Parity-Violating and Parity-Conserving Asymmetries in ep and eN Scattering in the Qweak Experiment

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Electroweak Box Workshop, Amherst Center for Fundamental Interactions

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CHARTERED 1693

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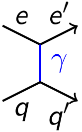
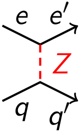
Parity-Violating Asymmetries are Typically Small

Asymmetry between + and − incoming electron helicity

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \quad \text{with} \quad \sigma = \Bigg|$$



$+$



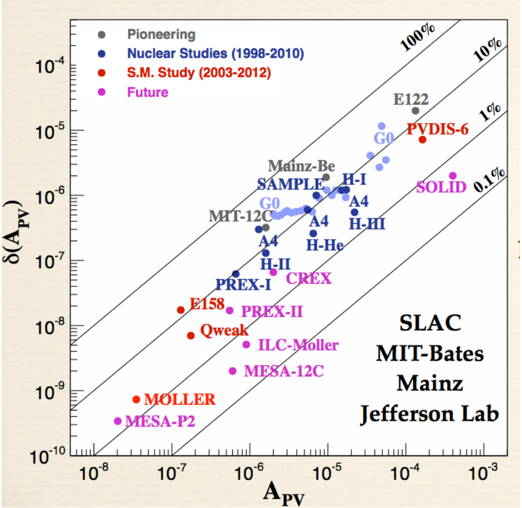
$$+ \ldots \Bigg|^2$$

Interference of photon and weak boson exchange

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

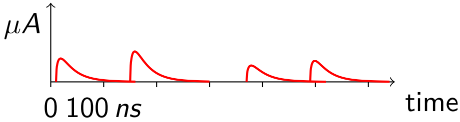
$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \propto \frac{\mathcal{M}^{NC}_{PV}}{\mathcal{M}^{EM}} \propto \frac{Q^2}{M_Z^2} \propto G_F Q^2 \approx \mathcal{O}(\text{ppm}, \text{ppb}) \text{ when } Q^2 \ll M_Z^2$$

Parity-Violating Asymmetry to Access Electroweak Parameters



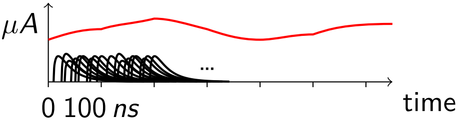
Strategy to Measure Parts-Per-Billion: Integration

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)

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

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 $\sin^2\theta_W$:

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

Determination of the Weak Charge of the Proton

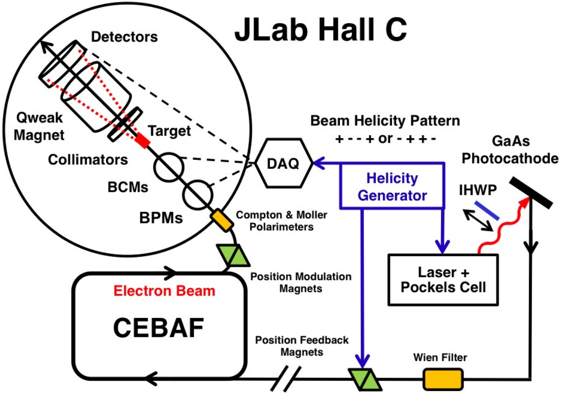
Pushing the envelope of intensity (more detected electrons)

- Higher beam current (180 μA versus usually $< 100\,\mu$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 $1.7 \times 10^{39}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, $\int \mathcal{L} dt = 1\,\mathrm{ab}^{-1}$

Pushing the envelope of precision (better measurements)

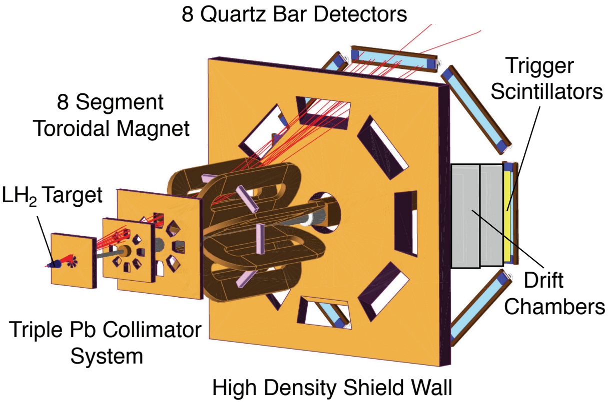
- Electron beam polarimetry precision of 1% at 1 GeV
- Helicity-correlated asymmetries at ppb level (beam position at nm level)
- Determination of Q^2 since $A_{PV} \propto Q^2$
- Isolate elastic scattering from background processes (f_i, A_i)

Determination of the Weak Charge of the Proton



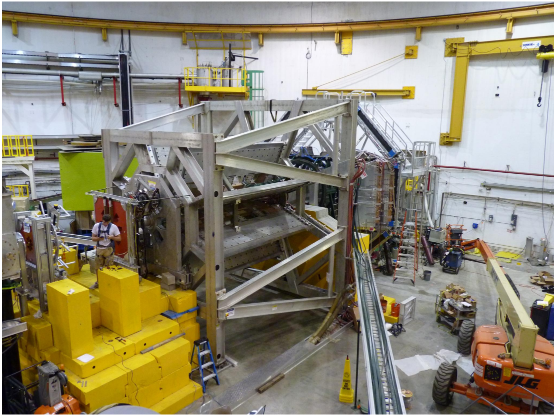
[1] *The Qweak Apparatus, NIM A 781, 105 (2015)*

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

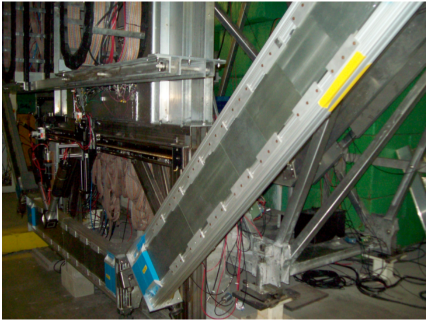


[1] *The Qweak Apparatus, NIM A 781, 105 (2015)*

Determination of the Weak Charge of the Proton

Azimuthal array of Čerenkov detector

- 8 fused silica radiators, 2 m long $\times$ 18 cm $\times$ 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



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
- Preliminary results were published in 2013 based on commissioning data[1] (4% compared to the independent full data set)

Long awaited final results are now here

- Unblinding on March 31, 2017
- Release of unblinded result at PANIC'17 in Beijing:
  - Sunday September 3, 2017, at PANIC in plenary session
  - Friday September 8, 2017, at Jefferson Lab
- Publication to be submitted in October 2017

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

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	
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%)

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

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

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	

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)*

Determination of the Weak Vector Charge of the Proton

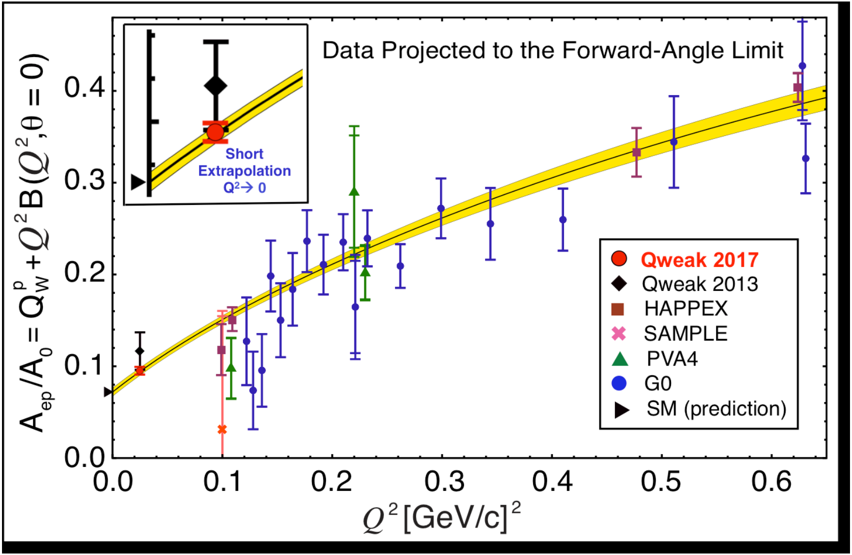
New global fit of all parity-violating electron scattering with full data set

- Fit of parity-violating asymmetry data on H, D, ^{4}He, $Q^2 < 0.63\,\mathrm{GeV}^2$
- 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 $G_A^{Z,T=1}$

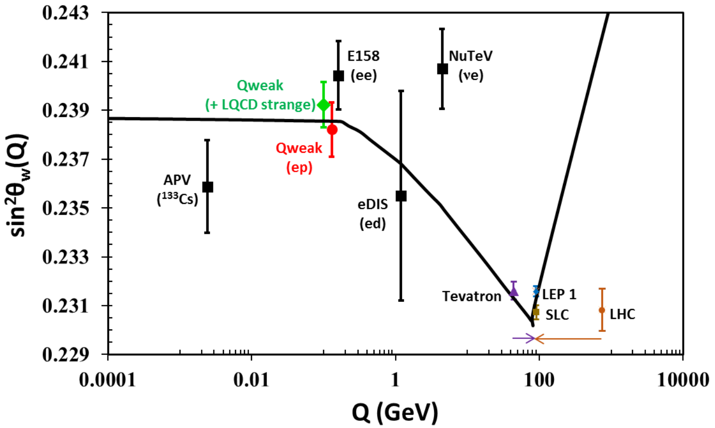
$$\begin{aligned}
Q_W^p(PVES)) &= 0.0719 \pm 0.0045 \\
\sin^2\theta_W &= 0.2382 \pm 0.0011 \\
\rho_s &= 0.19 \pm 0.11 \\
\mu_s &= -0.18 \pm 0.15 \\
G_A^{Z,T=1} &= -0.67 \pm 0.33
\end{aligned}$$

- After combination with atomic parity-violation on Cs:
  - $C_{1u} = -0.1874 \pm 0.0022$
  - $C_{1d} = 0.3389 \pm 0.0025$

Determination of the Weak Vector Charge of the Proton



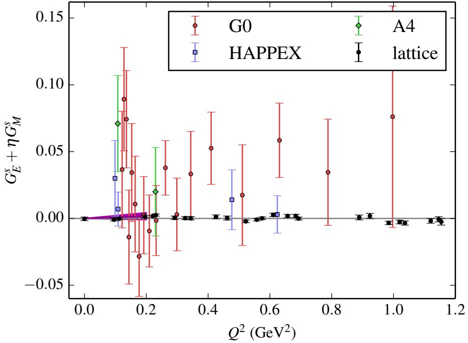
Determination of the Weak Vector Charge of the Proton

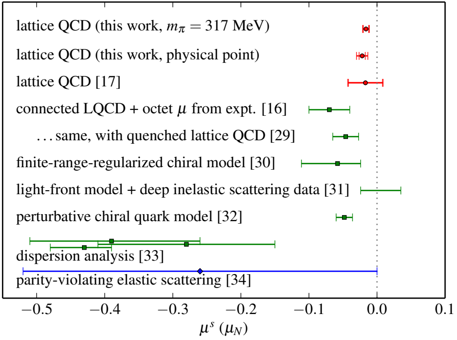


Determination of the Weak Vector Charge of the Proton

Using lattice QCD in the extraction

- It is possible to add the lattice strangeness form factor to the global fit.
- $Q_W^p(LQCD)) = 0.0684 \pm 0.0039$





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

Electroweak Radiative Corrections

Procedure per Erler *et al.*[1]

$$Q_W^p = (\rho_{NC} + \Delta_e)(1 - 4\sin^2\theta_W(0) + \Delta'_e) + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

Correction to Q_W^p	Uncertainty
$\Delta \sin\theta_W(M_Z)$	± 0.0006
$\Box_{\gamma Z}(6.4 \pm 0.6)\%$	± 0.00044
$\Delta \sin\theta_W(Q)$had	± 0.0003
$\Box_{WW}$, $\Box_{ZZ}$ (pQCD)	± 0.0001
Charge symmetry	0
Total	± 0.0008

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

Electroweak Radiative Corrections

Discussion of $\Box_{\gamma Z}$

- We use the most recent available treatment by Hall *et al.*[1] (which is the same treatment we used in the publication of the commissioning run in 2013)
- $\Box^{V}_{\gamma Z} = (5.4 \pm 0.4) \times 10^{-3}$ using [1]
- $\Box^{A}_{\gamma Z} = (-0.7 \pm 0.2) \times 10^{-3}$ using [2]
- Q^2 dependence using [3]

What if?

- If we use an uncertainty on $\Box_{\gamma Z}$ of ± 0.0020 as per Gorchtein *et al.*[1]
- $Q^p_W(PVES)$ changes from 0.0719 ± 0.0045 to 0.0716 ± 0.0048

[1] *Hall, Blunden, Melnitchouk, Thomas, Young, Phys. Lett. B753 (2016) 221-226*
[2] *Blunden, Melnitchouk, Thomas, Phys. Rev. Lett. 107, 081801 (2011)*
[3] *Gorchtein, Horowitz, Ramsey-Musolf, Phys. Rev. C 84, 015502 (2011)*

Sensitivity to New Physics

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

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

Limits on new physics energy scale if uncertainty ΔQ_W^p

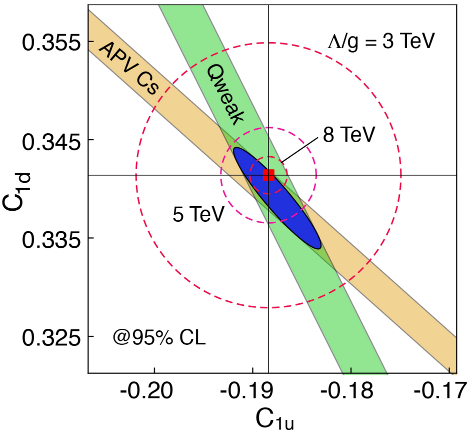
$$\frac{\Lambda}{g} = \frac{1}{2}\left(\sqrt{2}G_F \Delta Q_W^p\right)^{-1/2}$$

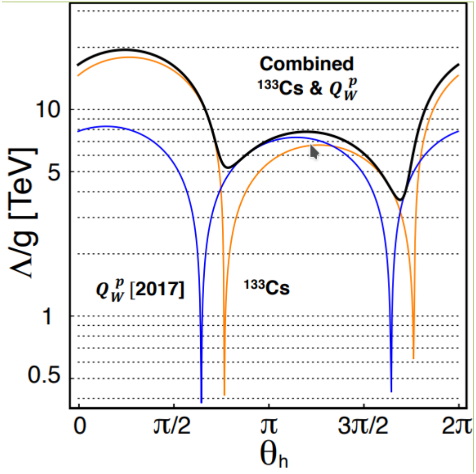
Assuming that we have an arbitrary flavor dependence of the new physics:

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

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

Sensitivity to New Physics





Sensitivity to New Physics

Leptoquarks

- Impact explored in Erler, Kurylov, Ramsey-Musolf, Phys. Rev. D 68, 016006
- Some other data has since been released (HERA), which may affect the opportunities for the Q_{Weak} result to distinguish

Dark parity-violation

- Davoudiasl, Lee, Marciano, Phys. Rev. D89, 095006 (2014)
- Q_{Weak} result rules out some of the allowed region

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: $N \to \Delta$, 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 recently

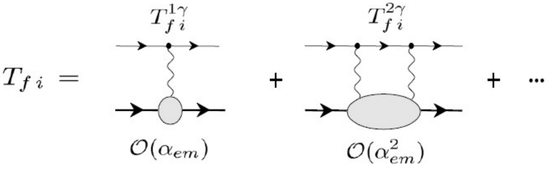
- First: corrections on $A_{PV}(p)$ due to A_{PV}(Al alloy), B_n(H + Al alloy)
- Then: extract B_n(H), turn Al alloy into ^{27}Al for $A_{PV}(^{27}\mathrm{Al})$
- Then: corrections due to B_n(Al alloy), extract $B_n(^{27}\mathrm{Al})$

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

$$B_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = \frac{2\Im(T^{1\gamma *} \cdot AbsT^{2\gamma})}{|T^{1\gamma}|^2} \approx \mathcal{O}(\alpha \frac{m}{E}) \approx \text{ppm}$$



Ancillary Measurements: Transverse Asymmetry

Azimuthal asymmetries

$$A_T(\phi) = \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)} = B_n S \sin(\phi - \phi_S) = B_n(P_V \cos\phi + P_H \sin\phi)$$

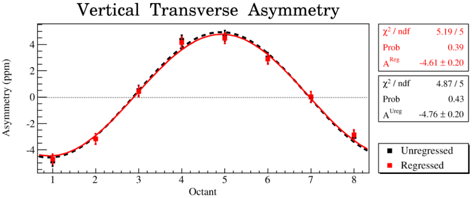
with $P_V = S \sin\phi_S$ and $P_H = S \cos\phi_S$

Available transverse single spin asymmetries

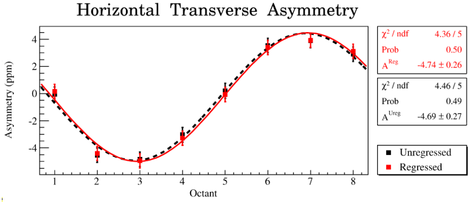
- Elastic $\vec{e}p$ in H, C, Al at $E = 1.165\,\mathrm{GeV}$
- Inelastic $\vec{e}p \rightarrow \Delta$ in H, C, Al at $E = 0.877\,\mathrm{GeV}$ and $1.165\,\mathrm{GeV}$
- Elastic $\vec{e}e$ in H at $E = 0.877\,\mathrm{GeV}$
- Deep inelastic $\vec{e}p$ in H at $W = 2.5\,\mathrm{GeV}$
- Pion photoproduction in H at $E = 3.3\,\mathrm{GeV}$

Ancillary Measurements: Transverse Asymmetry on H

Two hours of data taking in H: $A_T(oct) = A\sin\phi$

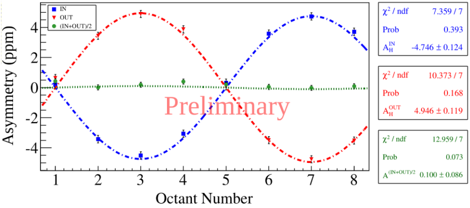


Two hours of data taking in V: $A_T(oct) = A\cos\phi$

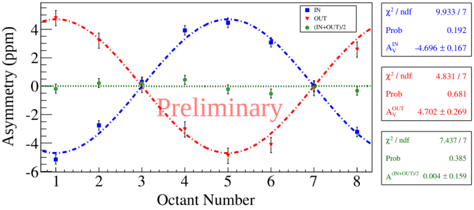


Ancillary Measurements: Transverse Asymmetry on H

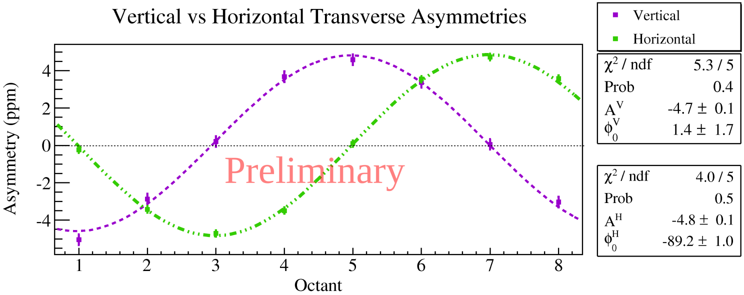
Cancellation with slow helicity reversal for *H*



Cancellation with slow helicity reversal for *H*



Ancillary Measurements: Transverse Asymmetry on H



- 90 degrees phase difference between *H* and *V* as expected
- Not corrected for polarization, backgrounds, acceptance,...

Ancillary Measurements: Transverse Asymmetry on H

- Background corrections (as for main experiment):

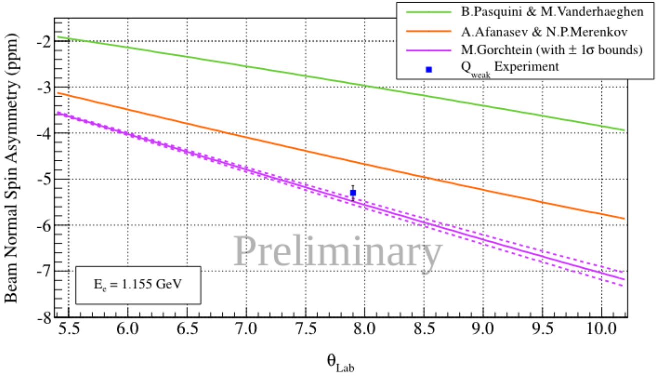
$$B_n = R_{total} \frac{\frac{A}{P} - \sum f_i A_i}{1 - \sum f_i}$$

- Measured corrections f_i and A_i for aluminum windows, $N \to \Delta$
- R_{total} includes radiative corrections, acceptance averaging, Q^2 variation with ϕ in each octant
- Most precise transverse asymmetry in *ep* in hydrogen (50 hours of data): $B_n = -5.35 \pm 0.07(\text{stat}) \pm 0.15(\text{syst})\,\text{ppm}$
- $\langle E \rangle = 1.155 \pm 0.003\,\text{GeV}$, $\langle \theta \rangle = 7.9 \pm 0.3\,\text{degrees}$

Ancillary Measurements: Transverse Asymmetry on H

Theoretical models:

- Pasquini, Vanderhaeghen, Phys. Rev. C 70, 045206 (2004)
- Afanasev, Merenkov, Phys. Lett. B 599, 48 (2004)
- Gorchtein, Phys. Rev. C 73, 055201 (2006)



Ancillary Measurements: Transverse Asymmetry on Al, C

Q_{Weak} wasn't made for this

- Large energy acceptance of spectrometer (150 MeV at 1.165 GeV)
- Nuclei are hardly ideal with low-lying levels

$B_n \approx -11\,\text{ppm}$ in elastic scattering off C

- Analysis complete but no result released yet by collaboration
- Dissertation of Martin McHugh (GWU) is available on UMI and consistent with PREX at $1\,\sigma$
- Target is 99% ^{12}C, no significant contaminations
- Correction for contribution from quasi-elastic scattering
- No attempts at separation of nuclear excited states and GDR from elastic scattering
- $B_n(\mathrm{C})$ is a quantity that does not correspond to a purely elastic state

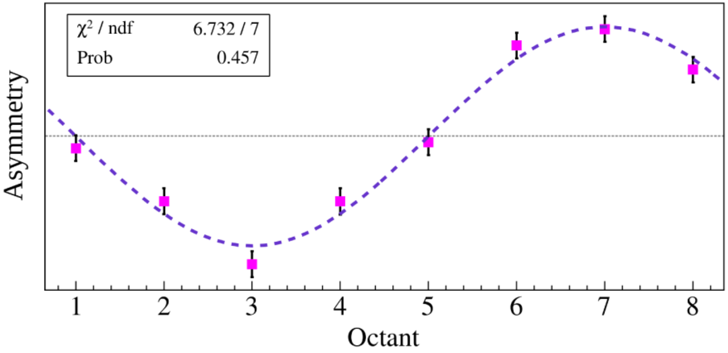
Ancillary Measurements: Transverse Asymmetry on Al, C

$B_n \approx [-11, -14]$ ppm in elastic scattering off ^{27}Al

- Some figures released by collaboration, no numbers, analysis nearing completion
- Alloy is a mixture with up to 10% other elements
- Attempts to treat quasi-elastic nuclear excited states and GDR more appropriately
- $B_n(^{27}\mathrm{Al})$ will be interpretable as referring to a purely elastic state
- Results to be shown at Fall 2017 DNP meeting by Kurtis Bartlett (W&M)

Ancillary Measurements: Transverse Asymmetry on Al

Aluminum azimuthal asymmetry is non-zero (uncorrected data)



- Aluminum alloy with $\approx 10\%$ contaminations
- Corrections needed for quasielastic, $N \to \Delta$, nuclear excited states

Ancillary Measurements: Transverse Asymmetry on Al

Contaminants

- Working with Chuck Horowitz on distorted wave σ and A_{PV}
- Similar approach as Horowitz, Phys. Rev. C89, 045503 (2014)
- Implementation into Q_{Weak} Monte Carlo simulations to determine their contributions

Element	% by weight
Al	88.70
Zn	6.3
Mg	2.7
Cu	1.8
Cr	0.21
Fe	0.12
Si	0.10
Total	99.93

Ancillary Measurements: Transverse Asymmetry on Al

Quasi-elastic scattering

- Free nucleon approximation and some heuristics related to isoscalar/isovector impact on sign of asymmetry
- However, free nucleon approximation may not be sufficient per E. Hadjimichael, G. I. Poulis, T. W. Donnelly, Phys. Rev. C 45, 2666 (1992)
- More detailed quasi-elastic implementation per Horowitz, Phys. Rev. C 47, 826 (1992), which his grad student Zidu Lin has adapted to ^{27}Al

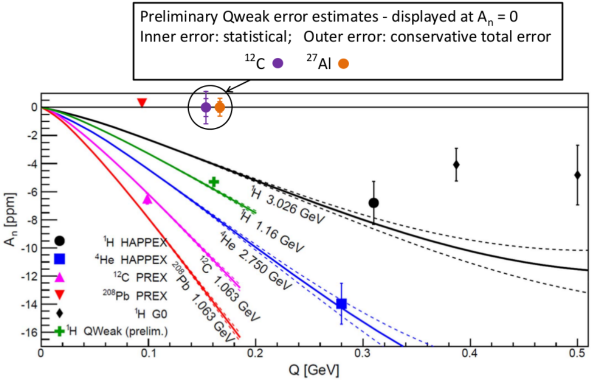
Ancillary Measurements: Transverse Asymmetry on Al

Nuclear excited states

- Fitting nuclear excited state form factors using MIT Bates data
  - R.S. Hicks, A. Hotta, J.B. Flanz, and H. deVries, Phys. Rev. C21, 2177 (1980)
  - P.J Ryan, R.S. Hicks, A. Hotta, J. Dubach, G.A. Peterson, and D.V. Webb, Phys. Rev. C27, 2515 (1983)
- Implementation into Q_{Weak} Monte Carlo simulations to determine their contributions

Ancillary Measurements: Transverse Asymmetry on C, Al

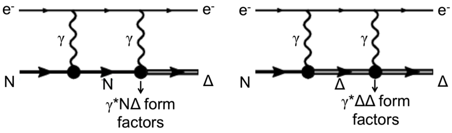
Projected uncertainties for B_n for C and Al



- $B_n \propto AQ/Z$: Gorchtein, Horowitz, Phys. Rev. C77, 044606 (2008)
- HAPPEX, PREX: Abrahamyan *et al.*, PRL 109, 192501 (2012)

Ancillary Measurements: Transverse Asymmetry in $N \to \Delta$

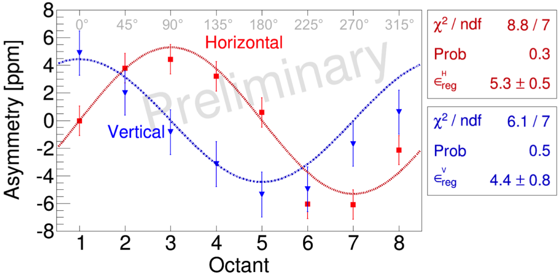
Access to the $\gamma * \Delta\Delta$ form factor



- Large asymmetries in the forward region
- Several possible intermediate states N, Δ

Ancillary Measurements: Transverse Asymmetry in $N \to \Delta$

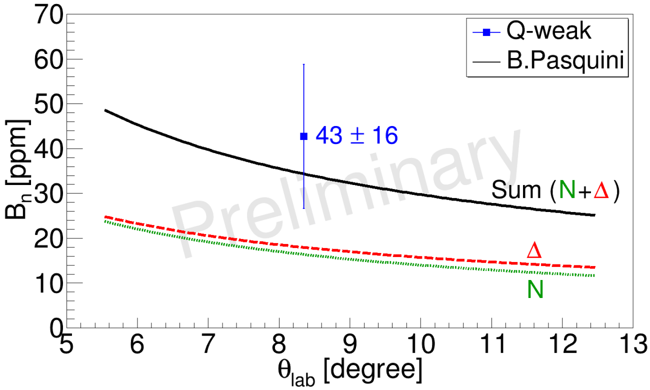
Before any background corrections



After background corrections

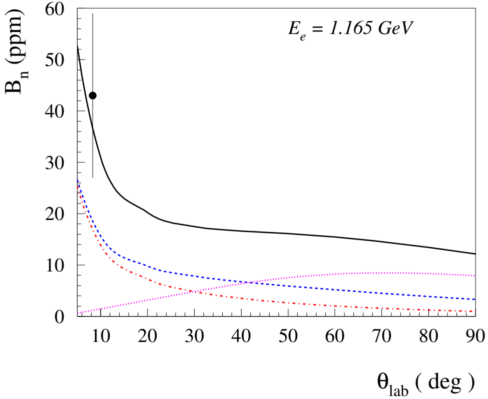
- Large radiative tail from elastic scattering as dilution with small asymmetry
- $B_n(N \to \Delta) = 43 \pm 16$ at $\langle\theta\rangle = 8.3\,$degrees
- Nuruzzaman, CIPANP2015, arXiv:1510.00449 [nucl-ex]

Ancillary Measurements: Transverse Asymmetry in $N \to \Delta$



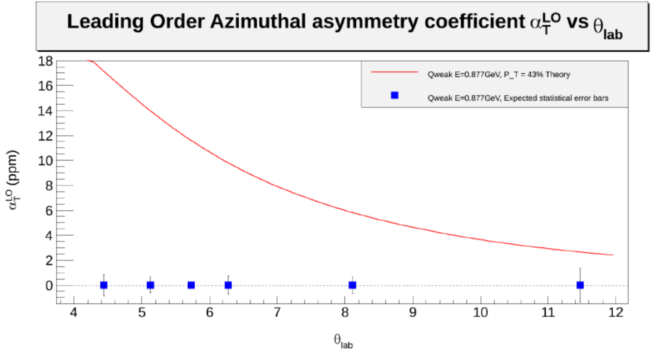
- Includes N, and $\Delta(1232)$

Ancillary Measurements: Transverse Asymmetry in $N \to \Delta$



- Includes N, $\Delta(1232)$, $S11(1535)$, and $D13(1520)$
- Carlson, Pasquini, Pauk, Vanderhaeghen, arXiv:1708.05316 [hep-ph]

Ancillary Measurements: Transverse Asymmetry in Møller



- Dixon, Schreiber, Phys. Rev. D 69, 113001 (2004)

Summary

Determination of the Weak Charge of the Proton

- Most precise parity-violating asymmetry measurement: $A_{PV} = -226.5 \pm 7.3(\text{stat}) \pm 5.8(\text{syst})\,\text{ppb}$ at $\langle Q^2 \rangle = 0.0249\,\text{GeV}^2$
- Weak charge $Q_W^p(PVES) = 0.0719 \pm 0.0045$ in excellent agreement with $Q_W^p(SM) = 0.0708 \pm 0.0003$
- Amplitudes above $8 \cdot 10^{-3} \cdot G_F$ ruled out
- Heavy new physics with $\Lambda/g < 7.5\,\text{TeV}$ ruled out
- Triad of high precision low energy weak charge measurements now complete

Summary

Many ancillary measurements for which data is available:

A_{PV} helicity asymmetries:

- Elastic ^{27}Al
- $N \to \Delta$ (E of 1.16 GeV, 0.877 GeV)
- Near $W = 2.5$ GeV (for $\Box_{\gamma Z}$)
- Pion photoproduction (E of 3.3 GeV)

B_n transverse asymmetries:

- Elastic ep, ^{27}Al, C
- $N \to \Delta$
- Near $W = 2.5$ GeV
- Pion photoproduction (E of 3.3 GeV)
- Møller

Topics for Discussion

Prioritization of ancillary analysis

- Currently in progress (or preliminary results):
  - B_n for *ep*
  - A_{PV} for $N \to \Delta$
  - A_{PV} for ^{27}Al
  - B_n for ^{27}Al, C

Ask a theorist

- Preference for g^2/Λ^2 over $g^2/4\Lambda^2$?
- Limits on leptoquarks?

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

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

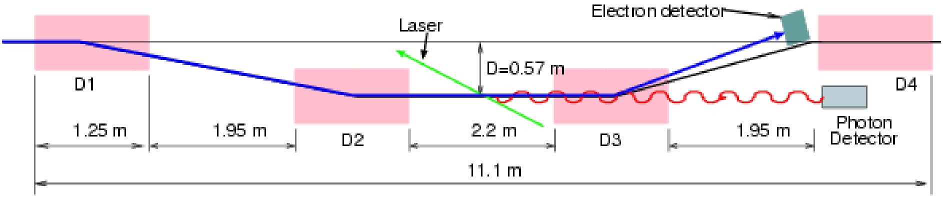
Construction new Compton polarimeter ($\vec{e} + \vec{\gamma} \to e + \gamma$)

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

The Q_{Weak} Experiment: Improved Beam Polarimetry

Compton polarimeter

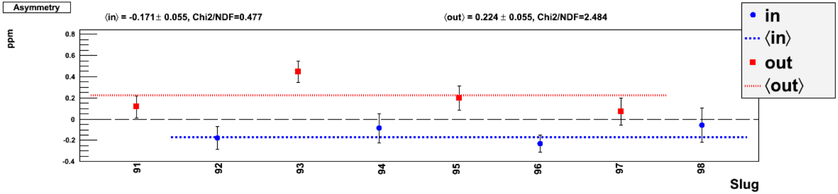
- Beam: 150 μA at 1.165 GeV
- Chicane: interaction region 57 cm below straight beam line
- Laser system: 532 nm green laser
  - 10 W CW laser with low-gain cavity
- Photons: $PbWO_4$ scintillator in integrating mode
- Electrons: Diamond strips with 200 μm pitch



Data Quality: Slow Helicity Reversal

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

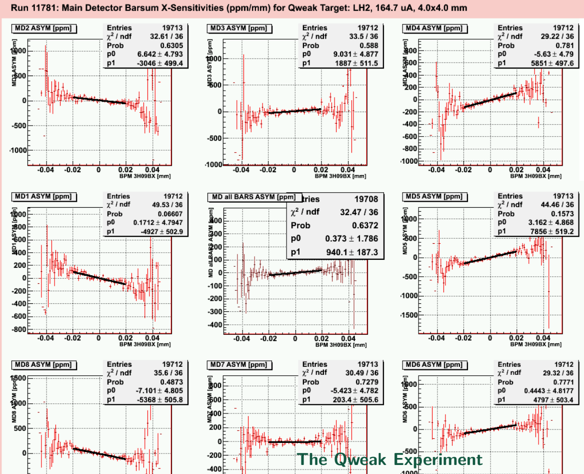
- Insertable $\lambda/2$-plate (IHWP) in injector allows 'analog' flipping helicity frequently
- Wien filter: another way of flipping helicity (several weeks)
- Each 'slug' of 8 hours consists of same helicity conditions



Helicity-Correlated Beam Properties Are Understood

Measured asymmetry depends on beam position, angle, energy

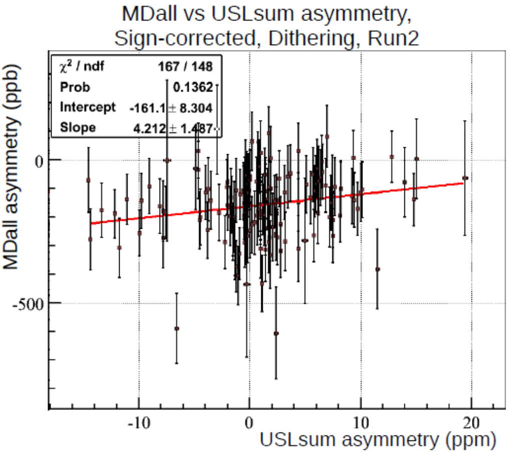
- Well-known and expected effect for PVES experiments
- "Driven" beam to check sensitivities from "natural" jitter



However, Some Beamline Background Correlations Remain

After regression, correlation with background detectors

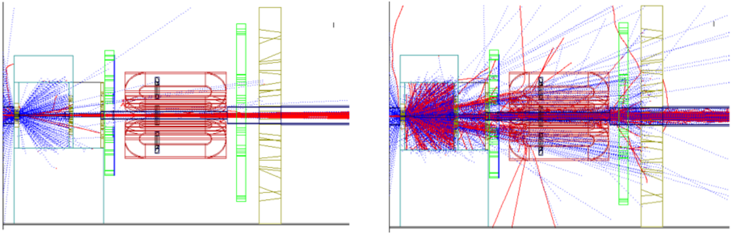
- Luminosity monitors & spare detector in super-elastic region
- Background asymmetries of up to 20 ppm (that's huge!)



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”

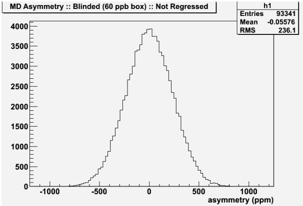


Qualitatively new background for PVES experiments at JLab

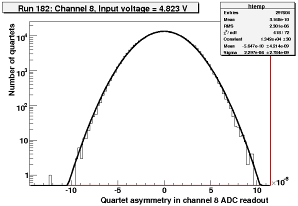
- Second regression using asymmetry in background detectors
- Measurements with blocked octants to determine dilution factor ($f_{b_2}^{MD} = 0.19\%$)

Data Quality: Understanding the Asymmetry Width

Asymmetry width



Battery width



Measurement

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

Asymmetry width

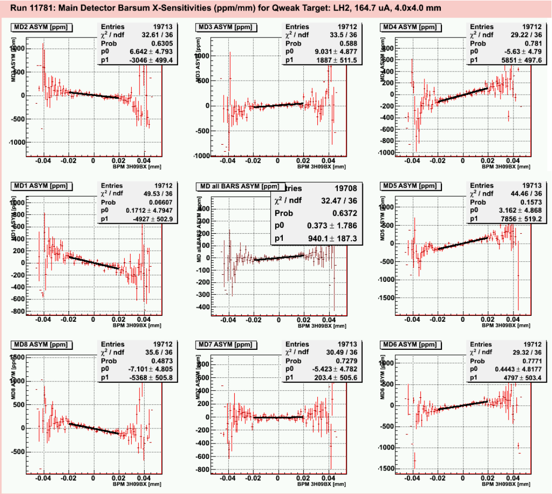
- Pure counting statistics $\approx$ 200 ppm
- $+$ detector resolution $\approx$ 90 ppm
- $+$ current monitor $\approx$ 50 ppm
- $+$ target boiling $\approx$ 57 ppm
- $=$ observed width $\approx$ 233 ppm

Data Quality: Helicity-Correlated Beam Properties

Natural beam motion

- Measured asymmetry correlated with beam position and angles
- Linear regression:

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



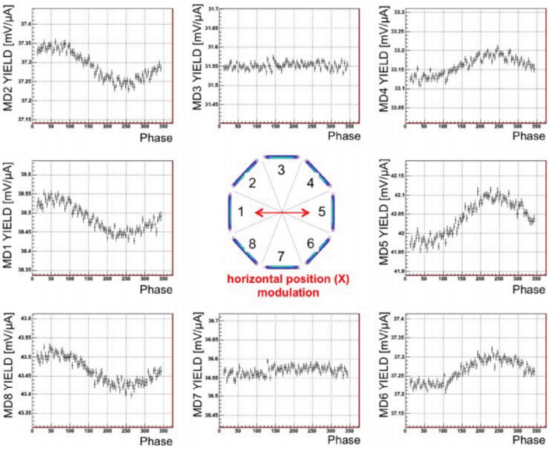
Data Quality: Helicity-Correlated Beam Properties

Natural beam motion

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

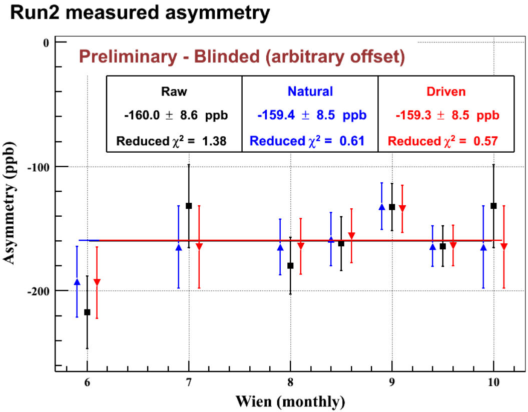
Driven beam motion

- Deliberate motion



Helicity-Correlated Beam Properties Are Understood

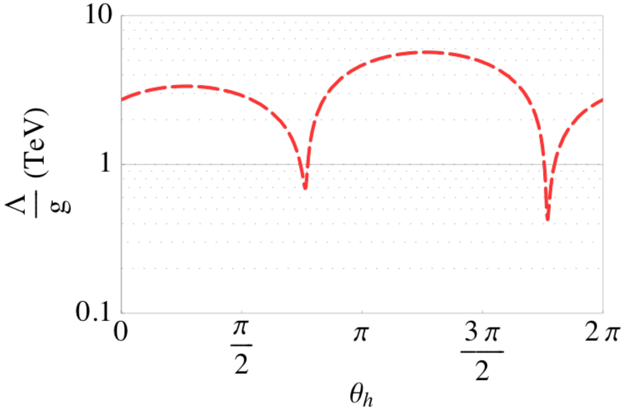
Excellent agreement between natural and driven beam motion



- 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)

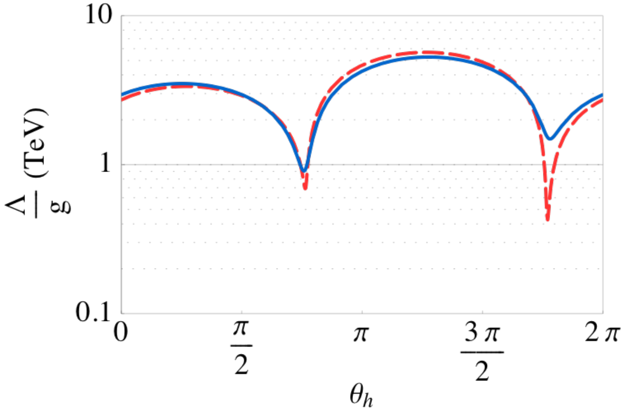


Constraints from

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

Sensitivity to New Physics

Lower bound on new physics (95% CL)

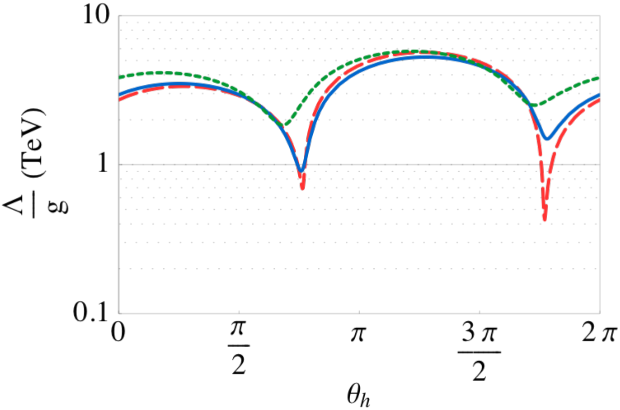


Constraints from

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

Sensitivity to New Physics

Lower bound on new physics (95% CL)



Constraints from

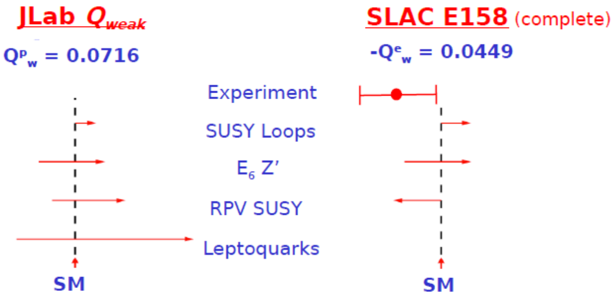
- Atomic PV: $\frac{\Lambda}{g} > 0.4\ TeV$
- PV electron scattering: $\frac{\Lambda}{g} > 0.9\ TeV$

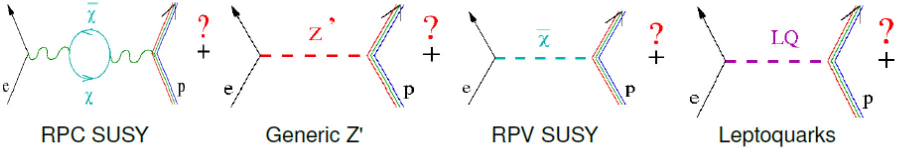
Projection Q_{Weak}

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

Sensitivity to New Physics

Different experiments sensitive to different extensions





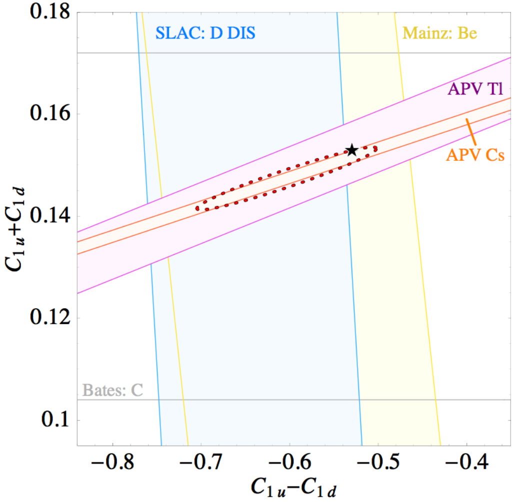
Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge *uud*

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

Early experiments

- SLAC and APV



Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge *uud*

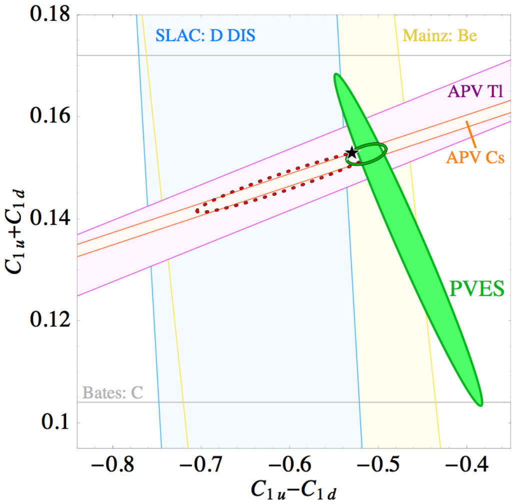
$Q_W^p = -2(2C_{1u} + C_{1d})$

Early experiments

- SLAC and APV

Electron scattering

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



Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge *uud*

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

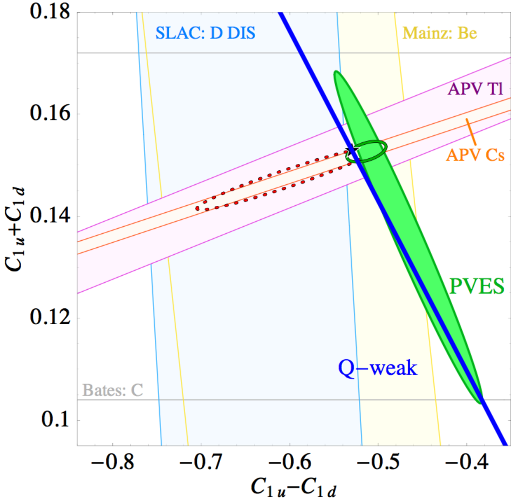
Early experiments

- SLAC and APV

Electron scattering

- HAPPEx, 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

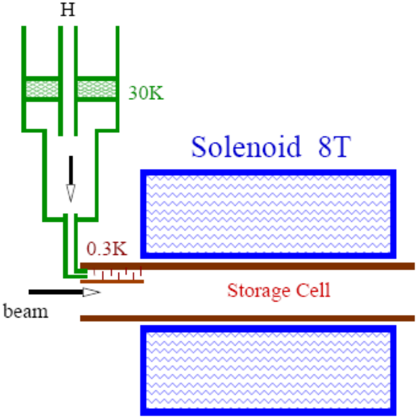
Møller Polarimetry

- $\vec{e}\vec{e} \rightarrow ee$ (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 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

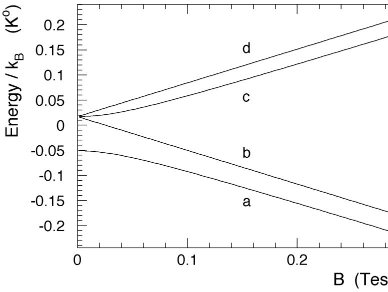
- High beam currents
- No Levchuk effect
- Non-invasive, continuous

[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

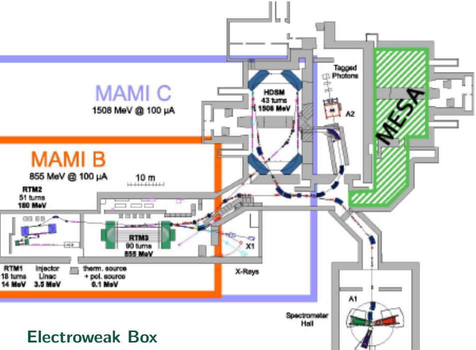
Projected Systematic Uncertainties ΔP_e in Møller polarimetry

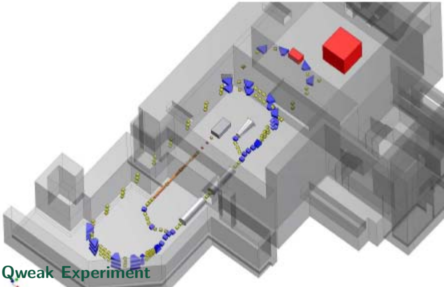
Source	Fe-foil	Hydrogen
Target polarization	0.63%	0.01%
Analyzing power	0.30%	0.10%
Levchuk effect	0.50%	0.00%
Deadtime	0.30%	0.10%
Background	0.30%	0.10%
Other	0.30%	0.00%
Unknown unknowns	0.00%	0.30%(?)
Total	1.0%	0.35%

Atomic Hydrogen Polarimetry: Collaboration with Mainz

P2 Experiment in Mainz: Weak Charge of the Proton

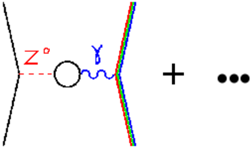
- "Q_{Weak} experiment" with improved statistical precision
- Dedicated 200 MeV accelerator MESA under construction
- Required precision of electron beam polarimetry $< 0.5\%$
- Strong motivation for collaboration on a short timescale (installation in 2017)

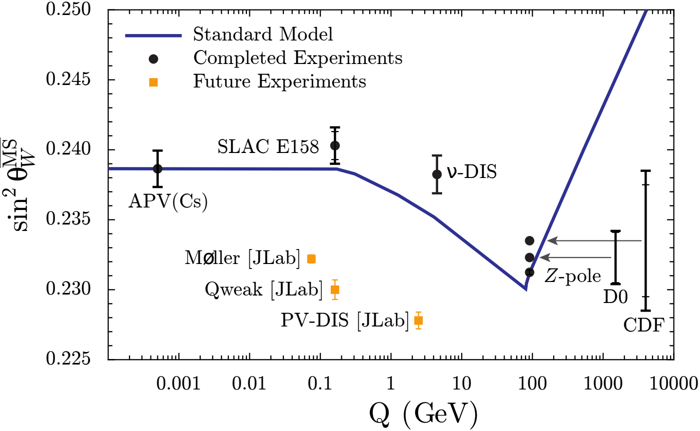




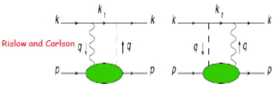
Running of $\sin^2\theta_W$ ($Q_W^p = 1 - 4\sin^2\theta_W$)

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





γZ Box Corrections near 1.16 GeV



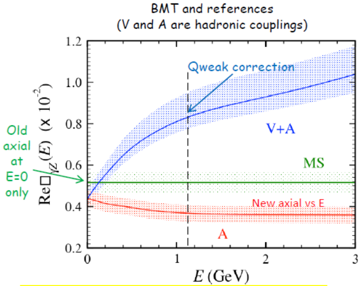
In 2009, Gorchtein and Horowitz showed the vector hadronic contribution to be significant and energy dependent.

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).



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

1

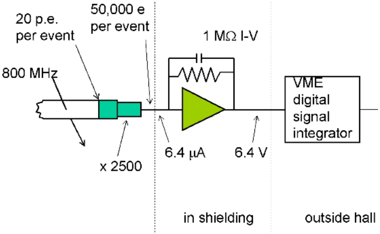
γZ Box Corrections near 1.16 GeV
A Partial Bibliography

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)

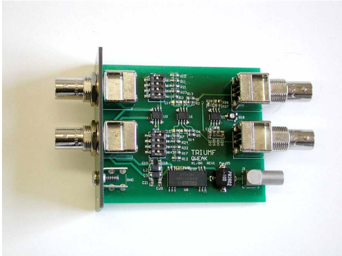
The Q_{Weak} Experiment: Main Detector

Low noise electronics

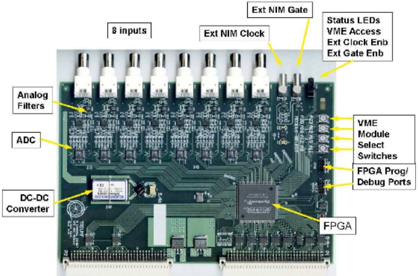
- Event rate: 800 MHz/PMT
- Asymmetry of only 0.2 ppm
- Low noise electronics (TRIUMF)



I-V Preamplifier



18-bit 500 kHz sampling ADC



The Q_{Weak} Experiment: Systematic Uncertainties

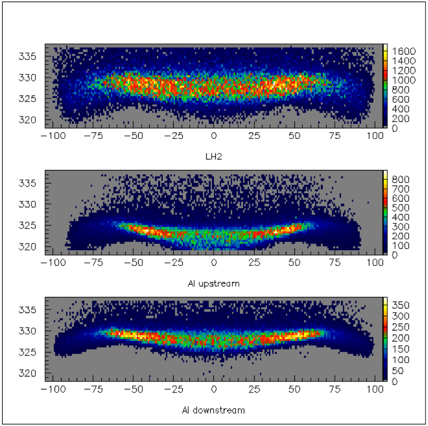
Reminder: weak vector charges

- 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

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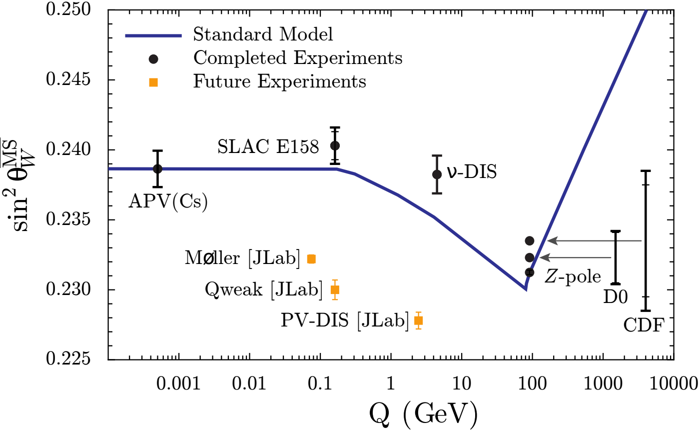
[1] *Phys. Rev. Lett. 102 (2009) 181601*
[2] *Phys. Rev. D67 (2003) 111901*
[3] *Phys. Lett. B693 (2010) 462-466*

NuTeV Nuclear Correction

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

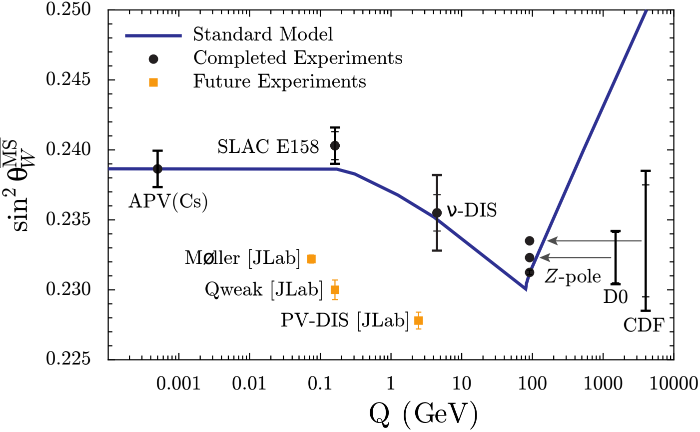


[1] *I. Cloët, W. Bentz, A. M. Thomas, Phys. Rev. Lett. 102, 252301 (2009)*

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

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)*