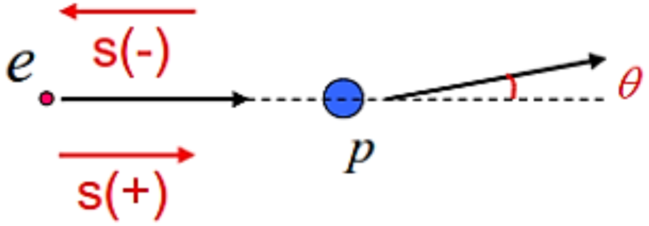
# Early Results from Qweak

A search for parity violating new physics at the TeV scale
by measurement of the Proton's weak charge.



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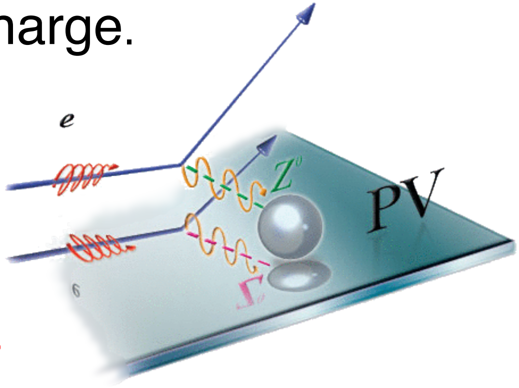


**(Content of this talk includes the work of students, postdocs and collaborators.)**

- Scatter longitudinally polarized electrons from liquid hydrogen
- Flip the electron spin and see how much the scattered fraction changes
- The difference is proportional to the weak charge of the proton
- Hadronic structure effects determined from global PVES measurements.

# Precision Tests of the Standard Model

- Standard Model is known to be the effective low-energy theory of a more fundamental underlying structure. (Meaning its not complete!)

- Finding new physics beyond the SM: Two complementary approaches:
  - Energy Frontier (direct) : *eg*. Tevatron (deceased), LHC (dry well so far)
  - Precision Frontier (indirect) : *Often at modest or low energy…*
    - $\mu$(g-2) , EDM, $\beta\beta$ decay, $\mu\rightarrow e\gamma$ , $\mu A\rightarrow eA$, $K^+\rightarrow\pi^+\nu\nu$, *etc.*
    - *$\nu$ - oscillations*
    - *Atomic Parity violation*
    - *Parity-violating electron scattering*

Hallmark of the Precision Frontier: Choose observables that are *"precisely predicted"* or *"suppressed"* in Standard Model.

If new physics is "eventually" found in direct measurements, precision measurements also useful to determine e.g. couplings…

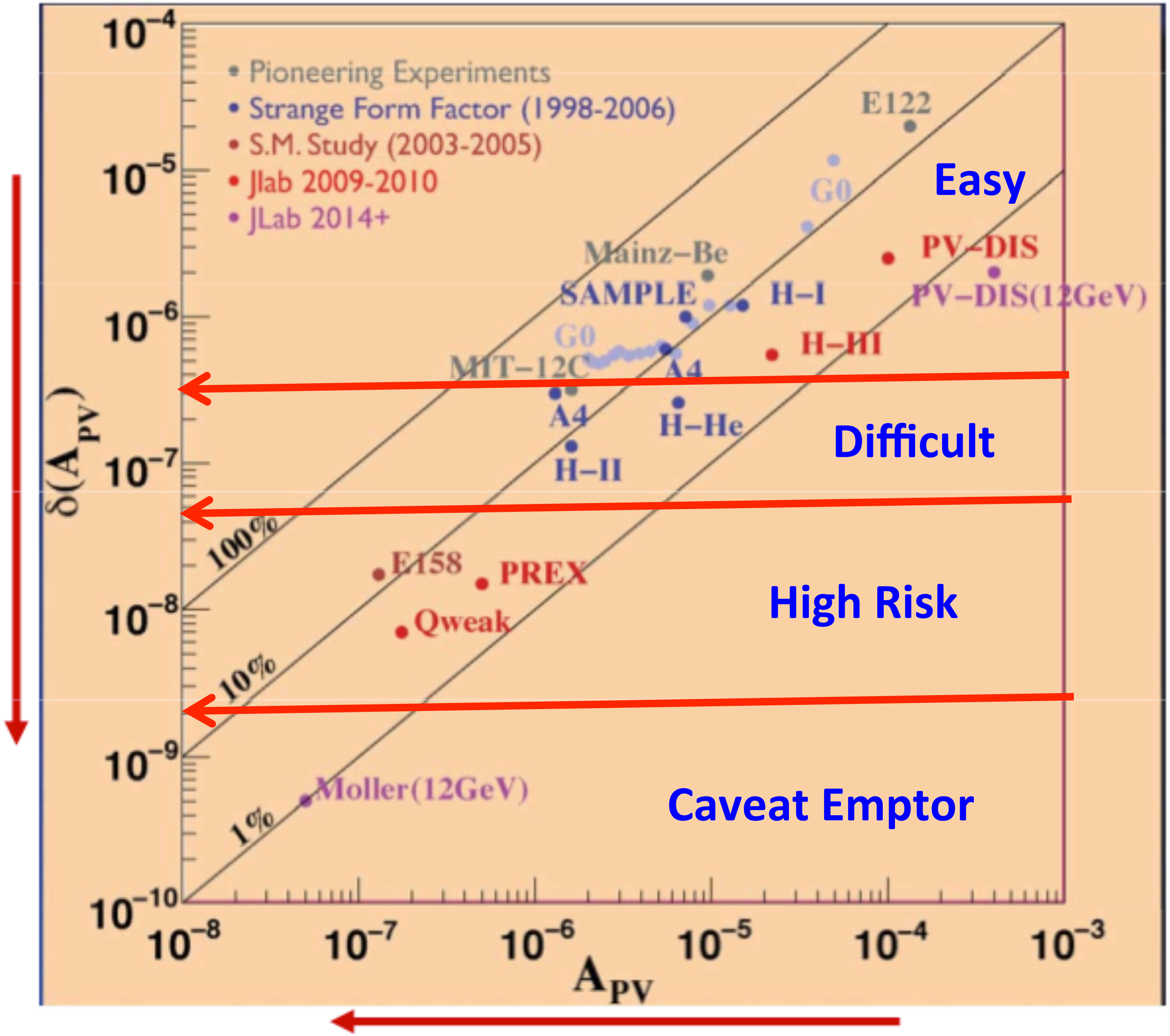
# PV Measurements Relative *"difficulty factor"*

Statistical Errors:

- Higher beam currents
- Higher polarizations
- High power targets

Normalization/
systematic errors:

- Polarimetry
- $Q^2$ measurements



Easy

Difficult

High Risk

Caveat Emptor

Additive systematic errors: improved control of helicity correlated beam properties

# Status

- The Qweak experiment finished successfully
  - Precise measurement of $\vec{e}$-p analyzing power at low $Q^2$
  - 2 years in situ, ~1 year of beam
  - Commissioning run analyzed:
    - ~ 4% of total data collected
    - Results presented here:

1st "Clean" Determination of $Q_w(p)$, $C_{1u}$, $C_{1d}$, & $Q_w(n)$

- Remainder of experiment still being analyzed
  - Expect final result by end of 2014
  - Expect final result will have ~5x better precision

# Qweak Experiment Objectives

10 years of development + 2 years on floor (~1 year beam time)
International Collaboration: **23 institutions, 95 Collaborators**
**(23 grad students,10 postdocs)**

- Measured parity-violating e-p analyzing power with high precision at $Q^2 \sim 0.025\ (\mathrm{GeV}/c)^2$. Determine: $\mathbf{Q^p_W, Q^n_W, \Lambda/g_{e\text{-}p}, C_{1u}, C_{1d}, \sin^2\theta_W}$

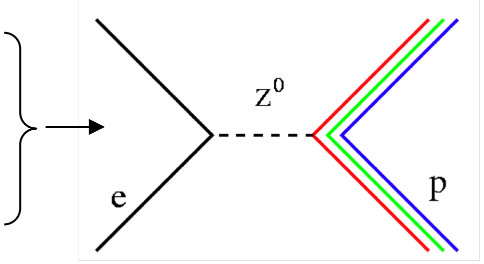
Ancillary / Calibration Measurements: (Will be published as standalone results.)

- Parity-violating and conserving e-C and e-Al analyzing powers.
- Parity-allowed analyzing power with transverse-polarized beam on H and Al.
- Parity-violating and allowed analyzing powers on H in the $N \rightarrow \Delta(1232)$ region.
- PV asymmetries in pion photo-production.
- Transverse asymmetries in pion photo-production.
- Non-resonant inelastic measurement at 3.3 GeV to constrain $\gamma$-Z Box uncertainty.
- Transverse asymmetry in the PV inelastic scattering region (3.3 GeV).

# Weak Charges

Govern strength of neutral current interaction with fermion

| Charge / Particle | Electric | Weak (vector) |
|---|---|---|
| u | +2/3 | $-2\,C_{1u} = +1 - 8/3\,\sin^2\theta_W$ |
| d | -1/3 | $-2\,C_{1d} = -1 + 4/3\,\sin^2\theta_W$ |
| *Proton*<br>uud | +1 | $Q_w^p = 1 - 4\,\sin^2\theta_W \approx 0.07$ |
| *Neutron*<br>udd | 0 | $Q_w^n = -1$ |



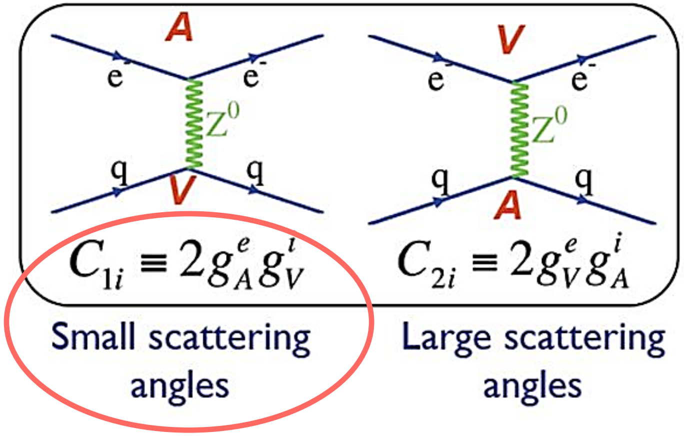
Note "accidental" suppression of $Q_w^p$ → *sensitivity to new physics*

- $Q^p_{weak}$ is a well-defined experimental observable.
- $Q^p_{weak}$ has a definite prediction in the electroweak Standard Model.
- $Q^e_{weak}$ : electron's weak charge was measured in PV Møller scattering (E158).

# The Weak Charges

$Q_w(p)$ is the neutral-weak analog of the proton's electric charge

The Standard Model makes a firm prediction of $Q_W^p$



$C_{1i} \equiv 2g_A^e g_V^i$ $C_{2i} \equiv 2g_V^e g_A^i$

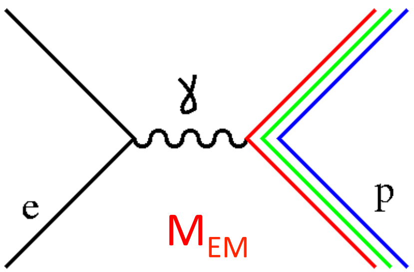
Small scattering angles

Large scattering angles

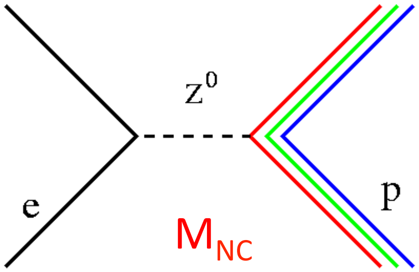
**Q-weak is particularly sensitive to the quark vector couplings $C_{1u}$& $C_{1d}$**

- General: $Q_w(Z,N) = -2\{C_{1u}(2Z+N) + C_{1d}(Z+2N)\}$
  - Ex: $Q_w(p) = -2(2C_{1u} + C_{1d})$ (this experiment)
    - Uses higher $Q^2$ PVES data to constrain hadronic corrections (about 20%)
  - Ex: $Q_w(^{133}Cs) = -2(188C_{1u} + 211C_{1d})$ (APV)
    - Latest atomic corrections from PRL 109, 203003 (2012)
- Combining Qw(p) and Qw($^{133}$Cs) → $C_{1u}$ & $C_{1d}$, $Q_w(n)$

# $Q^p_{Weak}$ : Extract from Parity-Violating Electron Scattering



As $Q^2 \to 0$



measures $Q^p$ – proton's electric charge

measures $Q^p_{Weak}$ – proton's weak charge

$$A = \frac{2M_{NC}}{M_{EM}} = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q^p_{weak} + F^p(Q^2,\theta)\right]$$

$$\xrightarrow[\theta \to 0]{Q^2 \to 0} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q^p_{weak} + Q^4 B(Q^2)\right]$$

$$Q^p_{weak} = 1 - 4\sin^2\theta_W \sim 0.072$$ (at tree level)

contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$

Correction involving hadronic form factors.
Exp determined using global analysis of recently completed PVES experiments.

The **lower** the momentum transfer, Q, the more the proton looks like a point and the less important are the form factor corrections.

# PVES and Hadronic Structure Effects

$$A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{\pi\alpha\sqrt{2}}\right] \frac{\varepsilon G_E^{p\gamma} G_E^{pZ} + \tau G_M^{p\gamma} G_M^{pZ} - \frac{1}{2}(1 - 4\sin^2\theta_W)\varepsilon' G_M^{p\gamma} \tilde{G}_A^p}{\varepsilon (G_E^{p\gamma})^2 + \tau (G_M^{p\gamma})^2}$$

Neutral-weak form factors

Axial form factor

assume charge symmetry:

$$4G_{E,M}^{pZ} = \underline{(1 - 4\sin^2\theta_W)} G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - \underline{G_{E,M}^{s}}$$

Proton weak charge
(tree level)

Strangeness

(Now measured to be
relatively small!)

Note: Parity-violating asymmetry is sensitive to both weak charges *and* to hadron structure.

# Qweak Apparatus

Parameters:

$E_{beam}$= 1.165 GeV

$\langle Q^2 \rangle = 0.025\ \mathrm{GeV}^2$

$\langle \theta \rangle = 7.9^\circ \pm 3^\circ$

$\phi$ coverage = 50% of $2\pi$

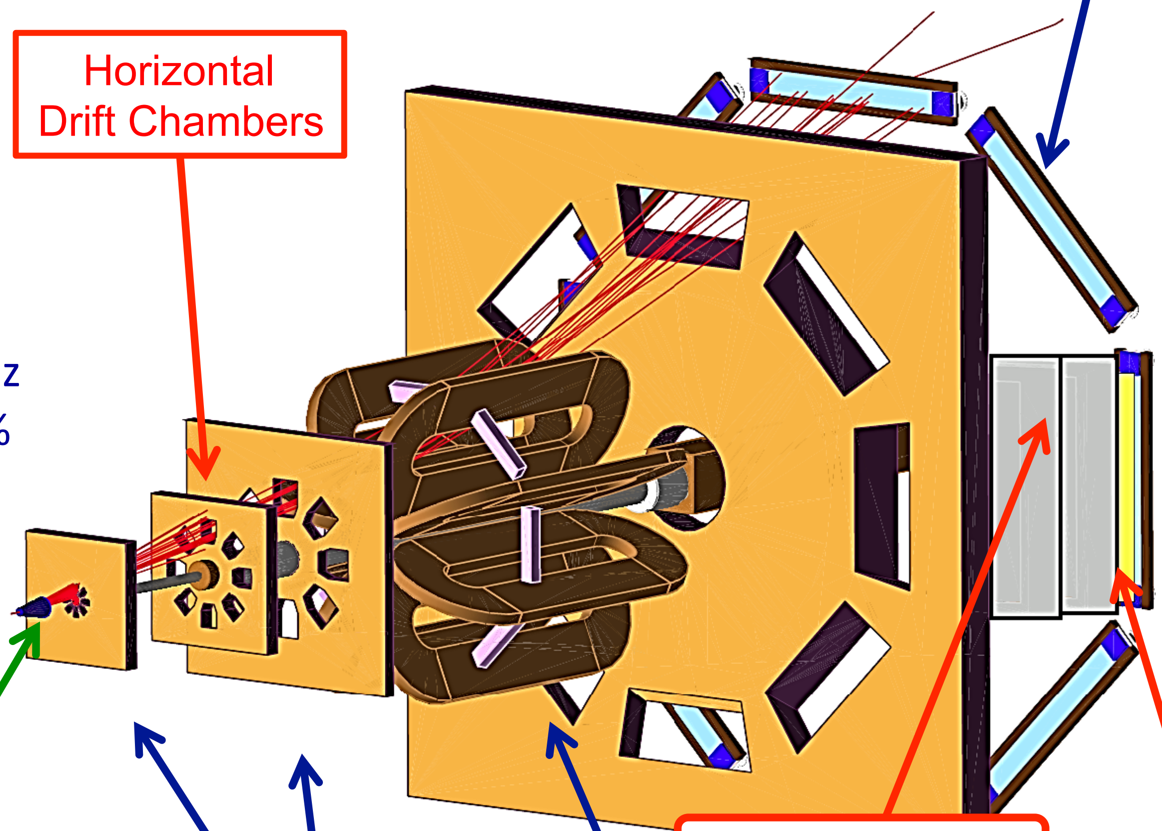
$I_{beam}$ = 180 μA

Integrated rate = 6.4 GHz

Beam Polarization = 88%

Target = 35 cm $LH_2$

Cryopower = 3 kW



Quartz Cerenkov Bars

Horizontal Drift Chambers

Electron beam

$LH_2$ Target

Collimators

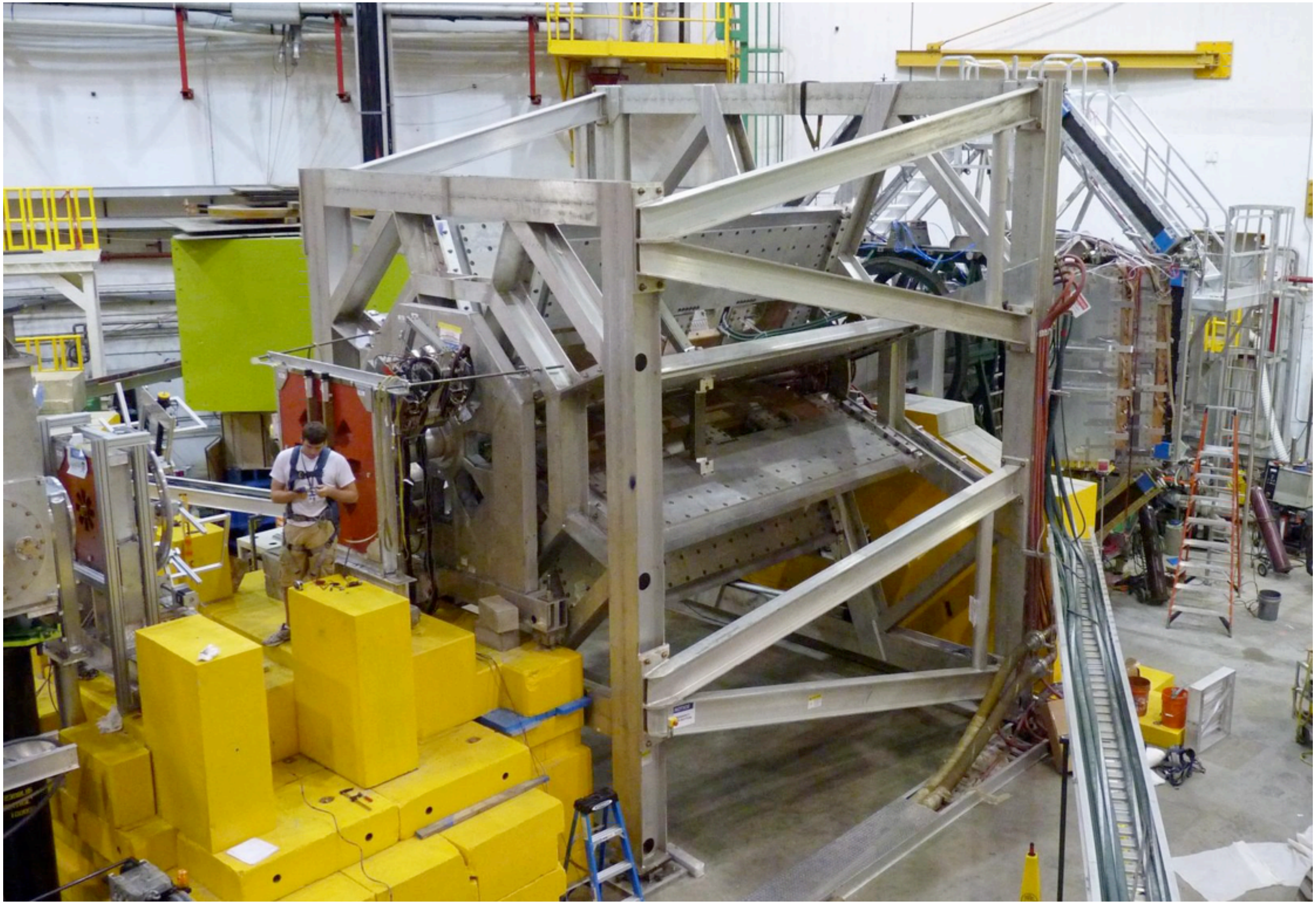
Toroidal Magnet Spectrometer

Trigger Scintillator

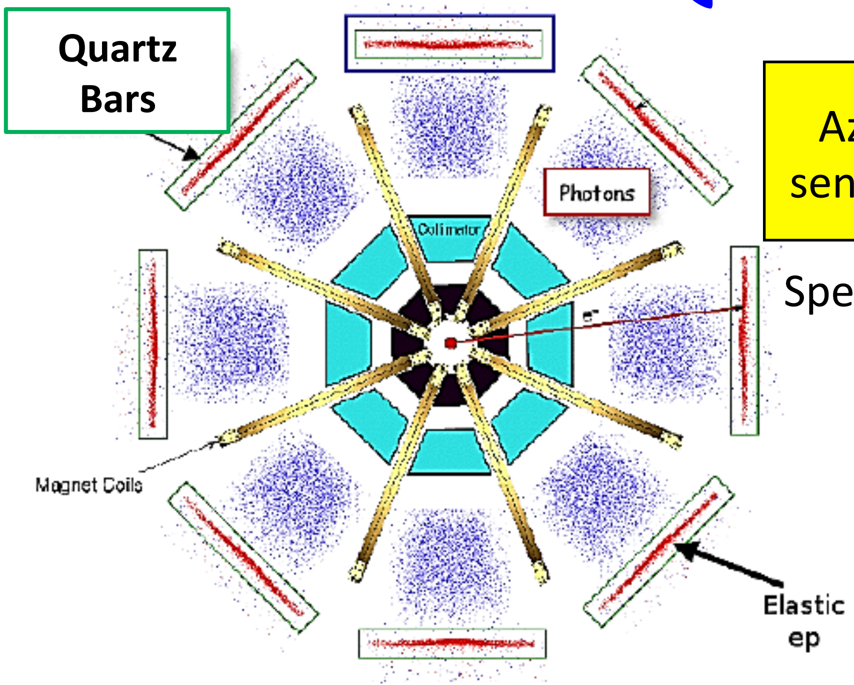
Vertical Drift Chambers

Red = low-current tracking mode only

# The Apparatus (before shielding)



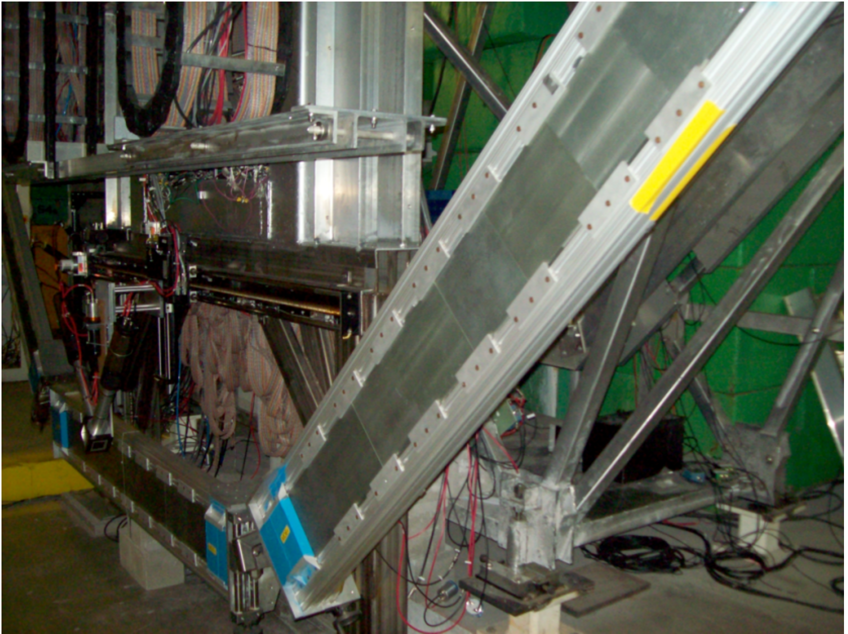
# Quartz Cerenkov Detectors



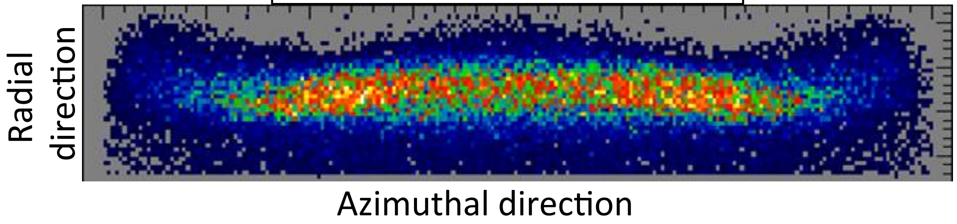
Azimuthal symmetry maximizes rate and decreases sensitivity to HC beam motion, transverse asymmetry.

Spectrosil 2000: Eight bars, each 2 m long, 1.25 cm thick

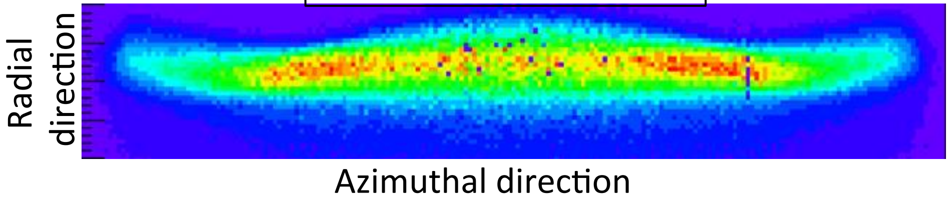
- Rad-hard
- Non-scintillating, low-luminescence



Simulation of MD face:

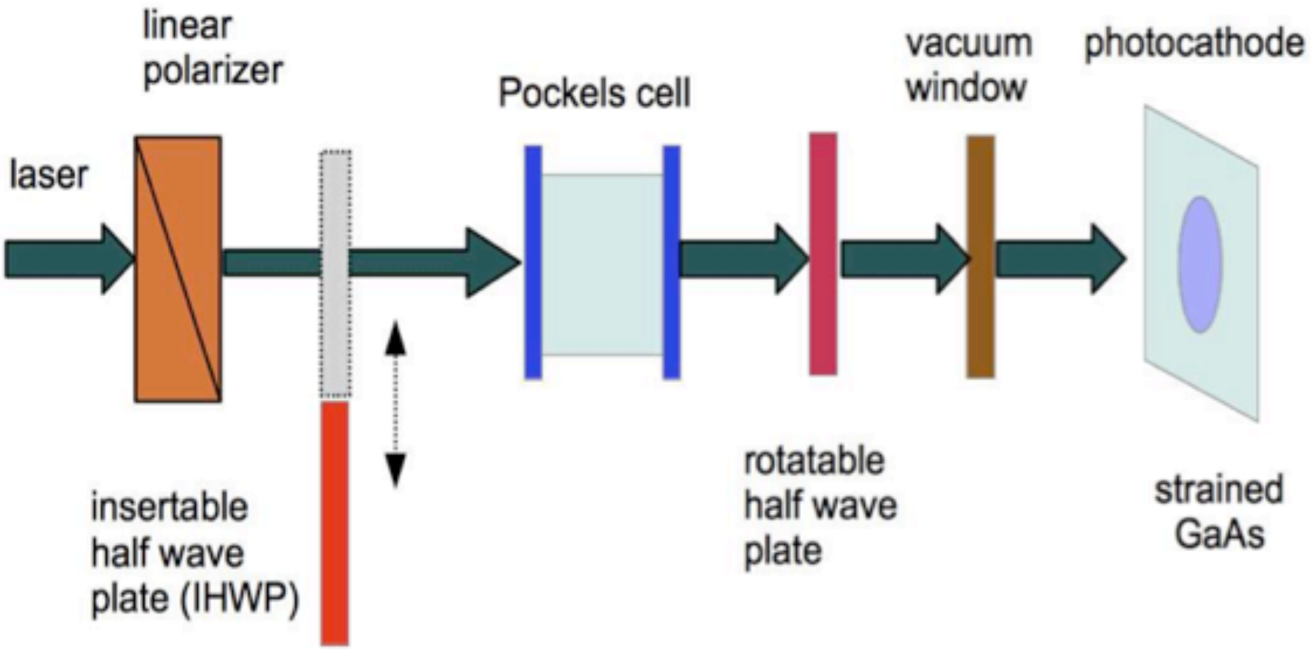


Measured



Yield 100 pe’s/track with 2cm Pb pre-radiators
Resolution limited by shower fluctuations.

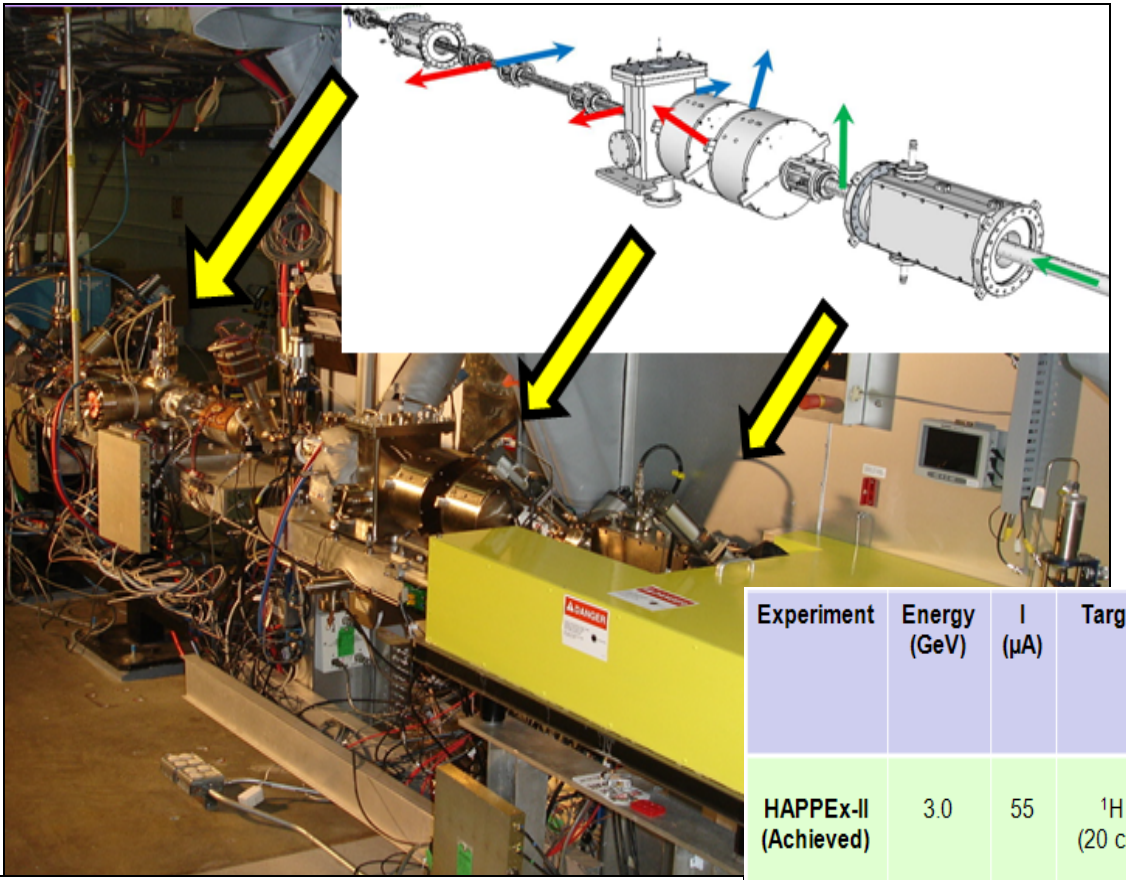
# Polarized Injector



- Pockels cell for fast helicity reversal
- Helicity reversal frequency: 960 Hz (to “freeze” bubble motion in the target)
- Helicity pattern: pseudo-random “quartets” (+--+ or -++-, asymmetry calculated for each quartet)
- Insertable Half-Wave Plate: for “slow reversal” of helicity to check systematic effects and cancel certain false asymmetries. Less frequently, by Wien filter.

# Two-Wien Spin Flipper

flip spin each month to cancel out HC laser spot variation



- Wien magnets at 10A and chopper magnets at 4A. Might be able to push to higher gun voltage but risk damaging magnets (note, chopper magnets are captured on beamline)
- Modeling suggests Capture Section optimized for 130kV beam….

| Experiment | Energy (GeV) | I (μA) | Target | $A_{pv}$ (ppb) | Maximum Charge Asym (ppb) | Maximum Position Diff (nm) | Maximum Angle Diff (nrad) | Maximum Size Diff (δσ/σ) |
|---|---|---|---|---|---|---|---|---|
| **HAPPEx-II (Achieved)** | 3.0 | 55 | $^{1}$H (20 cm) | 1400 | 400 | 1 | 0.2 | Was not specified |
| **HAPPEx-III (Achieved)** | 3.484 | 100 | $^{1}$H (25 cm) | 16900 | 200±100 | 3±3 | 0.5±0.1 | $10^{-3}$ |
| **PREx** | 1.063 | 70 | $^{208}$Pb (0.5 mm) | 500 | 100±10 | 2±1 | 0.3±0.1 | $10^{-4}$ |
| **QWeak** | 1.162 | 180 | $^{1}$H (35 cm) | 234 | 100±10 | 2±1 | 30±3 | $10^{-4}$ |
| **Møller** | 11.0 | 75 | $^{1}$H (150 cm) | 35.6 | 10±10 | 0.5±0.5 | 0.05±0.05 | $10^{-4}$ |

# Overview of Beam Properties

| | | Achieved | |
|---|---|---|---|
| Beam value | Requirement | Run I | Run II |
| X-position at target [nm] | <2 | 3.6 +/- 0.39 | -0.95 +/- 0.06 |
| Y-position at target [nm] | <2 | -6.9 +/- 0.39 | -0.24 +/- 0.28 |
| X-angle at target [nrad] | <30 | -0.22 +/- 0.012 | -0.07 +/- 0.017 |
| Y-angle at target [nrad] | <30 | -0.18 +- 0.015 | -0.06 +/- 0.011 |
| Position at dispersion (3c12X)[nm] | - | -13.6 +/- 0.23 | -0.83 +/- 0.30 |
| Energy dE/E [ppb] | <1 | <3.8 +/- 0.06 | <0.23 +/- 0.08 |

# Constructing the Asymmetry

## False Asymmetries

- $A_{msr} = A_{raw} + A_T - A_{reg}$
  - $A_{raw} = (Y^+ - Y^-) / (Y^+ + Y^-)$
    - Charge normalized ep yields for ± e-helicity
  - $A_T$ = remnant transverse asymmetry measured with explicitly $P_T$ beam
  - $A_{reg} = \sum \left(\frac{\partial A}{\partial \chi_i}\right) \Delta\chi_i$, measured with natural & driven beam motion for $(x, y, x', y', E)$ using BPMs
  - $A_Q$ driven to 0 with feedback

## Backgrounds

- $A_{ep} = R_{tot} \frac{A_{msr}/P - \sum_{i=1}^{4} f_i A_i}{1 - f_{tot}}$
  - $R_{tot} = R_{Q^2} R_{RC} R_{Det} R_{Bin} = 0.98$
  - $f_{tot} = \sum f_i = 3.6\%$
  - $f_i$ = fraction of yield from bkg i
  - $A_i$ = asymmetry of bkg i
  - $b_1$ from Al windows of tgt cell (dominant bkg)
  - $b_2$ from beamline bkg
  - $b_3$ from other soft neutral bkg
  - $b_4$ from N → Δ inelastic bkg

# Ex:/ Aluminum Window Background

Large *A* (asymmetry) & *f* (fraction) make this our largest correction. Determined from explicit measurements using Al dummy targets & empty $H_2$ cell.

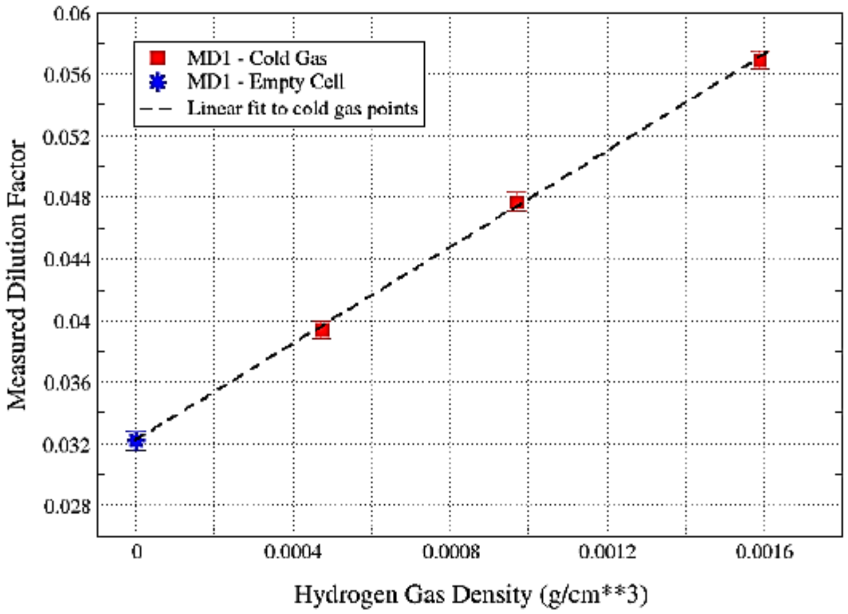
$$C_{\mathrm{Al}} = -64 \pm 10 \text{ ppb}$$
$$A_{\mathrm{Al}} = 1.76 \pm 0.26 \text{ ppm}$$

$$f_{\mathrm{Al}} = 3.23 \pm 0.24 \text{ \%}$$

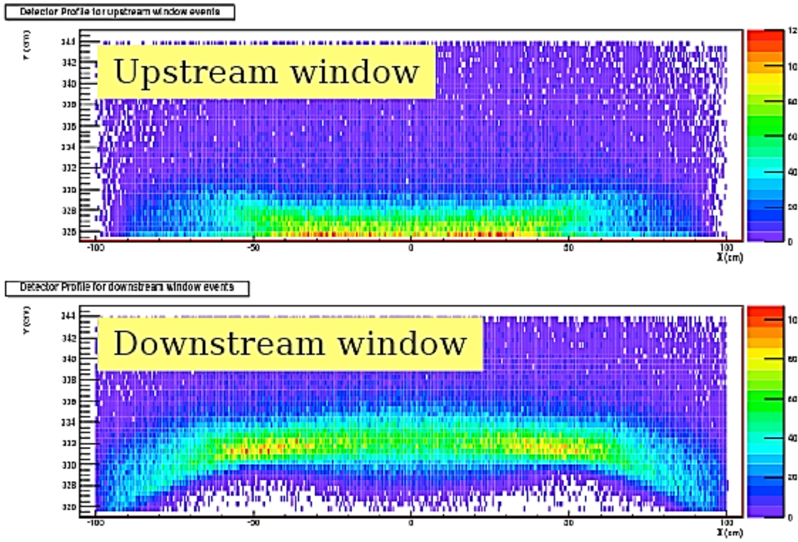
- Dilution from windows measured with empty target (actual target cell windows).
- Corrected for effect of $H_2$ using simulation and data driven models of elastic and quasi-elastic scattering.

- Asymmetry measured from thick Al targets
- Measured asymmetry agrees with expectations from scaling.

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



Simulated e- profile at detector:

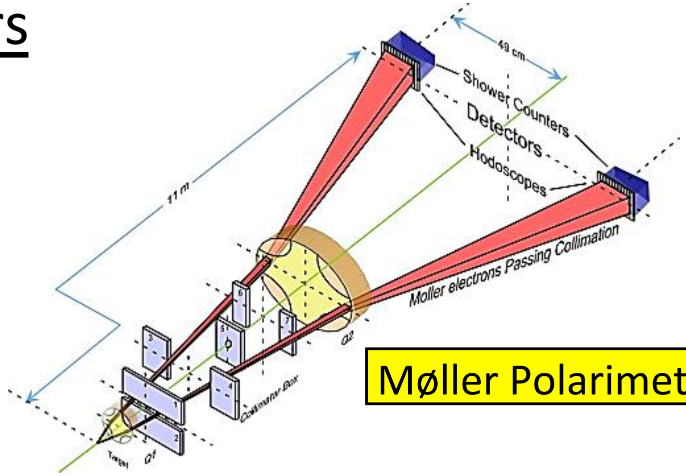


# Precision Polarimetry

Qweak requires $\Delta P/P \leq 1\%$

## Strategy: use 2 independent polarimeters

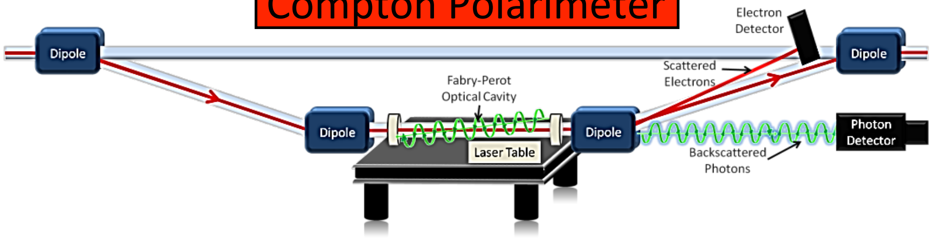
- Use existing <1% Hall C Møller polarimeter:
  - Low beam currents, invasive
  - Known analyzing power provided by polarized Fe foil in a 3.5 T field.

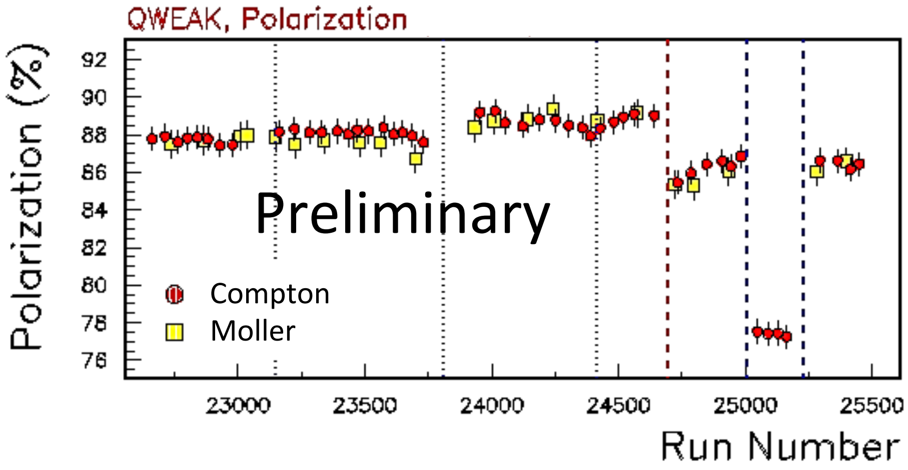


Møller Polarimeter

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

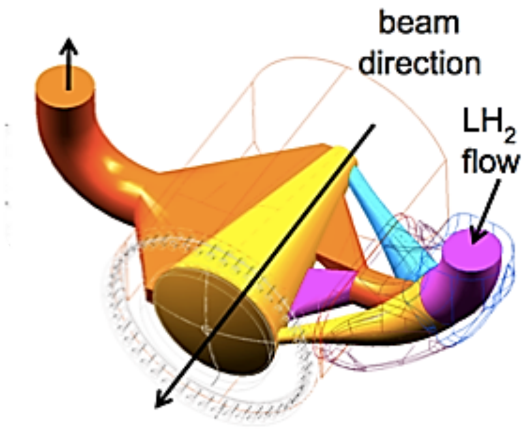
Compton Polarimeter



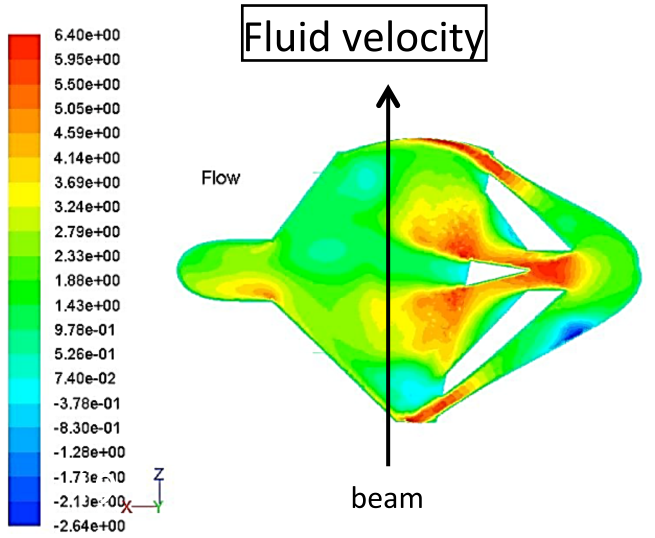


# LH$_2$ Target Design

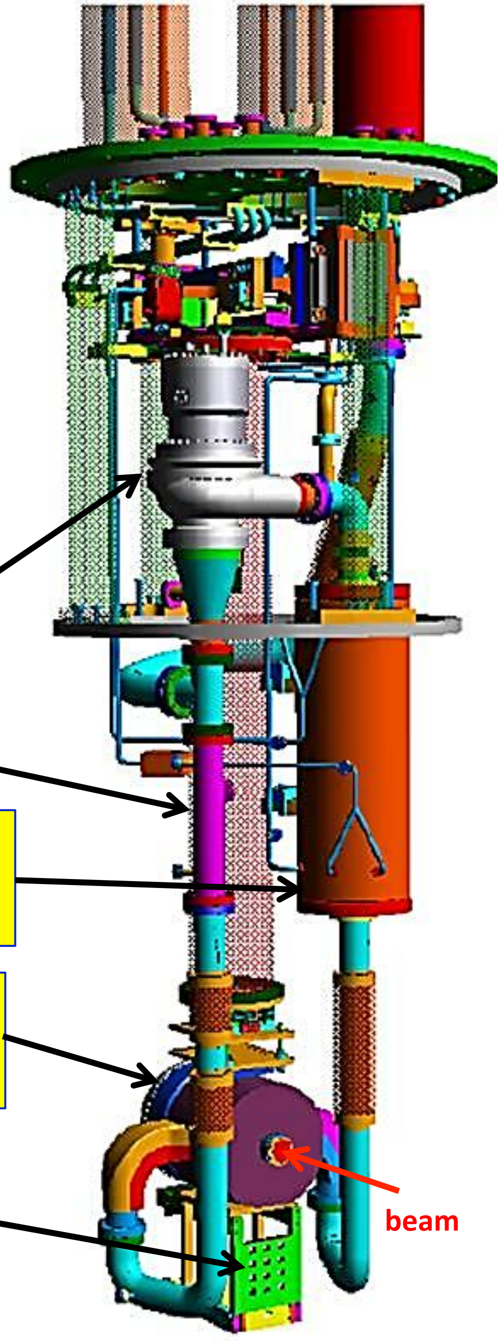
- World’s highest power cryogenic target ~3 kW
- Designed with computational fluid dynamics (CFD) to reduce density fluctuations



$I_{Beam}$ = 180 uA
L = 35 cm (4% $X_0$)
$P_{beam}$ = 2.2 kW
$A_{spot}$ = 4x4 mm$^2$
V = 57 liters
T = 20.00 K
P ~ 220 kPa



ANSYS



Centrifugal pump (15 l/s, 7.6 kPa)

3 kW Heater

3 kW HX utilizing 4K & 14K He coolant

35 cm cell (beam interaction volume)

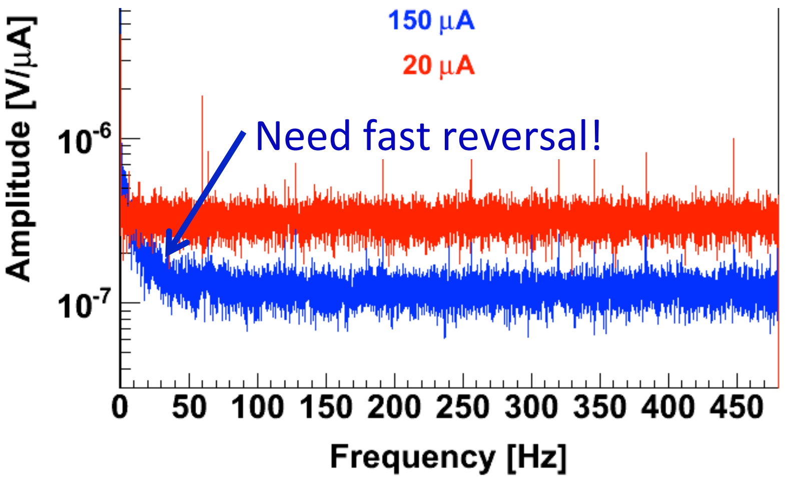
Solid Tgts

# Target Performance

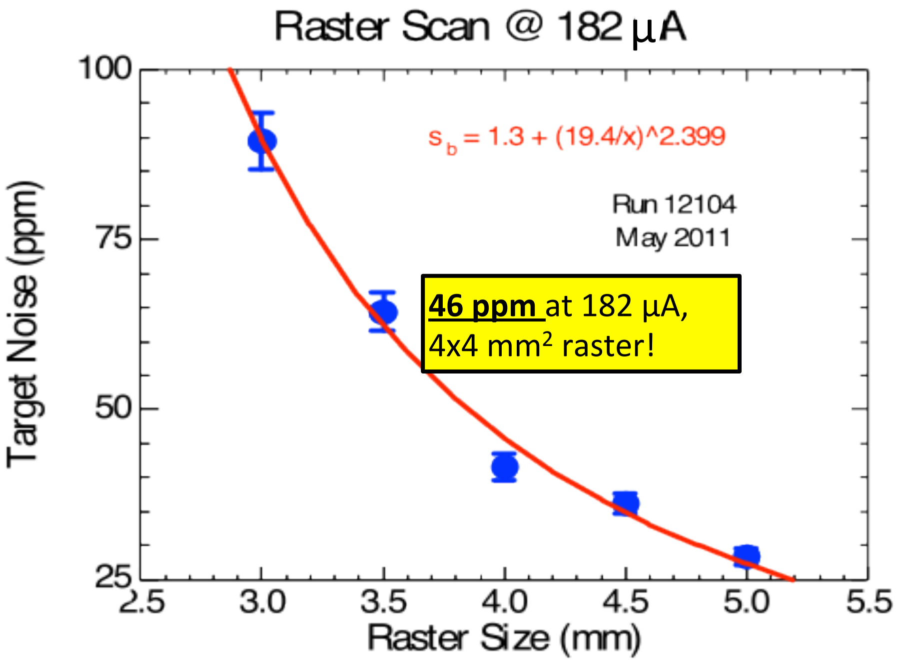
Measured helicity correlated target noise.

At **960 Hz reversal rate**, the target noise (< 50 ppm) is very small compared to our measured helicity quartet (± ∓ ∓ ±) asymmetry width (~230 ppm). (statistical power ~ $\Delta A_{\text{quartet}} / \sqrt{N_{\text{quartets}}}$ ).

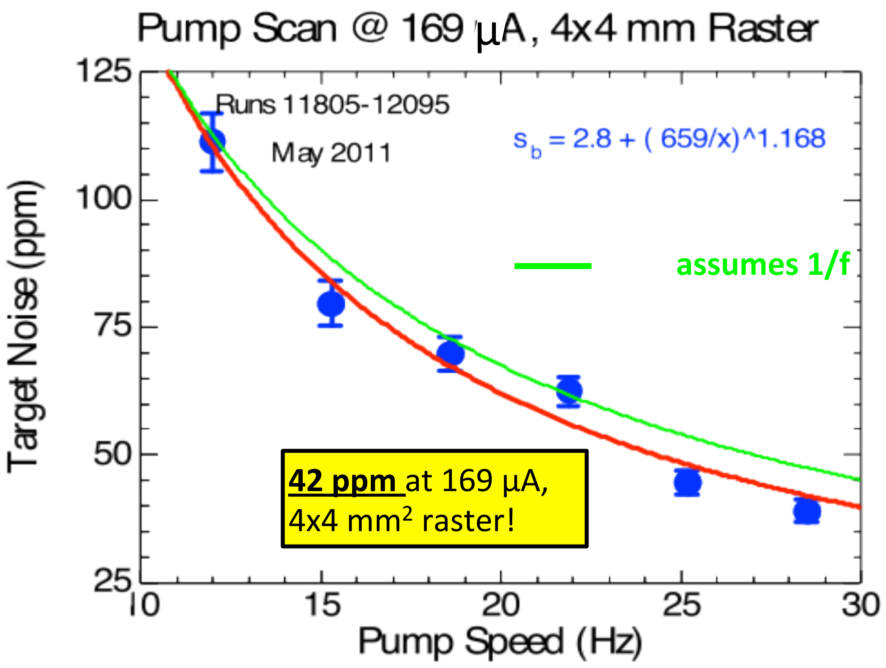
FFT of noise spectrum



Need fast reversal!



**46 ppm** at 182 µA, 4x4 mm$^2$ raster!

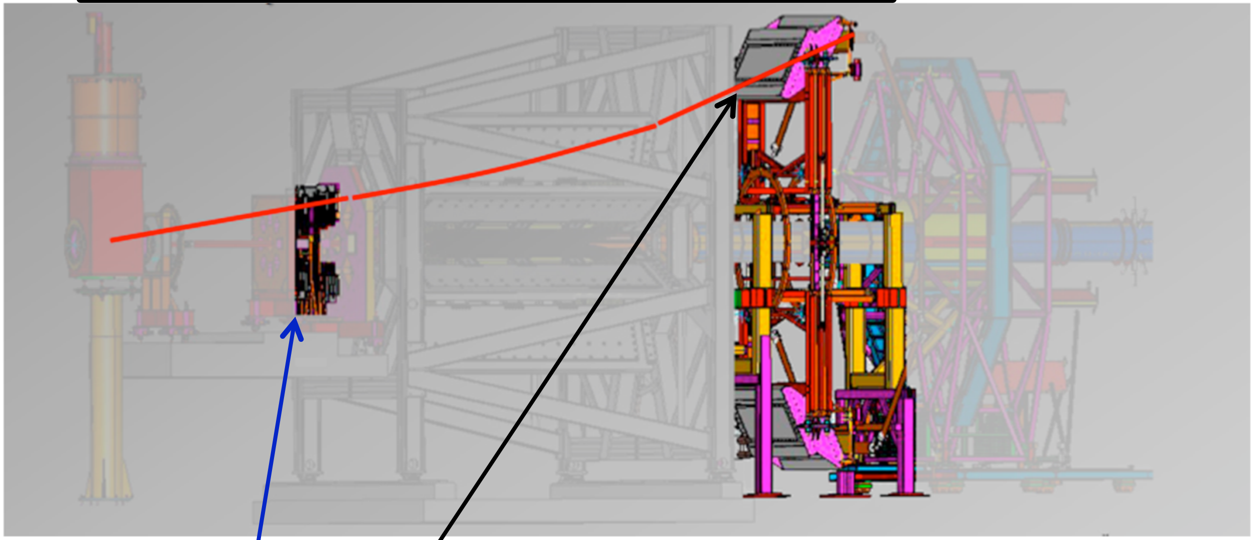


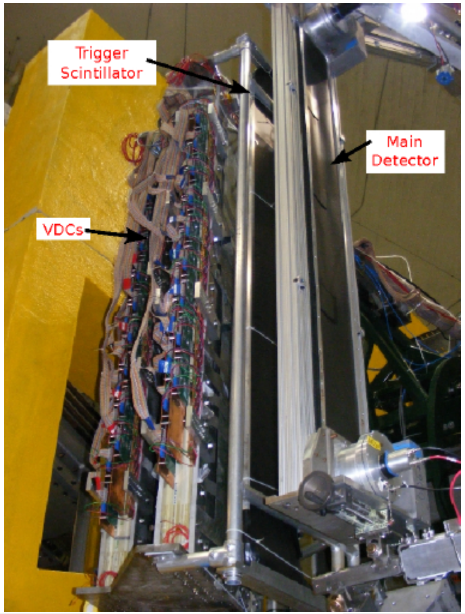
**42 ppm** at 169 µA, 4x4 mm$^2$ raster!

# Determining the Kinematics

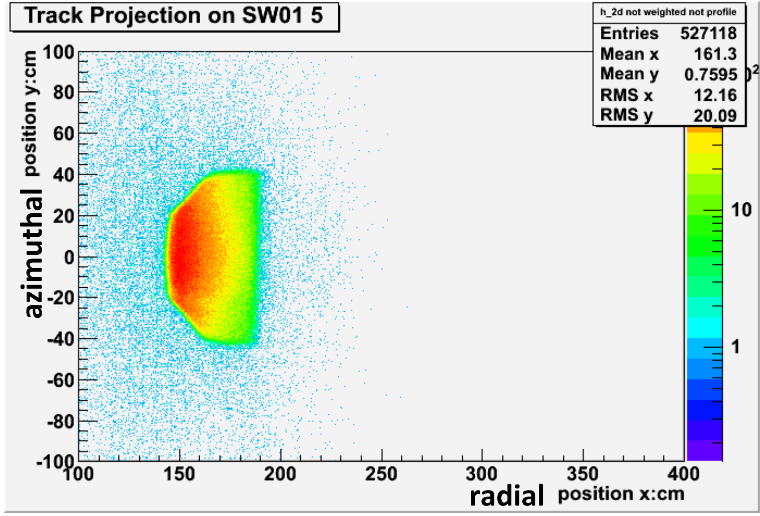
Required uncertainty on $Q^2$ is 0.5%
Combination of tracking and simulation

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





- 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



# Determining $Q_w(p)$

EM (PC) + neutral-weak (PV)

- $A_{ep} = \left[\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right] \sim \frac{|M_{weak}^{PV}|}{|M_{EM}|}$ where σ± is $\vec{e}p$ x-sec for e's of helicity ±1

- $A_{ep} = \left[\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{\epsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1-4\sin^2\theta_W)\epsilon' G_M^\gamma G_A^Z}{\varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}$
  - where $\varepsilon = [1+2(1+\tau)\tan^2(\theta/2)]^{-1}$, $\varepsilon' = \sqrt{\tau(1+\tau)(1-\varepsilon^2)}$, $\tau = Q^2/4M^2$, $G_{E,M}^\gamma$ are EM FFs, $G_{E,M}^Z$ & $G_A^Z$ are strange & axial FFs, and $\sin^2\theta_W = 1 - (M_W/M_Z)^2$ = weak mixing angle

- Recast $A_{ep} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[Q_w^p + Q^2 B(Q^2,\theta)\right]$
  - So in a plot of $A_{ep}/\left[\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right]$ vs $Q^2$:
    - **$Q_w^p$ is the *intercept*** (anchored by precise data near $Q^2$=0)
    - $B(Q^2,\theta)$ is the ***slope*** (determined from higher $Q^2$ PVES data)

**This Experiment**

# Global PVES Fit Details

- Effectively 5 free parameters:
  - $C_{1u}$, $C_{1d}$, $\rho_s$, $\mu_s$, & 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 $Q^2 = 0.63\ (\mathrm{GeV/c})^2$
  - 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 $\square_{\gamma Z}$ RC
  - Hall et al., arXiv:1304.7877 (2013) & Gorchtein et al., PRC84, 015502 (2011)
- Effects of varying $Q^2$, $\theta$, & $\lambda$ studied, found to be small

# Electroweak Corrections

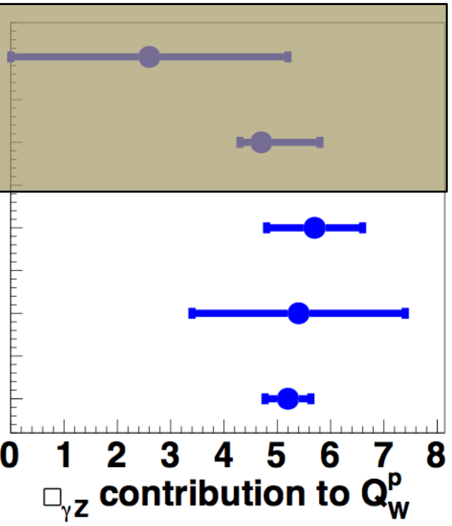
$$Q_W^p = [\rho_{\rm NC} + \Delta_e][1 - 4\sin^2\hat{\theta}_W(0) + \Delta'_e] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

~7% correction

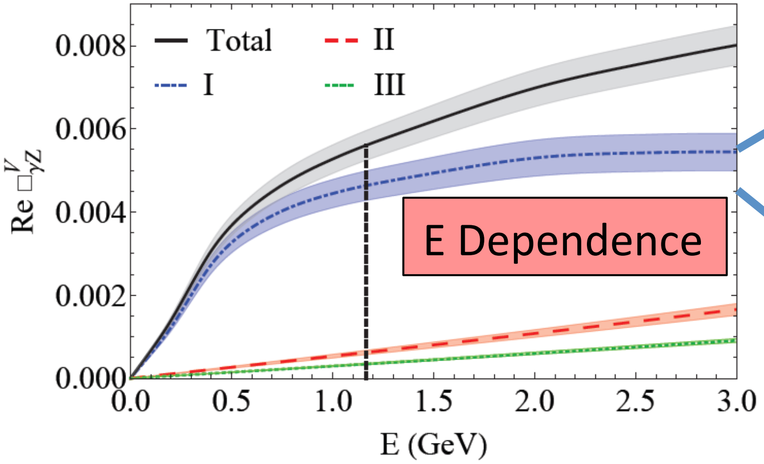
$\Box_{\gamma Z}$ contribution to $Q_W^p$ (Qweak kinematics)

OBSOLETE CALCULATIONS

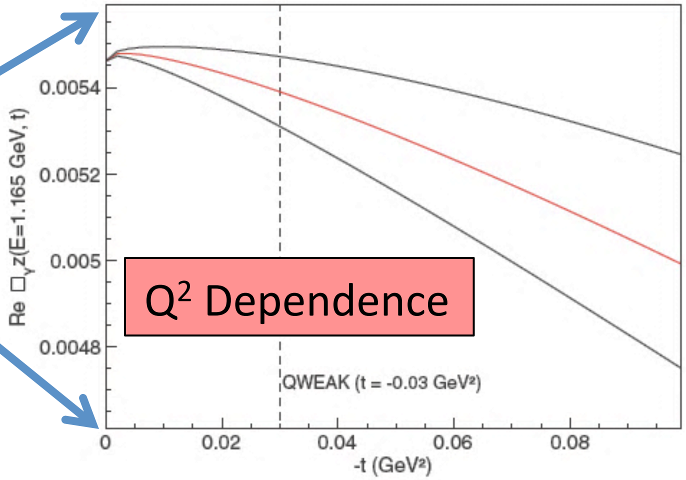
| | |
|---|---|
| **Gorchtein & Horowitz**<br>*PRL 102, 091806 (2009)* | $0.0026 \pm 0.0026$ |
| **Sibirtsev, Blunden & Melnitchouk, Thomas**<br>*PRD 82, 013011 (2010)* | $0.0047^{+0.0011}_{-0.0004}$ |
| **Rislow & Carlson**<br>*PRD 83, 13007 (2011)* | $0.0057 \pm 0.0009$ |
| **Gorchtein, Horowitz &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



- 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$^2$

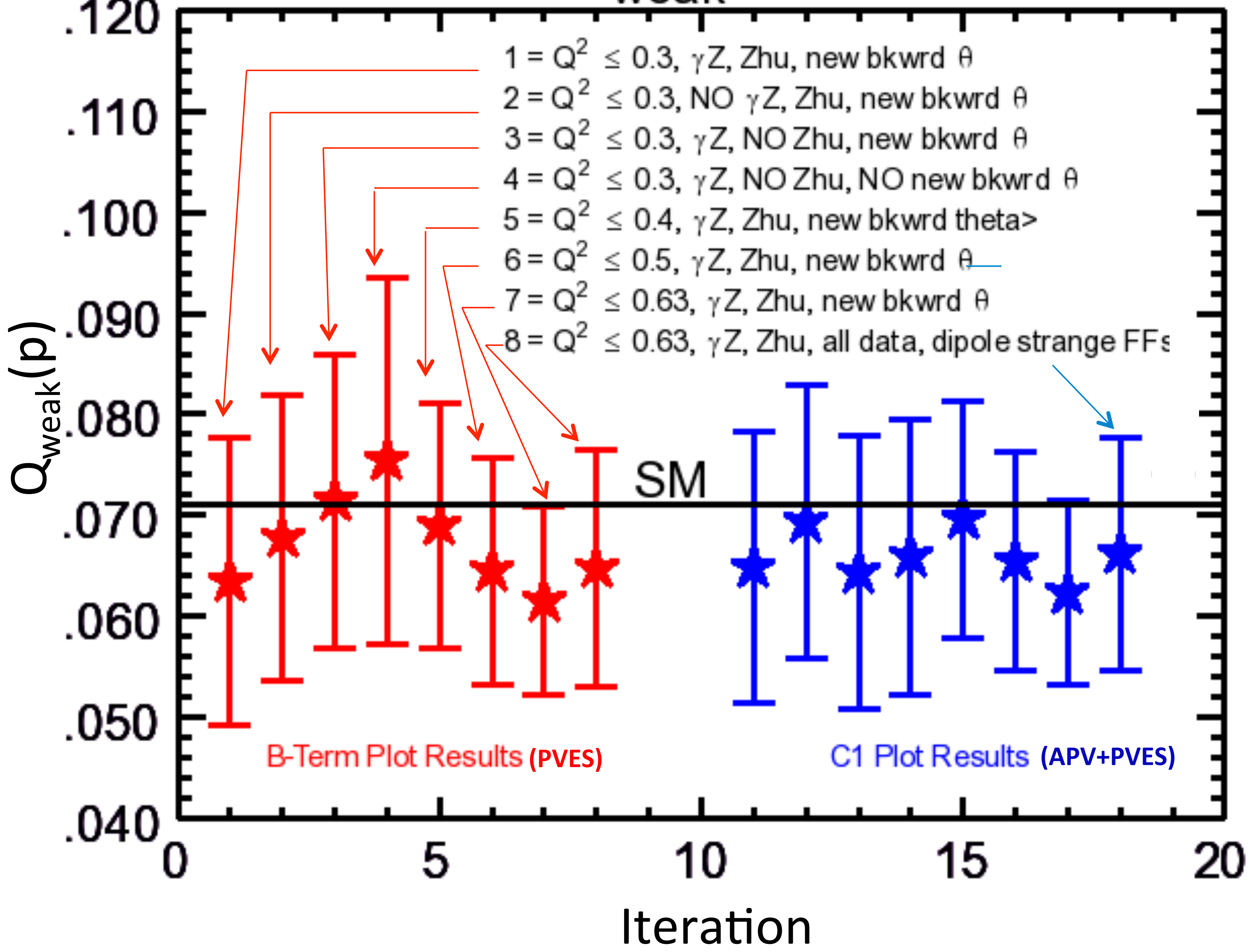


E Dependence

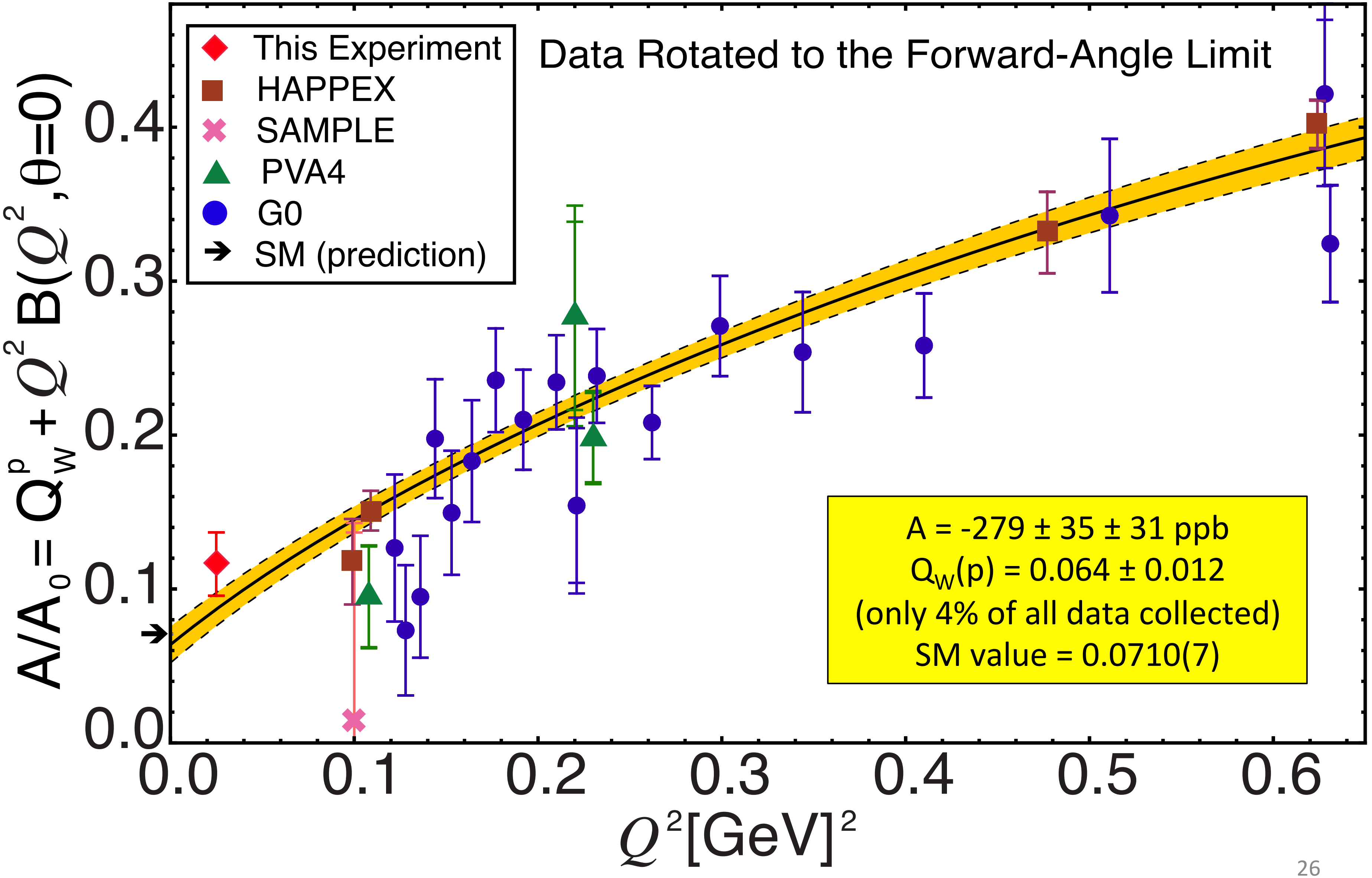


$Q^2$ Dependence

# Stability of $Q_{weak}$ Determination



# Global Fit of $Q^2<0.63\ (\mathrm{GeV}/c)^2$ PVES Data



A = -279 ± 35 ± 31 ppb

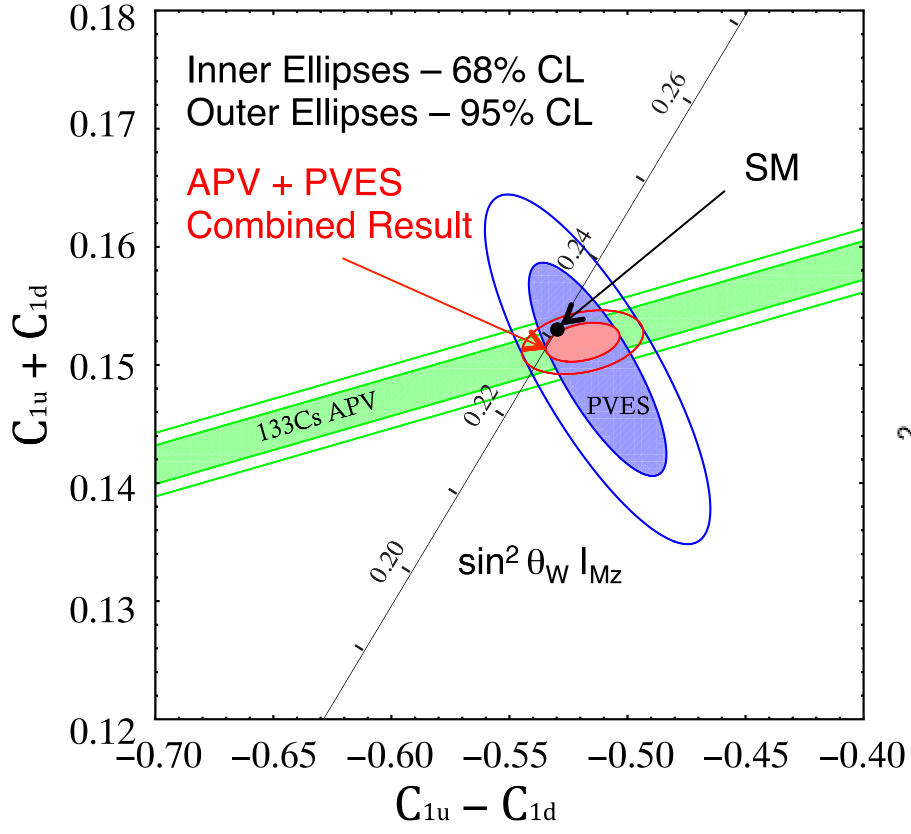
$Q_W(p) = 0.064 \pm 0.012$

(only 4% of all data collected)

SM value = 0.0710(7)

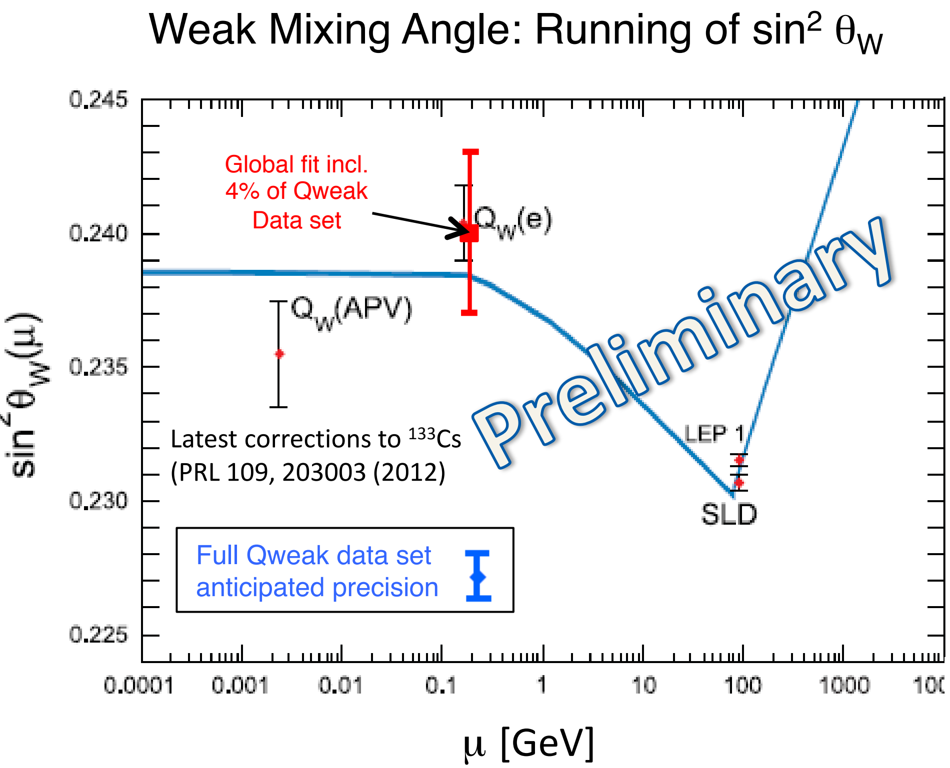
## Combined Analysis

**Extract: $C_{1u}$, $C_{1d}$, $Q^n_W$**



## Qweak + Higher $Q^2$ PVES

**Extract: $Q^p_W$, $\sin^2\theta_W$**



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

$= -0.975 \pm 0.010$

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

$C_{1d} = 0.336 \pm 0.005$

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

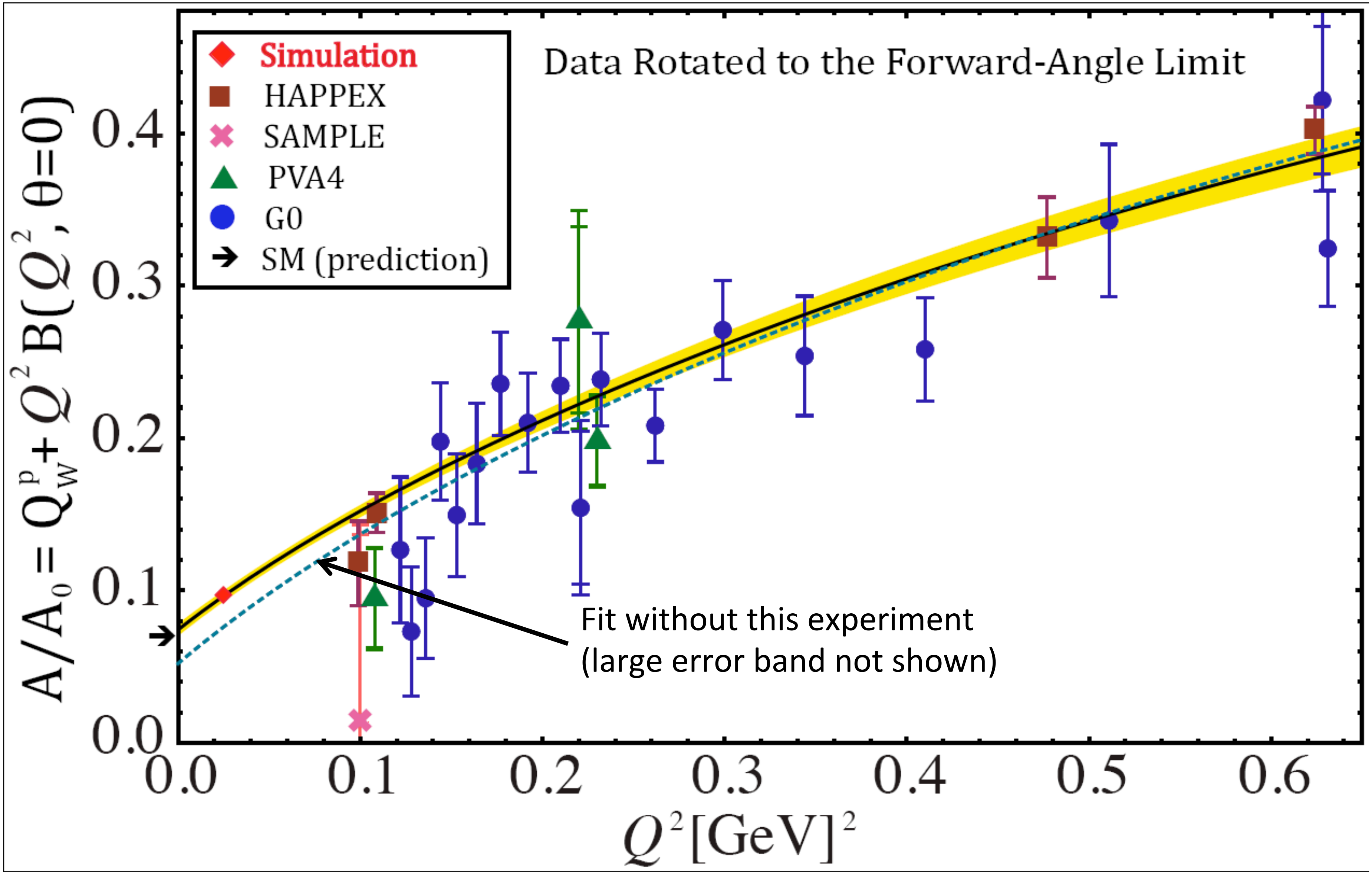
$= 0.064 \pm 0.012$

SM prediction = 0.0710(7)

Remainder of experiment still being analyzed, final result before end of 2014. Expect final $\Delta A_{e\text{-}p}$ result will have ~5 x better precision.

# **Teaser:** Simulated Fit !!

## (Assuming anticipated final uncertainties and SM result)



Fit without this experiment
(large error band not shown)

# Summary

- Measured $A_{ep}$ = -279 ± 35 (statistics) ± 31 (systematics) ppb
  - Smallest & most precise ep asymmetry ever measured!
- First determination of $Q_W(p)$:
  - $Q_w(p)$= 0.064 ± 0.012 (from only 4% of all data collected)
    - (SM value = 0.0710(7))
    - New physics reach $\Lambda/g > 1$ TeV
- First determination of $Q_W(n) = -2(C_{1u} + 2C_{1d})$:
  - By combining our result with APV
    - $Q_w(n)$= -0.975 ± 0.010 (SM value = -0.9890(7))
- Expect to report an $A_{ep}$ with about 5 times smaller uncertainty in about a year
  - Expected physics reach of $\Lambda/g > 2$ TeV.
  - SM test, sensitive to Z's and LQs

# The Qweak Collaboration

- 95 collaborators
- 23 grad students
- 10 post docs
- 23 institutions:

JLab, W&M, UConn, TRIUMF, MIT, UMan., Winnipeg, VPI, LaTech, Yerevan, MSU, OU, UVa, GWU, Zagreb, CNU, HU, UNBC, Hendrix, SUNO, ISU, UNH, Adelaide

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