Using the Q_{weak} Apparatus to Probe the γZ-Box

James Dowd

The College of William & Mary

(for the Q_{weak} Collaboration)

Sept. 28-30, 2017

WILLIAM & MARY
CHARTERED 1693

Jefferson Lab
Thomas Jefferson National Accelerator Facility

This work was supported in part by the National Science Foundation under Grant No. PHY-1405857.

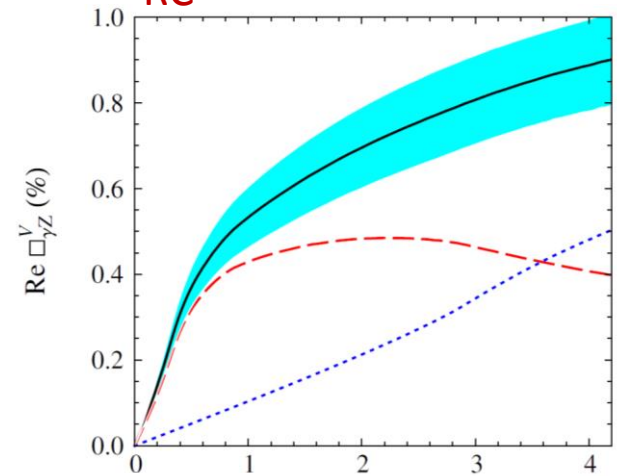
Overview

- Qweak experiment
  - Used elastic asymmetry of $\vec{e}p$ scattering to measure the weak charge of the proton, Q_w^p
- For ~2 weeks, Qweak received beam at higher energy (3.35 GeV)
  - Another experiment hall had priority
- Opportunity to use the apparatus to make an ancillary measurement
  - Relevant to the main Qweak experiment
  - Stands on its own merit
- Goal: Constrain and validate theoretical predictions of $\Re e \Box_{\gamma Z}^{V}$ correction to Q_W^p
  - Using inelastic asymmetry of $\vec{e}p$ scattering at 3.35 GeV

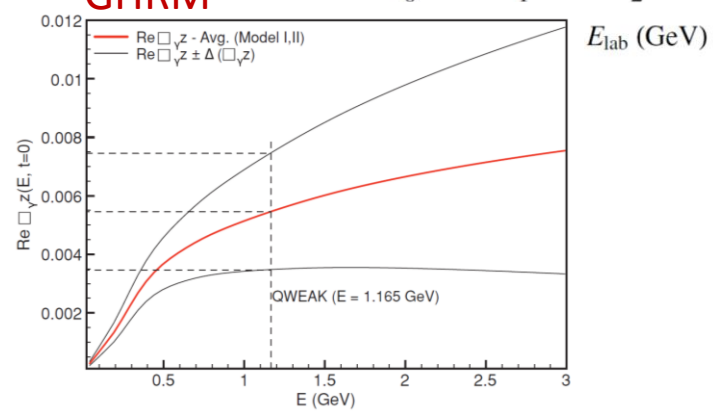
Motivation

- Qweak measured Q_W^p
  - Must include Electroweak Radiative Corrections
- Gorchtein and Horowitz* showed $\Box_{\gamma Z}^V$
  - Larger than previously expected
  - Significant hadronic physics uncertainties
  - Energy dependence
- Examined further by several groups
  - Gorchtein, Horowits, and Ramsey-Musolf
  - Sibirtsev, Blunden, Melnitchouk, and Thomas
  - Carlson and Rislow
  - Hall, Blunden, Melnitchouk, Thomas, and Young
- Could impact Qweak precision

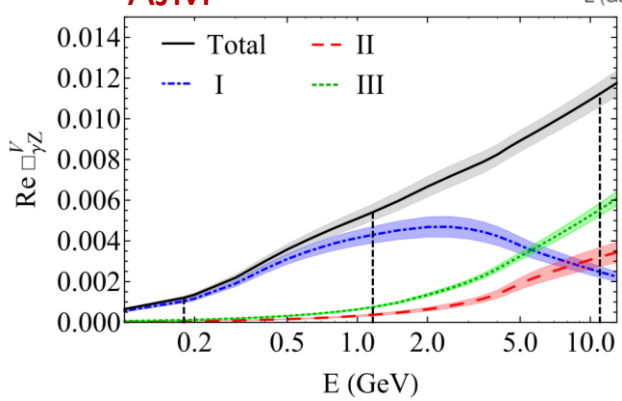
RC



GHRM



AJM



* Gorchtein and Horowitz. *Phys. Rev. Lett.* **102**, 091806 (2009)

Published Nucl.Instrum.Meth. A781 (2015) 105-133

The Q_{weak} Apparatus

Beam Properties

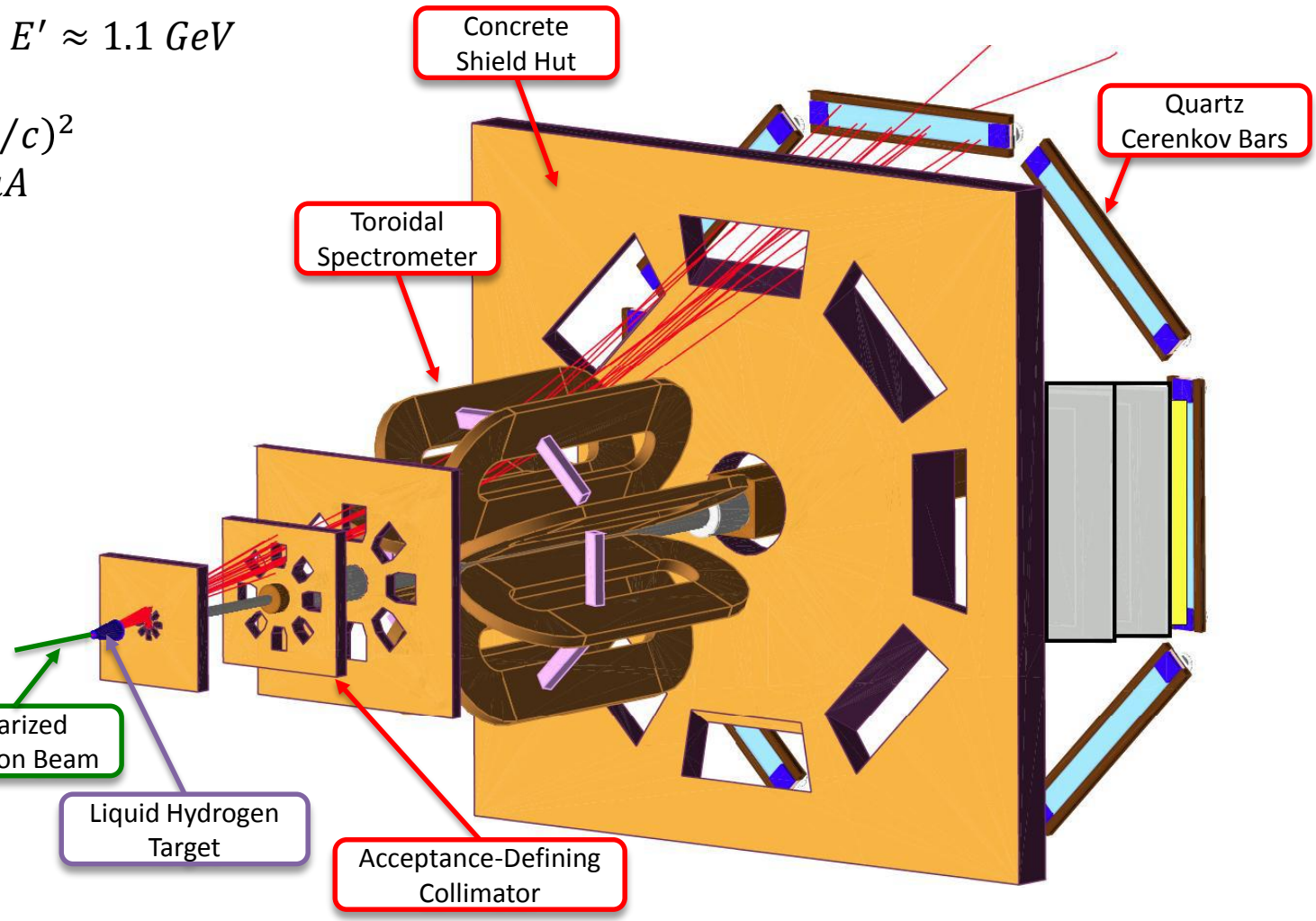
$E = 3.35\ GeV \qquad E' \approx 1.1\ GeV$

$W = 2.23\ GeV$

$Q^2 = 0.075\ (GeV/c)^2$

$I = 145 - 180\ \mu A$

$P_{beam} = 89\%$



Target

$34.4\ cm$ LH_2

$T \approx 20\ K$

$3.0\ kW$ Cryopower

Published Nucl.Instrum.Meth. A781 (2015) 105-133

The Q_{weak} Apparatus

Beam Properties

$E = 3.35\ GeV \qquad E' \approx 1.1\ GeV$

$W = 2.23\ GeV$

$Q^2 = 0.075\ (GeV/c)^2$

$I = 145 - 180\ \mu A$

$P_{beam} = 89\%$

Production Mode

$\theta_{Pol} = -19.1°$

Mixed Polarization

Transverse Mode

$\theta_{Pol} = 92.2°$

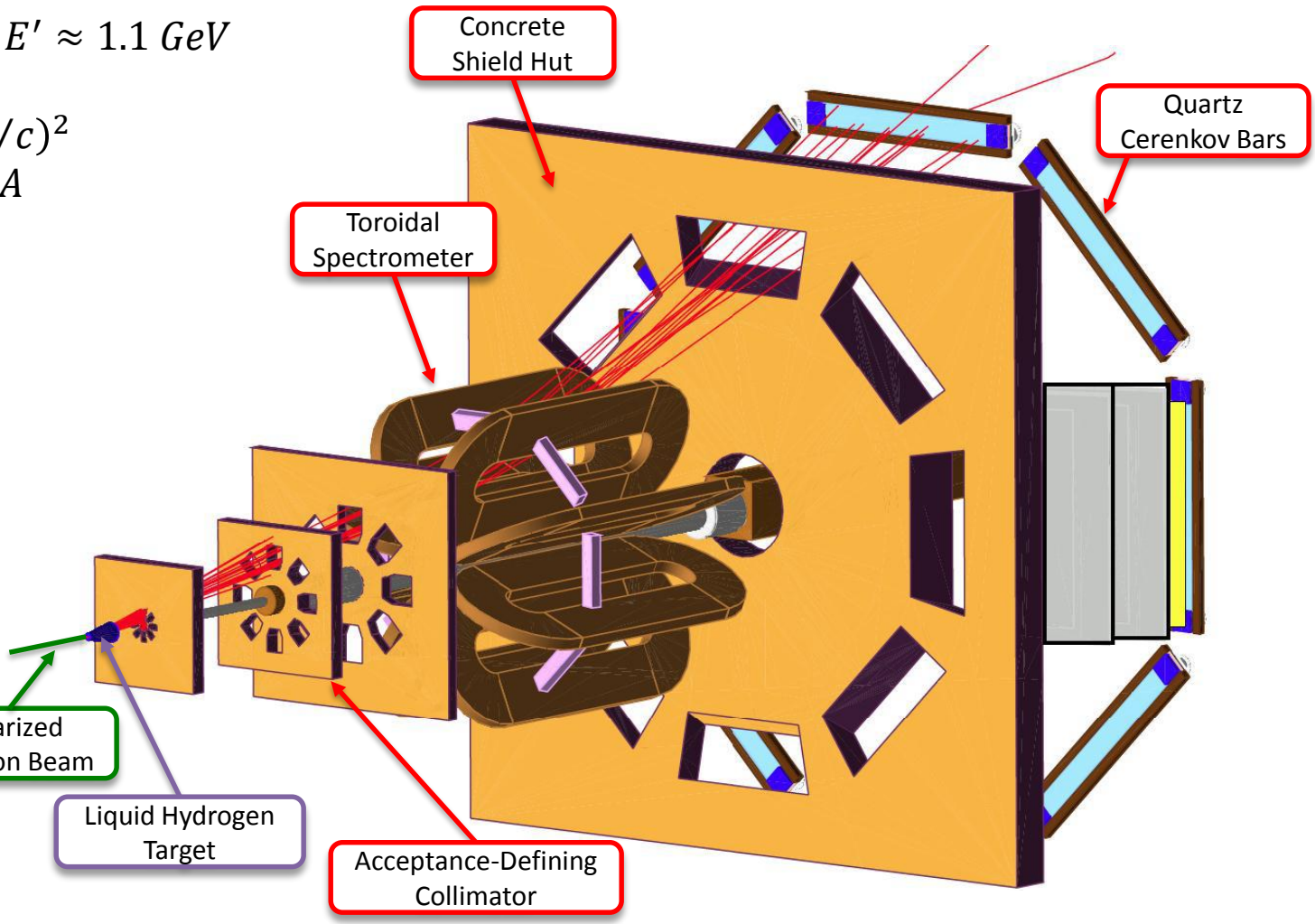
Only Transverse

Target

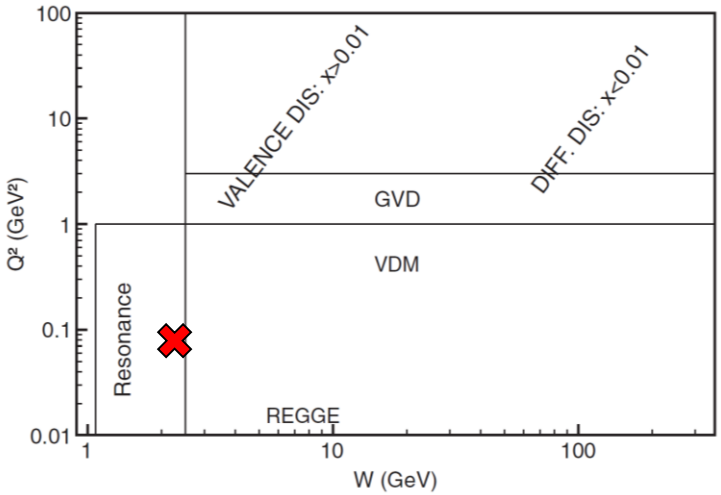
$34.4\ cm$ LH_2

$T \approx 20\ K$

$3.0\ kW$ Cryopower



Kinematics

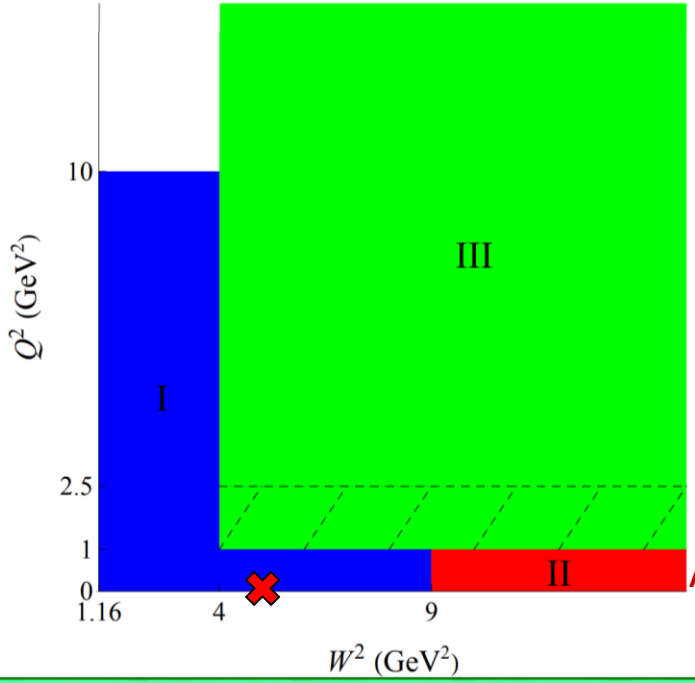


GHRM

Where does the Qweak Inelastic measurement sit?

$$W = 2.23\ GeV$$

$$Q^2 = 0.075\ GeV^2$$



AJM

- 3 Kinematic Regions contributing to $\square^V_{\gamma Z}$ integral
- Region I
  - Christy-Bosted parameterization
  - Uses $\gamma\gamma \rightarrow \gamma Z$ rotated structure functions
- Region II
  - VMD + Regge Parameterization
- Region III
  - DIS region

* Hall, Blunden, Melnitchouk, Thomas, and Young. Phys.Lett. B753 (2016) 221-226

Outline of Analysis

Measured Asymmetries

Remove Pion Background

- Asymmetry
- Signal fraction

Extract Longitudinal e^- Asymmetry

- Pure transverse runs
- Beam polarization angle

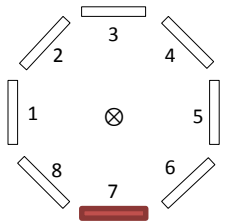
Remove other backgrounds

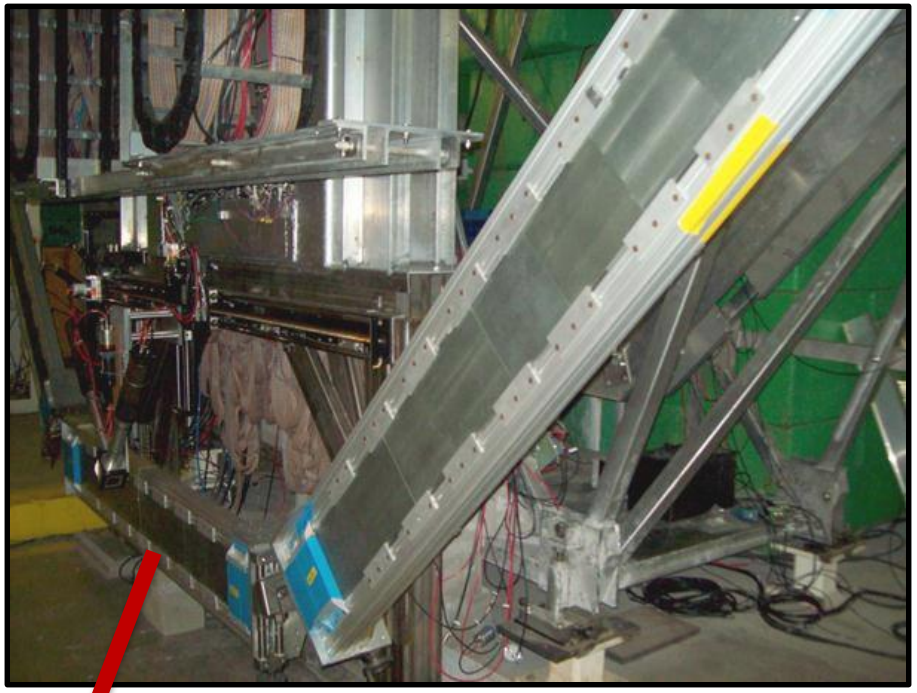
- Asymmetries & signal fractions
- Elastic radiative tail
- Al target windows
- Concrete bunker 'punch-through'
- Others

PV Inelastic $\vec{e}p$ Asymmetry

Characterization of Pion Background

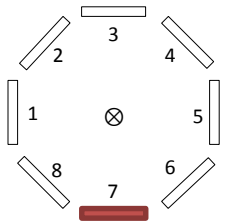
- Large difference between E & E'
  - Leads to large pion background
- 4” lead wall placed in front of lowest Čerenkov Detector
  - Ranges out most electrons
  - Leaves mostly pions
- Sacrifice statistics to make a ‘Pion detector’

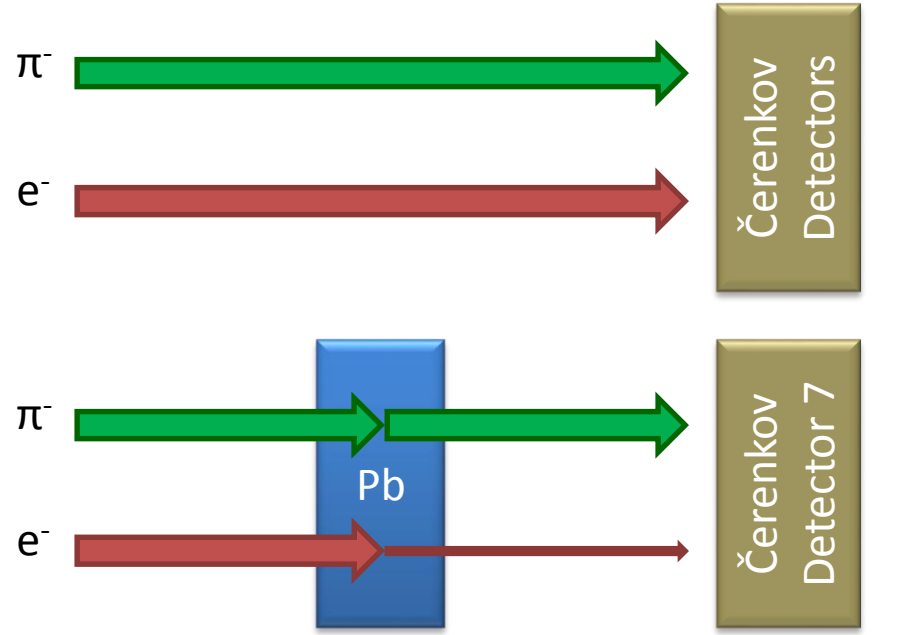




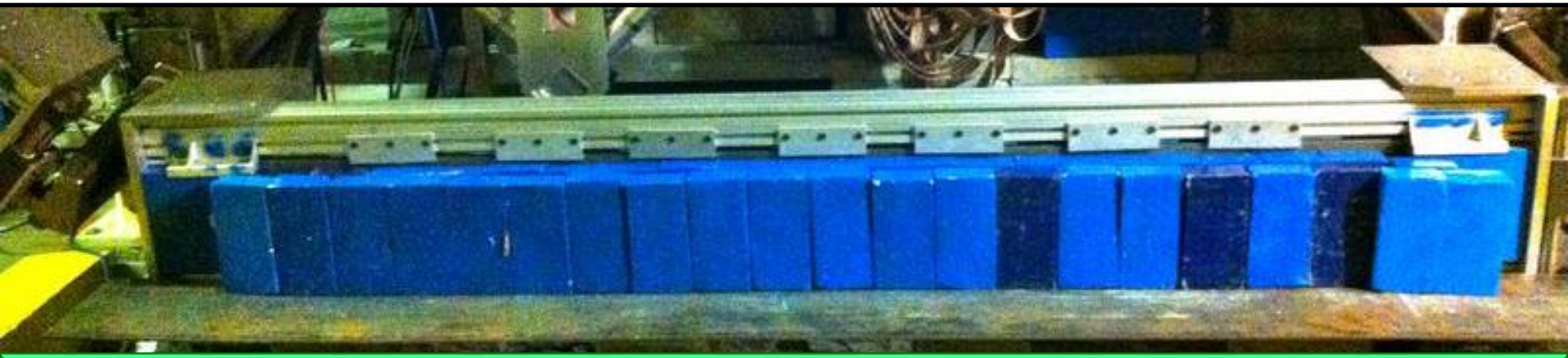
Characterization of Pion Background

- Large difference between E & E'
  - Leads to large pion background
- 4” lead wall placed in front of lowest Čerenkov Detector
  - Ranges out most electrons
  - Leaves mostly pions
- Sacrifice statistics to make a ‘Pion detector’

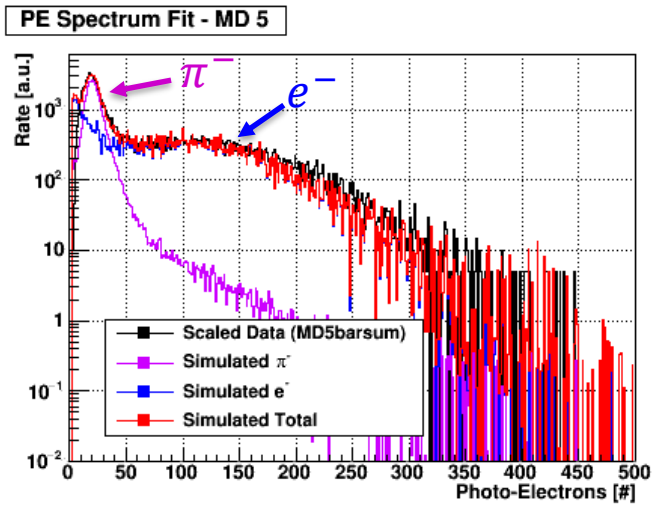


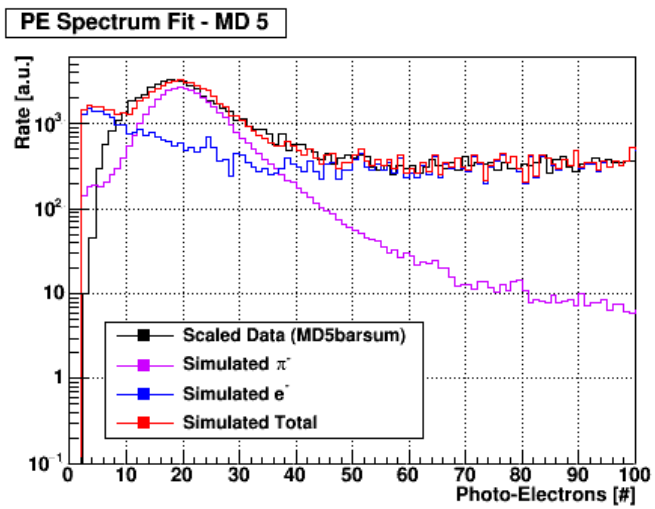


Main Detector 7 sees mostly pions

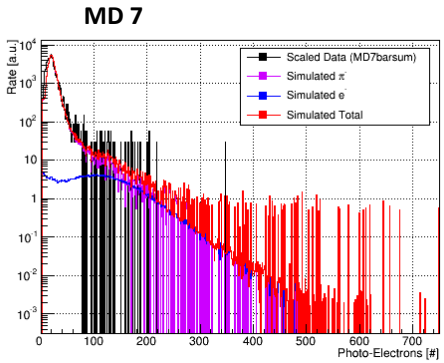


Pion Background Fraction





- Use ADC pulse height spectrum to distinguish particle type
  - Electrons deposit ~5 times more light
- Allow normalization of the simulations to float independently
  - Separate GEANT4 simulations: e^- & π^-
  - Fit to ADC spectrum with a Minuit minimization
- Integrate each scaled simulation to get total yields
  - 'Yield' - beam current normalized rate, weighted by pulse height
  - Y_π & $Y_e \rightarrow$ f_π^i, background fraction
- Will not work for main detector 7
  - 4" Pb wall installed in front
  - Made into an effective pion detector
  - Low electron count
  - Impossible to fit
- Pion yield fractions
  - $f_\pi^{i\neq 7} = 0.097 \pm 0.033$
  - $f_\pi^{i=7} = 0.81 \pm 0.06$

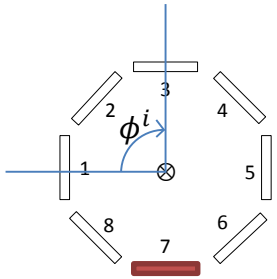


Asymmetry Extraction

$$A^{ij}_{meas} = A^{ij}_{calc} = (1 - f^i_\pi)\left(A^L_e \cos\theta^j_{Pol} + A^T_e \sin\theta^j_{Pol} \sin\phi^i\right) + f^i_\pi\left(A^L_\pi \cos\theta^j_{Pol} + A^T_\pi \sin\theta^j_{Pol} \sin\phi^i\right)$$

$$\chi^2 = \sum\left(A^{ij}_{meas} - A^{ij}_{calc}\right)^2$$

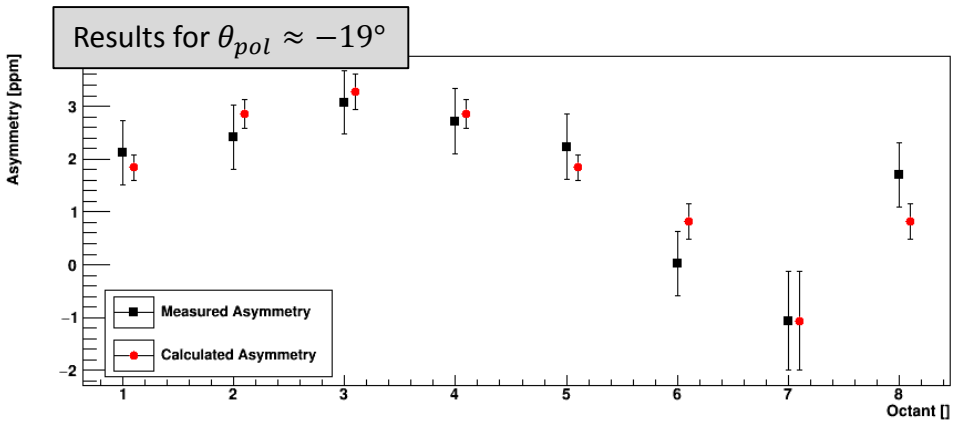
'Many-Worlds' Monte Carlo Minimization

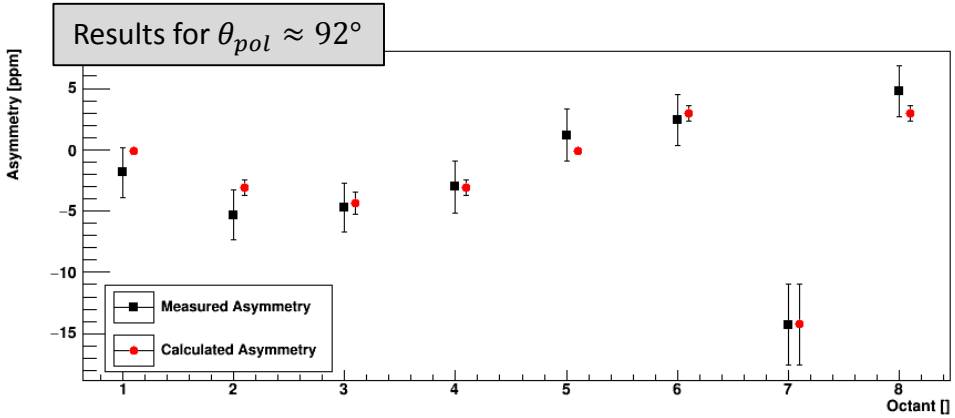


- The 16 measured asymmetries are parameterized
  - Longitudinal vs Transverse
  - Electron vs Pion
- Coefficients are in terms of input parameters
  - 2 pion yield fractions (w/ & w/o wall)
  - 2 polarization angles
- 4 extracted raw asymmetry components

A^L_e	-3.1 ± 0.6 ppm
A^T_e	6.9 ± 1.5 ppm
A^L_π	8.6 ± 2.4 ppm
A^T_π	-19.7 ± 4.7 ppm

Preliminary, not for quotation!



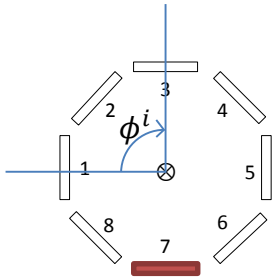


Asymmetry Extraction

$$A^{ij}_{meas} = A^{ij}_{calc} = (1 - f^i_\pi)\left(A^L_e \cos\theta^j_{Pol} + A^T_e \sin\theta^j_{Pol} \sin\phi^i\right) + f^i_\pi\left(A^L_\pi \cos\theta^j_{Pol} + A^T_\pi \sin\theta^j_{Pol} \sin\phi^i\right)$$

$$\chi^2 = \sum\left(A^{ij}_{meas} - A^{ij}_{calc}\right)^2$$

'Many-Worlds' Monte Carlo Minimization

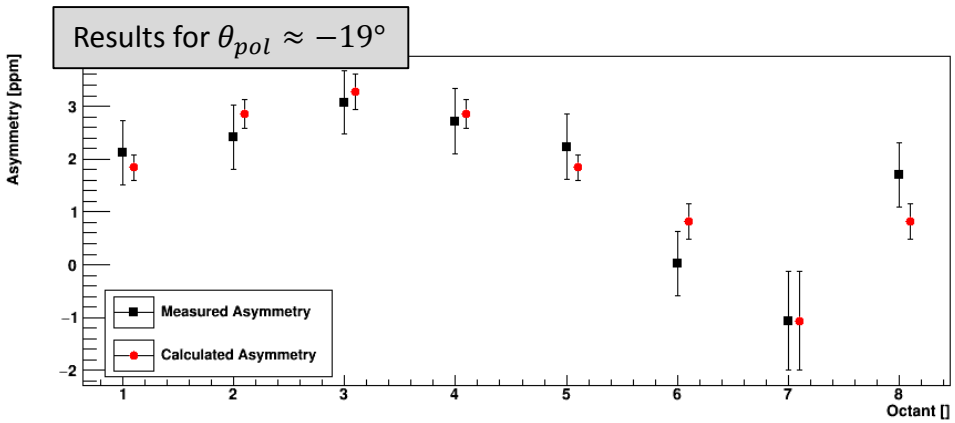


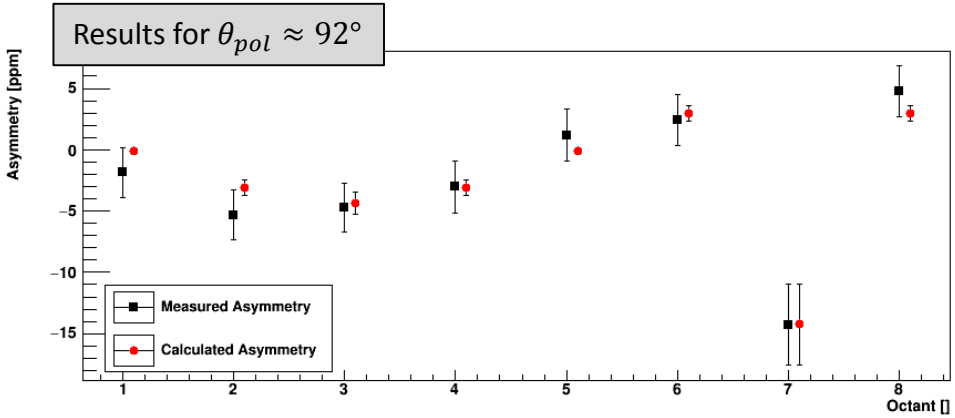
- The 16 measured asymmetries are parameterized
  - Longitudinal vs Transverse
  - Electron vs Pion
- Coefficients are in terms of input parameters
  - 2 pion yield fractions (w/ & w/o wall)
  - 2 polarization angles
- 4 extracted raw asymmetry components

A^L_e	-3.1 ± 0.6 ppm
A^T_e	6.9 ± 1.5 ppm
A^L_π	8.6 ± 2.4 ppm
A^T_π	-19.7 ± 4.7 ppm

FREE!

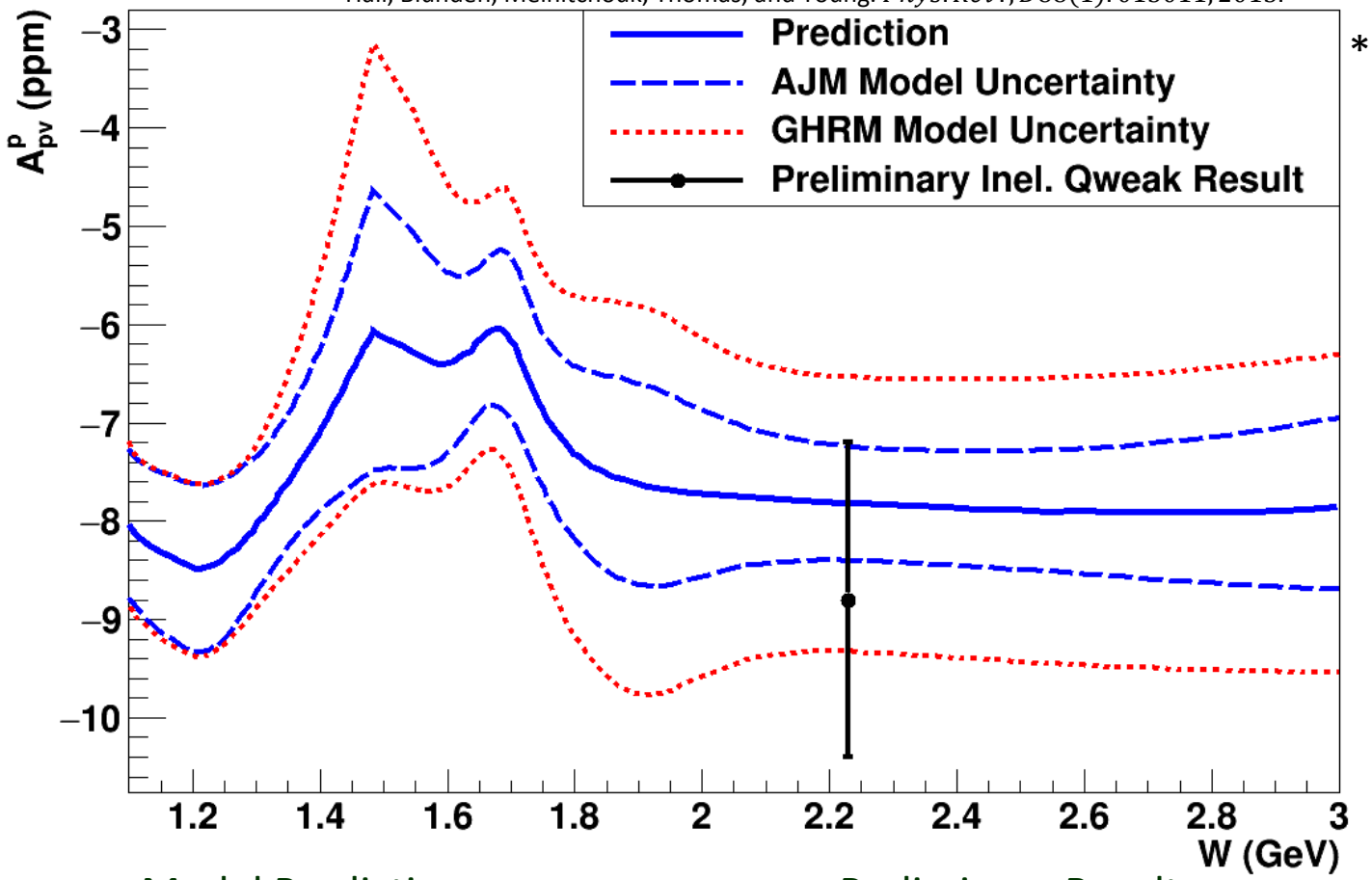
Preliminary, not for quotation!





Preliminary Result

* Hall, Blunden, Melnitchouk, Thomas, and Young. $Phys.Rev., D88(1): 013011, 2013.$



Model Predictions

$Q^2 = 0.09\ GeV^2$

$A^p_{PV} = -7.8 \pm 0.6$ ppm

$A^p_{PV} \approx -7.8 \pm 1.2$ ppm

Preliminary Result

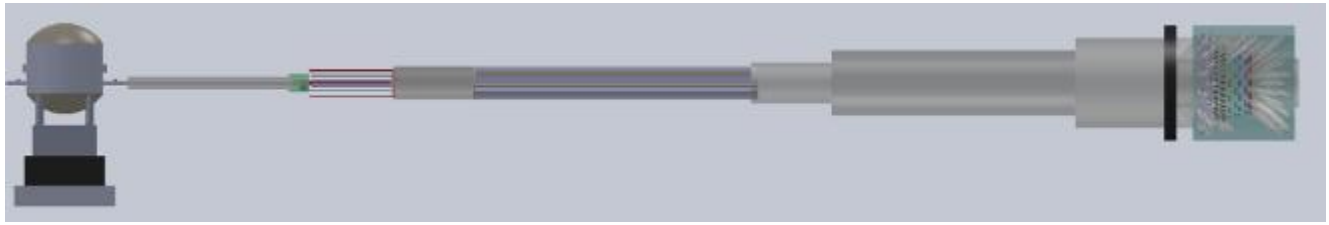
$Q^2 = 0.075\ GeV^2$

$A_{phys} = -8.8 \pm 0.9(stat) \pm 1.3(syst)$ ppm

Measurement Uncertainty

- Limited by statistical uncertainty
  - Only ~2 weeks of data
- Pion background fraction
  - Largest systematic uncertainty
  - Demonstrates that we can separate e^- & π^- when not in counting mode
- Systematic uncertainty dominated by
  - Pion background fraction
  - Asymmetry Separation

Future Experiment Wishlist



- Data that spans kinematic integral
  - E, W, and Q^2
  - Ex: Tune MOLLER apparatus to access various inelastic kinematics
- Dedicated pion detector
  - Cleaner pion separation
- More Statistics!

Summary

- Preliminary analysis complete
  - Final analysis will appear in my PhD thesis (Possibly a separate publication)
  - Preliminary result in good agreement with predictions

$$A_{phys} = -8.8 \pm 0.9(stat) \pm 1.3(syst) \text{ ppm}$$

- This measurement lies in a kinematic region with almost no experimental world data
  - Future experiments: MOLLER, P2, SoLID

- Valuable measurement that validates theory
  - Constrains γZ structure functions
  - Constrains $\Re e \Box_{\gamma Z}^{V}$ correction to Q_W^p

- Several other 'free' measurements
  - Need more analysis before getting to interesting physics

A_e^T	6.9 ± 1.5 ppm
A_π^L	8.6 ± 2.4 ppm
A_π^T	-19.7 ± 4.7 ppm

The Qweak Collaboration

101 collaborators 26 grad students
11 post docs 27 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
[24] Syracuse University
[25] Duquesne University

A SEARCH FOR NEW PHYSICS
Qweak

D. Androic,[1] D.S. Armstrong,[2] A. Asaturyan,[3] T. Averett,[2] J. Balewski,[4] K. Bartlett,[2] J. Beaufait,[5] R.S. Beminiwattha,[6] J. Benesch,[5] F. Benmokhtar,[7,25] 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], C. Gal,[9] 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] H. Nuhait,[16] 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] P. Zang,[24] and S. Zhamkochyan [3]

Jefferson Lab

Spokespersons Project Manager Grad Students

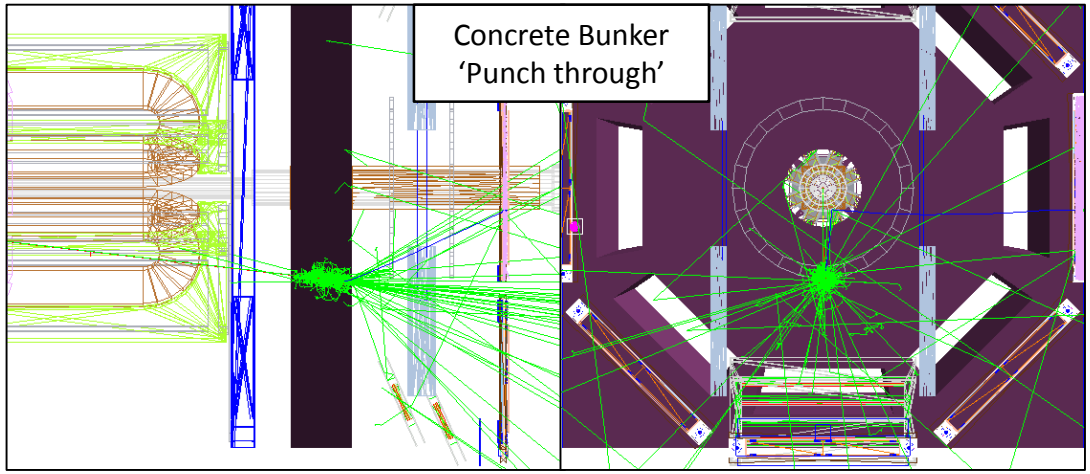
Hall C

Background Corrections

$$A_{phys} = \frac{\frac{A_e^L}{P} - \sum f_k A_k^{bkgd}}{1 - \sum f_k}$$

A_{El}^{bkgd}	-0.58 ± 0.02 ppm
f_{El}	0.607 ± 0.023
A_{Al}^{bkgd}	-2.4 ± 4.8 ppm
f_{Al}	0.0064 ± 0.0064
A_{PT}^{bkgd}	-3.96 ± 0.04 ppm
f_{PT}	0.037 ± 0.004

- Elastic radiative tail
  - By far the largest background
  - Rigorous Mo & Tsai* formulation of radiative cross section corrections
- Al target windows
  - Combination of data and MC simulation
  - Total correction size is small
- Concrete Bunker 'Punch through'
  - Some high energy (> 3 GeV) electrons penetrate the concrete bunker.
- Small background corrections not yet included
  - Beamline background
  - Detector non-linearity
  - PMT double difference



* Rev. Mod. Phys., 41:205–235, 1969