First Results from Qweak

P.M. King
Ohio University

for the Qweak Collaboration

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Thomas Jefferson National Accelerator Facility

Office of Nuclear Physics
Department of Energy

National Science Foundation
NSF
Dr. Rita Colwell
Director, National Science Foundation

NSERC
CRSNG

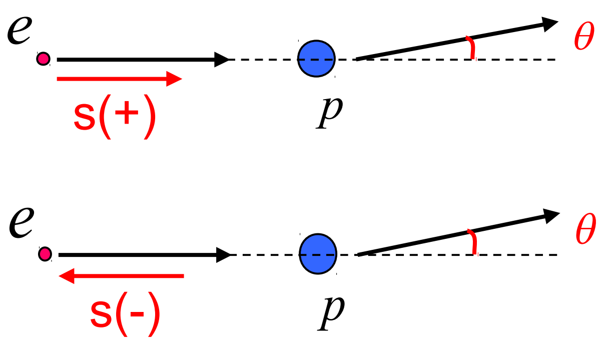
Overview

- Qweak measures the parity violating elastic asymmetry in e-p scattering at $Q^2 = 0.025$ GeV^2 in order to extract $Q_W(p)$ and $sin^2\theta_W$
  - Deviation from SM expectations would be a sign of new physics with a TeV mass-scale
- Qweak had three running periods in Hall C at Jefferson Lab
  - Run 0: (Jan-Feb 2011); about 1/25 of the total data set.

    Published Oct 2013; Phys.Rev.Lett. 111, 141803.
  - Run 1 (Feb-May 2011)
  - Run 2 (Nov 2011-May 2012)

  Ongoing analysis; results likely within a year or so
- Several ancillary measurements were taken to determine or constrain background processes or corrections

Parity-Violating Electron Scattering



Electromagnetic (PC) + Neutral-weak (PV)

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

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

Parity violated in the weak interaction: form a parity-violating asymmetry

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

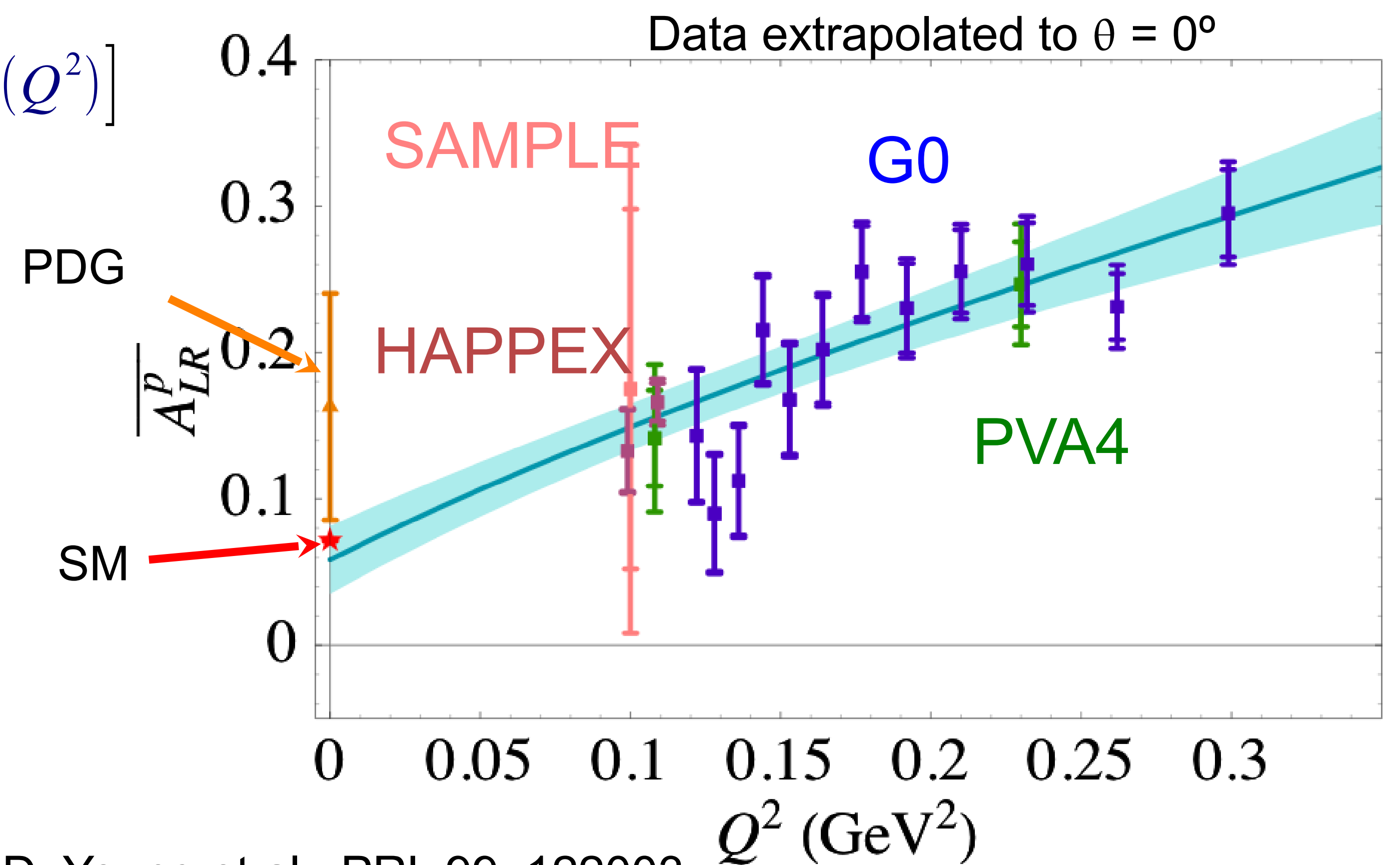
Parity violating electron scattering

$$A_{LR} = \frac{-G_\mu Q^2}{4\pi\alpha\sqrt{2}}\left[\frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1-4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^e}{\varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}\right]$$

$$A_{LR} = \frac{-G_\mu Q^2}{4\pi\alpha\sqrt{2}}\left[Q_{weak}^p + Q^2 B(Q^2)\right]$$

$$\overline{A_{LR}^p} \equiv \frac{A_{LR}^p}{-(G_\mu/4\pi\alpha\sqrt{2})Q^2}$$

$$\overline{A_{LR}^p} = Q_{weak}^p + Q^2 B(Q^2)$$

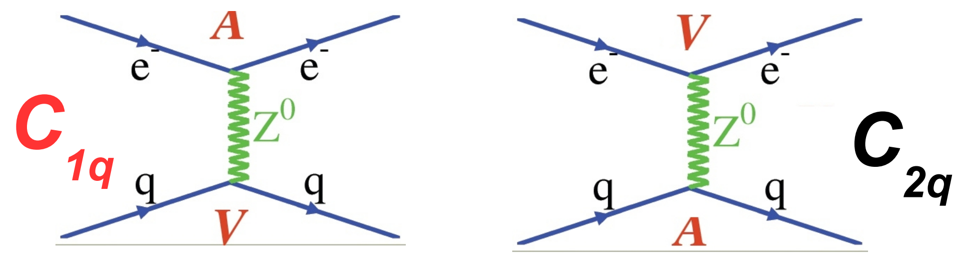


R.D. Young et al. PRL 99, 122003

Weak Charges

Electron-quark scattering, four-fermion contact interaction

$$\mathcal{L}^{PV}_{eq} = -\frac{G_F}{\sqrt{2}} \sum_i \left[C_{1i} \bar{e}\gamma_\mu\gamma_5 e \bar{q}\gamma^\mu q + C_{2q} \bar{e}\gamma_\mu e \bar{q}\gamma^\mu\gamma^5 q \right] + \mathcal{L}^{PV}_{new}$$



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	$Q^n_W = -1$

Note "accidental" suppression of $Q^p{}_{weak}$;
this leads to sensitivity to New Physics

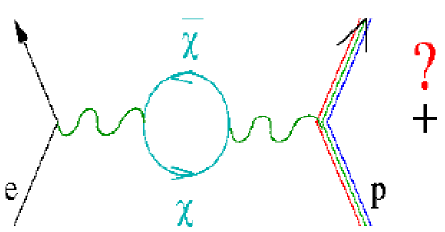
Sensitivity to new physics

- Suppose some new physics adds a contact term to the PV electron-quark Lagrangian, with coupling constant, *g*, and mass, Λ:

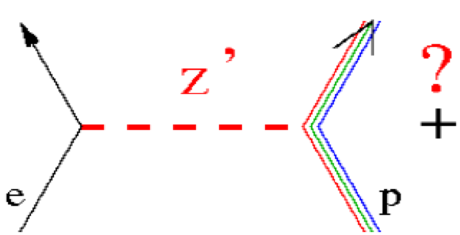
Erler et al. PRD 68, 016006 (2003)

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

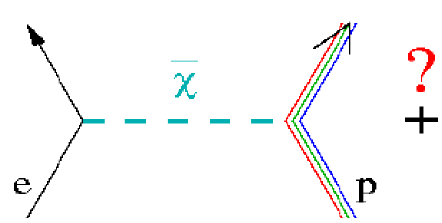
$$\frac{\Lambda}{g} \sim \left(\sqrt{2}\, G_F\, \Delta Q_W^p\right)^{-\frac{1}{2}} \sim O(TeV)$$



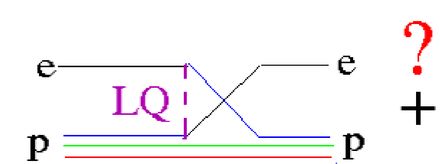
RPC SUSY



Generic Z'



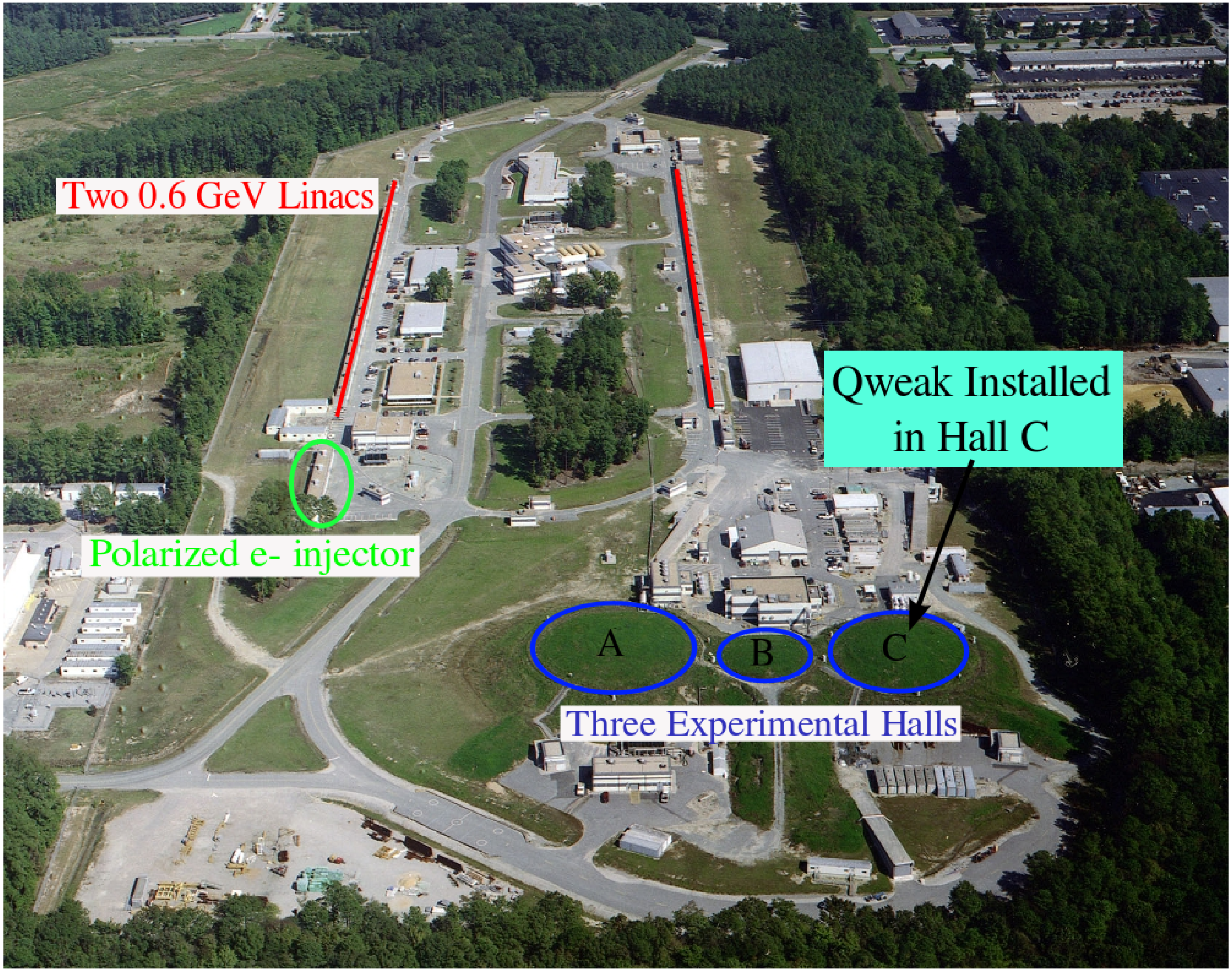
RPV SUSY



Leptoquarks

Qweak Overview

Jefferson Lab (6 GeV Era)



Qweak Installation:
May 2010-May 2012

~1 year of beam in 3 running periods:

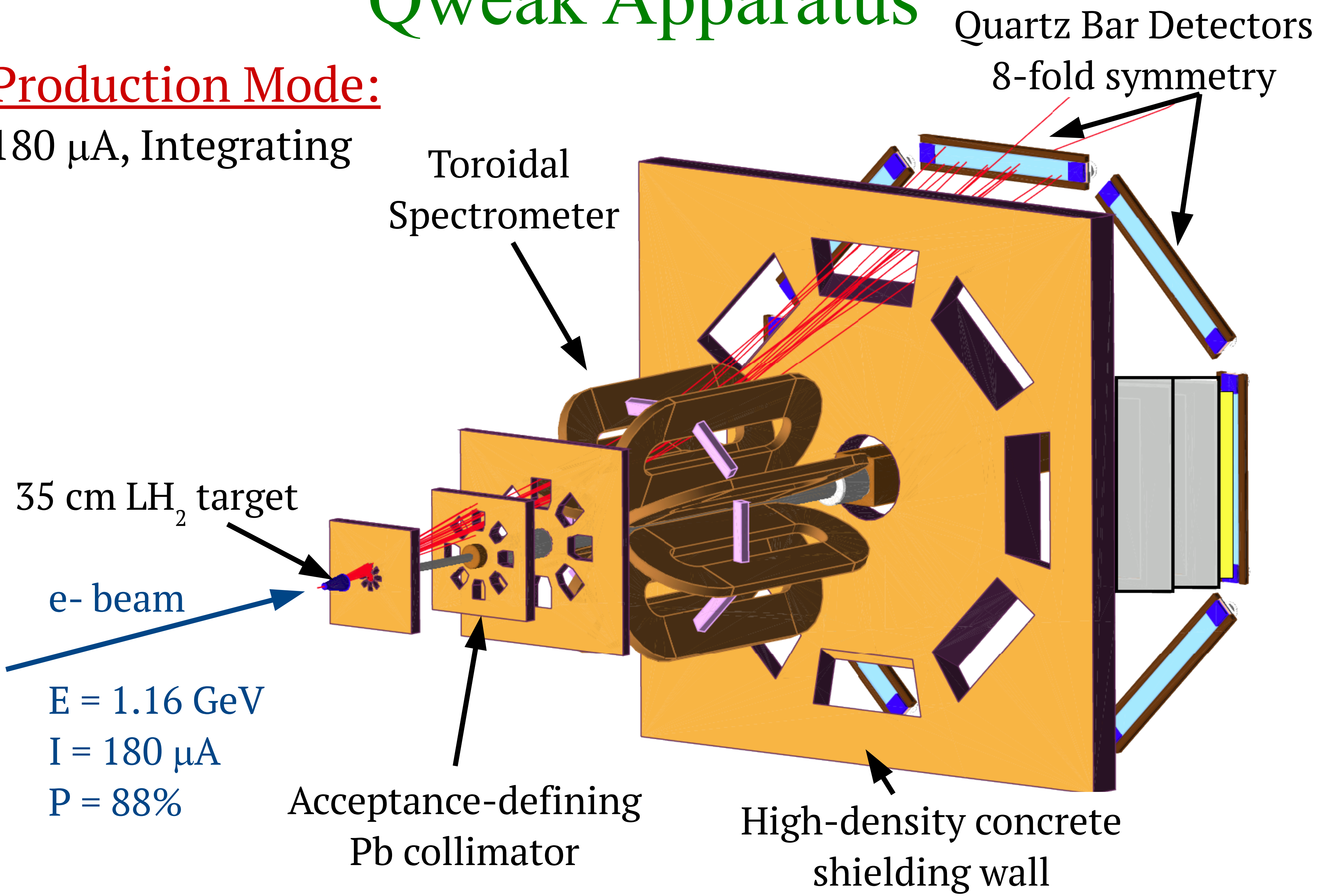
- Run 0
  Jan – Feb 2011
- Run 1
  Feb – May 2011
- Run 2
  Nov 2011 – May 2012

Asymmetry ~250 ppb
Error goal ~5 ppb

Qweak Apparatus

Production Mode:

180 μA, Integrating



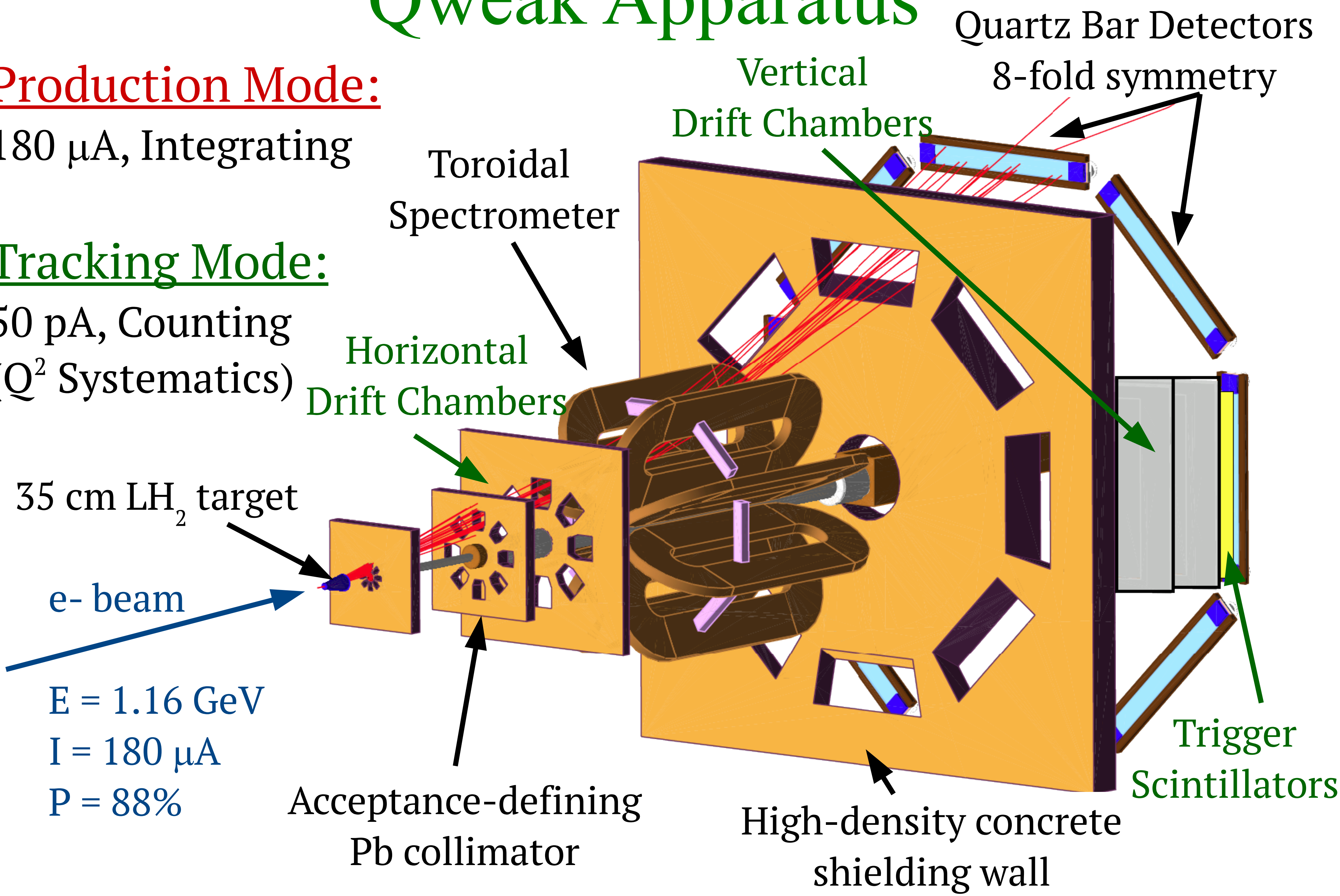
Qweak Apparatus

Production Mode:

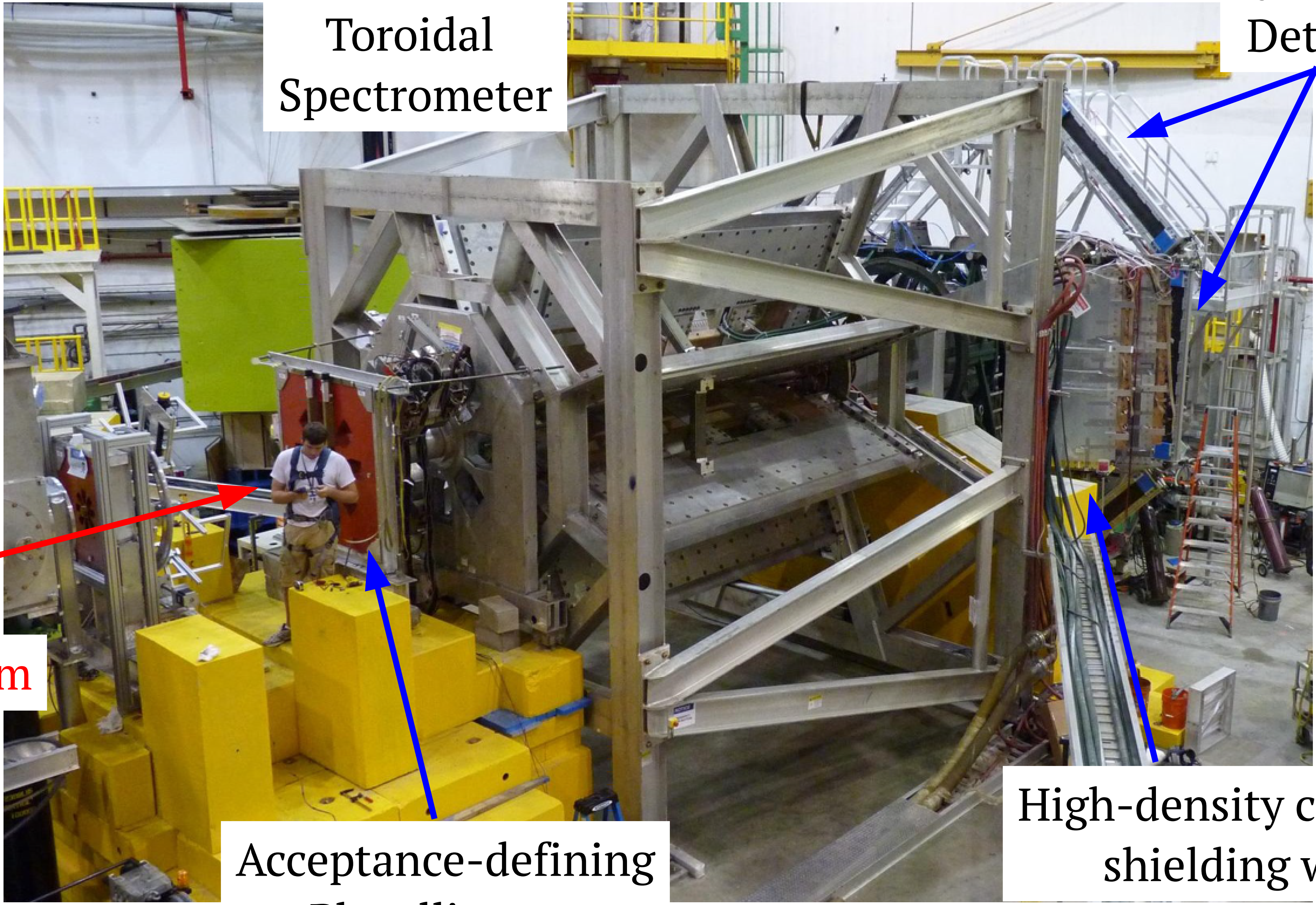
180 μA, Integrating

Tracking Mode:

50 pA, Counting
(Q^2 Systematics)

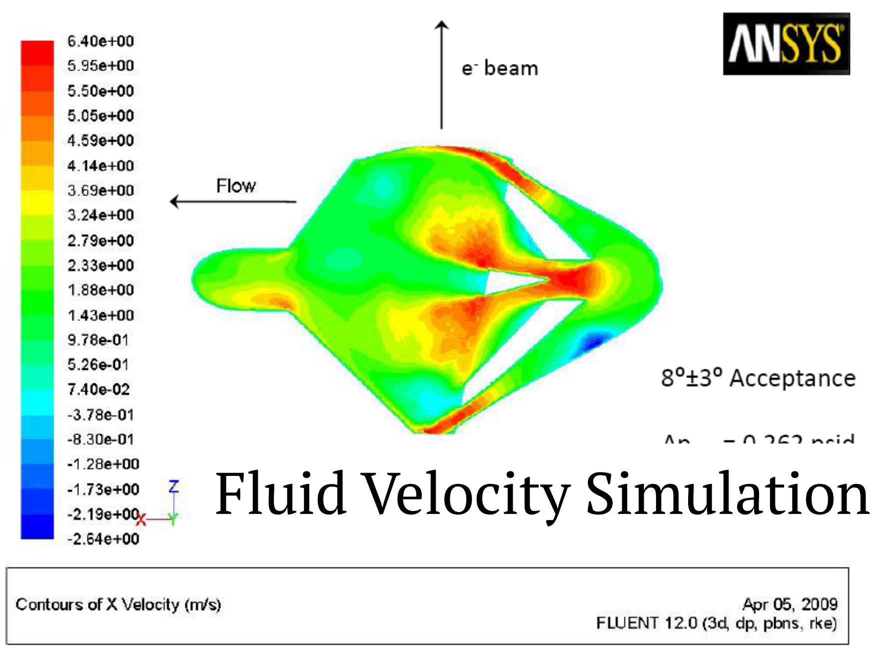


Qweak During Installation



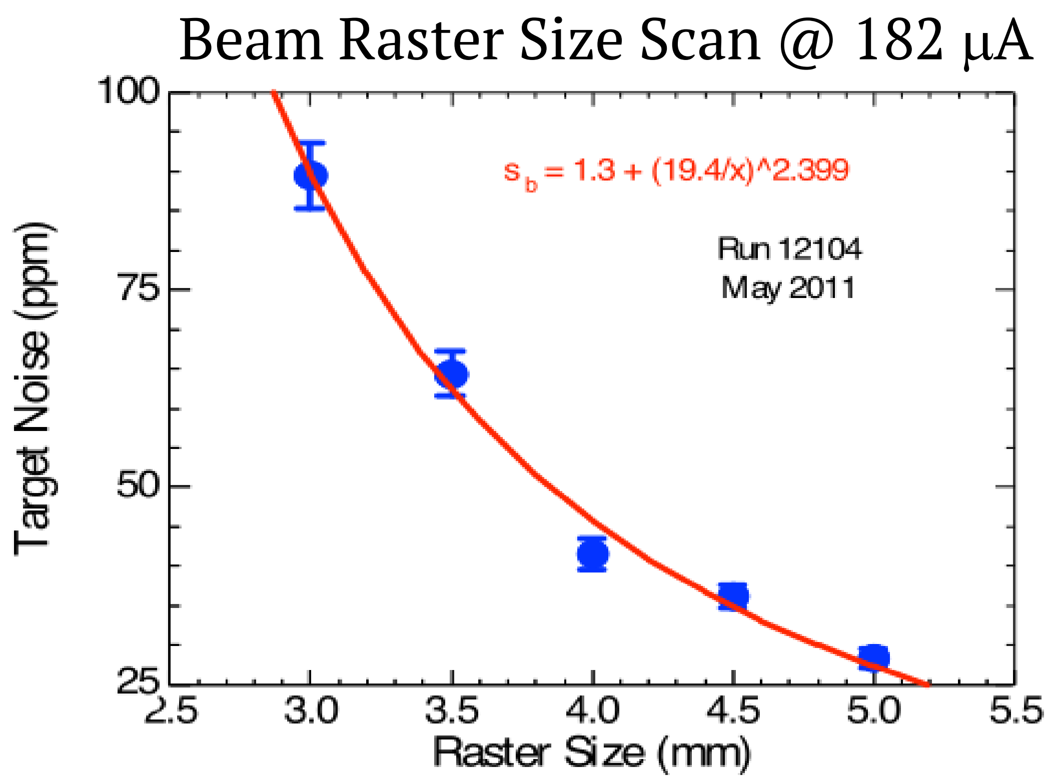
Target Design and Performance

- 35 cm LH_2 (4% X_0)
  - 20K, 30-35 psia
  - ~3 kW power
- Designed using CFD



Fluid Velocity Simulation

Target "Boiling" Noise:
target density fluctuations

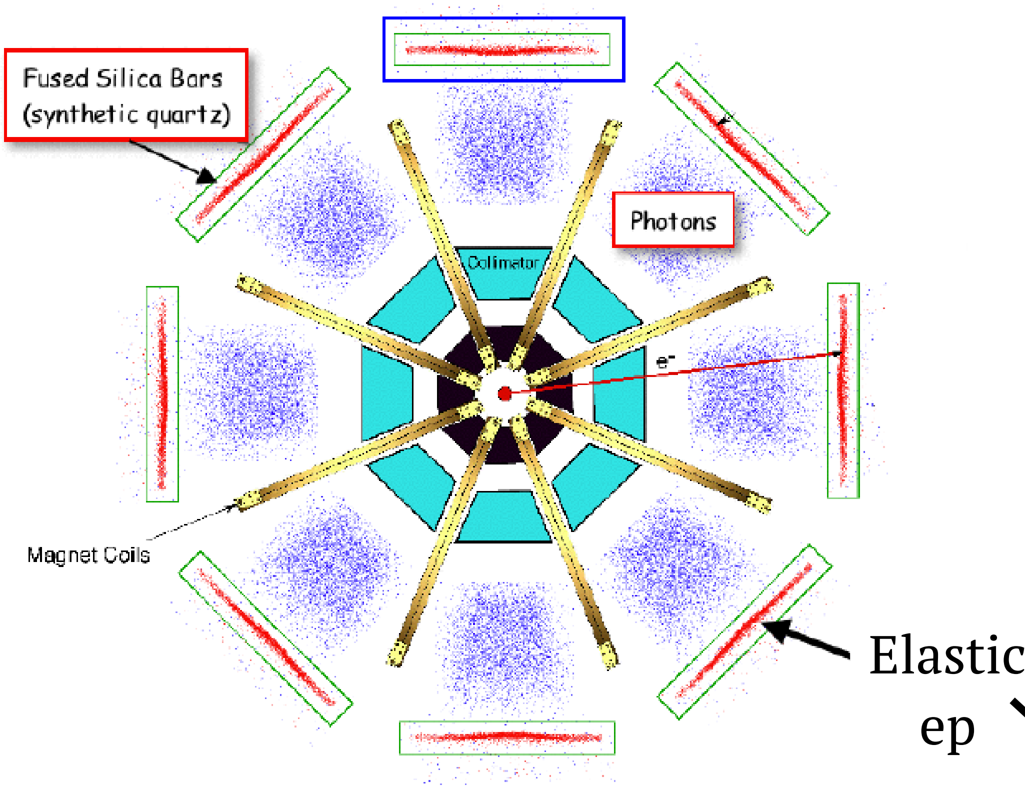


47 ppm/quartet; small contribution to ~230 ppm width from statistics

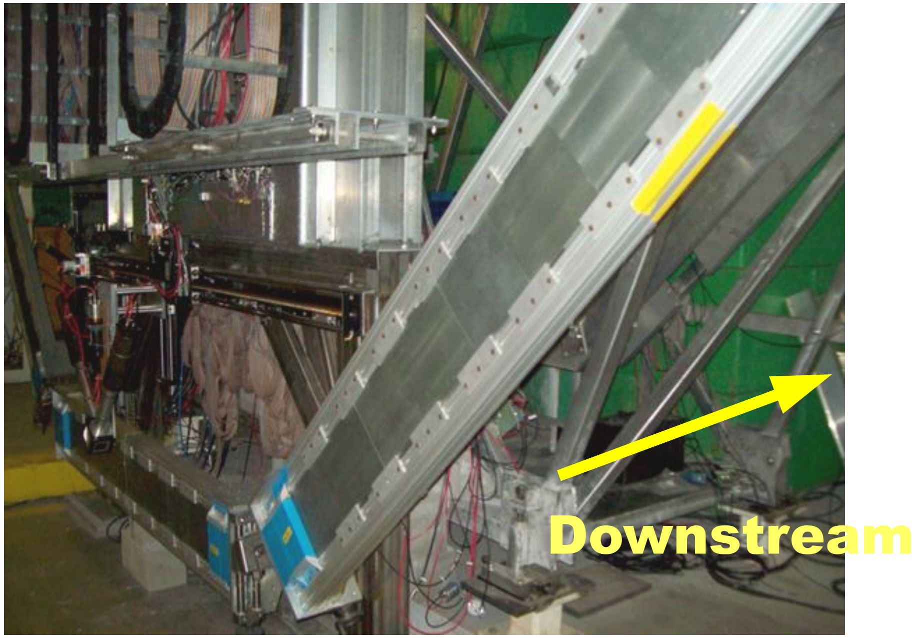
Main Detectors

- Eight 2m long radiation-hard fused silica Čerenkov detectors

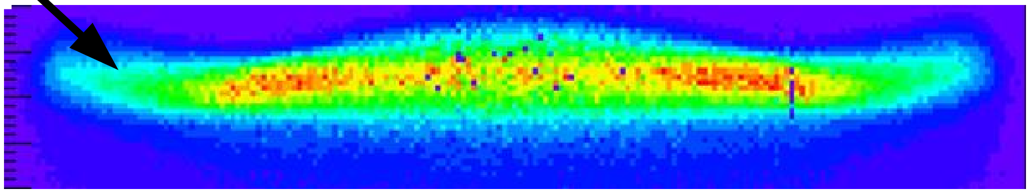
Azimuthal Symmetry



Installed 2cm lead pre-radiators



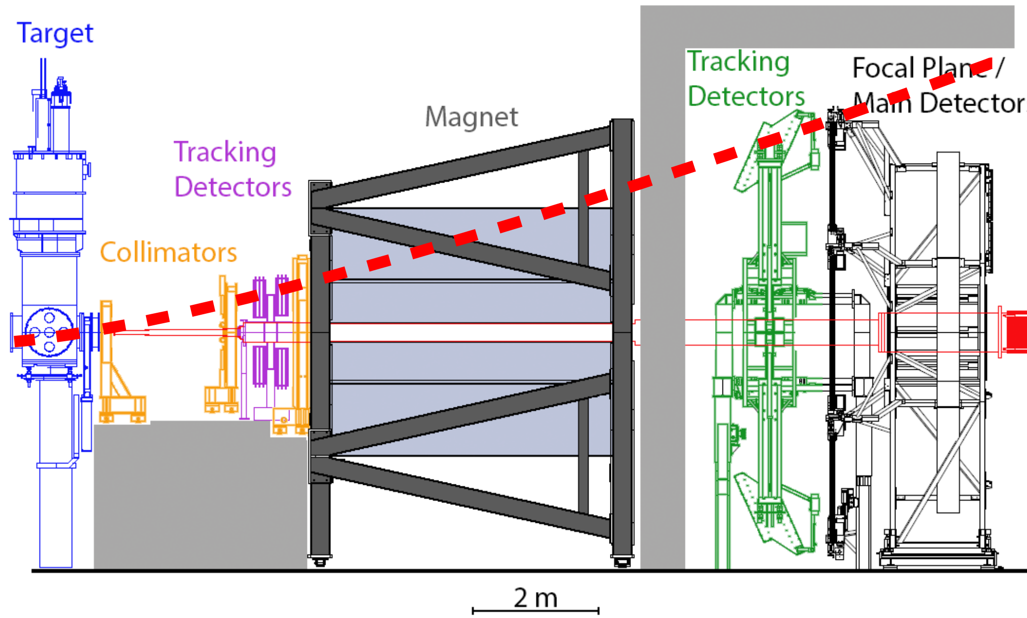
Measured profile in 6 o'clock octant

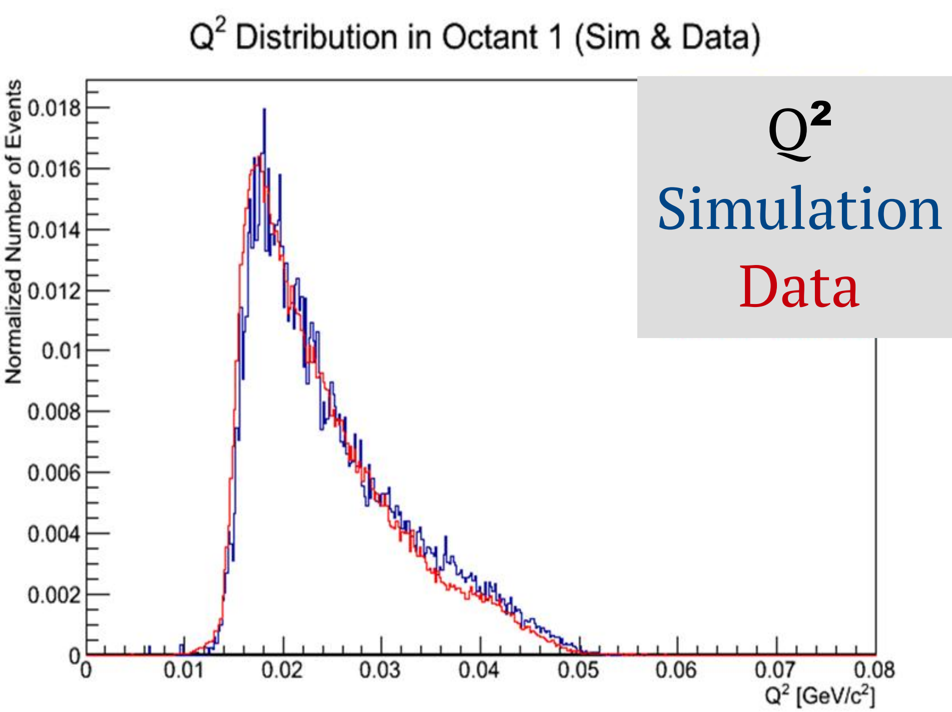


Electrons focused on detectors by QTOR
Photons show collimator aperture shape

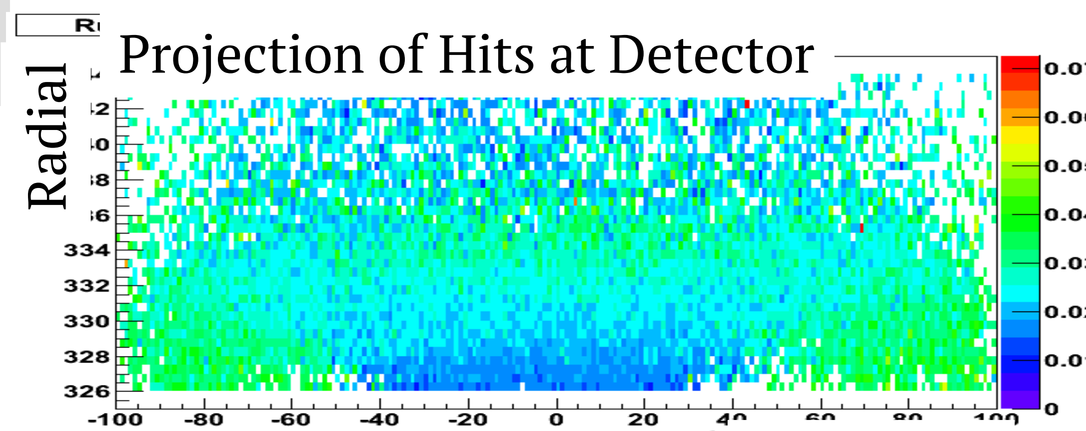
Kinematics Determination

- Drift chambers before and after magnetic field
- Low current, reconstruct individual events
- Systematic studies





Measure light-weighted acceptance
(Q^2 varies by factor of 2 over acceptance)

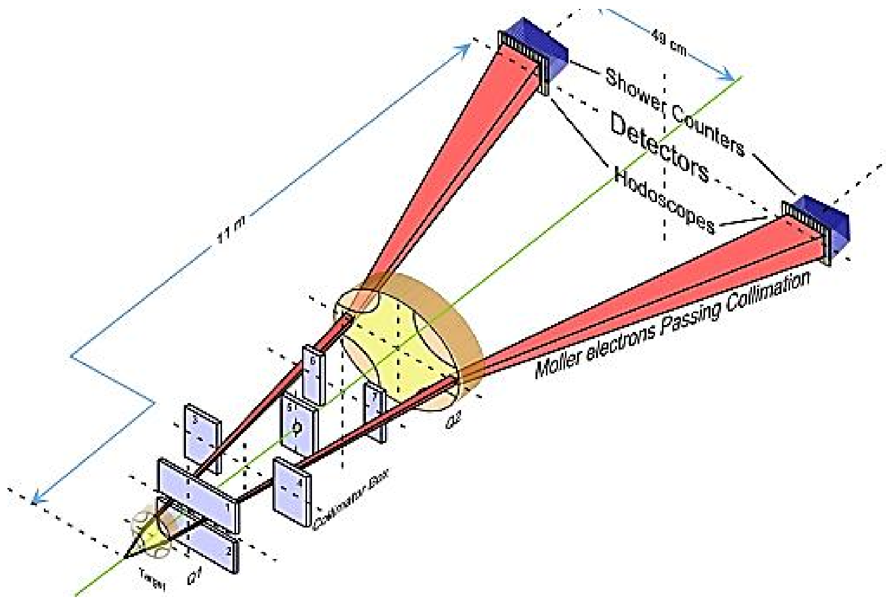


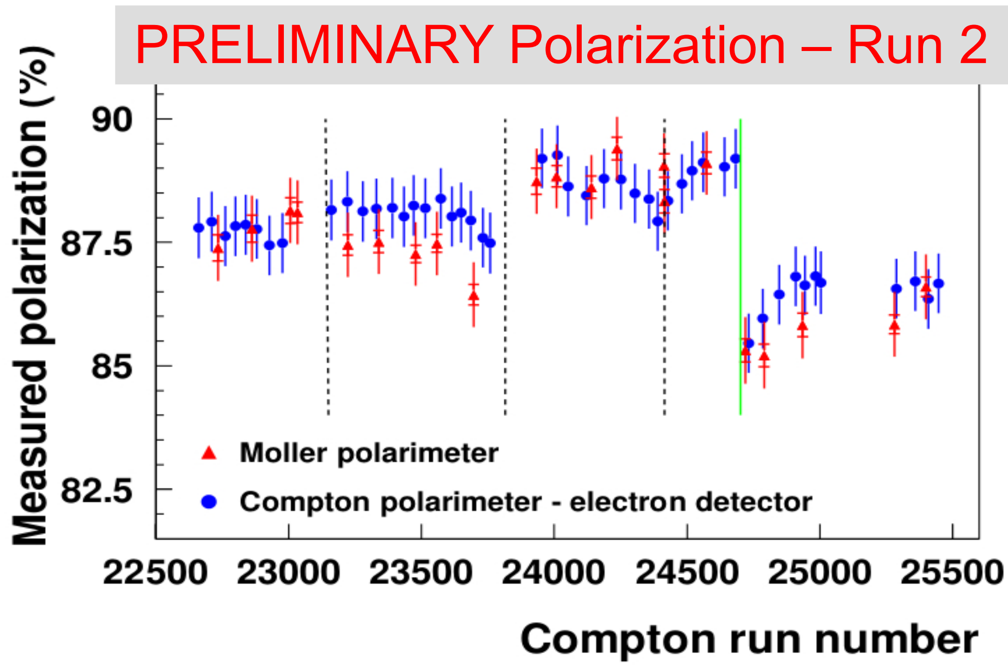
Precision Polarimetry

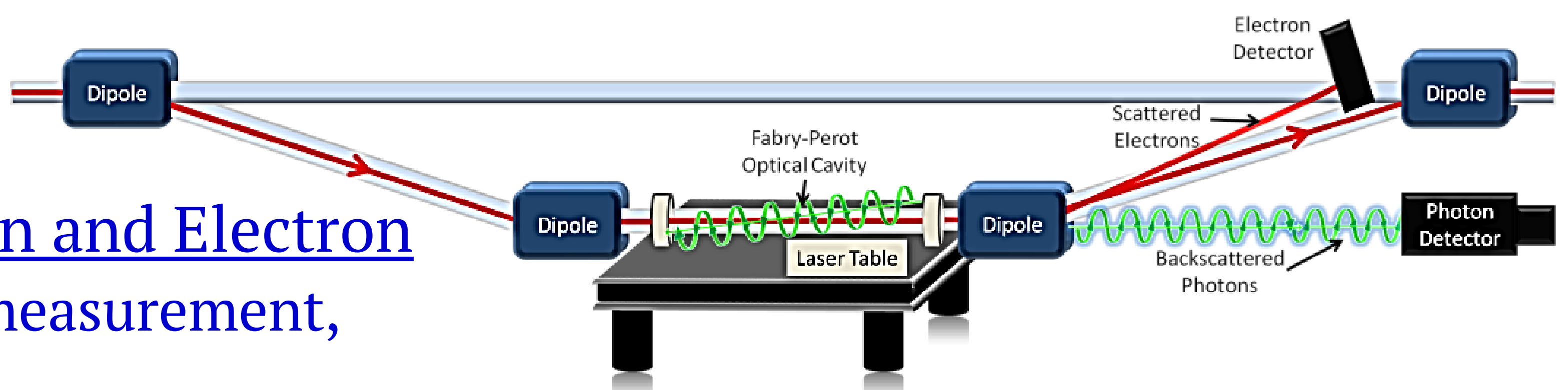
- Two independent devices for <1% polarization

Møller

- low current only, invasive







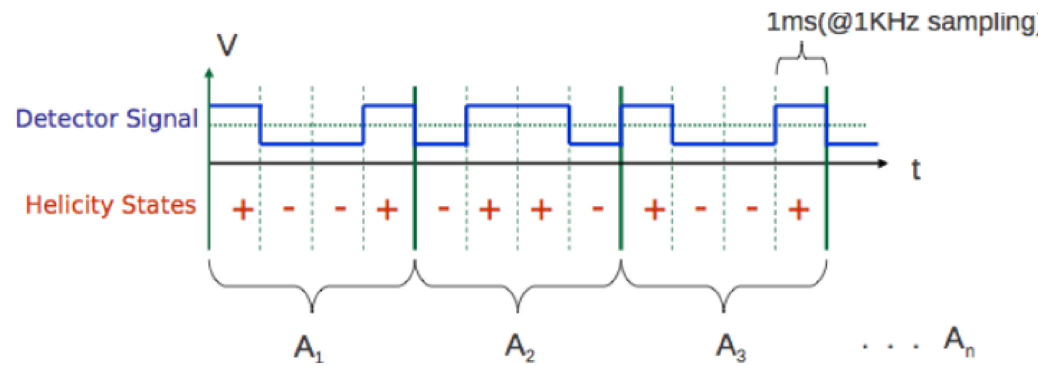
Compton: Photon and Electron

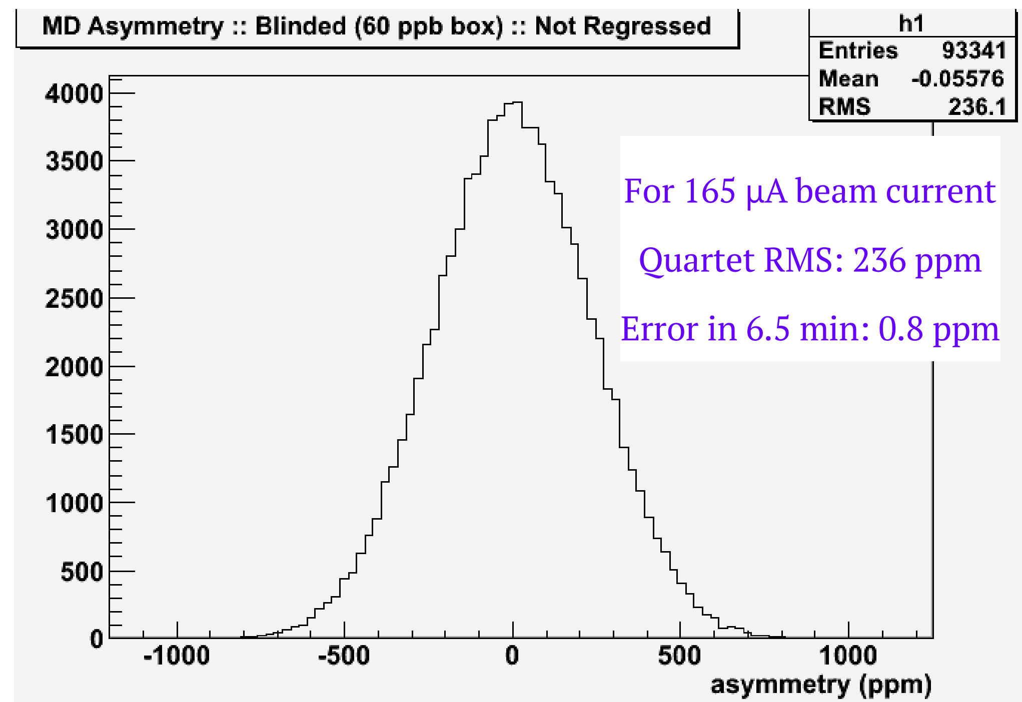
- continuous measurement, high current

Measurement process

- "Helicity windows" occur at about 960 Hz
  - Groups of four windows have helicity pattern +--+ or -++- chosen pseudorandomly
  - Helicity reporting is delayed
- Detector and beam monitor signals are integrated over the window
- Asymmetries are constructed for each pattern

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





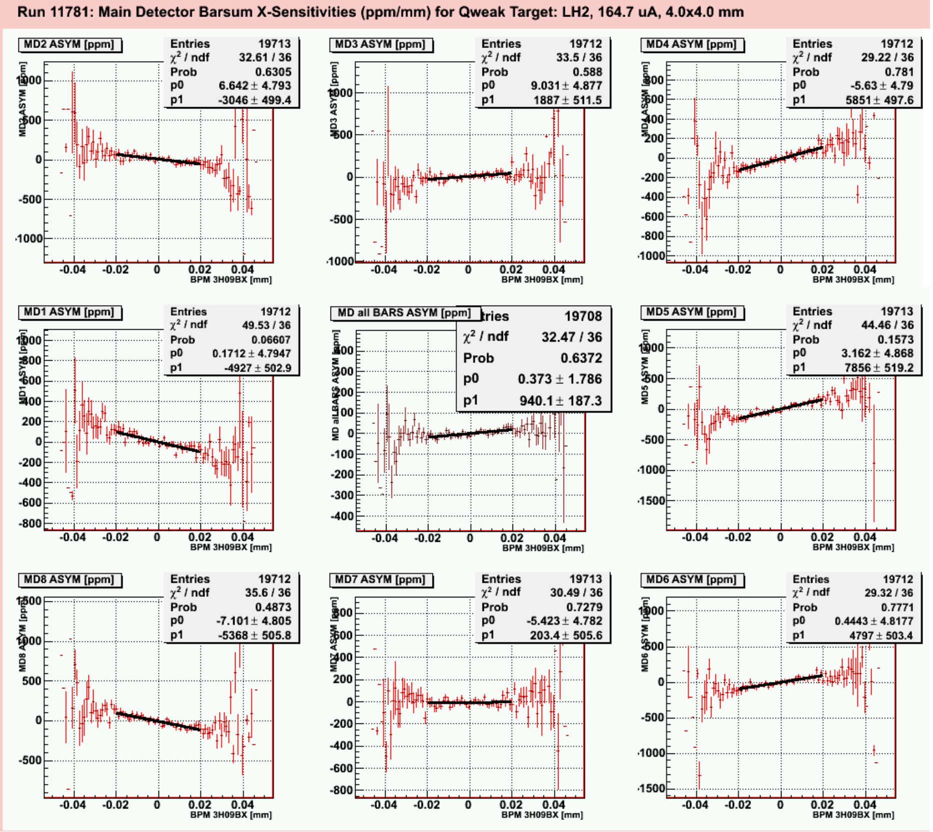
Beam Parameter Corrections

- Helicity correlated beam parameter variations can produce an asymmetry in the detectors
  - Symmetric detectors give partial cancellation
  - Large HC beam variations can be reduced by retuning
  - Measured detector-beam correlations can provide a correction

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

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

Example: Detector Sensitivity to X position variation

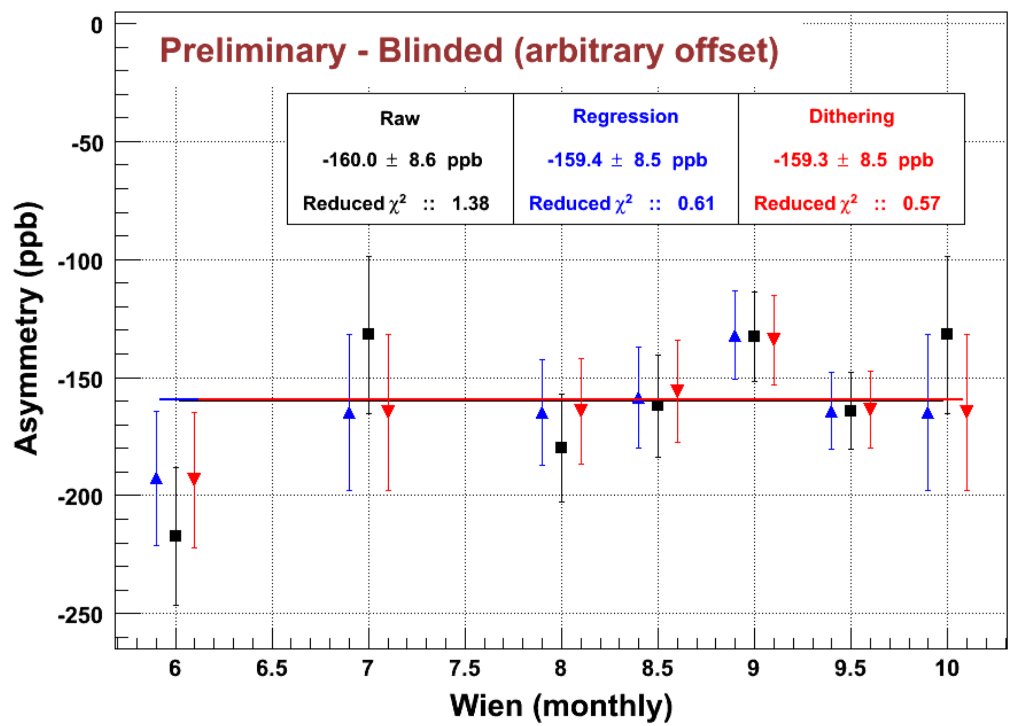


Regression Correction from Qweak "Wien0" (PRL 111, 141803): A_{corr} = -35 ± 11 ppb

Beam Parameter Corrections

- Two ways to determine sensitivity of the detector asymmetries to beam parameter variations
  - 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 where both are available

Run2 measured asymmetry



- About 77% of the run2 data-set
- Asymmetries have no corrections other than beam parameter correction

Some Backgrounds

- Target cell backgrounds
  - Recall that $Q^n_{weak} \sim 1$
    Scattering from the aluminum cell walls will contribute a large asymmetry
  - Need dilution and Al asymmetry
- Inelastic scattering from LH2
  - Measure the asymmetry with reduced magnetic field

- Two-boson exchange

  Longitudinal e- spin

  γ-Z box contributions lead to ~6% shift in Q^p_{weak} with error estimates of about 1%

  Transverse e- spin

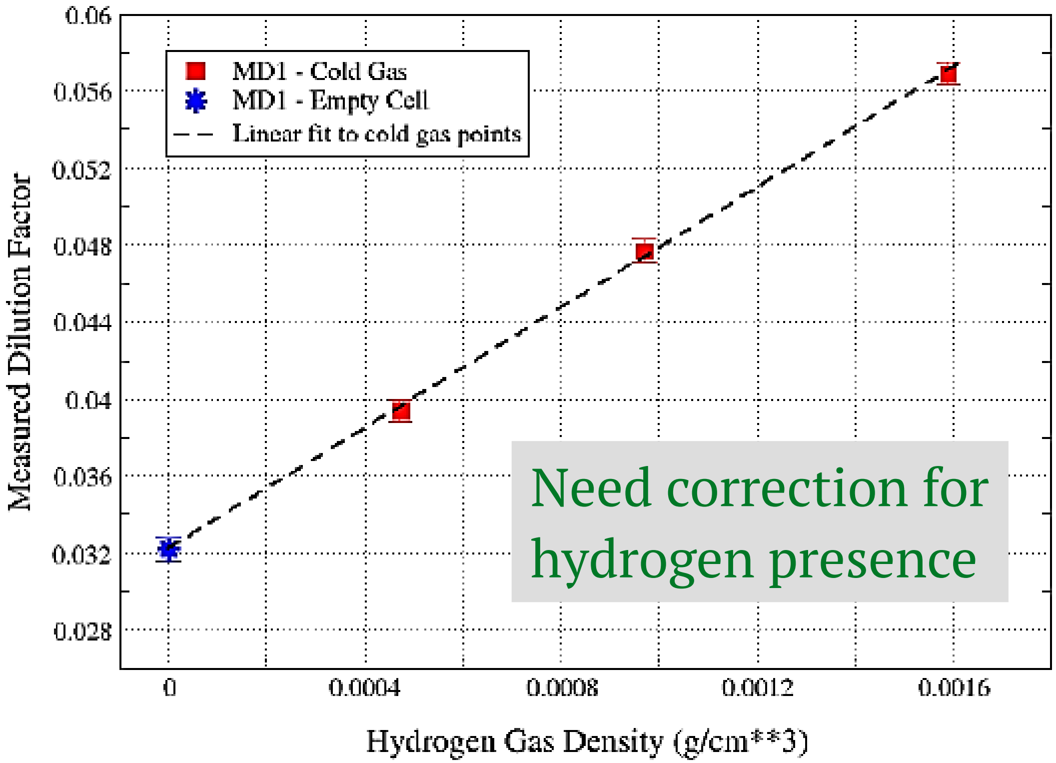
  2-γ exchange with transverse electron spin leads to a azimuthal asymmetry variation

Backgrounds: Aluminum

- Largest background correction from aluminum alloy target windows (0.25% X_0): -64 ± 10 ppb

Dilution measured with empty target and cold gas tracking runs

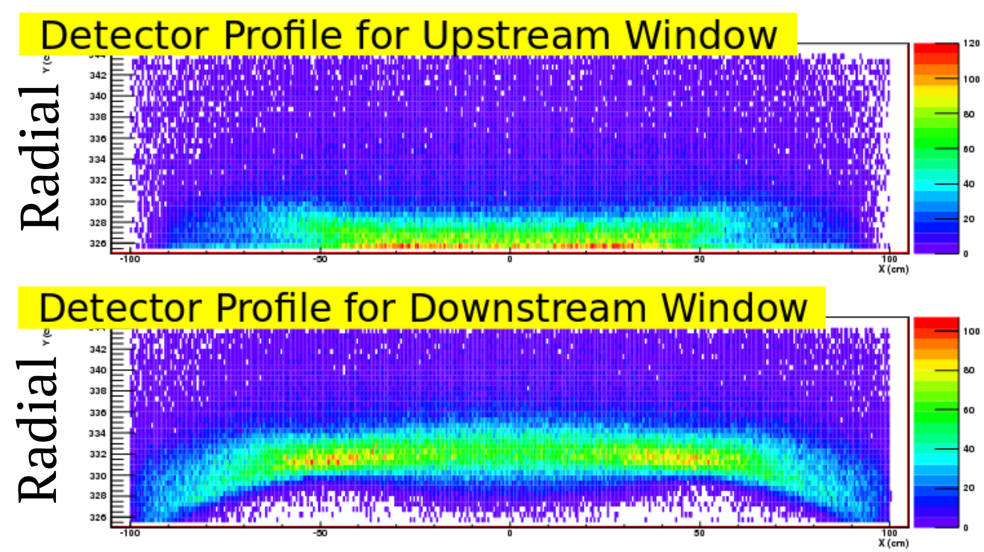
$$f_{\rm Al} = 3.23 \pm 0.24~\%$$



Asymmetry measured with thick dummy target (4%)

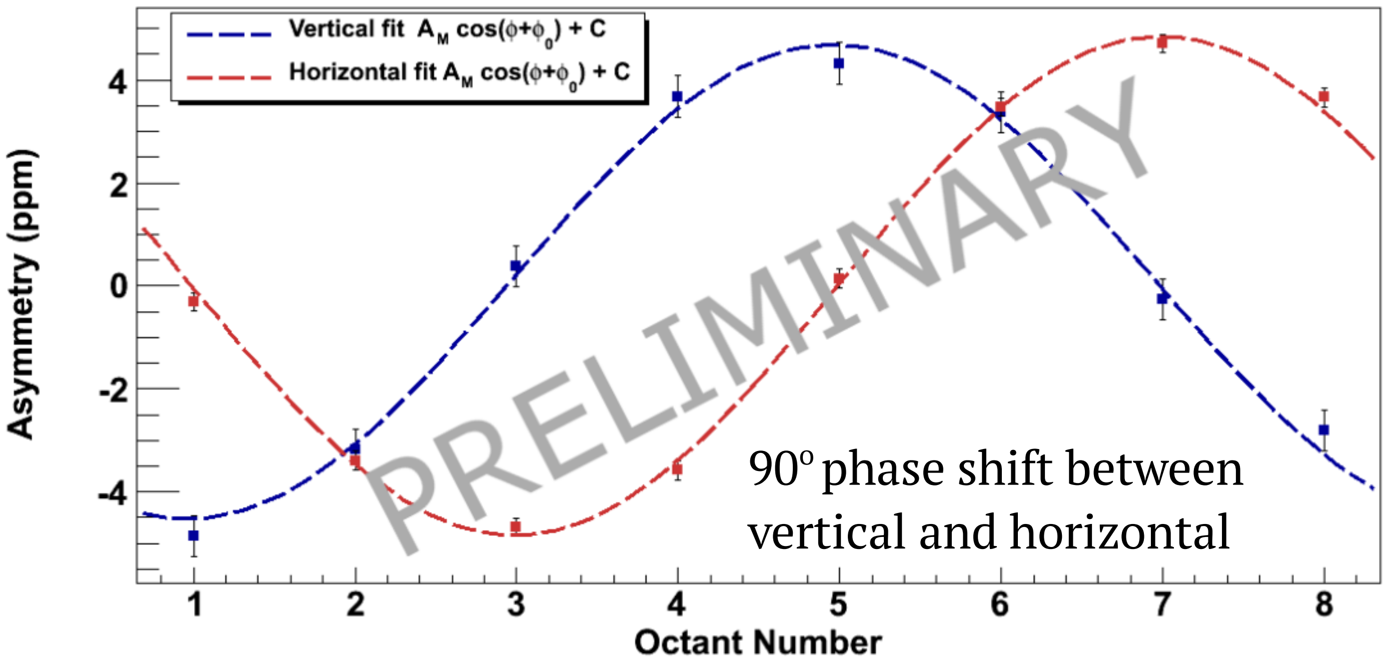
$$A_{PV} = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[Q_W^p + \left(\frac{N}{Z}\right) Q_W^n \right]$$

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



Transverse Asymmetry

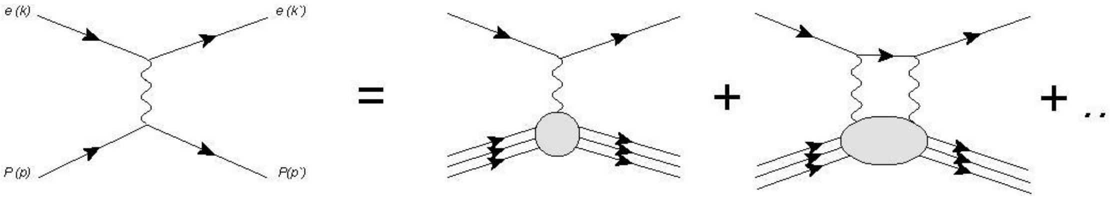
- Dedicated measurement with fully transverse beam
  - Constrains false asymmetry for A_{ep} result



- Good cancellation (symmetry factor)
- Small residual P_T when running
- Correction < 4 ppb

- Transverse result: nucleon structure and 2γ exchange

The data provide an integral test of all allowed virtual excitations of the proton up to E_{cm} = 1.7 GeV



Ancillary Measurements

Many additional measurements under analysis:

- PV asymmetry:
  - elastic ^{27}Al
  - N $\rightarrow$ Δ (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 $\rightarrow$ Δ
  - Møller
  - Near W = 2.5 GeV
  - Pion photoproduction (E = 3.3 GeV)

Published 10/2/2013: PRL **111,**141803 (2013)

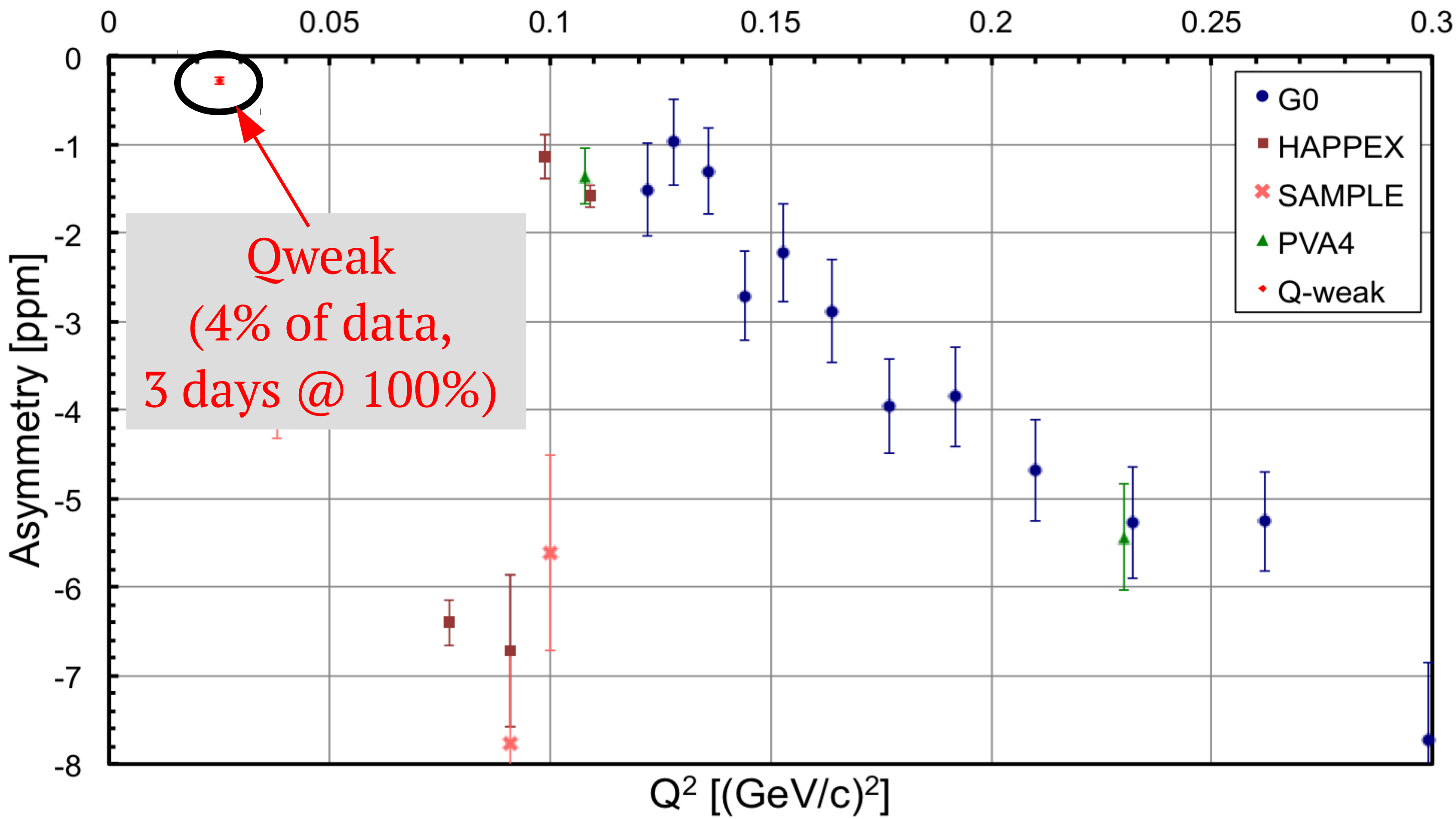
First Results: Asymmetry

- Run 0 Results (1/25th of total dataset)

Kinematics: $\langle Q^2 \rangle = 0.0250 \pm 0.0006\ \mathrm{GeV}^2$

$\langle E_{beam} \rangle = 1.155 \pm 0.003\ \mathrm{GeV}$

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



Extracting the Weak Charge

Global fit in Q^2 and θ to the reduced asymmetry

$$A_{LR}/A_0 = Q^p_{weak} + Q^2 B(Q^2) \qquad A_0 = -(G_\mu / 4\pi\alpha\sqrt{2})\, Q^2$$

- Using 5 free parameters: C_{1u}, C_{1d}, ρ_s, μ_s, & the isovector part of G_A^Z
  - G_E^S, G_M^S, and G_A^Z use a dipole, $(1+Q^2/\lambda^2)^{-2}$, with λ = 1 GeV/c
- Employs all PVES data up to Q^2 = 0.63 $(\mathrm{GeV/c})^2$
  - On p, d, & ^{4}He targets, forward and back-angle data
    - SAMPLE, HAPPEX, G0, PVA4
- Uses constraints on isoscalar part of G_A^Z
  - Zhu, et al., PRD 62, 033008 (2000)
- All ep data corrected for E & Q^2 dependence of γZ-box

Electroweak Corrections

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

- Most of these well known and precisely calculated – except for γZ-box
- γZ-box: significant energy-dependent correction first identified by Gorchtein & Horowitz
- Hall *et al* model dependence constrained by JLab PVDIS data

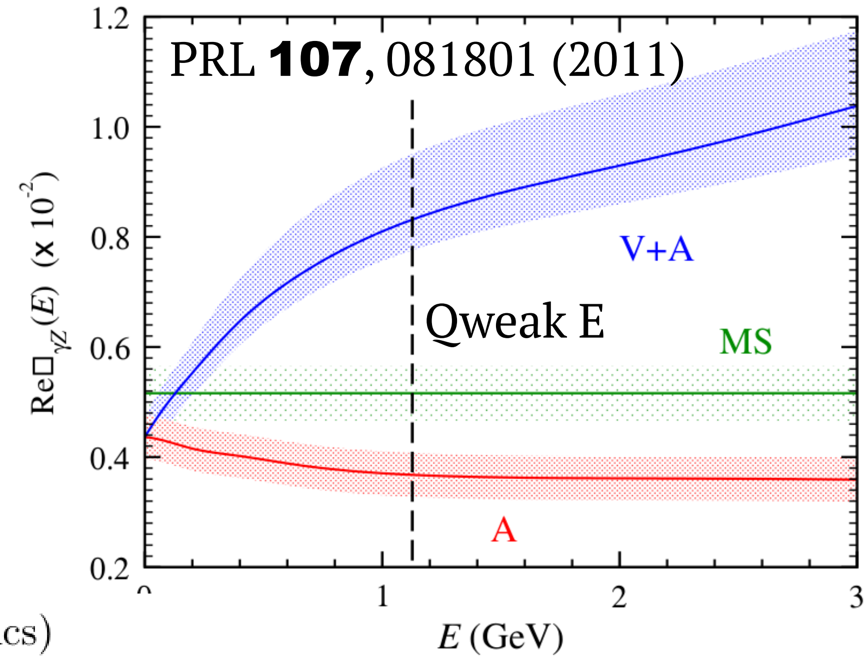
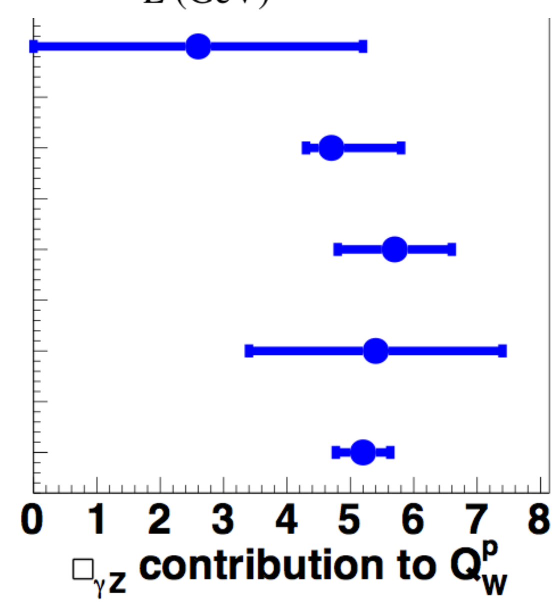


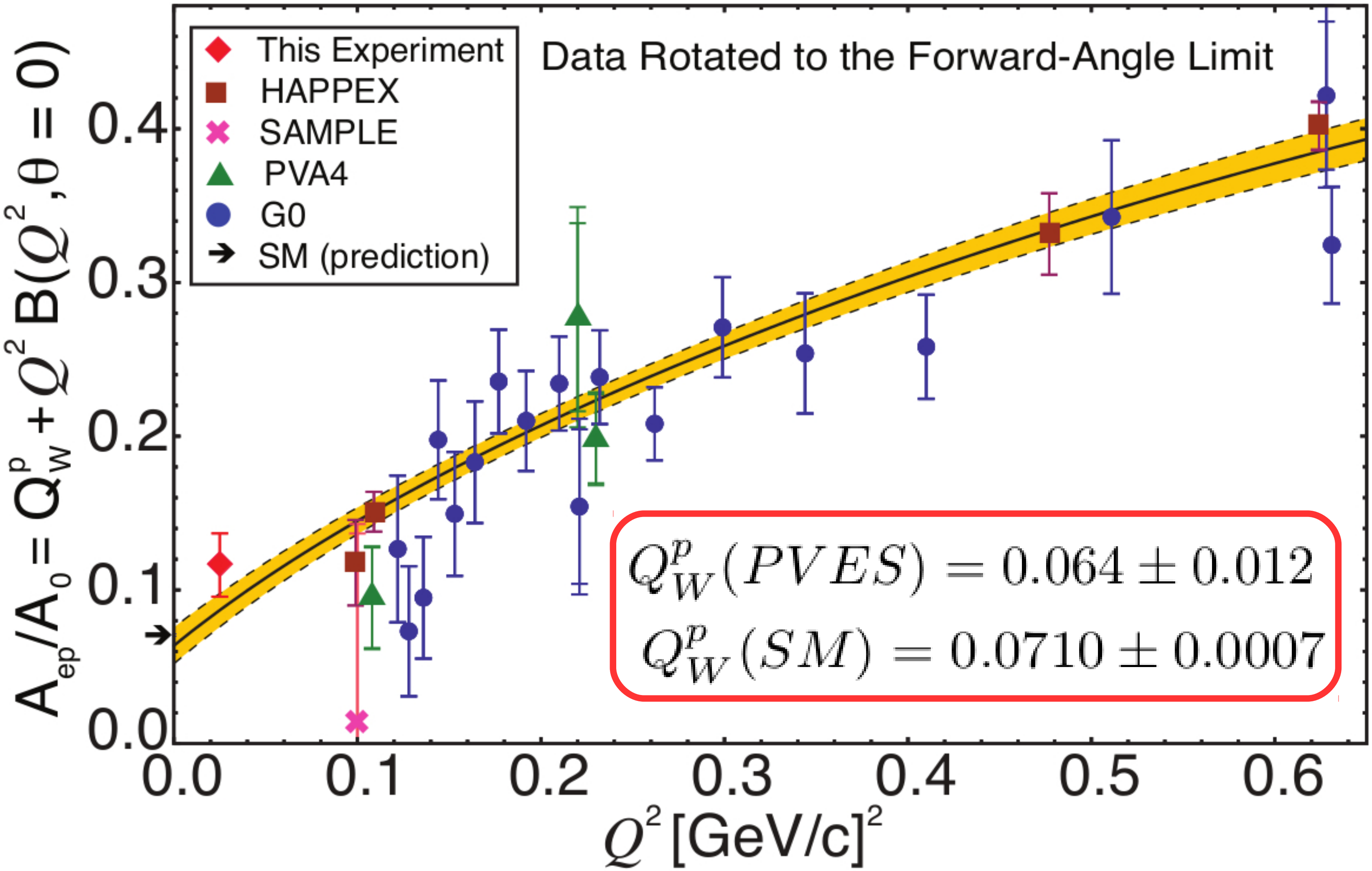
Table 1: $\Box^V_{\gamma Z}$ contribution to Q^p_W (Qweak kinetmatics)

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 (2011)	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



First Results: Weak Charge

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



Global fit of world PVES data up to $Q^2 = 0.63$ GeV^2

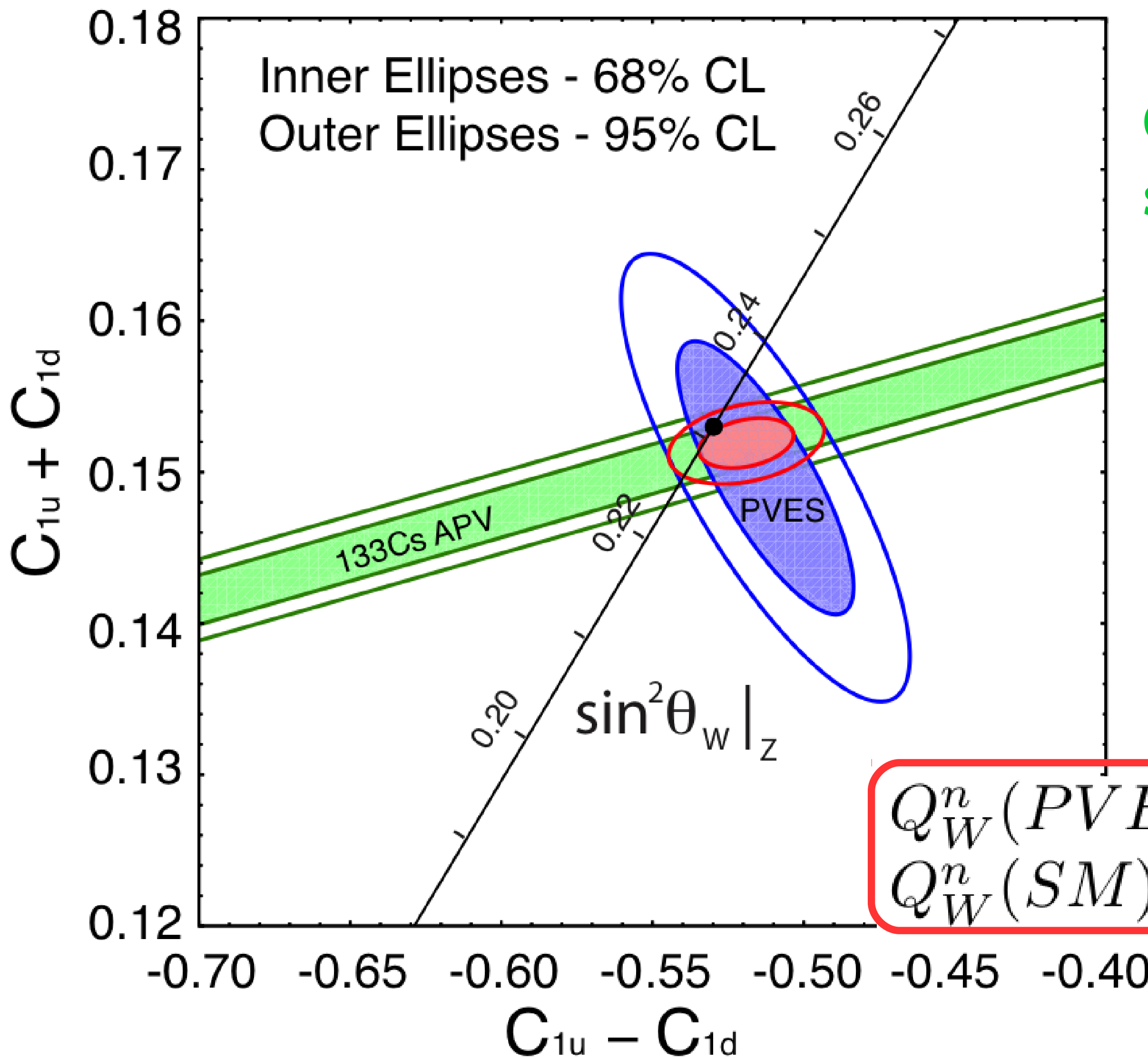
Data rotated to forward-angle for plotting

Remove energy- & Q^2 -dependence of γZ-box

4% of Qweak Data

Published 10/2/2013: PRL **111,**141803 (2013)

First Results: Quark Couplings



Black dot is SM value

Green band is Cesium APV – more sensitive to isoscalar combination

(Dzuba et al., PRL 109, 203003 (2012))

Blue ellipse is combined PVES (now with Qweak)

Red is combined APV+PVES fit

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

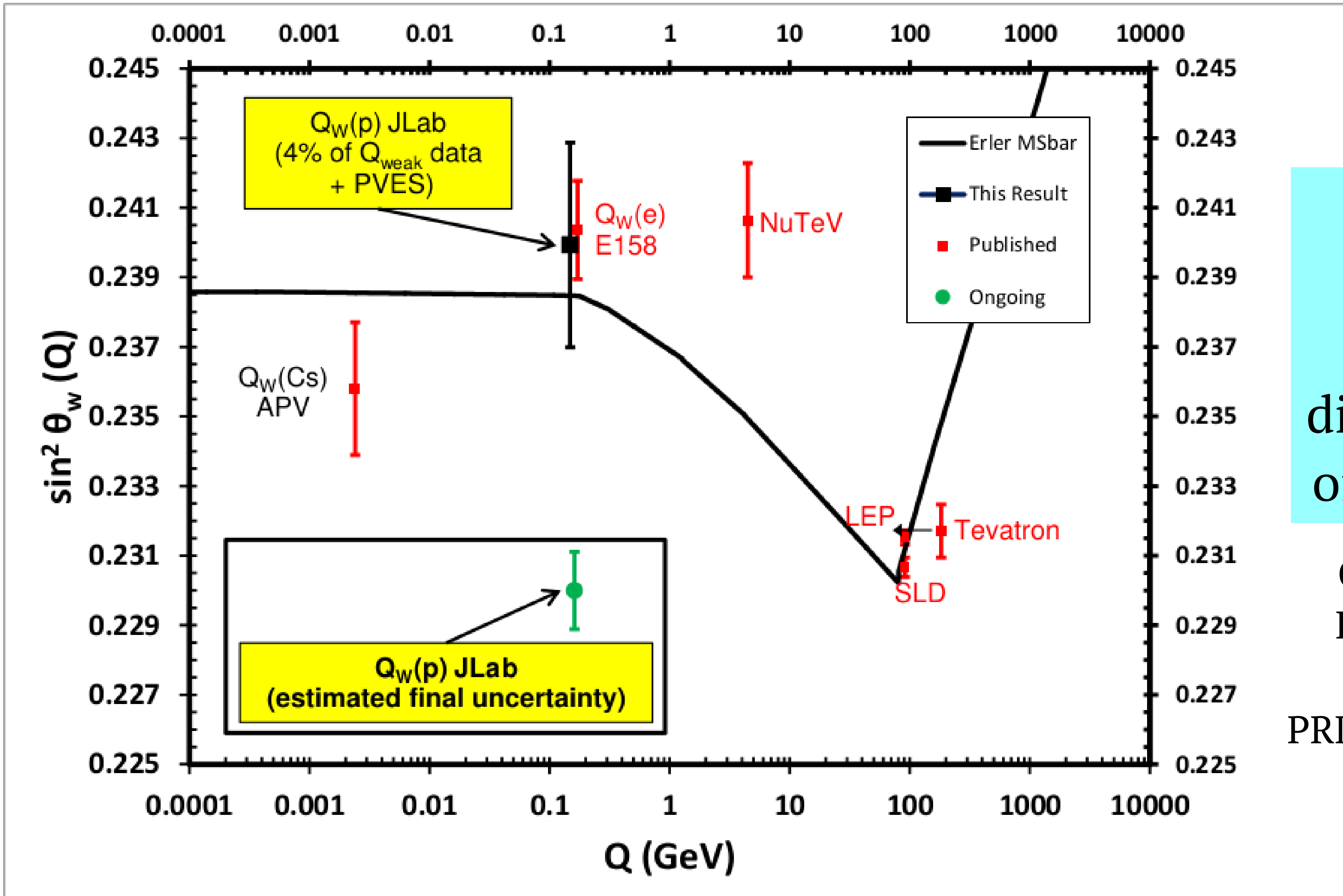
$$Q_W^n(PVES + APV) = -0.975 \pm 0.010$$
$$Q_W^n(SM) = -0.9890 \pm 0.0007$$

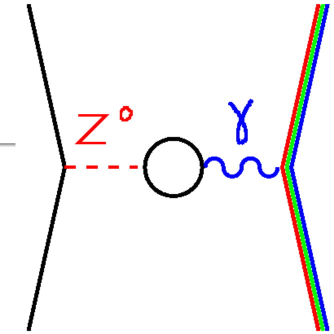
Published 10/2/2013: PRL **111,**141803 (2013)

4% of Qweak Data

First Results: Weak Mixing Angle

At tree level: $Q^{p}_{W} = 1 - 4\sin^2\theta_W$



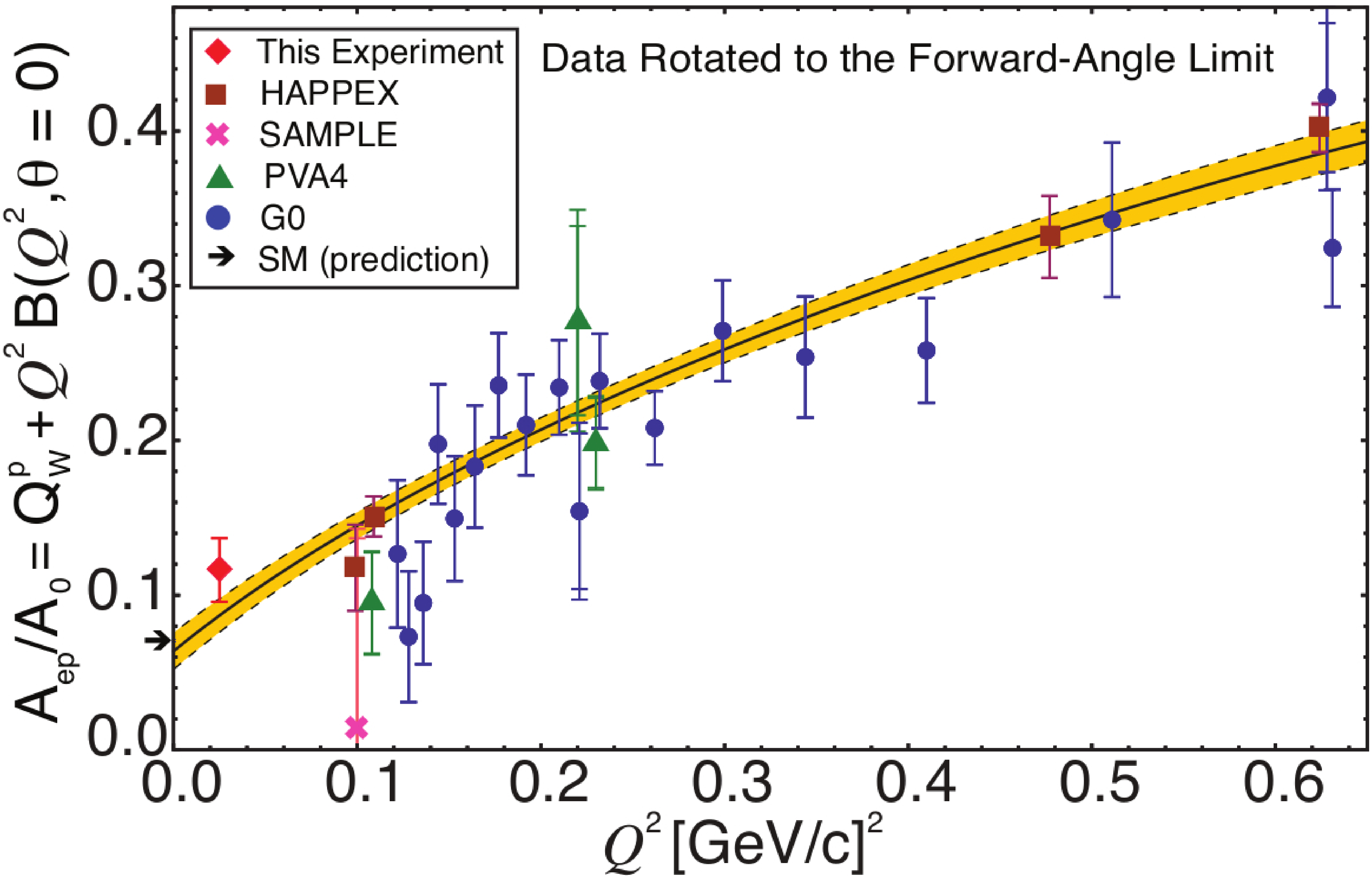


Each experiment sensitive to different types of new physics

Curve from Erler, Kurylov, Ramsey-Musolf, PRD **68**, 016006 (2003)

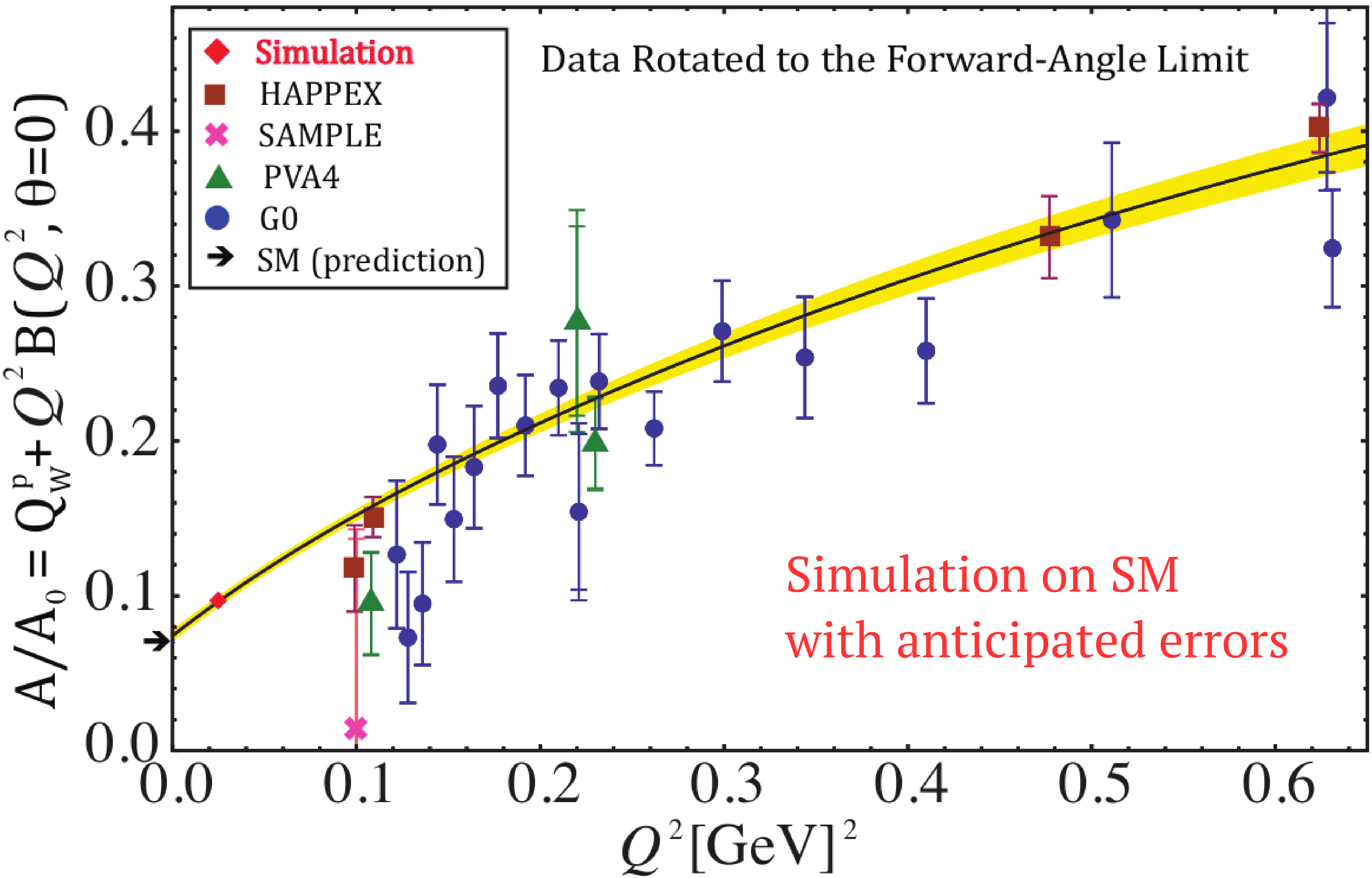
4% of Qweak Data

"Teaser"



This Experiment
HAPPEX
SAMPLE
PVA4
G0
SM (prediction)
Data Rotated to the Forward-Angle Limit
$A_{ep}/A_0 = Q^p_W + Q^2 B(Q^2, \theta = 0)$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Q^2 [GeV/c]^2

"Teaser"

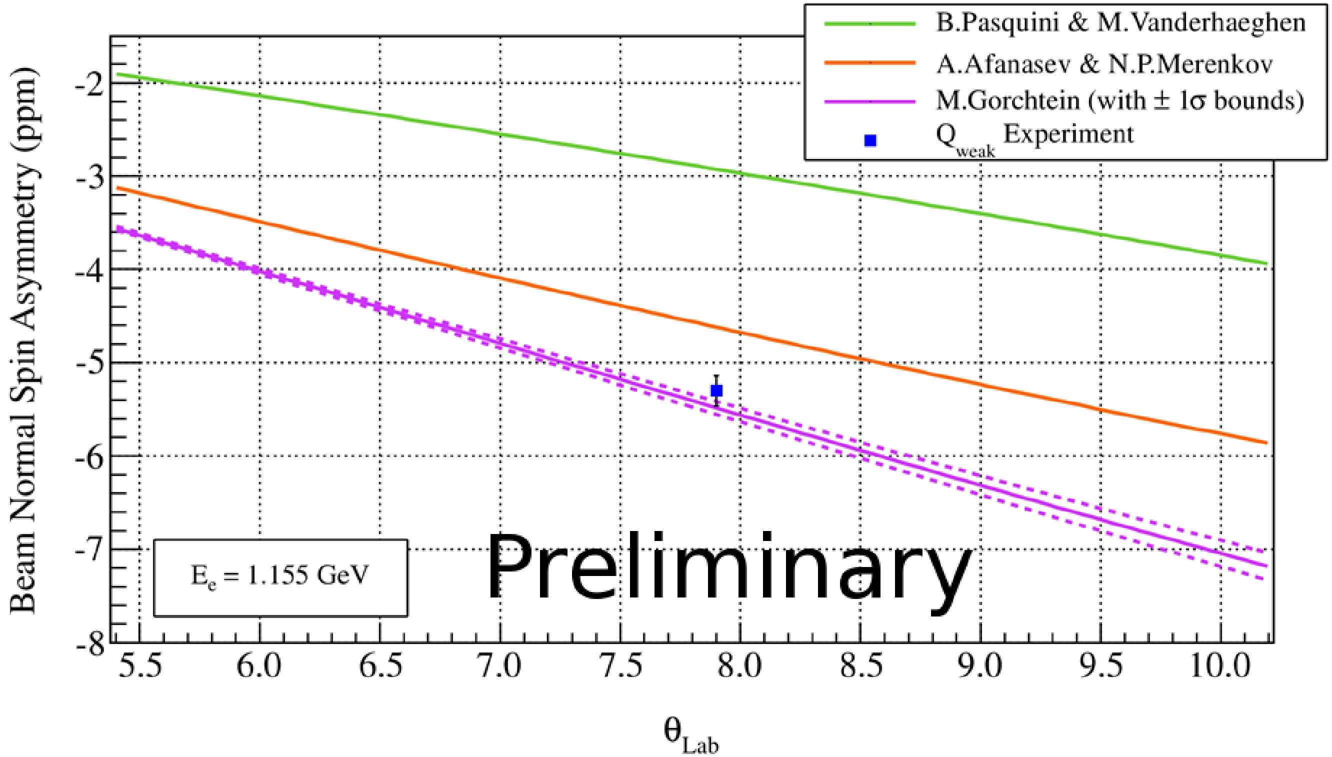


Simulation
HAPPEX
SAMPLE
PVA4
G0
SM (prediction)
Data Rotated to the Forward-Angle Limit
Simulation on SM
with anticipated errors
$A/A_0 = Q_W^p + Q^2 B(Q^2, \theta=0)$
Q^2 [GeV]^2
0.0
0.1
0.2
0.3
0.4
0.5
0.6

e-p transverse asymmetry

- Pasquini/Vanderhaeghen Model
  - Includes intermediate states: proton (elastic) and πN (inelastic)
  - Computed via N → πN electroproduction amplitudes from MAID
- Afanasev/Merenkov and Gorchtein Models
  - Optical theorem: relates forward Compton amplitude to total photoproduction cross section
  - Effectively includes both πN and ππN states
- For all models, inelastic dominates over elastic

- Kinematics:
  - Q2 = 0.0250 ± 0.006 (GeV/c)2
  - E = 1.155 ± 0.003 GeV
  - Scattering angle = 7.9° ± 0.3°
- Preliminary
  A_n = -5.30 ± 0.07 ± 0.15 ppm
  - No radiative corrections
  - Results from B. Waidyawansa Ph.D.thesis; being prepared for publication

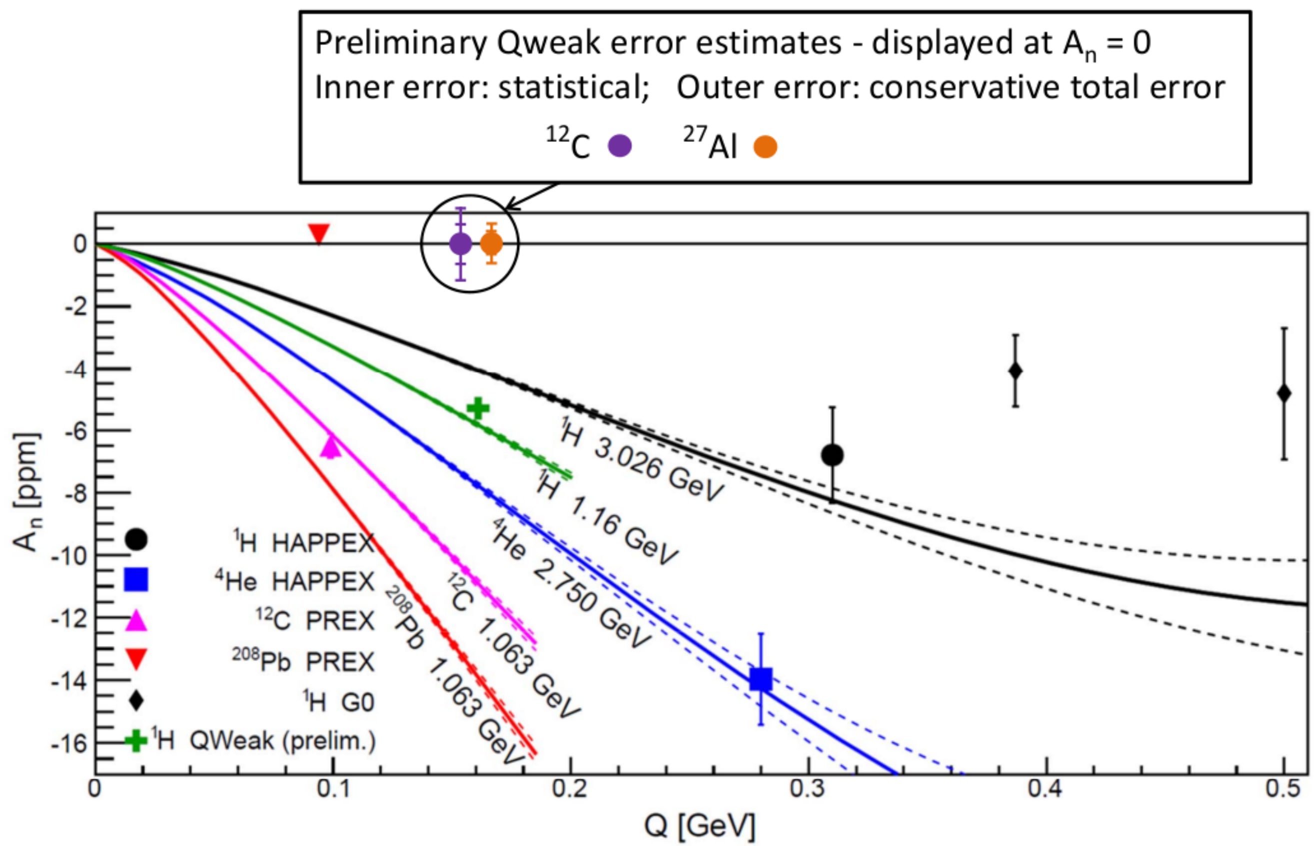


Transverse asymmetry on nuclei

- Calculations with inelastic intermediate hadronic states agree with experimental data up to A = 12, but fail to describe Pb (A = 208)
- No calculation includes both Coulomb distortion and a full range of excited intermediate states.
- Adding data between A=12 and A=208 (such as Al, A=27) will shed light on this issue

Figure adapted from PREX collaboration;
PRL 109, 192501 (2012)

Calulations by M. Gorchtein and C. J. Horowitz,
Phys. Rev. C 77, 044606 (2008).



Summary

- First published result from the Qweak experiment

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

4% of Qweak Data

  - Determination of the proton and neutron weak charge

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

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

In agreement with Standard Model predictions

- Final result expected ~year from now
  - Statistical error 5 times smaller, reduced systematics, no show stoppers found
  - Additionally, many ancillary results under analysis

The Qweak Collaboration

97 collaborators 23 grad students
10 post docs 23 institutions

Institutions:

[1] University of Zagreb
[2] College of William and Mary
[3] A. I. Alikhanyan National Science Laboratory
[4] Massachusetts Institute of Technology
[5] Thomas Jefferson National Accelerator Facility
[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
[21] University of New Hampshire
[22] Hendrix College, Conway
[23] University of Adelaide

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] 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]

Spokespersons Project Manager Grad Students