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

Josh Magee
for the Qweak Collaboration
September 11^{th},2014

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

Summary of recent paper: D. Androic *et al*, Phys. Rev. Lett. 111, 141803 (2013).

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

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, D. Meekins, 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

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

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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 Electroweak Sector

The proton's weak charge is highly suppressed in the standard model (SM), making a precise measurement particularly sensitive to "new" physics

→Q_W^p is the neutral-weak analog of the proton's electric charge

	EM Charge	Weak Charge (SM)
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: $Q_W^n = -1$

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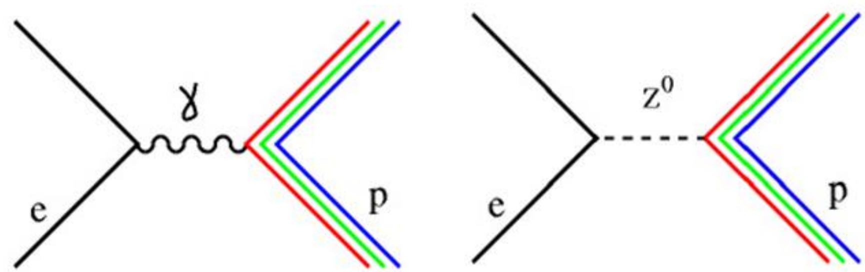
Typically the photon exchange dominates, but interference with the EM amplitude makes the neutral current accessible.



Tiny cross section asymmetry isolates weak interaction

SM prediction: ~ -216 parts per billion (ppb)!

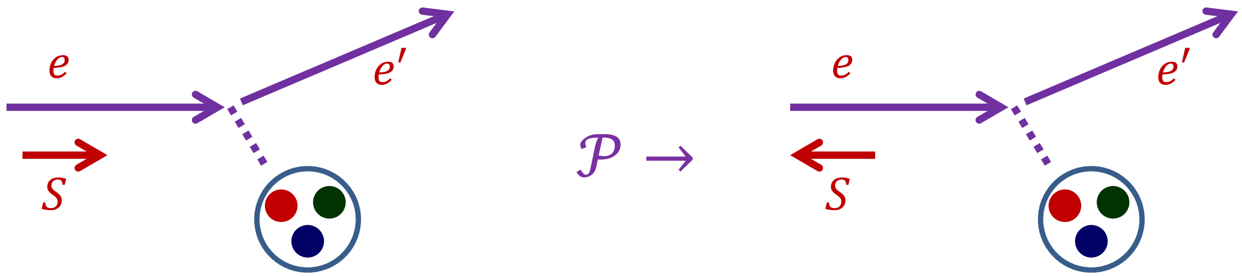
$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{|M_{PV}^{NC}|}{|M^{EM}|}$$

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

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



Key: Beam helicity change is equivalent to parity transformation

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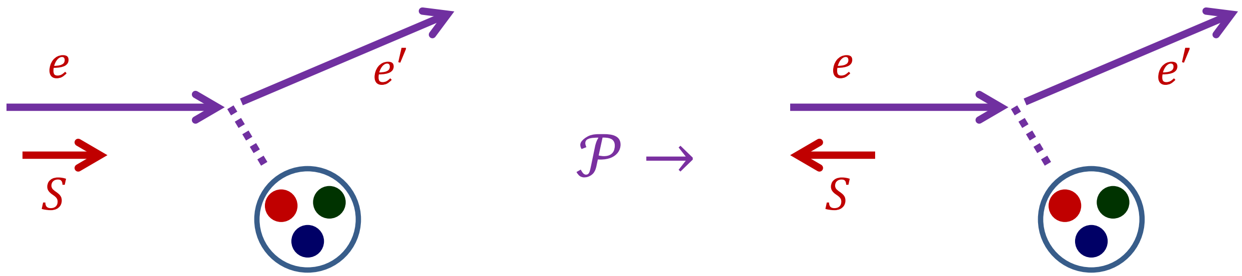


Key: Beam helicity change is equivalent to parity transformation

Rapid helicity reversal pattern
(960 Hz) “quartets”

+ − − +   − + + −

We *integrate* over this helicity period (rates too high to count)

$$\mathcal{L} \sim \mathcal{O}(10^{39}) cm^{-2} s^{-2}$$

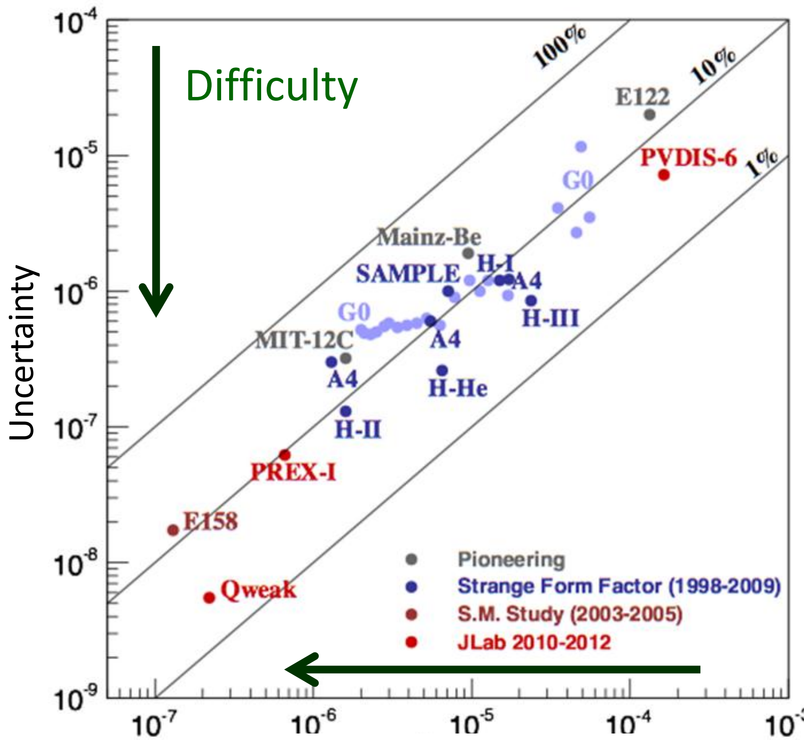
PVES Challenges

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

PVES Experiment Summary

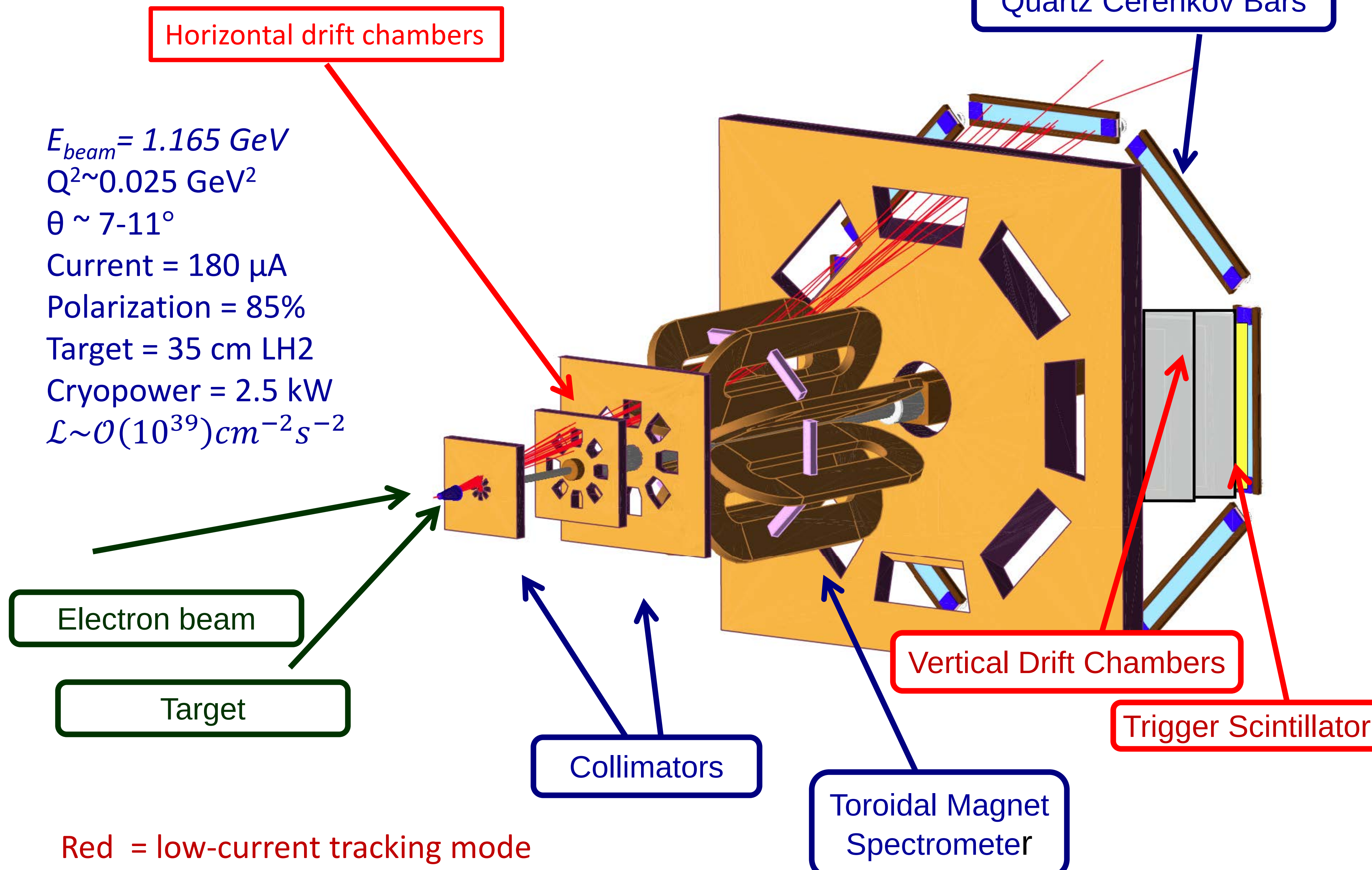


Small absolute *and* relative uncertainty (5ppb on A_{PV})

$$\delta A_{PV} \approx \pm 2.1\%$$
$$\delta Q_W^p \approx \pm 4\%$$
$$\delta(\sin^2\theta_W) \approx \pm 0.3\%$$

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
$\mathcal{L} \sim \mathcal{O}(10^{39}) cm^{-2} s^{-2}$



Red = low-current tracking mode
Blue = production ("integrating") mode

Q-weak Apparatus

Horizontal drift chambers

Quartz Cerenkov Bars

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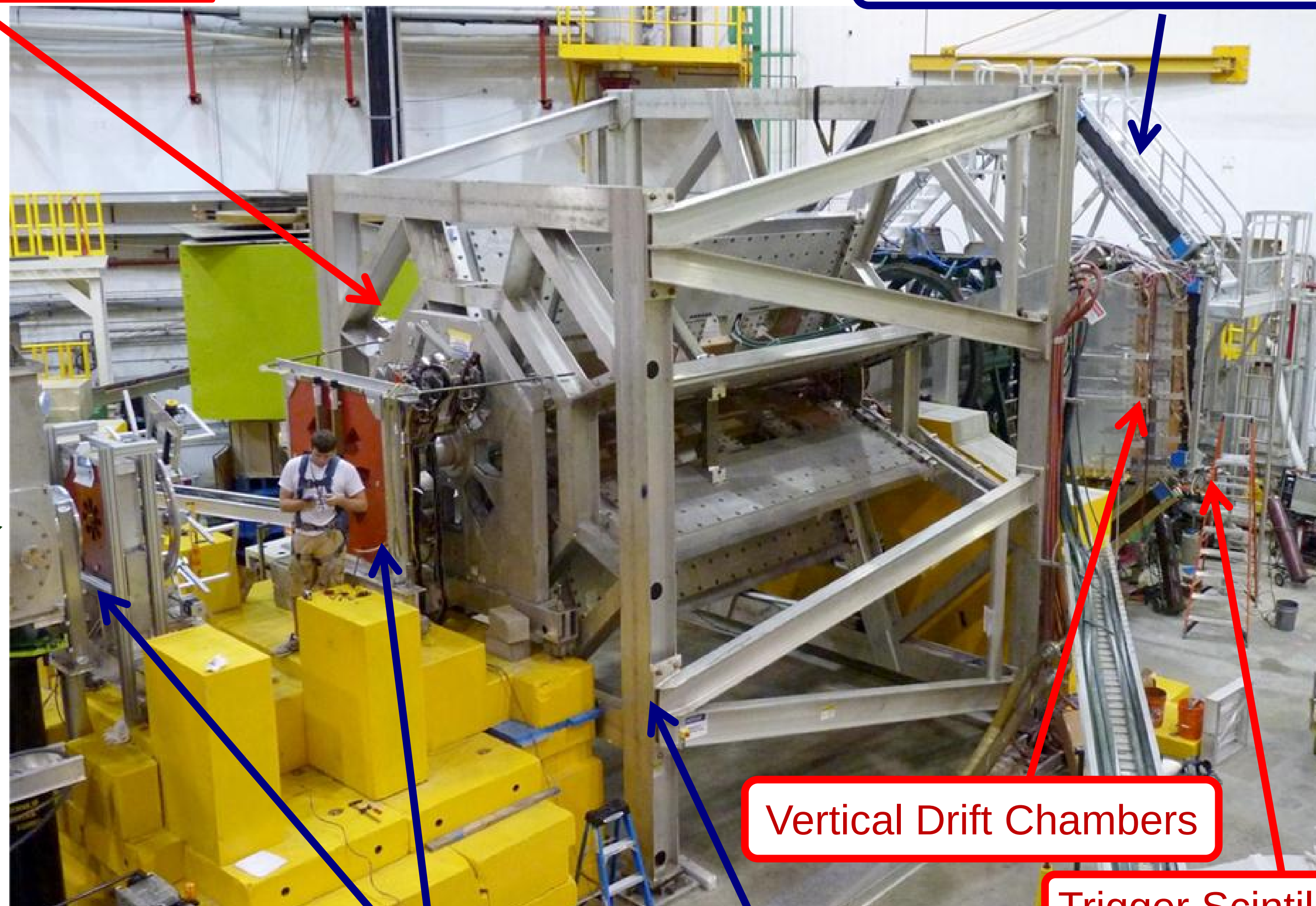


Electron beam

Vertical Drift Chambers

Trigger Scintillator

Collimators

Toroidal Magnet Spectrometer

Red = low-current tracking mode

Blue = production ("integrating") mode

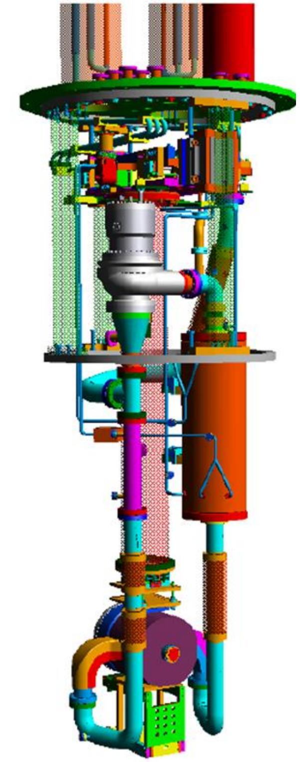
Qweak Target

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/density fluctuations could kill us!



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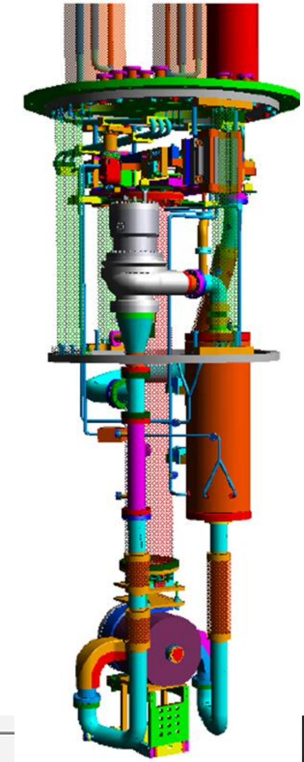
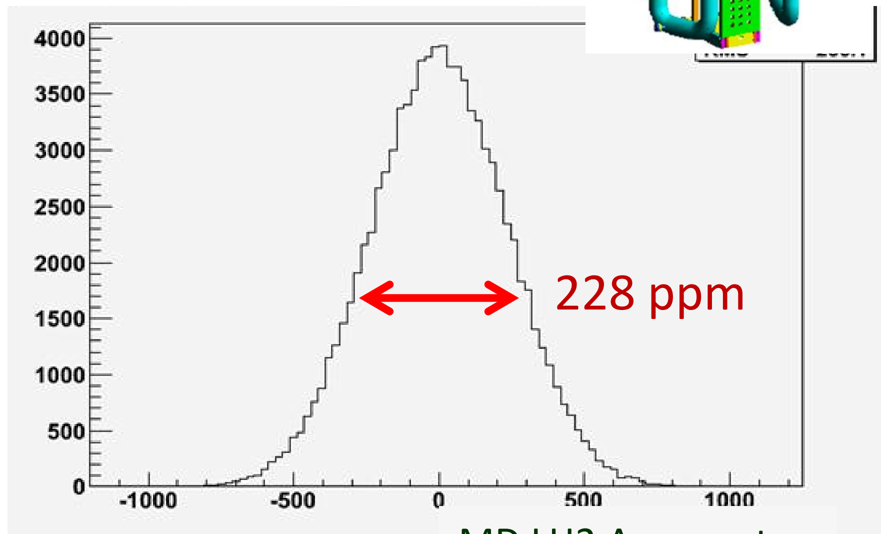


LH2 statistical width (per quartet):

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



Total: 228 ppm resolution *per quartet*

→50 ppb per *perfect* day!*

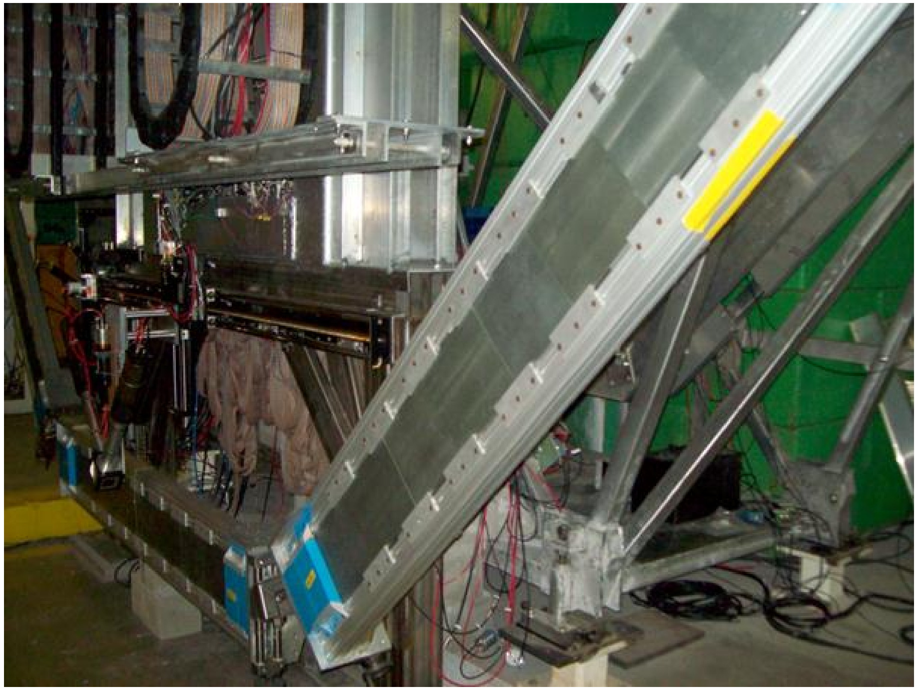
*perfect day: 100% efficiency

Main Detectors

- Main detectors

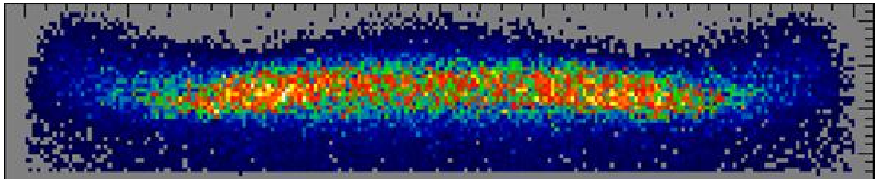
  The toroidal magnet focuses elastically scattered electrons onto each bar

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

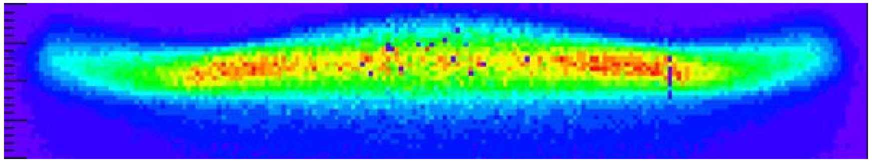


Close up of one detector in situ

Simulation of scattering rate MD face



Measured

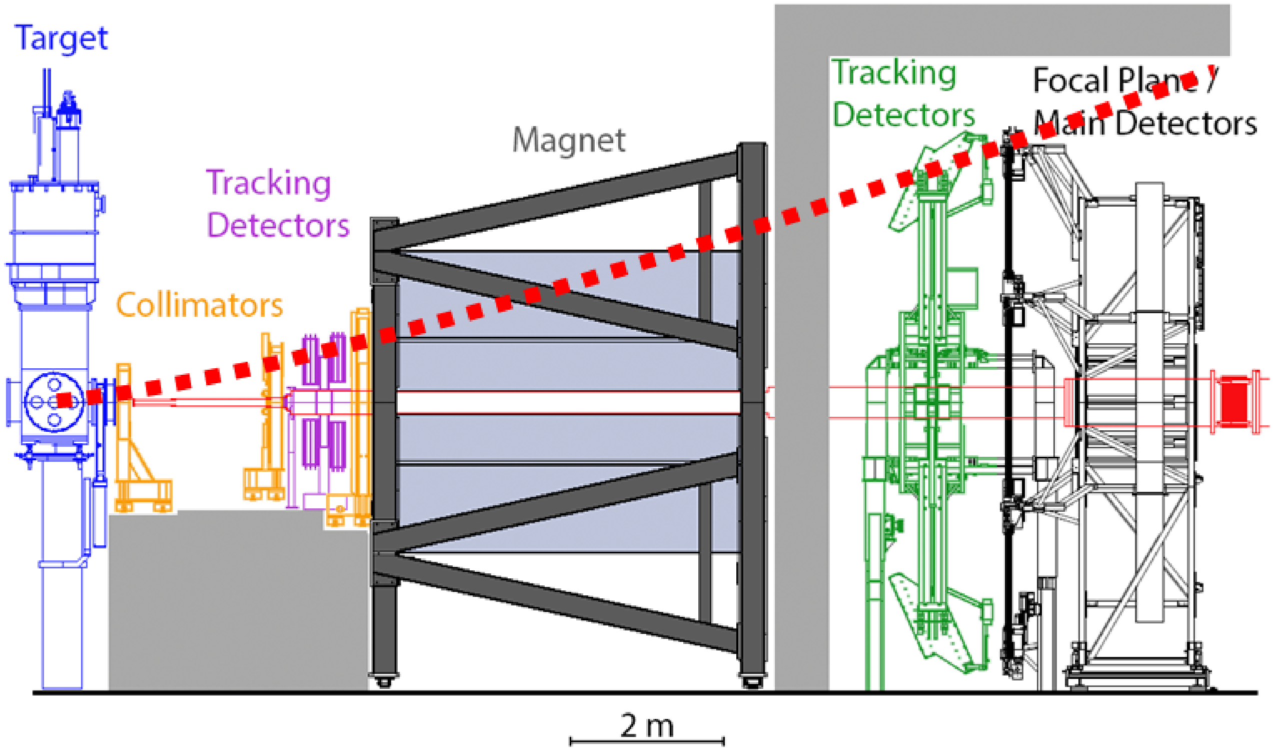


2 meters

Q^2 determination

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

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



Hall C Beam Polarimetry

Polarization is our largest systematic uncertainty (1% goal)

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

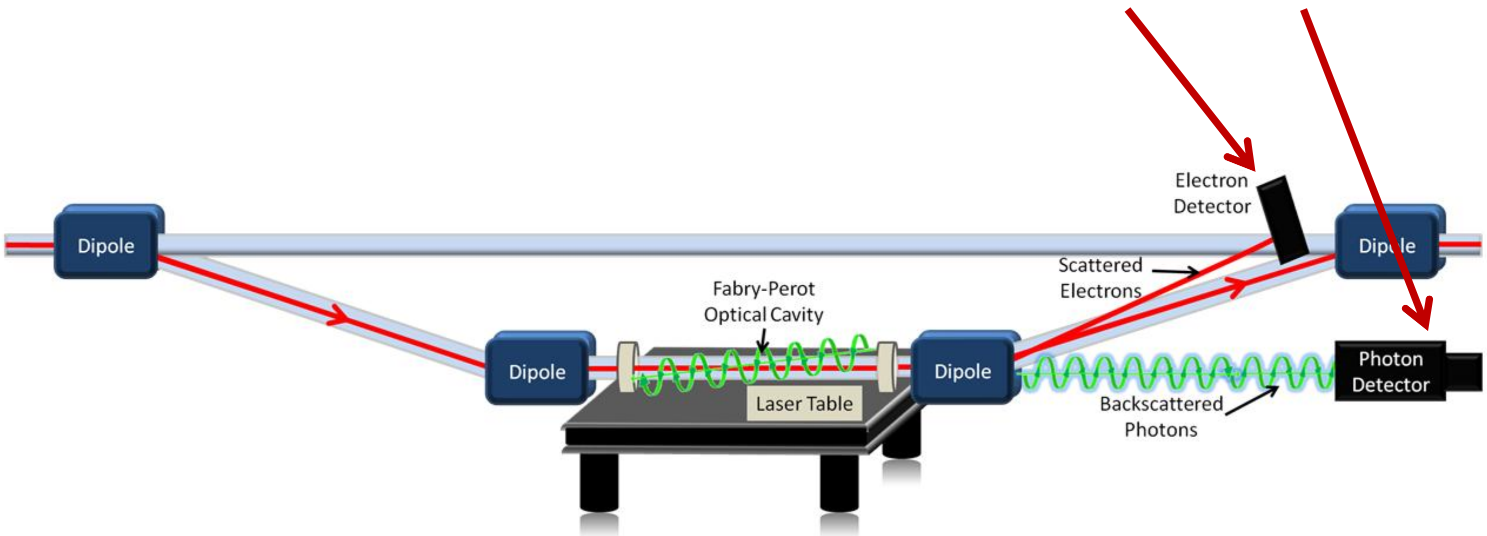
Møller polarimeter

- 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.



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….

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.

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

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

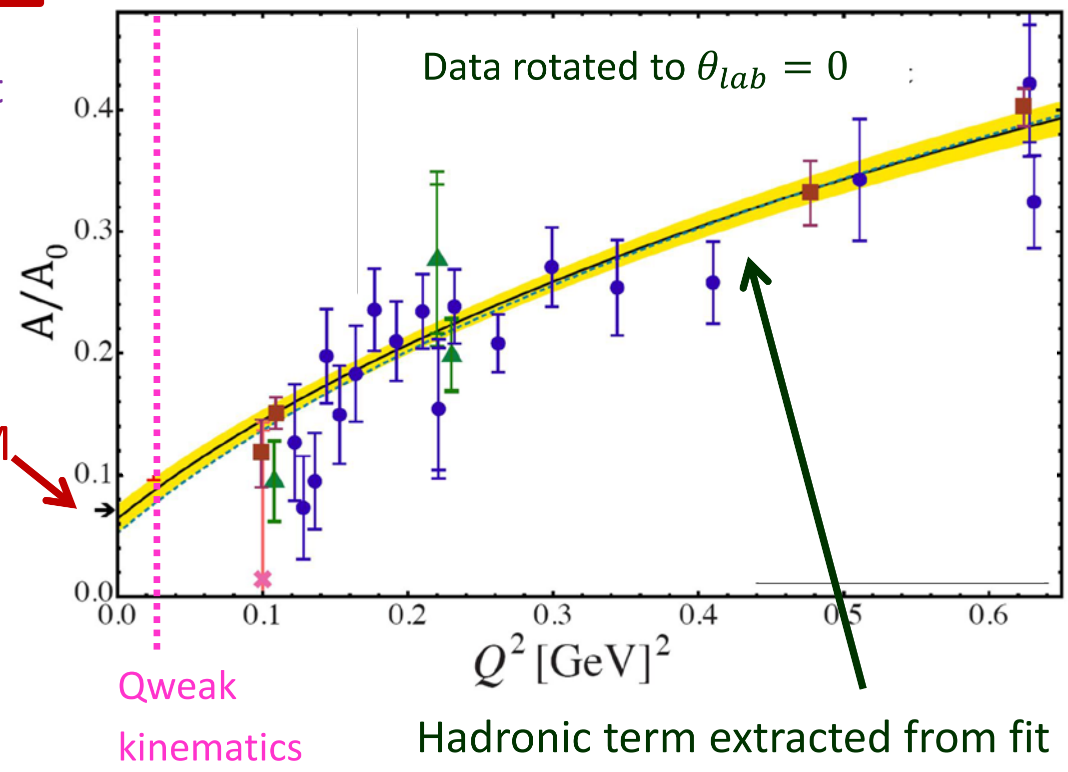
Reduced asymmetry more convenient

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

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

We measure A_{phys}^{PV}

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



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

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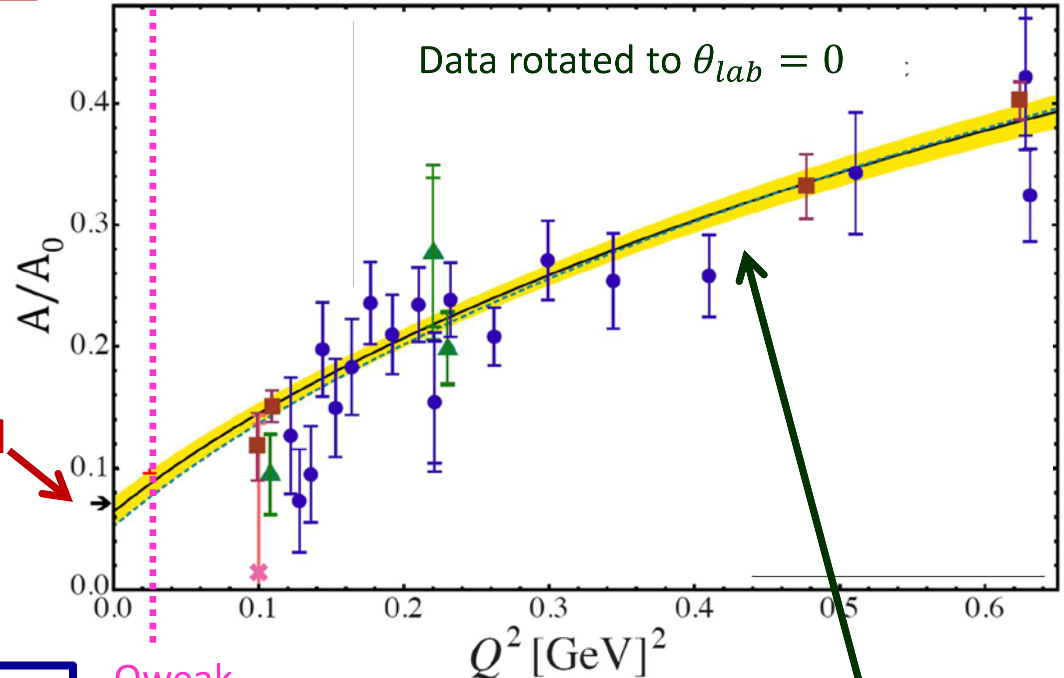
SM



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

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Q_W^p extraction

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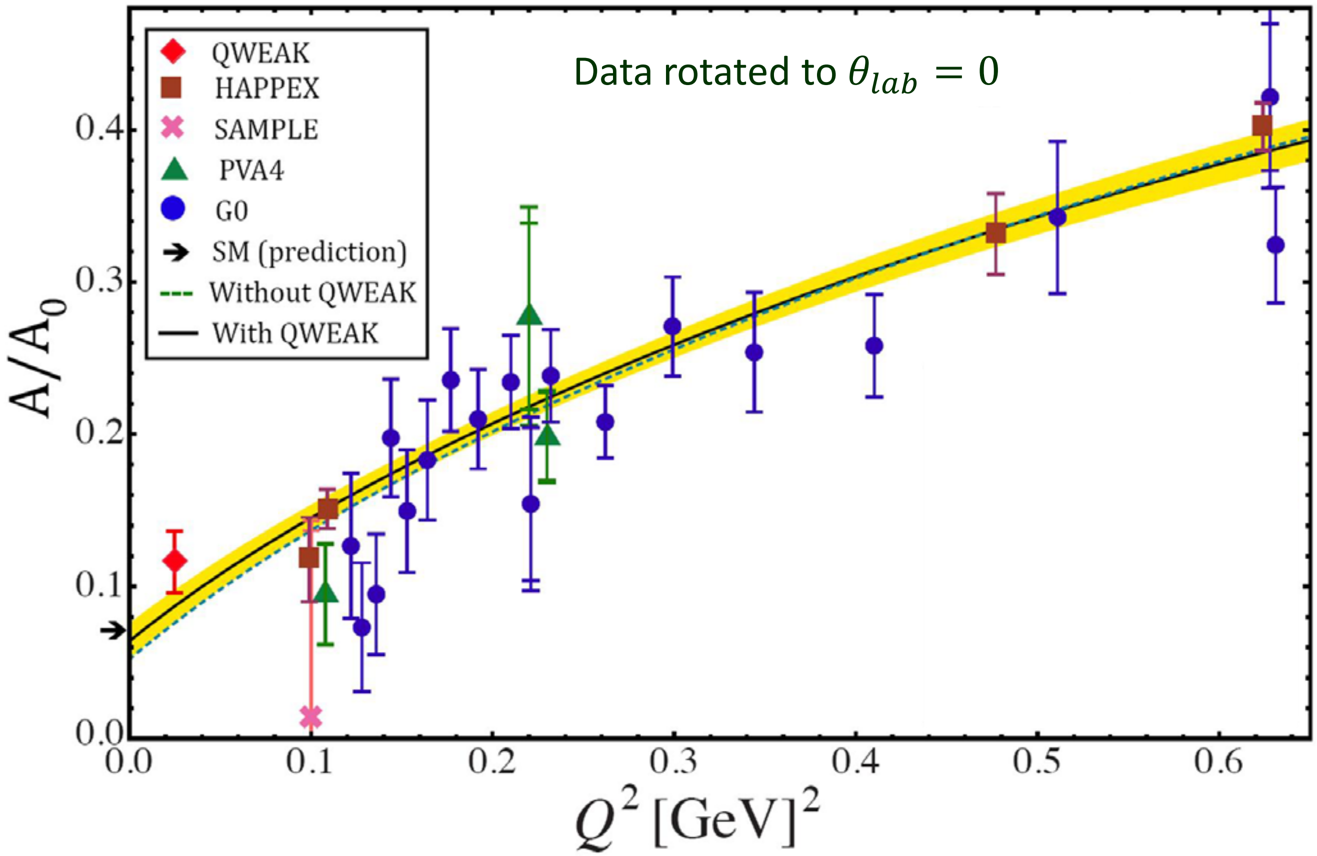

The fit takes into account the θ, Q^2 of each point. To plot: rotated data to forward angle, and corrected for the Q^2 and E dependence of the $\square_{\gamma Z}$.

$^A/_{A_0}$ is the reduced asymmetry.

Note the initial agreement with the standard model.

Our uncertainty band will eventually shrink by ~5.

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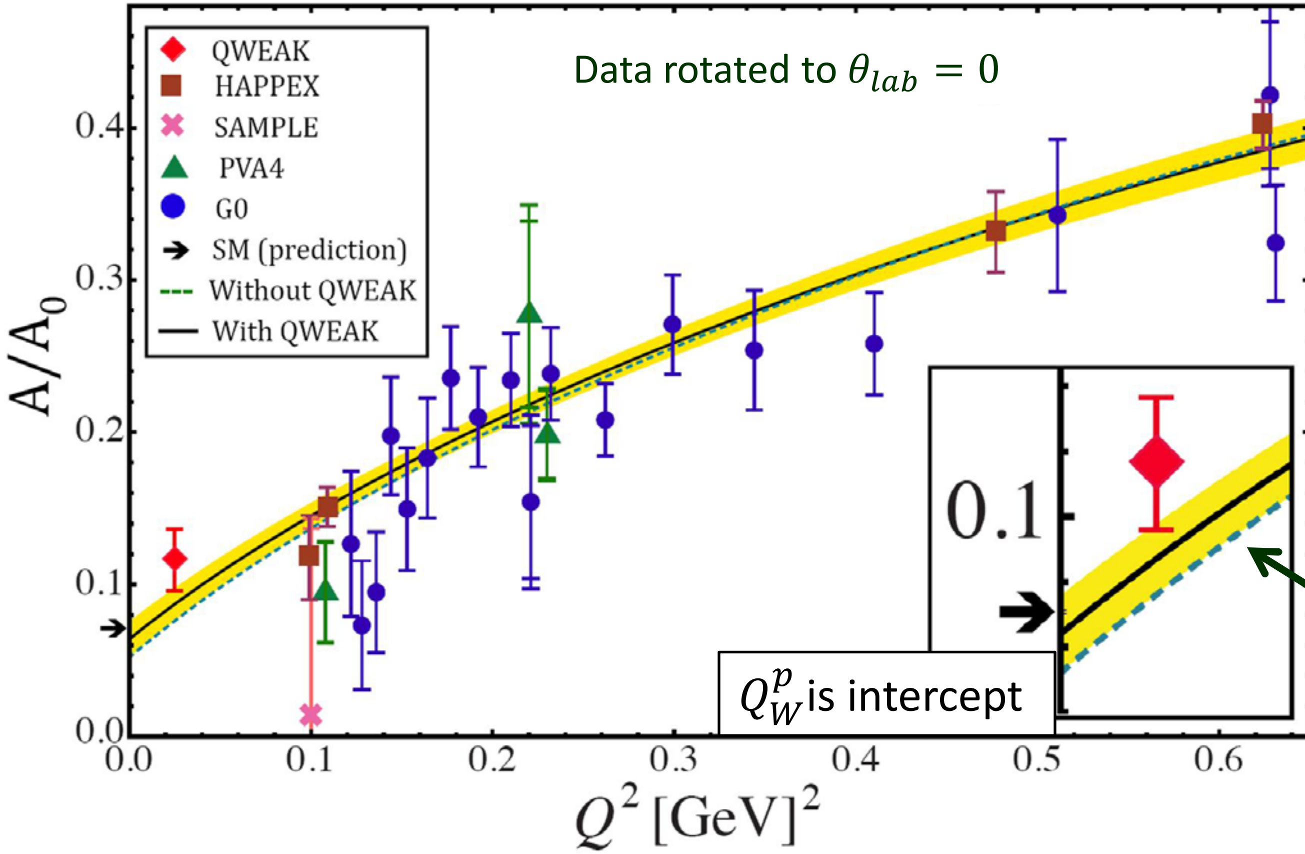

The fit takes into account the θ, Q^2 of each point. To plot: rotated data to forward angle, and corrected for the Q^2 and E dependence of the $\square_{\gamma Z}$.

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

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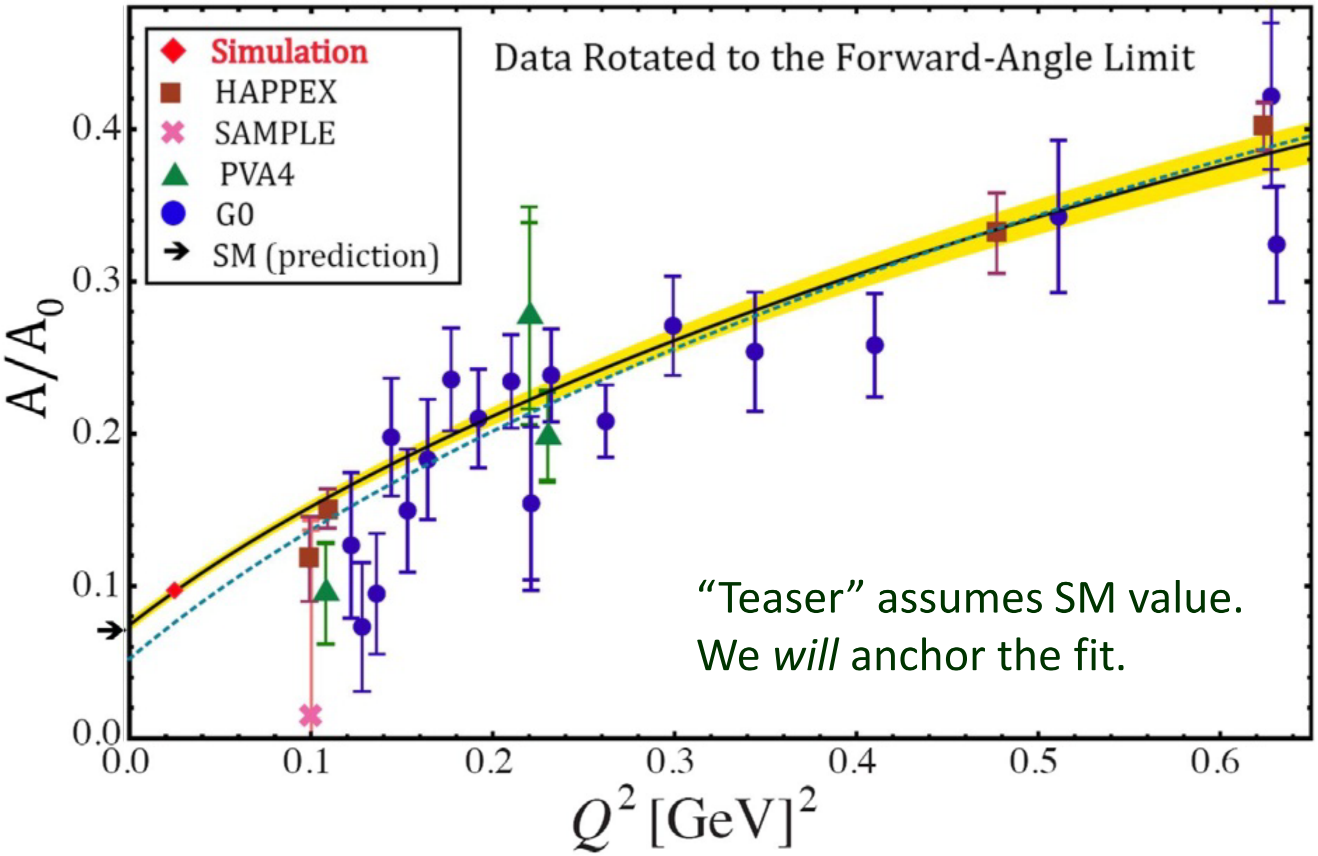
"Teaser"

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



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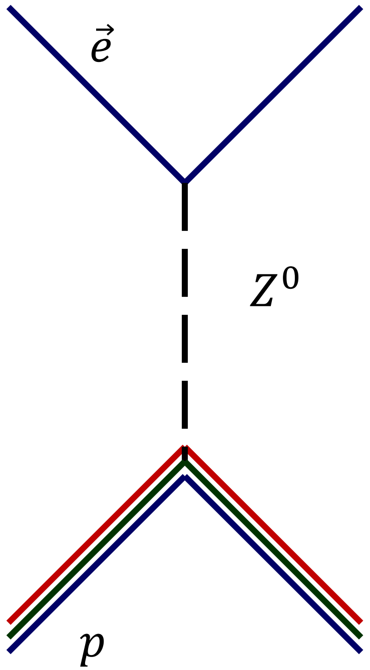
Extracting Individual Quark Charges

The weak neutral-current Lagrangian elegantly describes, and separates, the individual quark contributions:

$$L_{nc} = \frac{G_F}{\sqrt{2}} \sum_q \{ C_{1q} \bar{e} \gamma_\mu \gamma_5 e \bar{q} \gamma^\mu q + C_{2q} \bar{e} \gamma_\mu e \bar{q} \gamma^\mu \gamma_5 q \}$$

Sum over all relevant quark flavors (u,d)

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



C_{1q} is the quark vector coupling (helicity dependence in e^-)

C_{2q} the quark axial-vector coupling (not conserved)

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

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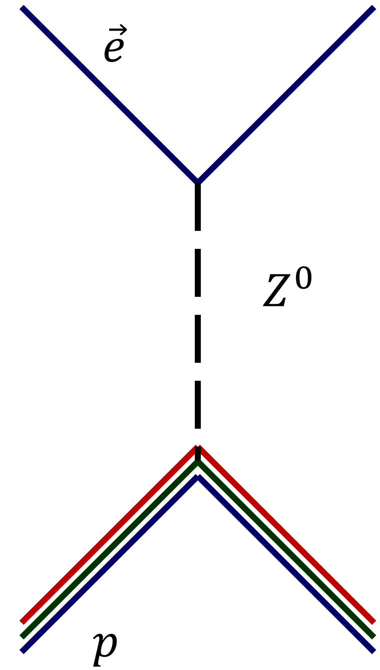

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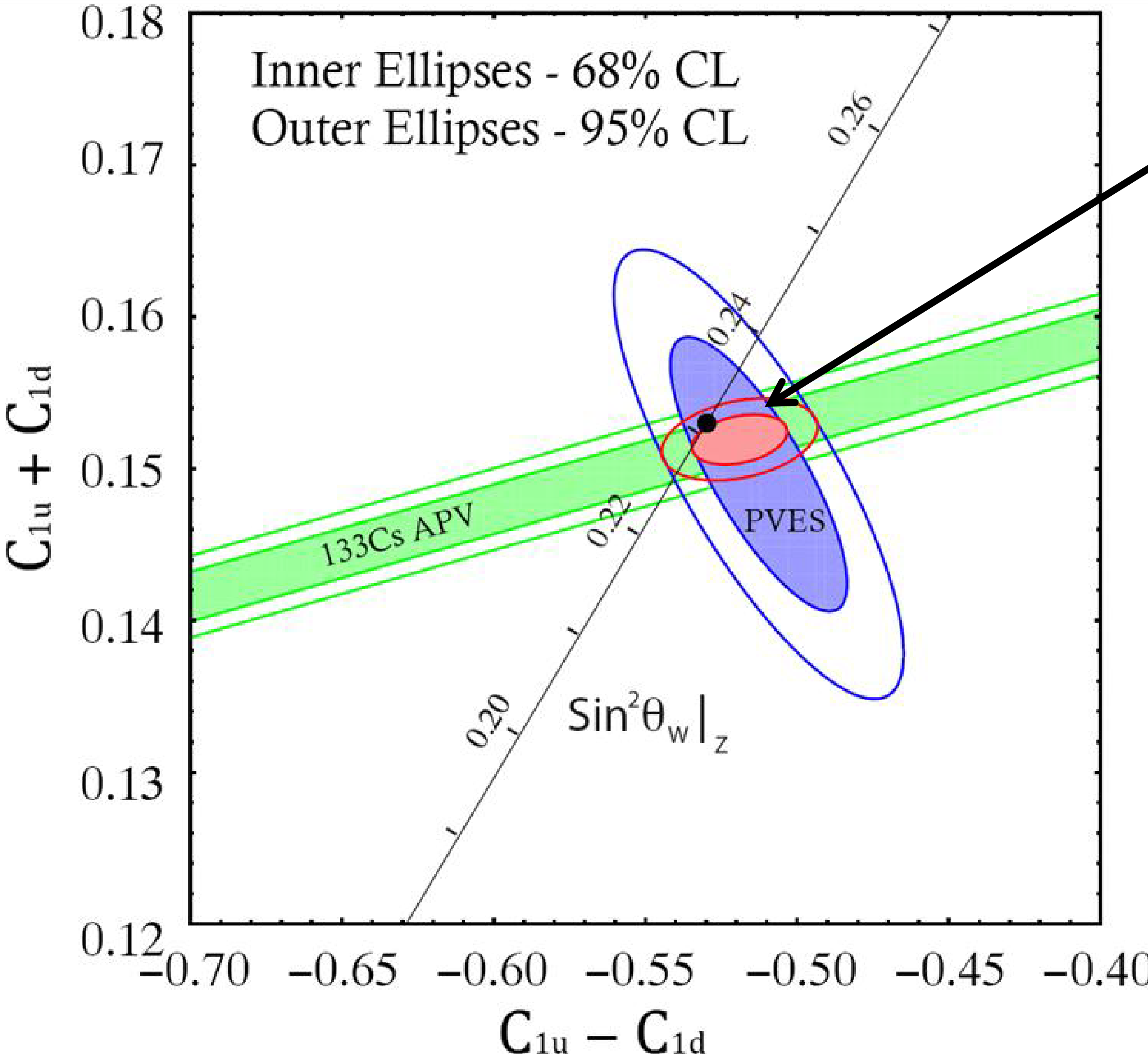
In general, nucleus weak charge: $Q_W = -2\{C_{1u}(2Z + N) + C_{1d}(Z + 2N)\}$

To extract C_{1u}/C_{1d} directly, we need another equation. Atomic parity violating experiments provide this.

We can therefore determine the neutrons weak charge!

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

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

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

$$C_{1d} = \quad 0.3355 \pm 0.0050$$

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

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

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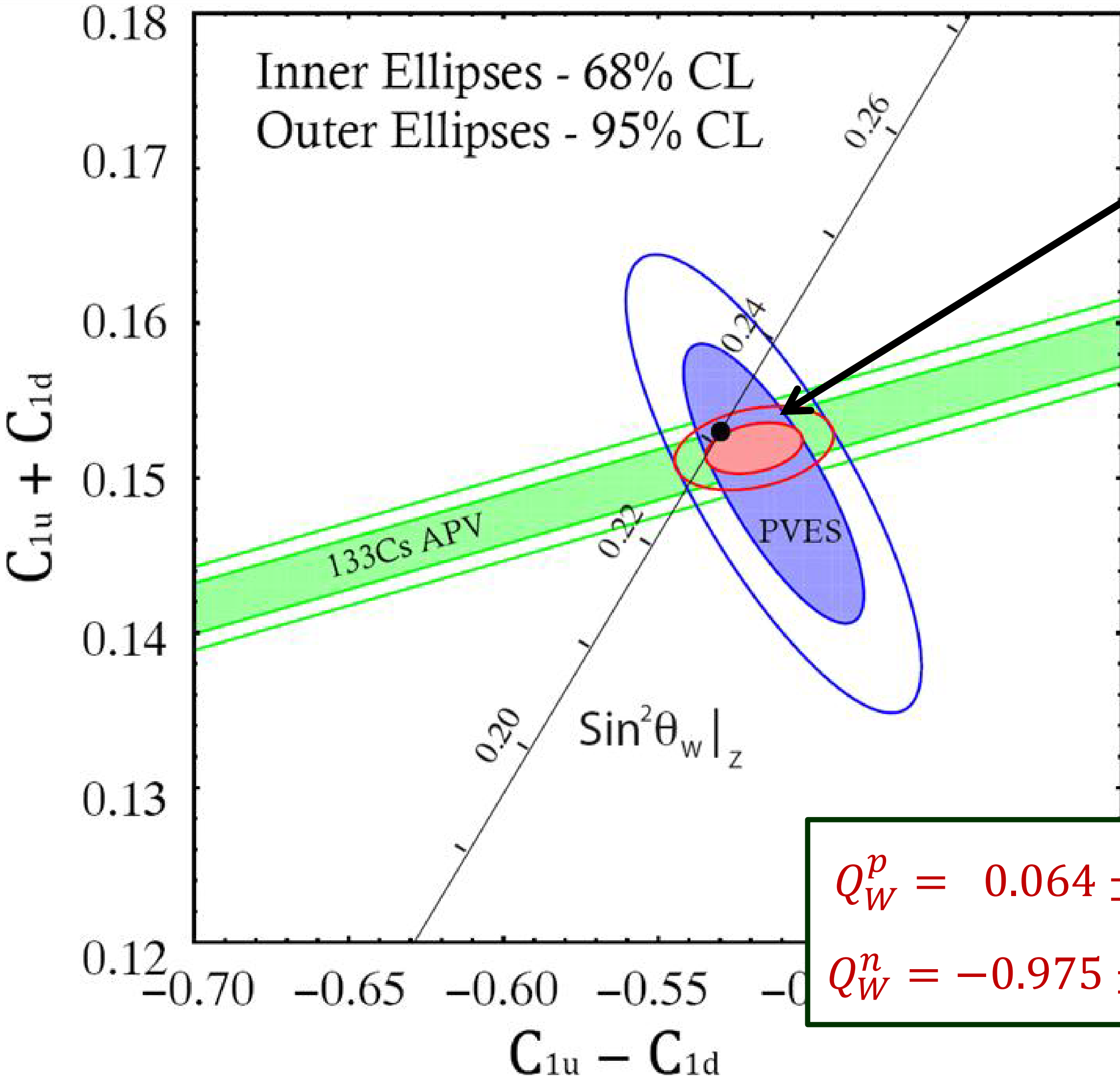

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$Q_W^p = 0.064 \pm 0.012$	$Q_W^p(SM) = 0.0710$
$Q_W^n = -0.975 \pm 0.010$	$Q_W^n(SM) = -0.9890$

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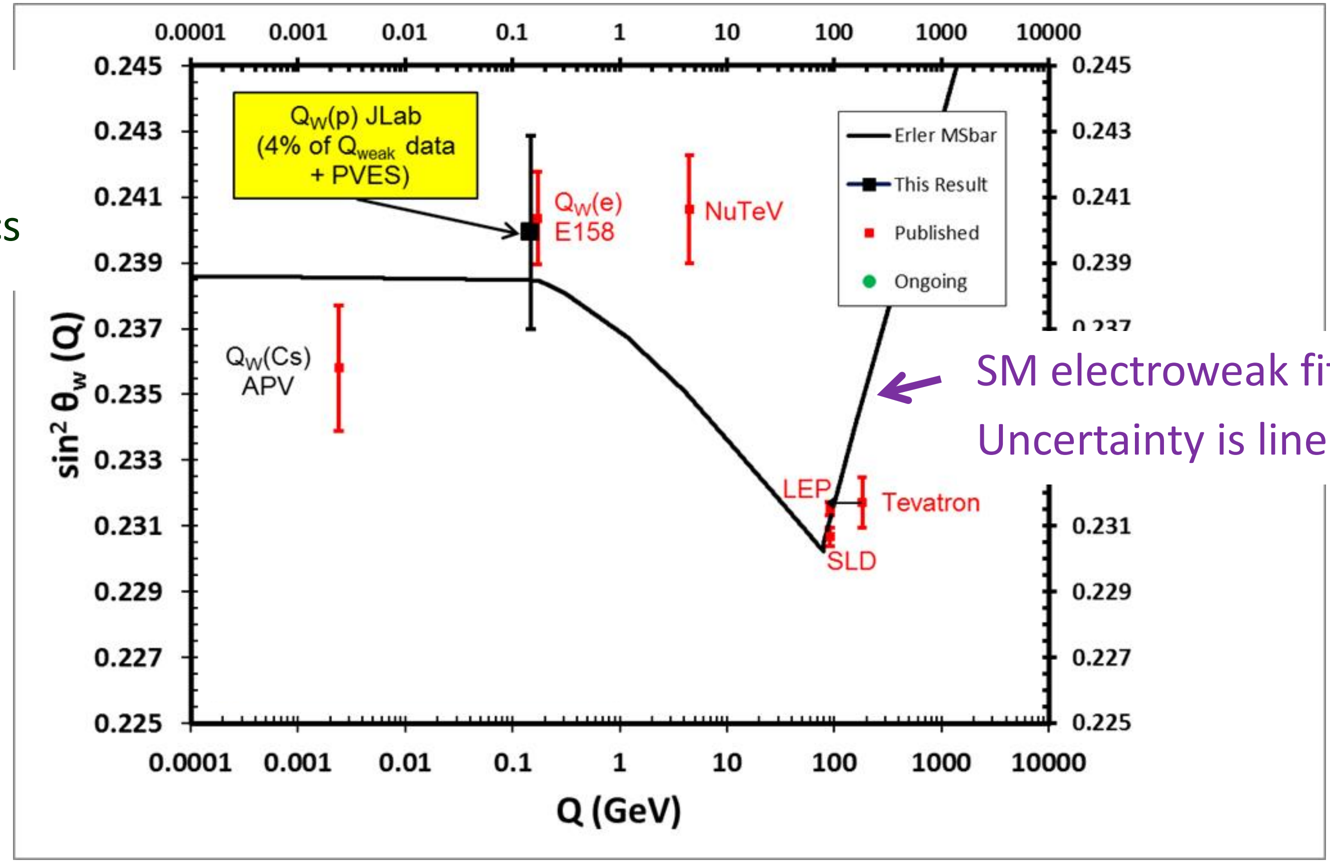
The Running of the Weak Mixing Angle

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.

Final Q-weak results will be most precise measurement of $\sin^2(\theta_W)$ at low-Q^2

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

V.A. Dzuba, J.C. Berengut, V. V. Flaumbaum, and B. Roberts. Phys. Rev. Lett. 109, 203003 (2012). (APV measurement)

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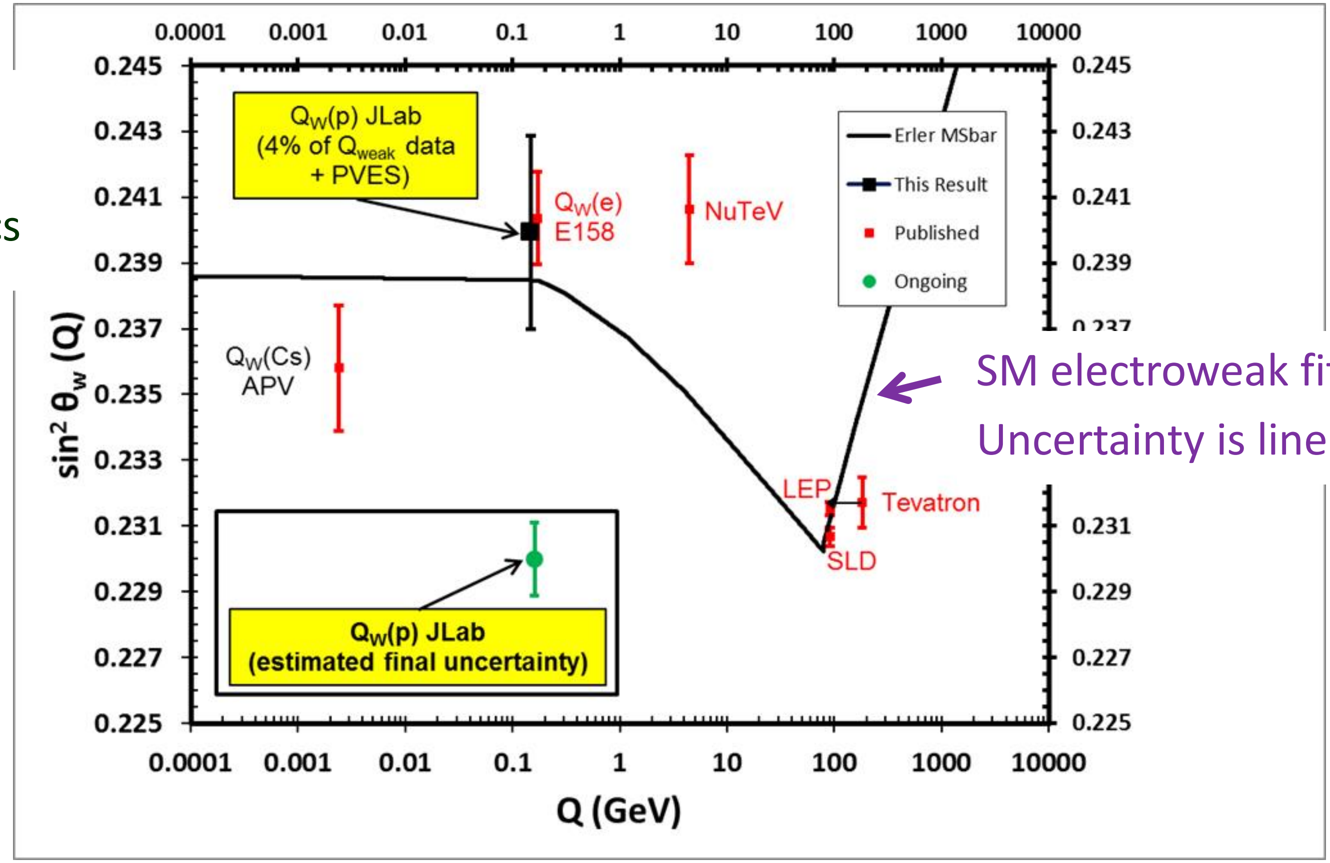

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Beyond the Standard Model

We are sensitive to potential new parity-violating physics that couples to electrons/quarks. Popular models we are sensitive to include:

- Scalar leptoquarks
- Z' models (such as from GUT's)
- R-parity violating supersymmetry ($B - L$ not conserved)

Our model-independent mass limit is given by:

$$\frac{\Lambda}{g} \sim \frac{1}{\left(2\sqrt{2}G_F\left|\Delta Q_W^p\right|\right)^{\frac{1}{2}}} \geq \mathcal{O}(TeV)$$

Mass-to-coupling ratio

This mass limit is for 2σ (95% confidence limit), and assuming the Q-weak value agrees with the SM prediction.

To set exact mass limits, one must choose a model (a value for the coupling).

Erler, Kurylov, Ramsey-Musolf, Phys. Rev. D68, 2003

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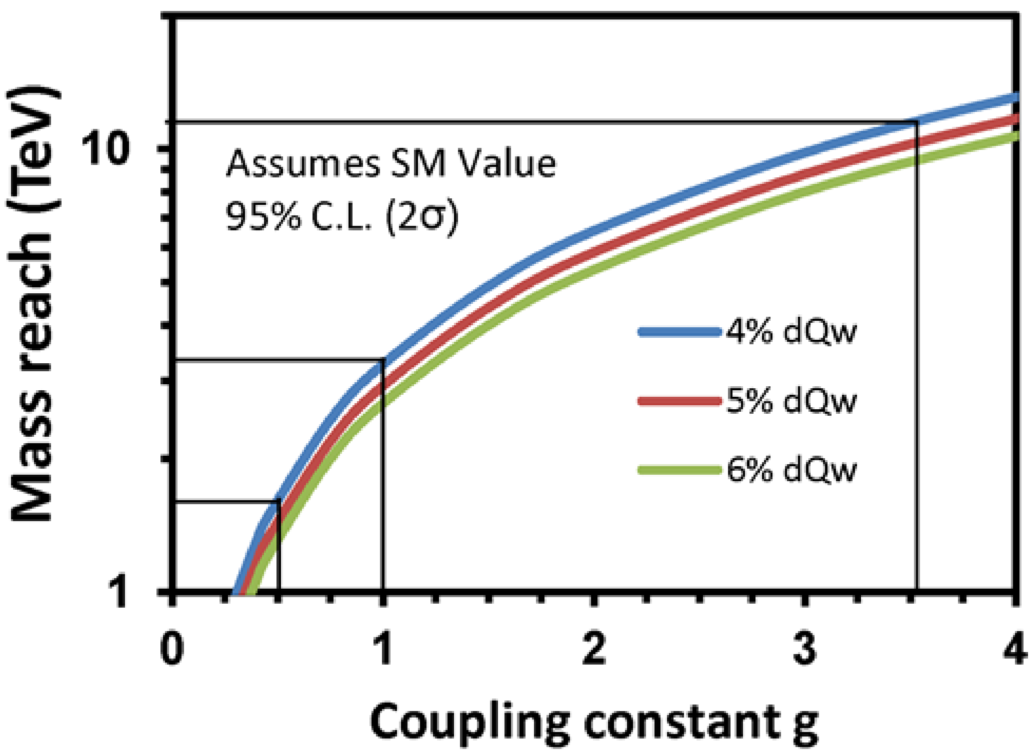


Conclusions and Future

We provide the first determination of the protons weak charge. Results presented are from our initial commissioning "Run 0" period (only 1/25th of our data). Future statistical uncertainty for asymmetry with decrease by ~5x.

- Our current measurement:

$A_{PV}^{p} = -279 \pm 35(stat) \pm 29\ (sys)$ ppb $\qquad \langle Q^2 \rangle = 0.0250 \pm 0.0006\ GeV^2$

$\langle E_{beam} \rangle = 1155\ MeV \qquad \theta_{eff} = 7.90\,°$

- We currently provide ½ σ agreement with the SM prediction on Q_W^p

$Q_W^p = \ 0.064 \pm 0.012 \qquad Q_W^p(SM) = \ 0.0710$

- Lastly, in combination with atomic parity violating Cesium results, we can extract the quark couplings and neutron's weak charge:

$Q_W^n = -0.975 \pm 0.010 \qquad Q_W^n(SM) = -0.9890$

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

- Our final results will provide the most precise measurement of $\sin^2\theta_w$ at low-Q^2

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

Qweak Collaboration

Thank you for your attention!

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, D. Meekins, 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

Extra slides!!

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

Josh Magee
for the Qweak Collaboration
September 11^{th},2014

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

Subsystems:
- Target
- Polarimetry
- Main detectors

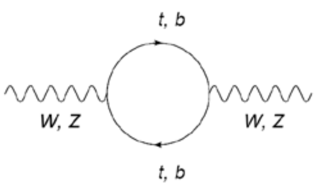
Backgrounds:
- Aluminum windows
- Inelastic ($N \rightarrow \Delta$)
- Transverse
- Beamline background

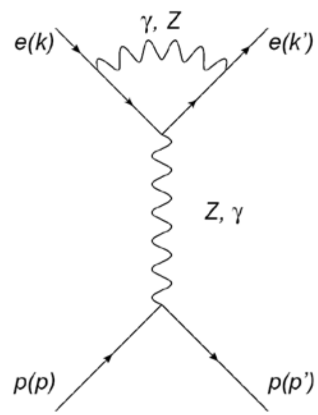
The College of WILLIAM & MARY
Jefferson Lab Thomas Jefferson National Accelerator Facility
NSF National Science Foundation WHERE DISCOVERIES BEGIN

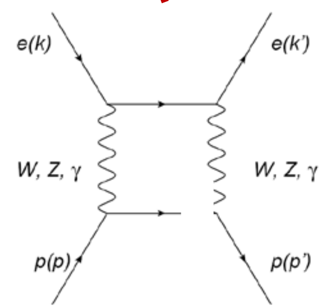
Electroweak Radiative Contributions

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.

To extract the weak mixing angle, $\sin^2\theta_w$, radiative corrections are important.

The values for ρ_{NC}, Δ_e, Δ'_e, $\square_{WW}$, and $\square_{ZZ}$ are well known and precisely calculated.

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

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

Electroweak Radiative Contributions

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

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

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

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

Electroweak Radiative Contributions

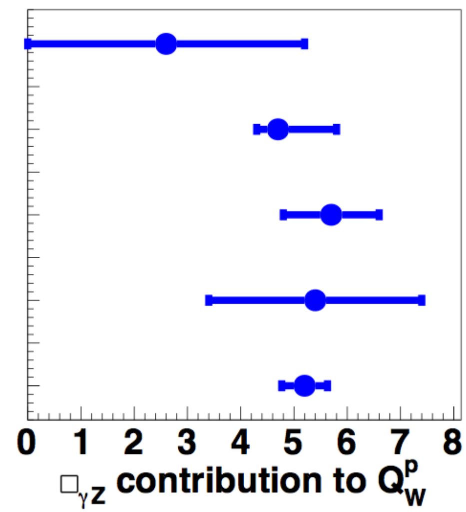
In the Standard Model, the weak charge is *defined* at $Q^2 = 0, E = 0.$

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

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

Electroweak Radiative Contributions

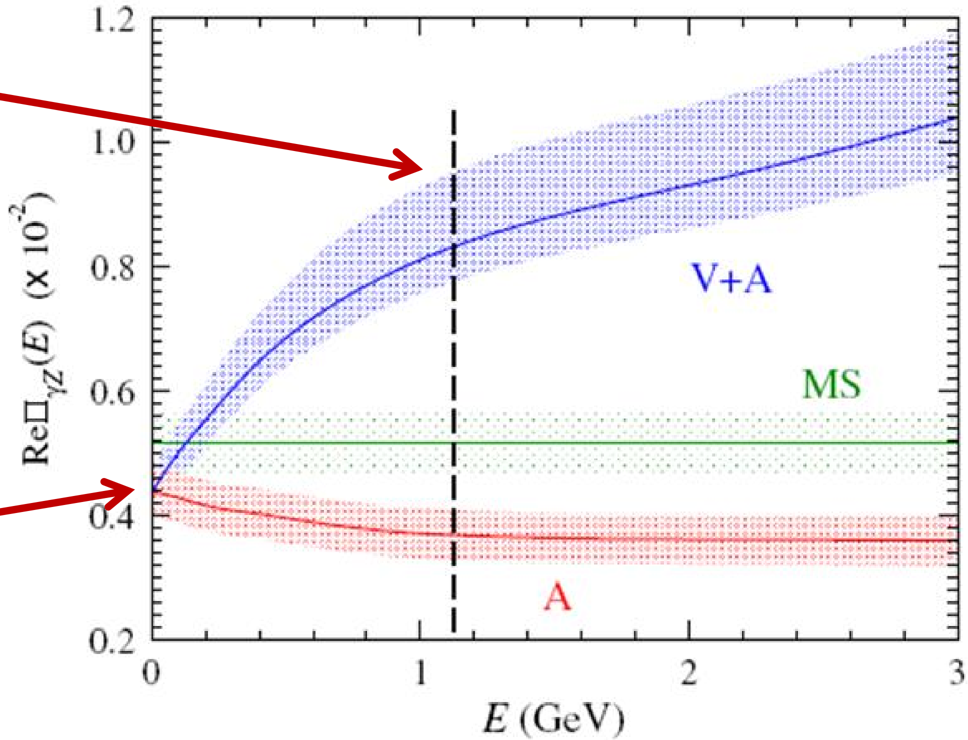
In the Standard Model, the weak charge is *defined* at $Q^2 = 0, E = 0$.

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

Energy dependent

To extract Q_W^p, we removed the energy *dependent* piece from the $\Box_{\gamma Z}$.

To extract $\sin^2\theta_w$ we remove the $E = 0$ contribution.



Blunden, Melnitchouk, Thomas (PRL) 107, 081801 (2011)

Electroweak Radiative Contributions

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

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

The values for ρ_{NC}, Δ_e, Δ_e', $\square_{WW}$, and $\square_{ZZ}$ are known and precisely calculated.

Piece	Value	Source
$\rho_{NC} = 1 + \Delta_\rho$	1.00833	PL B351, 331 (1995)
$\Delta_e = -{}^{\alpha}/_{2\pi}$	-0.00116	PRD 68, 016006 (2003) (Eq. 5)
$\Delta_e' = -\frac{\alpha}{3\pi}(1-4\hat{s}^2)\left[\ln\left(\frac{M_Z^2}{m_e^2}\right)+\frac{1}{6}\right]$	-0.00142	PRD 68, 016006 (2003) (Eq. 5)
$\hat{\alpha} \equiv \hat{\alpha}(M_z)$	0.007816	PDG2012, just after Eq. 10.7d
$\hat{s}^2 \equiv 1 - \hat{c}^2 \equiv \sin^2\hat{\theta}_w(M_Z)$	0.23116	PDG2012, Table 10.6
$\square_{WW} = \frac{\hat{\alpha}}{4\pi\hat{s}^2}\left[2+5\left(1-\frac{\alpha_s M_W^2}{\pi}\right)\right]$	0.01832	PRD 68, 016006 (2003) (Eq. 11)
$\square_{ZZ} = \frac{\hat{\alpha}}{4\pi\hat{s}^2\hat{c}^2}\left[\frac{9}{4}-5\hat{s}^2\right](1-4\hat{s}^2+8\hat{s}^2)$	0.00193	PRD 68, 016006 (2003) (Eq. 6)
${}_{\gamma Z}(0) = -\frac{5\hat{\alpha}}{2\pi}(1-4\hat{s}^2)\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right)+C_{\gamma Z}(\Lambda)\right]$	0.0044	PRL 107, 081801 (2011)

Total radiative correction uncertainty: 0.0001 (dominated by $\square_{\gamma Z}$).

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

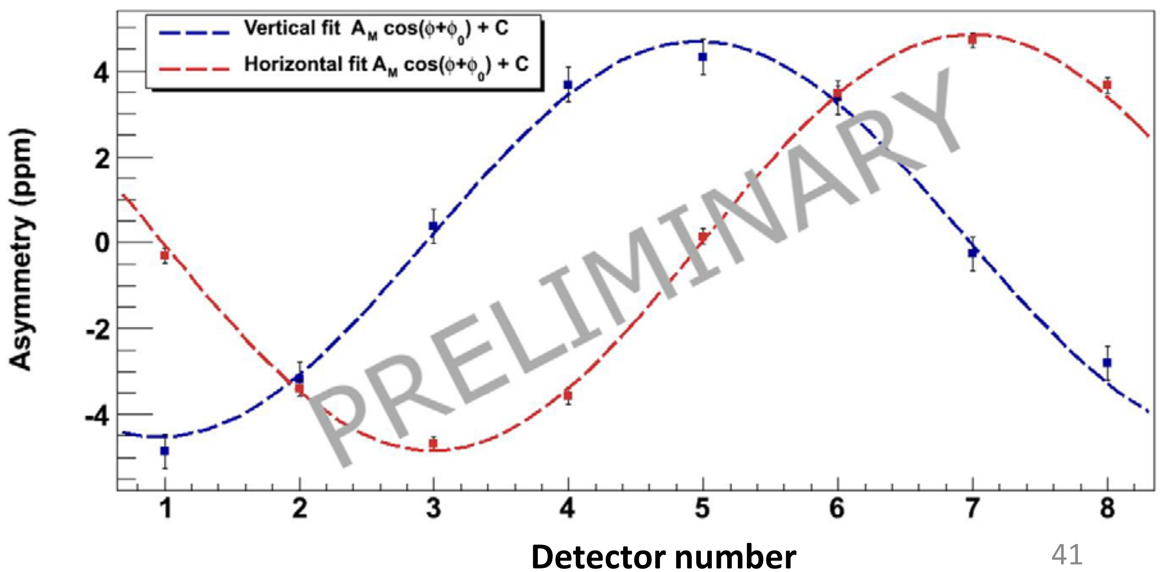
Measurements of the Beam Normal Single Spin Asymmetry (BNSSA) provide:

- Direct access to imaginary part of two-photon exchange

We need to correct for this!

Horizontal and vertical components measured separately

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



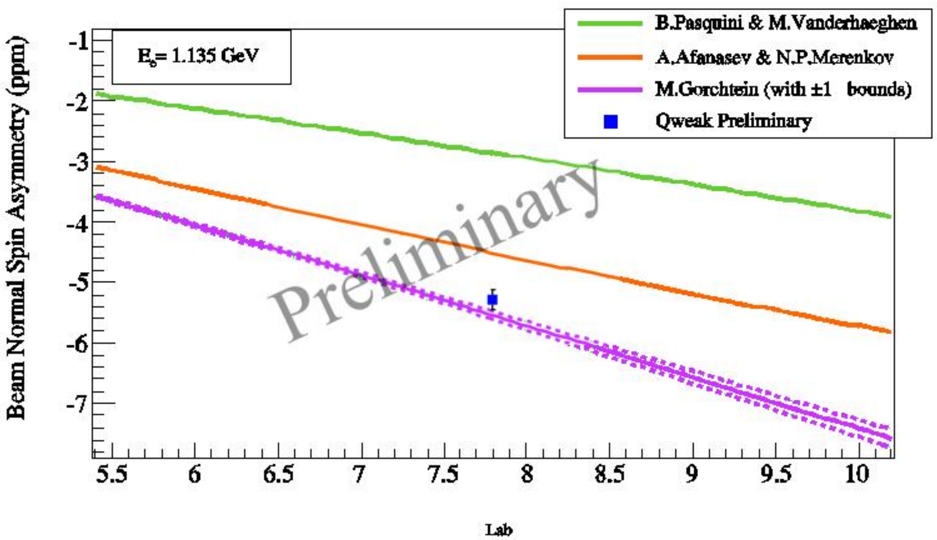
Transverse Asymmetry Measurement

Normal production running: 89% longitudinal beam polarization

Small amount of transverse polarization

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

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

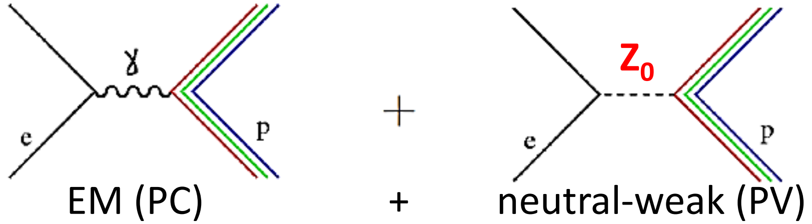


Source	Preliminary	Anticipated
Polarization	2.2%	~1.0%
Statistics	1.3%	~1.3%
Q^2	1.2%	~0.5%
Non-linearity	1.0%	~0.2%
Regression	0.9%	~0.9%
Backgrounds	0.3%	~0.3%

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

Private communication with Buddhini Waidyawansa

Determining $Q_w(p)$



- $A_{ep} = \left[\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right] \sim \frac{|M^{PV}_{weak}|}{|M_{EM}|}$ where $\sigma^{\pm}$ 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 $\varepsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}$, $\varepsilon' = \sqrt{\tau(1+\tau)(1-\varepsilon^2)}$,

  $\tau = Q^2/4M^2$, $G^\gamma_{E,M}$ 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

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)

Gorchtein & Horowitz *PRL 102, 091806 (2009)*	0.0026 ± 0.0026
Sibirtsev, Blunden & Melnitchouk, Thomas *PRD 82, 013011 (2010)*	$0.0047^{+0.0011}_{-0.0004}$
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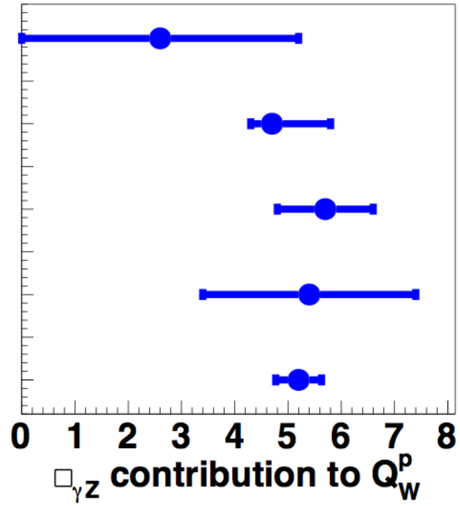
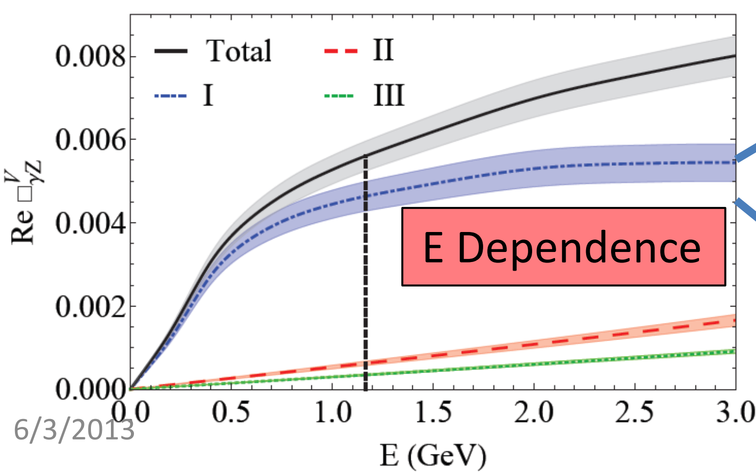
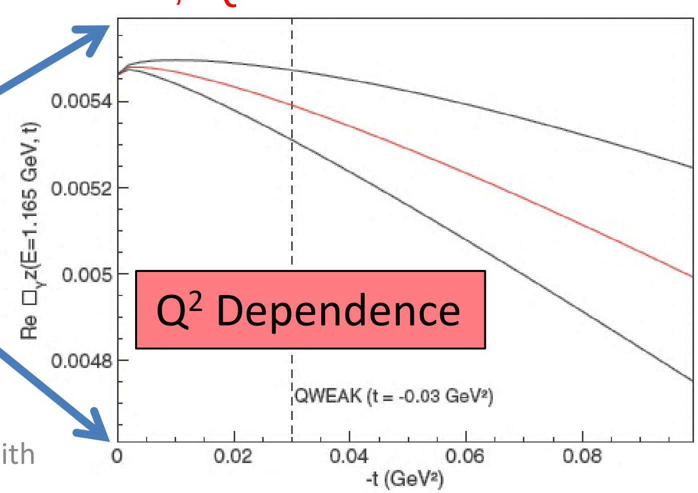


- Calculations are primarily dispersion theory type
  - error estimates can be firmed up with data!
- Qweak: inelastic asymmetry data taken at W ~ 2.3 GeV, Q^2 = 0.09 GeV^2



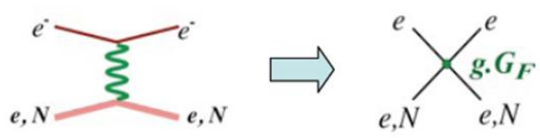


Global PVES Fit Details

- 5 free parameters ala 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 □$_{\gamma Z}$ RC
  - Hall et al., arXiv:1304.7877 (2013) & Gorchtein et al., PRC84, 015502 (2011)
- Effects of varying Q^2, θ, & λ studied, found to be small

The Standard Model

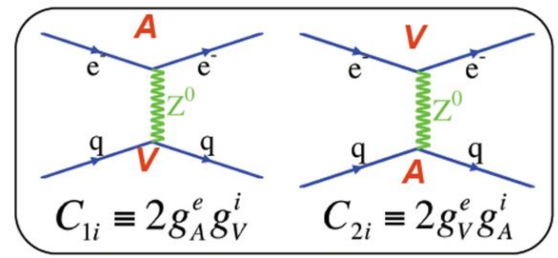
We can also look at a contact interaction to parameterize effective PV electron-quark couplings



$$\frac{1}{Q^2 - M^2} \xrightarrow{Q^2 \ll M^2} \frac{1}{M^2}$$

$$A_{PV} = \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e g_V^i + \beta g_V^e + g_A^i\right)$$

Qweak is particularly sensitive to the C_{1q}'s.



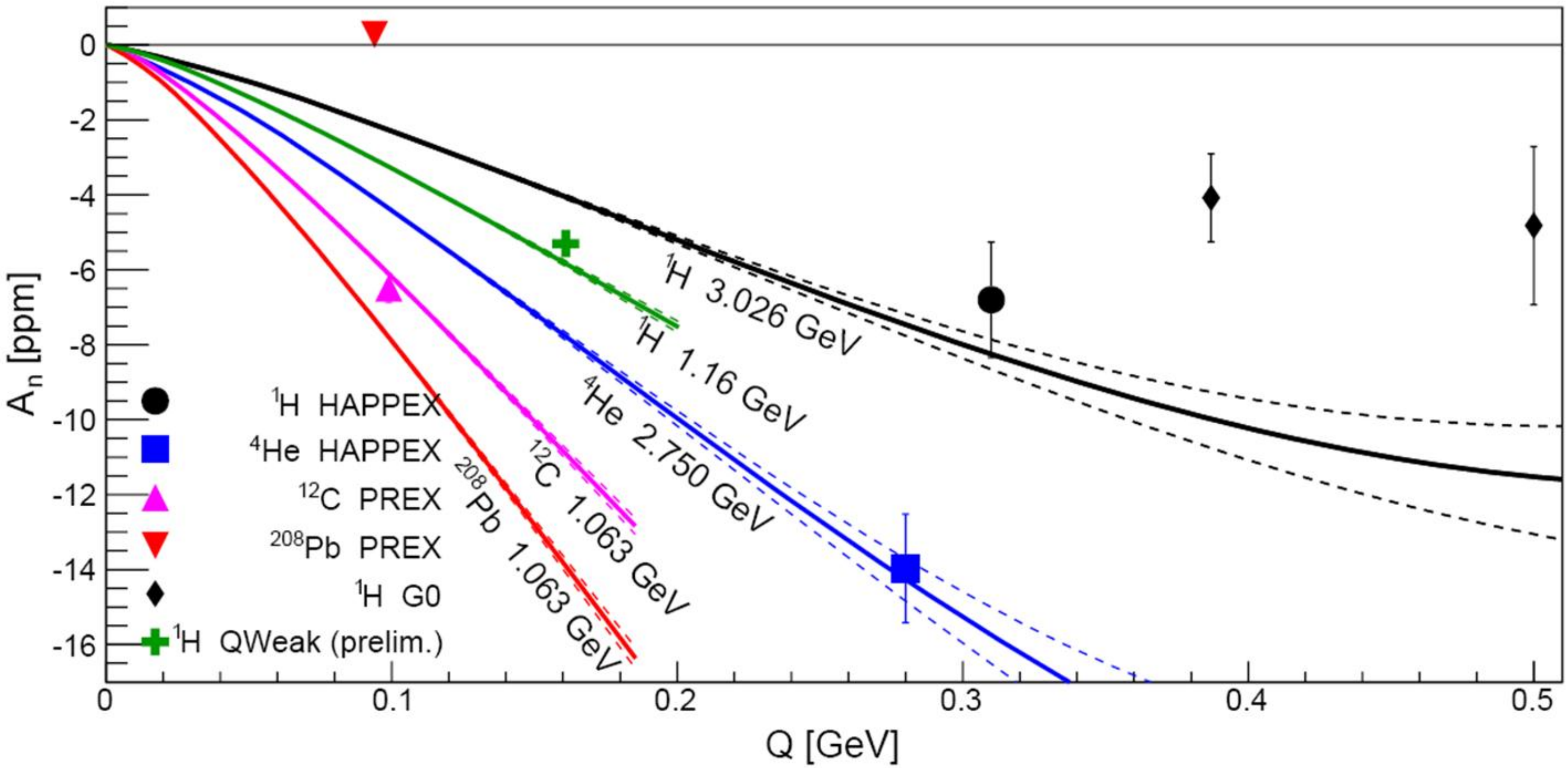
Small scattering angles

Large scattering angles

	Q_{EM}	Q_{weak}
Q_u	2/3	$1 - \frac{8}{3}sin^2(\theta_w) \approx 0.38$
Q_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"

Note: $Q_W^n = 1$



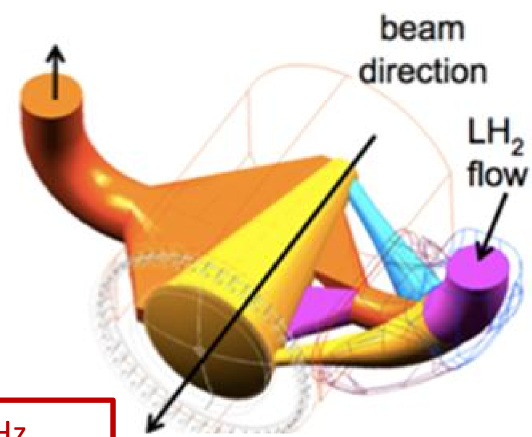
0
-2
-4
-6
-8
-10
-12
-14
-16
A_n [ppm]
0
0.1
0.2
0.3
0.4
0.5
Q [GeV]
1H HAPPEX
4He HAPPEX
12C PREX
208Pb PREX
1H G0
1H QWeak (prelim.)
1H 3.026 GeV
1H 1.16 GeV
4He 2.750 GeV
12C 1.063 GeV
208Pb 1.063 GeV

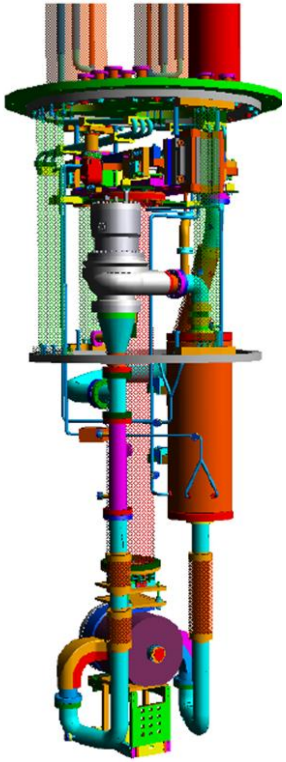
Qweak Target

35 cm, 2.5 kW liquid hydrogen target

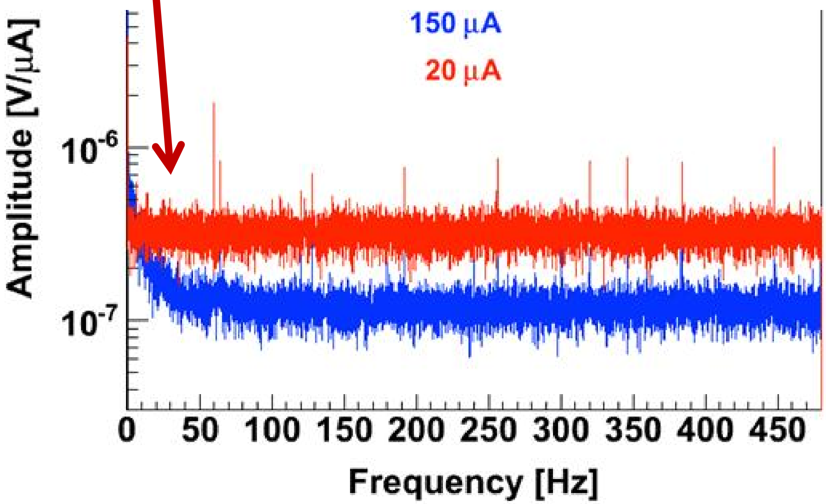
World's highest powered cryotarget

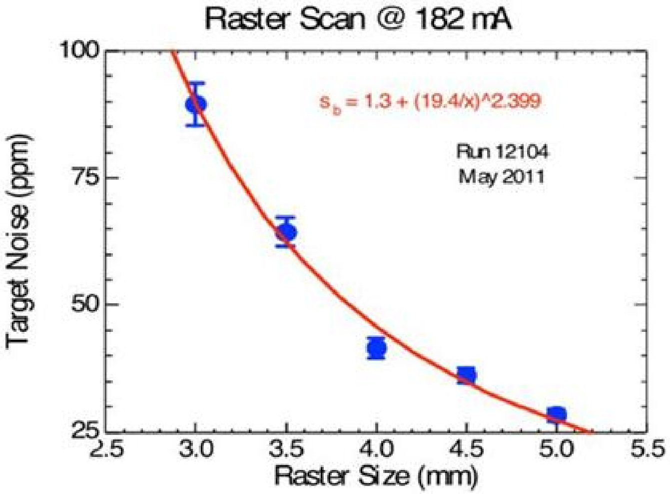
- Temperature ~20 K
- Pressure: 30-35 psia
- Beam at 150 – 180uA



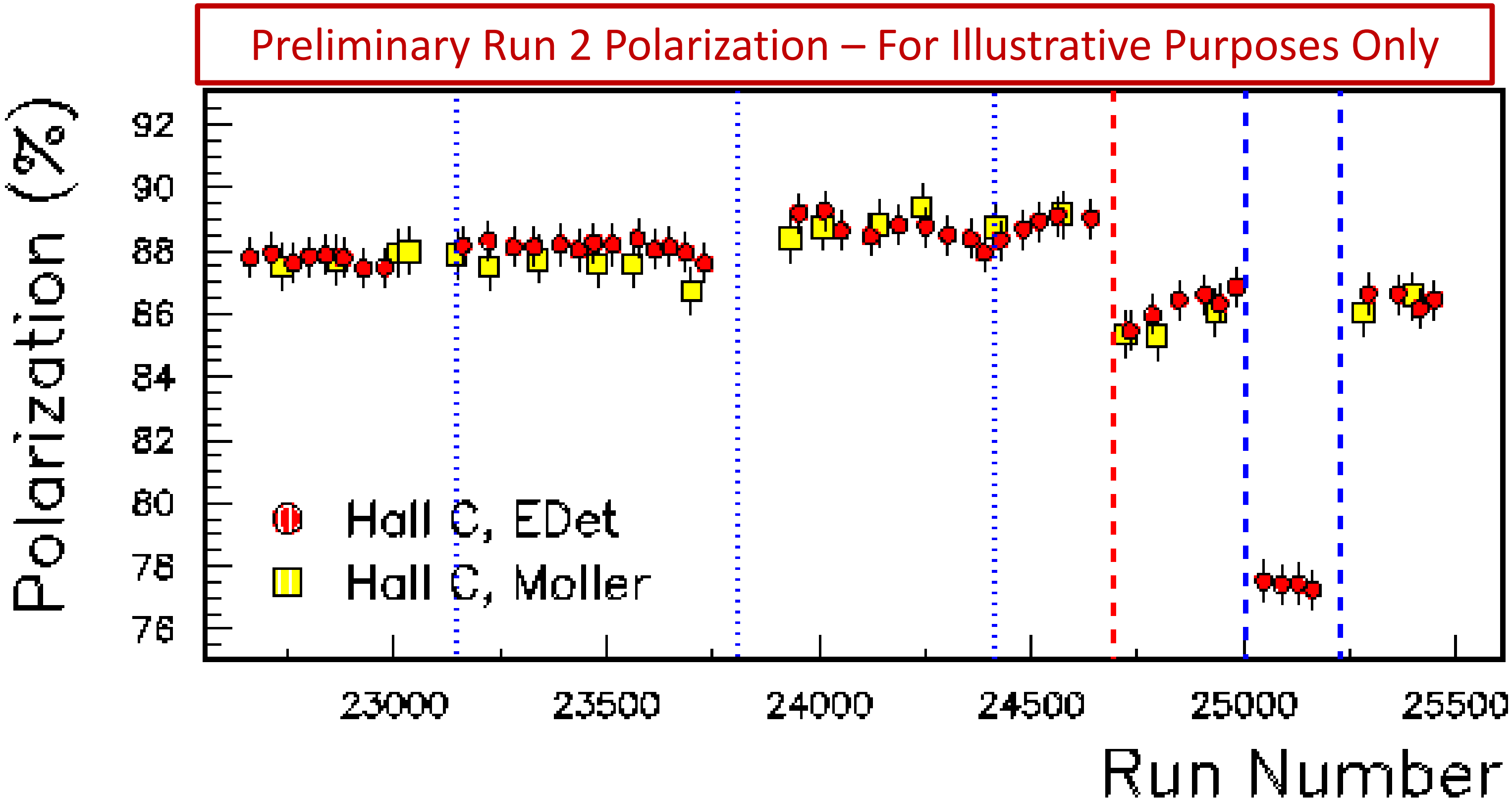


Target boiling not problematic; we sample at 960 Hz.





Beam Polarimetry



Note the wonderful agreement between both polarimeters!

Plot courtesy of Vladis Tvaskis

Qweak Proposed Error Budget

Qweak will be most precise (relative and absolute) PVES result to date.

$$A_{exp} = \frac{1}{1 - f_{total}} \left\{ \frac{A_{measured}}{P} - \sum_i f_i \, A_i^{bkgd} \right\}$$

Error source	Contribution to $\Delta A_{phys}/A_{phys}$ (%)	Contribution to $\Delta Q^p_W/Q^p_W$ (%)
Counting statistics	2.1	3.2
Hadronic structure	-	1.5
Beam polarimetry	1.0	1.5
Absolute Q^2	0.5	1.0
Backgrounds	0.7	1.0
Helicity-correlated beam properties	0.5	1.0
Total	2.5	4.2

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

Qweak "Run 0" error budget in terms of dilutions and asymmetries

$$A_{exp} = \frac{1}{1 - f_{total}} \left\{ \frac{A_{measured}}{P} - \sum_i f_i \, A_i^{bkgd} \right\}$$

Source (k_i)	Effective Contribution to A_{ep}	Contribution to ΔA from	
		Dilution f_i	Asym's
A_{raw}	-169.1	---	31
Regression	-35.1	---	13.8
Transverse Pol	0	---	4.9
Beam Polarization	-25.7	---	4.8
Target windows (b_1)	-57.6	4.4	8.5
Beamline bkg (b_2)	10.8	3.4	22.5
Neutral/soft bkg (b_2)	0	0.5	0.4
Inelastics (b_2)	0.6	0.6	0.2
$R_{RC} R_{Det} R_{Bin}$ $(= A_{R_{tot}})$	-2.8	---	3.7

Qweak "Run 0" corrections and their corresponding sizes

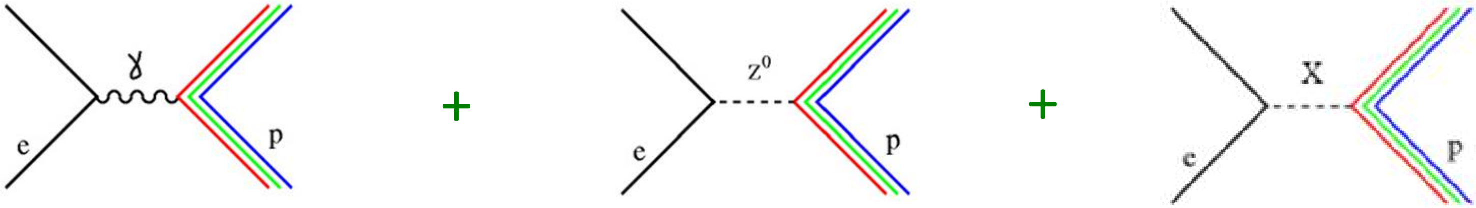
$$A_{ep} = R_{RC} R_{Det} R_{Bin} R_{Q^2} \frac{A_{msr}/_{P} - \sum_{i=1}^{4} f_i A_i}{1 - \sum_i f_i}$$

	Correction Value (ppb)	Contribution to ΔA_{ep} (ppb)	
Normalization Factors Applied to A_{Raw}			
Beam Polarization $1/P$	-21.3	4.7	
Kinematic Normalization R_{tot}	4.5	9.3	
Background Dilution $1/(1-f_t)$	-7.0	-	
Asymmetry corrections			
Beam Asymmetries κA_{reg}	-40.0	12.9	
Transverse Polarization κA_T	0.0	4.9	
Detector Linearity κA_L	0.0	3.9	
Backgrounds	$f_i A_i$	$\delta(f_i)$	$\delta(A_i)$
Target Windows (b_1)	-57.5	4.4	8.4
Beamline Scattering (b_2)	10.8	3.4	22.5
Other Neutral bkg (b_3)	0.0	0.6	0.4
Inelastics (b_4)	0.6	0.6	0.2

Target aluminum windows are our largest (~30%) correction

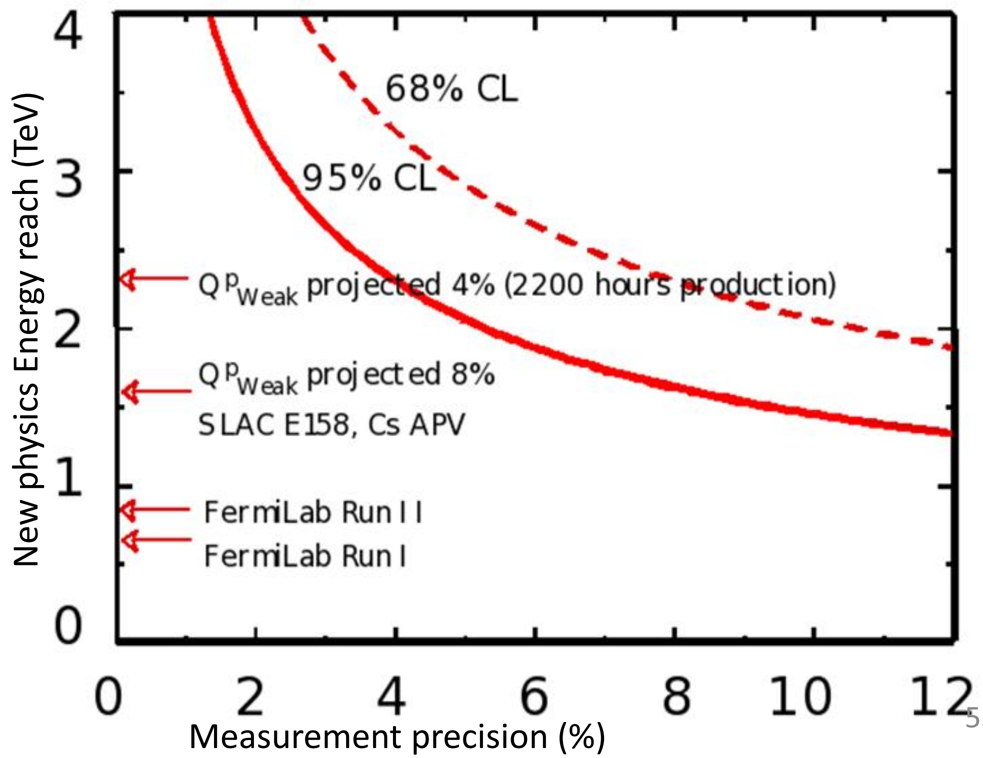
Beam line background is currently our largest uncertainty

Indirect probe of new physics



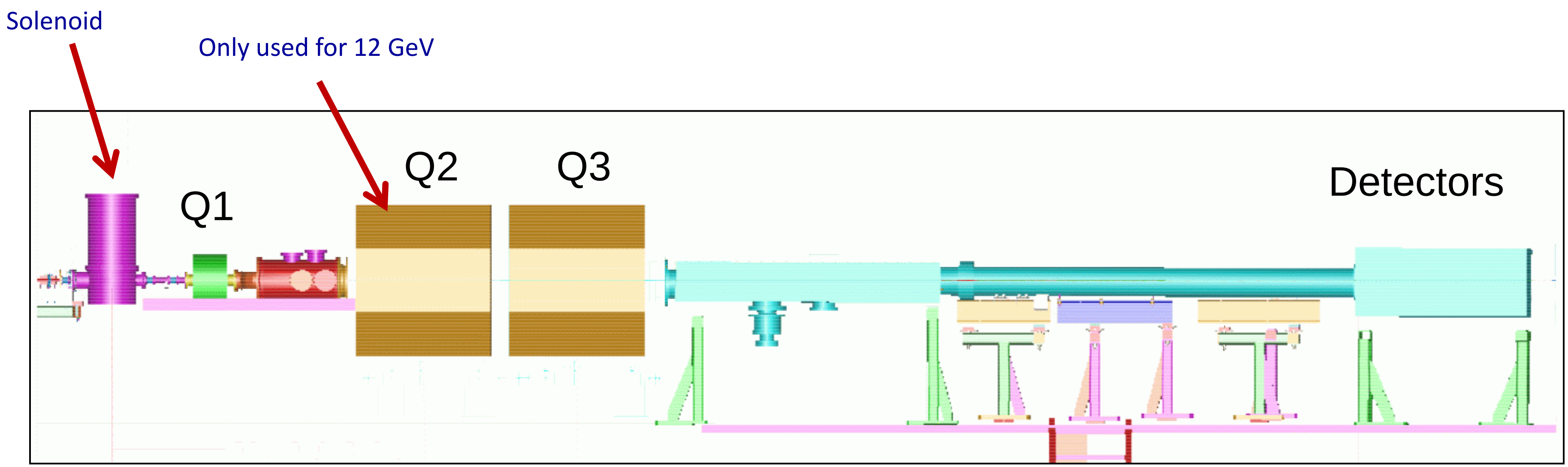
A 4% Q_W^p measurement probes new physics with 95% confidence level up to ~2.3 *TeV* (assuming $g = 1$)

$$\frac{\Lambda}{g} \sim \frac{1}{2\sqrt{((\sqrt{2})G_F|\delta Q_W^p|)}} \sim 2.3\ TeV$$



Hardware specs

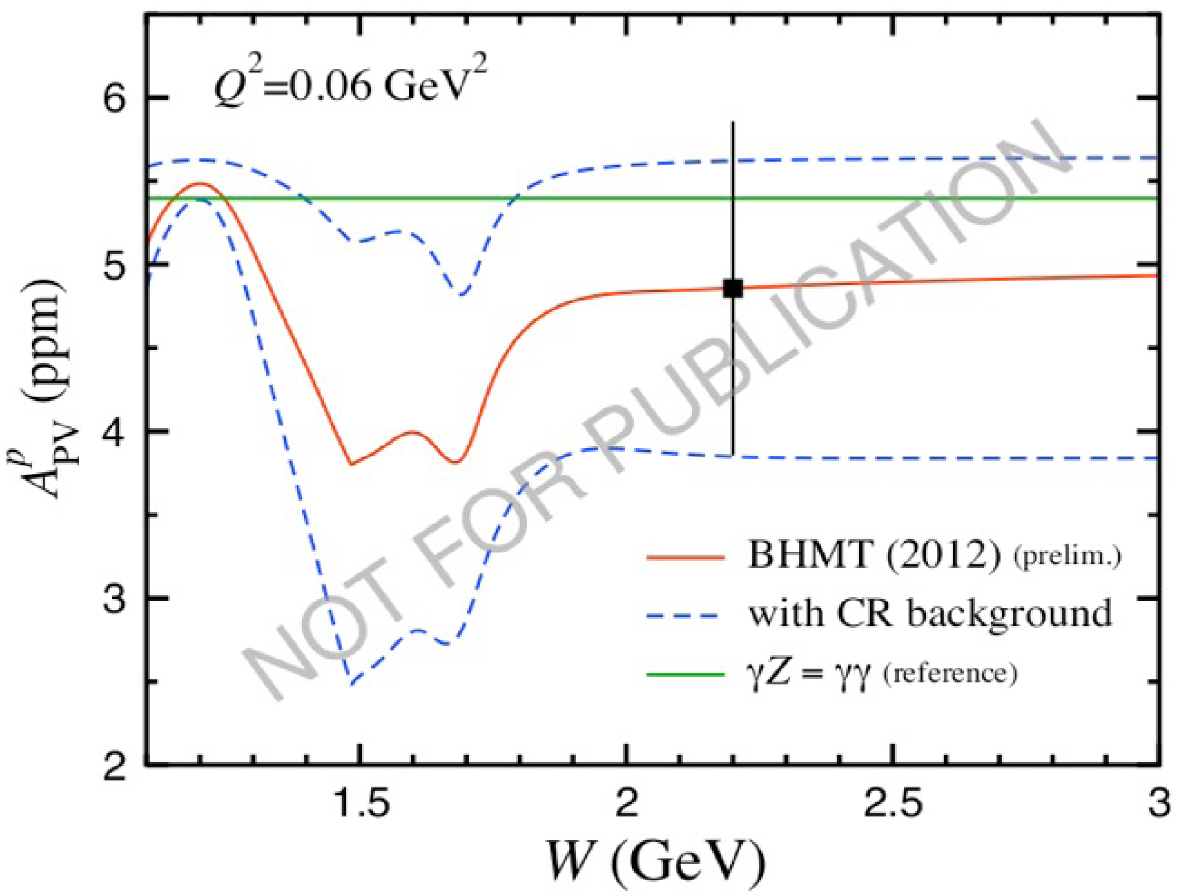
- Hall C Møller FACTS
  - Pure iron magnetically saturates at 2.2 T
  - We blast it at 3.5 T to polarize it out of plane.
    - Only polarize outer 2 electrons (8%)
  - Detectors in coincidence. (5 ns window)
    - Reduces backgrounds



3.3 GeV Data

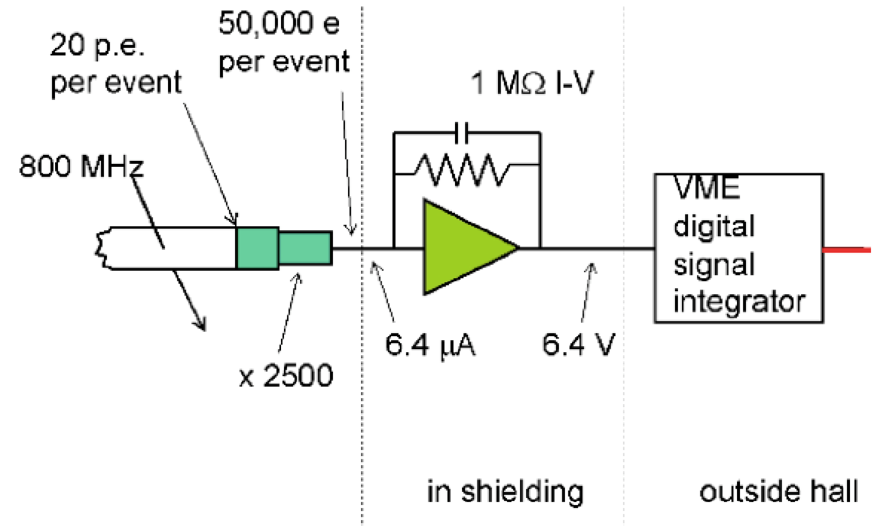
- Interesting for studying non-resonant inelastic transverse asymmetries → γZ-box diagrams
- PV asymmetries in pion photoproduction
- Transverse asymmetries in pion photoproduction

- Need to determine how to extract inelastic data from signal

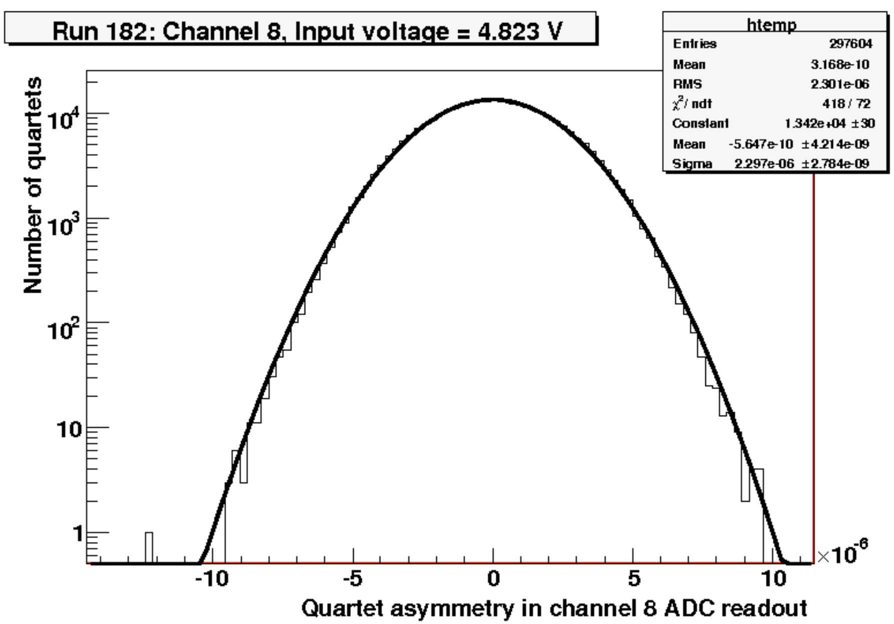


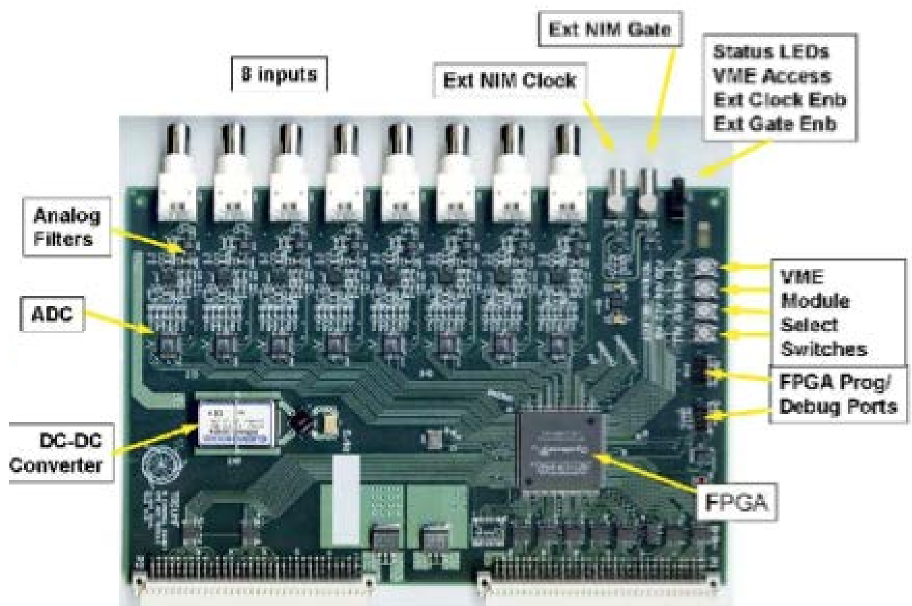
Electronics

Low noise electronics from PMT base through custom 18 bit ADC, sampling at 500 kHz and summed in FPGA.



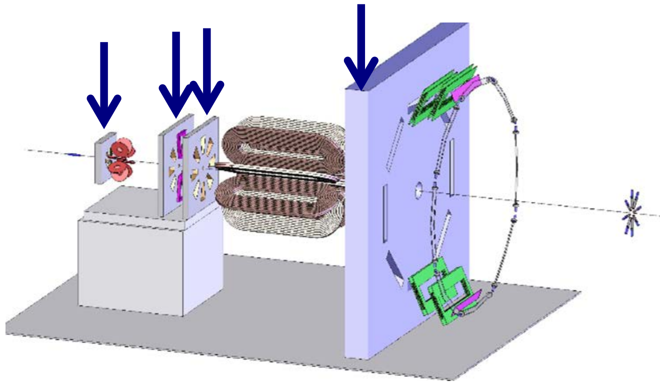
current source (battery) width 2.3 ppm

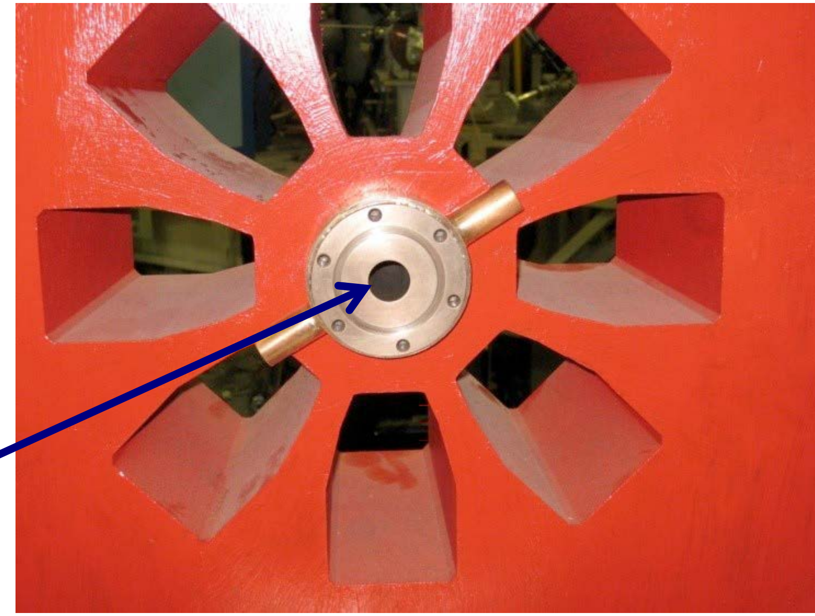




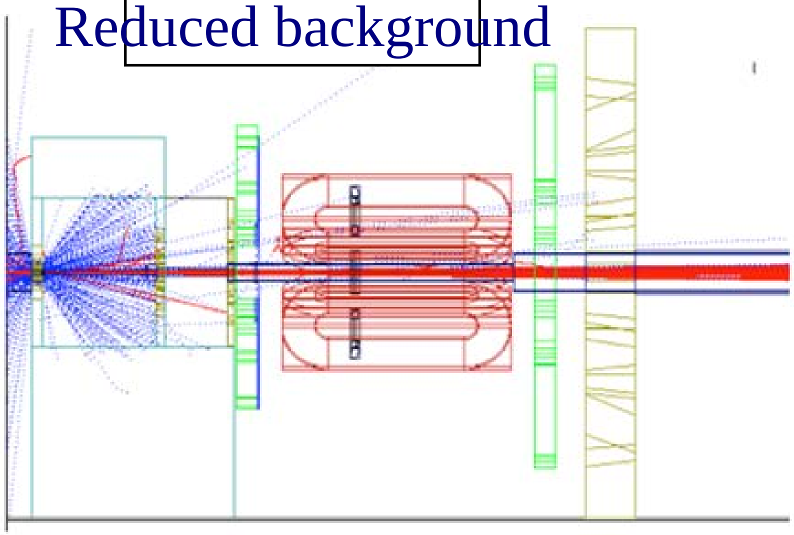
Collimation

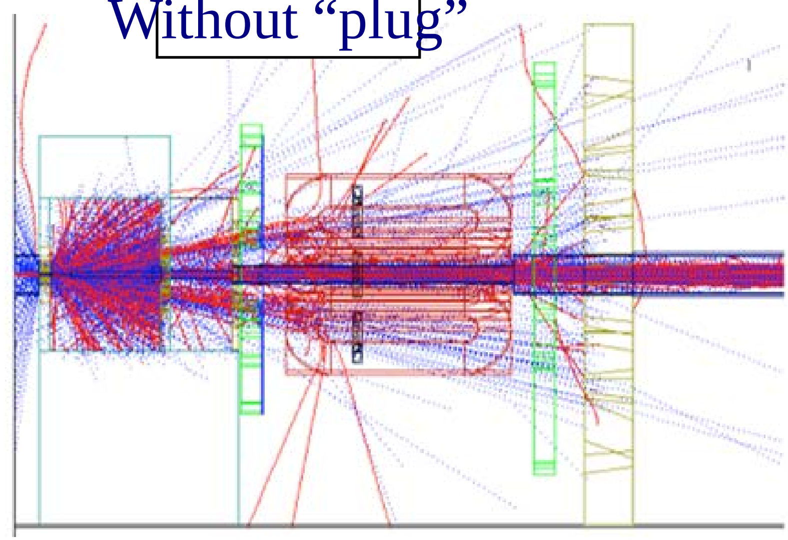
Three layers of lead collimation and concrete shield wall to control background.





Small aperture Tungsten collimator "plug" placed blocks low angle scatterers from interacting with the downstream beam pipe.

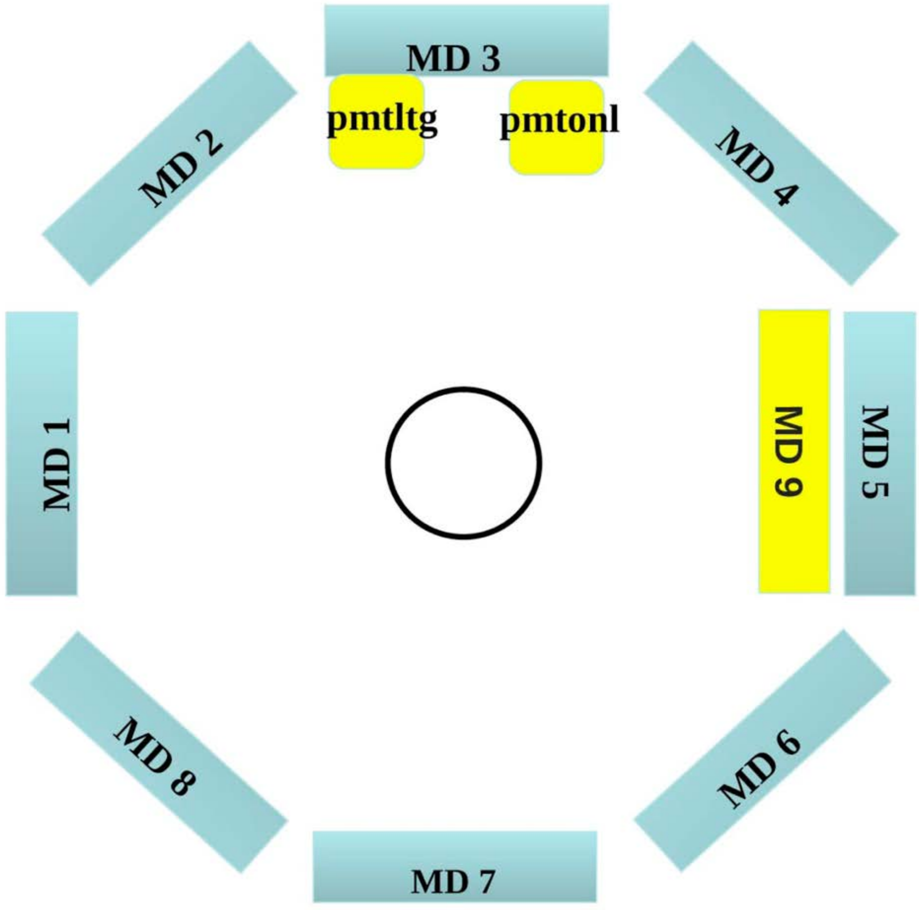




Beamline backgrounds

- Background detectors located inside detector hut, away from elastics, but still measured non-zero asymmetries
- Numerous shielding tests determined the source was beamline
- Correction: (-10.2 ± 23.5) ppb
  - Correlated background detectors with luminosity monitors

Artificially inflated



Hypothesis: "asymmetric beam halo" interacting with W plug

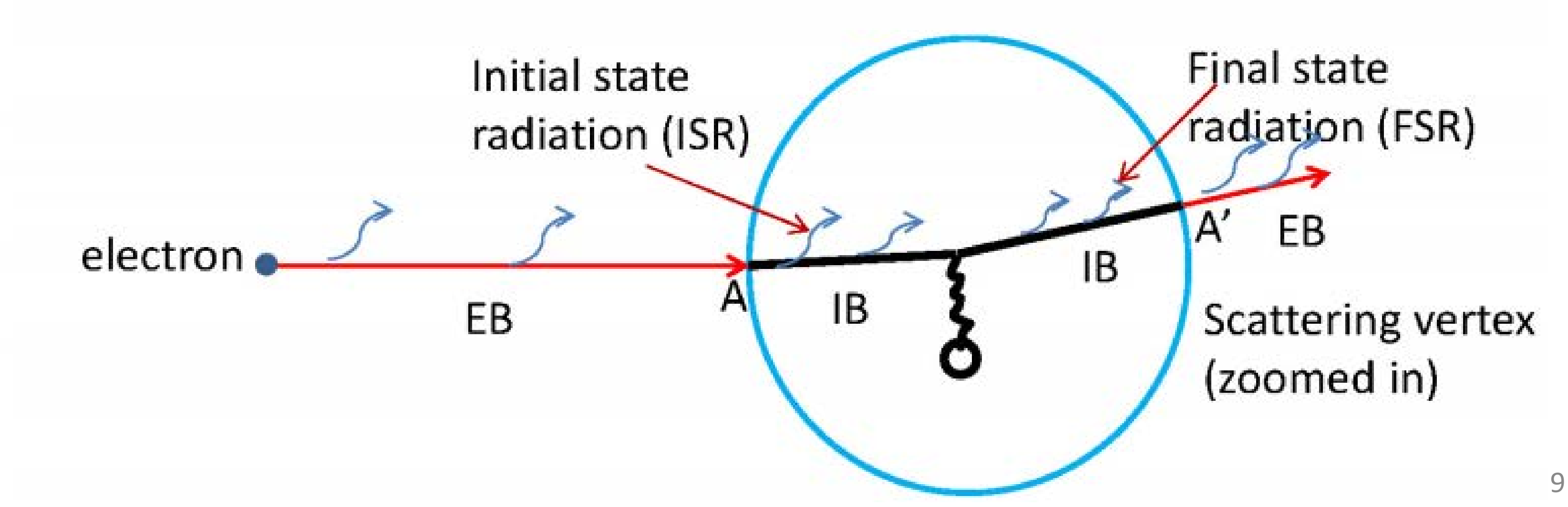
Radiative Corrections

Goal: make corrections such that quoted asymmetry and kinematics are concordant.

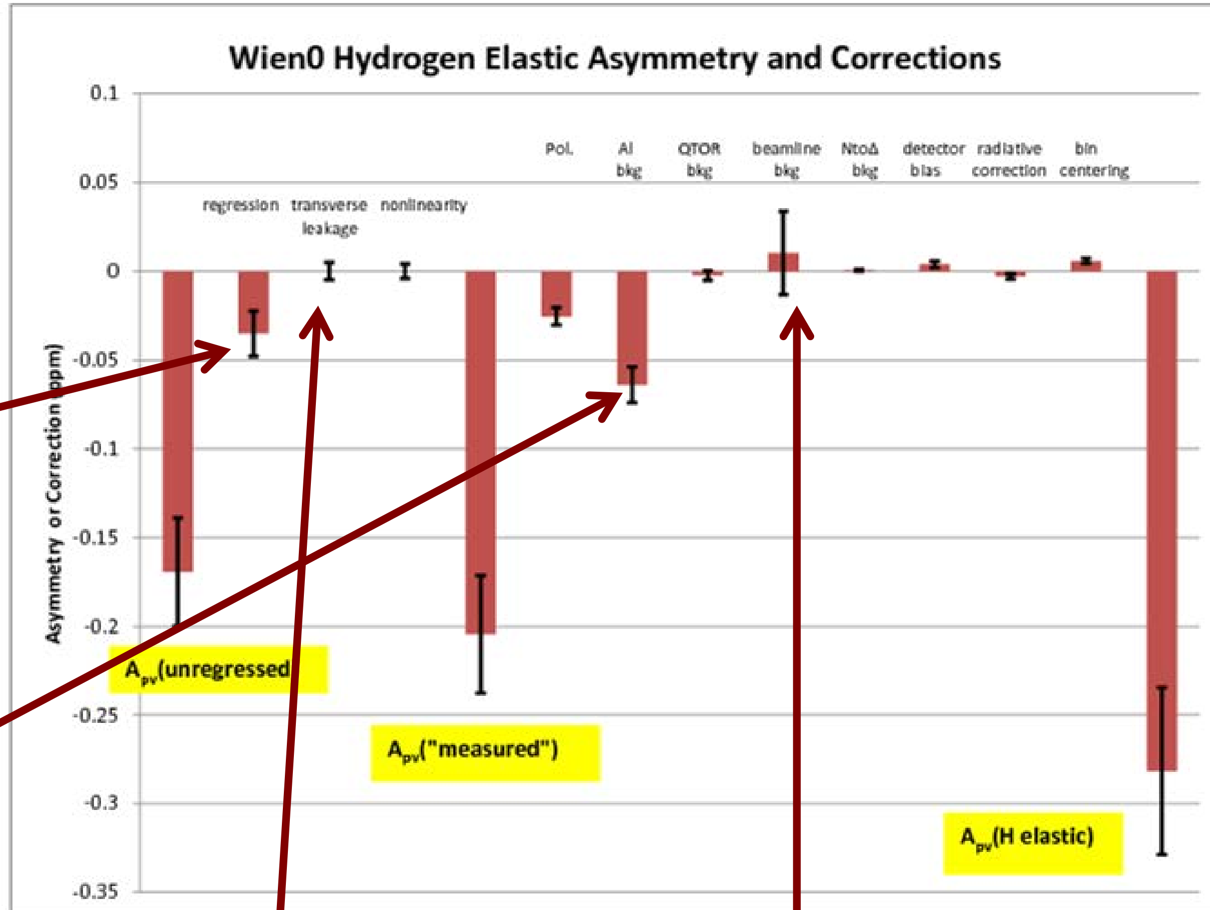
We quote the “measured” kinematics.

Average E_beam = 1155 MeV Average Q^2 = 0.0250 +- 0.0006 (GeV/c)^2Average Theta = 7.90 degrees

Vertex kinematics potentially has reduced energy and different angle.



PVES Asymmetry Analysis



Helicity-correlated beam systematics

Aluminum Target Windows

Transverse Asymmetry (Small uncertainty, but Interesting physics!)

Beamline Backgrounds

Aluminum Window Contribution

- To determine the aluminum target background asymmetry we need two things:
  - Dilution: [3.299 ± .01(stat) ± .07 (sys) ± .21(model)] %
  - Asymmetry signal size

1.0 uA

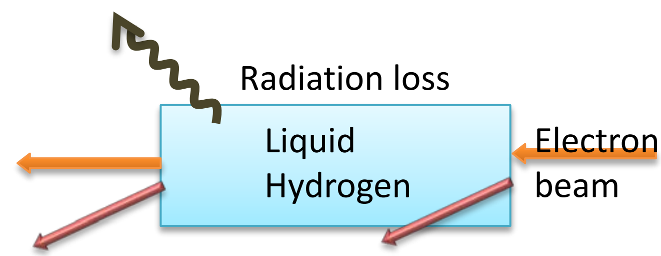
$$\frac{Y_{empty}/Y_{ref}}{Y_{full}/Y_{ref}}$$

0.1 uA

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

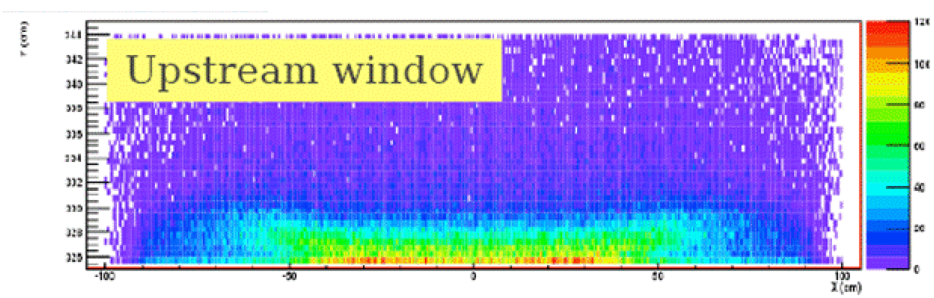
230 ppb

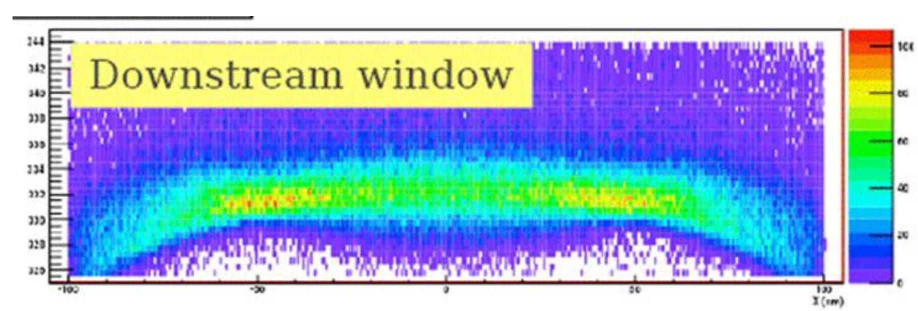
# of neutrons/# of protons.
0 for hydrogen.
~1 for aluminum.



Scattered electrons from DS window

Scattered electrons from US window

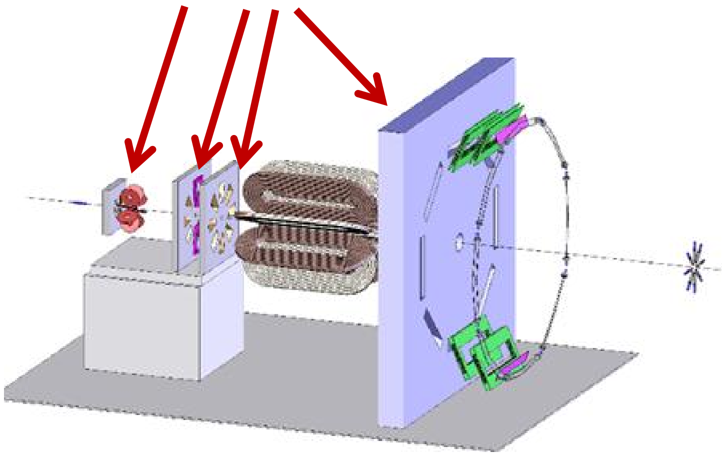


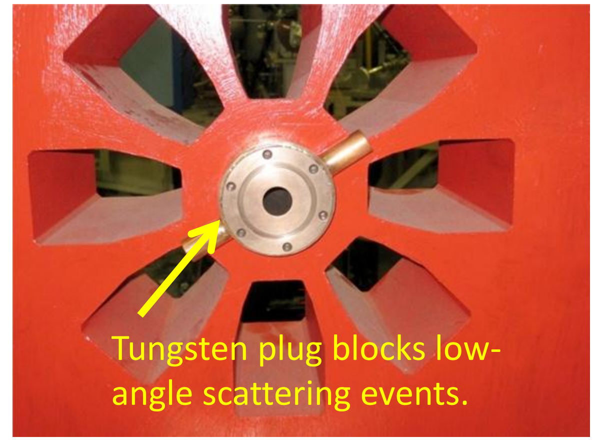


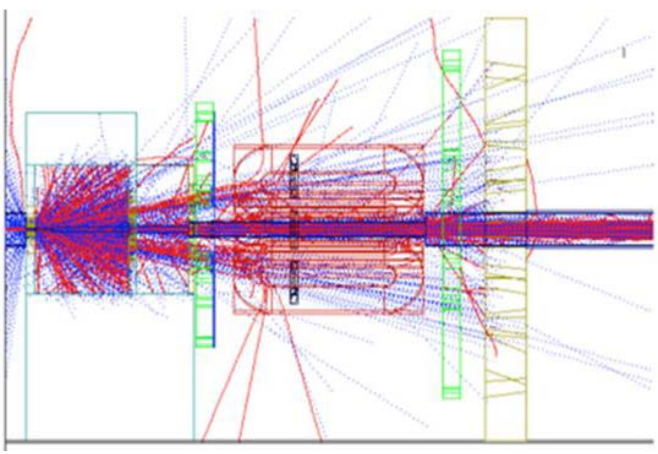
Computer simulation of scattered electrons on one main detector.

Other Backgrounds

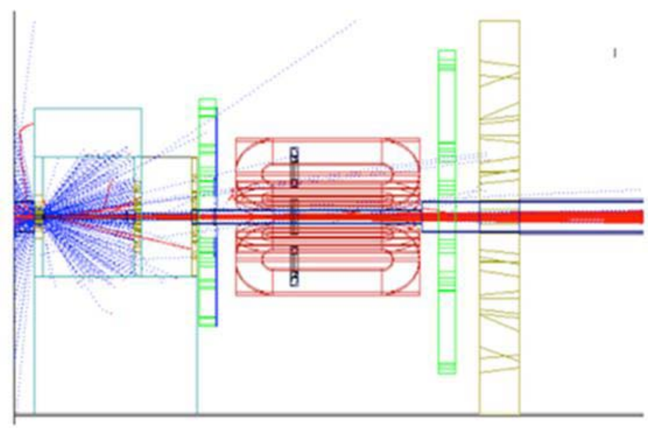
To reduce backgrounds, we added 3 layers of concrete shield wall and lead.







Without collimation.



With collimation.

We also had a spare main detector we moved around to measure these backgrounds.
They contribute ~ 10.2ppb correction.