

The Q_{weak} Experiment

A Precision Search for New Physics at the TeV Scale



Wouter Deconinck



MENU 2010 – College of William & Mary – June 2, 2010

Precision Tests of the Standard Model

Current status of the Standard Model

Standard Model is an effective low-energy theory of the more fundamental underlying physics.

Approaches to uncovering the underlying physics

- Energy frontier: direct searches for new particles
- Precision or intensity frontier: indirect searches

The Q_{weak} experiment at Jefferson Lab (Hall C)

- Precision measurement of a quantity suppressed by fundamental symmetries, and sensitive to new physics
- Elastic scattering of electron beam on proton target to measure the proton weak charge Q_W^p to a precision of 4%

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 $U(1)_Y$
- Left-handed leptons in doublets, right-handed in singlets
- Fundamental symmetry of left and right helicity broken

Parity symmetry is violated

- Weak interaction violates parity
- Electromagnetic interaction still satisfies parity
- Use parity-violation to measure electroweak parameters



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Electroweak symmetry breaking: $B_\mu, W_\mu^i \rightarrow A_\mu, Z_\mu^0, W_\mu^\pm$

$$\sin^2 \theta_W = \frac{g'^2}{g^2 + g'^2} = 0.23122 \pm 0.00015 \approx \frac{1}{4} \quad (\text{at } M_Z)$$

$$A_\mu = \cos \theta_W \cdot B_\mu + \sin \theta_W \cdot W_\mu^3 \quad (\text{massless photon field})$$

$$Z_\mu^0 = -\sin \theta_W \cdot B_\mu + \cos \theta_W \cdot W_\mu^3 \quad (M_W \approx 80.4 \text{ GeV}, M_Z \approx 91.2 \text{ GeV})$$

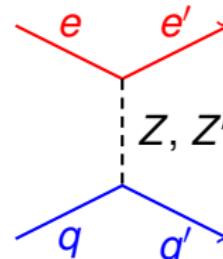
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Parity-violation neutral current

$$\mathcal{L}_{PV}^{EW} = -\frac{G_F}{\sqrt{2}} \left[g_A^e (\bar{e} \gamma_\mu \gamma_5 e) \cdot \sum_i g_V^q (\bar{q} \gamma^\mu q) + g_V^e (\bar{e} \gamma_\mu e) \cdot \sum_i g_A^q (\bar{q} \gamma^\mu \gamma_5 q) \right]$$



Electroweak Interaction

Parity-violating electron scattering couplings

- **Weak vector coupling:** $C_{1q} = g_A^e g_V^q$
- Weak axial coupling: $C_{2q} = g_V^e g_A^q$

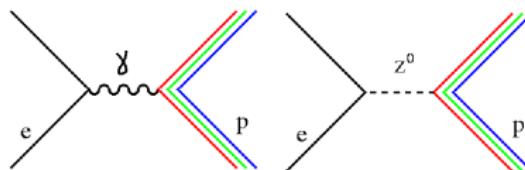
Particle	Electric charge	Weak vector charge ($\sin^2 \theta_W \approx \frac{1}{4}$)
u	$+\frac{2}{3}$	$-2C_{1u} = +1 - \frac{8}{3} \sin^2 \theta_W \approx +\frac{1}{3}$
d	$-\frac{1}{3}$	$-2C_{1d} = -1 + \frac{4}{3} \sin^2 \theta_W \approx -\frac{2}{3}$
p(uud)	+1	$Q_W^p = 1 - 4 \sin^2 \theta_W \approx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

Electron and proton weak charge Q_W^e and Q_W^p

Suppression of the proton and electron weak charge in Standard Model make them sensitive to new physics!

Parity-Violating Electron Scattering

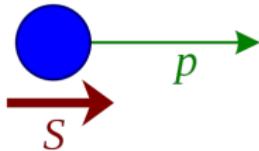
Interference of photon and weak boson exchange



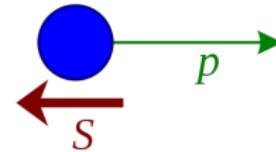
$$\mathcal{M}^{EM} \propto \frac{1}{Q^2} \quad \mathcal{M}_{PV}^{NC} \propto \frac{1}{M_Z^2 + Q^2}$$

$$\sigma = |\mathcal{M}^{EM}|^2 + 2\mathcal{M}^{EM}\mathcal{M}_{PV}^{NC} + |\mathcal{M}_{PV}^{NC}|^2$$

Right-handed:

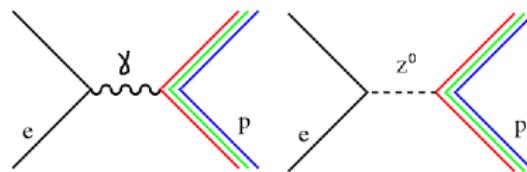


Left-handed:



Parity-Violating Electron Scattering

Interference of photon and weak boson exchange



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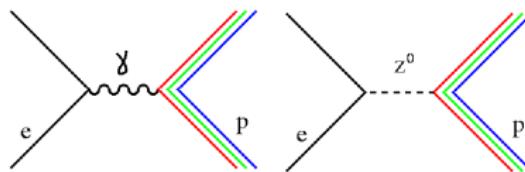
$$\sigma = |\mathcal{M}^{EM}|^2 + 2\mathcal{M}^{EM}\mathcal{M}_{PV}^{NC} + |\mathcal{M}_{PV}^{NC}|^2$$

Very small asymmetry between left and right helicity

$$A_{PV}(p) = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{\mathcal{M}_{PV}^{NC}}{\mathcal{M}^{EM}} \propto \frac{Q^2}{M_Z^2} \quad \text{when } Q^2 \ll M_Z^2$$

Parity-Violating Electron Scattering Off Protons

Interference of photon and weak boson exchange



Asymmetry between left and right helicity in nucleons

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

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

$$A_{PV}(p) \xrightarrow{Q^2 \rightarrow 0} \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[Q_W^p + Q^2 \cdot B(Q^2) \right] \propto 10^{-7}$$

Parity-Violating Electron Scattering: Quark Couplings

Weak charge

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

Early experiments

- SLAC and APV

Electron scattering

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

Q_{weak} experiment

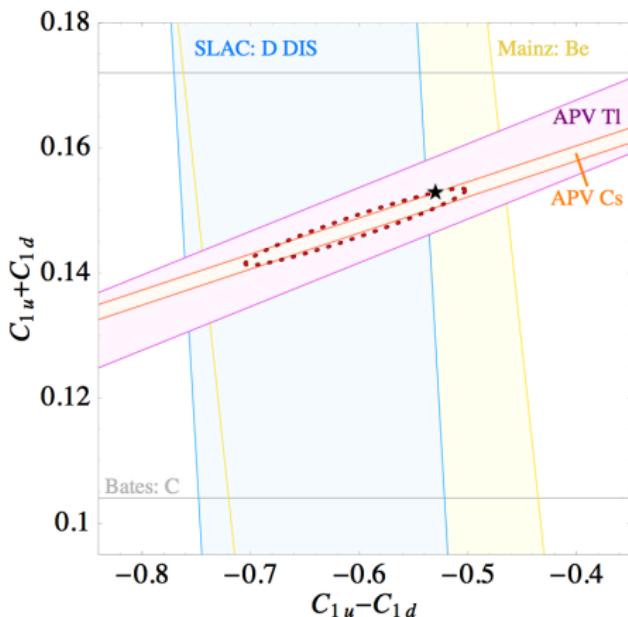


Figure: Young, Carlini, Thomas, Roche

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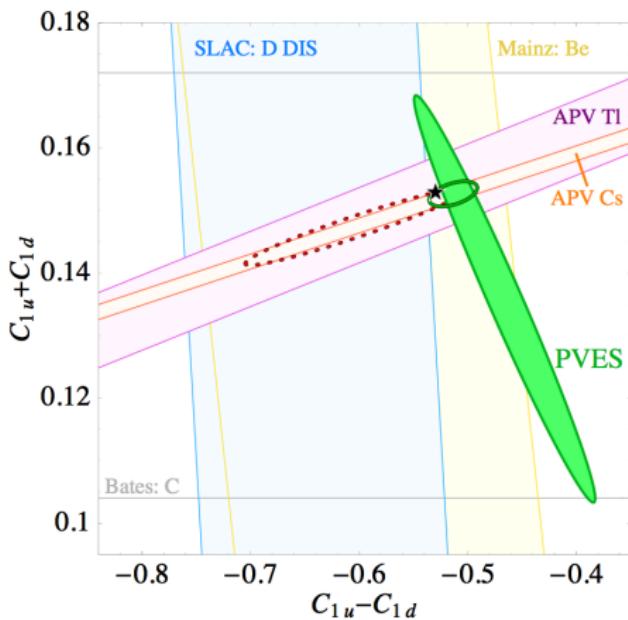


Figure: Young, Carlini, Thomas, Roche

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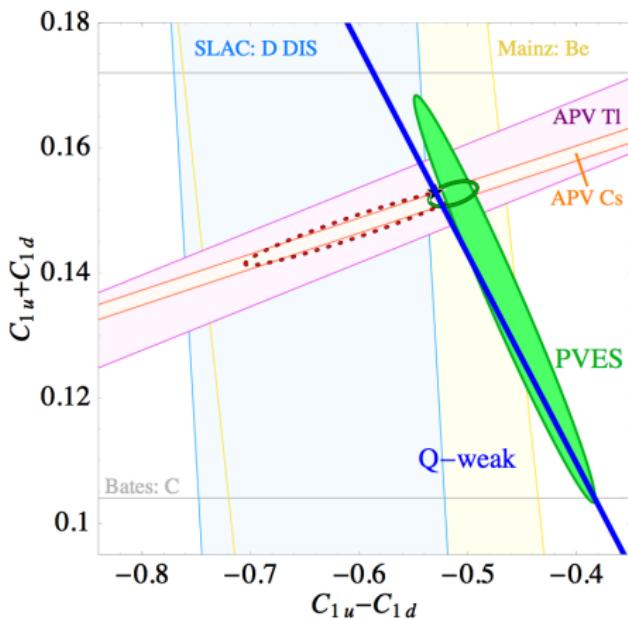
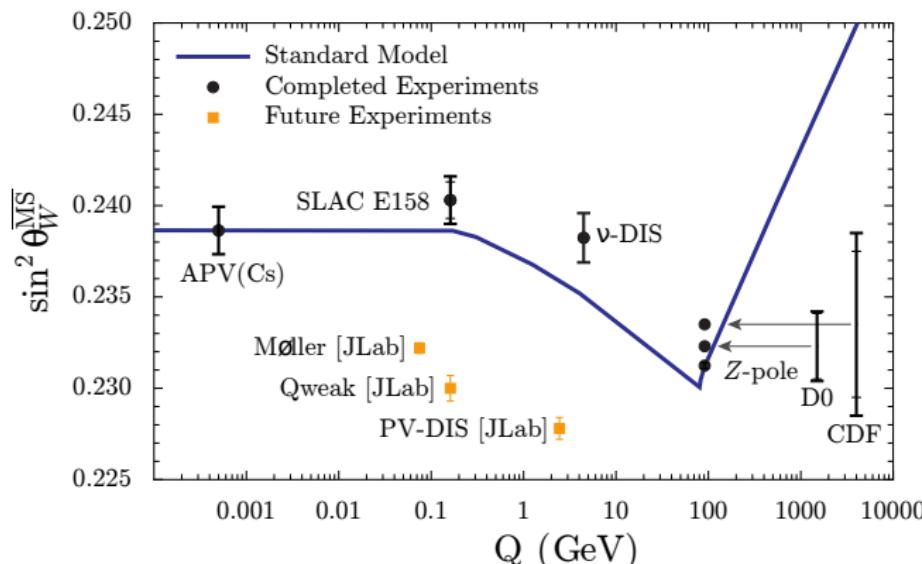
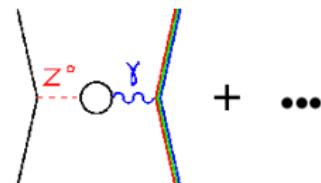


Figure: Young, Carlini, Thomas, Roche

Parity-Violating Electron Scattering: $\sin^2 \theta_W$

Running of $\sin^2 \theta_W$

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



The Q_{weak} Experiment

- Precision measurement of a quantity suppressed by fundamental symmetries ($Q_W^p \approx 0$, asymmetry of 270 ppb)
- Elastic scattering of electron beam on proton target to measure the proton weak charge Q_W^p to a precision of 4%

Pushing the envelope of intensity (more events)

- Higher beam current (150 μA versus usually 100 μA)
- Longer cryo-target (35 cm versus 20 cm)
- Higher event rates up to 800 MHz

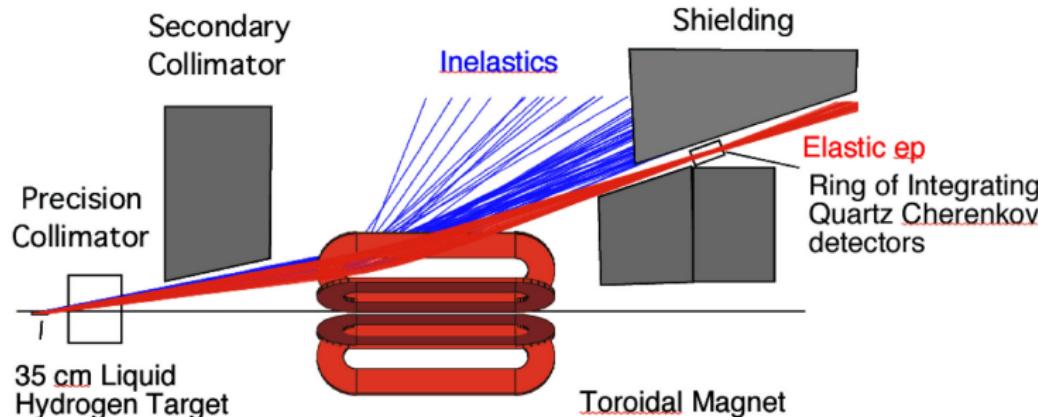
Pushing the envelope of precision

- Electron beam polarization precision of 1% at 1 GeV
- Helicity-correlated asymmetries at ppb level

The Q_{weak} Experiment

Conceptual overview

- Elastic $\vec{e} \cdot p$ scattering on liquid hydrogen target
- Toroidal magnet to provide energy dispersion
- Collimator and magnet system to select **elastic events** only
- Lower energy inelastic events bent **outside of acceptance**



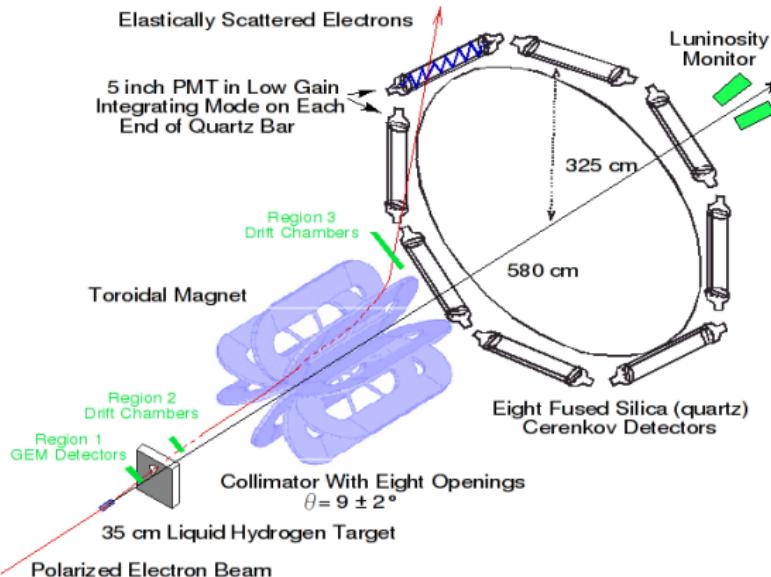
The Q_{weak} Experiment

Current mode

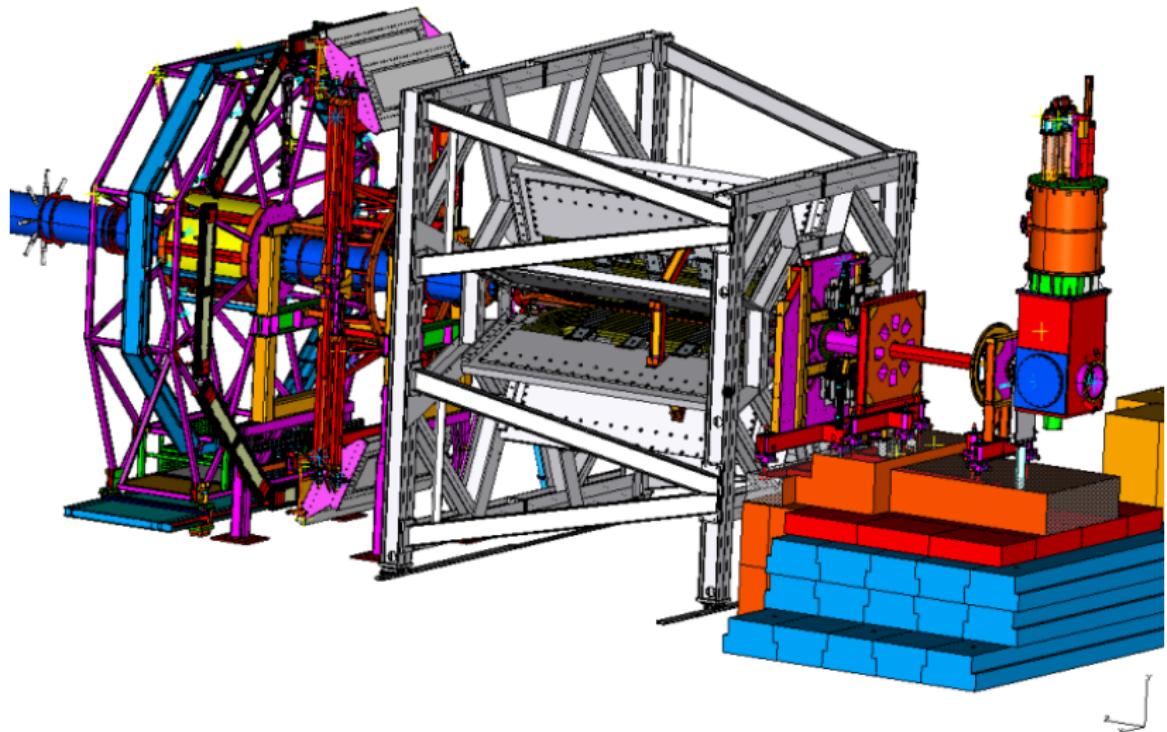
- Asymmetry measurement
- Using quartz bar detectors

Event mode

- Backgrounds, momentum
- Measure individual tracks



The Q_{weak} Experiment: Overview



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The Q_{weak} Experiment: Overview

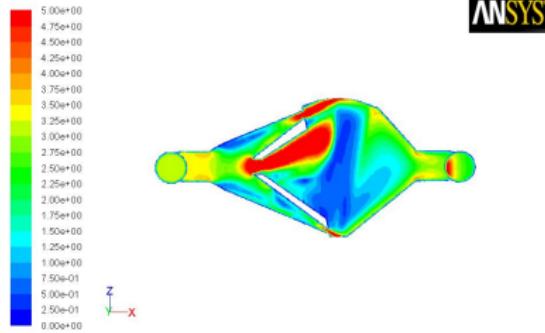


The Q_{weak} Experiment: High Power Cryotarget

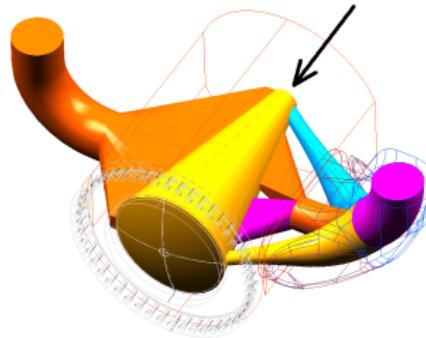
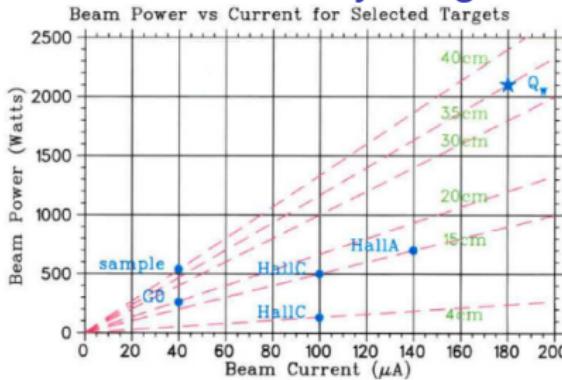
Operational Parameters

- Transverse flow: 2.8 m/s
- Target length: 35 cm
- Beam current: 150 μ A
- Heating power: 2.5 kW

Design using CFD



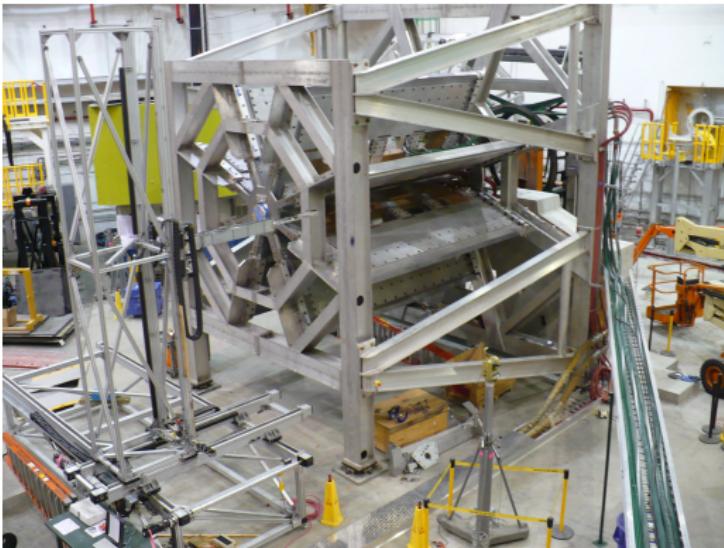
Power for other cryotargets



The Q_{weak} Experiment: Toroidal Magnet (QTOR)

QTOR installed in Hall C

- Full assembly and power supply tests
- Mapped at half field, within tolerances

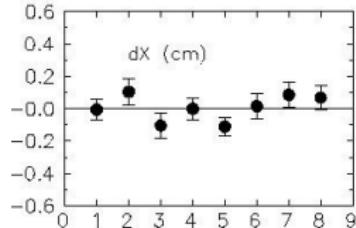


QTOR properties

- Warm coils
- 10000 A
- 6 m high

Large coils aligned
to 1 mm

At MIT/Bates

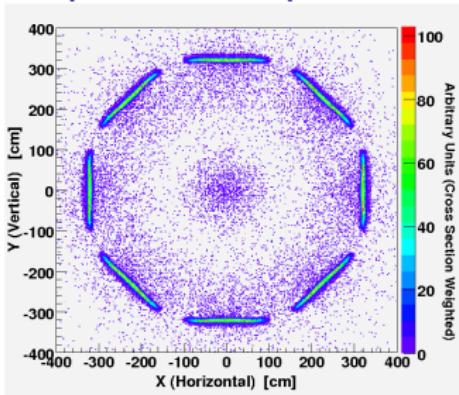


The Q_{weak} Experiment: Main Detector

Čerenkov detector bars

- 8 fused silica radiators, 2 m long \times 18 cm \times 1.25 cm
- Light collection: total internal reflection
- 5 in PMTs with gain of 2000, low dark current
- 800 MHz electron rate per bar, defines counting noise

Focal plane acceptance



Main detector bars

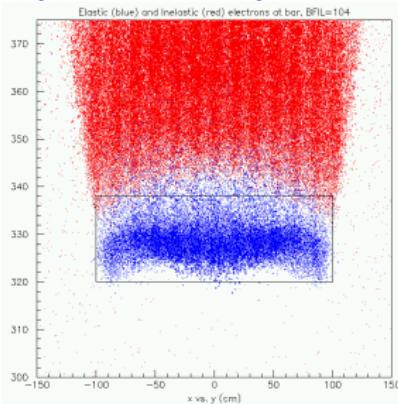


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Main detector bars



The Q_{weak} Experiment: Systematic Uncertainties

Largest projected uncertainties on Q_W^p

- Total uncertainty on Q_W^p : 4.1%
- Statistical uncertainty: 3.2%
- Hadronic structure: 1.5%
- Beam polarimetry: 1.5%
- Measurement of Q^2 : 1.0%
- Background events: 0.7%
- Helicity-correlated beam properties: 0.7%

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The Q_{weak} Experiment: Tracking Mode

Reasons for a tracking system?

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



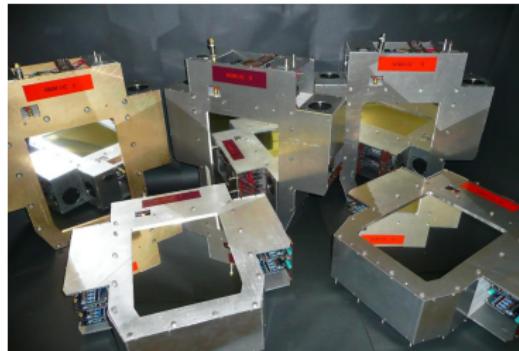
Instrumentation of two octants

- Gas-electron multiplier foils (GEM) close to target vertex
- Horizontal drift chambers (HDC) for front region
- Vertical drift chambers (VDC) for back region
- Rotation allows measurements in all 8 octants

The Q_{weak} Experiment: Tracking Mode

Horizontal drift chambers

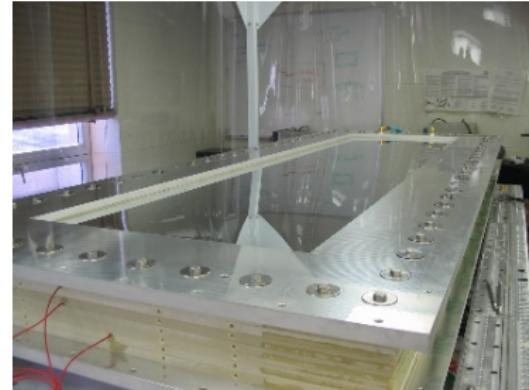
- 12 planes per octant
- Constructed at Va Tech



- Tested with cosmic rays
- Operating as expected
- Ready for installation

Vertical drift chambers

- 181 wires in 2 m long multiplexed planes
- 4 planes per octant
- Constructed at W&M
- Tested with cosmic rays



The Q_{weak} Experiment: Beam Polarimetry

Requirements on beam polarimetry

- Statistical precision of 1% after one hour
- Systematic uncertainty of 1% (on absolute measurements)

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

- Scattering off atomic electrons in magnetized iron foil
- Operation limited to **dedicated low current runs** ($I < 8 \mu\text{A}$)
- Development of fast kicker magnet for higher currents

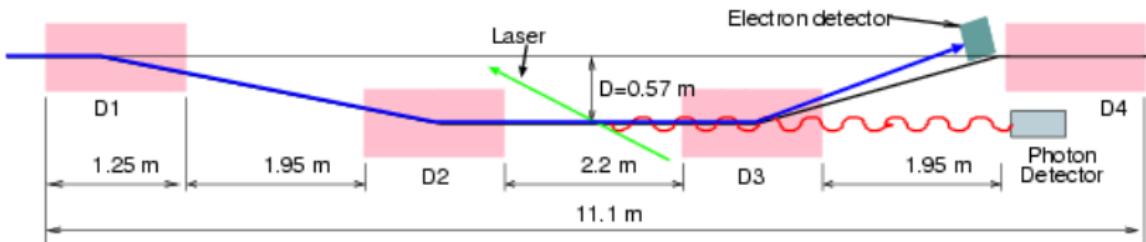
Construction new Compton polarimeter ($\vec{e} + \vec{\gamma} \rightarrow e + \gamma$)

- Compton scattering of electrons on polarized laser beam
- **Continuous, non-destructive, high precision** measurements
- Systematic uncertainty of 1% (for absolute measurements)

The Q_{weak} Experiment: Beam Polarimetry

Compton polarimeter

- **Beam:** $150 \mu\text{A}$ 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:** CsI scintillator in integrating mode
- **Electrons:** Diamond strips with $200 \mu\text{m}$ pitch



Summary

The Q_{weak} experiment

- Elastic $\vec{e}\text{-}p$ scattering on liquid hydrogen target
- Precision measurement of a proton weak charge $Q_W^p \approx 0$, suppressed by fundamental symmetries

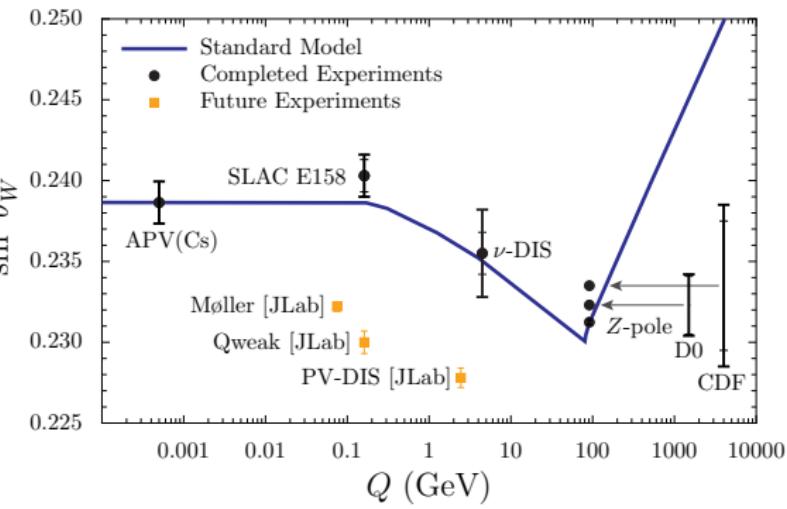
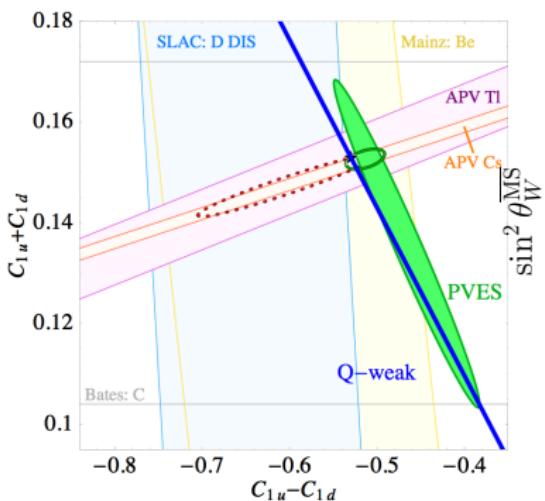
Schedule

- First beam: June 10, 2010 (next week!)
- Commissioning run: June 2010 – August 2010
- Engineering run: September 2010 – October 2010
- Production run 1: October 2010 – May 2011
- Production run 2: November 2011 – May 2012
- Shutdown for 12 GeV upgrade: May 10, 2012

Summary

First direct measurement of Q_W^p

The Q_{weak} experiment will perform the first direct measurement of the weak charge of the proton, and will measure the value of $\sin^2 \theta_W$ at moderate Q^2 .





D. Androic, D. Armstrong, A. Asaturyan, T. Averett, R. Beminiwattha, J. Benesch, J. Birchall, P. Bosted, C. Capuano, **R.D. Carlini (Principal Investigator)**, G. Cates, S. Covrig, M. Dalton, C.A. Davis, W. Deconinck, X. Deng, K. Dow, J. Dunne, D. Dutta, R. Ent, J. Erler, W. Falk, H. Fenker, **J.M. Finn**[†], T.A. Forest, W. Franklin, M. Furic, D. Gaskell, M. Gericke, J. Grames, K. Grimm, D. Higinbotham, M. Holtrop, J.R. Hoskins, K. Johnston, E. Ihloff, M. Jones, R. Jones, K. Joo, J. Kelsey, C. Keppel, M. Kohl, P. King, E. Korkmaz, **S. Kowalski**, J. Leacock, J.P. Leckey, J.H. Lee, L. Lee, A. Lung, S. MacEwan, D. Mack, R. Mahurin, J. Mammei, J. Martin, D. Meekins, A. Micherdzinska, A. Mkrtchyan, H. Mkrtchyan, N. Morgan, K.E. Myers, A. Narayan, Nuruzzaman, A.K. Opper, **S.A. Page**, J. Pan, K. Paschke, S. Phillips, M. Pitt, B.(Matt) Poelker, Y. Prok, W.D. Ramsay, M. Ramsey-Musolf, J. Roche, N. Simicevic, **G. Smith**, T. Smith, P. Souder, D. Spayne, R. Suleiman, E. Tsentalovich, W.T.H. van Oers, B. Waidyawansa, W. Vulcan, D. Wang, P. Wang, S. Wells, S.A. Wood, S. Yang, R. Young, X. Zheng, H. Zhu, C. Zorn

Spokespersons, Project Manager

[†] deceased

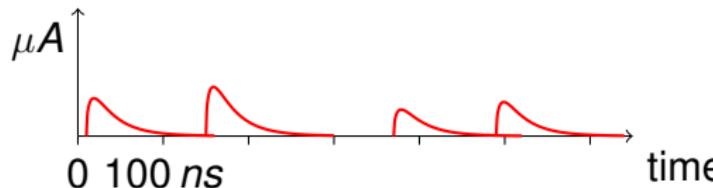
College of William & Mary, University of Connecticut, Instituto de Fisica, Universidad Nacional Autonoma de Mexico, University of Wisconsin, Hendrix College, Louisiana Tech University, University of Manitoba, Massachusetts Institute of Technology, Thomas Jefferson National Accelerator Facility, Virginia Polytechnic Institute & State University, TRIUMF, University of New Hampshire, Yerevan Physics Institute, Mississippi State University, University of Northern British Columbia, Ohio University, Hampton University, University of Winnipeg, University of Virginia, George Washington University, Syracuse University, Idaho State University, University of Connecticut, Christopher Newport University, University of Zagreb

Additional Material

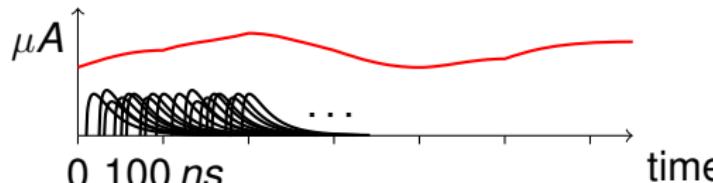
The Q_{weak} Experiment

Event versus current mode

- Event mode
 - each event individually registered
 - event selection or rejection possible

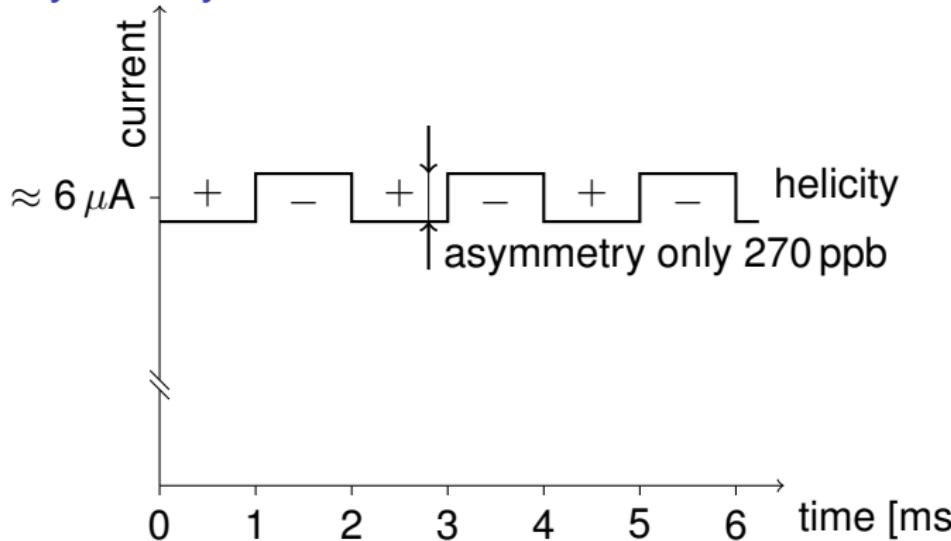


- Current or integrating mode
 - high event rates possible (event every nanosecond!)
 - no suppression of background events possible



The Q_{weak} Experiment

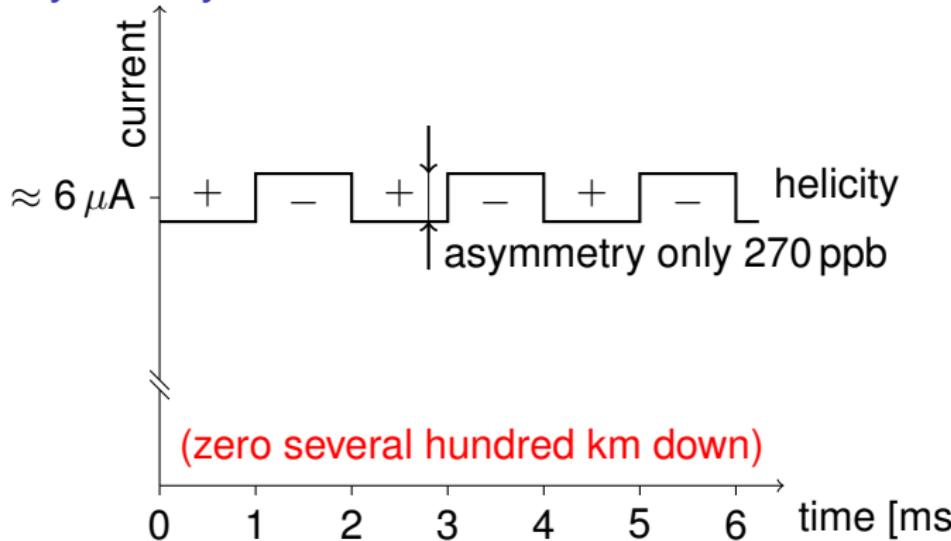
Asymmetry measurement in current mode



- Collect many helicity windows: 2 year long experiment
- Ensure that scatter is uncorrelated and perfectly Gaussian

The Q_{weak} Experiment

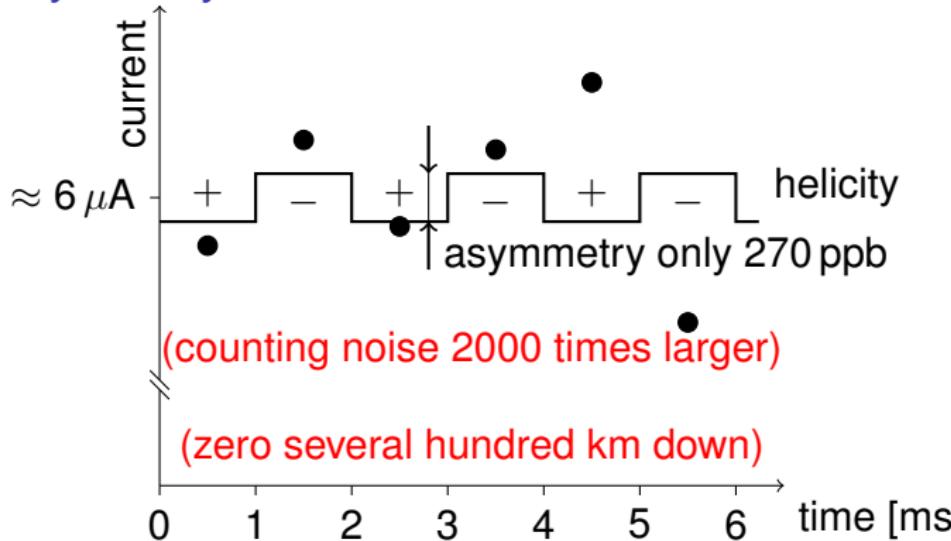
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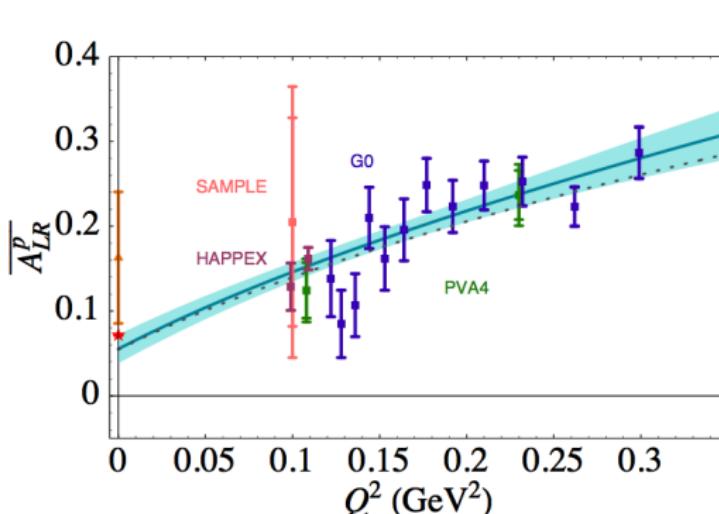


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Parity-Violating Electron Scattering

Reduced parity-violating asymmetry

$$\overline{A_{PV}}(p) = A_{PV}(p) \cdot \frac{4\pi\alpha\sqrt{2}}{-G_F Q^2} \xrightarrow{Q^2 \rightarrow 0} Q_W^p + Q^2 \cdot B(Q^2)$$



At $Q^2 = 0$

- PDG
 - SM

Q_{weak} Exp

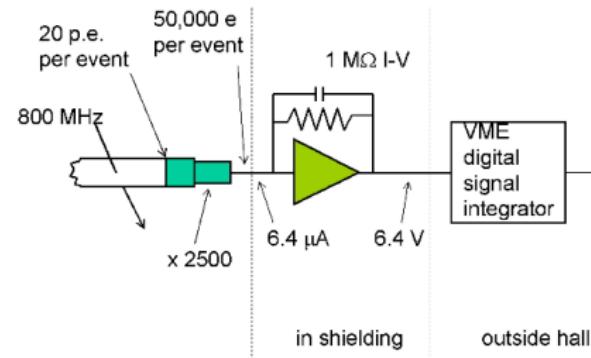
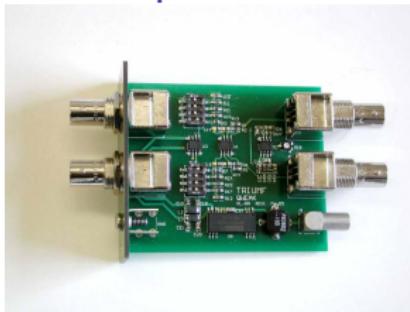
- $Q^2 =$
0.026 GeV²

The Q_{weak} Experiment: Main Detector

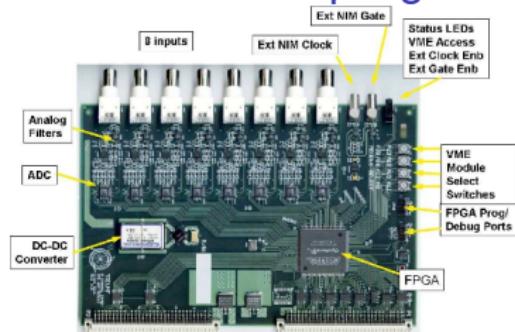
Low noise electronics

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

I-V Preamplifier



18-bit 500 kHz sampling ADC



Delivered, tested: noise is 3 times lower than counting statistics

The Q_{weak} Experiment: Systematic Uncertainties

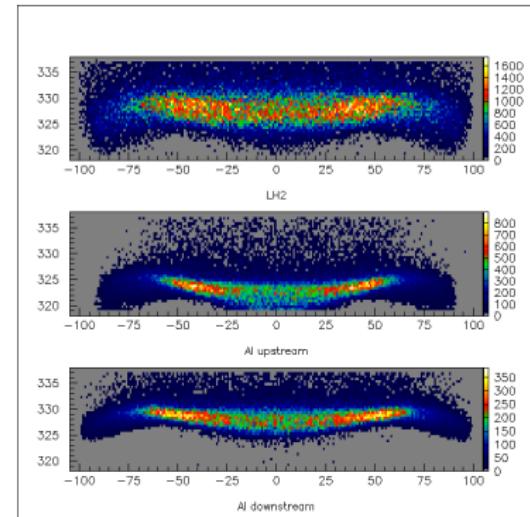
Reminder: weak vector charges

AI target windows

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

Sources of neutron scattering

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



The Q_{weak} Experiment: Systematic Uncertainties

Largest projected uncertainties on Q_W^p

- Total uncertainty on Q_W^p : 4.1%
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- Hadronic structure: 1.5%
- Beam polarimetry: 1.5%
- Measurement of Q^2 : 1.0%
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Responsibilities of MIT group

- Track reconstruction/momenta determination software
- Construction of Compton polarimeter

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- Measurement of Q^2 : 1.0%
- Background events: 0.7%
- Helicity-correlated beam properties: 0.7%

Responsibilities of MIT group

- Track reconstruction/momentum determination software
- Construction of Compton polarimeter

The Q_{weak} Experiment: Systematic Uncertainties

Largest projected uncertainties on Q_W^p

- Total uncertainty on Q_W^p : 4.1%
- Statistical uncertainty: 3.2%
- Hadronic structure: 1.5%
- Beam polarimetry: 1.5%
- Measurement of Q^2 : 1.0%
- Background events: 0.7%
- Helicity-correlated beam properties: 0.7%

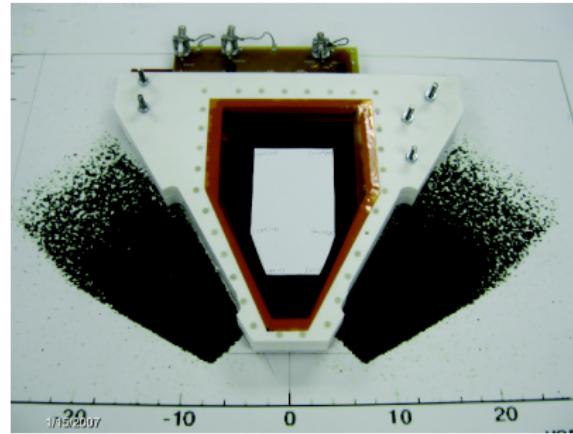
Responsibilities of MIT group

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The Q_{weak} Experiment: Tracking Mode

Gas-electron multiplier (GEM)

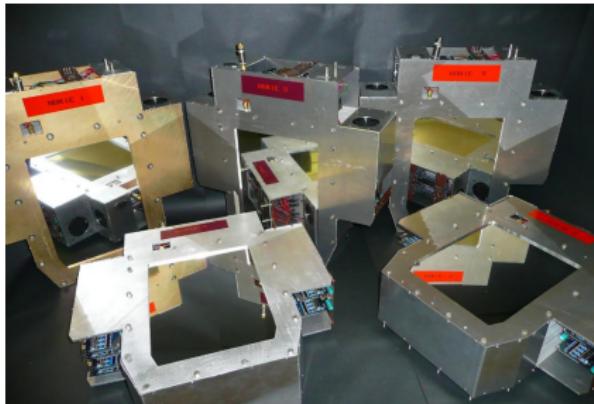
- Very close to target, very high dose
- GEMs have high radiation hardness
- Several days of radcon cool-down in GEM bunker
- Remotely controlled rotator mounted on collimator



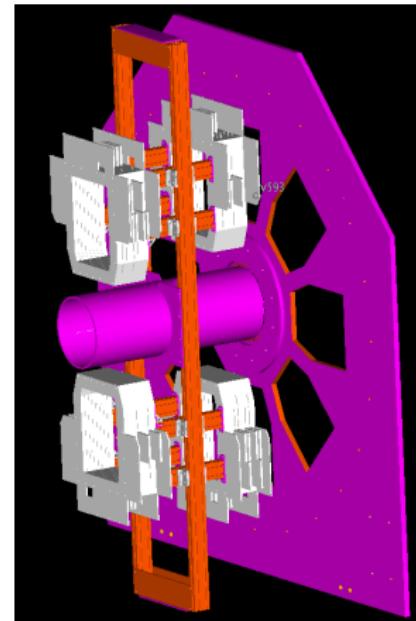
The Q_{weak} Experiment: Tracking Mode

Horizontal drift chambers (HDC)

- 12 planes per octant
- u, v, x, u, v, x planes per assembly



HDC rotator system

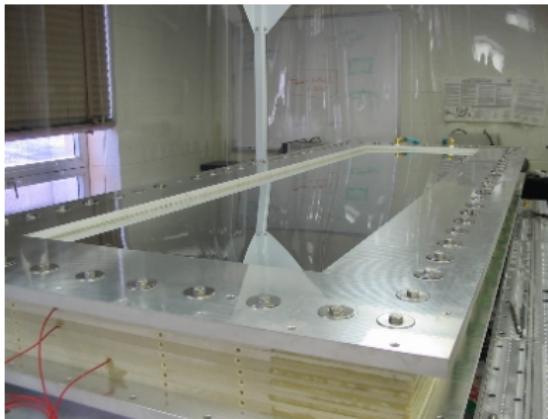


- 4 + 1 constructed, tested
- Residuals from cosmic events
- Ready for installation

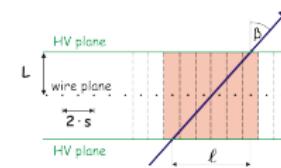
The Q_{weak} Experiment: Tracking Mode

Vertical drift chambers (VDC)

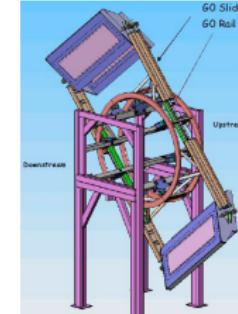
- 181 wires in 2 m wide planes
- u, v, u, v planes per assembly
- Multiplexed read-out on delay lines



Principle of operation



VDC rotator system



Electroweak Interaction: Running of $\sin^2 \theta_W$

Atomic parity-violation on ^{133}Cs

- New calculation in many-body atomic theory
- Porsev, Beloy, Derevianko; arXiv:0902.0335 [hep-ph]
- Experiment: $Q_W(^{133}\text{Cs}) = -73.25 \pm 0.29 \pm 0.20$
- Standard Model: $Q_W(^{133}\text{Cs}) = -73.16 \pm 0.03$

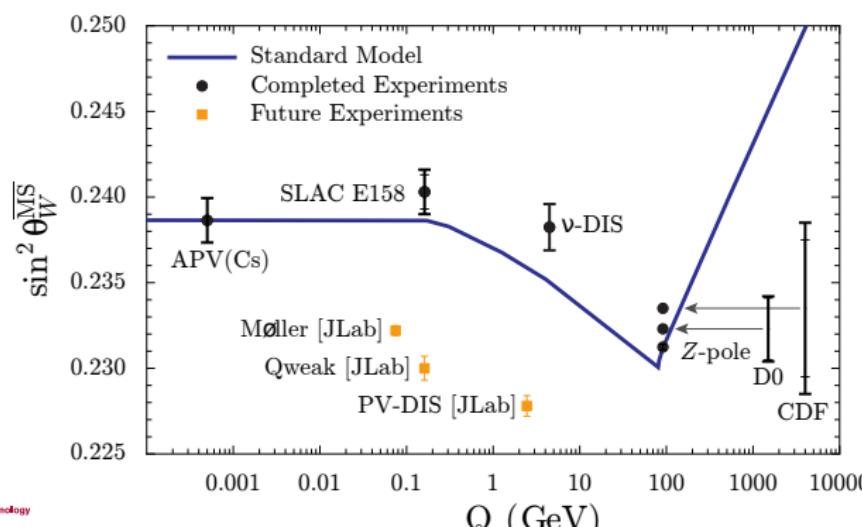
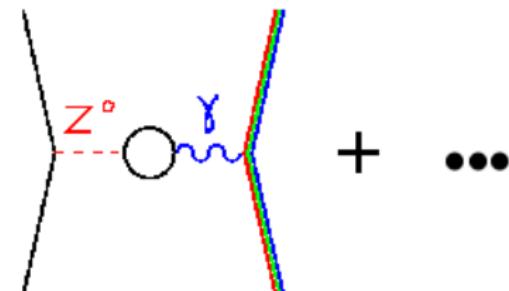
NuTeV anomaly explained

- Originally, 3σ deviation from Standard Model
- Erler, Langacker: strange quark PDFs
- Londergan, Thomas: charge symmetry violation, $m_u \neq m_d$
- Cloet, Bentz, Thomas: in-medium modifications to PDFs, isovector EMC-type effect
- Entire anomaly accounted for (everybody stops looking...)

Electroweak Interaction

Running of $\sin^2 \theta_W$

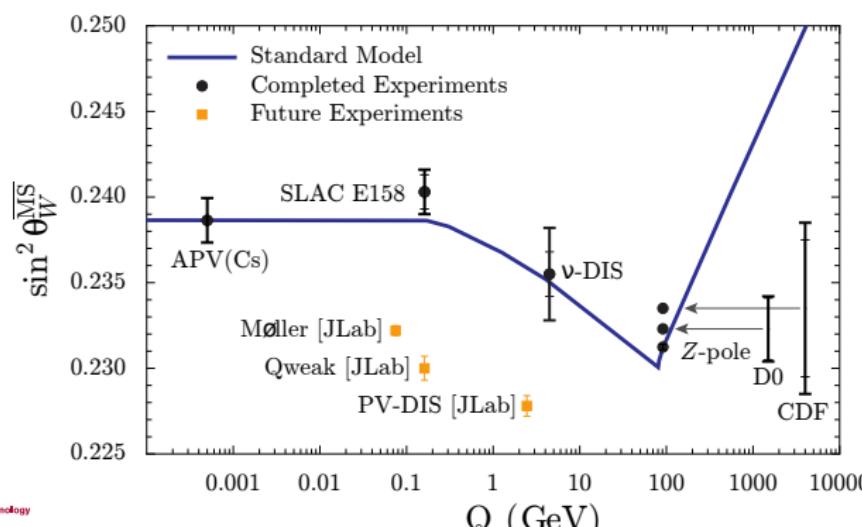
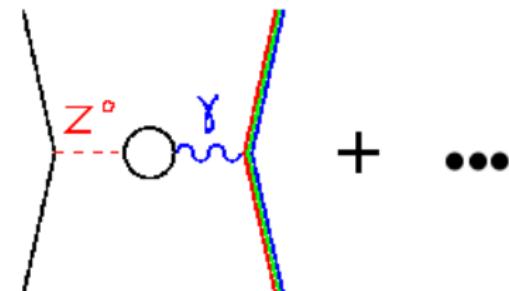
- Higher order loop diagrams
- $\sin^2 \theta_W$ varies with Q^2



Electroweak Interaction

Running of $\sin^2 \theta_W$

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



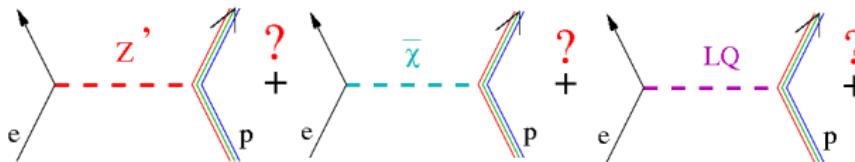
Sensitivity to New Physics

New physics

- Consider effective contact interaction
- Coupling constant g , mass scale Λ
- Effective charges $h_V^u = \cos \theta_h$ and $h_V^d = \sin \theta_h$

Effective Lagrangian

$$\begin{aligned}\mathcal{L}_{e-q}^{PV} &= \mathcal{L}_{SM}^{PV} + \mathcal{L}_{New}^{PV} \\ &= -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C_{1q} \bar{q} \gamma^\mu q + \frac{g^2}{4\Lambda^2} \bar{e} \gamma_\mu \gamma_5 e \sum_q h_q^V \bar{q} \gamma^\mu q\end{aligned}$$



Sensitivity to New Physics

Lower bound on new physics (95% CL)

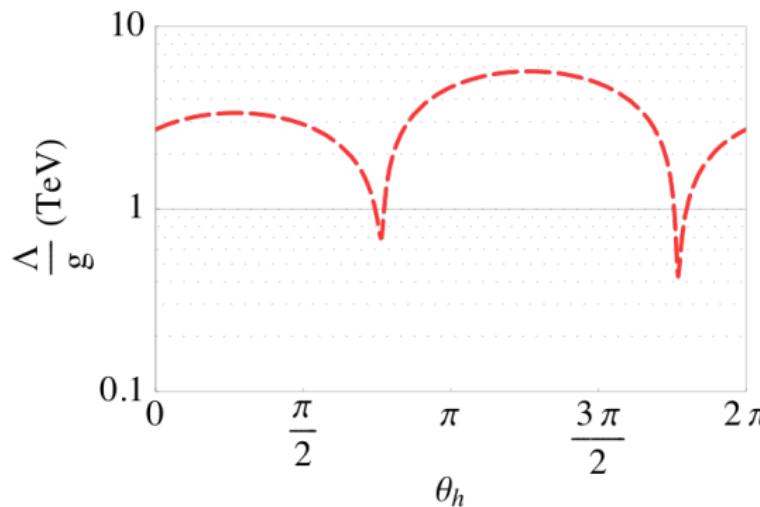


Figure: Young, Carlini, Thomas, Roche (2007)

Constraints from

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

Projection Q_{weak}

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

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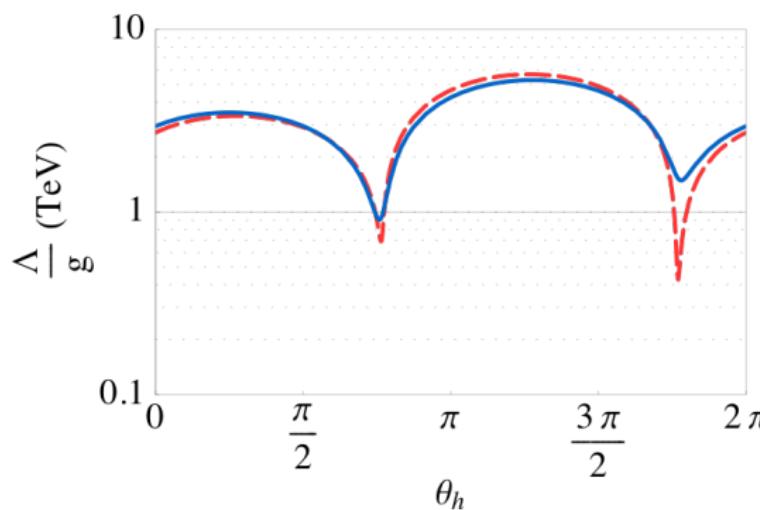


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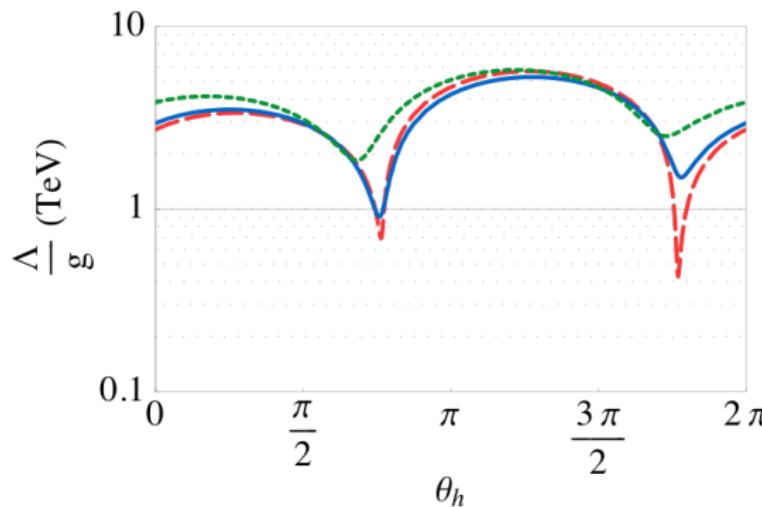


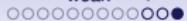
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Other Experiments

