Precision Electroweak Measurements with Leptons and Nuclei

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WILLIAM & MARY

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There are Two Main Classes of Standard Model Tests

Energy frontier

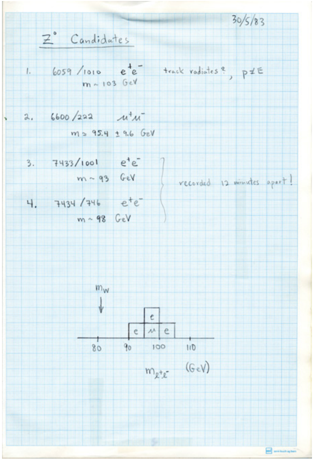
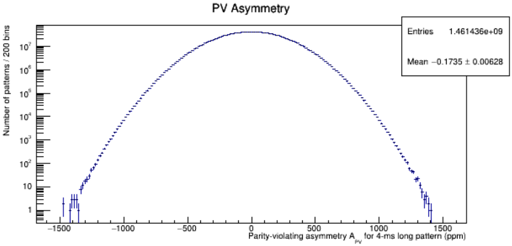


Image credit: James Rohlf, UA1/UA2

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 $1.7 \cdot 10^{39}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, accumulating $40\,\mathrm{fb}^{-1}$ in 20 seconds



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

Electroweak Interaction

Glashow–Weinberg–Salam theory of weak interaction

- Gauge symmetry: $SU(2)_L \times U(1)_Y$
- Gauge couplings: g for $SU(2)_L$, g' for $U(1)_Y$

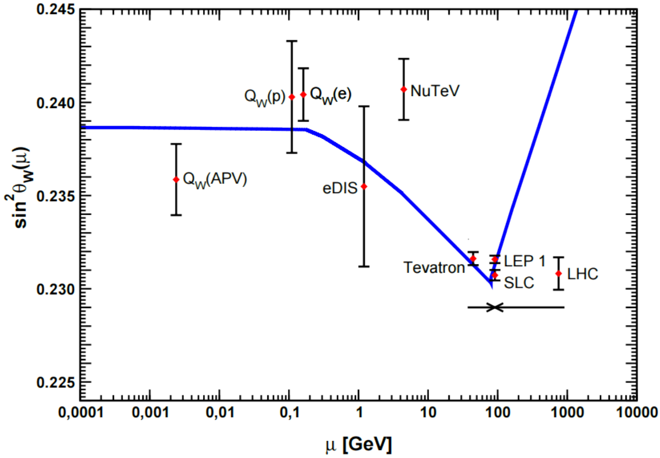
Electroweak symmetry breaking $(B_\mu, W^i_\mu \to A_\mu, Z^0_\mu, W^\pm_\mu)$

$$\sin^2\theta_W = \frac{g'^2}{g^2 + g'^2} = 0.23129 \pm 0.00005\,(\text{at } M_Z{}^1) \approx \frac{1}{4}$$

$$\begin{aligned} A_\mu &= \cos\theta_W \cdot B_\mu + \sin\theta_W \cdot W^3_\mu && (\text{massless}) \\ Z^0_\mu &= -\sin\theta_W \cdot B_\mu + \cos\theta_W \cdot W^3_\mu && (M_Z \approx 91.2\,\text{GeV}) \\ W^\pm_\mu &= (W^1_\mu \mp i W^2_\mu)/\sqrt{2} && (M_W = M_Z \cos\theta_W \approx 80.4\,\text{GeV}) \end{aligned}$$

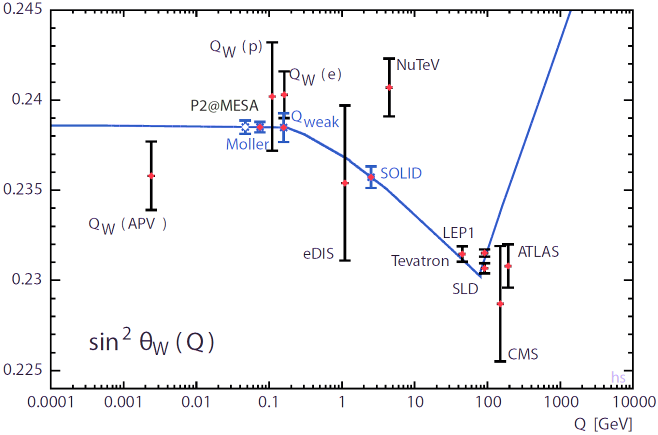
[1] *Review Particle Physics, J. Erler and A. Freitas, Chin. Phys. C, 40, 100001 (2016)*

Weak Mixing Angle Runs With Energy Scale



(Width of curve indicates theoretical uncertainty in $\overline{\text{MS}}$.)

Weak Mixing Angle Runs With Energy Scale



Electroweak Interaction

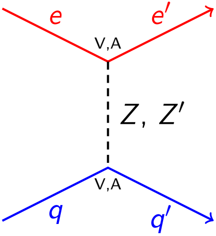
Parity symmetry is violated by $SU(2)_L$

- Weak interaction violates parity
- Electromagnetism conserves parity

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

$$\mathcal{L}^{NC}_{PV} = -\frac{G_F}{\sqrt{2}} \Big[g^e_A \left(\bar{e}\gamma_\mu\gamma_5 e\right) \cdot \sum_q g^q_V \left(\bar{q}\gamma^\mu q\right) + g^e_V \left(\bar{e}\gamma_\mu e\right) \cdot \sum_q g^q_A \left(\bar{q}\gamma^\mu\gamma_5 q\right) \Big]$$

$$= -\frac{G_F}{2\sqrt{2}} \Big[\sum_q C_{1q} \left(\bar{e}\gamma_\mu\gamma_5 e\right) \cdot \left(\bar{q}\gamma^\mu q\right) + \sum_q C_{2q} \left(\bar{e}\gamma_\mu e\right) \cdot \left(\bar{q}\gamma^\mu\gamma_5 q\right) \Big]$$



Several Electroweak Charges are Suppressed

Parity-violating electron scattering couplings

- Weak vector quark coupling: $C_{1q} = 2g_A^e g_V^q$ (γ^μ on q 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

Several Electroweak Charges are Suppressed

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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 charge of the neutron is large

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

Several Electroweak Charges are Suppressed

Parity-violating electron scattering couplings

- Weak vector quark coupling: $C_{1q} = 2g_A^e\, g_V^q$ (γ^μ on q vertex)
- 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

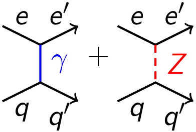
Accidental suppression of the weak axial charges in deep-inelastic scattering of quarks

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

Parity-Violating Asymmetries are Typically Small

Asymmetry between left and right incoming electron helicity

$$A_{PV} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \quad \text{with} \quad \sigma = \left| \text{(γ exchange)} + \text{(Z exchange)} + \ldots \right|^2$$



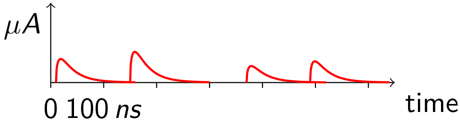
Interference of photon and weak boson exchange

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

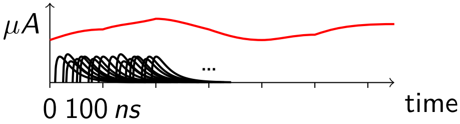
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{\mathcal{M}^{NC}_{PV}}{\mathcal{M}^{EM}} \propto \frac{Q^2}{M_Z^2} \propto G_F Q^2 \approx \mathcal{O}(\text{ppm}, \text{ppb}) \text{ when } Q^2 \ll M_Z^2$$

Strategy to Measure Parts-Per-Billion: Integration

Event or counting mode



Integrating or current 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

- 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

Parity-Violating Asymmetry to Access Electroweak Parameters

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 $Q^2 \to 0$, $\theta \to 0$ (plane wave):

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

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

$$A_{PV}(p) \propto -1 + 4\sin^2\theta_W$$

- Completed: Q_{Weak} at Jefferson Lab, $\sin^2\theta_W$ to ± 0.0010
- Planned: P2 at Mainz, $\sin^2\theta_W$ to ± 0.0003

Q_{Weak}: First Determination of the Weak Charge of the Proton

First experiment with direct access to proton's weak charge

- Experiment collected data between 2010 and 2012 with toroidal spectrometer and integrating quartz detectors[1]
- Preliminary results were published in 2013 based on commissioning data[2] (4% compared to the independent full data set)
- Today presenting uncertainty for full data set (but not central value)

Long awaited final results really soon now, I promise

- Unblinding happened on March 31, 2017
- Publication and release of unblinded result at PANIC'17 in Beijing:
  - Sunday September 3, 2017, at 12:15pm in PANIC plenary session
  - Monday September 4, 2017, at 11am in JLab colloquium (TBC)

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

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

Q_{Weak}: First 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

Q_{Weak}: First 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	
Beamline Background: A_{BB}	5.1	1.2	
Beam Asymmetries: A_{beam}	4.7	1.2	Note:
Rescattering bias: A_{bias}	3.4	3.4	correlations
Beam Polarization: P	2.2	(1.2)	between
Al target windows: A_{b1}	(1.9)	1.9	factors
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%)

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

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

Q_{Weak}: First Determination of the Weak Charge of the Proton

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

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

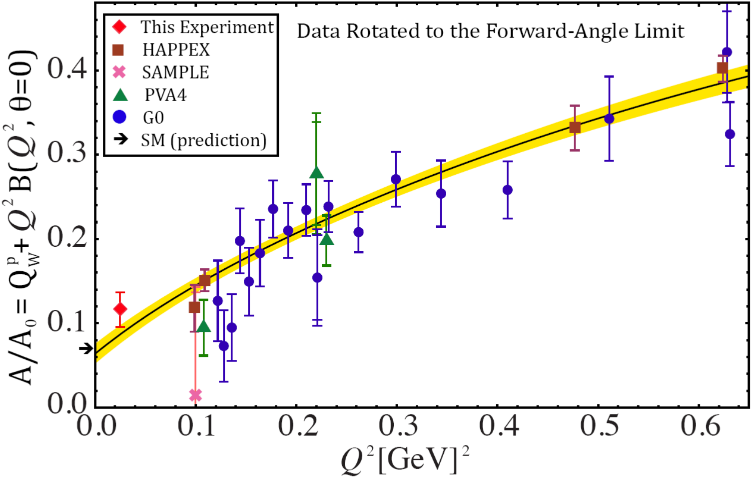
Global fit[1] of all parity-violating electron scattering with 4% data[2]

- Fit of parity-violating asymmetry data on H, D, ^{4}He, $Q^2 < 0.63\,\text{GeV}^2$
- Free parameters are C_{1u}, C_{1d}, strange charge radius ρ_s and magnetic moment μ_s ($G^s_{E,M} \propto G_D$), and isovector axial form factor $G_A^{Z,T=1}$
  - $Q_W^p(\text{SM}) = 0.0710 \pm 0.0007$ (theoretical expectation)
  - $Q_W^p(\text{PVES}) = 0.064 \pm 0.012$ (global fit of 4% data[2])
  - After combination with atomic parity-violation on Cs:
    - $C_{1u} = -0.1835 \pm 0.0054$
    - $C_{1d} = 0.3355 \pm 0.0050$

[1] *R. Young, R. Carlini, A.W. Thomas, J. Roche, Phys. Rev. Lett. 99, 122003 (2007)*
[2] *First Determination of the Weak Charge of the Proton, Phys. Rev. Lett. 111, 141803 (2013)*

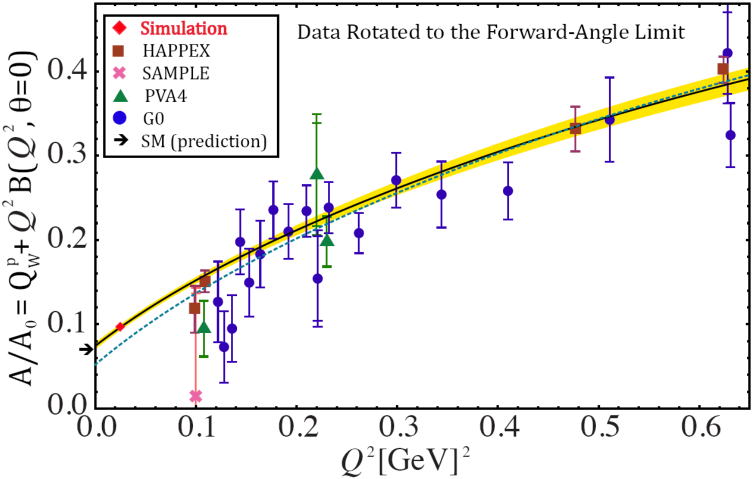
Q_{Weak}: First Determination of the Weak Charge of the Proton:

Based on commissioning run data set (4% compared to full data set):



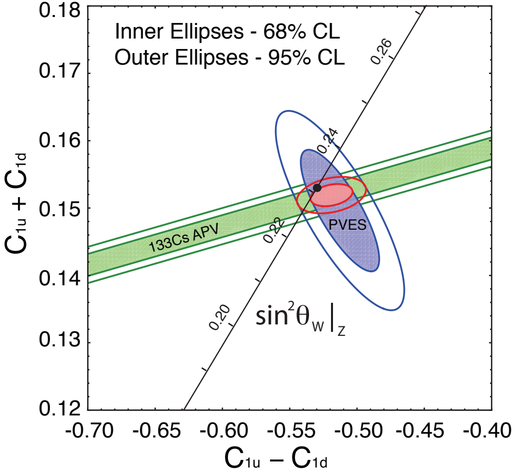
Q_{Weak}: First Determination of the Weak Charge of the Proton:

Uncertainty of the full data set, but with central value fixed at SM:



Q_{Weak}: Determination of the Weak Vector Charge of the Proton

Based on commissioning run data set (4% compared to full data set):



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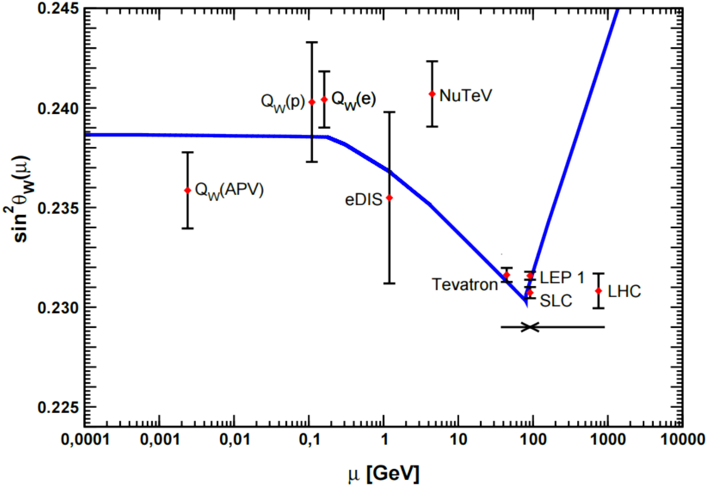


Q_{Weak}: Determination of the Weak Vector Charge of the Proton

New global fit of all parity-violating electron scattering with full data set

- Fit of parity-violating asymmetry data on H, D, ^{4}He, $Q^2 < 0.63\,\text{GeV}^2$
- Free parameters were C_{1u}, C_{1d}, strange charge radius ρ_s and magnetic moment μ_s ($G^s_{E,M} \propto G_D$), and isovector axial form factor $G_A^{Z,T=1}$
- But also consider improved knowledge of strangeness form factors:
  - Without lattice QCD: leave ρ_s and μ_s free in G^s_E and G^s_M
  - With lattice QCD: using G^s_E and G^s_M from lattice QCD[1]

$$
\begin{aligned}
Q_W(p)(4\%) &= 0.064 \pm 0.0120 \\
\text{PRELIM}\ Q_W(p)(\text{full}) &= 隐 \pm 0.0047 \quad \text{(Qweak, with LQCD)} \\
\text{PRELIM}\ Q_W(p)(\text{full}) &= 隐 \pm 0.0044 \quad \text{(PVES, without LQCD)} \\
\text{PRELIM}\ Q_W(p)(\text{full}) &= 隐 \pm 0.0037 \quad \text{(PVES, with LQCD)}
\end{aligned}
$$

[1] *J. Green et al, Phys. Rev. D92, 031501 (2015)*

Q_{Weak}: Determination of the Weak Vector Charge of the Proton

From weak charge to $\sin^2\theta_W$ with radiative corrections

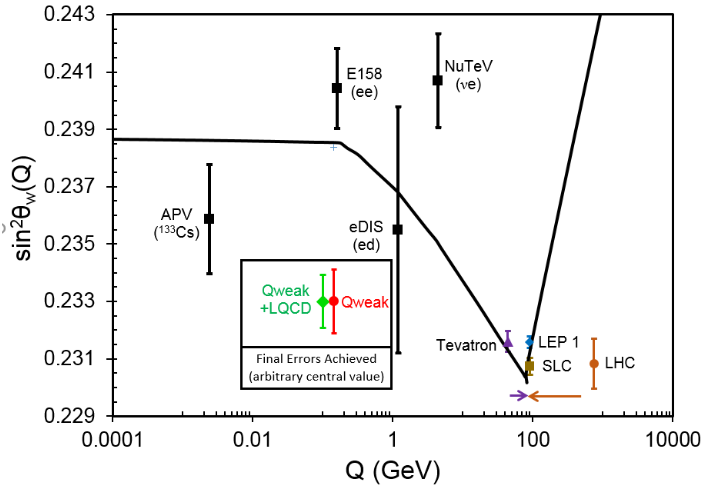
- $Q_W^p = (\rho_{NC} + \Delta_e)(1 - 4\sin^2\theta_W(0) + \Delta'_e) + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$
- $\Delta\sin^2\theta_W(M_Z)$, $\Box_{WW}$, $\Box_{ZZ}$ box diagrams: uncertainties small
- $\Box_{\gamma Z} = 0.00459 \pm 0.00044$ for Q_{Weak} conditions ($E = 1.165\,\mathrm{GeV}$)

PRELIM $\sin^2\theta_W$ = 隐 $\pm$ 0.0011 (PVES, without LQCD)

PRELIM $\sin^2\theta_W$ = 隐 $\pm$ 0.0009 (PVES, with LQCD)

Q_{Weak}: Determination of the Weak Vector Charge of the Proton

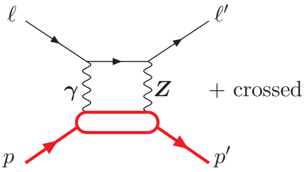
PRELIMINARY

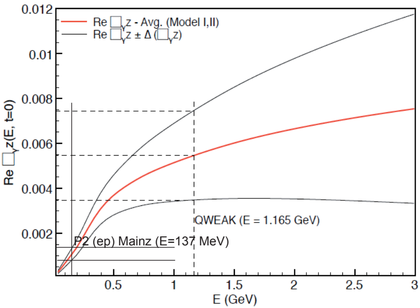


P2: High Precision Measurement of Proton's Weak Charge

Radiative corrections on weak charge

- $Q_W^p = (\rho_{NC} + \Delta_e)(1 - 4\sin^2\theta_W(0) + \Delta'_e) + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$
- $\Box_{\gamma Z}$: relatively large correction and uncertainty[1]
- Improving measurements of Q_W^p benefits from smaller beam energies



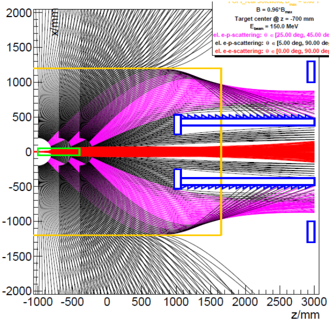


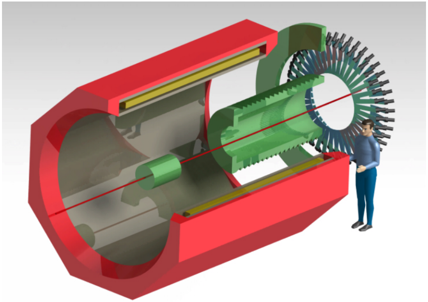
[1] M. Gorchtein, C. J. Horowitz, M. J. Ramsey-Musolf, Phys. Rev. C 84, 015502 (2011)

P2: High Precision Measurement of Proton's Weak Charge

New Experiment: P2 Experiment in Mainz[1]

- 155 MeV energy-recovery superconducting accelerator MESA
- Projected precision of $\sin^2\theta_W$ of 0.00032 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





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

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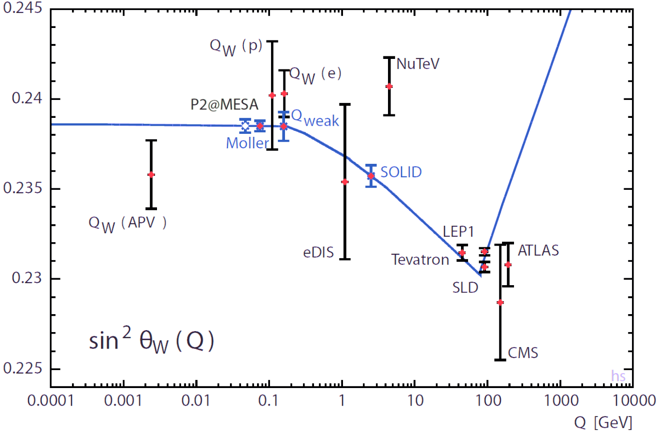


Proton's Weak Charge: If In Agreement with Standard Model

Effective four-point interactions of some higher mass scale[1]

$$\mathcal{L}^{PV}_{e-q} = -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q} \bar{q}\gamma^\mu q + \frac{1}{4}\frac{g^2}{\Lambda^2} \bar{e}\gamma_\mu\gamma_5 e \sum_q h^V_q \bar{q}\gamma^\mu q$$

Limits on new physics energy scale if uncertainty ΔQ^p_W

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

Assuming $\Delta Q^p_W = 0.005$ and central value exactly at SM value:

- $\frac{\Lambda}{g} > 7.4\,\text{TeV}$ at 95% C.L.; or $\Lambda > 26.4\,\text{TeV}$ for $g^2 = 4\pi$

For P2 experiment: precision to exclude PV interactions with $\Lambda > 50\,\text{TeV}$

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

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

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)

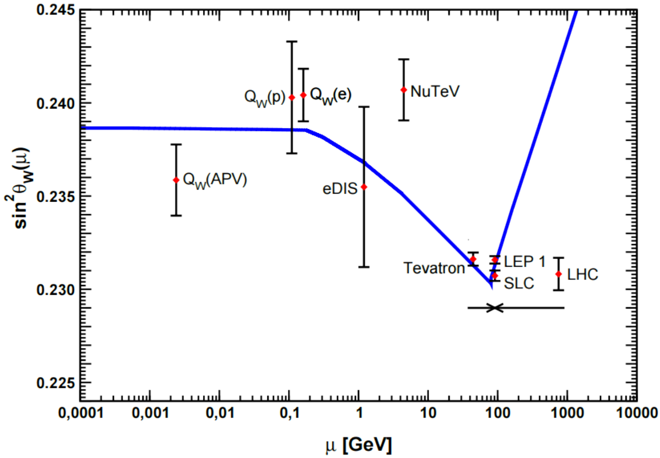
$$A_{PV}(e) \propto Q_W^e$$

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

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

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

Weak Mixing Angle Runs With Energy Scale



(Width of curve indicates theoretical uncertainty in $\overline{\text{MS}}$.)

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

Most precise measurement of $\sin^2\theta_W$ at low energy[1]

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

Pushing the envelope of intensity

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

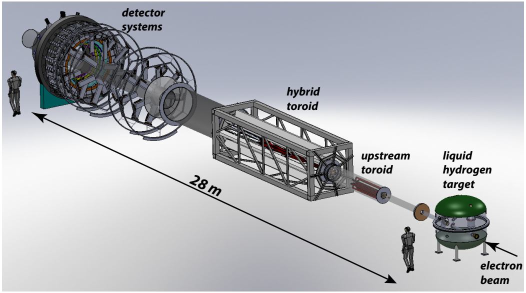
Pushing the envelope of precision

- Electron beam polarization precision of 0.4% at 11 GeV

[1] *The MOLLER Experiment, arXiv:1411.4088*

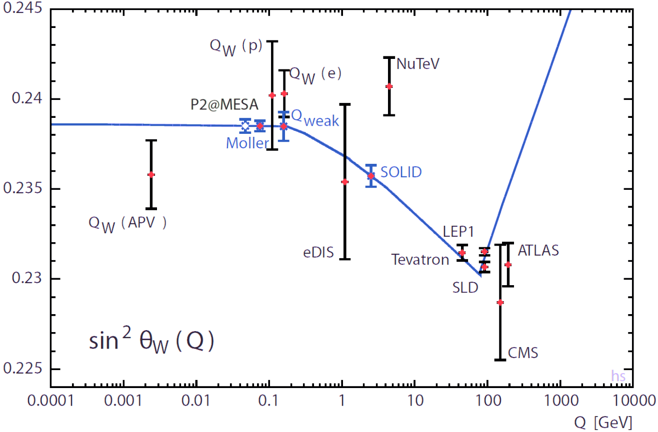
MOLLER: Ultra-Precise Measurement of Electron's Weak Charge

Forward toroidal spectrometer with 7-fold symmetry

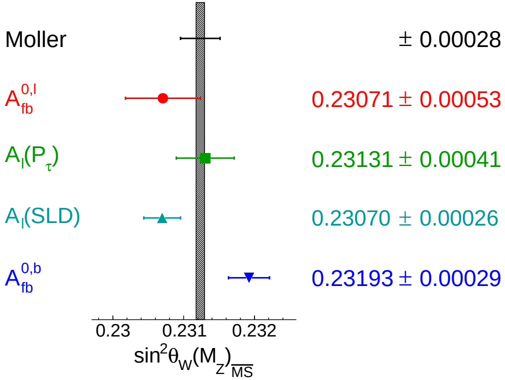


- Long, narrow hybrid toroidal spectrometer system to select forward events
- Passed Department of Energy CD-0, approximately $25M project
- Anticipated running in the first half of 2020s, hopefully before LHC-HL

Weak Mixing Angle Runs With Energy Scale

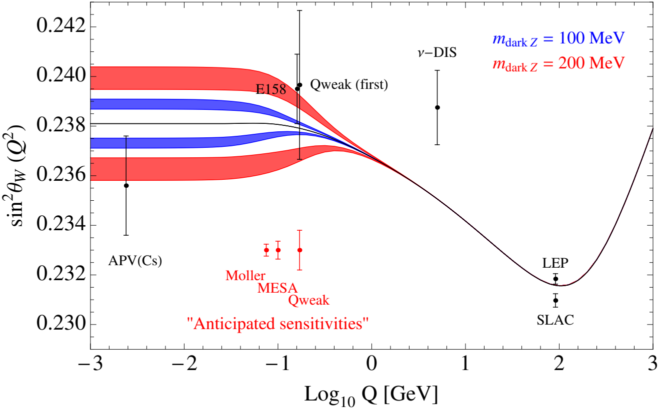


MOLLER: Ultra-Precise Measurement of Electron's Weak Charge



Weak Vector Charges: If In Disagreement with Standard Model

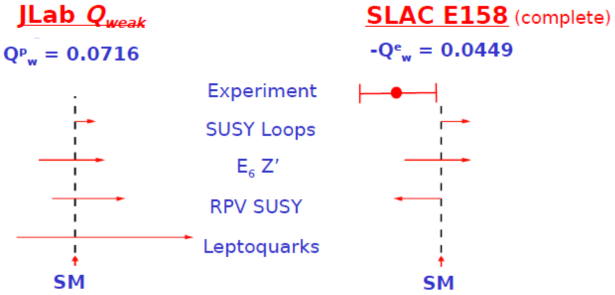
Sensitivity to dark Z bosons[1] (which accommodated muon $g-2$)

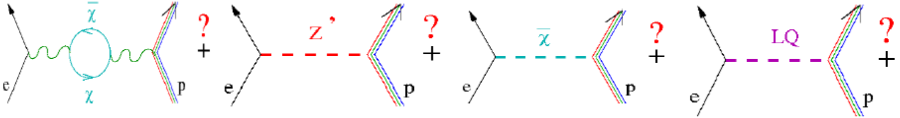


[1] *H. Davoudiasl, H.-S. Lee, W. J. Marciano, Phys. Rev. D 89, 095006 (2014)*

Weak Vector Charges: If In Disagreement with Standard Model

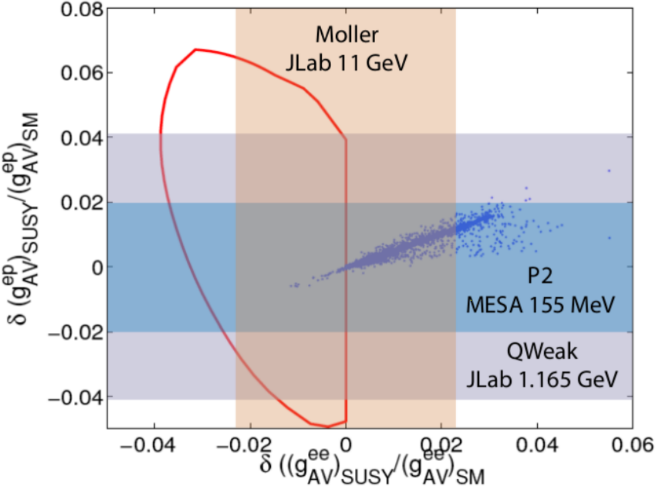
Different experiments sensitive to different extensions





RPC SUSY | Generic Z' | RPV SUSY | Leptoquarks

Weak Vector Charges: If In Disagreement with Standard Model



Dots: MSSM models, Contour: R-parity violating supersymmetry

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

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:

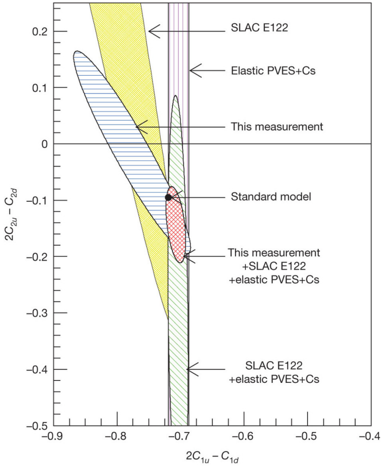
$$A_{PV}(d) = \frac{G_F Q^2}{\pi\alpha\sqrt{2}} \frac{3}{10} \left[(2C_{1u} - C_{1d}) + (2C_{2u} - C_{2d}) \frac{1-(1-y)^2}{1+(1-y)^2} \right]$$

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

PV-DIS: Measurement of Weak Axial Quark Couplings

Jefferson Lab 6 GeV spectrometers

- Kinematic conditions determine coefficient in combination of a_1 and a_2
- Constraint to a different orientation in $2C_{2u} - C_{2d}$ vs $2C_{1u} - C_{1d}$
- First evidence at 95% C.L. that the weak axial quark couplings C_{2q} are non-zero (even if small)
- Exclusion limits for contact interactions $\Lambda^- > 4.8\,\text{TeV}$ and $\Lambda^+ > 5.8\,\text{TeV}$ at 95% C.L.

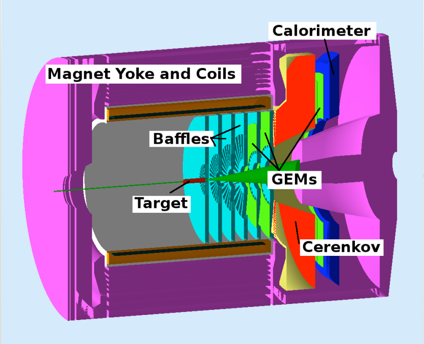


[1] *Nature 506, p67 (2014)*

SoLID: Precision Measurement of Weak Axial Quark Couplings

Solenoidal Large Intensity Device

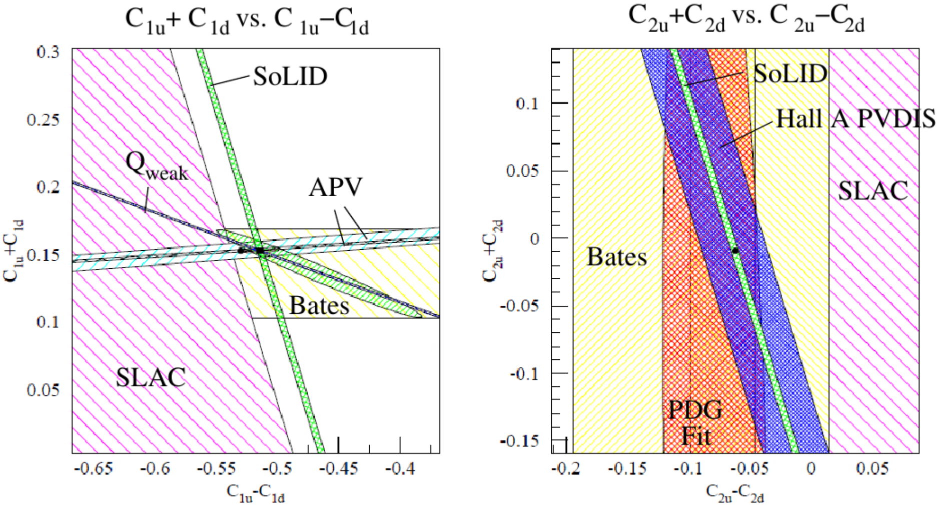
- $2\,\text{GeV} < p < 8\,\text{GeV}$
- $2\,\text{GeV}^2 < Q^2 < 10\,\text{GeV}^2$
- $0.2 < x < 1$
- 40% azimuthal acceptance
- $\mathcal{L} \approx 5 \cdot 10^{35}\,\text{s}^{-1}\text{cm}^{-2}$
- Counting mode (PID)



Experimental design

- Counting mode at rate $> 200\,\text{kHz}$, 30 independent sectors
- Baffles filter low energy and neutral particles (no line of sight)
- Light gas Čerenkov for 1000–200 : 1 rejection of low-E π^-
- Electromagnetic calorimeter for 50 : 1 π^- rejection

Projected constraints on weak quark couplings



SoLID: Precision Measurement of Weak Axial Quark Couplings

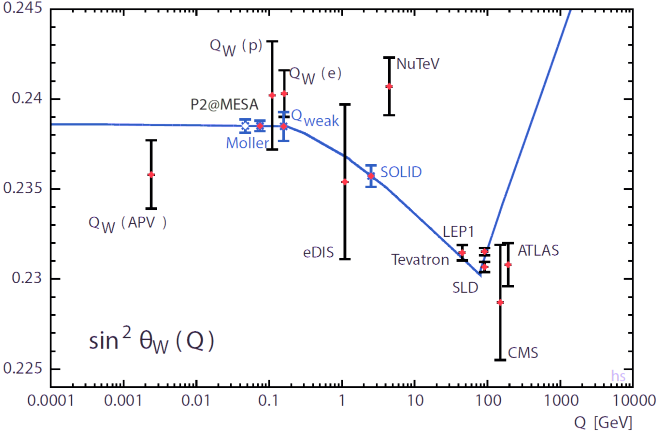
Multipurpose detector and collaboration

- Additional physics goals for SoLID: J/ψ, SIDIS, transversity
- Large investment, at least \$65M

Involvement of many Chinese groups in SoLID

- 3 proposed experiments have co-spokespersons at Chinese institutions, 10 universities are collaborating institutions
- Significant Chinese contributions in R&D for 3 detector systems
  - Large GEM: USTC, CIAE, Lanzhou, Tsinghua and IMP
  - Shashlyk-style ECal: Shandong, Tsinghua
  - MRPC-TOF: Tsinghua, USTC
- Yearly Hadron-China workshop
- R&D funding from NSFC

Weak Mixing Angle Runs With Energy Scale



SoLID: Measuring Hadronic Structure Through PV-DIS

Analogy with Deep Inelastic Scattering

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left(\frac{2}{M} F_1(x) \sin^2 \frac{\theta}{2} + \frac{1}{\nu} F_2(x) \cos^2 \frac{\theta}{2} \right)$$

Quark structure through **DIS**

- $F_2(x) = x \sum_q e_q^2 (q + \bar{q}) \approx 2x F_1(x)$ (Callan-Gross)

Quark structure through **PV-DIS**: interference of γZ

- $F_2^{\gamma Z}(x) = x \sum_q e_q g_q^V (q + \bar{q}) \to a_1(x) \sim \sum_q e_q C_{1q} (q + \bar{q})$
- $F_3^{\gamma Z}(x) = x \sum_q e_q g_q^A (q - \bar{q}) \to a_3(x) \sim \sum_q e_q C_{2q} (q - \bar{q})$

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

Parity-Violating Asymmetry to Access Electroweak Parameters

Weak charge of nuclei (elastic scattering)

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

- 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

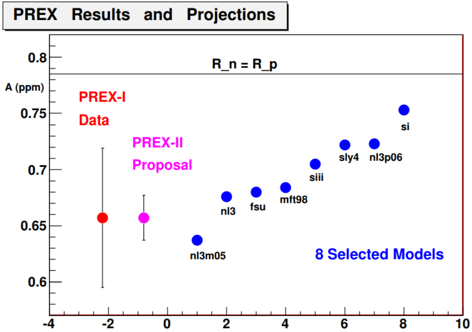
$$A_{PV}(A) \propto N Q_W^n \propto 2C_{1d} + C_{1u}$$

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

PREX and CREX: Neutron Density Distributions for Astrophysics

Standard Jefferson Lab spectrometers

- PREX-I: 1 GeV beam energy on Pb, reached systematic goals, but statistics limited: R_n is different from R_p at 95% C.L.
- PREX-II: scheduled for 'soon', recently completed experimental readiness reviews (2018)
- CREX on Calcium to run in same experiment run group



Constraints on equation of state of neutron matter

- Pressure as function of density, $P(\rho)$
- Impact from $R_n - R_p$ on neutron star radii

So much to present, so little time...

I hope to have given you a flavor of the electron scattering subfield maybe most closely relevant to high energy physics, and I apologize for any areas left out of this short presentation.

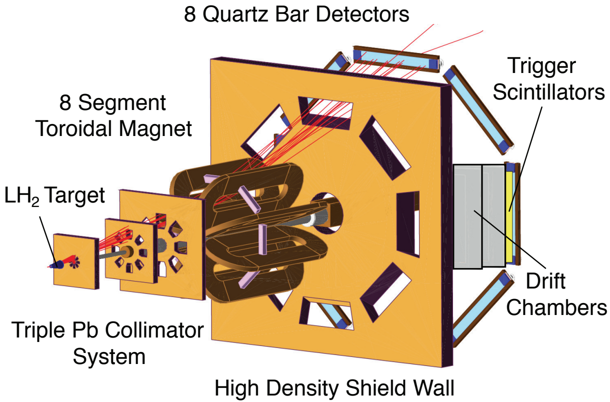
Parity-violating electron scattering can explore the tiny effects of the electroweak sector by leveraging the enormous number of detected electrons, sometimes in a more general way than electroweak factories (e.g. Z-pole).

In particular, the Q_{Weak} *experiment recently completed an ambitious determination of* $\sin^2\theta_W$ *with a total uncertainty of* ± 0.0010 *and sensitivity to physics at the multi-TeV scale.*

Additional Material

First Determination of Proton's Weak Charge

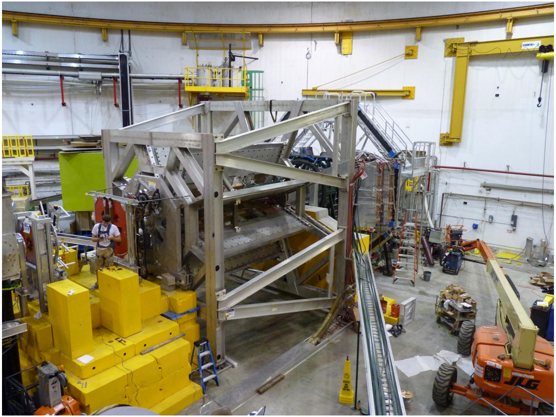
Q_{Weak} Experiment: Collimator-Magnet-Collimator[1]



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

First Determination of Proton's Weak Charge

Q_{Weak} Experiment: Collimator-Magnet-Collimator[1]



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

Q_{Weak}: Largest Uncertainties in Preliminary Q_{Weak} Result

All uncertainties in ppb	Commissioning run (4%) ΔA_{corr}	$\delta(A_{PV})$	
Beam polarization P	-21		5
Kinematics R_{total}	5		9
Dilution $1/(1-\sum f_i)$	-7		
Beam asymmetry	-40		13
Transverse pol. A_T	0		5
Detector non-linearity	0		4
Backgrounds:		$\delta(f_i)$	$\delta(A_i)$
Aluminum (b_1)	-58	4	8
Beamline (b_2)	11	3	23
Neutrals (b_3)	0	1	1
Inelastic (b_4)	1	1	1

Q_{Weak}: Largest Uncertainties in Precision Q_{Weak} Result

	Full data run 1			Full data run 2		
All uncertainties in ppb	ΔA_{corr}	$\delta(A_{PV})$		ΔA_{corr}	$\delta(A_{PV})$	
Beam polarization P	-23		2	-21		1
Kinematics R_{total}	7		2	5		2
Dilution $1/(1-\sum f_i)$	-6			-6		
Beam asymmetry	21		5	0		1
Transverse pol. A_T	0		1	0		1
Detector non-linearity	0		1	0		1
Charge normalization	0		5	0		2
Rescattering bias	4		3	4		3
Beamline (b_2)	4		5	-3		1
Backgrounds:		$\delta(f_i)$	$\delta(A_i)$		$\delta(f_i)$	$\delta(A_i)$
Aluminum (b_1)	-37	1	2	-38	1	2
Neutrals (b_3)	0.5	< 1	< 1	0.5	< 1	< 1
Inelastic (b_4)	0.6	< 1	< 1	0.6	< 1	< 1

Q_{Weak}: Largest Uncertainties in Precision Q_{Weak} Result

	Run 1		Run 2	
All uncertainties in ppb	$\delta(A_{PV})$	fraction	$\delta(A_{PV})$	fraction
Charge Normalization: A_{BCM}	5.1	25%	2.3	17%
Beamline Background: A_{BB}	5.1	25%	1.2	5%
Beam Asymmetries: A_{beam}	4.7	22%	1.2	5%
Rescattering bias: A_{bias}	3.4	11%	3.4	37%
Beam Polarization: P	2.2	5%	$< 5\%$	
Al target windows: A_{b1}		$< 5\%$	1.9	12%
Kinematics: R_{Q^2}		$< 5\%$	1.3	5%
Total of others	3.4	11%	2.5	20%
Combined in quadrature	10.1		5.6	

Q_{Weak}: Largest Uncertainties in Precision Q_{Weak} Result

All uncertainties in ppb	Run 1 $\delta(A_{PV})$	Run 2 $\delta(A_{PV})$
Charge Normalization: A_{BCM}	5.1	2.3
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
Combined in quadrature	10.1	5.6

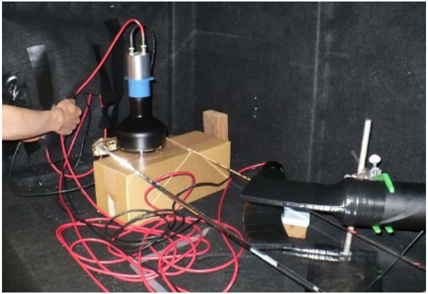
Q_{Weak}: Largest Uncertainties in Precision Q_{Weak} Result

Period	ΔA(stat)	ΔA(syst)	ΔA(total)
Commissioning result: $A_{PV} = -279$	35	31	47
Run 1	15.0	10.1	18.0
Run 2	8.3	5.6	10.0
Precision result:	7.3	5.8	9.3

The Q_{Weak} Experiment: Main Detector

Azimuthal array of Čerenkov detector

- 8 fused silica radiators, 2 m long × 18 cm × 1.25 cm
- Pb preradiator tiles to suppress low-energy/neutral yield
- 5 inch PMTs with gain of 2000, low dark current
- 800 MHz electron rate per bar, defines counting noise



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 ($\vec{e} + \vec{e} \to e + e$)

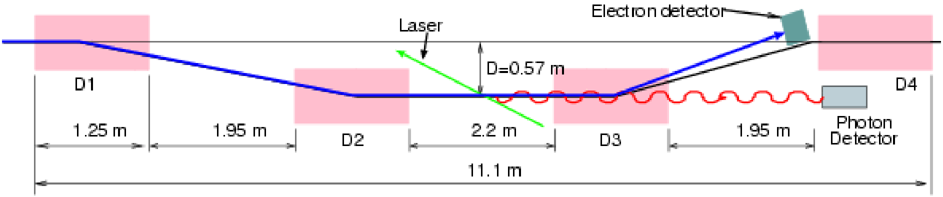
- Scattering off atomic electrons in magnetized iron foil
- Limited to separate, low current runs ($I \approx 1\,\mu$A)

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

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

Compton polarimeter

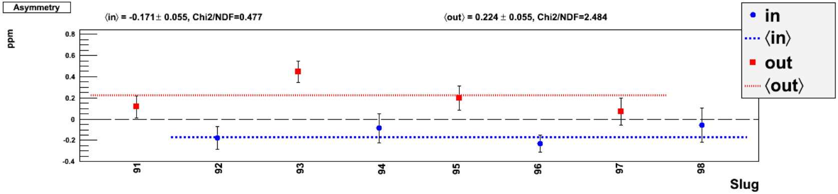
- Beam: 150 μA at 1.165 GeV
- Chicane: interaction region 57 cm below straight beam line
- Laser system: 532 nm green laser
  - 10 W CW laser with low-gain cavity
- Photons: $PbWO_4$ scintillator in integrating mode
- Electrons: Diamond strips with 200 μm pitch



Data Quality: Slow Helicity Reversal

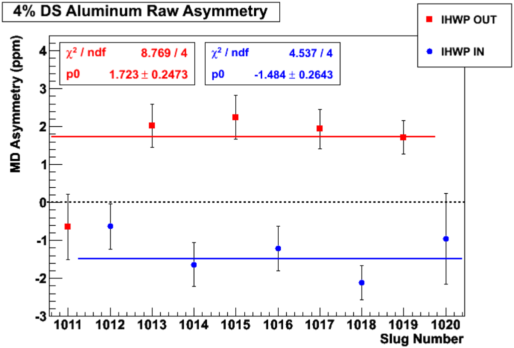
$\lambda/2$-plate and Wien filter changes

- Insertable $\lambda/2$-plate (IHWP) 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



Ancillary Measurements: Aluminum Target Walls

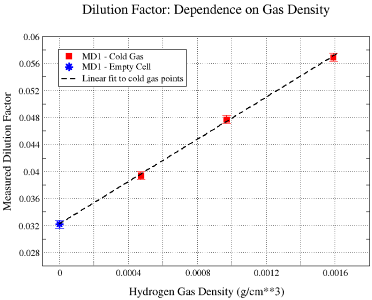
Aluminum asymmetry (preliminary)



- Asymmetry consistent with order of magnitude expected

- Asymmetry: few ppm
- Dilution f of 3%
- Correction ≈ 20%

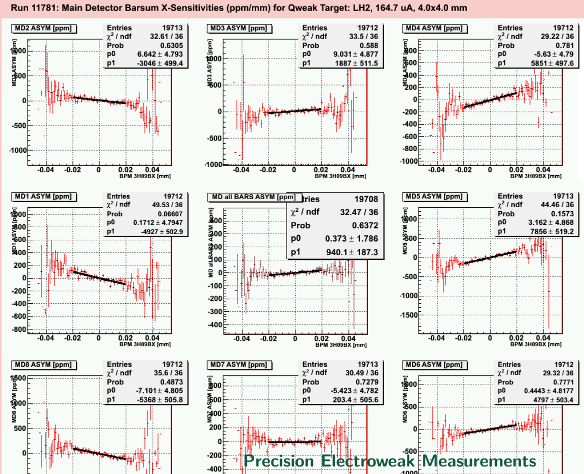
Dilution measurement



Helicity-Correlated Beam Properties Are Understood

Measured asymmetry depends on beam position, angle, energy

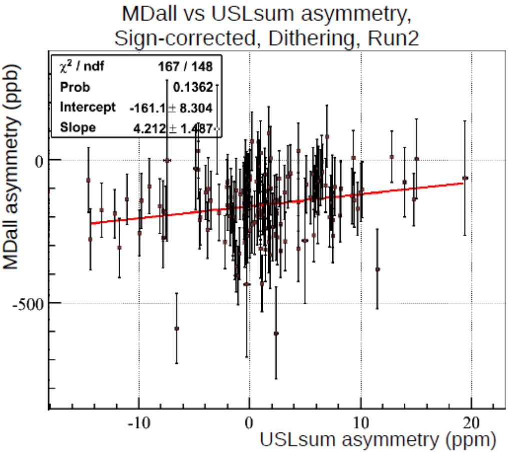
- Well-known and expected effect for PVES experiments
- “Driven” beam to check sensitivities from “natural” jitter



However, Some Beamline Background Correlations Remain

After regression, correlation with background detectors

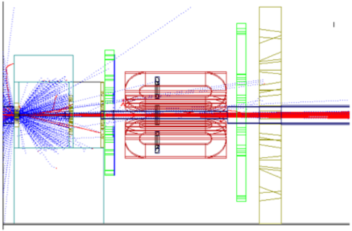
- Luminosity monitors & spare detector in super-elastic region
- Background asymmetries of up to 20 ppm (that's huge!)

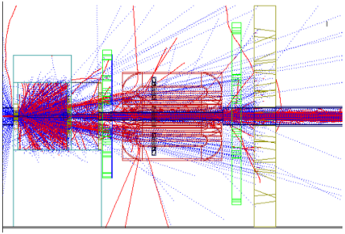


Beamline Background Correlations Remain

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”



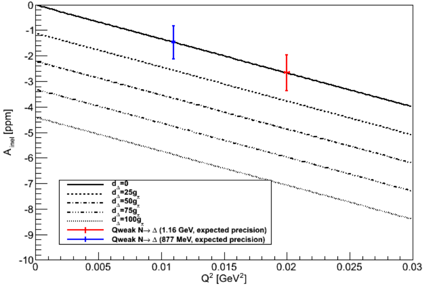


Qualitatively new background for PVES experiments at JLab

- Second regression using asymmetry in background detectors
- Measurements with blocked octants to determine dilution factor ($f_{b_2}^{MD} = 0.19\%$)

Ancillary Measurements: Inelastic Transitions

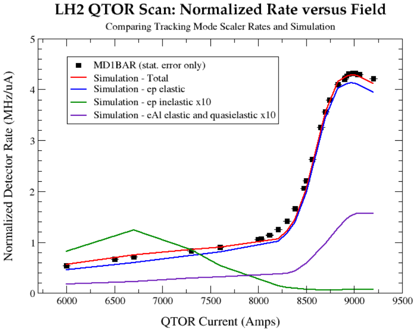
$N \to \Delta$ asymmetry (projected)



- Expected precision 1 ppm
- $Q^2 = 0.025\,\text{GeV}^2$

- Expected asymmetry: few ppm
- Dilution f of 0.1%
- Correction $\approx$ 1%

Simulation benchmark (preliminary)



Ancillary Measurements: Transverse Asymmetry

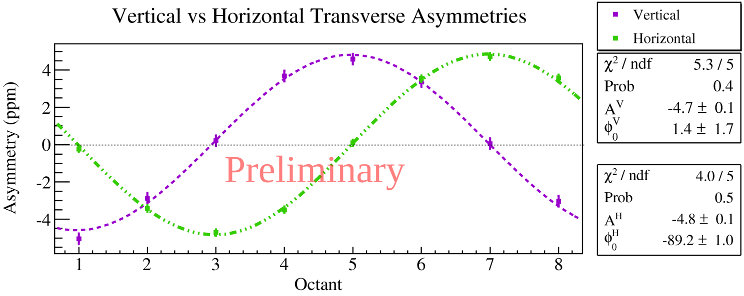
Transverse single spin asymmetries

- Some transverse polarization, slightly broken azimuthal symmetry
- Measure with transversely polarized beam (H or V)
- Parity-conserving T-odd transverse asymmetry of order ppm

$$B_n = \frac{2\Im(T_{1\gamma}^* \cdot T_{2\gamma})}{|T_{1\gamma}|^2}$$

- Access to imaginary part of 2-photon exchange amplitude $T_{2\gamma}$
  - elastic $\vec{e}p$ in H, C, Al at $E = 1.165\,\text{GeV}$
  - inelastic $\vec{e}p \to \Delta$ in H, C, Al at $E = 0.877\,\text{GeV}$ and $1.165\,\text{GeV}$
  - elastic $\vec{e}e$ in H at $E = 0.877\,\text{GeV}$
  - deep inelastic $\vec{e}p$ in H at $W = 2.5\,\text{GeV}$
  - pion electro-production in H at $E = 3.3\,\text{GeV}$

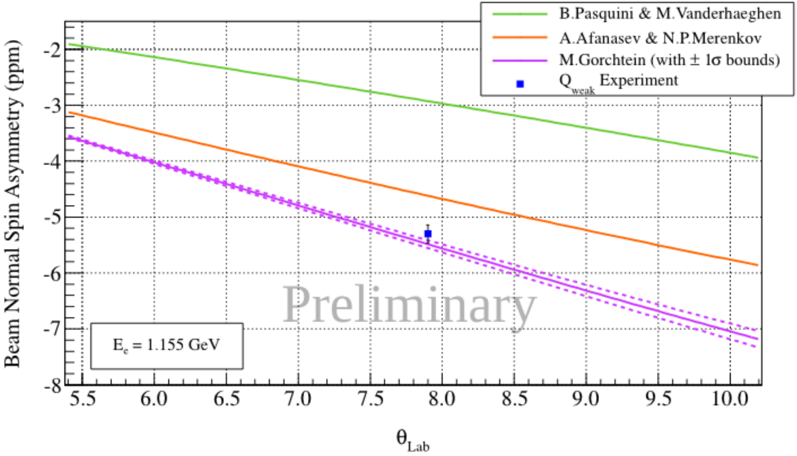
Ancillary Measurements: Transverse Asymmetry on H



- Shown asymmetries not corrected for backgrounds or polarization
- Preliminary transverse asymmetry in $\vec{e}p$ in hydrogen:
  $B_n = -5.35 \pm 0.07(\text{stat}) \pm 0.15(\text{syst})\,\text{ppm}$
- More precise than any other measurement by a factor 5

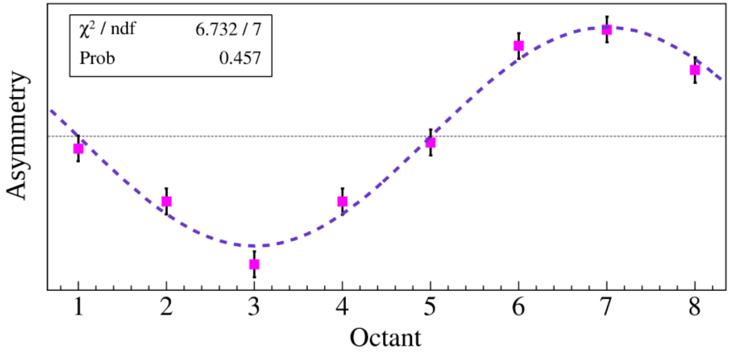
Ancillary Measurements: Transverse Asymmetry on H

Theoretical interpretation



Ancillary Measurements: Transverse Asymmetry on C, Al

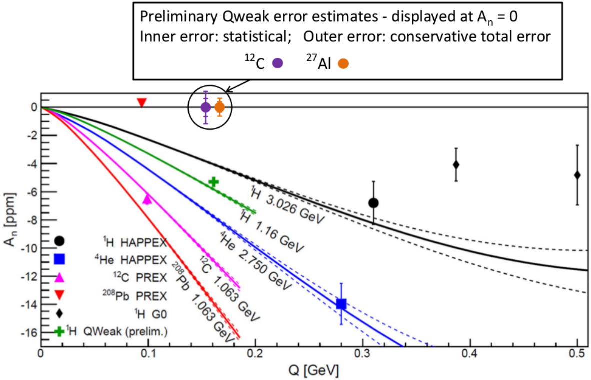
Aluminum: non-zero transverse asymmetry (uncorrected data)



- Aluminum target was alloy with ~10% contamination
- Needs corrections for quasielastic and inelastic scattering, and for nuclear excited states(?)

Ancillary Measurements: Transverse Asymmetry on C, Al

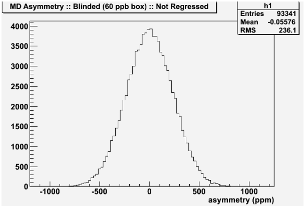
Projected uncertainties for C and Al transverse asymmetries



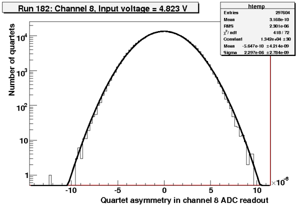
- Theory from Phys. Rev. C77, 044606 (2008)
- Pb data from PRL 109, 192501 (2012)

Data Quality: Understanding the Asymmetry Width

Asymmetry width



Battery width



Measurement

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

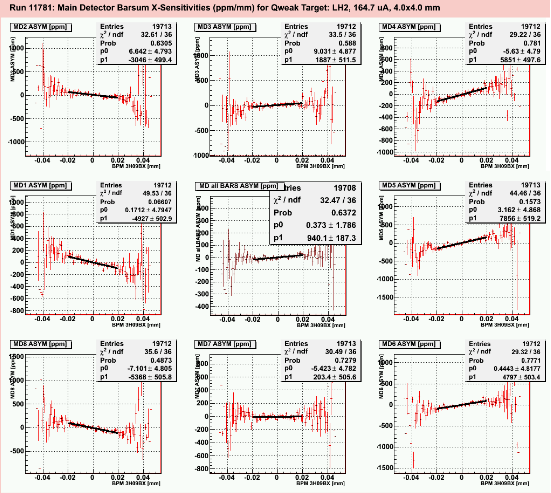
Asymmetry width

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

Data Quality: Helicity-Correlated Beam Properties

Natural beam motion

- Measured asymmetry correlated with beam position and angles
- Linear regression:
  $A_c = \sum_i \frac{\partial A}{\partial x_i} \Delta x_i$
  $i = x, y, x', y', E$



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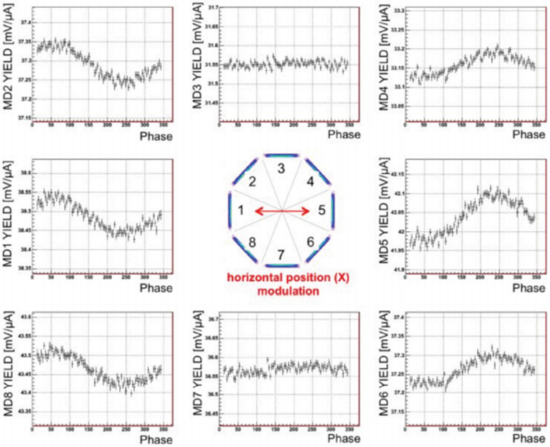
Natural beam motion

- 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

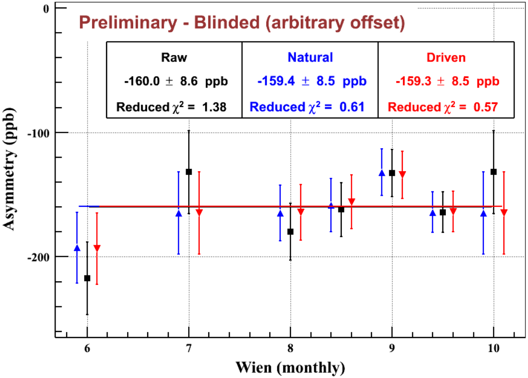
- Deliberate motion



Helicity-Correlated Beam Properties Are Understood

Excellent agreement between natural and driven beam motion

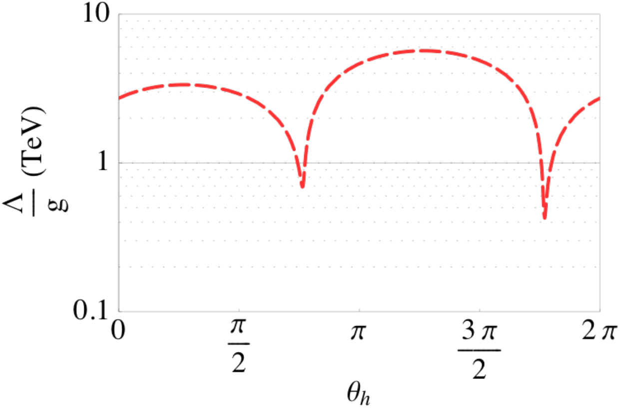
Run2 measured asymmetry



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

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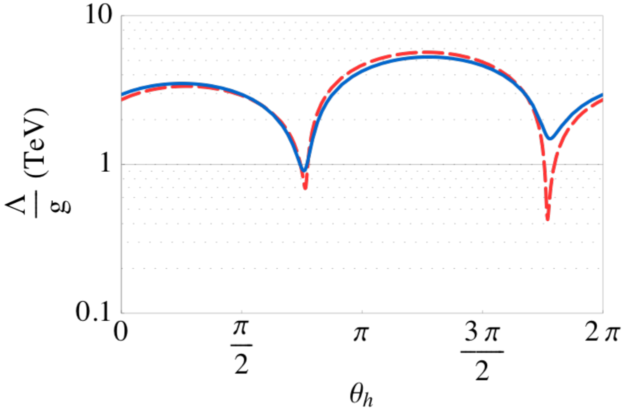
Lower bound on new physics (95% CL)



Constraints from

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

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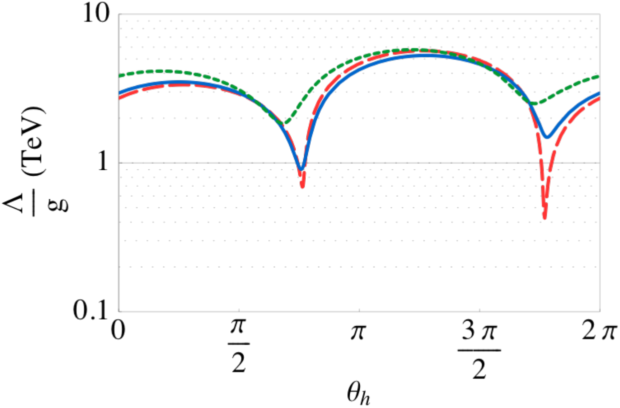


Constraints from

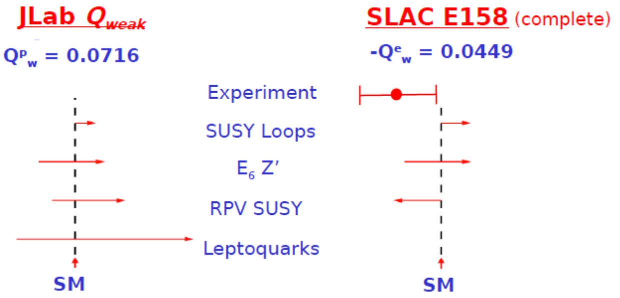
- Atomic PV: $\frac{\Lambda}{g} > 0.4\ TeV$
- PV electron scattering: $\frac{\Lambda}{g} > 0.9\ TeV$

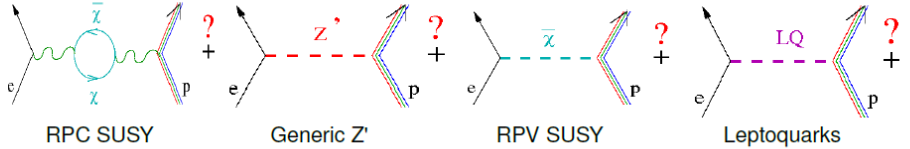
Projection Q_{Weak}

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

Sensitivity to New Physics

Different experiments sensitive to different extensions





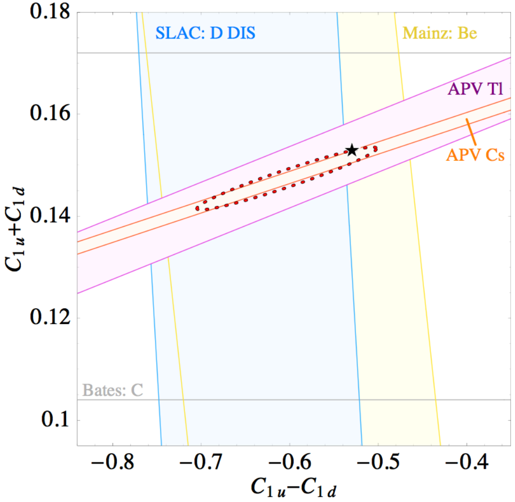
Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge *uud*

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

Early experiments

- SLAC and APV



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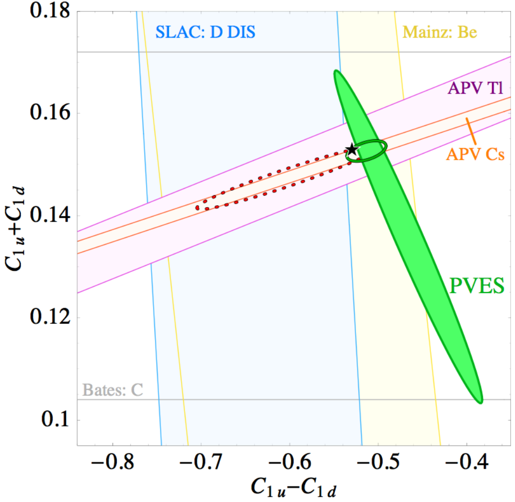
Electron scattering

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



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Electron scattering

- HAPPEx, G0
- PVA4/Mainz
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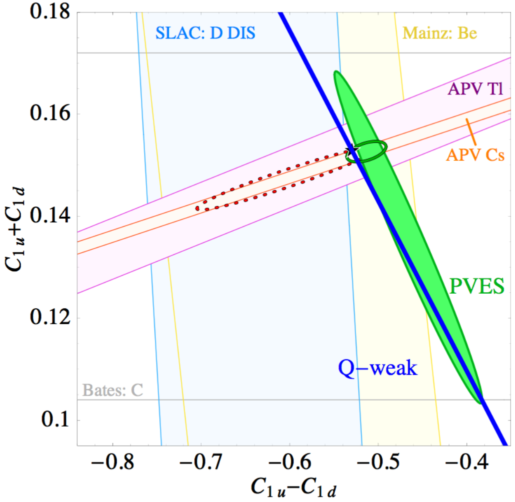
Q_{Weak} experiment



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

- $\vec{e}\vec{\gamma} \to e\gamma$ (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

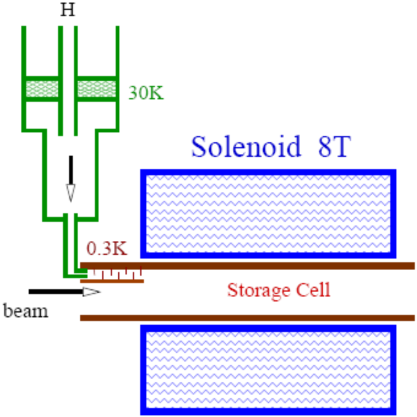
Møller Polarimetry

- $\vec{e}\vec{e} \to ee$ (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 concept[1]

- 300 mK cold atomic H
- 8 T solenoid trap
- $3 \cdot 10^{16}$ atoms/cm^2
- $3 \cdot 10^{15-17}$ atoms/cm^3
- 100% polarization of e



Advantages

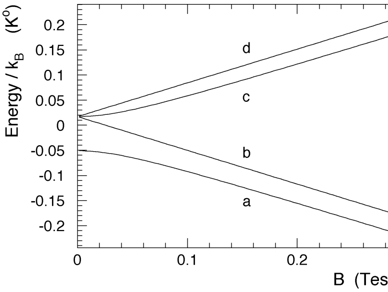
- High beam currents
- No Levchuk effect
- Non-invasive, continuous

[1] *E. 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 $B = 8\,\mathrm{T}$
- $P_p(\Uparrow) \approx 0.06$ 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 μA 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 ~ 1 V/cm, uncertainty $\sim 10^{-5}$

Atomic Hydrogen Polarimetry: Projected Uncertainties

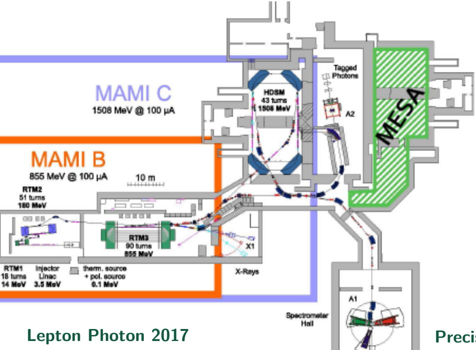
Projected Systematic Uncertainties ΔP_e in Møller polarimetry

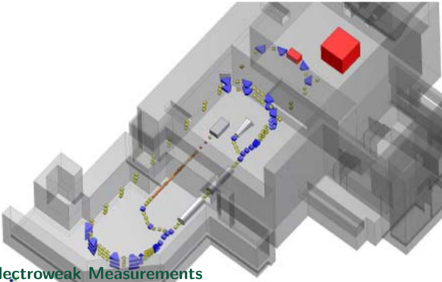
Source	Fe-foil	Hydrogen
Target polarization	0.63%	0.01%
Analyzing power	0.30%	0.10%
Levchuk effect	0.50%	0.00%
Deadtime	0.30%	0.10%
Background	0.30%	0.10%
Other	0.30%	0.00%
Unknown unknowns	0.00%	0.30%(?)
Total	1.0%	0.35%

Atomic Hydrogen Polarimetry: Collaboration with Mainz

P2 Experiment in Mainz: Weak Charge of the Proton

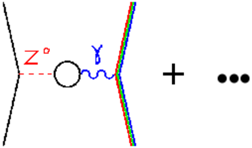
- "Q_{Weak} experiment" with improved statistical precision
- Dedicated 200 MeV accelerator MESA under construction
- Required precision of electron beam polarimetry $< 0.5\%$
- Strong motivation for collaboration on a short timescale (installation in 2017)

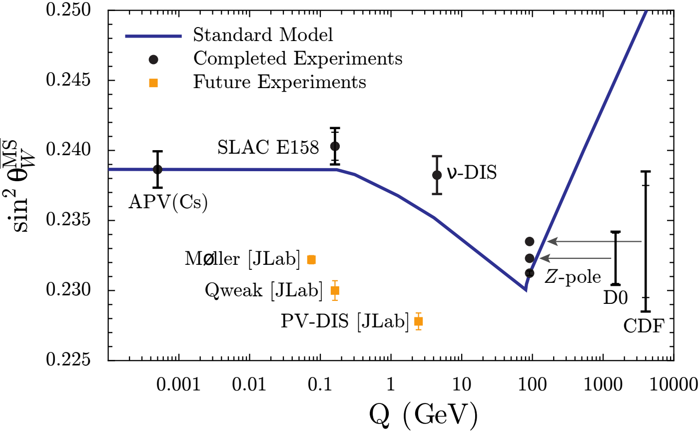




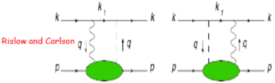
Running of $\sin^2\theta_W$ ($Q_W^p = 1 - 4\sin^2\theta_W$)

- 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.

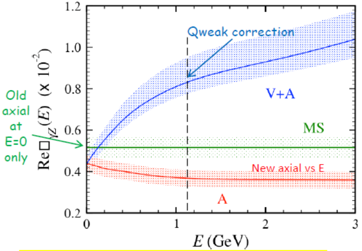
This soon led to more refined calculations with corrections of ~8% and error bars ranging from ±1.1% to ±2.8%.

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)
$A^e \times V^p$ (vanishes as E→0)	GH	0.0026+-0.0026**
	SBMT	$0.0047^{+0.0011}_{-0.0004}$
	RC	0.0057±0.0009
	GHR-M	0.0054±0.0020
$V^e \times A^p$ (finite as E→0)	MS (as updated by EKR-M)	0.0052±0.0005***
	BMT	0.0037±0.0004

*Does not include a small contribution from the elastic.
** 5.7%×Q_w^p(LO) = 0.0026. Q_w^p(LO) = 0.04532.
***Included in Q_w^p. For reference, Q_w^p =0.0713(8).

BMT and references
(V and A are hadronic couplings)



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

1

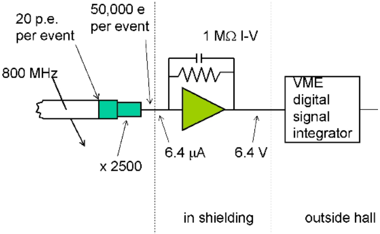
γZ Box Corrections near 1.16 GeV
A Partial Bibliography

PV Amplitude	Authors	Reference
$A^e \times V^p$ (vanishes as E→0)	GH	Gorchtein & Horowitz, PRL **102**, 091806 (2009)
	SBMT	Sibirtsev, Blunden, Melnitchouk, andThomas, 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→0)	MS	Marciano and Sirlin, PRD **27**, 552 (1983), PRD **29**, 75 (1984)
	EKR-M	Erler, Kurylov, and Ramsey-Musolf, PRD **68**, 016006 (2003)
	BMT	Blunden, Melnitchouk, and Thomas, PRL **107**, 081801 (2011)

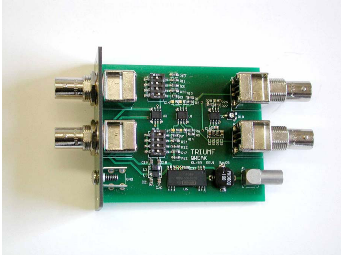
The Q_{Weak} Experiment: Main Detector

Low noise electronics

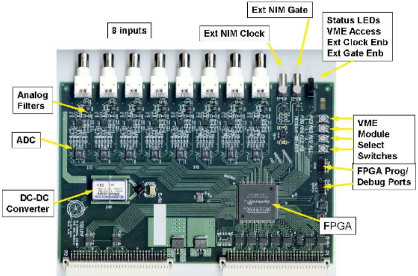
- Event rate: 800 MHz/PMT
- Asymmetry of only 0.2 ppm
- Low noise electronics (TRIUMF)



I-V Preamplifier



18-bit 500 kHz sampling ADC



The Q_{Weak} Experiment: Systematic Uncertainties

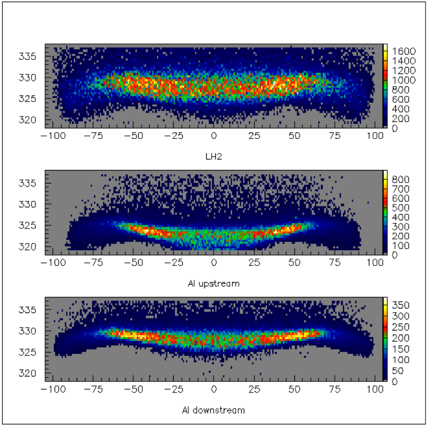
Reminder: weak vector charges

- 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, Derevianko[1]: Updated calculations in many-body atomic theory
- Experiment: $Q_W(^{133}\mathrm{Cs}) = -73.25 \pm 0.29 \pm 0.20$
- Standard Model: $Q_W(^{133}\mathrm{Cs}) = -73.16 \pm 0.03$

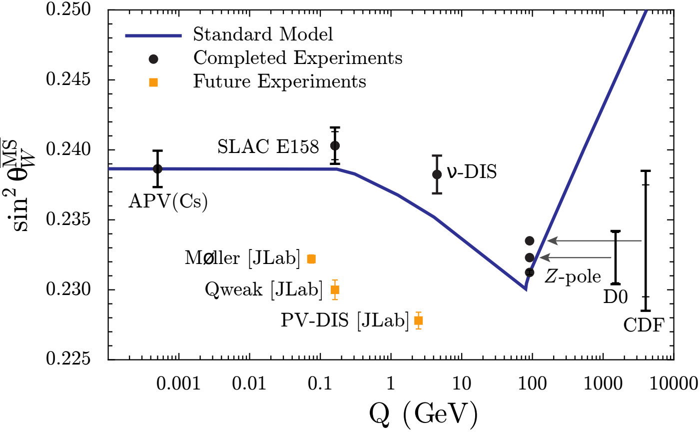
NuTeV anomaly

- Reported $3\,\sigma$ deviation from Standard Model
- Erler, Langacker: strange quark PDFs
- Londergan, Thomas[2]: charge symmetry violation, $m_u \neq m_d$
- Cloet, Bentz, Thomas[3]: in-medium modifications to PDFs, isovector EMC-type effect

[1] *Phys. Rev. Lett. 102 (2009) 181601*
[2] *Phys. Rev. D67 (2003) 111901*
[3] *Phys. Lett. B693 (2010) 462-466*

NuTeV Nuclear Correction

Isovector EMC effect[1] affects NuTeV point[2]



[1] *I. Cloët, W. Bentz, A. M. Thomas, Phys. Rev. Lett. 102, 252301 (2009)*
[2] *W. Bentz, Phys. Lett. B693, 462-466 (2010)*

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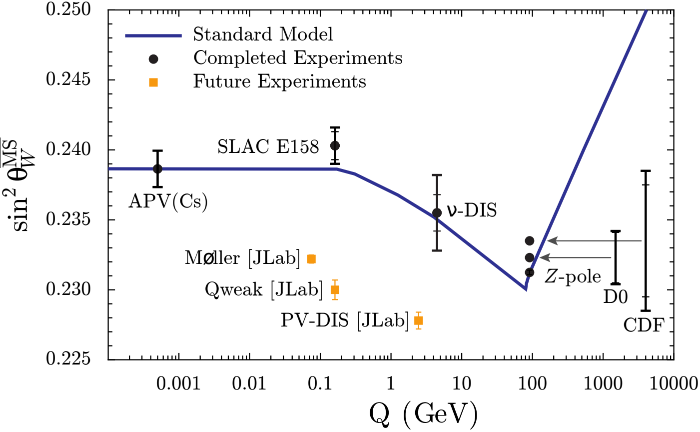

[1] *I. Cloët, W. Bentz, A. M. Thomas, Phys. Rev. Lett. 102, 252301 (2009)*

[2] *W. Bentz, Phys. Lett. B693, 462-466 (2010)*

Other Experiments