha \sqrt{2}} \left[\frac{1-y}{1+y^4+(1-y)^4} \right] Q_W^e$$

Direct connection from asymmetry to weak charge of electron:

- No theoretical uncertainty due to hadronic structure (G_E , G_M , s)

$$A_{PV}(e) \propto Q_W^e$$

Precision electroweak Standard Model test of $\sin^2 \theta_W$:

$$A_{PV}(e) \rightarrow Q_W^e \rightarrow -1 + 4 \sin^2 \theta_W$$

- Completed: E158 at SLAC, $\sin^2 \theta_W$ to ± 0.0013
- Planned: MOLLER at Jefferson Lab, $\sin^2 \theta_W$ to ± 0.0003

MOLLER: Ultra-Precise Measurement of Electron's Weak Charge

Most precise measurement of $\sin^2 \theta_W$ at low energy¹

- Elastic scattering of electrons on electrons in hydrogen
- Measurement of the weak charge of the electron $Q_W^e \approx 0$ at 11 GeV
 - Asymmetry $A_{PV} \approx 35.6$ ppb, with precision $\delta A_{PV} \approx 0.5$ ppb
 - Precision $\delta Q_W^e \approx \pm 2.1\%$, $\delta \sin^2 \theta_W = \pm 0.1\% = \pm 0.00028$

Pushing the envelope of intensity

- Even higher luminosity: 85 μ A on 1.5 m long cryo-target, 5 kW
- Total event rates up to 150 GHz in integrated mode

Pushing the envelope of precision

- Electron beam polarization precision of 0.4% at 11 GeV

¹ The MOLLER Experiment, arXiv:1411.4088

Parity-Violating Asymmetry to Access Electroweak Parameters

Electroweak measurements with quarks (deep-inelastic scattering)

$$A_{PV}(N) = Q^2 \left[a_1 + a_2 \frac{1 - (1 - y)^2}{1 + (1 - y)^2} \right]$$

For isoscalar targets like deuterium, ignoring strange quarks:

$$A_{PV}(d) = \frac{G_F Q^2}{\pi \alpha \sqrt{2}} \frac{3}{10} \left[(2C_{1u} - C_{1d}) + (2C_{2u} - C_{2d}) \frac{1 - (1 - y)^2}{1 + (1 - y)^2} \right]$$

- Completed: Strange form factors at MIT-Bates, Jefferson Lab, Mainz
- Completed: E122 at SLAC, PV-DIS¹ at Jefferson Lab
- Planned: SoLID at Jefferson Lab

¹ *Nature* 506, p67 (2014)

Parity-Violating Asymmetry to Access Electroweak Parameters

Weak charge of nuclei (elastic scattering)

$$Q_W^{Z,N} \approx ZQ_W^p + NQ_W^n = Z(1 - 4\sin^2 \theta_W) + N$$

- Electron scattering: sensitive to nuclear neutron density distributions

$$A_{PV}(A) = \frac{G_F Q^2}{\pi \alpha \sqrt{2}} \left[(1 - 4\sin^2 \theta_W) - \frac{F_n(Q^2)}{F_p(Q^2)} \right]$$

- Atomic parity-violation: constraint on $2C_{1d} + C_{1u} \perp 2C_{1u} + C_{1d}$ for proton

$$A_{PV}(A) \propto NQ_W^n \propto 2C_{1d} + C_{1u}$$

- Completed: PREX at Jefferson Lab
- Planned: PREX-II & CREX at Jefferson Lab, C12 at Mainz

Q_{Weak} and P2 Experiments

- Measurement of Q_W^p in $\vec{e}p \rightarrow e'p$ on **protons in hydrogen**
- **Full precision Q_{Weak} results** published in Nature in 2018

MOLLER Experiment

- Measurement of Q_W^e in $\vec{e}e \rightarrow ee$ on **electrons in hydrogen**
- Planned at Jefferson Lab, \$25M project, DOE CD-0 approved

PV-DIS and SoLID Experiments

- Measurement of $C_{1,2q}$ in $\vec{e}q \rightarrow e'X$ on **hydrogen, deuterium**
- PV-DIS completed at 6 GeV, SoLID planned, \$65M project

PREX and CREX Experiments

- Measurement of R_n in $\vec{e}A \rightarrow e'X$ on **lead-208, calcium-40**
- PREX-I completed, PREX-II/CREX planned for Summer 2019

Additional Material

Uncertainties

Parity-Violating and Parity-Conserving Nuclear Asymmetries

- Tracking Detectors

- Beam Polarimetry

- Helicity-Correlated Beam Properties

- Data Quality

Precision Polarimetry

- Atomic Hydrogen Polarimetry

Radiative Corrections

The Q_{Weak} Experiment: Kinematics in Event Mode

Reasons for a tracking system?

- Determine Q^2 , note: $A_{meas} \propto Q^2 \cdot (Q_W^p + Q^2 \cdot B(Q^2))$
- Main detector light output and Q^2 position dependence
- Contributions from inelastic background events

Instrumentation of only two octants

- Horizontal drift chambers for front region (Va Tech)
- Vertical drift chambers for back region (W&M)
- Rotation allows measurements in all eight octants

Track reconstruction

- Straight tracks reconstructed in front and back regions
- Front and back partial tracks bridged through magnetic field

The Q_{Weak} Experiment: Improved Beam Polarimetry

Requirements on beam polarimetry

- Largest experimental uncertainty in Q_{Weak} experiment
- Systematic uncertainty of 1% (on absolute measurements)

Upgrade existing Møller polarimeter ($\vec{e} + \vec{e} \rightarrow e + e$)

- Scattering off atomic electrons in magnetized iron foil
- Limited to separate, low current runs ($I \approx 1 \mu\text{A}$)

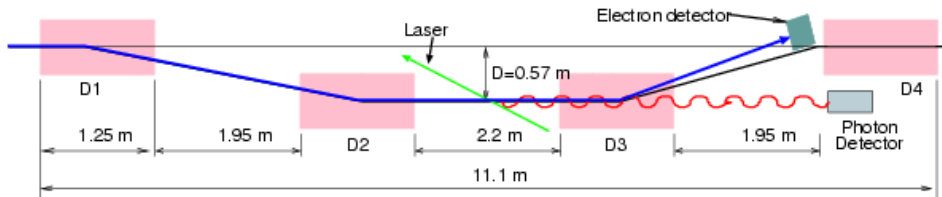
Construction new Compton polarimeter ($\vec{e} + \vec{\gamma} \rightarrow e + \gamma$)

- Compton scattering of electrons on polarized laser beam
- Continuous, non-destructive, high precision measurements

The Q_{Weak} Experiment: Improved Beam Polarimetry

Compton polarimeter

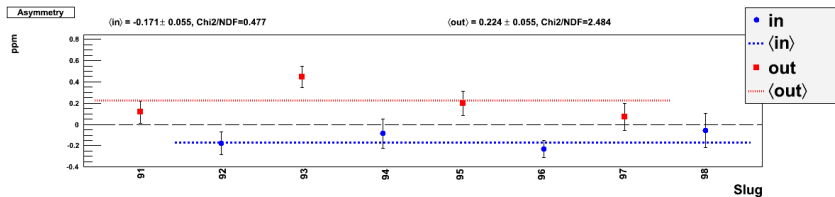
- **Beam:** 150 μA at 1.165 GeV
- **Chicane:** interaction region 57 cm below straight beam line
- **Laser system:** 532 nm green laser
 - 10 W CW laser with low-gain cavity
- **Photons:** PbWO_4 scintillator in integrating mode
- **Electrons:** Diamond strips with 200 μm pitch



Data Quality: Slow Helicity Reversal

$\lambda/2$ -plate and Wien filter changes

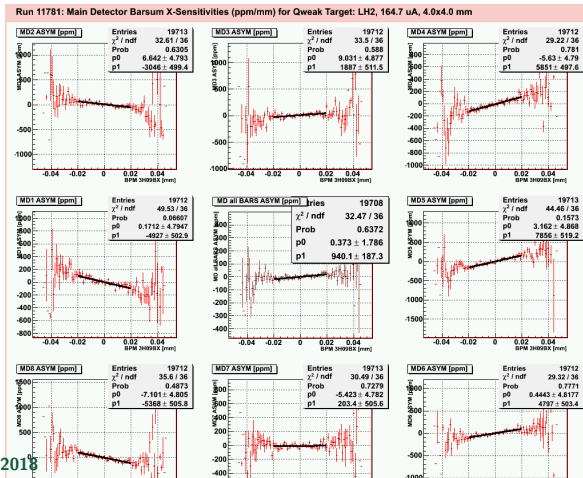
- **Insertable $\lambda/2$ -plate** (IHW P) in injector allows 'analog' flipping helicity frequently
- **Wien filter**: another way of flipping helicity (several weeks)
- Each 'slug' of 8 hours consists of same helicity conditions



Helicity-Correlated Beam Properties Are Understood

Measured asymmetry depends on beam position, angle, energy

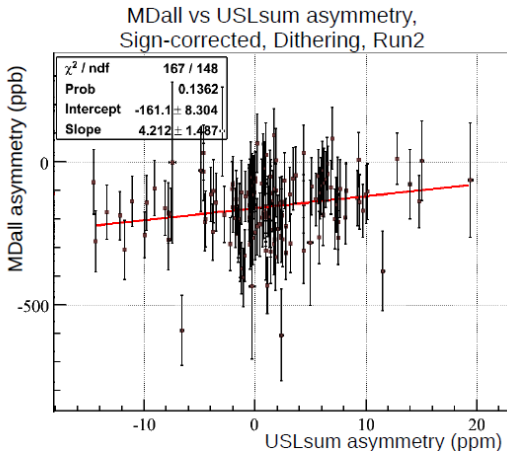
- Well-known and expected effect for PVES experiments
- “Driven” beam to check sensitivities from “natural” jitter



However, Some Beamline Background Correlations Remain

After regression, correlation with background detectors

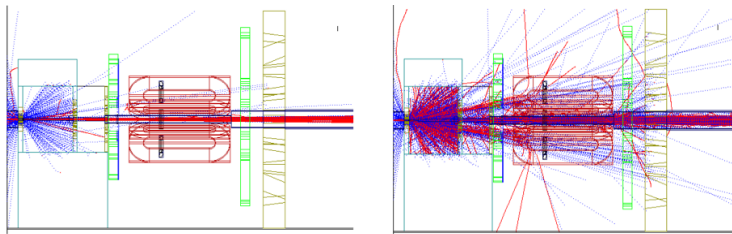
- Luminosity monitors & spare detector in super-elastic region
- Background asymmetries of up to 20 ppm (that's huge!)



Beamline Background Correlations Remain

Hard work by grad students: now understood, under control

- Partially cancels with slow helicity reversal (half-wave plate)
- Likely caused by large asymmetry in small beam halo or tails
- Scattering off the beamline and/or “tungsten plug”



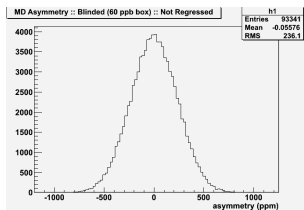
Qualitatively new background for PVES experiments at JLab

- Second regression using asymmetry in background detectors
- Measurements with blocked octants to determine dilution factor

$$(f_{b_2}^{MD} = 0.19\%)$$

Data Quality: Understanding the Asymmetry Width

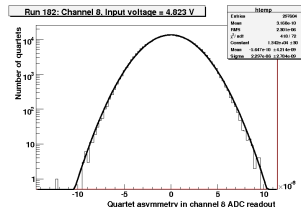
Asymmetry width



Measurement

- 240 Hz helicity quartets (+ - - + or - + + -)
- Uncertainty = RMS/\sqrt{N}
- 200 ppm in 4 milliseconds
- < 1 ppm in 5 minutes

Battery width



Asymmetry width

- Pure counting statistics ≈ 200 ppm
- + detector resolution ≈ 90 ppm
- + current monitor ≈ 50 ppm
- + target boiling ≈ 57 ppm
- = observed width ≈ 233 ppm

Data Quality: Helicity-Correlated Beam Properties

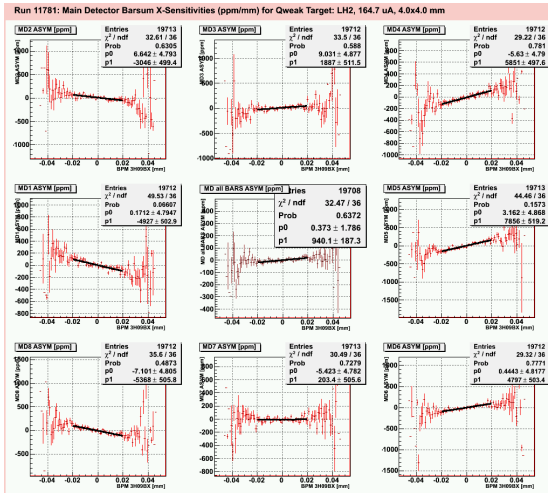
Natural beam motion

- Measured asymmetry correlated with beam position and angles

- Linear regression:

$$A_c = \sum_i \frac{\partial A}{\partial x_i} \Delta x_i$$

$i = x, y, x', y', E$



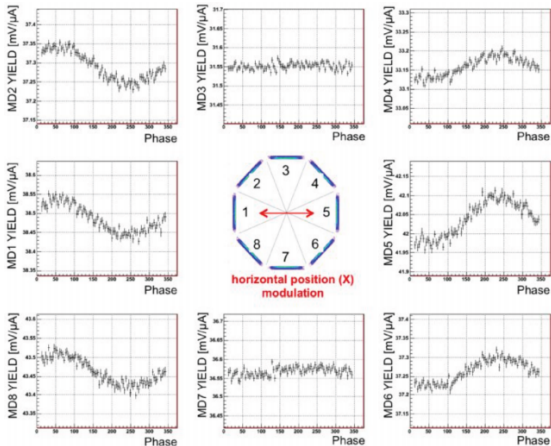
Data Quality: Helicity-Correlated Beam Properties

Natural beam motion

- Measured asymmetry correlated with beam position and angles

- Linear regression:

$$A_c = \sum_i \frac{\partial A}{\partial x_i} \Delta x_i$$
$$i = x, y, x', y', E$$



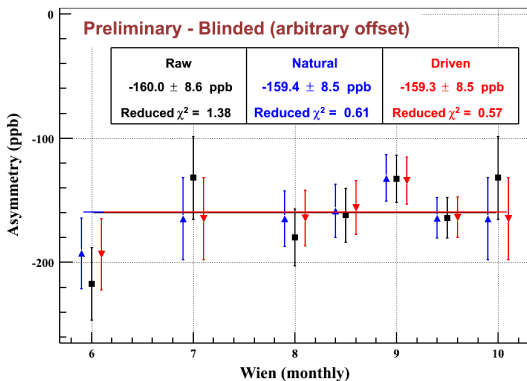
Driven beam motion

- Deliberate motion

Helicity-Correlated Beam Properties Are Understood

Excellent agreement between natural and driven beam motion

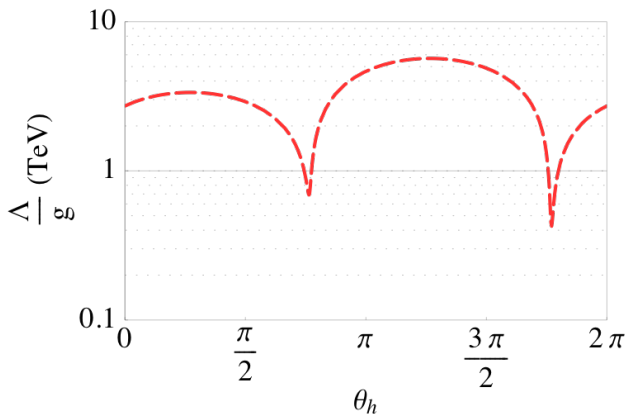
Run2 measured asymmetry



- Figure includes about 50% of total dataset for Q_{Weak} experiment
- No other corrections applied to this data

Sensitivity to New Physics

Lower bound on new physics (95% CL)

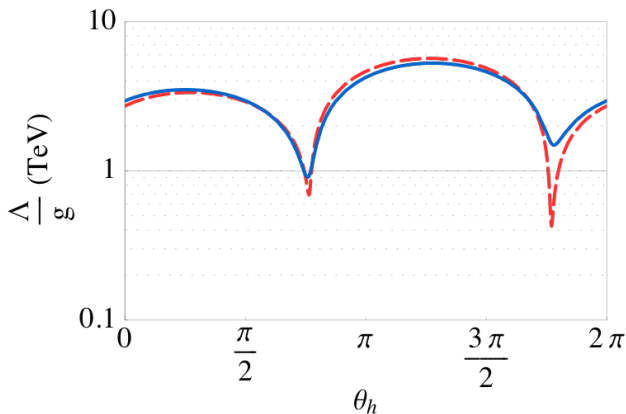


Constraints from

- Atomic PV:
 $\frac{\Lambda}{g} > 0.4 \text{ TeV}$

Sensitivity to New Physics

Lower bound on new physics (95% CL)

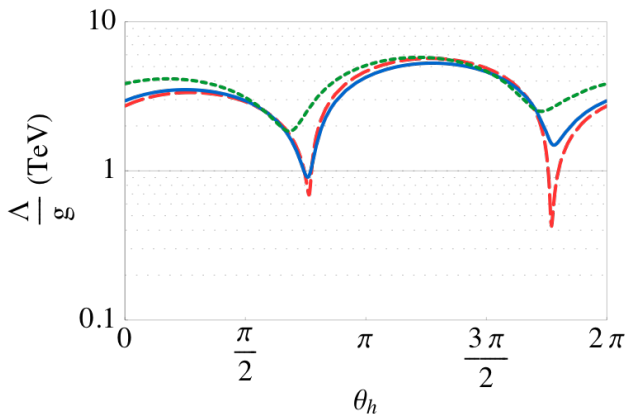


Constraints from

- Atomic PV:
 $\frac{\Lambda}{g} > 0.4 \text{ TeV}$
- PV electron scattering:
 $\frac{\Lambda}{g} > 0.9 \text{ TeV}$

Sensitivity to New Physics

Lower bound on new physics (95% CL)



Constraints from

- Atomic PV:
 $\frac{\Lambda}{g} > 0.4 \text{ TeV}$
- PV electron scattering:
 $\frac{\Lambda}{g} > 0.9 \text{ TeV}$

Projection Q_{Weak}

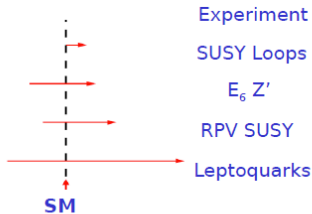
- $\frac{\Lambda}{g} > 2 \text{ TeV}$
- 4% precision

Sensitivity to New Physics

Different experiments sensitive to different extensions

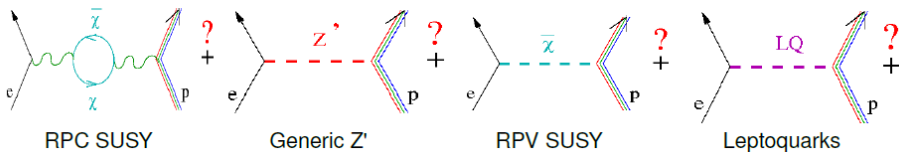
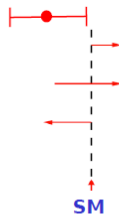
JLab Q_{weak}

$$Q_w^p = 0.0716$$



SLAC E158 (complete)

$$-Q_w^e = 0.0449$$



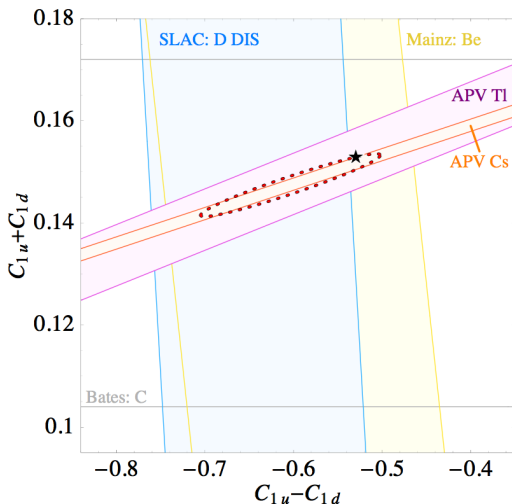
Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge uud

$$Q_W^p = -2(2C_{1u} + C_{1d})$$

Early experiments

- SLAC and APV



Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge uud

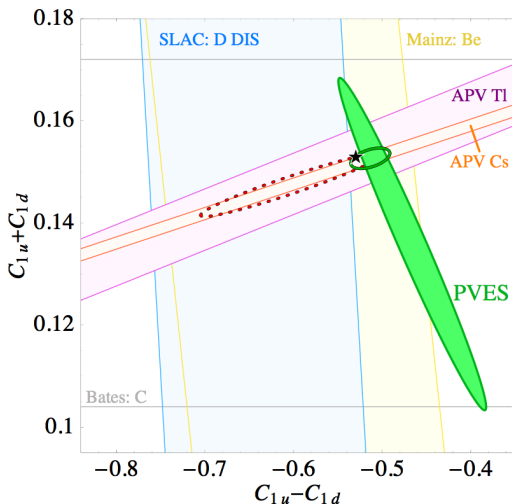
$$Q_W^p = -2(2C_{1u} + C_{1d})$$

Early experiments

- SLAC and APV

Electron scattering

- HAPPE_x, G0
- PVA4/Mainz
- SAMPLE/Bates



Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge uud

$$Q_W^P = -2(2C_{1u} + C_{1d})$$

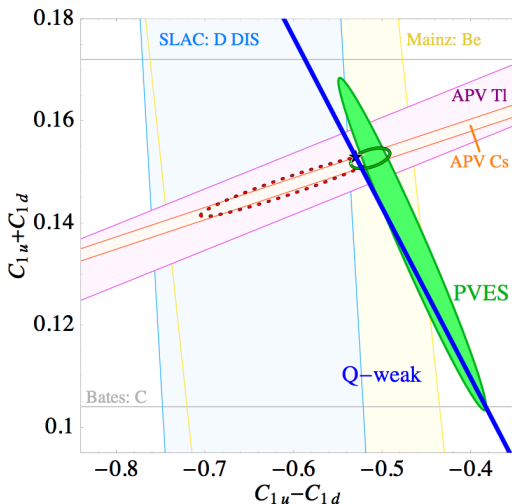
Early experiments

- SLAC and APV

Electron scattering

- HAPPE_x, G0
- PVA4/Mainz
- SAMPLE/Bates

Q_{Weak} experiment



Precision Electroweak Experiments: JLab 12 GeV

MOLLER Experiment

Source	ΔA_{PV}
Mom. transfer Q^2	0.5%
Beam polarization	0.4%
2 nd order beam	0.4%
Inelastic ep	0.4%
Elastic ep	0.3%

SoLID PV-DIS Experiment

Source	ΔA_{PV}
Beam polarization	0.4%
Rad. corrections	0.3%
Mom. transfer Q^2	0.5%
Inelastic ep	0.2%
Statistics	0.3%

Precision beam polarimetry is crucial to these experiments.

Precision Electroweak Experiments: Polarimetry

Compton Polarimetry

- $\vec{e}\vec{\gamma} \rightarrow e\gamma$ (polarized laser)
- Detection e and/or γ
- Only when beam energy above few hundred MeV
- High photon polarization but low asymmetry
- Total systematics $\sim 1\%$
 - laser polarization
 - detector linearity

Møller Polarimetry

- $\vec{e}\vec{e} \rightarrow ee$ (magnetized Fe)
- Low current because temperature induces demagnetization
- High asymmetry but low target polarization
- Levchuk effect: scattering off internal shell electrons
- Intermittent measurements at different beam conditions
- Total systematics $\sim 1\%$

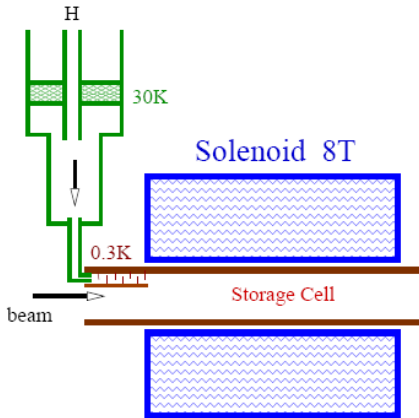
Atomic Hydrogen Polarimetry

New polarimetry concept¹

- 300 mK cold atomic H
- 8 T solenoid trap
- $3 \cdot 10^{16}$ atoms/cm²
- $3 \cdot 10^{15-17}$ atoms/cm³
- 100% polarization of e

Advantages

- High beam currents
- No Levchuk effect
- Non-invasive, continuous

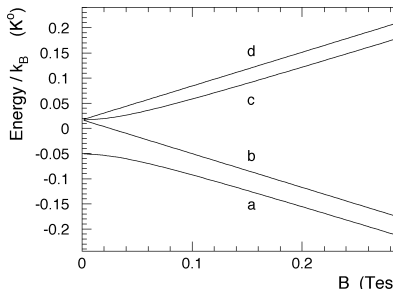


¹E. Chudakov, V. Luppov, *IEEE Trans. on Nucl. Sc.* 51, 1533 (2004).

Atomic Hydrogen Polarimetry: 100% Polarization of e

Hyperfine Splitting in Magnetic Field

- Energy splitting of $\Delta E = 2\mu B$:
 $\uparrow / \downarrow = \exp(-\Delta E/kT) \approx 10^{-14}$
- Low energy states with $|s_e s_p\rangle$:
 - $|d\rangle = |\uparrow\uparrow\rangle$
 - $|c\rangle = \cos\theta |\uparrow\downarrow\rangle + \sin\theta |\downarrow\uparrow\rangle$
 - $|b\rangle = |\downarrow\downarrow\rangle$
 - $|a\rangle = \cos\theta |\downarrow\uparrow\rangle - \sin\theta |\uparrow\downarrow\rangle$
 - with $\sin\theta \approx 0.00035$
- $P_e(\downarrow) \approx 1$ with only 10^5 dilution from $|\uparrow\downarrow\rangle$ in $|a\rangle$ at $B = 8\text{ T}$
- $P_p(\uparrow) \approx 0.06$ because 53% $|a\rangle$ and 47% $|b\rangle$



- Force $\vec{\nabla}(-\vec{\mu} \cdot \vec{B})$ will pull $|a\rangle$ and $|b\rangle$ into field

Atomic Hydrogen Polarimetry: Expected Contaminations

Without beam

- Recombined molecular hydrogen suppressed by coating of cell with superfluid He, $\sim 10^{-5}$
- Residual gasses, can be measured with beam to $< 0.1\%$

With $100\ \mu\text{A}$ beam

- 497 MHz RF depolarization for 200 GHz $|a\rangle \rightarrow |c\rangle$ transition, tuning of field to avoid resonances, uncertainty $\sim 2 \cdot 10^{-4}$
- Ion-electron contamination: builds up at 20%/s in beam region, cleaning with \vec{E} field of $\sim 1\text{ V/cm}$, uncertainty $\sim 10^{-5}$

Atomic Hydrogen Polarimetry: Projected Uncertainties

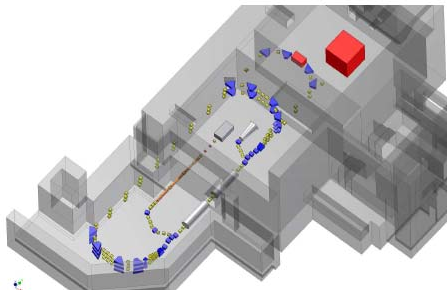
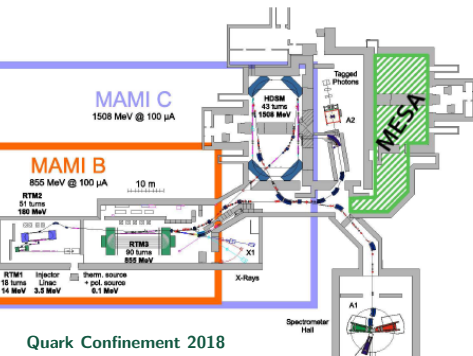
Projected Systematic Uncertainties ΔP_e in Møller polarimetry

Source	Fe-foil	Hydrogen
Target polarization	0.63%	0.01%
Analyzing power	0.30%	0.10%
Levchuk effect	0.50%	0.00%
Deadtime	0.30%	0.10%
Background	0.30%	0.10%
<i>Other</i>	0.30%	0.00%
<i>Unknown unknowns</i>	0.00%	0.30%(?)
Total	1.0%	0.35%

Atomic Hydrogen Polarimetry: Collaboration with Mainz

P2 Experiment in Mainz: Weak Charge of the Proton

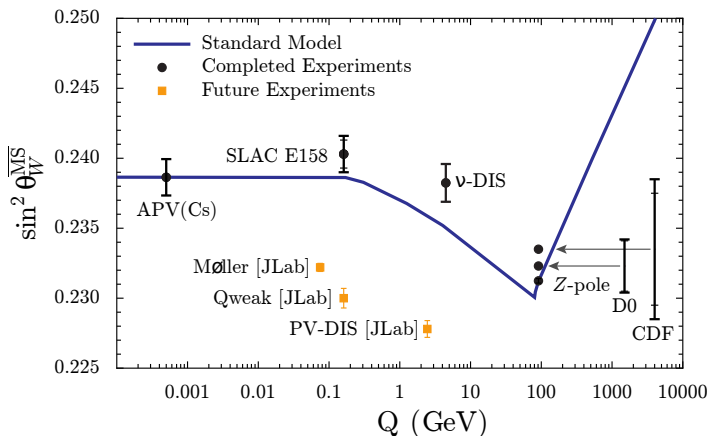
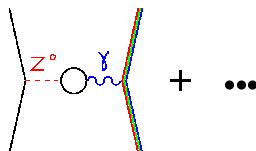
- “ Q_{Weak} experiment” with improved statistical precision
- Dedicated 200 MeV accelerator MESA under construction
- Required precision of electron beam polarimetry $< 0.5\%$
- Strong motivation for collaboration on a short timescale (installation in 2017)



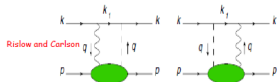
Parity-Violating Electron Scattering: Running of Weak Mixing Angle

Running of $\sin^2 \theta_W$ ($Q_W^p = 1 - 4 \sin^2 \theta_W$)

- Higher order loop diagrams
- $\sin^2 \theta_W$ varies with Q^2



γZ Box Corrections near 1.16 GeV



In 2009, Gorchtein and Horowitz showed the vector hadronic contribution to be significant and energy dependent.

This soon led to more refined calculations with corrections of $\sim 8\%$ and error bars ranging from $\pm 1.1\%$ to $\pm 2.8\%$.

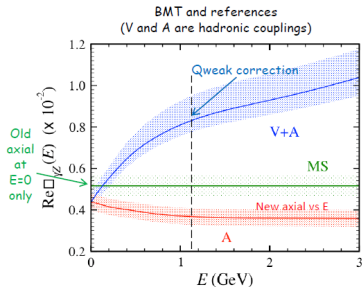
It will probably also spark a refit of the global PVES database used to constrain G_E^s , G_M^s , G_A .

PV Amplitude	Authors	Correction* @ E=1.165 (GeV)
$A^s \times V^p$ (vanishes as $E \rightarrow 0$)	GH	0.0026 \pm 0.0026**
	SBMT	0.0047 \pm 0.0011 \pm 0.0004
	RC	0.0057 \pm 0.0009
	GHR-M	0.0054 \pm 0.0020
$V^s \times A^p$ (finite as $E \rightarrow 0$)	MS (as updated by EKR-M)	0.0052 \pm 0.0005***
	BMT	0.0037 \pm 0.0004

*Does not include a small contribution from the elastic.

** 5.7% $\times Q_w^p(\text{LO}) = 0.0026$. $Q_w^p(\text{LO}) = 0.04532$.

***Included in Q_w^p . For reference, $Q_w^p = 0.0713(8)$.



Forthcoming axial results for Q_w^n have the potential to impact the interpretation of Cs APV.

1

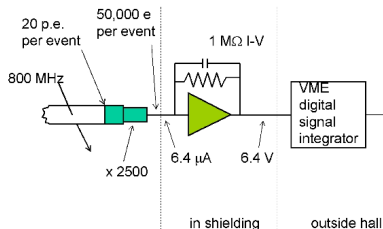
γZ Box Corrections near 1.16 GeV A Partial Bibliography

PV Amplitude	Authors	Reference
$A^e \times V^p$ (vanishes as $E \rightarrow 0$)	GH	Gorchtein & Horowitz, PRL 102 , 091806 (2009)
	SBMT	Sibirtsev, Blunden, Melnitchouk, and Thomas, PRD 82 , 013011 (2010)
	RC	Rislow & Carlson, PRD 83 , 113007 (2011)
	GHR-M	Gorchtein, Horowitz, and Ramsey-Musolf, PRC 84 , 015502 (2011)
$V^e \times A^p$ (finite as $E \rightarrow 0$)	MS	Marciano and Sirlin, PRD 27 , 552 (1983), PRD 29 , 75 (1984)
	EKR-M	Erlar, Kurylov, and Ramsey-Musolf, PRD 68 , 016006 (2003)
	BMT	Blunden, Melnitchouk, and Thomas, PRL 107 , 081801 (2011)

The Q_{Weak} Experiment: Main Detector

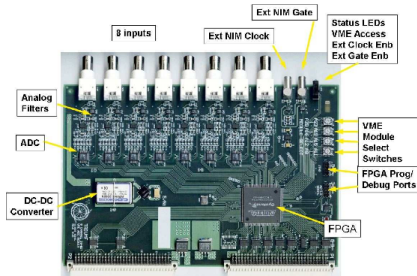
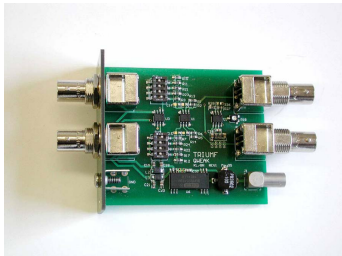
Low noise electronics

- Event rate: 800 MHz/PMT
- Asymmetry of only 0.2 ppm
- Low noise electronics (TRIUMF)



I-V Preamplifier

18-bit 500 kHz sampling ADC



The Q_{Weak} Experiment: Systematic Uncertainties

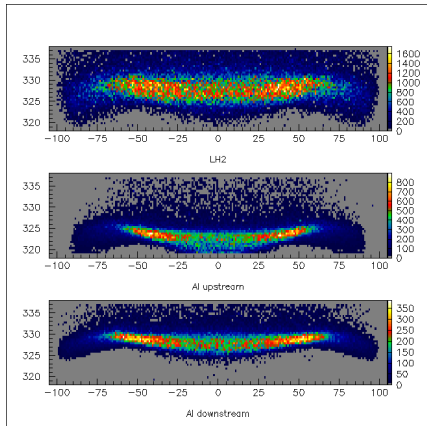
Reminder: weak vector charges

- Proton weak charge $Q_W^p \approx -0.072$
- Neutron weak charge $Q_W^n = -1$

Sources of neutron scattering

- Al target windows
- Secondary collimator events
- Small number of events, but huge false PV asymmetry

Al target windows



Electroweak Interaction: Running of Weak Mixing Angle

Atomic parity-violation on ^{133}Cs

- Porsev, Beloy, Derevianko¹: Updated calculations in many-body atomic theory
- Experiment: $Q_W(^{133}\text{Cs}) = -73.25 \pm 0.29 \pm 0.20$
- Standard Model: $Q_W(^{133}\text{Cs}) = -73.16 \pm 0.03$

NuTeV anomaly

- Reported 3σ deviation from Standard Model
- Erler, Langacker: strange quark PDFs
- Londergan, Thomas²: charge symmetry violation, $m_u \neq m_d$
- Cloet, Bentz, Thomas³: in-medium modifications to PDFs, isovector EMC-type effect

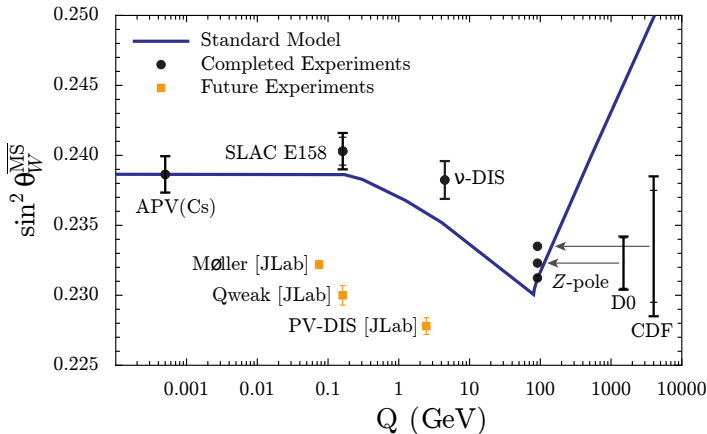
¹*Phys. Rev. Lett.* 102 (2009) 181601

²*Phys. Rev. D* 67 (2003) 111901

³*Phys. Lett. B* 693 (2010) 462-466

NuTeV Nuclear Correction

Isovector EMC effect¹ affects NuTeV point²

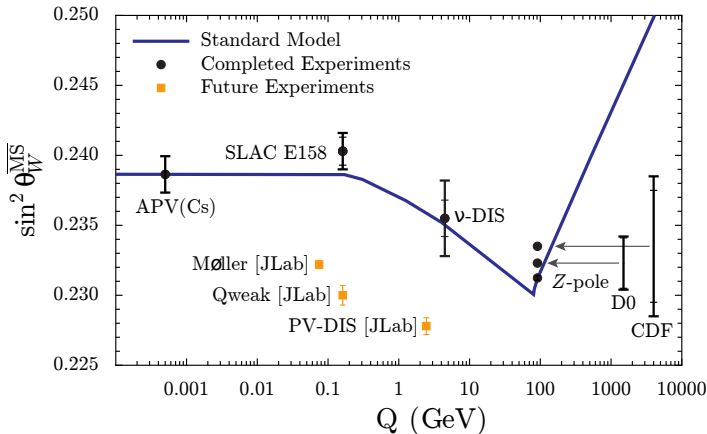


¹I. Cloët, W. Bentz, A. M. Thomas, *Phys. Rev. Lett.* 102, 252301 (2009)

²W. Bentz, *Phys. Lett. B* 693, 462-466 (2010)

NuTeV Nuclear Correction

Isovector EMC effect¹ affects NuTeV point²



¹I. Cloët, W. Bentz, A. M. Thomas, *Phys. Rev. Lett.* 102, 252301 (2009)

²W. Bentz, *Phys. Lett. B* 693, 462-466 (2010)