First Determination of the Proton's Weak Charge

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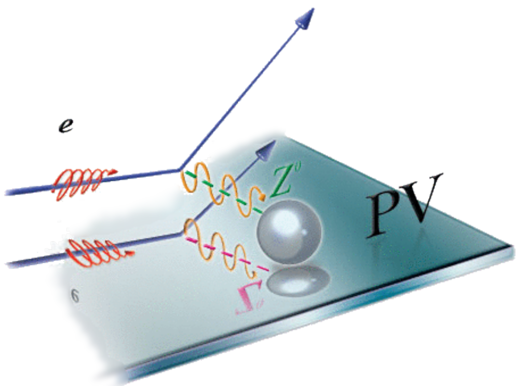
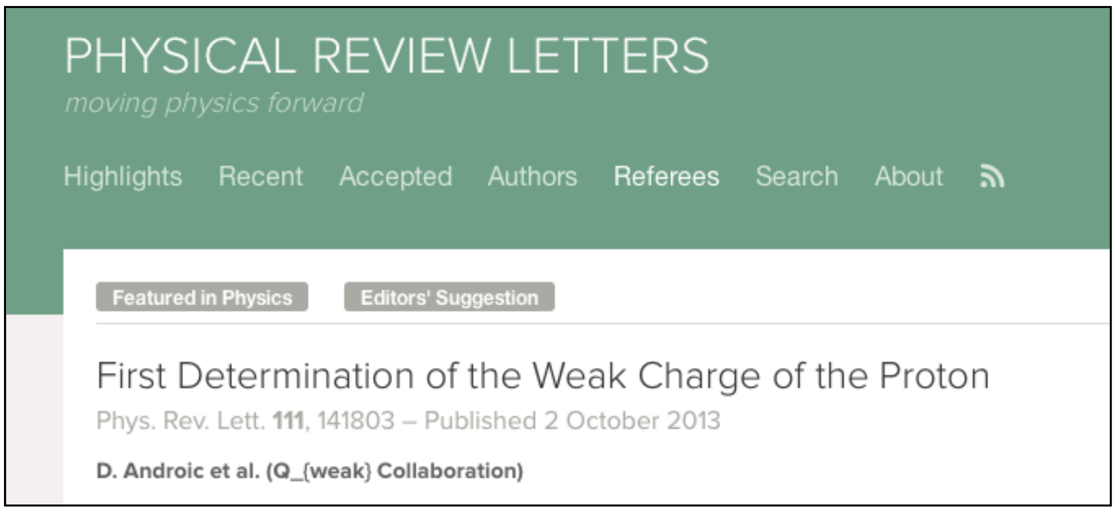
For the Qweak Collaboration



The Q_{weak} Experiment – First Results

- *proposal, 2001*
- *development and construction: 2002 – 2010*
- *data taking 2010 – 2012 (~ 1 calendar year)*

first 4% of data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First Determination of the Weak Charge of the Proton
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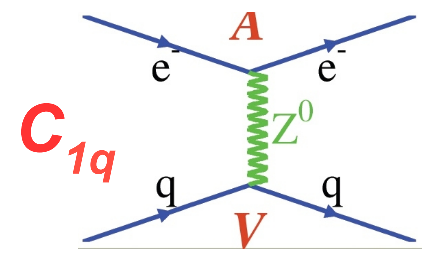
D. Androic et al. (Q_{weak} Collaboration)

PRL 111, 141803 (2013)

What is proton's weak (vector) charge ?

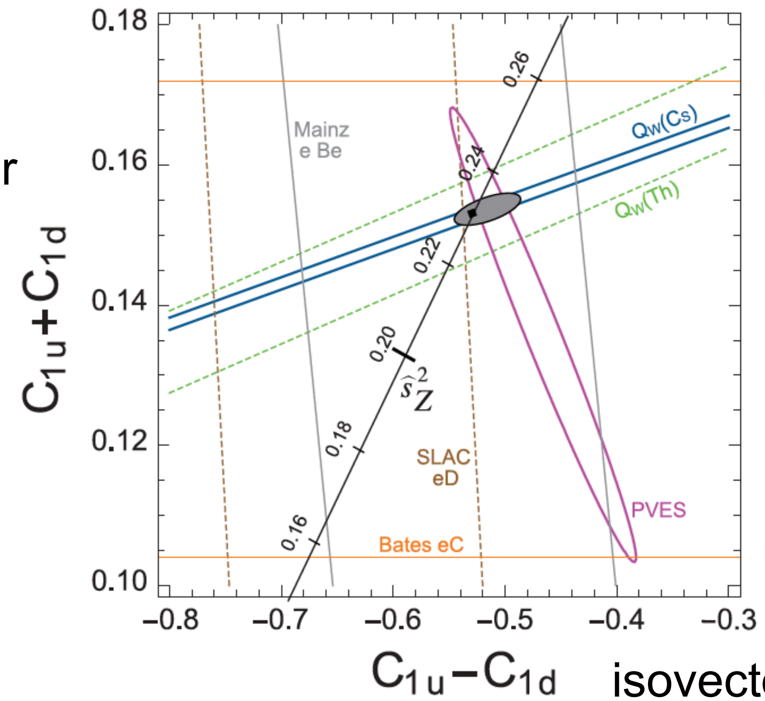
- analog to the electric charge
- vector coupling to the Z boson summed over quark constituents



Charge (e) / Particle	Electric	Weak (vector)
u	+2/3	$-2C_{1u} = +1 - 8/3\sin^2\theta_W$
d	-1/3	$-2C_{1d} = -1 + 4/3\sin^2\theta_W$
Proton uud	+1	$Q_w^p = -2(2C_{1u}+C_{1d}) = 1 - 4\sin^2\theta_W$
Neutron udd	0	$Q_w^n = -1$

What do we know about the weak charges?

isoscalar



isovector

Figure 10.2: Constraints on the effective couplings, C_{1u} and C_{1d}, from recent (PVES) and older polarized parity violating electron scattering, and from atomic parity violation (APV) at 1 σ, as well as the 90% C.L. global best fit (shaded) and the SM prediction as a function of the weak mixing angle $\widehat{s}^2_Z$. (The SM best fit value $\widehat{s}^2_Z = 0.23116$ is also indicated.)

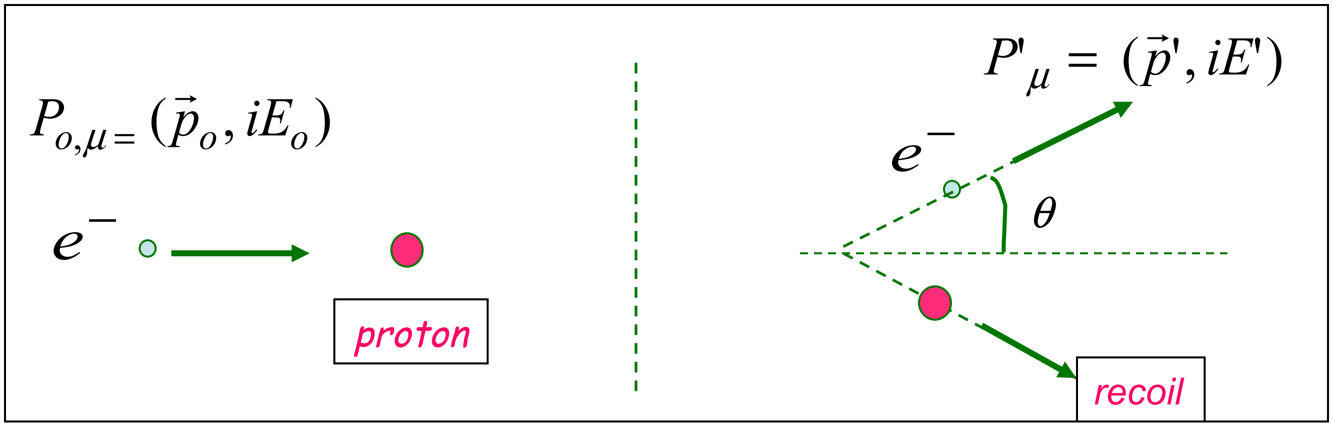
Particle data group, 2013

Tree level:

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

Standard model value:
$Q^P_W = 0.0710 \pm 0.007$

electron- proton scattering: 4-momentum transfer Q^2



$$Q^2 = 2 p_o p'(1-\cos\theta)$$; sets a scale for the interaction

(Q is the energy scale in the "running of $\sin^2\theta_W$" plot; we do our measurements at small Q^2)

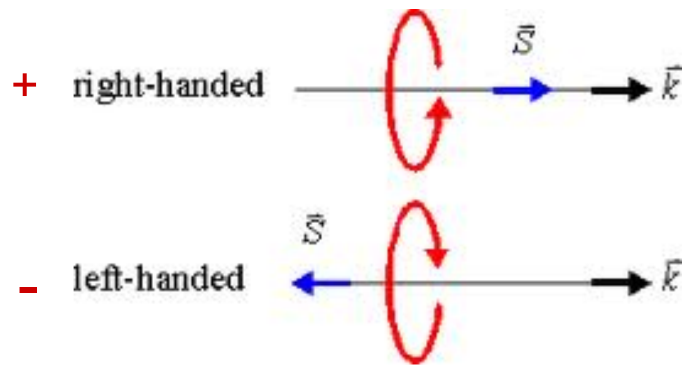
Scattering measurements as $Q^2 \rightarrow 0$ see the target as <u>pointlike</u>; higher Q^2 probes its spatial distribution *('form factors' …)*

Parity violating (PV) asymmetry and Q_{weak}

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

" form factor" correction.

PV asymmetry
A ~ -3 x 10^{-7} for
+, - beam helicities:



We can't "do" $Q^2 = 0$ or there is no signal! → At $Q^2 = 0.03\ GeV^2$

$\delta A/A = 2\%$ → $\delta Q_w^p / Q_w^p = 4\%$ $\boxed{\rightarrow \delta \sin^2\theta_W / \sin^2\theta_W = 0.3\%}$

CEBAF Accelerator at JLab

- superconducting RF accelerators
- continuous e- beam (499 MHz)
- ~~3~~ 4 experimental halls
- 12 GeV upgrade ~~underway~~ essentially complete

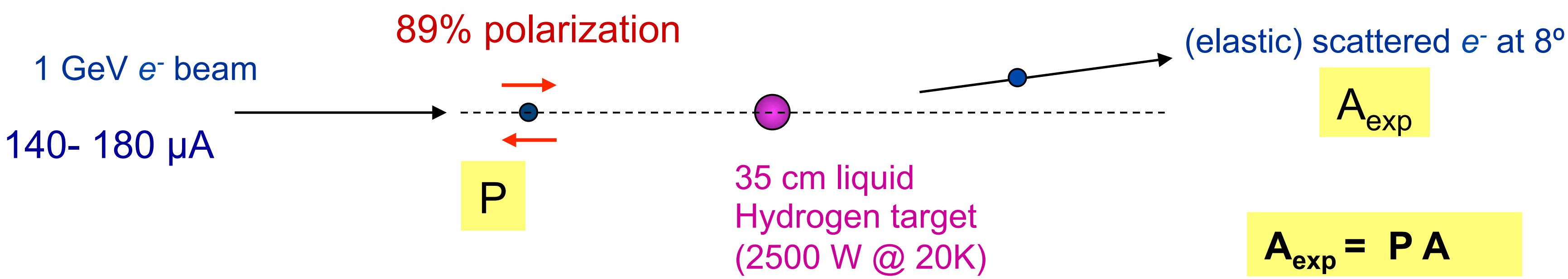
Coordinates: 37°05′41″N 76°28′54″W

Thomas Jefferson National Accelerator Facility

Jefferson Lab

Motto	"Exploring the nature of matter."
Established	1984
Research Type	Nuclear physics
Budget	US$72 million (2004)
Director	Hugh E. Montgomery
Staff	675
Location	Newport News, Virginia
Campus	214 acres (87 ha)
Operating Agency	Jefferson Science Associates, LLC
Website	www.jlab.org

The Q_{weak} Experiment -- practicalities



Key requirements:

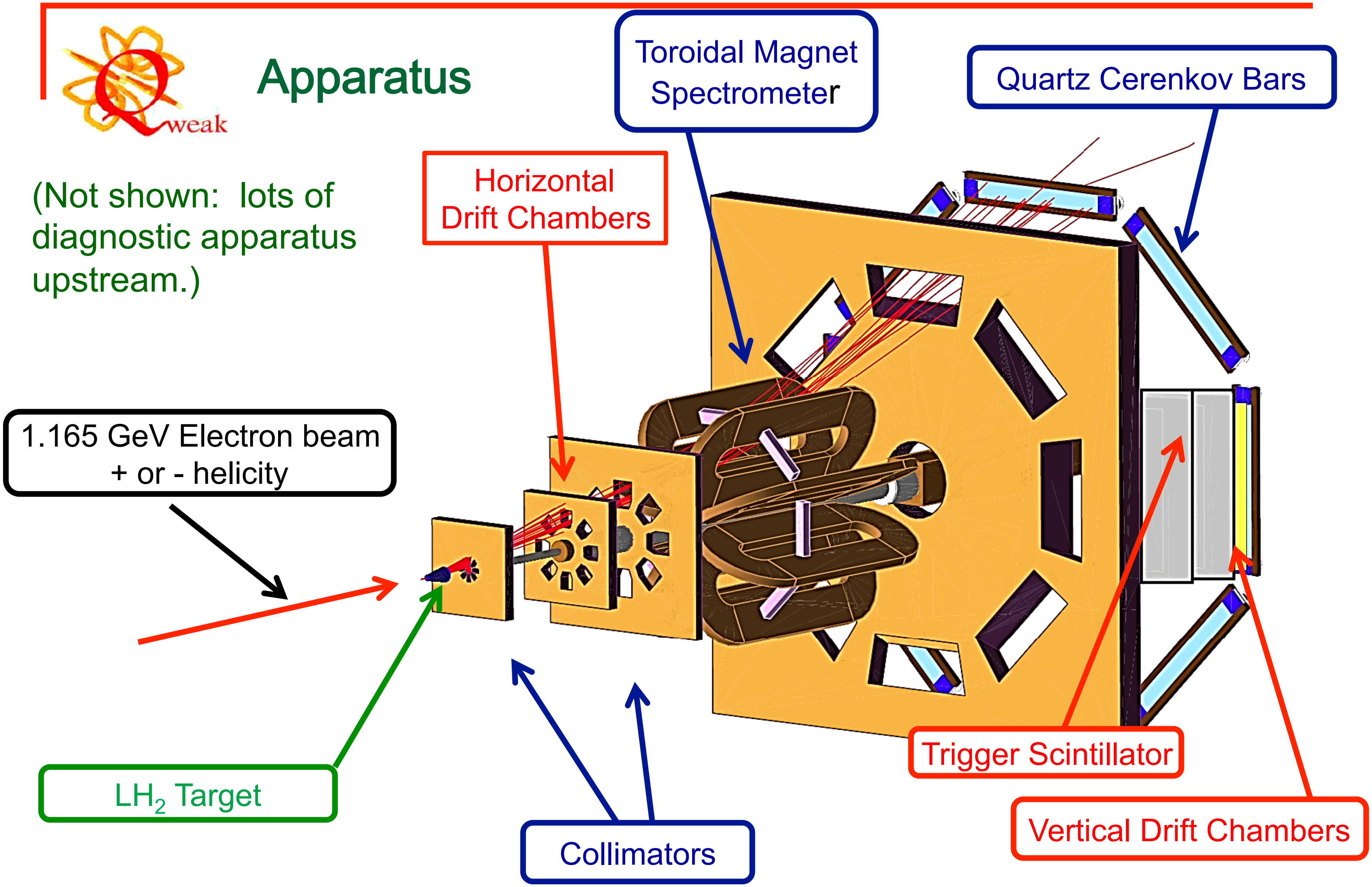
- minimize the statistical error
  → high beam current, high power target, integrating mode electronics, large acceptance detectors….

- maximize the signal
  → high beam polarization, background-insensitive detectors, tight collimation and shielding ….

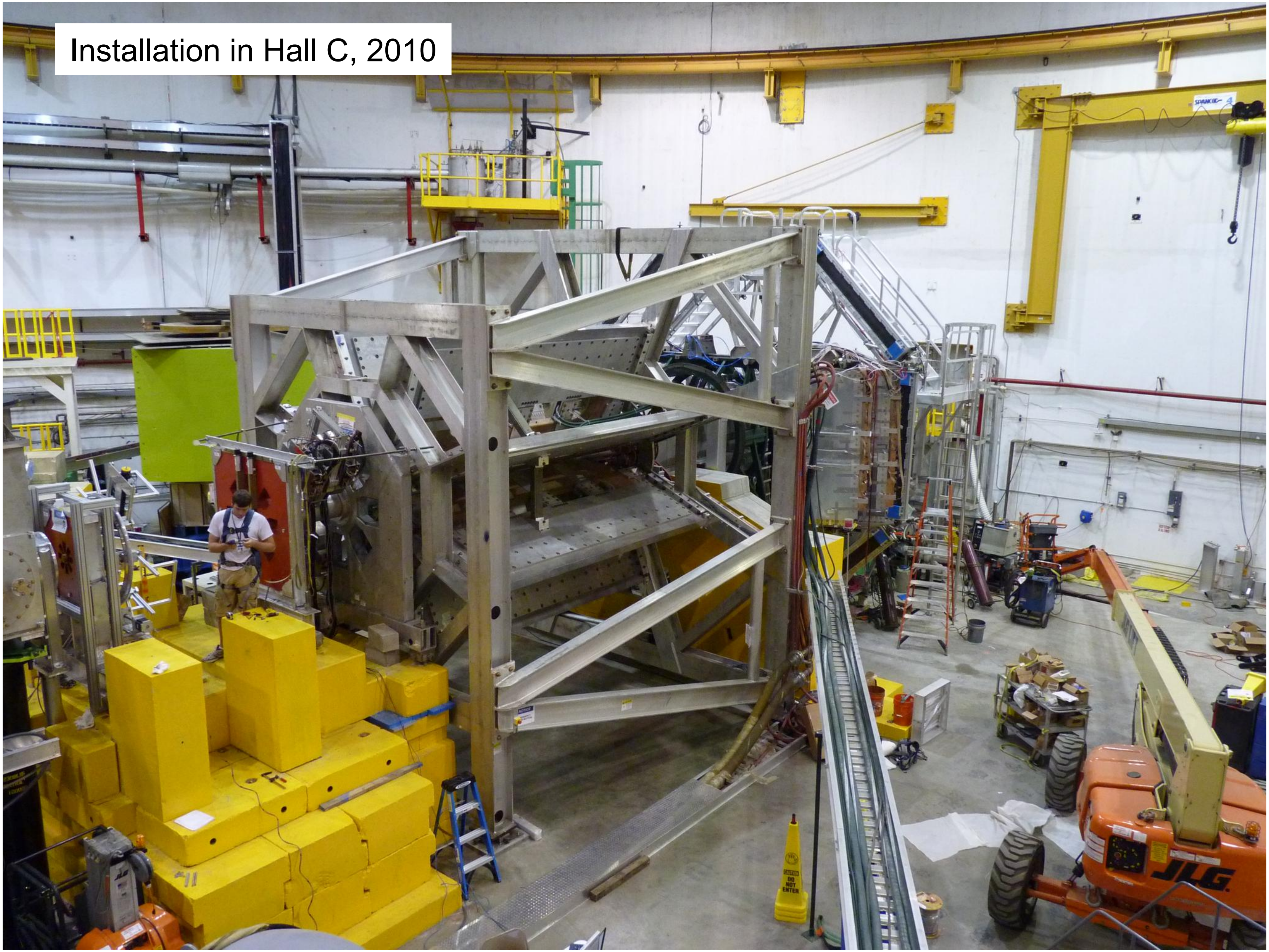
- minimize systematic errors
  → beam properties should not change when the spin flips, polarization should be well-measured…

Apparatus

(Not shown: lots of diagnostic apparatus upstream.)



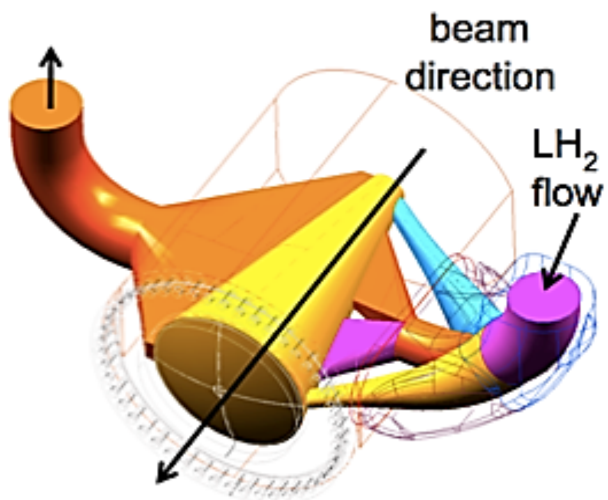
Red = low-current tracking mode only

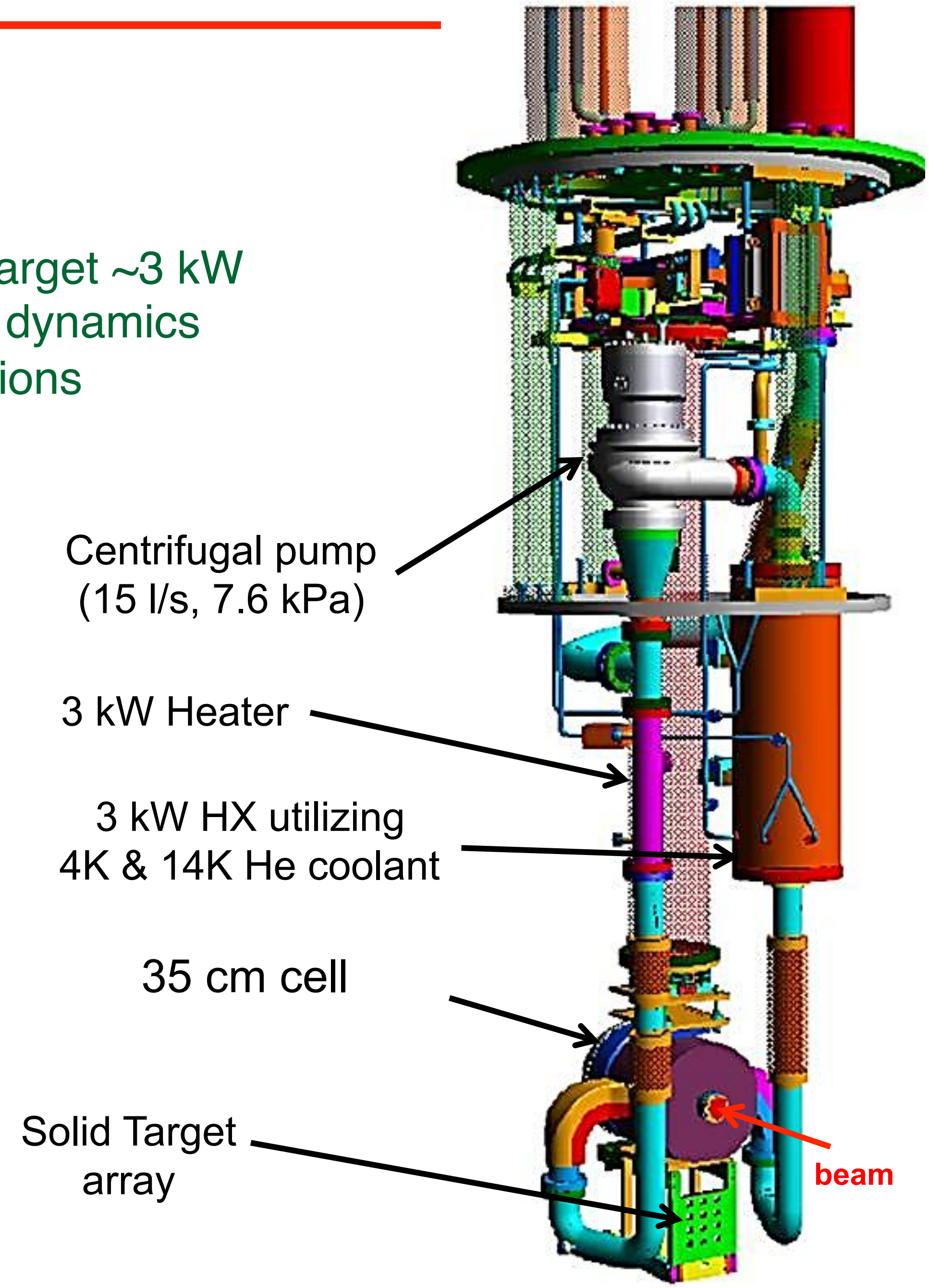


Installation in Hall C, 2010

LH2 Target

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



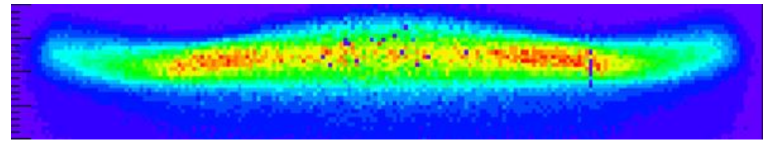


Bottom line: fluctuations in target density did not significantly impact the measurement statistics

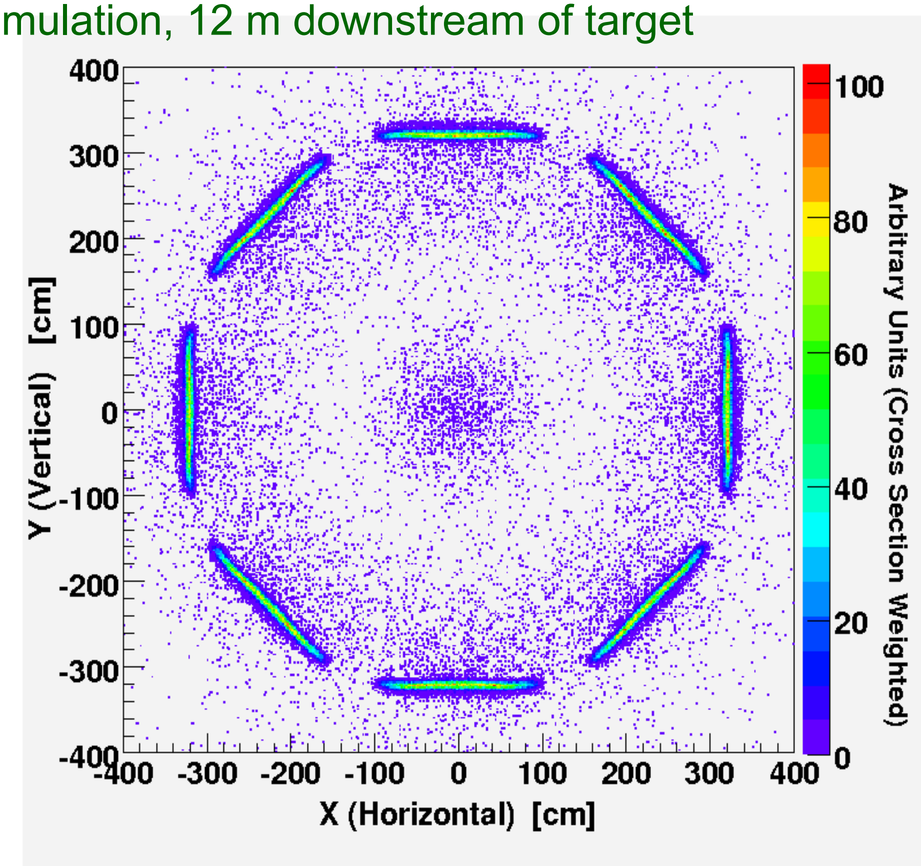
Main Detector – elastic electron image on quartz bars

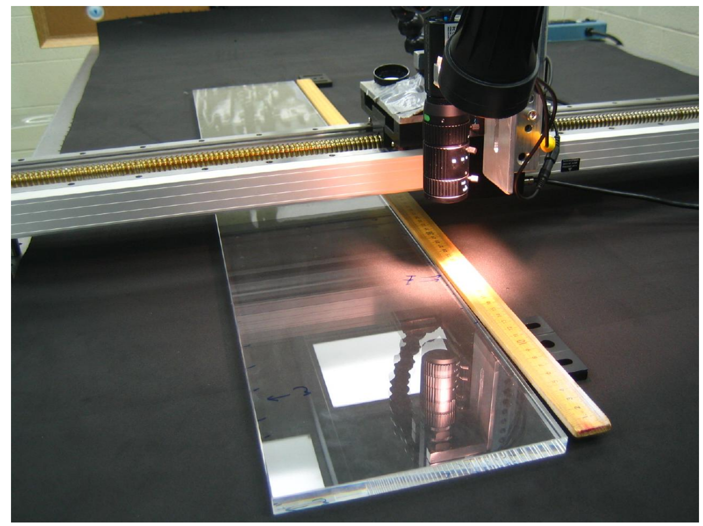
- Toroidal Spectrometer produces 8 elastic e- foci

Measured elastic image (bottom bar) :



Simulation, 12 m downstream of target

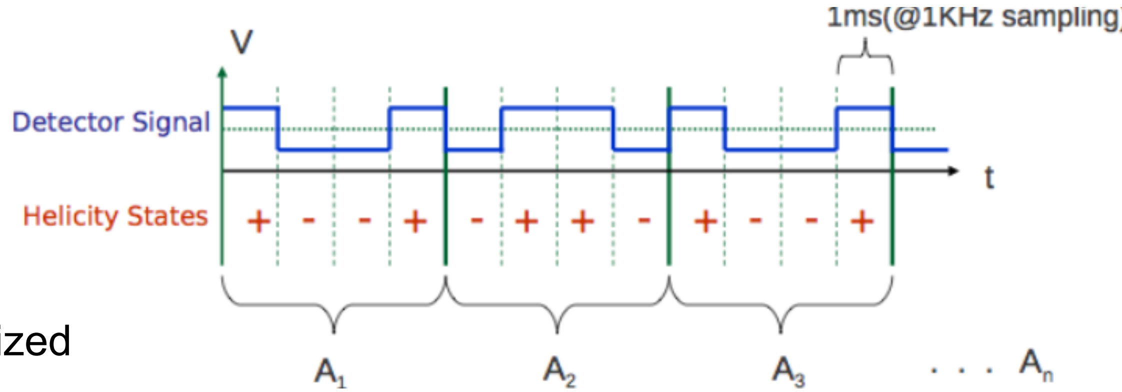


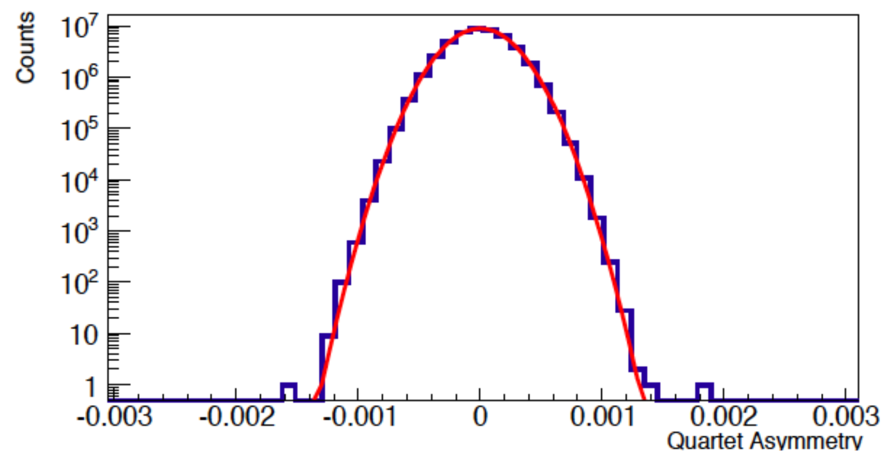


- 900 MHz e^- per bar
- Current mode readout (I_a = 6 μA)

Helicity reversal pattern and signal integration

- 960 Hz helicity flip (fast!)
- PMT anode current integrated for each helicity window, normalized to beam charge
- Quartet asymmetries calculated (4 ms)
- Statistical width ~ 230 ppm per quartet at 180 μA is dominated by counting statistics; target noise contributes ~ 50 ppm
- Unknown additive “blinding factor” applied for analysis

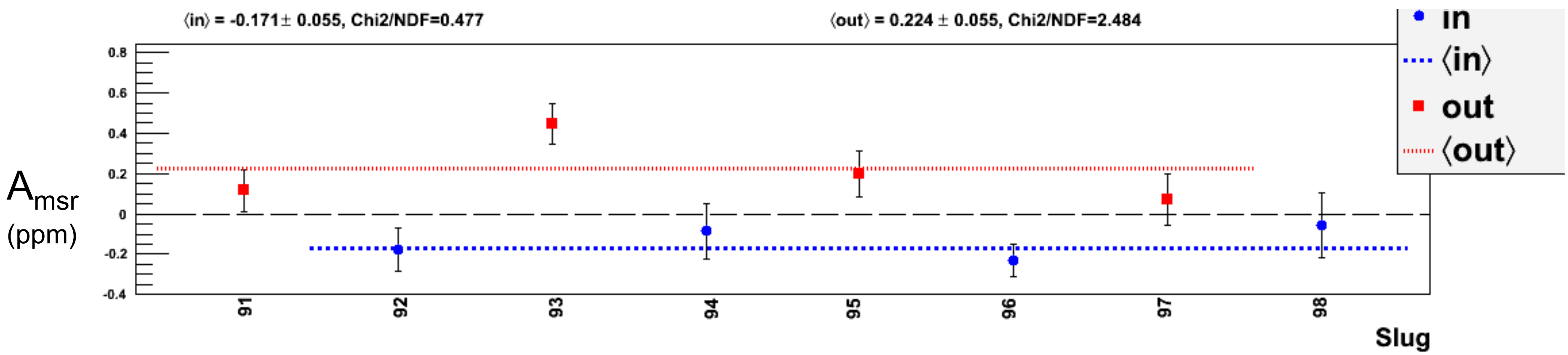




(over several days, run 2)

Extracting the physics asymmetry, A_{ep}

- Data averaged over 8 hr “Slugs” with slow helicity reversal
- Central value “blinded” by additive constant
- E.g. Slug plot for RUN 0 :



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

False asymmetry corrections

$$A_{ep} = \boxed{R_{tot} \frac{A_{msr}/P - \sum_{i=1}^{4} f_i A_i}{1 - f_{tot}}}$$

Polarization, backgrounds, radiative corrections

Corrections and uncertainties: first result

UNITS: parts per billion (ppb)

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

$$\begin{aligned} A_{msr} &= -204 \quad \pm 31\,(stat) \quad \pm 13\,(sys) \\ A_T &= \quad 0 \;\pm\; 4 \\ A_L &= \quad 0 \;\pm\; 3 \\ A_{reg} &= -35 \;\pm\; 11 \end{aligned}$$

17 % ~ 1σ correction to A_{raw}

f_i : *fraction of light from background i*

$f_{tot} = \Sigma f_i = 3.6\%$

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

R: product of factors ~ unity:

(Rad. corr, kinematics, detector response)

$$A_{ep} = -279 \quad \pm\; 35\,(stat) \quad \pm\; 31\,(sys)$$

$$R_{TOT} \,/\, (P\,(1 - f_{tot})) \quad = \quad 1.139$$

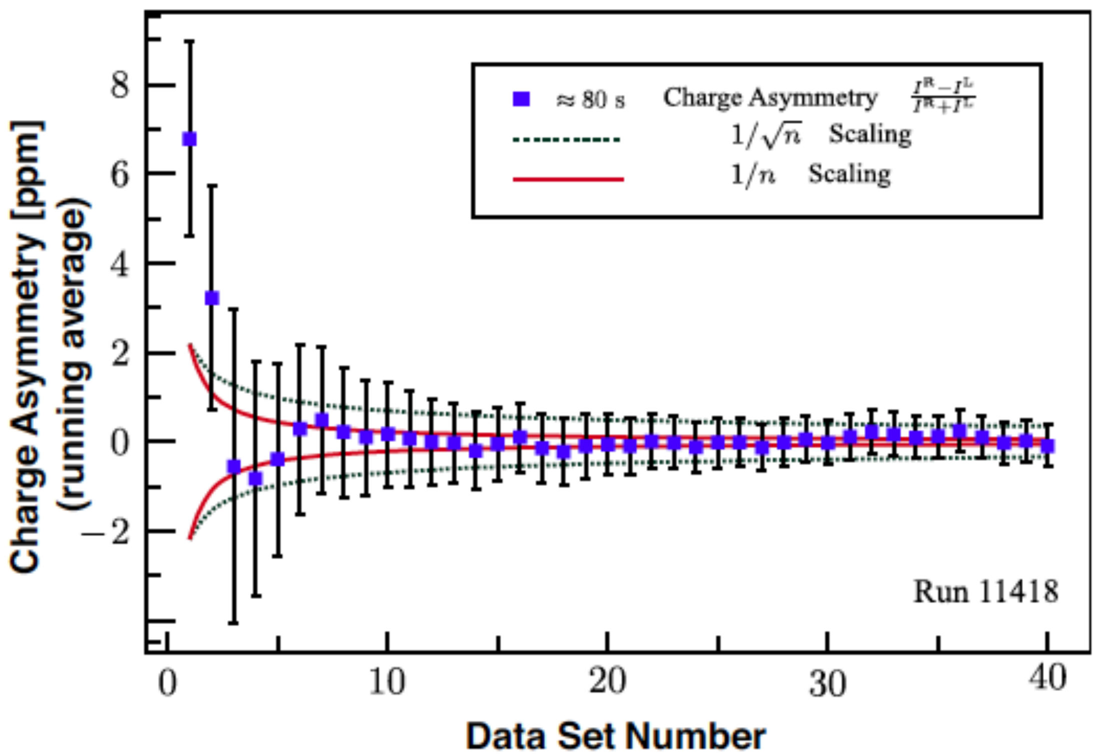
$$P\, f_i\, A_i = \quad -51 \quad + \quad 11 \quad + \quad 0 \quad + \quad 1 \quad = \quad -39$$

14 % ~ 1σ correction

(Al windows + beamline bgd. + soft neutrals + inelastic)

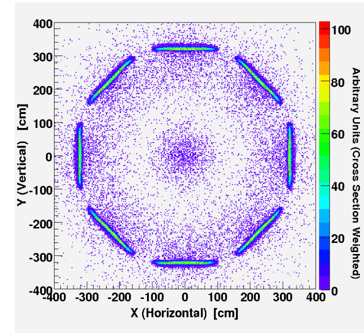
Additive correction, linearity: $A_L = 0 \pm 3$ ppb

- Scales with beam charge asymmetry
- Suppressed by feedback loop to polarized source

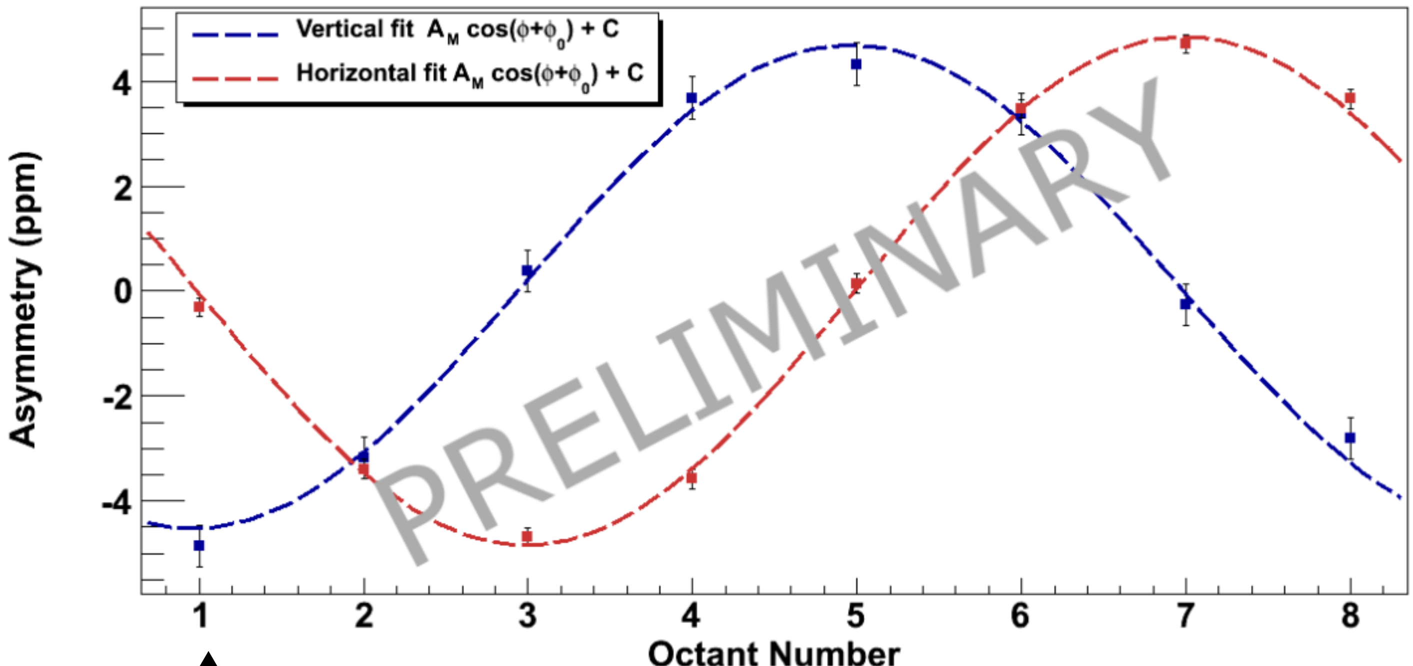


(~ 1 hr run)

Transverse Asymmetry, $A_T = 0 \pm 4$ ppb



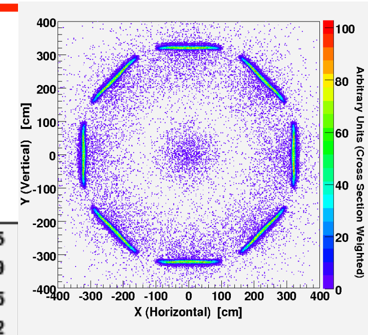
- Dedicated measurements with FULLY transverse polarization
- Physics origin: nucleon structure and 2-photon exchange
- Highly suppressed by azimuthal symmetry

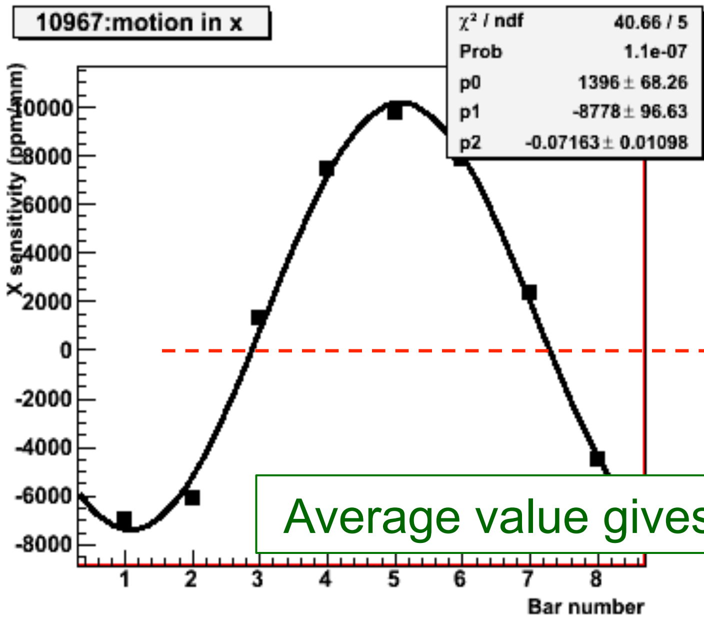


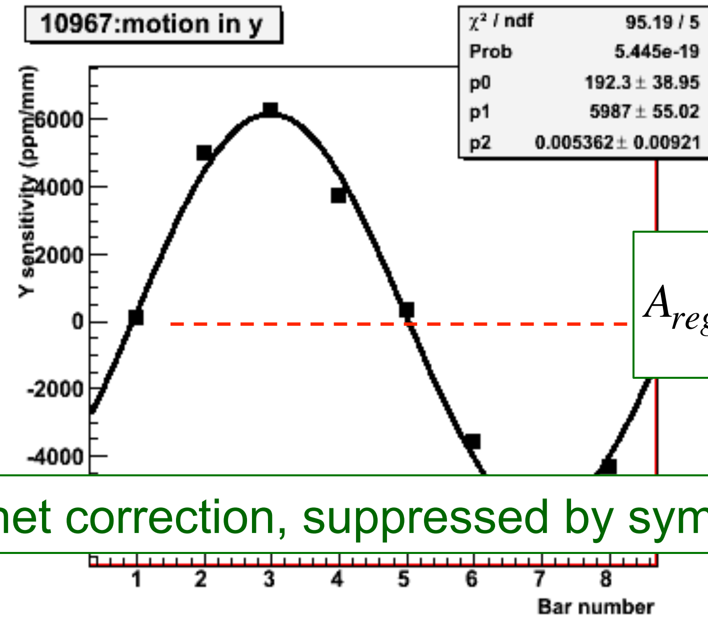
Beam left: Φ = 0

(90° phase shift between vertical and horizontal)

Beam parameter corrections, A_{reg} = -35 ± 11 ppb

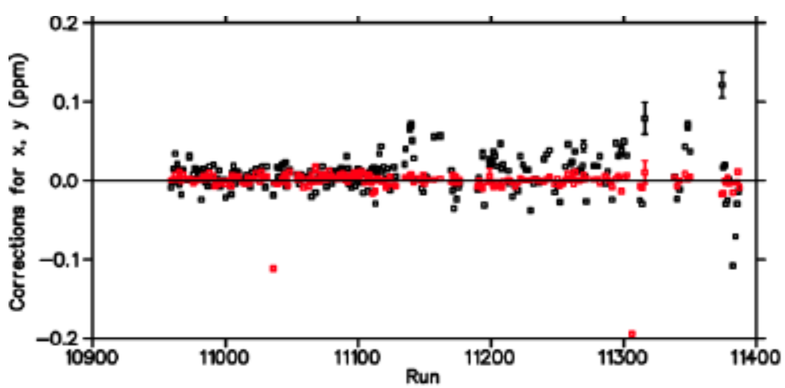


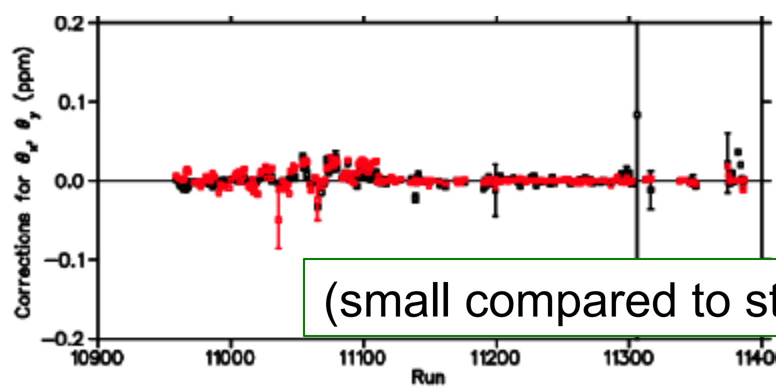




$$A_{reg} = -\sum_{i=1}^{5} \frac{\partial A}{\partial \chi_i} \Delta \chi_i$$

Average value gives net correction, suppressed by symmetry





(small compared to statistics)

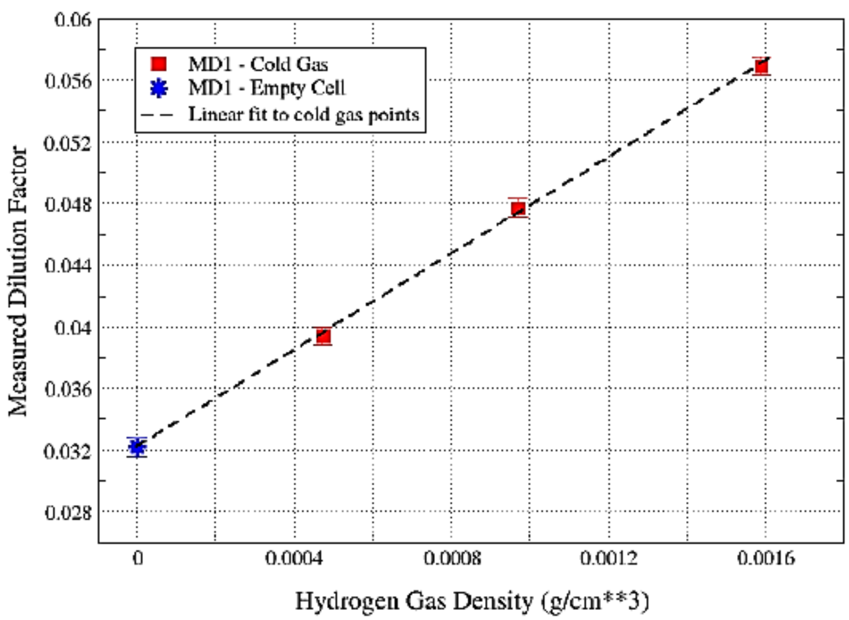
Background: Aluminum windows (dominant)

$$f_{\mathrm{Al}} = 3.23 \pm 0.24\ \% \qquad A_{\mathrm{Al}} = 1.76 \pm 0.26\ \mathrm{ppm}$$

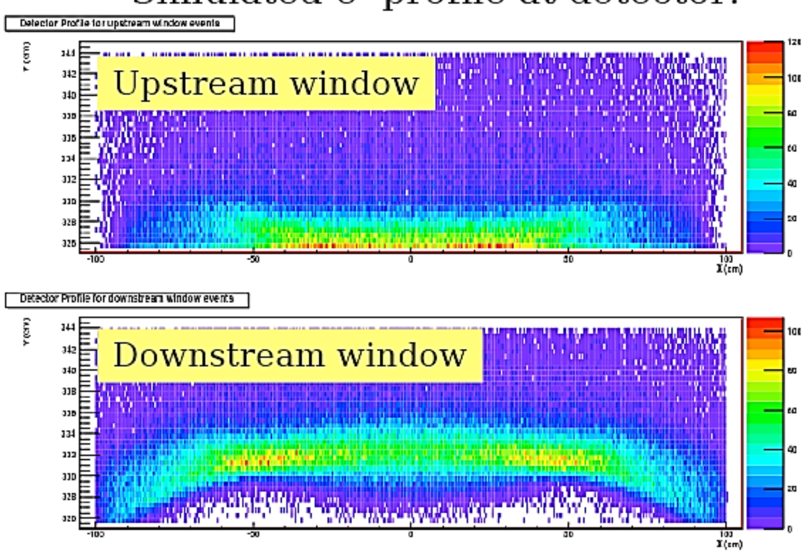
- Dilution from windows measured with empty target
- Corrected for effect of H_2 using simulation and data driven models of elastic and quasi-elastic scattering.

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

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

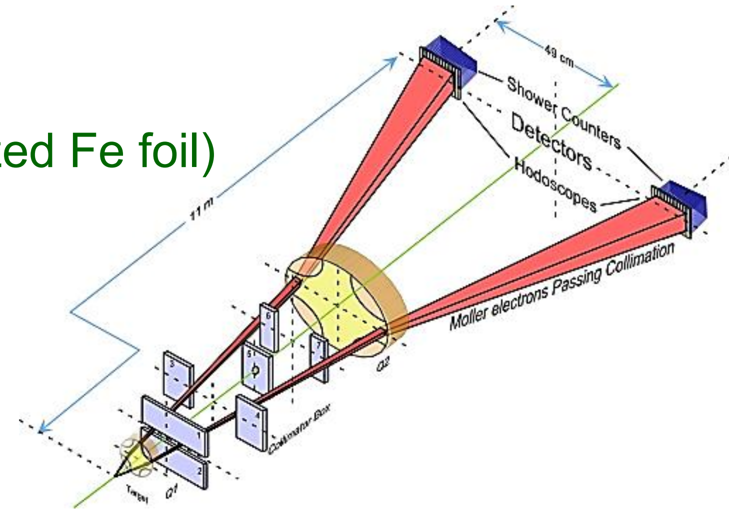


Simulated e- profile at detector:

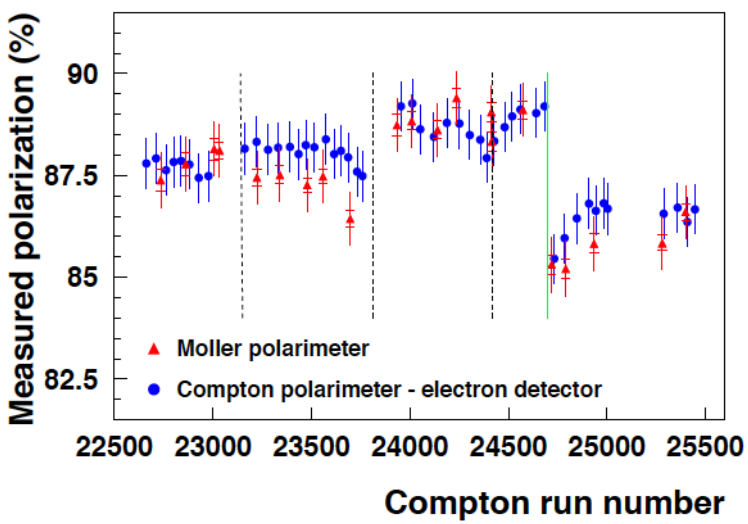


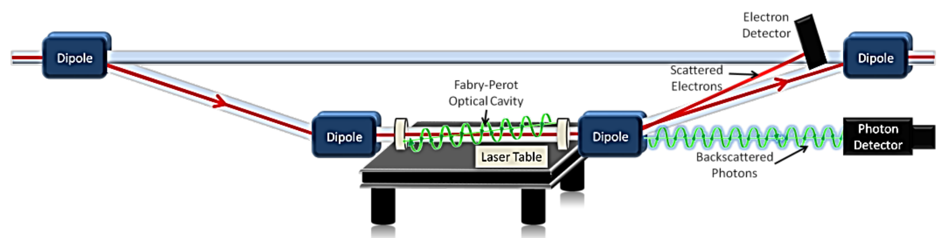
P: two polarimeters for ultimate precision

- First results only used Hall C Møller polarimeter
  (low beam current; *e-e* scattering from polarized Fe foil)

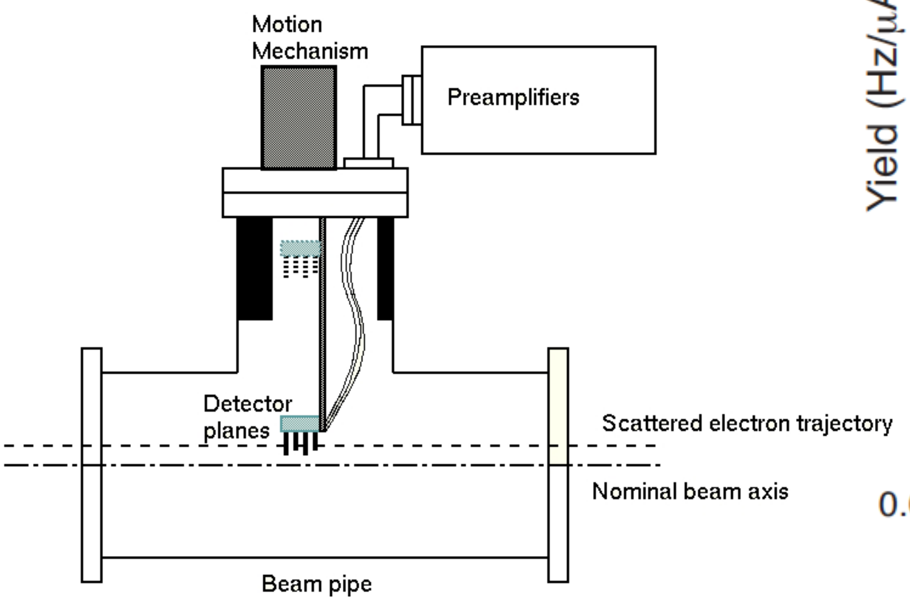


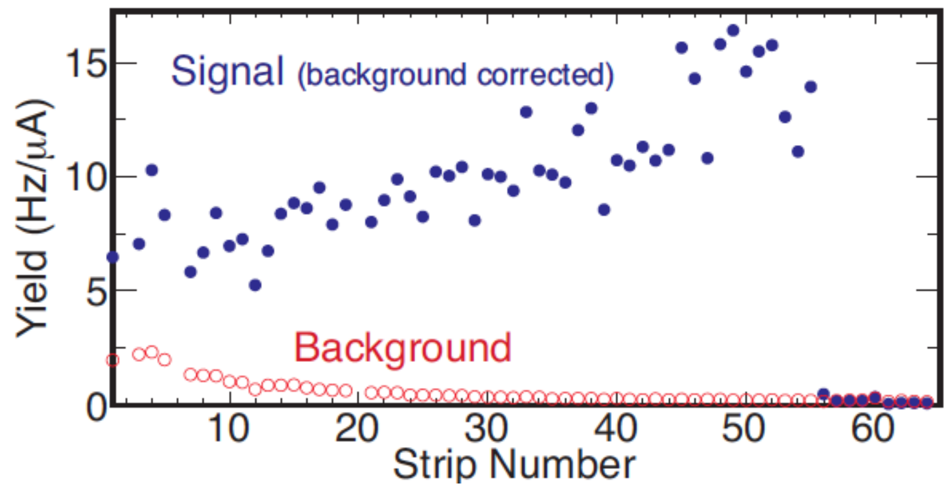
- **Run 2** used both Møller and Compton polarimetry – cross checked for absolute normalization

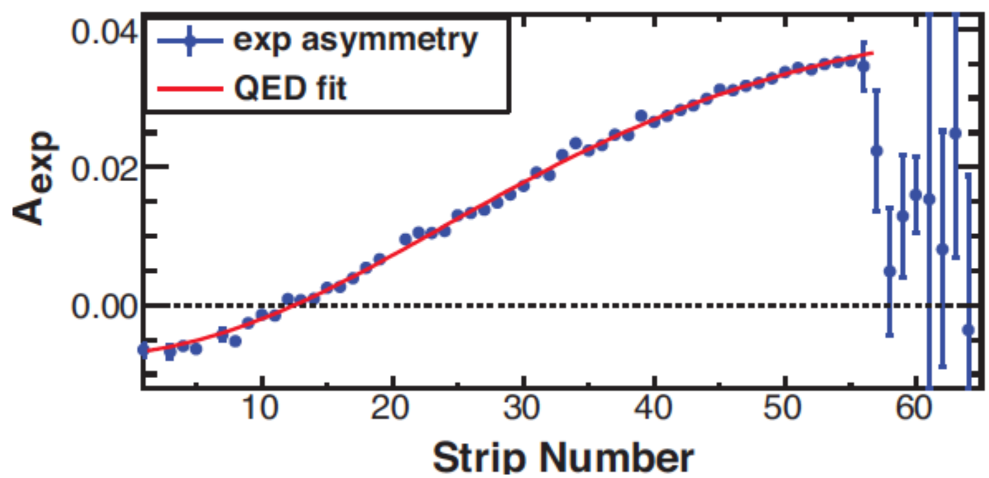




Compton polarimeter diamond microstrip detectors



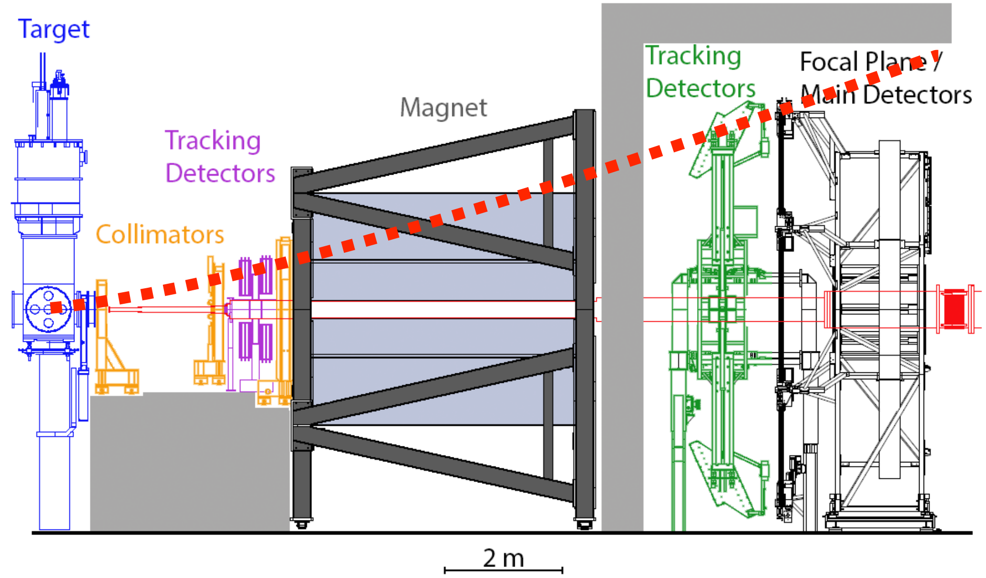


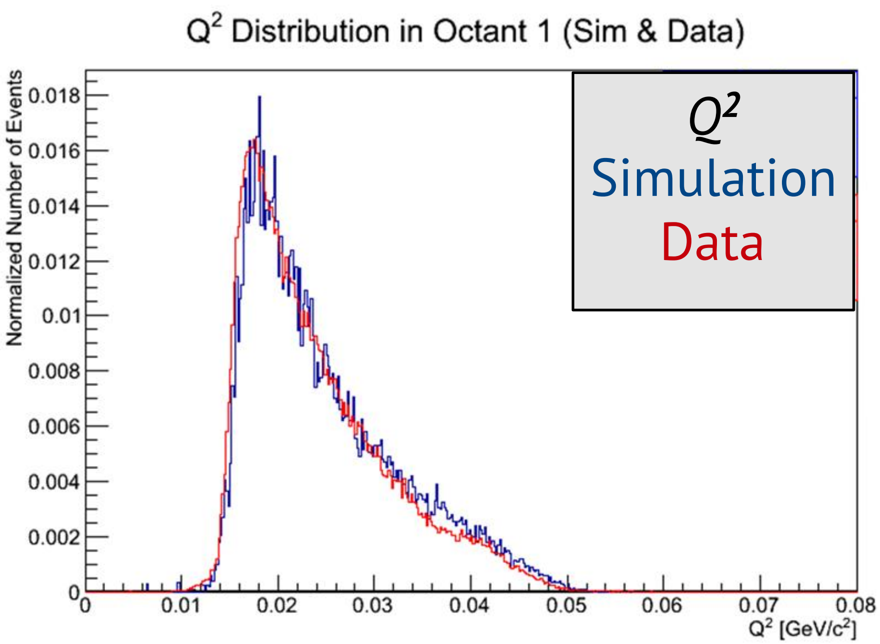


QED asymmetry exactly known;
"self calibrating" feature

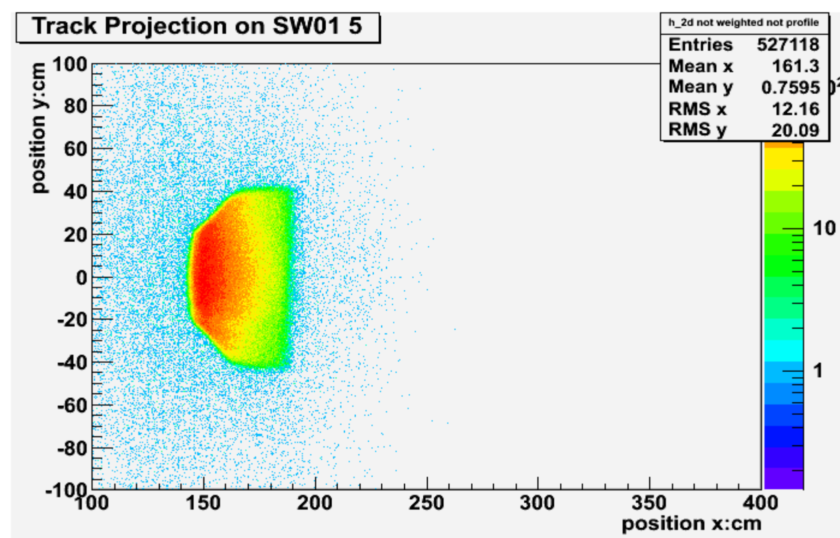
Momentum transfer: Q^2

- Drift chambers before and after magnetic field
- Low current, counting mode data taking
- Systematics studies: acceptance, light yield vs Q^2





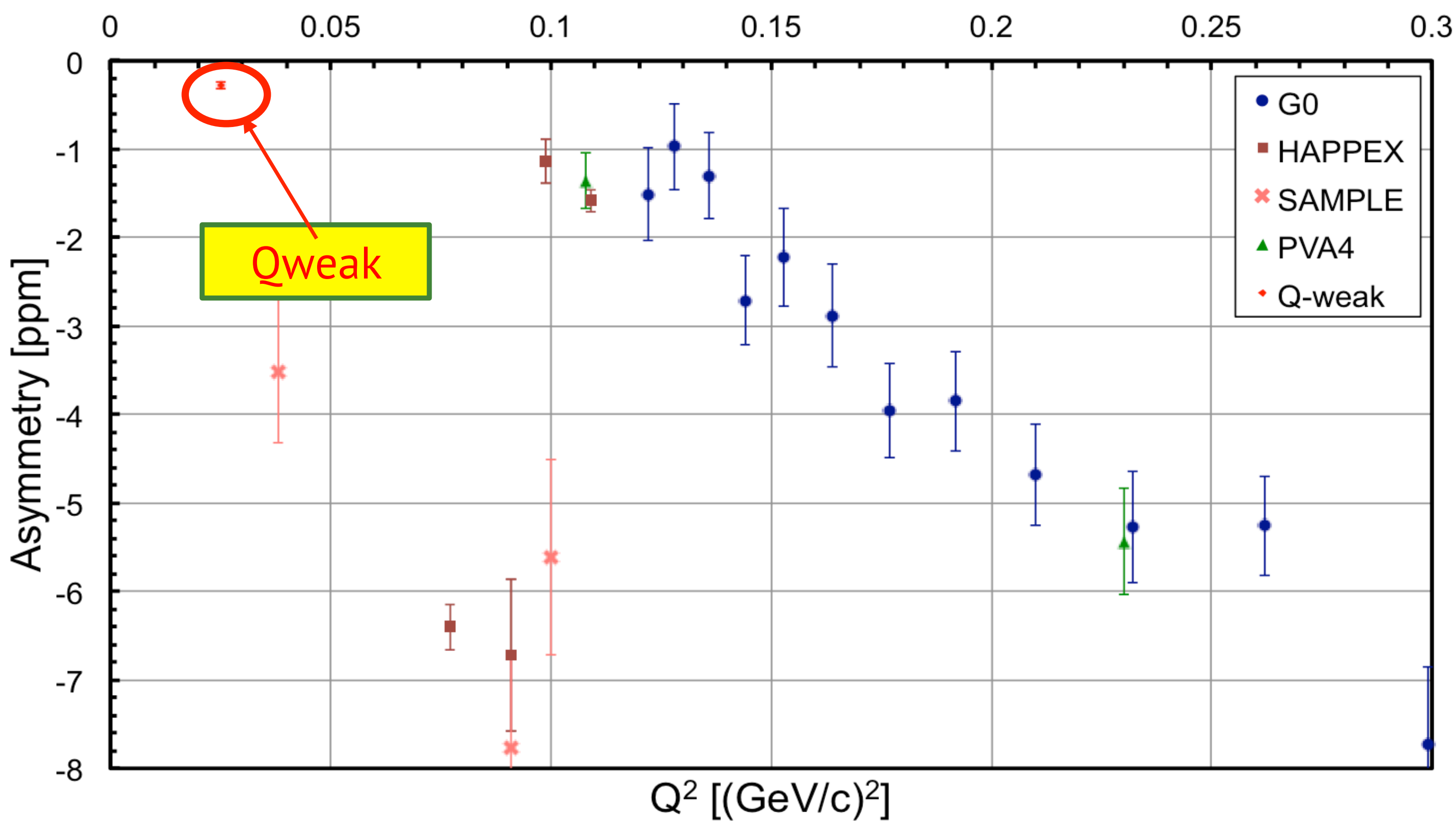
Radial



Run 0 Asymmetry Results (4% of full data)

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

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



Determining the weak charge - details

$$A_{ep} = \boxed{\left[A_o\right]} \frac{\epsilon G_E^{\gamma} G_E^{Z} + \tau G_M^{\gamma} G_M^{Z} - (1-4\sin^2\theta_W)\epsilon' G_M^{\gamma} G_A^{Z}}{\varepsilon (G_E^{\gamma})^2 + \tau (G_M^{\gamma})^2}$$

- 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

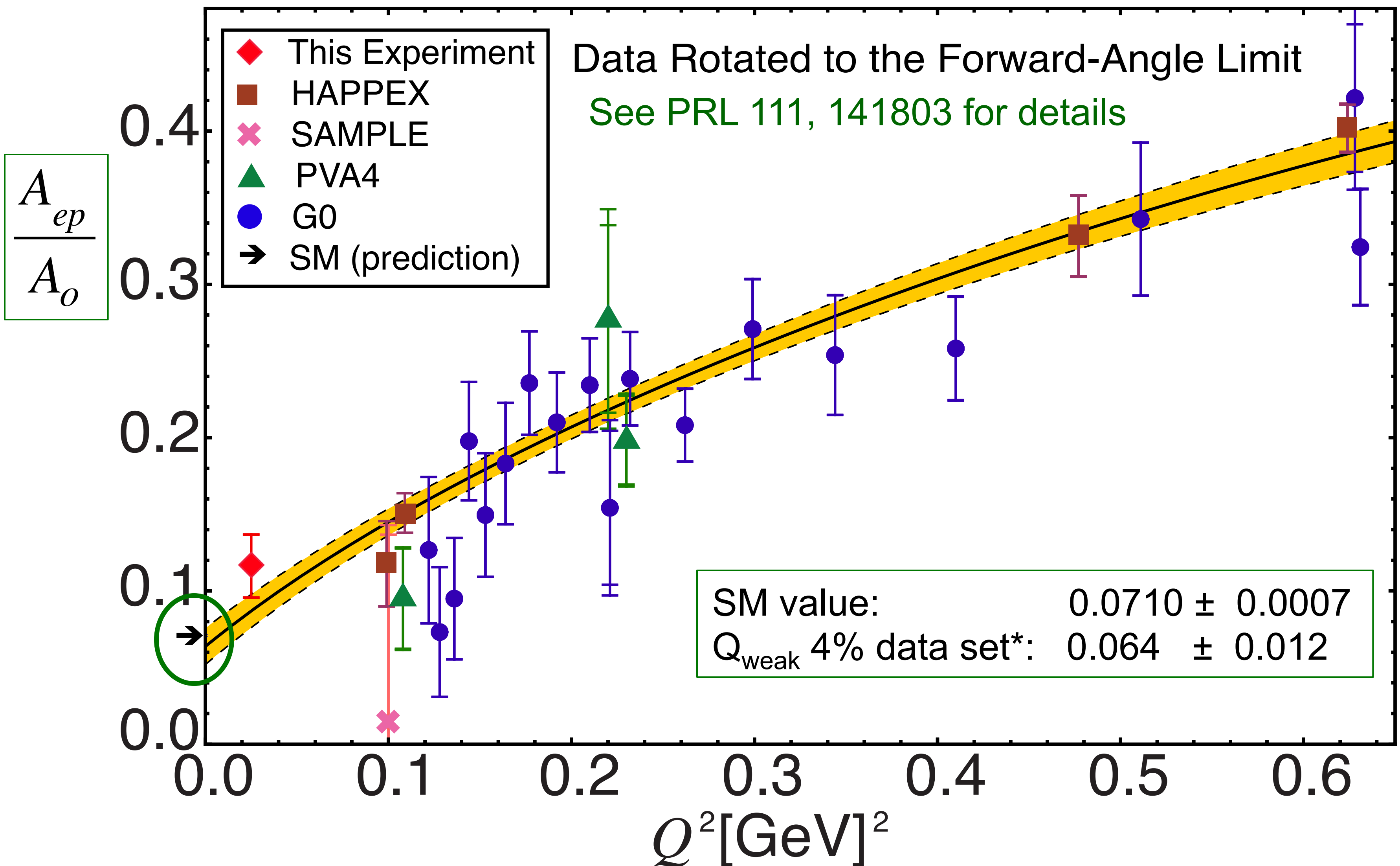
Reformulate at low Q^2

$$\boxed{\frac{A_{ep}}{A_o} = Q_W^P + Q^2\, B(Q^2, \theta)}$$

intercept

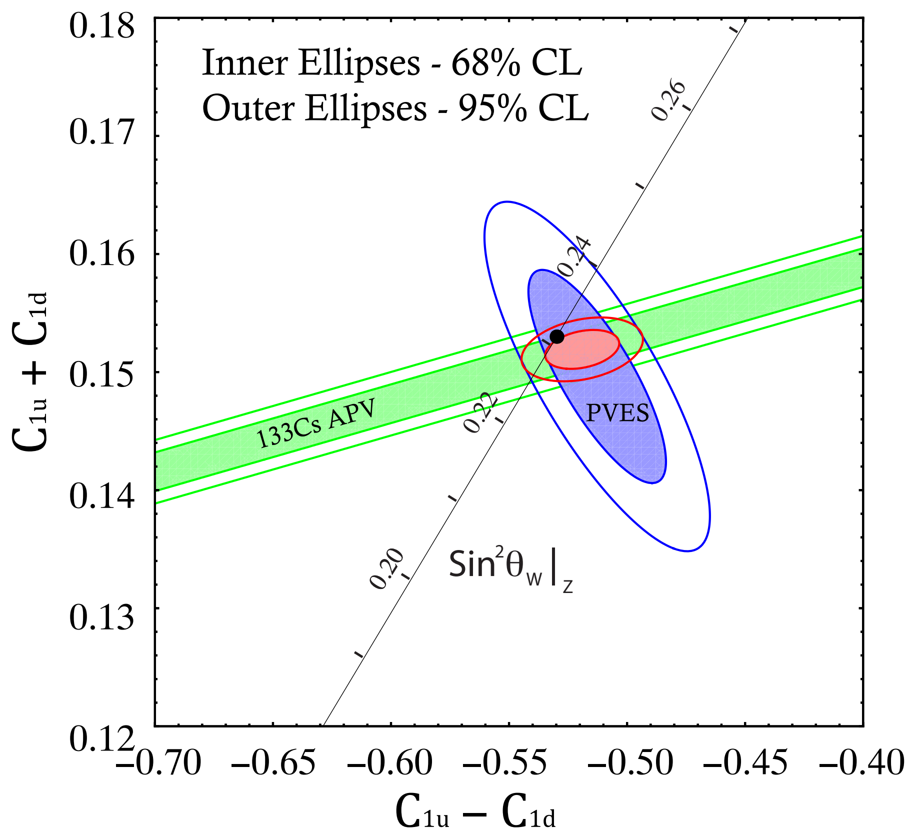
Main point: we have to do the extrapolation to $Q^2 = 0$ using world data for $B(Q^2, \theta)$

Global fit of low Q^2 PVES data, Qweak Run 0



Constraints on quark weak charges, neutron:

isoscalar



isovector

C_{1u} = -0.184 ± 0.005
C_{1d} = 0.336 ± 0.005

Standard model is the tiny black dot.

$Q^n_W = -2\,(C_{1u} + 2\,C_{1d})$
$= -0.975 \pm 0.010$

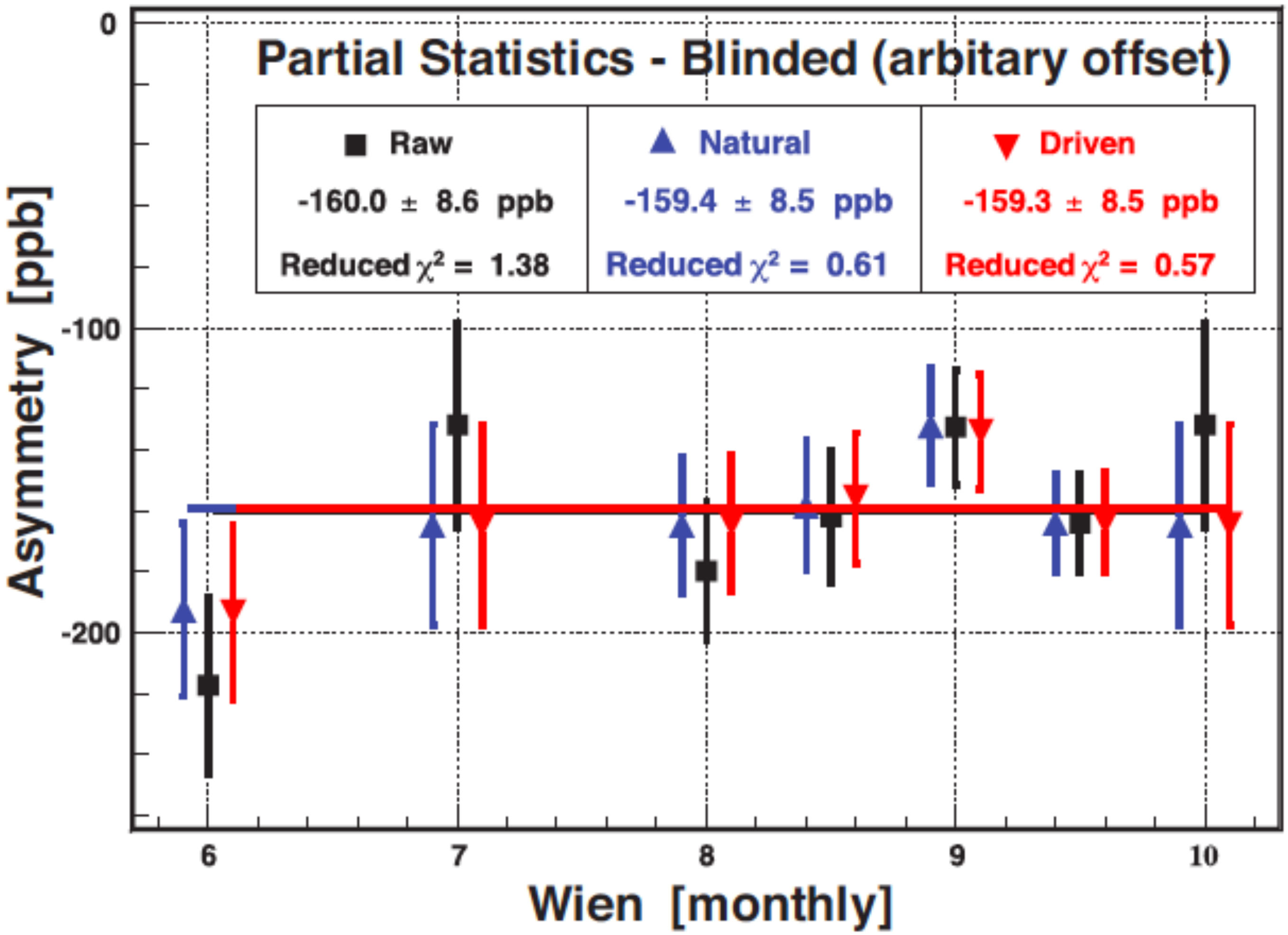
Coming soon: a wealth of new results

Full data set ‘almost ready’ for unblinding (this fall), 25x more elastic ep data!

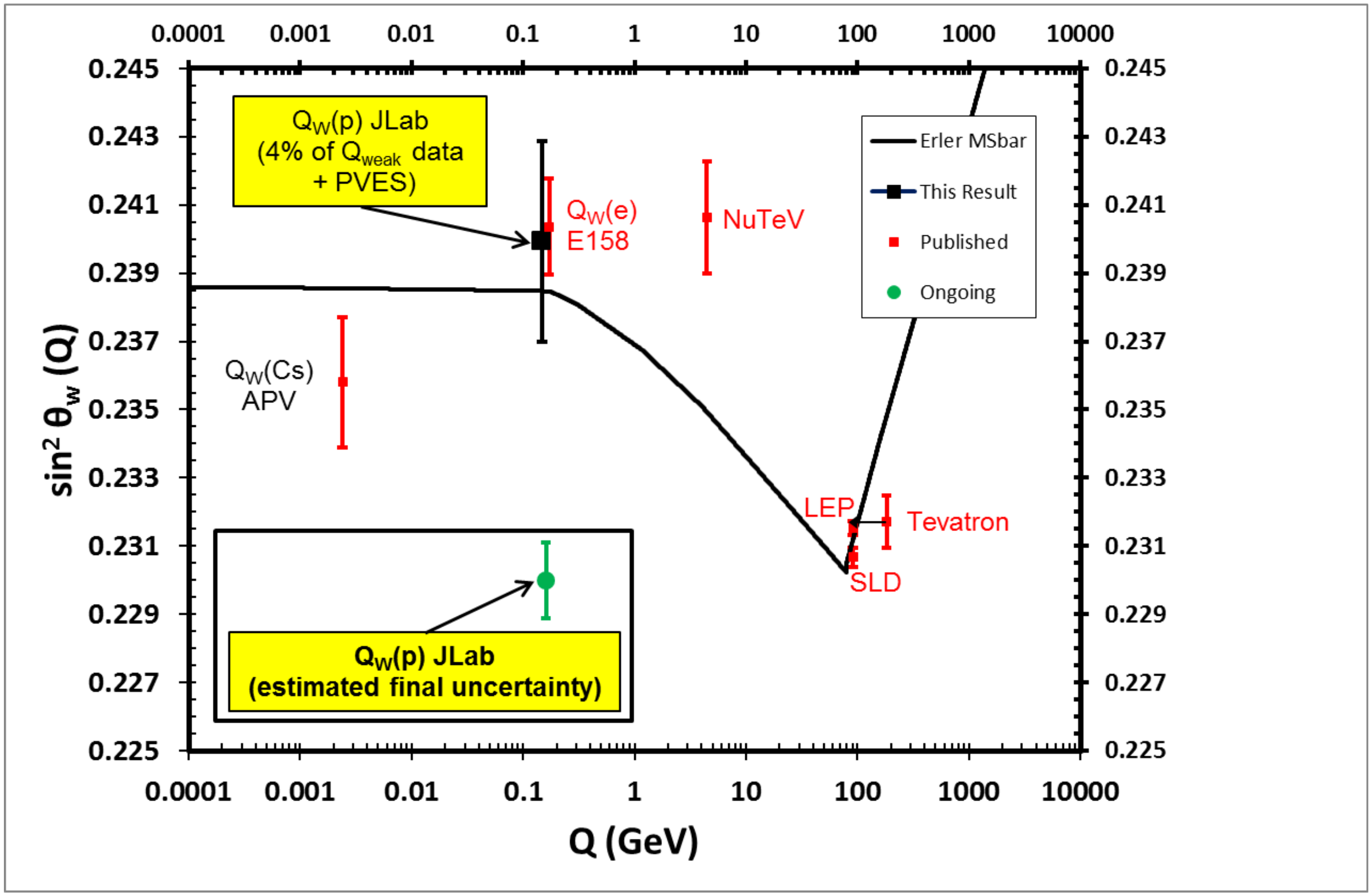
Plus, additional physics results from ancilliary measurements to assess systematic errors and backgrounds in Qweak:

- 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 γ-Z Box uncertainty.
- Transverse asymmetry in the PV inelastic scattering region (3.3 GeV).

Run 2: beam motion corrections two ways!



Running of $\sin^2\theta_W$ -- final data set → SM test



The Q_{weak} Collaboration

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[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
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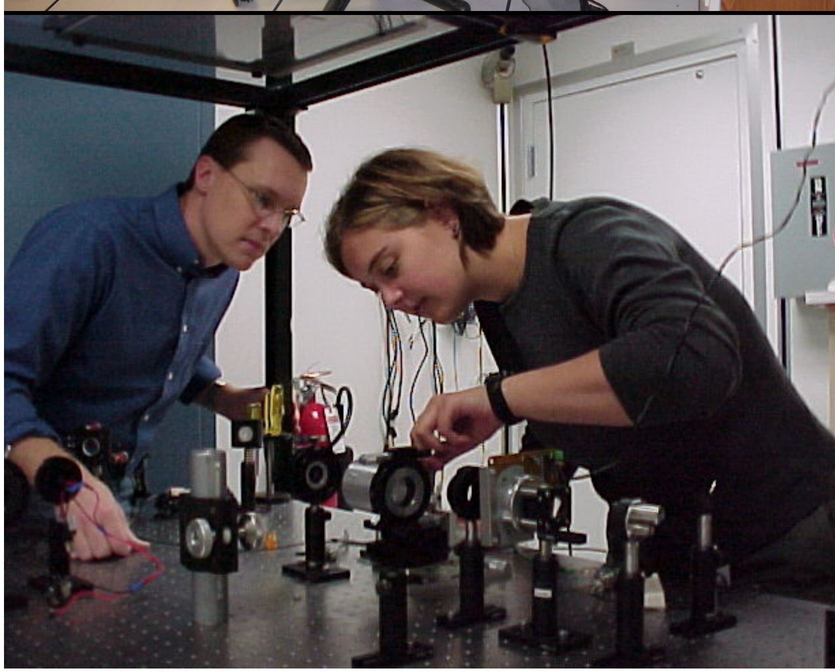
Spokespersons Project Manager Grad Students

In the counting house…



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  - DOE, NSF (USA)
  - **NSERC Canada (>$3M over 12 years)**
- National Lab support:
  - Jefferson Lab
  - **TRIUMF**
- Many hardworking collaborators, students and postdocs

Canadian hardware contributions:

- TRIUMF built ALL the custom low noise analog electronics for Qweak
- NSERC funded the Qweak spectrometer (coils), 50% of Compton electron detectors + electronics, and quartz scanning detector

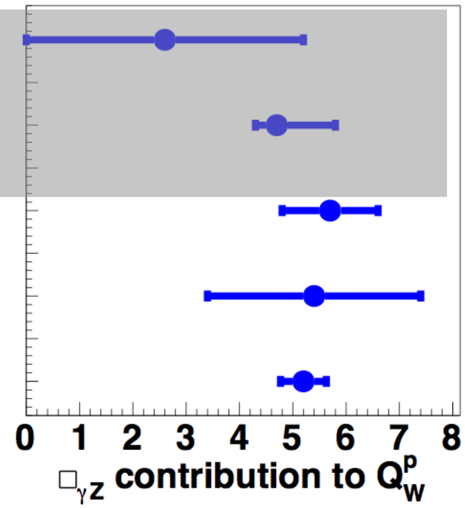
Electroweak Radiative Corrections to Q^P_W

$\Box_{\gamma Z}$ contribution to Q^p_W (Qweak kinematics)

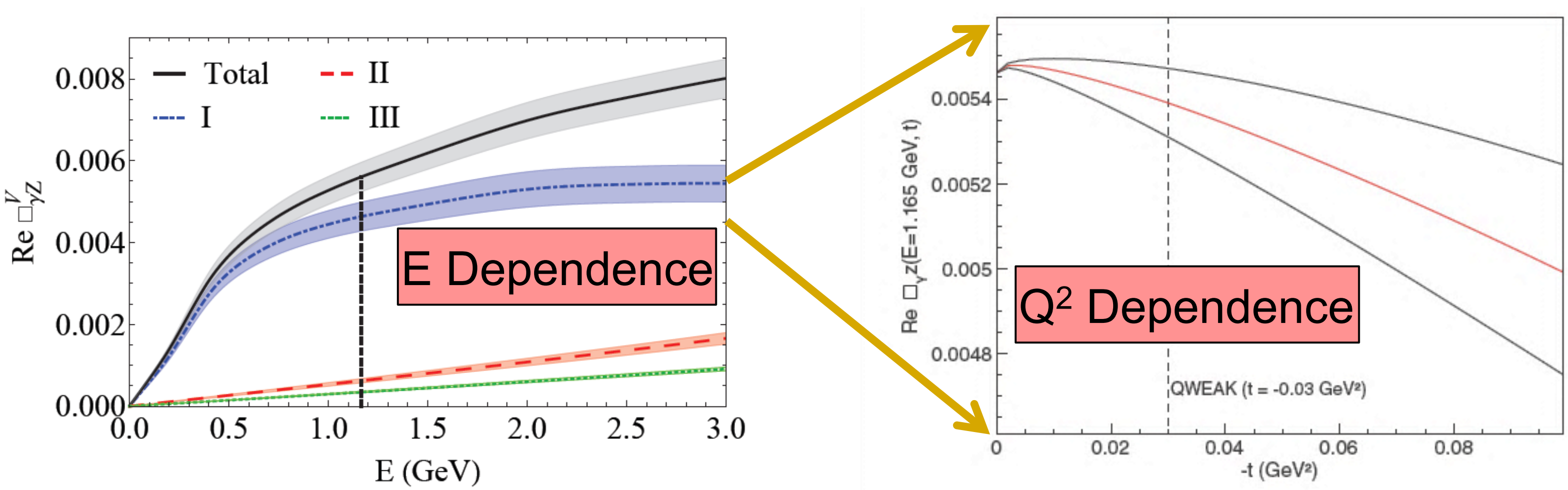
~7% correction

OLDER CALCULATIONS

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



Qweak's Inelastic asymmetry data taken at W ~ 2.3 GeV, Q^2 = 0.09 GeV^2 can check these



Model-independent search for new physics:

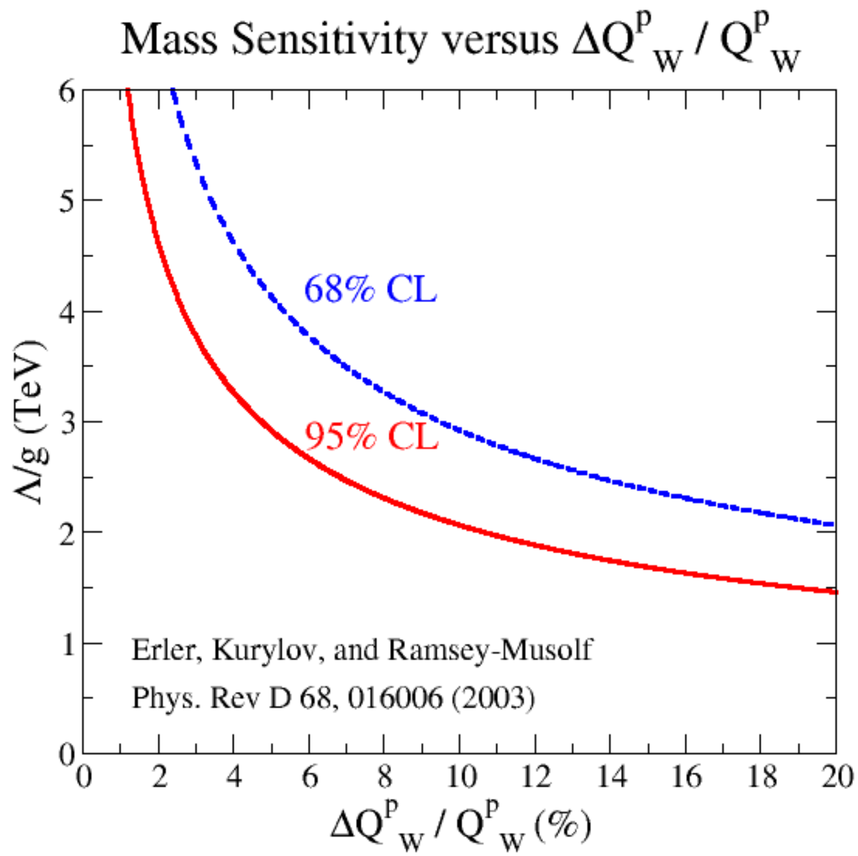
$$\mathcal{L}^{PV}_{e-q} = \mathcal{L}^{PV}_{SM} + \mathcal{L}^{PV}_{New}$$

New physics term:

$$\frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h^q_V \bar{q}\gamma^\mu q$$

At 95% CL,

$$\frac{\Lambda}{g} \sim \frac{1}{2\sqrt{\sqrt{2}G_F|\Delta Q^p_W|}} \simeq 2.3 \text{ TeV}$$



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