The Qweak Experiment: Early Results and Outlook

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UNIVERSITY OF MANITOBA

Jefferson Lab

Outline

- Motivation
- Qweak apparatus
- Early Results
- Recent Progress
- Results & Conclusion

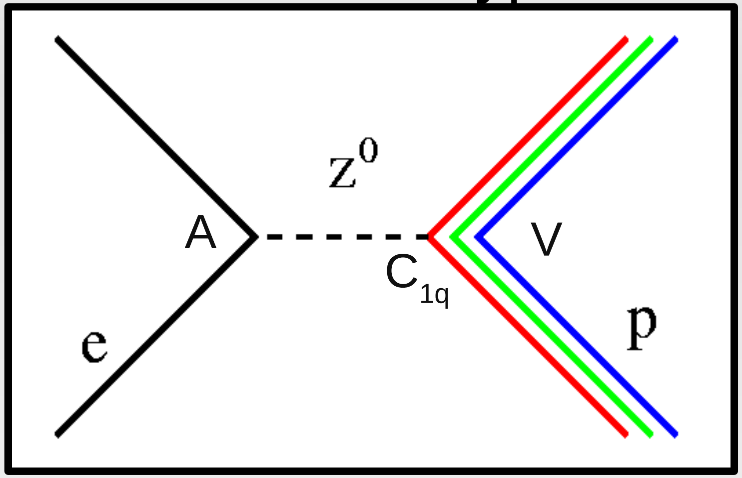
Motivation and Formalism

The Electroweak Interaction

- The proton's weak charge is highly suppressed in the standard model. A high precision measurement could be sensitive to certain types of new parity-violating physics!

$$\mathcal{L}_{SM}^{PV} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\bar{q}\gamma^\mu q$$

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

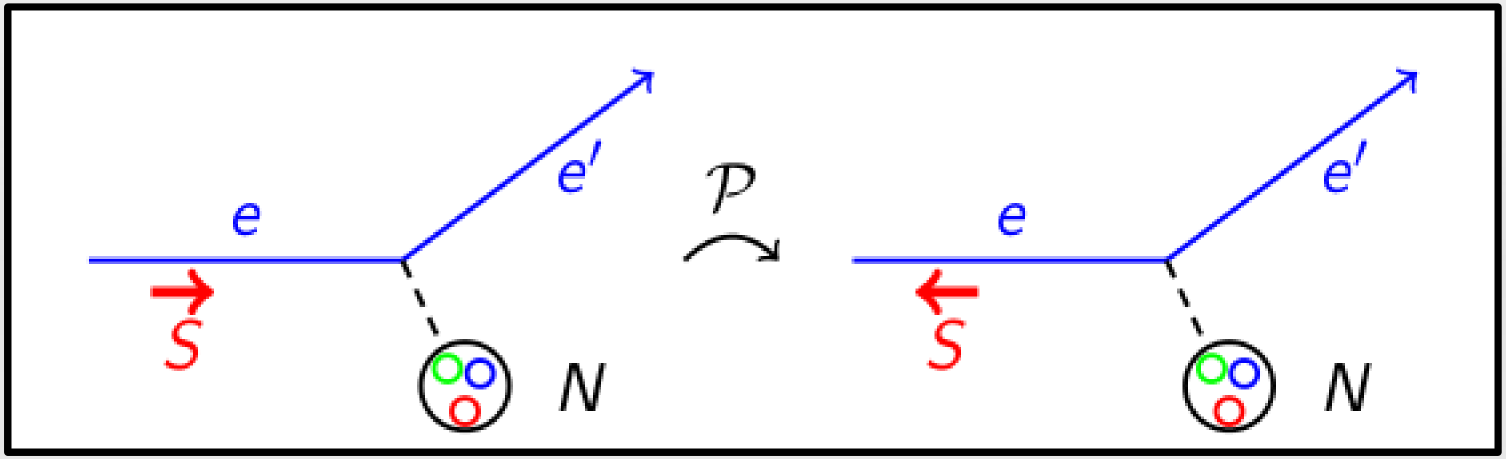


Tree level electric and weak charges

	Q_{EM}	Q_{weak}
q_u	$+\frac{2}{3}$	$+1 - \frac{8}{3}\sin^2\theta_W \approx 0.38$
q_d	$-\frac{1}{3}$	$-1 + \frac{4}{3}\sin^2\theta_W \approx -0.69$
P	$+1$	$+1 - 4\sin^2\theta_W \approx 0.07$
n	0	-1

← suppression

Parity-Violating Electron Scattering



- Scattering amplitudes will have both EM and weak contributions.

$$\sigma \propto \left|M^{\mathrm{PC}}_{\mathrm{EM}} + M^{\mathrm{PV}}_{\mathrm{weak}}\right|^2 = \left|M^{\mathrm{PC}}_{\mathrm{EM}}\right|^2 + 2M^{\mathrm{PC}}_{\mathrm{EM}} M^{*\mathrm{PV}}_{\mathrm{weak}} + \left|M^{\mathrm{PV}}_{\mathrm{weak}}\right|^2$$

- Measure the *parity-violating asymmetry:*

$$A_{\mathrm{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{2M^{\mathrm{PC}*}_{\mathrm{EM}} M^{\mathrm{PV}}_{\mathrm{weak}}}{\left|M^{\mathrm{PC}}_{\mathrm{EM}}\right|^2} \sim -220\ \mathrm{ppb}$$

Parity-Violating Electron Scattering

- Left-right helicity asymmetry for **protons**:

$$A_{\rm ep} = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \times \left[\frac{\epsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z + g_V^e \epsilon' G_M^\gamma G_A^Z}{\epsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}\right]$$

$$\epsilon = \frac{1}{1 + 2(1+\tau)\tan^2\frac{\theta}{2}} \quad \epsilon' = \sqrt{\tau(1+\tau)(1-\epsilon^2)} \quad \tau = \frac{Q^2}{4M_p^2}$$

- As $Q^2 \rightarrow 0$ and $\theta \rightarrow 0$:

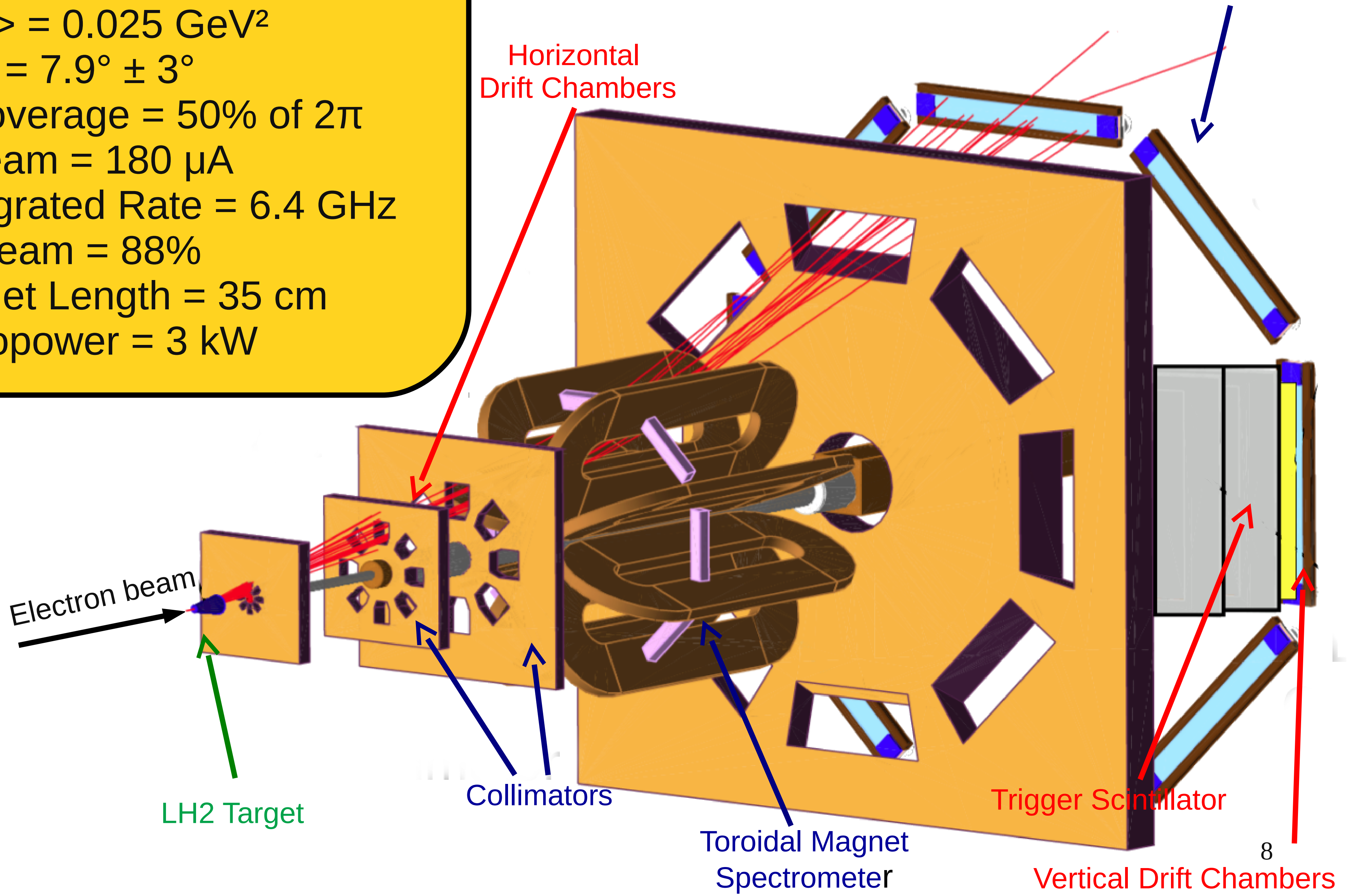
$$A_{\rm ep} \rightarrow \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[Q_W^p + Q^2 B(Q^2, \theta)\right]$$

Hadronic structure
Constrained by older PVES data

Apparatus

Q-weak Apparatus

Parameters:
E_beam = 1.165 GeV
$\langle Q^2 \rangle = 0.025$ GeV^2
$\langle \theta \rangle = 7.9° \pm 3°$
φ-coverage = 50% of 2π
I_beam = 180 μA
Integrated Rate = 6.4 GHz
P_beam = 88%
Target Length = 35 cm
Cryopower = 3 kW

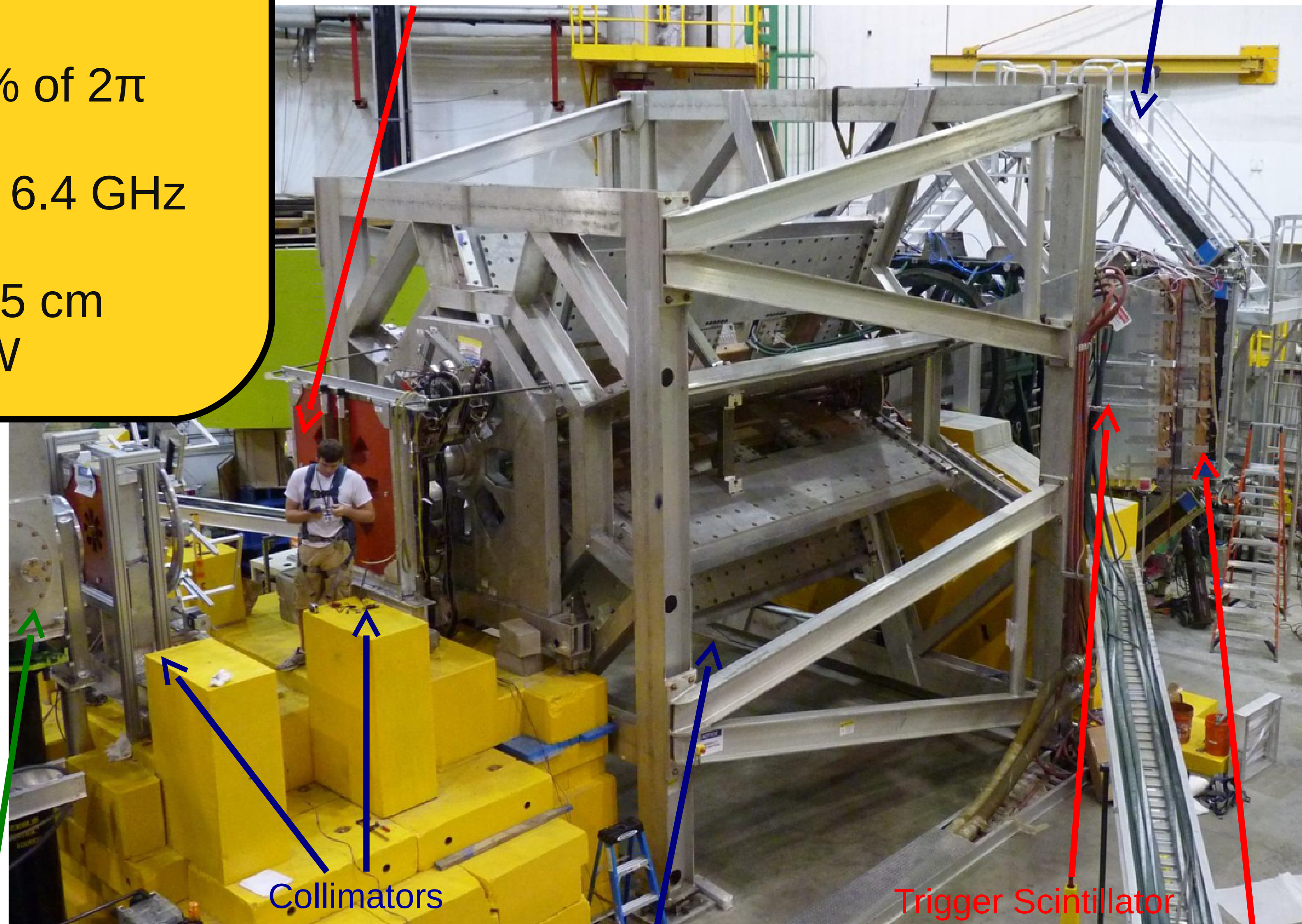


Red = Low current “tracking mode” only

Q-weak Apparatus

<u>Parameters:</u>

E_beam = 1.165 GeV
$\langle Q^2 \rangle = 0.025\ GeV^2$
$\langle\theta\rangle = 7.9° \pm 3°$
φ-coverage = 50% of 2π
I_beam = 180 μA
Integrated Rate = 6.4 GHz
P_beam = 88%
Target Length = 35 cm
Cryopower = 3 kW



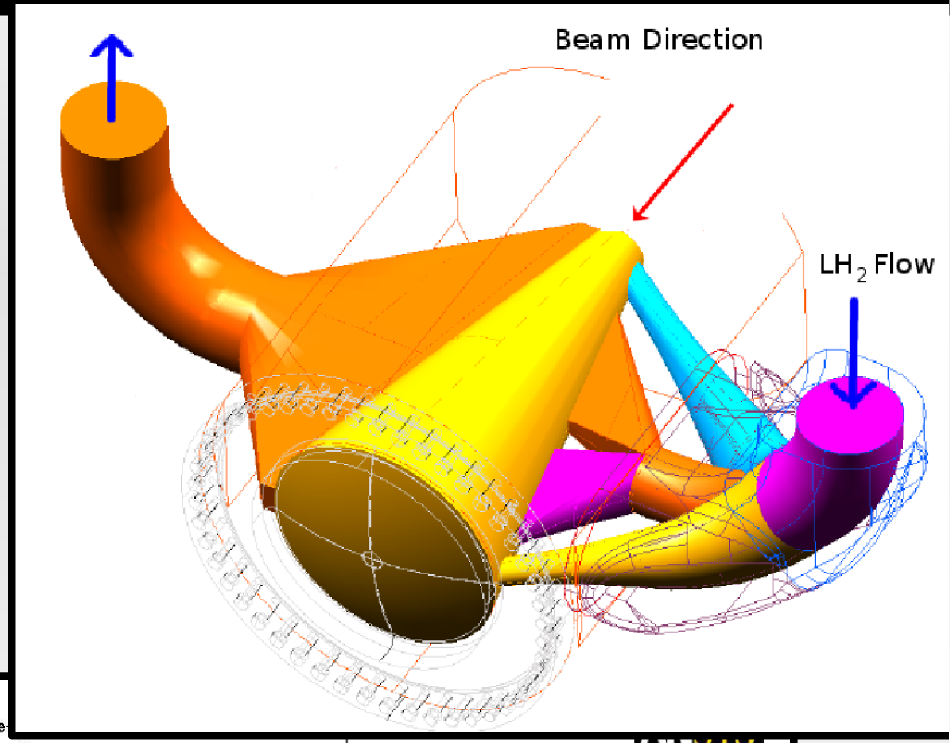
Red = Low current "tracking mode" only

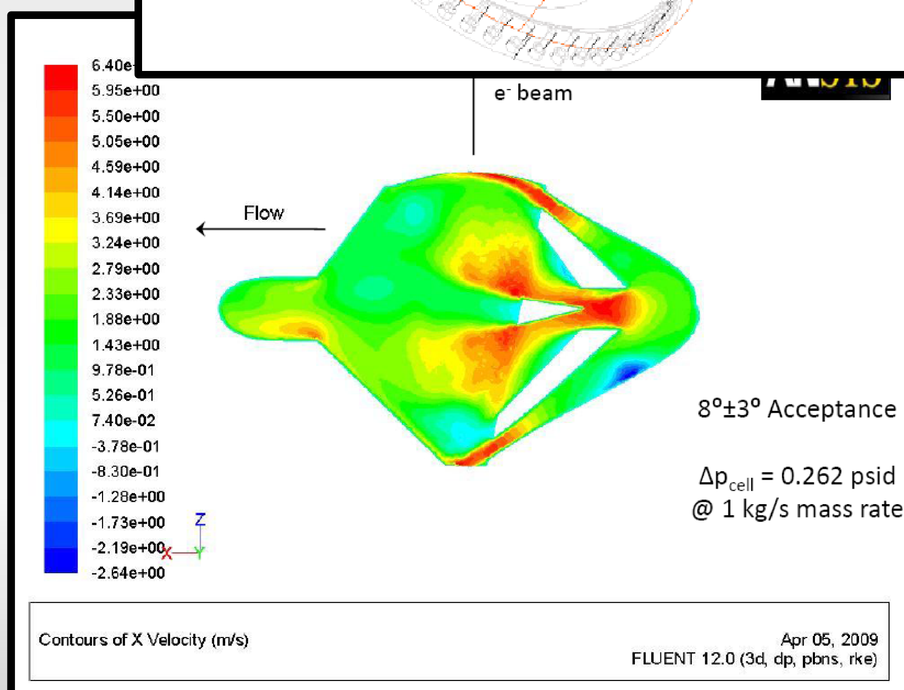
Liquid Hydrogen Target

- 35 cm long. Aluminum housing with high purity thin target windows

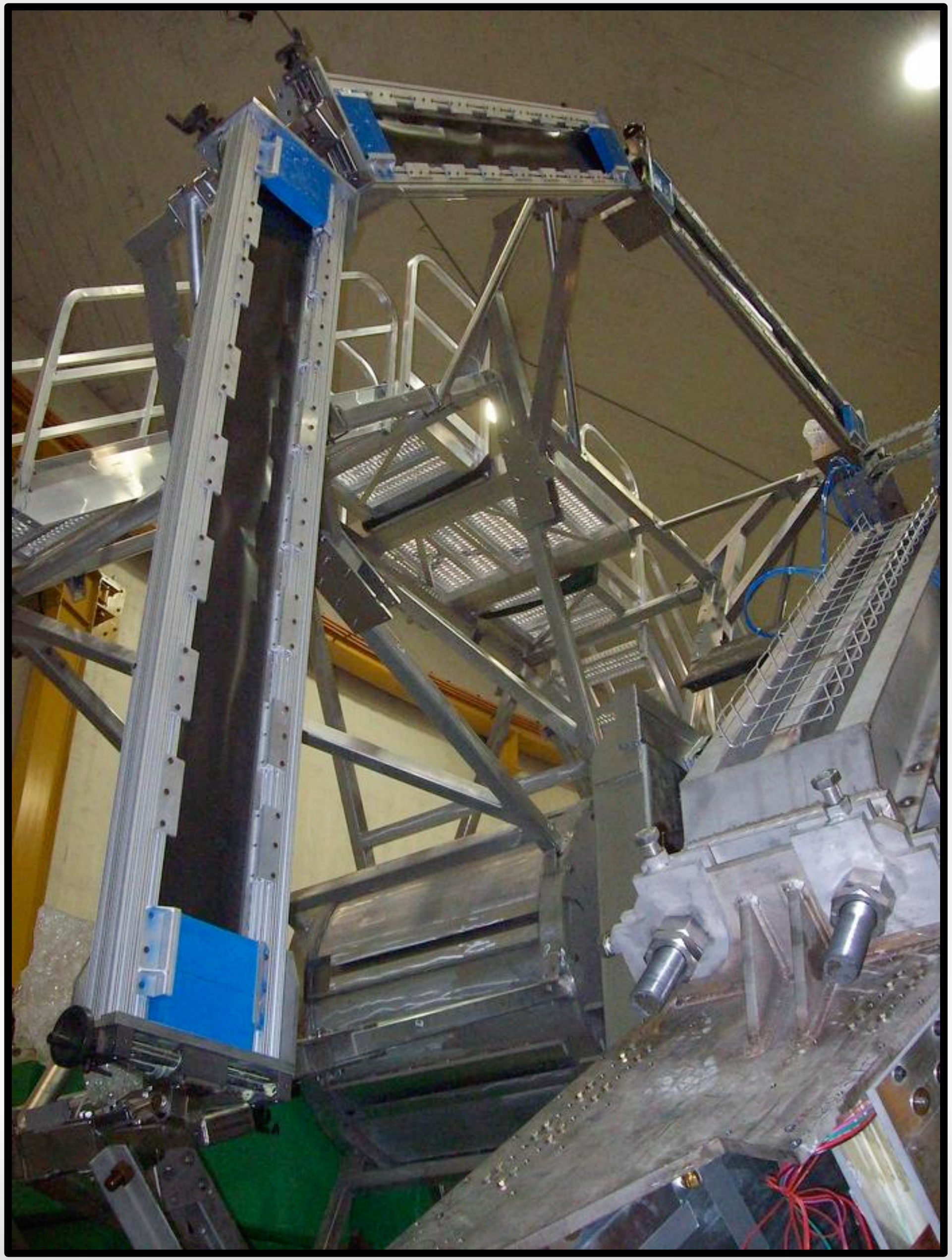
- Designed using computational fluid dynamics...a new procedure for JLab!

- Dissipated ~3 kW of power
  - **The world's highest power LH2 cryotarget!**



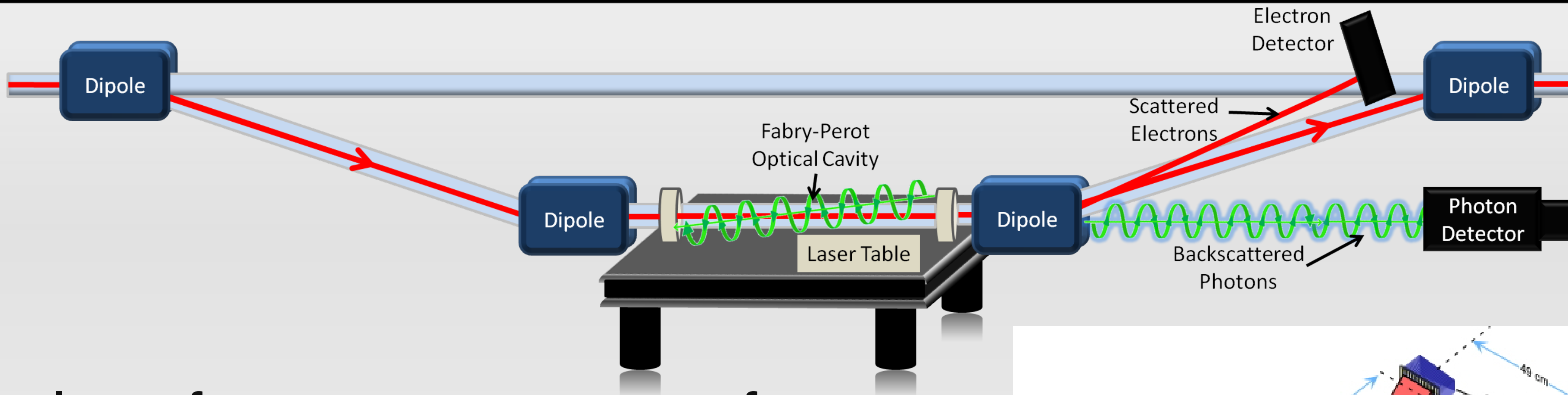


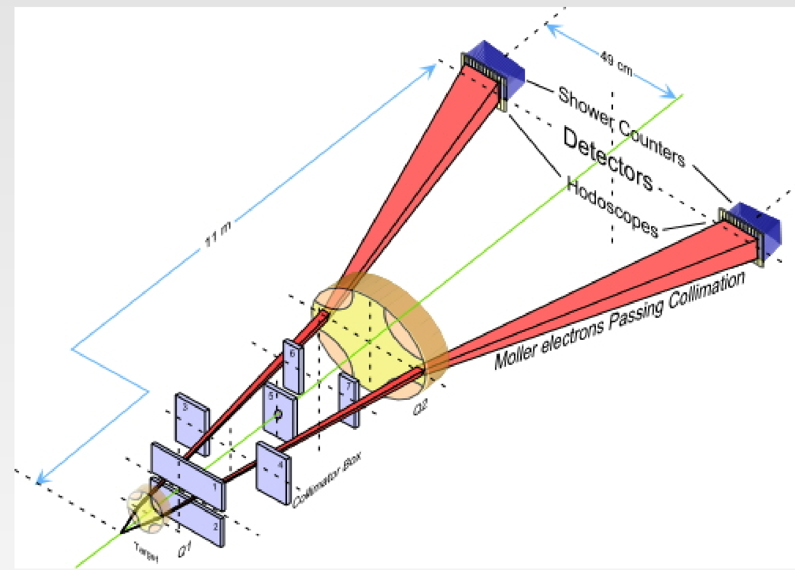
Main Detectors



- Quartz bar Cherenkov detectors (200 cm x 18 cm). 2 PMT's each
- Radiation hard, low scintillation, uniform response.
- 13 cm diameter PMTs on either end. Swappable bases:
  - Counting mode – High gain (JLab)
  - Integrating mode – Low gain (Manitoba)
- Pb pre-radiators to provide low-E shielding and boost signal.
- 800 MHz per bar in int. mode.

Polarimetry





- Goal: perform measurement of polarization to $\delta P/P = 1\%$

- Use two different polarimeters:
    - Existing Hall-C Møller polarimeter
        - Invasive to production
        - Known analyzing power from polarized Fe foil in high B-field
    - New Compton polarimeter
        - Non-invasive
        - Known analyzing power from circularly-polarized laser

Early Result

Extracting A_{ep} from A_{msr}

False Asymmetries

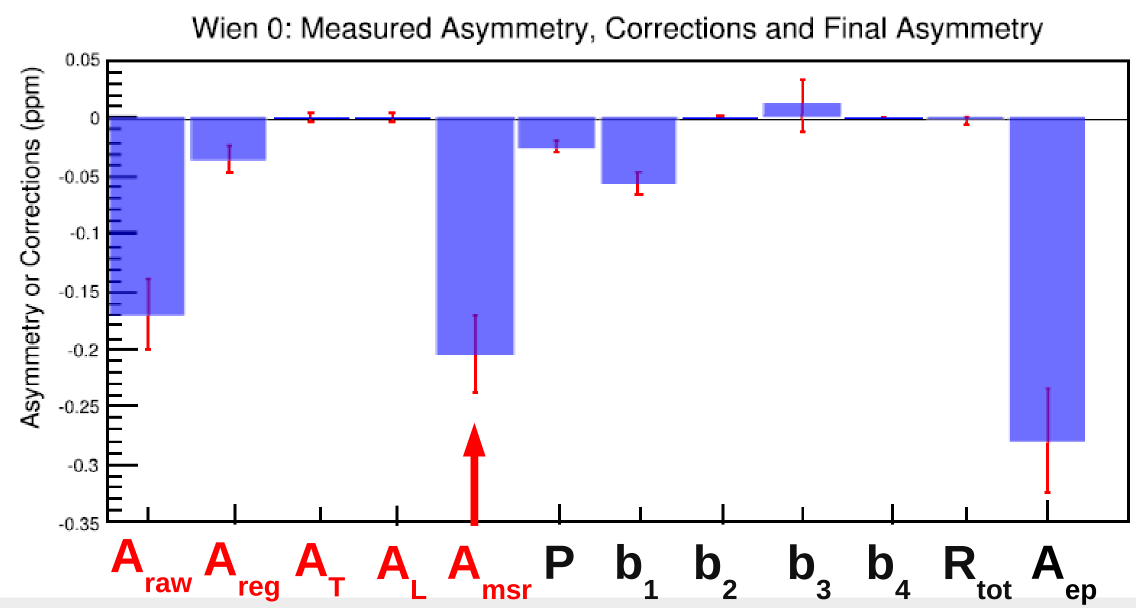
$$A_{\mathrm{msr}} = A_{\mathrm{raw}} + A_{reg} + A_T + A_L$$

A_{reg} = Linear Regression

A_T = Transverse Asymmetry

A_L = Detector Non-linearity

Background Asymmetries



$$b_i = A_i f_i$$

$$A_{\mathrm{ep}} = R_{\mathrm{tot}} \frac{\left(\frac{A_{\mathrm{msr}}}{P} - \sum_{i=0}^{4} f_i A_i \right)}{1 - \sum_{i=0}^{4} f_i}$$

A_i = Measured asymmetry for source i

f_i = Fractional yield for source i

i	
1	Al windows
2	Beamline bkgd
3	Soft neutrals
4	N→Δ

Extracting A_{ep} from A_{msr}

4% of total Qweak data set result:

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

Extraction Details

- 5 parameter fit using PVES data up to Q^2=0.63 $(GeV/c)^2$

$C_{1\{u,d\}},\ \rho_s,\ \mu_s,\ G_A^{Z(T=1)}$

HAPPEX, SAMPLE, G0, PVA4, Q-weak

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

- Result is a function of $A_{\rm ep}$ in Q^2 and θ.

- Kelly form factors used, including conventional dipole form for strange quark form factors:

$$G_D = \frac{1}{(1+\frac{Q^2}{\lambda^2})^2}, \qquad \lambda = 1\,(\mathrm{GeV/c})^2$$

$$G_E^s = \rho_s Q^2 G_D \quad G_M^s = \mu_s G_D$$

- $G_A^{Z(T=0)}$ is constrained by past calculations.

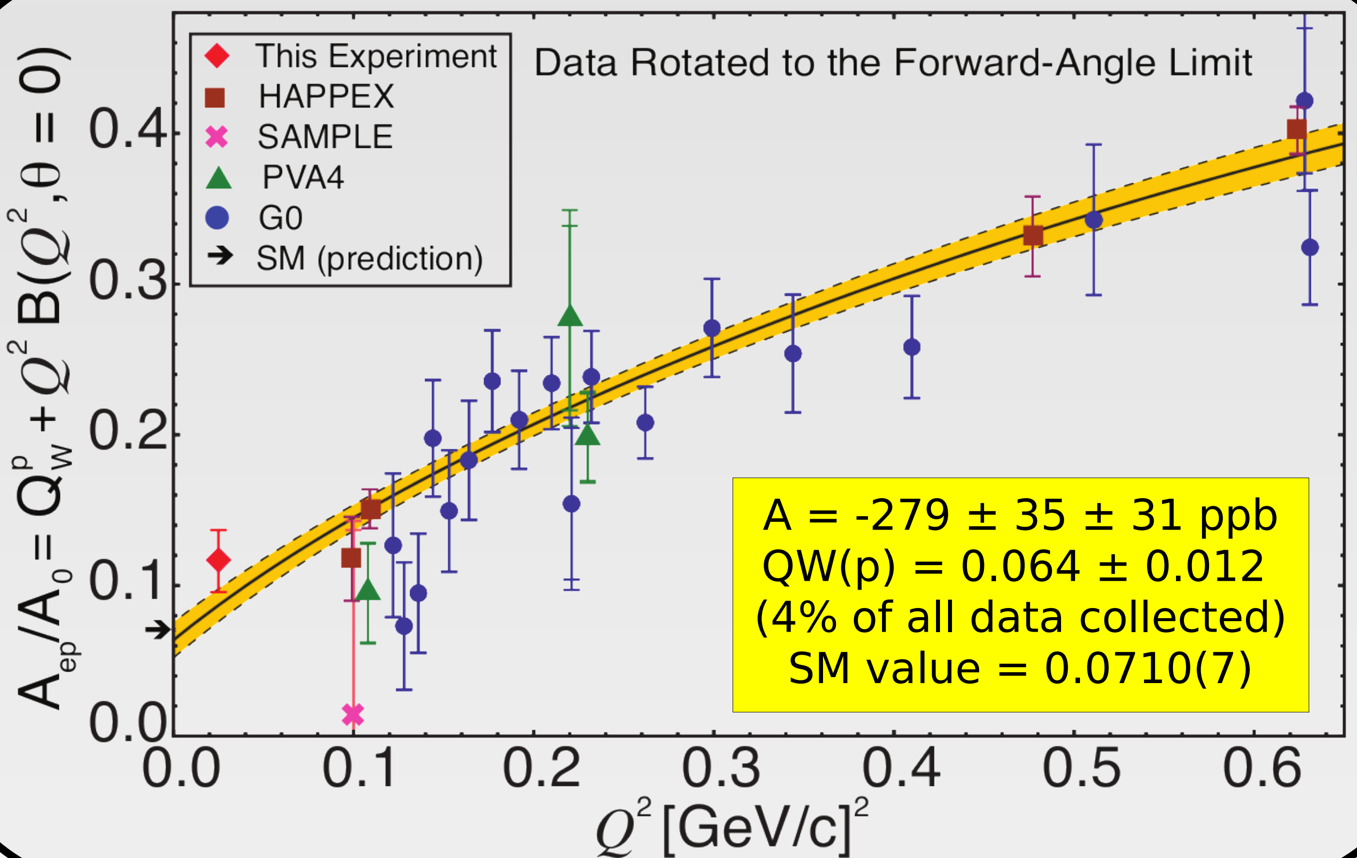
Reduced Asymmetry

•Rotate point to θ=0 in order to show on one plot:

$$A^{\rm data}(\theta=0,Q^2) = A^{\rm data}(\theta^{\rm data},Q^2) - [A^{\rm fit}(\theta^{\rm data},Q^2) - A^{\rm fit}(\theta=0,Q^2)]$$

•Negligible effect when making cuts on Q² for this result.

•Correct *all* ep data for $\Box_{\gamma Z}$ energy and Q^2 dependences.



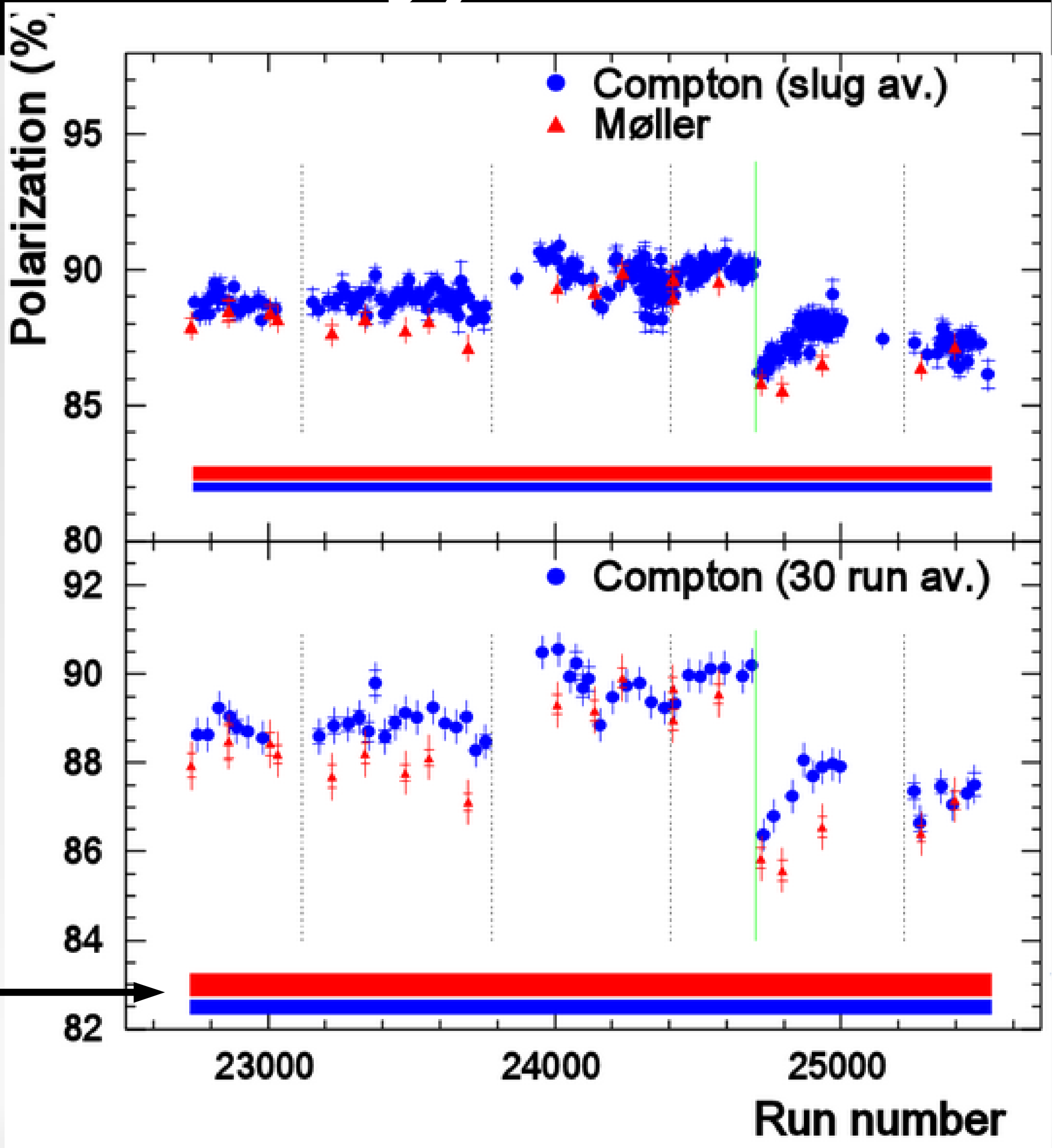
Recent Progress

Polarimetry (Preliminary)

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

- Both techniques agree to <0.8%

- Final results to use using Compton with comparison to Møller to improve normalization uncertainty.



Normalization uncertainty bands

▲ *PMoller* +/- stat (inner) +/- point-to-point systematic (0.53%)

● *PCompton* +/- stat +/- point-to-point syst. (0.41%)

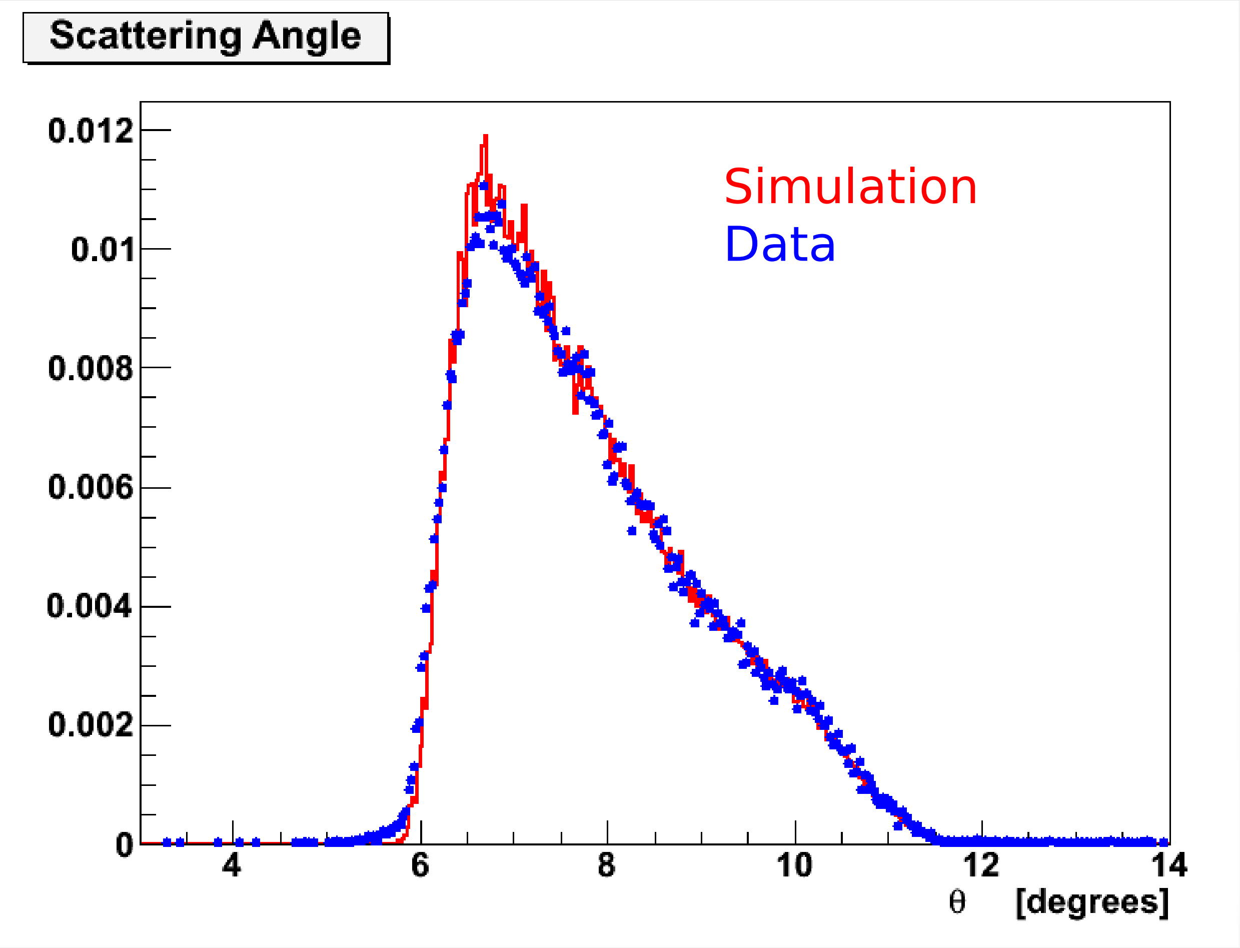
Q^2 Measurement (θ Determination)

$$Q^2 = 2E^2 \frac{(1-\cos\theta)}{1+\frac{E}{M}(1-\cos\theta)}$$

- Dominant uncertainty:

  θ determination

- Data from Tracking system.
- GEANT4 simulation & data analyzed with the same code.
- <θ>: Data and simulation currently agree to <0.5%



Aluminum

- Large PV asymmetry:
  - ~2 ppm (compared to ~-220ppb!)
- More Al data analyzed:

  180ppb $\rightarrow$ 70ppb
- Systematics also to improve over initial PRL2013 result.

- Ongoing analysis improvements to extraction of the aluminum dilution as well.

$$f_1 \approx 3.2\%$$

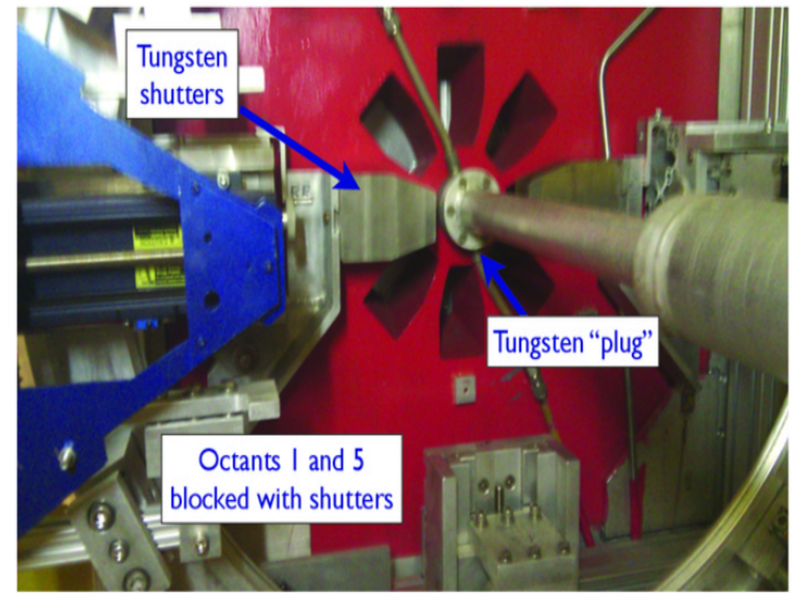
Beamline Backgrounds

Highest contribution to systematic uncertainty for the PRL2013 result.

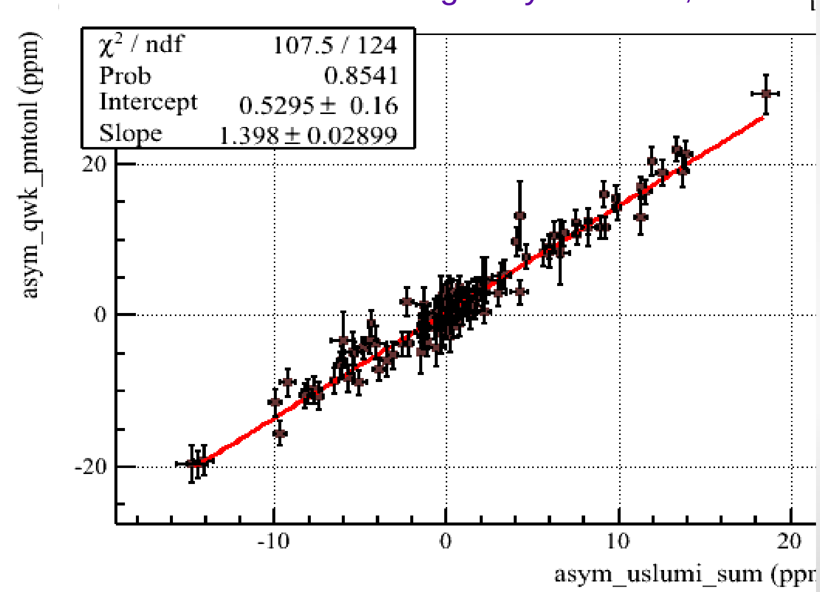
- Background from electrons scattering on beamline or tungsten plug collimator.
- Thought to be associated with large asymmetries on outer part of the beam (“halo”).
- Yield fraction on Main Detector measured directly by blocking primary e^- on two octants:

$$f_{b2}^{\mathrm{MD}} \approx 0.19\%$$

- Background detectors in various locations monitored this component and measured highly correlated asymmetries.
- Scaling of background asymmetries also consistent with expectation from dedicated measurement.



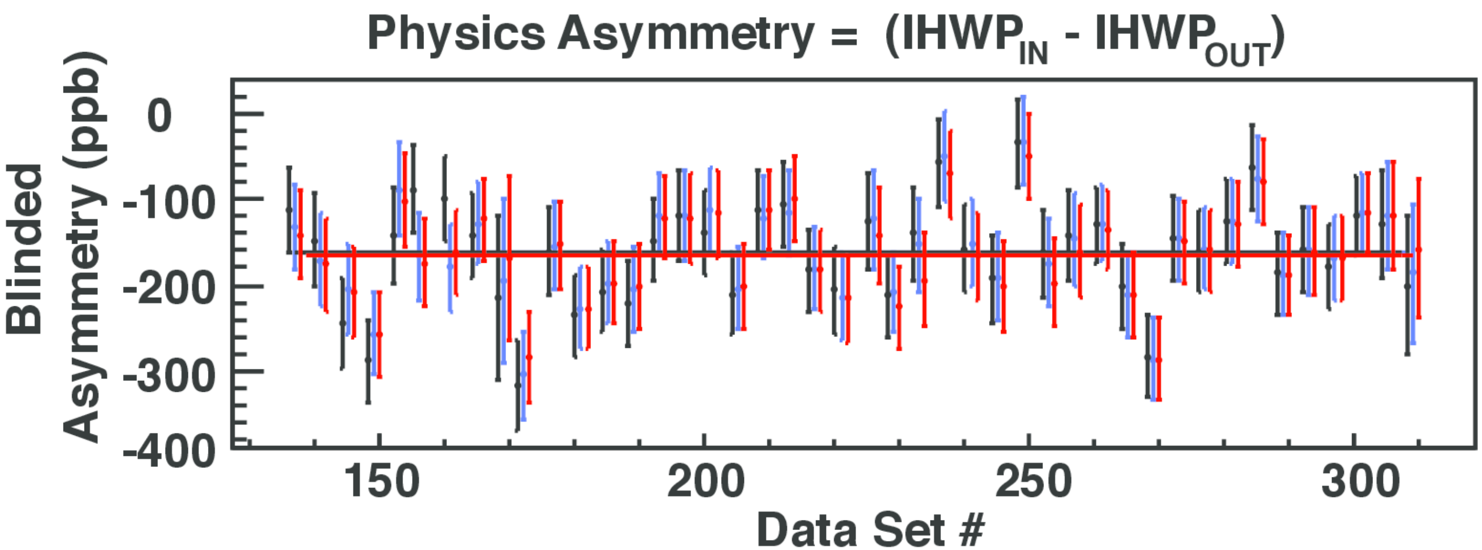
Correlation between bkgd asymmetries, Run2



Blinded Asymmetries

Qweak Run 2 - Blinded Asymmetries

(statistics only - not corrected for beam polarization, Al target windows, ΔQ^2, etc.)



Raw = -161.8 ± 7.6

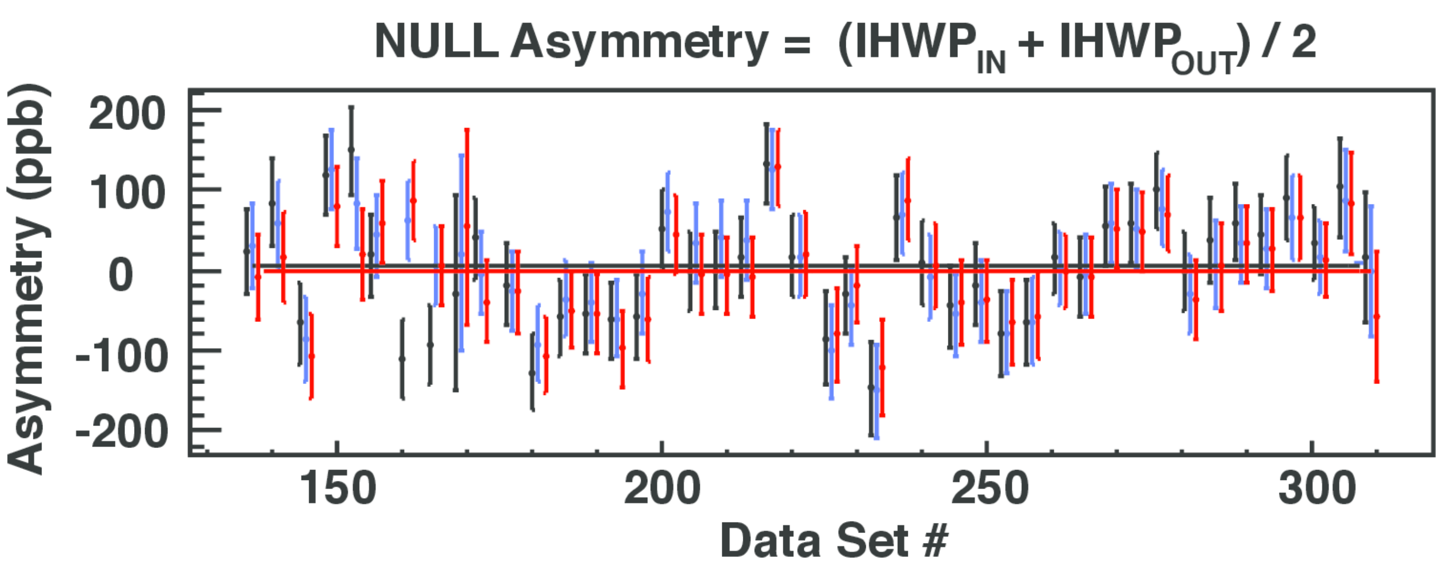
(χ^2/ NDF = 1.40, Prob = 0.043)

Regressed = -160.9 ± 7.6

(χ^2/ NDF = 1.19, Prob = 0.18)

Beamline Bkgd Corrected = -164.5 ± 7.6

(χ^2/ NDF = 1.08, Prob = 0.33)



Raw = 4.7 ± 7.7

(χ^2/ NDF = 1.84, Prob = 0.001)

Regressed = 7.9 ± 7.7

(χ^2/ NDF = 1.38, Prob = 0.048)

Beamline Bkgd Corrected = -1.4 ± 7.7

(χ^2/ NDF = 1.29, Prob = 0.097)

Electromagnetic Form Factor Sensitivity

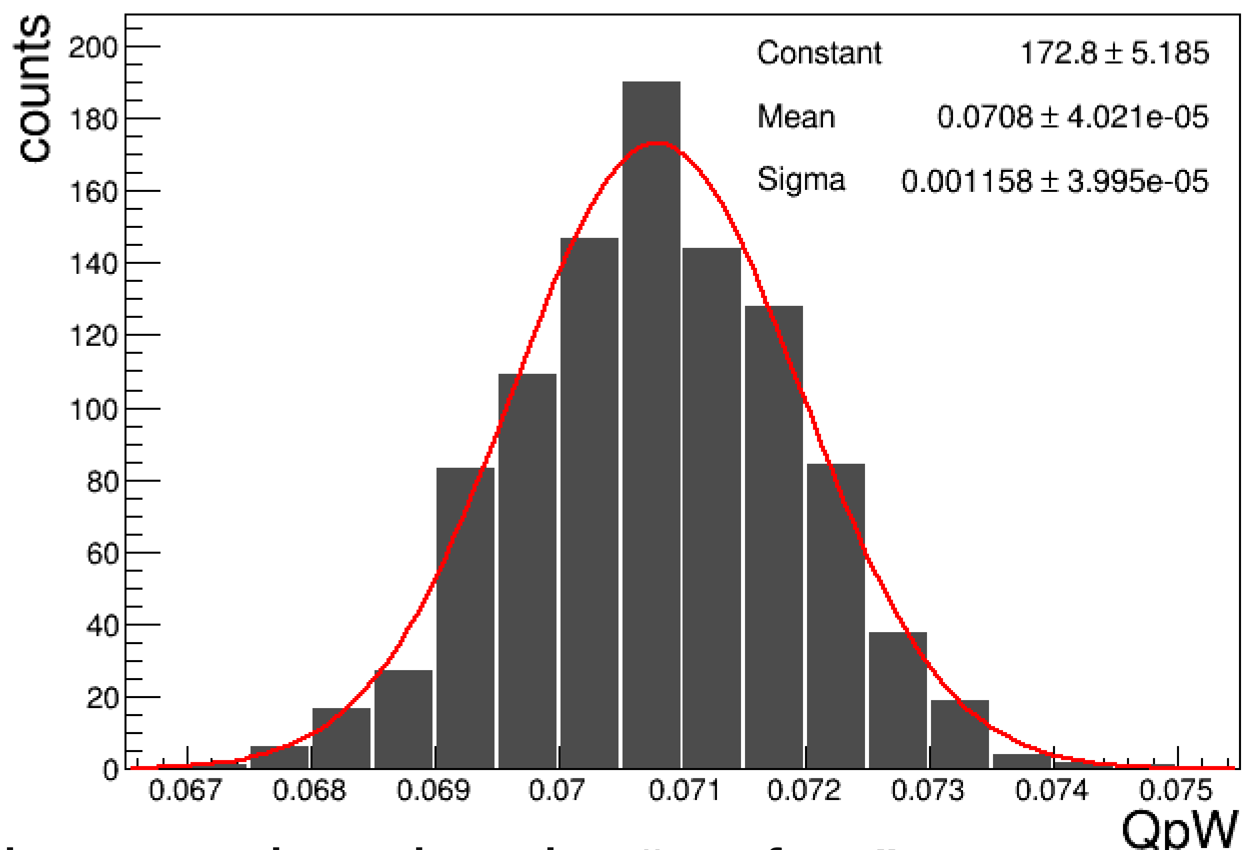
- Compute Q^p_W using a "perfect" SM asymmetry at our kinematics with 4 different EMFF's:

EMFF Fit	Q^p_W	dQ^p_W
Arrington & Sick	0.0705	0.0023
Kelly	0.0702	0.0023
Simple Dipole	0.0702	0.0022
Friedrich & Walcher	0.0683	0.0022

- What about errors on EMFF's?
  - Compute Q^p_W 1000 times varying FF's within errors provided by fit authors.
  - Arrington & Sick most appropriate for our low Q^2 in fit methodology AND error analysis.

J. Friedrich and Th. Walcher. EPJ A 17(4):607–623, 2003.
J. Kelly. Phys. Rev. C, 70:068202, 2004
John Arrington and Ingo Sick. Phys. Rev. C, 76:035201, 2007.

Electromagnetic Form Factor Sensitivity



- Efforts ongoing...study using the “perfect” asymmetry point.
- Use RMS width of Q^p_W distribution to quantify error from EMFF's
- 1.6% fractional uncertainty on Q^p_W using Arrington & Sick.

Conclusion

- Initial results already available in 2013PRL:

$$A_{\rm ep} = -279 \pm 35({\rm stat}) \pm 31({\rm sys}){\rm ppb} \qquad {\rm Q}_W^p = 0.064 \pm 0.012$$

$$C_{1u} = -0.1835 \pm 0.0054 \qquad {\rm C}_{1d} = +0.3355 \pm 0.0050$$

- Finalizing analysis efforts being made on polarimetry, kinematics, backgrounds, extraction methodology...

- Large bounty of physics results from primary and ancillary measurements (aluminum, transverse, alternate kinematics...).

- Final result expected ***SOON***.

Thank You

[1] University of Zagreb
[2] College of William and Mary
[3] Yerevan Physics Institute
[4] MIT
[5] JLab
[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 Tech
[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
[23] University of Adelaide
[24] Syracuse University

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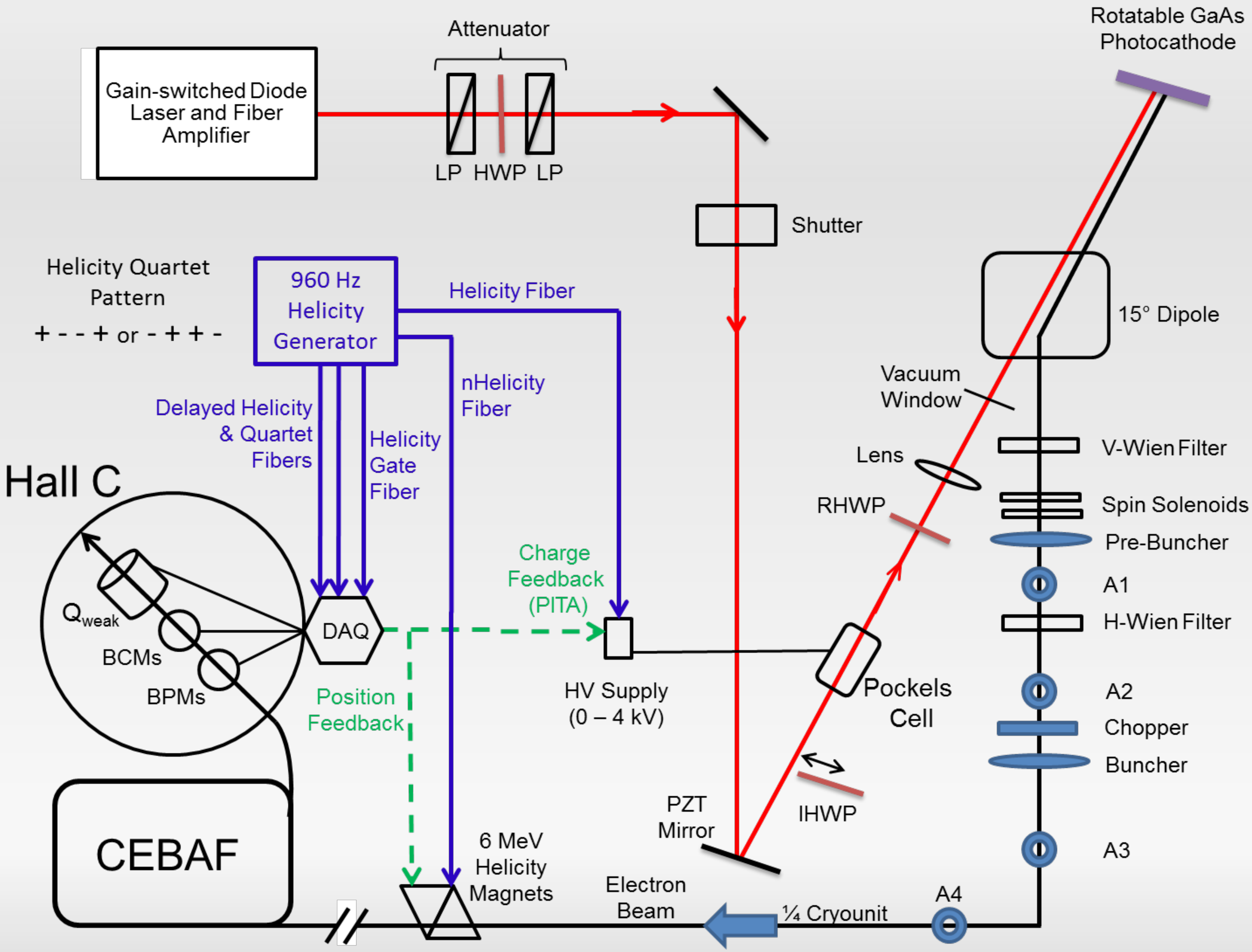
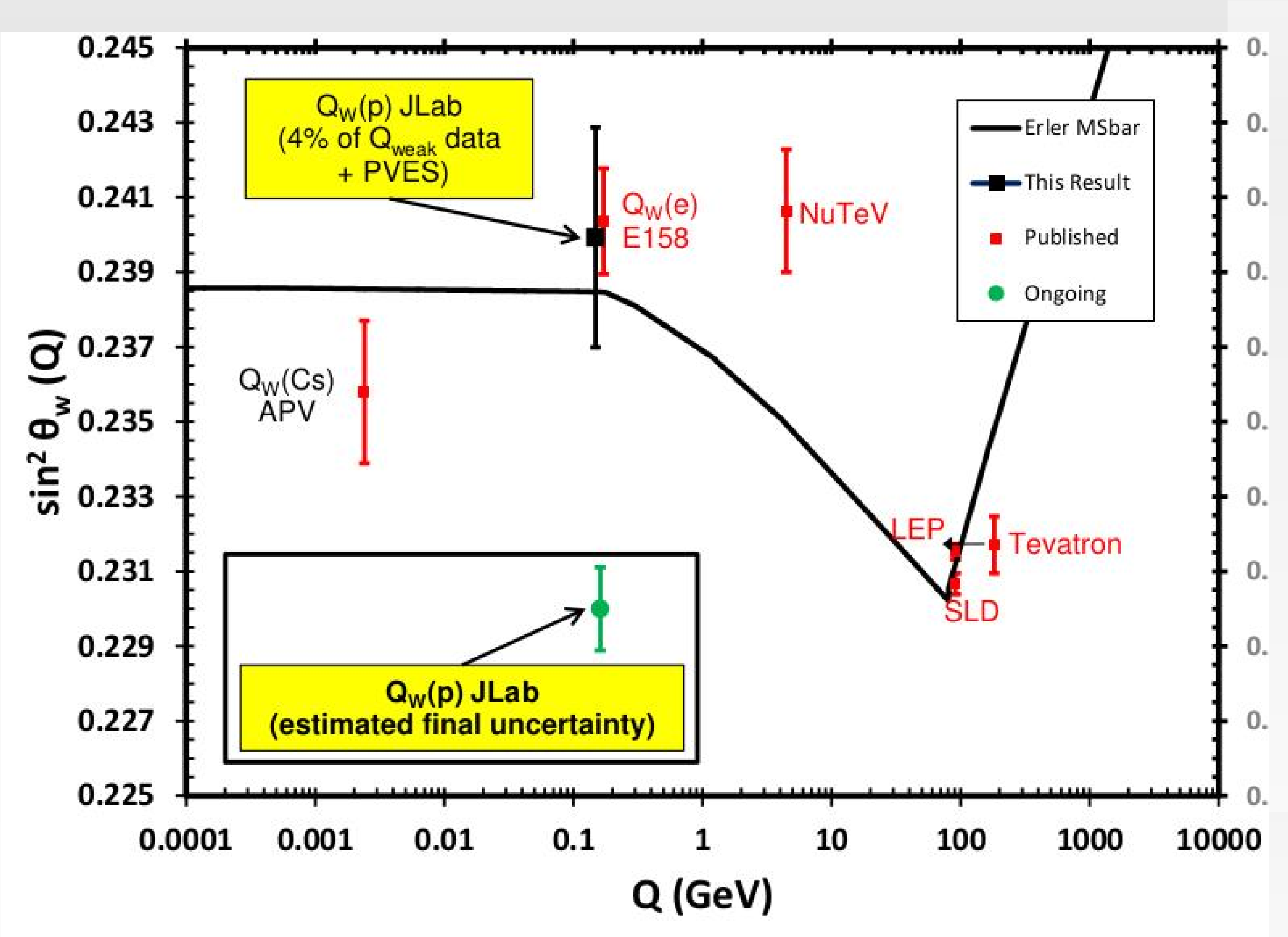
Polarized Source



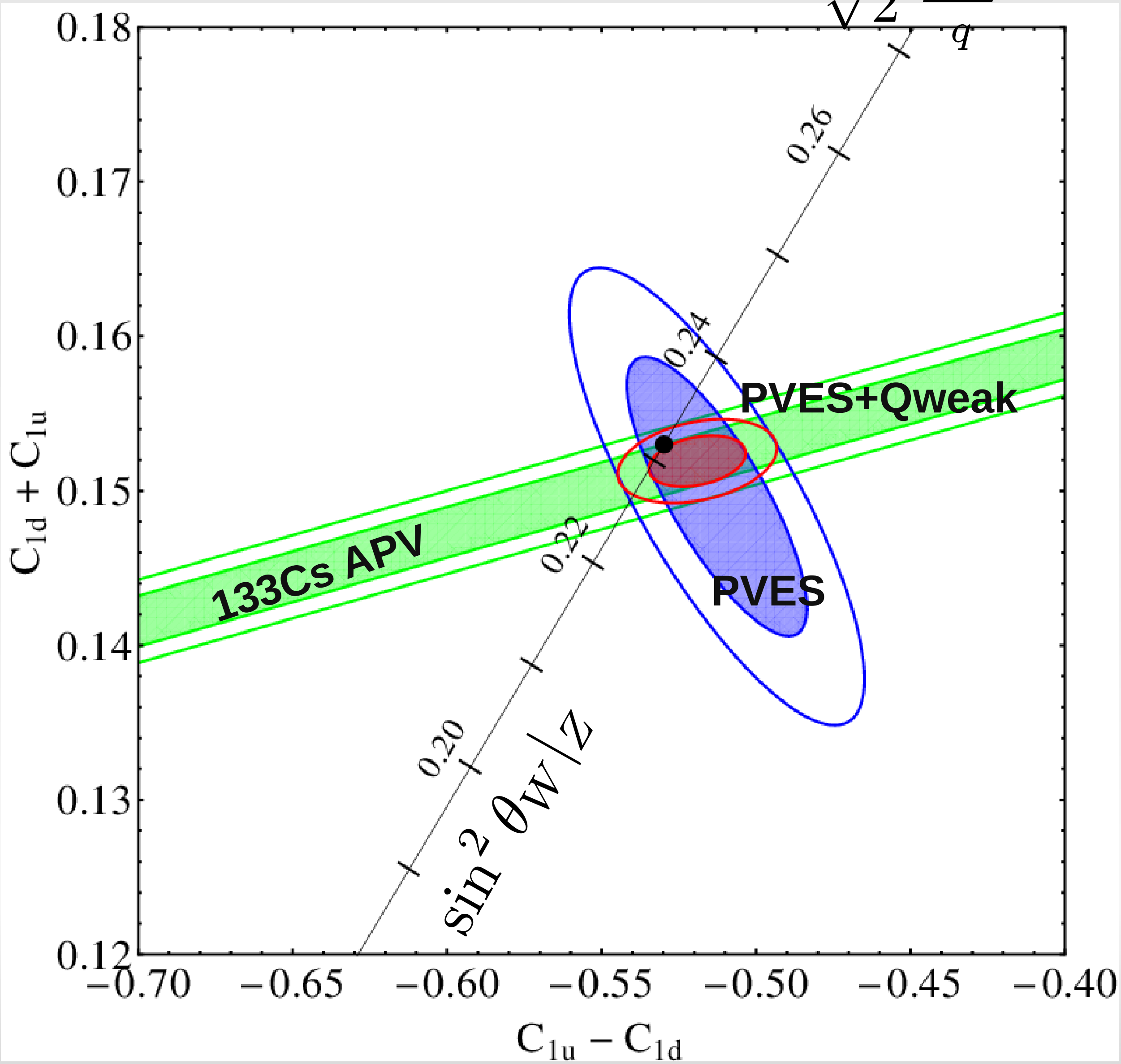
$Sin^2\theta_W$



$Q_W(p)$ JLab (4% of Q_{weak} data + PVES)
$Q_W(e)$ E158
NuTeV
Erler MSbar
This Result
Published
Ongoing
$Q_W(Cs)$ APV
LEP
Tevatron
SLD
$Q_W(p)$ JLab (estimated final uncertainty)
$\sin^2\theta_w$ (Q)
Q (GeV)
0.245
0.243
0.241
0.239
0.237
0.235
0.233
0.231
0.229
0.227
0.225
0.0001
0.001
0.01
0.1
1
10
100
1000
10000

Quark Couplings

$$L_{NC} = \frac{G_F}{\sqrt{2}} \sum_q (C_{1q}\bar{e}\gamma_\mu\gamma_5 e\bar{q}\gamma^\mu q + C_{2q}\bar{e}\gamma_\mu e\bar{q}\gamma^\mu\gamma_5 q)$$



- L_{NC} separates the individual quark contributions.
- Qweak sensitive to vector couplings $C_{1\{u,d\}}$

- Using all world data, extract couplings:

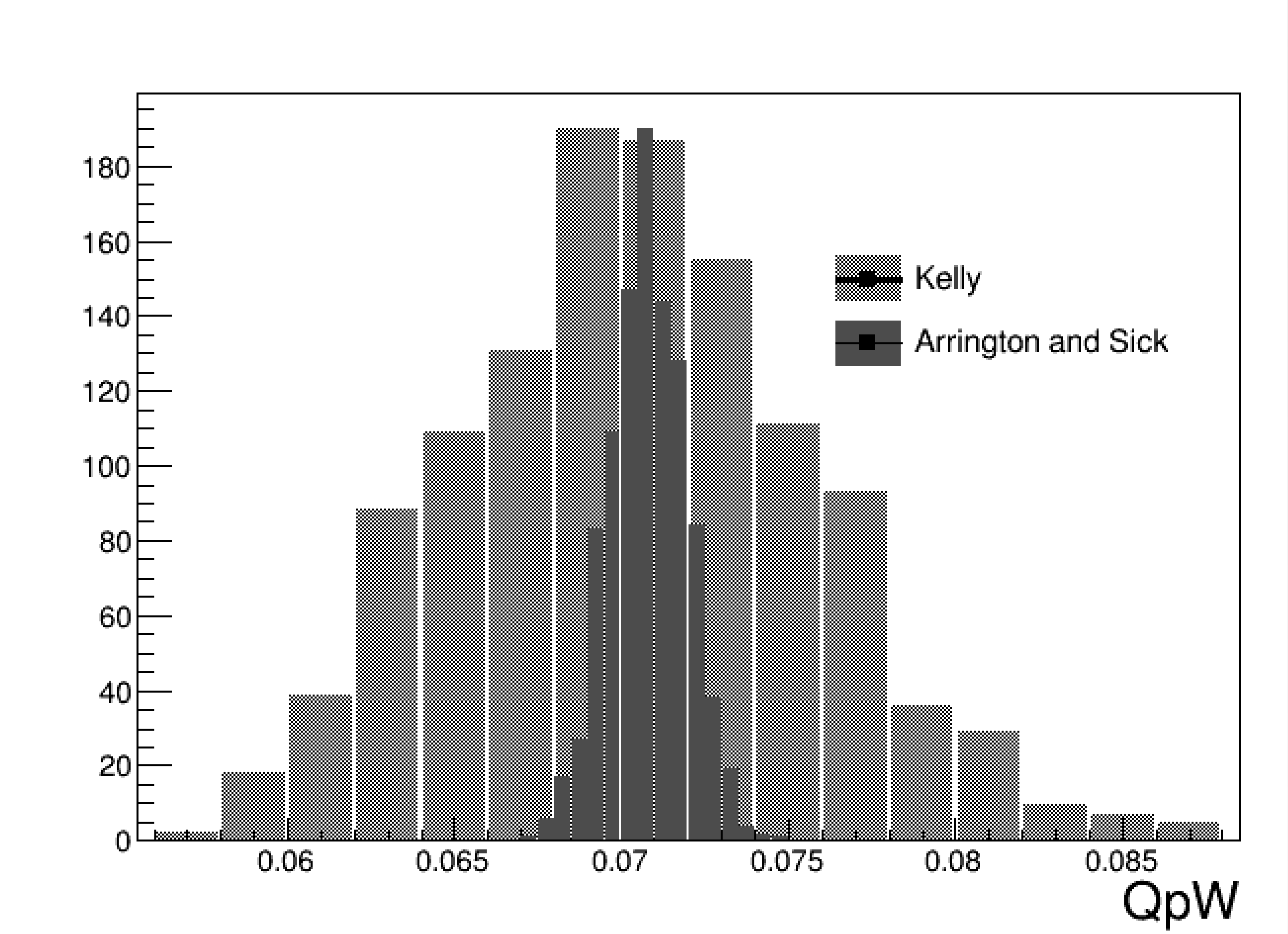
$$C_{1u} = -0.1835 \pm 0.0054$$

$$C_{1d} = +0.3355 \pm 0.0050$$

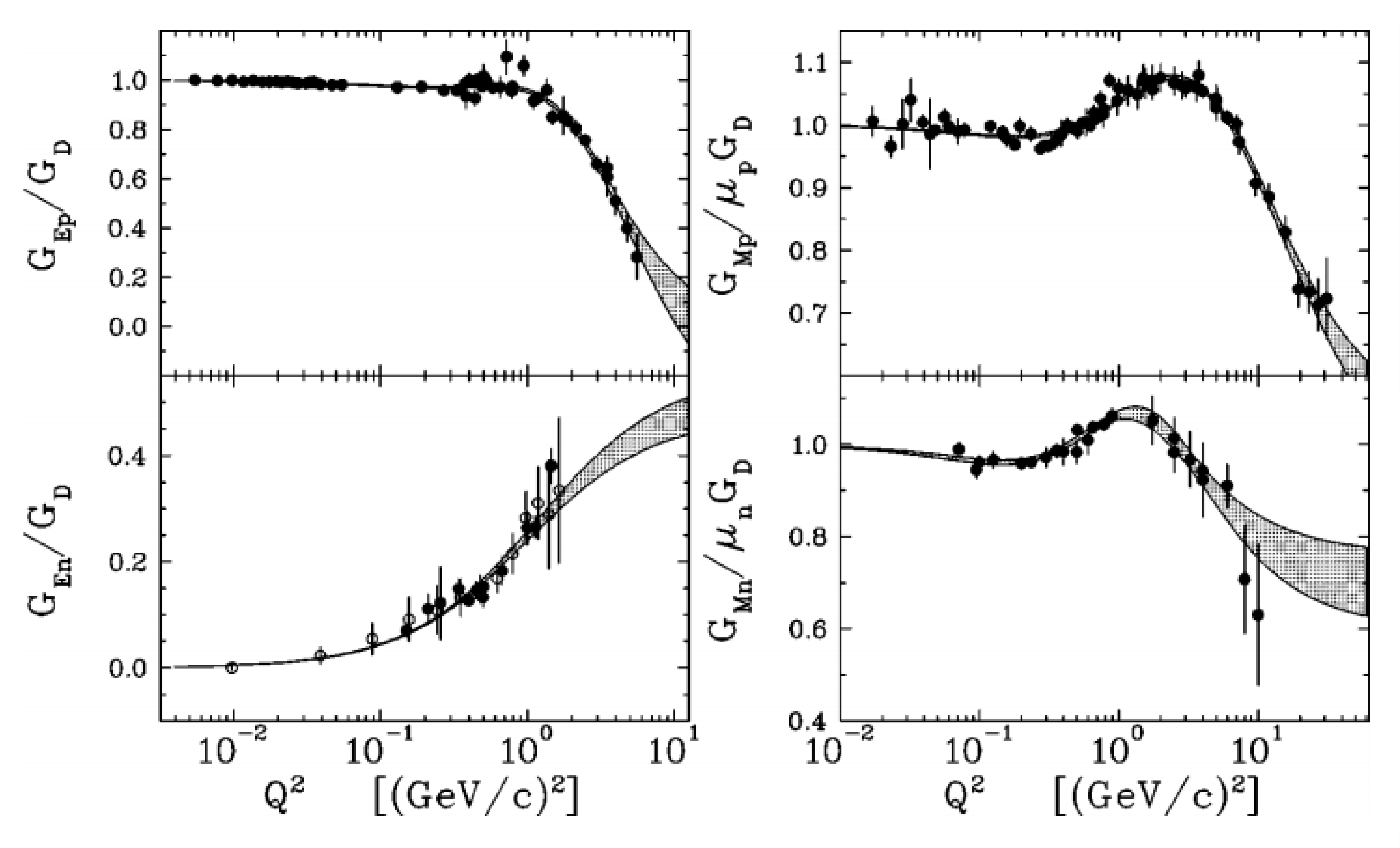
Electromagnetic Form Factor Sensitivity

- Compute QpW 1000 times, varying the EMFF's within errors quoted by the fit authors.

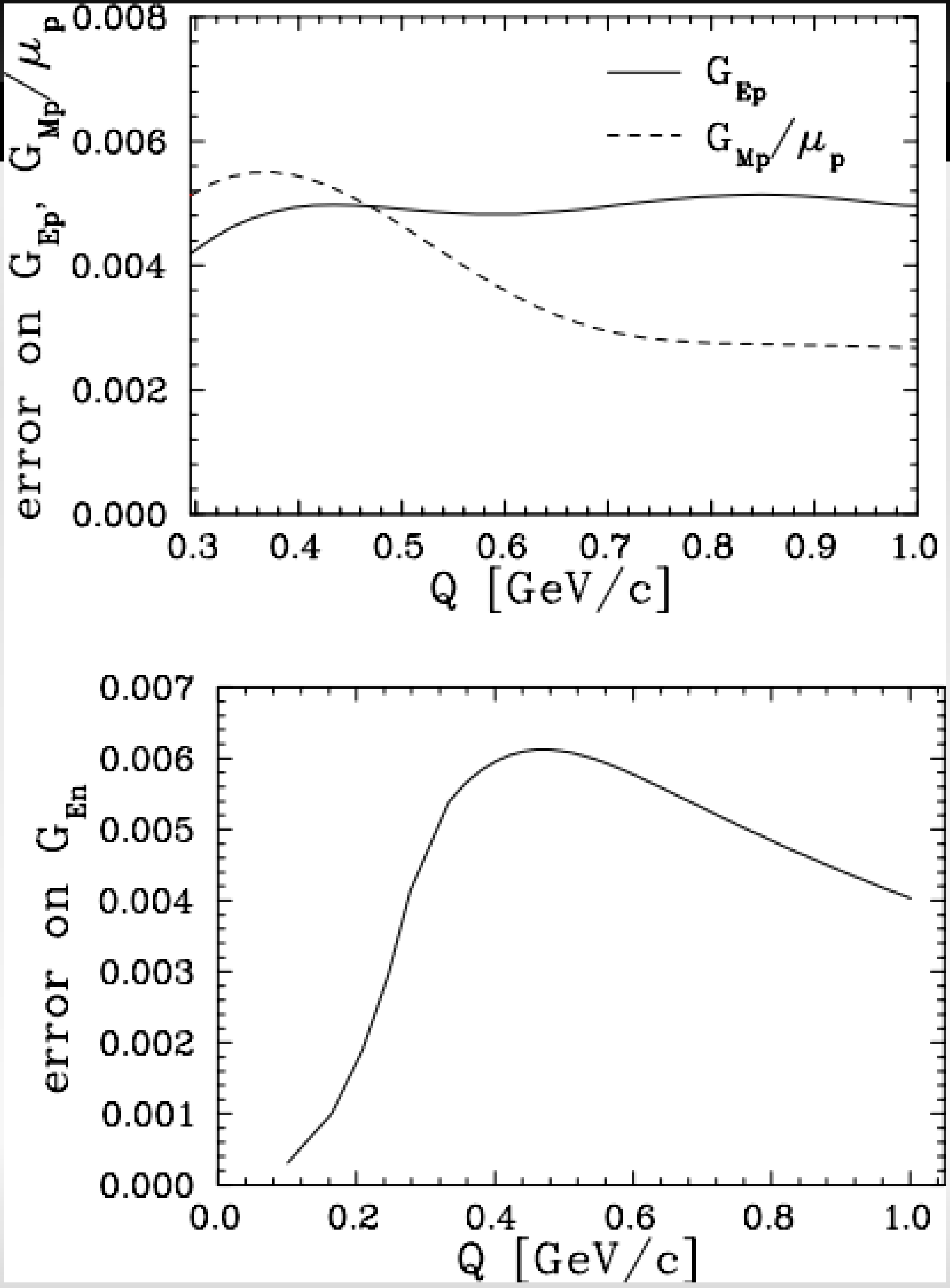
- Ongoing analysis! Kelly width is very sensitive to:
  - Asymmetry point
  - Strangeness parameterization



Kelly EMFF Errors



Arrington&Sick EMFF Errors

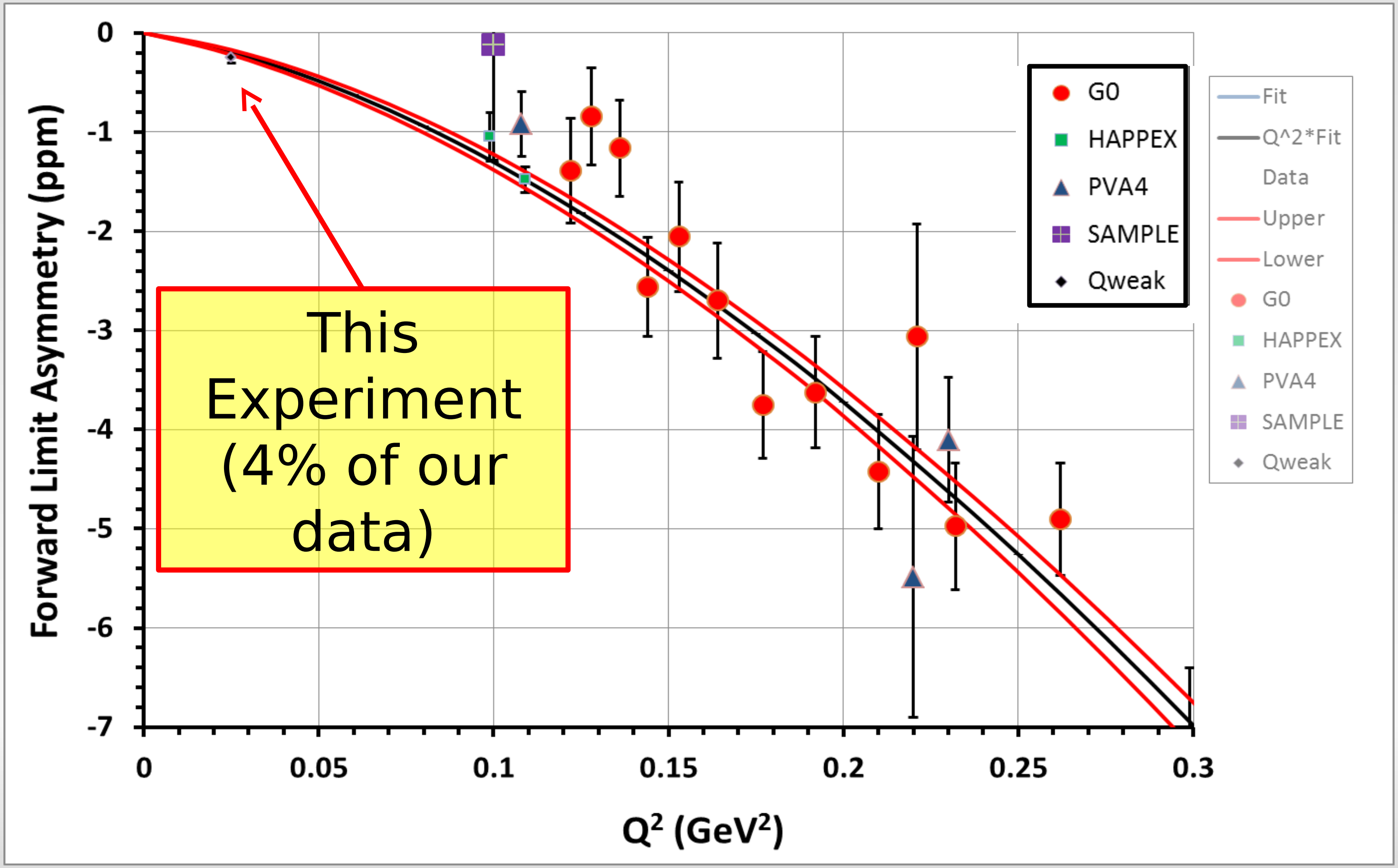


Raw Asymmetry

APV = -279 ± 35 (statistics) ± 31 (systematics) ppb

<Q2> = 0.0250 ± 0.0006 (GeV/c)2

<E> = 1.155 ± 0.003 GeV

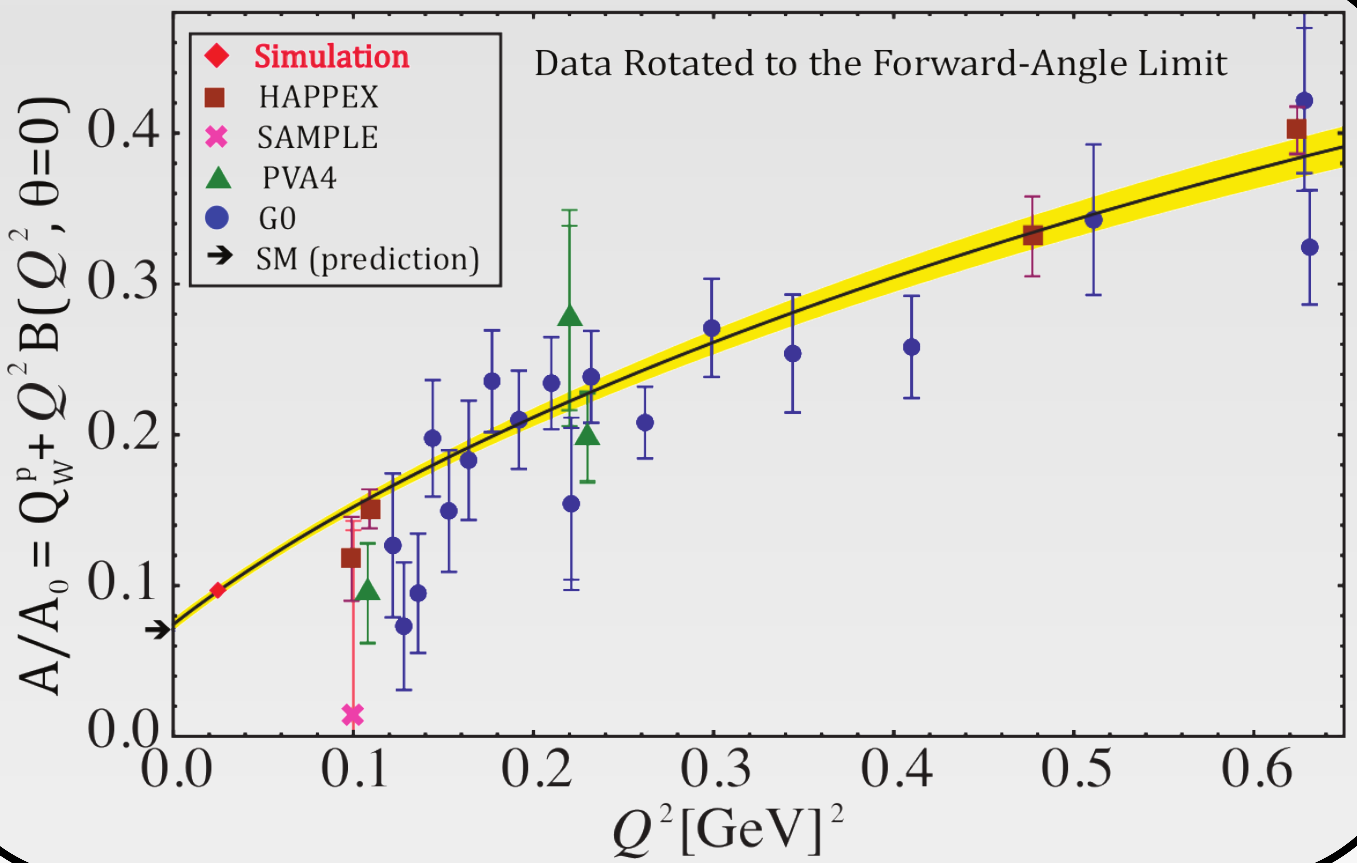


Teaser to Final Result

SIMULATED FIT ***SIMULATED FIT*** ***SIMULATED FIT***

Assumes anticipated final uncertainties and SM result.

- A fake Qweak point with an estimated final error bar at the SM value.

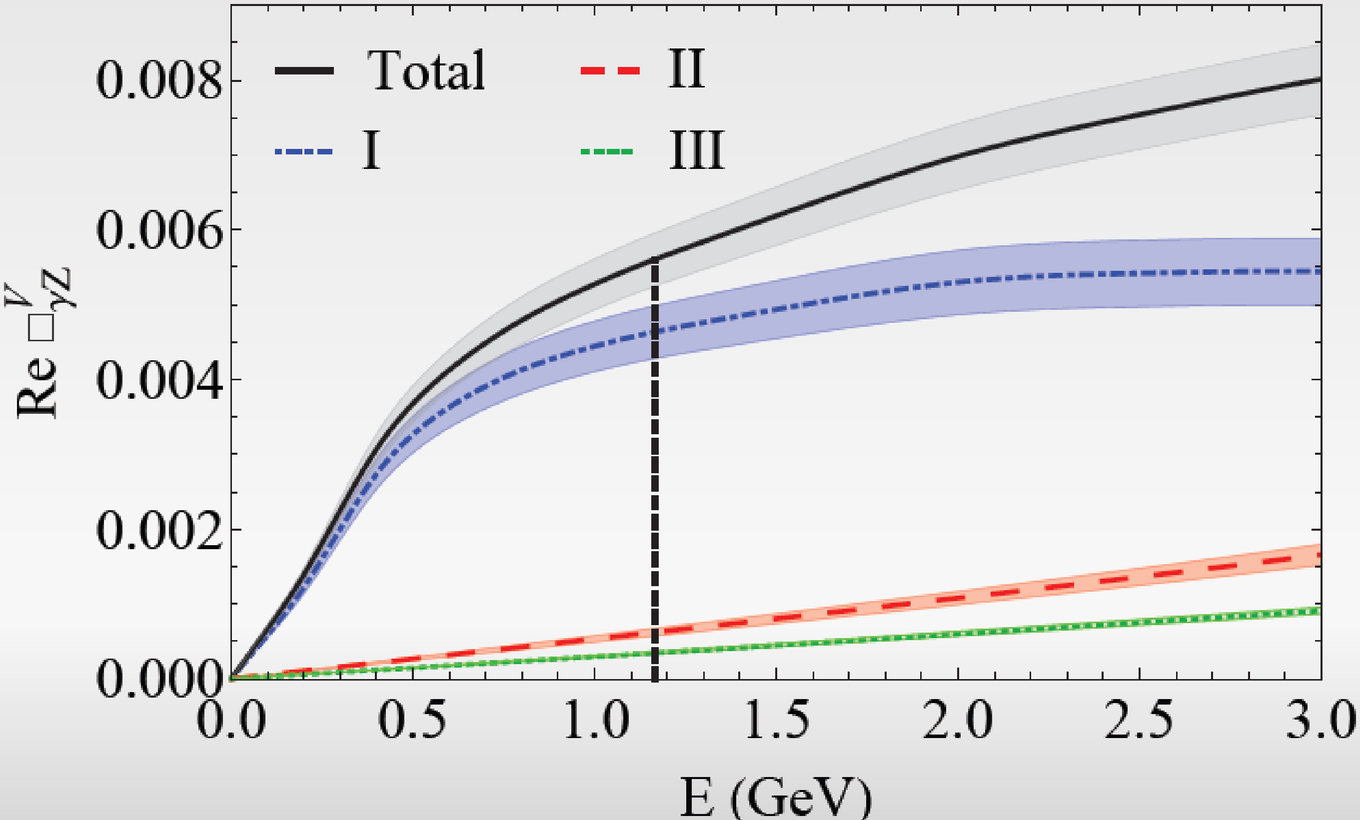


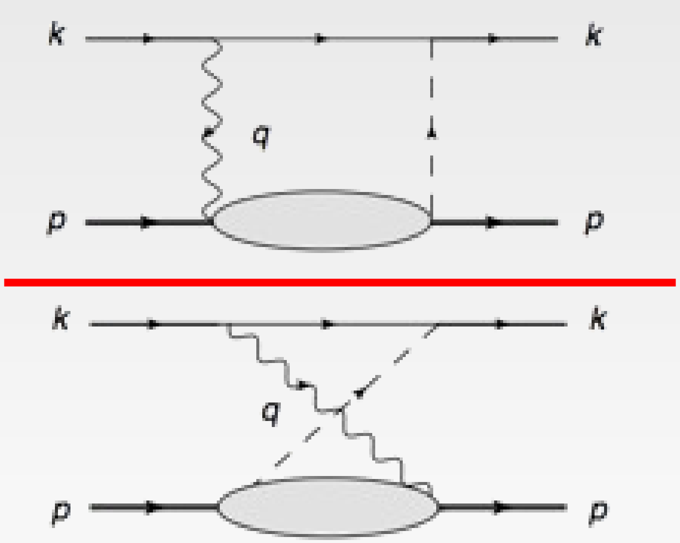
SIMULATED FIT ***SIMULATED FIT*** ***SIMULATED FIT***

Radiative Corrections: γZ-Box

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

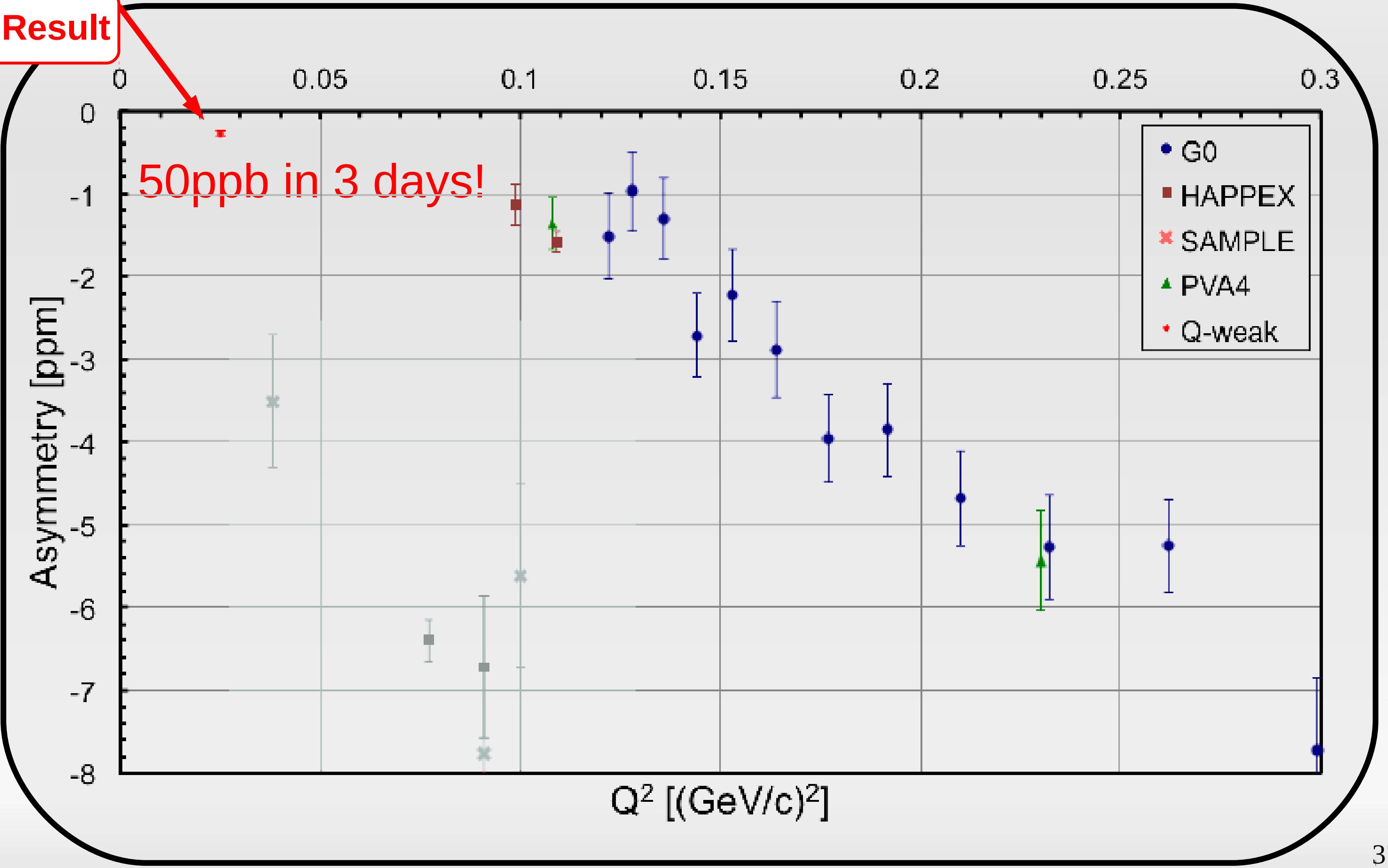
- Significant energy-dependent correction
  - Identified by Gorchtein and Horowitz in 2009, extensive studies since.
- Hall et al (Phys.Rev.D 88, 013011, 2013)
  - Constrains model-dependence using parton distribution functions and recent JLab PV data.
  - 7.8±0.5% shift of SM value of Q_W^p .





Raw Asymmetry

2013 Result



Q^2-Dependent γZ-Box Correction