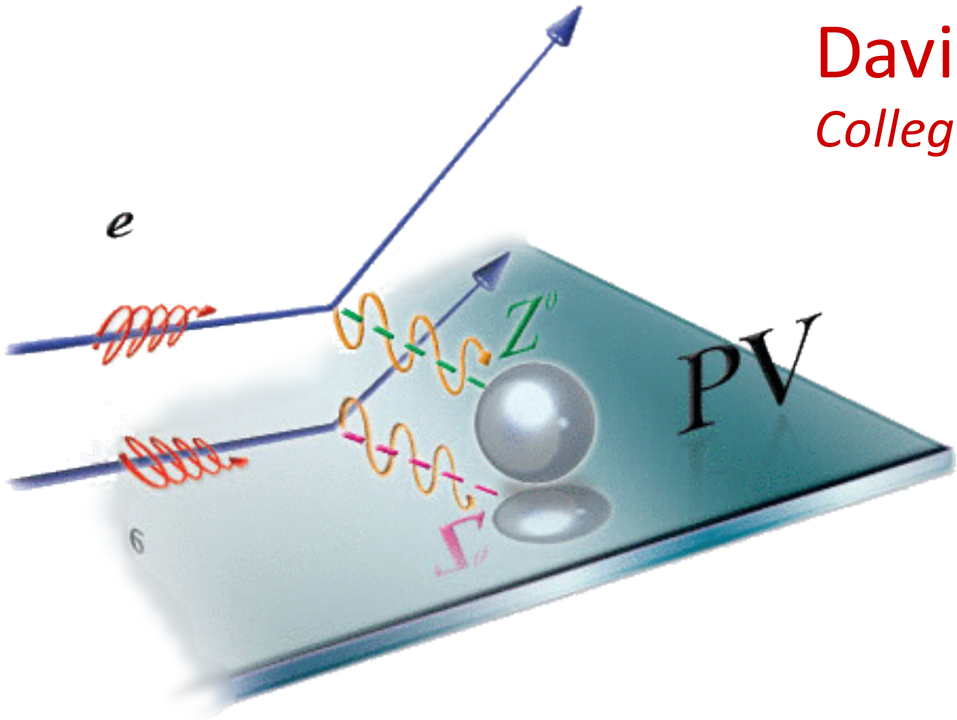
Experiences from Q_{weak}



David S. Armstrong
College of William & Mary

Physics Beyond the Standard Model and
Precision Nucleon Structure Measurements
with Parity-Violating Electron Scattering
ECT, Trento   August 1 2016*

WILLIAM & MARY
CHARTERED 1693

Jefferson Lab

Caveat Emptor

What this talk is not:

- Detailed motivation/theory review for the Q_{weak} experiment
- No new physics result: we are not ready to unblind *(yet)*

What this talk is:

- Review of some of important experimental issues & where the analysis stands
- Emphasis on topics that were unexpected and/or relevant for future PVES measurements
- My own (personal) choice of emphasis

Weak Charge

Electroweak Lagrangian → Parity-Violating electron-quark term:

$$\mathcal{L}_{PV}^{EW} = \frac{G_F}{\sqrt{2}}\left[g_A^e(\bar{e}\gamma_\mu\gamma_5 e)\cdot\sum_q g_V^q(\bar{q}\gamma^\mu q) + g_V^e(\bar{e}\gamma_\mu e)\cdot\sum_q g_A^q(\bar{q}\gamma^\mu\gamma_5 q)\right]$$

$$C_{1q} = 2g_A^e g_V^q$$

-Electroweak Charges-

Particle	Electric Charge	Weak Vector Charge ($\sin^2\theta_W \approx \frac{1}{4}$)
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)	$+1$	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0$
n(udd)	0	$Q_W^n = -1$

← Proton's Weak Charge

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{2M_{EM}^* M_{Weak}}{|M_{EM}|^2}$$

For forward angle scattering at low Q^2 :
A_{PV} accesses Q_W^p

Extracting the Weak Charge

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

Hadron structure enters here: electromagnetic and electroweak form factors…

Reduced asymmetry more convenient:

$$A_{red} = \frac{A_{PV}}{A_0} \qquad A_0 = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}$$

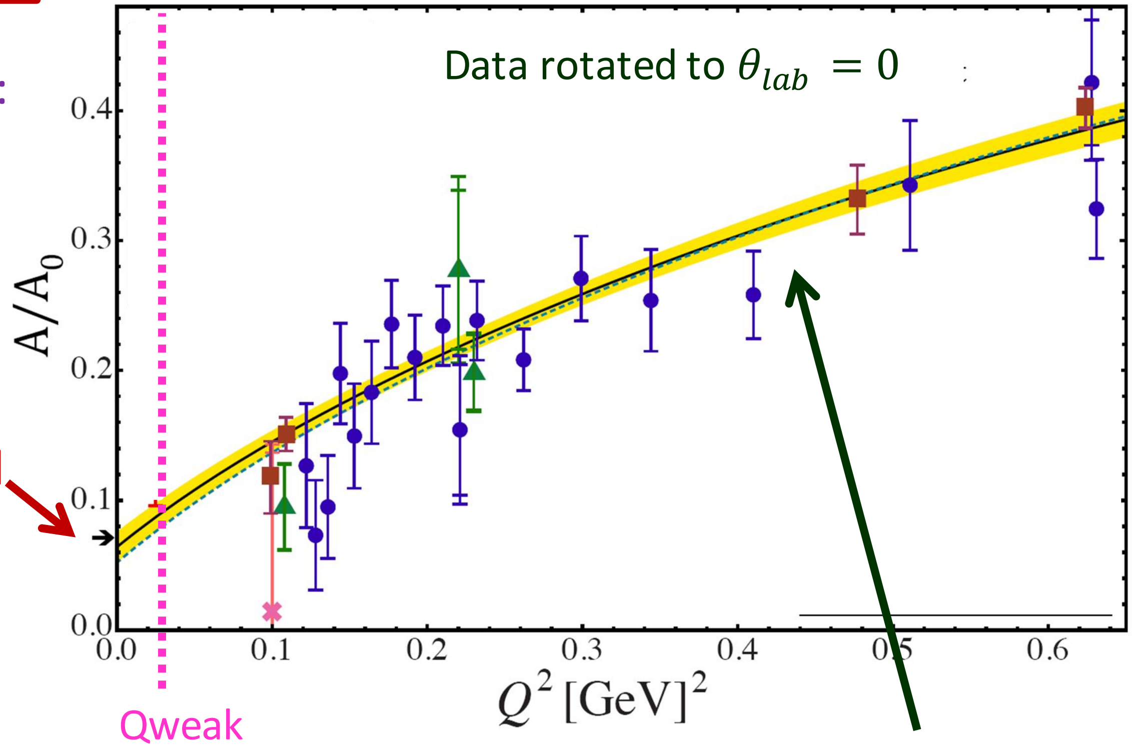
One must extrapolate to $Q^2 = 0$.

We measure A_{PV}

at $Q^2 = 0.025\ \mathrm{GeV}^2$.

Precision Standard Model test

SM



Data rotated to $\theta_{lab} = 0$

Qweak kinematics

Hadronic term extracted from fit

Previous experiments (strange form factor program: SAMPLE, HAPPEX, G0, PVA4) explored hadron structure; allow subtraction of hadronic contribution

First result

Q_{weak} ran from Fall 2010 – May 2012 (Hall C at JLab)

Four distinct running periods:

- Hardware checkout (Fall 2010-January 2011)
- Run 0 (Jan-Feb 2011)
- Run 1 (Feb – May 2011)
- Run 2 (Nov 2011 – May 2012)

We have completed and unblinded the analysis of "Run 0"
(about 1/25th of our total dataset).

D. Androic *et al.* Phys. Rev. Lett. 111 (2013)141803.

$A_{PV}^{p} = -279 \pm 35(stat) \pm 29\ (sys)$ ppb

$\langle Q^2 \rangle = 0.0250 \pm 0.0006\ \mathrm{GeV}^2$

$\langle E_{beam} \rangle = 1155\ \mathrm{MeV}$

$\theta_{eff} = 7.90\ ^\circ$

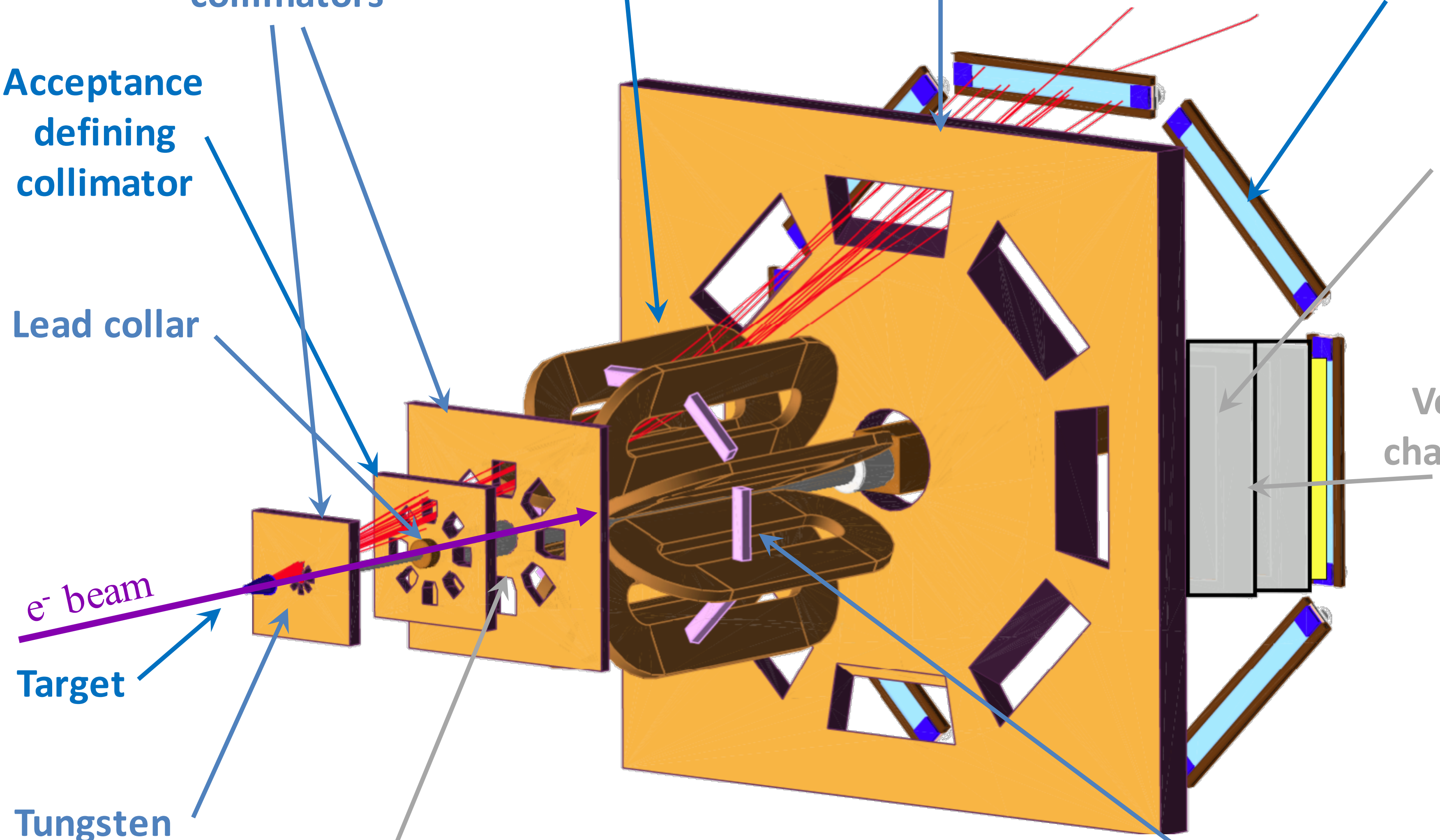
Good agreement with Standard Model prediction

In this talk, I focus on the Run 1 & Run 2 data

Meeting PVES Challenges

- 180 μA beam current (JLab record)
- High power cryogenic target
- Rapid helicity reversal (960 Hz)
- Small scattering angle: toroidal magnet, large acceptance
- GHz detected rates: data-taking in integrating mode
- Radiation hard detectors
- Low noise 18-bit ADCs
- Exquisite control of helicity-correlated beam parameters
- Four different kinds of helicity reversal:
  - Rapid (Pockels cell at source)
  - Slow (insertable λ/2 plate)
  - Ultra slow (Wien-reversal, g-2 spin flip)
- Two independent high-precision beam polarimeters
- High resolution Beam Current monitors
- Dedicated Tracking system for kinematics determination

The Q_{weak} Apparatus



Cleanup collimators

QTOR

Shield wall

Main detectors 8-fold symmetry

Acceptance defining collimator

Trigger scintillator

Lead collar

Vertical drift chambers (VDC) (rotate)

e⁻ beam

Target

Tungsten plug

Horizontal drift chambers (HDC) (rotate)

Lintels

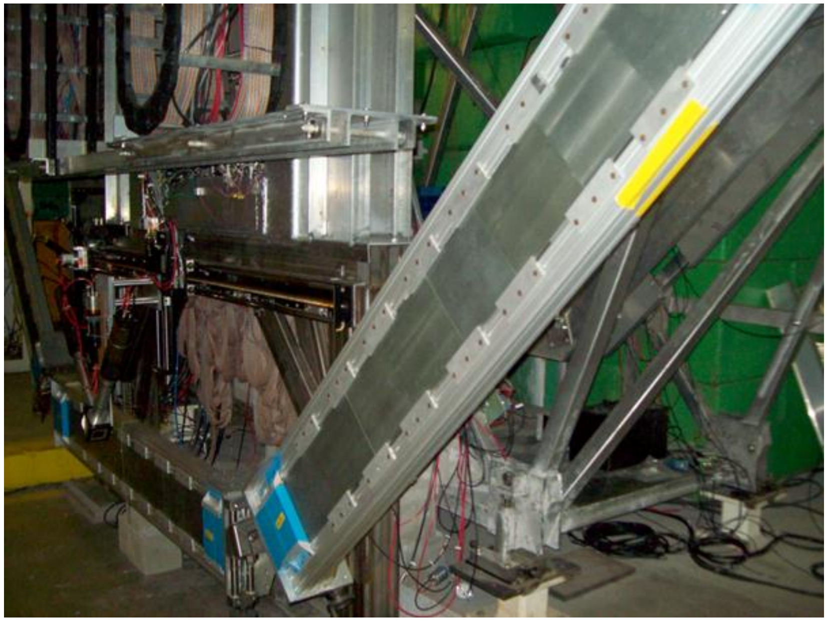
Main Detectors

- Main detectors

  Toroidal magnet focuses elastic electrons onto each bar

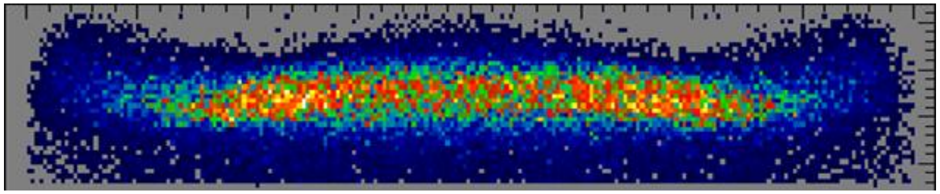
  - 8 Quartz Cerenkov bars
  - Azimuthal symmetry maximizes rates & reduces systematic uncertainties
  - 2 cm lead pre-radiators: a) reduce soft backgrounds discovered in commissioning
    b) boost signal size (but cost to energy resolution)

(see Michael Gericke's talk)

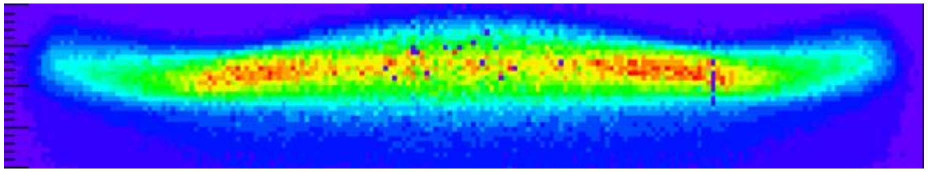


Close up of one detector *in situ*

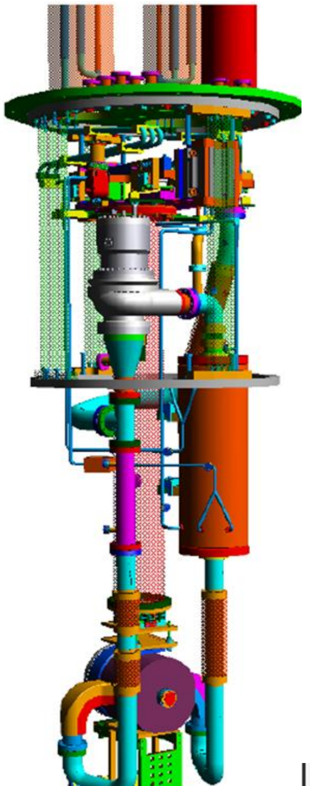
Simulation of scattering rate MD face



Measured



Hydrogen Target



35 cm, 2.5 kW liquid hydrogen target (world's highest power cryotarget)

Designed using Computational Fluid Dynamics (see Silviu Covrig's talk)

- Temperature ~20 K
- Pressure: 30-35 psia
- Beam at 150 – 180uA

Target boiling might have been problematic!

960 Hz helicity reversal rate (240 Hz quartets)

1/960 Hz = 1042 μs

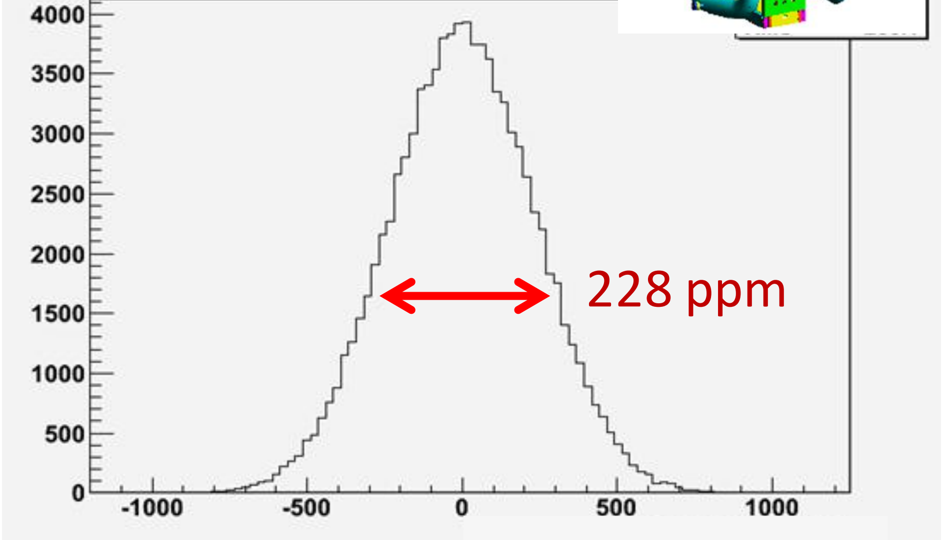
settling time after reversal: 112 μs

integration time: 928 μs (89% live)

LH2 statistical width (per quartet):

Counting statistics:	200 ppm
Main detector resolution:	92 ppm
BCM width:	50 ppm
Target noise/boiling:	37 ppm

Redundant, low-noise Beam Current Monitors essential (see Mark Pitt's talk)



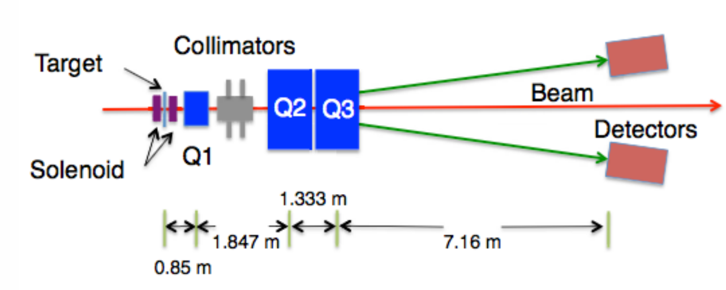
MD LH2 Asymmetry

Beam Polarimetry

Originally, was expected to be largest systematic uncertainty

Møller polarimeter $(\vec{e} + \vec{e} \rightarrow e + e)$

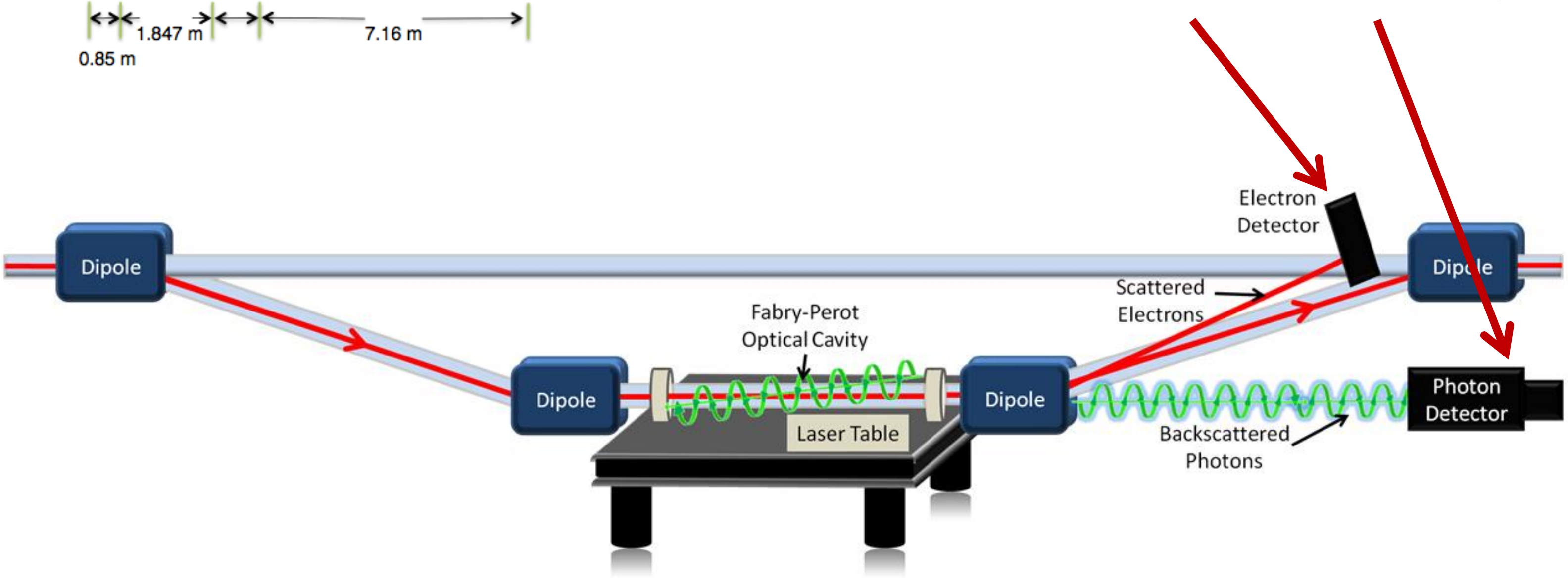
- Precise, but invasive
- Thin, polarized Fe target
- Brute force polarization
- Limited to low current



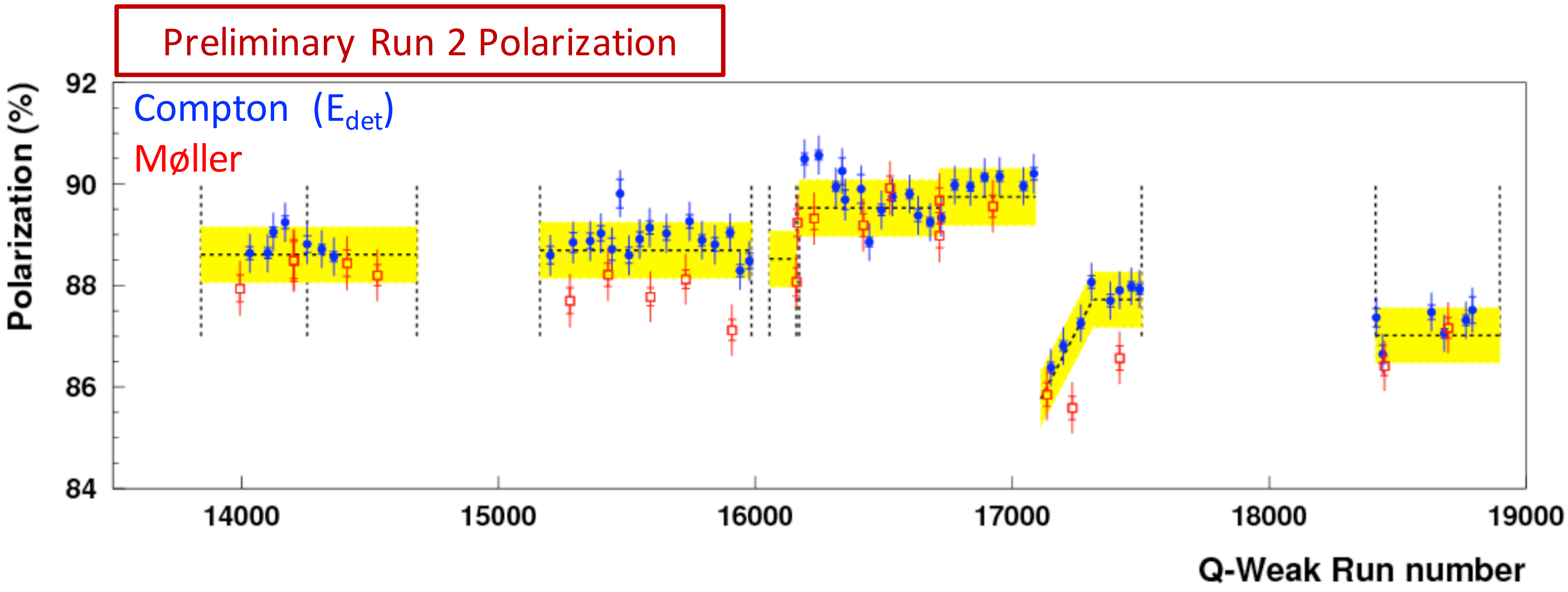
Compton polarimeter $(\vec{e} + \gamma \rightarrow e + \gamma)$

- Installed for Q-weak
- Runs continuously at high currents
- Statistical precision: 1% per hour
- Electron Detector: Diamond strips

Detect *both* recoil electron and photon.



Beam Polarimetry



Good agreement between Møller & Compton (electron detector)

Compton photon detector: issues with $PbWO_4$ calorimeter *(afterglow?)*

Systematics:

- Compton (E_{det}) : $\Delta P/P = 0.42\%$
- Møller: $\Delta P/P = 0.65\%$

Combined Total: $\Delta P/P = 0.61\%$ *(systematics + statistics + scaling)*

(see Bob Michaels' talk)

Compton: A. Narayan et al, Phys. Rev. X 6.011013 (2016)

Helicity-Correlated Beam Parameters

- Beam Intensity asymmetry: active (≈ 60 s scale) feedback system (Pockels cell voltage)
- Careful alignment of Pockels cell in source essential:
  → smallest position differences after photocathode yet seen at JLab

- Did not (generally) benefit from “kinematic damping”: $X, X' \propto \sqrt{\frac{p_0}{p}}$
  (theoretical reduction factor ~ 60)

- Mis-matched beam transport distorts phase-space ellipse
- One time, we devoted significant time to allow good “matching”:
  did see suppression of helicity-correlated differences

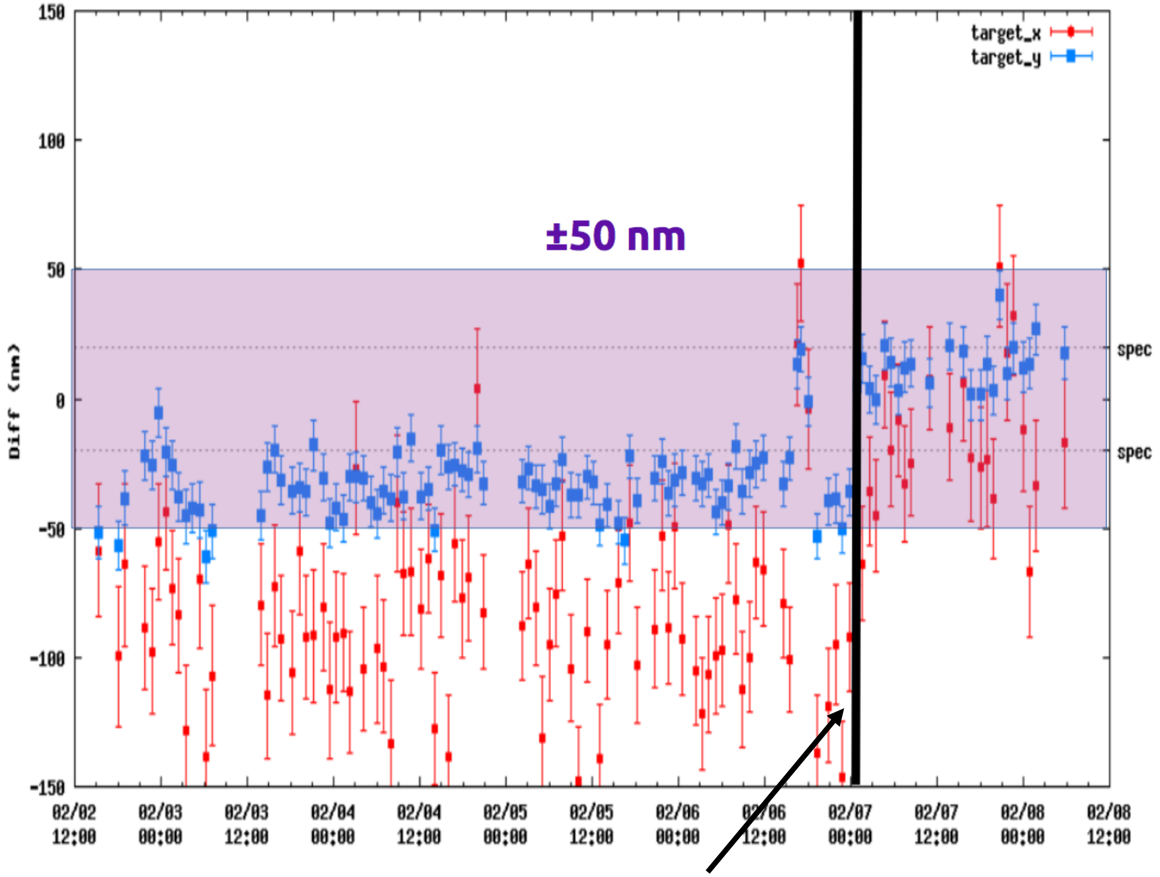
Parameter	Max run-averaged HC value	Run1 (Modulation set)	Run2 (Modulation set)
Beam intensity	$\langle A_Q \rangle < 10^{-7}$	$-5.0 \pm 2.9\ (10^{-}8)$	$2.8 \pm 1.4\ (10^{-}8)$
Beam energy	$\langle \Delta E/E \rangle \leq 10^{-9}$	$-2.0 \pm 0.3\ (10^{-}9)$	$0.36 \pm 0.18\ (10^{-}9)$
Beam position	$\langle \Delta X \rangle < 2$ nm	1.6 ± 1.2 nm	2.2 ± 0.9 nm
	$\langle \Delta Y \rangle < 2$ nm	-6.3 ± 0.9 nm	0.2 ± 0.4 nm
Beam angle	$\langle \Delta \theta_X \rangle < 30$ nrad	-0.15 ± 0.04 nrad	-0.05 ± 0.02 nrad
	$\langle \Delta \theta_Y \rangle < 30$ nrad	0.04 ± 0.04 nrad	-0.05 ± 0.01 nrad

(see Arne Freyberger’s and Caryn Palatchi’s talks)

Helicity-Corrector Magnets

- Set of fast pulsed magnets (5 MeV region of injector)
- Kick beam trajectory with helicity (position and angle)
- Measured response at target: stable, as long as accelerator tune unchanged
- “grad student feedback” (daily)

ΔX and ΔY position differences



Helicity magnets turned on

No need for different size kicks for different IWHP (slow flip) states:
Good setup of polarized source

Helicity magnets used for much of our 2nd run.

Helicity-Correlated Beam Parameter Sensitivities

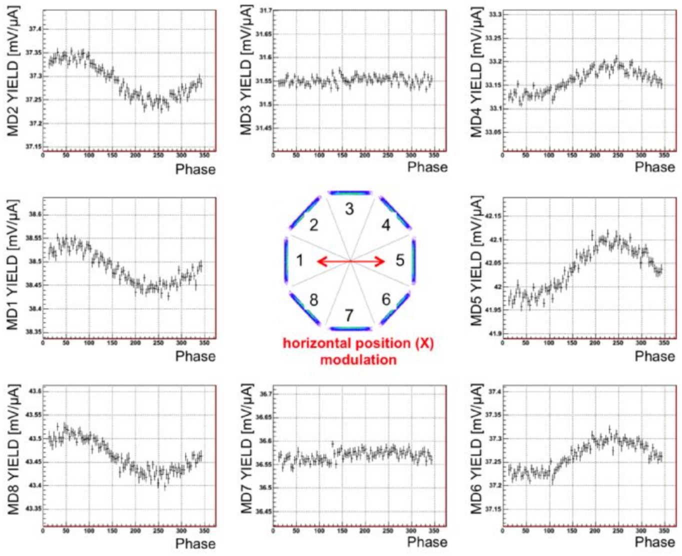
$$A_{beam} = \sum_i \frac{\partial A}{\partial \chi_i} \Delta \chi_i$$

where i runs over x,y,x'(angle),y'(angle), and energy.

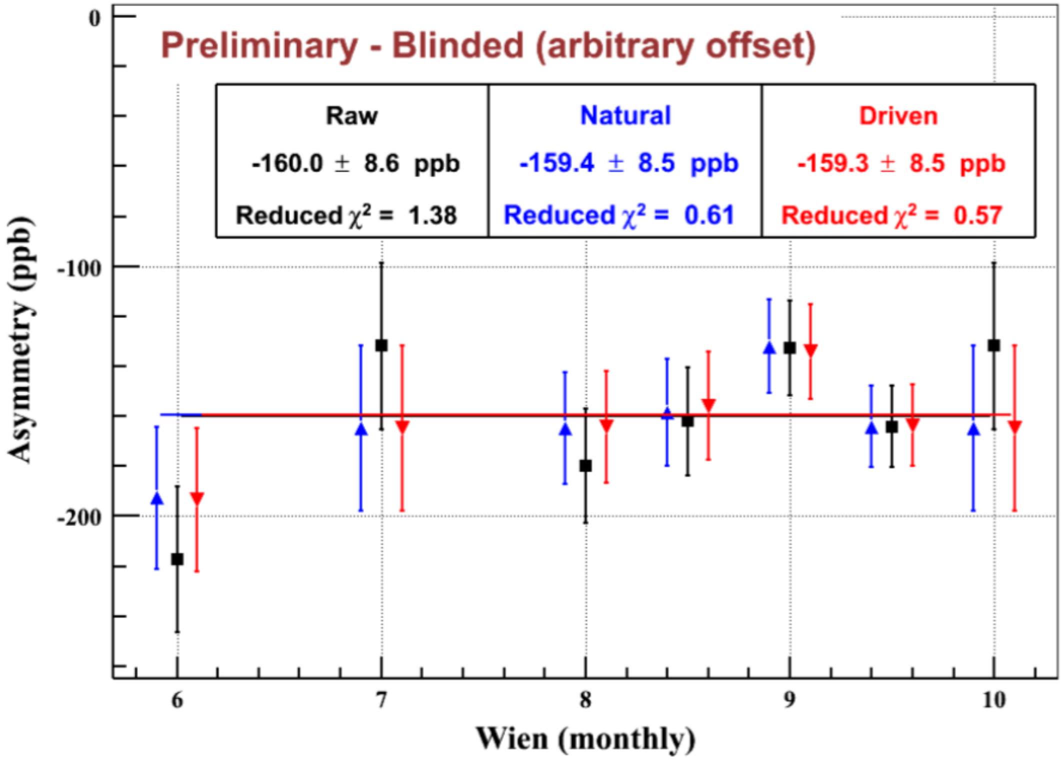
Need to determine the sensitivities: $\frac{\partial A}{\partial \chi_i}$

Natural: Linear regression of natural beam motion

Driven: Drive sinusoidal beam oscillations with large amplitude



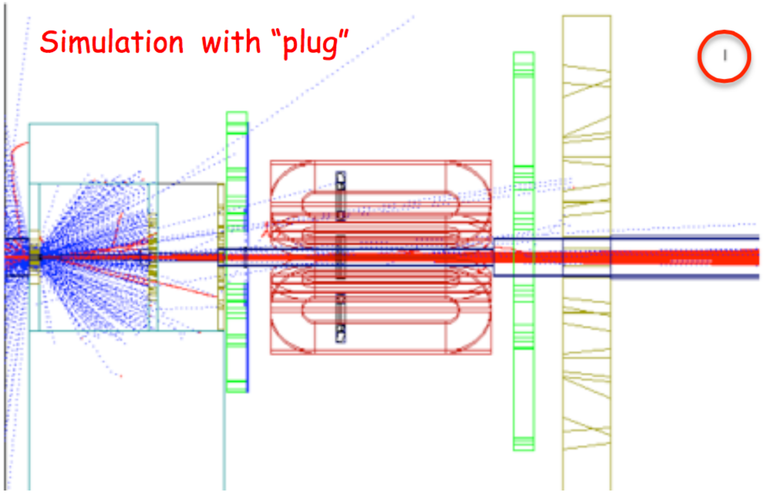
Run2 measured asymmetry

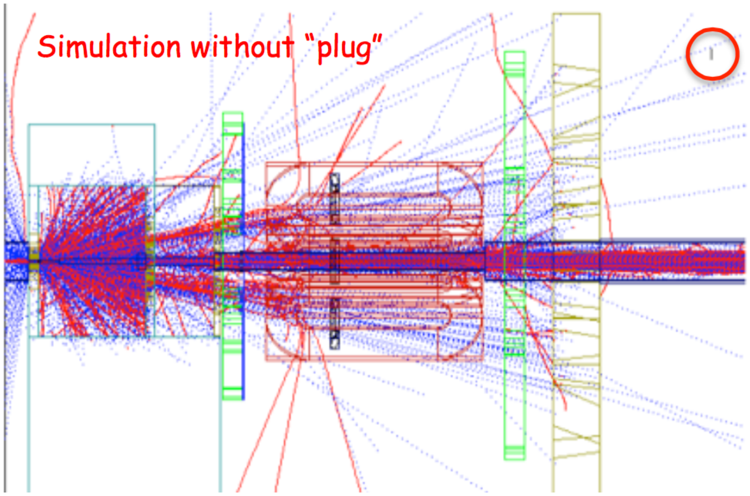


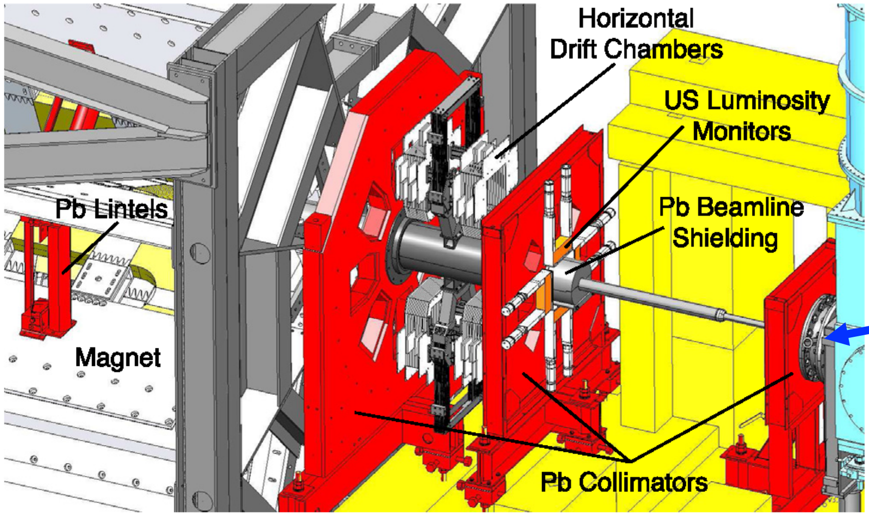
Beamline Background

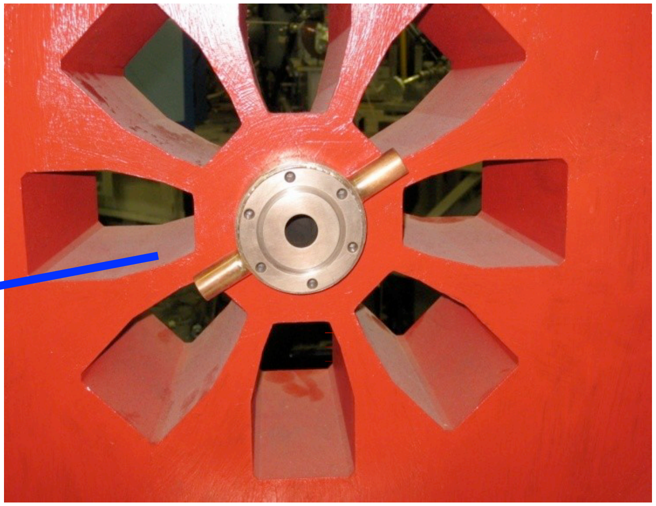
Concern: Small-angle scattered beam interacting with downsteam beamline components

∴ small-aperture W-Cu “beam collimator’ (1.6 kW deposited power)









Beamline Background: Halo

Beam Halo:

- measured beam outside of 13 mm diameter (intrinsic beam spot 150 μm)
- typically 10^{-7} to 10^{-6} of beam, but varied up to 10^{-3} in uncontrolled manner.
- could interact in beam collimator, generating backgrounds in Main Detector

Measured directly by blocking signal electrons at primary collimator:

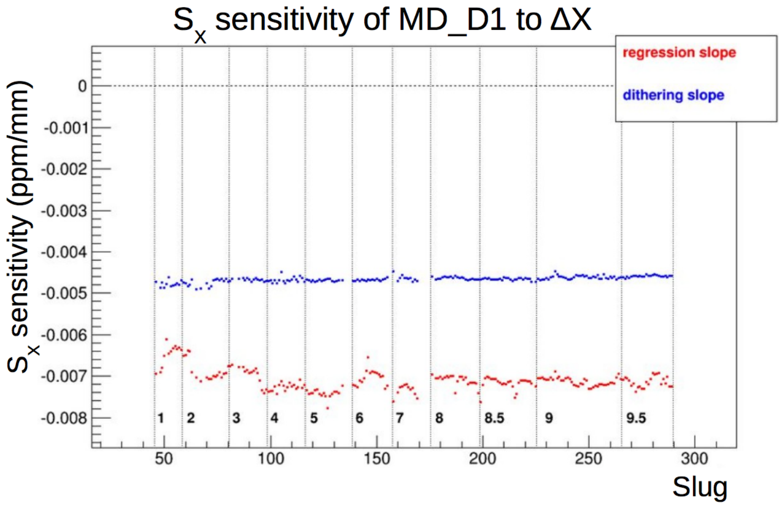
Typical background yield: 0.2% of signal

But: Halo had helicity-correlated component (position and/or intensity)

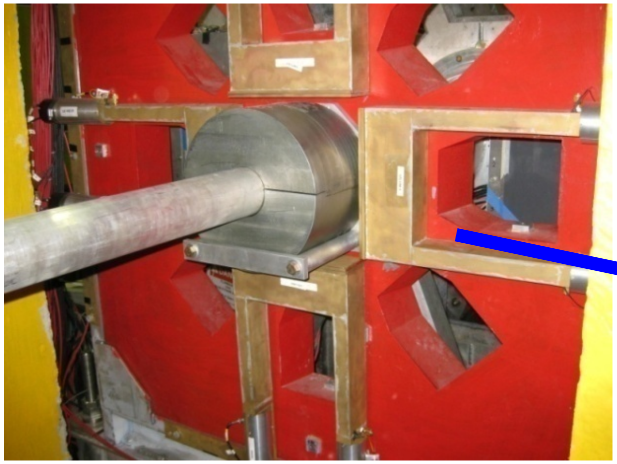
Large halo asymmetry (up to 20 ppm) scaled down by small fraction (0.2%)

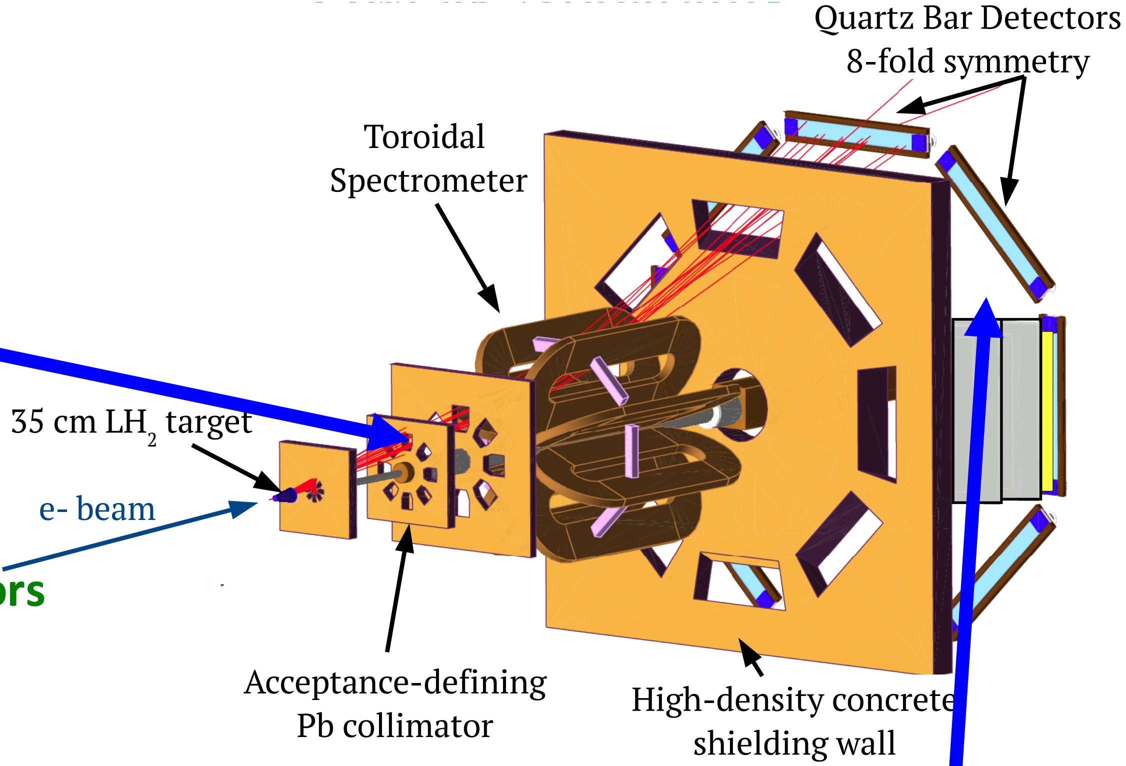
Was largest systematic error in our “Run 0” published result (23 ppb).

Causes helicity-correlated beam sensitivities measured using linear regression to be unstable and to differ from the (stable) sensitivities measured using driven beam motion.



Beamline Background: Monitors



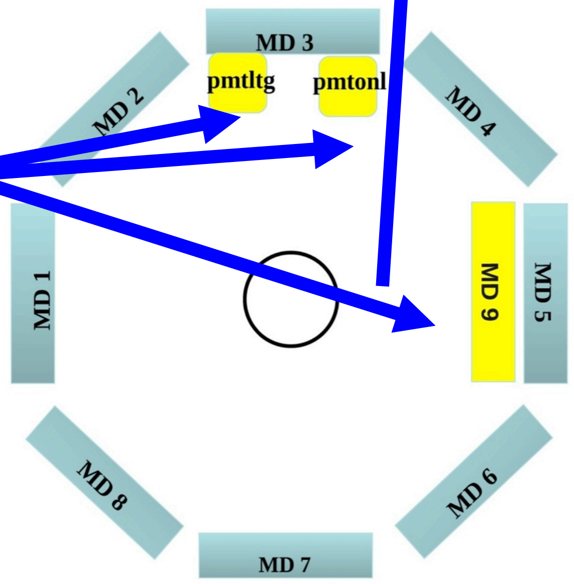


Qweak upstream luminosity monitors

~ 50% of their signal comes from "beamline background"

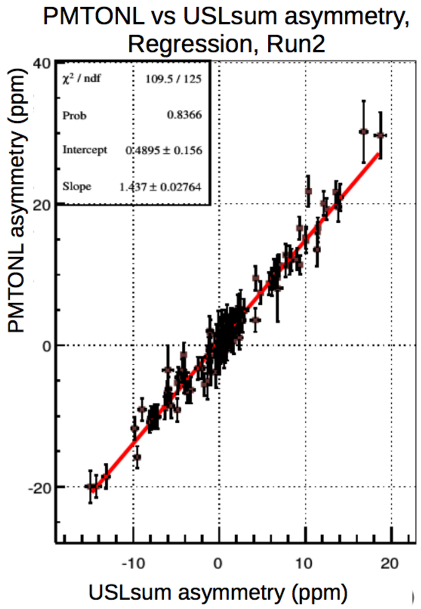
Qweak diffuse background monitors

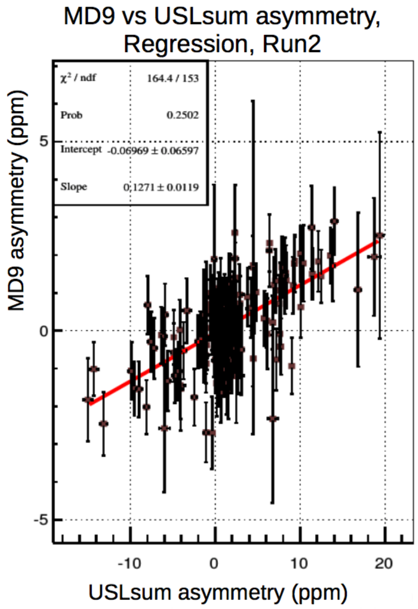
- in focal plane at locations where minimal direct signal
- ≈ 10 – 70% of signal from "beamline background"



Background detectors measured large (up to 20 ppm) false (only partly cancels with slow reversals) asymmetries

Beamline Background: Correlations



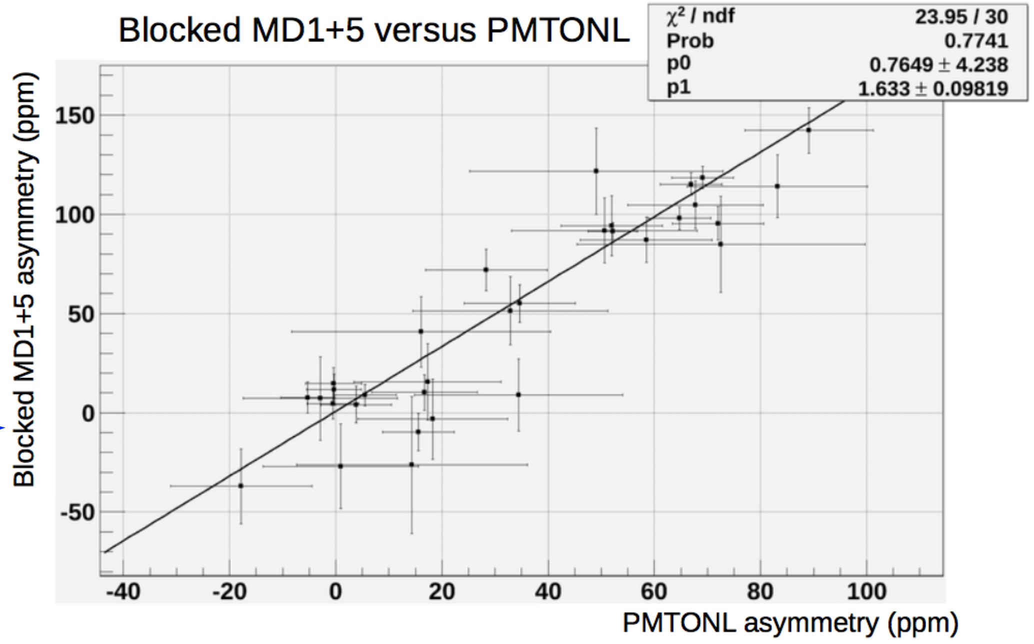


Asymmetries from different background detectors highly correlated

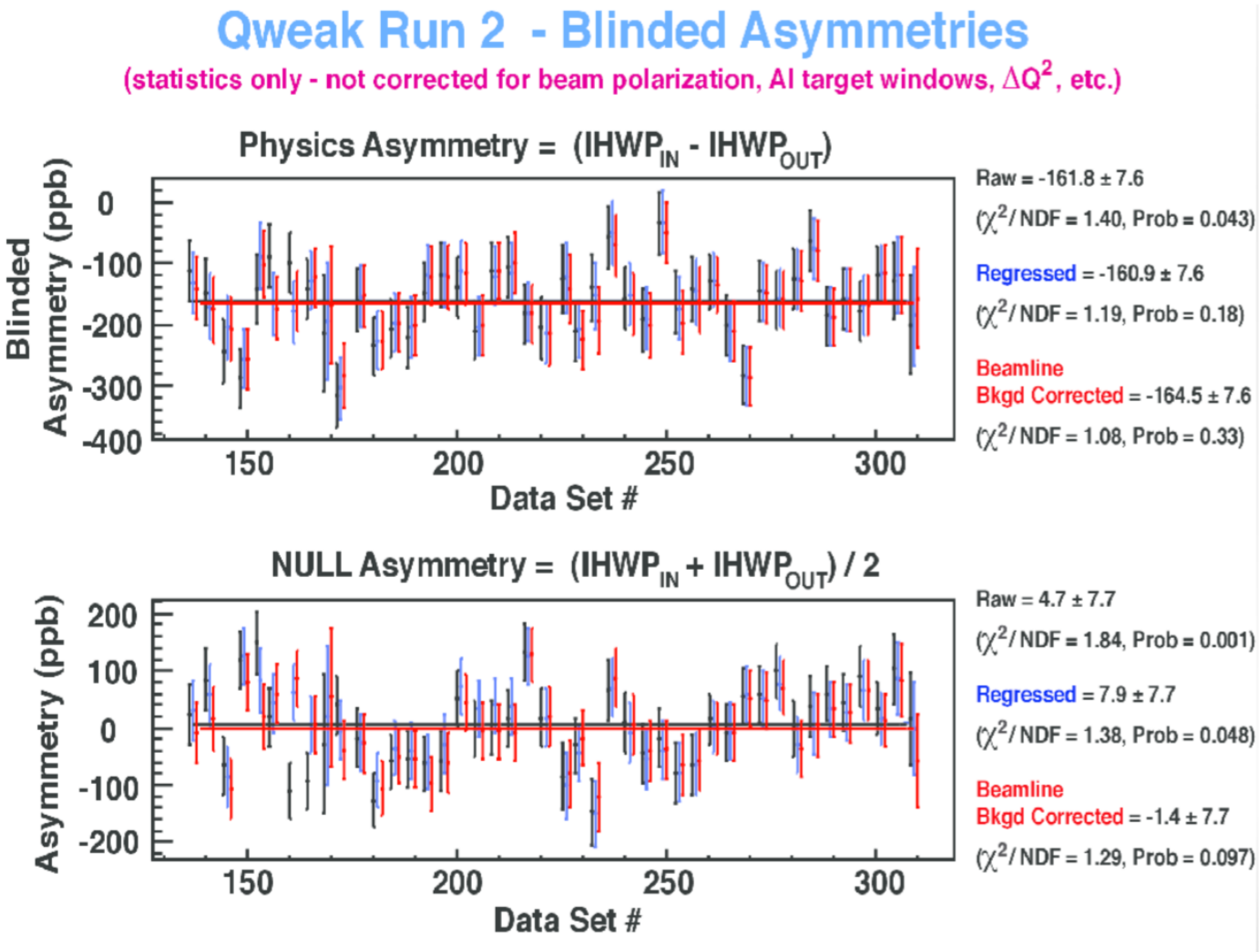
1) Measure Main Detector to Background Detector asymmetry correlation during data-taking (long time-scale averaging)

2) Confirm correlation with blocked-octant study.

3) Using correlation slope and background detector asymmetry, make corrections

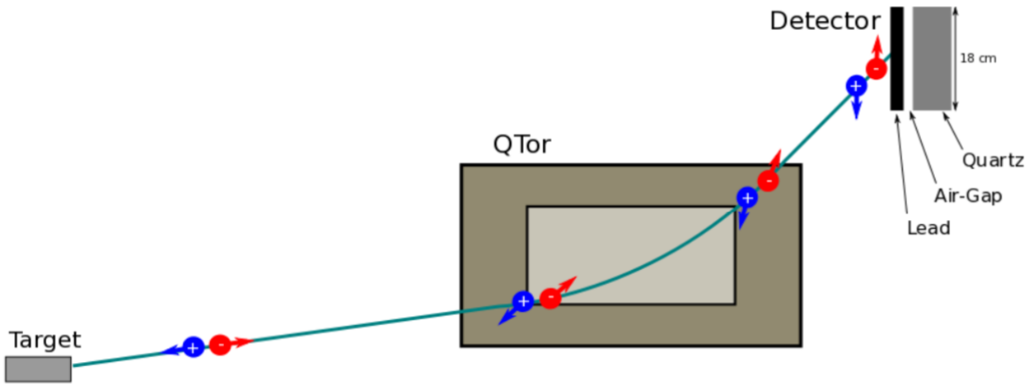


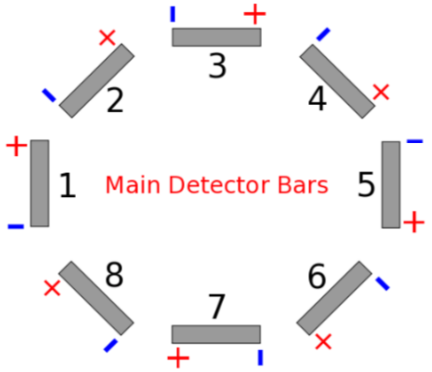
Beamline Background: Corrections



Correcting for beamline background improves statistical consistency of data (correction size: 3.6 ppb)

Secondary Scattering





- Spin precession of scattered electron in QTor magnet: some transverse polarization P_T

- P_T analyzed by scattering in Pb pre-radiators → transverse asymmetry in detectors: opposite sign in the two PMTs (+ & −) in each detector

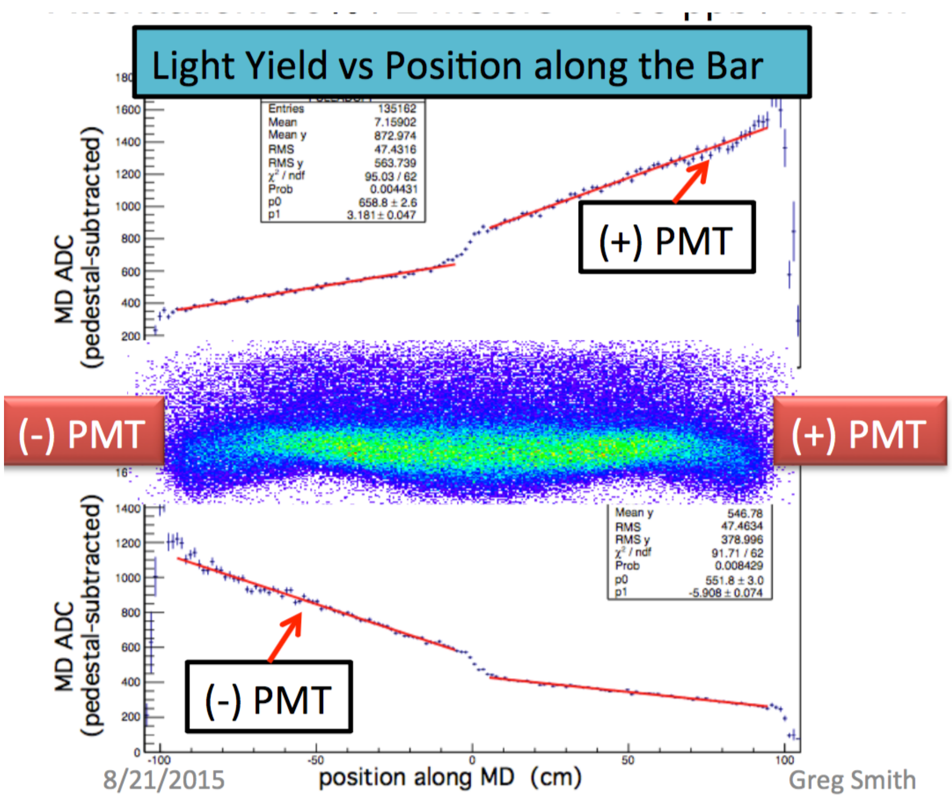
$$A_{diff} = A_+ - A_- \qquad \text{Parity Signal} = \frac{A_+ + A_-}{2} \qquad \therefore \text{Effect cancels to first order}$$

- Analyzing power in Pb:
  1. Beam-normal single spin asymmetry (high energy): 2γ exchange
  2. Mott scattering (low energy in shower)

A_{diff} is of same scale (hundreds of ppb) as A_{PV}

Secondary Scattering

- This transverse asymmetry couples with position & angle dependence of optical response of detectors
- Any non-cancellation between + and – PMTs: detector imperfections & non-symmetric flux distributions
- Optical properties and flux distributions measured with tracking system
- Quantifying any non-cancellation with detailed GEANT 4 simulation
- Any non-cancellation likely averages down in the 8 independent detectors



8/21/2015

Greg Smith

Last significant systematic uncertainty to quantify before we unblind

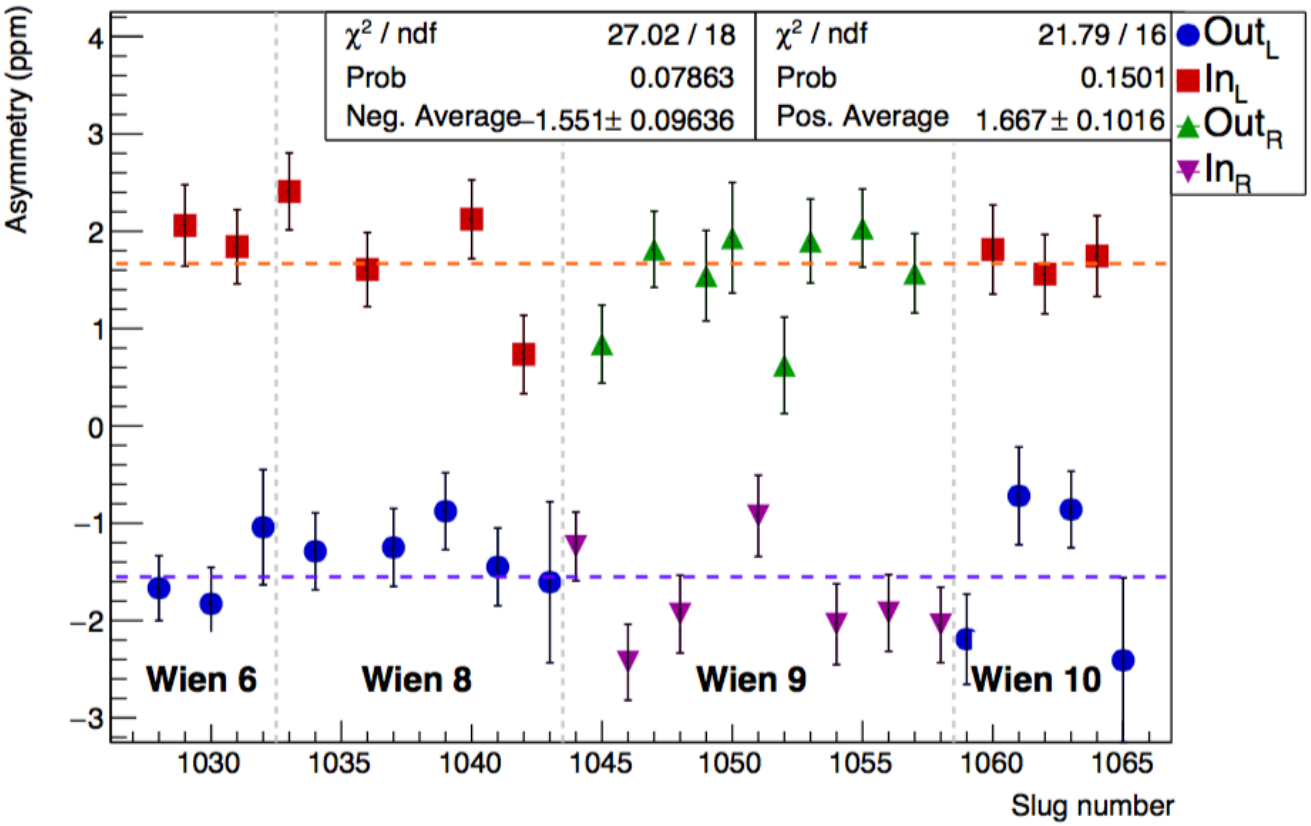
Target Windows

Background from detected electrons that scattered from thin Aluminum entrance and exit windows:

1. Measure ≈1600 ppb asymmetry from thick dummy target (identical Al alloy).
2. Precisely measure that ≈ 2.8% "dilution" from windows.

- Net correction is ≈25% of hydrogen signal

Aluminum Parity-Violating Asymmetry



Two kinds of slow flips: IHWP at source (IN/OUT) and Wien filter

Statistical error: 4.3%
Systematic error: 0.7%

Plan to extract the ^{27}Al elastic asymmetry, Theoretical support from Chuck Horowitz.

Target Windows

Dilution:

- Reduce beam current to $< 1\ \mu$A
- “Counting mode” measurement of rates from empty target and full lH_2 target
- Simulation to account for radiative effects on window signal due to hydrogen

At present dilution uncertainty 2.8% (relative). Errors shared equally between:

- BCM calibration
- Detector deadtime (unexpectedly large)
- Simulation

Working on an alternate approach that essentially eliminates the first two of these. Uses low-density lH_2 gas target data. Challenge is density determination.

Radiative Corrections to **Asymmetry:**

- Simulation to account for small (8%) kinematic shift in asymmetry for upstream Al window, due to presence of lH_2

Net target window correction: 5% relative error (on 25% correction): 1.2% error,
dominated by statistics on Al asymmetry determination

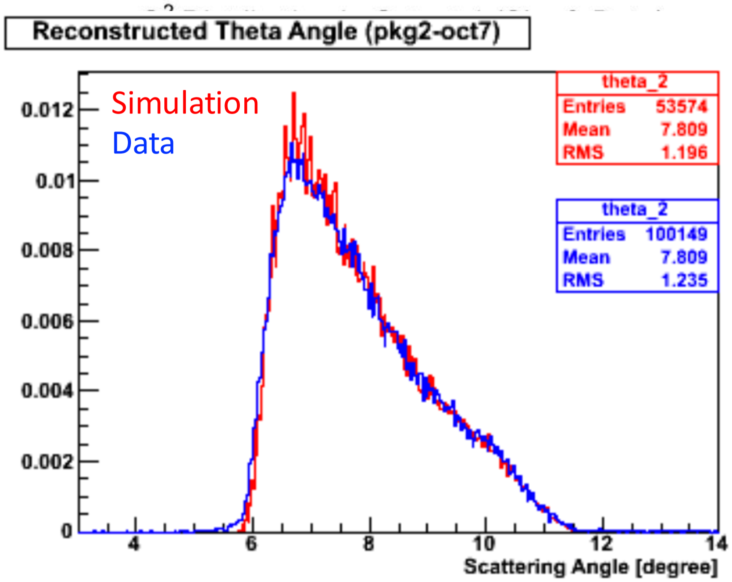
Kinematics (Q^2) determination

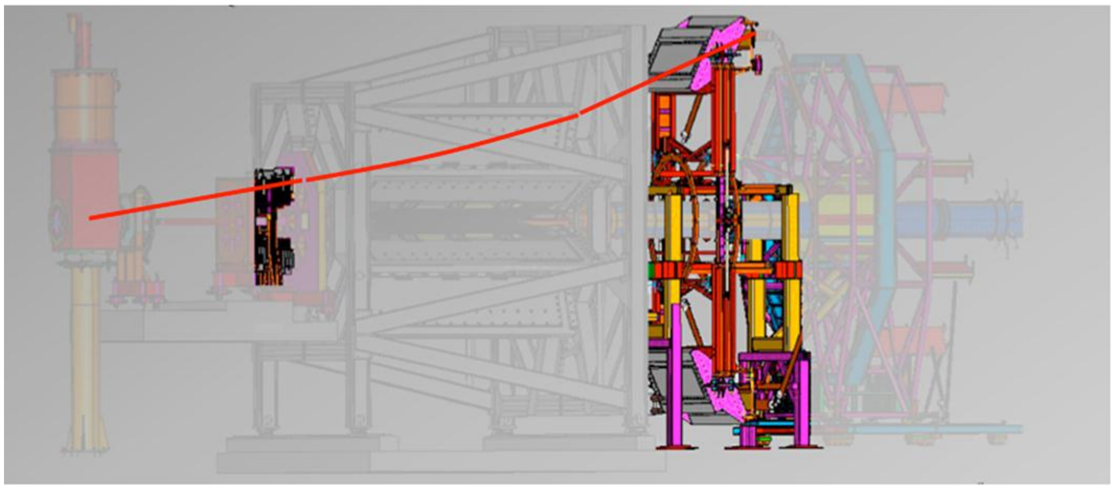
To determine Q^2, we go to "tracking" mode:

$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\{Q_w^p + B(\theta, Q^2)Q^2\}$$

- Currents ~ 50 pA
- Use Vertical + Horizontal Drift Chambers
- Reconstruct individual scattering events

Correct for radiative effects in target with Geant 4 simulations, benchmarked with gas-target & solid target studies





One challenge: no beam position monitors at 50 pA

Lessons Learned Summary

Secondary scattering from pre-radiators
Helicity-correlated halo (leading to beamline background)
  - need “blocked octant” capability
  - multiple background detectors
  - generated in injector?
Accelerator Optics matching (kinematic damping)
Helicity magnets
Driven Beam modulation not just linear regression of natural beam motion
  - coupling of driven modulation and accelerator feedback systems
Wien reversal – not as passive as one would like
Redundant polarimetry
BCMs and BPMs for low current: tracking, dilution measurements
Detector Deadtime (dilution)
Target – great success (need rapid helicity reversal – Pockels cell settling time)

Error Summary

- Final result will be statistics-limited 25× as much data as Run 0 result
- One remaining systematic error to nail down: secondary scattering effect
- Other leading systematics (in order of decreasing size):
    - Q^2 calibration
    - Target Window (Aluminum) asymmetry
    - Beamline Background
    - Target Window (dilution)
    - Polarimetry

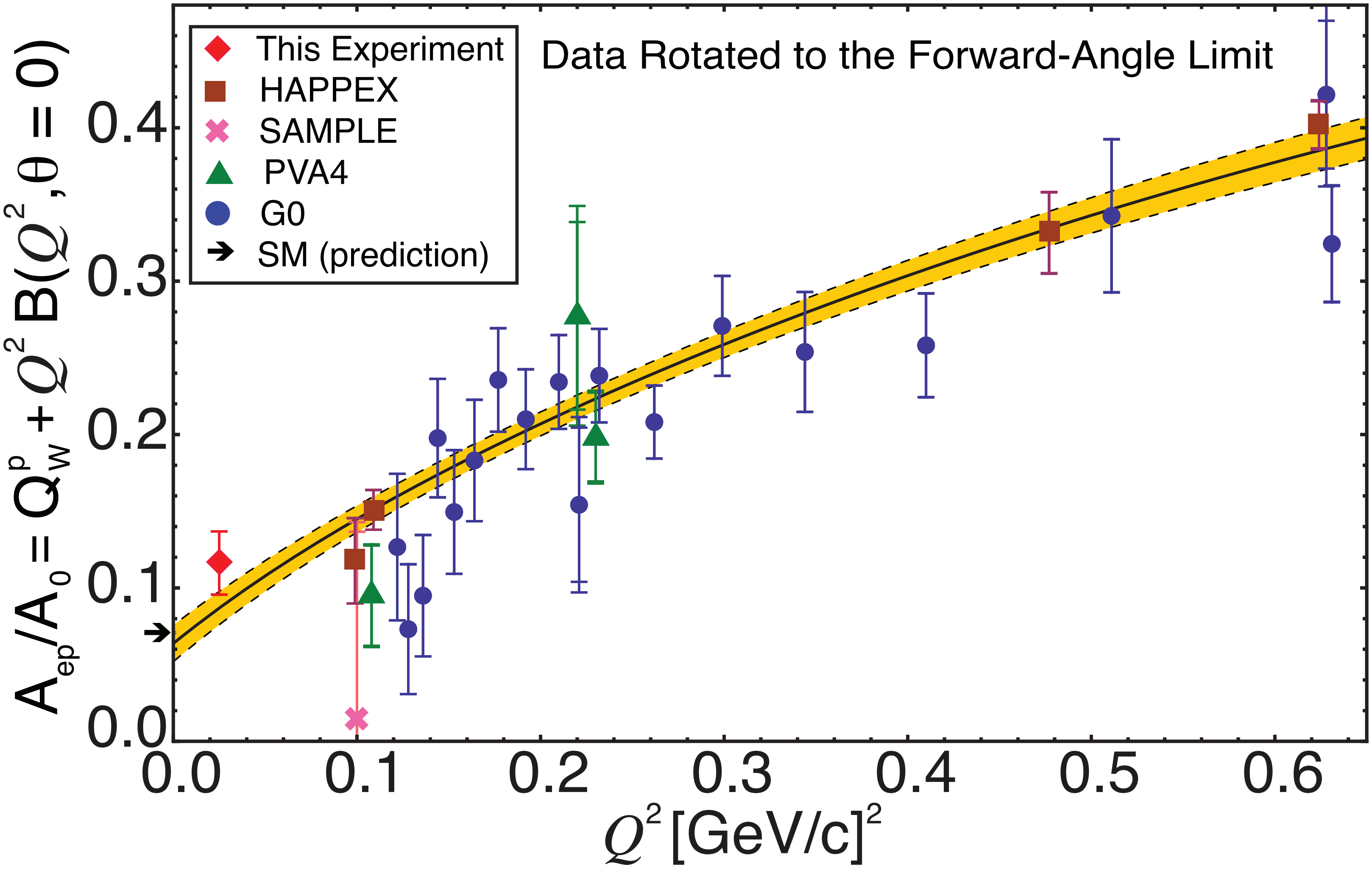
Anticipate unblinding the result in a few months.

Reduced Asymmetry

4% of total data

in the forward-angle limit (θ=0)

$$A_0 = -\frac{Q^2 G_F}{4\sqrt{2}\pi\alpha} \qquad \overline{A^p_{\mathrm{LR}}} = \frac{A_{LR}}{A_0} \xrightarrow{\theta\to 0} [Q^p_W + \boxed{Q^2 B(Q^2)}]$$



Hadronic part extracted through global fit of PVES data.

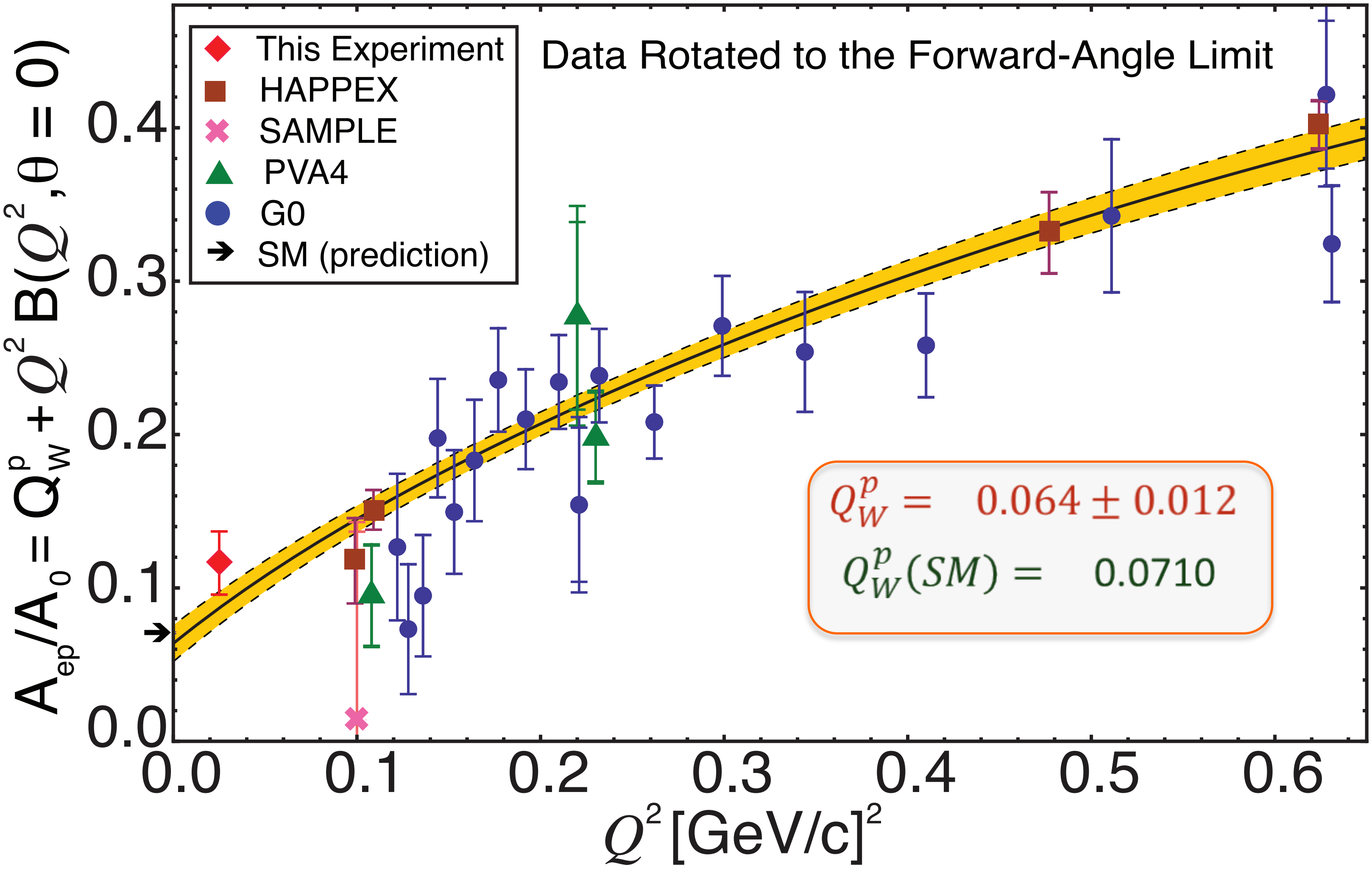
Reduced Asymmetry

4% of total data

in the forward-angle limit (θ=0)

$$A_0 = -\frac{Q^2 G_F}{4\sqrt{2}\pi\alpha}$$

$$\overline{A^p_{\rm LR}} = \frac{A_{LR}}{A_0} \xrightarrow{\theta\to 0} [Q^p_W + \boxed{Q^2B(Q^2)}]$$

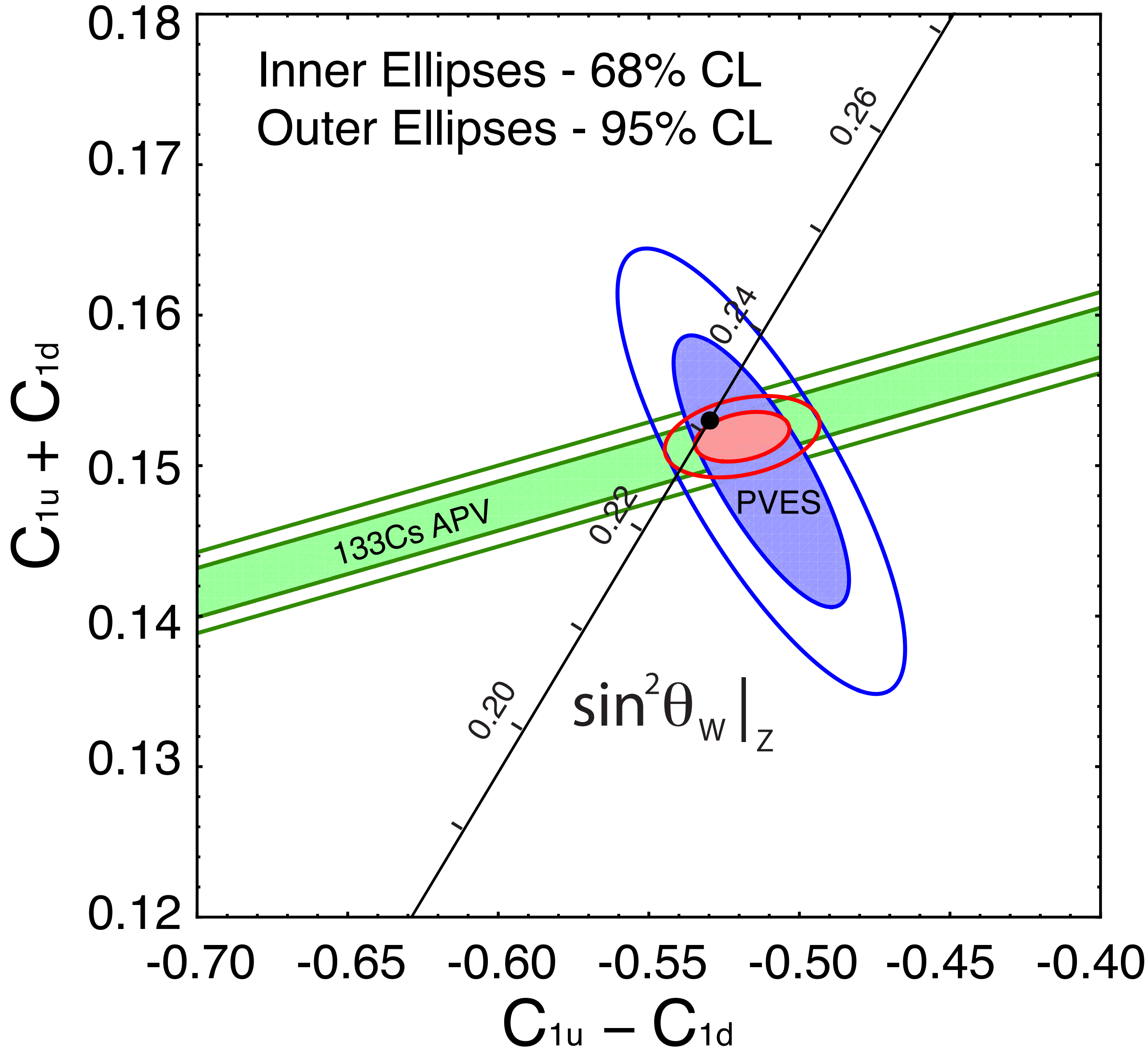


$Q^p_W = 0.064 \pm 0.012$

$Q^p_W(SM) = 0.0710$

Hadronic part extracted through global fit of PVES data.

The C_{1q} & the neutron's weak charge

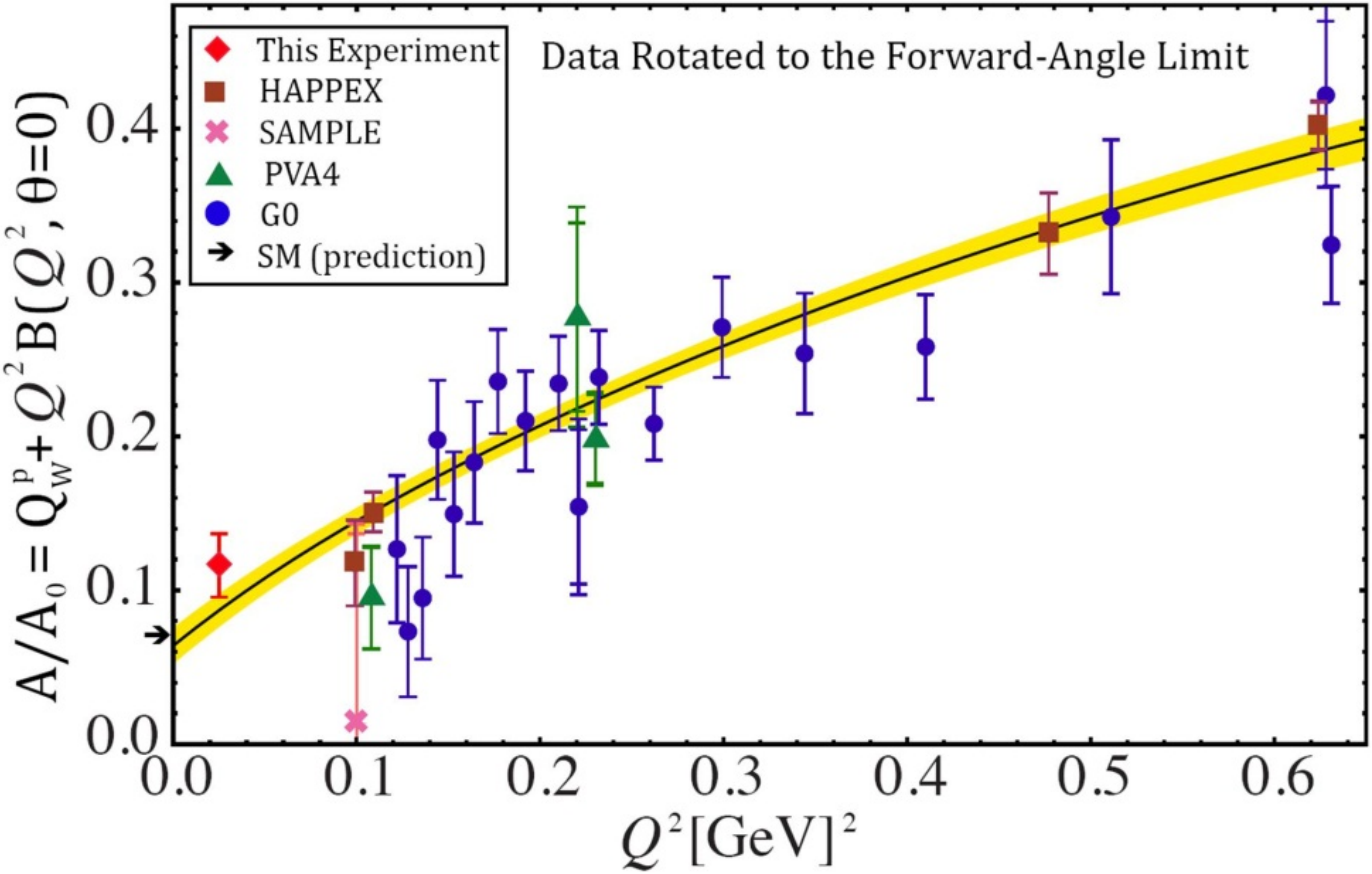


Combining this result with the most precise atomic parity violation experiment we also extract, for the first time, the neutron's weak charge:

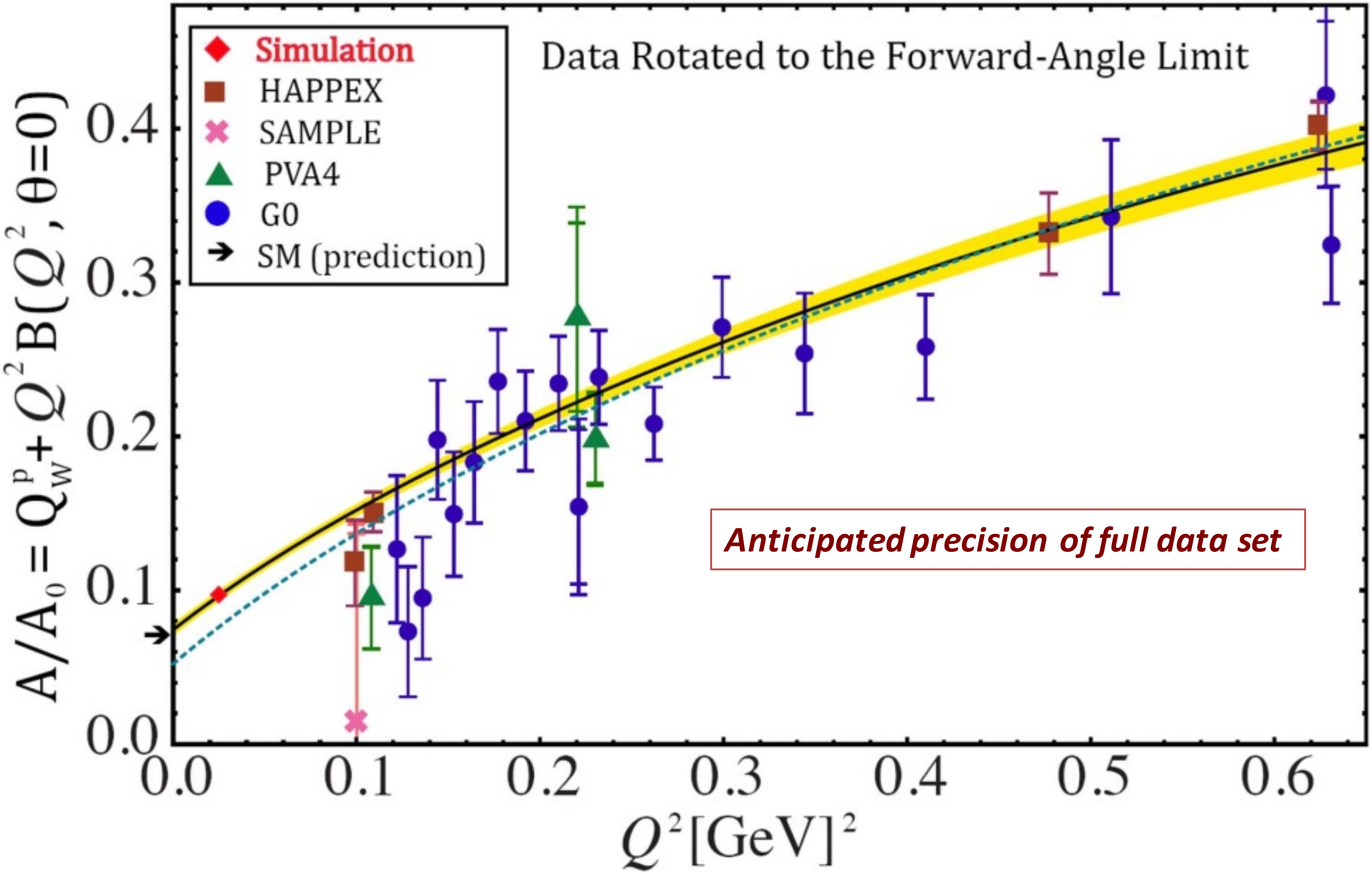
$$Q_W^n = -0.975 \pm 0.010$$

$$Q_W^n(SM) = -0.9890$$

"Teaser"


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

“Teaser”



Anticipated precision of full data set

A suite of Auxiliary Measurements

Q_{weak} has data (under analysis) on a variety of observables of potential interest for Hadron physics:

- PV asymmetry for elastic/quasielastic from ^{27}Al
- Beam normal single-spin asymmetry* for elastic scattering on proton
- Beam normal single-spin asymmetry for elastic scattering on ^{27}Al & ^{12}C
- PV asymmetry in the $N \rightarrow \Delta$ region.
- Beam normal single-spin asymmetry in the $N \rightarrow \Delta$ 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 diagram)
- PV asymmetry in pion photoproduction

*: *aka* vector analyzing power *aka* transverse asymmetry;
generated by imaginary part of two-photon exchange amplitude

Q_{weak} Collaboration

97 collaborators **23 grad students**
10 post docs **23 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

D. Androic,[1] D.S. Armstrong,[2] A. Asaturyan,[3] T. Averett,[2] J. Balewski,[4] J. Beaufait,[5] R.S. Beminiwattha,[6] J. Benesch,[5]
F. Benmokhtar,[7] 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] 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]
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] and S. Zhamkochyan[3]

Spokespersons Project Manager Grad Students

Summary

First result (4% of data set):

$$A_{PV} = -279 \pm 35(stat) \pm 29\ (sys)\ \text{ppb}$$

The weak charges:

Q_W^p = 0.064 ± 0.012 Q_W^p(SM) = 0.0710

Q_W^n = -0.975 ± 0.010 Q_W^n(SM) = -0.9890

Expect final result in a few months.

Will be statistics-dominated.