The Qweak Experiment at Jefferson Lab:
A Direct Measurement of the Proton's Weak Charge

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Overview

- Qweak determines Q^p_W and $\sin^2\theta_W$ to high precision via measuring parity-violation asymmetry (~300 ppb) in e-p elastic scattering at low Q^2 (0.025 GeV^2)
  - Deviation from the SM predictions would be a sign of new physics
- First results based on 4% of total dataset published in **PRL 111, 141803 (2013)**
- Experimental apparatus described in **NIM A781, 105 (2015)**
- The performance of the Compton polarimeter described in **Phys. Rev. X 6, 011013 (2016)**
- Analysis of full dataset is continuing, results expected late this fall
- Several ancillary measurements were taken to constrain background contributions and to make corrections

Outline

- Qweak's Physics Motivation
- Experimental Apparatus
- First Results
- Status of Current Analysis
- Ancillary Measurements

Search for Physics beyond the Standard Model

- The Standard Model (SM)
  - A successful low energy effective theory of more fundamental physics, yet incomplete

- Two complimentary approaches in testing SM and searching for new physics
  - Direct searches for new particles at high energy (Tevatron, LHC)
  - Indirect searches to test the SM via precision measurements at low energy (PVES, including Qweak)

- The Qweak experiment at Jefferson Lab
  - Elastic scattering of electron beam from proton target ($\vec{e}+p \rightarrow \vec{e}+p$)
  - Measure significantly suppressed SM observable ($Q_W(p)$) to high precision
  - Sensitive search for new physics at TeV scale

Proton's Weak Charge in the Standard Model

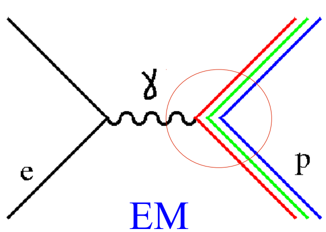
- Weak charges - neutral current analog to the electric charges

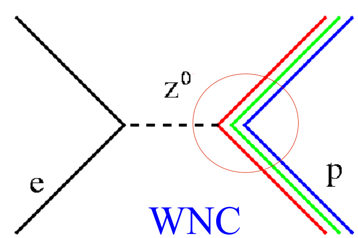
- Firm predictions have been made on Q^p_W in the Standard Model

Particle	Electric charge	Weak vector charge ($\sin^2\theta_W \approx \frac{1}{4}$)
e	-1	$Q^e_W = -1 + 4\sin^2\theta_W \approx 0$
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)	$+1$	$Q^p_W = 1 - 4\sin^2\theta_W \approx 0.07$
n(udd)	0	$Q^n_W = -1$

The accidental suppression of Q^p_W in the SM makes it sensitive to new physics!

$$Q^p_W = -2(2C_{1u} + C_{1d})$$
$$Q^n_W = -2(C_{1u} + 2C_{1d})$$



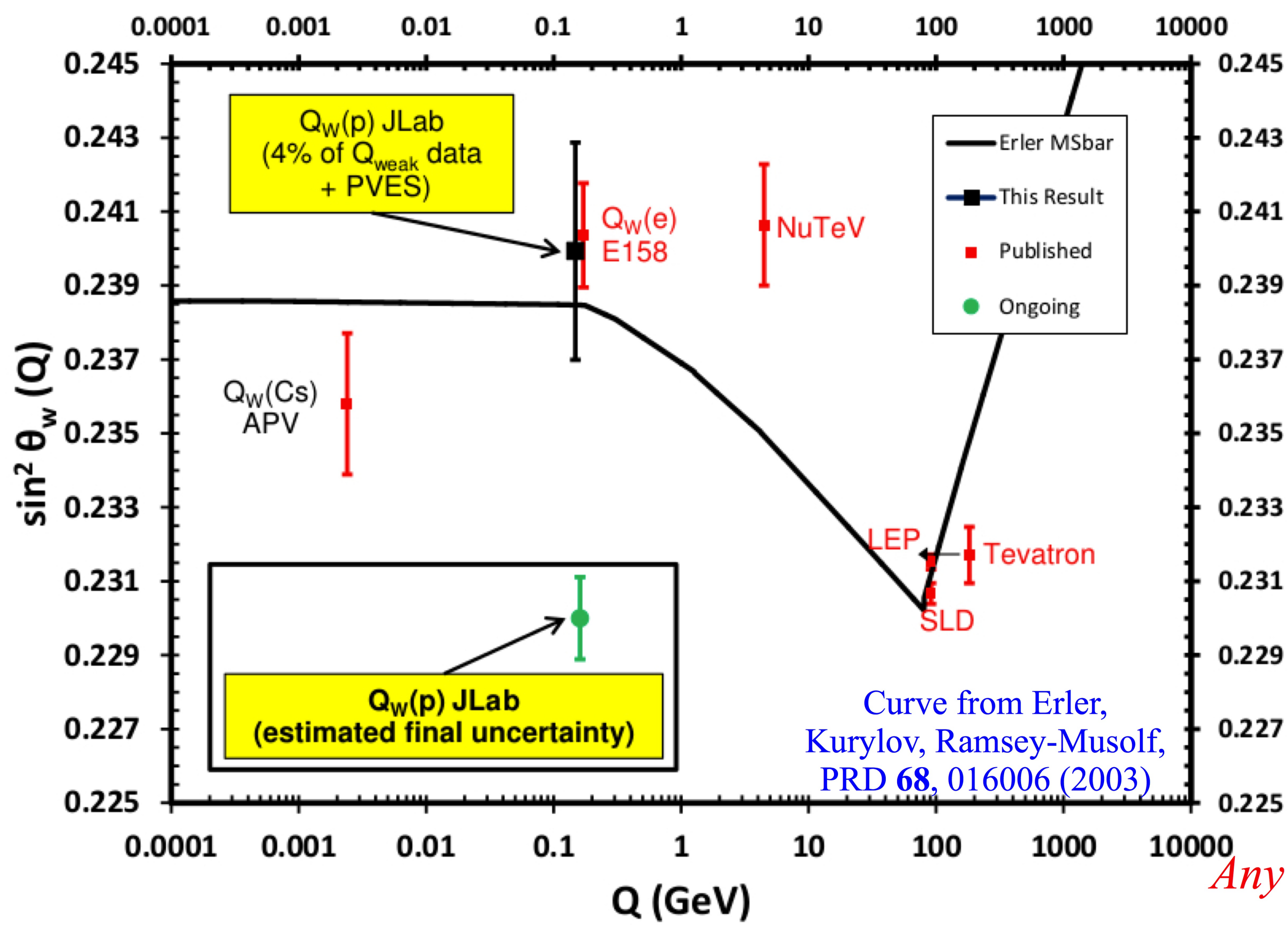


Qweak is very sensitive to weak vector coupling of light quarks

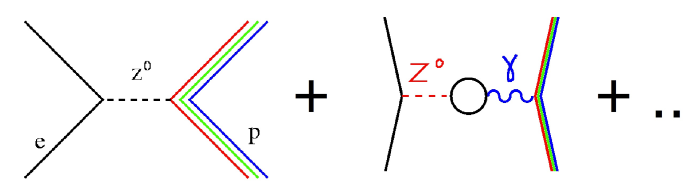
- At tree level, $Q^p_W = 1 - 4\sin^2\theta_W$ (θ_W - weak mixing angle)
- Qweak's accurate measurement of Q^p_W will lead to a high precision test of $\sin^2\theta_W$ at low energy ($Q^2 << M_Z$)

Running of $\sin^2\theta_W$

The "running" feature of $\sin^2\theta_W$ is well known in the SM



- The curve is a SM prediction which includes γ-Z mixing in addition to the tree level exchange:



- Each experiment sensitive to different types of new physics

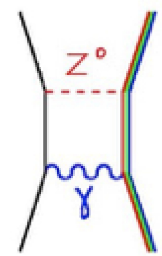
- Precision low energy measurements are very sensitive to new physics;

Any deviation may indicate new physics!

Electroweak Radiative Corrections

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

- Most significant radiative correction:
  γ-Z box diagram



- Much theoretical efforts focus on γZ box:

Significant E-dependence first identified by Gorchtein & Horowitz;
Hall *et al* model dependence constrained by Jlab PVDIS data

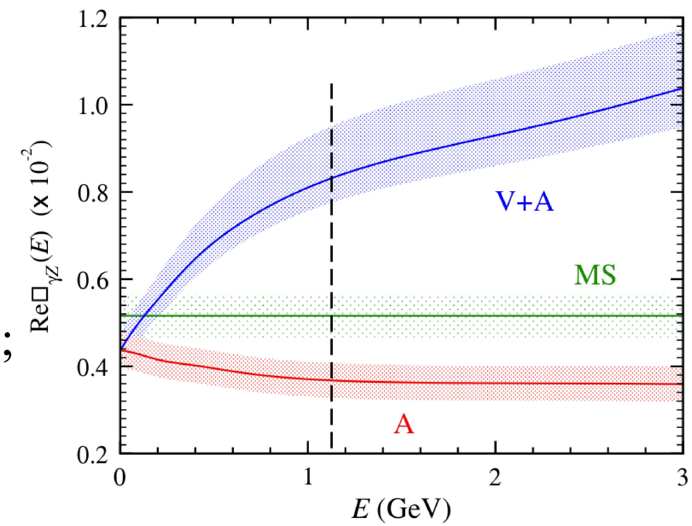
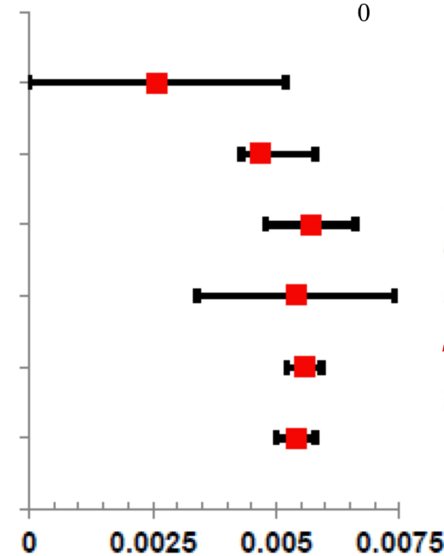


Table 1: $\Box^V_{\gamma Z}$ contribution to Q^p_W (Qweak kinetmatics)

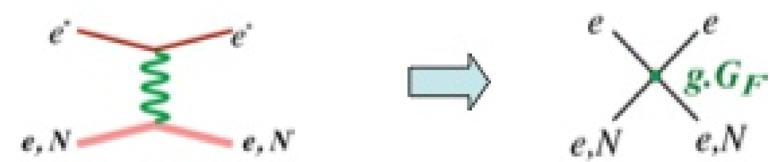
Gorchtein & Horowitz Phys. Rev. Lett. **102**, 091806 (2009)	0.0026 ± 0.0026
Sibirtsev, Blunden, Melnitchouk, & Thomas Phys. Rev. D **82**, 013011 (2010)	$0.0047^{+0.0011}_{-0.0004}$
Rislow & Carlson Phys. Rev. D **83**, 113007 (2007)	0.0057 ± 0.0009
Gorchtein, Horowitz, & Ramsey-Musolf Phys. Rev. C **84**, 015502 (2011)	0.0054 ± 0.0020
Hall, Blunden, Melnitchouk, Thomas, & Young Phys. Rev. D **88**, 013011 (2013)	0.00557 ± 0.00036
Hall, Blunden, Melnitchouk, Thomas & Young arXiv:1504.03973 **(2015)**	0.0054 ± 0.0004



The uncertainty of γZ box is calculated to ~1%, well below Qweak experimental sensitivity & smaller than that of Z pole data

Sensitivity to New Physics

- For low-energy electroweak tests, the parity-violating e-q scattering can be expressed as a four-fermion contact interaction



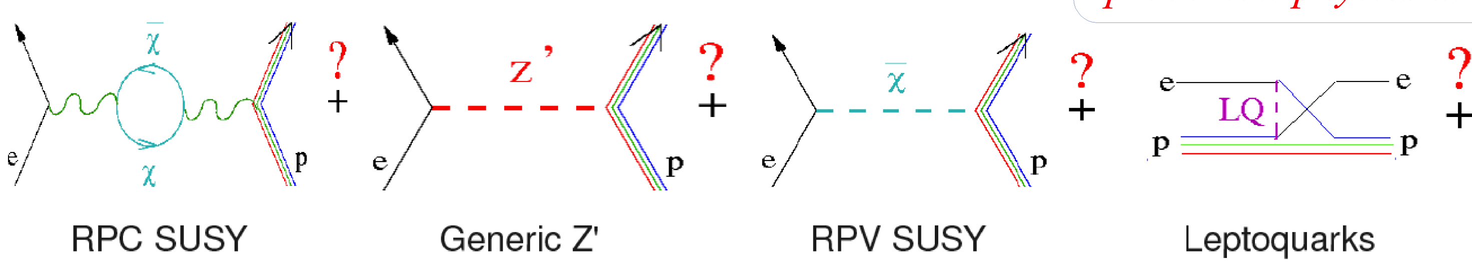
- Suppose some new physics adds a contact term to the PV e-q Lagrangian, with coupling constant, g, and mass, Λ: Erler et al. PRD 68, 016006 (2003)

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

- The sensitivity to new physics Mass/Coupling ratio can be estimated

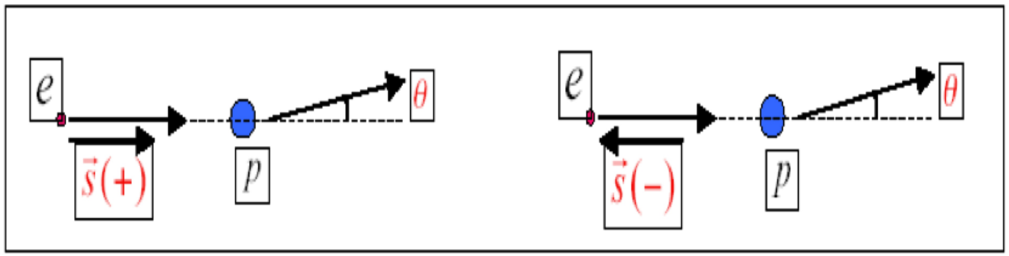
$$
\frac{\Lambda}{g} \sim \left(\sqrt{2} G_F \Delta Q_W^p\right)^{-\frac{1}{2}} \sim O(\mathrm{TeV})
$$

A 4% measurement of Q^p_W would probe new physics at TeV scale



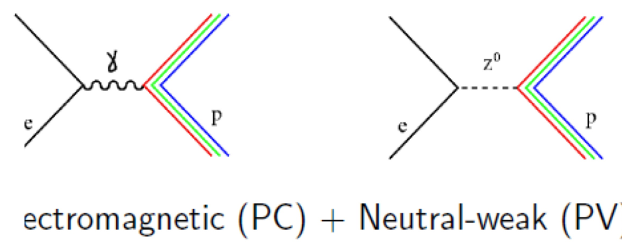
Accessing Q^p_W from PV Electron Scattering

- Scatter electrons of opposite helicity from an unpolarized target



right-handed e^- beam   left-handed e^- beam

- The scattering process involves the EM interaction and the WNC interaction



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

scattering cross-section:

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

- The interference term gives rise to a parity-violating asymmetry

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

~ -200 ppb

- In the limit of $Q^2 \rightarrow 0$ and $\theta \rightarrow 0$, the leading order term for elastic scattering contains Q^p_W

$$A_{PV} = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\left[Q^p_W + B(\theta, Q^2)Q^2\right]$$

Extraction of the Proton's Weak Charge

- Qweak determines Q^p_W by measuring the PV asymmetry in elastic scattering of longitudinally polarized electrons on proton.

- At Qweak kinematics ($Q^2 \rightarrow 0$ and $\theta \rightarrow 0$): *The Q^p_W term dominates the total asymmetry (~2/3)*

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

hadron structure: contains G^{γ}_{EM} & G^{Z}_{EM} form factors, constrained by other expts

Divide out A_0 and use the reduced asymmetry to express:

$$\overline{A^p_{PV}} = \frac{A_{PV}}{A_0} = Q^p_W + Q^2 B\left(Q^2\right)$$

- The hadronic term could be extracted from a global fit of previous PVES data (SAMPLE, HAPPEX, G0, PVA4); Intercept of reduced asymmetry gives access to Q^p_W.

[R.D. Young et al. PRL 99, 122003]

The Qweak Experiment at JLab

- Qweak ran in Hall C at Jefferson Lab, Newport News, VA

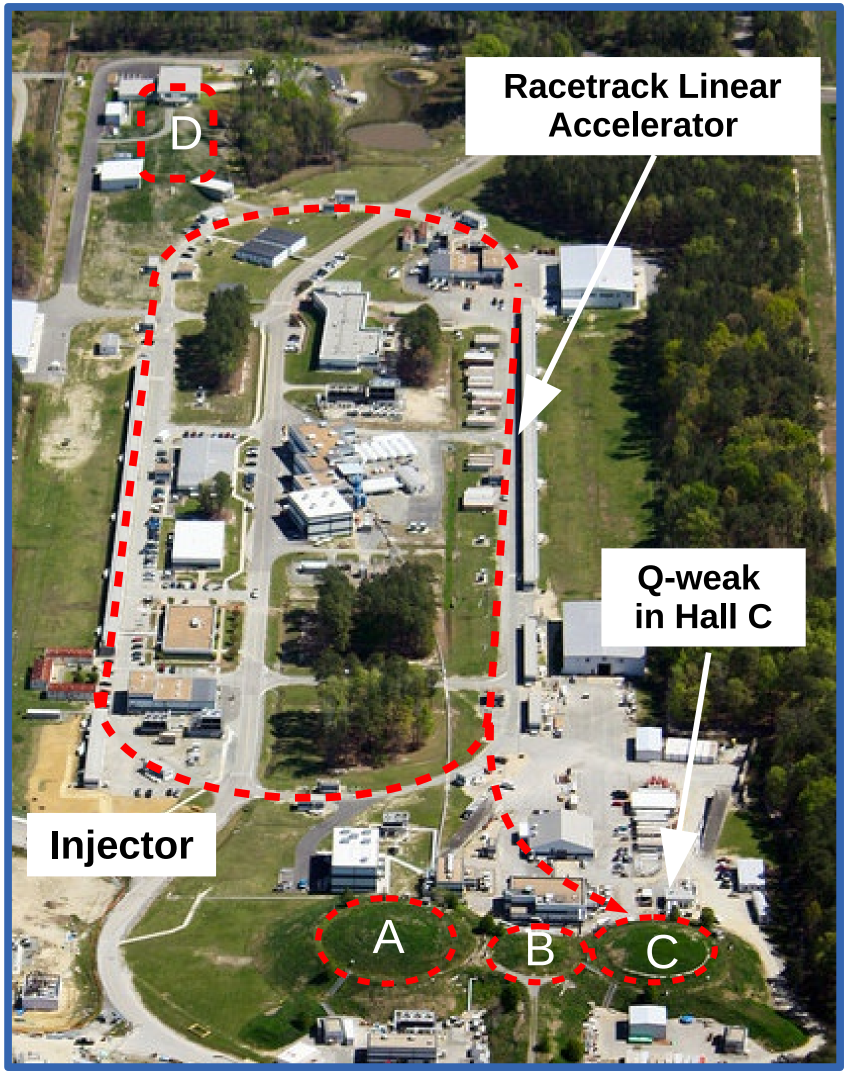
- Data taken over one year of beam
  - Commissioning run: Jan – Feb 2011
  - Run1: Feb – May 2011
  - Run2: Nov 2011 – May 2012

- Qweak was well designed to meet the following technical challenges:

Statistics (high rates)
- High polarization,
- High beam current
- High powered targets
- Large acceptance

Low noise
- Electronics
- Target density fluctuations
- Detector resolution

Systematics
- Minimized helicity correlated beam properties
- Separate backgrounds from elastic events
- High precision polarimetry
- Precise Q^2 determination



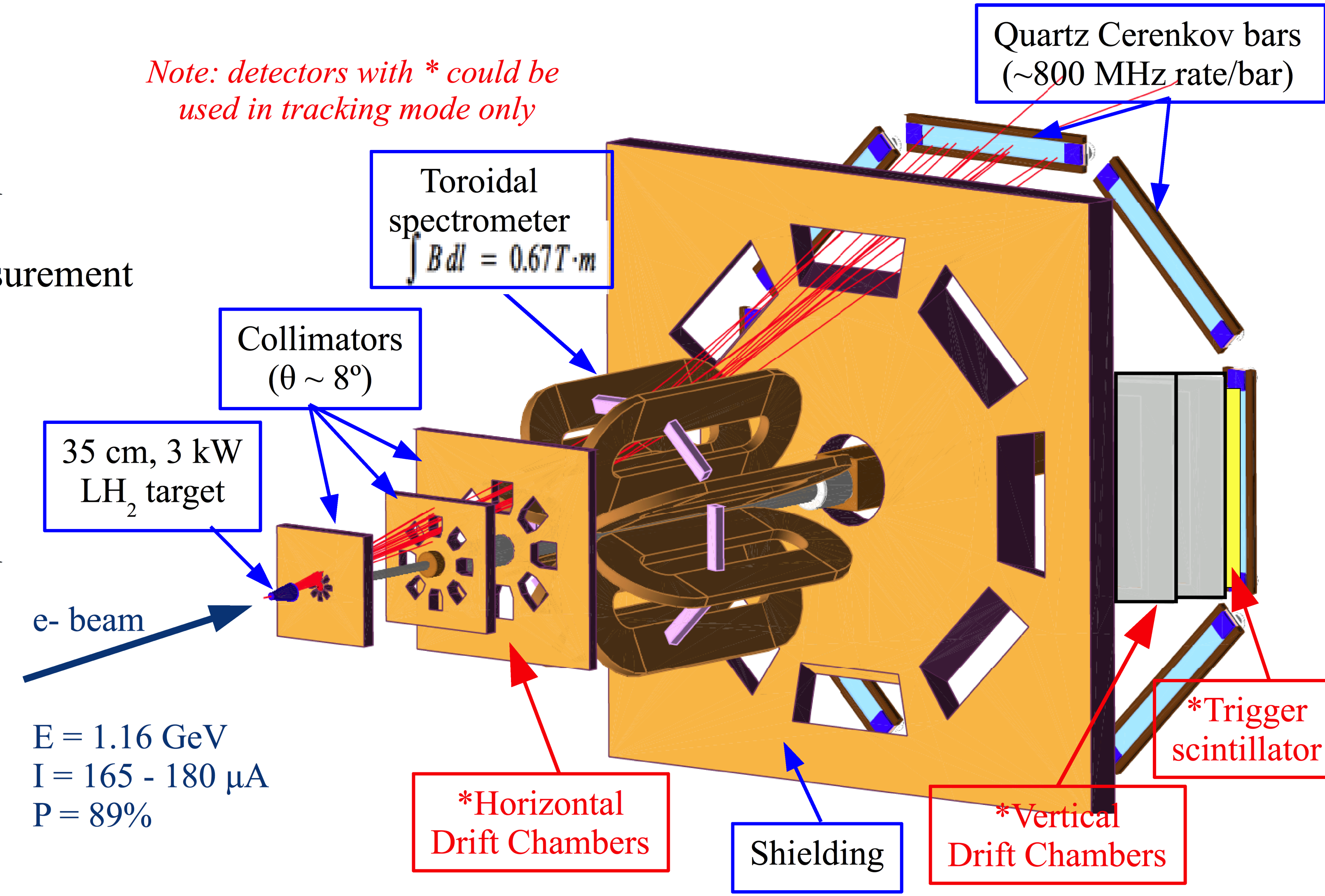
Qweak Apparatus

Production Mode:

- I = 165 - 180 μA
- Detectors read out in integration mode
- For asymmetry measurement

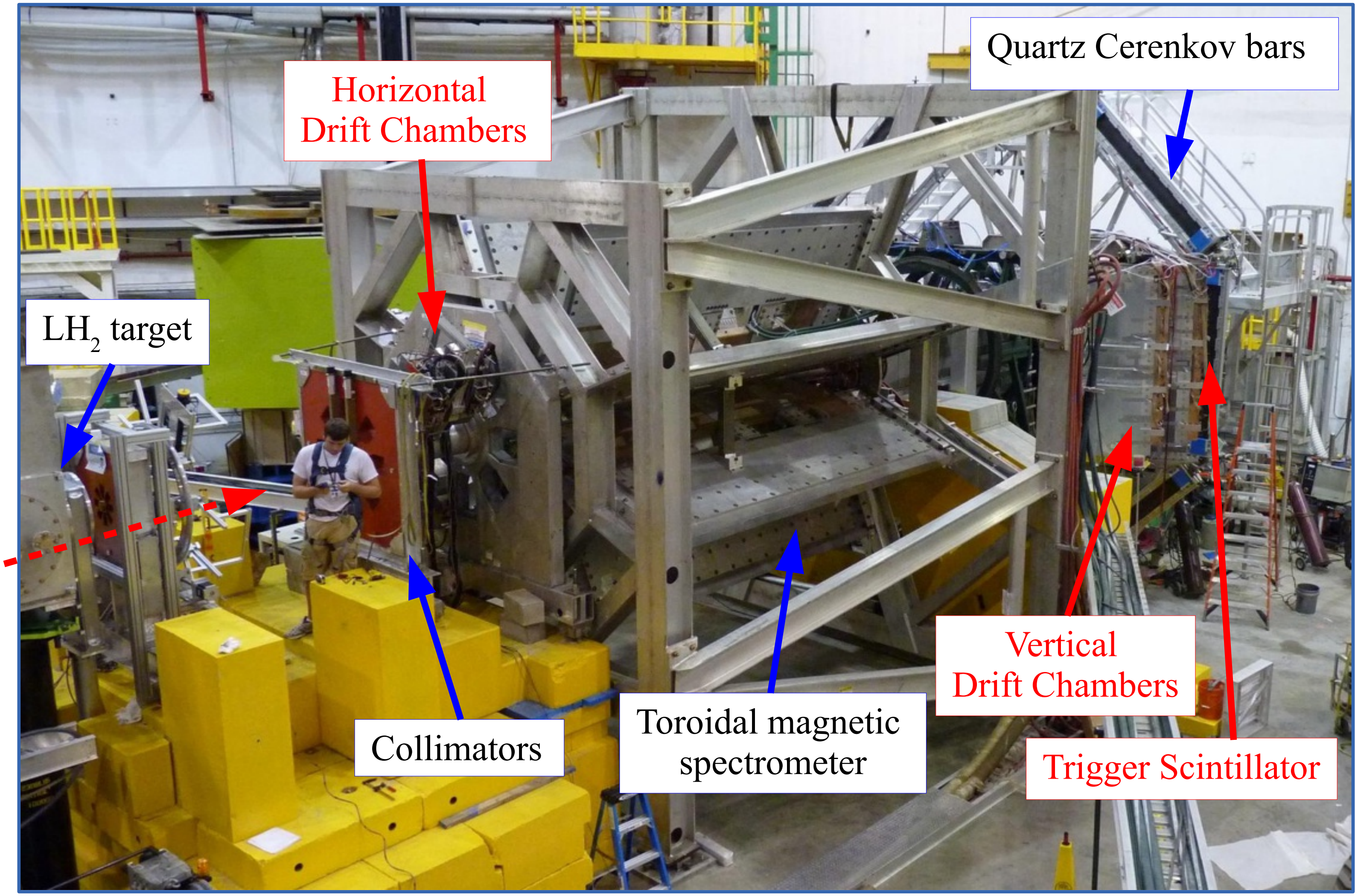
Tracking Mode:

- I = 50 pA - 100 nA
- Detectors read out in counting mode
- Measure individual tracks with tracking chambers
- For kinematics determination and background study



[T. Allison et al. Nuclear Instruments and Methods in Physics Research A 781 (2015) 105-133]

Qweak During Installation

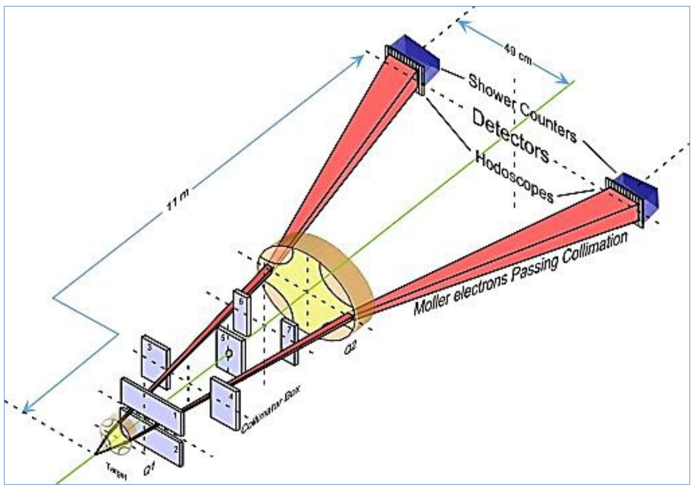


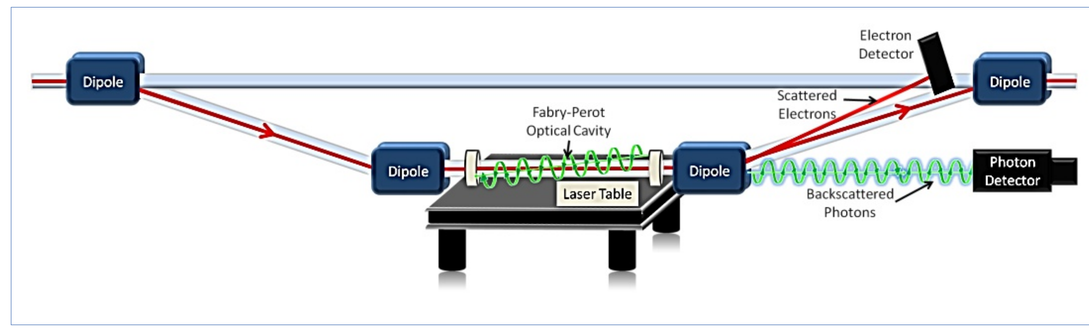
[T. Allison et al. Nuclear Instruments and Methods in Physics Research A 781 (2015) 105-133]

Beam Polarimetry

- Measure beam polarization to <1% using two independent devices

["The Qweak Experimental Apparatus," NIM A 781, 105 (2015) & A. Narayan et al. Phys. Rev. X 6, 011013 (2016)]





Møller polarimeter: $\vec{e}+\vec{e} \rightarrow e+e$

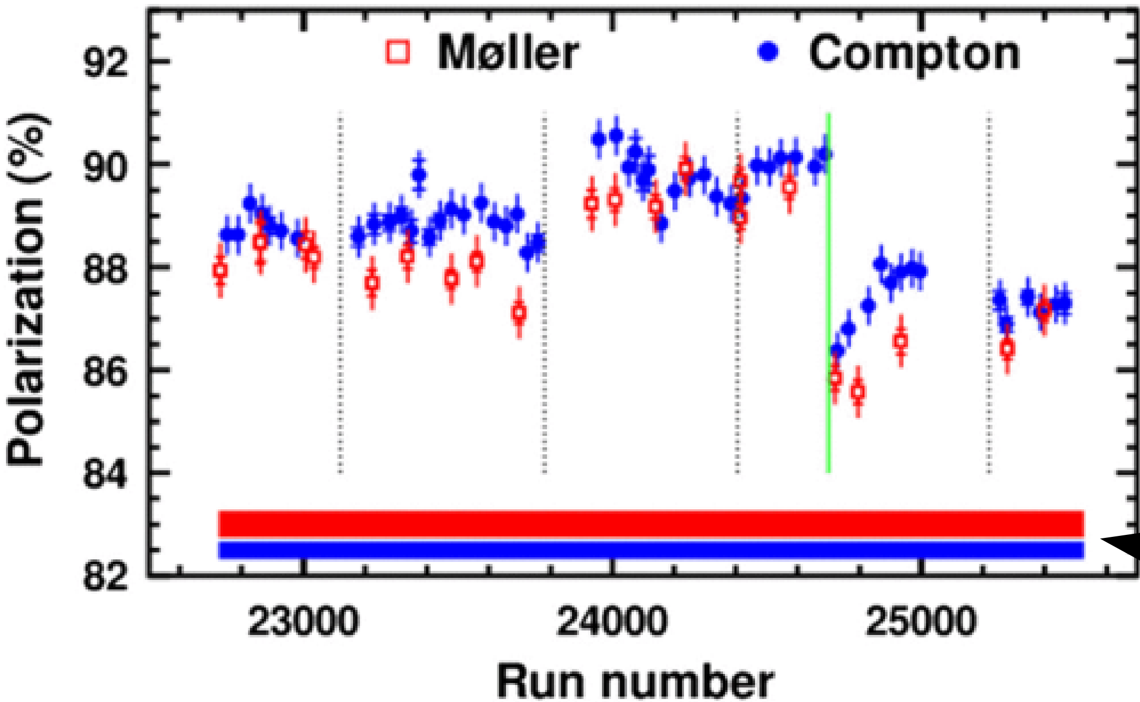
- electrons scatter from polarized Fe foil
- invasive measurement
- limit to low current

Compton polarimeter: $\vec{e}+\gamma \rightarrow e+\gamma$

- electrons scatter from polarized laser beam
- detect both recoil electron and photon
- continuous measurements at optimal beam currents

Beam Polarimetry

Run 2 data: (I = 180 uA, E = 1.16 GeV)



Systematic uncertainties:

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

Two techniques agree to <0.8%

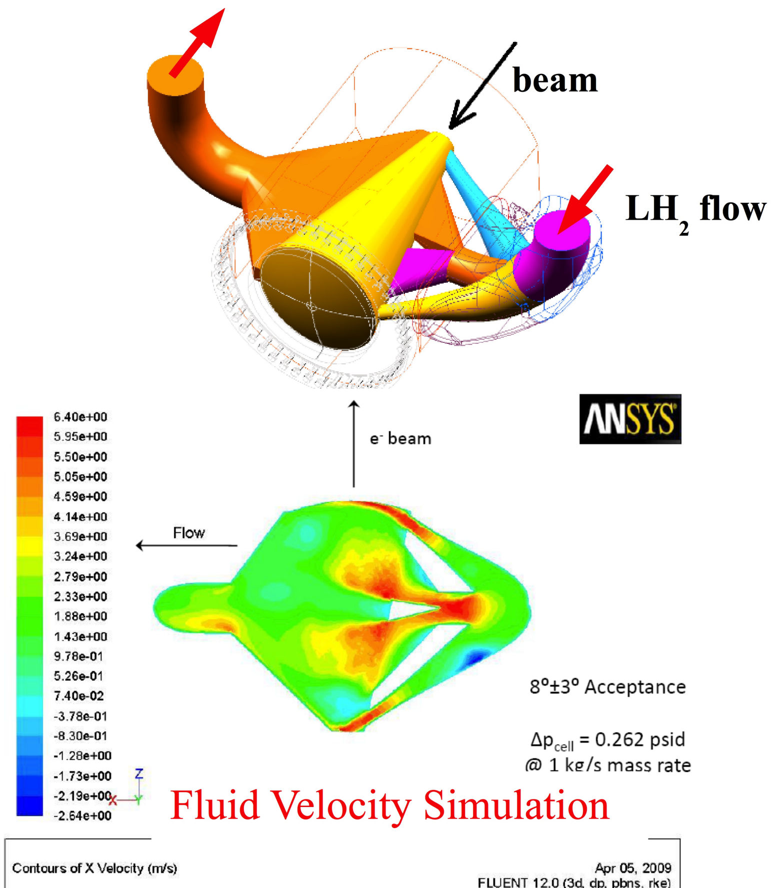
Normalization uncertainty (0.42% Compton & 0.65% Møller)

$P_{Møller}$ +/- stat (inner) +/- point-to-point syst. (0.53%)
$P_{Compton}$ +/- stat (inner) +/- point-to-point syst. (0.41%)

A. Narayan et al. Phys. Rev. X 6, 011013 (2016)

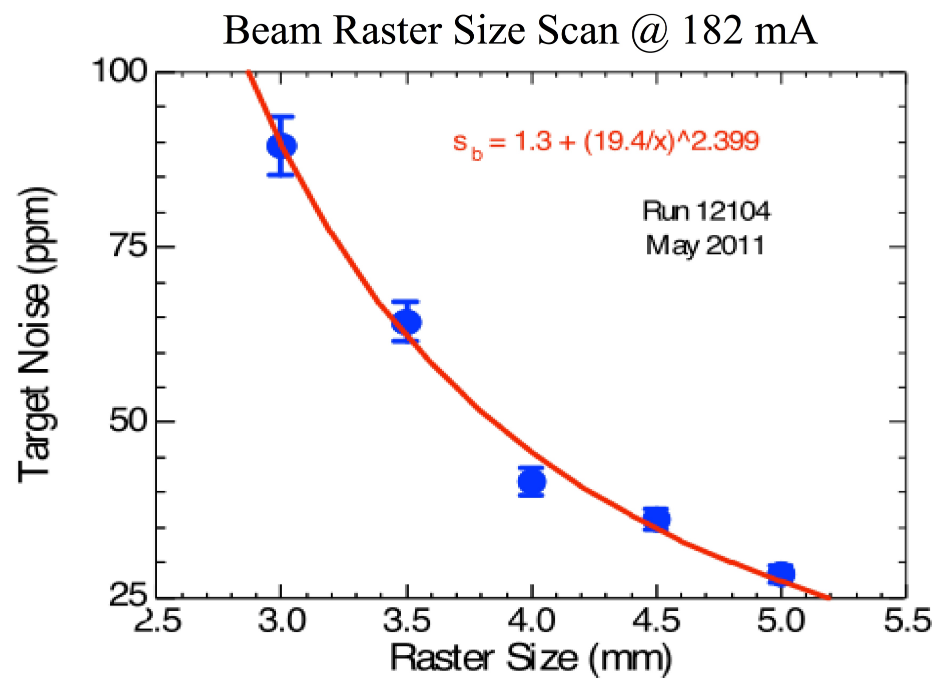
Target Design and Performance

- World's highest power cryotarget (~ 3 kW)
- Designed using computational fluid dynamics to minimize noise from density fluctuations



Fluid Velocity Simulation

Target "boiling" noise studies

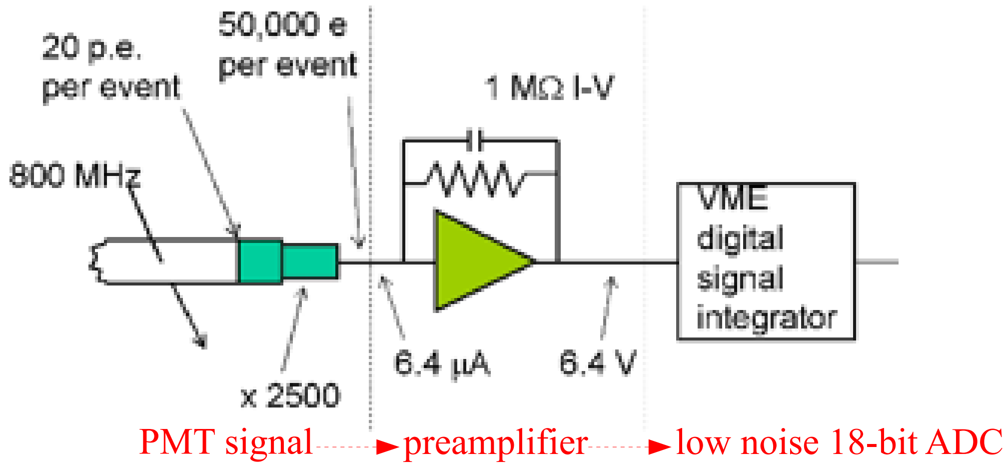


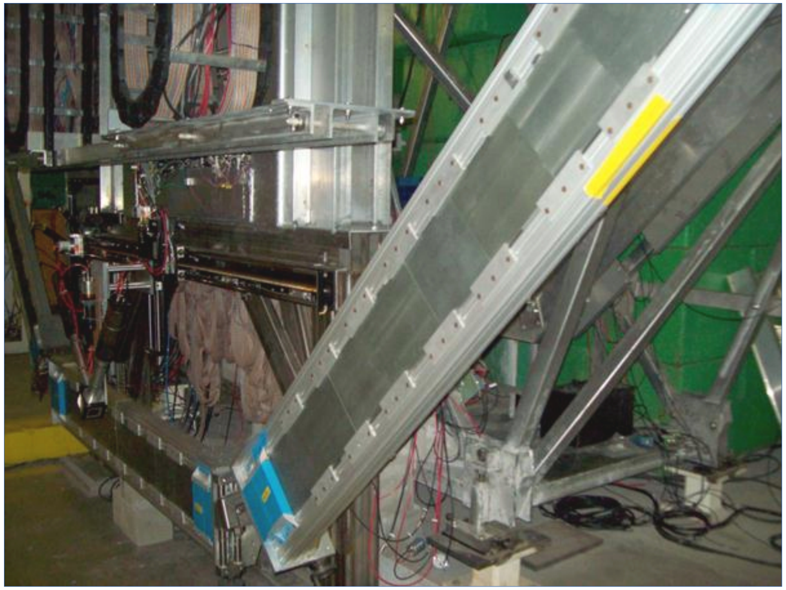
Target "boiling" made very small contribution (~ 47 ppm) to our asymmetry width (236 ppm)

Main Detectors

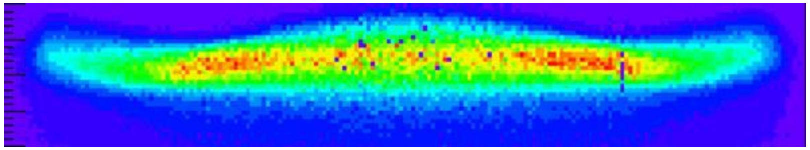
<u>Pre-radiated main Cerenkov detectors:</u>

- Eight radiation-hard Quartz Cerenkov bars (2 m x 18 cm x 1.25 cm)
- Toroidal magnet focuses elastically scattered electrons onto each bar
- Azimuthal symmetry maximizes rates and reduces systematic uncertainties
- 2 cm thick Pb pre-radiator tiles installed to reduce low-energy backgrounds
- PMT signals recorded by low noise electronics





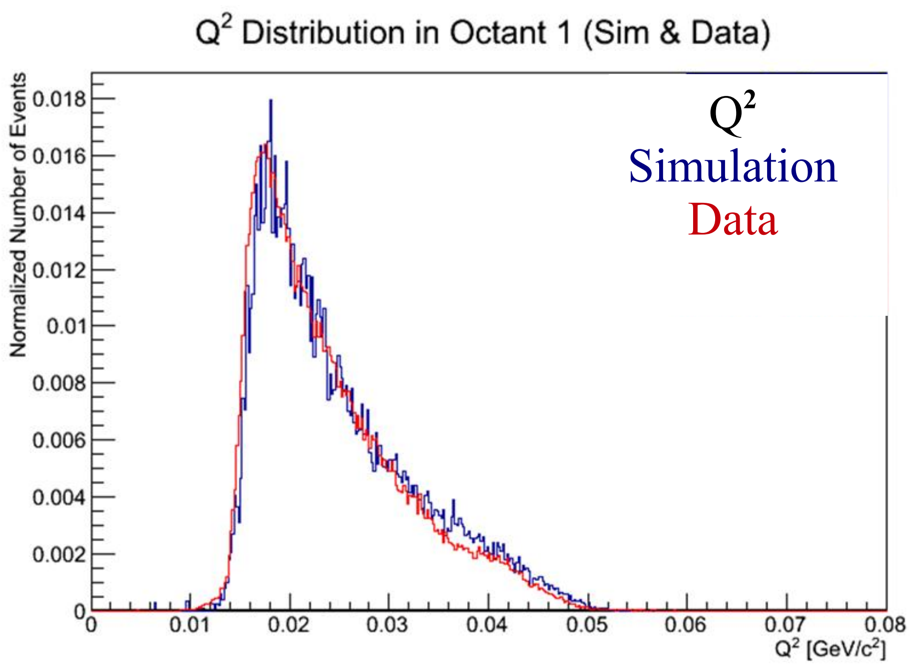
Measured profile in bottom octant

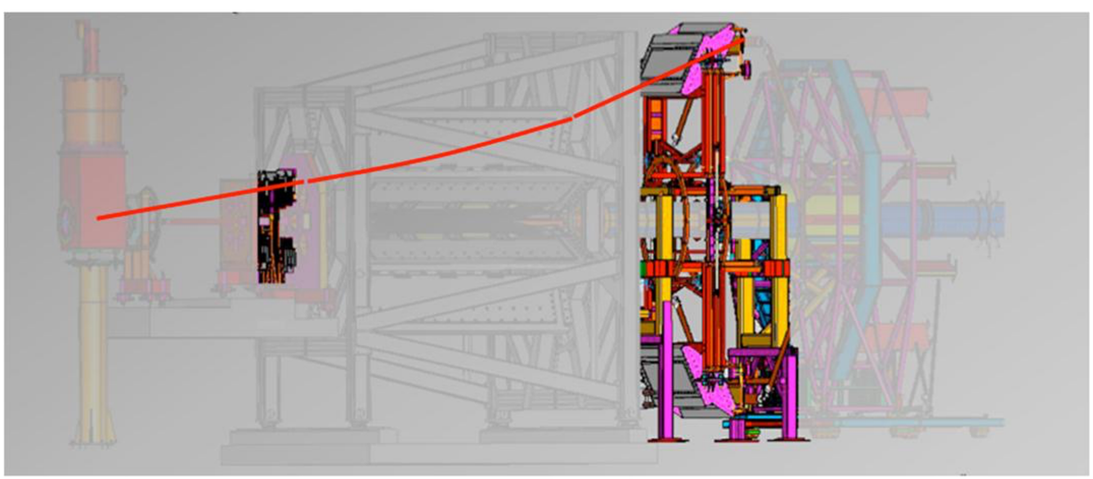


Kinematics Determination

To determine Q^2, run tracking mode periodically:
- Low current, ~50 pA – 100 nA
- Use high resolution drift chambers before and after magnetic field
- Re-construct individual scattering events

Systematic studies:
- Correct for radiative effects in target with Geant4 simulations, benchmarked with tracking measurements (gas-target & solid targets)
- Correct for light-weighting effects in main detectors





Signal Manipulation

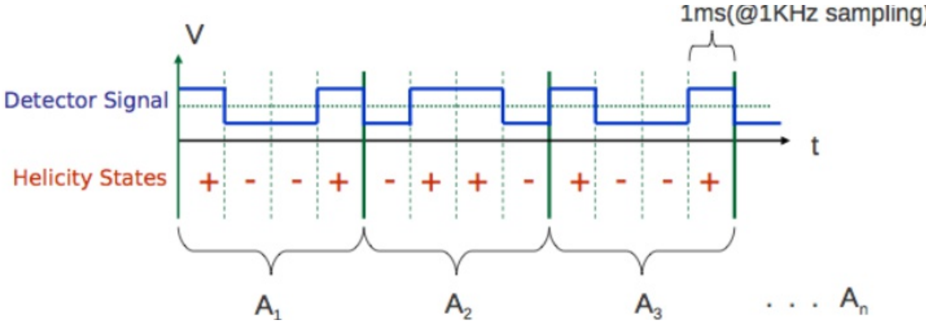
- Helicity reversal at 960 Hz, pseudorandomly generated in +--+ or -++- quartet pattern

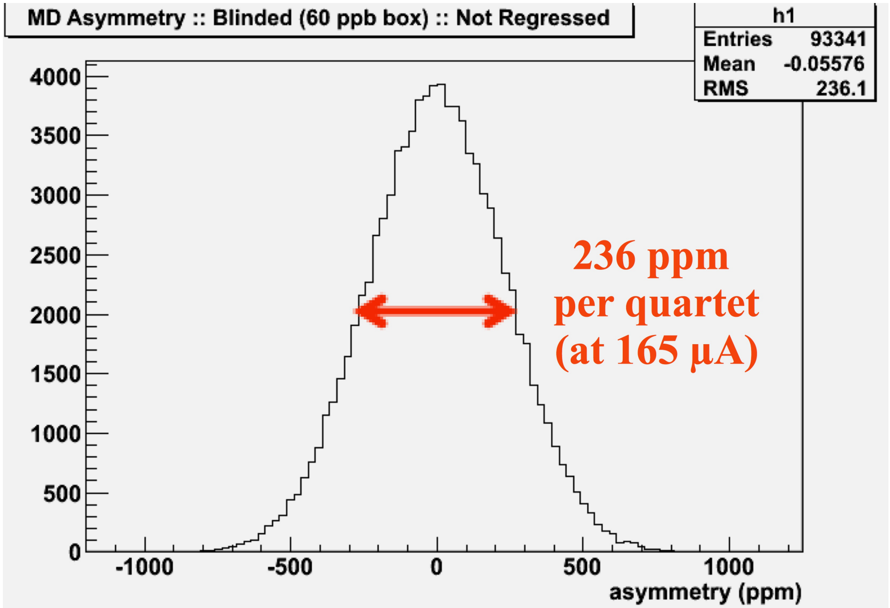
- Integrate detector signal (S) over each helicity state and normalized to beam charge (Q)

$$Y = S / Q$$

- Calculate asymmetries for each quartet pattern

$$A = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$





"Blind" analysis applied

Constructing the Asymmetry

To obtain physics asymmetry, some corrections are needed

STEP 1:

$$A_{msr} = A_{raw} + A_T + A_L + A_{reg}$$

- A_T - remnant transverse asymmetry
- A_L - potential non-linearity in PMT
- A_{reg} - helicity-correlated false asymmetry due to beam parameter variations

STEP 2:

$$A_{PV} = R_{tot} \frac{A_{msr}/P - \sum_{i=1}^{4} f_i A_i}{1 - f_{tot}}$$

- R_{tot} = includes radiative corrections and correction for light-variation
- P – beam polarization
- Background corrections: Al windows, neutrals, scattering from beamline, inelastic scattering
  - f_i - background dilution factor
  - A_i - background asymmetry

First Results

Published Run 0 results: PRL **111**, 141803 (2013)
(1/25th of total dataset, taken during commissioning period)

$$A_{ep}/A_0 = Q^p_W + Q^2 B(Q^2, \theta = 0)\ , \qquad A_0 = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}$$

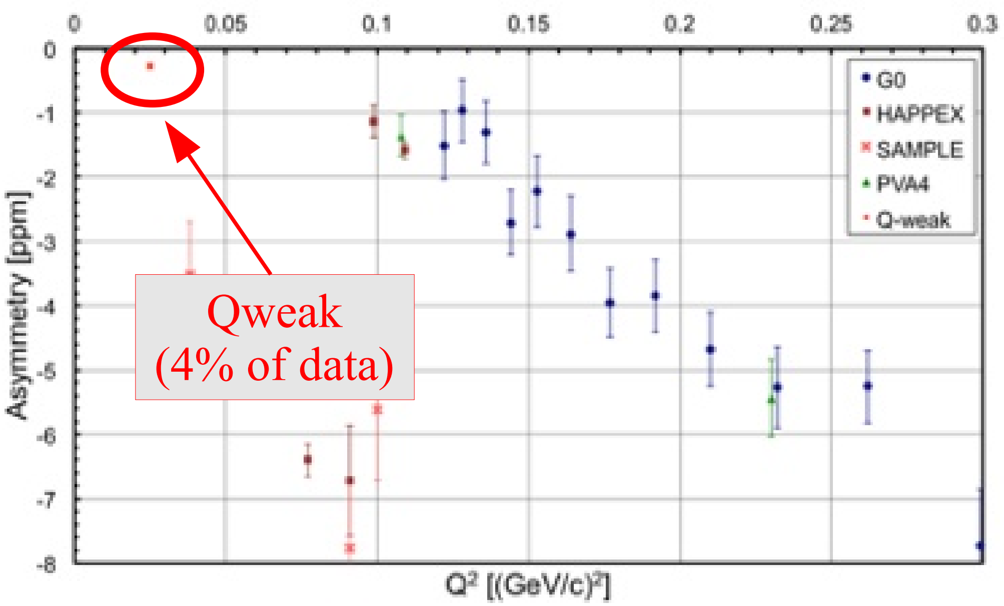
A_{PV} = -279 ± 35 (statistics) ± 31 (systematics) ppb

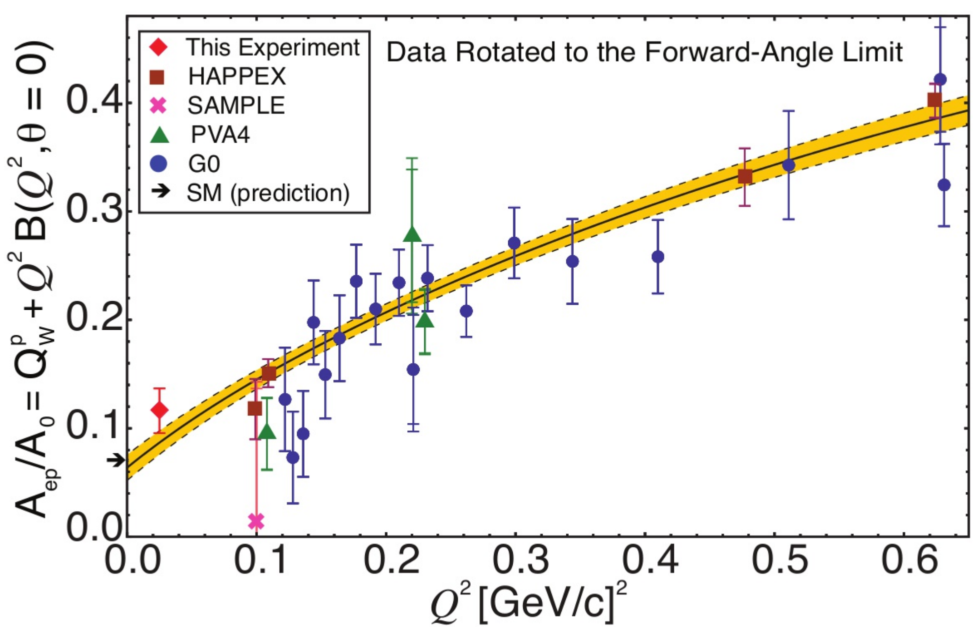
Kinematics:

$\langle Q^2 \rangle = 0.0250 \pm 0.0006\ (\mathrm{GeV}/c)^2$
$\langle E \rangle = 1.155 \pm 0.003$ GeV

Extract Q^p_W via global fit of world PVES data

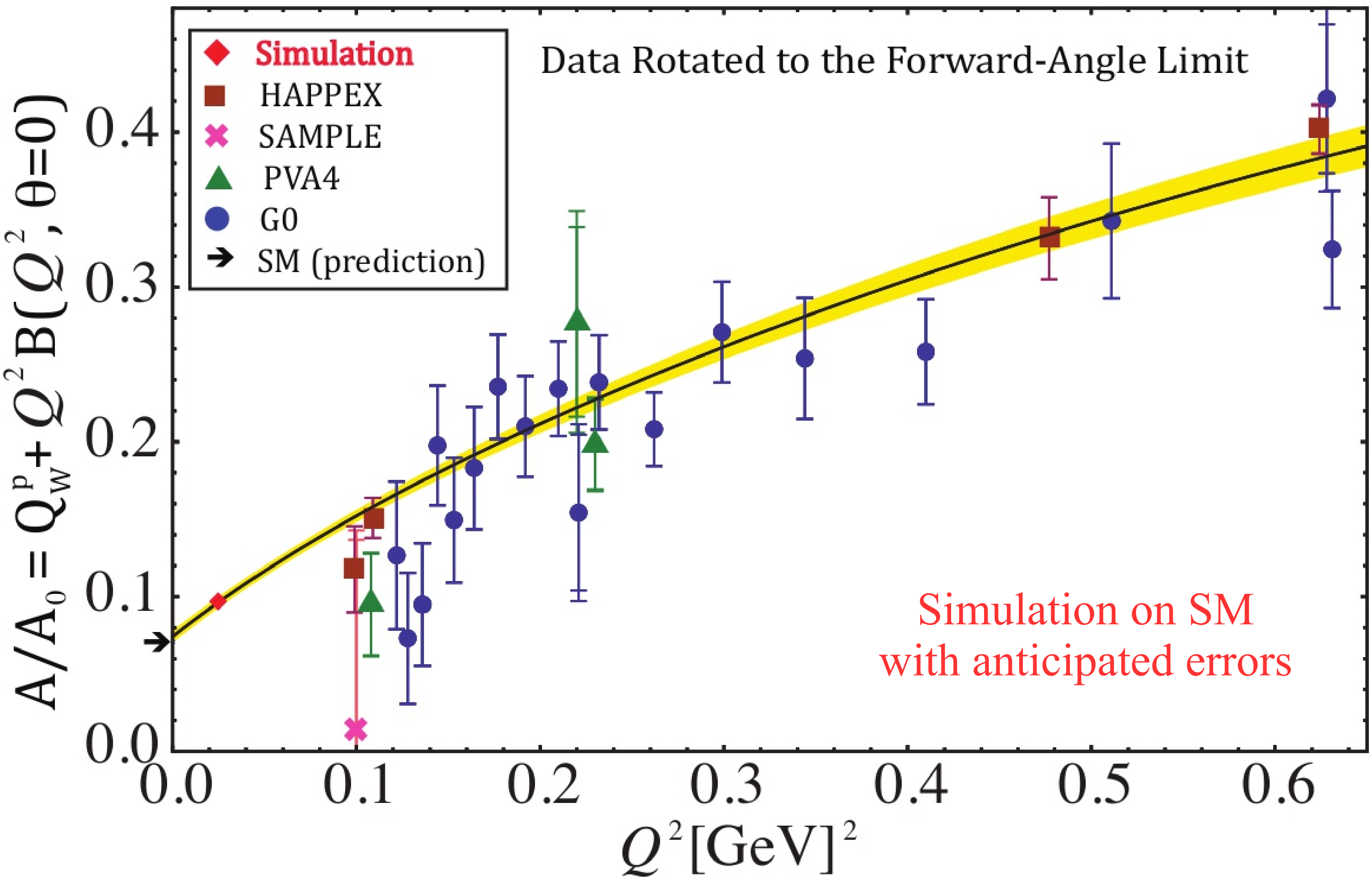
$$Q^p_W(PVES) = 0.064 \pm 0.012$$
$$Q^p_W(SM) = 0.0710 \pm 0.0007$$





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

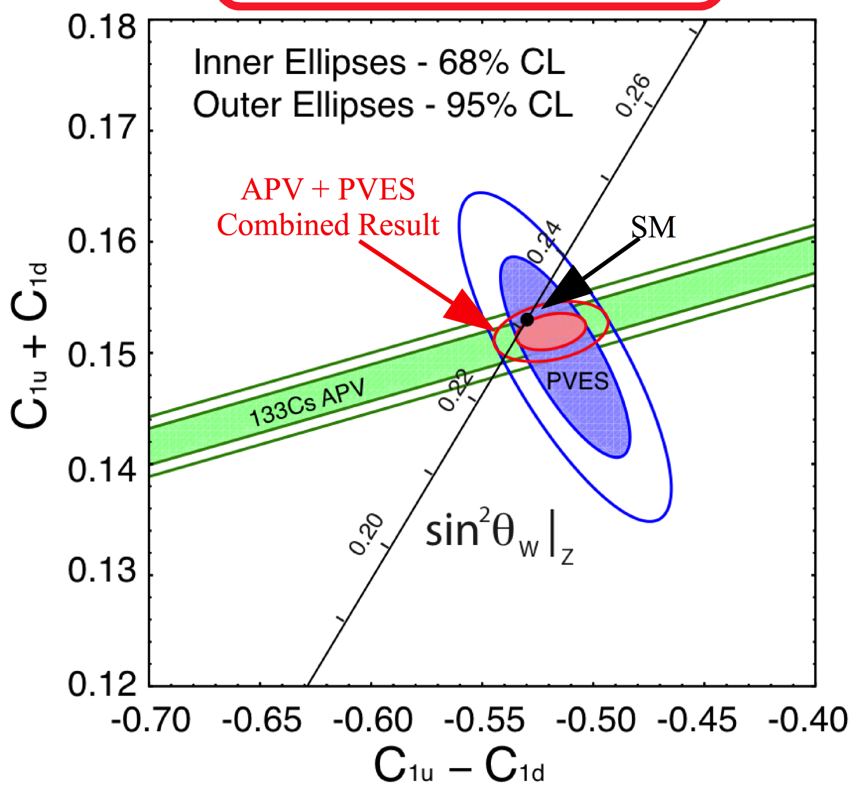
“Teaser” with Anticipated Final Errors



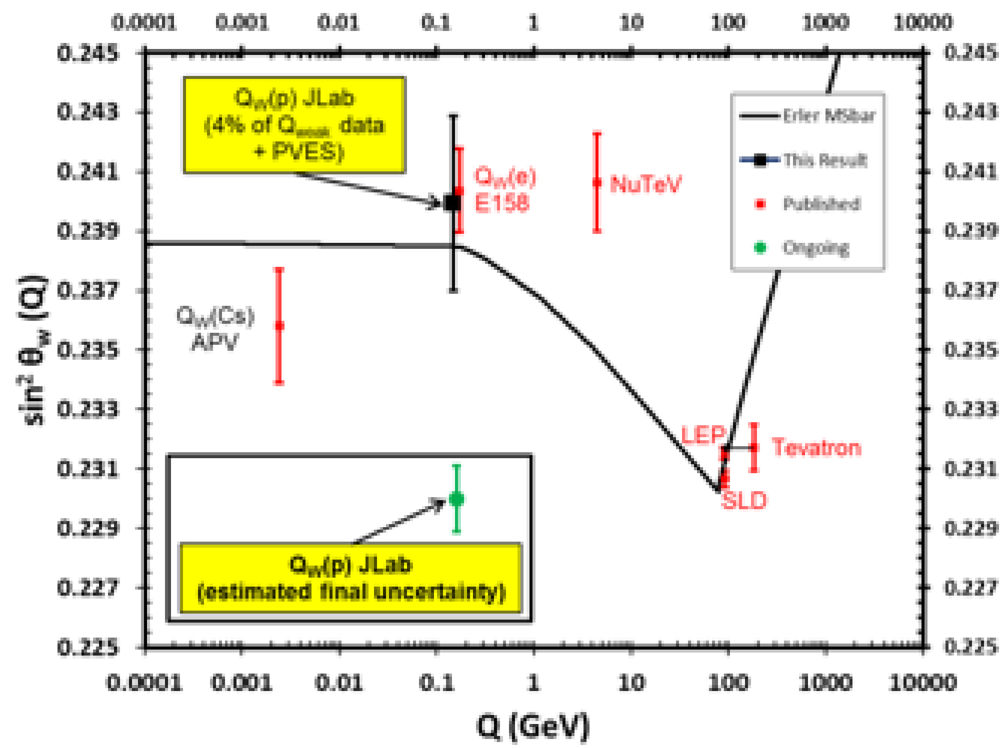
First Results

Improved precision on quark vector coupling

$$C_{1u} = -0.1835 \pm 0.0054$$
$$C_{1d} = 0.3355 \pm 0.0050$$



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



- First e-p elastic data point in the running plot
- The full result will be the most precise determination below Z pole

Corrections and Uncertainty from First Results

$$A_{PV} = R_{total}\left(\frac{\frac{A_{msr}}{P} - \sum_{i=1}^{4} A_i f_i}{1 - \sum_{i=1}^{4} f_i}\right)$$

Corrections and uncertainty table for Run 0 results

	Correction Value (ppb)	Contribution to ΔA_{ep} (ppb)	
Normalization Factors Applied to A_{Raw}			
Beam Polarization $1/P$	-21	5	
Kinematics R_{tot}	5	9	
Bckgrnd Dilution $1/(1-f_{tot})$	-7	-	
Asymmetry corrections			
Beam Asymmetries κA_{reg}	-40	13	
Transverse Polarization κA_T	0	5	
Detector Linearity κA_L	0	4	
Backgrounds	$\kappa P f_i A_i$	$\delta(f_i)$	$\delta(A_i)$
Target Windows (b_1)	-58	4	8
Beamline Scattering (b_2)	11	3	23
Other Neutral bkg (b_3)	0	1	< 1
Inelastics (b_4)	1	1	< 1

Largest uncertainty contributions:

- False asymmetries due to helicity-correlated differences in beam parameters

- Backgrounds from beamline scattering

- Target windows contribution to asymmetry

Beam Corrections

Helicity-correlated beam parameter variations can produce false asymmetry

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

(X, X',Y,Y',E)

Sensitivity

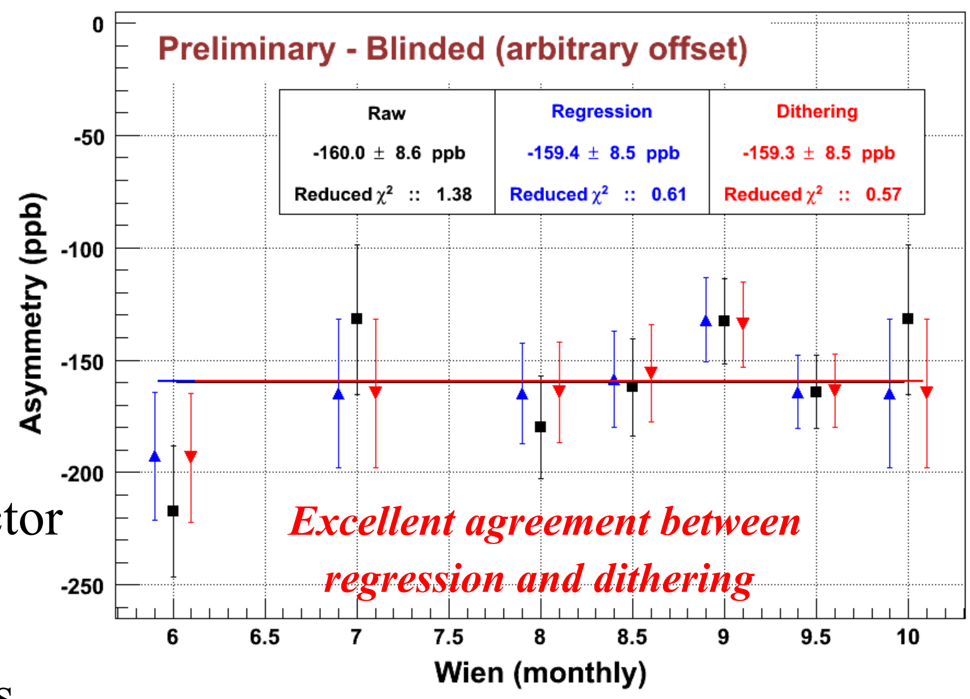
Beam variations

Two ways to determine the sensitivity of detector asymmetries to beam parameter variations:

- Regression: Natural jitter of beam parameters

- Dithering: Large driven variation of beam parameters

Run2 measured asymmetry



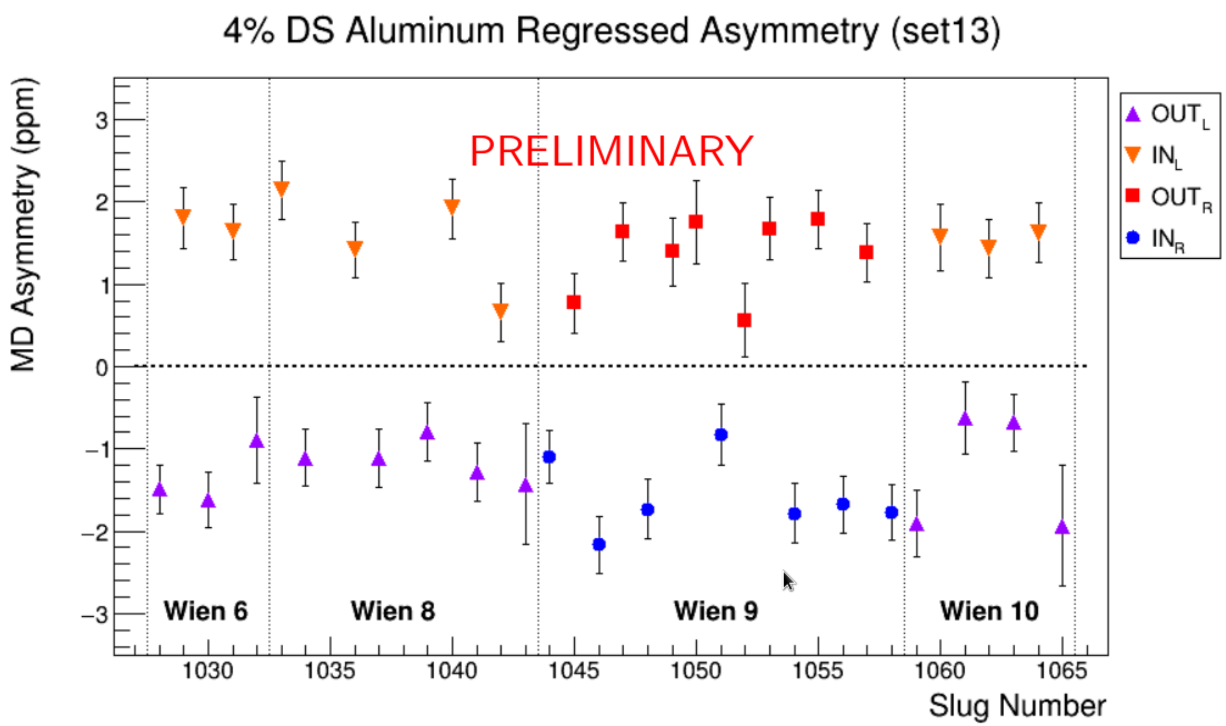
- ~ 77% of the run2 data-set
- No corrections other than beam parameter correction

Aluminum Target Window Backgrounds

Largest correction to Run 0 data (~ 60 ppb → ~21%)

Dilution (f_{Al})

- 5 mil window, expected signal fraction ~ 3%
- Measured with empty target, corrected for effect using simulation and data driven models of elastic and QE scattering
- Recently reduced δf_{Al} contribution to ~2 ppb (~5 ppb in first result)



Asymmetry (A_{Al})

- Measured from thick Al target
- Preliminary uncertainty for A_{Al}:

± 72 (stat) ± 34 (sys) ± 26model ppb → $\delta A_{ep}(A_{Al}) = f_{Al} A_{Al}$ ~ 2.5 ppb

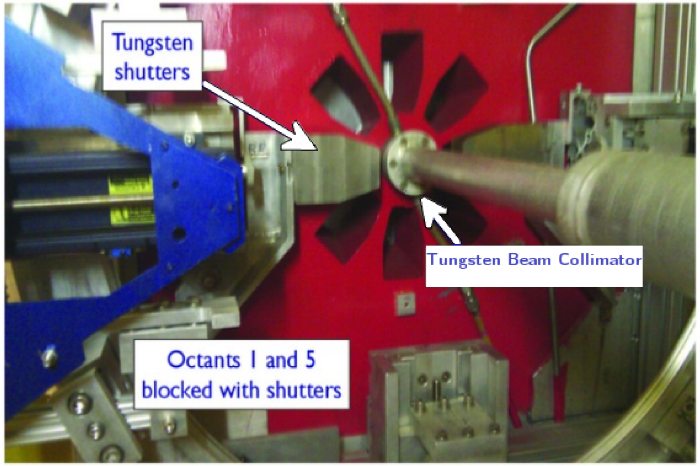
Beamline Backgrounds

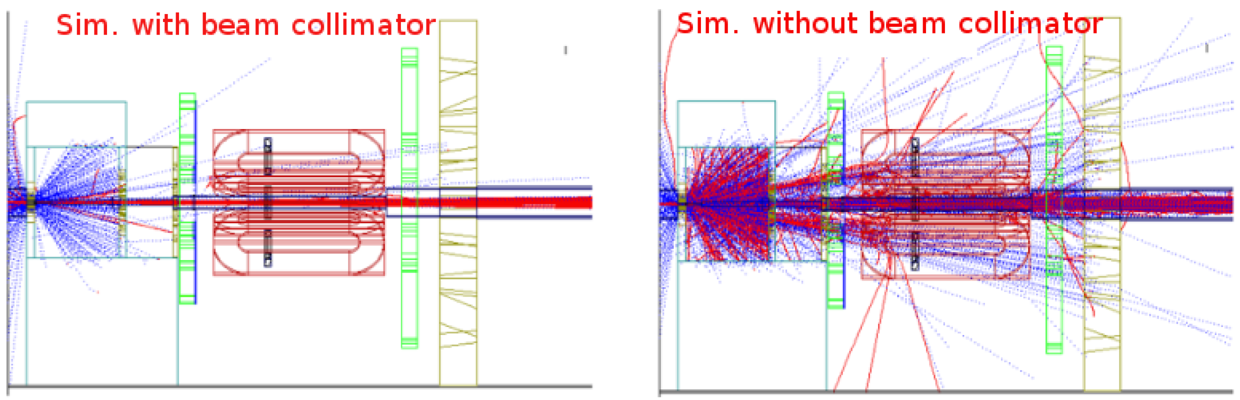
Highest contribution to systematic uncertainty in first result

- Background caused by electron scattering on beamline or small tungsten beam collimator after target

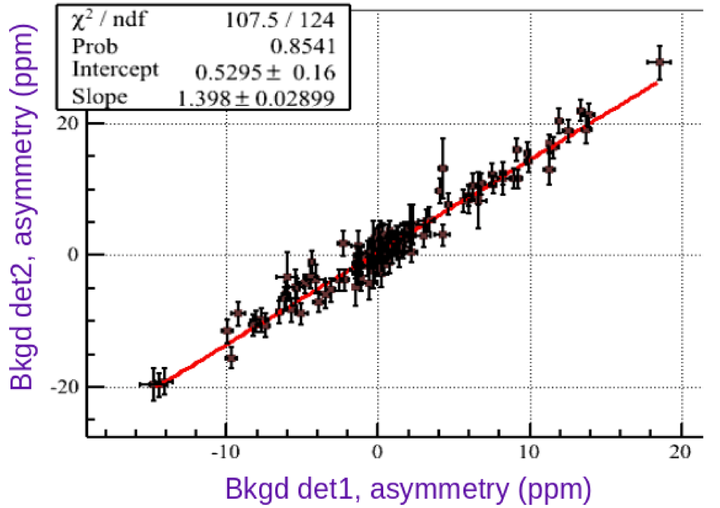
- Tungsten shutters allowed direct measurement of the yield fraction by blocking octant 1 & 5 ($f_{b2} \sim 0.19\%$)

- The asymmetry was measured using background detectors close to beamline



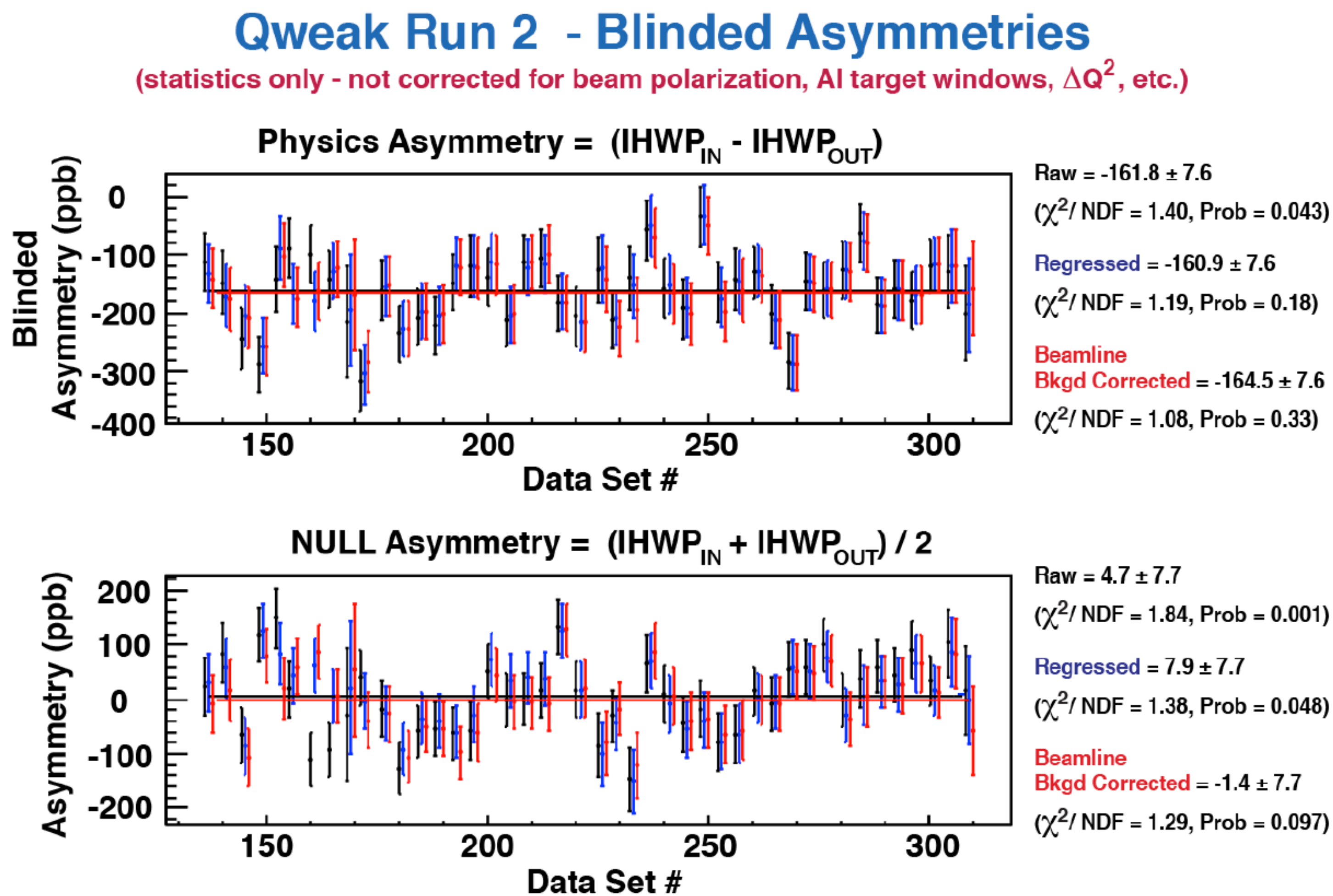


Correlation between bkgd asymmetries, Run2



Background detector asymmetries up to 20 ppm

Beamline Backgrounds



Inclusion of beamline background correction improves the statistical consistency of both the Physics and "NULL" asymmetry

Ancillary Measurements

Qweak additional measurements are under analysis, including:

Parity violating asymmetry:

- Elastic ^{27}Al
- N→Δ
  (E = 1.16 GeV, 0.877 GeV)
- Near W = 2.5 GeV
  (related to γZ box)
- Pion photoproduction
  (E = 3.3 GeV)

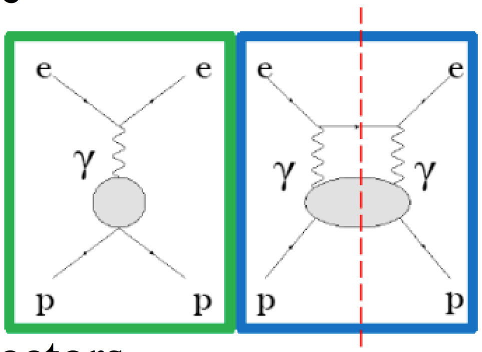
Parity conserving transverse asymmetry:

- Elastic e-p
- Elastic ^{27}Al, Carbon
- N→Δ
- Moller
- Near W = 2.5 GeV
- Pion photoproduction
  (E = 3.3 GeV)

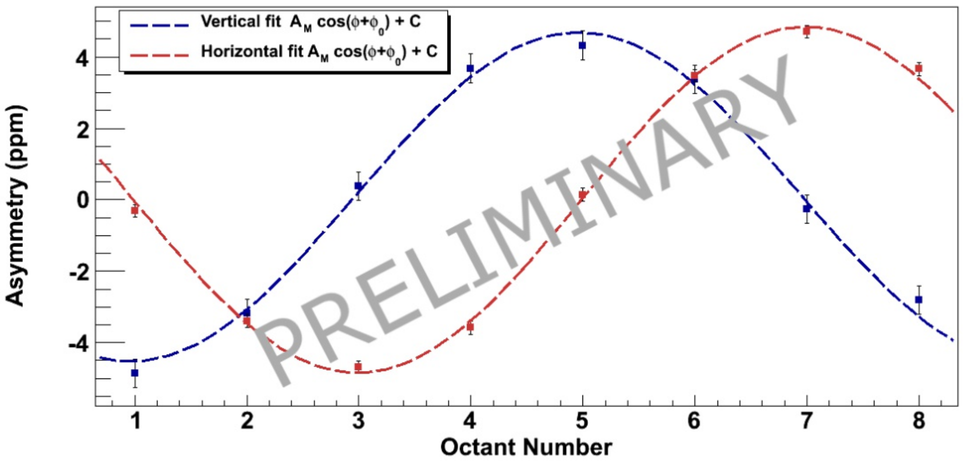
Transverse Asymmetry in e-p Elastic Scattering

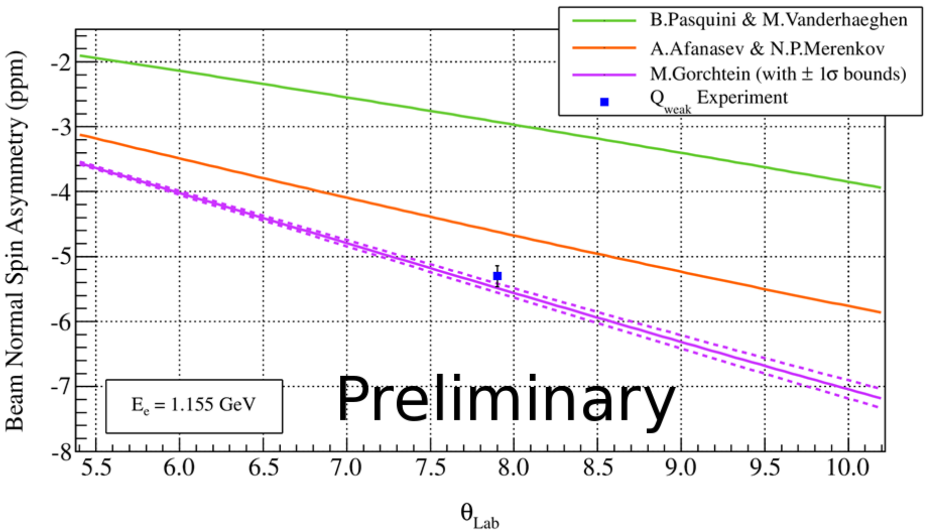
- B_n is a parity conserving transverse asymmetry due to 2γ exchange

$$B_n = \frac{2 T_{1\gamma} \times \Im T_{2\gamma}}{|T_{1\gamma}|}$$



- It can lead to a ppb-level correction in PV data due to not fully longitudinally polarized beam and small broken asymmetry in detectors
- Measured with fully transverse beam to make the correction





B Waidyawansa talk at PAVI14, http://pavi14.syr.edu/Slides.html

Transverse Asymmetry in Δ Resonance

Q-weak has measured Beam Normal Single Spin Asymmetry (B_n) in the N-to-Δ transition on H_2

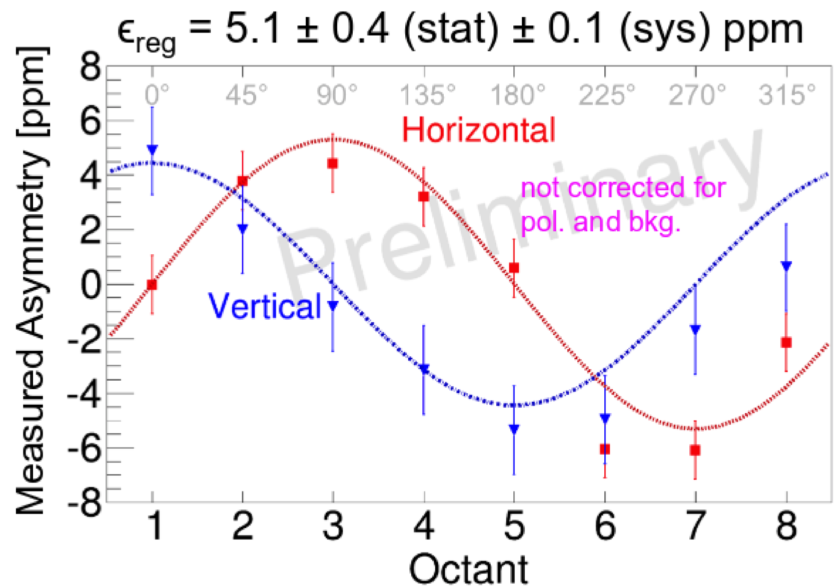
$$B_n = \frac{\sigma\uparrow - \sigma\downarrow}{\sigma\uparrow + \sigma\downarrow} = \frac{2T_{1\gamma} \times \mathrm{Im}\, T_{2\gamma}}{|T_{1\gamma}|}$$

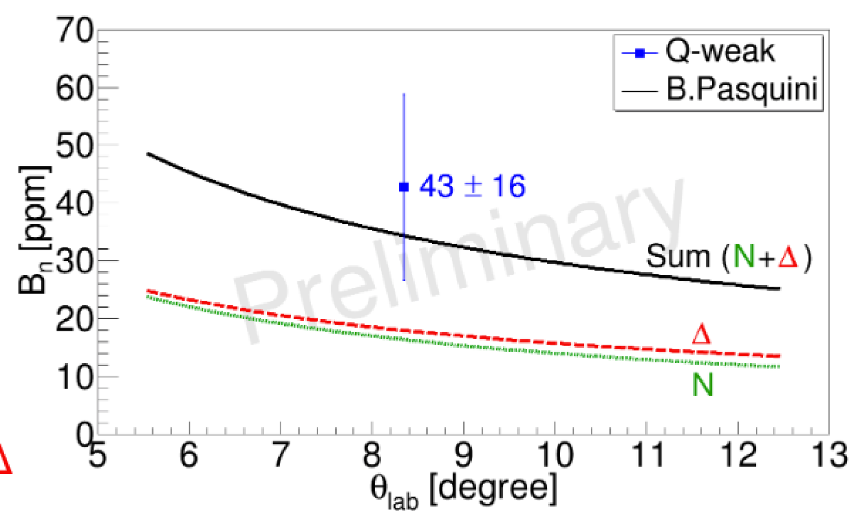
After correcting for polarization and backgrounds

B_n = 43 ± 16 ppm

at kinematics

- $\langle E \rangle$ = 1.16 GeV
- $\langle W \rangle$ = 1.2 GeV
- $\langle \theta \rangle$ = 8.3°
- $\langle Q^2 \rangle$ = 0.021 GeV^2





- Unique tool to study $\gamma^*\Delta\Delta$ form factors
- Q-weak along with world data has potential to constrain models and study charge radius and magnetic moment of Δ

http://arxiv.org/abs/1510.00449

Summary

- Qweak is a precision measurement of the proton's weak charge with the aim of searching for new PV physics at the TeV scale

- First published results (4% of Qweak data):
  - Measured the smallest and most precise e-p PV asymmetry

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

  - First determination of the proton's weak charge

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

  - Extracted the quark couplings (C_{1u}, C_{1d}) and determined the neutron's weak charge

$$C_{1u} = -0.1835 \pm 0.0054$$
$$C_{1d} = 0.3355 \pm 0.0050$$

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

- Final results expected this fall
  - Statistical error ~5 times smaller, with reduced systematics
  - Many ancillary results under analysis

The Qweak Collaboration

Thank you!