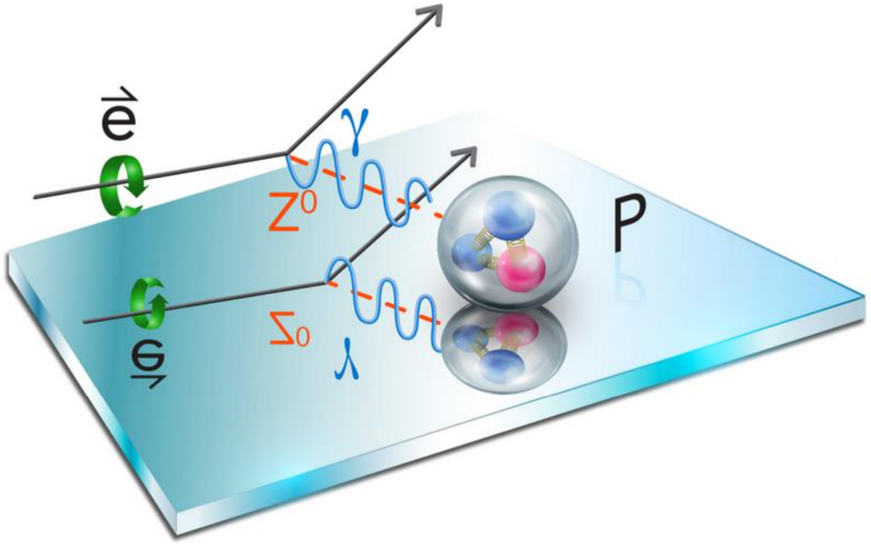
Measurement of the Weak Charge of the Proton by the Qweak Collaboration



CIPANP 2018
Palm Springs, California

Kent Paschke
University of Virginia

Outline

- Introduction to PVES and weak charge of the proton
- Apparatus and analysis
- Results and implications for new physics
- Future measurements

PHE/PPHI Joint session on Weak Parameters
Friday, Parallel 7

- Mikhail Gorshteyn, Calculations for interpreting the weak charge
- Frank Maas, P2 and MOLLER experiments
- Gerald Gwinner, Atomic parity violation

PPHI session on Electrons and Muons
Friday, Parallel 7

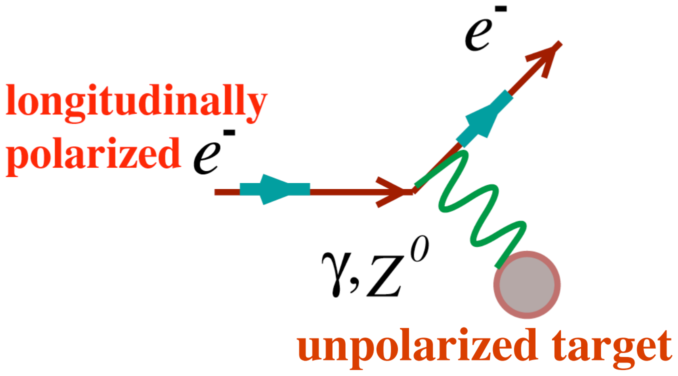
- Paul Souder, PVDIS with SOLID
- Nils Feege, Electroweak physics at an EIC

Parity-Violating Electron Scattering

Low Q^2 offers complementary probes of new physics at multi-TeV scales

EDM, g_μ-2, weak decays, β decay, 0νββ decay, DM, LFV…

Parity-Violating Electron Scattering: *Low energy weak neutral current couplings, precision weak mixing angle (SLAC, Jefferson Lab, Mainz)*



- **Incident beam is longitudinally polarized**
- **Change sign of longitudinal polarization**
- **Measure fractional rate difference**

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$\sigma \propto |A_\gamma + A_Z|^2 \sim |A_\gamma|^2 + \underline{2A_\gamma(A_Z)^*} + \ldots$$

Electroweak interference

leading term in asymmetry, enhances weak signal

Parity violating electron scattering provides a sensitive probe for possible new neutral current interactions

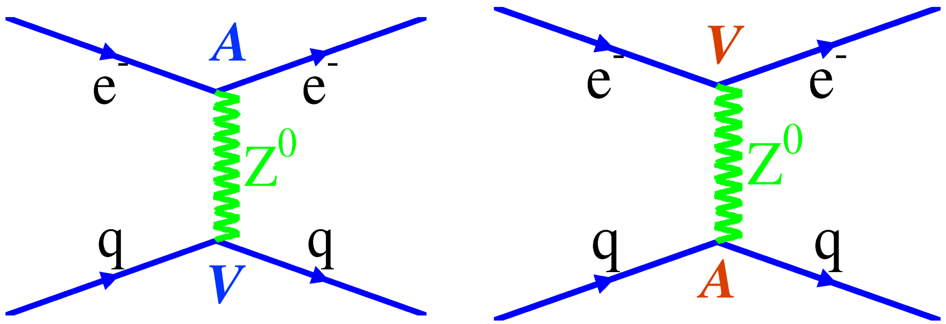
Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

$$\left|A_\gamma + A_Z + A_{\text{new}}\right|^2 \rightarrow A_\gamma^2\left[1 + 2\left(\frac{A_Z}{A_\gamma}\right) + 2\left(\frac{A_{\text{new}}}{A_\gamma}\right)\right]$$

Weak Neutral Current Charge in the Standard Model

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

Effective electron-quark couplings



$$C^{SM}_{1q} = 2\,g^e_A\,g^q_V \qquad C^{SM}_{2q} = 2\,g^e_V\,g^q_A$$

At tree level:	EM Charge	WNC Vector Charge
u	$+2/3$	$Q^u_W = -2\,C_{1u}$
d	$-1/3$	$Q^d_W = -2\,C_{1d}$
$p = 2u + d$	$+1$	$Q^p_W = -2(2\,C_{1u} + C_{1d})$
$n = u + 2d$	0	$Q^n_W = -2(C_{1u} + 2\,C_{1d})$

Electroweak fermion couplings

	Left	**Right**
γ Charge	$0,\pm1,\pm\frac{1}{3},\pm\frac{2}{3}$	$0,\pm1,\pm\frac{1}{3},\pm\frac{2}{3}$
W Charge	$T=\pm\frac{1}{2}$	zero
Z Charge	$T-q\sin^2\theta_W$	$-q\sin^2\theta_W$

Radiative corrections incorporated in weak charge definition and scale dependence of $\sin^2\theta_W$ are well controlled

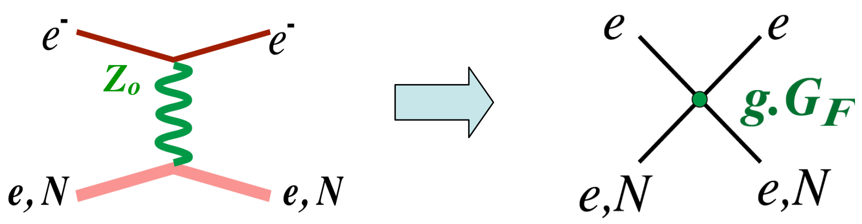
$$\sin^2\theta_W \sim \frac{1}{4}$$

so $Q^p_W = 1 - 4\sin^2\theta_W$ is strongly suppressed

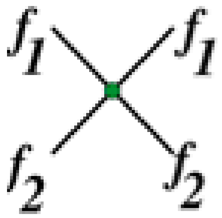
Search for new neutral current contact interactions

Low energy WNC interactions ($Q^2 \ll M_Z^2$)

Heavy mediators = contact interactions



Consider $f_1 f_1 \rightarrow f_2 f_2$ **or** $f_1 f_2 \rightarrow f_1 f_2$



$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g^{12}_{i\,j})^2}{\Lambda^2_{ij}} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$

Eichten, Lane and Peskin, PRL50 (1983)

mass scale Λ, coupling g
for **each fermion** and **handedness** combination

New neutral current interactions with axial-vector electron, vector quark couplings would add in the effective neutral current coupling:

$$\mathcal{L} = \mathcal{L}_{\mathtt{SM}} + \mathcal{L}_{\mathtt{new}} \qquad \frac{G_F}{\sqrt{2}} C_{1q} = \frac{G_F}{\sqrt{2}} C^{SM}_{1q} + \left(\frac{g^{eq}_{AV}}{\Lambda}\right)^2$$

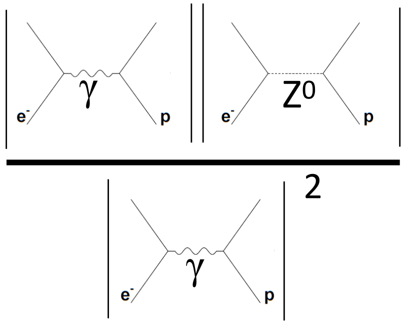
Conventional “mass limits” for new contact interaction: assume coupling with compositeness scale $g^2 = 4\pi$.

example: 4% measurement of Q^p_W corresponds to a mass limit of 33 TeV

Erler *et al.*, Ann.Rev.Nucl.Part.Sci. 64 (2014)

PVES and Nucleon Structure

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \rightarrow$$



$$= \left[\frac{-G_F Q^2}{\pi\alpha\sqrt{2}}\right] \frac{\epsilon G_E^{p\gamma} G_E^{pZ} + \tau G_M^{p\gamma} G_M^{pZ} - \frac{1}{2}(1 - 4\sin^2\theta_W)\epsilon' G_M^{p\gamma} \tilde{G}_A^p}{\epsilon (G_E^{p\gamma})^2 + \tau((G_M^{p\gamma})^2}$$

Axial
Form
Factor

Assuming charge symmetry, the weak form-factors relate to electromagnetic form factors of the proton and neutron

$$4G_{E,M}^{pZ} = (1 - 4\sin^2\theta_W) G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - G_{E,M}^{s}$$

Proton
Weak
Charge

Electromagnetic
Form Factors

Strange Quark
Form Factor

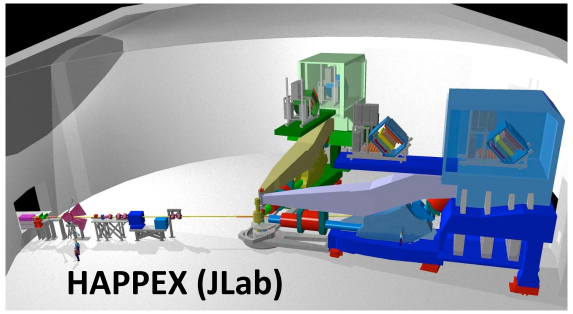
At forward angles and small Q^2, A_{PV} accesses the weak charge

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \xrightarrow[\theta \rightarrow 0]{Q^2 \rightarrow 0} -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^p + Q^2 \boxed{B(Q^2, \theta)}\right]$$

$B(Q^2,\theta)$ is a form-factor term. About 30% correction to A_{PV} for Qweak. Well determined by existing PVES data.

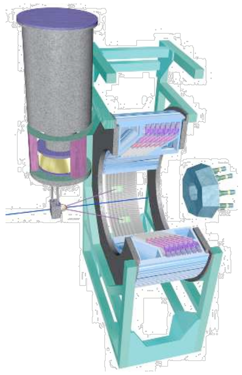
APV and Extracting Qweak

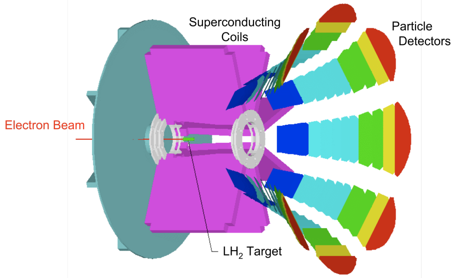
WNC elastic form-factors have been well studied in search of intrinsic nucleonic strangeness



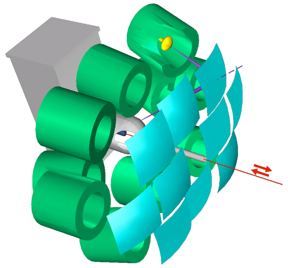
HAPPEX (JLab)

A4 (Mainz)





G0 (JLab)



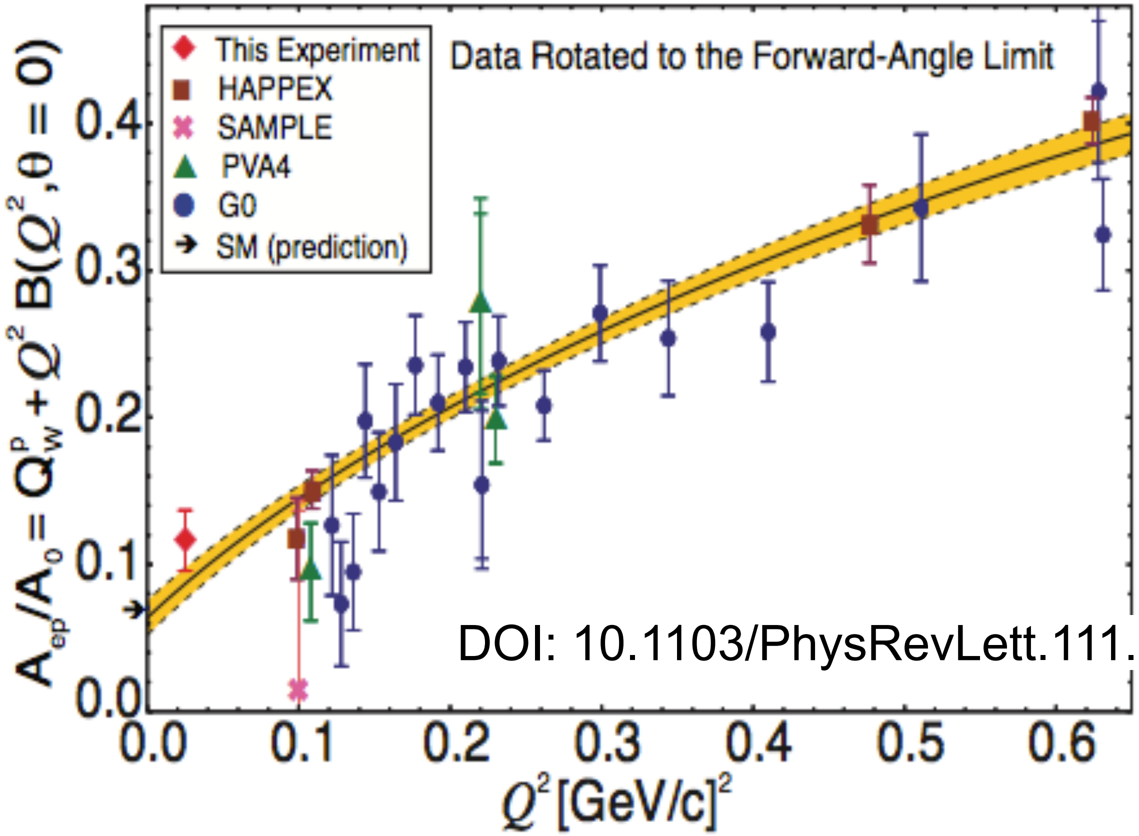
SAMPLE (Bates)

Hadronic corrections for QWeak constrained in fit of all PVES data over various nuclear targets, E, θ, Q²

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

Global fit, first results on Q_W^p

- All nuclear PVES data (hydrogen, deuterium, helium).
- 5 parameters (C_{1u}, C_{1d}, isovector axial FF, ρ_s, μ_s)
- Illustration shown here at forward angle.



DOI: 10.1103/PhysRevLett.111.141803

A SEARCH FOR NEW PHYSICS
Qweak

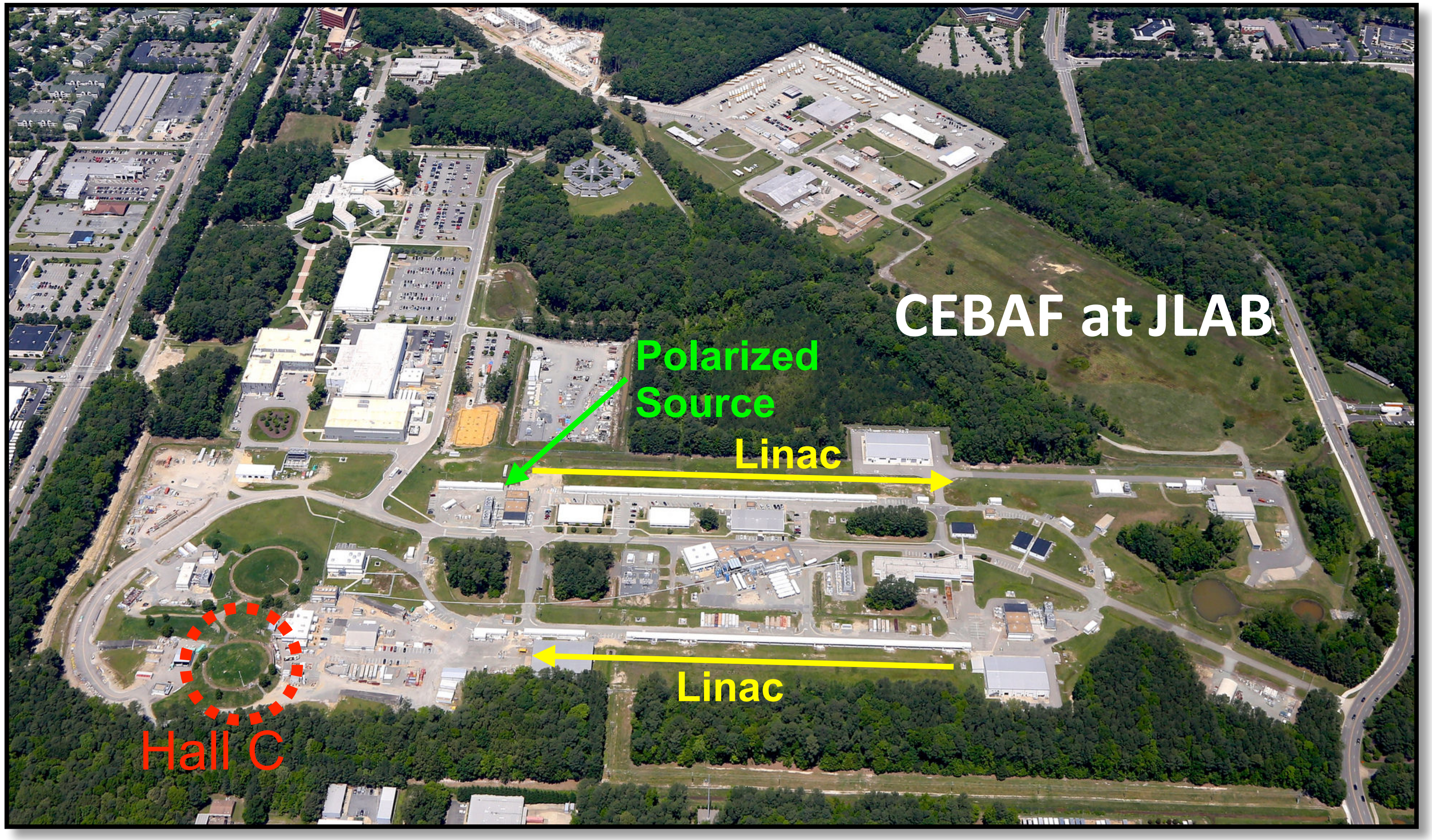
101 collaborators **26 grad students**
11 post docs **27 institutions**

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
[24] Syracuse University
[25] Duquesne University

Final results from the full Qweak data set, collected 2010-2012

Nature 557 (2018) no.7704, 207-211

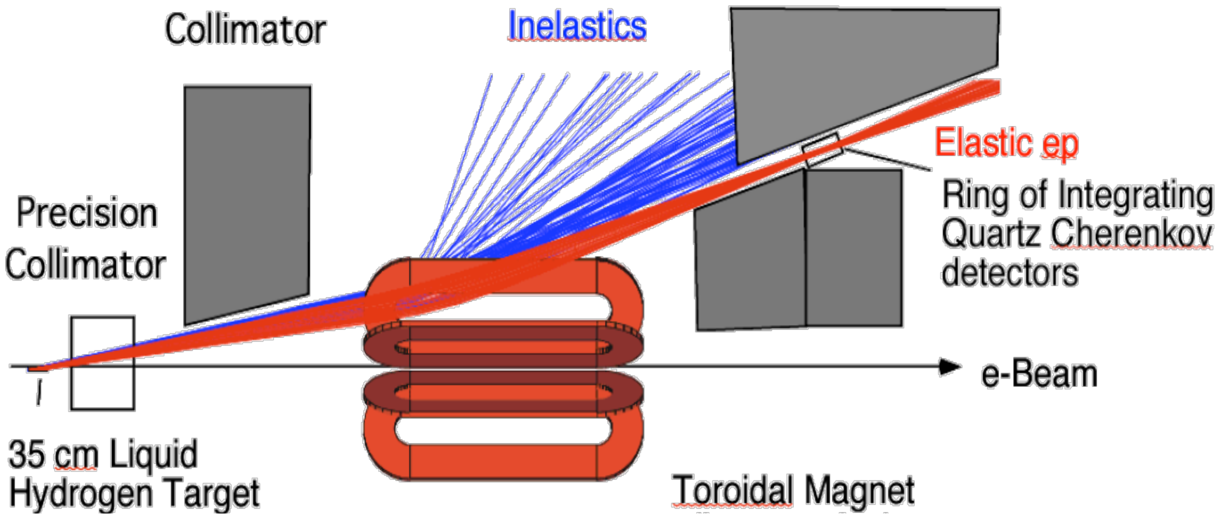
Nuclear Instruments and Methods A781 (2015) 105-133.



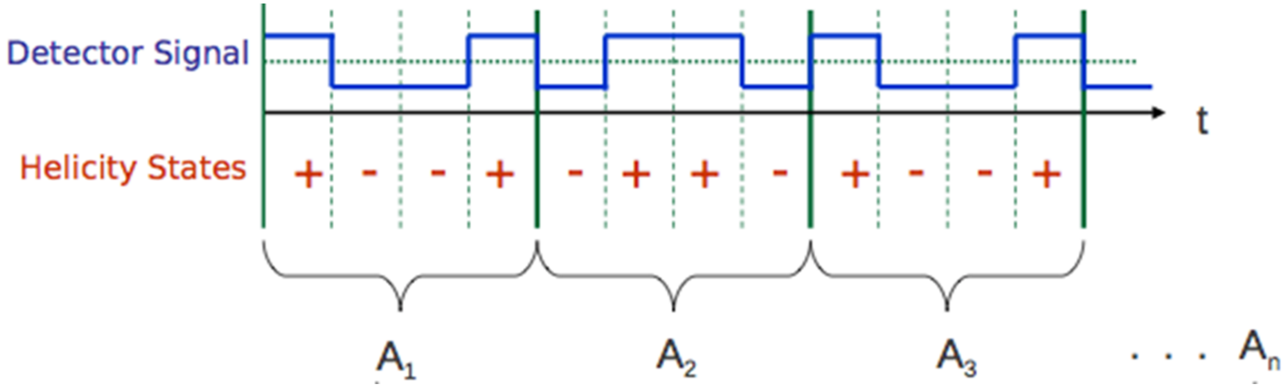
Measuring A_{PV}

Goal: measure beam helicity-correlated elastic scattering asymmetry to high precision

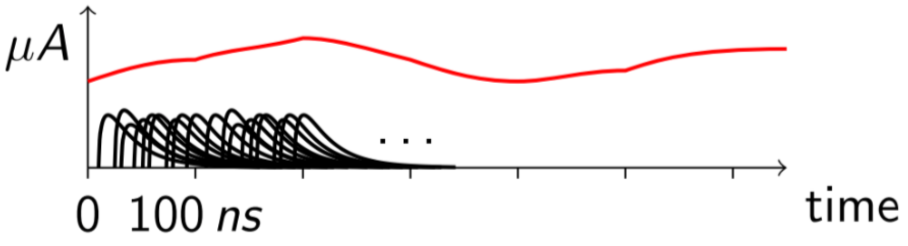
Elastic signal focused on detector



Rapid (1kHz) measurement over helicity reversals to cancel noise

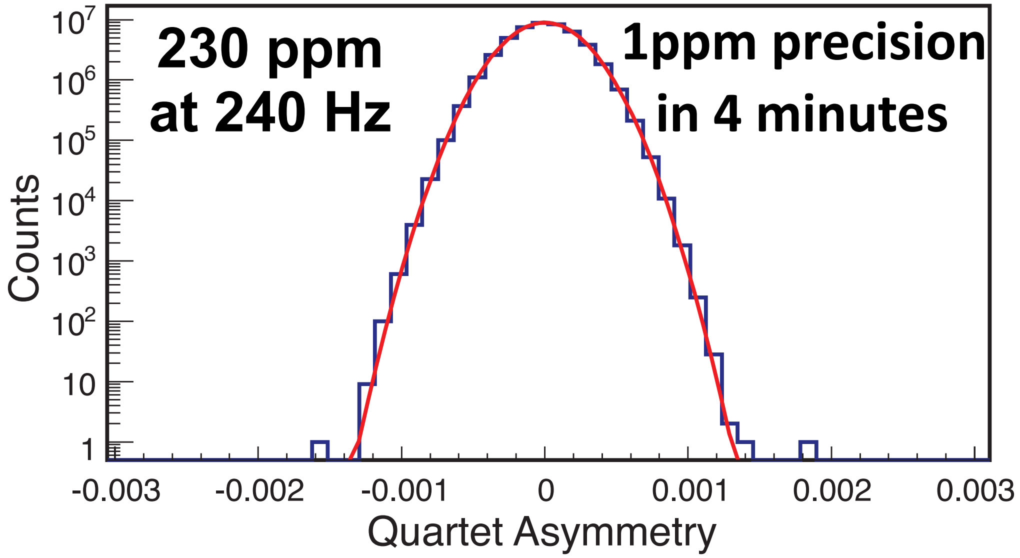


Analog integration of detector current



~7 GHz total rate

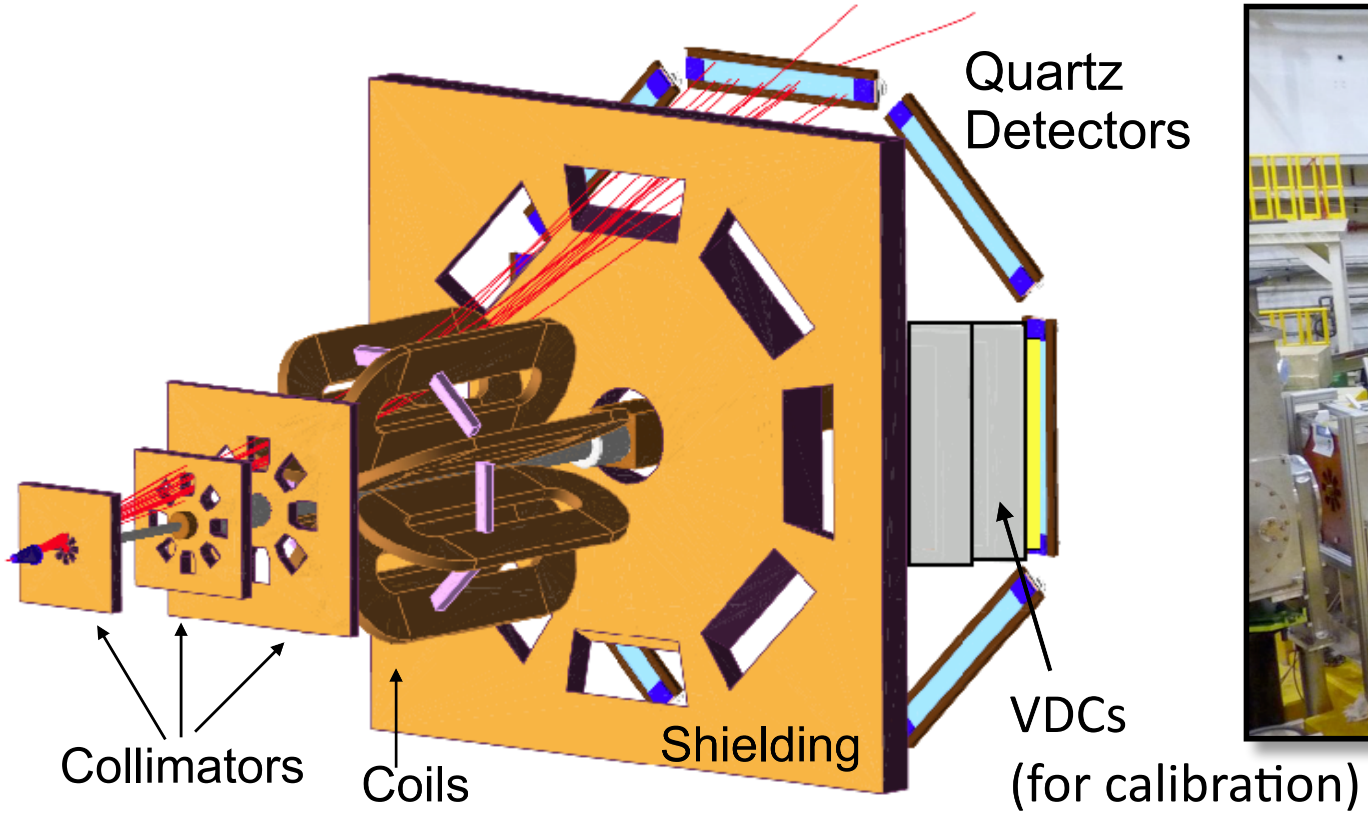
1 GeV, 180 µA, 1.5 years

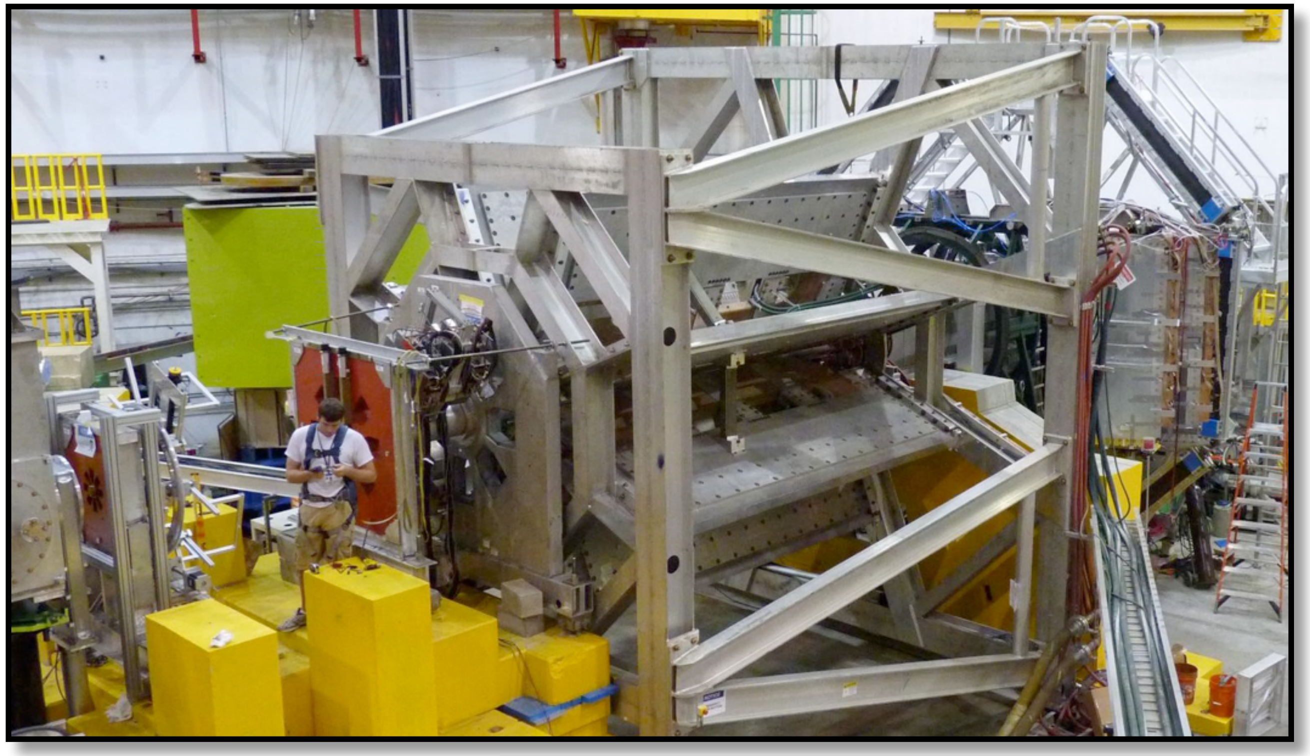


230 ppm at 240 Hz

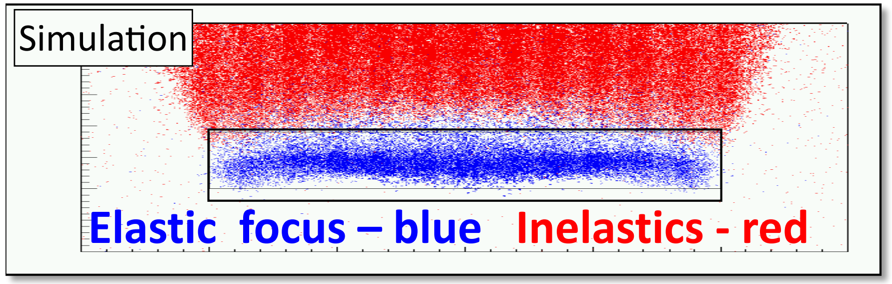
1ppm precision in 4 minutes

The Qweak Spectrometer

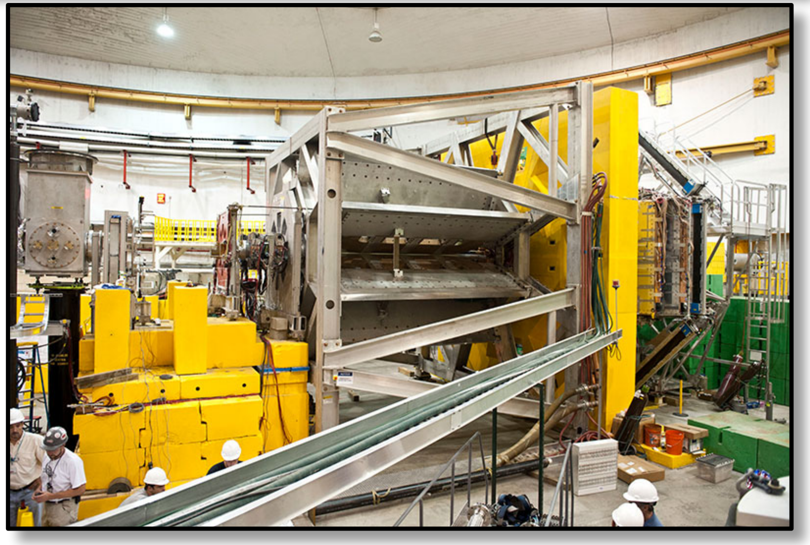




Toroidal Spectrometer directs elastics onto one of 8 detectors



Detectors:
- 2 meters long, fused silica
- Lead radiator (2 cm thickness)
- phototube at each end
- ~900 MHz per detector

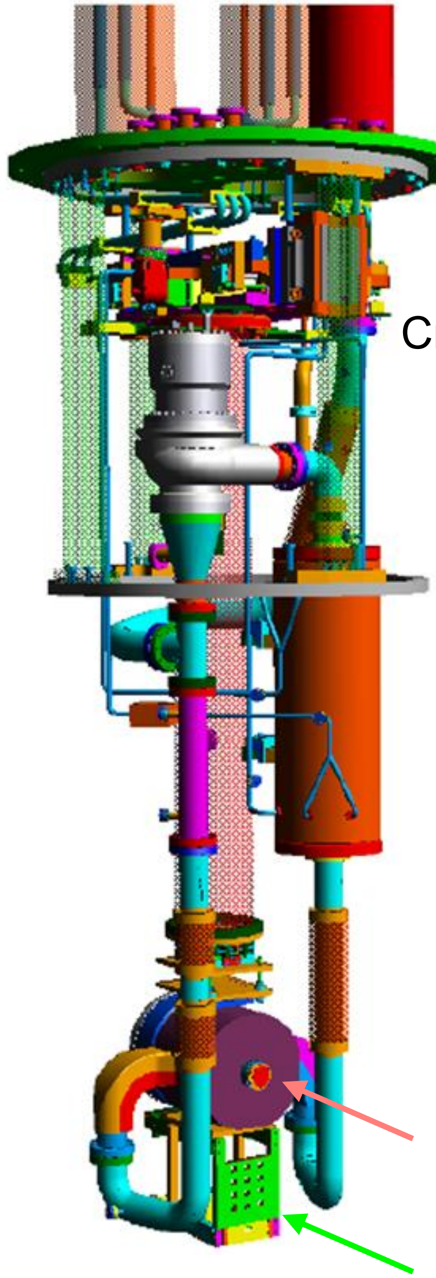


Liquid Hydrogen Target

World's highest power and lowest noise cryogenic target

35 cm, 180 µA electron beam, 2.5 kW deposited power

Very low density variation: ~50 ppm over 4 ms at 180 µA

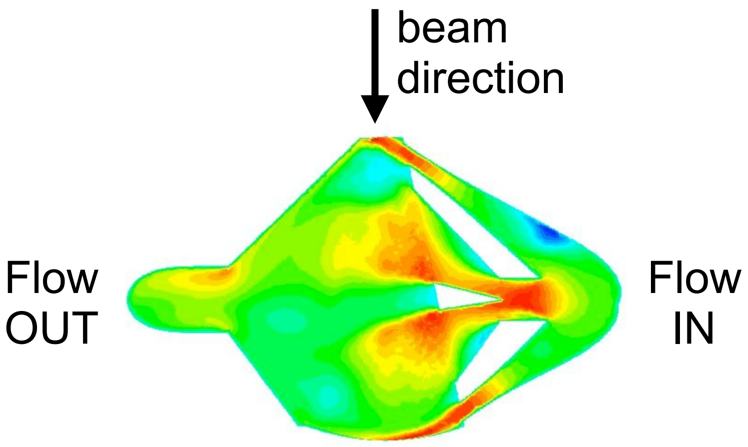


Cryogenics and
XY motion
platform

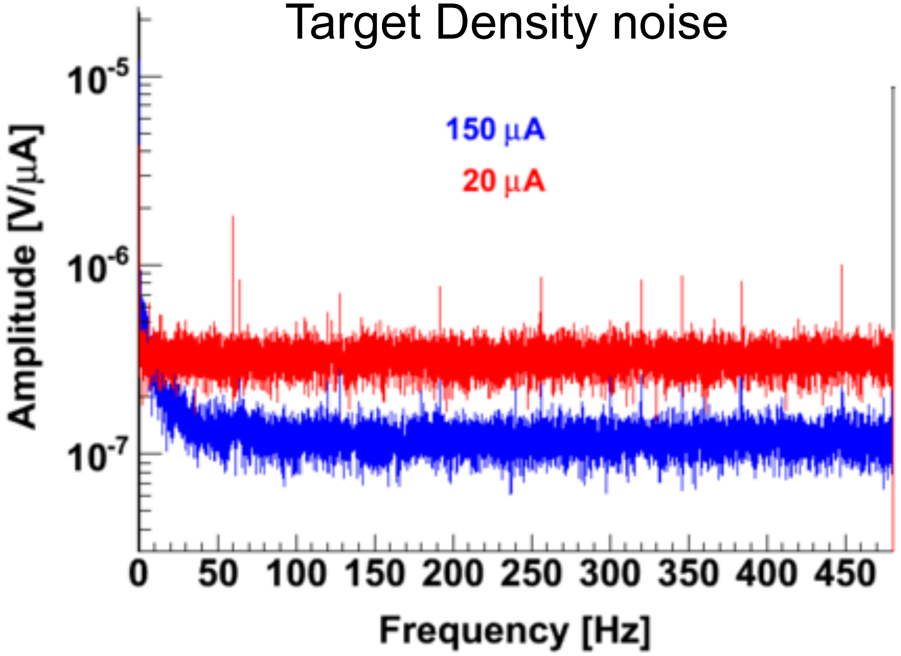
LH_2 target

Calibration Targets

Designed with CFD
simulation



Flow rate



Fast helicity reversal (1 ms)
cancelled density fluctuations

Beam Corrections and Beam quality

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

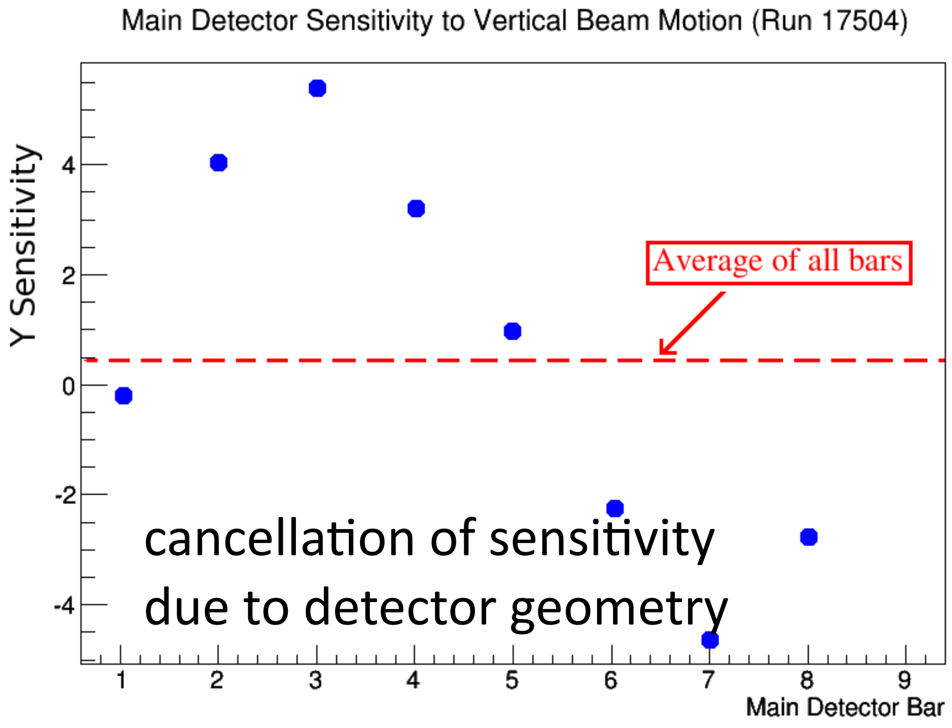
where i runs over x,y,x'(angle),y'(angle), and energy.

Calibrate detector sensitivity with harmonic modulation of beam parameters to determine $\frac{\partial A}{\partial \chi_i}$

Careful setup of the polarized source

minimized helicity-correlated beam asymmetry

Parameter	Helicity-Correlated Difference Average	Typical Sensitivity
X	-2.7 nm	-2 ppb/nm
X’	-0.14 nrad	50 ppb/nrad
Y	-1.9 nm	<0.2 ppb/nm
Y’	-0.05 nrad	<3 ppb/nrad
Energy	-0.6 ppb	-6 ppb/ppb



cancellation of sensitivity due to detector geometry

Average beam asymmetries were small over course of run

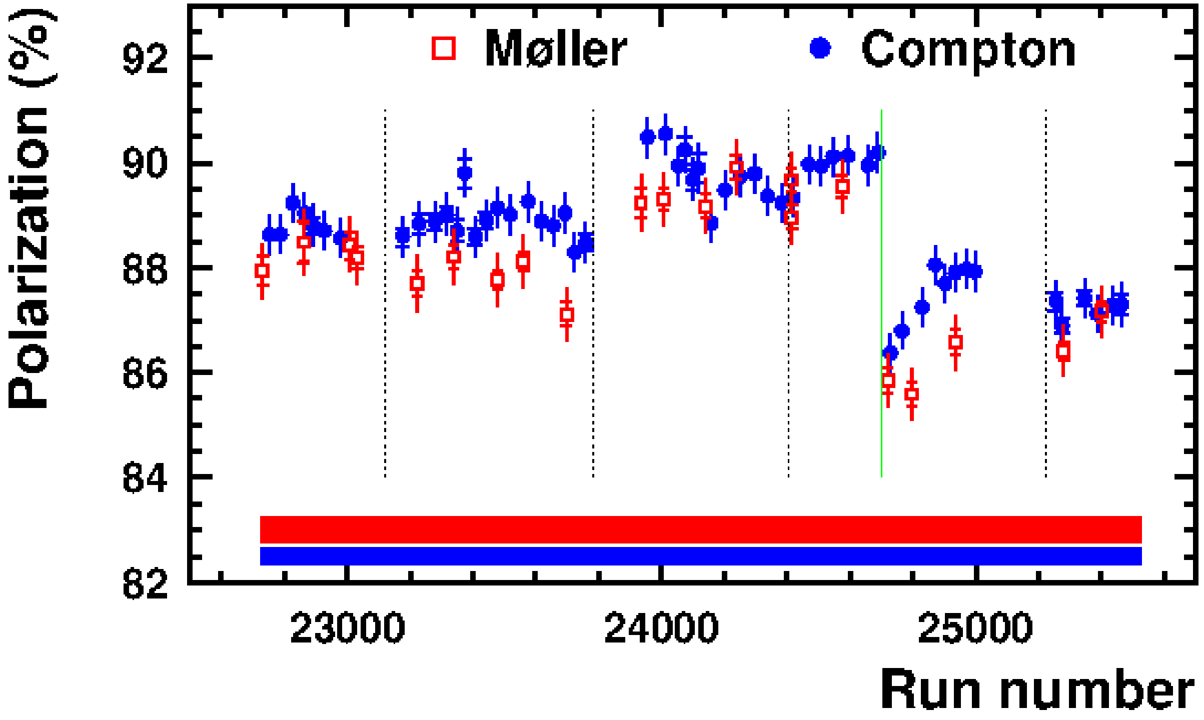
Net Correction: 3.5 ± 1.7 ppb

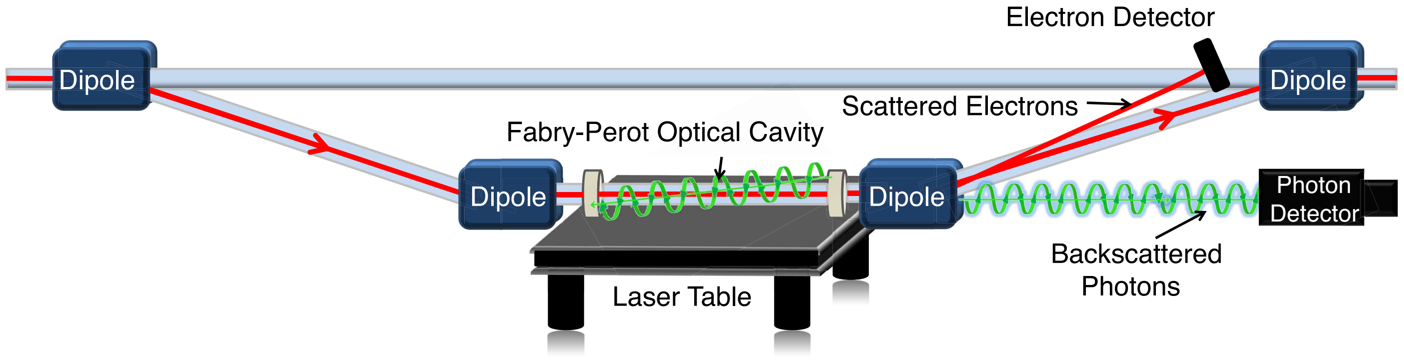
Electron Beam Polarimetry

Moller: *ee* scattering with iron foil
- 4T field, saturated magnetization
- experience with ~1% precision in Hall C
- modified spectrometer for 1 GeV
- invasive, low current only

Compton: $e\gamma$ scattering with polarized green laser light
- new polarimeter in Hall C
- low E_{beam}: low analyzing power, low scattering energies
- novel diamond microstrip detector
- *per mille* control of laser polarization inside cavity

Comparison of independent polarimeters





Result: ~0.6% precision on 89% polarization

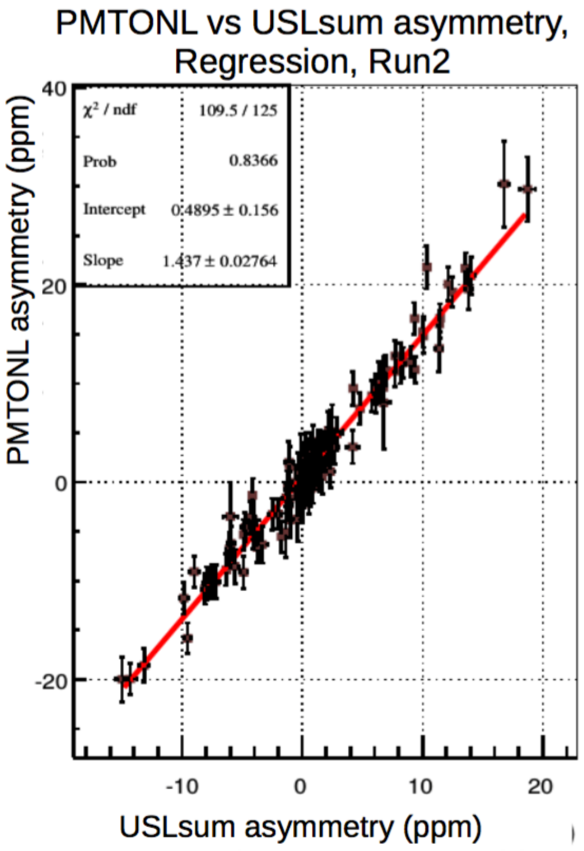
Important milestone for high precision polarimetry needed for future program

Physical Review X6 (2016) no.1, 011013

Physics Letters B 766, 339 (2017)

Beamline Backgrounds

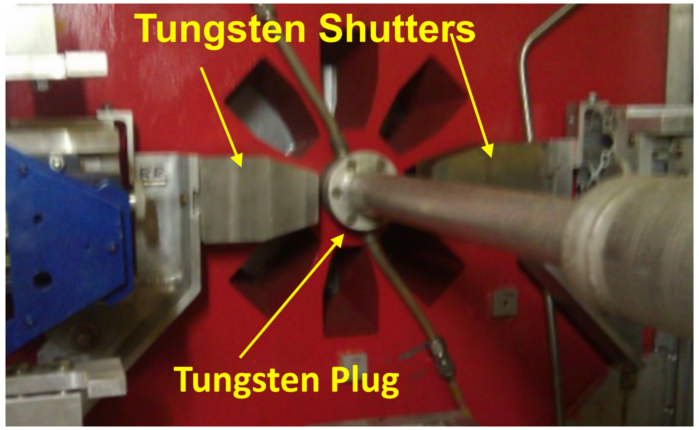
Large asymmetries seen in background monitors were correlated with main detectors


PMTONL vs USLsum asymmetry, Regression, Run2

- A background associated with re-scattering in the beam line eluded our collimation
- Radiators were added to the main detector reduce background importance
- Signal fraction f ~ 0.2%
- Unstable background asymmetry, correlated with beam halo

Studies included blocking octants

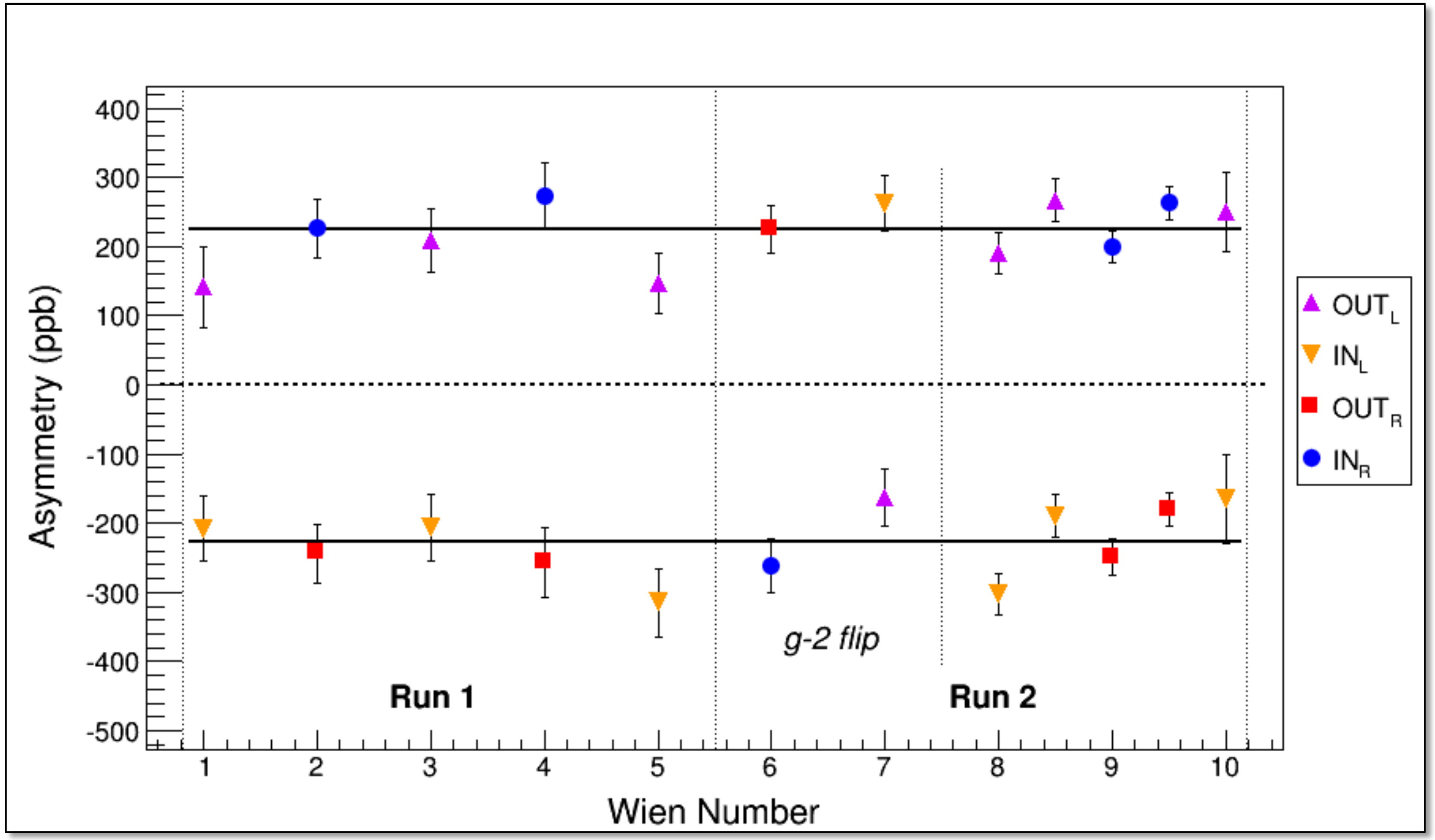
Asymmetry well measured by background detectors



Measured in various background monitors. Correlations between detectors were stable.

Net Correction: -1.2 ± 1.7 ppb

Summary of Asymmetry Measurements

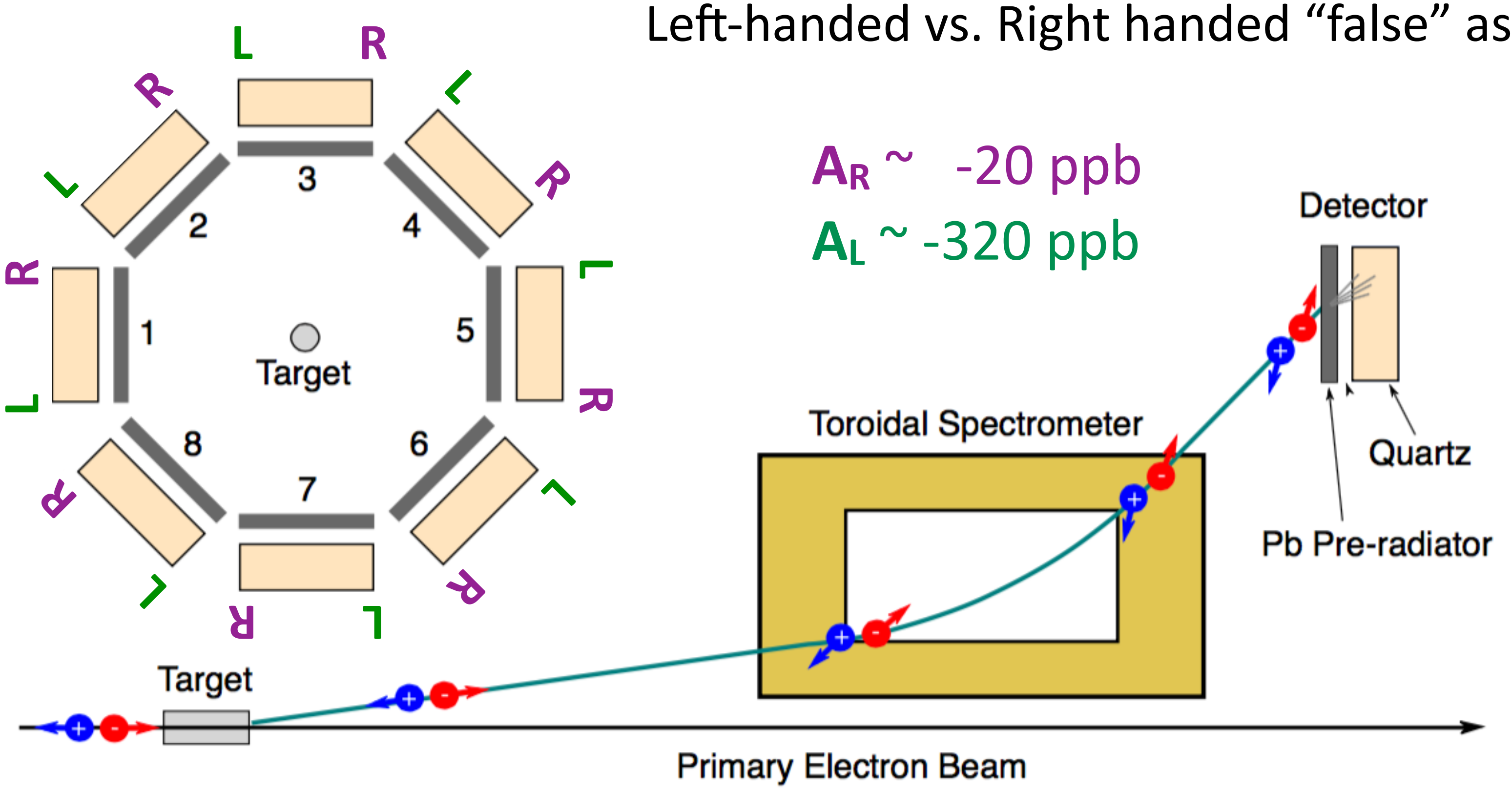


Data subsets, with various methods of polarization reversal

- Half-wave plate in source optics
- E x B spin manipulation (injector)
- energy (g-2 precession)

Polarization sensitive detectors

Left-handed vs. Right handed “false” asymmetry



$A_R \sim$ -20 ppb

$A_L \sim$ -320 ppb

Precession in spectrometer, so electrons arrive at detector with large radial polarization component

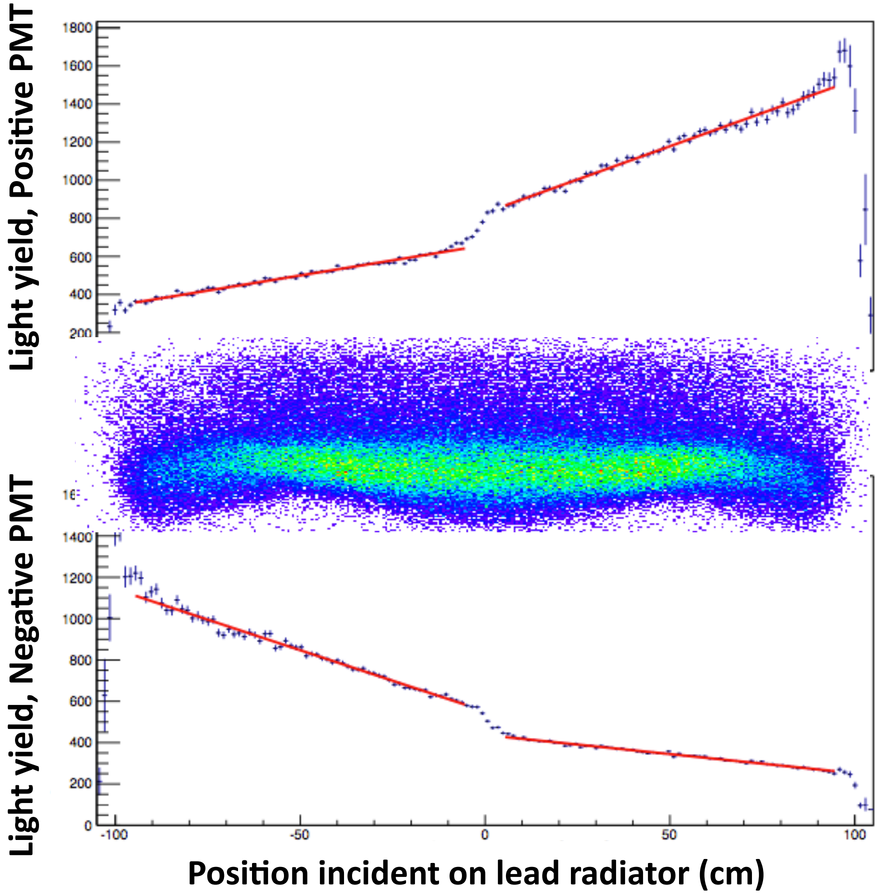
Polarization analyzing effect: PMTs on opposite ends of each detector bar see opposite sign asymmetry shifts

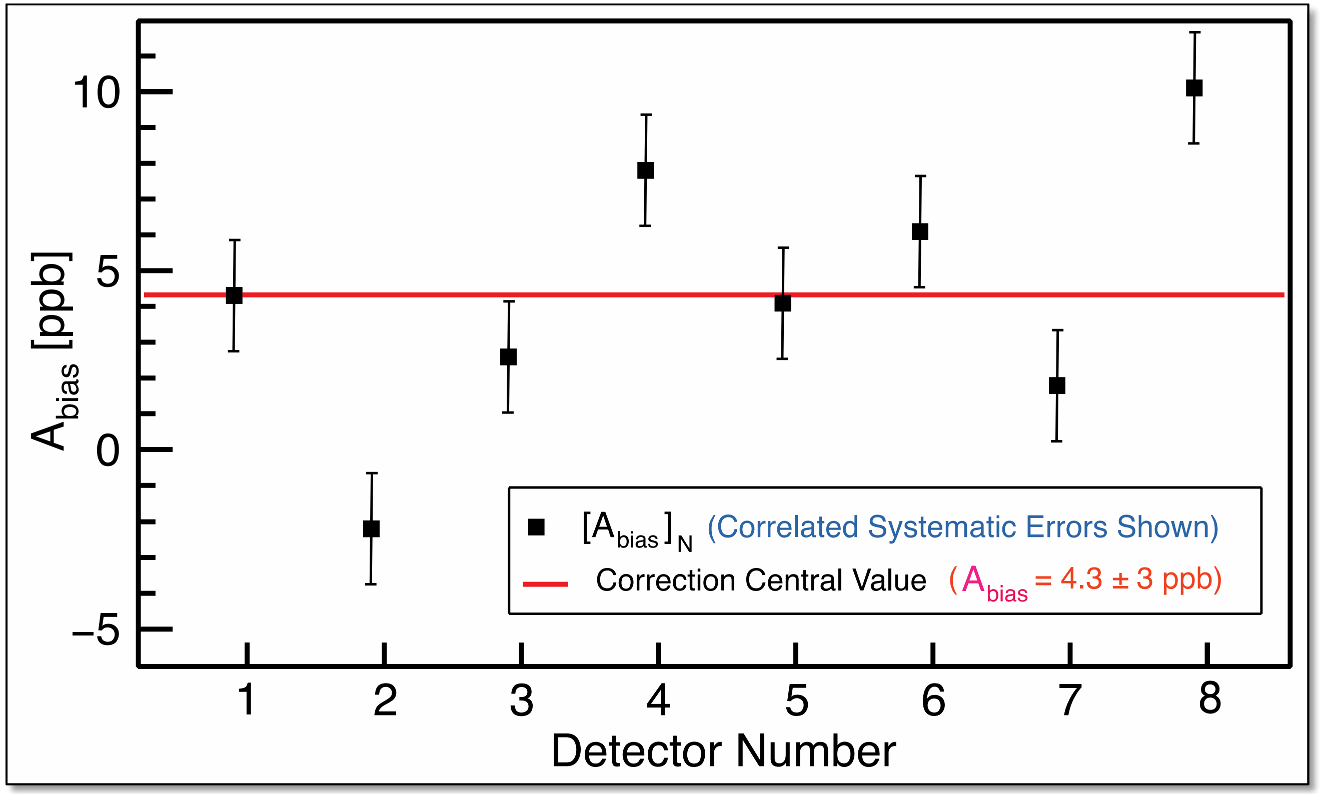
- Spin-orbit coupling in e-Nuclear scattering does this: large asymmetries for large angles, at low energy (Mott polarimetry)
- Incident electron loses energy in lead radiator, analyzes in multiple scattering
- Only significant after is E<30 MeV or so, for large angles

Electron more likely to point towards one PMT or the other, depending on its incident polarization

Estimated Residual Bias from Polarization Sensitive Detectors

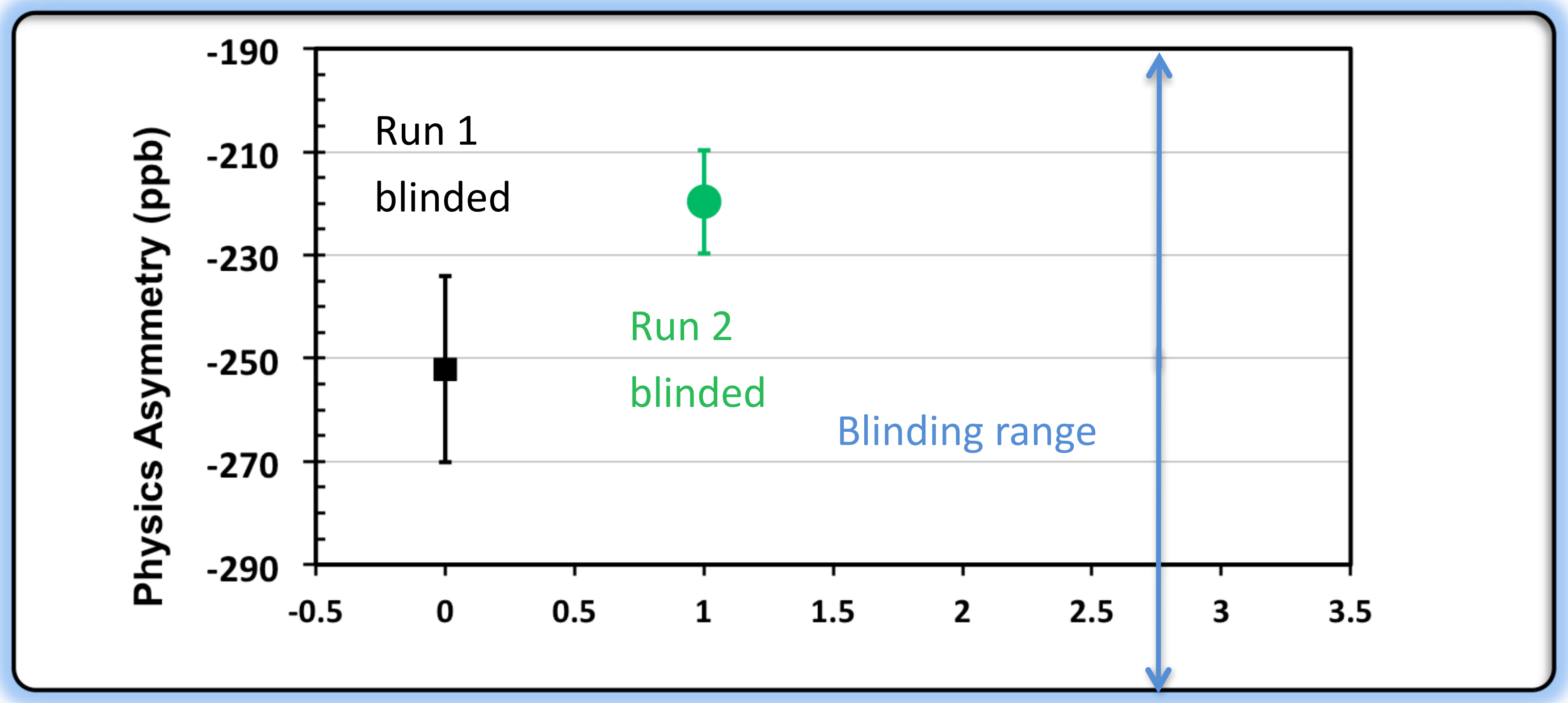
- This cancels: positive asymmetry in one PMT, negative in the other
- Quality of cancellation depends on imperfections in each bar optical properties and alignment
- Abias dominated by optical and mechanical imperfections of each bar (*e.g.* mismatches, bevels, glue joint)
- Monte Carlo simulation of light collection for each bar, based on measured geometries and checked with observed responses





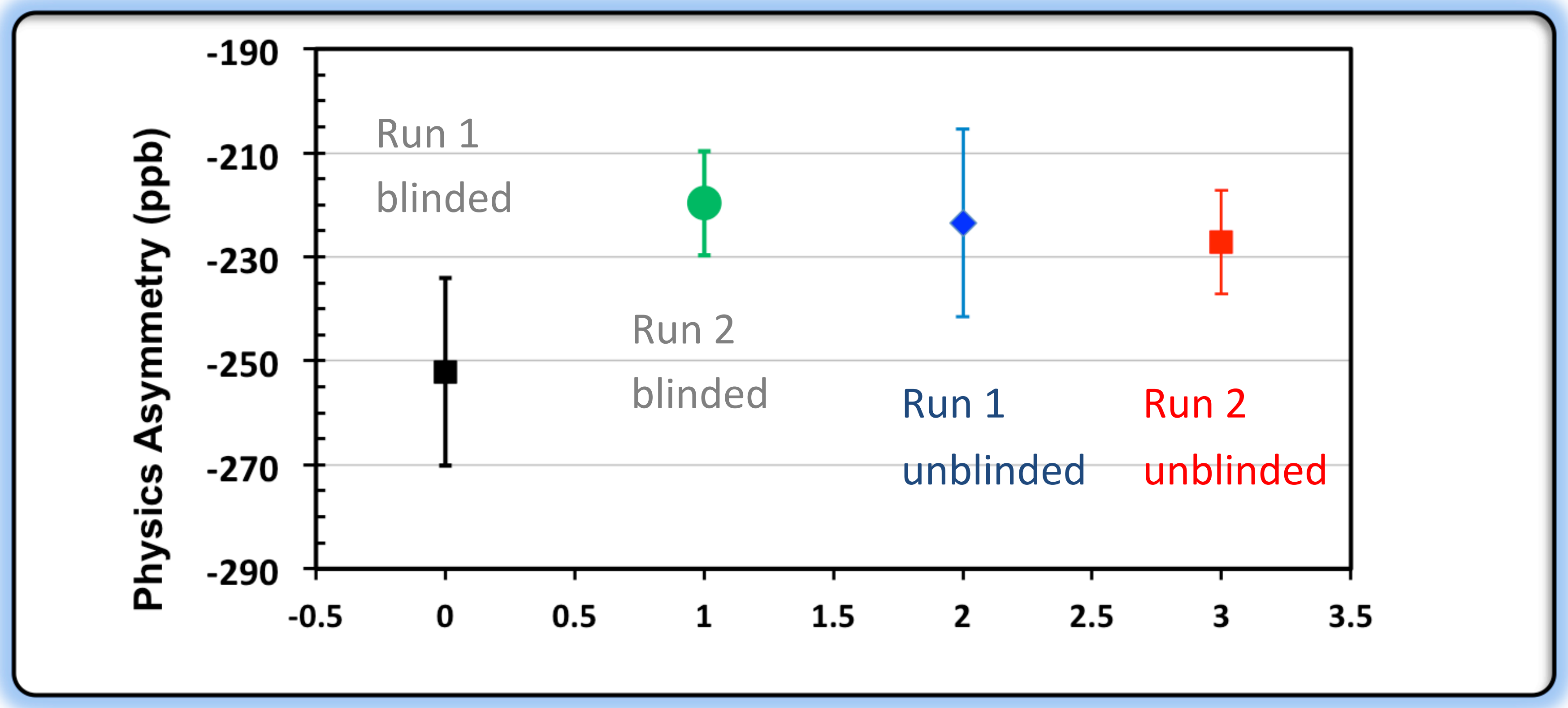
$A_{bias} = 4.3 \pm 3.0$ ppb

Blinded Analysis



Two data sets (Runs 1 & 2), each blinded independently
(hidden constant additive offset with ±60 ppb range) to avoid analysis bias

Completed Analysis

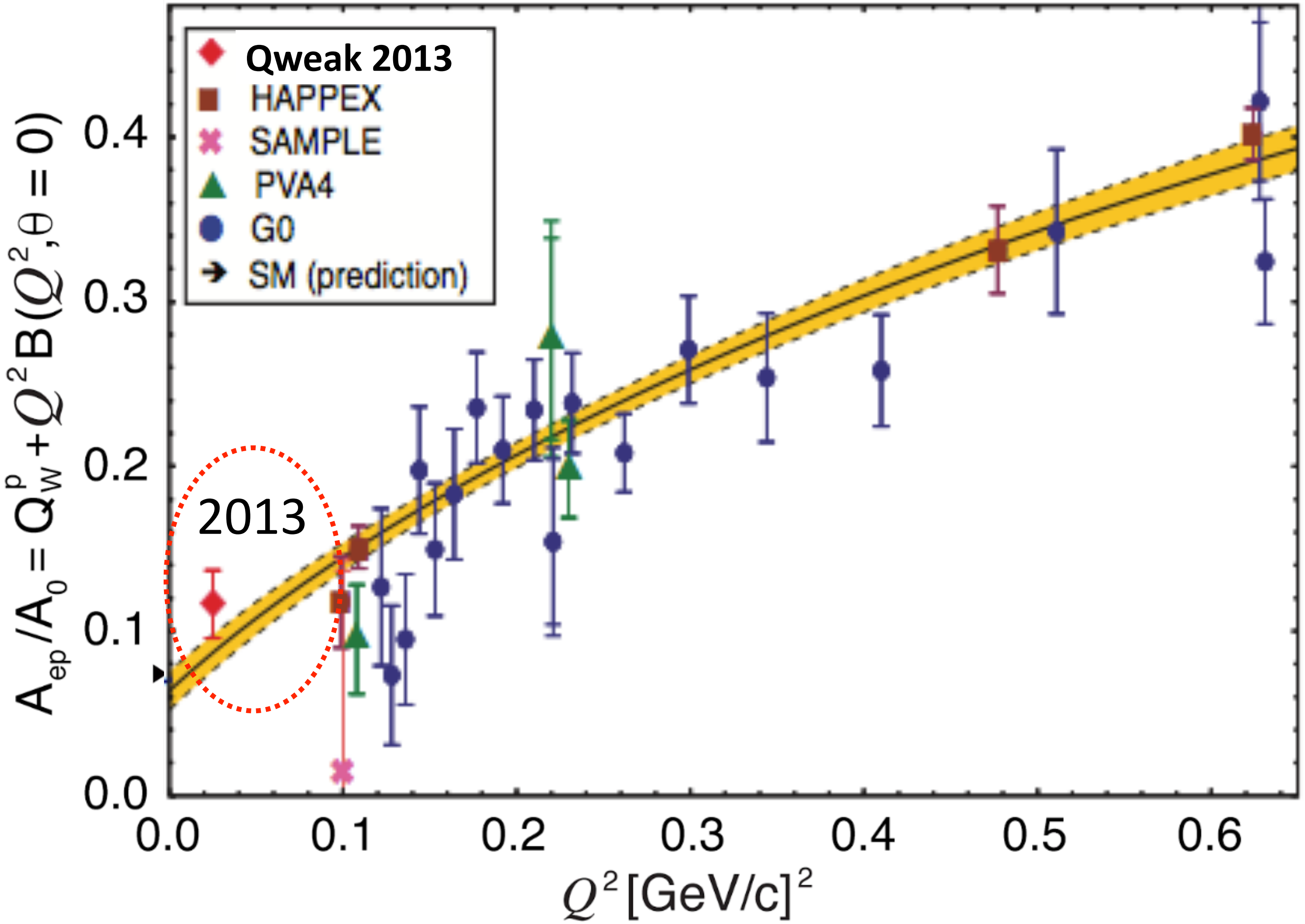


Combined data sets, including accounting for correlated systematic uncertainty

Period	Asymmetry (ppb)	Stat. Unc. (ppb)	Syst. Unc. (ppb)	Tot. Uncertainty (ppb)
Run 1	-223.5	15.0	10.1	18.0
Run 2	-227.2	8.3	5.6	10.0
Run 1 and 2 combined with correlations	-226.5	7.3	5.8	9.3

Extrapolating to $Q^2 = 0$

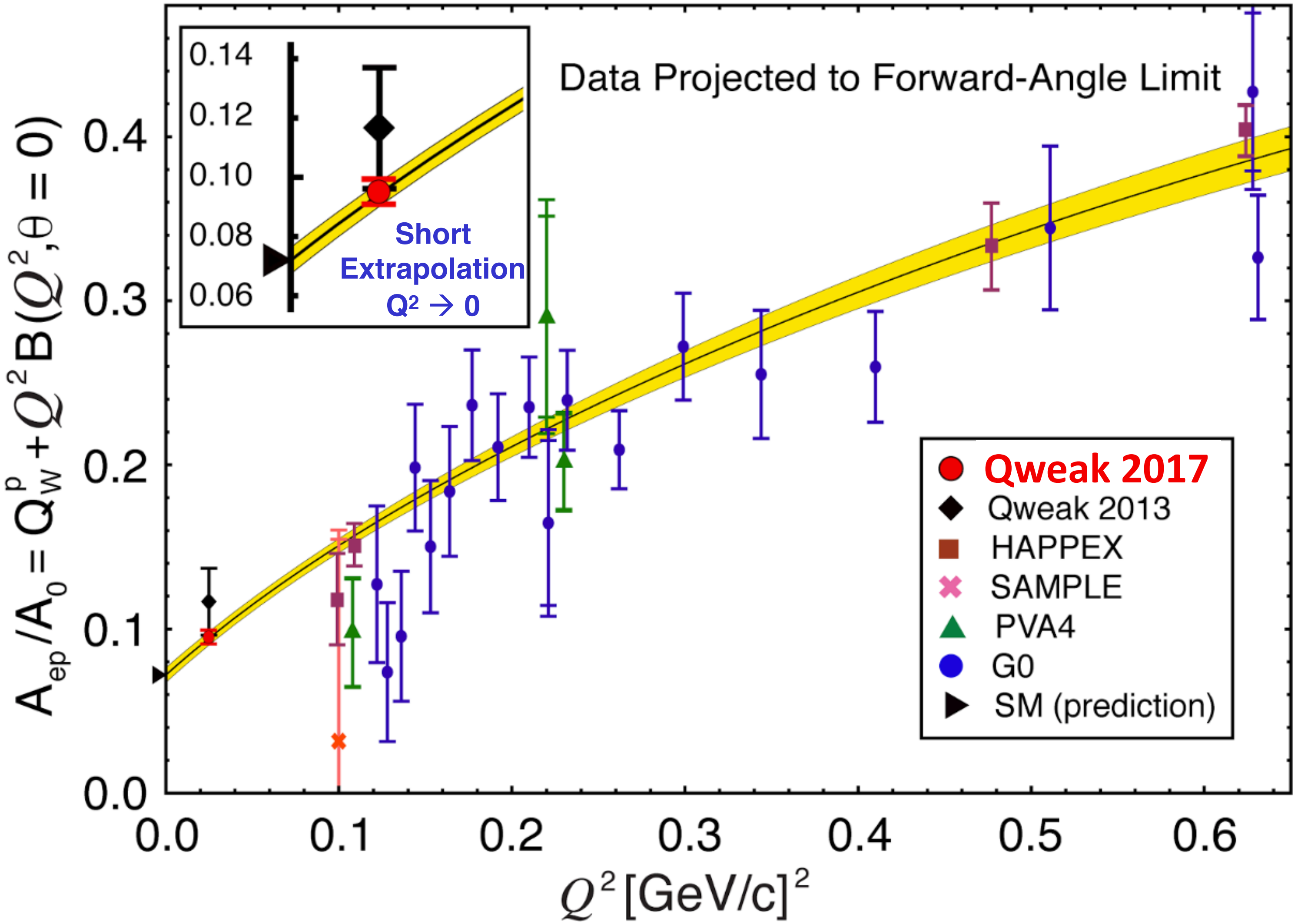
2013 Qweak result (commissioning data)



- All nuclear PVES data up to $Q^2 \sim 0.7$ GeV^2 (hydrogen, deuterium, helium)
- 5 parameters (C_{1u}, C_{1d}, isovector axial FF, ρ_s, μ_s)
- Fit and data shown corrected to forward angle limit

Qweak of the Proton

$$A_{PV} = -226.5 \pm 7.3(\text{stat}) \pm 5.8(\text{syst})\ \text{ppb at } Q^2 = 0.0249(\text{GeV/c})^2$$



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- 5 parameters (C_{1u}, C_{1d}, isovector axial FF, ρ_s, μ_s)
- Fit and data shown corrected to forward angle limit

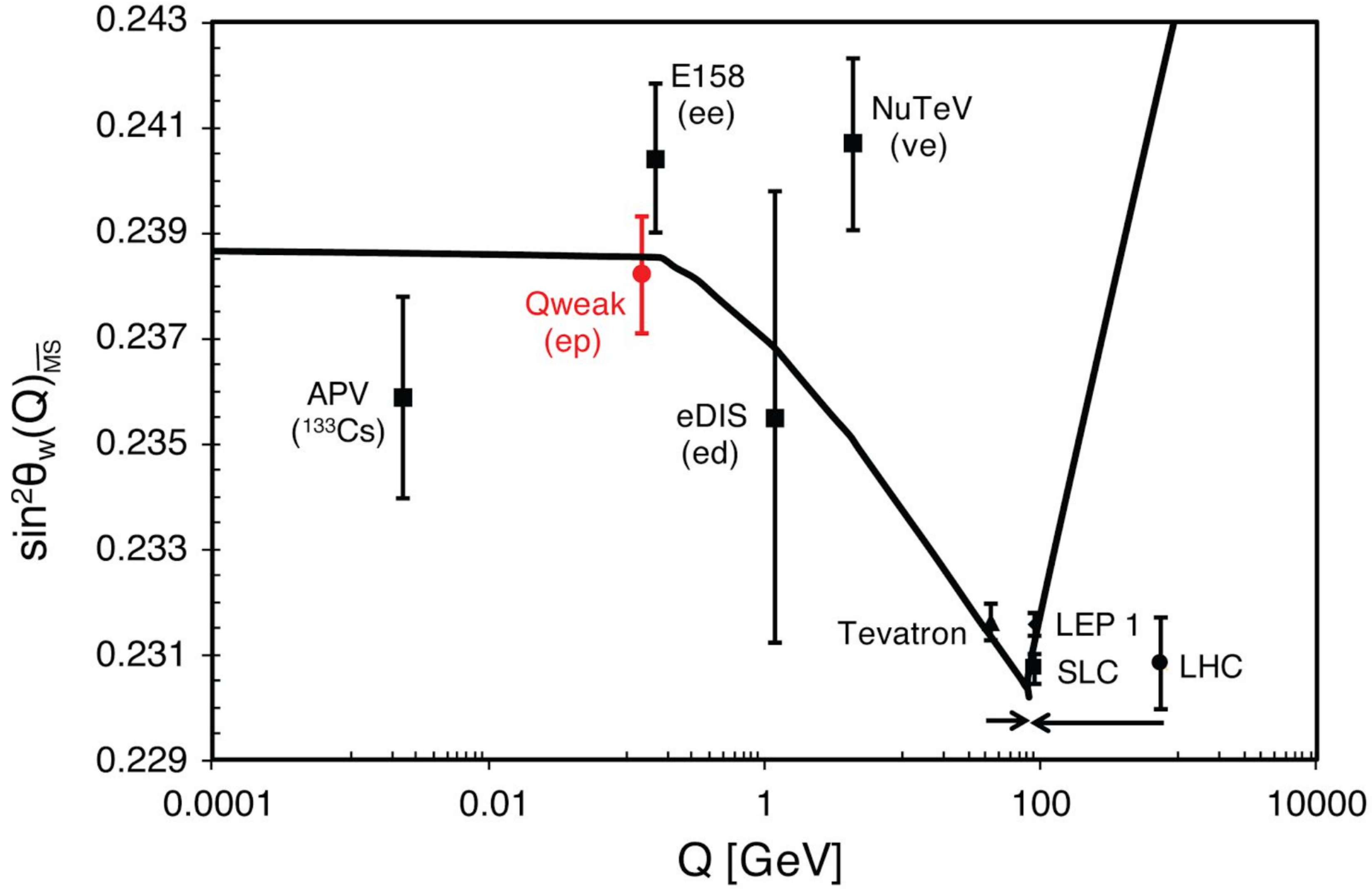
Standard Model:

$$Q_W^p = 0.0708 \pm 0.0003$$

Qweak + PVES data base:

$$Q_W^p = 0.0719 \pm 0.0045$$

Weak mixing angle $\sin^2\theta_W$



Qweak 2017 + PVES data base:

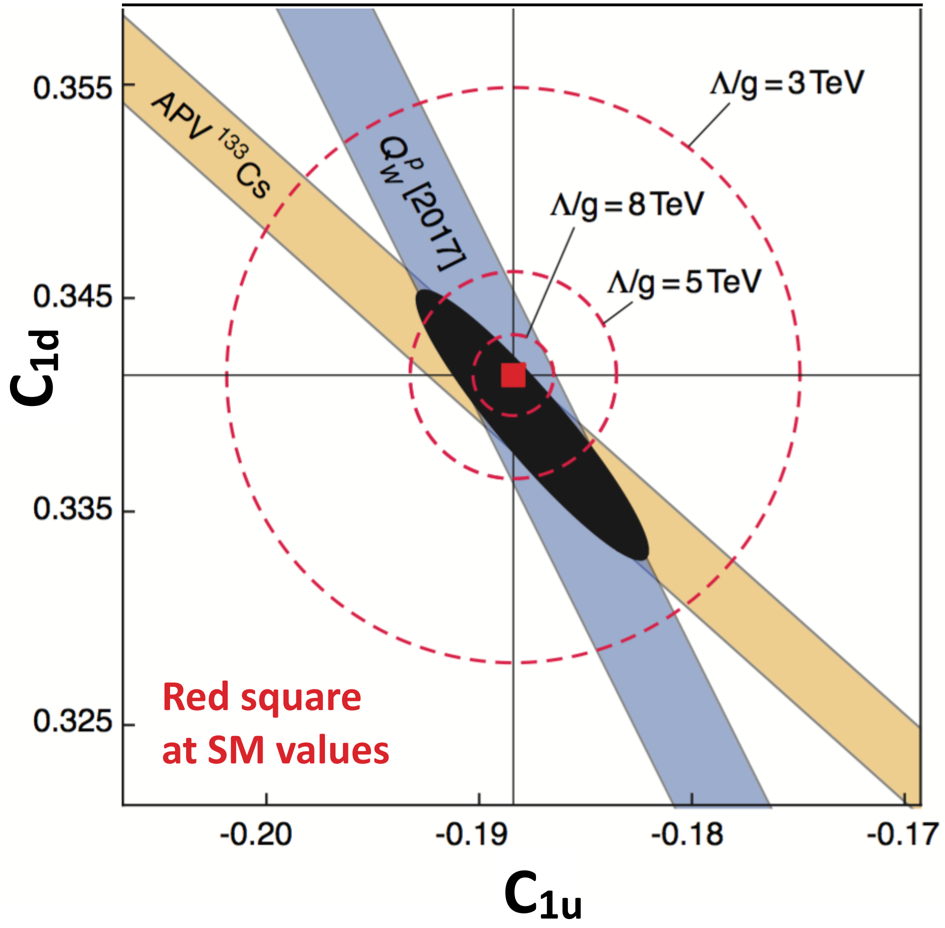
$\sin^2\theta_W = 0.2382 \pm 0.0011$

Solid Curve: J. Erler, M. Ramsey-Musolf, P. Langacker

Contact Interactions

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

New Physics Ruled Out
@95% CL Below Mass Scale of Λ/g



Red square
at SM values

Including ^{133}Cs APV result allows extraction of neutron weak charge & separation of C_{1u} , C_{1d} quark coupling constants

Qweak 2017 + PVES data base + APV ^{133}Cs

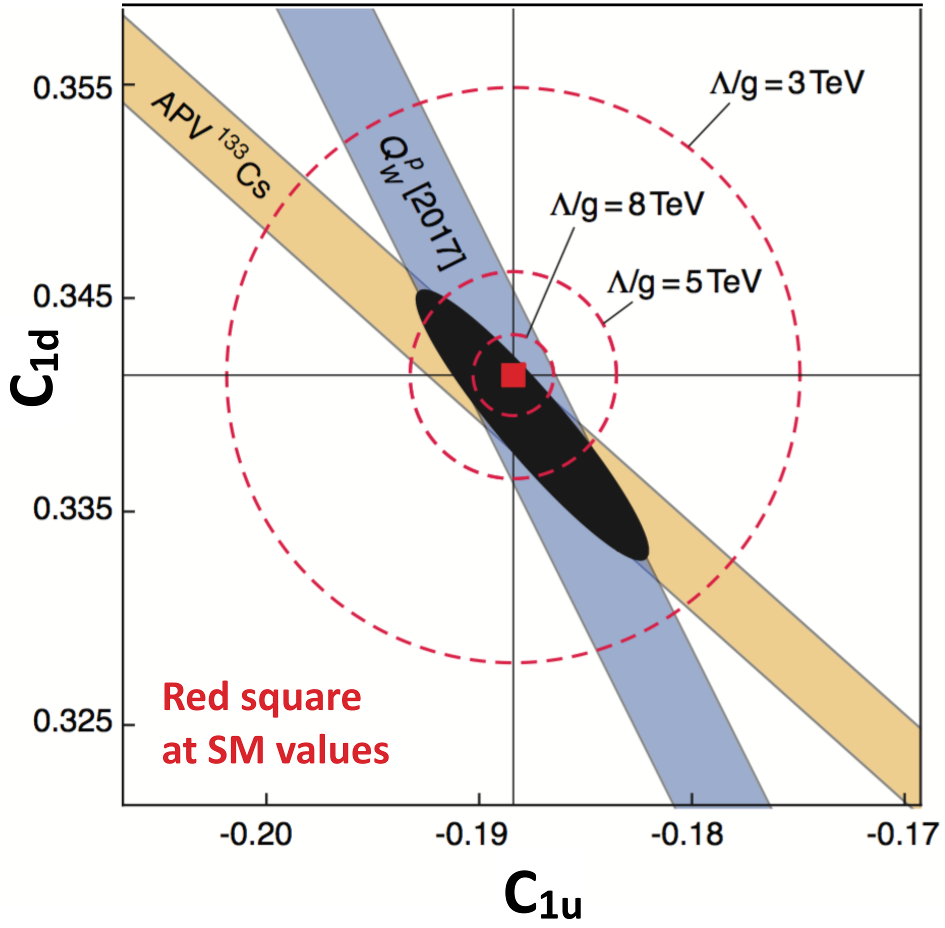
	Value	Error
Q_W^p	0.0718	0.0045
Q_W^n	-0.9808	0.0063
C_{1u}	-0.1874	0.0022
C_{1d}	0.3389	0.0025

APV: atomic parity violation ^{133}Cs
C.S. Wood et al. Science **275**, 1759 (1997);
Dzuba et al. PRL **109**, 203003 (2012)

Contact Interactions

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

New Physics Ruled Out
@95% CL Below Mass Scale of Λ/g

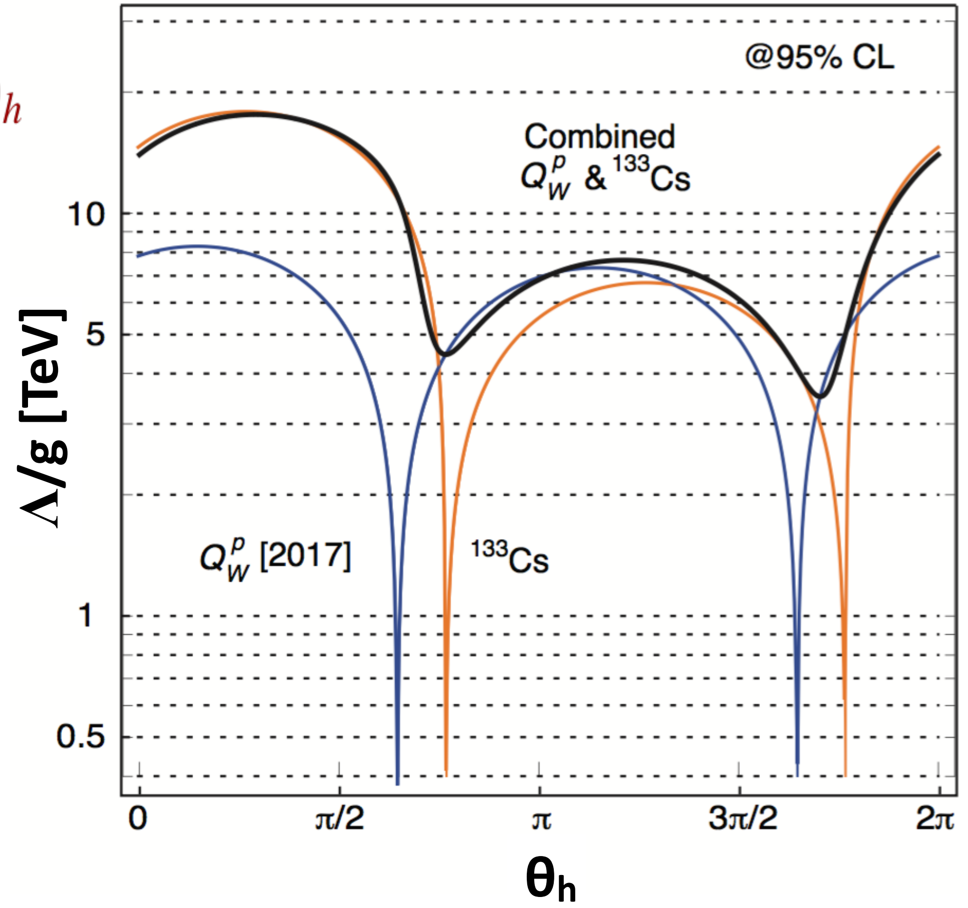


Red square
at SM values

$$\mathcal{L}_{\rm NP}^{\rm PV} = -\frac{g^2}{\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$

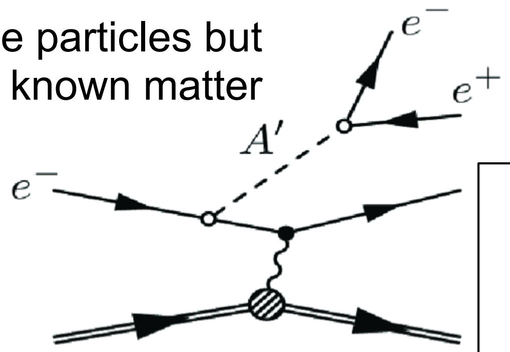
θ_h is "flavor mixing angle" in Lagrangian $\mathcal{L}_{\rm NP}^{\rm PV}$



In conventional "strong coupling" limit, $g^2 = 4\pi$ Λ/g ~7.5 TeV → 27 TeV

New (light) physics: the Dark Z

Dark photon: couples to Dark Sector massive particles but with small E&M couplings to known matter



$(g\text{-}2)_\mu$ discrepancy, 511keV line in galactic core, Pamela high energy positron excess

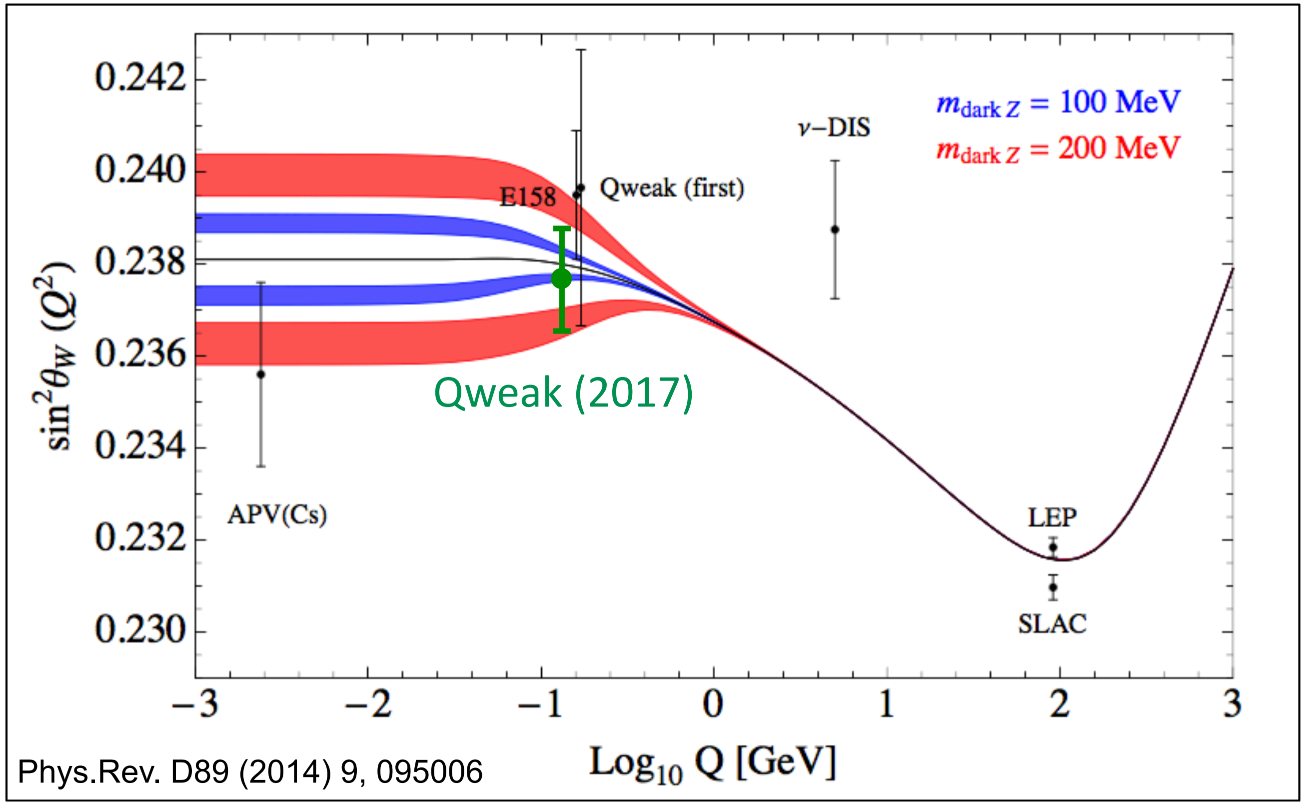
But what if the dark Z_d^0 had no couplings at all to the 3 known generations of matter?

Beyond kinetic mixing: introduce mass mixing with Z^0

$$M_0^2 = m_Z^2 \begin{pmatrix} 1 & -\varepsilon_Z \\ -\varepsilon_Z & m_{Z_d}^2/m_Z^2 \end{pmatrix}$$

$$\boxed{\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta}$$

Requires $\delta <\sim 10^{-3}$ to have remained hidden at the Z-pole and in meson decay



Phys.Rev. D89 (2014) 9, 095006

Davoudiasl, Lee, Marciano

Phys.Rev.Lett. 109 (2012) 031802
Phys.Rev. D85 (2012) 115019
Phys.Rev. D89 (2014) 9, 095006
Phys.Rev. D92 (2015) 5, 055005

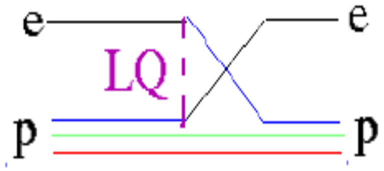
BSM Models and Constraints

SM is low energy limit of effective field theory with towers of higher dimension operators

$$L = L_{SM} + \Sigma \frac{c_i}{\Lambda^2} O_i^{d=6} + \sigma \frac{c_i}{\Lambda^4} O_i^{d=8} + \ldots$$

(h/t Sally Dawson)

Leptoquarks



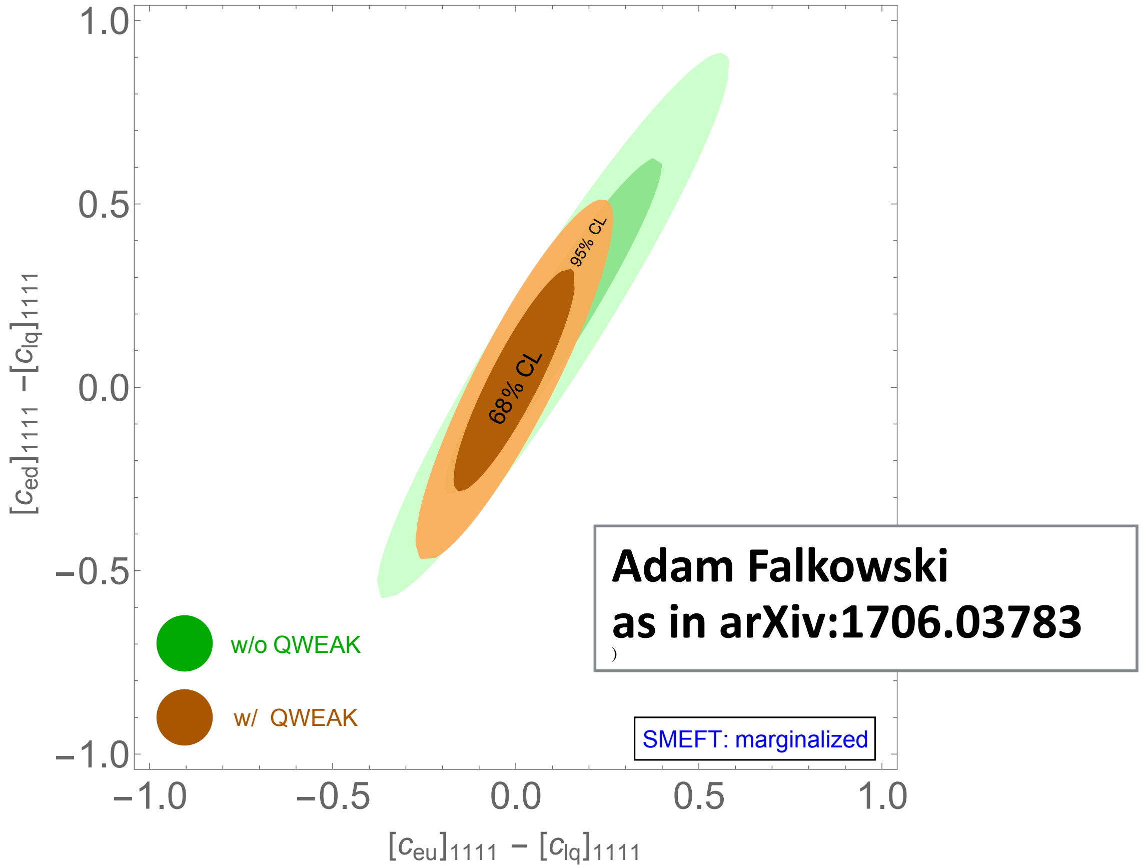
e.g. Erler, Kurylov, Ramsey-Musolf, Phys. Rev. D **68**, 016006 (2003)

Right-handed Charge Currents

ε_L vs. ε_R

Vincenzo Cirigliano, arXiv:1703.074751

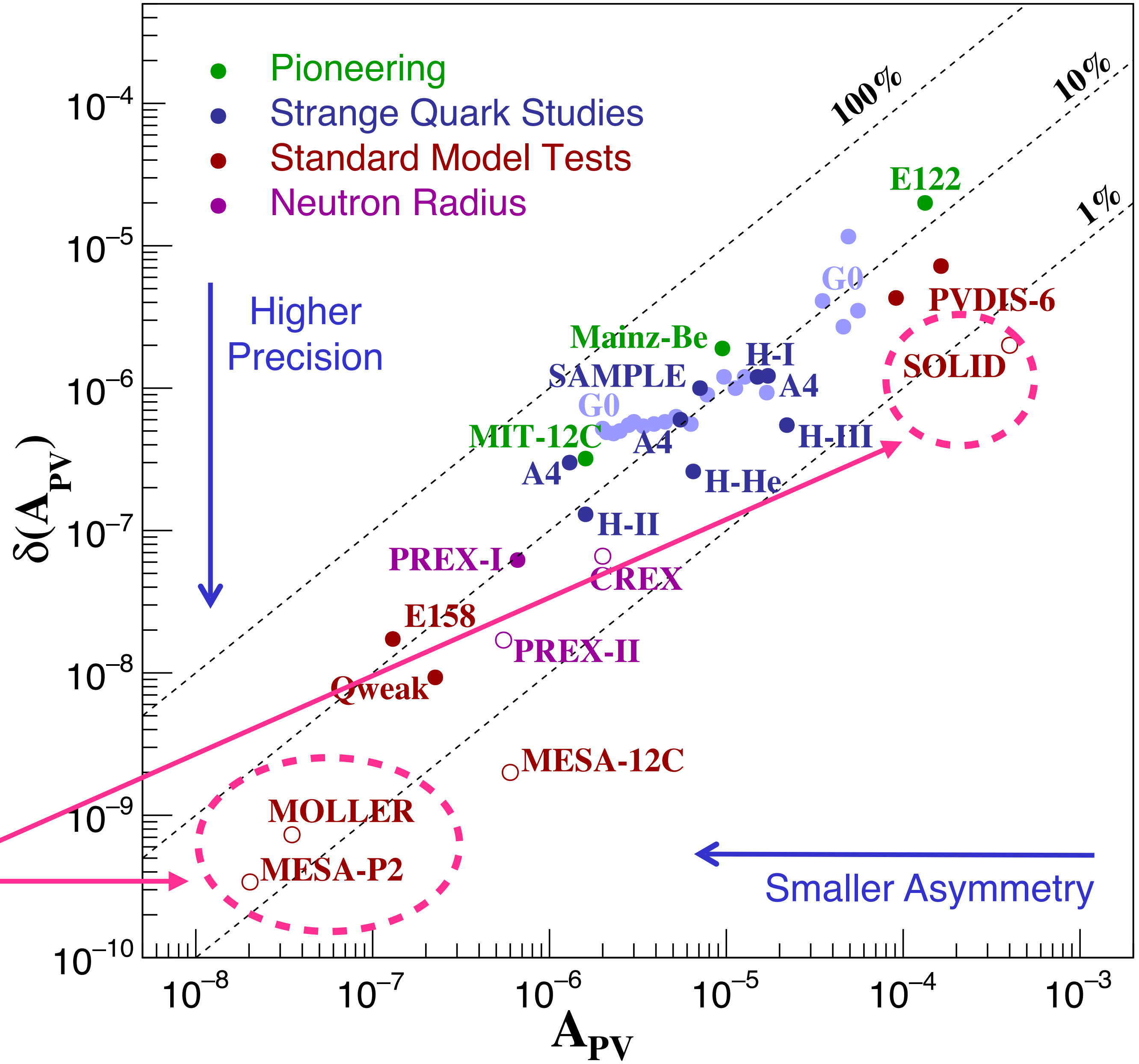
dimension-6 operators



Adam Falkowski as in arXiv:1706.03783

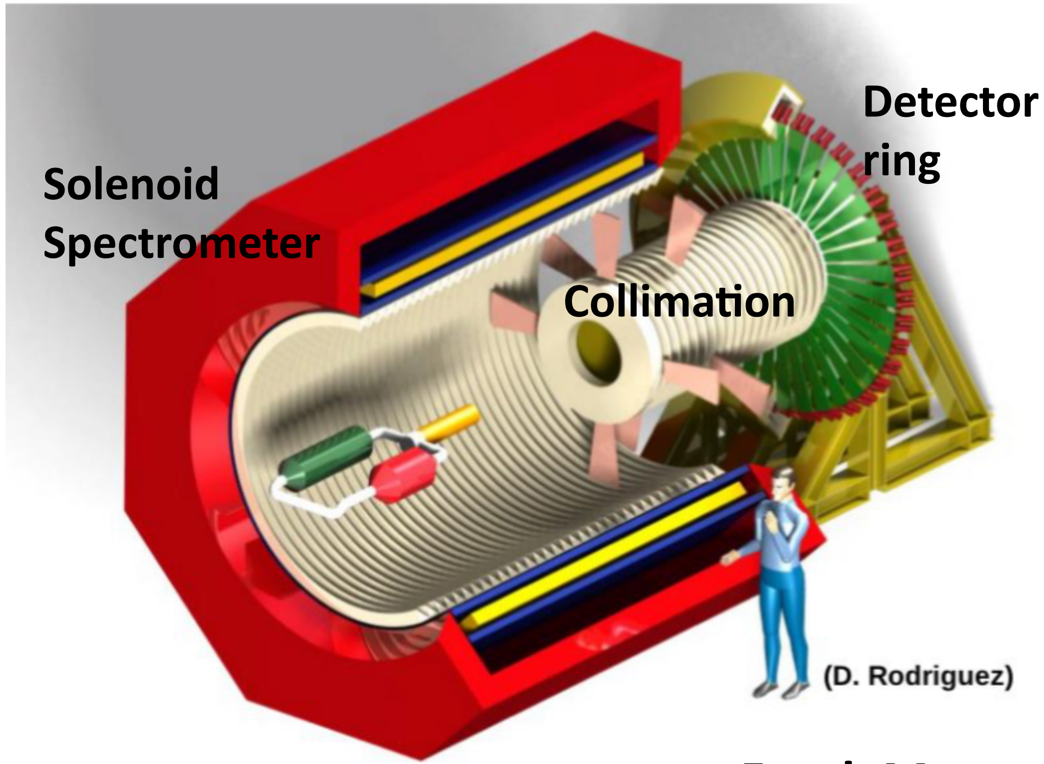
Future PVES

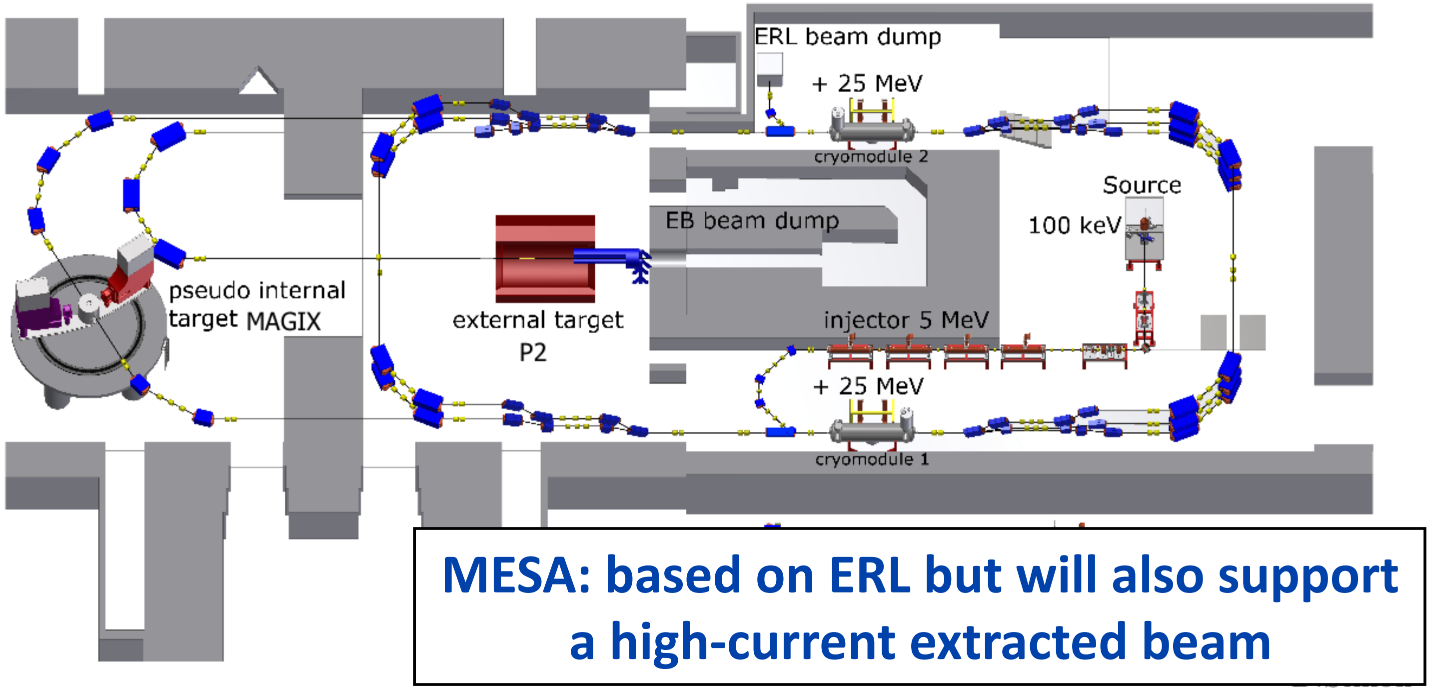
Qweak experimental precision is the best yet for a PVES experiment



Future standard model tests will build on the Qweak experience to improve or complement bounds on new physics

P2 at MESA / Mainz





MESA: based on ERL but will also support a high-current extracted beam

Frank Maas *et al.*, arXiv:1802.04759

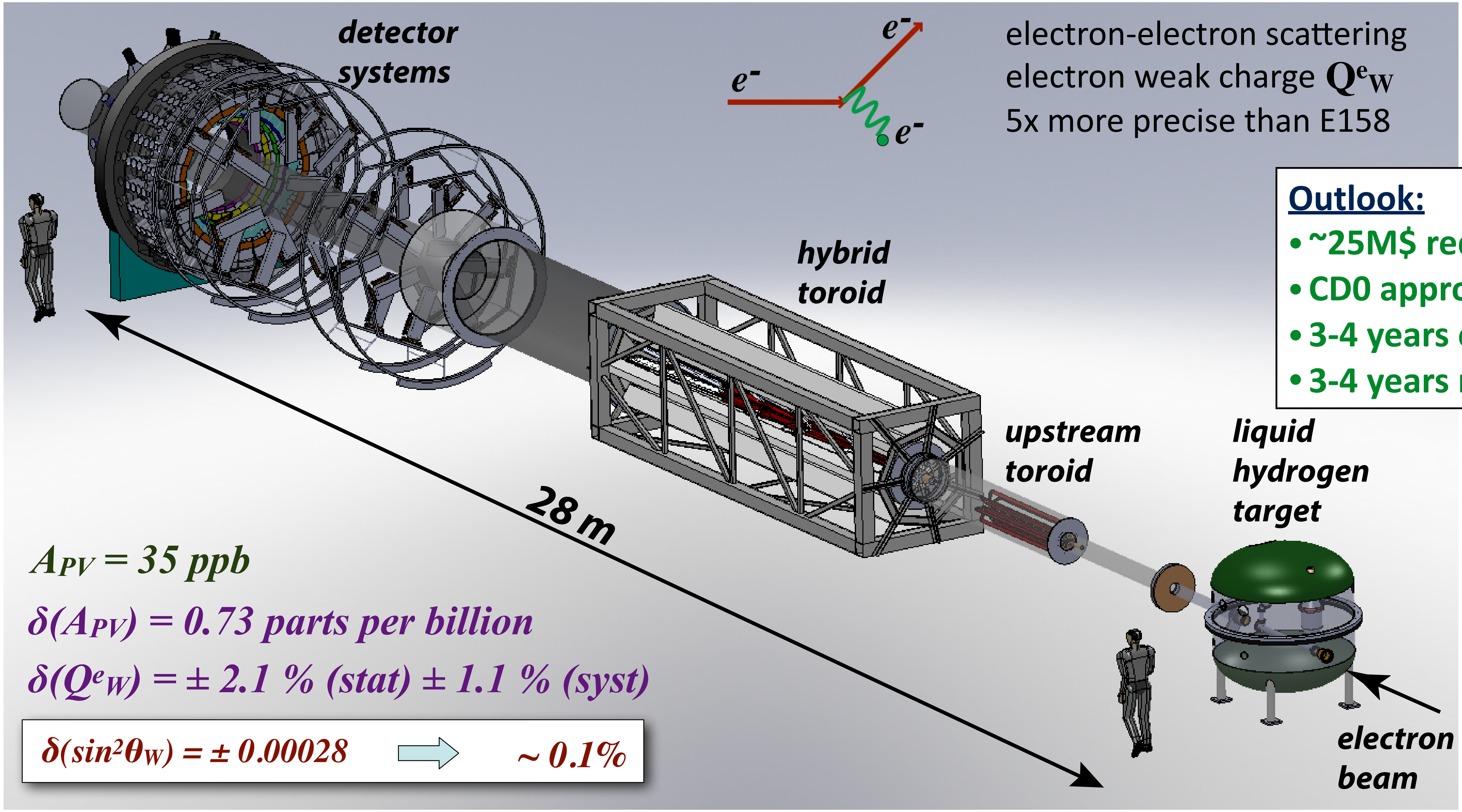
- E_{beam} = 155 MeV, 25-45^o
- $Q^2 = 0.0045$ GeV^2
- 60 cm target, 150 uA, 10^4 hours

- A_{PV} = -40 ppb to 1.4% (0.56ppb)
- **$\delta(\sin^2\theta_W) = 0.00033$ (0.14%)**

3.3x more precise than Qweak, similar to best collider measurements

- **Development underway**
- **Funding approved**
- **Start 2020+**

MOLLER at 11 GeV JLab



electron-electron scattering
electron weak charge Q^e_W
5x more precise than E158

Outlook:
- ~25M$ required
- CD0 approved
- 3-4 years construction
- 3-4 years running

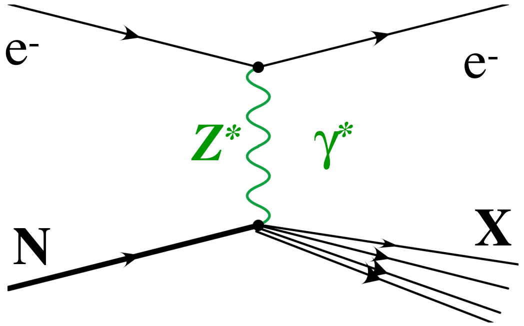
$A_{PV} = 35\ ppb$

$\delta(A_{PV}) = 0.73$ parts per billion

$\delta(Q^e_W) = \pm\, 2.1\ \%\ (stat) \pm 1.1\ \%\ (syst)$

$\delta(\sin^2\theta_W) = \pm\, 0.00028 \Rightarrow \sim 0.1\%$

PV-DIS

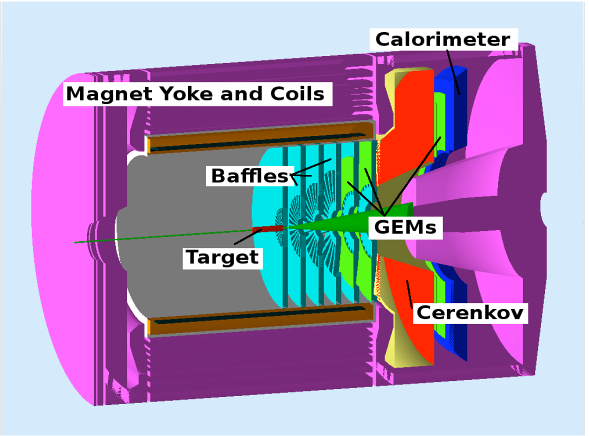


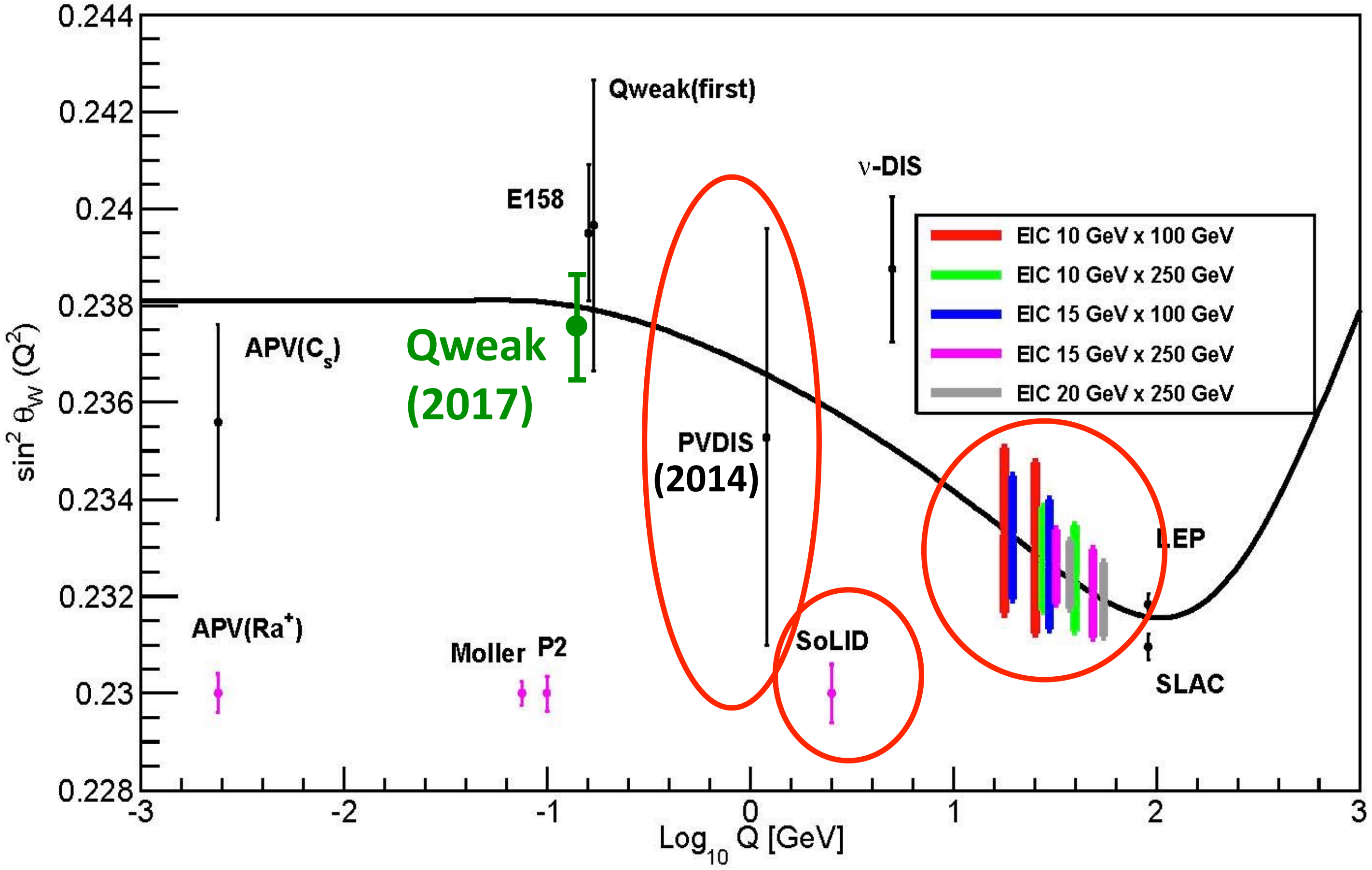
Deep Inelastic Scattering from Deuterium

at high x_b sensitive to quark vector (C_{1q}) and *axial* (C_{2q}) weak charges

PV-DIS-6 JLab at 6 GeV
Nature 506, no. 7486, 67 (2014);

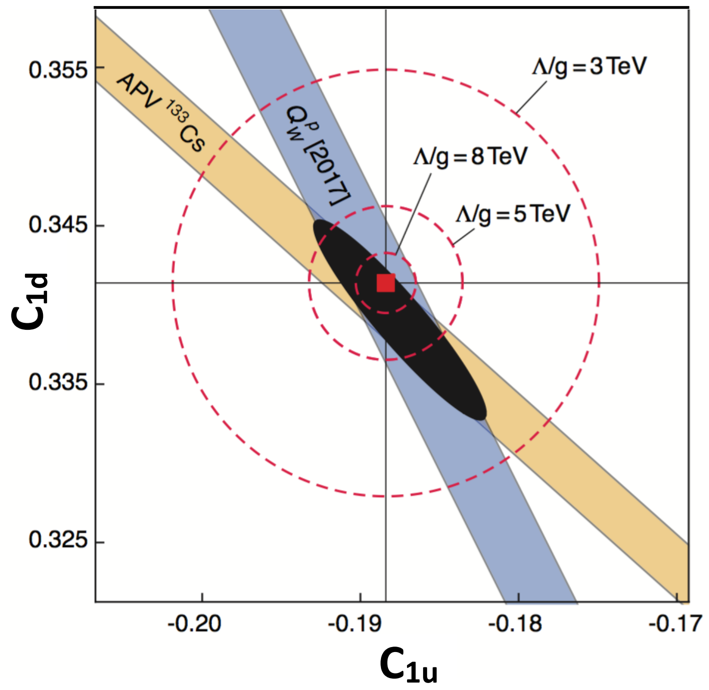
SOLID-PVDIS at JLab,
11 GeV, part of SOLID
spectrometer project





PVDIS at EIC requires high luminosity
Simulations from Yuxiang Zhao

Summary



A precise measurement of the proton weak charge has been completed, providing a new tight constraint on possible new physics

Interpretable, robust measurement

- hadronic structure correction well known from global PVES data set
- Radiative corrections are small and now precisely calculated

Unprecedented precision enabled by technological advances, preparing for the next generation of PVES experiments

Electroweak physics with PVES is a powerful component of the low energy fundamental symmetries program

- P2, MOLLER, SOLID: Complementary, competitive with collider for precision on $\sin^2\theta_W$
- Search for new interactions from 100 MeV to 10s of TeV

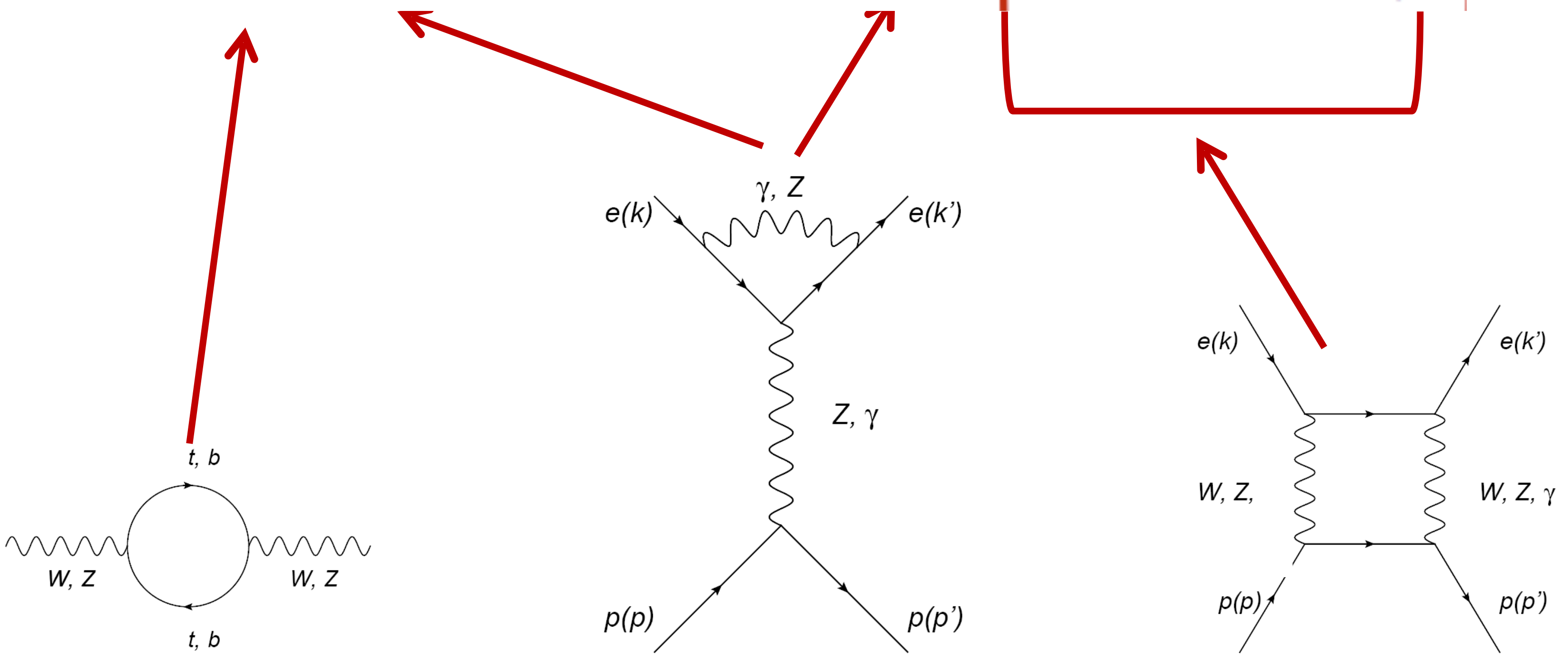
A rich experimental program is envisioned over the next 10 years at Jefferson Lab and Mainz MESA facility

Backup

Electroweak Radiative Corrections

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

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



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

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

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

Electroweak Radiative Corrections

Q_W^p Standard Model ($Q^2 = 0$) [2016]	**0.0708 ± 0.0003**
Q_W^p Experiment Final Uncertainty [2017]	**± 0.0045**

$$Q_W^p = [1+\Delta\rho+\Delta_e]\left[(1-4\sin^2\theta_W(0))+\Delta_{e'}\right] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

Correction to Q^p_{Weak}	**Uncertainty**
$\Delta \sin\theta_W (M_Z)$	± 0.0006
Zγ box (6.4% ± 0.6%)	0.00459 ± 0.00044
$\Delta \sin\theta_W (Q)_{hadronic}$	± 0.0003
WW, ZZ box - pQCD	± 0.0001
Charge symmetry	0
Total	**± 0.0008**

Erler et al., PRD 68(2003)016006.

Calculations of Two Boson Exchange effects on Q_W^p at our Kinematics:

Recent theory calculations applied to entire data set of PV measurements as appropriate in global analysis.

Our ΔA_{ep} precise enough that corrections to higher Q^2 points make little difference in extrapolation to zero Q^2.

Energy Dependence γZ correction:

Hall, N.L., Blunden, P.G., Melnitchouk, W., Thomas, A.W., Young, R.D. Quark-hadron duality constraints on γZ box corrections to parity-violating elastic scattering. Phys. Lett. B 753, 221-226 (2016).

Axial Vector γZ correction:

Peter Blunden, P.G., Melnitchouk, W., Thomas, A.W. New Formulation of γZ Box Corrections to the Weak Charge of the Proton. Phys. Rev. Lett. 107, 081801 (2011).

Q^2 Dependence γZ:

Gorchtein, M., Horowitz, C.J., Ramsey-Musolf, M.J. Model dependence of the γZ dispersion correction to the parity-violating asymmetry in elastic ep scattering. Phys. Rev. C 84, 015502 (2011).

Axial FF

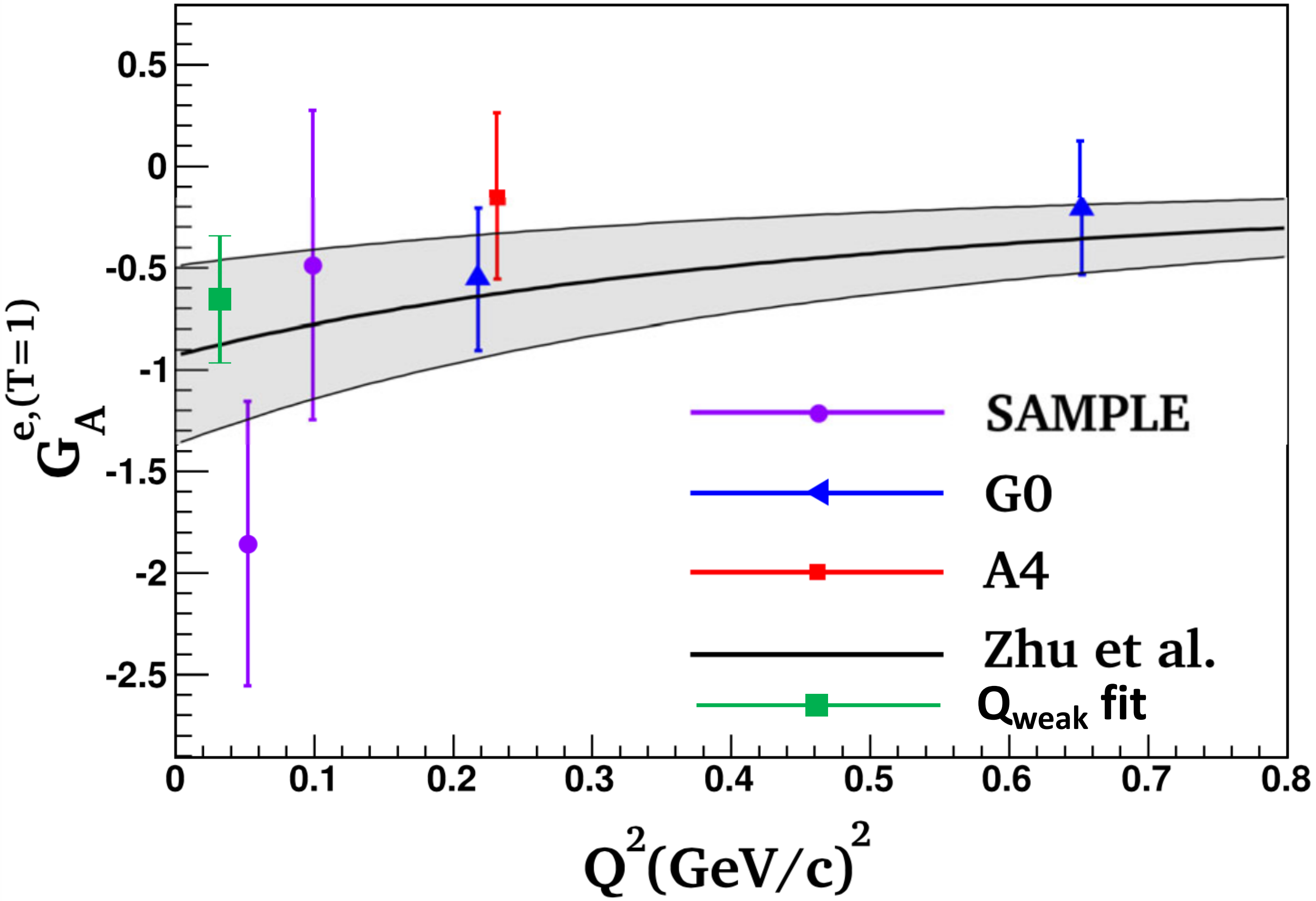


Figure adapted from D. Balaguer Rios *et al.* (PVA4)

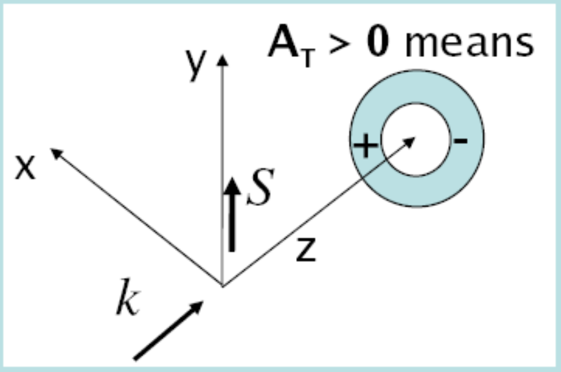
Global fit including Q_{weak} is in good agreement with theory

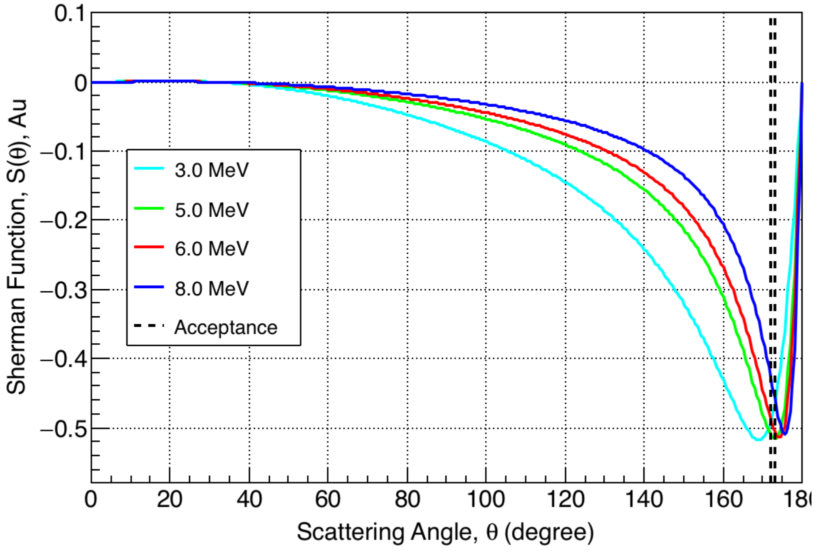
[S.L. Zhu, S.J. Puglia, B.R. Holstein, M.J. Ramsey-Musolf, Phys. Rev. D **62**, 033008 (2000)]

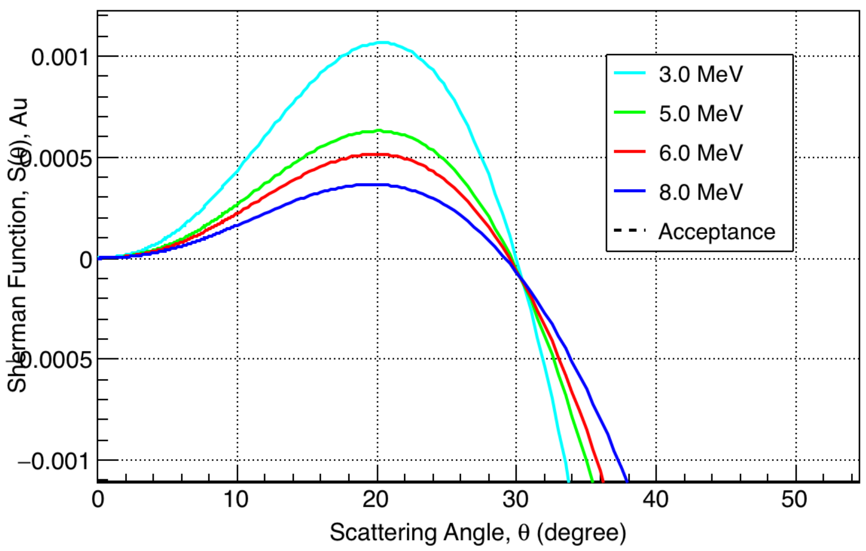
Polarization Sensitive Detector

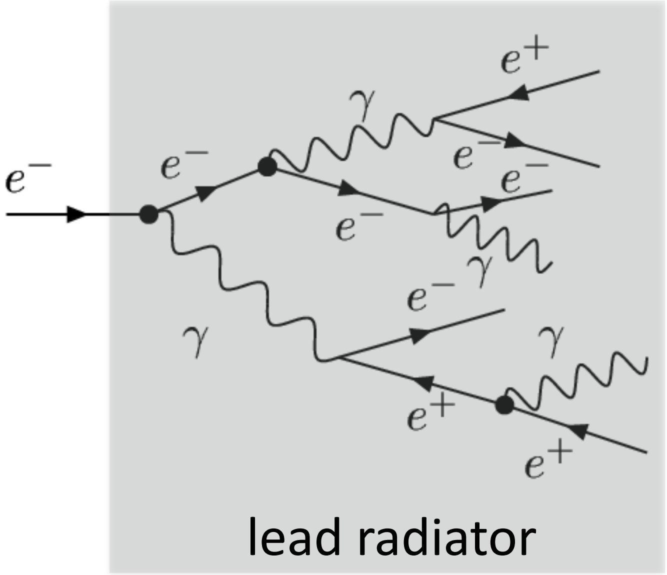
Mott scattering asymmetry: low energy phenomenon

$$A_T = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \propto \vec{S}_e \cdot \frac{\vec{k}_e \times \vec{k}_e'}{|\vec{k}_e \times \vec{k}_e'|}$$









lead radiator

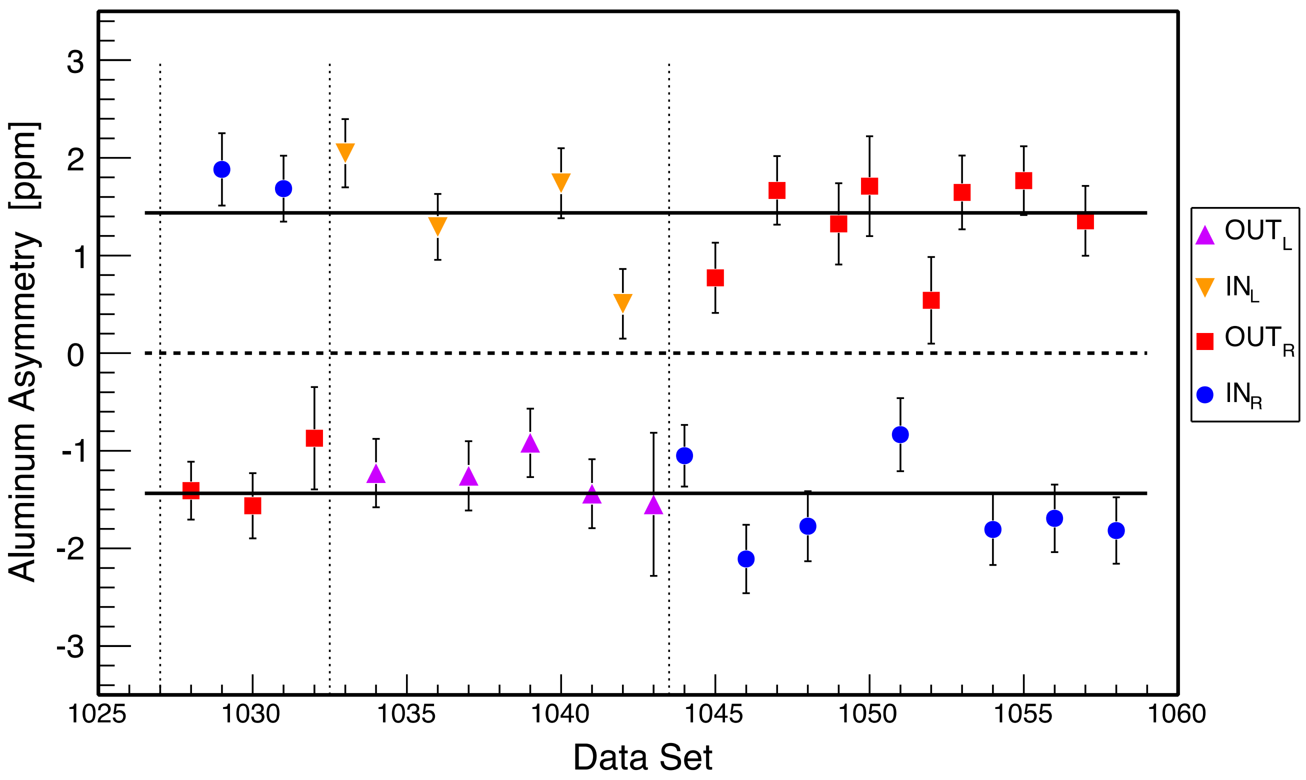
- The electron showering through lead radiator can become polarization-dependent via multiple scattering
- Only significant after is E<30 MeV or so, for large angles
- Cancellation between positive asymmetry for small angle scattering, negative for large angle scattering
- Electron ends up more likely to point toward one PMT, depending on its incident polarization

Aluminum Windows

Background from detected electrons which scattered from thin Aluminum entrance and exit windows

- Measure ~1500 ppb asymmetry using thick calibration targets (identical Al alloy)
- Measure the (2.52 ± 0.06)% signal fraction from windows
- Small corrections for radiative effects (MC simulation)

Aluminum Parity-Violating Asymmetry



Aluminum Asymmetry

Statistical uncertainty: 5.0%

Systematic uncertainty: 0.7%

Net Correction: ~20% ± 1.2% of proton A_{PV}

Asymmetry and Net Corrections

weight: 20% 80%

Quantity	Run 1	Run 2
A_{raw}	-192.7 ± 13.2 ppb	-170.7 ± 7.3 ppb
A_{T}	0 ± 1.1 ppb	0 ± 0.7 ppb
A_{L}	1.3 ± 1.0 ppb	1.2 ± 0.9 ppb
A_{BCM}	0 ± 4.4 ppb	0 ± 2.1 ppb
A_{BB}	3.9 ± 4.5 ppb	-2.4 ± 1.1 ppb
A_{beam}	18.5 ± 4.1 ppb	0.0 ± 1.1 ppb
A_{bias}	4.3 ± 3.0 ppb	4.3 ± 3.0 ppb
P	$87.7 \pm 1.1\%$	$88.71 \pm 0.55\%$
f_1	$2.471 \pm 0.056\%$	$2.516 \pm 0.059\%$
A_1	1.514 ± 0.077 ppm	1.515 ± 0.077 ppm
f_2	$0.193 \pm 0.064\%$	$0.193 \pm 0.064\%$
f_3	$0.12 \pm 0.20\%$	$0.06 \pm 0.12\%$
A_3	-0.39 ± 0.16 ppm	-0.39 ± 0.16ppm
f_4	$0.018 \pm 0.004\%$	$0.018 \pm 0.004\%$
A_4	-3.0 ± 1.0 ppm	-3.0 ± 1.0ppm
R_{RC}	1.010 ± 0.005	1.010 ± 0.005
R_{Det}	0.9895 ± 0.0021	0.9895 ± 0.0021
R_{Acc}	0.977 ± 0.002	0.977 ± 0.002
R_{Q^2}	0.9927 ± 0.0056	1.0 ± 0.0056

Beamline rescattering background
Beam asymmetries
Polarization sensitive detectors

Aluminum windows