Qweak Ancillary Measurement:

Parity-Violating Inelastic $\vec{e}p$ Asymmetry at 3.35 GeV

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For the Qweak Collaboration

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Jefferson Lab

Thomas Jefferson National Accelerator Facility

Ancillary Measurement

- For ~2 weeks, Qweak received polarized electron beam at higher than nominal beam energy
- Opportunity to make an ancillary measurement
- Kinematics tuned to the inelastic region
  - Conducive to probing $F_{1,3}^{\gamma Z}$
- We quickly developed a detector system

Kinematics

$E_{Beam} =$ ~~$1.165\ GeV$~~ $3.35\ GeV$

$Q^2 \approx$ ~~$0.025\ GeV^2$~~ $0.09\ GeV^2$

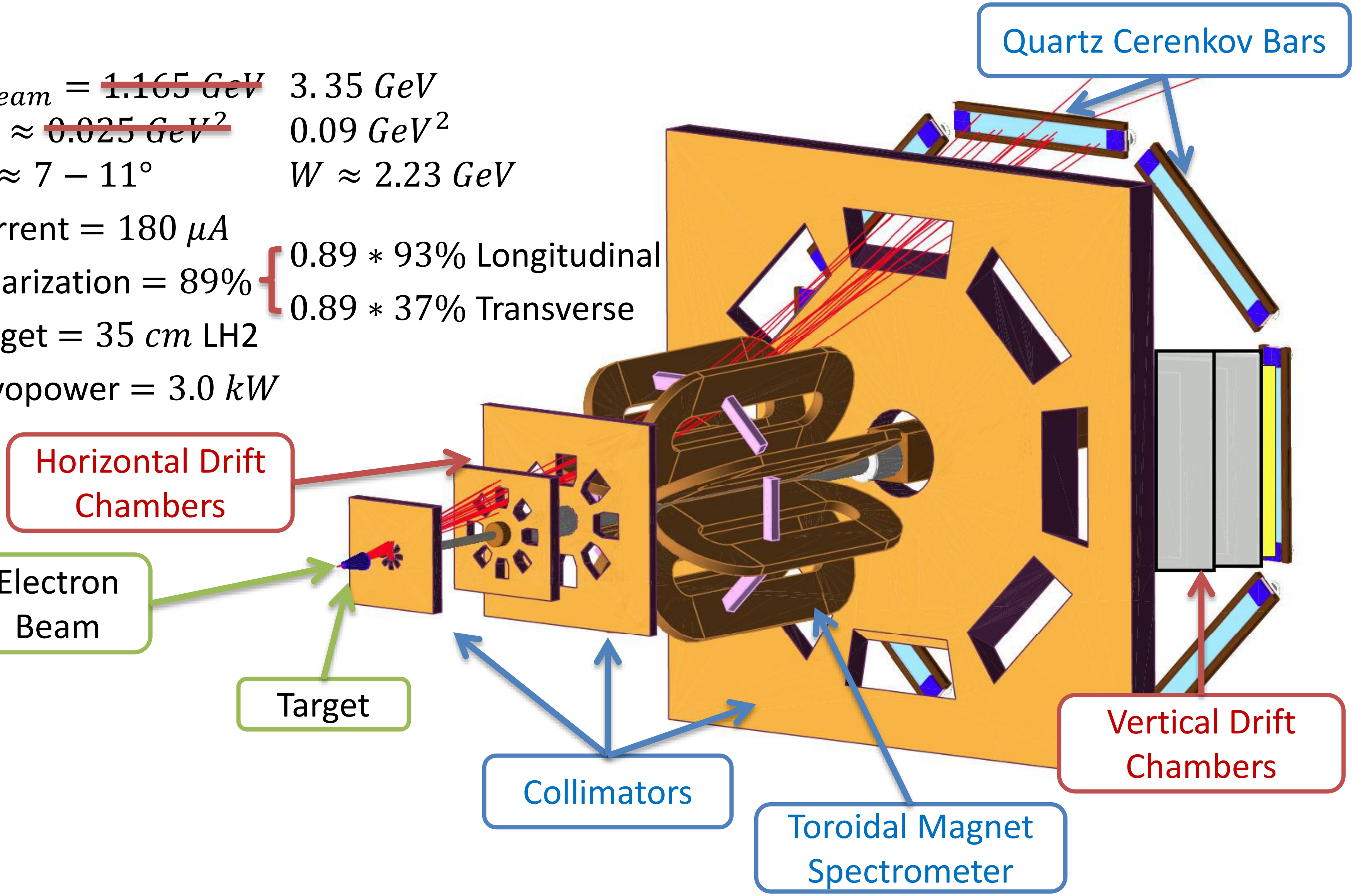
$\theta \approx 7 - 11°$ $\quad W \approx 2.23\ GeV$

Current $= 180\ \mu A$

Polarization $= 89\%$ { $0.89 * 93\%$ Longitudinal; $0.89 * 37\%$ Transverse }

Target $= 35\ cm$ LH2

Cryopower $= 3.0\ kW$



Radiative Corrections

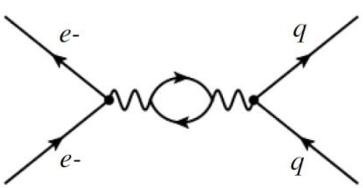
Including 1st order corrections, the proton's weak charge is:

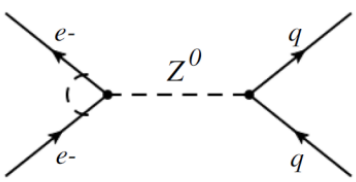
W and Z mass renormalization

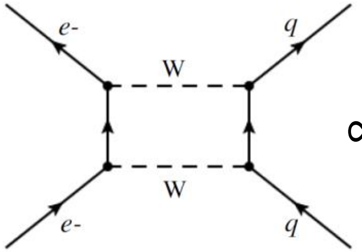
Vertex corrections

$$Q_W^p = [(\rho_{NC} + \Delta_e)(1 - 4\sin^2\theta_W(0)_{\overline{MS}} + \Delta'_e)$$
$$+ \Re e \Box_{WW} + \Re e \Box_{ZZ} + \Re e \Box_{\gamma Z}]\Big|_{E=0, Q^2=0}$$

Dominated by large momentum transfer & can be calculated by perturbative QCD







$$\propto \frac{1}{q^2 - M^2}$$

γZ-Box

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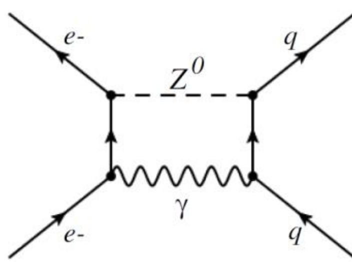
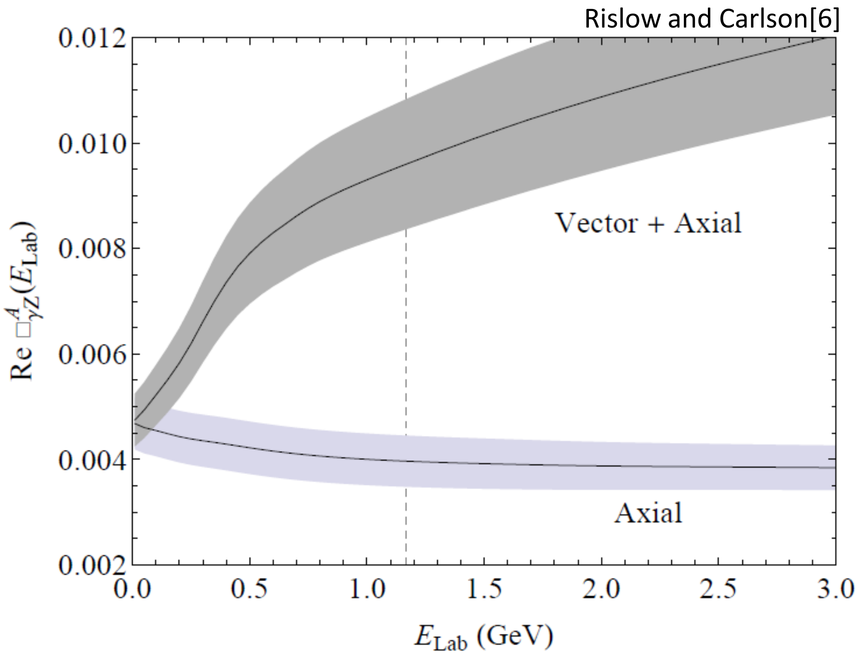
Less well known



$$\propto \frac{1}{q^2}$$

γZ-Box



$\Re e\square^{V}_{\gamma Z} \times 10^3$ evaluated at E = 1.165 GeV.

Oldest → Newest

Sibirtsev *et al.* [1]	$4.7^{+1.1}_{-0.4}$
Rislow and Carlson [2]	5.7 ± 0.9
Gorchtein *et al.* [3]	5.4 ± 2.0
Hall *et al.* [4]	5.60 ± 0.36

$\Re e\square^{A}_{\gamma Z} \times 10^3$ evaluated at E = 1.165 GeV.

Oldest → Newest

Blunden *et al.* [5]	3.7 ± 0.4
Rislow and Carlson [6]	4.0 ± 0.5

*See reference slide

- Gorchtein and Horowitz showed γZ-box contribution
  - Energy dependent
  - Larger than originally expected (~8% of Q^p_W)
  - Uncertainty of correction could affect precision aim of Qweak
- Recent thorough analysis of both axial and vector components

$F_{1,2,3}^{\gamma Z}$ Structure Functions

For forward scattering, the dispersion relation is:

$$\Re\mathfrak{e}\Box_{\gamma Z}^{V}(E) = \frac{2E}{\pi}\mathcal{P}\int_0^\infty dE' \frac{1}{E'^2 - E^2}\,\Im\mathfrak{m}\Box_{\gamma Z}^{V}(E')$$

Using the optical theorem,

$$2\Im\mathfrak{m}\mathcal{M}_{\gamma Z}^{(PV)} = -4\sqrt{2}\pi M G_F \int \frac{d^3k'}{(2\pi)^3 2E_{k'}}\left(\frac{4\pi\alpha}{Q^2}\right)\frac{1}{1+Q^2/M_Z^2} L_{\mu\nu}^{\gamma Z} W_{\gamma Z}^{\mu\nu}$$

where

$$L_{\mu\nu}^{\gamma Z} = \bar{u}(k,\lambda)\left(g_V^e\gamma_\mu - g_A^e\gamma_\mu\gamma_5\right)\not{k}'\gamma_\nu u(k,\lambda)$$

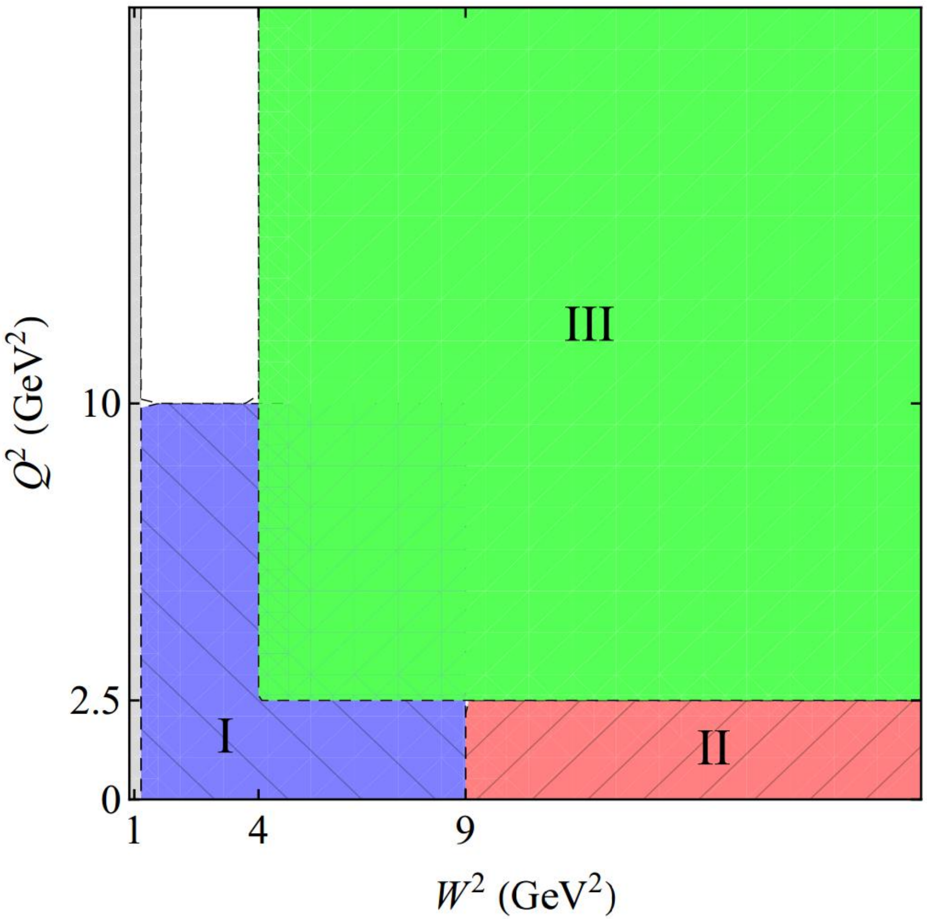
$$M W_{\gamma Z}^{\mu\nu} = -g^{\mu\nu}F_1^{\gamma Z} + \frac{p^\mu p^\nu}{p\cdot q}F_2^{\gamma Z} - i\epsilon^{\mu\nu\lambda\rho}\frac{p_\lambda p_\rho}{2p\cdot q}F_3^{\gamma Z}$$

Combining everything, the imaginary part of the correction becomes

$$\Im\mathfrak{m}\Box_{\gamma Z}^{V}(E') = \frac{1}{(s-M^2)^2}\int_{W_\pi^2}^{s} dW^2 \int_0^{Q_{max}^2} dQ^2 \frac{\alpha(Q^2)}{1+Q^2/M_Z^2}\left[F_1^{\gamma Z} + \frac{s(Q_{max}^2 - Q^2)}{Q^2(W^2 - M^2 + Q^2)}F_2^{\gamma Z}\right]$$

With $s = M^2 + 2ME$, $W_\pi^2 = (M + m_\pi)^2$, *and* $Q_{max}^2 = 2ME(1 - W^2/s)$

$F_{1,2,3}^{\gamma Z}$ Structure Functions



[4]

Integral divided into several regions:

- Region I – Described by the Christy-Bosted $F_{1,2}^{\gamma\gamma}$ fit, transformed to the γZ case
- Region II – GHRM Model II, transformed to γZ
- Region III – Global PDF fits to high-energy data

$$\Im\mathfrak{m}\Box_{\gamma Z}^{V}(E') = \frac{1}{(s-M^2)^2}\int_{W_\pi^2}^{s} dW^2 \int_0^{Q^2_{max}} dQ^2 \, \frac{\alpha(Q^2)}{1+Q^2/M_Z^2}\left[F_1^{\gamma Z} + \frac{s(Q^2_{max}-Q^2)}{Q^2(W^2-M^2+Q^2)}F_2^{\gamma Z}\right]$$

Non-Resonant inelastic PV measurement

Beam Energy = 3.35 GeV

W = 2.23 GeV

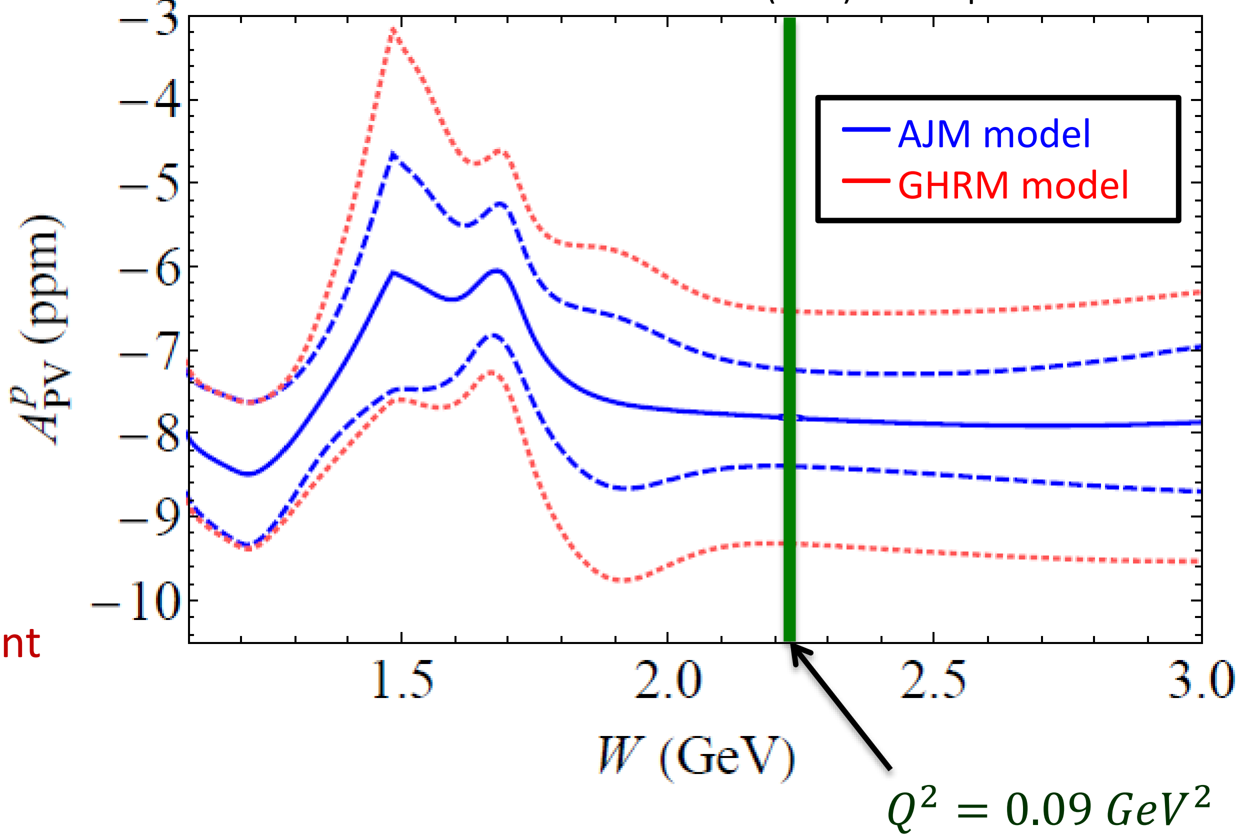
Q^2 = 0.09 GeV^2

Predicted

A_{PV}^{p} ~ (-7.8±0.6) ppm

An asymmetry measurement will constrain $F_{1,3}^{\gamma Z}$

Adelaide - Jefferson Lab - Manitoba (AJM) model prediction[4]



- Asymmetry measurement lies in the non-resonant inelastic region
- In a kinematic region with almost no experimental data

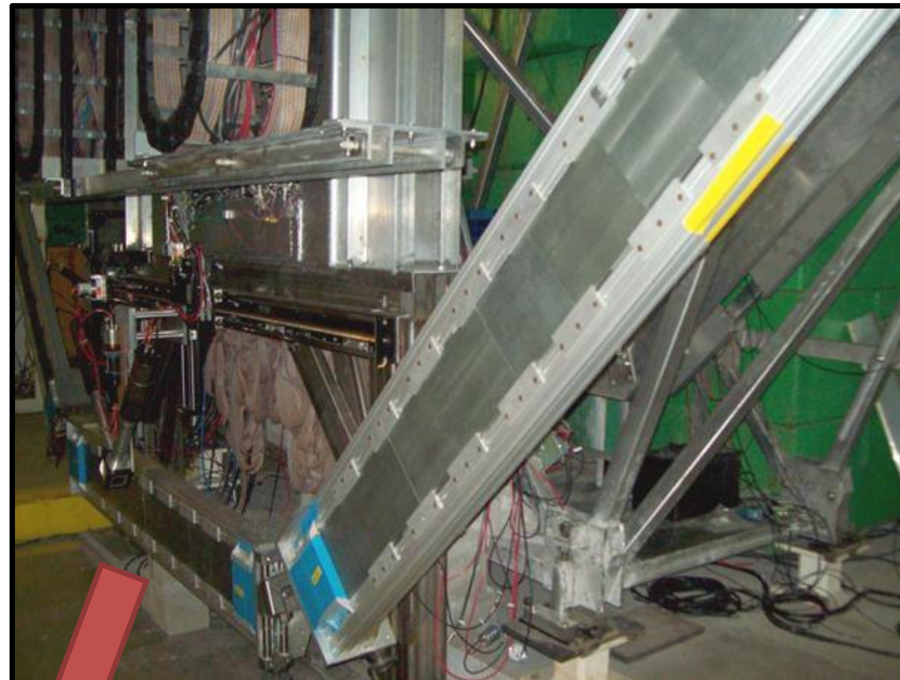
[4] N. L. Hall, P. G. Blunden, W. Melnitchouk, A. W. Thomas, and R. D. Young (2013), arXiv:1304.7877v1 [nucl-th].

Data Analysis

- Large W leads to large pion background
  - Pion and electron signals are integrated together
  - Pion dilution is the largest systematic uncertainty
- Elastic *ep* radiative tail
  - Well understood
- Partially transversely polarized beam
  - ~37% transverse
  - Pions have a large transverse asymmetry

Signal Extraction

- At 3.35 GeV, signals in the Čerenkov detectors will be a combination of π^- & e^-
- Majority of data was taken with 4” lead in front of lowest Čerenkov Detector
- The lead wall ranges out most of the electrons.
  - ~18 radiation lengths



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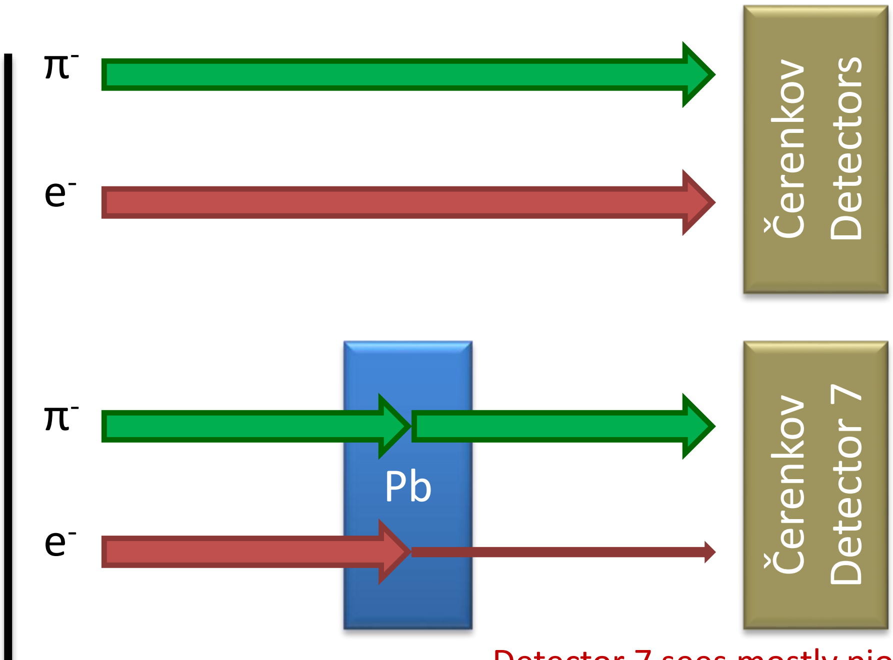
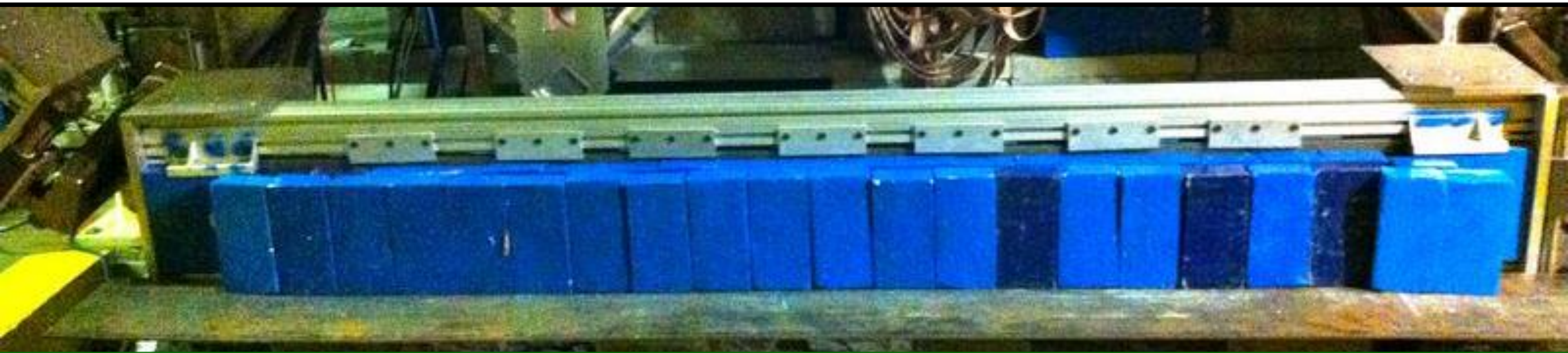
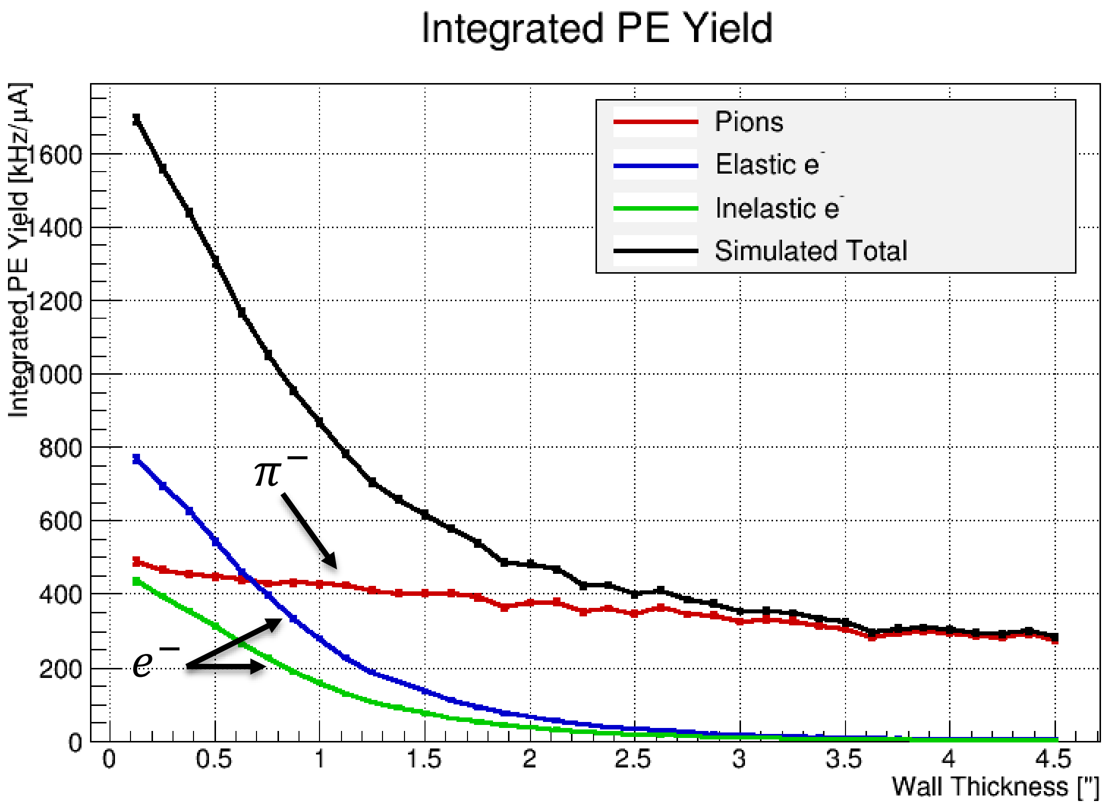


Detector 7 sees mostly pions



Lead Wall Simulation

- GEANT4 Simulation
- Electron signal is highly suppressed with increasing wall thickness
- Lead wall isolates pions
- Blocked Čerenkov detector becomes a pion detector



ADC Light Spectra

- Some event mode data taken
  - Each event is tracked and counted separately
- Pion rate greater than electron rate by factor of ~2
- Pions produce less light than electrons by a factor of ~6
  - Electron signal enhanced by lead pre-radiators
- Fitting spectra will help us determine the pion fraction

Light Spectrum of an Unblocked Octant

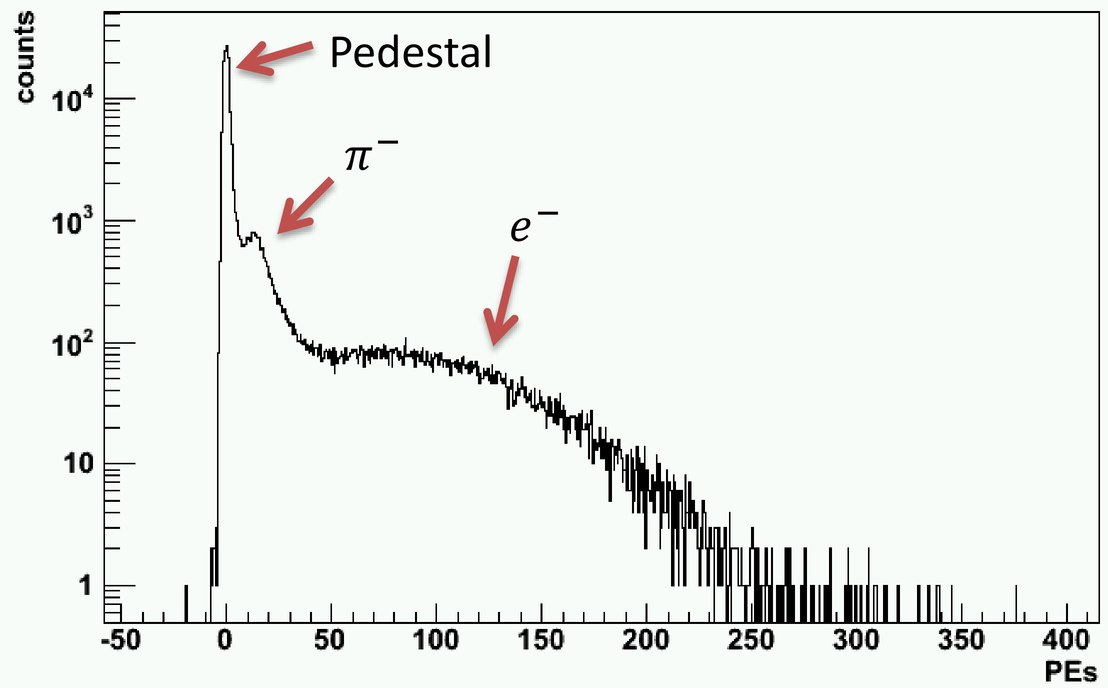
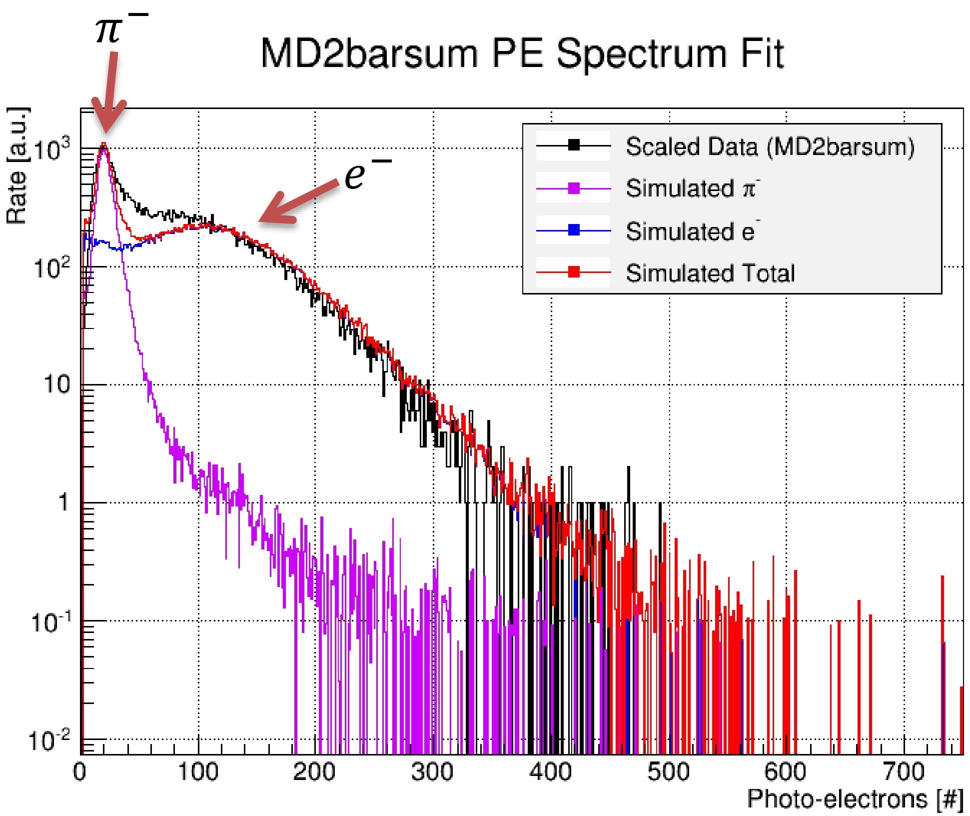


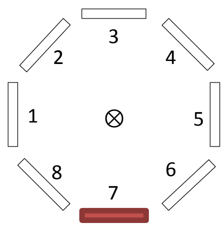
Photo-Electron Spectrum Fit

- Fit data with GEANT4 pion and electron simulations
- Removed electronic pedestal
- Applied a 3 parameter fit
  - Pion Amplitude
  - Electron Amplitude
  - Gain Factor [PEs/ADC channel]
- Simulation under-predicts between electron and pion peaks



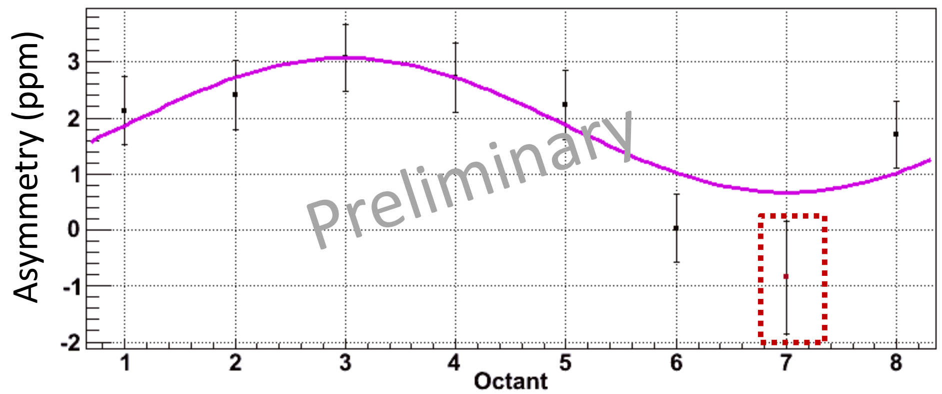
Beam Polarization at 3.35 GeV

- Data shown
  - Uncorrected
  - Blinded

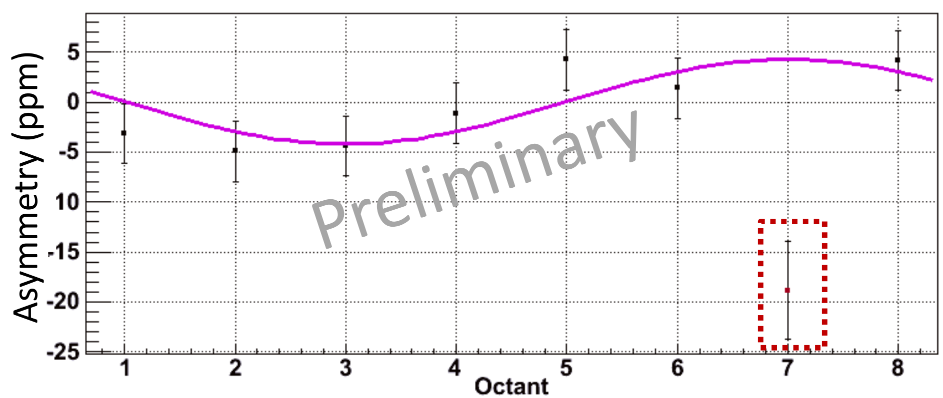


- Main measurement beam polarization
  - $\sim 0.93 * P_{Beam}$ Longitudinal
  - $\sim 0.37 * P_{Beam}$ Transverse
- Azimuthally symmetric detectors
- Pure transverse measurement beam polarization
  - $\sim 1.0 * P_{Beam}$ Transverse
- Note the large transverse pion asymmetry with opposite sign

Main Measurement



Transverse Calibration Measurement



* Octant 7 with lead wall excluded from fit

Extracting A_{PV}^{e}

Parity-Violating Pion Asymmetry

$$A_{mix}^{MD7} = P_T A_T^{MD7} + P_L A_{PV}^{MD7}$$

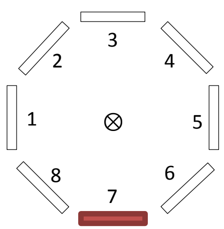
$$\Longrightarrow A_{PV}^{MD7} = \frac{1}{P_L}\left(A_{mix}^{MD7} - P_T A_T^{MD7}\right) \approx \mathrm{A}_{\mathrm{PV}}^{\pi}$$

Parity-Violating Electron Asymmetry

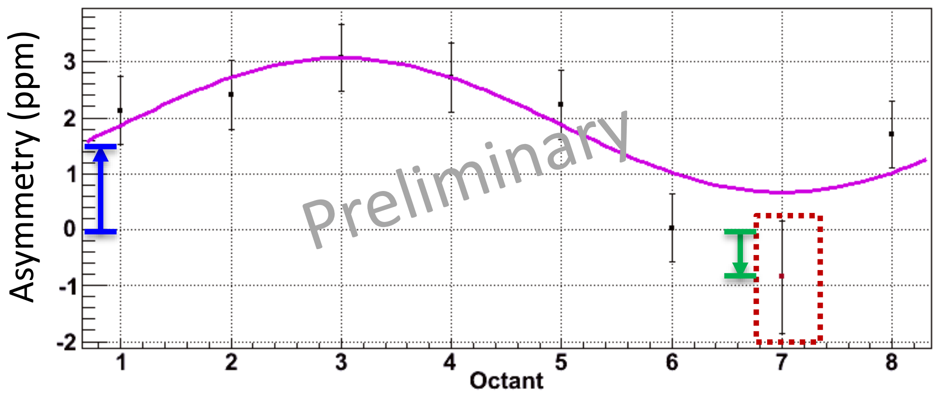
$$A_{PV} = (1 - \boldsymbol{f_\pi}) A_{PV}^{e} + \boldsymbol{f_\pi} A_{PV}^{\pi}$$

$$\Longrightarrow A_{PV}^{e} = \frac{A_{PV} - f_\pi A_{PV}^{\pi}}{1 - \boldsymbol{f_\pi}}$$

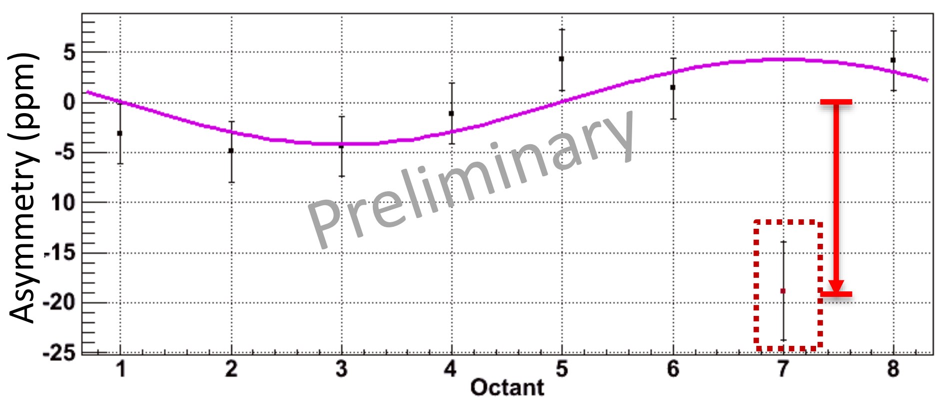
Asymmetry result is highly dependent on $\boldsymbol{f_\pi}$



Main Measurement



Transverse Calibration Measurement



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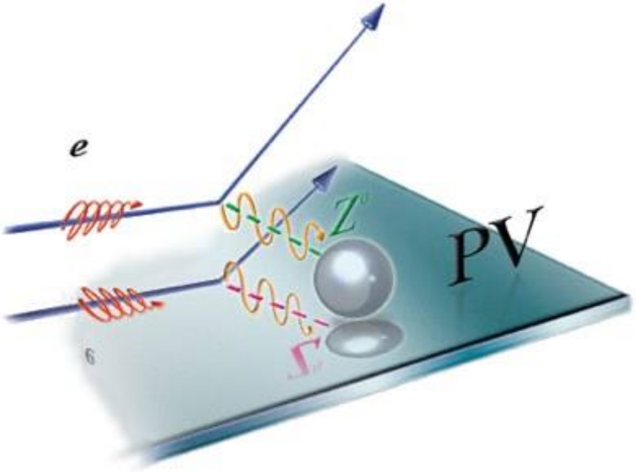
Summary

- Pion fraction will be determined by
  - Čerenkov detector with the lead wall
  - Light spectra in the PMTs
  - Monte Carlo simulation



- Asymmetry measurement at 3.35 GeV
  - Constrain γZ structure functions, $F_{1,3}^{\gamma Z}$
  - Part of a small unique dataset
  - Relevant for Qweak and upcoming experiments

- Additional measurements that we get for 'free'
  - Non-resonant inelastic transverse asymmetries
  - PV asymmetries in pion photoproduction at 3.35 GeV
  - Transverse asymmetries in pion photoproduction at 3.35 GeV

The Qweak Collaboration

95 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

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Spokespersons Project Manager Grad Students

References

[1] A. Sibirtsev, P. G. Blunden, W. Melnitchouk, and A. W. Thomas, Phys. Rev. **D82**, 013011 (2010), 1002.0740.

[2] B. C. Rislow and C. E. Carlson, Phys.Rev. **D83**, 113007 (2011), 1011.2397.

[3] M. Gorchtein, C. Horowitz, and M. J. Ramsey-Musolf, Phys.Rev. **C84**, 015502 (2011), 1102.3910.

[4] N. L. Hall, P. G. Blunden, W. Melnitchouk, A. W. Thomas, and R. D. Young (2013), arXiv:1304.7877v1 [nucl-th].

[5] P. Blunden, W. Melnitchouk, and A. Thomas, Phys.Rev.Lett. **107**, 081801 (2011), 1102.5334.

[6] B. C. Rislow and C. E. Carlson, arXiv:1304.8113v1 [hep-ph].

Backup Slides

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Parity-Violating Pion Asymmetry

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Parity-Violating Electron Asymmetry

$$A_{PV} = (1 - f_\pi) A_{PV}^{e} + f_\pi A_{PV}^{\pi}$$

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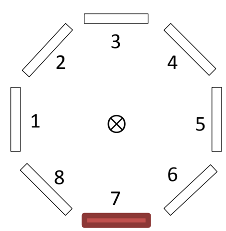
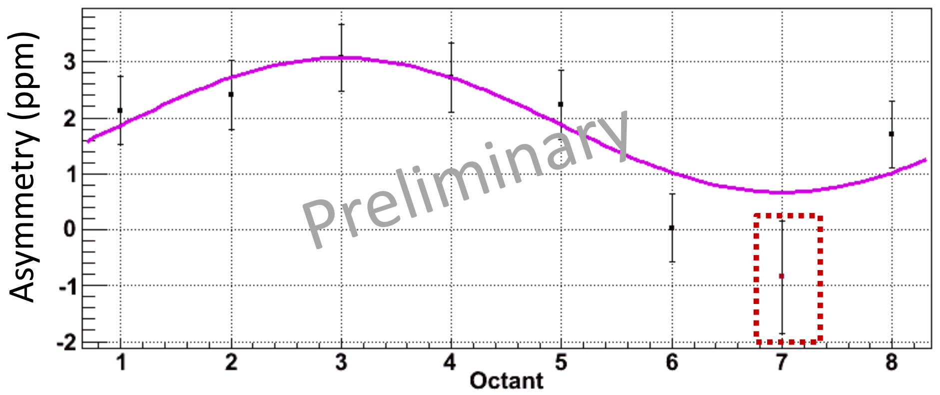


Main Measurement



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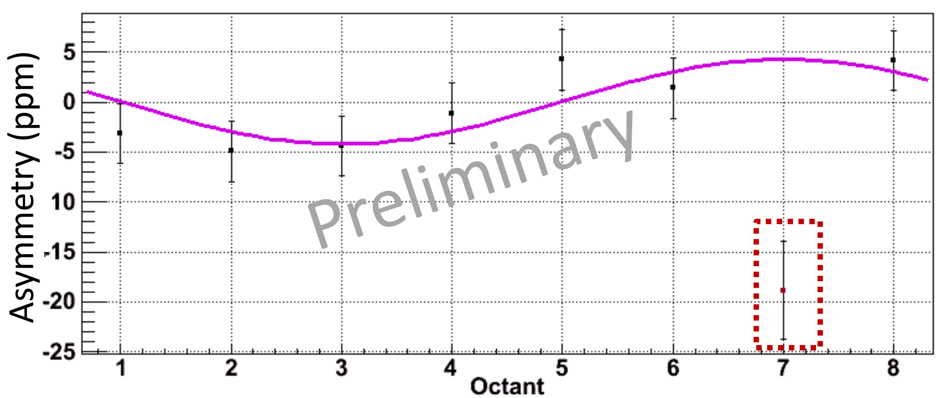

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Non-Resonant inelastic PV measurement

Beam Energy = 3.35 GeV

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Q^2 = 0.09 GeV^2

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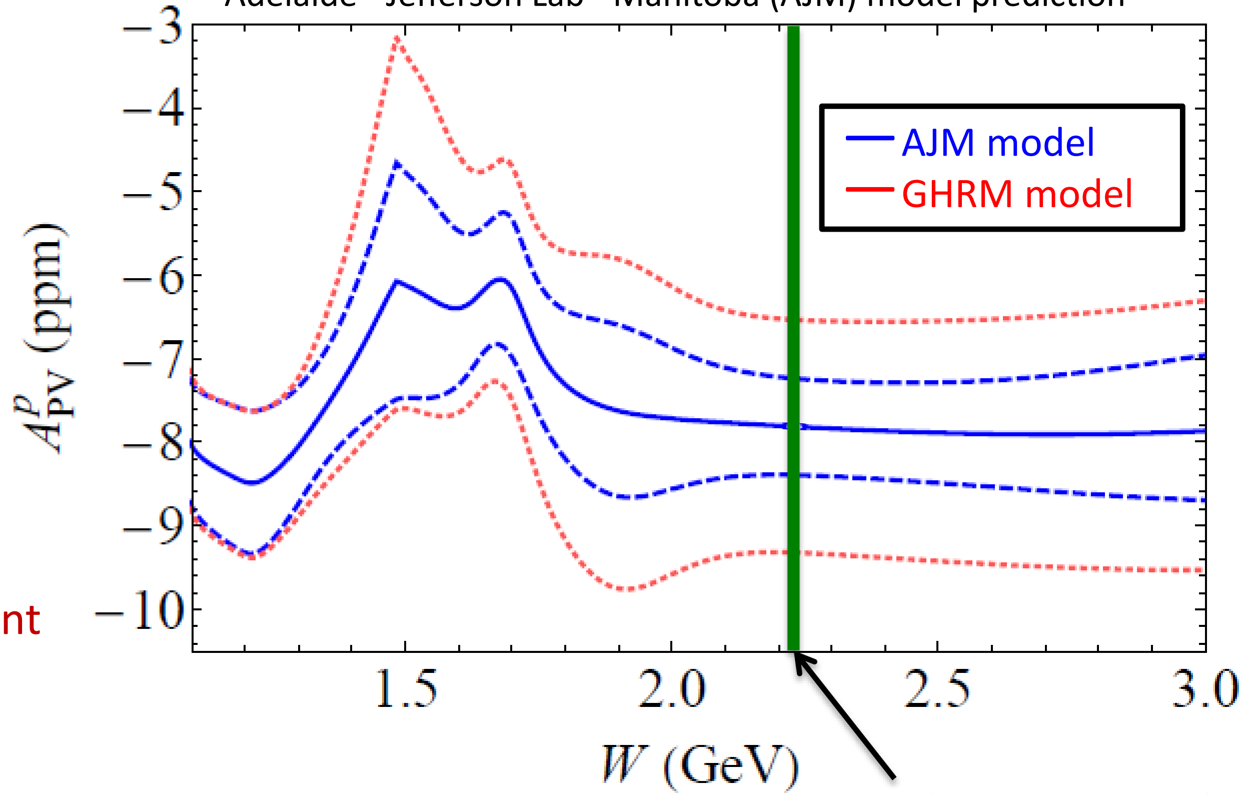

- Asymmetry measurement lies in the non-resonant inelastic region

$$A_{PV} = g_A^e\left(\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\right)\frac{xy^2F_1^{\gamma Z} + \left(1 - y - \frac{x^2y^2M^2}{Q^2}\right)F_2^{\gamma Z} + \frac{g_V^e}{g_A^e}\left(y - \frac{1}{2}y^2\right)xF_3^{\gamma Z}}{xy^2F_1^{\gamma\gamma} + \left(1 - y - \frac{x^2y^2M^2}{Q^2}\right)F_2^{\gamma\gamma}}$$

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Noise Correction w/ TDC Cut

Run 17956 – MD triggered

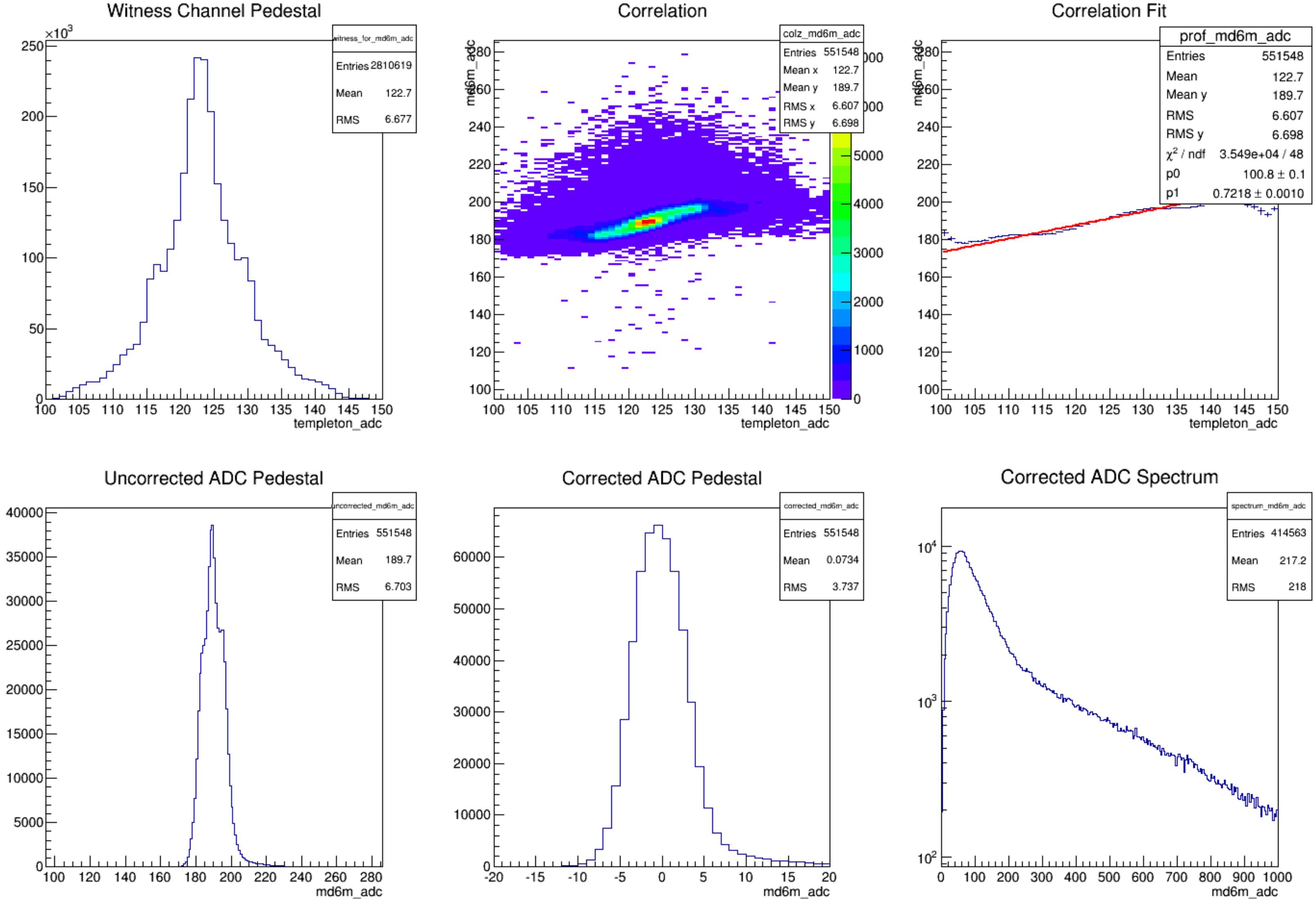

Photo-Electron Spectrum Fit

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- Removed electronic pedestal
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  - Pion Amplitude
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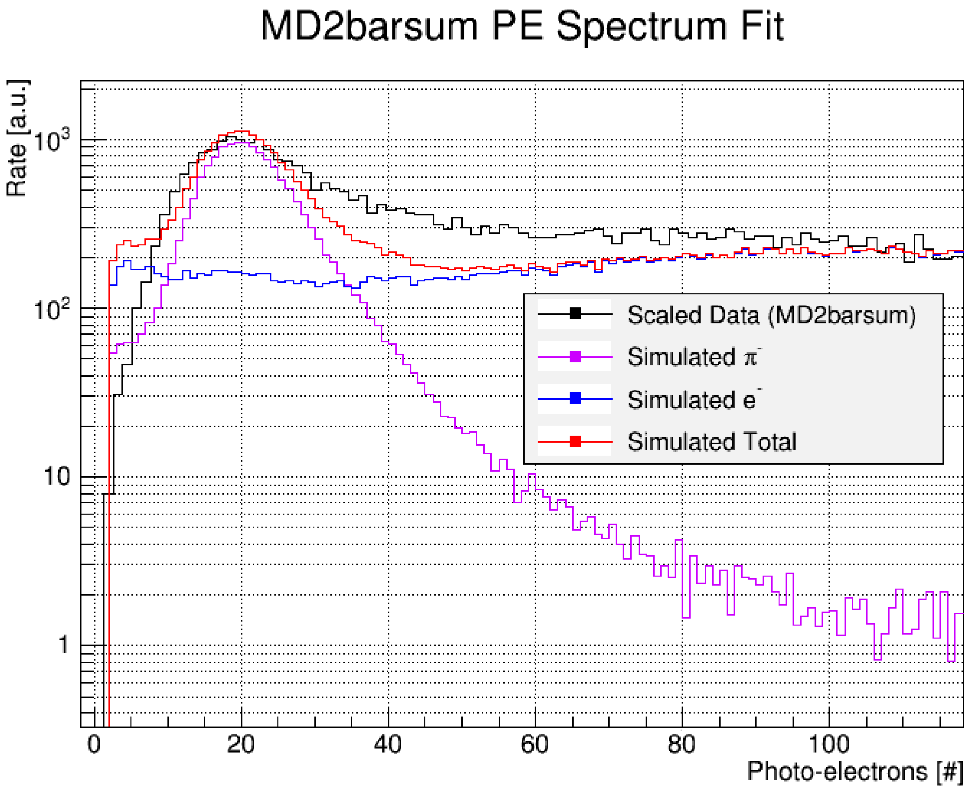
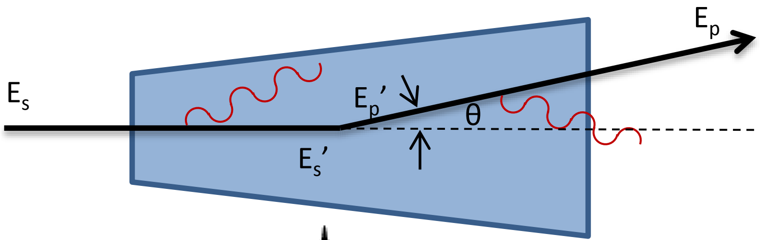
  - Gain Factor [PEs/ADC channel]
- Fit matches well
- Simulation under-predicts between electron and pion peaks



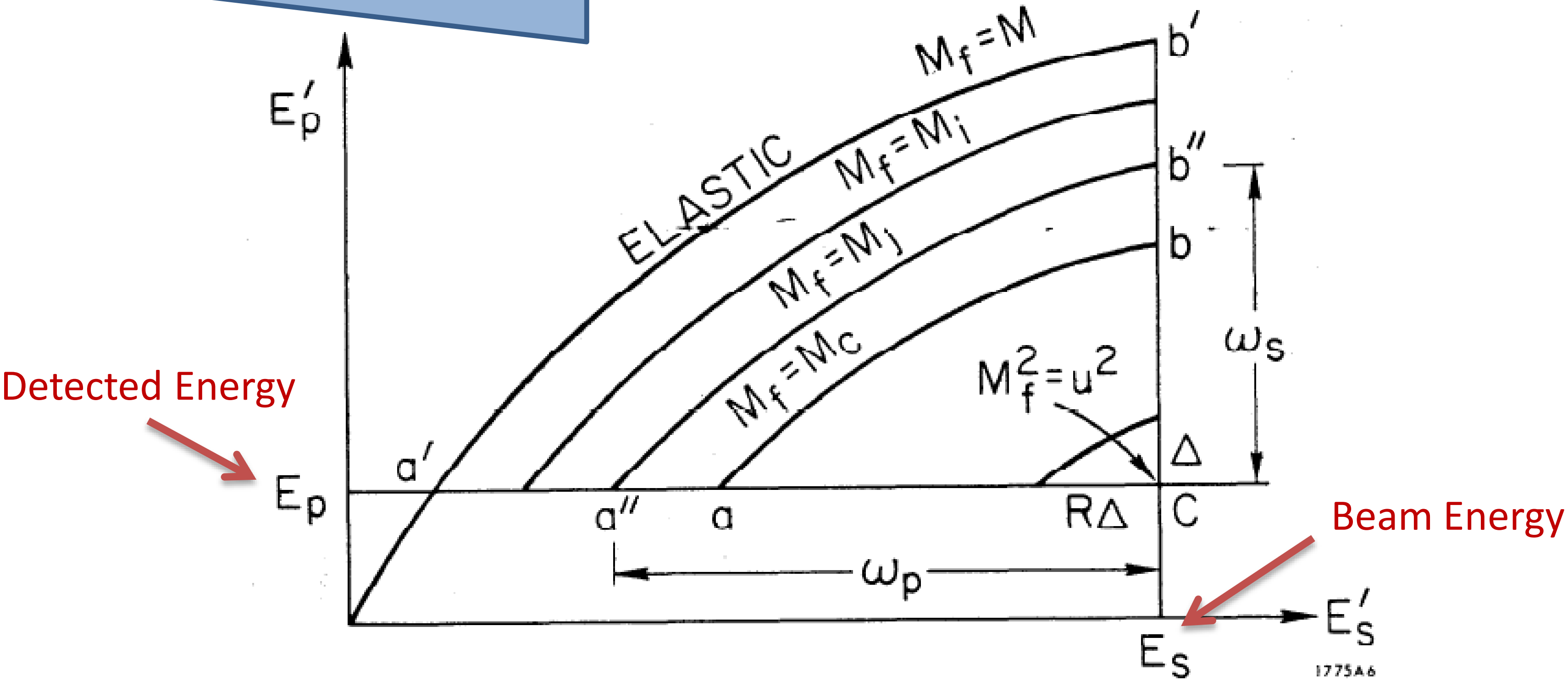
Available Data Set

- Asymmetry and Yields
  - Main Measurement
  - Purely Transverse
  - Aluminum and Carbon Targets
- ADC Spectra
- Tracking Data
- One Čerenkov detector with Lead Wall
  - 4” wall
  - 2” wall
  - Nominal Energy (1.16 GeV)
- Magnet spectrometer current scans
  - LH2
  - Aluminum
  - Reverse Polarity
- Blocked Octant

Radiative Corrections



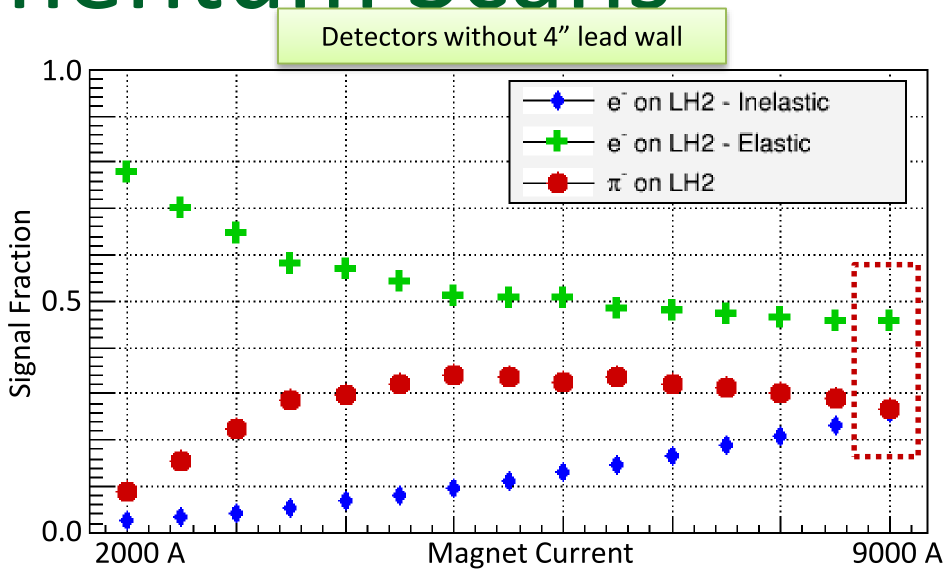
Large scattering phase space can radiate into our acceptance

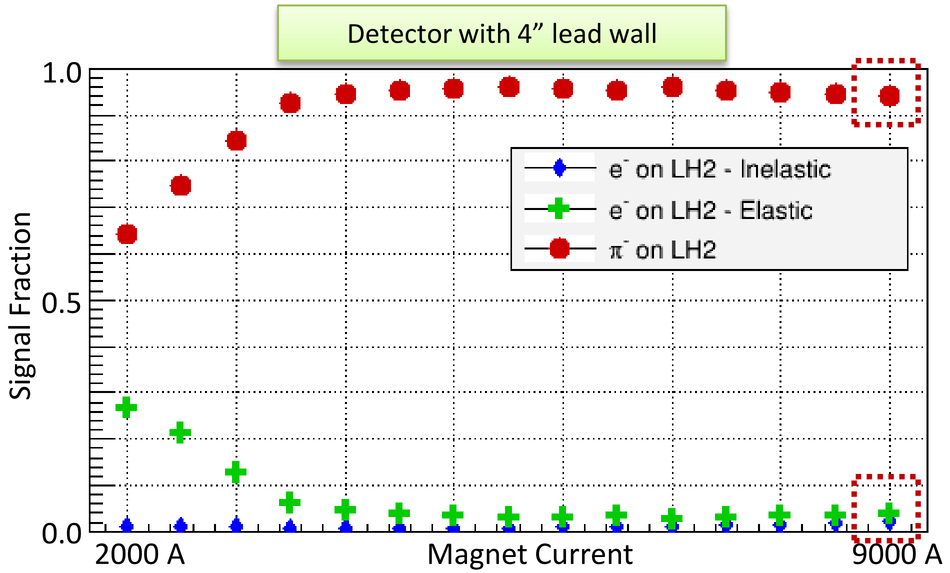


$$\sigma_{exp}(E_s, E_p) = \int_0^T \frac{dt}{T} \int_{E_{s,min}(E_p)}^{E_s} dE_s' \int_{E_p}^{E_{p,max}(E_s')} dE_p' \, I(E_s, E_s', t) \, \boldsymbol{\sigma_r(E_s', E_p')} \, I(E_p', E_p, T - t)$$

Simulated Momentum Scans

- Magnet current selects outgoing momentum
- Simulated signal fractions at various magnet currents
  - At 9000 A inelastic signal is maximized at ~25% of total signal
  - At 9000 A elastic signal is minimized
- Most data taken at 9000 A magnet current
- Wall attenuates most electrons
  - ~95% signal comes from pions





Proton's Weak Charge

At tree level, the proton's weak charge is:

$$Q_W^p = 1 - 4\sin^2\theta_W = -2(2C_{1u} + C_{1d})$$

The Qweak experiment goal is to measure Q_W^p to ~4%

Qweak Apparatus

$E_{Beam} = 1.165\ GeV$
$Q^2 \approx 0.025\ GeV^2$
$\theta\ \approx 7 - 11°$
Current $= 180\ \mu A$
Polarization $= 89\%$
Target $= 35\ cm$ LH2
Cryopower $= 3.0\ kW$