The Qweak Experiment
First Determination of the Proton's Weak Charge

Josh Magee
for the Qweak Collaboration
May 29th,2013

- Introduction & background
  - The electroweak sector and PVES
  - Electroweak/model corrections
- Instrumentation & methodology
  - Experimental setup
  - Subsystem overview
- Initial results
  - Measured A_{phys}^{PV}
  - Implications and "new" physics

The College of WILLIAM & MARY
Jefferson Lab
Thomas Jefferson National Accelerator Facility
National Science Foundation
WHERE DISCOVERIES BEGIN

Qweak Collaboration

~24 institutions
~23 grad students
~10 post docs

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[1]Spokespersons [2]Project Manager Grad Students

The Standard Model

The SM is believed to be the effective low-energy theory of some "new" fundamental physics.

Finding new physics - two complementary approaches:

Energy frontier: Tevatron, LHC

Precision frontier:

- μ(g-2), EDM, 0νββdecay, etc
- ν-oscillations
- Atomic parity violation (APV)
- Parity-violating electron scattering (PVES)

Should direct measurements find new physics, precision measurements provide important information, such as strength of couplings

Hallmark of precision frontier: choose observables that are zero or "highly suppressed"

One such observable is the proton's weak charge (Q_W^p)

The weak charges

What exactly is the proton's weak charge (Q_W^p)?

Neutral-weak analog of the proton's electric charge

Dirac form factor of the neutral-weak interaction

The Standard Model makes a firm prediction of Q_W^p

	EM Charge	Weak Charge
u	2/3	$1 - \frac{8}{3} sin^2(\theta_w) \approx 0.38$
d	-1/3	$-1 + \frac{4}{3} sin^2(\theta_w) \approx -0.69$
P (uud)	+1	$1 - 4\, sin^2(\theta_w) \approx 0.07$
N (udd)	0	-1

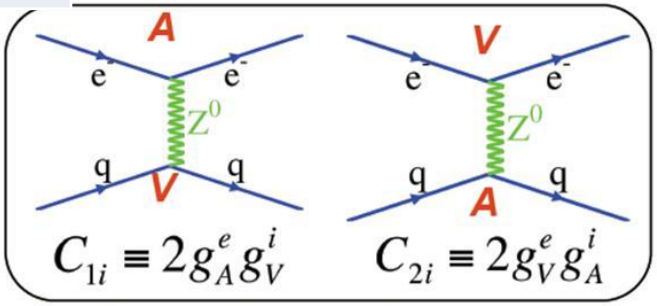
"Accidental suppression"

→sensitivity to new physics

Note: $Q_W^n = -1$

Q-weak is particularly sensitive to the quark *vector* couplings (C_{1u} and C_{1d}) .

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



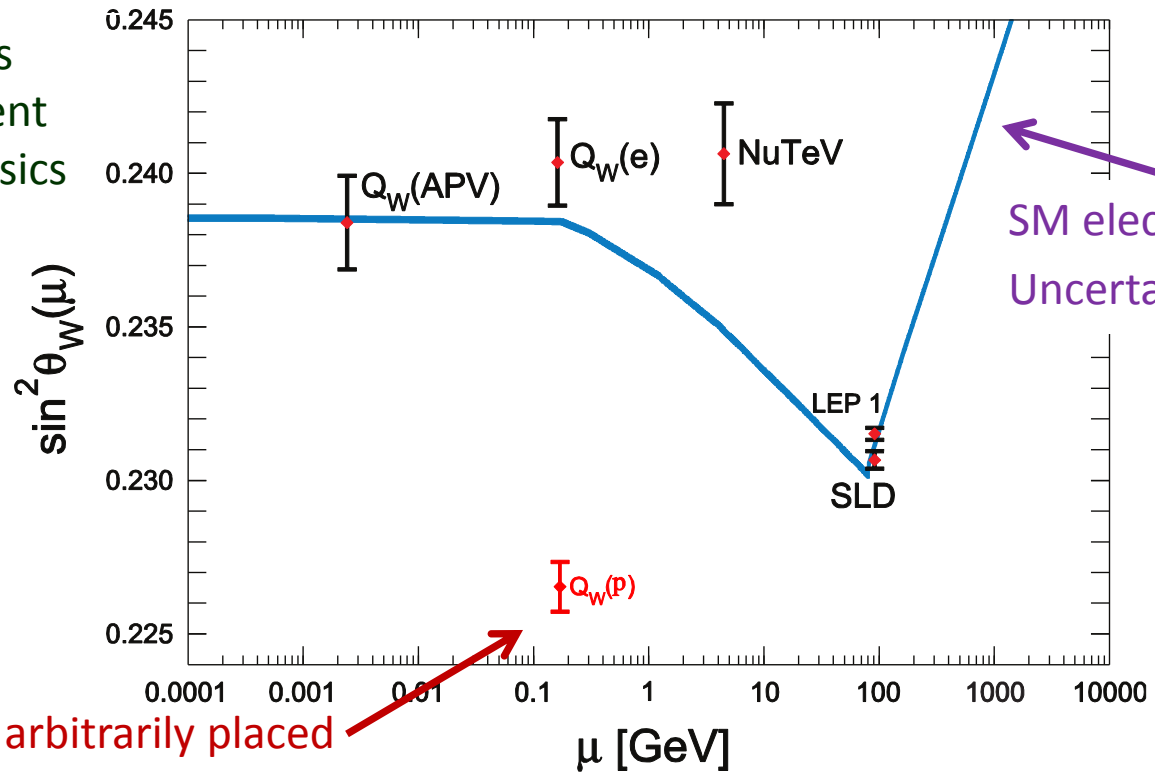
Small scattering angles

Large scattering angles

The Running of the Weak Mixing Angle

The measurements at the Z-pole pin down the scale; they don't describe the evolution in the low Q^2 regime.

Each experiment is sensitive to different potential new physics



SM electroweak fit.

Uncertainty is line width.

Vertical position arbitrarily placed

Error bar is proposed goal

Q-weak will make the most precise measurement of $\sin^2(\theta_W)$ at low-Q^2

$$\delta(\sin^2\theta_W) \approx \pm 0.3\%$$

Beringer et al, (PDG), Phys. Rev D86, 010001 (2012)

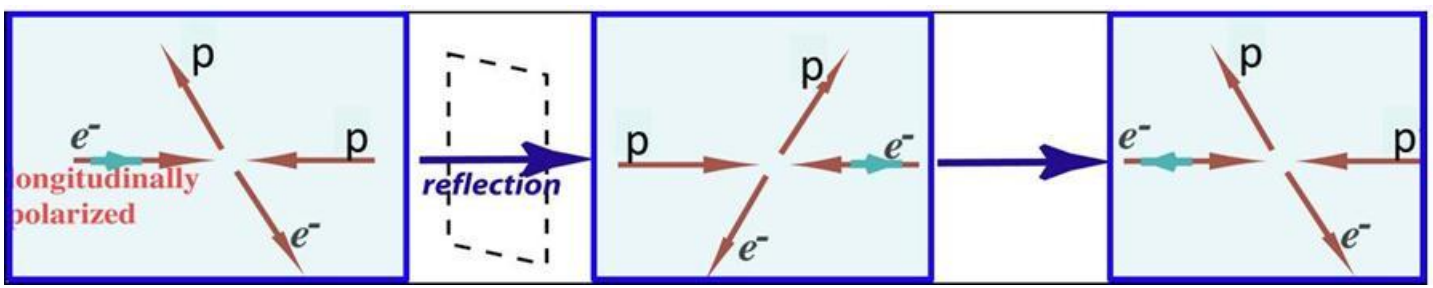
Probing the Weak Charge

The weak force is *unique*: it violates parity

To extract Q_W^p: measure the parity violating asymmetry in electron-proton scattering

$$\vec{e} + p \rightarrow e + p$$

Beam helicity change is equivalent to parity transformation



Rapid helicity reversal pattern (960 Hz) "quartets"

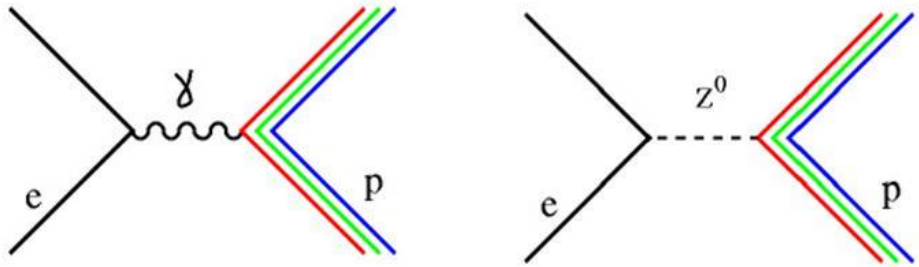
+--+ -++-

Probing the Weak Charge

The weak force is *unique*: it violates parity

To extract Q_W^p: measure the parity violating asymmetry in electron-proton scattering

Typically the photon exchange dominates, but interference with EM amplitude makes the neutral current accessible



$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{|M_{PV}^{NC}|}{|M^{EM}|}$$

The SM prediction is
~ -216 parts per billion (ppb)

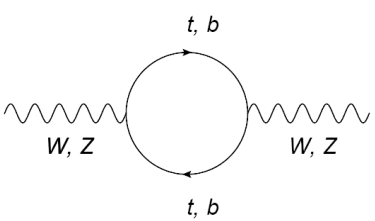
Tiny ($\sim 10^{-6}$) cross section
asymmetry isolates weak interaction

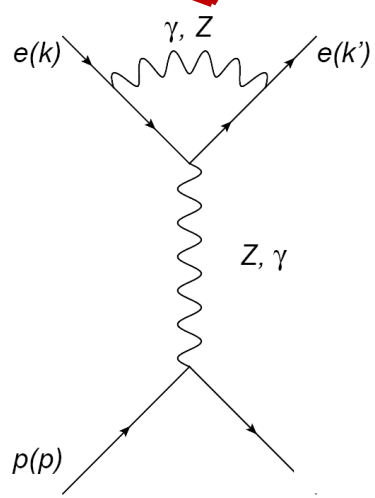
For $Q^2 \ll (M_Z)^2,\ A \approx \frac{Q^2}{(M_Z)^2}$

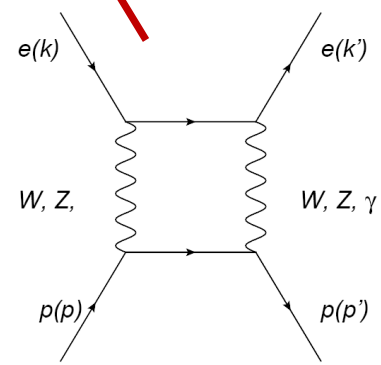
Energy Dependence

In the Standard Model, the weak charge is *defined* at $Q^2 = 0, E = 0$.

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







Full expression for Q_W^p has energy dependent corrections – need precise calculations

The $\square_{WW}$ and $\square_{ZZ}$ are well determined from pQCD ($\propto \frac{1}{q^2 - M_{W(Z)}^2 + i\epsilon}$)

The $\square_{\gamma Z}$ isn't pQCD friendly due to the photon leg ($\propto \frac{1}{q^2 + i\varepsilon}$)

Energy Dependence

In the Standard Model, the weak charge is *defined* at $Q^2 = 0, E = 0$.

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

Uncertainty from these corrections on *current* results is irrelevant.

Previously the uncertainty on this calculation was believed to be problematic for *final* result

Energy Dependence

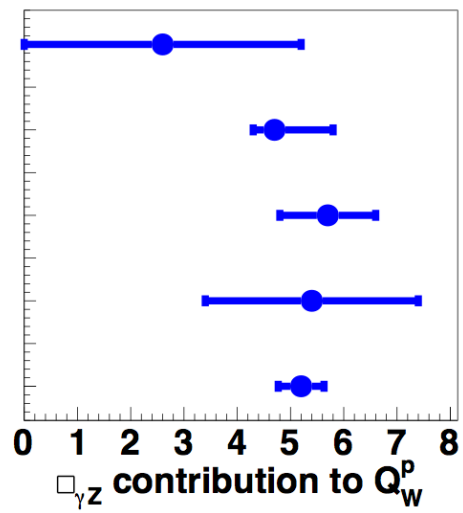
In the Standard Model, the weak charge is *defined* at $Q^2 = 0, E = 0$.

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

Uncertainty from these corrections on *current* results is irrelevant.

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

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 (2013)* (calculation constrained by PVDIS data)	0.0052 ± 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

Extracting the weak charge

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

Hadronic structure enters here

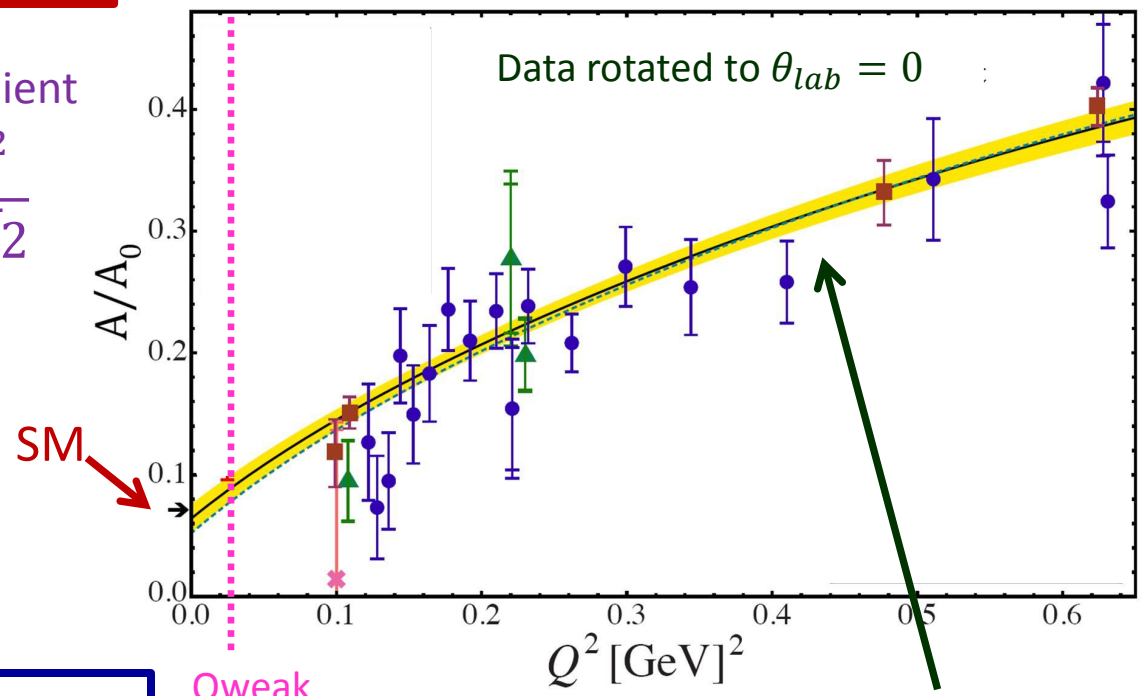
Reduced asymmetry more convenient

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

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

We measure A_{phys}^{PV}

at $Q^2 = 0.025\ GeV^2$.



Qweak kinematics

Hadronic term extracted from fit

Consequences of low Q^2 measurement:

- Relatively insensitive to proton's internal structure
- Short extrapolation distance

→First determination: proton's weak charge

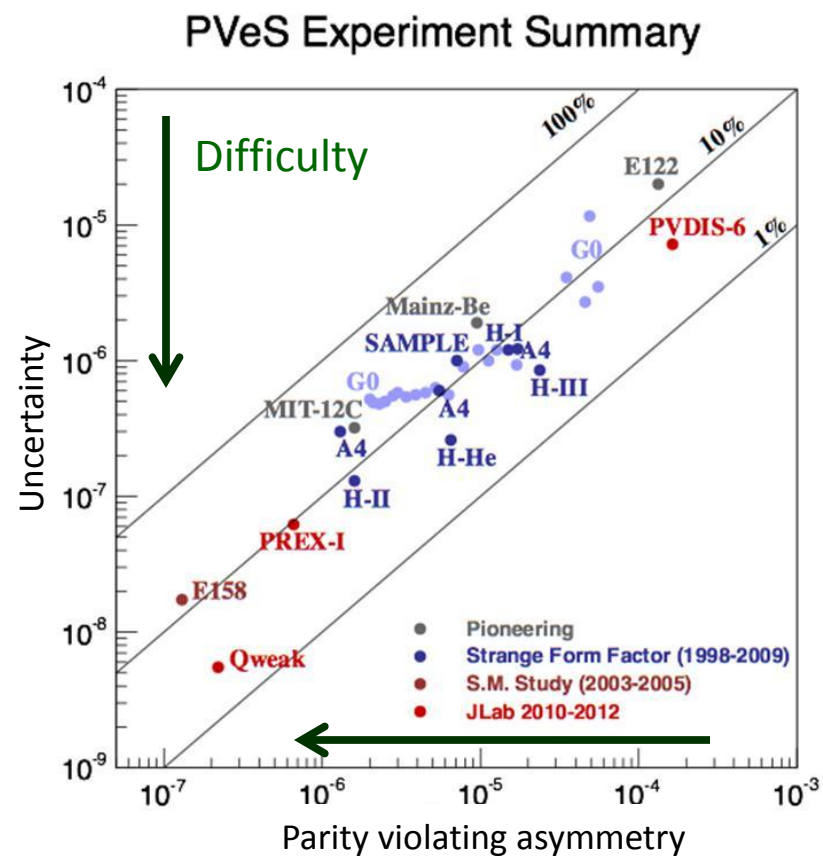
Previous experiments explored hadronic structure more directly; help constrain our hadronic contribution

PVES Challenges

Qweak is the most precise (relative and absolute) PVES result to date, and will use past results to bound theoretical backgrounds

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



Small absolute *and* relative uncertainty (5ppb on A_{PV})

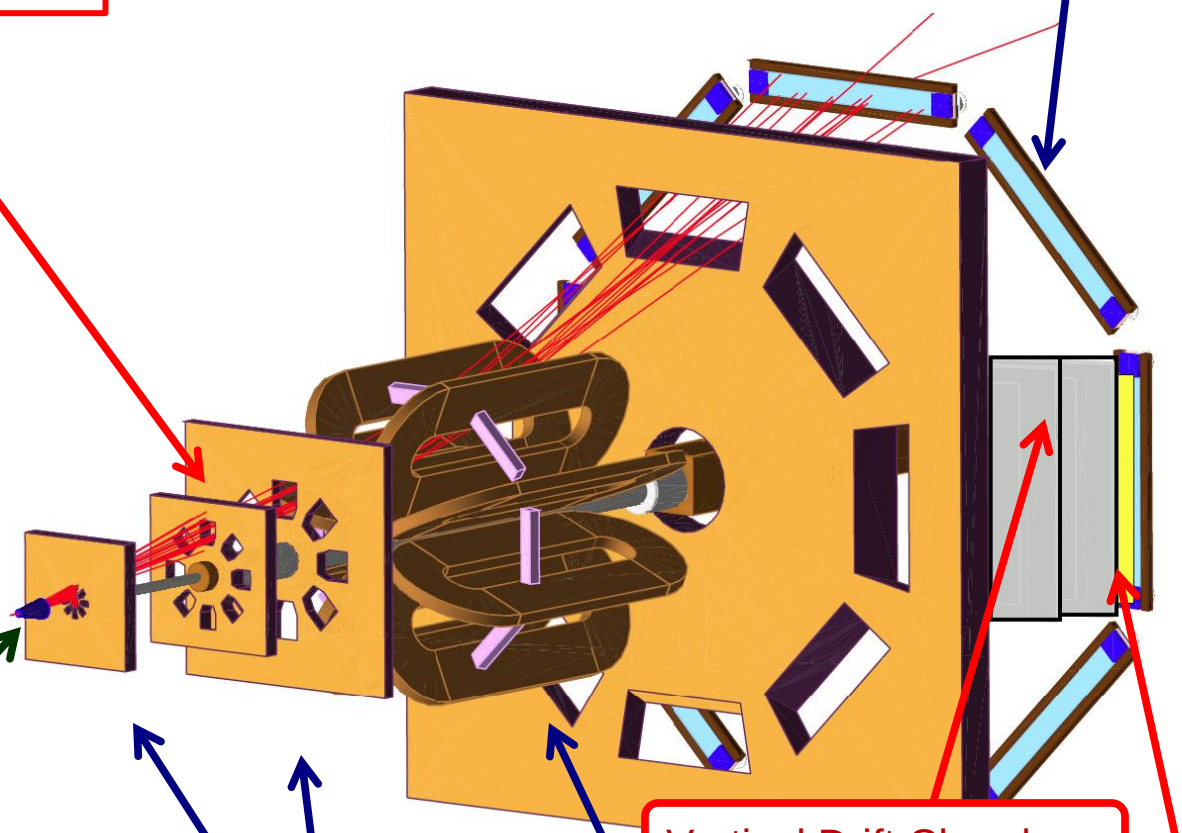
$$\delta A_{PV} \approx \pm 2.1\%$$

$$\delta Q_W^p \approx \pm 4\%$$

$$\delta(\sin^2\theta_W) \approx \pm 0.3\%$$

Q-weak Apparatus

E_{beam}= *1.165 GeV*
Q^2~0.025 GeV^2
θ ~ 7-11°
Current = 180 μA
Polarization = 85%
Target = 35 cm LH2
Cryopower = 2.5 kW



Red = low-current tracking mode

Blue = production ("integrating") mode

Q-weak Apparatus

Horizontal drift chambers

Quartz Cerenkov Bars

E_{beam}= *1.165 GeV*
Q^2~0.025 GeV^2
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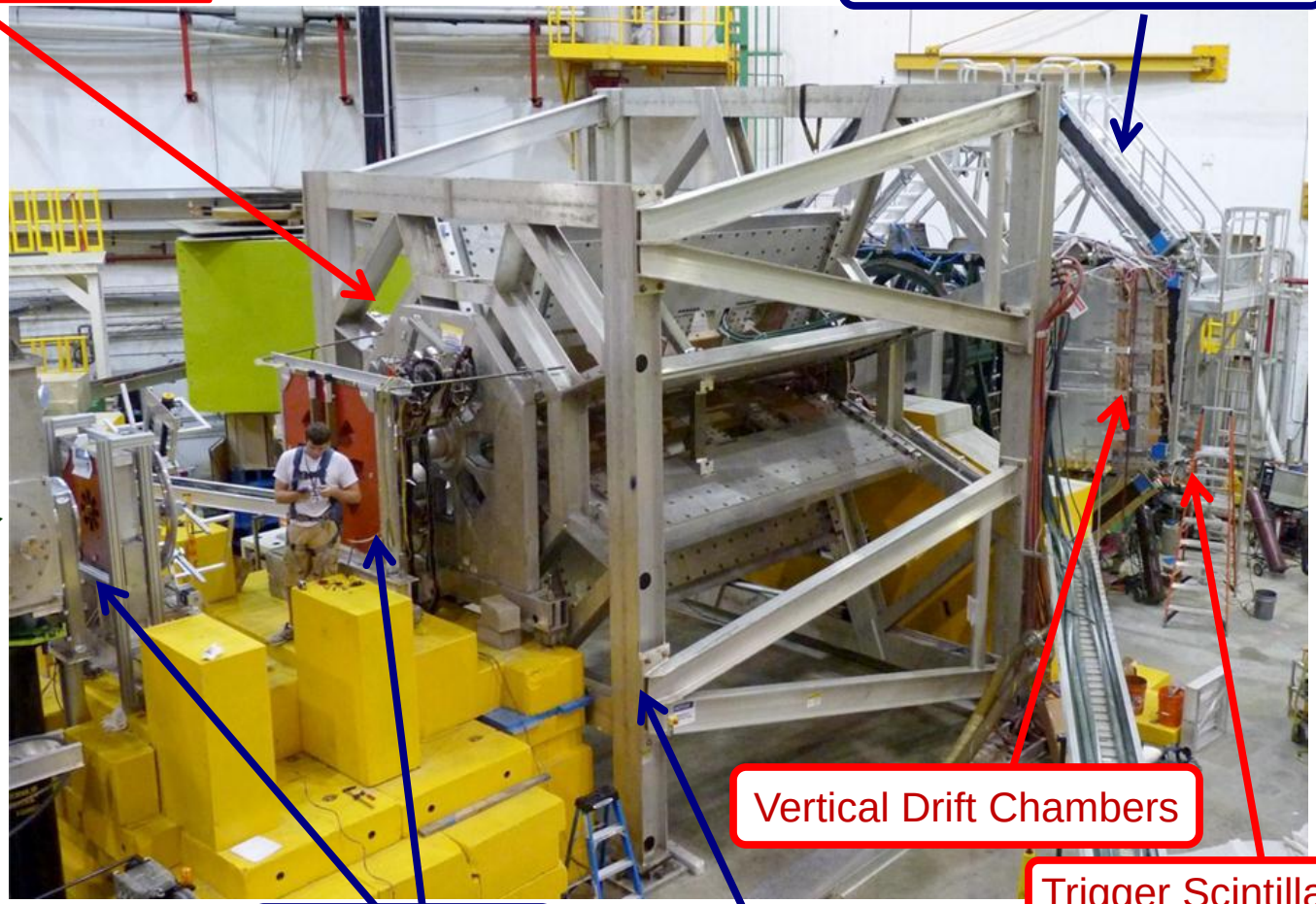


Electron beam

Vertical Drift Chambers

Trigger Scintillator

Collimators

Toroidal Magnet Spectrometer

Red = low-current tracking mode

Blue = production ("integrating") mode

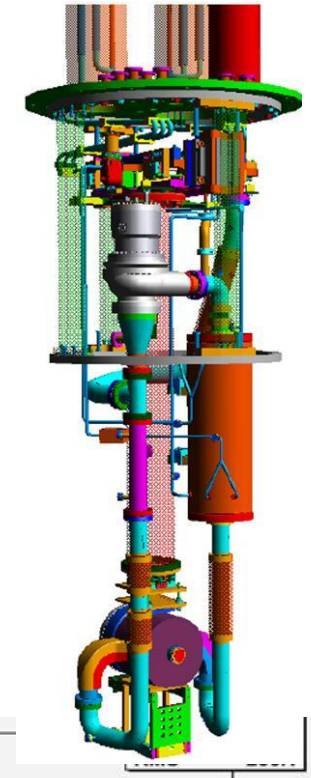
Qweak Target

35 cm, 2.5 kW liquid hydrogen target

World's highest powered cryotarget

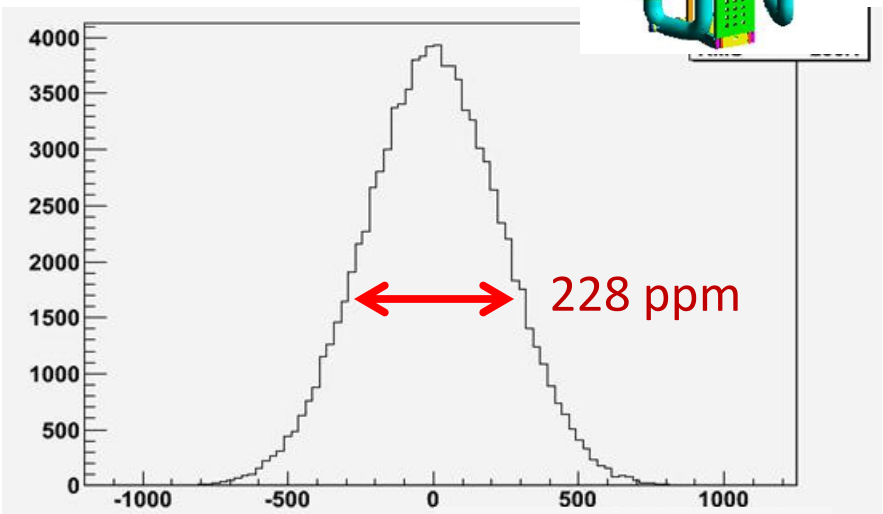
- Temperature ~20 K
- Pressure: 30-35 psia
- Beam at 150 – 180uA

Target boiling might have been problematic!



LH2 statistical width (per quartet):

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



MD LH2 Asymmetry

Total: 228 ppm resolution *per quartet*

→50 ppb per *perfect* day!*

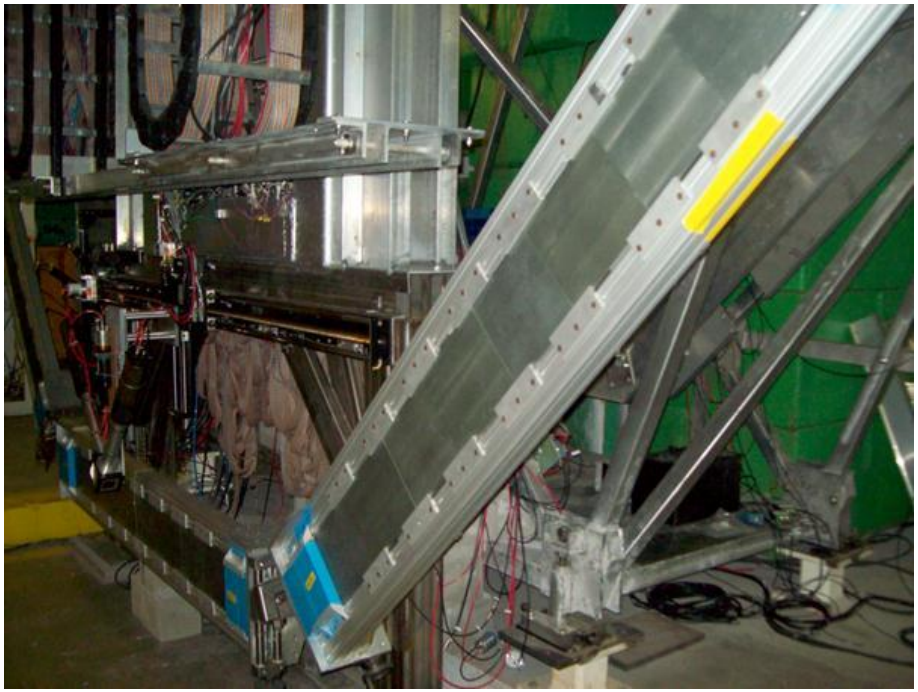
*perfect day: 100% efficiency

Main Detectors

- Main detectors

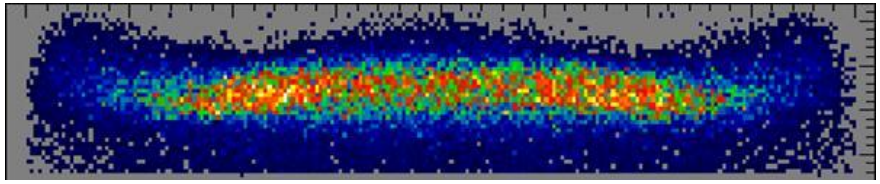
  The toroidal magnet focuses elastically scattered electrons onto each bar

  - 8 Quartz Cerenkov bars
  - Azimuthal symmetry maximizes rates and reduces systematic uncertainties
  - 2 cm lead pre-radiators reduce background
  - Each electron produces ~100 photoelectrons

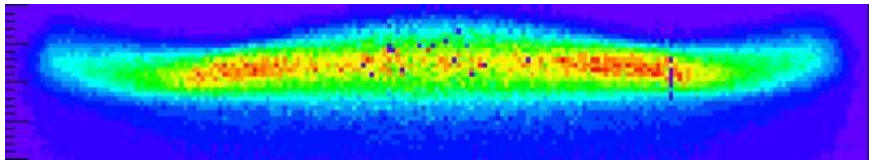


Close up of one detector in situ

Simulation of scattering rate MD face



Measured



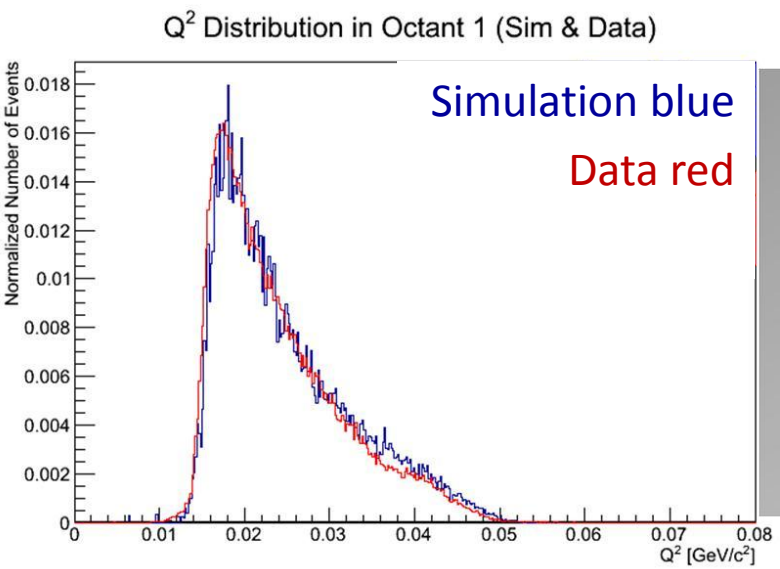
Q^2 determination

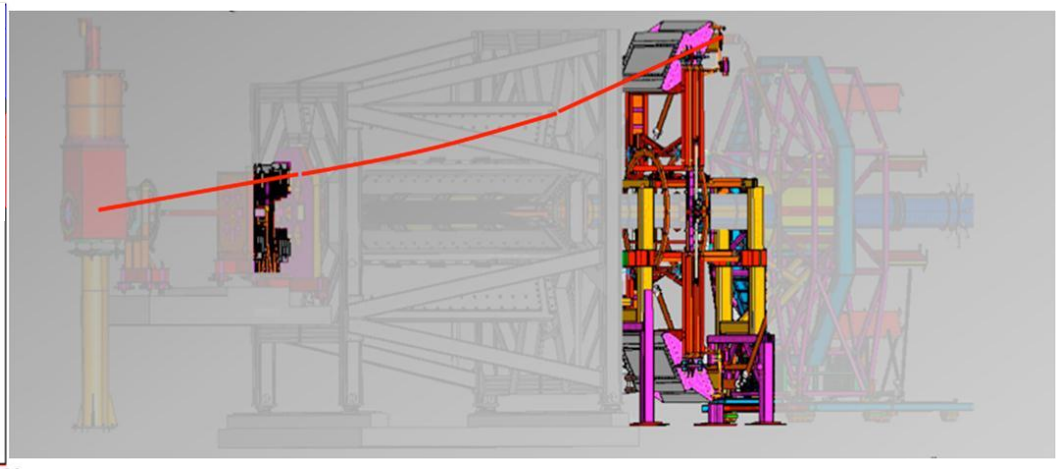
To determine Q^2, we go to "tracking" mode:

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

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

Ultimately need to match data with Geant 3 and 4 simulations





Hall C Beam Polarimetry

Polarization is our largest systematic uncertainty (1%)

This is a challenging goal; so we built a *second*, independent measurement device.

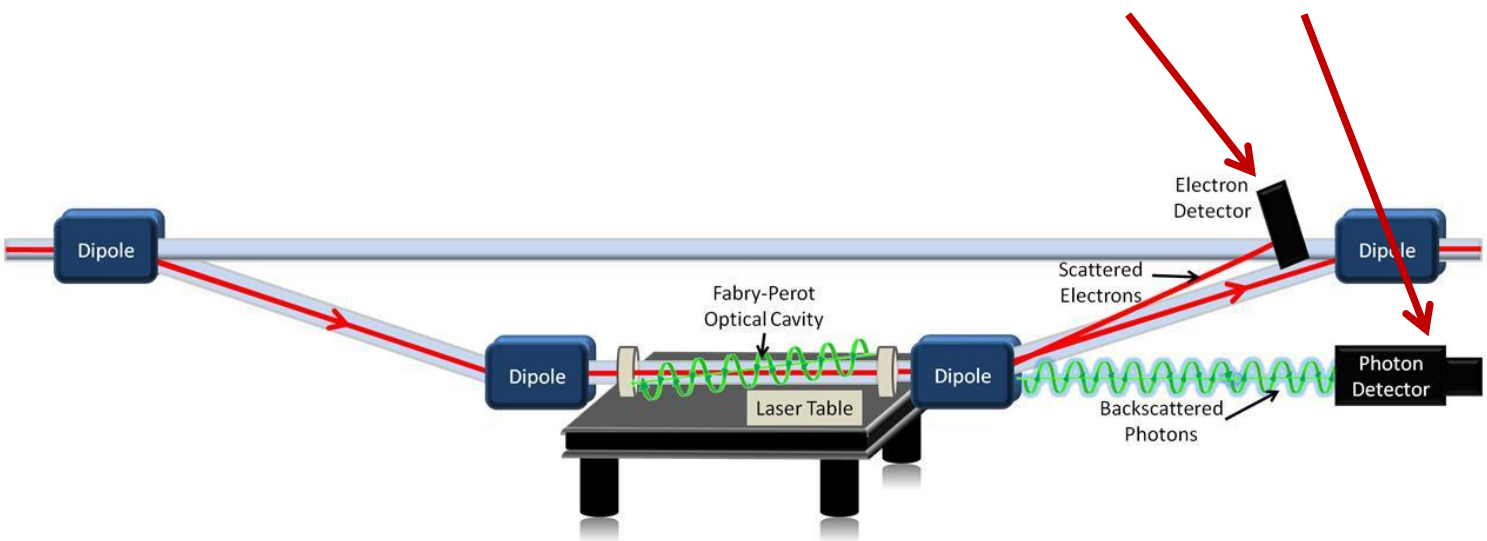
Møller polarimeter

- First of its kind 15 years ago
- Thin, pure iron target
- Brute force polarization
- Limited to low current

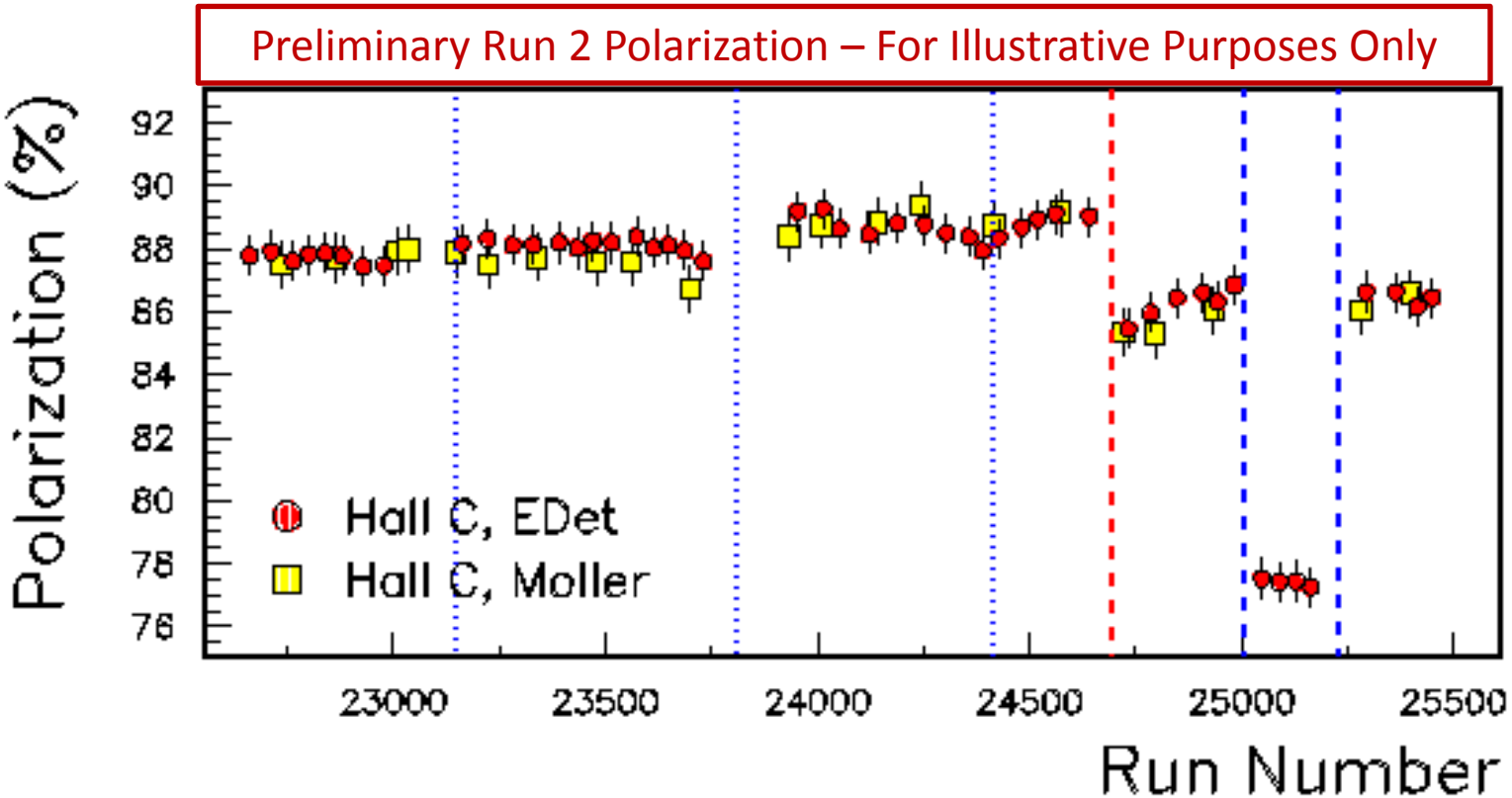
Compton polarimeter

- Installed for Q-weak
- Run continuously at high currents
- Statistical precision: 1% per hour

We can detect *both* recoil electron and photon.



Beam Polarimetry



Note the wonderful agreement between both polarimeters!

Plot courtesy of Vladis Tvaskis

Auxiliary Measurements

In addition to the ~4% measurement of the proton's weak charge,

Q-weak conducted numerous other ancillary measurements:

- Elastic transverse asymmetry (proton)*
- Elastic transverse asymmetry (Aluminum)
- PV asymmetry in the $N \rightarrow \Delta$ region
- Transverse asymmetry in the $N \rightarrow \Delta$ region
- PV non-resonant inelastic scattering γZ box diagram constraining
- Transverse asymmetry in the PV inelastic scattering region (3.3 GeV)
- PV asymmetries in pion photoproduction
- Transverse asymmetries in pion photoproduction
- Measurements of elastic PV asymmetry on aluminum (alloys) / carbon

*Beam normal single spin asymmetry

Plenty of projects, plenty of results, 20+ theses….

Due to time constraints, highlight only the Transverse Elastic $\vec{e}p$

Transverse Asymmetry Measurement

Normal production running: 89% longitudinal beam polarization

Small amount of transverse polarization

- Large parity conserving asymmetry (~5ppm)
- Leaks into the experimental asymmetry through broken azimuthal symmetry

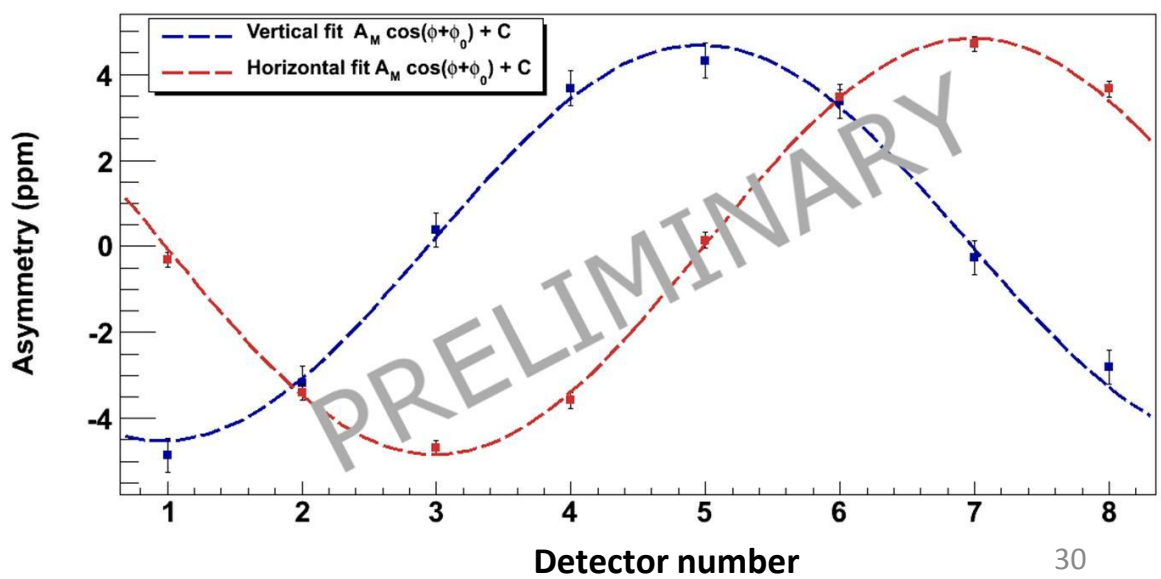
Measurements of the Beam Normal Single Spin Asymmetry (BNSSA) provide:

- Direct access to imaginary part of two-photon exchange

We need to correct for this!

Horizontal and vertical components measured separately

$$A_{BNSS}(\phi_{det}) = B_n|P_T|\sin(\phi_{det} - \phi_s)$$



Transverse Asymmetry Measurement

Normal production running: 89% longitudinal beam polarization

Small amount of transverse polarization

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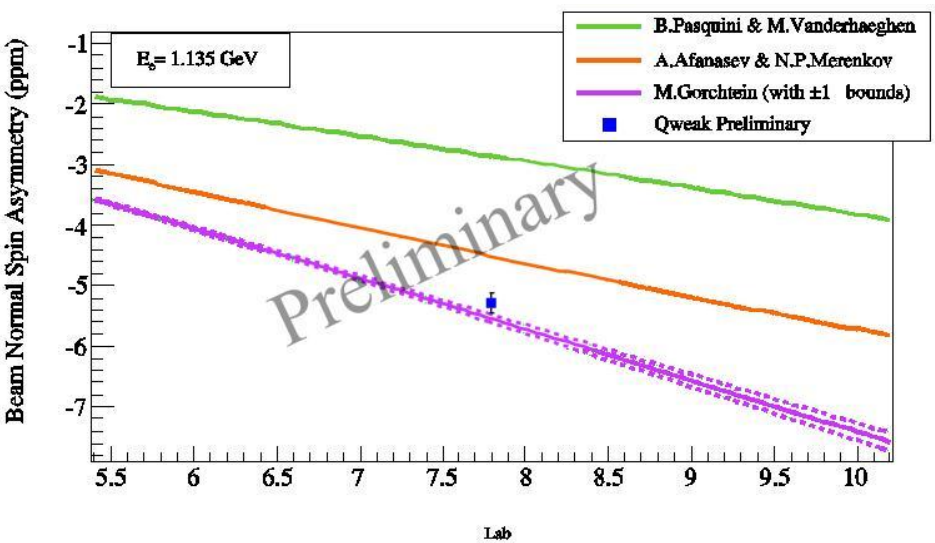
$$B_n = -5.30 \pm 0.07(stat) \pm 0.15(sys) \text{ ppm}$$



Source	Preliminary	Anticipated
Polarization	2.2%	~1.0%
Statistics	1.3%	~1.3%
Q^2	1.2%	~0.5%
Non-linearity	1.0%	~0.2%
Regression	0.9%	~0.9%
Backgrounds	0.3%	~0.3%

This is the most precise measurement of Beam Normal Single Spin Asymmetry to date.

Private communication with Buddhini Waidyawansa

Run periods

Q-weak ran from Fall 2010 – May 2012 in four distinct running periods

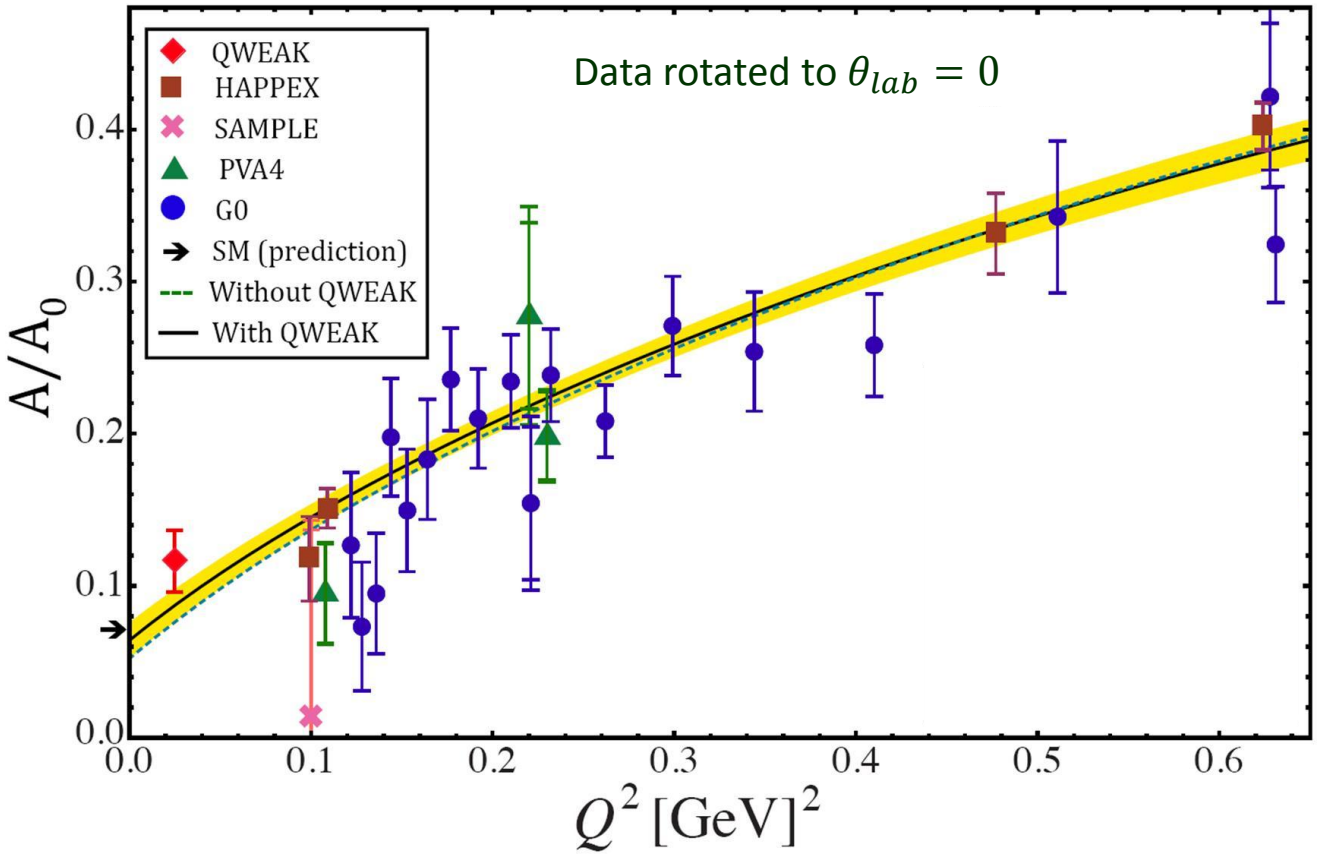
- Hardware checkout (Fall 2010-January 2011)
- Run 0 (Jan-Feb 2011)
- Run 1 (Feb – May 2011)
- Run 2 (Nov 2011 – May 2012)

This talk focuses only on the Run 0 period (about 1/25th of our total dataset).

This small bit already enables us to constrain possible “new” physics and is competitive with previous experiments.

Q_W^p extraction

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



The fit takes into account the θ, Q^2 of each point. To plot: rotated data to forward angle, and corrected for the Q^2 and E dependence of the $\square_{\gamma Z}$.

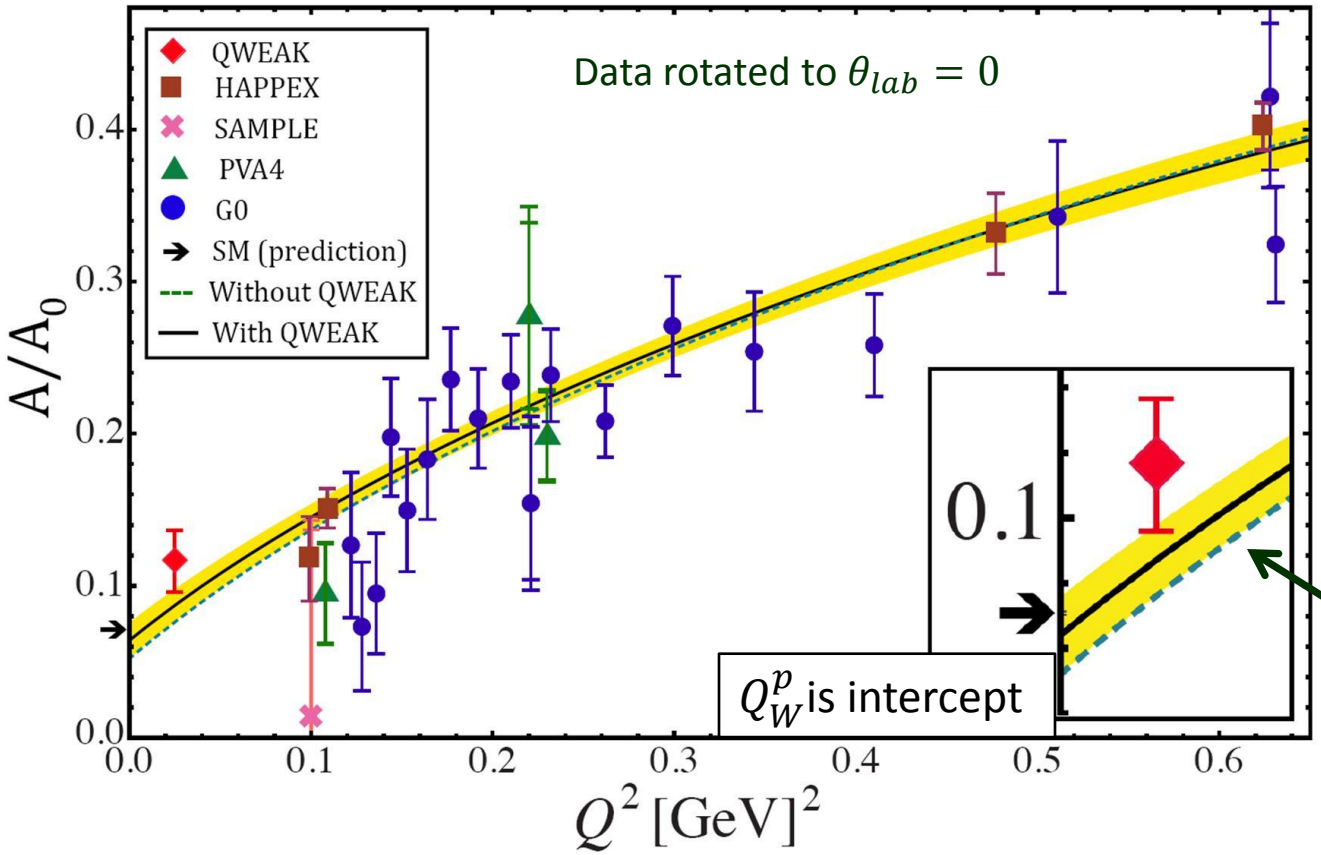
$\overline{A_{LR}^P}$ is the reduced asymmetry.

Note the initial agreement with the standard model.

Our uncertainty band will eventually shrink by ~5.

Q_W^p extraction

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



The fit takes into account the θ, Q^2 of each point. To plot: rotated data to forward angle, and corrected for the Q^2 and E dependence of the $\square_{\gamma Z}$.

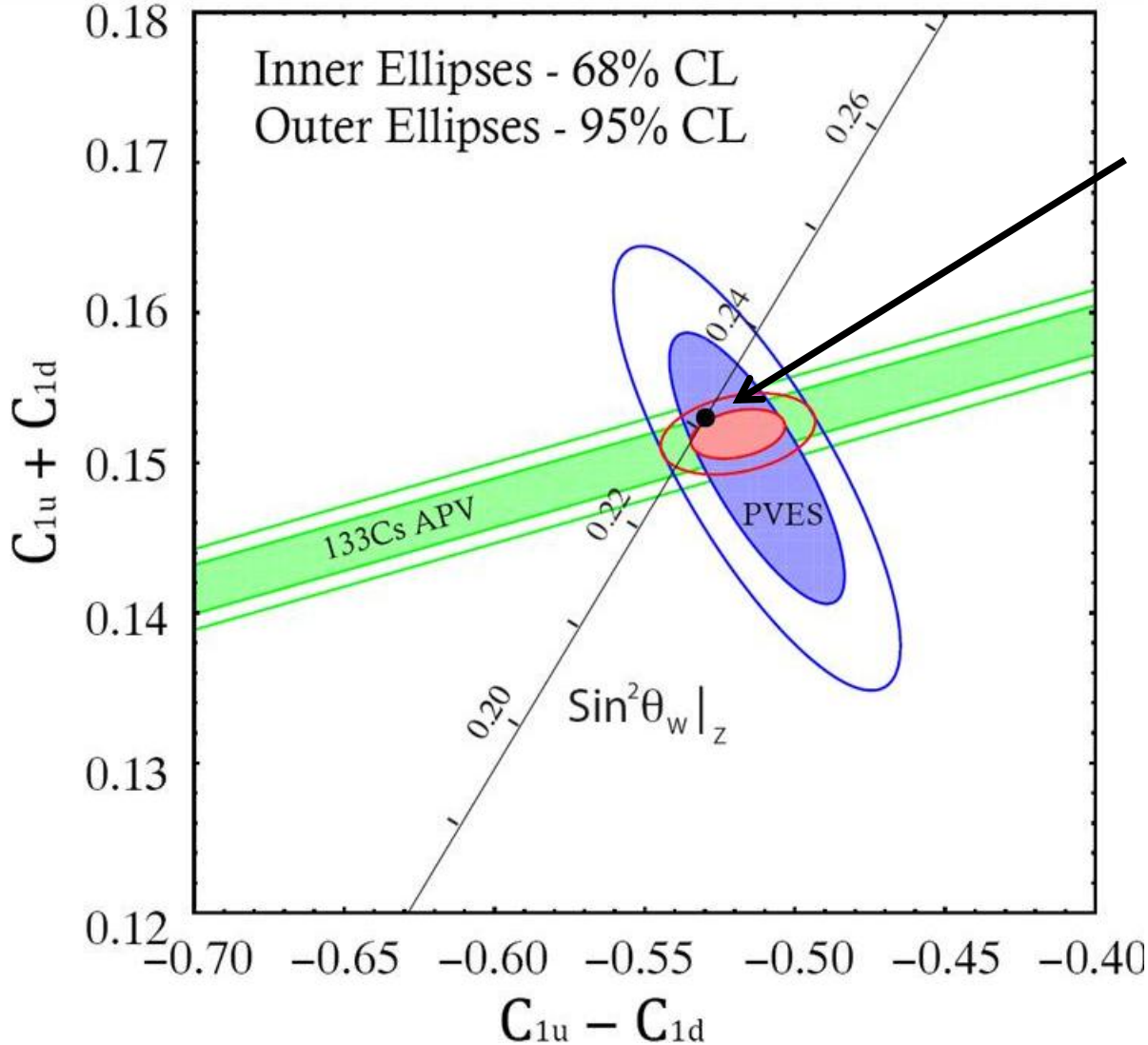
Green line is fit without Q-weak. Note: already significant measurement; we "anchor" the fit.

$\overline{A_{LR}^P}$ is the reduced asymmetry.

Note the initial agreement with the standard model.

Our uncertainty band will eventually shrink by ~5.

Constraints on quark couplings



Black dot is SM value

PVES includes Q-weak and world data

APV is more sensitive to isoscalar combinations due to large neutron contribution

Red is combined fit

$$C_{1u} = -0.1849 \pm 0.0053$$

$$C_{1d} = \quad 0.3370 \pm 0.0050$$

Individual weak vector-couplings to the quarks are given by the C_1's.

The final result will form a tight band, providing the most precise measurement to date.

Conclusions and Future

Our initial Run 0 measurement (only 1/25th of our data):

- Our current measurement:

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

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

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

$\theta_{eff} = 7.90\ °$

- The weak charges

$Q_W^p = \quad 0.064 \pm 0.012$

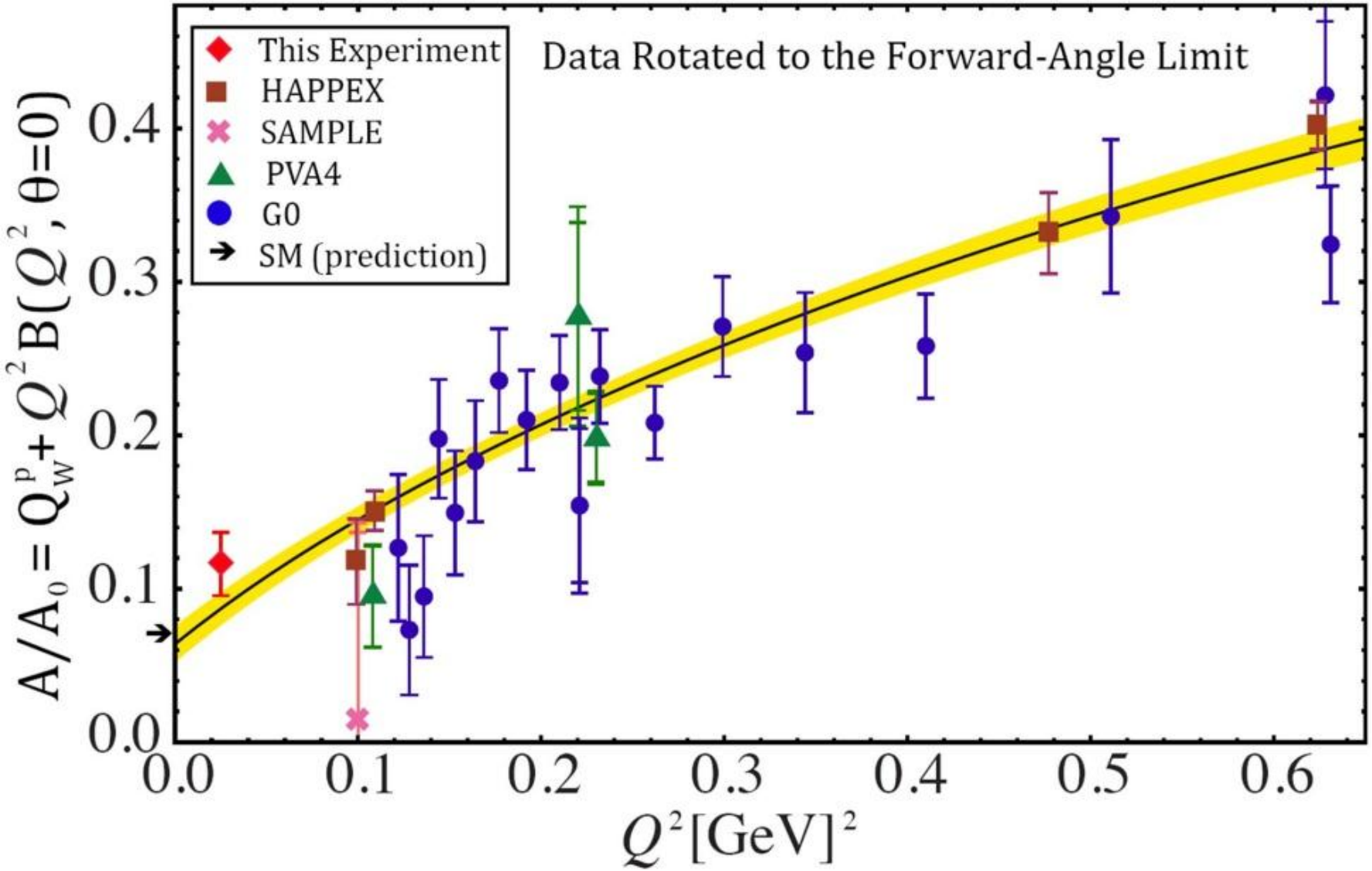
$Q_W^p(SM) = \quad 0.0710$

$Q_W^n = -0.975 \pm 0.010$

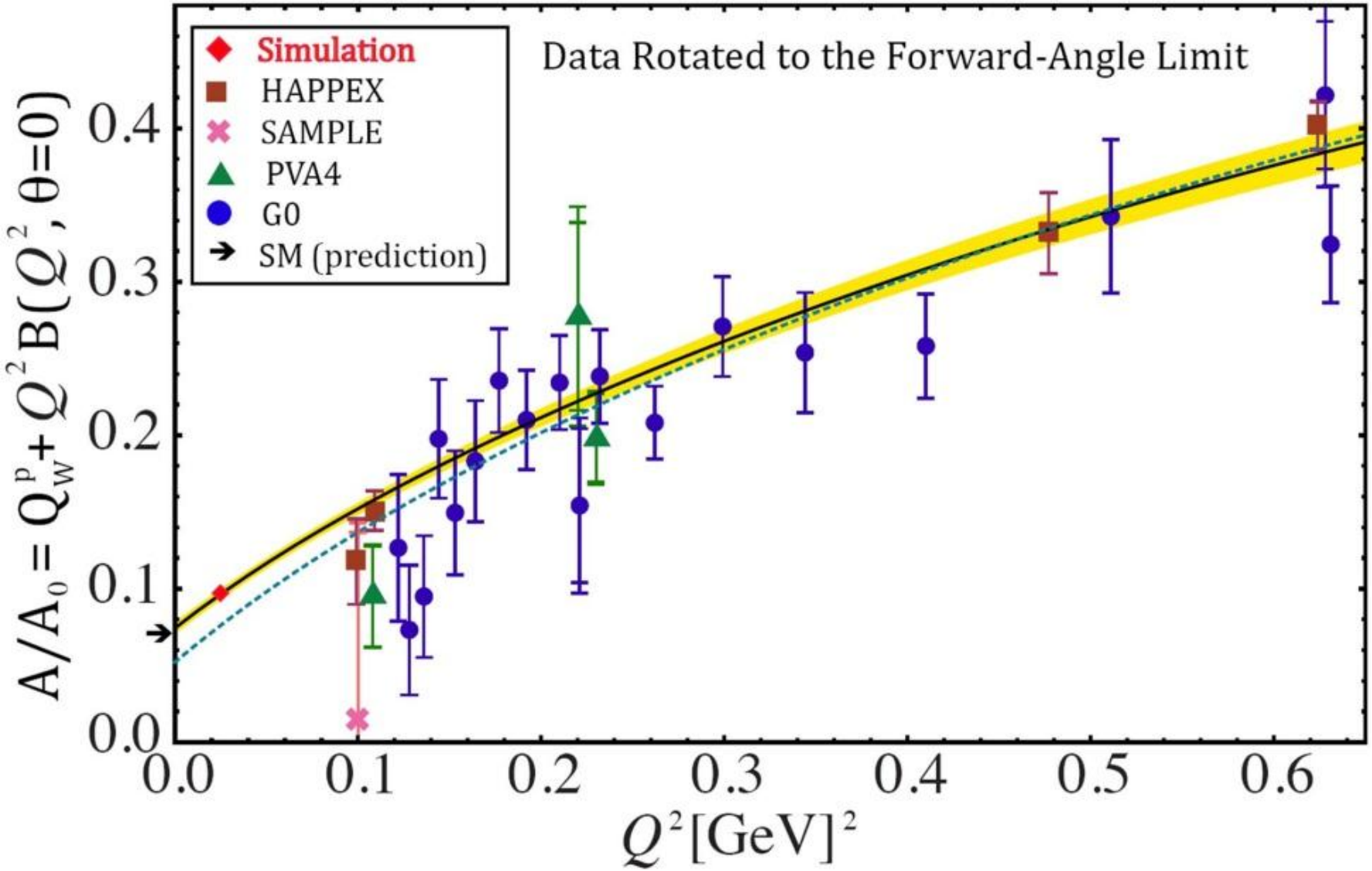
$Q_W^n(SM) = -0.9890$

These results are being submitted for publication.
Analysis of full dataset underway, final results expected next year.
Perhaps, some ancillary measurement results sooner.

"Teaser"


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

"Teaser"


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

Qweak Collaboration

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