The Qweak Experiment:
First Determination of the Weak Charge of the Proton

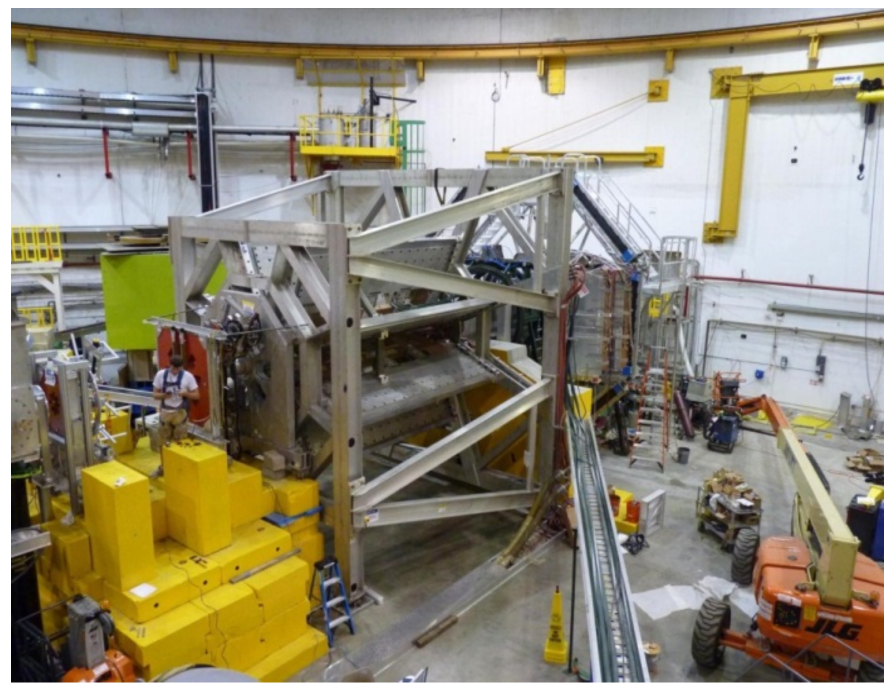
Mark Pitt, Virginia Tech for the Qweak Collaboration

MESON 2014:

13th International Workshop on Meson Production, Properties and Interaction

KRAKÓW, POLAND

29 May – 3 June 2014



Qweak uses parity-violating elastic electron-proton scattering to measure the proton's neutral weak charge at Jefferson Lab

- Precision Standard Model test
- tests "running of $\sin^2\theta_W$" from M^2_Z to low Q^2
- sensitive to new TeV scale physics

Outline

- Motivation and formalism
- Experiment: technical challenges and achievements
- First measurement of proton's weak charge – results and implications
- Status of analysis towards final precision result

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Proton's Neutral Weak Charge

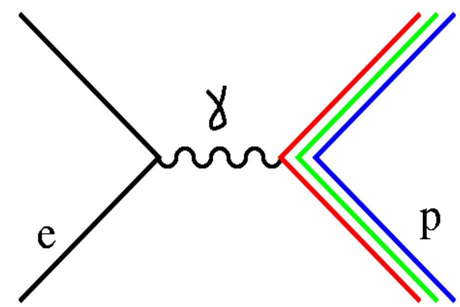
The Standard Model prescribes the couplings of the fundamental particles to each other →

	Q^{γ}	Q^{Z}
u	+2/3	$1 - 8/3\sin^2\theta_W$
d	−1/3	$-1 + 4/3\sin^2\theta_W$

$\sin^2\theta_W$ → "weak mixing angle"

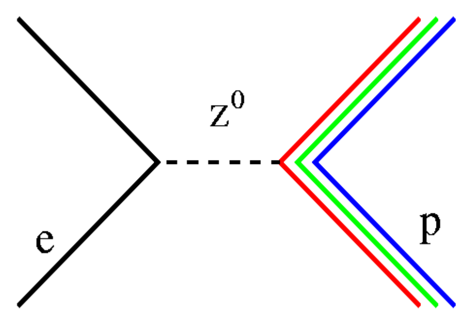
Electromagnetic force → proton's electric charge

$$Q^p = 2\left(+\frac{2}{3}\right) + 1\left(-\frac{2}{3}\right) = +1$$



Weak force → proton's neutral weak charge - Q_{weak}

$$Q^p_{weak} = 2\left(1 - 8/3\sin^2\theta_W\right) + 1\left(-1 + 4/3\sin^2\theta_W\right)$$
$$= 1 - 4\sin^2\theta_W \sim 0.07$$

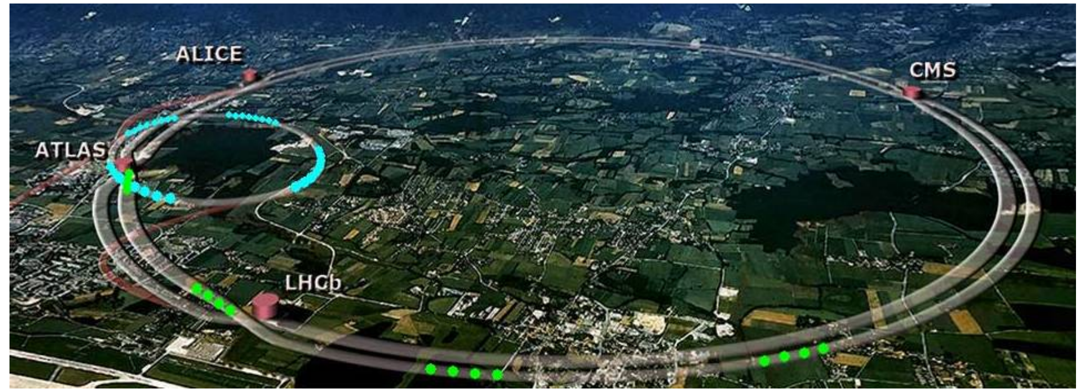


→ Accidental suppression

sensitivity to new physics

The Hunt for New Physics

Two complementary approaches to searching for "New Physics"

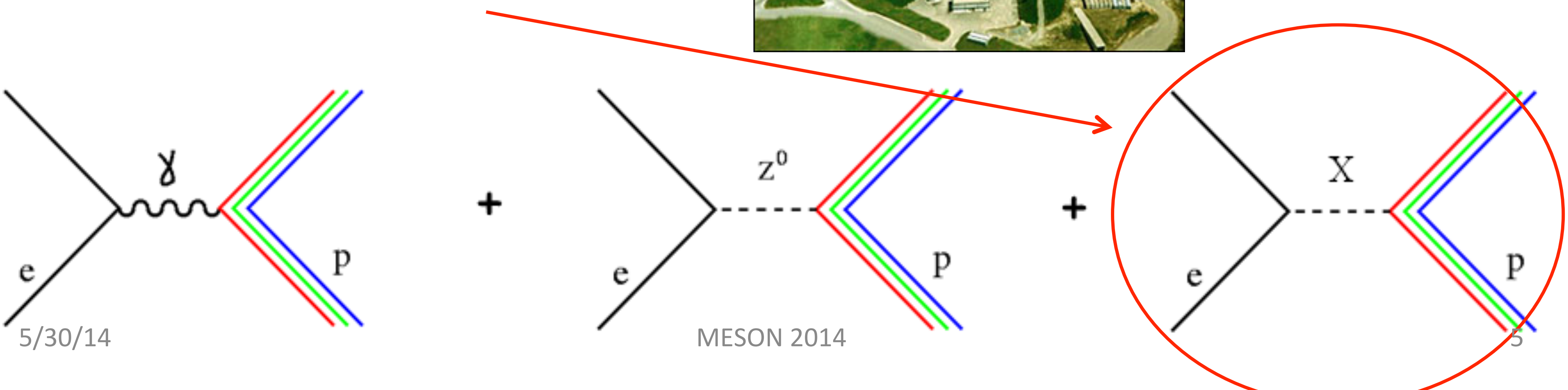


"Energy frontier"
- like LHC – Large Hadron Collider

→ Make new particles ("X") directly in high energy collisions

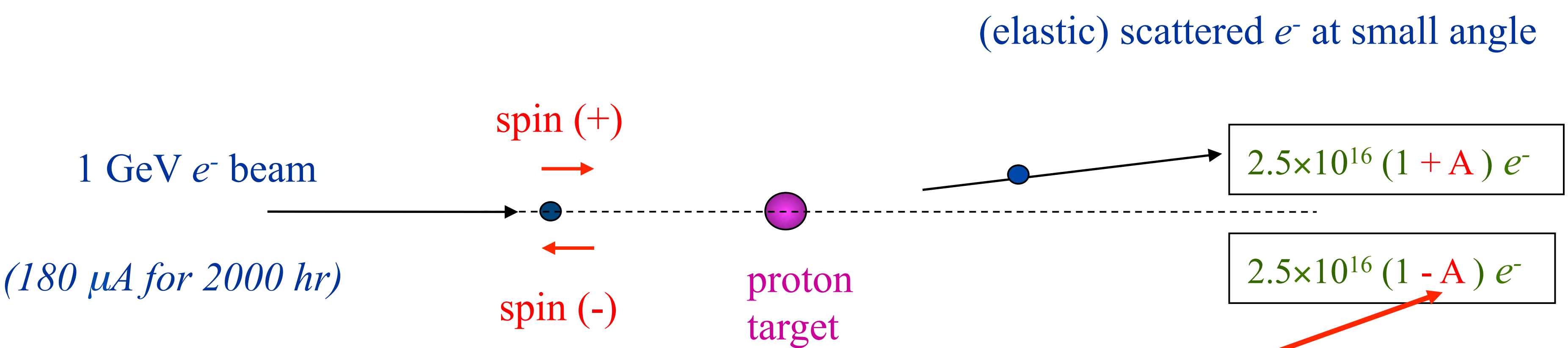
"Precision frontier"
- examples: Qweak at JLab, μ(g-2), EDM, ββ decay, n β decay, etc.

→ Look for indirect effect of new particles ("X") made virtually in low energy processes



The Q_{weak} Experiment: The Essentials

Elastic scattering of longitudinally polarized electrons on protons $\vec{e}^- + p \rightarrow e^- + p$



Parity violating asymmetry:
A ~ -2.3×10^{-7} or -230 ppb (parts per billion)

proportional to the proton's weak charge ("Qweak")

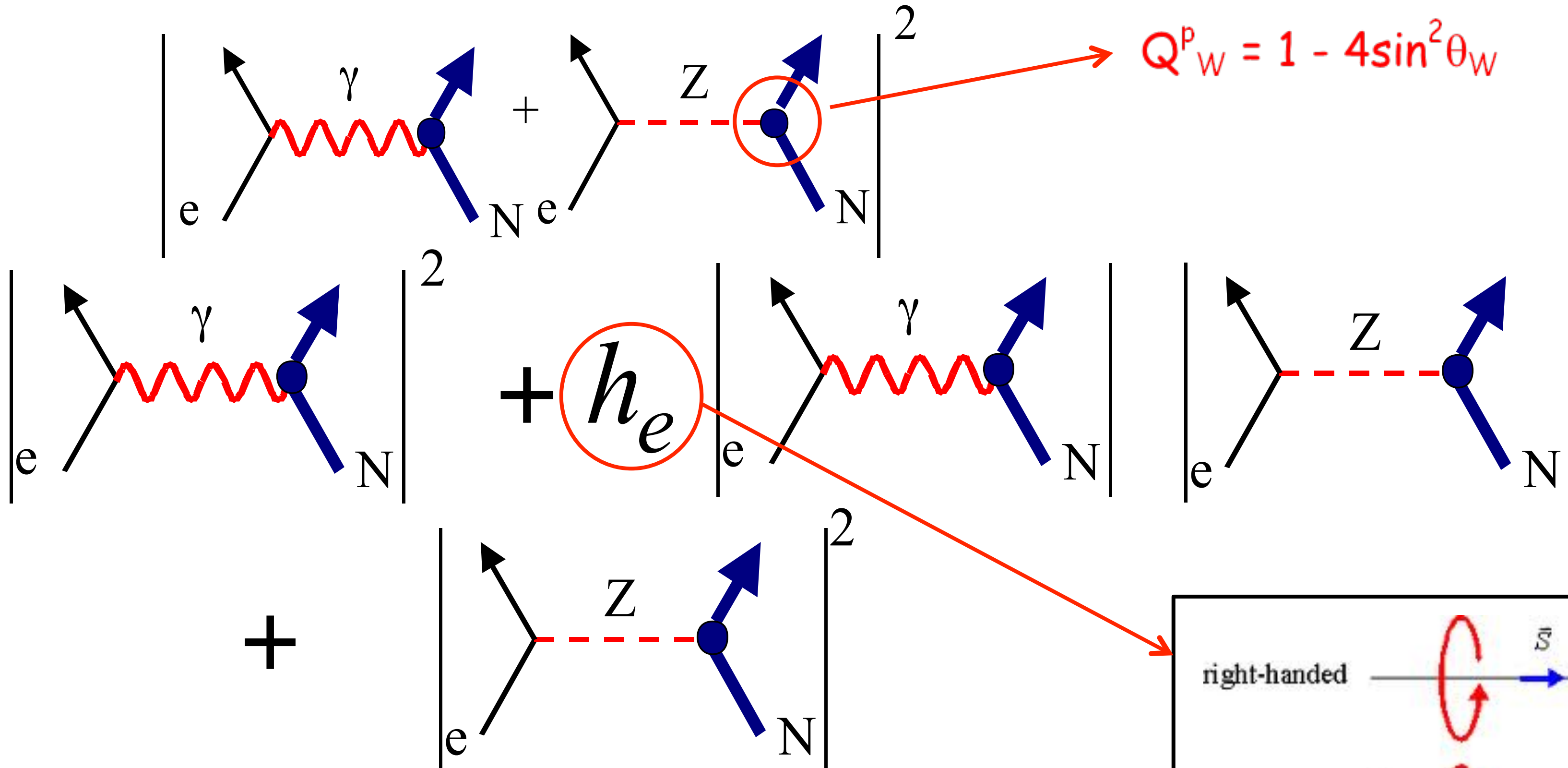
Asymmetry measured with precision of ~2% (5 ppb) → sensitive Standard Model test
→ probe for certain types of "New Physics"

Parity-Violating Asymmetry –Accessing the Neutral Weak Sector

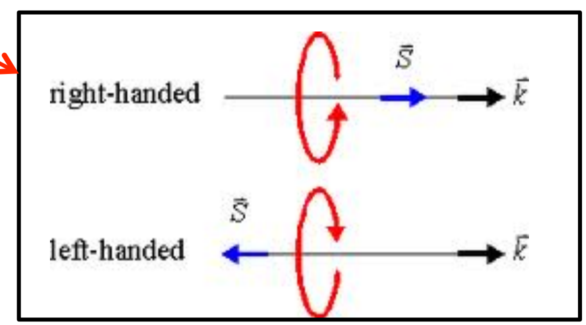
Qweak experiment :

exploit the interference between EM and weak interactions

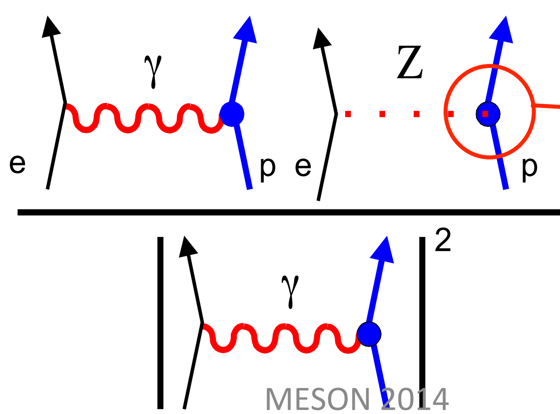
$\sigma \propto$



$Q^p_W = 1 - 4\sin^2\theta_W$



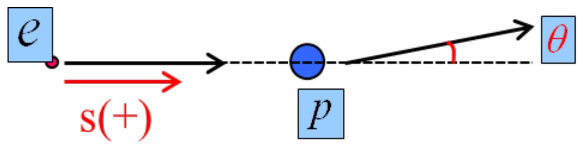
$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto$$

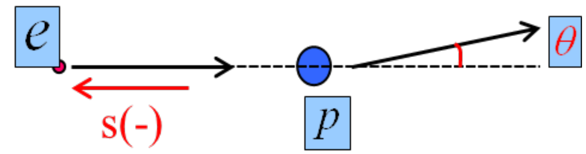


$\sim -230\,\text{ppb}$

$Q^p_W = 1 - 4\sin^2\theta_W$

Parity-Violating Asymmetry for the Q_{weak} Experiment





The Qweak experiment at JLAB determines the proton's weak charge by measuring the parity-violating asymmetry in elastic scattering of longitudinally polarized electrons on proton.

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

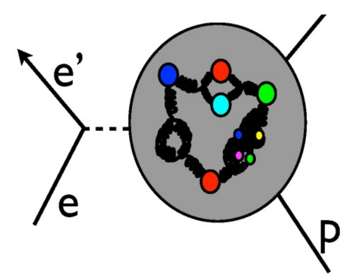
At forward scattering angles and low 4-momentum transfer:

$$A \equiv \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} \xrightarrow[\theta \to 0]{Q^2 \to 0} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q^p_{weak} + Q^4 B(Q^2)\right]$$

proton's weak charge:
$Q^p_{weak} = 1 - 4\sin^2\theta_W$ at tree level

"Form factor" term due to finite proton size – hadronic structure (~ 30% for Qweak)

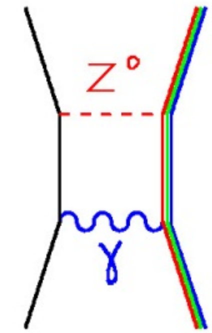
By running at a small value of Q^2 (small beam energy, small scattering angle) we minimize our sensitivity to the effects of the proton's detailed spatial structure.



Energy Dependent Electroweak Radiative Corrections

→ For useful Standard Model test all electroweak radiative corrections need to be under good theoretical control

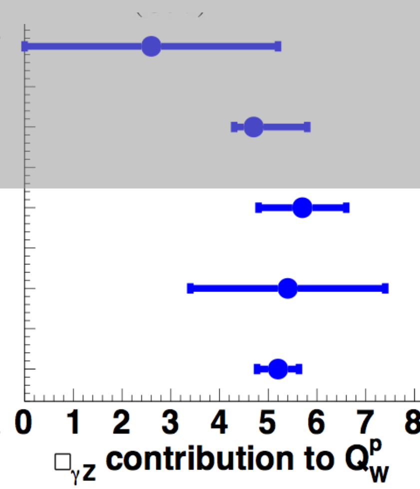
Most significant radiative correction: γ-Z Box Diagram



OLDER CALCULATIONS

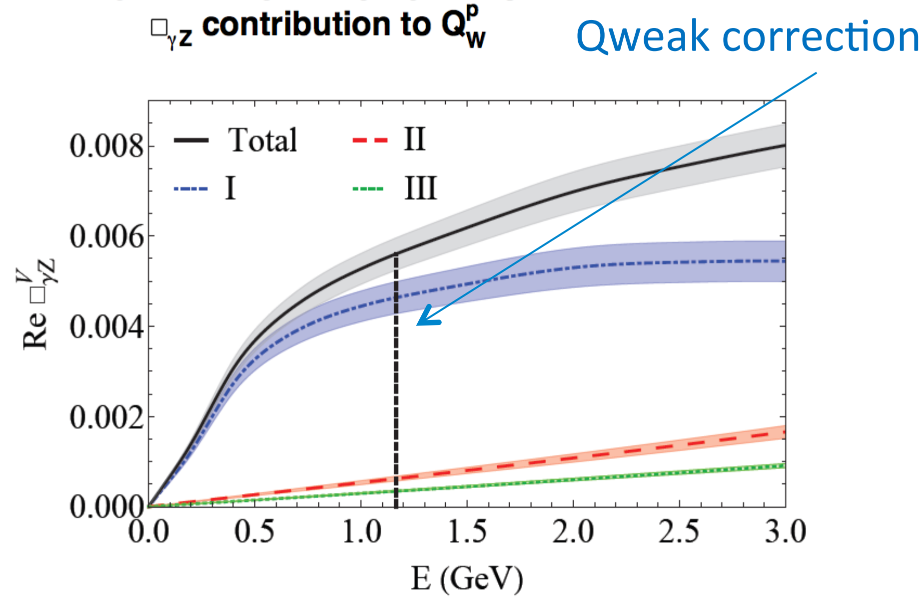
Table 1: $\Box^V_{\gamma Z}$ contribution to Q^p_W (Qweak kinetmatics)

Gorchtein & Horowitz Phys. Rev. Lett. **102**, 091806 (2009)	0.0026 ± 0.0026
Sibirtsev, Blunden, Melnitchouk, & Thomas Phys. Rev. D **82**, 013011 (2010)	$0.0047^{+0.0011}_{-0.0004}$
Rislow & Carlson Phys. Rev. D **83**, 113007 (2007)	0.0057 ± 0.0009
Gorchtein, Horowitz, & Ramsey-Musolf Phys. Rev. C **84**, 015502 (2011)	0.0054 ± 0.0020
Hall, Blunden, Melnitchouk, Thomas, & Young Phys. Rev. D **88**, 013011 (2013)	0.00557 ± 0.00036



Example: latter correction is ~ 7.8 ± 0.5% of Q^p_w
(Hall, *et al*., Phys. Rev. D **88**,013011 (2013))

- calculations are primarily dispersion theory type
- error estimates can be firmed up with PVDIS data



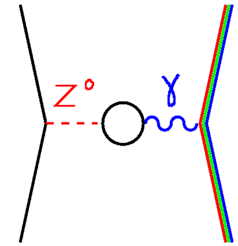
Standard Model Test – "Running of $\sin^2\theta_W$"

Full expression for proton's weak charge with all radiative corrections:

$$Q_W^p = [1 + \Delta\rho + \Delta_e]\left[(1 - 4\sin^2\theta_W(0)) + \Delta_{e'}\right] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

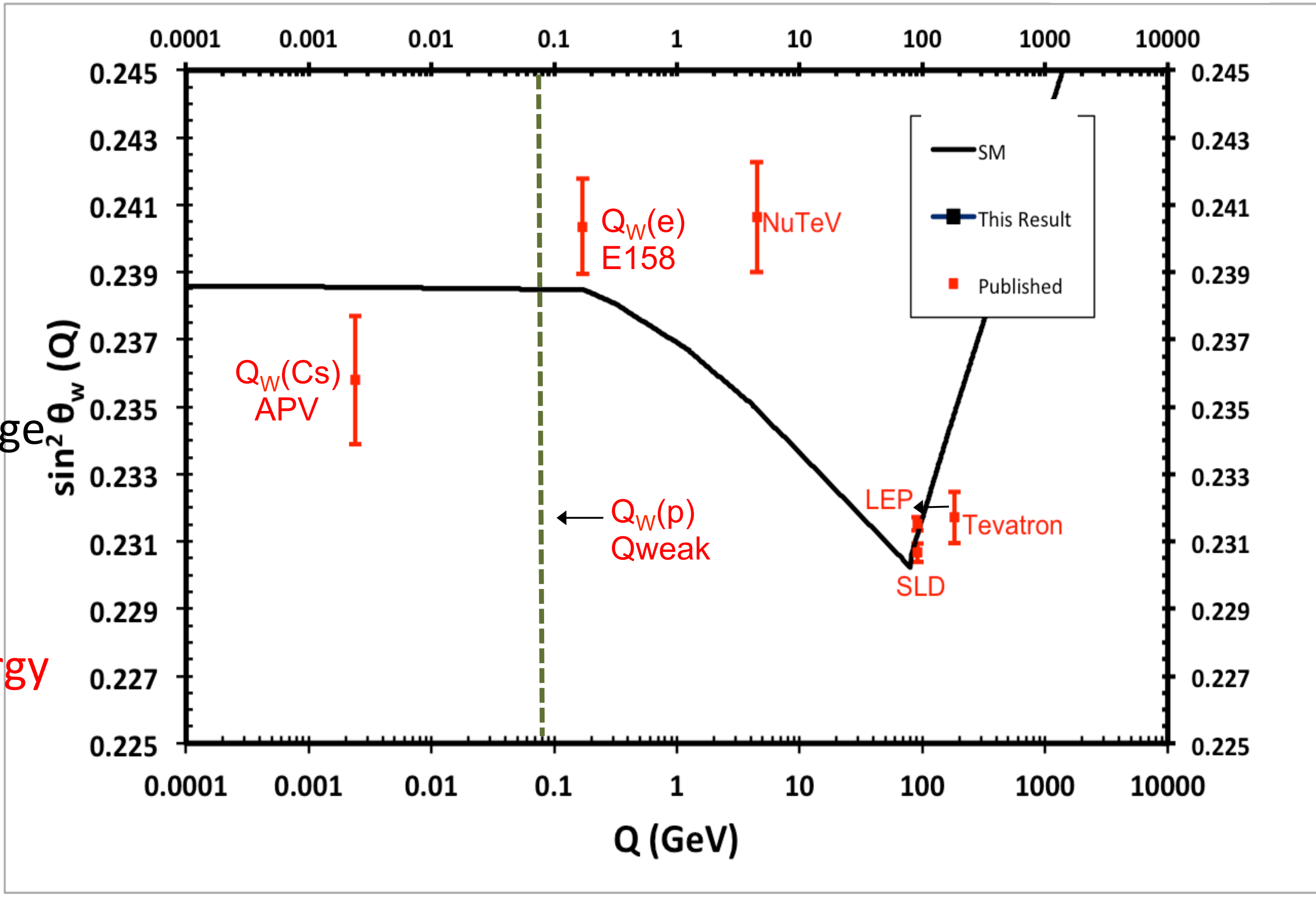
Correct for all calculated electroweak radiative corrections

Extract $\sin^2\theta_W$ for comparison with other probes



Precise low energy measurements:

- E158 Moller
  electron's weak charge
- Cs Atomic Parity Violation
  mostly neutron weak charge
- Qweak's measurement of proton weak charge
  will complete this low energy weak charge "triad"



Sensitivity to New Physics at TeV Scales

Parameterize new physics with a new contact interaction in the Lagrangian:

$$\mathcal{L}_{NP}^{PV} = -\frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

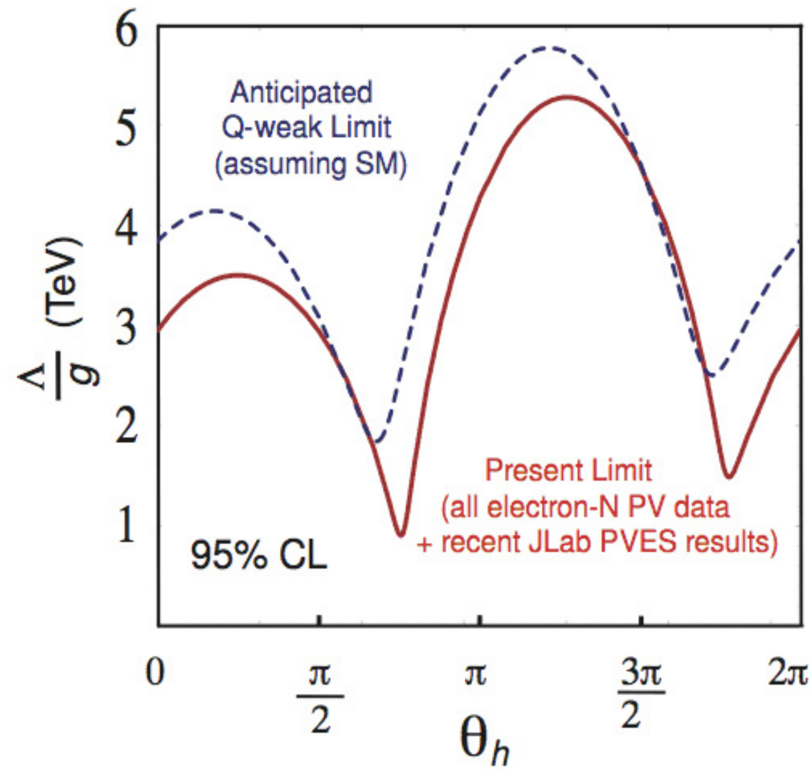
g=coupling
Λ=mass scale

Arbitrary quark flavor dependence of new physics:

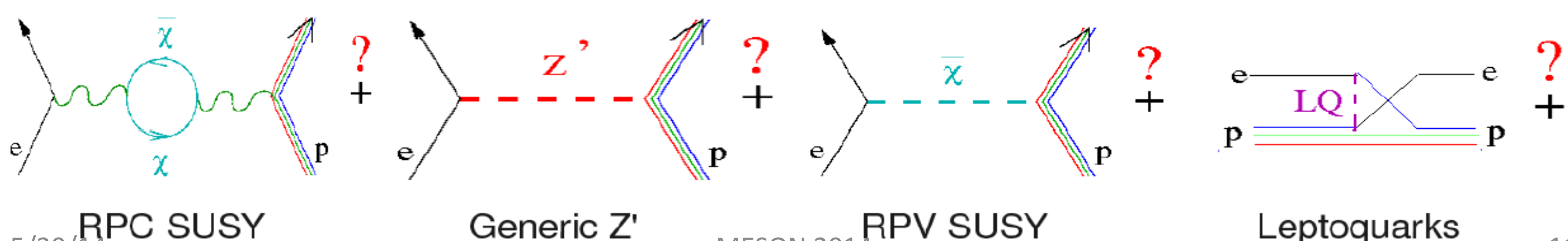
$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$

Qweak constrains new PV physics to beyond 2 TeV

Young, Carlini, Thomas & Roche, PRL 99, 122003 (2007)



Possible New Physics Scenarios:

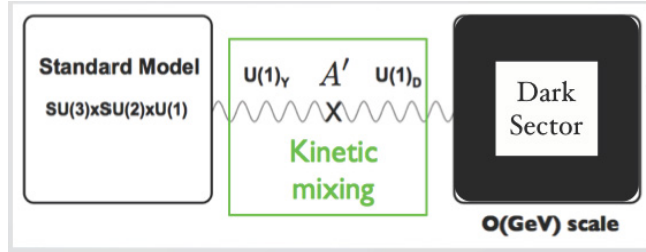


Ramsey-Musolf, Phys. Rev. C 60, 015501 (1999), Erler, et al. Phys. Rev. D 68, 016006 (2003)

New Physics Scenarios – A Recent Example

"Dark photon" – possible portal for new force to communicate with SM

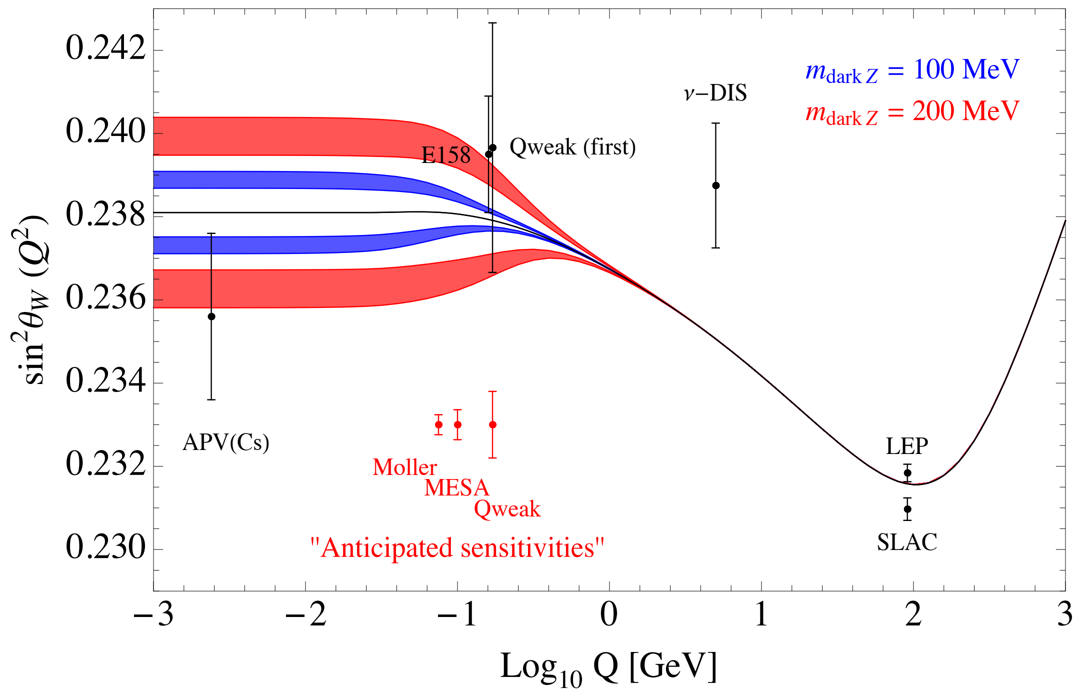
- Astrophysical motivation: observed excess in positron data
- Could explain muon g-2 anomaly



"Dark parity violation"

(Davoudiasl, Lee, Marciano, arXiv 1402.3620)

- Introduces a new source of low energy parity violation through mass mixing between Z and Z_d with observable consequences
- Complementary to direct searches for heavy dark photons



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Parity-Violating Electron Scattering Experiments – A Brief History

Pioneering (1978) early SM test

SLAC E122 PVDIS – Prescott *et al.*

A = -152 ppm

Strange Form Factors

(1998 – 2009)

SAMPLE, G0, A4, HAPPEX

A ~ 1 – 50 ppm

Standard Model Tests

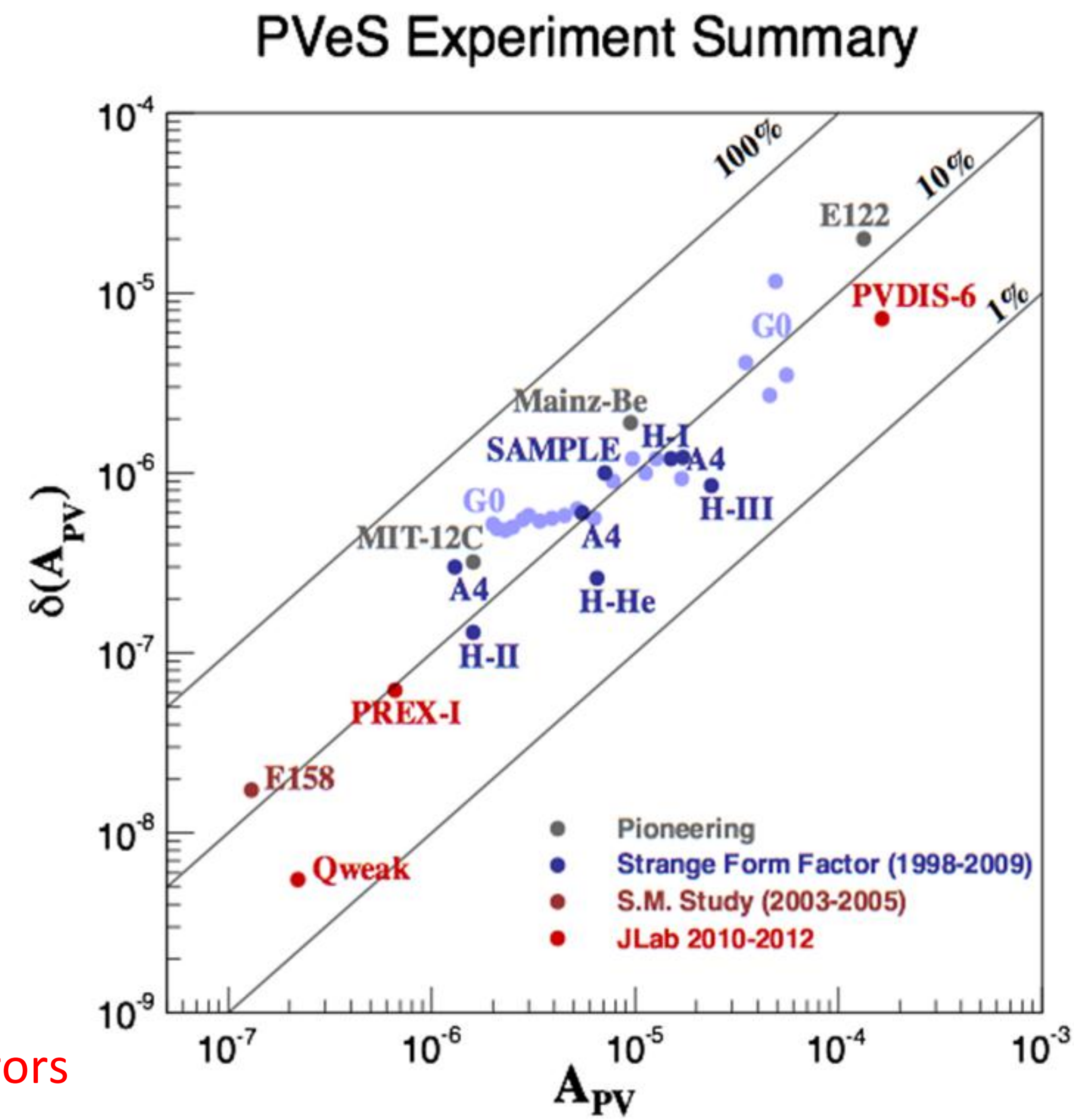
(2003 – present)

SLAC E158 Moller: A = - 131 ppb

JLAB Qweak: A ~ -230 ppb

→ smaller asymmetries,

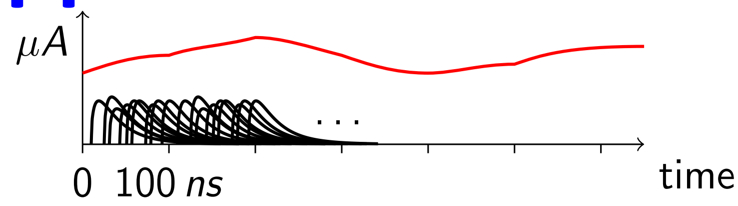
smaller absolute and relative errors



Qweak Experimental Apparatus

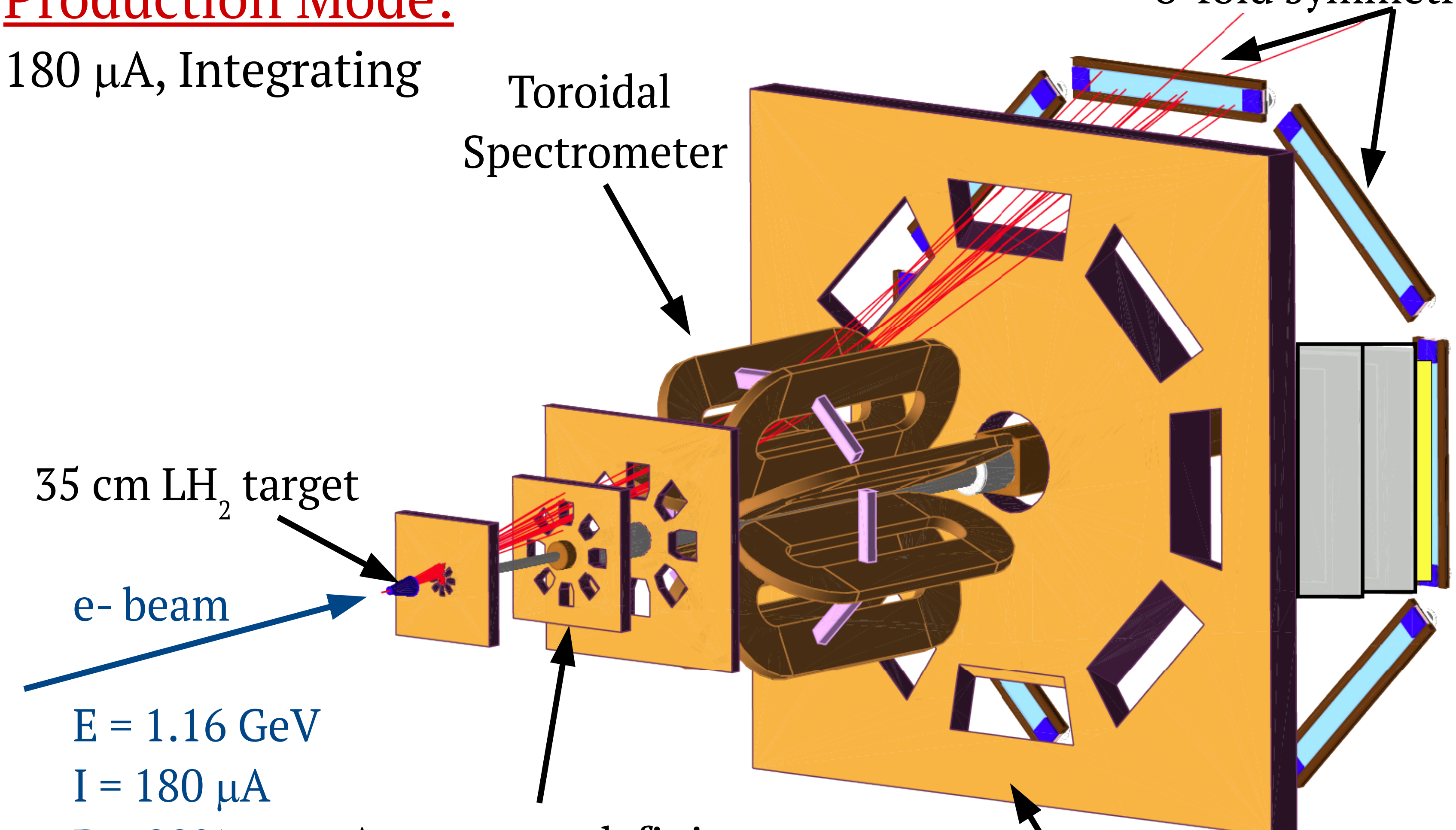
Production: ~ 800 MHz rates

must integrate PMT current



Production Mode:

180 μA, Integrating



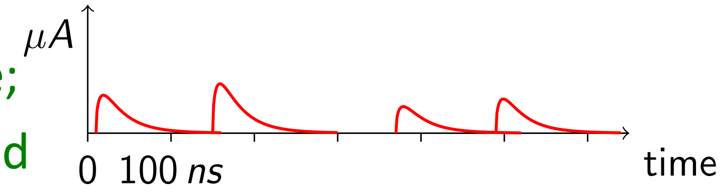
E = 1.16 GeV

I = 180 μA

P = 88%

Qweak Experimental Apparatus

Tracking (event) mode: low rate;
each event individually registered

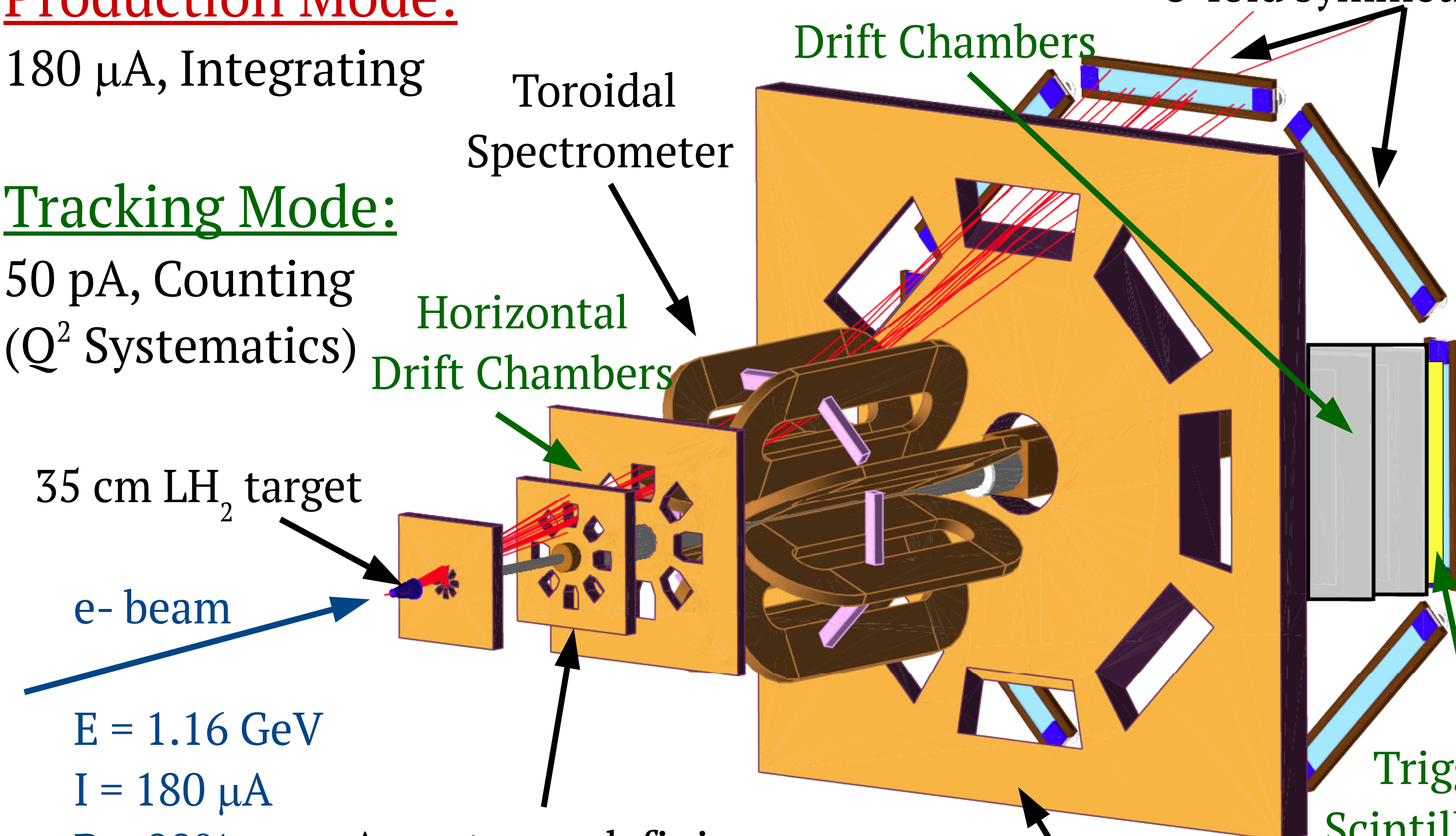


Production Mode:

180 μA, Integrating

Tracking Mode:

50 pA, Counting
(Q^2 Systematics)



E = 1.16 GeV
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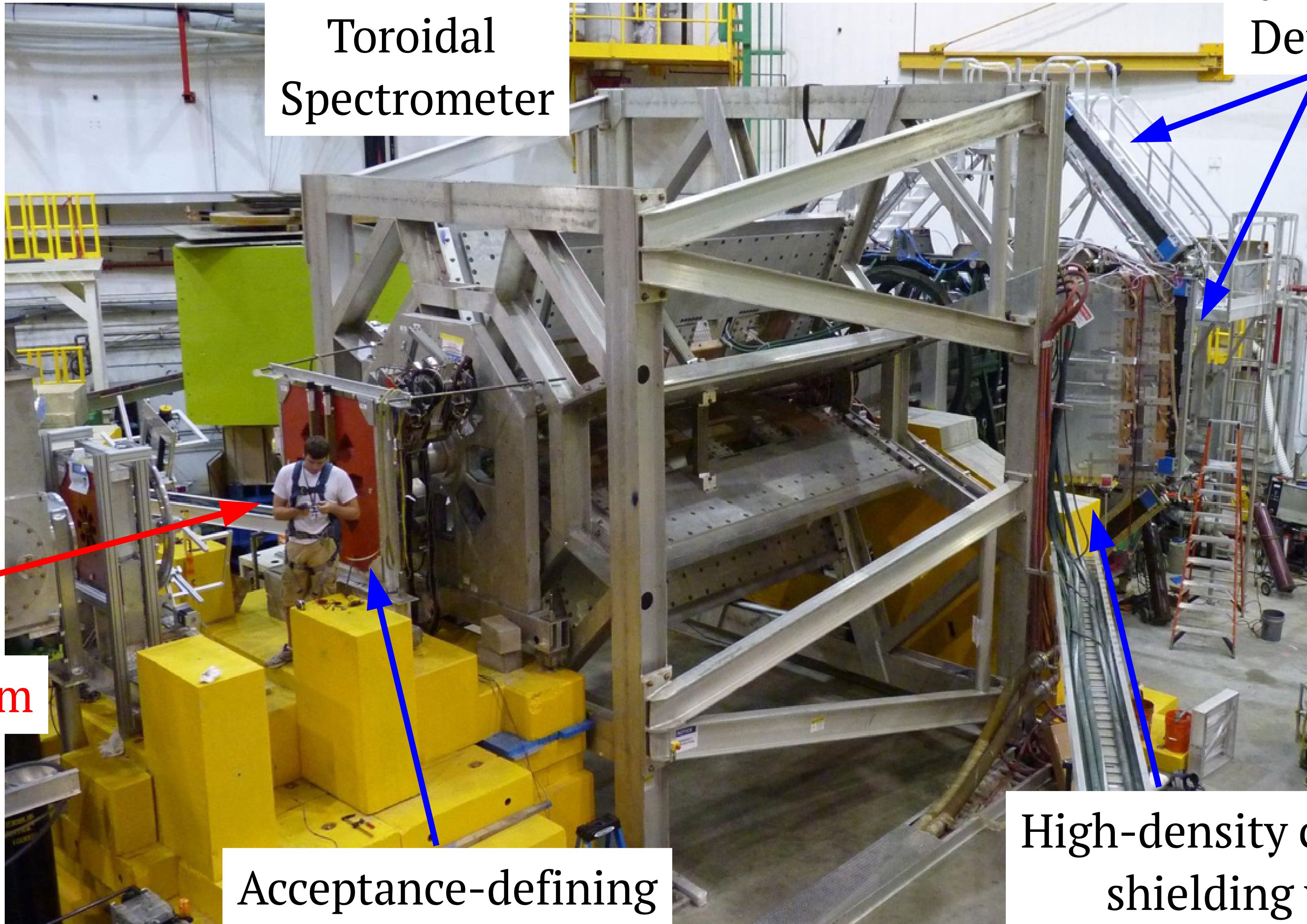
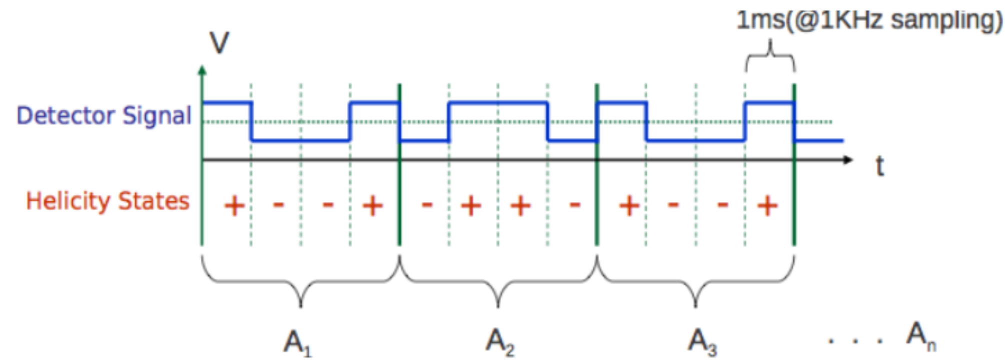
Qweak During Installation



Parity-Violating Electron Scattering Method

How do we take the bulk of our data? Pretty simple actually…

• Integrate the light signal in the Cerenkov detectors, sum them, and record the value every 1 msec



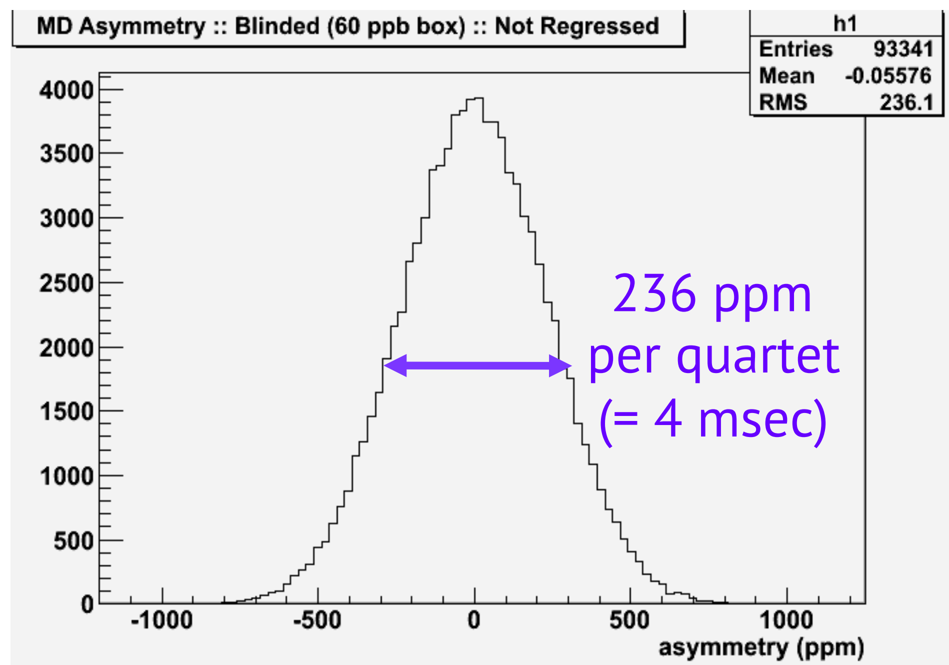
• "Normalize" the integrated signal (S) to the amount of charge (Q) in the beam

$$Y = \frac{S}{Q}$$

• Flip the electron beam helicity and form the asymmetry from four adjacent data samples:

$$A_{PV} = \frac{Y^+ - Y^-}{Y^+ + Y^-}$$

• Repeat 2 billion times! (2200 hours of data-taking) to get desired statistical error



Qweak Technical Challenges

$$A_{ep} = \frac{A_{meas} - A_{false}}{P_{beam}} - f_{back} A_{back} \quad \text{(for } f_{back} << 1)$$

Statistics on A_{meas}

- Small counting statistics error requires →
  - reliable high polarization, high current polarized source
  - high power cyrogenic LH_2 targets
  - large acceptance high count rate detectors/electronics

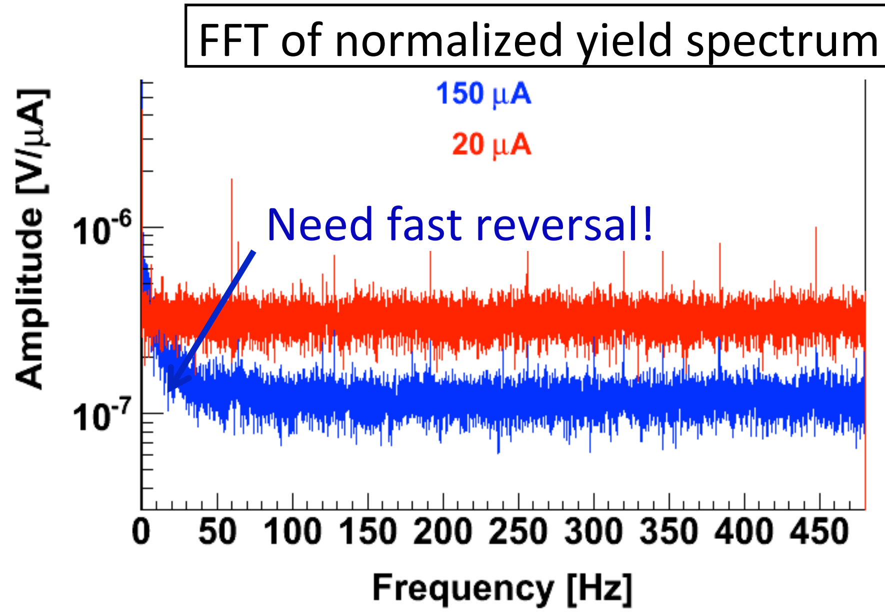
while minimizing contributions of random noise from
  - target density fluctuations
  - electronics noise (in integrating mode)

Systematics:

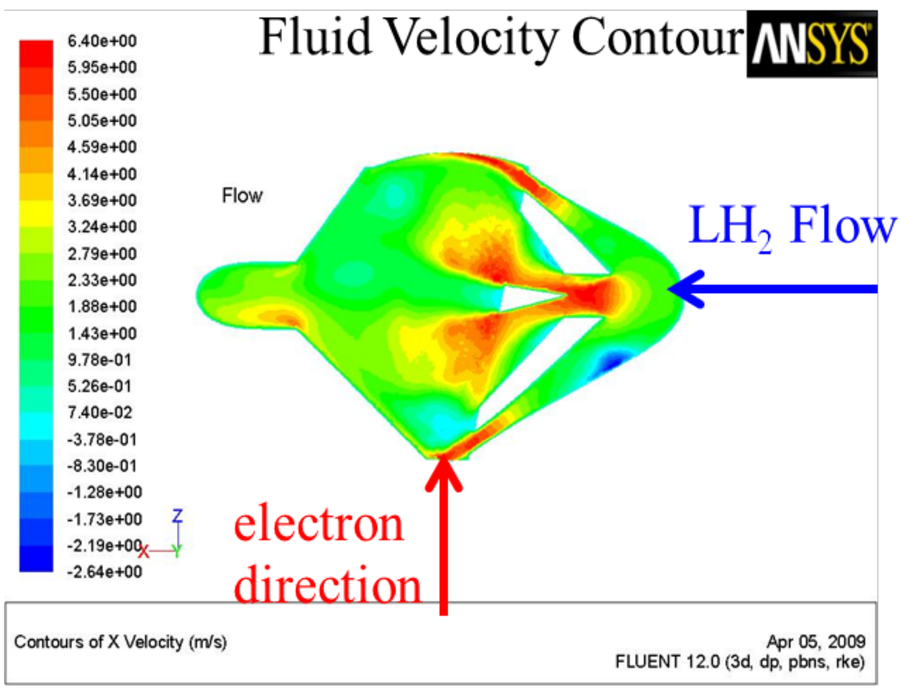
- Minimize helicity-correlated beam properties (A_{false})
- Capability to isolate elastic scattering from other background processes (dilution factor f_{back}, background asymmetry A_{back})
- High precision electron beam polarimetry (P_{beam})
- Precision Q^2 determination ($A_{ep} \propto Q^2$)

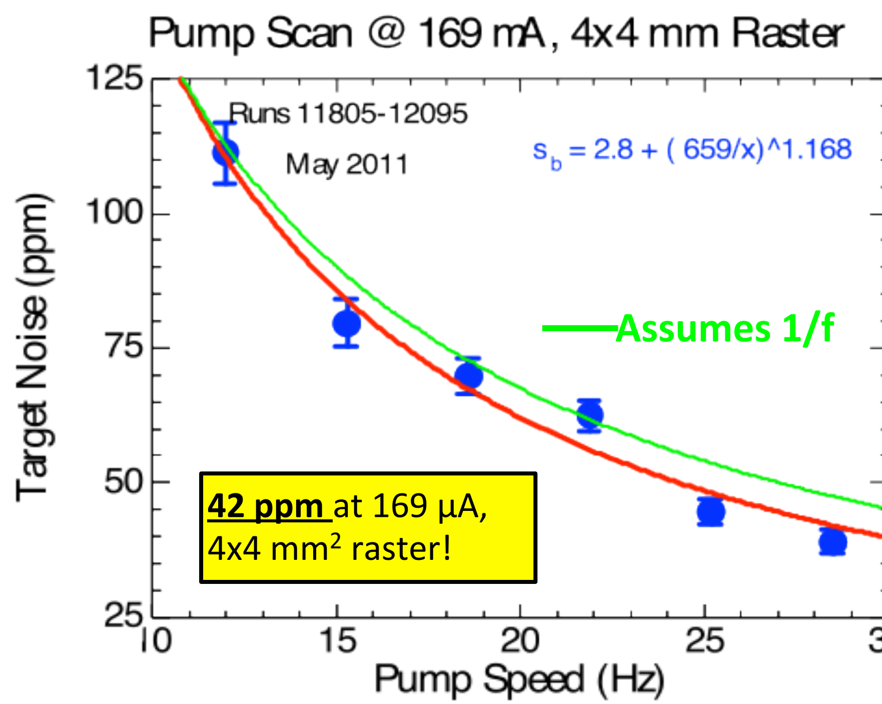
Liquid Hydrogen Target

- World's highest power cryotarget ~ 3 kW
- Used computational fluid dynamics (CFD)
- Designed to minimize contribution to random noise from target density fluctuations – "boiling"



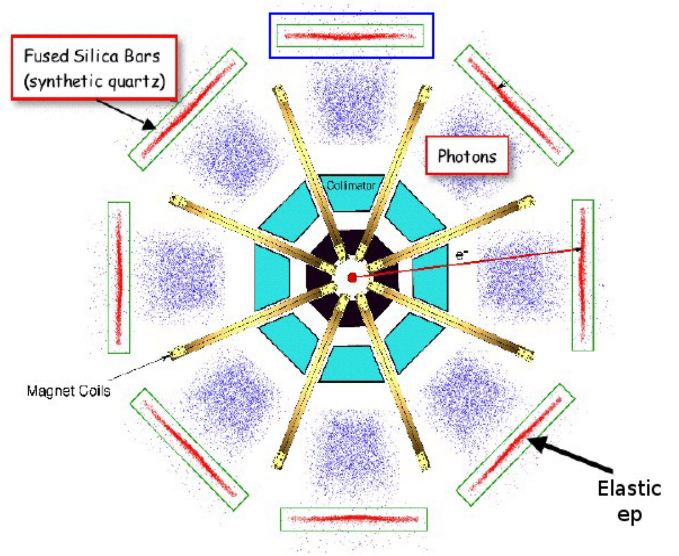
Achieved! 46 ppm < 236 ppm counting statistics noise

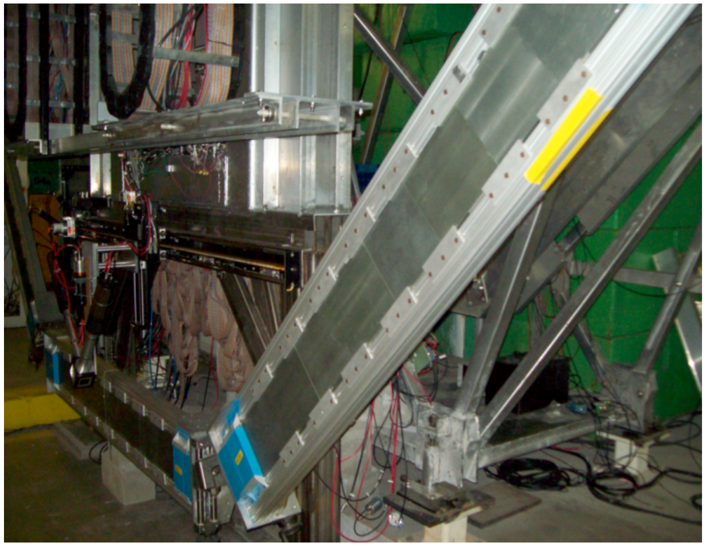




Qweak Main Detector

- Main detector: Large array of eight Cerenkov radiator bars (each 200 x 18 x 1.25 cm^3)
- artificial fused silica for UV transmission, polished to 25 Angstroms (rms)
- **Spectrosil 2000: rad-hard, non-scintillating, low-luminescence**
- Two 5" PMTs per bar, S20 cathodes for high light levels
- Yield 100 pe's/track with 2 cm Pb pre-radiators



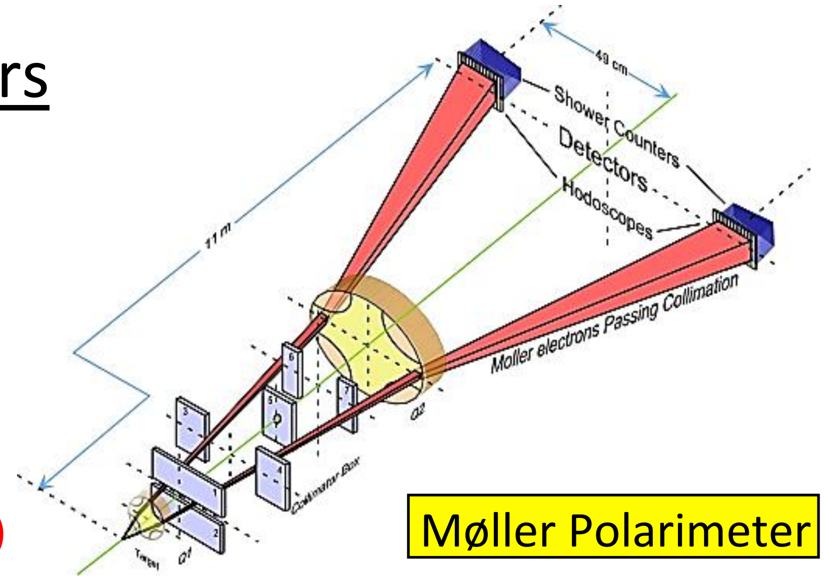


Precision Polarimetry

Qweak requires ΔP/P ≤ 1%

Strategy: use 2 independent polarimeters

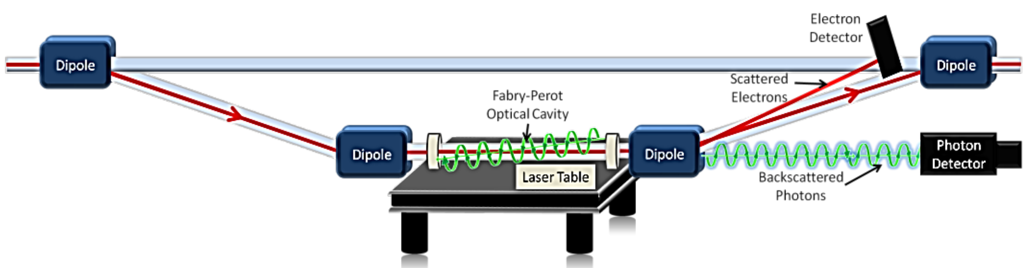
- Use existing <1% Hall C Møller polarimeter:
  - Low beam currents, invasive
  - Known analyzing power provided by polarized "saturated" Fe foil in a 3.5 T field.

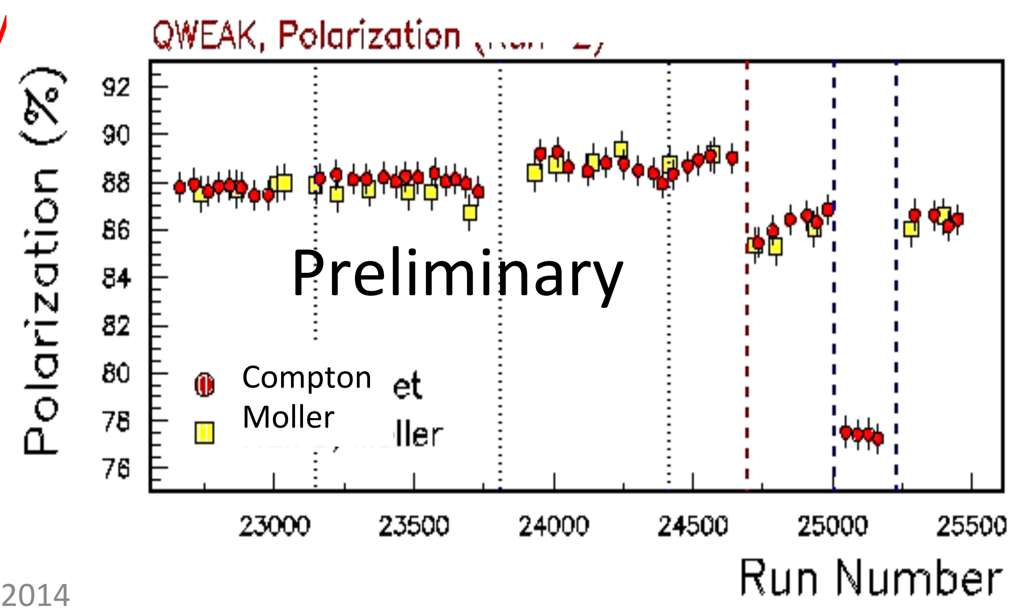


Møller Polarimeter

- Compton (photon & electron) polarimeter (1%/h)
  - Continuous, non-invasive
  - Known analyzing power provided by circularly-polarized laser

Compton Polarimeter





Aluminum Window Background

Large *A* (asymmetry) & *f* (fraction) make this our largest correction. Determined from explicit measurements using Al dummy targets & empty H_2 cell.

(from published Run 0 result)

$$C_{\rm Al} = -64 \pm 10 \text{ ppb}$$

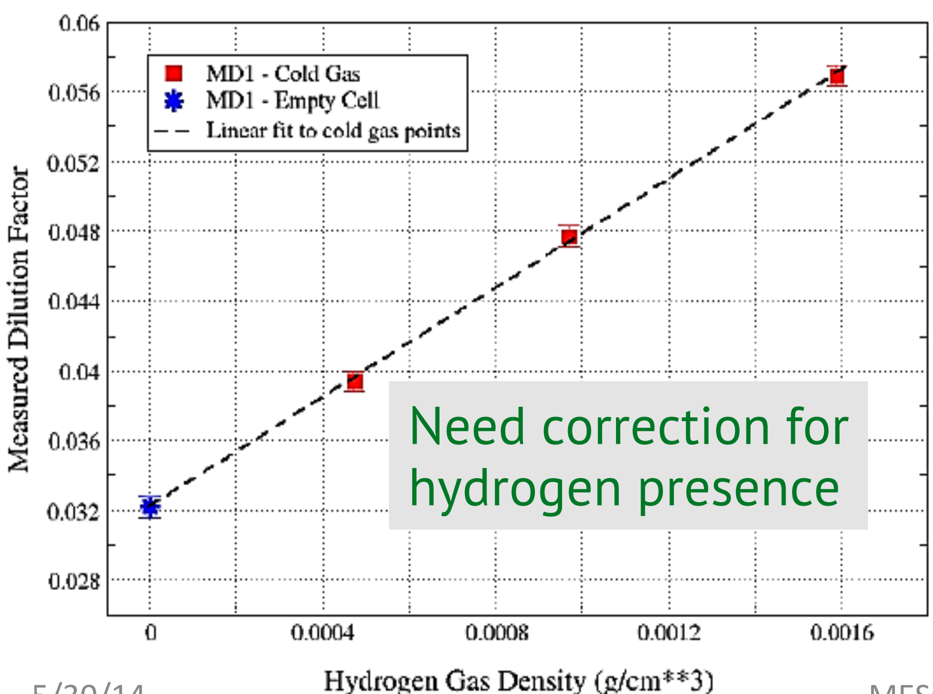
$$A_{\rm Al} = 1.76 \pm 0.26 \text{ ppm}$$

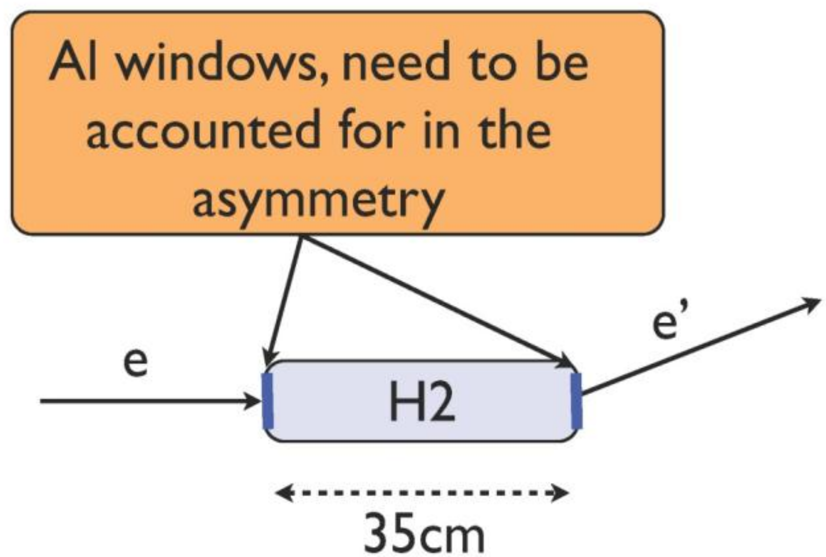
$$f_{\rm Al} = 3.23 \pm 0.24\ \%$$

- Dilution from windows measured with empty target (actual target cell windows).
- Corrected for effect of H_2 using simulation and data driven models of elastic and quasi-elastic scattering.

- Asymmetry measured from thick Al targets
- Measured asymmetry agrees with expectations from scaling.

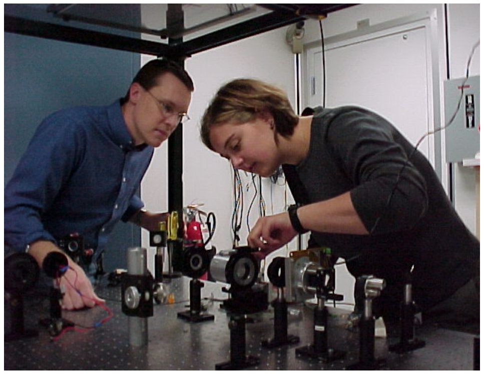
$$A_{PV}({}^N_Z X) = -\frac{Q^2 G_F}{4\pi\alpha\sqrt{2}}\left[Q_W^p + \left(\frac{N}{Z}\right) Q_W^n\right]$$

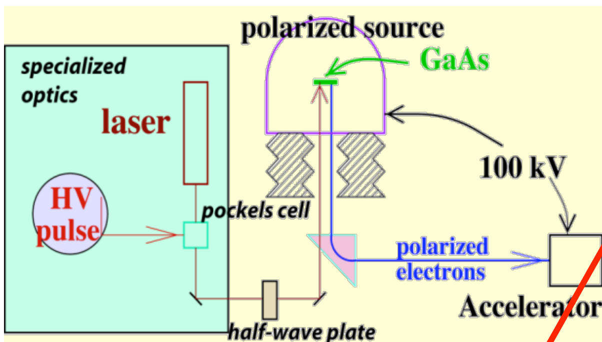




False Asymmetry Corrections – Beam Related

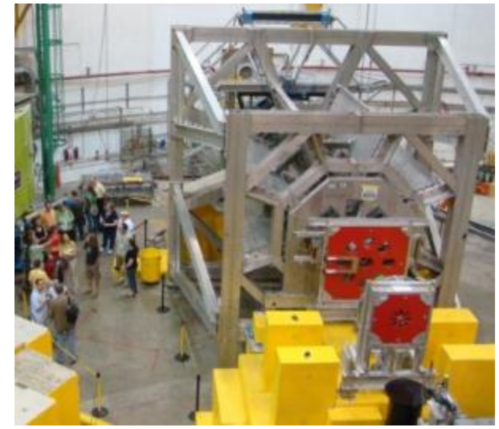
Parity-violating electron scattering - the whole accelerator is part of the experiment!





Polarized source

CEBAF Linear Accelerators



Qweak in Hall C

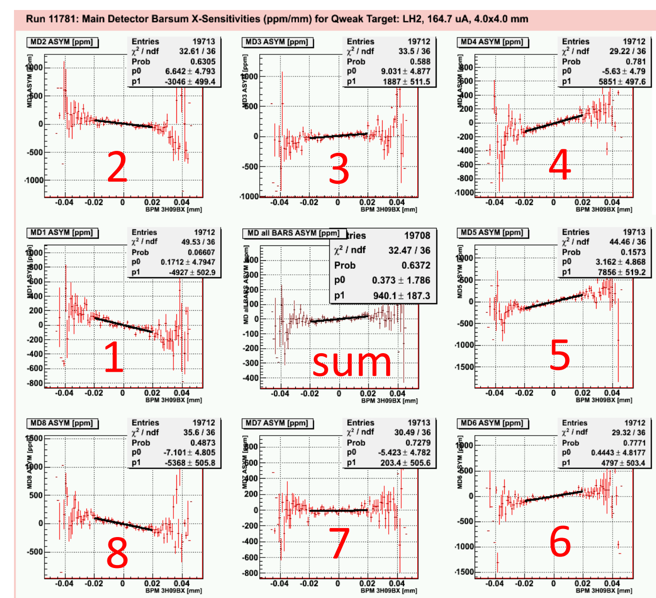
$$A_{corr} = \sum_{i=1}^{5} \left(\frac{\partial A}{\partial x_i}\right) \Delta x_i$$

(x, x', y, y', E)

Helicity-correlated beam parameters

(position, size, energy):

- Controlled by careful laser setup at polarized source (kept to < few nm in Hall C)
- Corrected for by measuring parameter differences and sensitivity slopes with 2 techniques: natural and driven beam motion



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- Data-taking 2010 – 2012
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May 18,2012: JLAB Director Hugh Montgomery "pulls the plug" on the "6 GeV Era"

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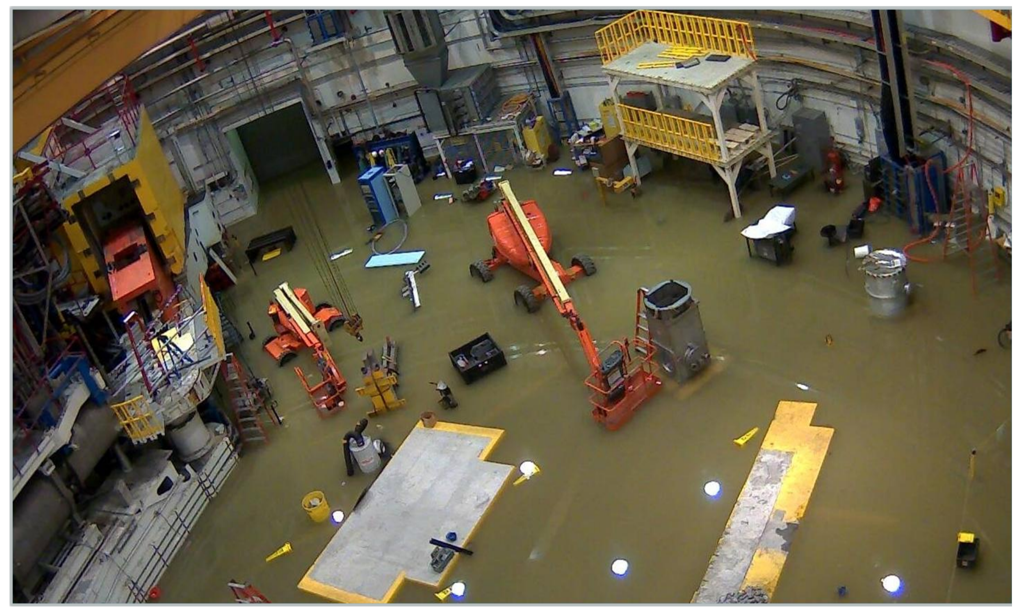
- Finished in May 2012 when Jlab "6 GeV Era" ended

May 18,2012: JLAB Director Hugh Montgomery "pulls the plug" on the "6 GeV Era"



"and then the rains came" – Great Hall C flood – Aug. 25, 2012

May 2014: Jefferson Lab has begun 12 GeV commissioning; first physics beams in fall 2014

Qweak Data Taking Periods and First Results

Qweak had ~ 1 calendar year of beam split into 3 running periods

Each period had its own "blinding factor" to avoid analysis bias:

- Run 0: January – February 2011
- Run 1: February – May 2011
- Run 2: November 2011 – May 2012

Run 0 results (about 1/25 of data set) published in PRL in Oct. 2013

PRL **111,** 141803 (2013) PHYSICAL REVIEW LETTERS week ending 4 OCTOBER 2013

First Determination of the Weak Charge of the Proton

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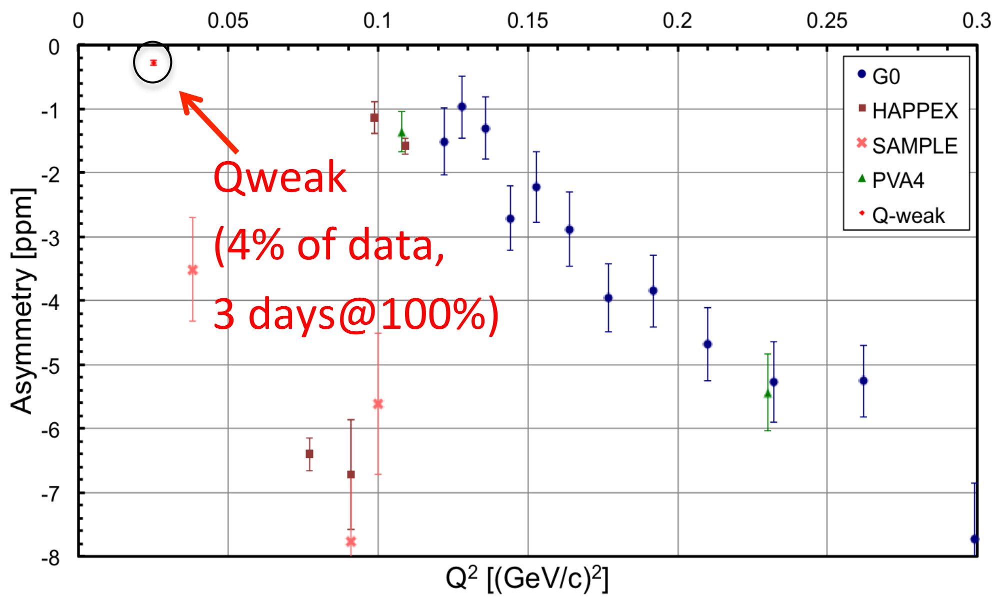
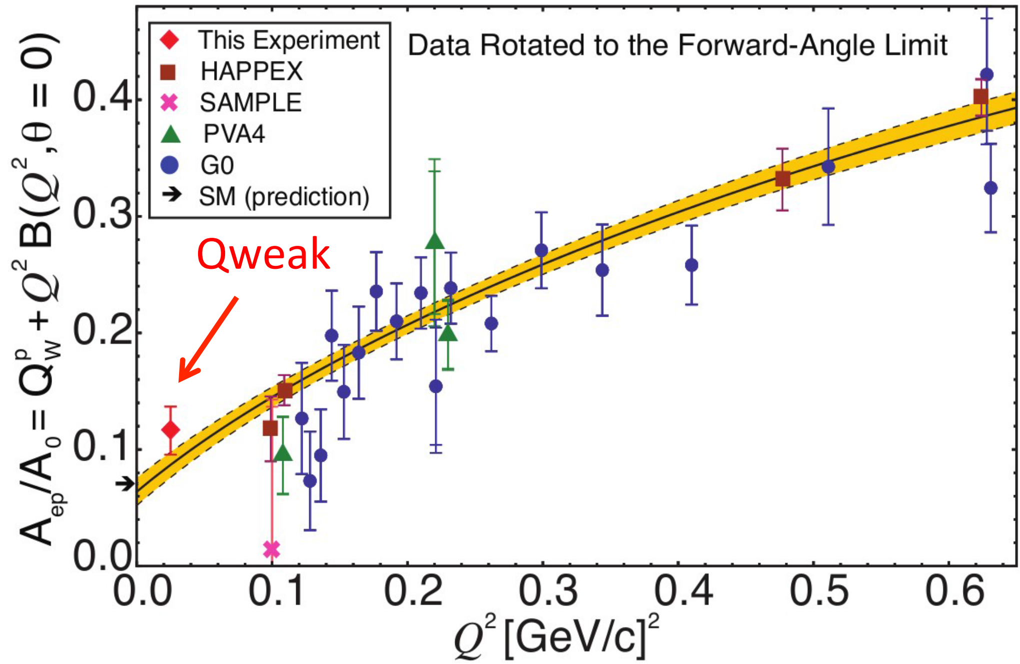
Extraction of Qweak from e-p Asymmetry

Run 0 Results (1/25th of total dataset) – published in PRL **111**, 141803 (2013)

$$A_{ep} = -279 \pm 35(\text{stat}) \pm 31(\text{syst})\ \text{ppb} \quad \text{at} \quad \langle Q^2 \rangle = 0.0250\ (\text{GeV}/c)^2$$





Global fit of world PVES data up to Q^2 = 0.63 GeV^2 is done to extract the proton's weak charge

$$A_{ep}/A_0 = Q_W^p + Q^2 B(Q^2, \theta), \qquad A_0 = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right].$$

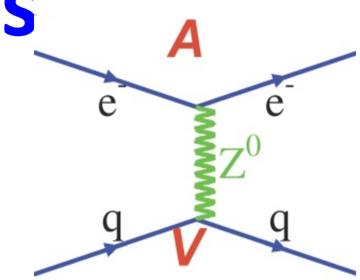
$$Q_W^p(\text{PVES}) = 0.064 \pm 0.012 \qquad Q_W^p(\text{SM}) = 0.0710 \pm 0.0007$$

First determination of proton's weak charge in good agreement with Standard Model

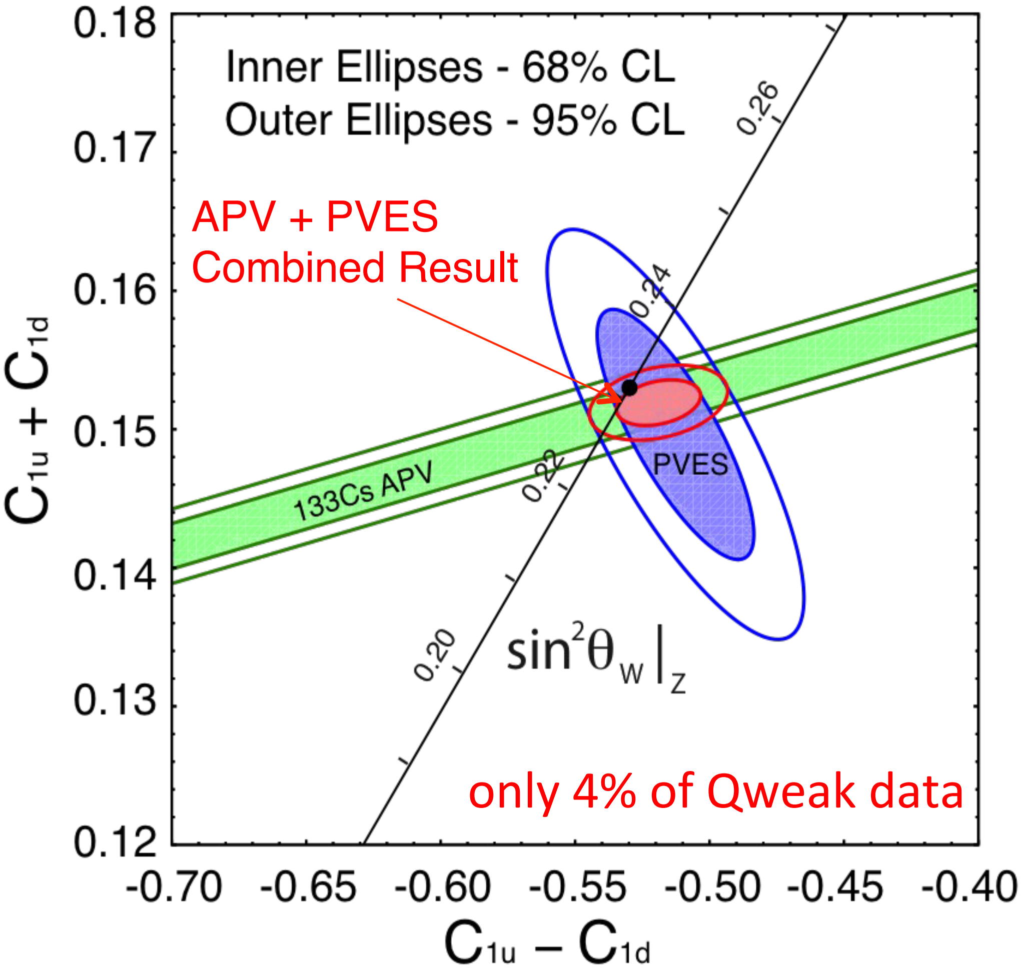
Quark Vector Coupling Constants

$$L^{PV}_{e\text{-}q} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e\sum_q C_{1q}\bar{q}\gamma^\mu q$$

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



$$C_{1i} \equiv 2g_A^e g_V^i$$



Improved precision on quark coupling constants

$$C_{1u} = -0.1835 \pm 0.0054$$

$$C_{1d} = 0.3355 \pm 0.0050$$

Combining this result with the most precise atomic parity violation experiment we can also extract, for the first time, the neutron's weak charge:

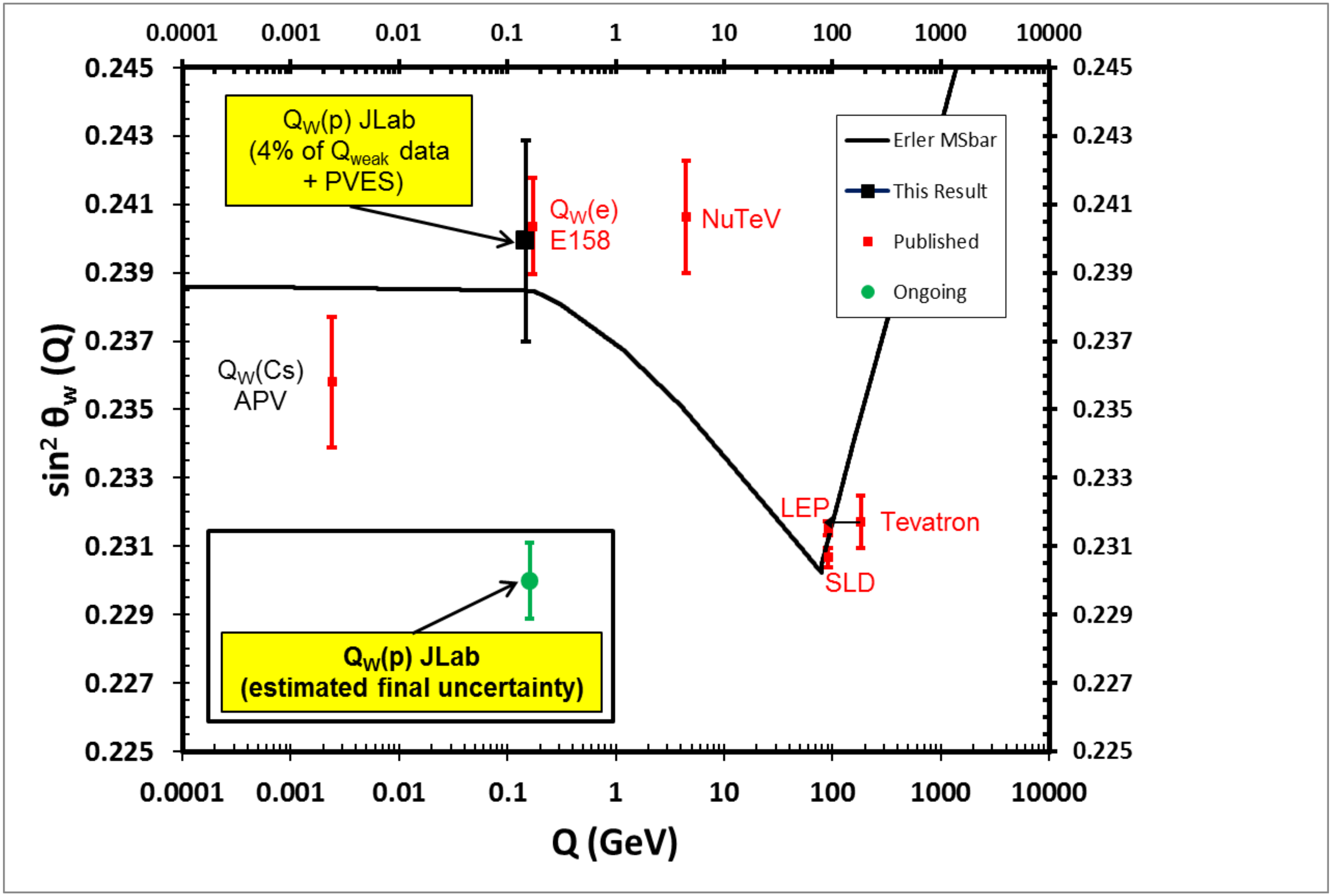
$$Q_W^n(\text{PVES+APV}) = -0.975 \pm 0.010$$

$$Q_W^n(\text{SM}) = -0.9890 \pm 0.0007$$

Running of Weak Mixing Angle

Using calculated electroweak radiative corrections can extract mixing angle for comparison with other observables:

$$Q_W^p = [1 + \Delta\rho + \Delta_e]\left[(1 - 4\sin^2\theta_W(0)) + \Delta_{e'}\right] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$



Outline

- Motivation and formalism
- Experiment: technical challenges and achievements
- First measurement of proton's weak charge – results and implications
- Status of analysis towards final precision result

Status of Analysis of Full Qweak Dataset

Data analysis in progress for the full dataset

Example: Status of corrections for helicity-correlated beam parameters

(sensitivity of detector asymmetries to beam position variations) $A_{corr} = \sum_{i=1}^{5} \left(\frac{\partial A}{\partial x_i}\right) \Delta x_i$

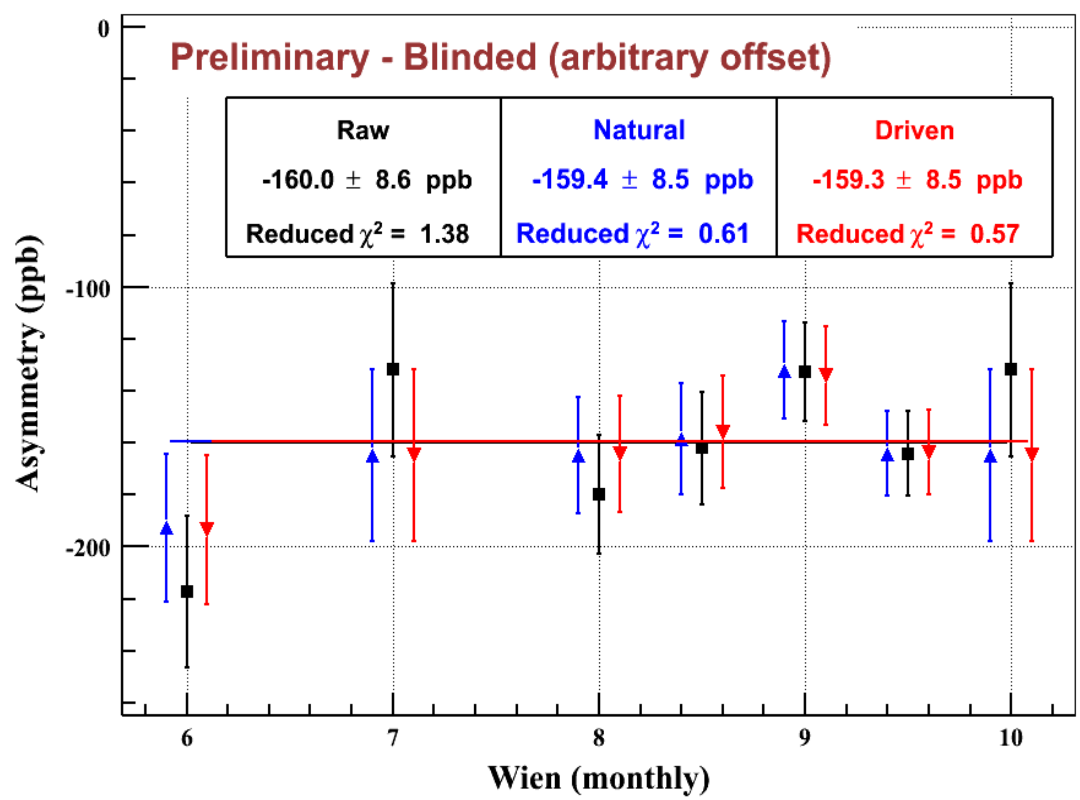
(x, x', y, y', E)

- "Regression": Natural jitter of beam parameters
- "Dithering": Occasional "large" driven variation of each beam parameter

- Corrections based on the two methods are in excellent agreement for this subset of our data

- Includes about 77% of Run 2 dataset (~ 50% of overall dataset)
- Asymmetries have no corrections other than beam parameter corrections

Run2 measured asymmetry



Conclusions

First published result from the Qweak experiment

PRL **111**,141803 (2013) - based on just 4% of data taken

$$A_{ep} = -279 \pm 35(\text{stat}) \pm 31(\text{syst})\ \text{ppb} \qquad \langle Q^2 \rangle = 0.0250\ (\text{GeV}/c)^2$$

First determination of proton and neutron weak charges:

$$Q_W^p(\text{PVES}) = 0.064 \pm 0.012 \qquad Q_W^n(\text{PVES+APV}) = -0.975 \pm 0.010$$

$$Q_W^p(\text{SM}) = 0.0710 \pm 0.0007 \qquad Q_W^n(\text{SM}) = -0.9890 \pm 0.0007$$

In good agreement with Standard Model predictions

Final result using full dataset expected ~ 1 year from now

- Statistical error 5 times smaller, reduced systematics, no show stoppers found in analysis so far
- Additionally, many ancillary results under analysis

The Qweak Collaboration

97 collaborators 23 grad students
10 post docs 23 institutions

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[3] A. I. Alikhanyan National Science Laboratory
[4] Massachusetts Institute of Technology
[5] Thomas Jefferson National Accelerator Facility
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[9] University of Virginia
[10] TRIUMF
[11] Hampton University
[12] Mississippi State University
[13] Virginia Polytechnic Institute & State Univ
[14] Southern University at New Orleans
[15] Idaho State University
[16] Louisiana Tech University
[17] University of Connecticut
[18] University of Northern British Columbia
[19] University of Winnipeg
[20] George Washington University
[21] University of New Hampshire
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[23] University of Adelaide

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Spokespersons Project Manager Grad Students

Funded by DOE, NSF, NSERC

Backups

Ancillary Measurements

Qweak made several ancillary measurements to determine and constrain background processes and corrections –

many will result in physics publications

- PV asymmetry:
  - elastic ^{27}Al
  - $N \rightarrow \Delta$ (E = 1.16 GeV, 0.877 GeV)
  - Near W = 2.5 GeV (related to γZ box)
  - Pion photoproduction (E = 3.3 GeV)
- PC Transverse asymmetry:
  - elastic ep
  - elastic ^{27}Al, Carbon
  - $N \rightarrow \Delta$
  - Møller
  - Near W = 2.5 GeV
  - Pion photoproduction (E = 3.3 GeV)