First Results from QWEAK

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(for the QWEAK Collaboration)

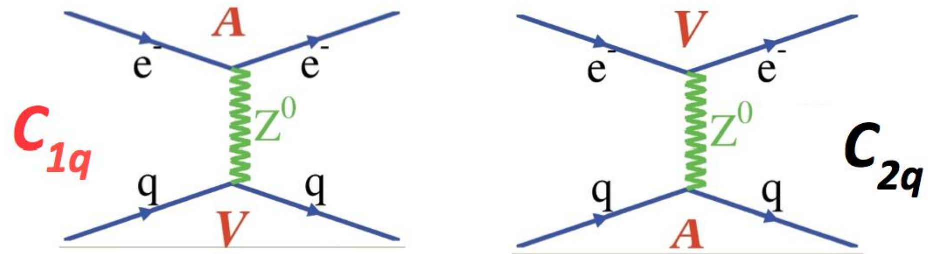
Jefferson Lab

The Sixth Workshop on Hadron Physics in China and Opportunities in the US
Lanzhou, China (July 23, 2014)

The Weak Charges

Electron-quark scattering, general four-fermion contact interaction:

$$\mathcal{L}_{eq}^{PV} = -\frac{G_F}{\sqrt{2}} \sum_i \left[C_{1i} \bar{e}\gamma_\mu\gamma_5 e \bar{q}\gamma^\mu q + C_{2q} \bar{e}\gamma_\mu e \bar{q}\gamma^\mu\gamma^5 q \right] + \mathcal{L}_{new}^{PV}$$

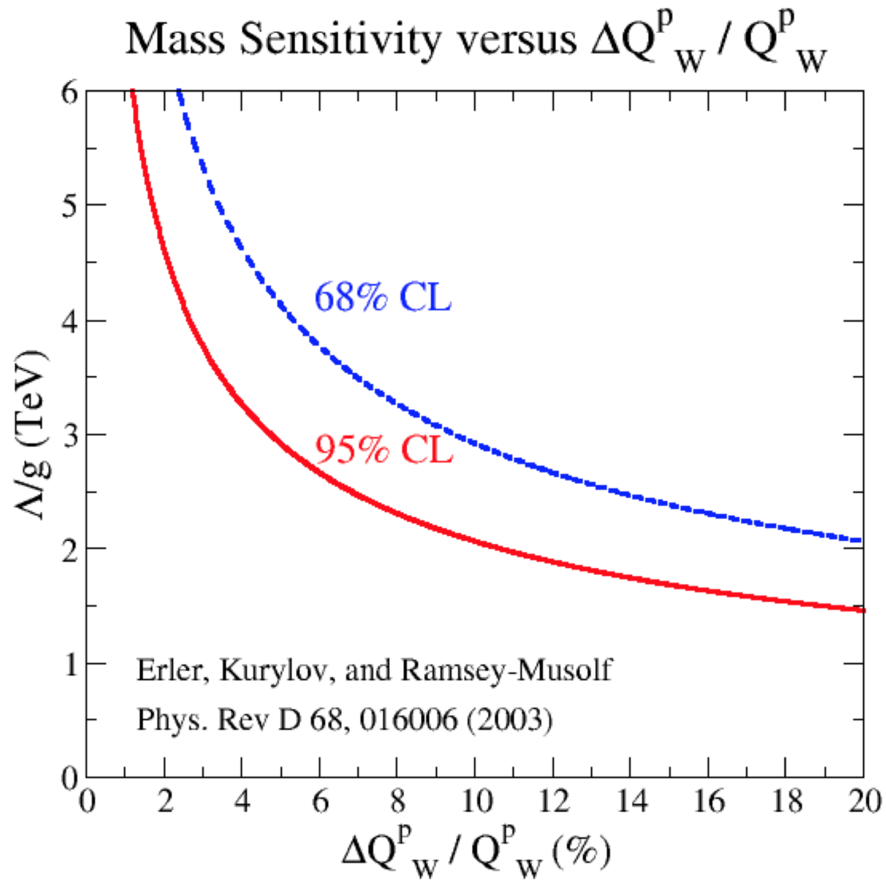


Note "accidental" suppression of Q^p_{weak} → ***sensitivity to new physics***

Particle	Electric charge	Weak vector charge ($\sin^2\theta_W \approx \frac{1}{4}$)
e	-1	$Q_W^e = -1 + 4\sin^2\theta_W \approx 0$
u	$+\frac{2}{3}$	$-2C_{1u} = +1 - \frac{8}{3}\sin^2\theta_W \approx +\frac{1}{3}$
d	$-\frac{1}{3}$	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_W \approx -\frac{2}{3}$
p(uud)	$+1$	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0.07$
n(udd)	0	$Q_W^n = -1$

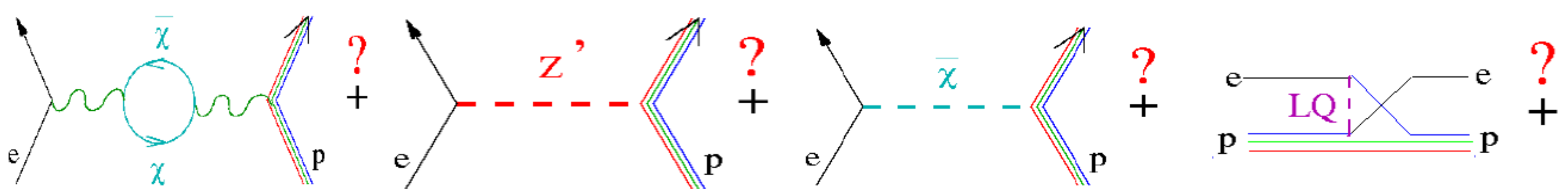
Q^p_{weak} has a definite prediction in the electroweak Standard Model

Sensitivity to New Physics



Qweak proposal:
$\Delta Q^p_w / Q^p_w = 4.2\%$

Depending on how the PV "new physics" Lagrangian is constructed, and the value of model dependent value g, the mass scale can be much greater



RPC SUSY

Generic Z'

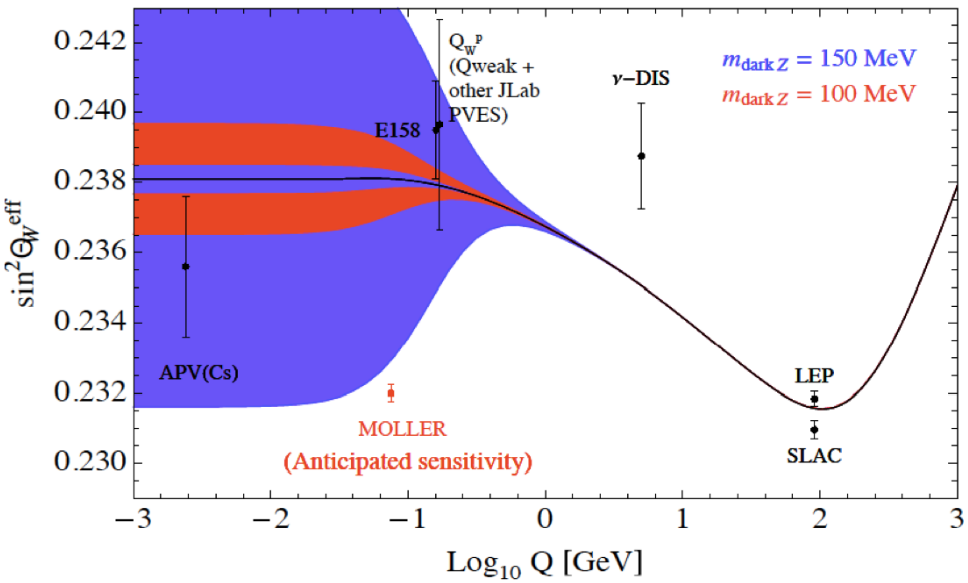
RPV SUSY

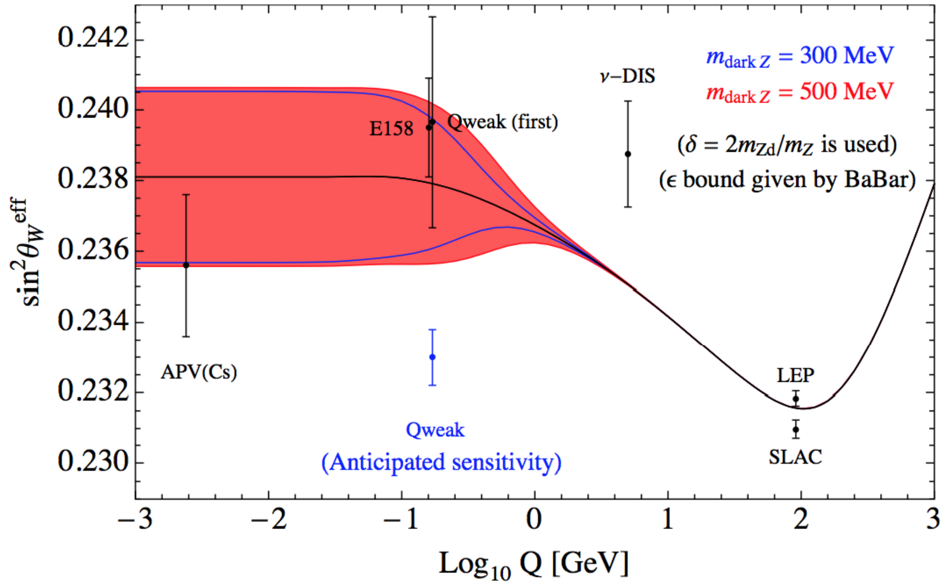
Leptoquarks

New Physics Example - Dark Z

"Dark parity violation" (Davoudiasl, Lee, Marciano, arXiv 1402.3620)

- Introduces a new source of low energy parity violation through mass mixing between *Z* and Z_d with observable consequences.
- Complementary to direct searches for heavy dark photons.





Low-E experiments most sensitive to deviations from SM due to Dark Z

Determining Q^p_w

- $A_{ep} = \left[\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right] \sim \frac{|M^{PV}_{weak}|}{|M_{EM}|}$

EM (PC) neutral-weak (PV)

- $A_{ep} = \left[\frac{G_F\, Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{\epsilon G^\gamma_E G^Z_E + \tau G^\gamma_M G^Z_M - (1-4\sin^2\theta_w)\epsilon' G^\gamma_M G^Z_A}{\varepsilon (G^\gamma_E)^2 + \tau (G^\gamma_M)^2}$
  - where $\varepsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}$, $\varepsilon' = \sqrt{\tau(1+\tau)(1-\varepsilon^2)}$,

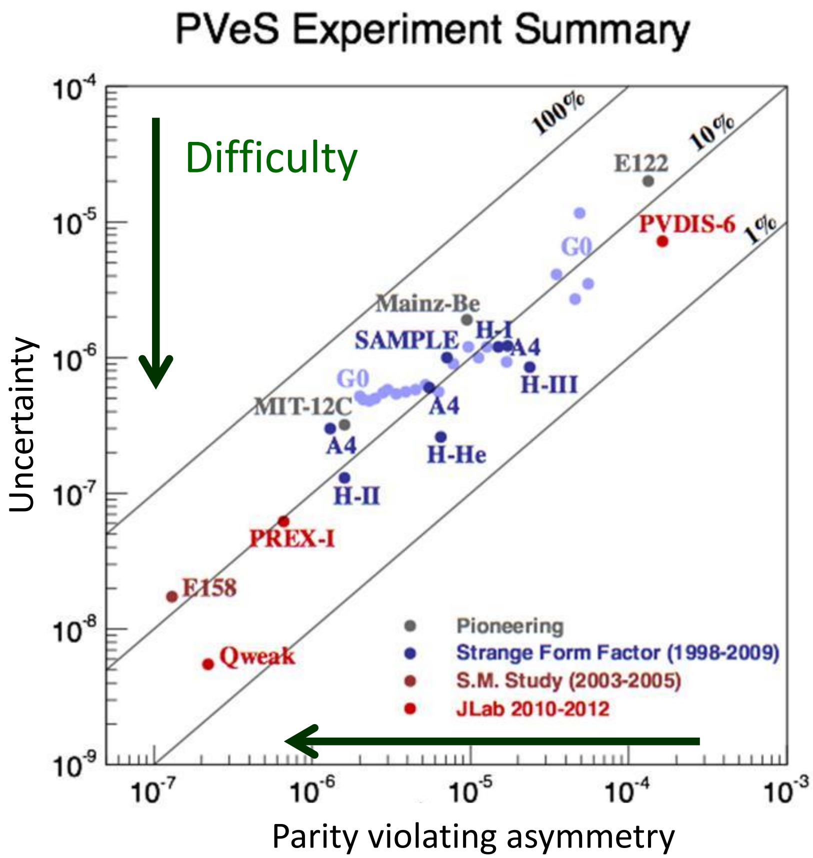
    $\tau = Q^2/4M^2$, $G^\gamma_{E,M}$ are EM FFs, $G^Z_{E,M}$ & G^Z_A are strange & axial FFs,

    and $\sin^2\theta_W = 1 - (M_W / M_Z)^2$ = weak mixing angle

- Recast $A_{ep} = \frac{G_F\, Q^2}{4\pi\alpha\sqrt{2}}\left[Q^p_w + Q^2 B(Q^2,\theta)\right]$
  - So in a plot of $A_{ep} / \left[\frac{G_F\, Q^2}{4\pi\alpha\sqrt{2}}\right]$ vs Q^2:
    - ***Q^p_w* 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

PVES Challenges



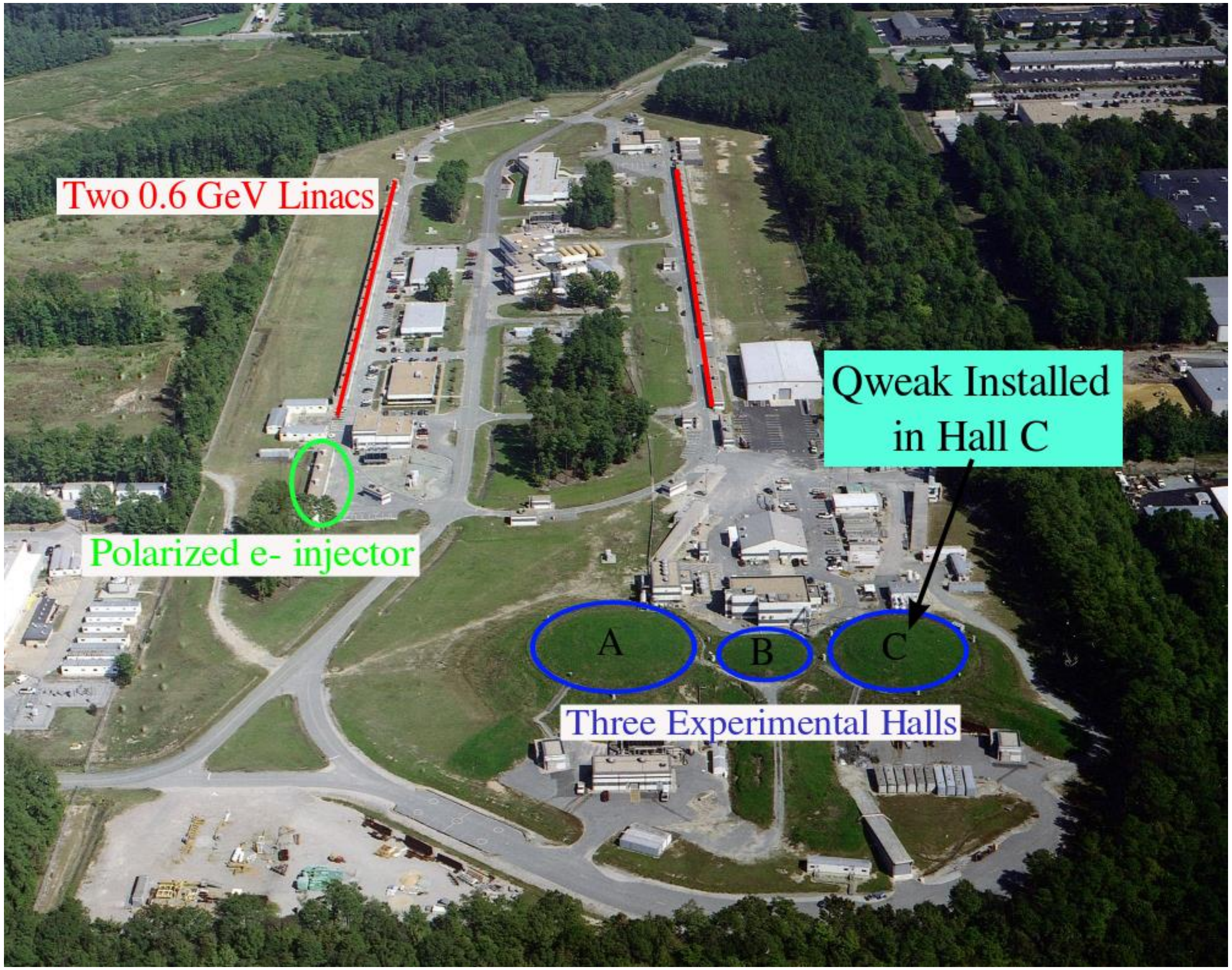
PVES challenges:

- Statistics
  - High rates required
    - High polarization, current
    - High powered targets with large acceptance
- Low noise
  - Electronics, target density fluctuations
  - Detector resolution
- Systematics
  - Helicity-correlated beam parameters
  - Backgrounds (target windows)
  - Polarimetry
  - Parity-conserving processes

Qweak's goal: most precise (relative and absolute) PVES result to date.

QWEAK JLab Site

Jefferson Lab (6 GeV)



Qweak Installation:
May 2010-May 2012

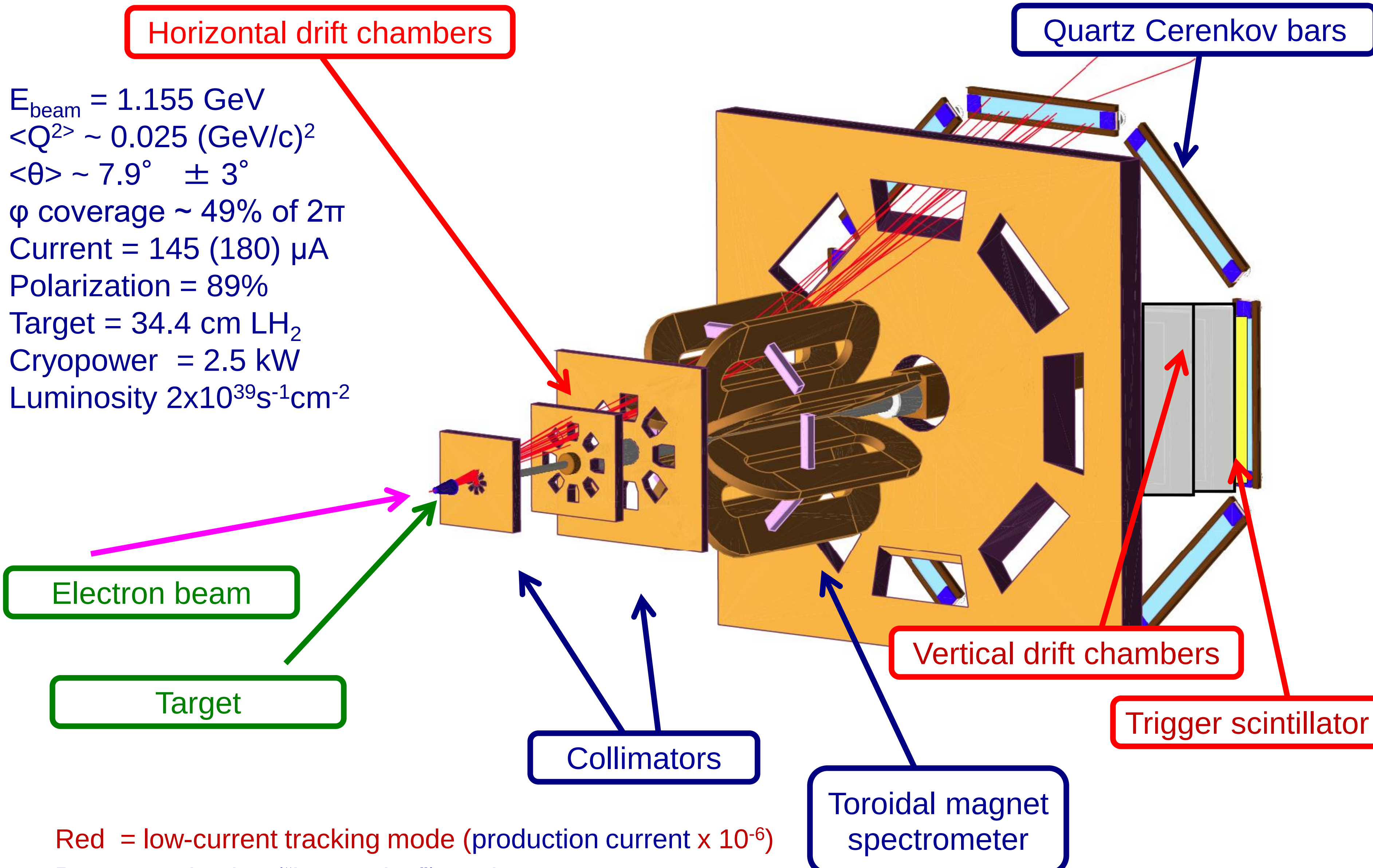
~1 year of beam in 3 running periods:

- Run 0
  Jan – Feb 2011
- Run 1
  Feb – May 2011
- Run 2
  Nov 2011 – May 2012

Asymmetry ~250 ppb
Error goal ~5 ppb

QWEAK Apparatus

E_{beam} = 1.155 GeV
$<Q^2>$ ~ 0.025 $(GeV/c)^2$
$<\theta>$ ~ 7.9° ± 3°
φ coverage ~ 49% of 2π
Current = 145 (180) μA
Polarization = 89%
Target = 34.4 cm LH_2
Cryopower = 2.5 kW
Luminosity $2x10^{39} s^{-1} cm^{-2}$



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

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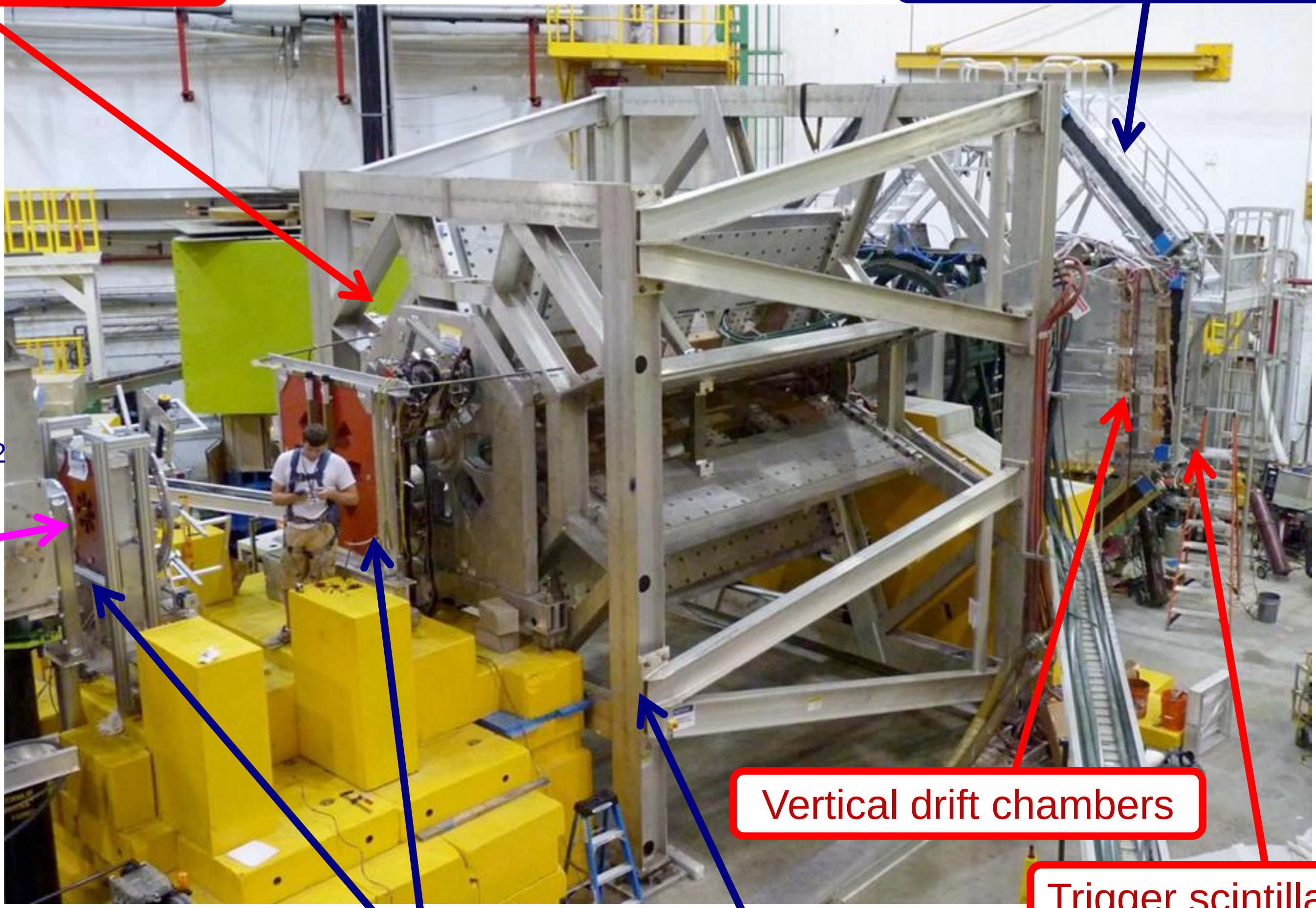

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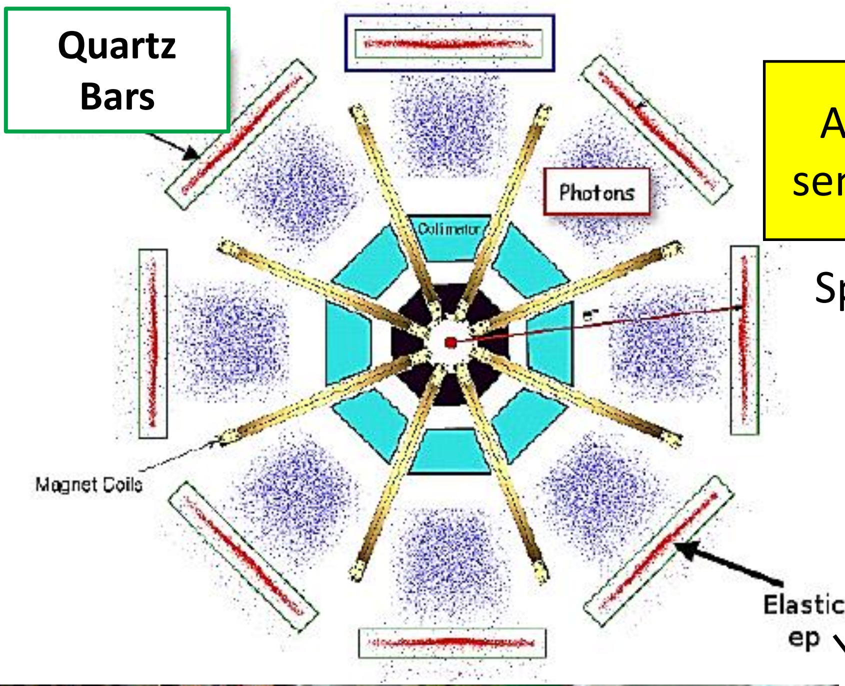
Quartz Cerenkov Detectors

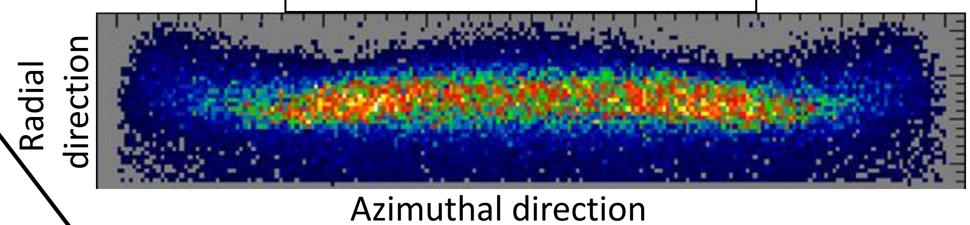


Azimuthal symmetry maximizes rate and decreases sensitivity to HC beam motion, transverse asymmetry.

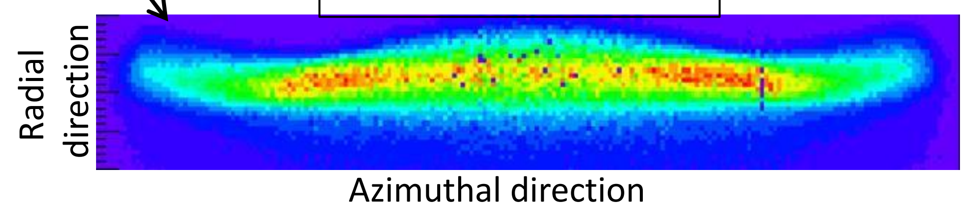
Spectrosil 2000 (fused silica) Cerenkov radiators:

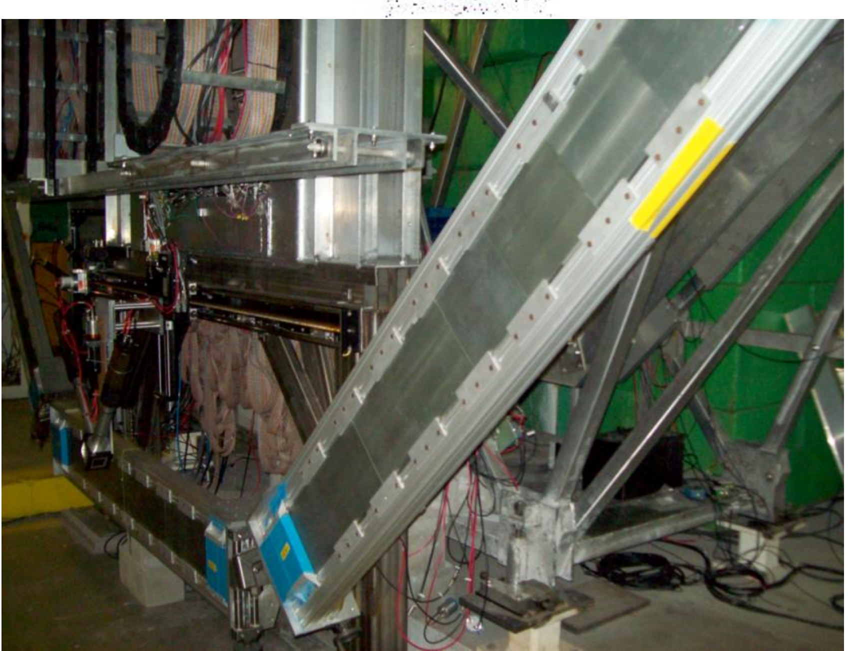
- Eight bars, each 2 m long, 18 cm hi, 1.25 cm thick
- Rad-hard. non-scintillating, low-luminescence

Simulation of MD face:



Measured

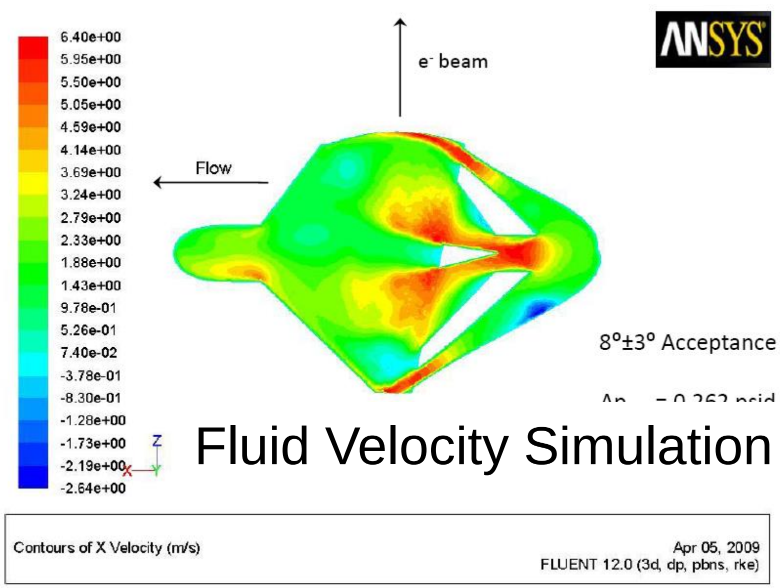




Yield 100 pe's/track with 2 cm Pb pre-radiators
Resolution (~10%) limited by shower fluctuations.

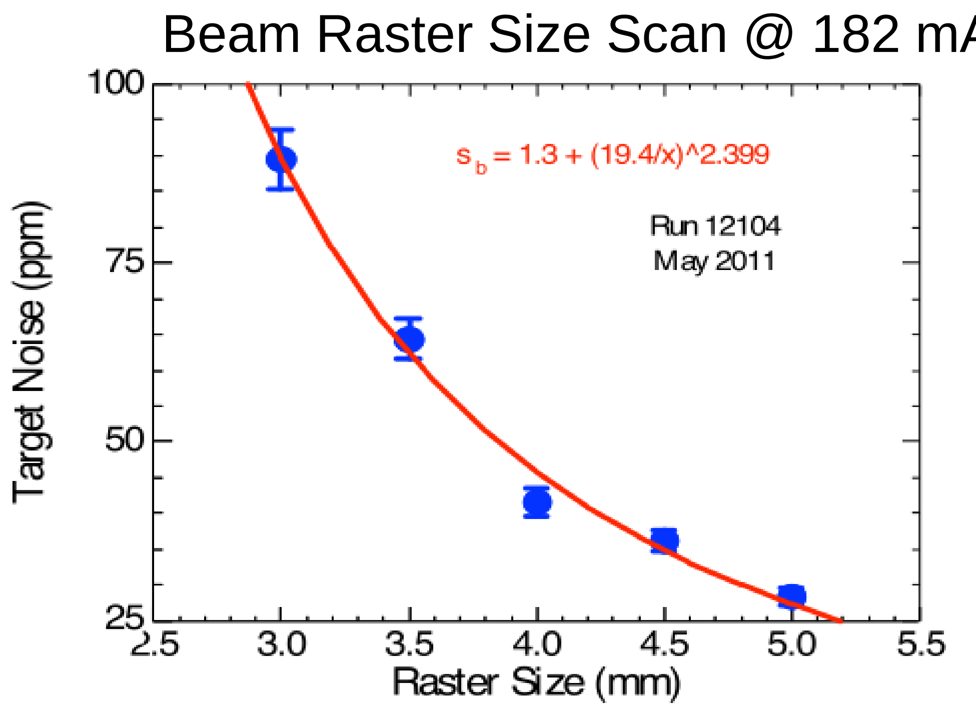
Target Design and Performance

- 35 cm LH_2 (4% X_0)
  - 20K, 30-35 psia
  - ~3 kW power
- Designed using CFD



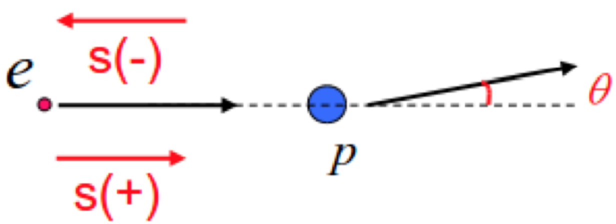
Fluid Velocity Simulation

Target “Boiling” Noise:
target density fluctuations

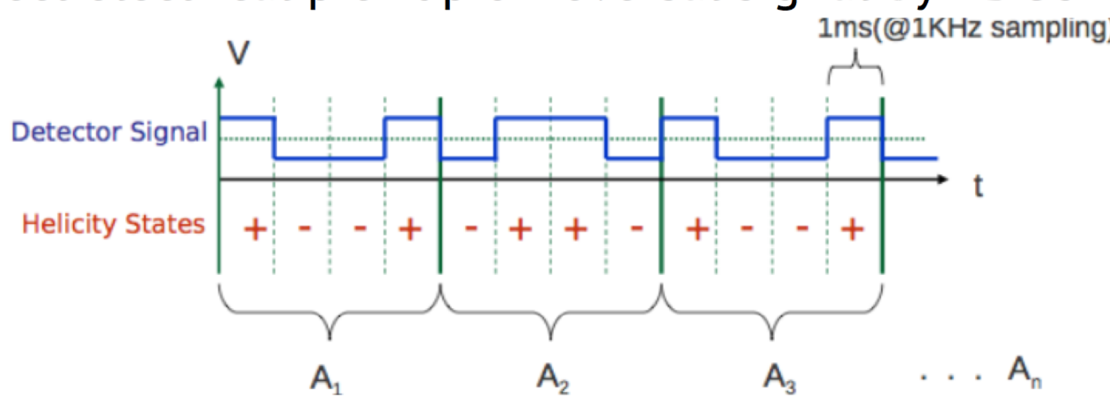


47 ppm/quartet; small contribution to ~230 ppm width from statistics

Measuring Asymmetry



Helicity of electron beam flipped at up to 960 times/sec. Delayed helicity reporting to prevent direct electrical pick up of reversal signal by ADC's



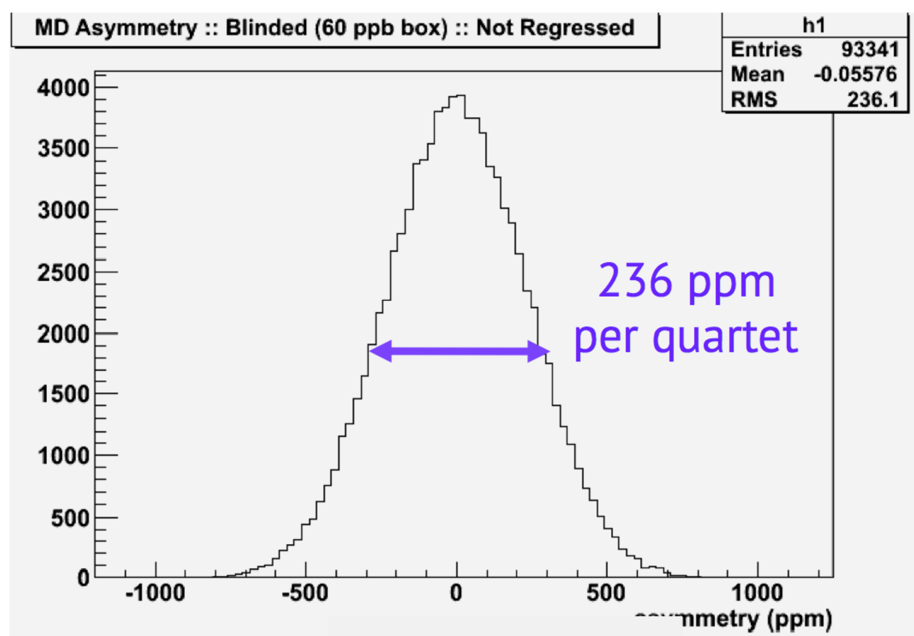
Detector signal integrated
For each helicity window

Asymmetry formed by quartet (4 ms)

Statistical power is

$$\Delta A = s_{width}/\sqrt{N_{quartets}}$$

Measured asymmetry has unknown additive "blinding factor" for analysis (± 60 ppb blinding box)



Constructing 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 $N \rightarrow \Delta$ inelastic bkg

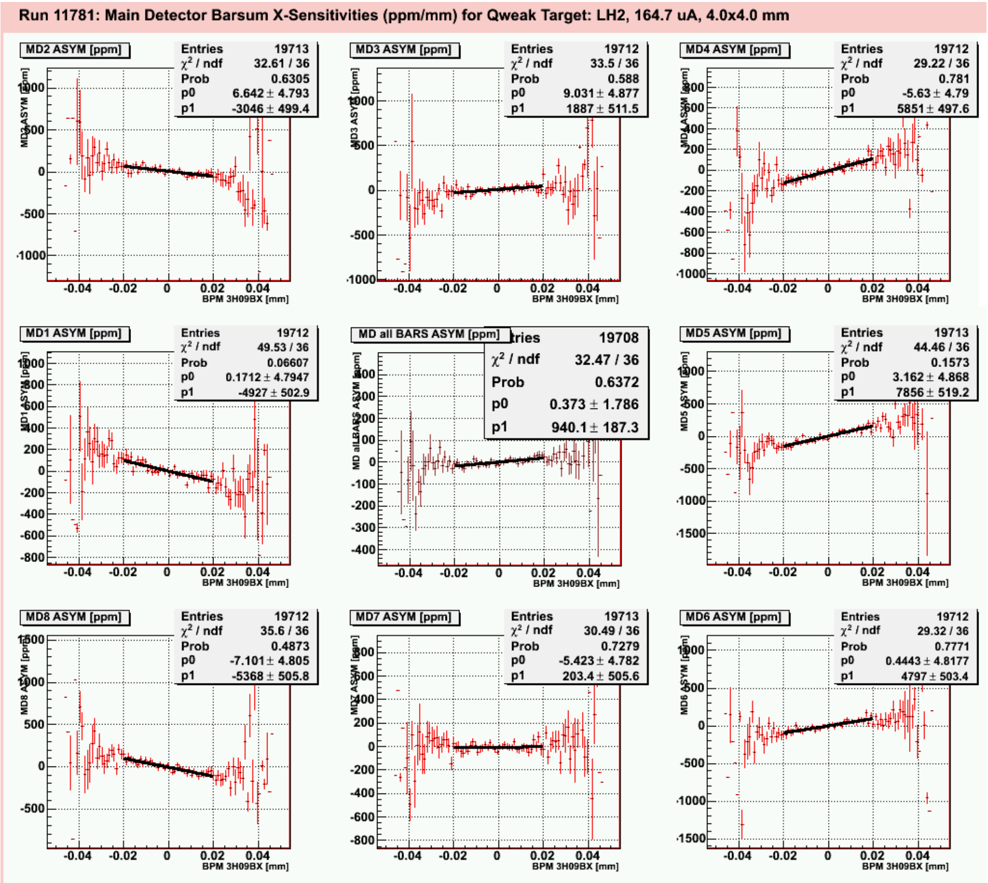
Beam Parameter Corrections

- Helicity correlated beam parameter variations can produce an asymmetry in the detectors
  - Symmetric detectors give partial cancellation
  - Large HC beam variations can be reduced by retuning
  - Measured detector-beam correlations can provide a correction

$$A_{corr} = \sum_{i=1}^{5} \left(\frac{\partial A}{\partial x_i} \right) \Delta x_i$$

(x, x', y, y', E)

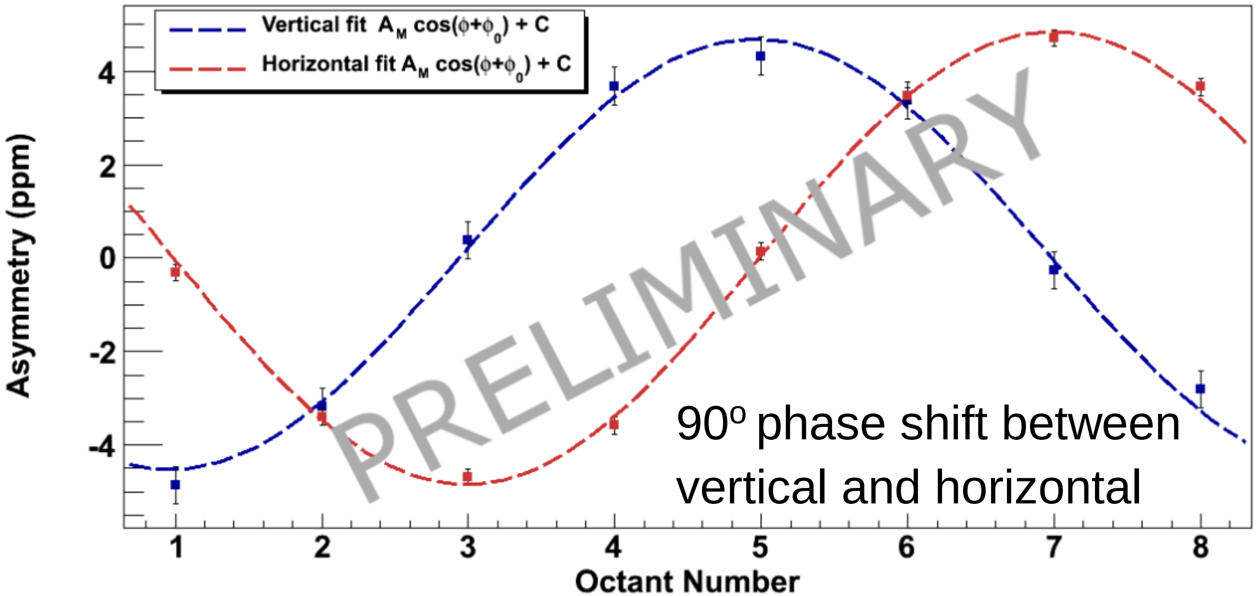
Example: Detector Sensitivity to X position variation



Regression Correction from Qweak "Wien0" (PRL 111, 141803): A_{corr} = -35 ± 11 ppb

Transverse Asymmetry

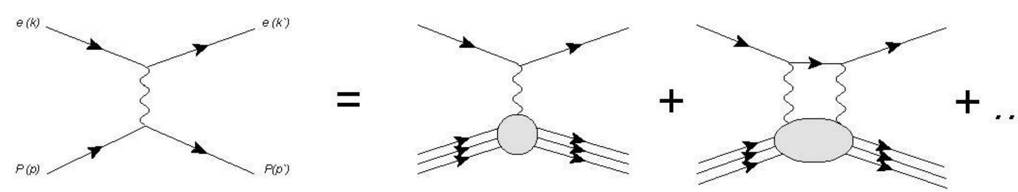
- Dedicated measurement with fully transverse beam
  - Constrains false asymmetry for A_{ep} result



- Good cancellation (symmetry factor)
- Small residual P_T when running
- Correction < 4 ppb

- Transverse result: nucleon structure and 2γ exchange

The data provide an integral test of all allowed virtual excitations of the proton up to E_{cm} = 1.7 GeV

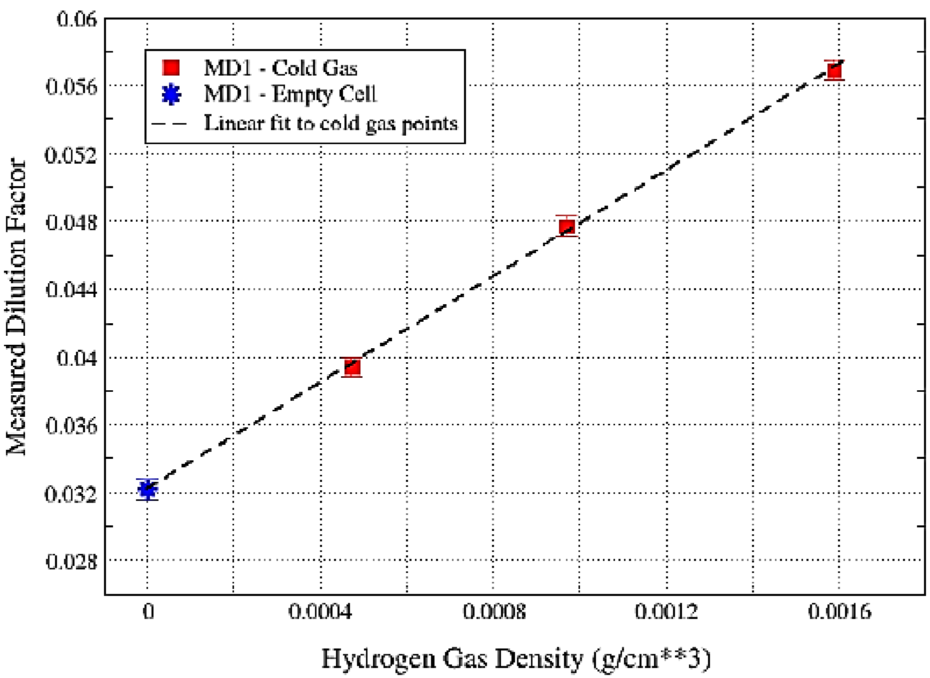


Aluminum Window Background

Large A & f make this our largest correction. Determined from explicit measurements using Al dummy tgts & empty H_2 cell.

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

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



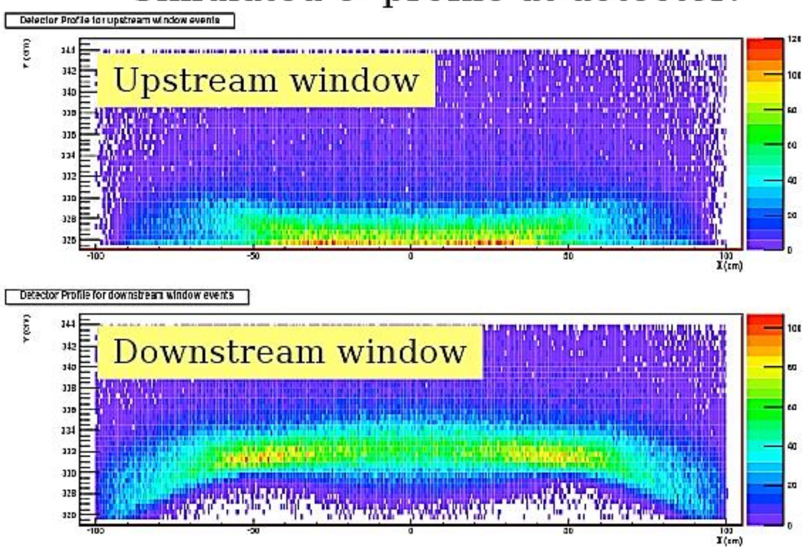
$$C_{\mathrm{Al}} = -64 \pm 10\ \mathrm{ppb}$$

$$A_{\mathrm{Al}} = 1.76 \pm 0.26\ \mathrm{ppm}$$

- 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:

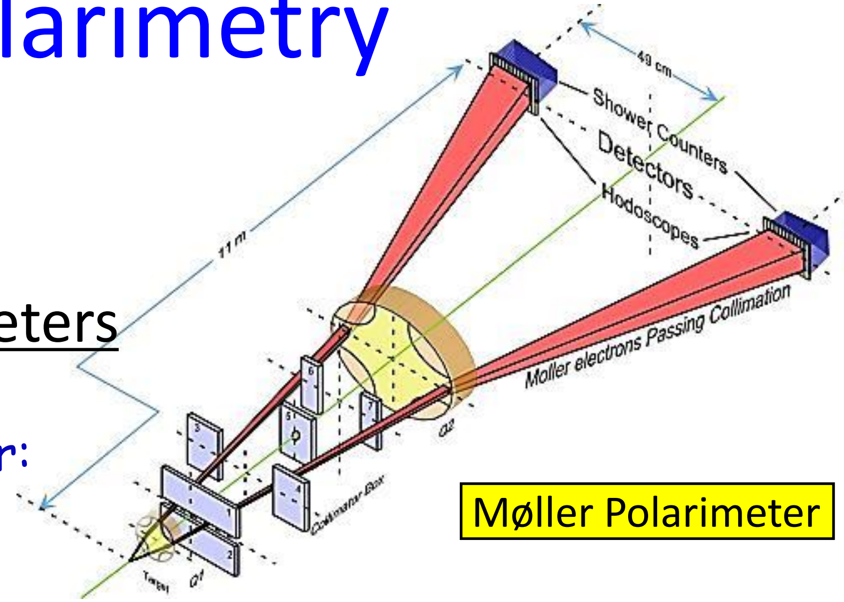


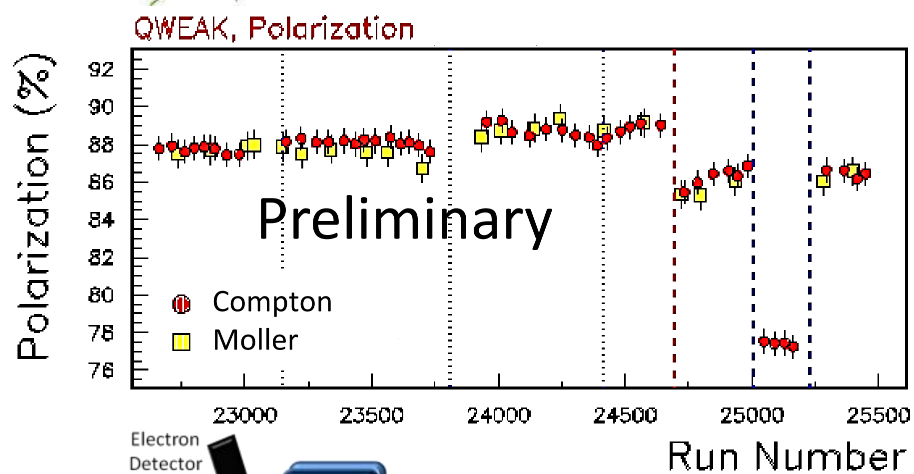
Precision Polarimetry

Qweak requires ΔP/P ≤ 1%

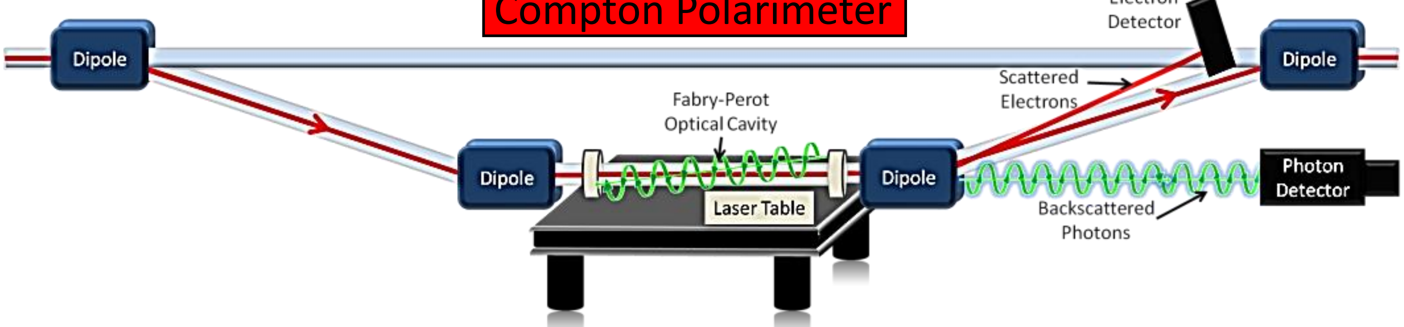
<u>Strategy: use 2 independent polarimeters</u>

- 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.
- Use new Compton polarimeter (1%/h)
  - High current, non-invasive
  - Continuous
  - Photon & Electron
  - Known analyzing power provided by circularly-polarized laser





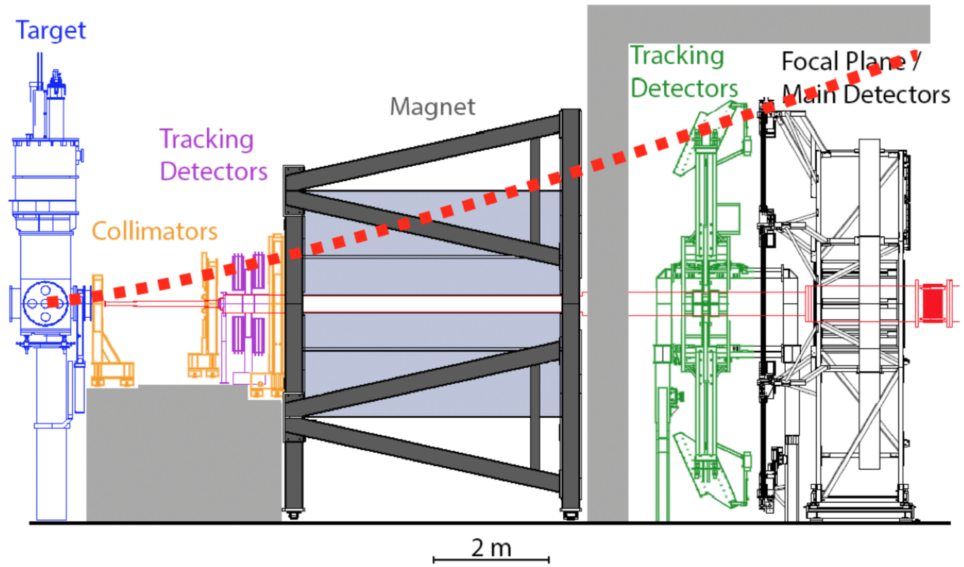
Compton Polarimeter

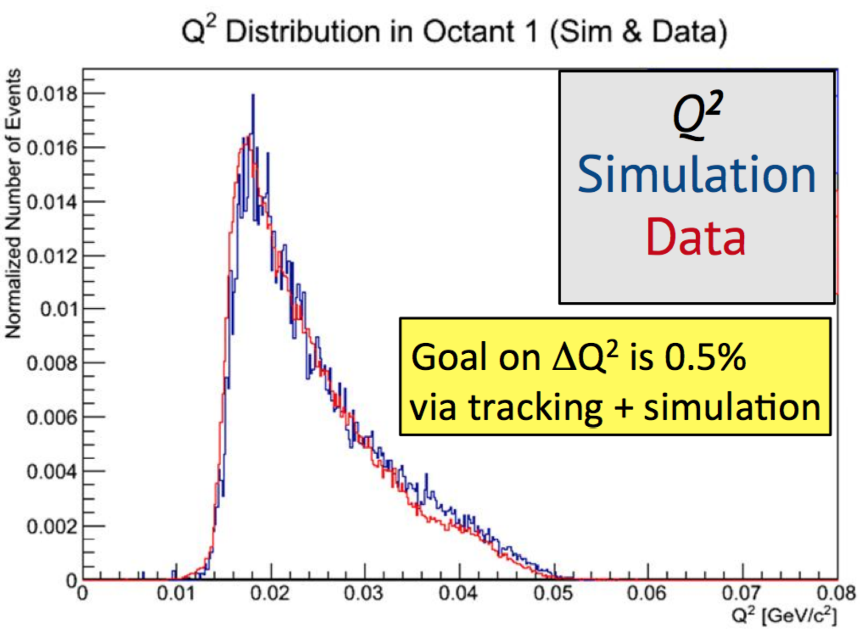


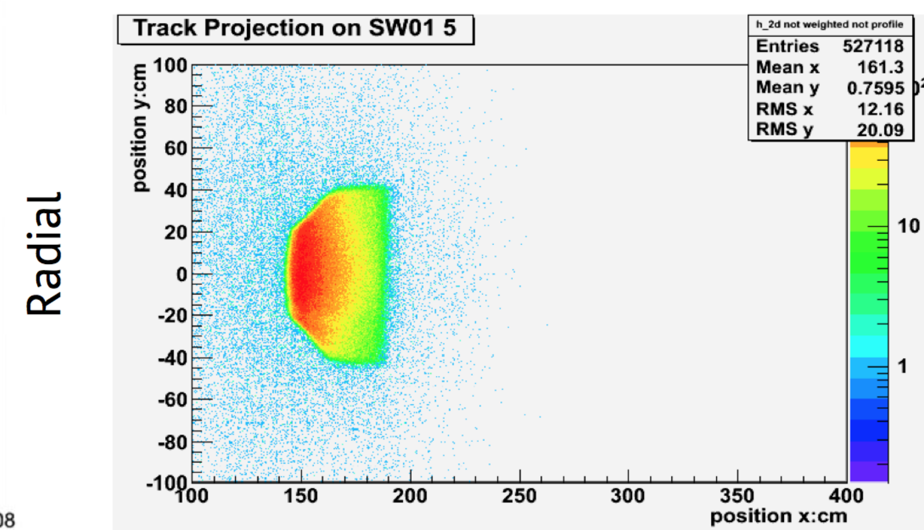
Kinematics Determination

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

- Drift chambers before and after magnetic field
- Low current, reconstruct individual events
- Systematic studies





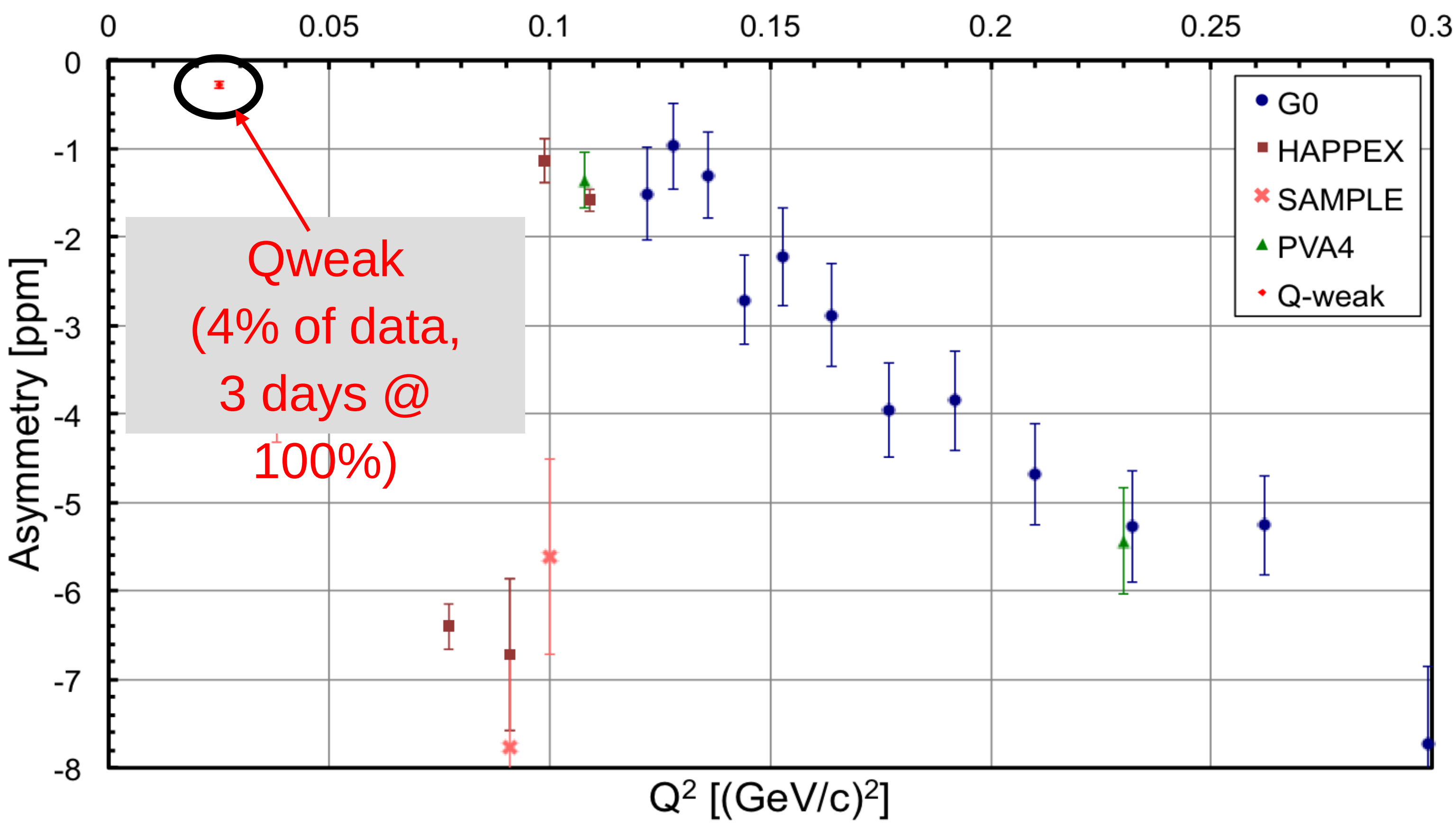


First Results: Asymmetry

- Run 0 Results
  (1/25th of total dataset)

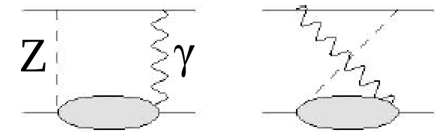
Kinematics: $\langle Q^2 \rangle = 0.0250 \pm 0.0006\ \mathrm{GeV}^2$
$\langle E_{beam} \rangle = 1.155 \pm 0.003\ \mathrm{GeV}$

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



PRL **111**,141803 (2013)

Electroweak Corrections

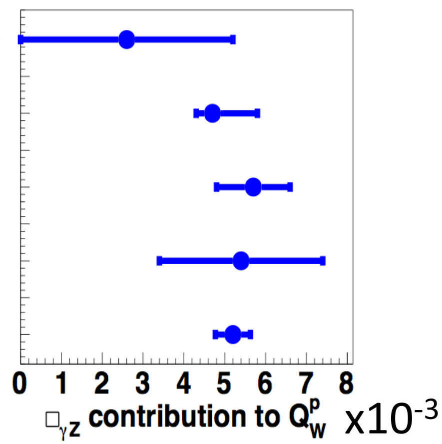


$$Q_W^p = [\rho_{NC} + \Delta_e][1 - 4\sin^2\hat{\theta}_W(0) + \Delta'_e] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

~7% correction

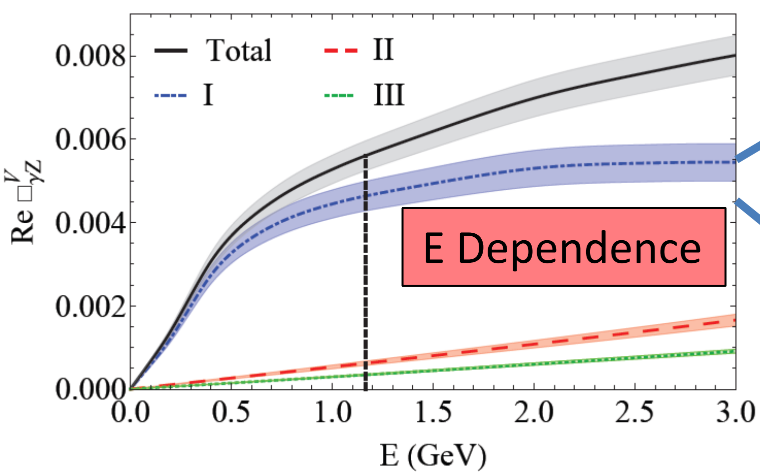
Table 1: $\Box^V_{\gamma Z}$ contribution to Q^p_W (Qweak kinetmatics)

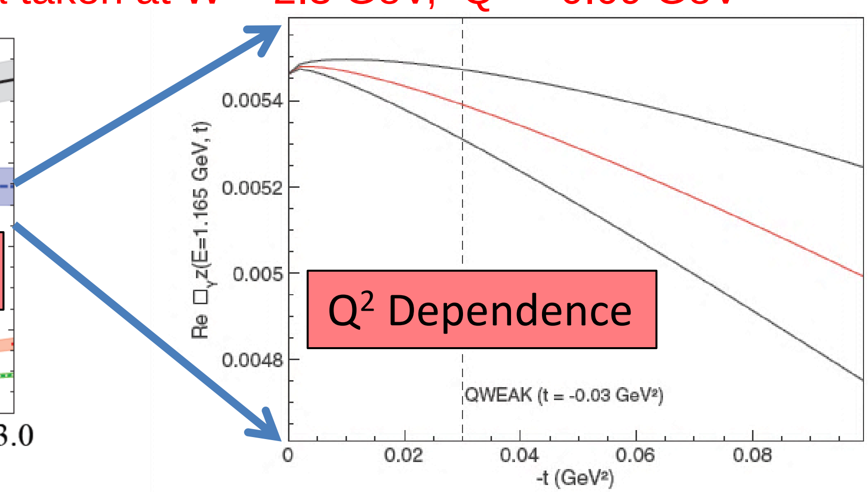
Gorchtein & Horowitz Phys. Rev. Lett. **102**, 091806 (2009)	$\mathbf{0.0026 \pm 0.0026}$
Sibirtsev, Blunden, Melnitchouk, & Thomas Phys. Rev. D **82**, 013011 (2010)	$\mathbf{0.0047^{+0.0011}_{-0.0004}}$
Rislow & Carlson Phys. Rev. D **83**, 113007 (2007)	$\mathbf{0.0057 \pm 0.0009}$
Gorchtein, Horowitz, & Ramsey-Musolf Phys. Rev. C **84**, 015502 (2011)	$\mathbf{0.0054 \pm 0.0020}$
Hall, Blunden, Melnitchouk, Thomas, & Young Phys. Rev. D **88**, 013011 (2013)	$\mathbf{0.00557 \pm 0.00036}$



The $\Box_{\gamma Z}$ is the only E & Q^2 dependent EW correction.
→ Correct the PVES data for this E & Q^2 dependence.

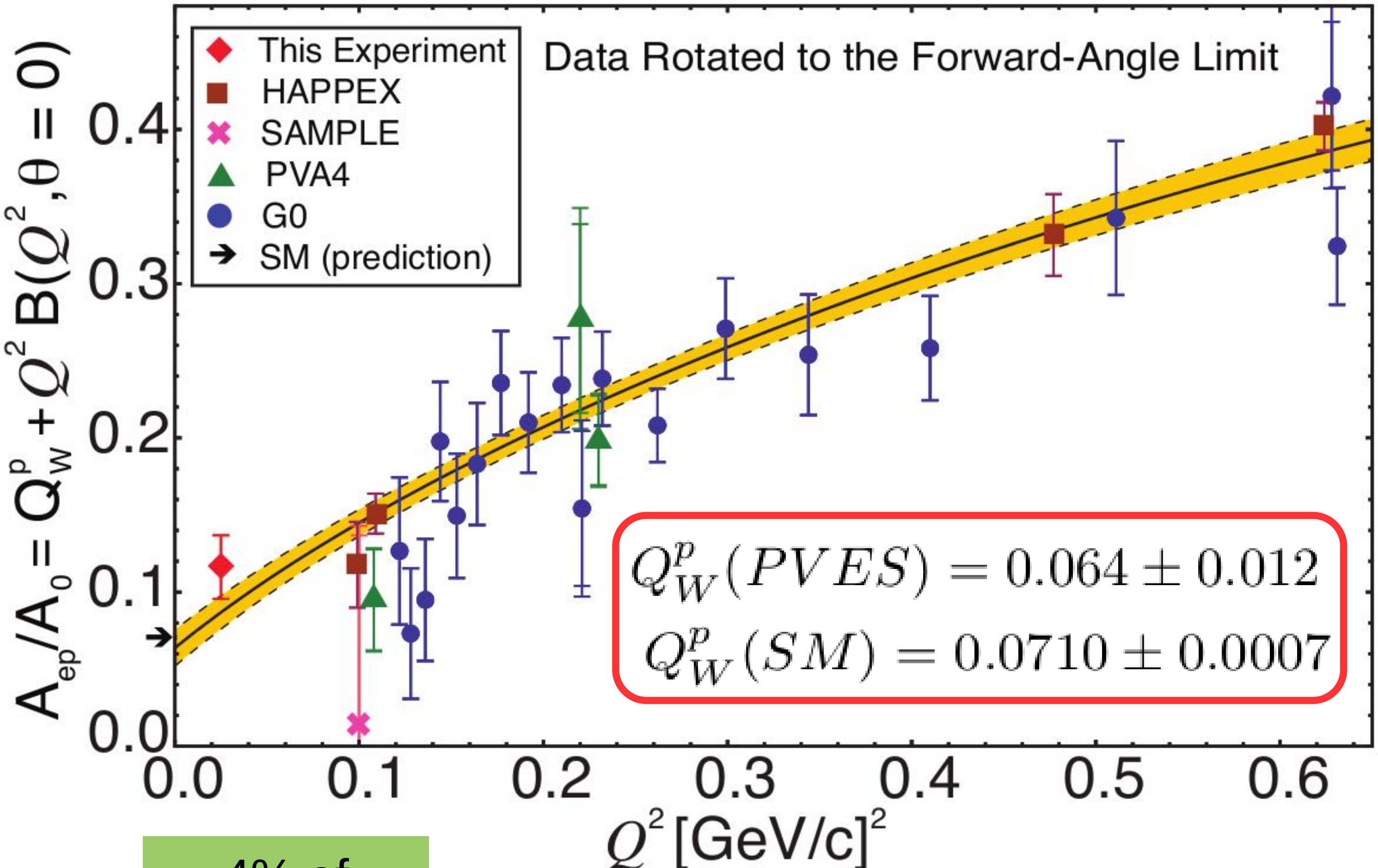
- Calculations are primarily dispersion theory type
  - error estimates can be firmed up with data!
- Qweak: inelastic asymmetry data taken at W ~ 2.3 GeV, Q^2 = 0.09 GeV^2





First Results: Weak Charge

$$A_{ep}/A_0 = Q_W^p + Q^2 B(Q^2, \theta = 0) \ , \qquad A_0 = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}$$



Global fit of world PVES data up to Q^2 = 0.63 GeV^2

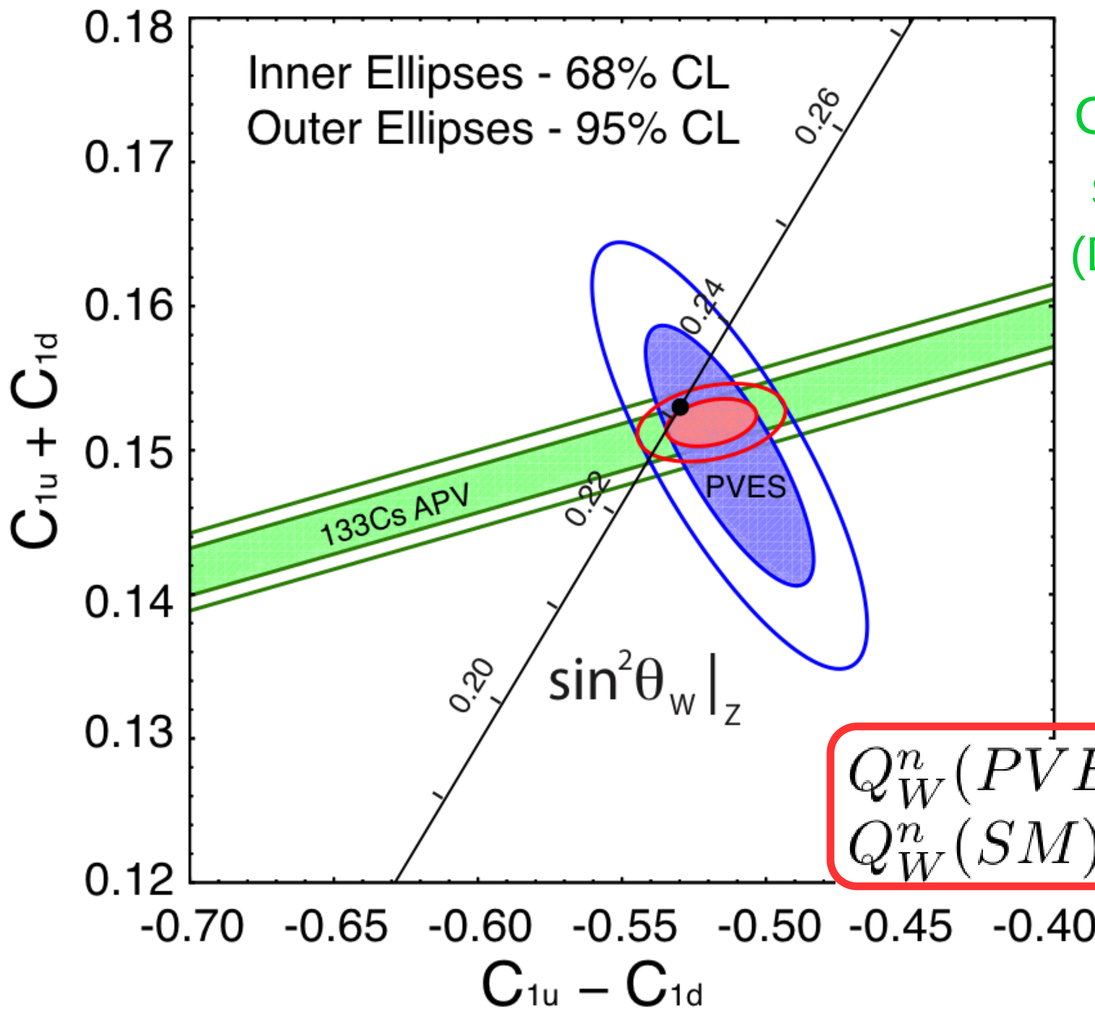
Data rotated to forward-angle for plotting

Remove energy- & Q^2 -dependence of gZ-box

4% of Qweak Data

PRL **111,**141803 (2013)

First Results: Quark Couplings



Black dot is SM value

Green band is Cesium APV – more sensitive to isoscalar combination (Dzuba et al., PRL 109, 203003 (2012))

Blue ellipse is combined PVES (now with Qweak)

Red is combined APV+PVES fit

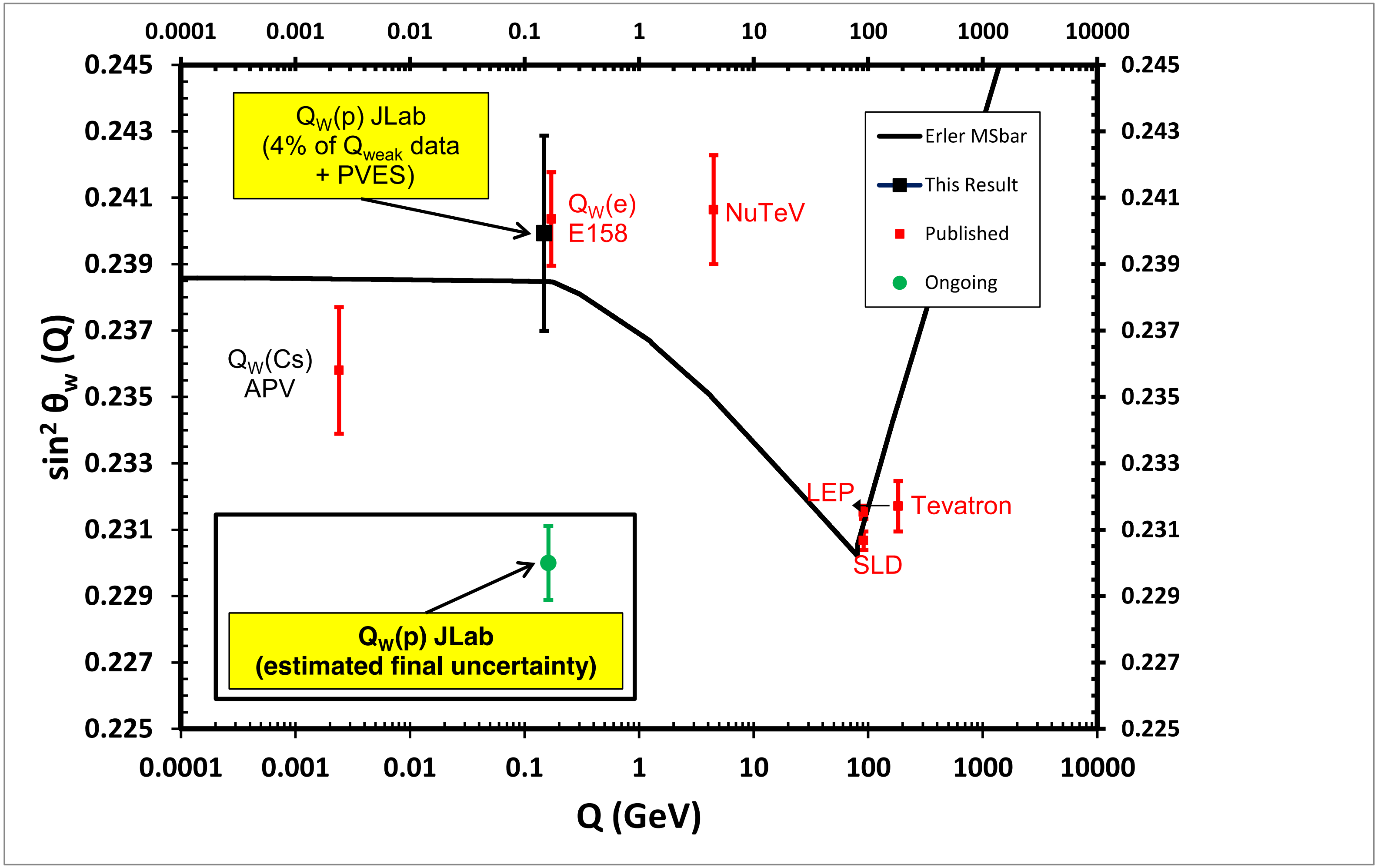
$$C_{1u} = -0.1835 \pm 0.0054$$
$$C_{1d} = 0.3355 \pm 0.0050$$

$$Q_W^n(PVES + APV) = -0.975 \pm 0.010$$
$$Q_W^n(SM) = -0.9890 \pm 0.0007$$

4% of Qweak Data

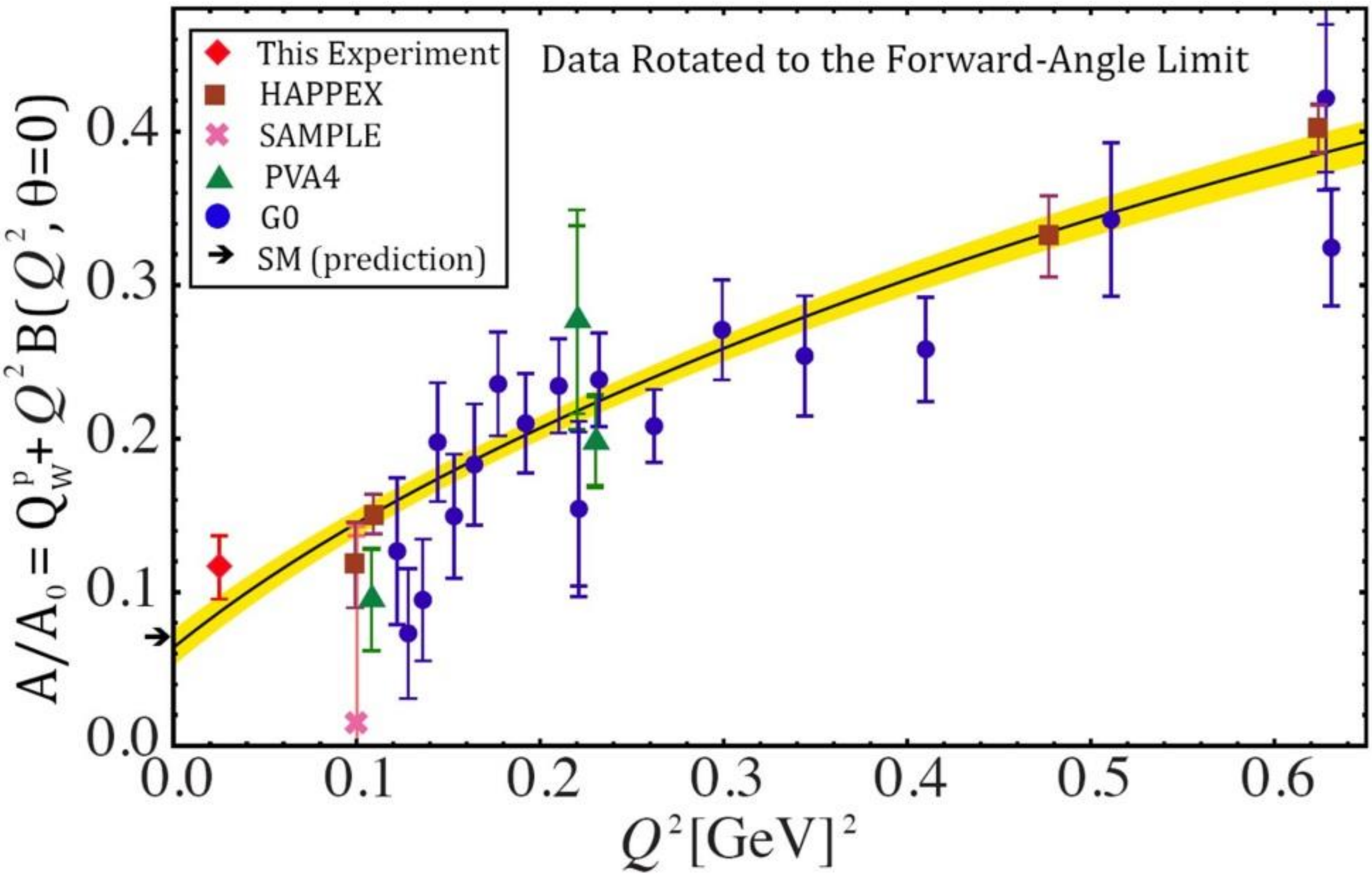
PRL **111,**141803 (2013)

Weak mixing angle



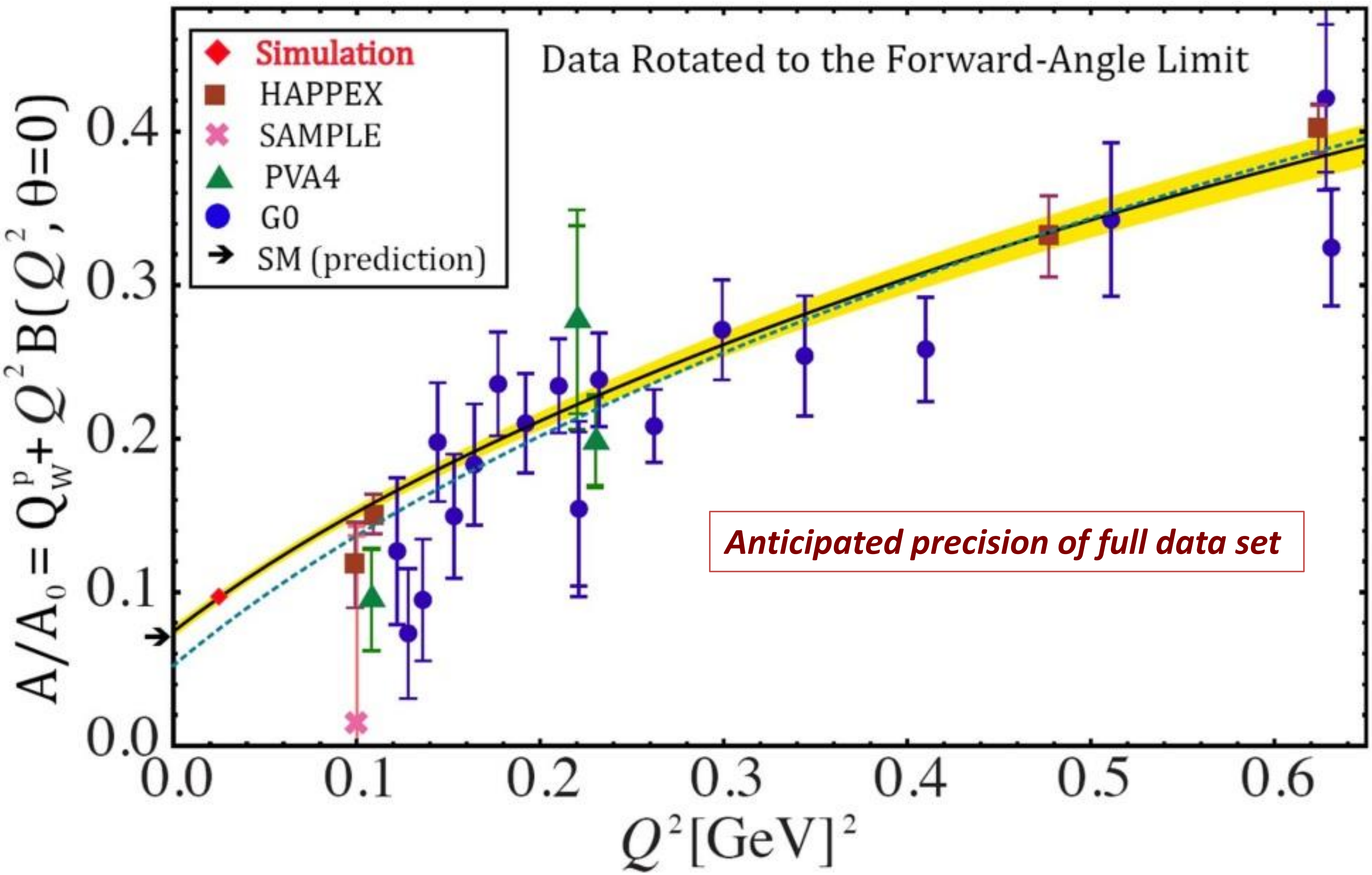
* Uses electroweak radiative corrections from Erler, Kurylov, Ramsey-Musolf, PRD 68, 016006 (2003)

“Teaser”



This Experiment
HAPPEX
SAMPLE
PVA4
G0
SM (prediction)
Data Rotated to the Forward-Angle Limit
$A/A_0 = Q_W^p + Q^2 B(Q^2, \theta=0)$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
$Q^2 [\mathrm{GeV}]^2$

“Teaser”


Simulation
HAPPEX
SAMPLE
PVA4
G0
SM (prediction)
Data Rotated to the Forward-Angle Limit
Anticipated precision of full data set
$A/A_0 = Q_W^p + Q^2 B(Q^2, \theta=0)$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Q^2 [GeV]^2

Auxiliary Measurements

Qweak has data (under analysis) on a variety of observables of potential interest for Hadron physics:

- Beam normal single-spin asymmetry for elastic scattering on proton
- Beam normal single-spin asymmetry for elastic scattering on ^{27}Al
- PV asymmetry in the N ➔ Δ region.
- Beam normal single-spin asymmetry in the N ➔ Δ region.
- Beam normal single-spin asymmetry near W= 2.5 GeV
- Beam normal single-spin asymmetry in pion photoproduction
- PV asymmetry in inelastic region near W=2.5 GeV (related to γZ box diagrams)
- PV asymmetry for elastic/quasielastic from ^{27}Al
- PV asymmetry in pion photoproduction

Summary

- Measured A_{ep} = -279 ± 35 (statistics) ± 31 (systematics) ppb
  - Smallest & most precise ep asymmetry measurement to date
- First determination of $Q_W(p)=-2(2C_{1u} + C_{1d})$
  - $Q_w(p)$= 0.063 ± 0.012 (from only 4% of all data collected)
    - (SM value = 0.0710(7))
    - New physics reach $\lambda/g = (2\sqrt{2}\, G_F\, \Delta Q_W)^{-1/2} > 1.5$ TeV
      - Based on 18% commissioning rslt, 95% CL, Erler, Kurylov, Musolf PRD68, 016006 (2003)
- First determination of $Q_W(n) = -2(C_{1u} + 2C_{1d})$:
  - By combining our result with APV: $Q_W(^{133}Cs) = -2(188C_{1u} + 211C_{1d})$
    - $Q_w(n)$= -0.975 ± 0.010 (SM value = -0.9890(7))
- Final results from full data set (~5 times smaller ΔA) in 2015
  - Expected PV new physics reach λ/g of ~ multi TeV level
  - Very precise measurement of Q^p_W

Thanks to Qweak collaborators, from whom I have borrowed many slides

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

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[1]Spokespersons [2]Project Manager Grad Students

Extra Slides

Global PVES Fit Details

- 5 free parameters (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 $\square_{\gamma Z}$ RC
  - Hall et al., PRD88, 013011 (2013) & Gorchtein et al., PRC84, 015502 (2011)
- Effects of varying Q^2, θ, & λ studied, found to be small