The Q_{weak} Experiment:
The First Direct Measurement of the Proton's Weak Charge

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For the Q_{weak} Collaboration

SPIN 2016

September 26, 2016

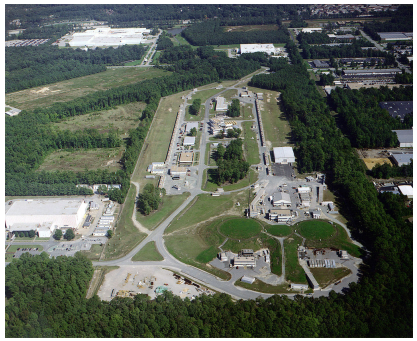
Overview

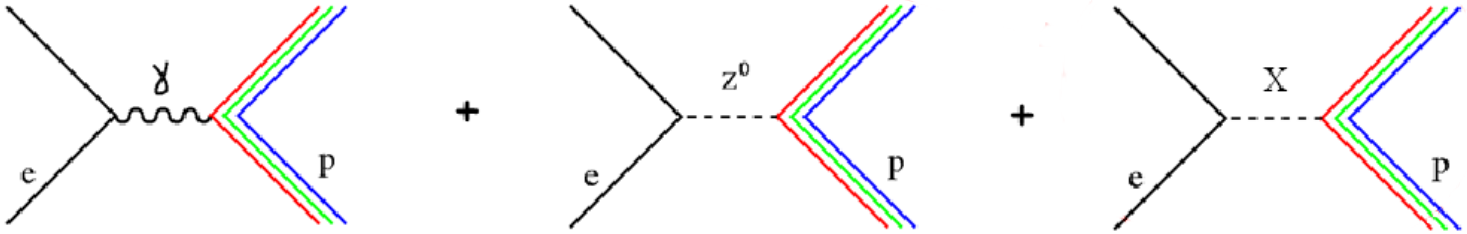
- Motivation:
  - Precision grants sensitivity to physics beyond Standard Model
  - First direct measurement of Q_W^p
- Q_{weak} Methods & Preliminary Results:
  - Experimental Overview
  - Commissioning Data Results (2013)
- Path to final result:
  - Improved beam corrections and polarization
  - Systematic effect from secondary scattering

Physics Beyond the Standard Model

- Energy frontier
  - Large Hadron Collider.
  - Creates particle X directly though high energy collisions.

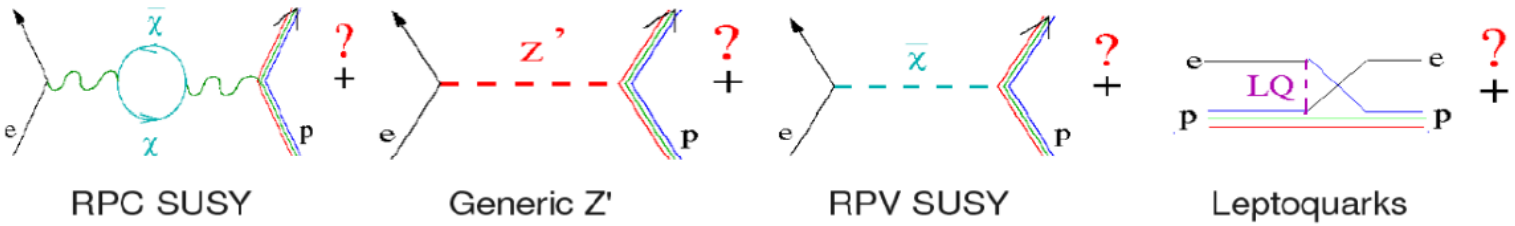
- Precision frontier
  - Jefferson Lab.
  - Looks for the indirect effect of process X.





Extensions to SM

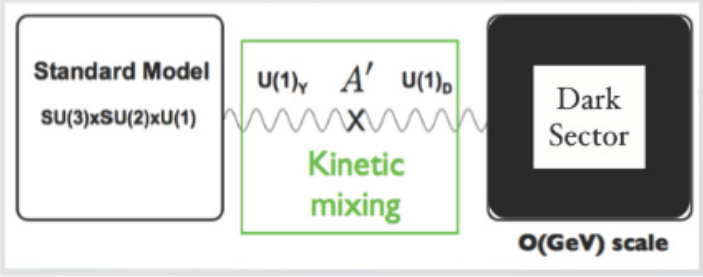
Examples of TeV scale new physics that Q_{weak} would be sensitive to are:



Q_{weak} is also sensitive to MeV-GeV scale mediators such as:

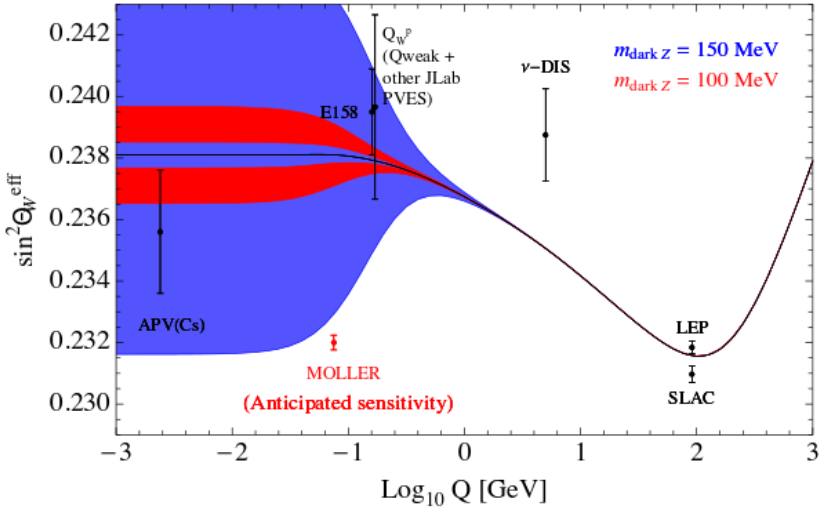
Dark Photon:

- Astrophysical motivation, observed in positron data
- Might be linked to muon g-2 anomaly



Dark Parity Violation: (Davoudiasl, Lee, Marciano, arXiv 1402.3620)

- New source of low energy PV via mass mixing between Z and Z_d with observable consequences
- Complementary to direct search for heavy dark photons



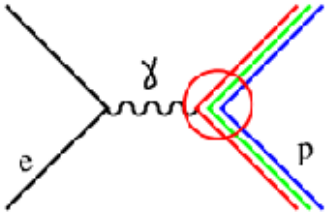
Standard Model

Standard model describes the couplings between fundamental particles.

	Q	Q_W
u	$+2/3$	$1 - 8/3\sin^2\theta_W = -2C_{1u}$
d	$-1/3$	$-1 + 4/3\sin^2\theta_W = -2C_{1d}$

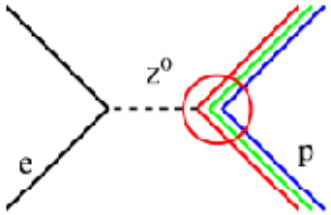
Proton's electric charge:

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



Proton's neutral weak charge:

$$\begin{aligned} Q_W^p &= 2\left(1 - 8/3\sin^2\theta_W\right) + 1\left(-1 + 4/3\sin^2\theta_W\right) \\ &= 1 - 4\sin^2\theta_W \approx 0.07 \end{aligned}$$

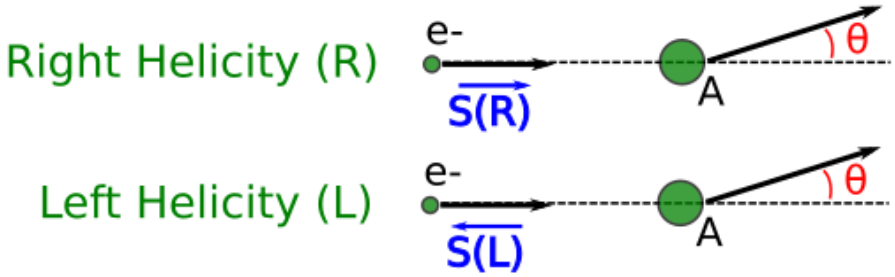


Weak mixing angle parametrizes the mixing between the two neutral currents in the model. With the discovery of the Higgs boson, it is now predicted by the SM.

$$\begin{pmatrix} |\gamma\rangle \\ |Z^0\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} |B^0\rangle \\ |W^0\rangle \end{pmatrix}$$

Parity-Violating Electron Scattering Measurement

Q_{weak} experiment: scatter longitudinally polarized electrons off of unpolarized hydrogen.



An asymmetry is formed by counting scattered electrons from each helicity state:

$$A_{ep} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{2\mathcal{M}_\gamma^* \mathcal{M}_Z}{|\mathcal{M}_\gamma|^2}.$$

A_{ep} comes from the interference of the electromagnetic and weak exchange amplitudes.

Extracting Q_W^p from A_{ep}

$$\mathcal{M}_Z \propto \frac{\mathrm{g}^2}{-Q^2 + m_Z^2} \qquad \mathcal{M}_\gamma \propto \frac{\mathrm{e}^2}{-Q^2}$$

$$\text{As } Q^2 \to 0,\ \mathcal{M}_Z \sim \frac{\mathrm{g}^2}{m_Z^2} \sim G_F$$

$$\Longrightarrow \frac{\mathcal{M}_Z}{\mathcal{M}_\gamma} = \frac{G_F}{\alpha} Q^2$$

Where $\mathcal{M}_Z$ is the weak neutral current, $\mathcal{M}_\gamma$ is the electromagnetic current, Q^2 is the momentum transfer, G_F is the Fermi coupling constant and α is the fine structure constant.

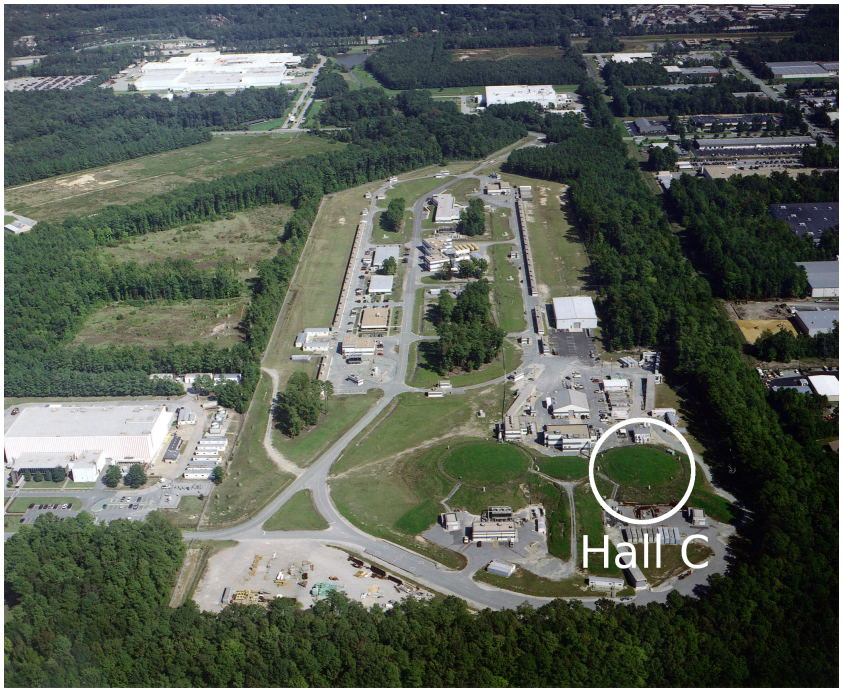
$$A_{ep} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{2\mathcal{M}_Z}{\mathcal{M}_\gamma} = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q_W^p + \ F^p(Q^2, \Theta)\ \right]$$

A_{ep} depends on hadronic form factors

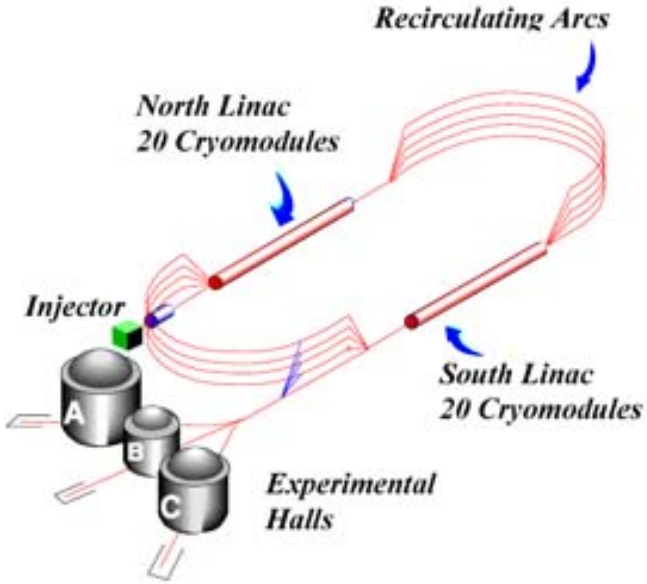
As $Q^2 \to 0, \Theta \to 0$

$$A_{ep} = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q_{weak}^p + Q^4 B(Q^2, \Theta)\right] \approx -0.23 \text{ ppm}$$

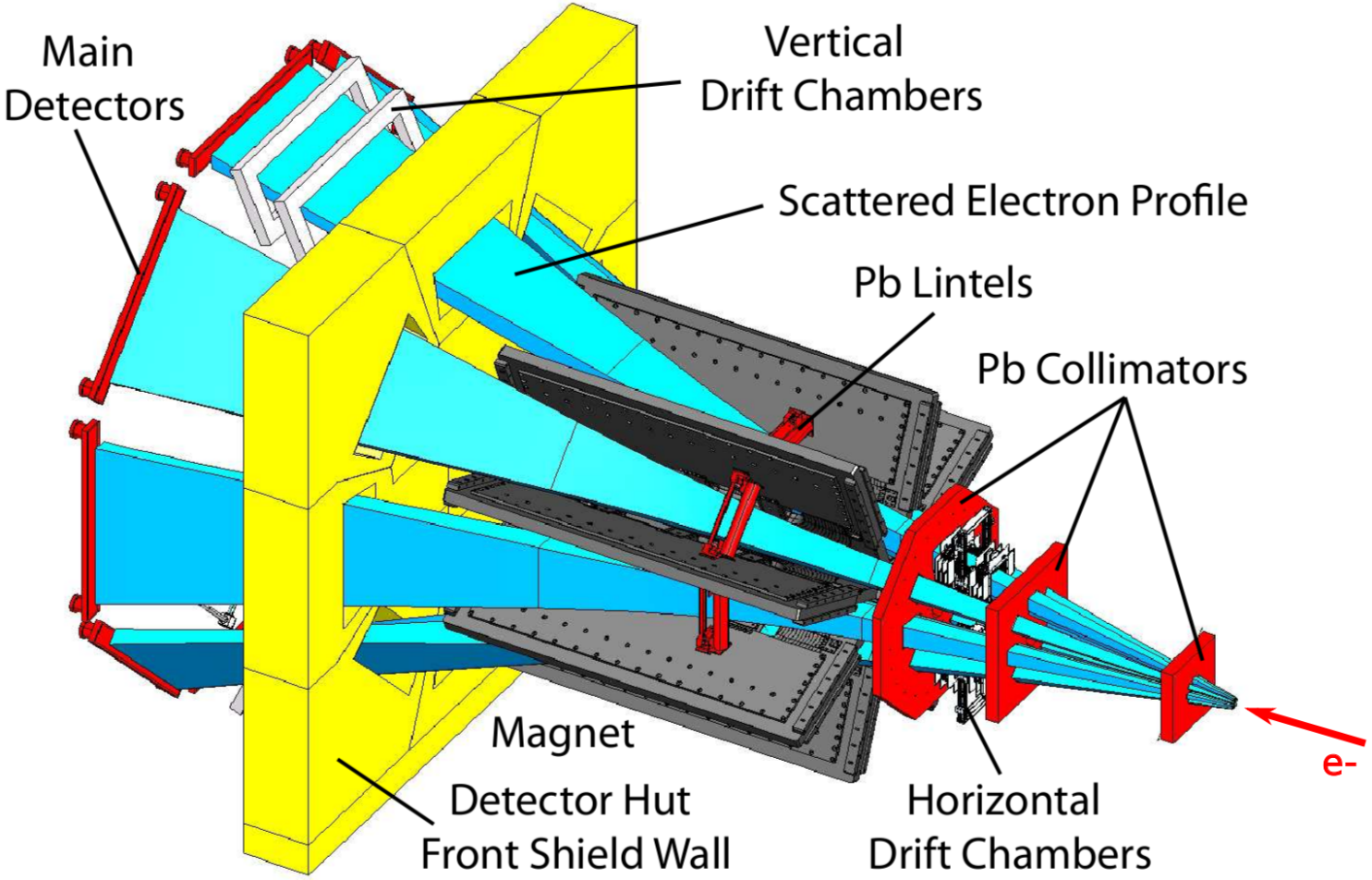
Jefferson Lab and CEBAF



- Q_{weak} ran in Hall C of Jefferson Lab
  - Three data taking periods:
    - Run 0: Nov 2010 - Jan 2011 (Published)
    - Run I: Feb - May 2011
    - Run II: Nov 2011 - May 2012 (Analysis ongoing)
- Target:
  - Liquid H_2 (≈34 cm thick)
  - Al alloy windows (≈0.12 mm thick)
- Kinematics:
  - $E = 1.155 \pm 0.003\mathrm{GeV}$
  - $I_{\text{beam}} = 180\mu A$
  - $P_L = 89\%$
  - $\mathrm{Q}^2 = 0.0250 \pm 0.006\mathrm{GeV/c}^2$
  - $\theta_{\mathrm{lab}} = 7.9^\circ \pm 0.3^\circ$

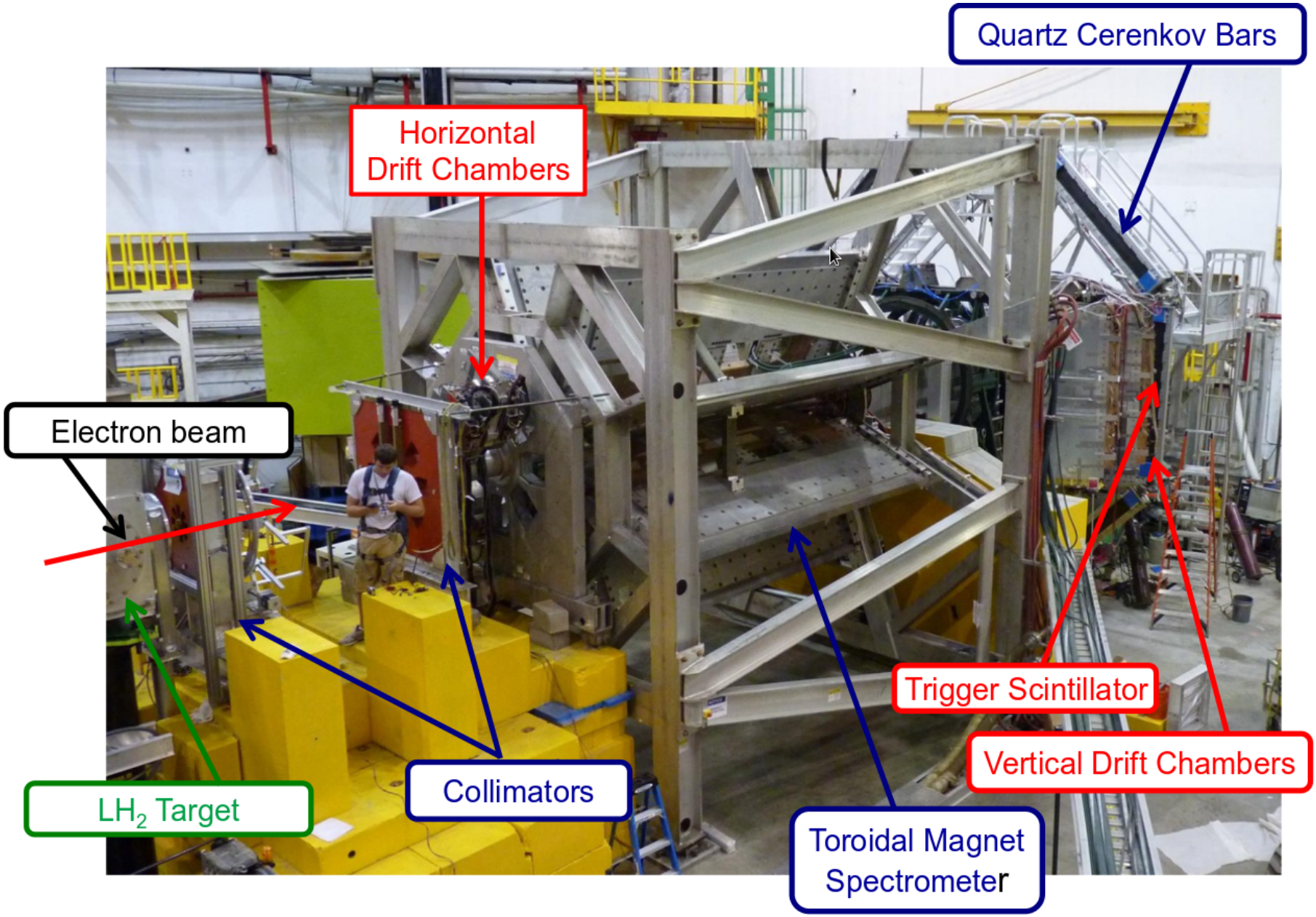


The Q_{weak} apparatus



"The Q_{weak} Experimental Apparatus," NIM A 781, 105 (2015)

The Q_{weak} apparatus



Measuring the PV Asymmetry

- Flip helicity at 960 Hz in quartet pattern [(+,-,-,+) or (-,+,+,-)]
- Integrate PMT current for each helicity state
- Normalize integrated signal (S) with beam charge (Q) to get yield (Y):

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

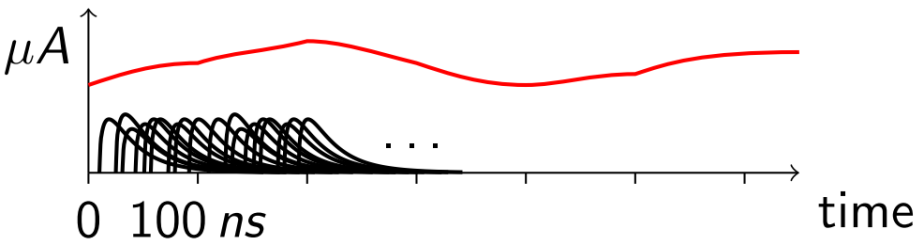
- Form asymmetry for each quartet:

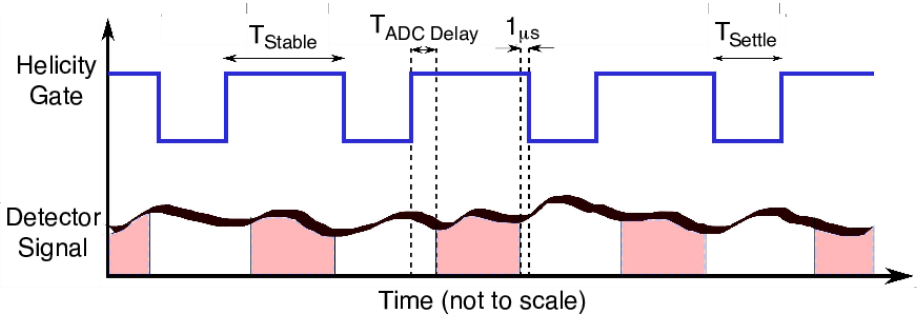
$$A_{\text{raw}} = \frac{Y_R - Y_L}{Y_R + Y_L}$$

- Correct A_{raw} for beam systematics

$$A_{\text{msr}} = A_{\text{raw}} + A_T + A_L - \sum_i \frac{\partial A}{\partial \chi_i} \Delta\chi_i$$

  - A_T - Transverse polarization leakage
  - A_L - PMT non-linearity
  - $\frac{\partial A}{\partial \chi_i}$ - sensitivity to helicity-correlated beam parameters





Q_{weak} Backgrounds

There are several backgrounds that dilute the parity-violating asymmetry and need to be corrected.

$$A_{ep} = R\frac{\frac{A_{\text{msr}}}{P} - \sum_i f_i A_i}{1 - \sum_i f_i}$$

- A_{ep}: Parity-violating asymmetry
- R: Radiative and acceptance correction
- A_{msr}: Measured asymmetry by experiment
- P: Measured beam polarization
- f_i: Background dilution (Y_i/Y_T)
- A_i: Background asymmetry

Backgrounds:

1. Aluminum target windows
2. Beamline background
3. Neutral scattered events
4. Inelastic scattered events

First Results

The following results were published using the small ($\sim 4\%$) data set taken during commissioning.

Run	Dates	Data taken (Coulomb)
Run 0	Nov 2010-Jan 2011	$\sim$ 40 C
Run 1	Feb 2011-May 2011	$\sim$ 360 C
Run 2	Nov 2011-May 2012	$\sim$ 680 C

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

First Determination of the Weak Charge of the Proton

D. Androic,[1] D. S. Armstrong,[2] A. Asaturyan,[3] T. Averett,[2] J. Balewski,[4] J. Beaufait,[5] R. S. Beminiwattha,[6] J. Benesch,[5] F. Benmokhtar,[7] J. Birchall,[8] R. D. Carlini,[5,2,†] G. D. Cates,[9] J. C. Cornejo,[2] S. Covrig,[5] M. M. Dalton,[9] C. A. Davis,[10] W. Deconinck,[2] J. Diefenbach,[11] J. F. Dowd,[2] J. A. Dunne,[12] D. Dutta,[12] W. S. Duvall,[13] M. Elaasar,[14] W. R. Falk,[8] J. M. Finn,[2,*] T. Forest,[15,16] D. Gaskell,[5] M. T. W. Gericke,[8] J. Grames,[5] V. M. Gray,[2] K. Grimm,[16,2] F. Guo,[4] J. R. Hoskins,[2] K. Johnston,[16] D. Jones,[9] M. Jones,[5] R. Jones,[17] M. Kargiantoulakis,[9] P. M. King,[6] E. Korkmaz,[18] S. Kowalski,[4] J. Leacock,[13] J. Leckey,[2,‡] A. R. Lee,[13] J. H. Lee,[6,2,§] L. Lee,[10,8] S. MacEwan,[8] D. Mack,[5] J. A. Magee,[2] R. Mahurin,[8] J. Mammei,[13,‖] J. W. Martin,[19] M. J. McHugh,[20] D. Meekins,[5] J. Mei,[5] R. Michaels,[5] A. Micherdzinska,[20] A. Mkrtchyan,[3] H. Mkrtchyan,[3] N. Morgan,[13] K. E. Myers,[20,¶] A. Narayan,[12] L. Z. Ndukum,[12] V. Nelyubin,[9] Nuruzzaman,[11,12] W. T. H. van Oers,[10,8] A. K. Opper,[20] S. A. Page,[8] J. Pan,[8] K. D. Paschke,[9] S. K. Phillips,[21] M. L. Pitt,[13] M. Poelker,[5] J. F. Rajotte,[4] W. D. Ramsay,[10,8] J. Roche,[6] B. Sawatzky,[5] T. Seva,[1] M. H. Shabestari,[12] R. Silwal,[9] N. Simicevic,[16] G. R. Smith,[5] P. Solvignon,[5] D. T. Spayde,[22] A. Subedi,[12] R. Subedi,[20] R. Suleiman,[5] V. Tadevosyan,[3] W. A. Tobias,[9] V. Tvaskis,[19,8] B. Waidyawansa,[6] P. Wang,[8] S. P. Wells,[16] S. A. Wood,[5] S. Yang,[2] R. D. Young,[23] and S. Zhamkochyan[3]

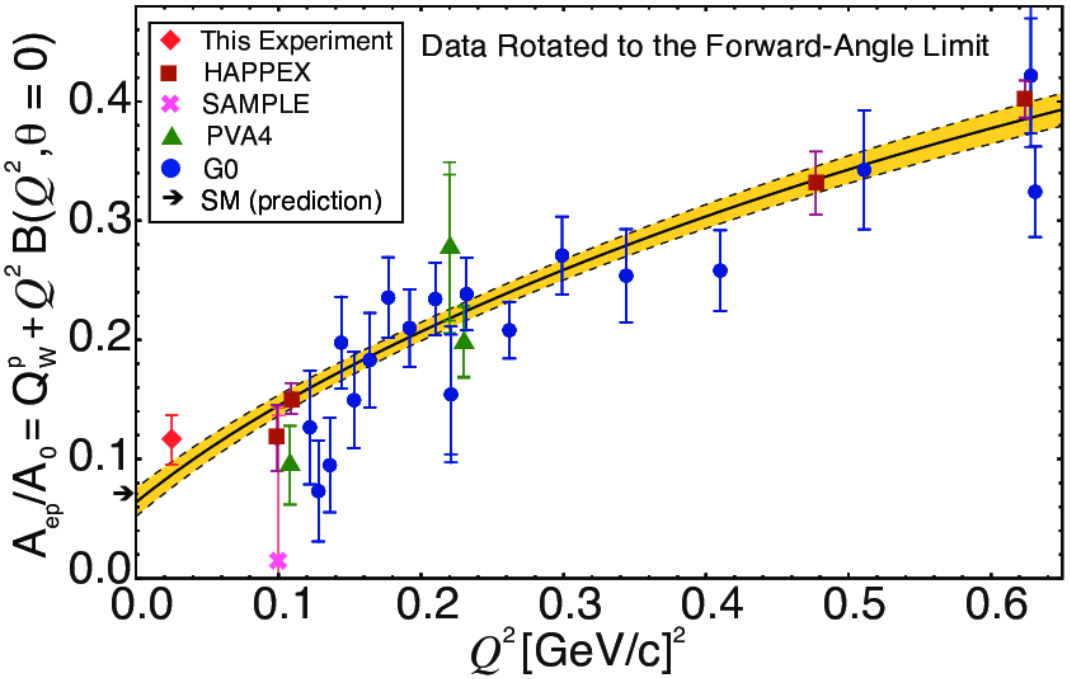
(Q_{weak} Collaboration)

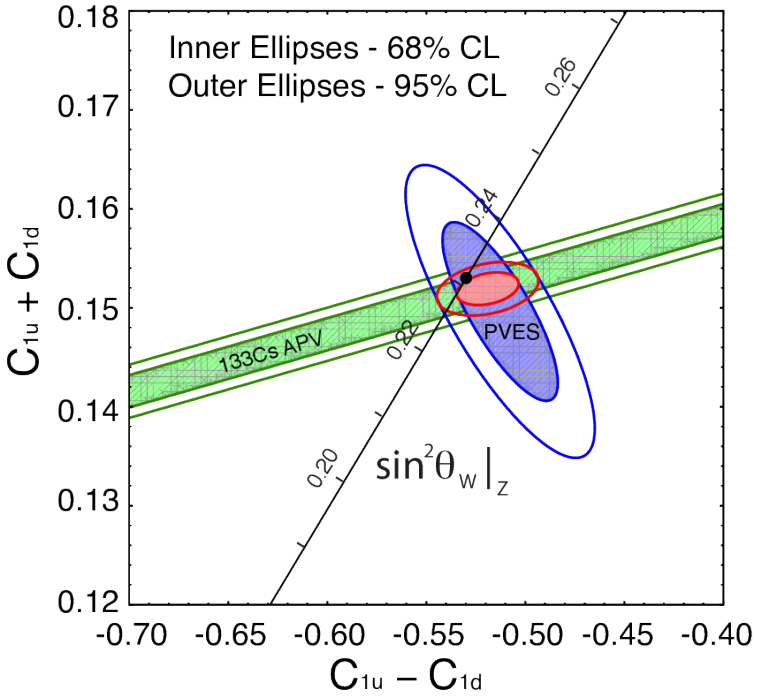
Published in 2013: Phys. Rev. Lett. 111, 141803 (2013)

$$A_{PV} = A_{ep} = -279 \pm 35(stat) \pm 31(sys) \text{ ppb}$$

First Results

Global analysis method by Young et al. [Phys. Rev. Lett. 99, 122003, (2007)] used to extract Q_W^p.





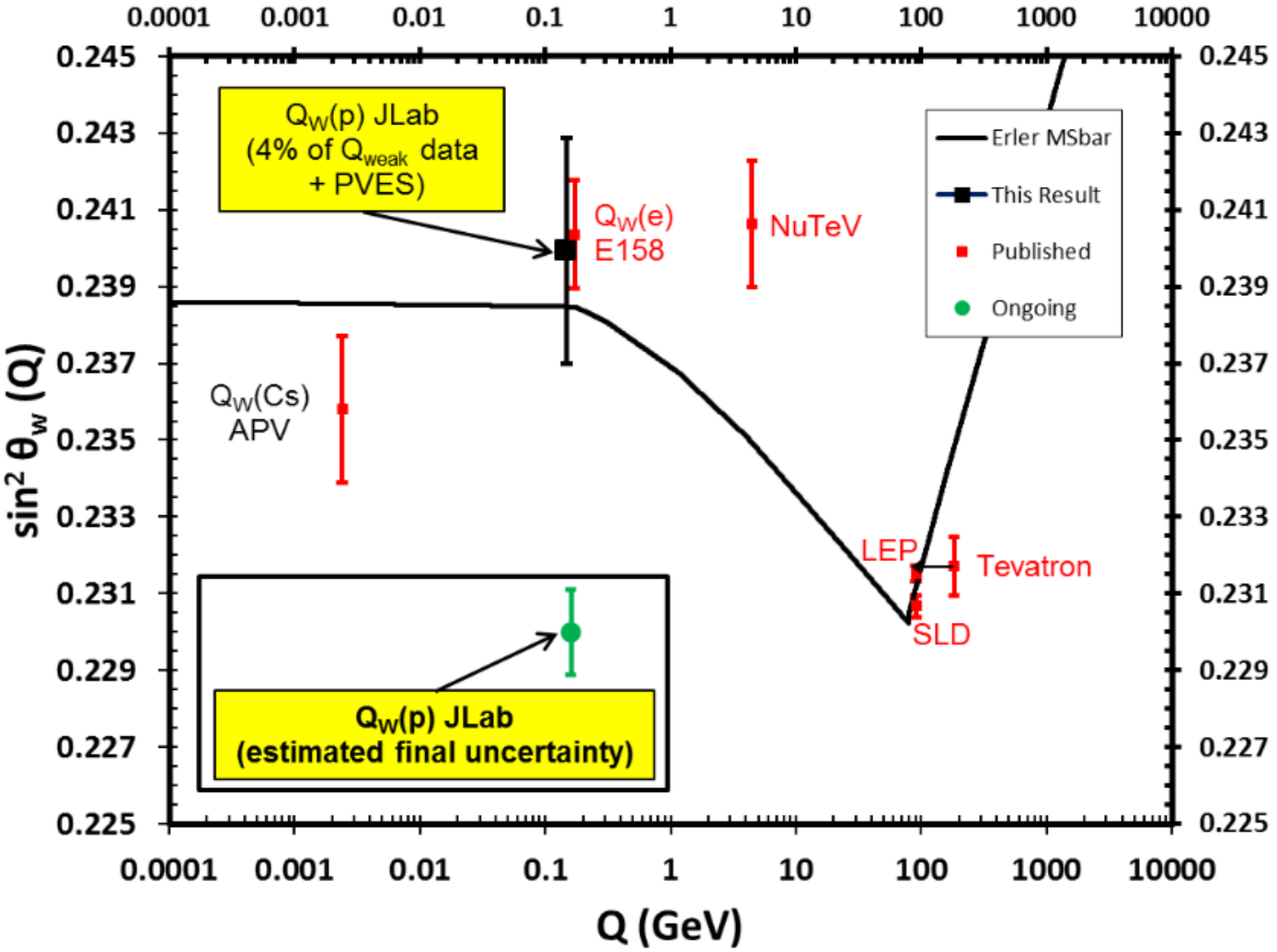
Extracted proton's weak charge:

- $Q_W^p(PVES) = 0.064 \pm 0.012$
- $Q_W^p(SM) = 0.0710 \pm 0.0007$

Extracted neutron's weak charge:

- $Q_W^n(PVES) = -0.975 \pm 0.010$
- $Q_W^n(SM) = -0.9890 \pm 0.0007$

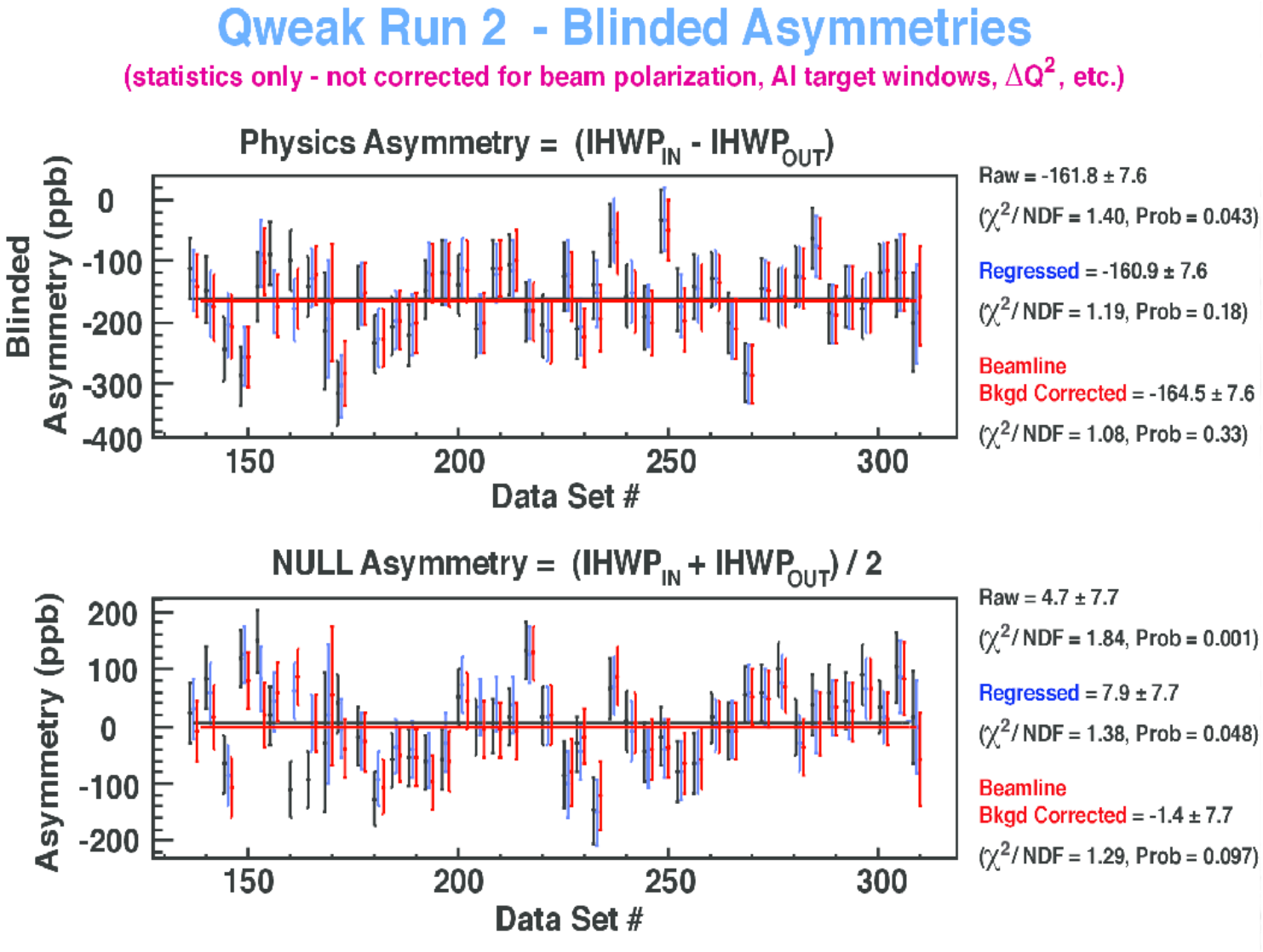
Weak Mixing Angle



- Black line is Standard Model prediction based on Z-pole results.
- Black point is $\sin^2\theta_W$ from Run 0.
- Green point is estimated error bar on final complete set.

Beamline Background

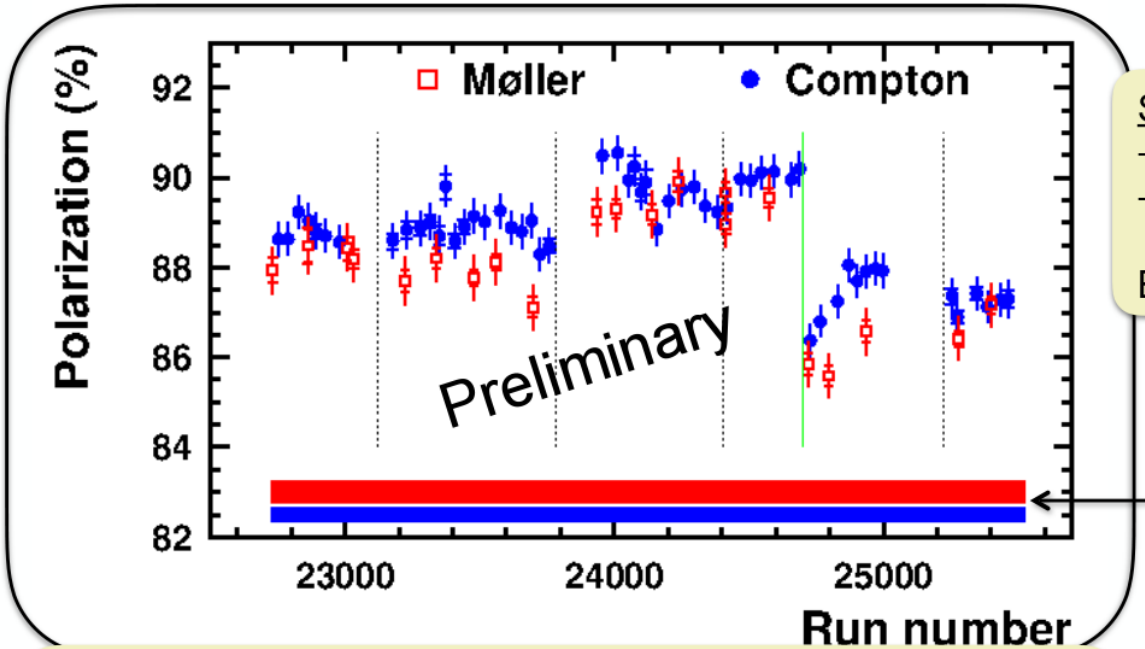
Correction is made by measuring background dilution and correcting with correlations from background detector.



Correction makes improvement to fit.

Beam Polarization

Run 0: Only Møller data
Run I & 2: Hall-C Compton polarimeter online



Normalization uncertainties

Systematic uncertainties
- Compton: dP/P = 0.59%
- Møller: dP/P = 0.84%

Both techniques agree to < 0.8%

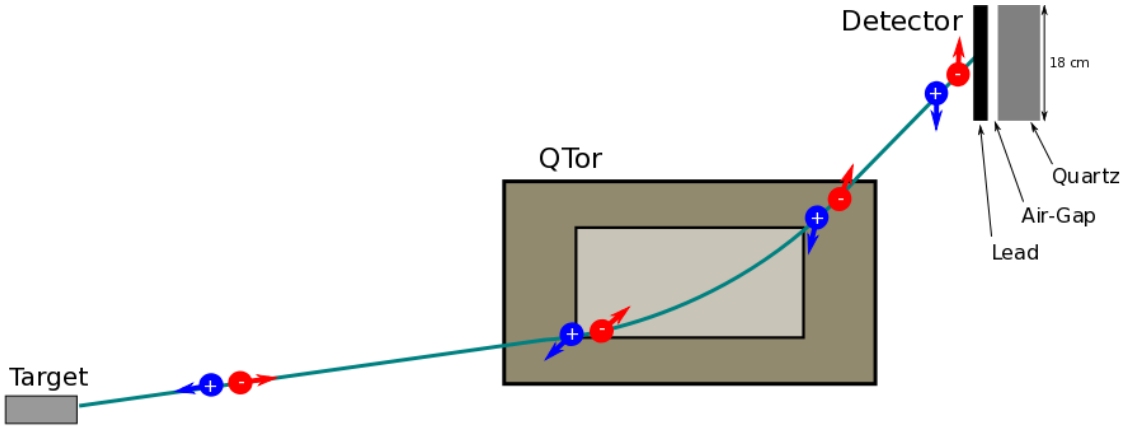
P_{Moller} +/- stat (inner) +/- point-to-point systematic (0.53%)

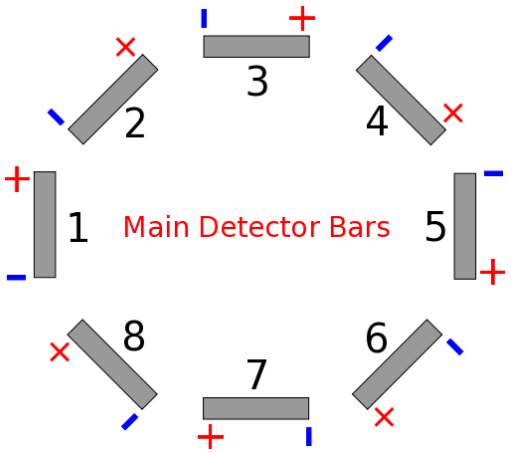
$P_{Compton}$ +/- stat +/- point-to-point syst. (0.41%)

Expt. strategy: minimize systematics

Compton: A. Narayen et al. Phys. Rev. X 6, 011013 (2016)
Moller + Compton: "The Q_{weak} Experimental Apparatus," NIM A 781, 105 (2015)

Secondary Scattering





- Spin precession of scattered electron through spectrometer magnet give some transverse polarization, $P_\perp$.
- $P_\perp$ in combination with lead pre-radiators in front of quartz bars causes a transverse asymmetry that is the **same order** but **opposite sign** in the + and - PMTs.

Effect:

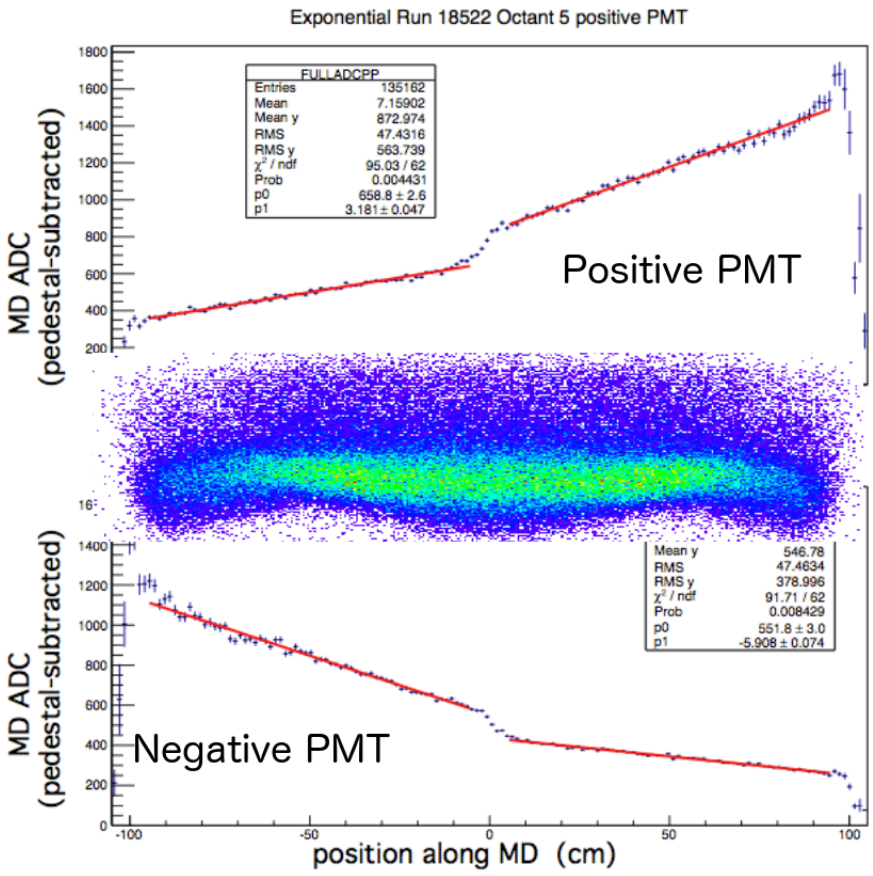
$$A_{diff} = A_- - A_+$$

Q_{weak} measures:

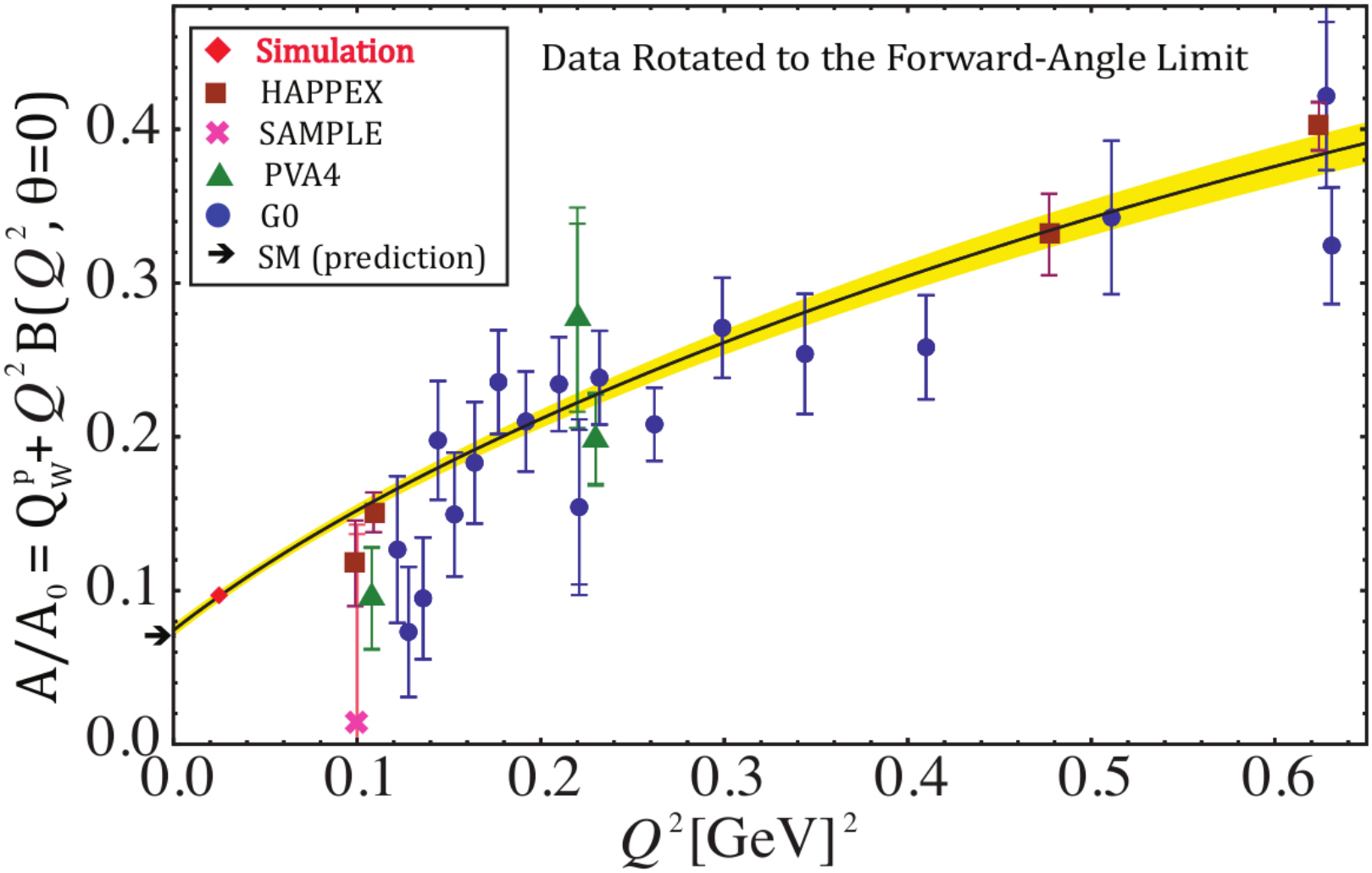
$$A_{PV} = \frac{A_- + A_+}{2}$$

Secondary Scattering Effect

- **Should cancel with symmetric detectors**. We live in the real world.
- Level of cancellation is being investigated with GEANT4 simulation and bench tests.
- Each of the 8 bars has slightly different physical properties and a separate correction will be made for each.
- **Last significant systematic uncertainty before we unblind.**



Projected Final Asymmetry Error



This figure shows anticipated final uncertainty placed on the SM prediction line.

Summary

- Initial PRL published in 2013 with $\sim 4\%$ of total collected data.
- Analysis is nearing completion on the full data set. Unblinding in early spring.
- Final result is anticipated to be statistically limited.
- Ancillary physics analyses are ongoing, with future publications planned.

The Qweak Collaboration

97 collaborators 23 grad students
10 post docs 23 institutions

Institutions:
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[2] College of William and Mary
[3] A. I. Alikhanyan National Science Laboratory
[4] Massachusetts Institute of Technology
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[6] Ohio University
[7] Christopher Newport University
[8] University of Manitoba,
[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
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[22] Hendrix College, Conway
[23] University of Adelaide
[24] Syracuse University

A SEARCH FOR NEW PHYSICS
Qweak

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Jefferson Lab

Spokespersons Project Manager Grad Students

Hall C