The Q-weak Experiment: First Direct Determination of the Proton's Weak Charge

Nuruzzaman
(https://userweb.jlab.org/~nur/)
for the Qweak Collaboration

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Jefferson Lab

HAMPTON UNIVERSITY

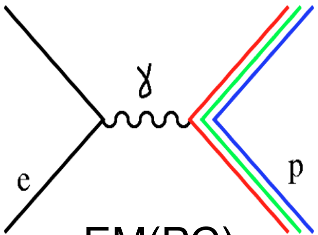
Overview

- Q-weak basics and motivation.
- Experimental setup and design.
- Analysis and preliminary results.
- Summary

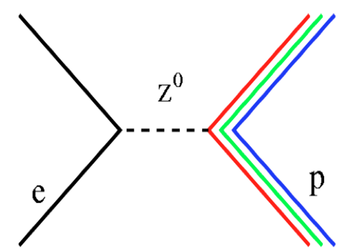
The Standard Model (SM) is the most successful elementary particle theory developed so far. But missing phenomena like gravity and dark matter suggest it is a “low energy” effective theory.

Particle	EM Charge	Weak Charge	
u	2/3	$-2C_{1u} = 1 - (8/3)\sin^2\theta_W$	~ 1/3
d	-1/3	$-2C_{1d} = -1 + (4/3)\sin^2\theta_W$	~ -2/3
p(uud)	1	$Q^p_W = -2(2C_{1u} + C_{1d}) = 1 - 4\sin^2\theta_W$	~ 0.07
n(udd)	0	$Q^n_W = -2(C_{1u} + 2C_{1d})$	~ -1

PV asym. $A_{ep} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx \frac{|M^{PV}_{weak}|}{|M_{EM}|}$



EM(PC)



neutral-weak(PV)

Where $\sigma_+(\sigma_-)$ is positive(negative) helicity correlated electron-proton scattering cross section. M^{PV}_{weak} and M_{EM} are the parity violating (PV) neutral current and parity conserving (PC) electromagnetic (EM) scattering amplitudes, respectively

helicity $h = \vec{S} \cdot \hat{p}$

$h = \pm 1/2$

Q-weak Basics

Tree level PV asymmetry can be written as

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

G^γ_E, G^γ_M: EM form factors (FF)
G^Z_E, G^Z_M: weak neutral FF
G^Z_A: axial FF
G_F: Fermi constant

$$\varepsilon = \frac{1}{1+2(1+\tau)\tan^2\frac{\theta}{2}}, \varepsilon' = \sqrt{\tau(1+\tau)(1-\varepsilon^2)}, \tau = \frac{Q^2}{4M}$$

Q^2 is four momentum transfer squared
$\sin^2\theta_W$ the weak mixing angle
M is the proton mass
θ is scattering angle

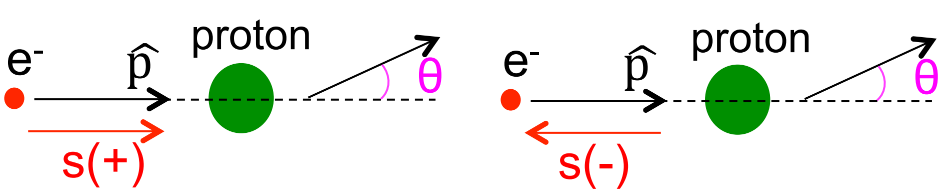
As $\theta \to 0,\ \varepsilon \to 1,$ and $\tau << 1$

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

$Q^p{}_W = 1 - 4\sin^2\theta_W$

$$A_0 = \frac{-G_F Q^2}{4\sqrt{2}\pi\alpha}$$

In a A_{ep}/A_0 vs Q^2 plot $Q^p{}_W$ is the intercept and $B(Q^2,\theta)$ is slope



$$A_{msr} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

The scattered electron yield is integrated during each helicity state. The helicity is flipped pseudo-randomly at 960Hz

The PV asymmetry can be extracted after correcting for polarization, false asymmetry and backgrounds.

Q-weak Goal

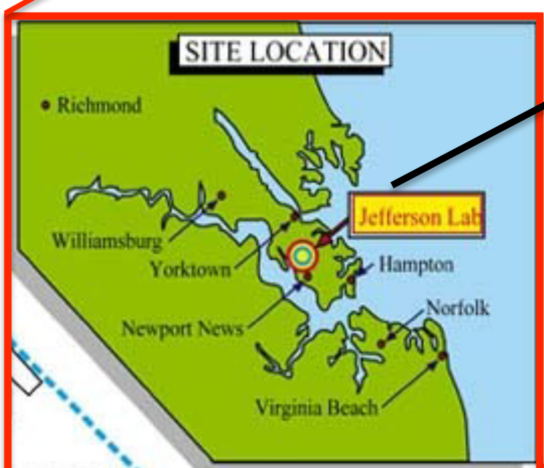
- The objective of Q-weak experiment is to measure the parity violating asymmetry (A_{ep}) in elastic electron-proton scattering in order to extract Q^p_W.
- A_{ep} has a size of ~230 ppb (measuring very small number very precisely).

Expected uncertainty goal with full statistics (from 2007 proposal)

Error Source	$\delta(A_{ep})/A_{ep}$ [%]	$\delta(Q^p_W)/Q^p_W$ [%]
Statistical	2.1	3.2
Hadronic Structure	–	1.5
Polarimetry	1.0	1.5
Q^2 Determination	0.5	1.0
Backgrounds	0.5	0.7
Helicity-Correlated Beam Properties	0.5	0.8
Total	2.5	4.2

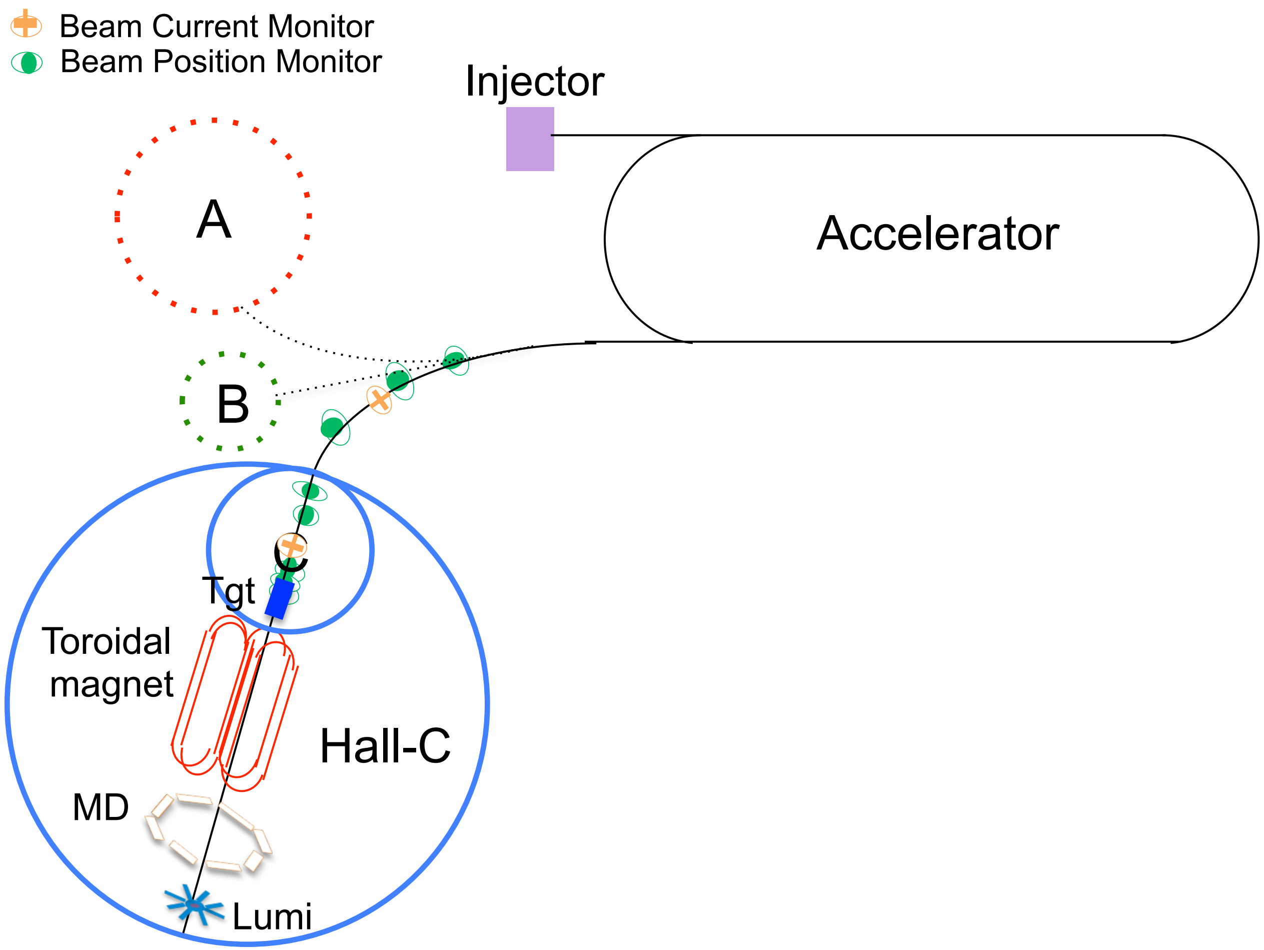
This presentation includes ~ 4% of total data set.

Jefferson Lab

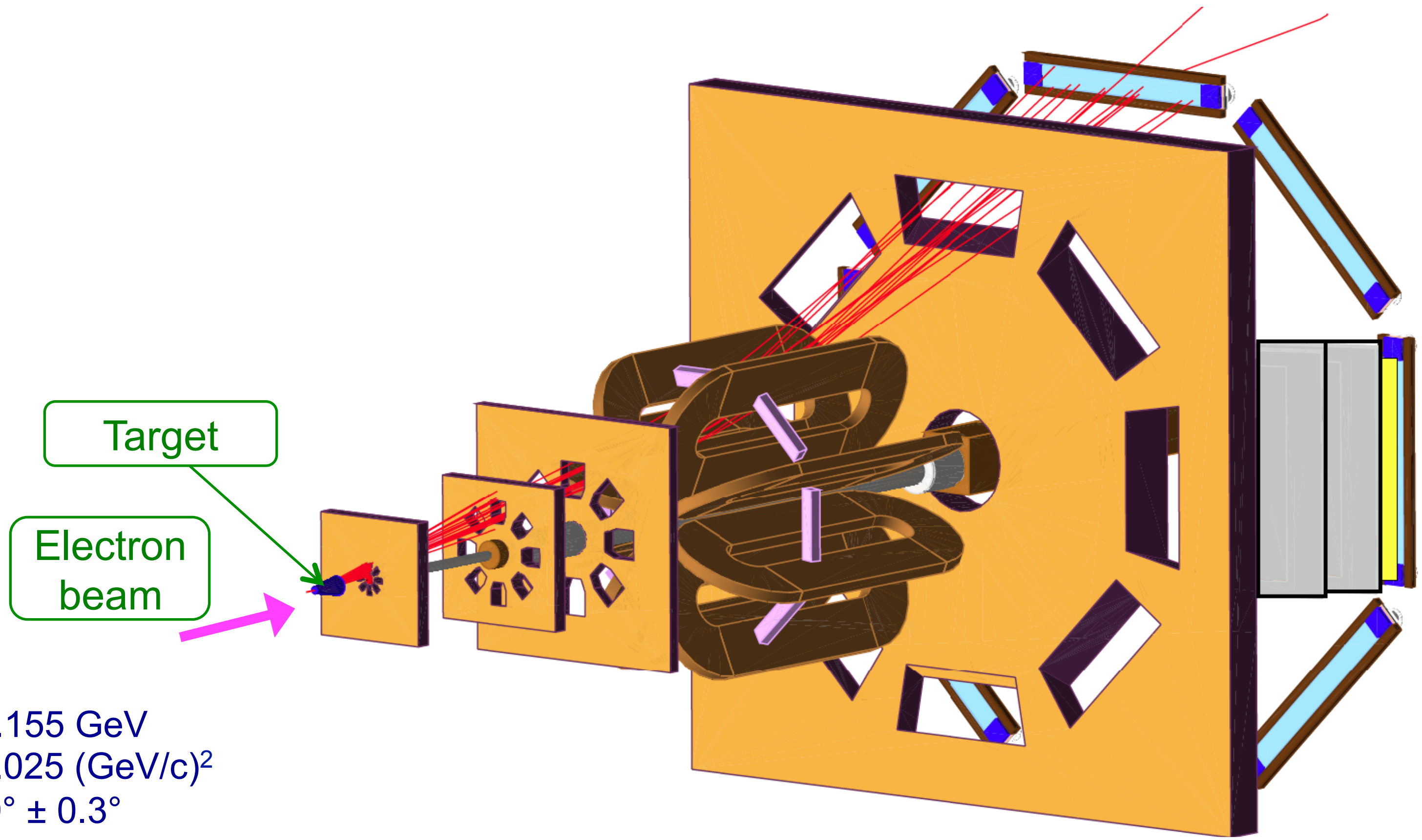


The Q-weak experiment was performed at Hall-C of Thomas Jefferson National Accelerator Facility (Jlab) at Newport News, VA, USA during November 2010 to May 2012 although preparation started in 2001.

Jefferson Lab Beamline Sketch



Q-weak Apparatus



E_{beam} = 1.155 GeV
$\langle Q^2 \rangle \sim 0.025\ (GeV/c)^2$
$\langle\theta\rangle \sim 7.9° \pm 0.3°$
φ coverage ~ 49% of 2π
Current = 145 (180) μA
Polarization = 89%
Target = 34.4 cm LH_2
Cryopower = 2.5 kW
Luminosity $2 \times 10^{39} s^{-1} cm^{-2}$

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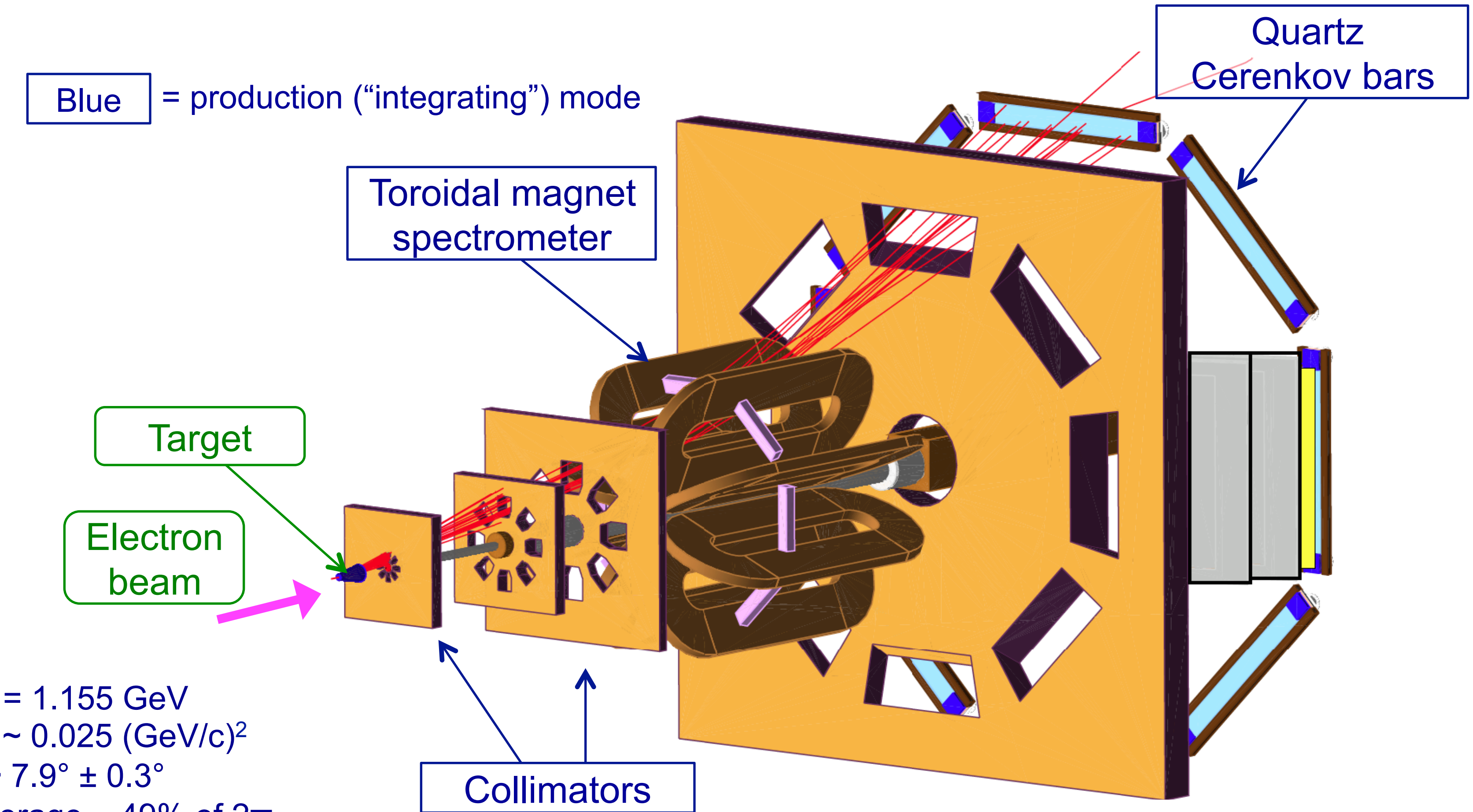

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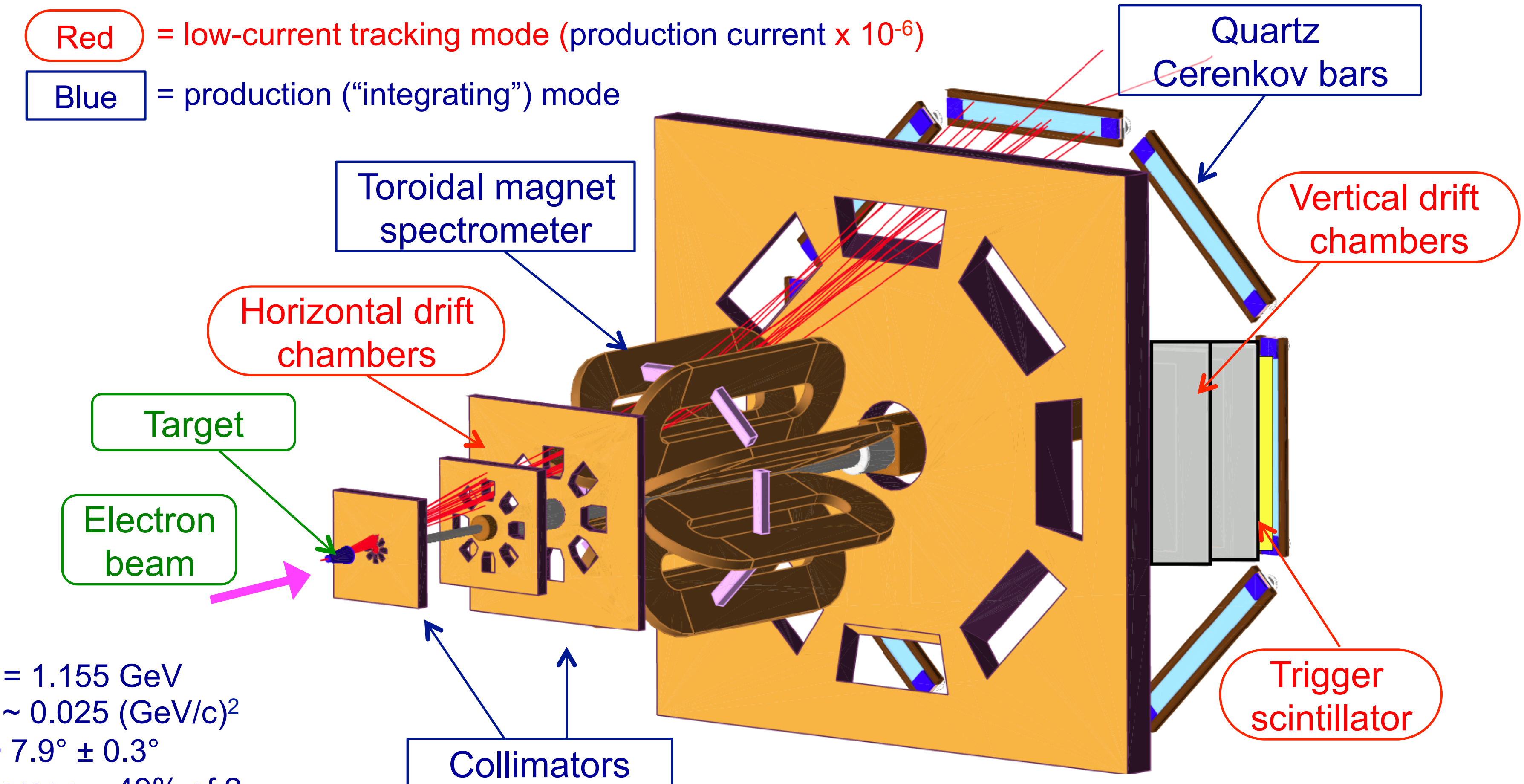

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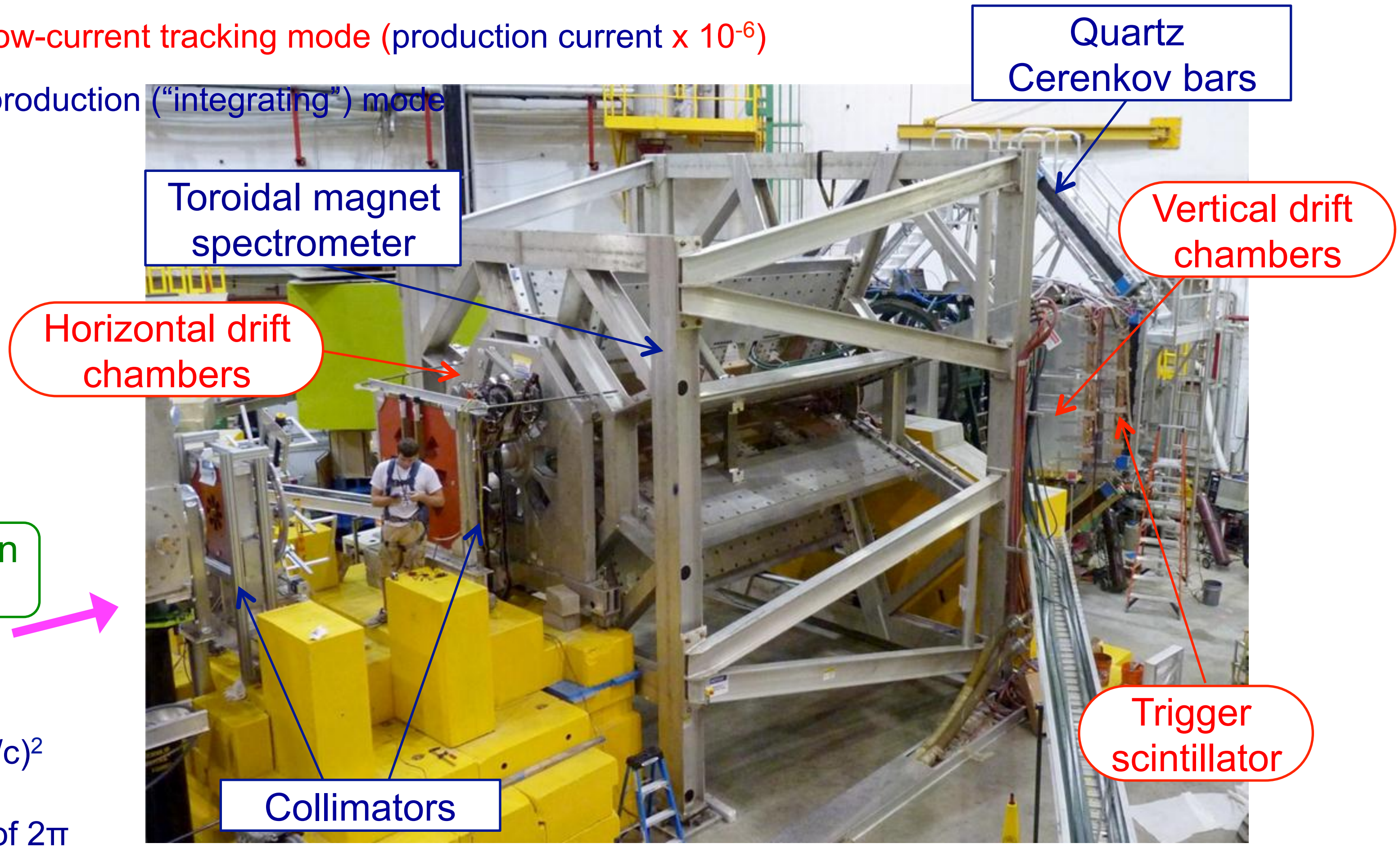
Q-weak Apparatus

Red = low-current tracking mode (production current x 10^{-6})

Blue = production ("integrating") mode



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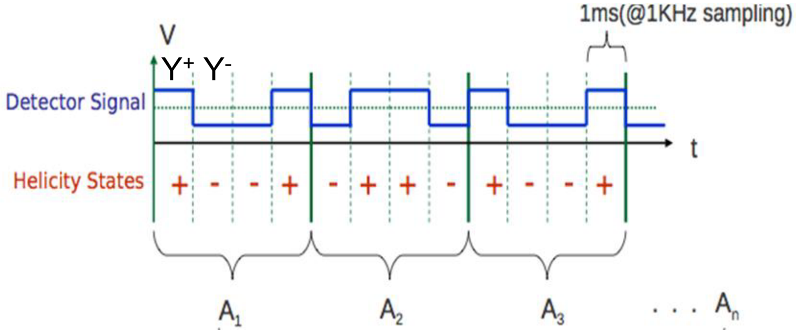
Main Detector and Experimental Asymmetry

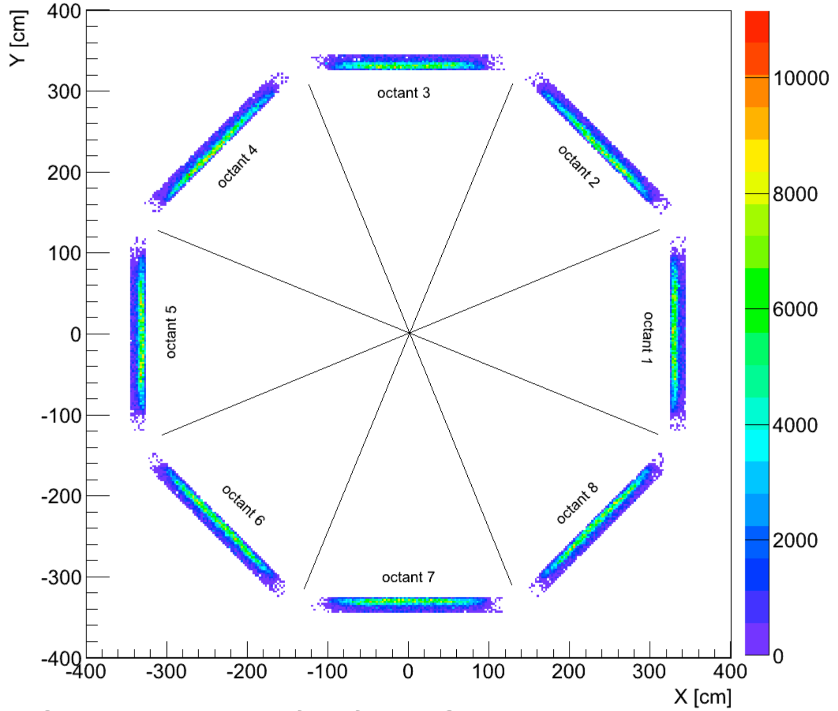
- 2 m long radiation hard, fused quartz Cherenkov detectors.
- Azimuthal symmetry decreases sensitivity to HC beam motion, transverse asymmetry.

Pseudo random quartet ordering frequency ~ 1 kHz



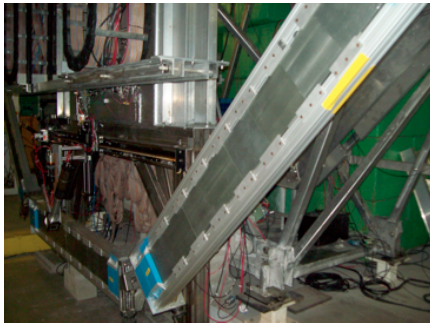
For each quartz bar, $A^{pmt}_{raw} = \frac{Y^+ - Y^-}{Y^+ + Y^-}$

Raw asymmetry, $A_{raw} = \frac{\sum_{j=1}^{16} A^{pmt}_{raw,j}}{16}$



Scattered e profile from GEANT-IV on MD bars

Two quartz bars

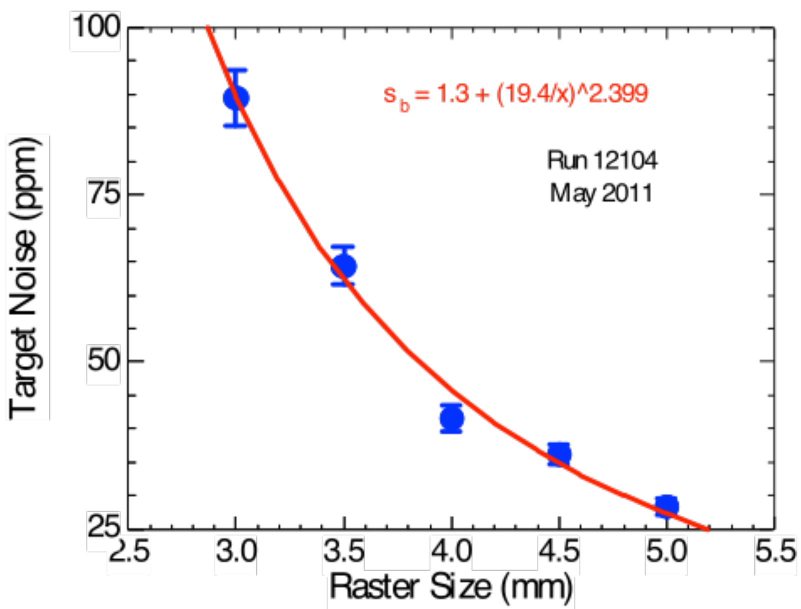


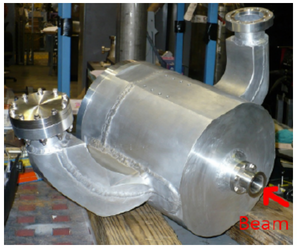
Installed MD at Hall-C

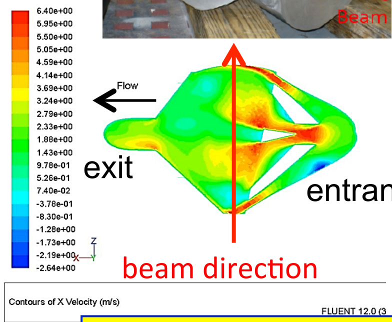
Target Design and Performance

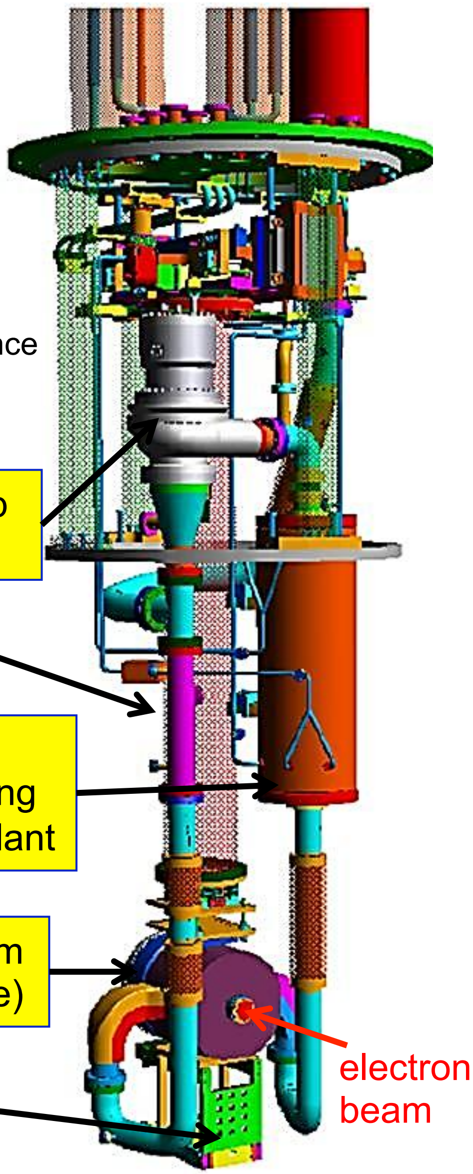
- World's highest power cryogenic target ~3 kW
- Designed with computational fluid dynamics (CFD) to reduce density fluctuations

Target noise < 50 ppm<< statistical asymmetry width per quartet (~ 230 ppm) @ 180 μA







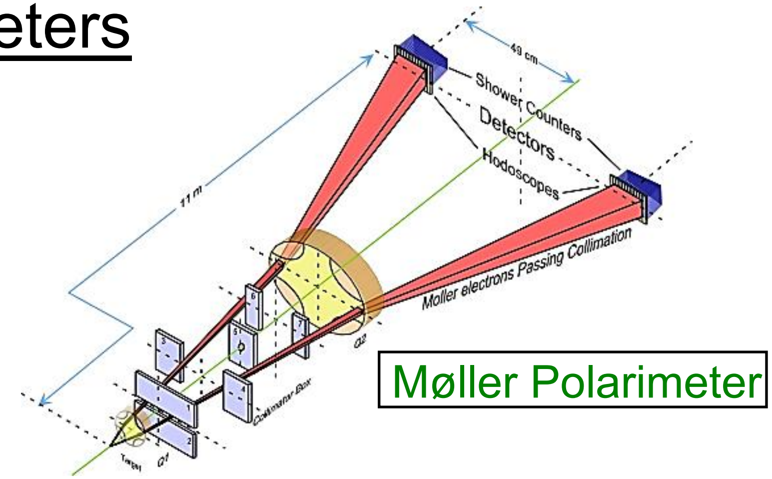


Precision Polarimetry

Q-weak requires ΔP/P ≤ 1%

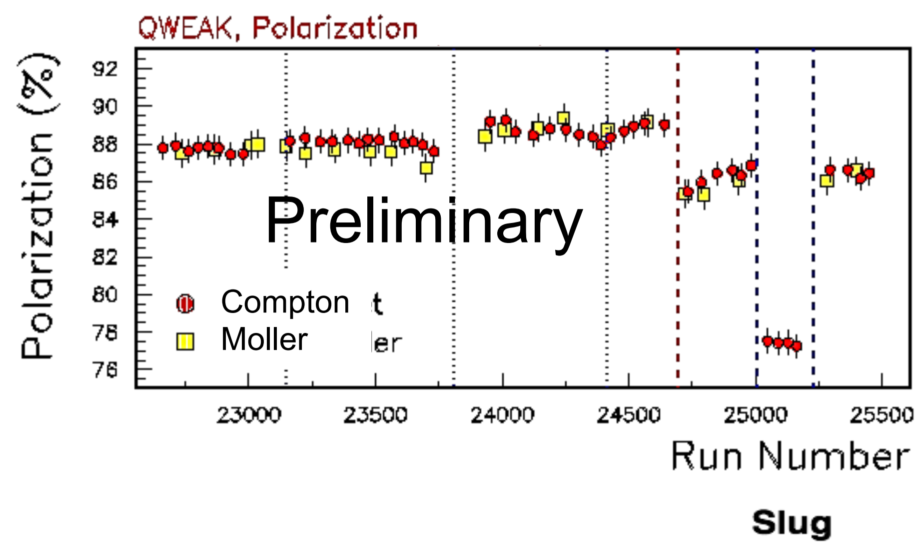
Strategy: use 2 independent polarimeters

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

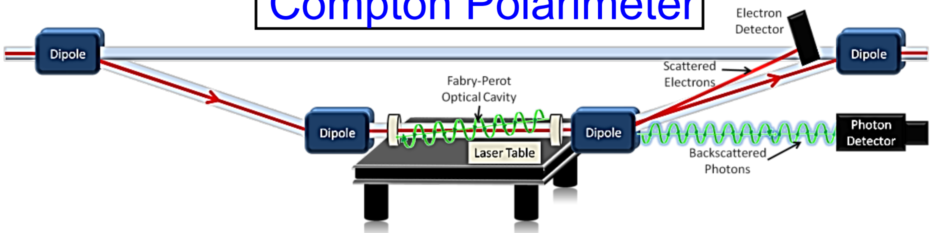


Møller Polarimeter

- Use new Compton polarimeter (1%/h):
  - Continuous, non-invasive
  - Known analyzing power provided by circularly-polarized laser



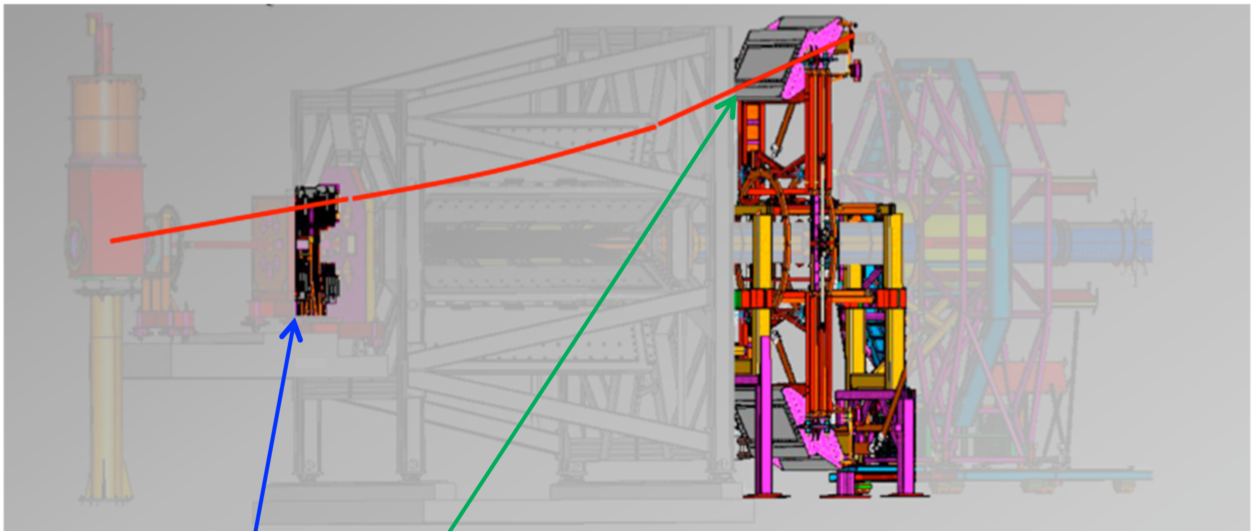
Compton Polarimeter

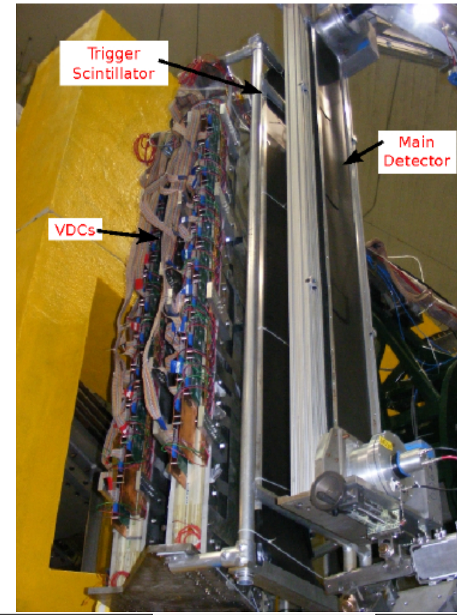


Determining the Kinematic

Q-weak requires uncertainty on $Q^2 \leq 0.5\%$

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

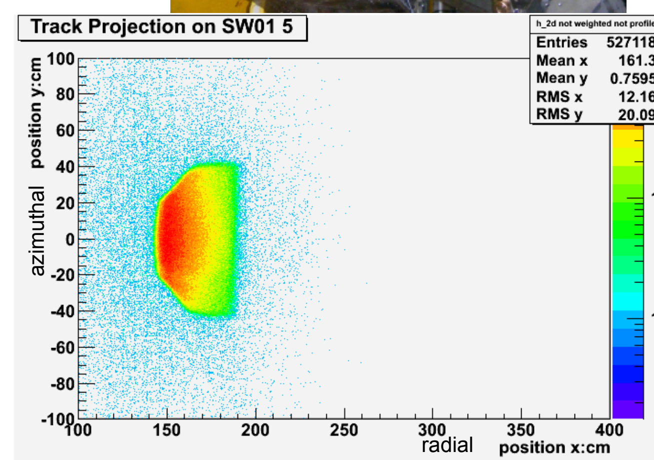




HDCs before magnet to msr θ
$Q^2 = 2E^2\,(1-\cos\theta) / [1 + E/M(1-\cos\theta)]$

VDCs & trigger scintillators after magnet to msr light weighted Q^2 across quartz bars

$\langle Q^2 \rangle \sim 0.025\ (\mathrm{GeV}/c)^2$



Extracting PV Asymmetry

Extracting physics asymmetry

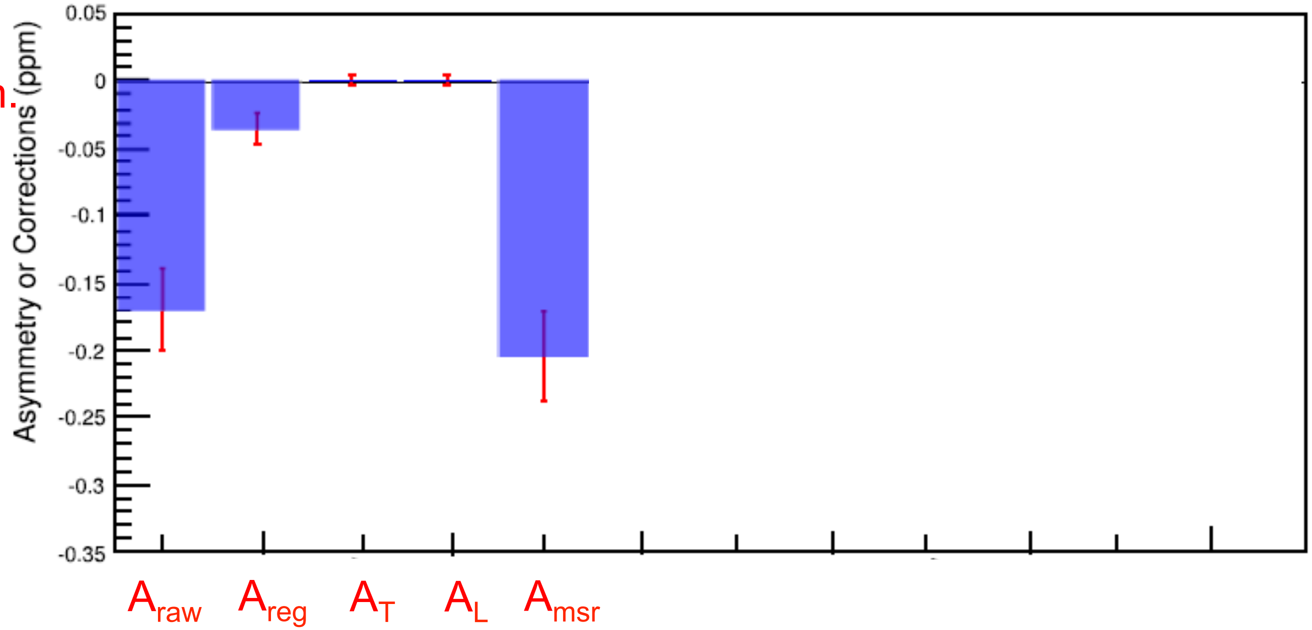
$$A_{ep} = R_{total}\left[\frac{\frac{A_{msr}}{P} - \sum_{i=1}^{4} A_{bi} f_{bi}}{1 - \sum_{i=1}^{4} f_{bi}}\right]$$

Extracting physics asymmetry, A_{ep}, from the experimental measured asymmetry by

- removing false asymmetries, parity conserving contamination
- correcting for the beam polarization
- removing background asymmetries
- correcting for radiative tails and other kinematic correction

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

A_{reg} = Linear regression asym.
A_T = Residual transverse asym.
A_L = Non-linearity in PMT



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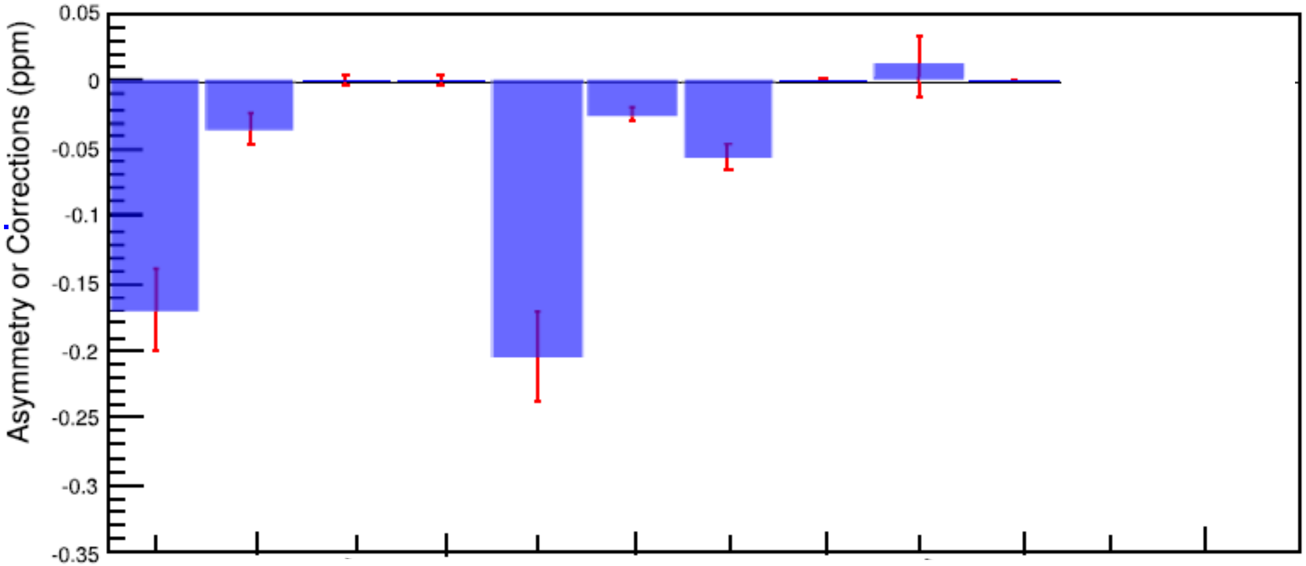
b1 = Al. window bkg.
b2 = Beam line scattering.
b3 = Other neutral background.
b4 = Inelastics.



A_{raw} A_{reg} A_T A_L A_{msr} P Δb1 Δb2 Δb3 Δb4

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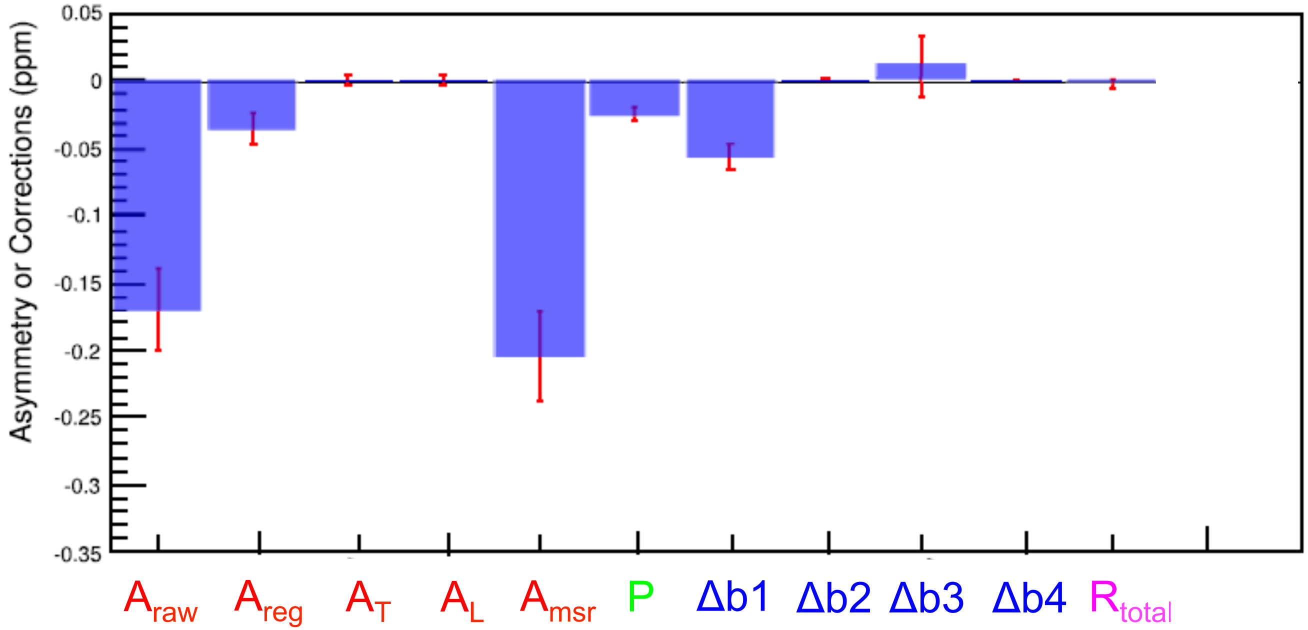
$R_{total} = R_{RC} R_{Det} R_{Bin} R_{Q2}$

R_{RC} = Radiative corr.
R_{Det} = Detector bias corr.
R_{Bin} = Effective kinematic corr.
R_{Q2} = Q^2 calibration corr.



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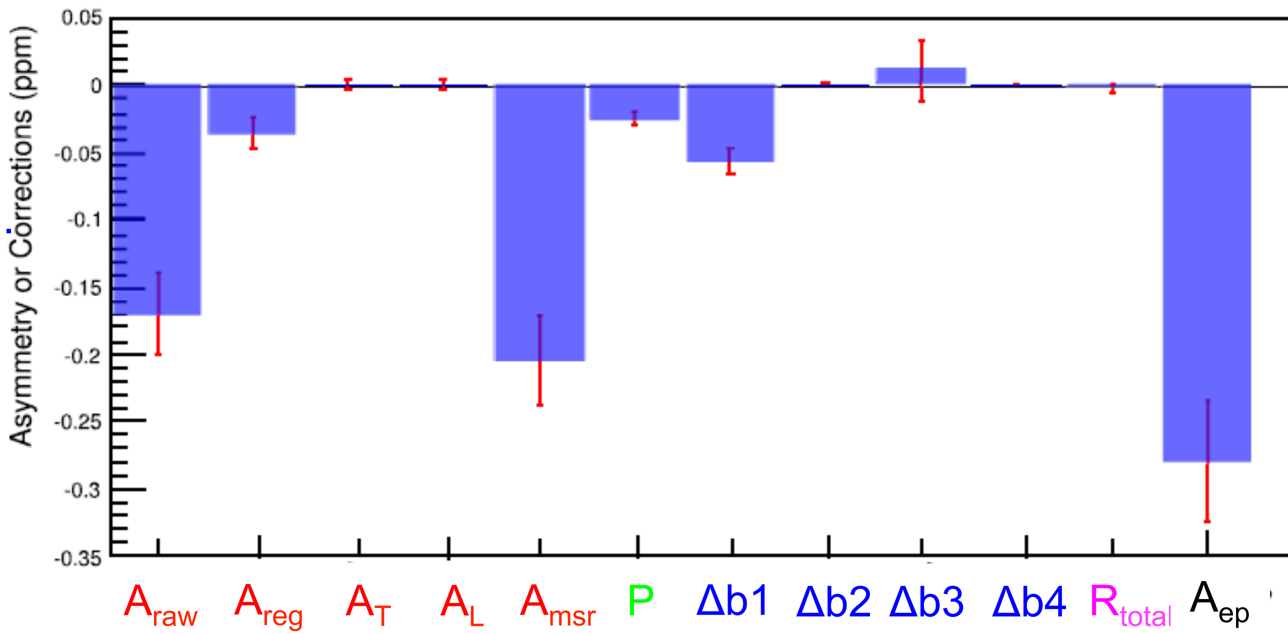

Extracting PV Asymmetry

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	Correction Value [ppb]		Contribution to ΔA_{ep} [ppb]
Normalization Factors Applied to A_{raw}			
Beam Polarization $1/P$	-21		5
Kinematics R_{total}	5		9
Background Dilution $1/(1-f_{total})$	-7		-
Asymmetry Corrections			
Beam Asymmetries κA_{reg}	-40		13
Transverse Polarization κA_T	0		5
Detector Linearity κA_L	0		4
Backgrounds	$\kappa P f_{bi} A_{bi}$	$\delta(f_{bi})$	$\delta(A_{bi})$
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

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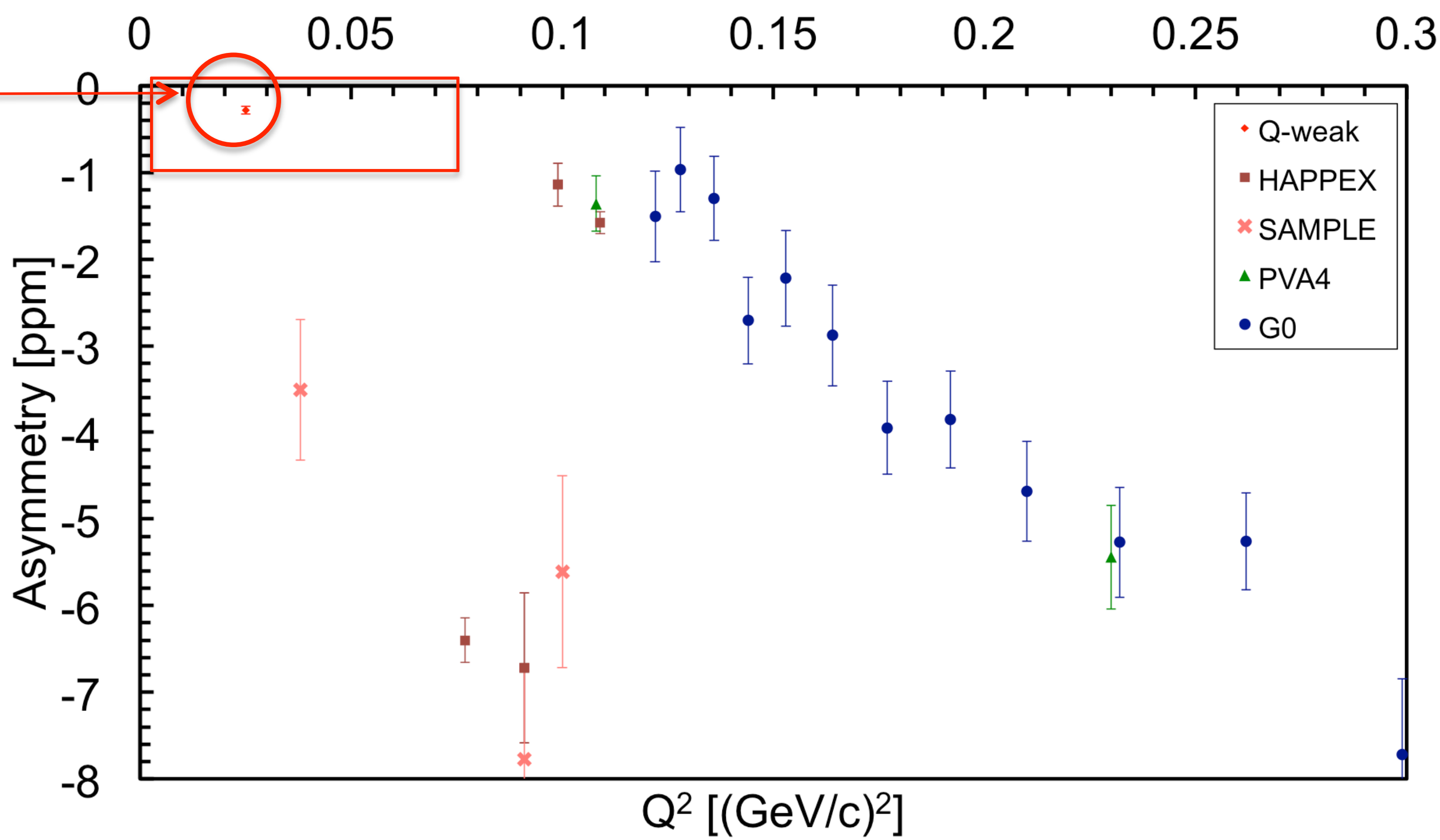
Extracting PV Asymmetry

Error bar is hard to visualize!

Our A & ΔA are ~3 times smaller than nearest competitor.

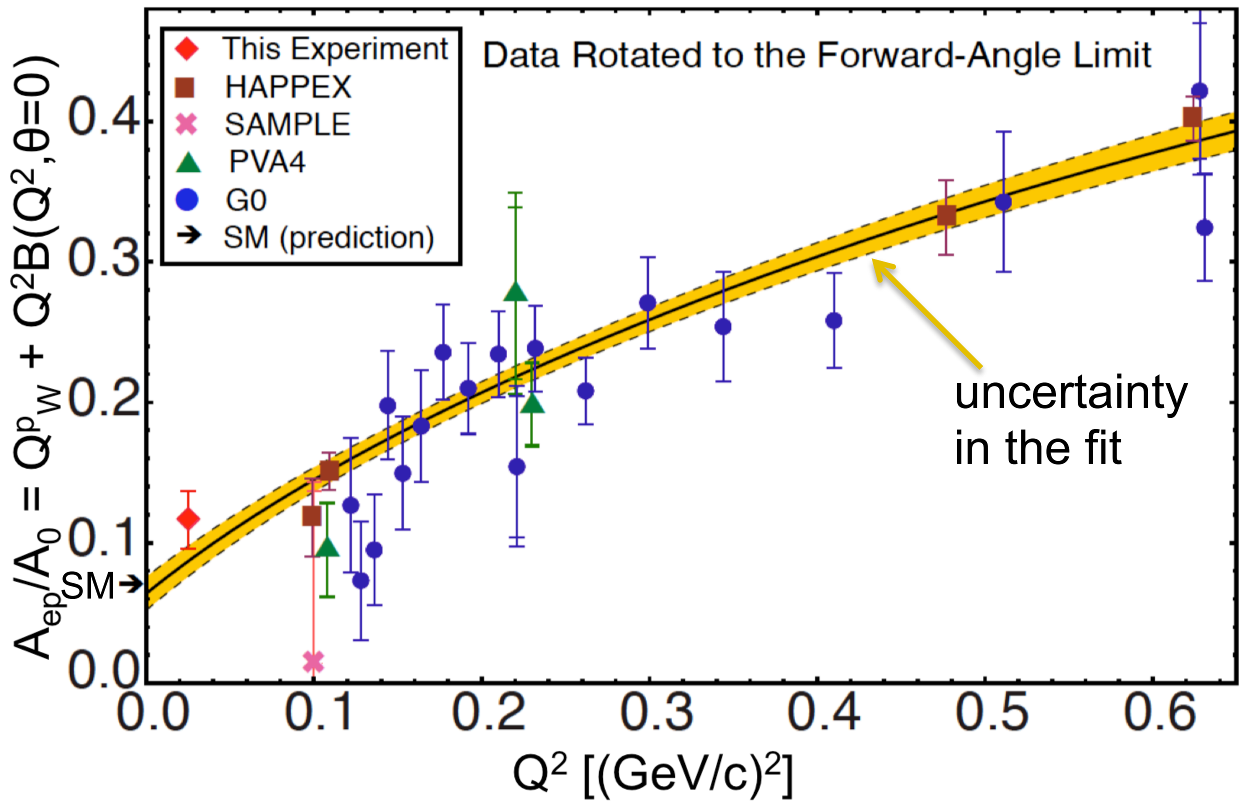


Smallest asymmetry and absolute error bar measured in e-p scattering to date

This is ~ 4% of total data set

Q-weak

Global fit (solid line) presented in the forward angle limit as reduced asymmetries derived from this measurement as well as other Parity Violating Electron Scattering (PVES).



Our result increased consistency with SM calculation Q^p_W(SM) = 0.0710 ± 0.0007

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Phys. Rev. Lett. 111, 141803 (2013)

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

Q^p_W(PVES) = 0.064 ± 0.012

Impact on C_{1u} and C_{1d}

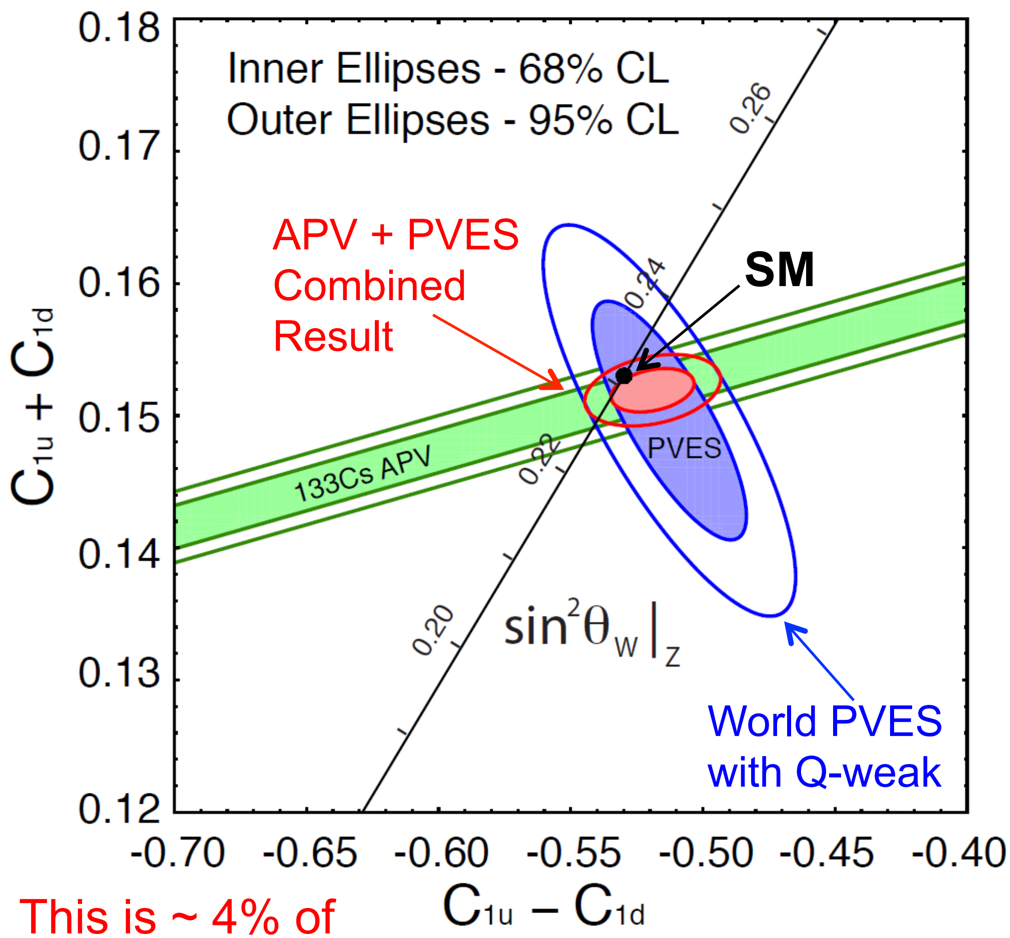
$Q^p_W = -2(2C_{1u} + C_{1d})$
$Q^n_W = -2(C_{1u} + 2C_{1d})$

Q^p_W along with Atomic Parity Violation (APV) constrain on the neutral-weak quark coupling constants $C_{1u} - C_{1d}$ (isovector) and $C_{1u} + C_{1d}$ (isoscalar).

$C_{1u} = -0.184 \pm 0.005$
$C_{1d} = 0.336 \pm 0.005$

Neutron weak charge is extracted for the first time.

Our result for neutron is in agreement with SM value $Q^n_W(SM) = -0.9890 \pm 0.0007$



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Phys. Rev. Lett. 111, 141803 (2013)

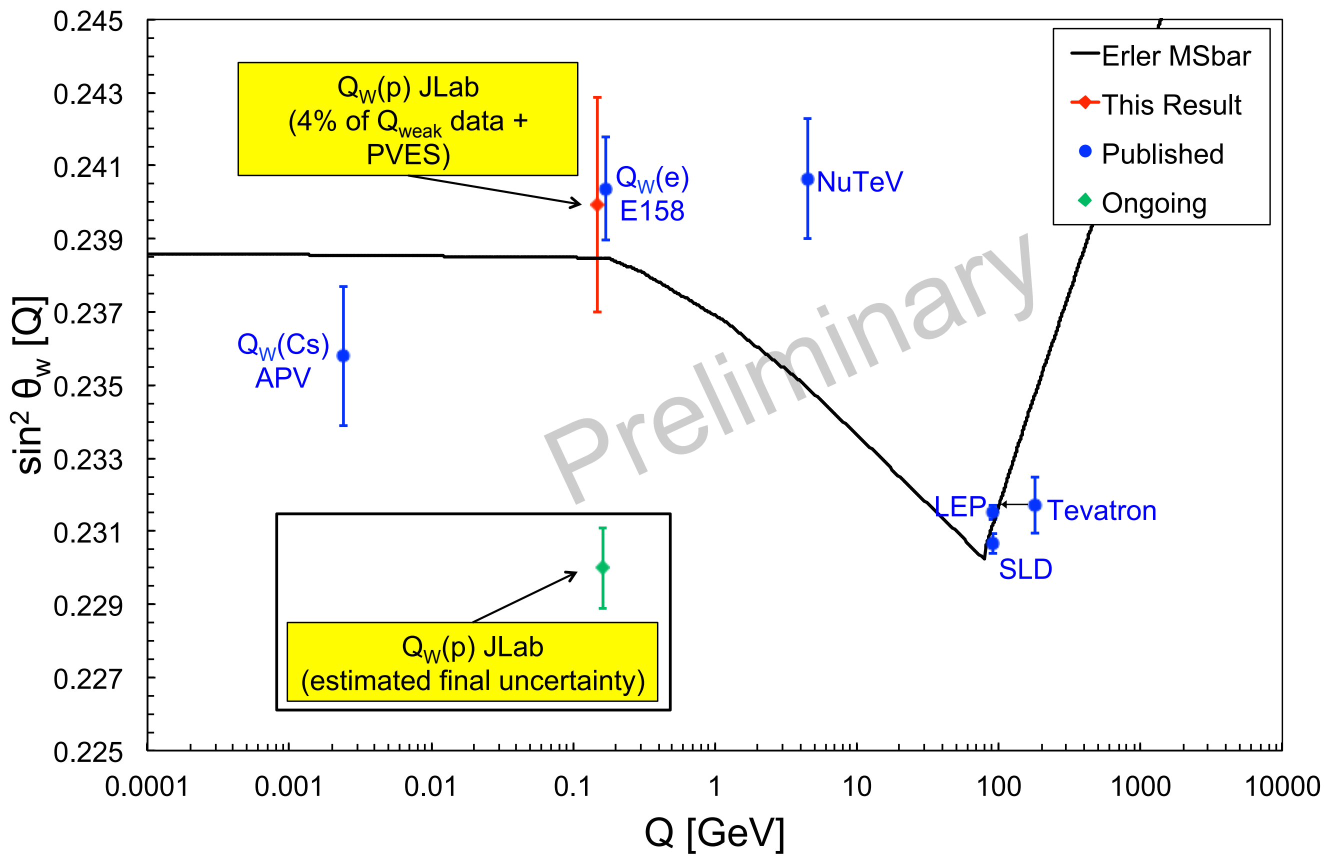
$Q^n_W(PVES+APV) = -0.975 \pm 0.010$

Running of $\sin^2\theta_W$

The SM predicts the running of $\sin^2\theta_W(Q)$ based on the measurement done at the Z-pole.

Running of $\sin^2\theta_W$ is due to higher order RC varies with Q^2.

Q-weak will measure the $\sin^2\theta_W(Q)$ to 0.3% with full statistics.



The running of the weak mixing angle with momentum transfer, Q , as depend in the MS renormalization scheme

Ancillary Measurements

In addition to the ~ 4% measurement of the proton's weak charge, numerous other interesting ancillary measurements:

- Elastic transverse asymmetry (proton)
- Elastic transverse asymmetry (aluminum, carbon)
- PV asymmetry in $N \rightarrow \Delta$ region.
- Transverse asymmetry in the $N \rightarrow \Delta$ region (proton)
- Transverse asymmetry in the $N \rightarrow \Delta$ region (aluminum, carbon)
- PV deep inelastic scattering γZ box diagram constraining
- Transverse asymmetry in the PVDIS region (3.3 GeV)
- PV asymmetries in pion photoproduction
- Transverse asymmetries in pion photoproduction
- Measurements of elastic PV asymmetry on aluminum(alloys)/ carbon

Plenty of projects, plenty of results, 20+ theses….

Summary

Q-weak has produced the first direct measurement of the weak charge of the proton, with ~4% of the total data set.

The result is a 16.8% measurement of the PV asymmetry at $\langle Q^2 \rangle = 0.0250 \pm 0.0006\ (\mathrm{GeV}/c)^2$

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

This is a 18.7% measurement of the weak charge of the proton

$$Q^p_W(\text{PVES}) = 0.064 \pm 0.012$$

At the effective kinematics $Q^p_W(\text{SM}) = 0.0710 \pm 0.0007$

Weak charge of neutron using this data along with PVES and APV extracted as

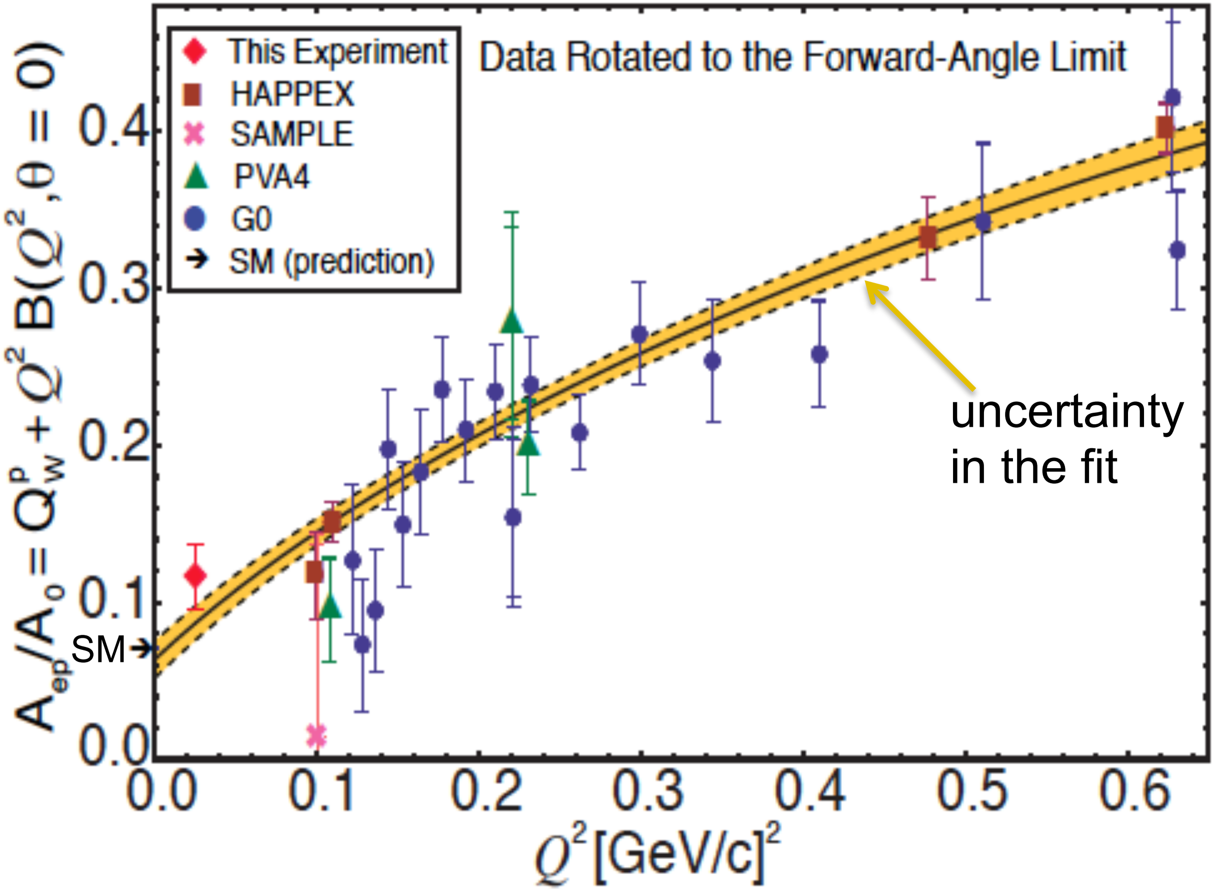
$$Q^n_W(\text{PVES+APV}) = -0.975 \pm 0.010$$

- Expect to report results with 5 times smaller uncertainties in about a year.
- Demonstrated the technological base for future high precision SM tests using PVES at an upgraded 12 GeV Jefferson Lab.

Q-weak with 4% Statistics

Global fit (solid line) presented in the forward angle limit as reduced asymmetries derived from this measurement as well as other Parity Violating Electron Scattering (PVES).

This is ~ 4% of total data set



Phys. Rev. Lett. 111, 141803 (2013)

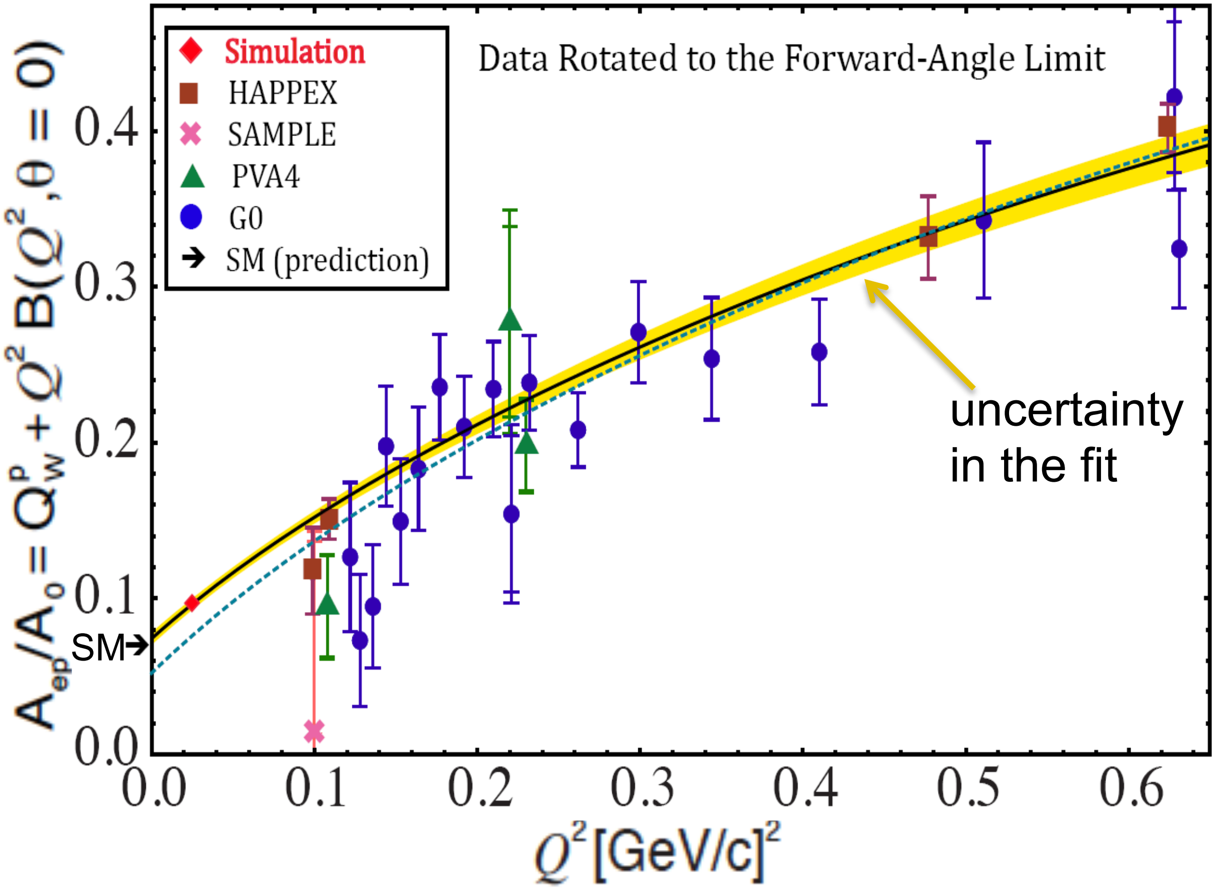
$$A_{ep} = \left[\frac{-G_F Q^2}{4\sqrt{2}\pi\alpha}\right]\left[Q^p_W + Q^2 B(Q^2,\theta)\right] = A_0\left[Q^p_W + Q^2 B(Q^2,\theta)\right]$$

$Q^p_W(\text{PVES}) = 0.064 \pm 0.012$

Simulated Q-weak with Full Statistics

Global fit (solid line) presented in the forward angle limit as reduced asymmetries derived from this measurement as well as other Parity Violating Electron Scattering (PVES).

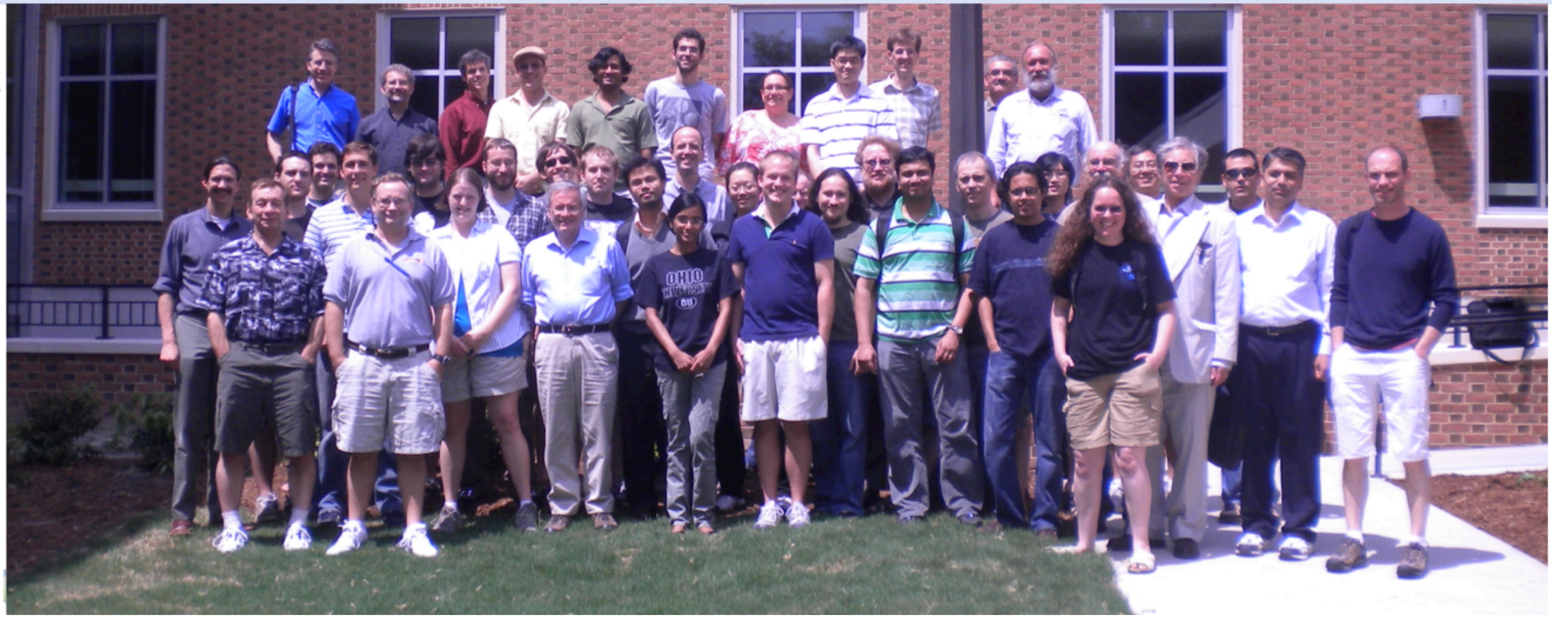
Simulated prediction for total data set.



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

The simulated Q-weak point is through SM prediction.

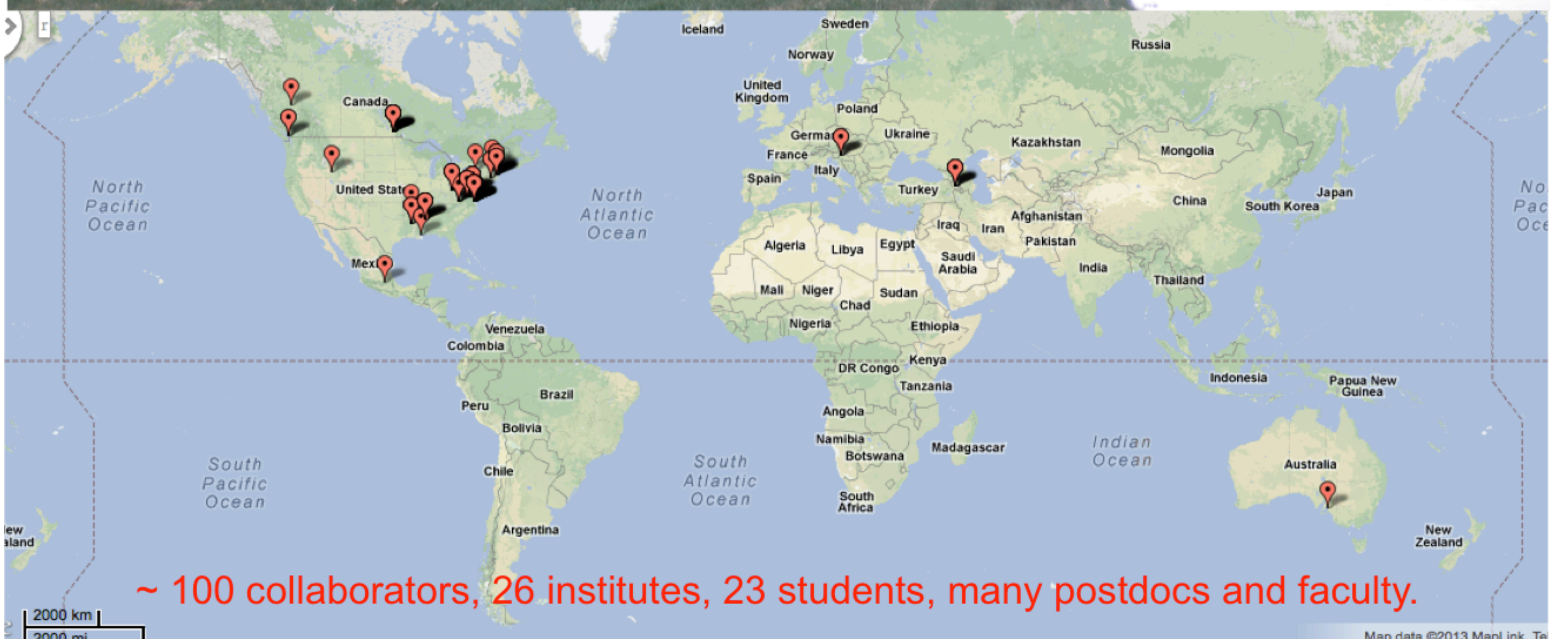
Q-weak Collaboration



D.S. Armstrong, A. Asaturyan, T. Averett, J. Balewski, J. Beaufait, R.S. Beminiwattha, J. Benesch, F. Benmokhtar, J. Birchall, R.D. Carlini[1], J.C. Cornejo, S. Covrig, M.M. Dalton, C.A. Davis, W. Deconinck, J. Diefenbach, K. Dow, J.F. Dowd, J.A. Dunne, D. Dutta, W.S. Duvall, M. Elaasar, W.R. Falk, J.M. Finn[1], T. Forest, D. Gaskell, M.T.W. Gericke, J. Grames, V.M. Gray, K. Grimm, F. Guo, J.R. Hoskins, K. Johnston, D. Jones, M. Jones, R. Jones, M. Kargiantoulakis, P.M. King, E. Korkmaz, S. Kowalski[1], J. Leacock, J. Leckey, A.R. Lee, J.H. Lee, L. Lee, S. MacEwan, D. Mack, J.A. Magee, R. Mahurin, J. Mammei, J. Martin, M.J. McHugh, J. Mei, R. Michaels, A. Micherdzinska, K.E. Myers, A. Mkrtchyan, H. Mkrtchyan, A. Narayan, L.Z. Ndukum, V. Nelyubin, Nuruzzaman, W.T.H van Oers, A.K. Opper, S.A. Page[1], J. Pan, K. Paschke, S.K. Phillips, M.L. Pitt, M. Poelker, J.F. Rajotte, W.D. Ramsay, J. Roche, B. Sawatzky,T. Seva, M.H. Shabestari, R. Silwal, N. Simicevic, G.R. Smith[2], P. Solvignon, D.T. Spayde, A. Subedi, R. Subedi, R. Suleiman, V. Tadevosyan, W.A. Tobias, V. Tvaskis, B. Waidyawansa, P. Wang, S.P. Wells, S.A. Wood, S. Yang, R.D. Young, S. Zhamkochyan

[1]Spokespersons [2]Project Manager Grad Students

Q-weak Collaboration



~ 100 collaborators, 26 institutes, 23 students, many postdocs and faculty.

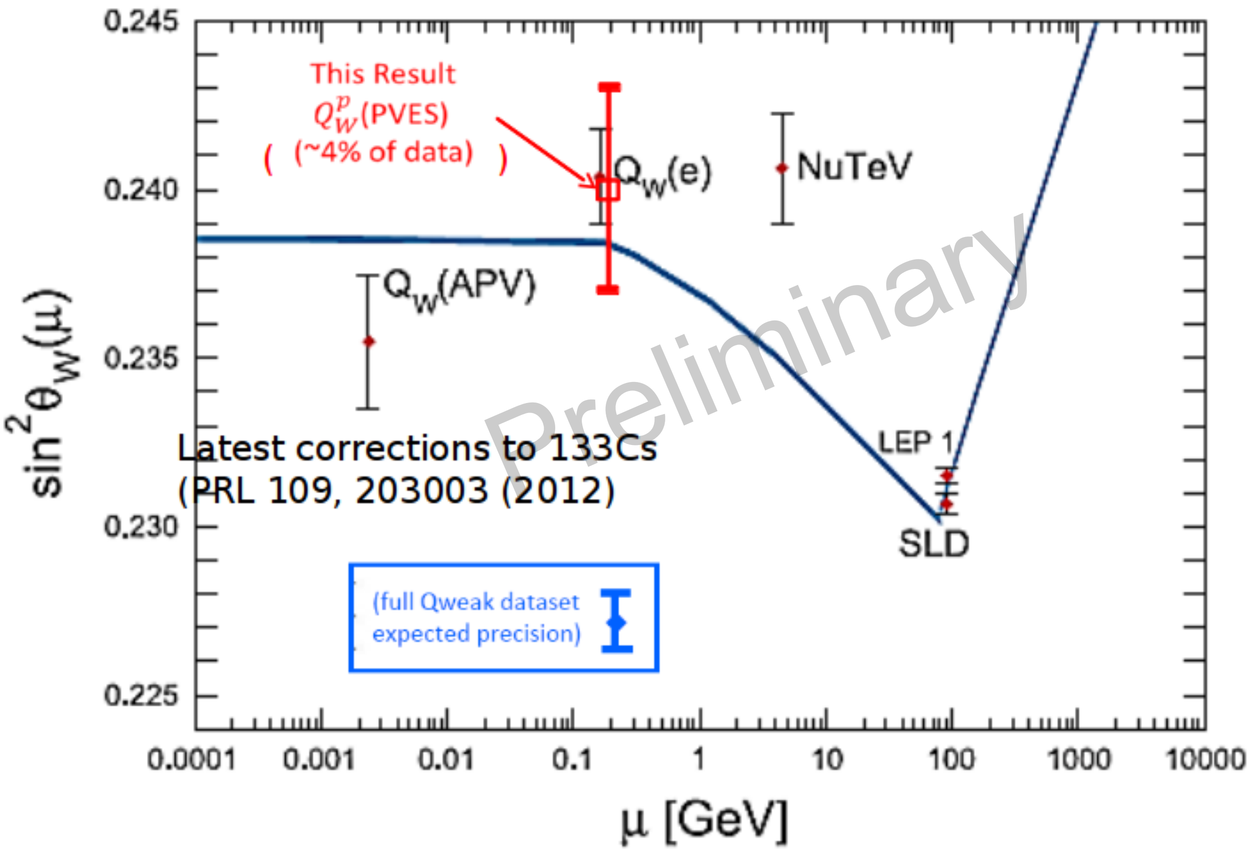
Backup Slides

Running of $\sin^2\theta_W$

The SM predicts the running of $\sin^2\theta_W(Q)$ based on the measurement done at the Z-pole.

Running of $\sin^2\theta_W$ is due to higher order RC varies with Q^2.

Q-weak will measure the $\sin^2\theta_W(Q)$ to 0.3% with full statistics.



Basics

Four forces: strong, weak, electromagnetic and gravitational.

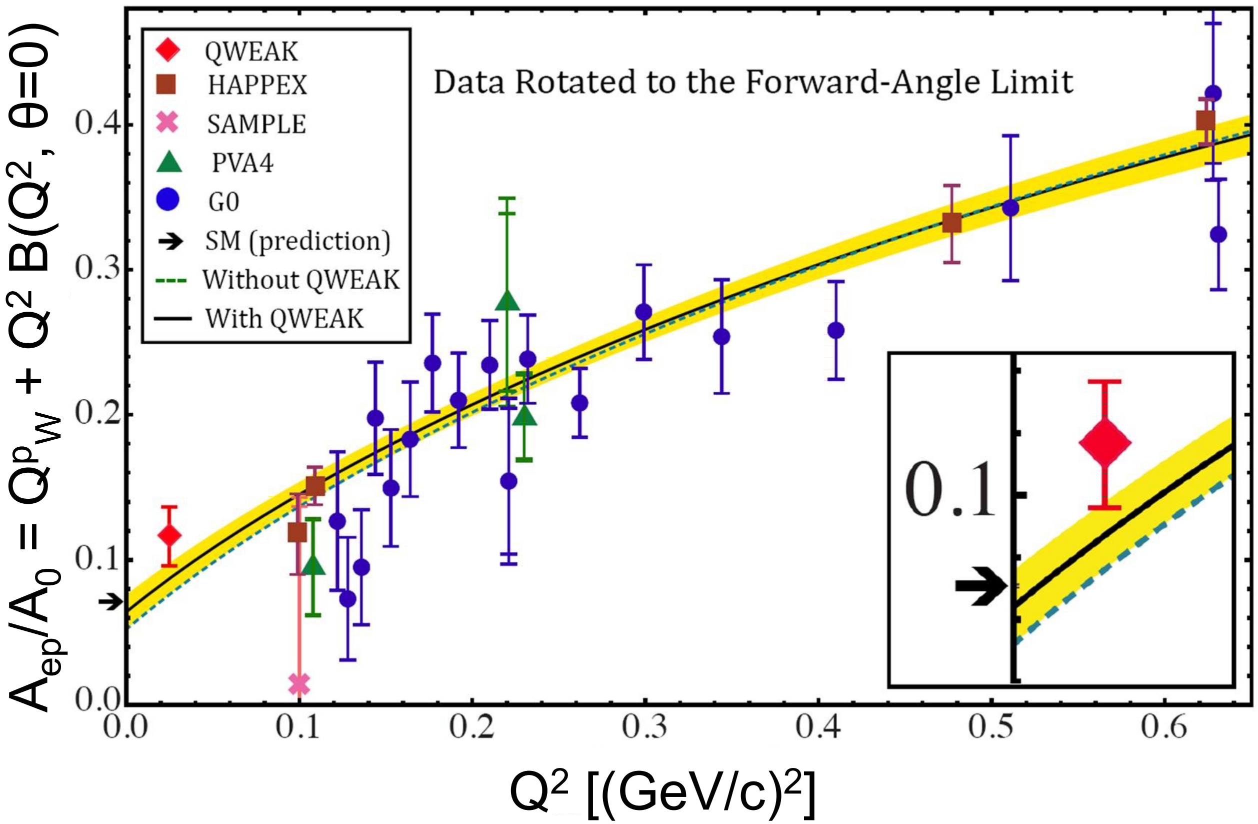
The proton, consisting of three quarks, is the simplest particle that experiences all the fundamental forces.

The strength of the weak force between interacting quarks and other weakly interacting particles can be characterized by their weak charge (distinct from their electric charge).

The weak force stands distinct because it violates a fundamental symmetry of nature called parity. This distinctness is often exploited to measure properties related to the weak force.

Result from 4% of Total Data

Global fit (solid line) presented in the forward angle limit as reduced asymmetries derived from this measurement as well as other Parity Violating Electron Scattering (PVES).



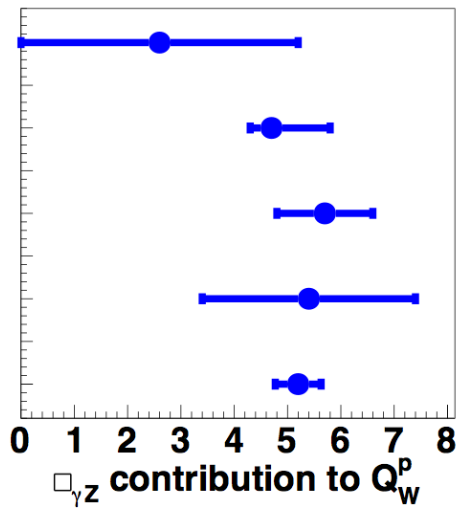
Electroweak Corrections

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

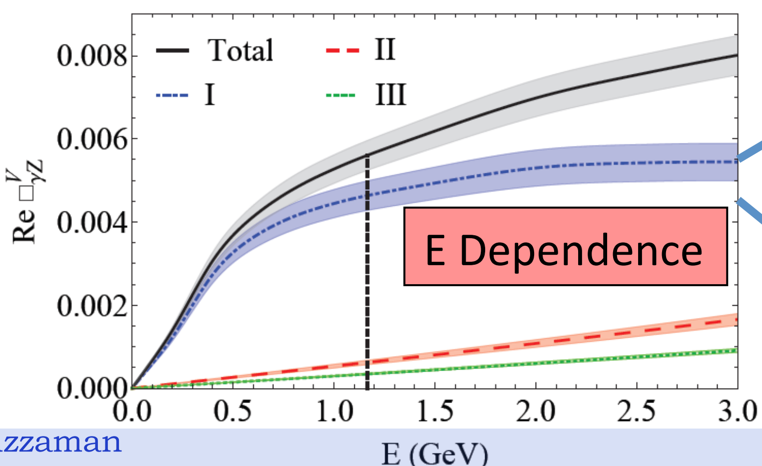
~7% correction

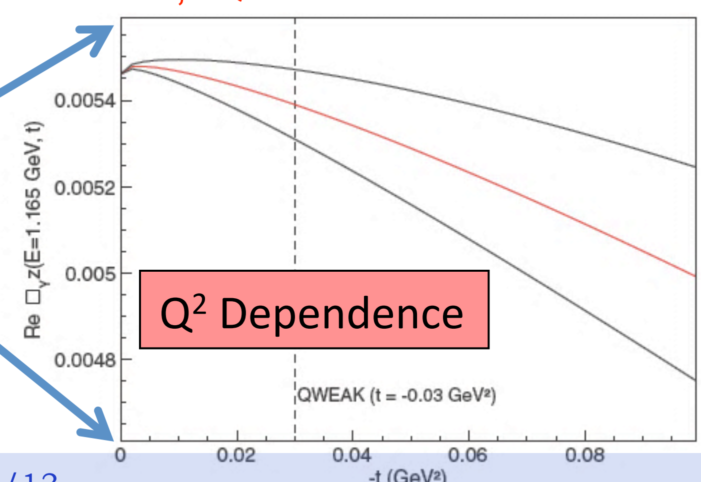
$\Box_{\gamma Z}$ contribution to Q_W^p (Qweak kinematics)

Gorchtein & Horowitz *PRL 102, 091806 (2009)*	0.0026 ± 0.0026
Sibirtsev, Blunden & Melnitchouk, Thomas *PRD 82, 013011 (2010)*	$0.0047^{+0.0011}_{-0.0004}$
Rislow & Carlson *PRD 83, 13007 (2011)*	0.0057 ± 0.0009
Gorchtein, Horowitz & Ramsey-Muslof *PRC 84, 015502 (2011)*	0.0054 ± 0.0020
Hall, Blunden, Melnitchouk, Thomas & Young *arXiv:1304:7877 (2013)* (calculation constrained by PVDIS data)	0.0052 ± 0.00043



- Calculations are primarily dispersion theory type
  - error estimates can be firmed up with data!
- Qweak: inelastic asymmetry data taken at W ~ 2.3 GeV, Q^2 = 0.09 GeV^2





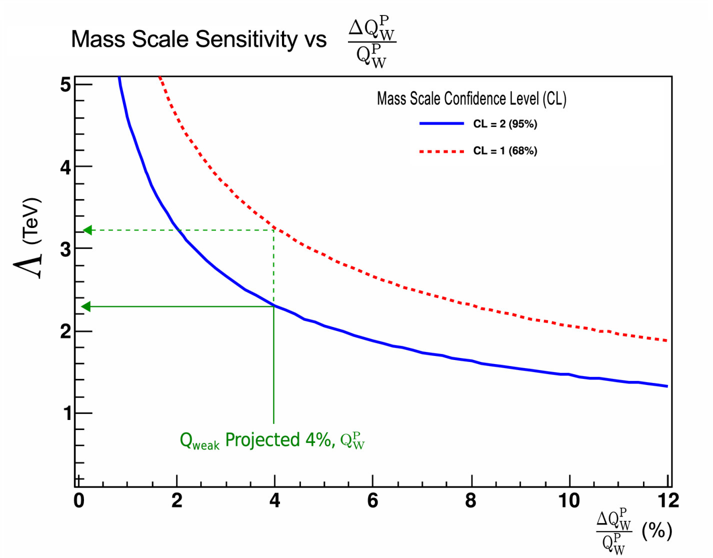
Global PVES Fit Details

- 5 free parameters ala Young, et al. PRL 99, 122003 (2007):
  - C_{1u}, C_{1d}, ρ_s, μ_s, & isovector axial FF G_A^Z
  - $G_E^S = \rho_s Q^2 G_D$, $G_M^S = \mu_s G_D$, & G_A^Z use G_D where
    - $G_D = (1 + Q^2/\lambda^2)^{-2}$ with $\lambda = 1$ GeV/c
- Employs all PVES data up to Q^2=0.63 $(GeV/c)^2$
  - On p, d, & ^{4}He targets, forward and back-angle data
    - SAMPLE, HAPPEX, G0, PVA4
- Uses constraints on isoscalar axial FF G_A^Z
  - Zhu, et al., PRD 62, 033008 (2000)
- All data corrected for E & Q^2 dependence of $\Box_{\gamma Z}$ RC
  - Hall et al., arXiv:1304.7877 (2013) & Gorchtein et al., PRC84, 015502 (2011)
- Effects of varying Q^2, θ, & λ studied, found to be small

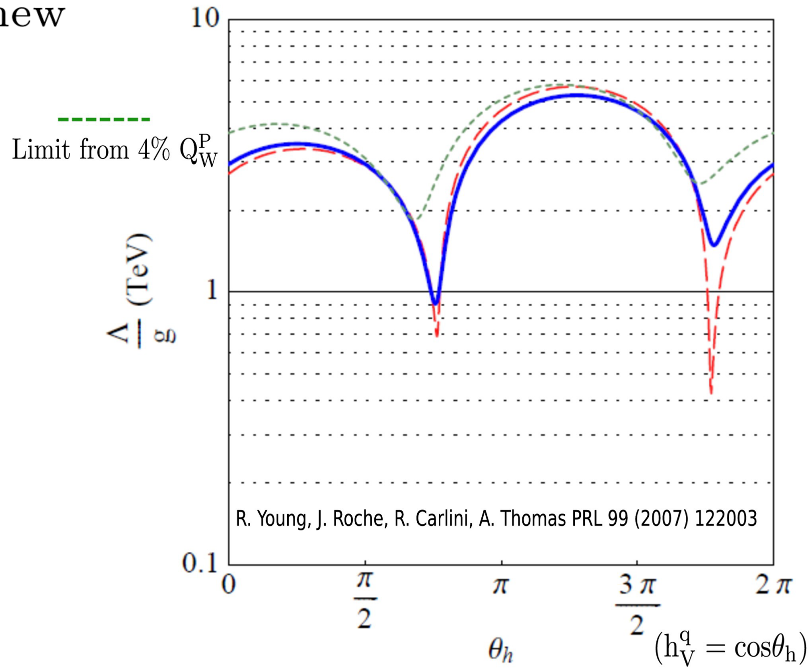
Model Independent Constraint, New PV Physics

$$L^{PV}_{eff} = \underbrace{-\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \cdot \sum_q C_{1q}\bar{q}\gamma^\mu q}_{L^{PV}_{SM}} + \underbrace{\frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h^q_V \bar{q}\gamma^\mu q}_{L^{PV}_{new}}$$

$$h^u_V = \cos\theta_h$$
$$h^d_V = \sin\theta_h$$



g is the new physics coupling while Λ is the new PV physics mass scale



The bounds on new quark-lepton PV physics scale

New physics is ruled out below the curve at 95% C.L.

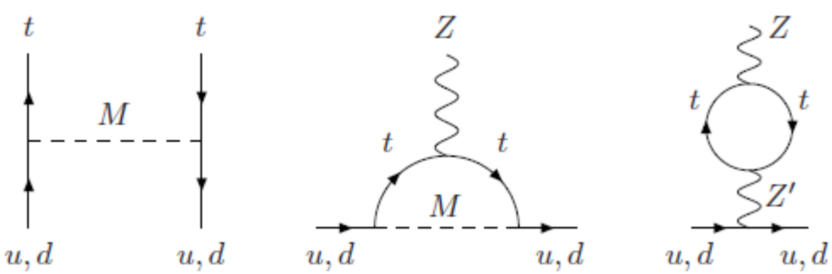
$$\delta Q^P_W = (Q^P_W)_{Q_{Weak}} - (Q^P_W)_{SM}$$

Model Dependent New Physics

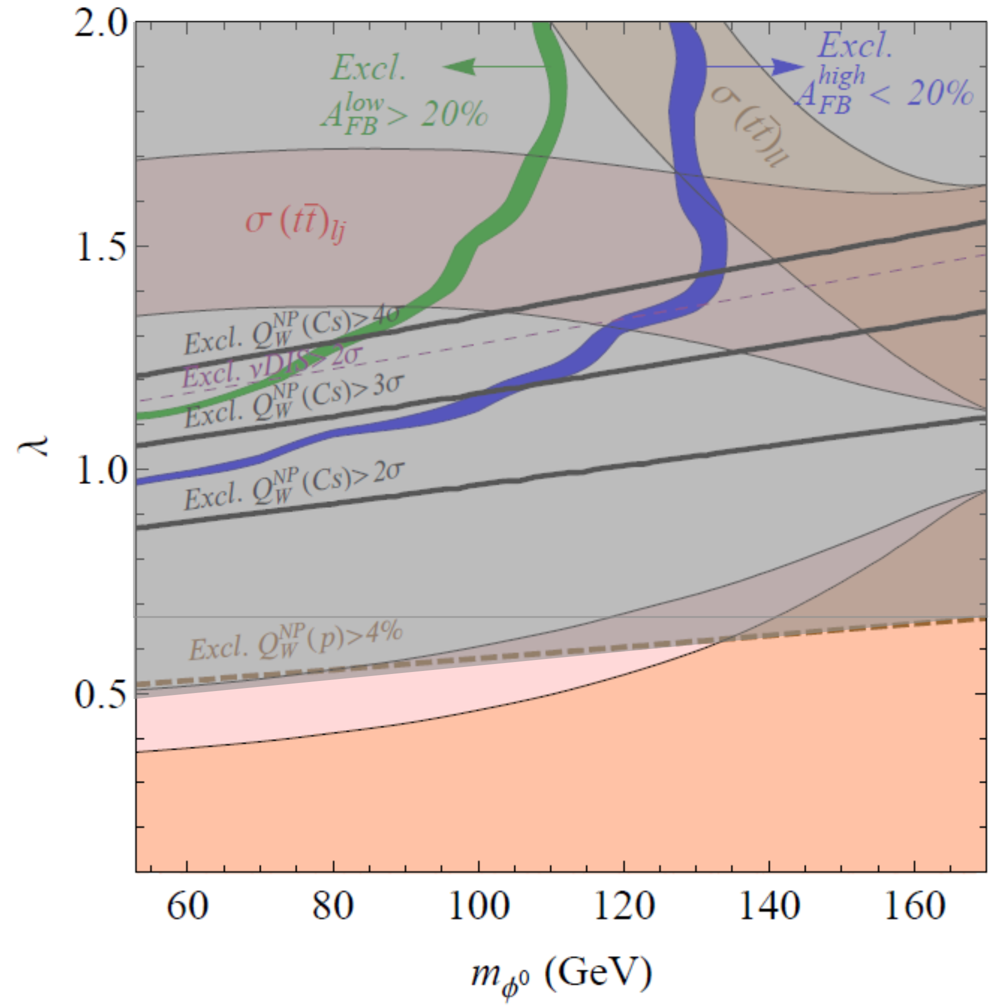
CDF and D0 results of the forward backward asymmetry A_{FB}

- Results favored t production in the incoming proton direction and $\bar{t}$ in the anti-proton direction
- Observed A_{FB} = 0.475 ± 0.114 a 3.4σ deviation from SM next-to-leading order prediction of 0.088 ± 0.013

New physics models could account for the excess



Plot show how PV constraints could exclude certain models as the source of excess A_{FB}



Gresham et.al. arXiv:1203.1320 [hep-ph]

title

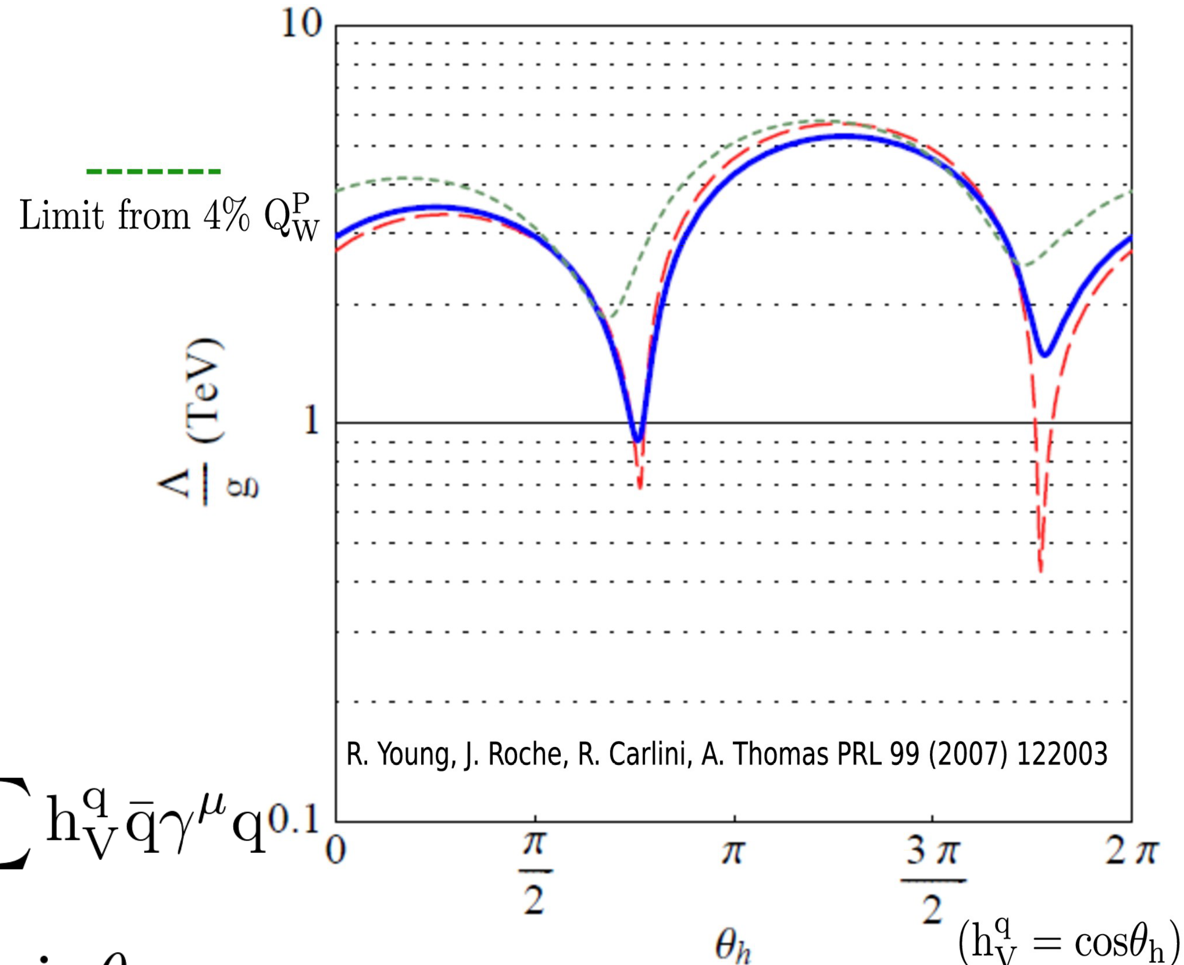
Even with only 4% of the full data set, Q-weak significantly constrains new physics scenarios.

Model independent mass reach (95% CL) comparable to LHC limits:

Mass scale over coupling of new physics

$$\frac{\Lambda}{g} \approx \frac{1}{2} \frac{1}{\sqrt{\sqrt{2}\, G_F \left|\Delta Q_w^p\right|}} \sim 1.1\ TeV$$

Strongly coupled theories have g2~4π.
Separate limits can be quoted for models that interfere constructively and destructively with the Standard Model.



$$L_{new}^{PV} = \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

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

Why Considering Only C_{1u}, C_{1d}

Standart Model Parameters		
	Tree Level	Rad. Corr. + New Phys.
C_{1u}	$-\frac{1}{2}\left(1-\frac{8}{3}\sin^2\theta_W\right)$	$-\frac{1}{2}\rho'_{eq}\left(1-\frac{8}{3}\kappa'_{eq}\sin^2\theta_W\right)+\lambda_{1u}$
C_{1d}	$-\frac{1}{2}\left(-1+\frac{4}{3}\sin^2\theta_W\right)$	$-\frac{1}{2}\rho'_{eq}\left(-1+\frac{4}{3}\kappa'_{eq}\sin^2\theta_W\right)+\lambda_{1d}$
C_{1s}	$-\frac{1}{2}\left(1-\frac{8}{3}\sin^2\theta_W\right)$	$-\frac{1}{2}\rho'_{eq}\left(1-\frac{8}{3}\kappa'_{eq}\sin^2\theta_W\right)+\lambda_{1s}$
C_{2u}	$-\frac{1}{2}\left(1-4\sin^2\theta_W\right)$	$-\frac{1}{2}\rho_{eq}\left(1-4\kappa_{eq}\sin^2\theta_W\right)+\lambda_{2u}$
C_{2d}	$\frac{1}{2}\left(1-4\sin^2\theta_W\right)$	$\frac{1}{2}\rho_{eq}\left(1-4\kappa_{eq}\sin^2\theta_W\right)+\lambda_{2d}$
C_{2s}	$\frac{1}{2}\left(1-4\sin^2\theta_W\right)$	$\frac{1}{2}\rho_{eq}\left(1-4\kappa_{eq}\sin^2\theta_W\right)+\lambda_{2s}$

Strongly suppressed by design kinematics

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

Parity Violating Electron Scattering

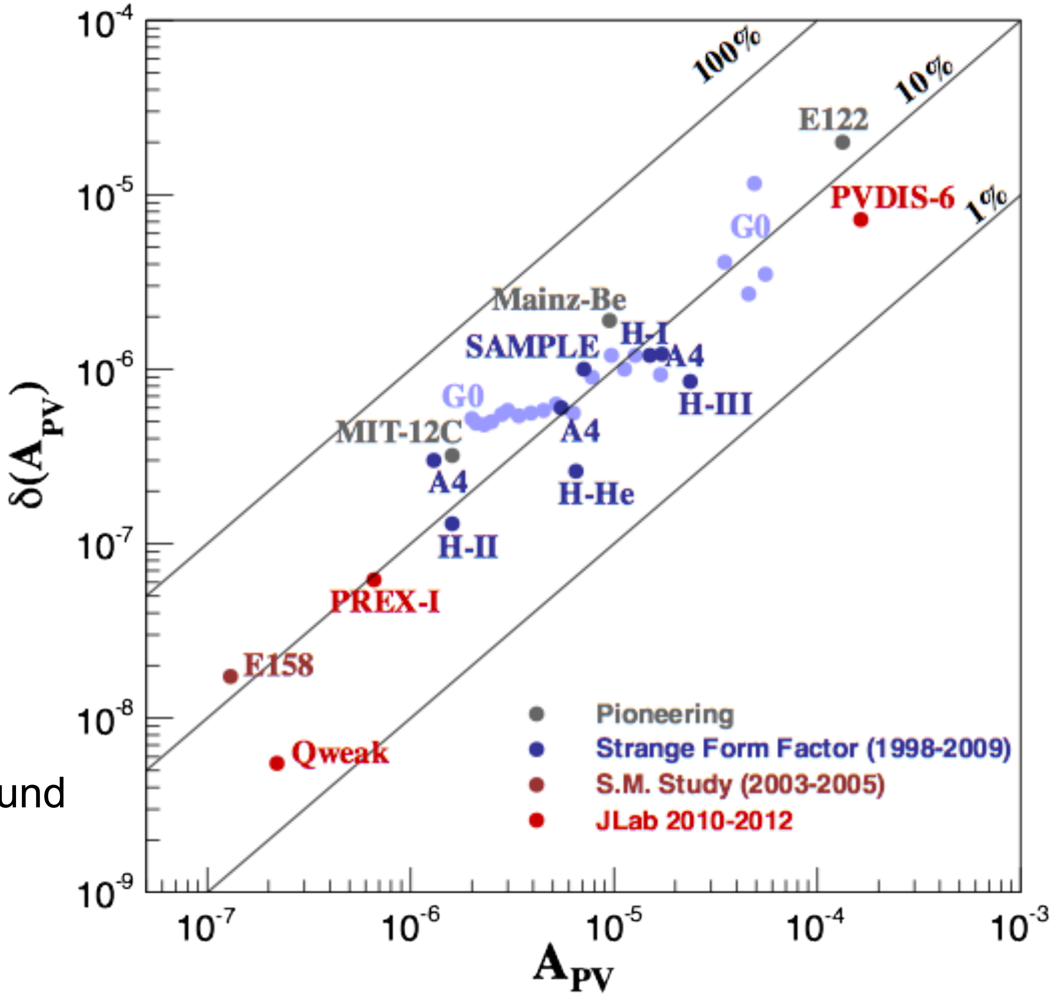
Strategy

Maximize Statistics:
Small counting statistics
high polarization, high current
high power cyrogenic hydrogen target
large acceptance high count rate
detectors/electronics

Minimize Noise:
target density fluctuations
electronics noise (in integrating mode)
detector resolution

Systematics:
Minimize helicity-correlated beam properties
Isolate elastic scattering from background
Precision electron beam polarimetry
Precision Q^2 determination

Q-weak will be most precise (relative and absolute) PVES result to date.



Backgrounds and Corrections

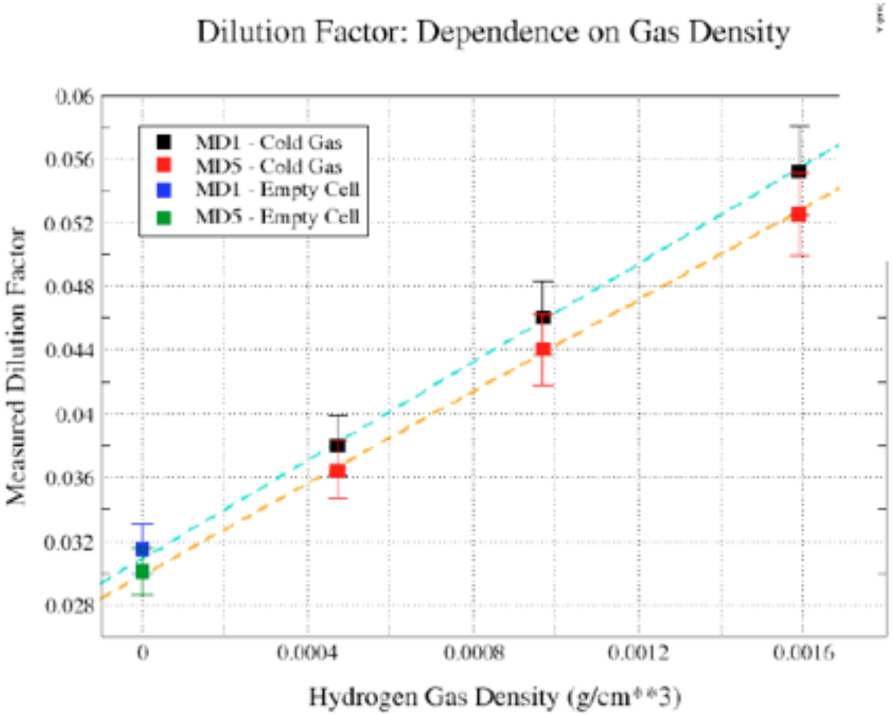
Aluminum Window Background

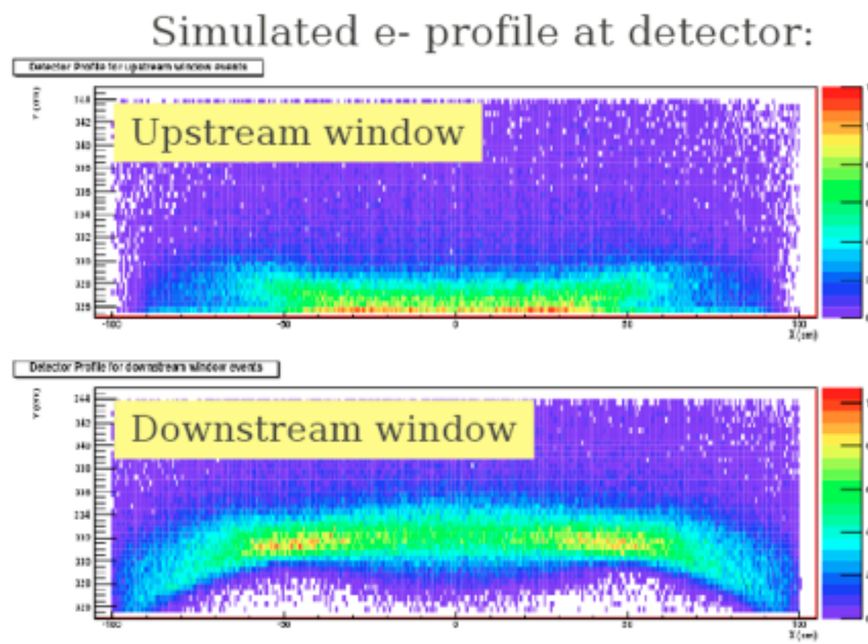
Large asymmetry and high fraction make this a big effect.

Correction driven by measurement.

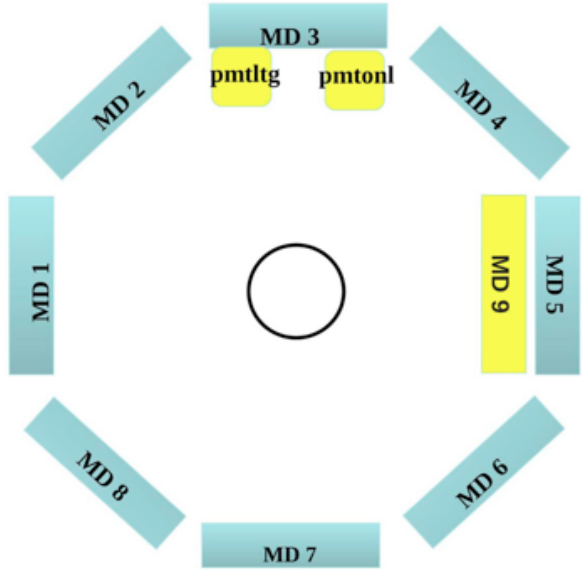
A_{b1} = 1.76 ± 0.26 ppm
f_{b1} = 3.23 ± 0.24 %

- Rate from windows measured with empty target (actual windows)
- Corrected for effect of hydrogen using simulation and data driven models of elastic and QE scattering.
- Asymmetry measured from thick Al target
- Measured asymmetry agrees with expectations from scaling.





Beamline Scattering

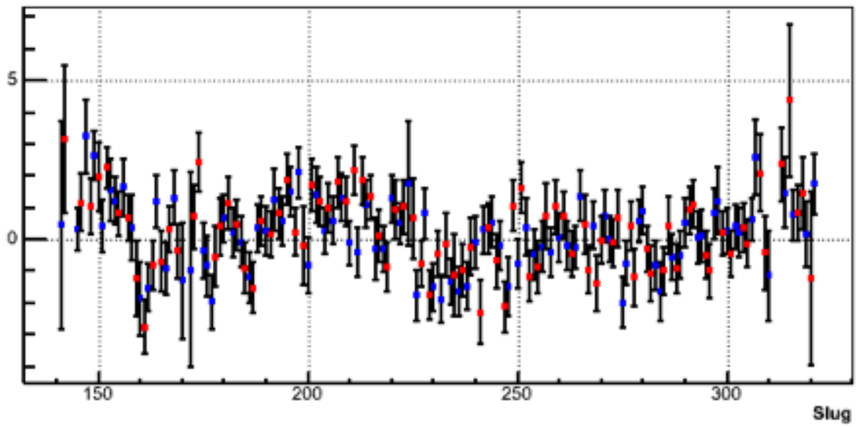


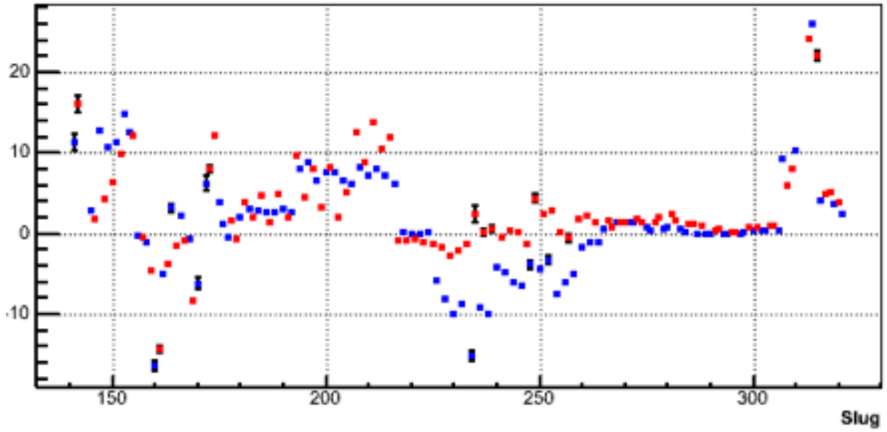
- Various "background" detectors observed
- highly correlated non-zero asymmetriesAsymmetries were primarily from beamline background (hypothesis: asymmetric “beam halo” events interacting in Tungsten beam collimator and beamline)
- Beamline background contributes only ~0.19% to the signal of the main detectors.Background detectors provided continuous monitoring of any asymmetry associated with this background
- Correction is determined from the upstream lumis.
- Relationship to main detector determined using a variety of methods (including direct blocking of primary events), appears to be well understood.

$f_{b2} = 0.19 \pm 0.10$ %

$C_{b2} = 11 \pm 3$ ppb

Example of the correlation between background detectors.





Other Neutrals

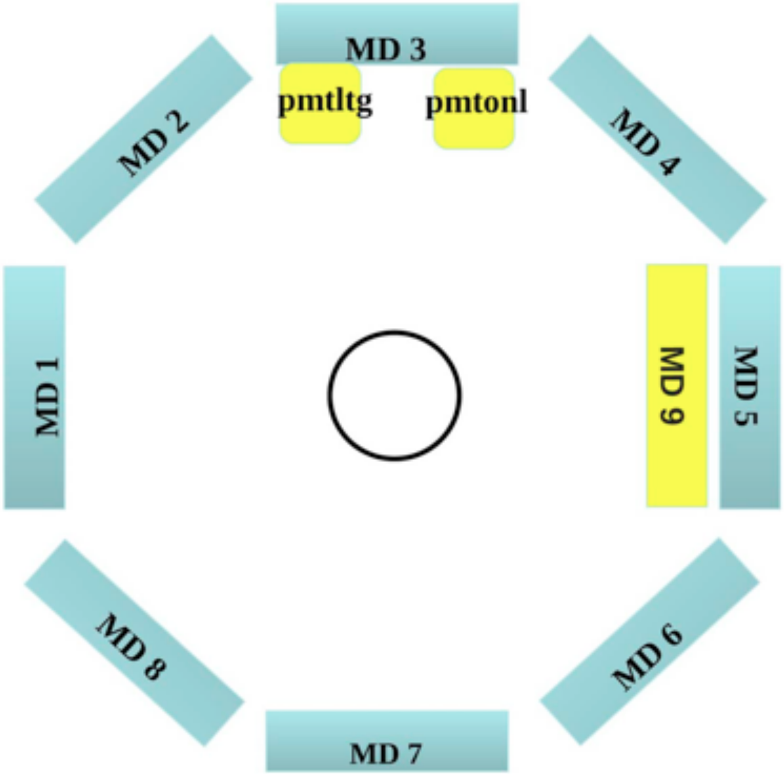
Blocked octant studies allow measurement of background fraction

Background fraction Main detectors - 0.19%
MD9 - 9.4%
USlumi - 60%
background detectors -100%

Ratio of background fraction
pmtonl/uslumi = 1.7
pmtltg/uslumi = 1.7
MD9/uslumi = 0.16

Ratios of measured asymmetries replicate these numbers well.

A_{b3} = -5.5 +/- 11.5 ppm
f_{b3} = 0.2 ± 0.2 %

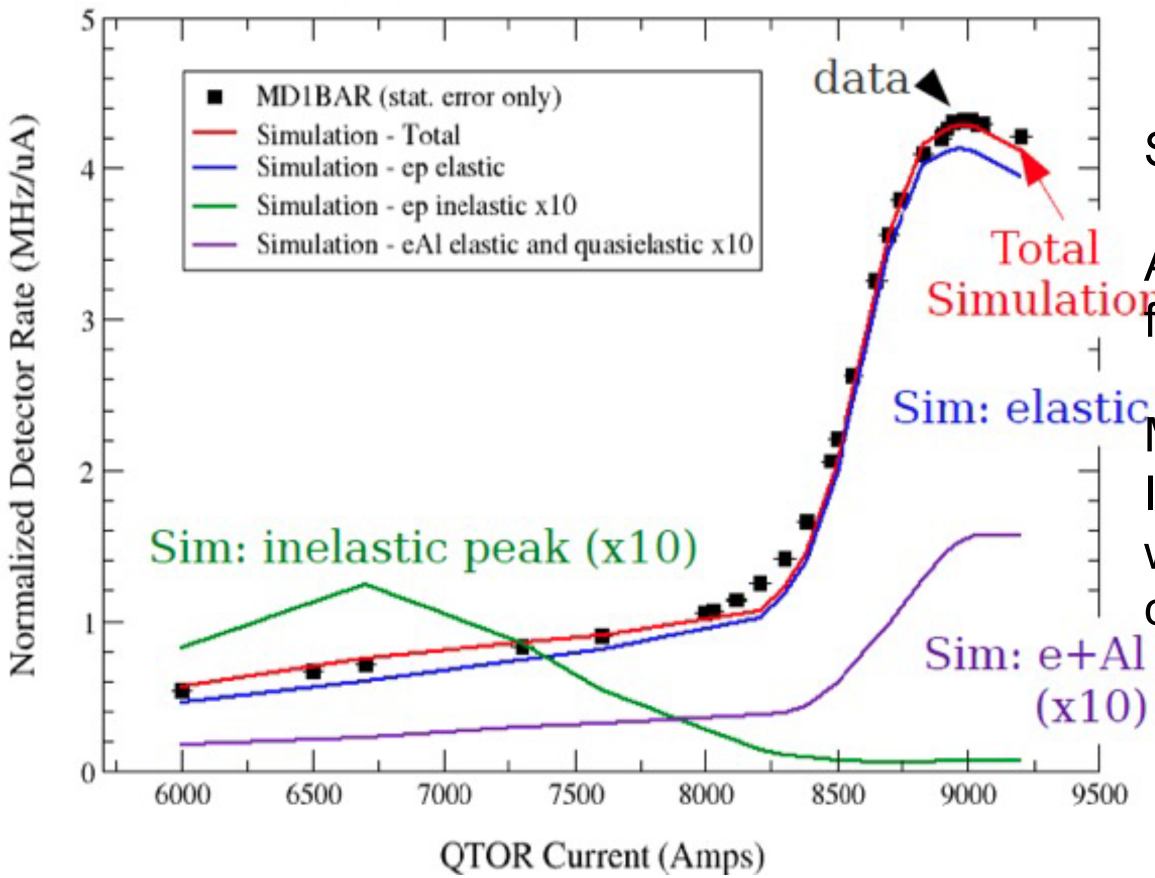


Background detector orientations

Inelastic Background

Negligible effect for Run-0

Spectrometer magnet current scan

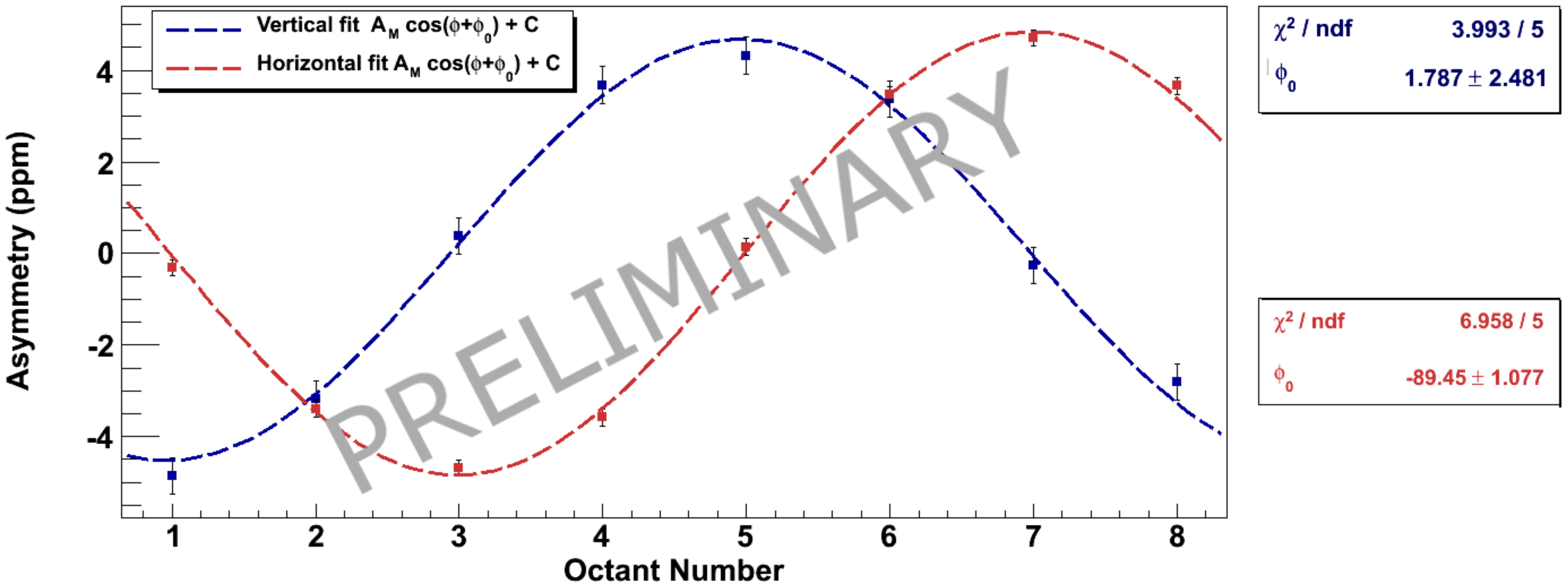


Simulated contribution very small.

A_{b4} = 3.02 ± 0.97 ppm
f_{b4} = 0.02 ± 0.02 %

More asymmetry data on tape.
Improved simulation efforts will yield much more precise contribution.

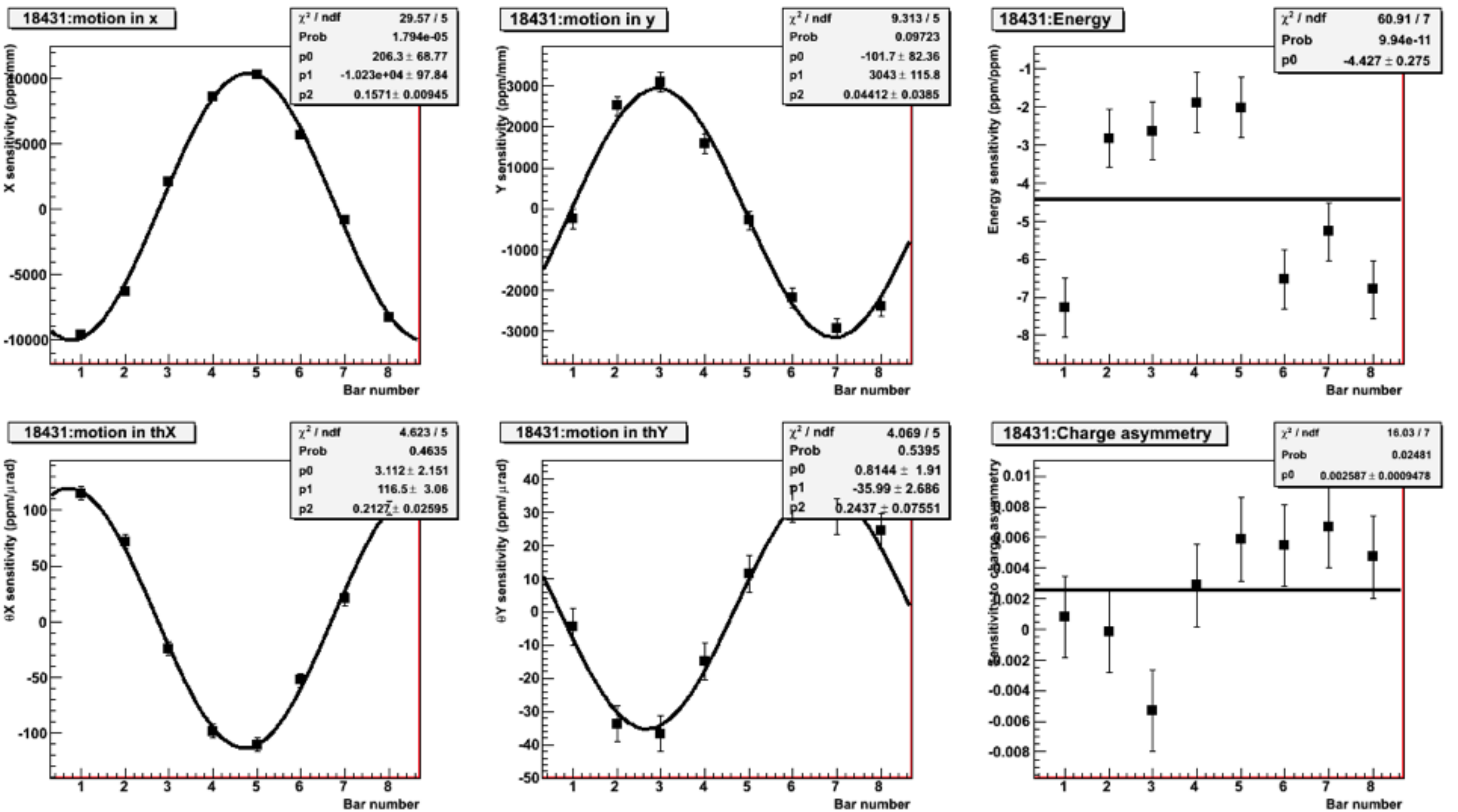
Transverse Asymmetries



Raw physics asymmetries = AVG(IN asymmetry – OUT asymmetry)

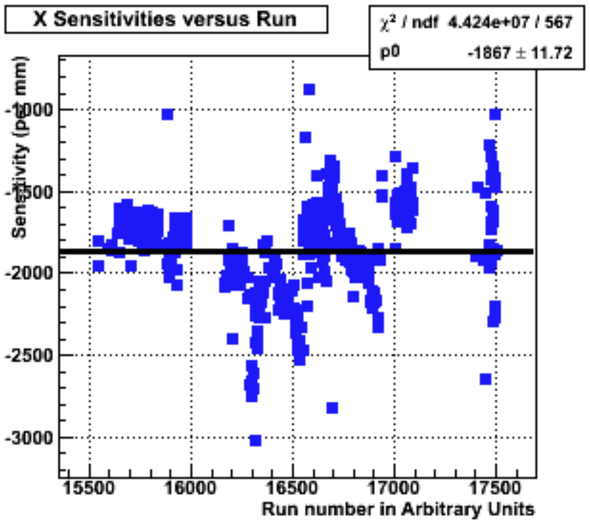
- Not corrected for backgrounds and polarization.
- 90 degree phase offset seen between Vertical and Horizontal fits (as expected).

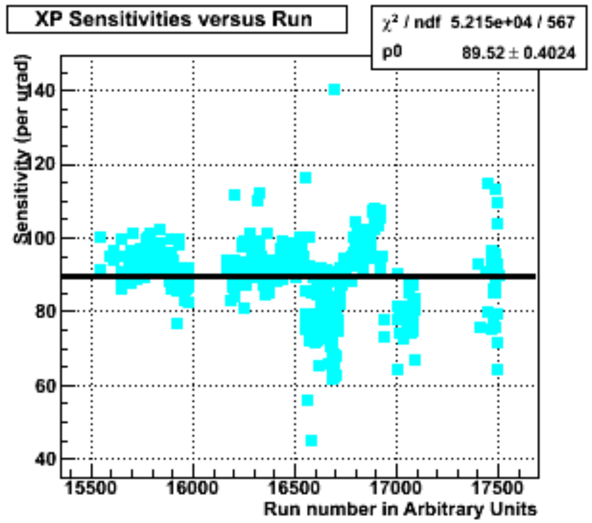
MD Sensitivities from Natural Beam Jitter

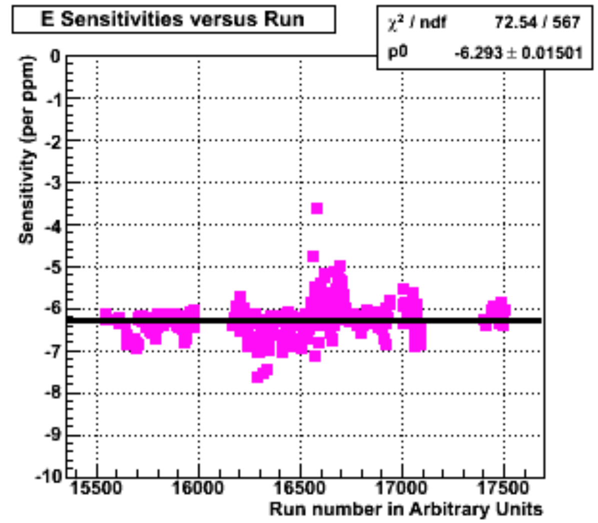


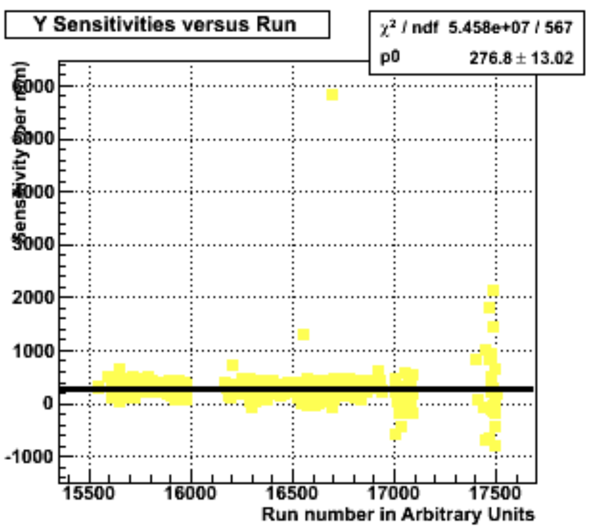
MD Sensitivities from Beam Modulation

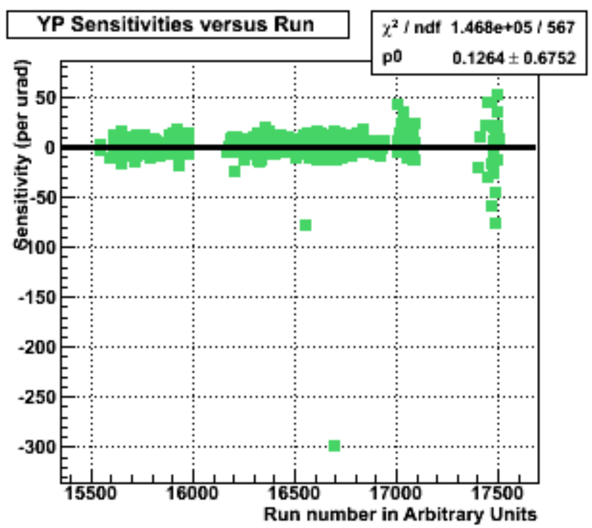
Stability of modulation sensitivities over time







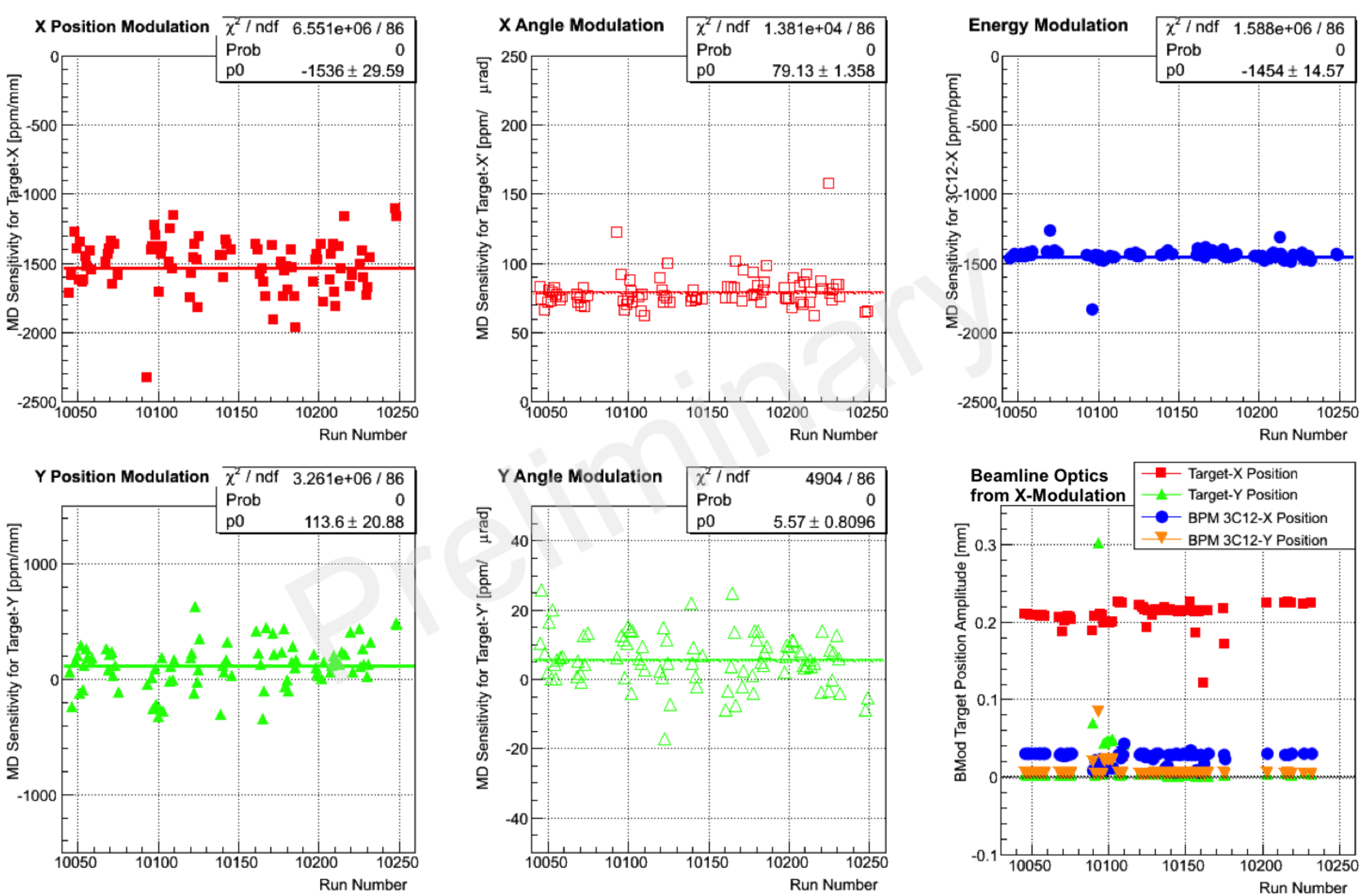




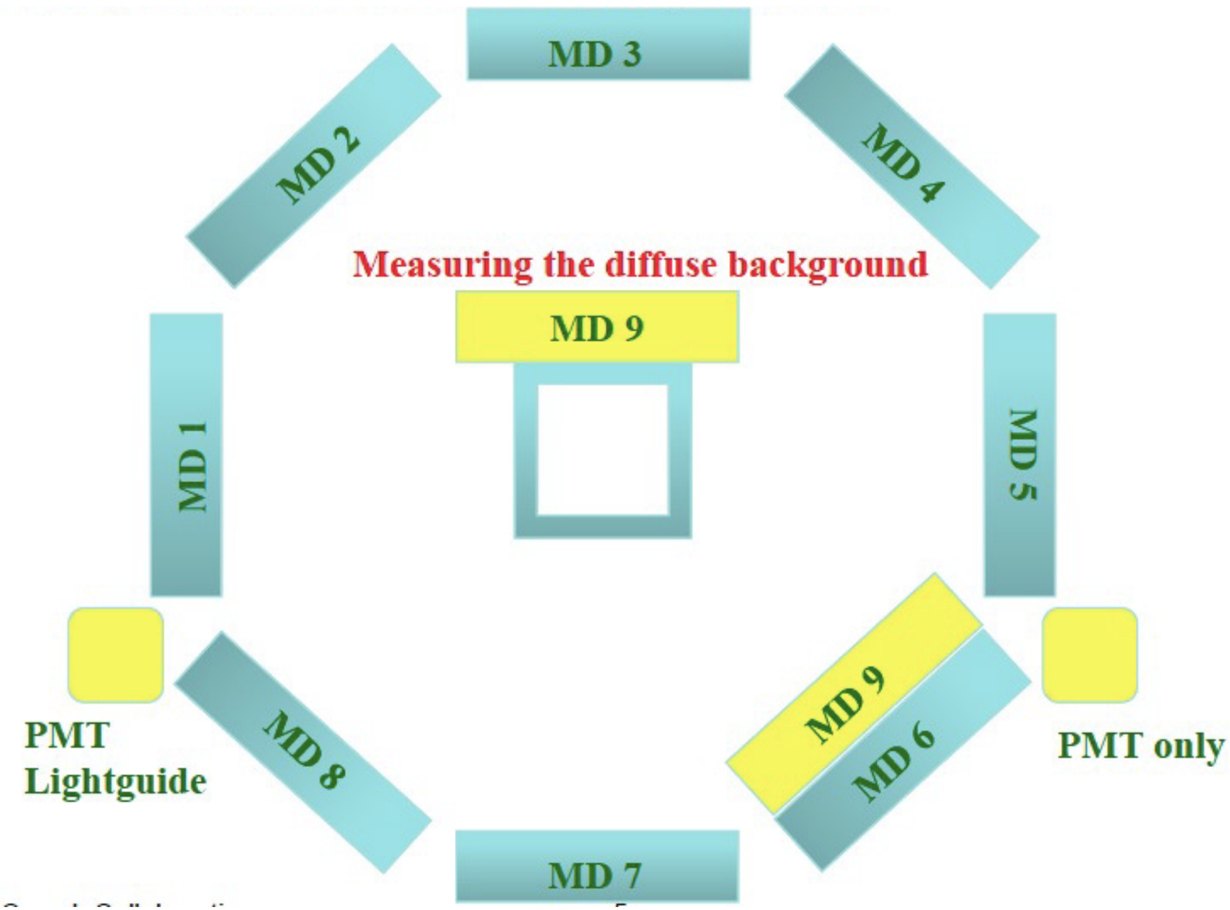
Position diferences:
dX = 100 um
dX' = 3 urad
dY = 100 um
dY' = 3 urad
d(3c12X) = 250 um

MD Sensitivities from Beam Modulation

Stability of modulation sensitivities over time



Background Detectors During Run-0

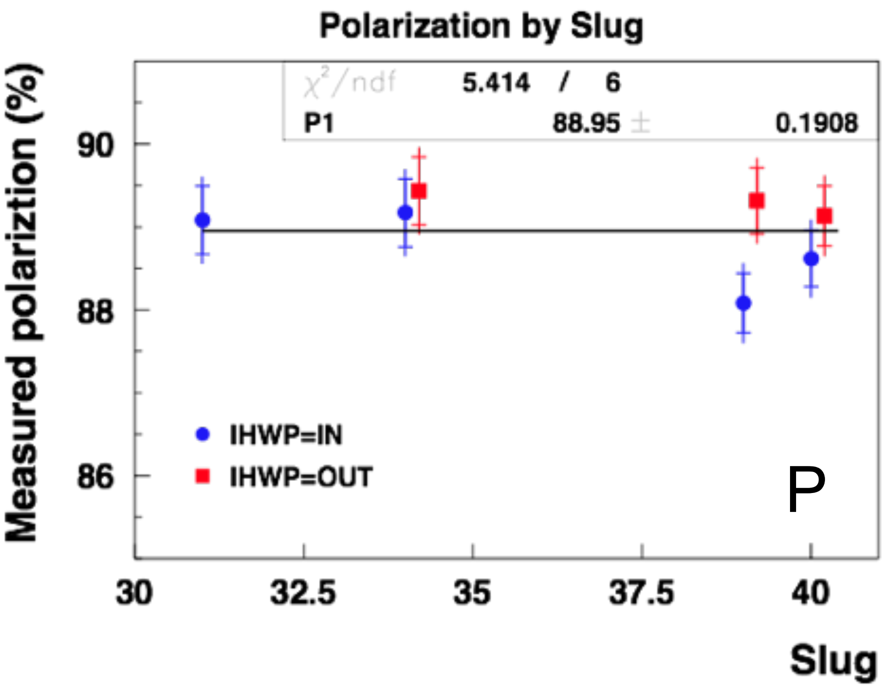


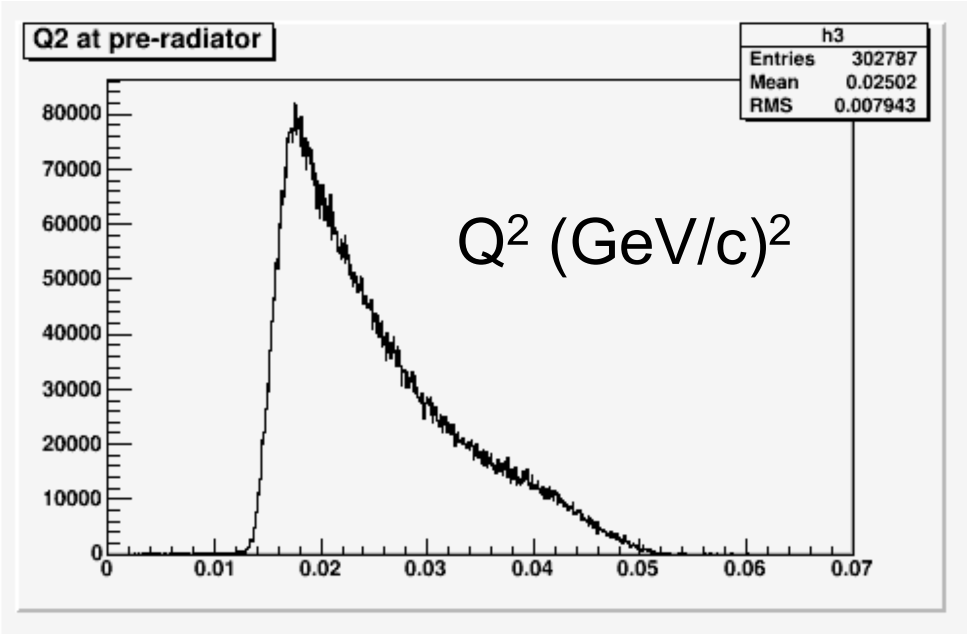
Normalization

Kinematics determined from detailed simulation. Radiative corrections are applied to the asymmetry.

$\langle E_{beam} \rangle = 1155$ MeV
$\langle Q^2 \rangle = 0.0250 \pm 0.0006\ (GeV/c)^2$(2.4% rel)
$\theta_{eff} = 7.90$

Measured polarization using Moller Polarimeter P = 88.95 ± 1.83 % (2% rel)

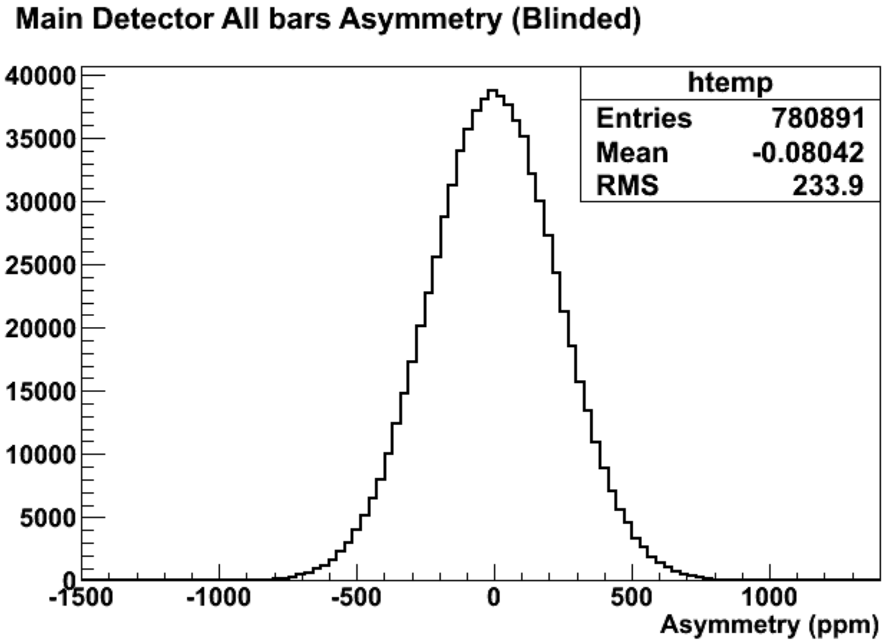




Q-weak Performance

$$A_{msr} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

$$\Delta A = \frac{\sigma_A}{\sqrt{N_{quartets}}}$$

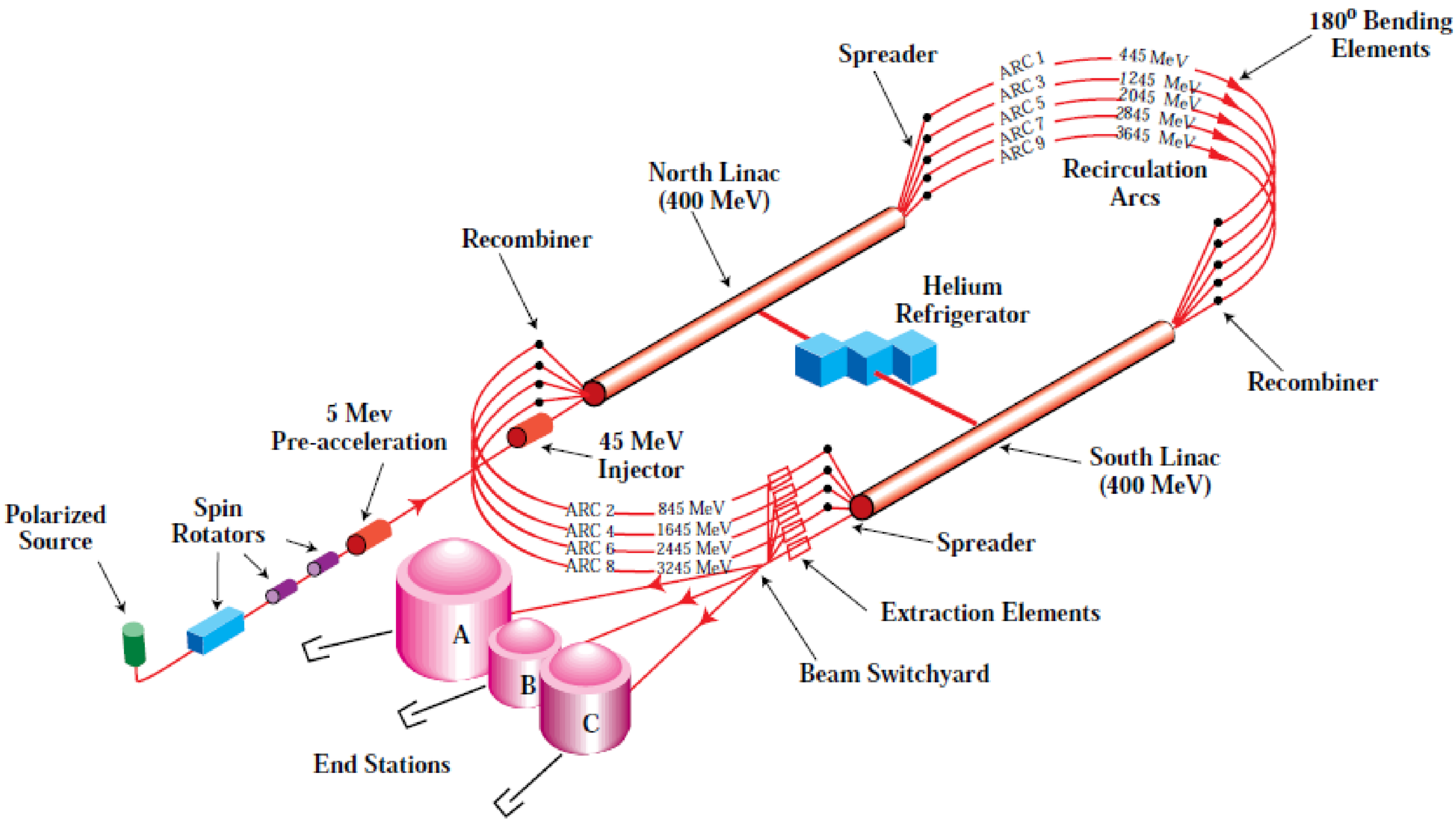


Sample asymmetry at beam current of ~180 μA

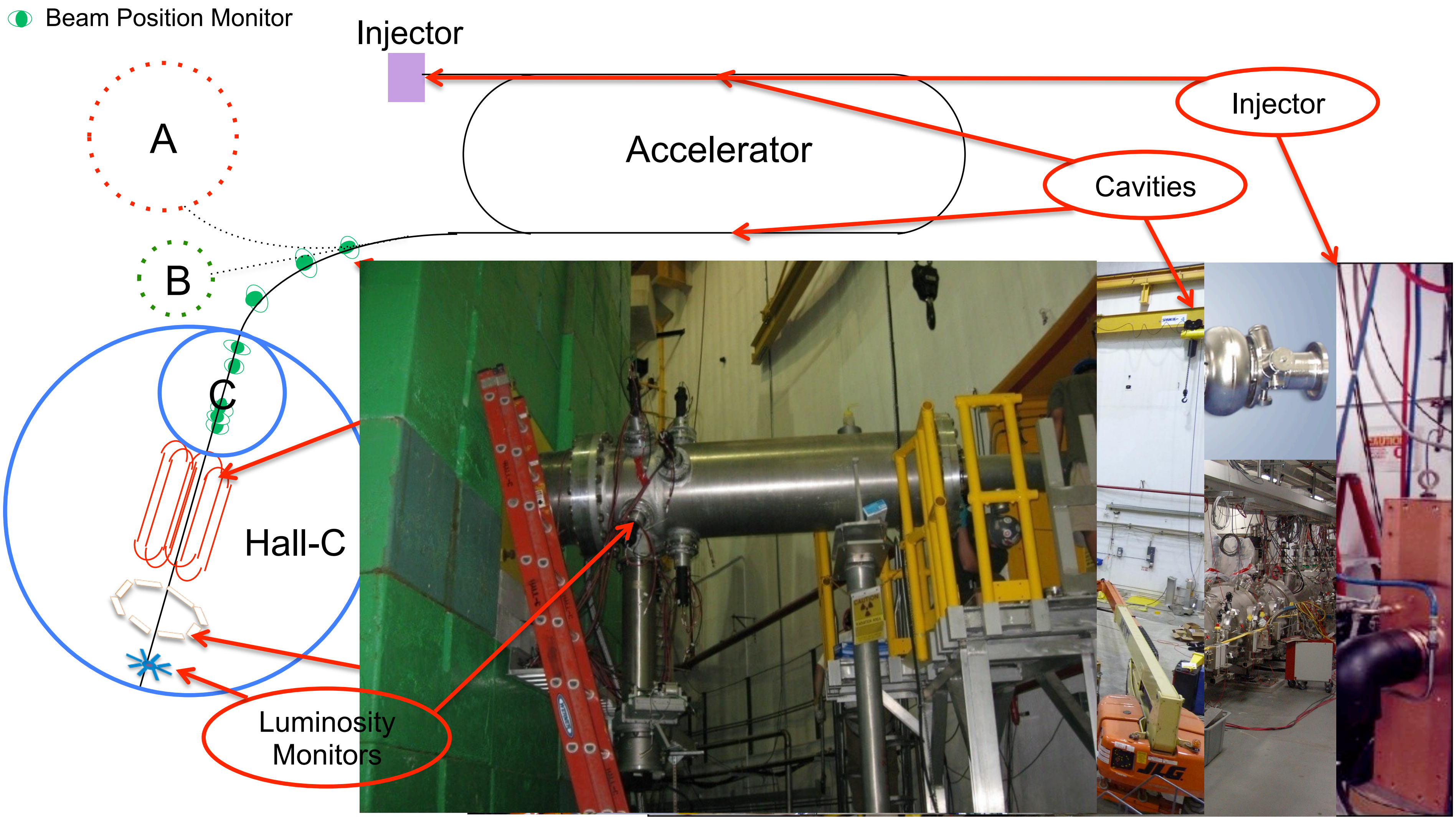
Contribution	Width	
Pure counting statistics	201	ppm
Detector Resolution	92	ppm
Current monitor resolution	50	ppm
Target boiling	57	ppm
Total (observed)	233.7	ppm

Experimental

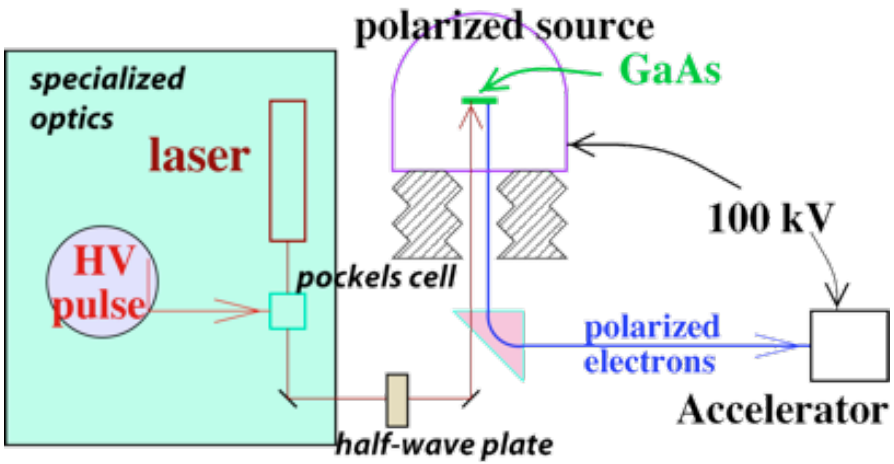
Jefferson Lab

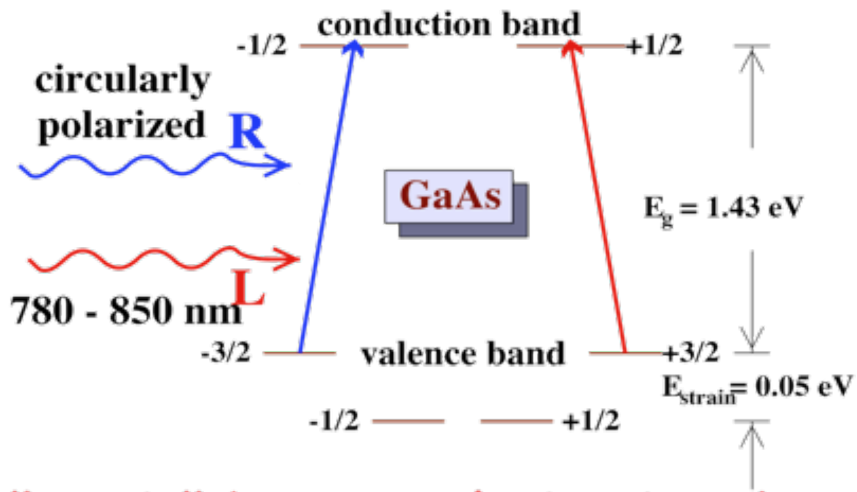


Jefferson Lab Beamline Sketch



Polarized Source

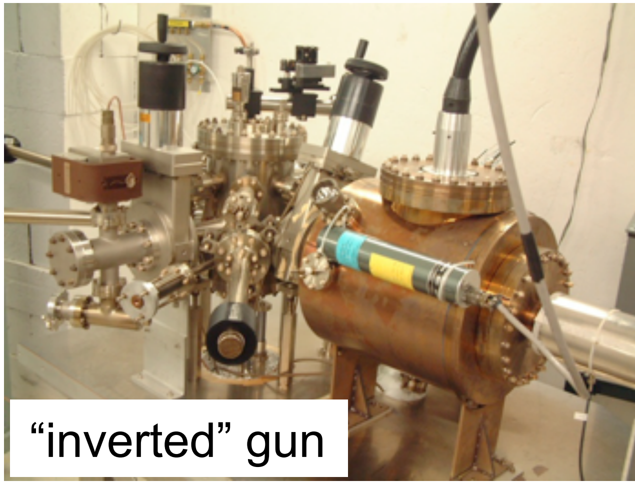




"strain" boosts polarization, but introduces anisotropy in response

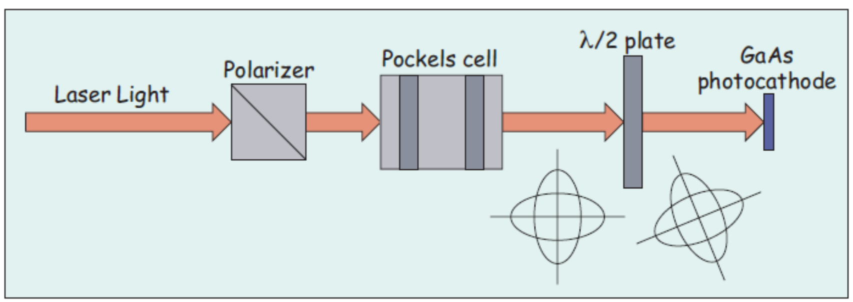
Helicity changed by changing Pockels Cell voltage.

Recent developments
- New “inverted” gun
- 130 kV extraction: increase cathode lifetime, decrease space charge blowup for high current,
- New vertical Wien and solenoid to allow a second slow flip

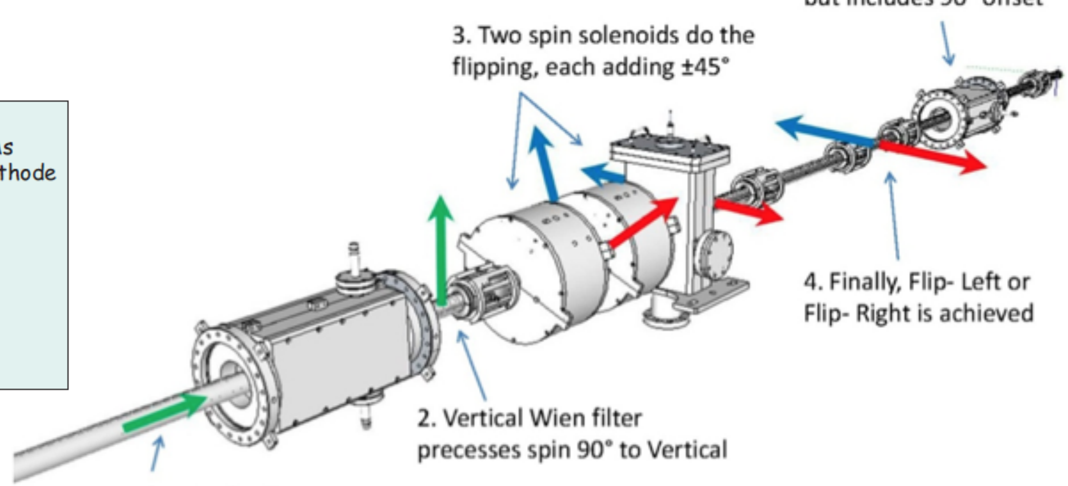

“inverted” gun

Slow Reversals of Signal

Insertable Half Wave Plate
Optical element on laser table which reverses
the sign of the laser helicity with respect to the sign Pockels Cell high voltage.
~300 total HWP reversals, each about 8 hours of good data, called “slugs”
Measurements should have same magnitude
and opposite sign. The sum (or null asymmetry) should be zero.



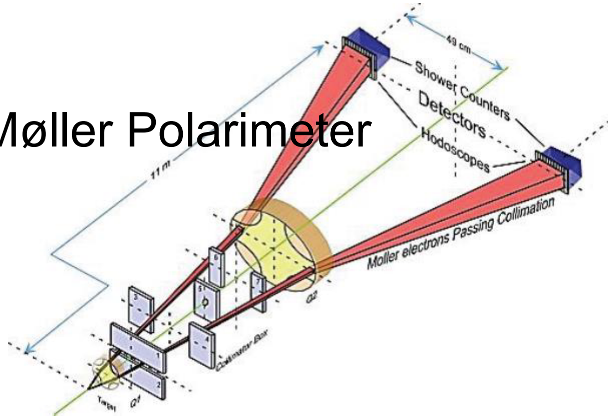
“Double Wien” spin manipulator
Vertical Wien filter followed by a solenoid and
then a horizontal-Wien. Allows reversal between the laser helicity and the experimental electrons.
11 total opposing “Wien” periods ~1 month of data in each

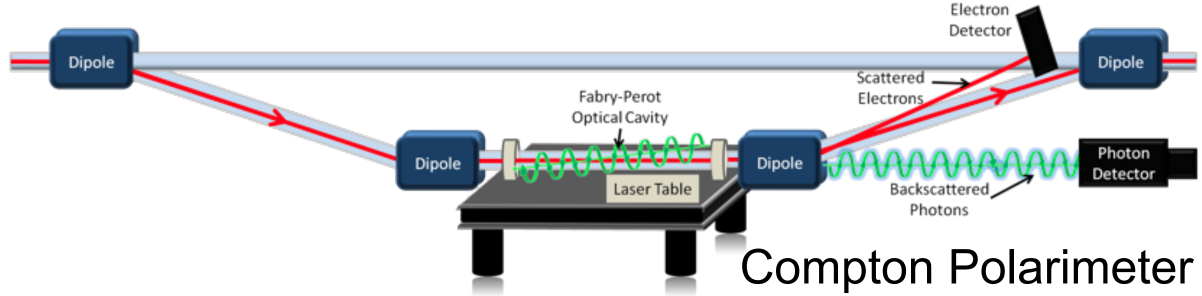


Polarimetry

Two independent polarimeters were used to measure beam polarization:

Møller Polarimeter



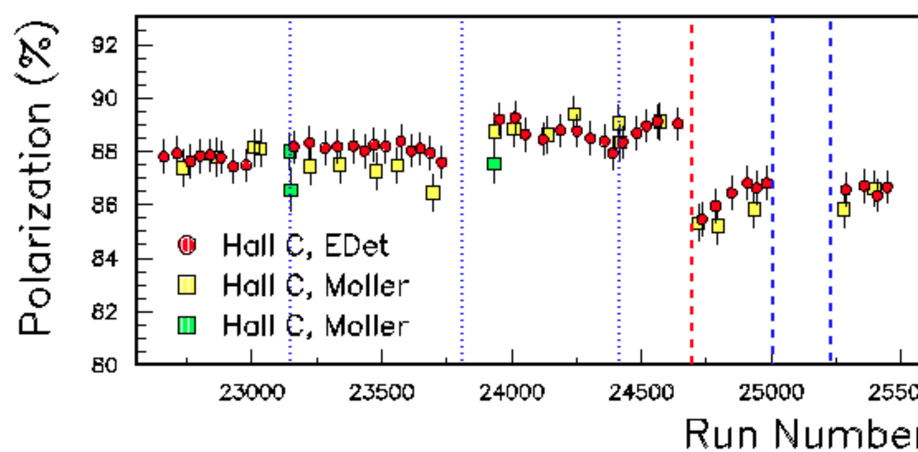


Compton Polarimeter

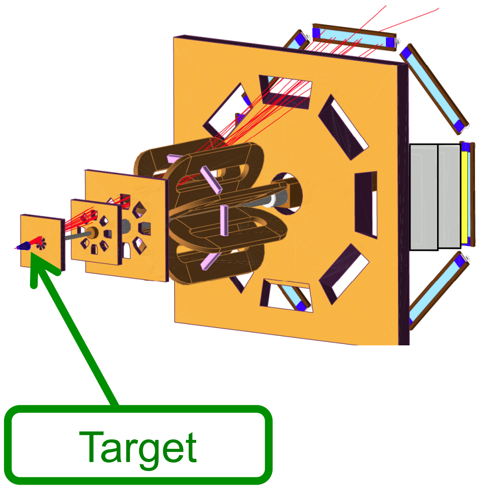
- existing Hall C Møller polarimeter to measure absolute beam polarization to <1% at low beam currents.
- New Compton polarimeter is used to provide continuous, nondestructive measurement of beam polarization at nominal experiment beam current.

A typical measured polarization is shown in the figure.

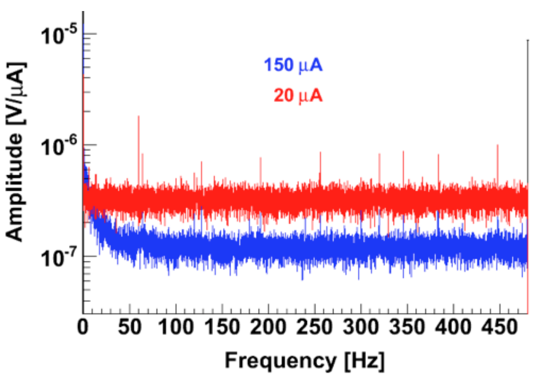
Measured beam polarization during commissioning period using Moller polarimeter is ~ 89 ± 2 % (Compton results during commissioning was not available)

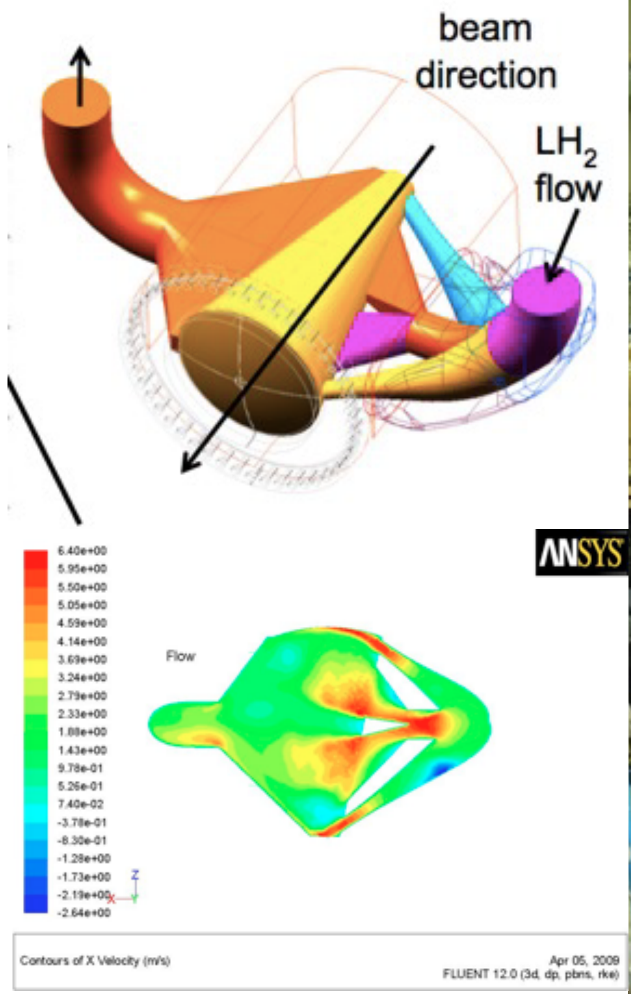


Q-weak Target

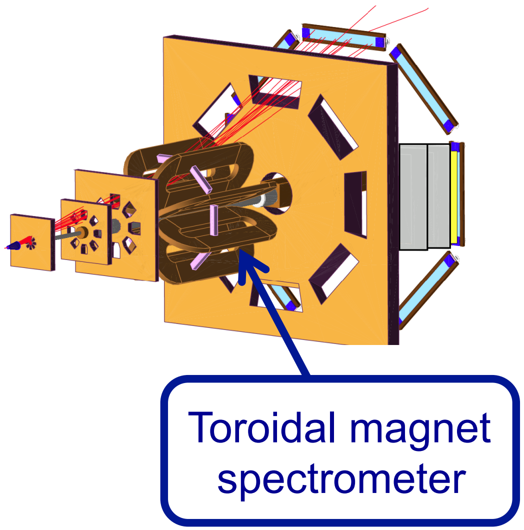


- World's highest power cryogenic target ~2.5 kW.
- 35 cm long liquid H2.
- Designed with computational fluid dynamics (CFD) to reduce density fluctuations.

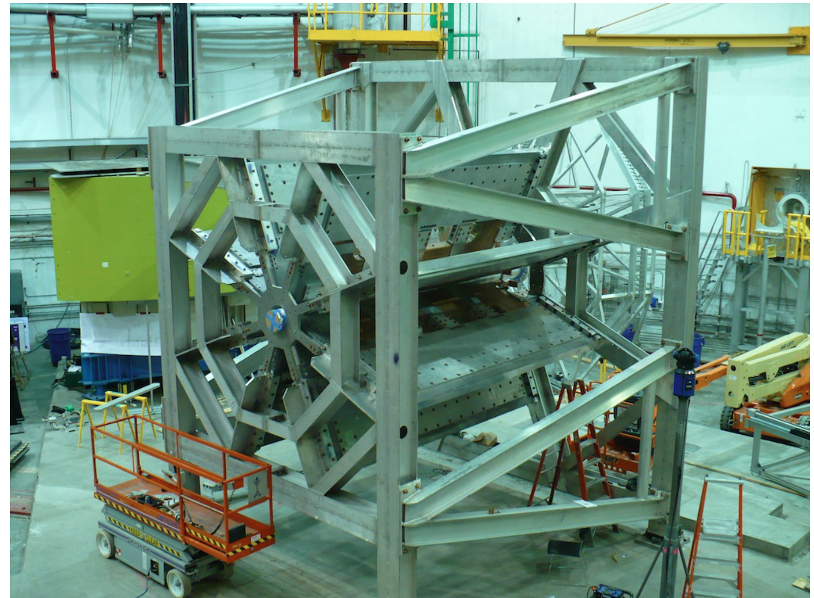




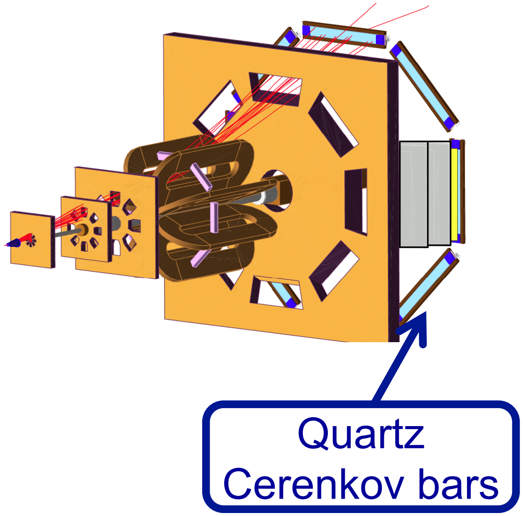
Q-weak Toroidal Magnet Spectrometer

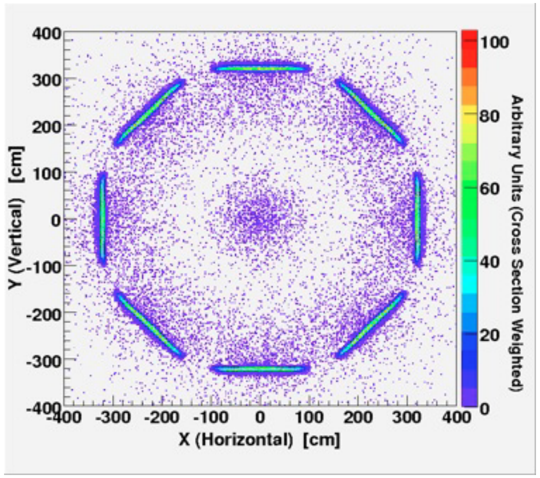


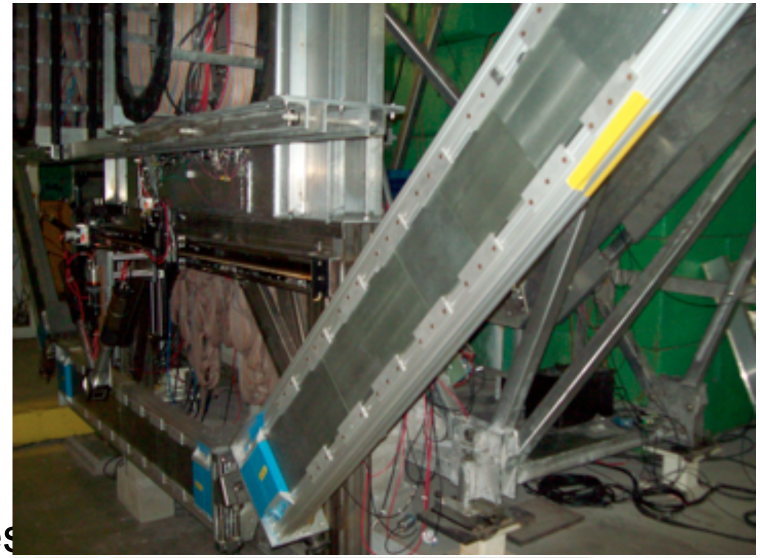
- Length = 3.7 m
- I ~ 8900 A
- ∫BdI ~ 0:67 Tm
- θ_{scat} = 7.9° ± 2°
- Q^2 = 0.025 $(GeV/c)^2$
- ϕ acceptance ~ 1/2(2π)

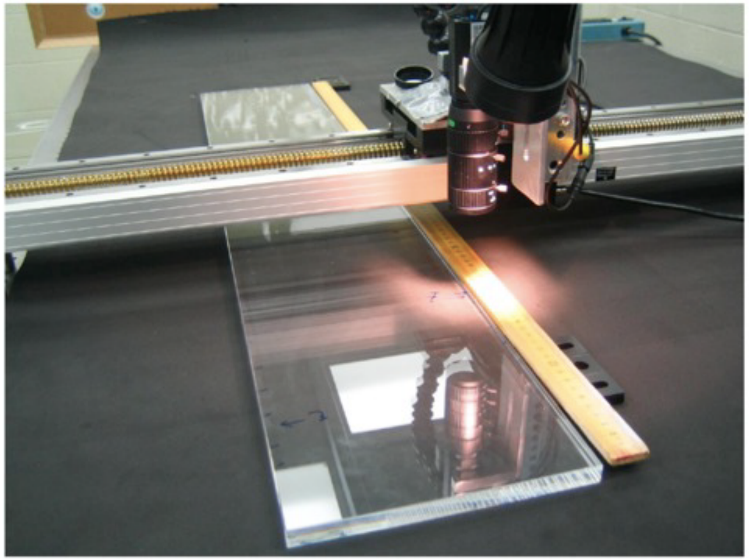


Q-weak Cherenkov Detectors







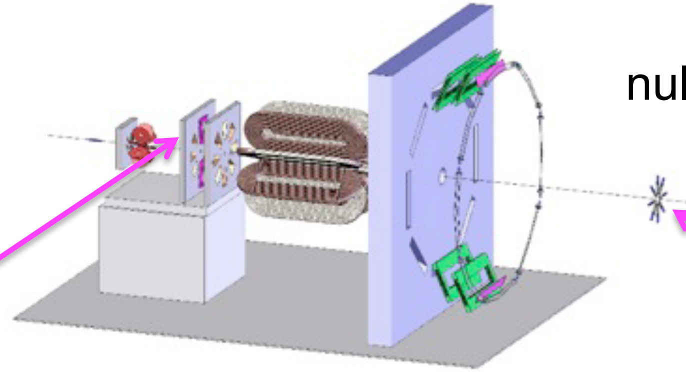


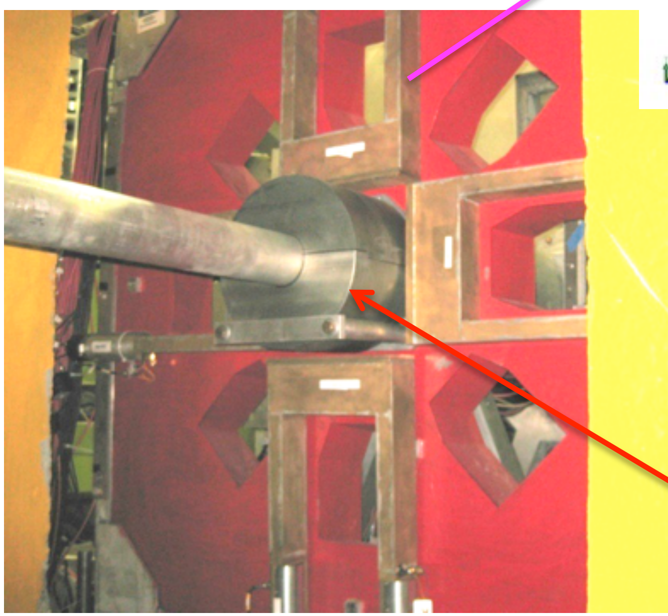
- Azimuthal symmetry maximizes rate and decreases sensitivity to HC beam motion, transverse asymmetry
- 8 synthetic quartz Cerenkov detector bars 2m long
- low noise, radiation hard Installed a 2 cm thick Pb pre-radiators decrease the background by showering electrons and attenuating low energy neutrals
- Signal normalized to beam current
- Scattered e focused on the detector bars at a rate of 800MHz per

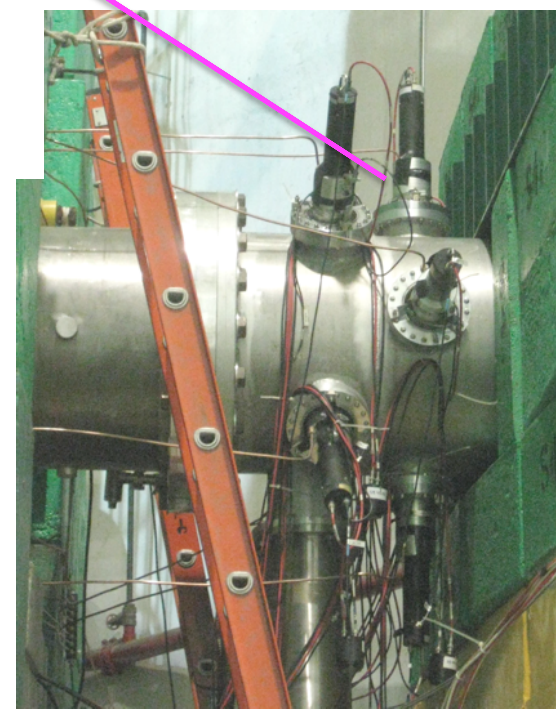
Luminosity Monitors

Upstream lumis:
4 detectors at ~5 degrees
100 GHz / detector
50-60% of signal from "plug" scattering
Mainly functions like a background detector

Downstream lumis:
8 detectors at ~0.5 degrees
100 GHz / detector
null asymmetry monitor and beam diagnostic



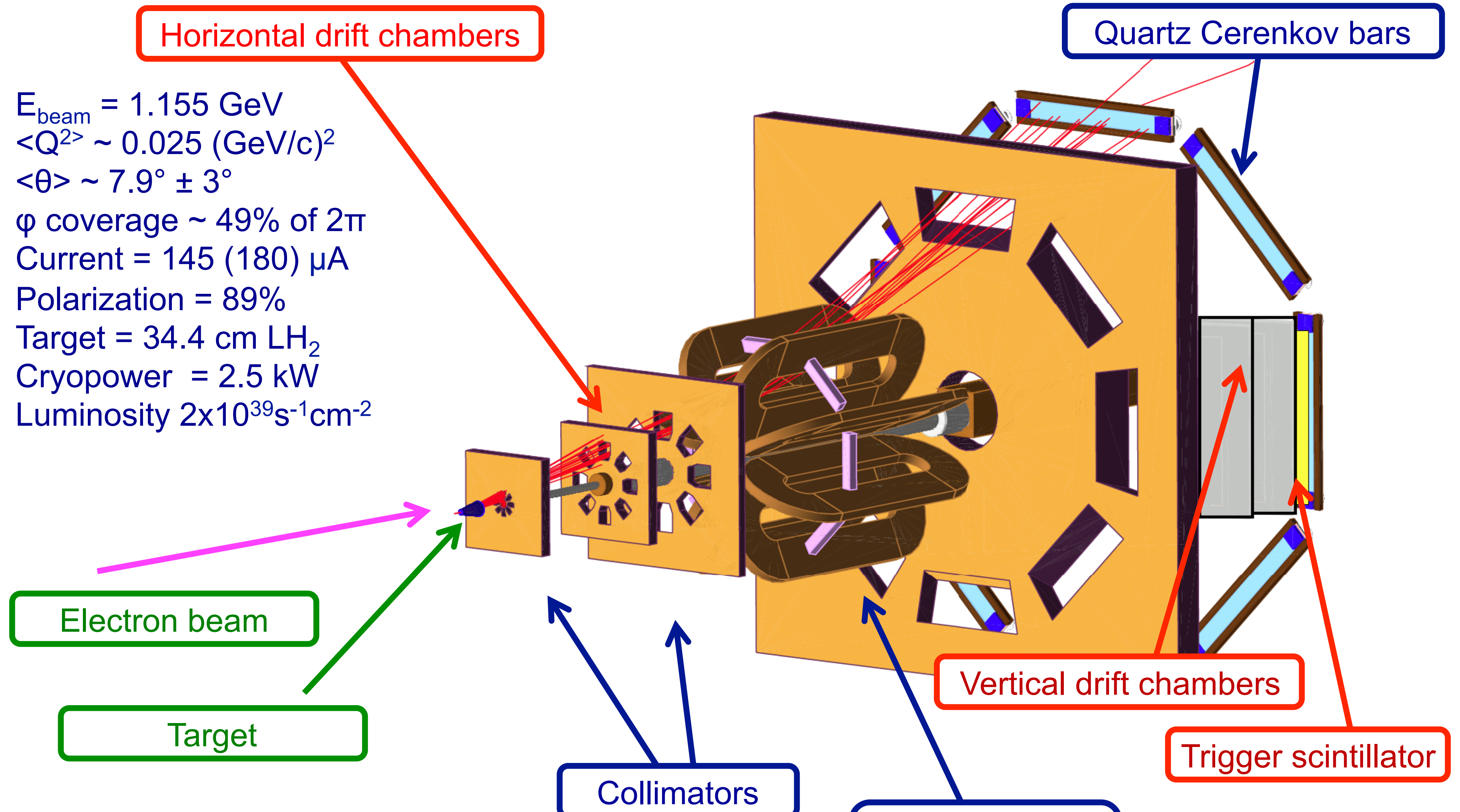




"Lead donut" added for additional shielding.

Q-weak Apparatus

E_{beam} = 1.155 GeV
$\langle Q^2 \rangle \sim 0.025\ (GeV/c)^2$
$\langle\theta\rangle \sim 7.9° \pm 3°$
φ coverage ~ 49% of 2π
Current = 145 (180) μA
Polarization = 89%
Target = 34.4 cm LH_2
Cryopower = 2.5 kW
Luminosity $2 \times 10^{39} s^{-1} cm^{-2}$



Red = low-current tracking mode (production current x 10^{-6})
Blue = production ("integrating") mode

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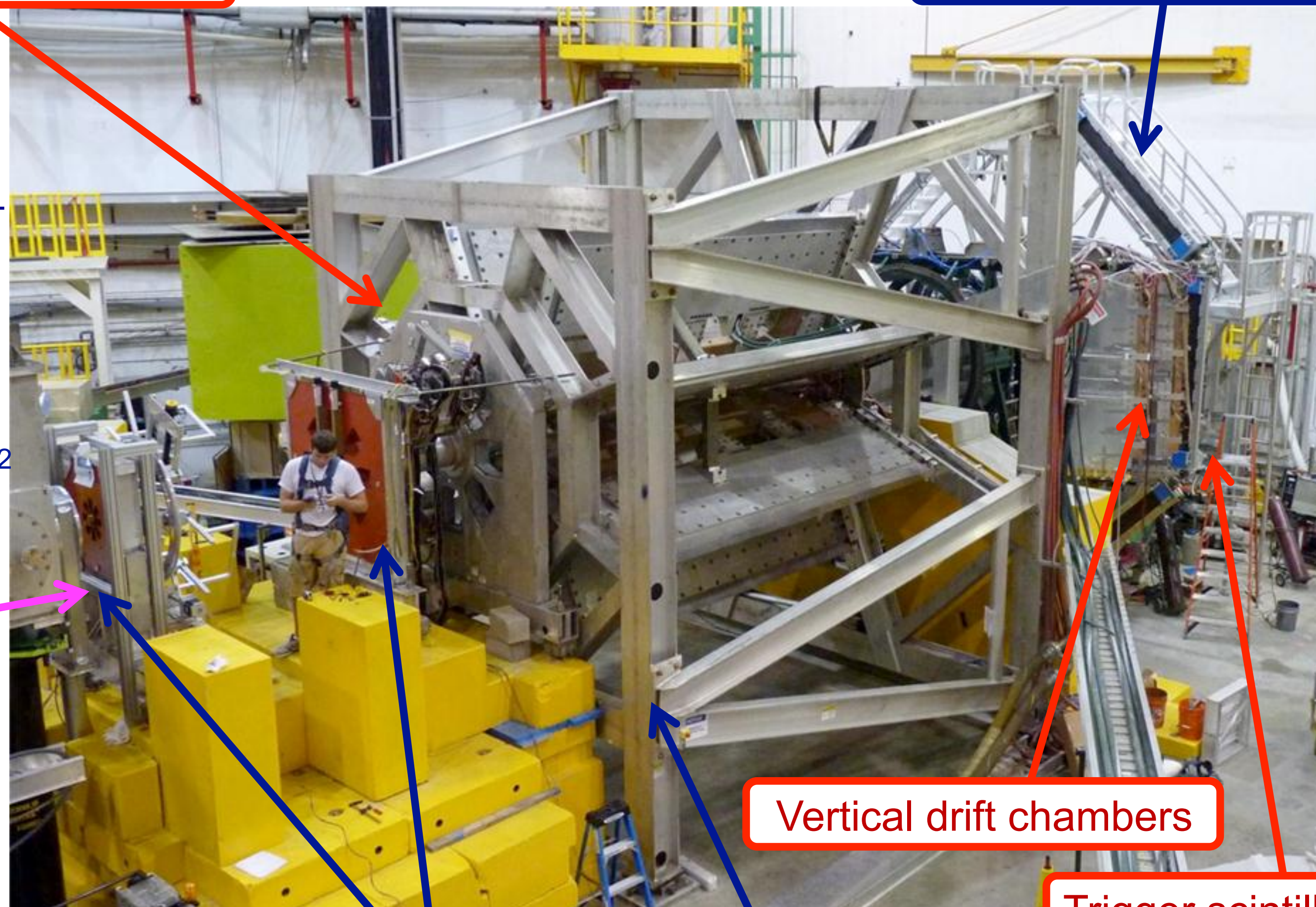

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Extracting PV Asymmetry

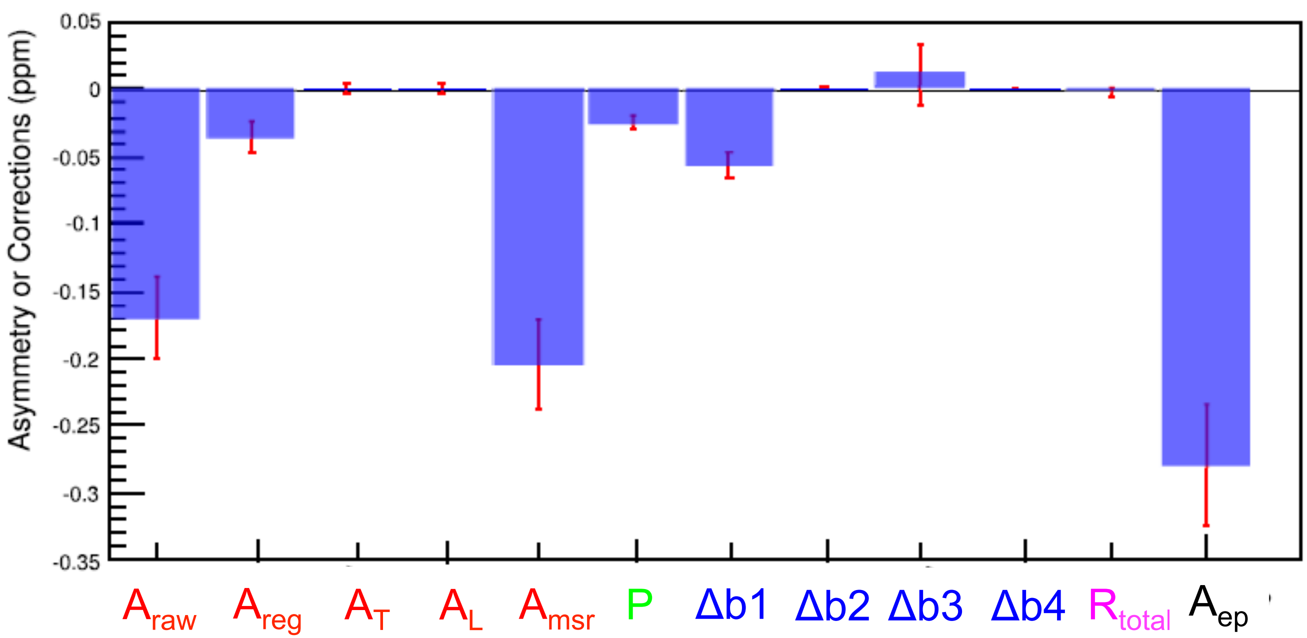
Extracting physics asymmetry $$A_{ep} = R_{total} \left[\frac{\frac{A_{msr}}{P} - \sum_{i=1}^{4} A_{bi} f_{bi}}{1 - \sum_{i=1}^{4} f_{bi}} \right]$$

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

$$R_{total} = R_{RC} R_{Det} R_{Bin} R_{Q^2}$$

Extracting physics asymmetry, A_{ep}, from the experimental measured asymmetry by

- removing false asymmetries, parity conserving contamination
- correcting for the beam polarization
- removing background asymmetries
- correcting for radiative tails and other kinematic correction.



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$$R_{total} = R_{RC} R_{Det} R_{Bin} R_{Q^2}$$

Radiative correction (1.010±0.005)

Detector Bias (1.010±0.005)

Kinematic correction (1.010±0.005)

Q^2 calibration (1.010±0.005)

	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

Smallest asymmetry and absolute error bar measured in e-p scattering to date

Phys. Rev. Lett. 111, 141803 (2013)

at $\langle Q^2 \rangle = 0.0250 \pm 0.0006$ (GeV/c)^2

$A_{ep} = -279 \pm 35$ (statistics) ± 31 (systematics) ppb

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