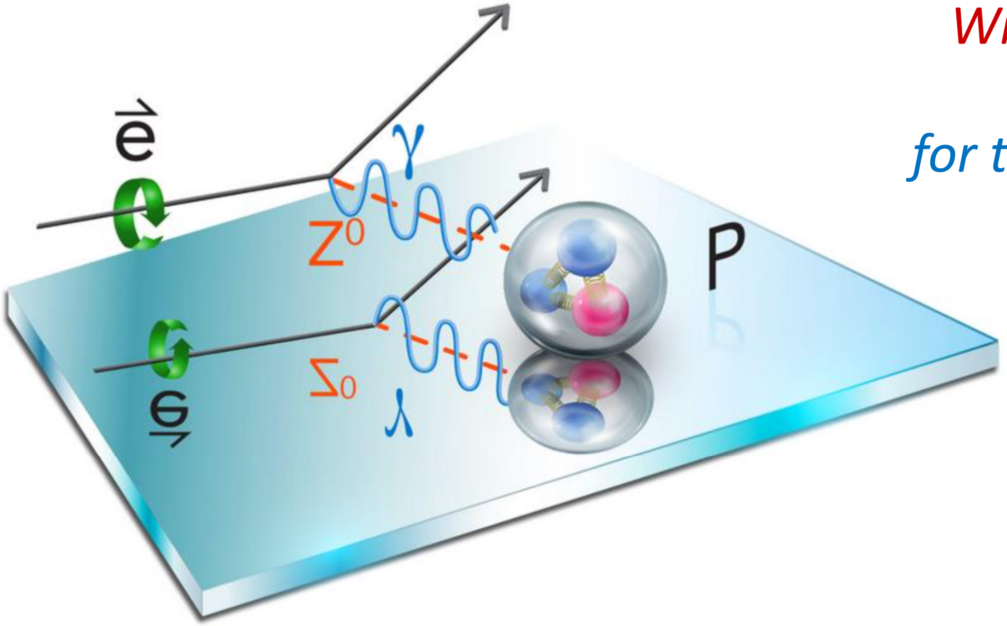
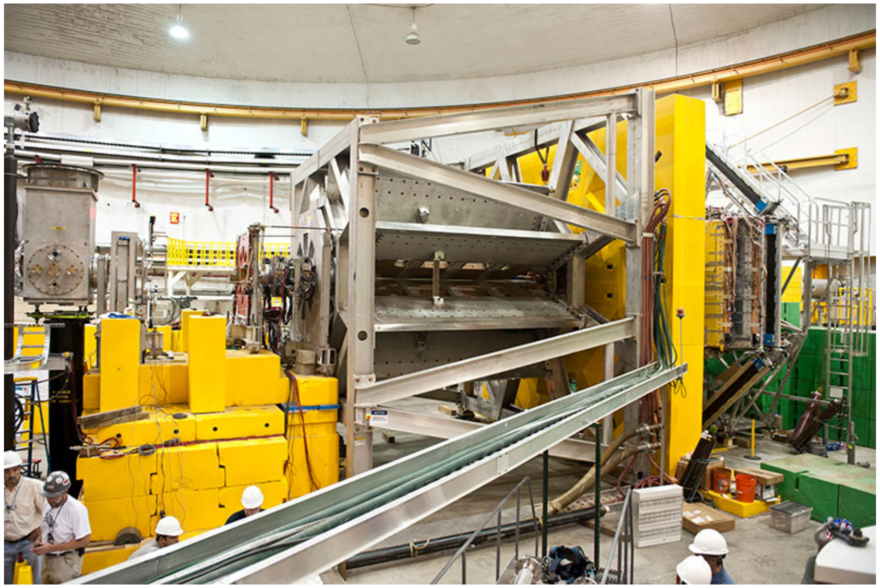
New Measurement of the Proton's Weak Charge



David S. Armstrong
William & Mary

for the Qweak Collaboration



EINN 2017
Paphos, Cyprus, Oct 31 – Nov 3

Search for physics *Beyond the Standard Model*

- Received Wisdom: Standard Model is incomplete, and is low-energy effective theory of more fundamental physics
- Low energy ($Q^2 << M^2$): Precision Frontier
  complementary to Energy Frontier measurements (LHC)

- ***Neutrino masses and role in the early universe*** 0νββ *decay*, θ_{13}, β *decay,…*
- ***Matter-antimatter asymmetry in the present universe*** *EDM, DM, LFV,* 0νββ, θ_{13}
- ***Unseen Forces of the early Universe*** *Weak decays, **PVES**,* g_μ*-2,…*

LHC new physics signals likely will need additional indirect evidence to pin down their nature

- ***Neutrons:*** *Lifetime, P- & T-Violating Asymmetries (LANSCE, NIST, SNS...)*
- ***Muons:*** *Lifetime, Michel parameters, g-2, Mu2e (PSI, TRIUMF, FNAL, J-PARC...)*
- ***PVES:*** *Low-energy weak neutral current couplings, precision weak mixing angle (SLAC, Jefferson Lab, Mainz)*
- ***Atoms:*** *atomic parity violation*

Idea - *select observables that are:*

1) zero, or significantly suppressed, in Standard Model

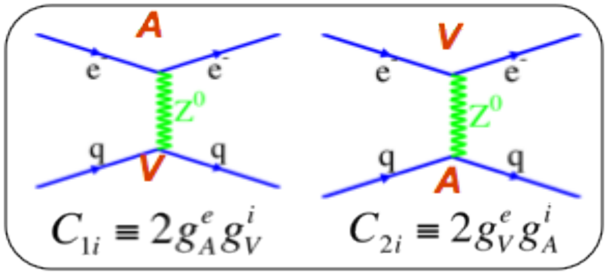
2) Robust predictions within Standard Model

Weak Charge

Electroweak Lagrangian → Parity-Violating electron-quark term:

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

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



Small θ Large θ

-Electroweak Charges-

Particle	Electric Charge	Weak Vector Charge ($\sin^2\theta_W \approx \frac{1}{4}$)
u	$+\frac{2}{3}$	$-2C_{1u} = +1 - \frac{8}{3}\sin^2\theta_W \approx +\frac{1}{3}$
d	$-\frac{1}{3}$	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_W \approx -\frac{2}{3}$
p(uud)	$+1$	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0$
n(udd)	0	$Q_W^n = -1$

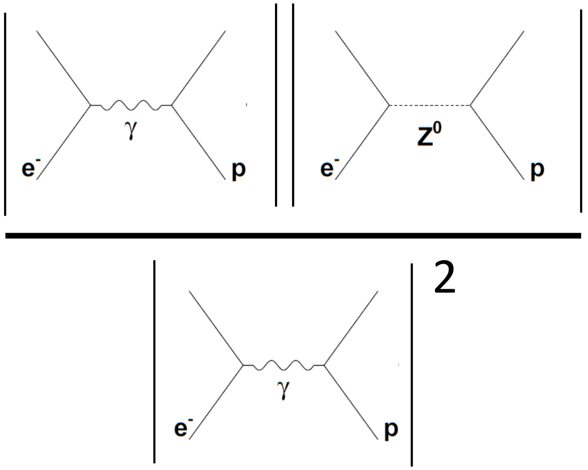
← Proton's Weak Charge

PVES: Parity-violating electron scattering

Scatter longitudinally-polarized electrons from unpolarized target
Originally proposed by Ya. B. Zeldovich JETP 36 (1959)

Electroweak interference

$$A \equiv \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} \rightarrow$$



For e-p scattering:

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

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

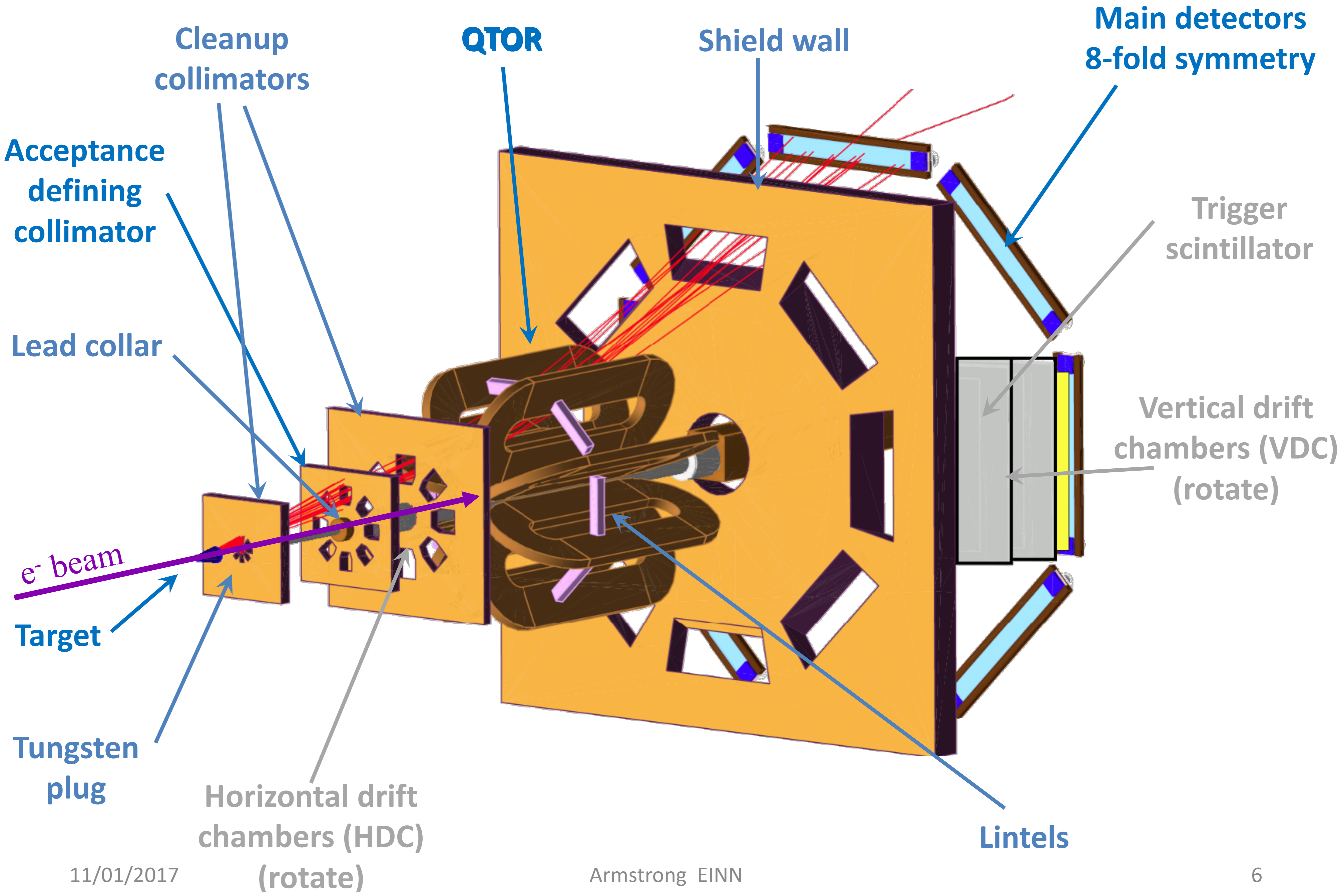
"Form factor" term due to finite proton size – hadronic structure (~ 30% for Qweak) – determined well by existing PVES high-Q^2 data

Meeting PVES Challenges

$A_{ep} \approx 200\,ppb$ want $\approx 5\%$ precision

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

The Q_{weak} Apparatus



Cleanup collimators

QTOR

Shield wall

Main detectors 8-fold symmetry

Acceptance defining collimator

Trigger scintillator

Lead collar

Vertical drift chambers (VDC) (rotate)

e^- beam

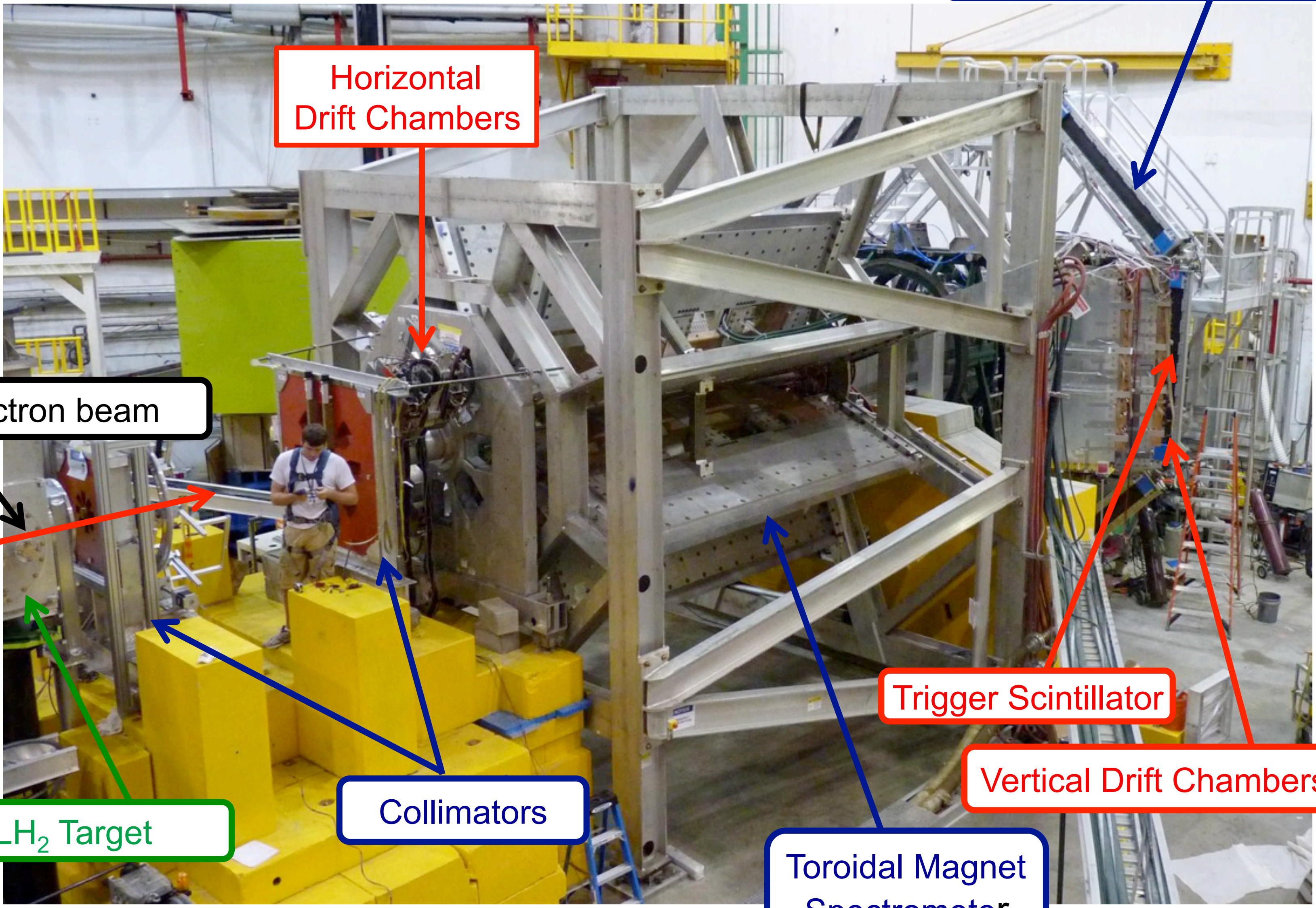
Target

Tungsten plug

Horizontal drift chambers (HDC) (rotate)

Lintels

The Q_{weak} Apparatus – during installation



Quartz Cerenkov Bars

Horizontal Drift Chambers

Electron beam

Trigger Scintillator

Vertical Drift Chambers

LH_2 Target

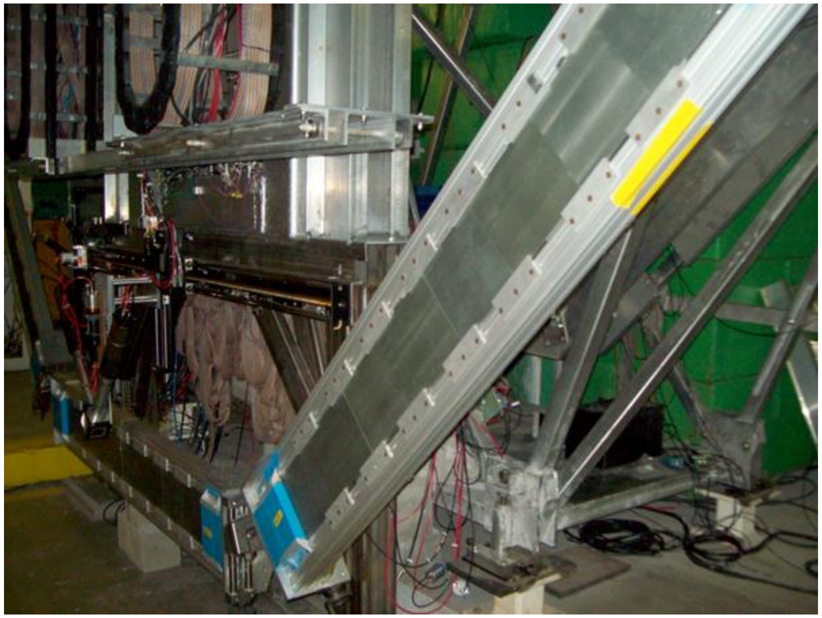
Collimators

Toroidal Magnet Spectrometer

Main Detectors

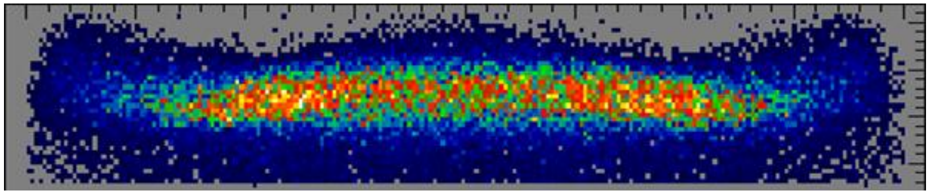
- Main detectors

  Toroidal magnet focuses elastic electrons onto each bar
  - 8 fused-silica Cerenkov bars: 200 cm x 18 cm x 1.25 cm
  - Rad-hard, low luminescence
  - 900 MHz e^- per detector
  - Azimuthal symmetry maximizes rates & reduces systematic uncertainties
  - 2 cm lead pre-radiators: a) reduce soft backgrounds discovered in commissioning
    b) boost signal size (but cost to energy resolution)

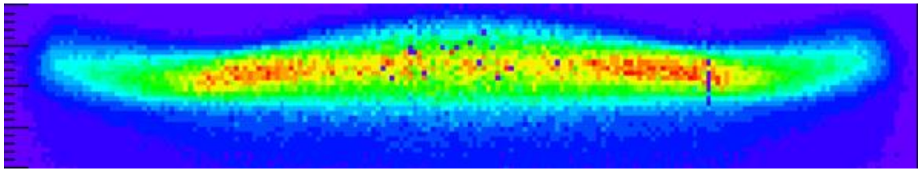


Close up of one detector *in situ*

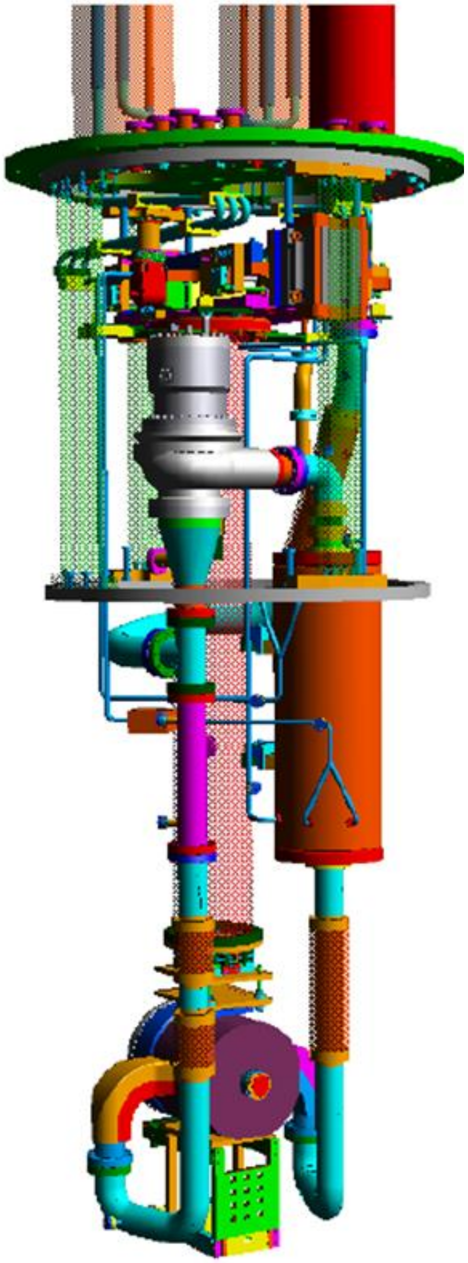
Simulation of scattering rate MD face



Measured



Hydrogen Target



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

Designed using Computational Fluid Dynamics

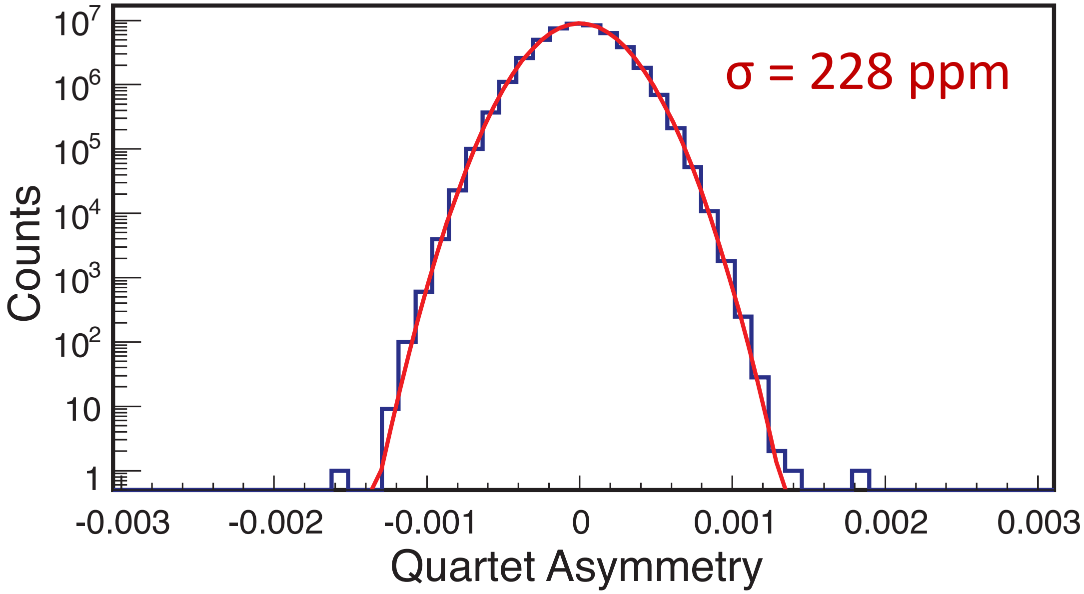
- Temperature ~20 K
- Pressure: 220 kPa
- Beam: 150 – 180 μA
- 4% X_0

Target boiling might have been problematic!

Rapid helicity-reversal: 960 Hz

common-mode rejection of boiling noise

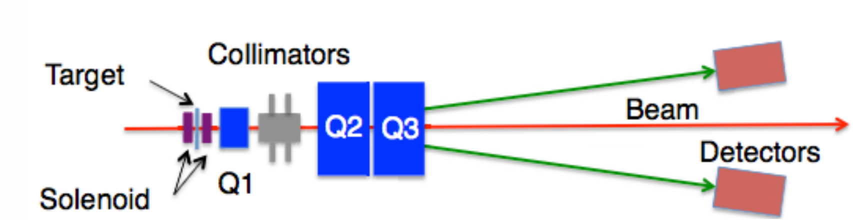
Achieved ~50 ppm noise (< 225 ppm counting statistics)



Beam Polarimetry

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

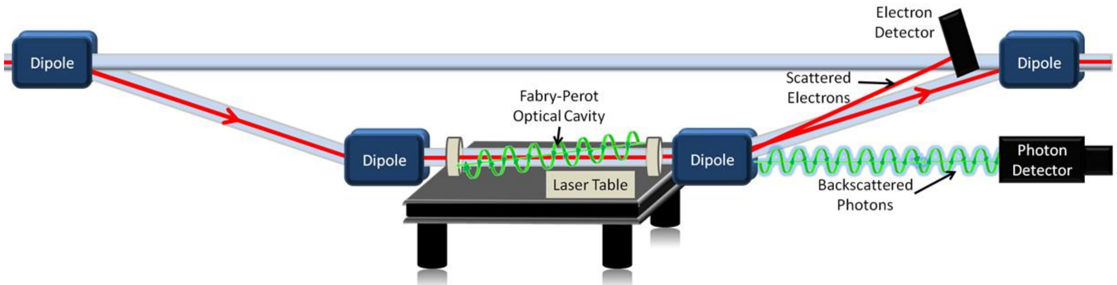
- Precise, but invasive
- Thin, polarized Fe target
- Brute force polarization
- Limited to low current

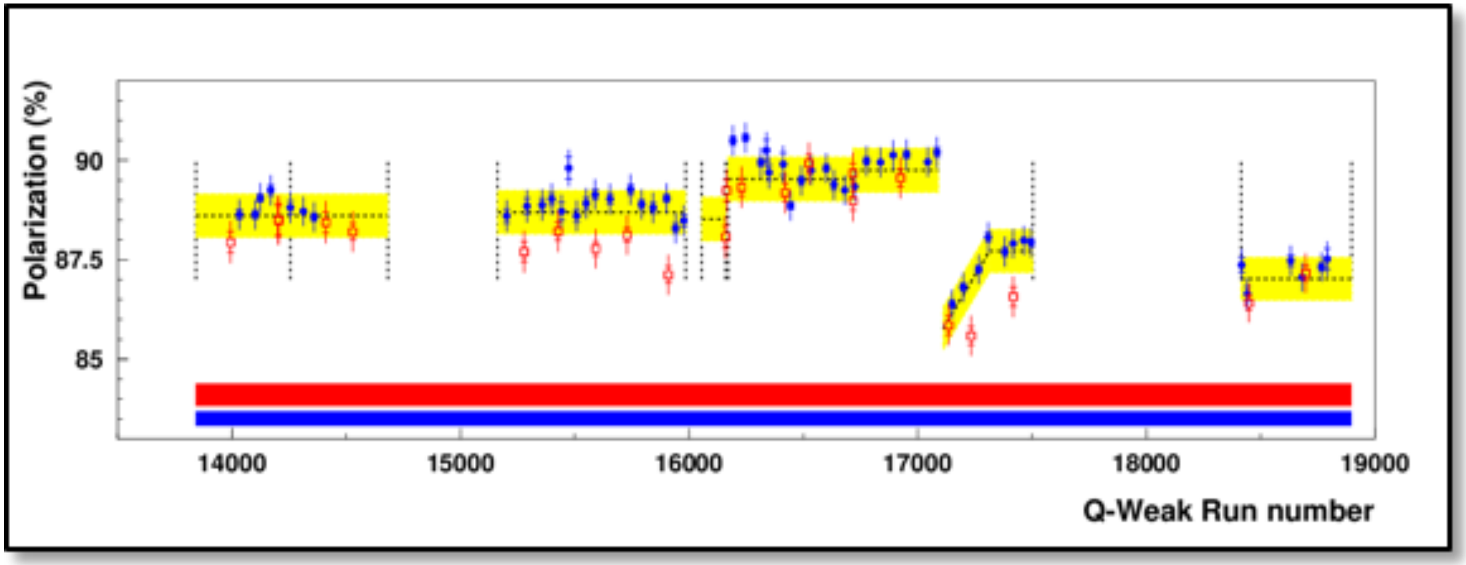


Compton polarimeter $(\vec{e} + \gamma \rightarrow e + \gamma)$

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

Detect *both* recoil electron and photon.





0.6% precision achieved in Run 2

Phys. Rev. X **6**, 011013 (2016)

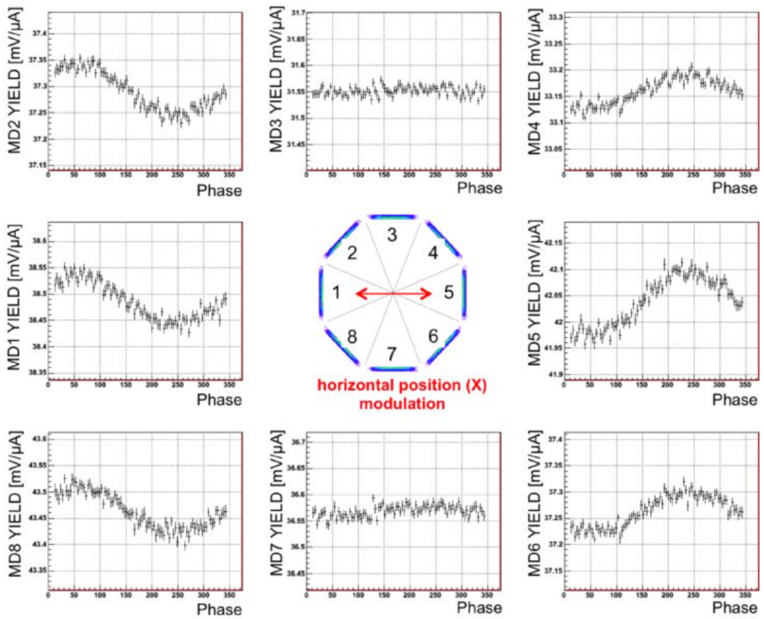
Phys. Lett. B **766**, 339 (2017)

Helicity-Correlated Beam Parameter Sensitivities

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

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

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



Natural: Linear regression of natural beam motion

Driven: Drive sinusoidal beam oscillations with large amplitude

Beam Parameter	Run 1 $\Delta\chi_i$	Run 2 $\Delta\chi_i$	Typical $\partial A/\partial\chi_i$
X	-3.5 ± 0.1 nm	-2.3 ± 0.1 nm	-2 ppb/nm
X'	-0.30 ± 0.01 nrad	-0.07 ± 0.01 nrad	50 ppb/nrad
Y	-7.5 ± 0.1 nm	0.8 ± 0.1 nm	< 0.2 ppb/nm
Y'	-0.07 ± 0.01 nrad	-0.04 ± 0.01 nrad	< 3 ppb/nrad
Energy	-1.69 ± 0.01 ppb	-0.12 ± 0.01 ppb	-6 ppb/ppb

Run 1: $A_{\text{beam}} = 18.5 \pm 4.1\,\text{ppb}$ Run 2: $A_{\text{beam}} = 0.0 \pm 1.1\,\text{ppb}$

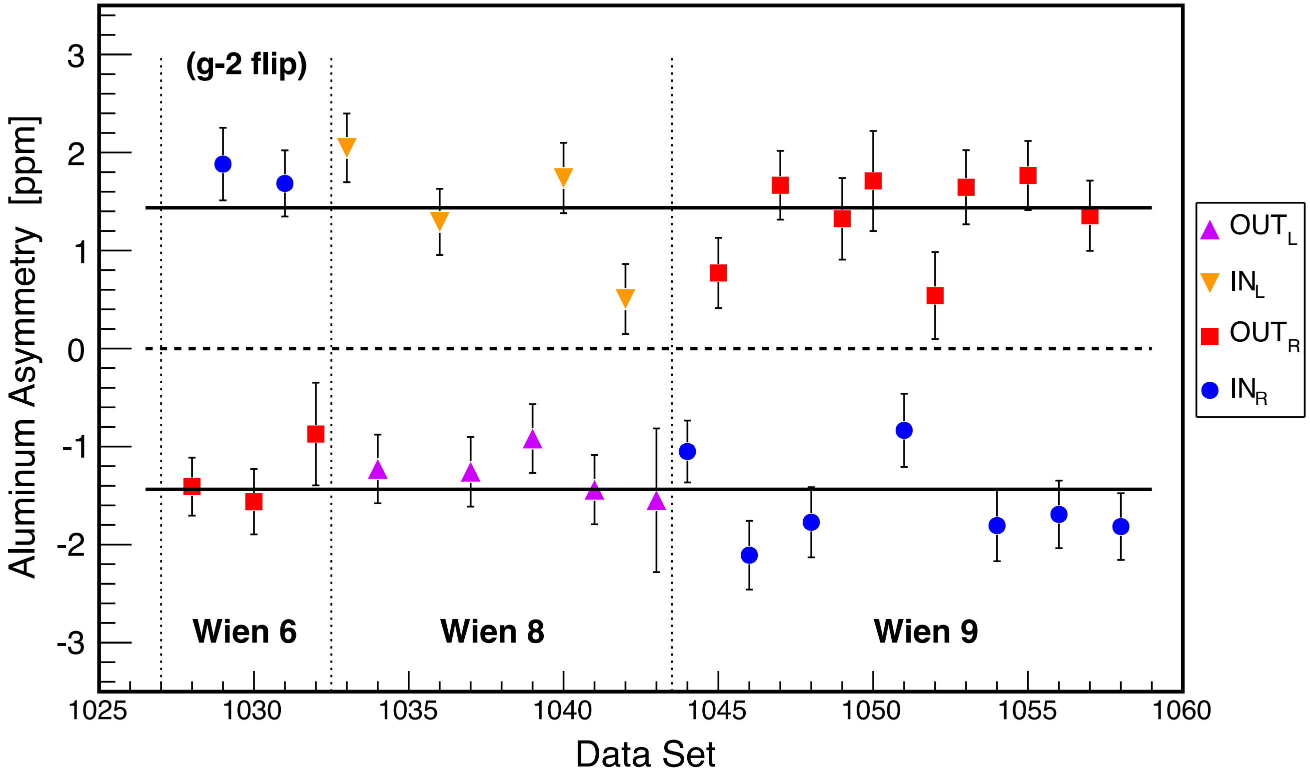
Target Windows

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

1. Measure ≈1500 ppb asymmetry from thick dummy target (identical Al alloy).
2. Precisely measure the $(2.52 \pm 0.06)\%$ “dilution” from windows.

- Net correction is ≈25% of hydrogen signal

Aluminum Parity-Violating Asymmetry



Statistical error: 5.0%
Systematic error: 0.7%

Three slow reversal types

IN/OUT: reversal of laser helicity (IWHP)

L/R: reversal of electron beam via Wien filter

g-2 flip: reversal of electron via spin precession in accelerator

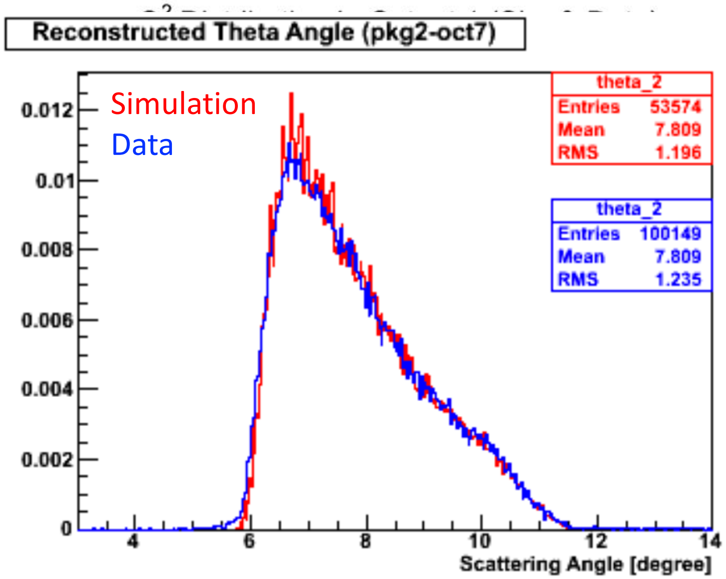
Kinematics (Q^2) determination

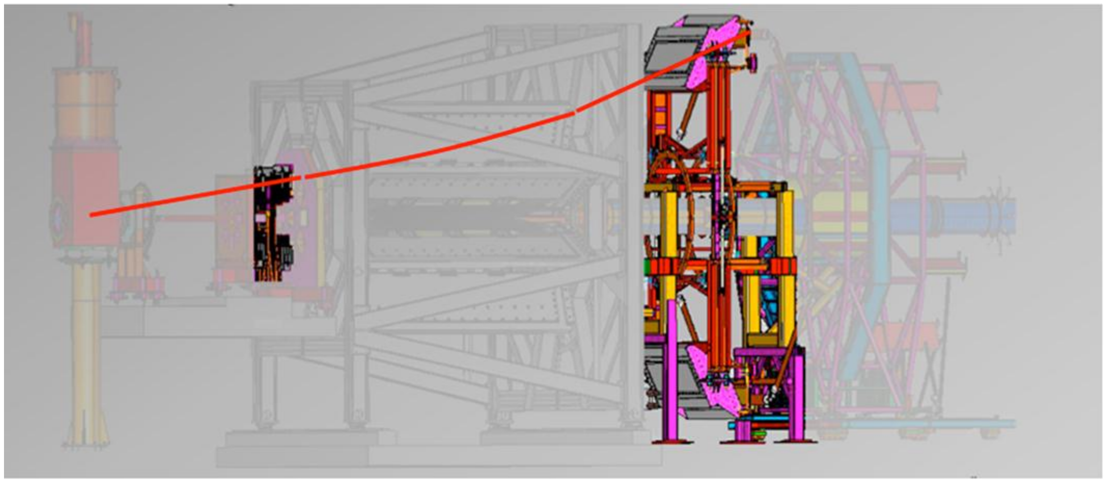
To determine Q^2, we go to “tracking” mode:

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

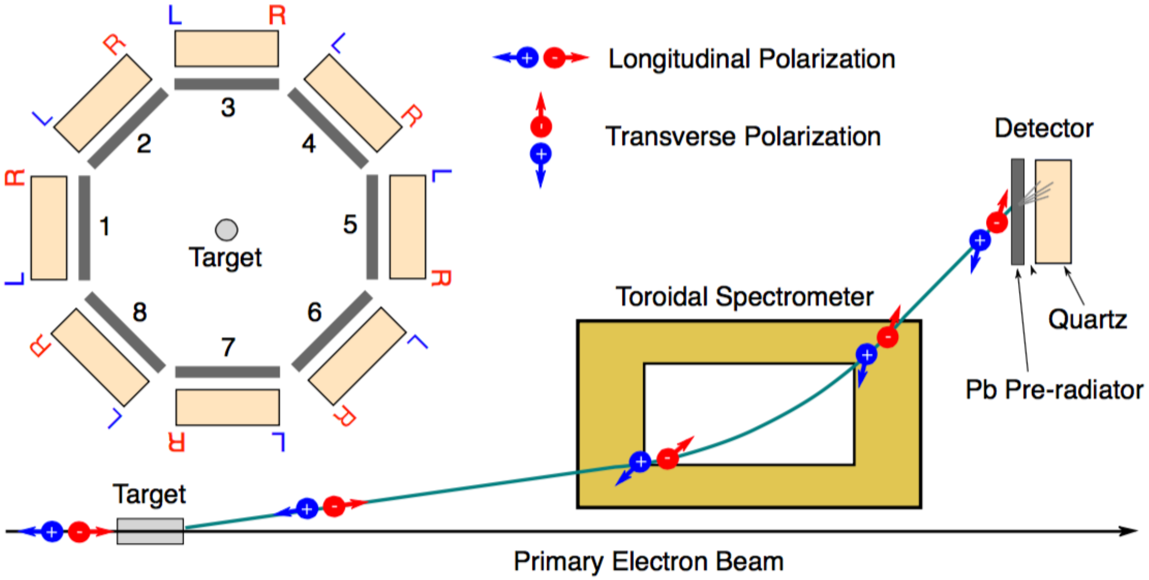
- Currents ~ 50 pA
- Use Vertical + Horizontal Drift Chambers
- Reconstruct individual scattering events

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





Secondary Scattering



- Spin precession of scattered e⁻ in magnet: some transverse polarization P_T
- P_T analyzed by scattering in Pb pre-radiators → transverse asymmetry in detectors: opposite sign in the two PMTs (R & L) in each detector

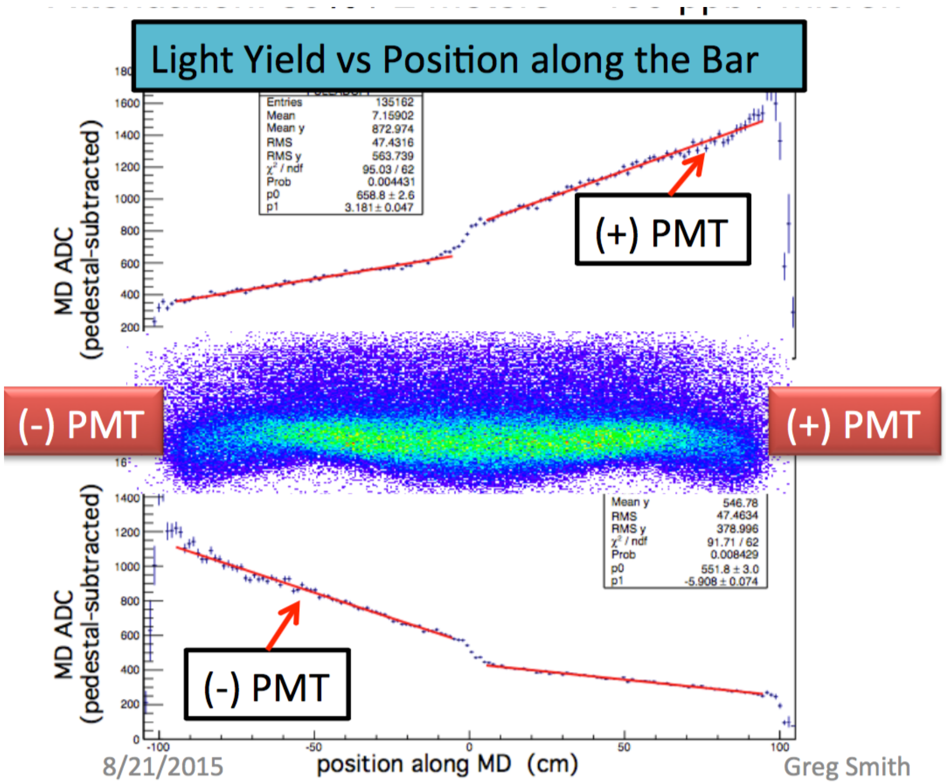
$A_{diff} = A_R - A_L$ Parity Signal = $\frac{A_R + A_L}{2}$ ∴ Effect cancels to first order

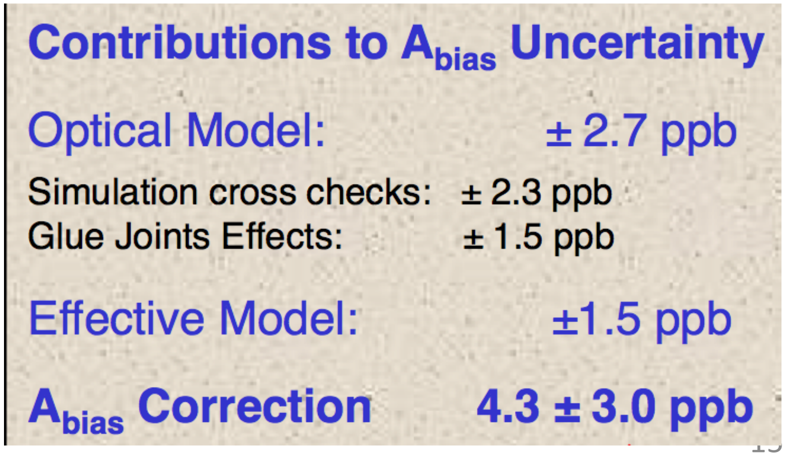
- Analyzing power in Pb:
  1. Beam-normal single spin asymmetry (high energy): 2γ exchange
  2. Mott scattering (low energy in shower) → dominant effect

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

Secondary Scattering

- This transverse asymmetry couples with position & angle dependence of optical response of detectors
- Any non-cancellation between R and L PMTs: detector imperfections & non-symmetric flux distributions
- Optical properties and flux distributions measured with tracking system
- Quantified non-cancellation with detailed GEANT 4 simulation





Contributions to A_{bias} Uncertainty

Optical Model:	± 2.7 ppb
Simulation cross checks:	± 2.3 ppb
Glue Joints Effects:	± 1.5 ppb
Effective Model:	±1.5 ppb
A_{bias} Correction	**4.3 ± 3.0 ppb**

Asymmetry: Dominant Systematic Uncertainties

Quantity	Run 1 error (ppb)	Run 1 fractional	Run 2 error (ppb)	Run 2 fractional
BCM Normalization: A_{BCM}	5.1	25%	2.3	17%
Beamline Background: A_{BB}	5.1	25%	1.2	5%
Beam Asymmetries: A_{beam}	4.7	22%	1.2	5%
Rescattering bias: A_{bias}	3.4	11%	3.4	37%
Beam Polarization: P	2.2	5%	1.2	4%
Target windows: A_{b1}	1.9	4%	1.9	12%
Kinematics: R_{Q^2}	1.2	2%	1.3	5%
Total of others	2.5	6%	2.2	15%
Combined in quadrature	10.1		5.6	

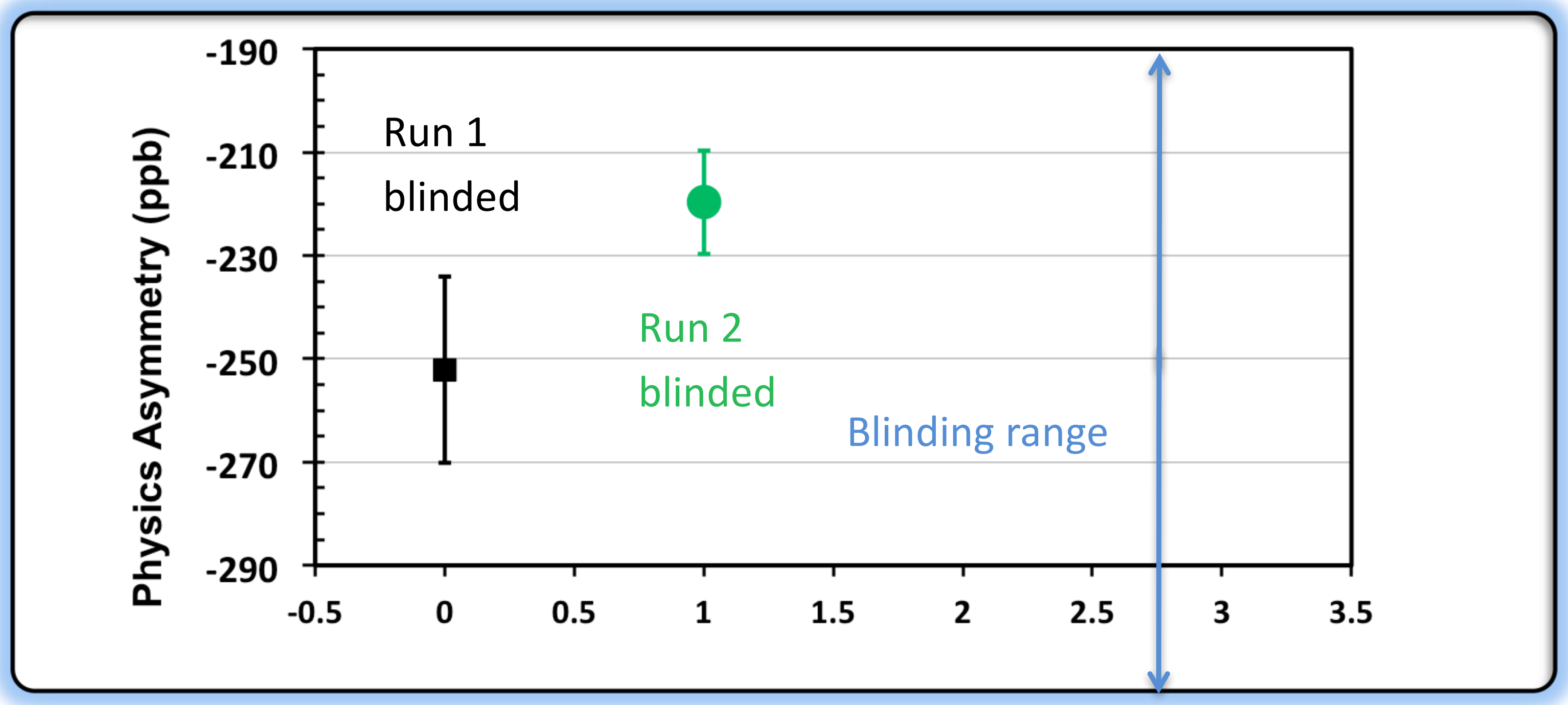
$$A_{\mathrm{msr}} = A_{\mathrm{raw}} + A_T + A_L + A_{\mathrm{BCM}} + A_{\mathrm{BB}} + A_{\mathrm{beam}} + A_{\mathrm{bias}}$$

$$A_{ep} = R_{\mathrm{tot}} \frac{A_{\mathrm{msr}}/P - \sum_{i=1,3,4} f_i A_i}{1 - \sum_{i=1}^{4} f_i}$$

$$R_{\mathrm{tot}} = R_{\mathrm{RC}} R_{\mathrm{Det}} R_{\mathrm{Acc}} R_{Q^2}$$

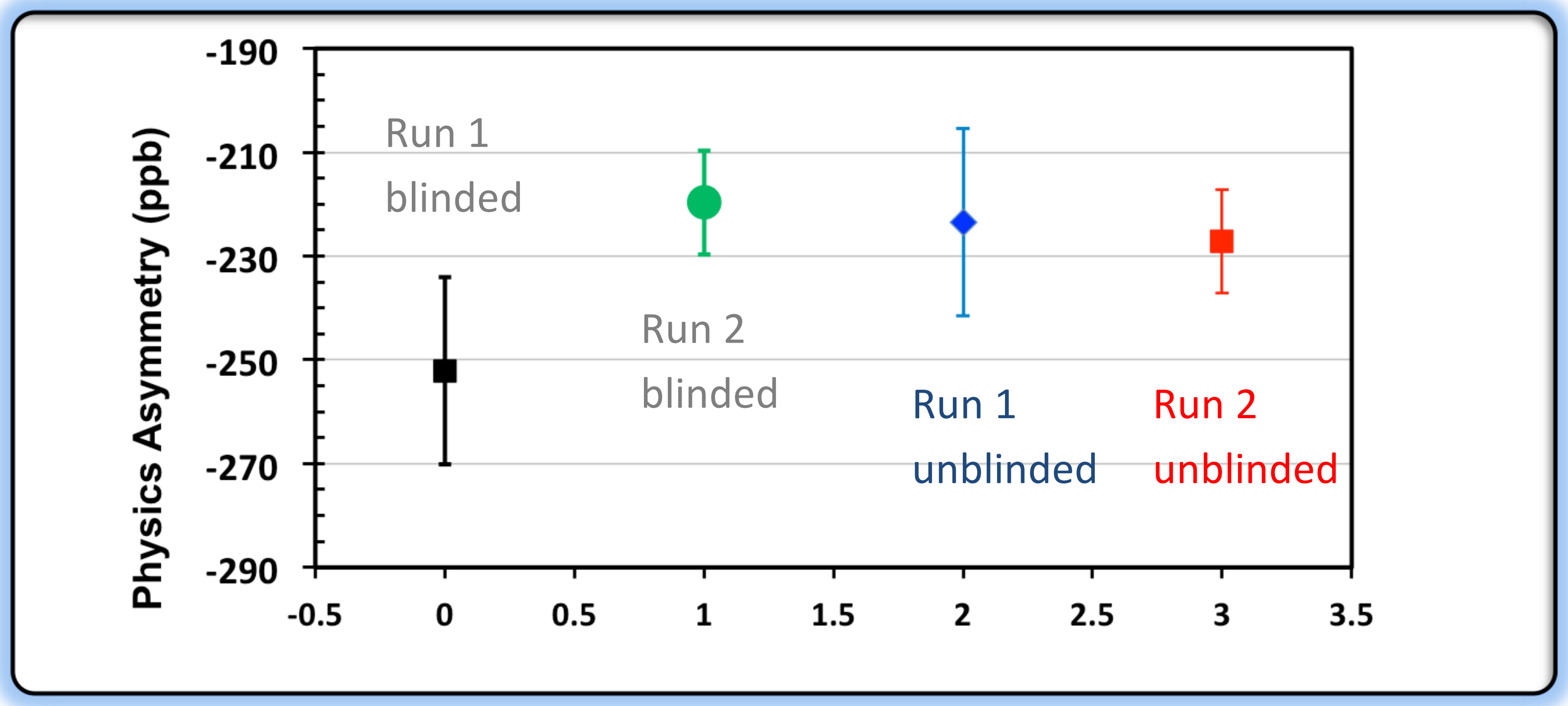
Blinded Analysis

Run 1 and 2 *each* had their own independent "blinding factor" (additive offset in range ± 60 ppb) to avoid analysis bias.



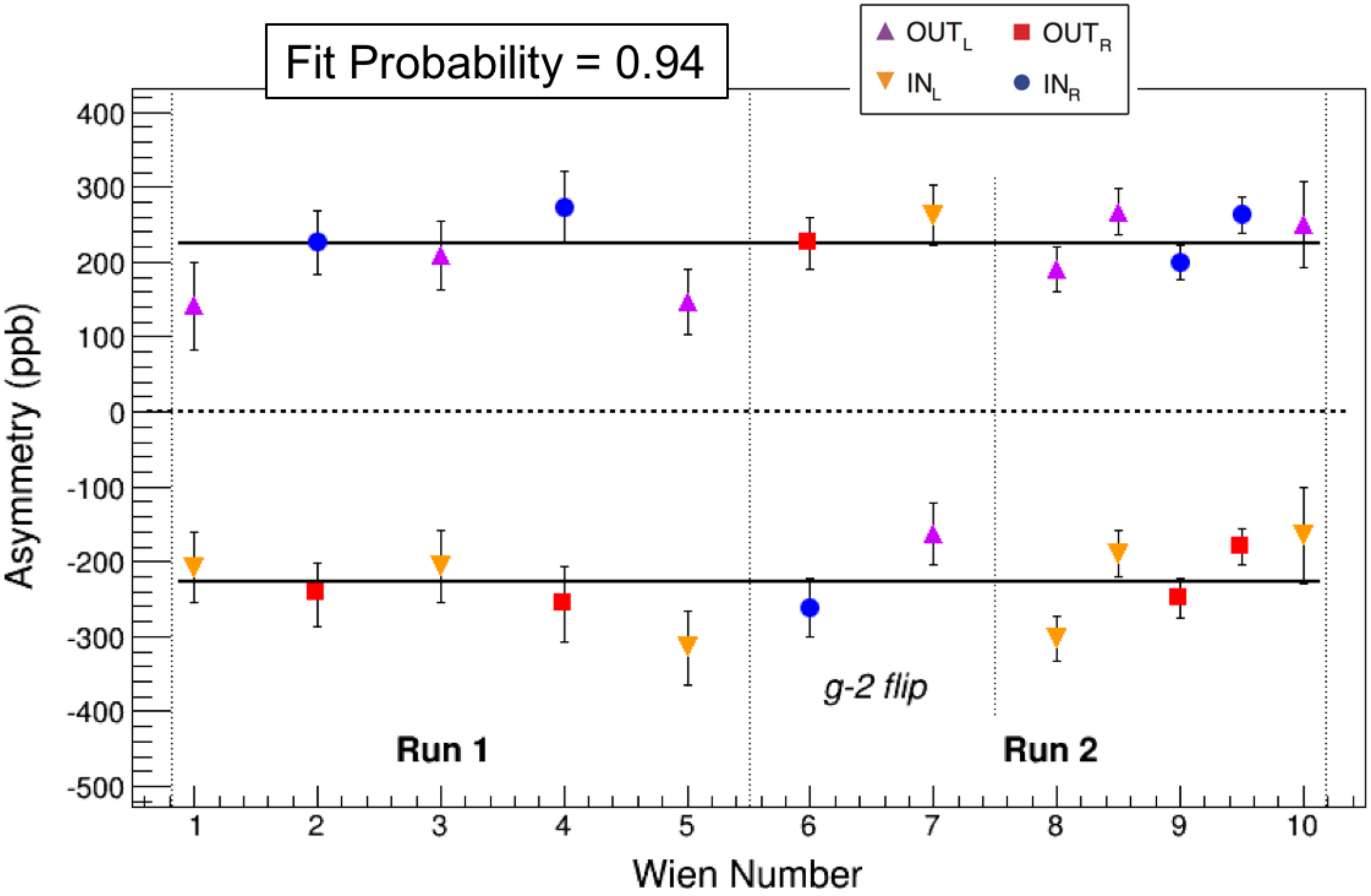
Un-Blinded Results

Marvelous agreement between the two Runs
(several systematic corrections rather different in the two Runs)



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

Behavior of Asymmetry under Slow Reversals



Three slow reversal types

IN/OUT: reversal of laser helicity (IWHP)

L/R: reversal of electron beam via Wien filter

g-2 flip: reversal of electron via spin precession in accelerator

The data behaved as expected under all three types of slow helicity reversal.

Combining the data without sign corrections gives

NULL average = -1.75 ± 6.51 ppb

- consistent with zero, as expected

Electroweak Radiative Corrections

Q_W^p expt. precision : $\pm\, 0.0045$

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

Correction to Q_W^p	Uncertainty
$\Delta\sin^2\theta_W(M_Z)$	± 0.0006
$\Box_{WW}, \Box_{ZZ}$ - pQCD	± 0.0003
$\Delta\rho$ (hadronic loops)	± 0.0003
$\Box_{\gamma Z}$	0.00459 ± 0.00044

Erler, Kurylov
& Ramsey-Musolf
PRD **68**, 016006 (2008)

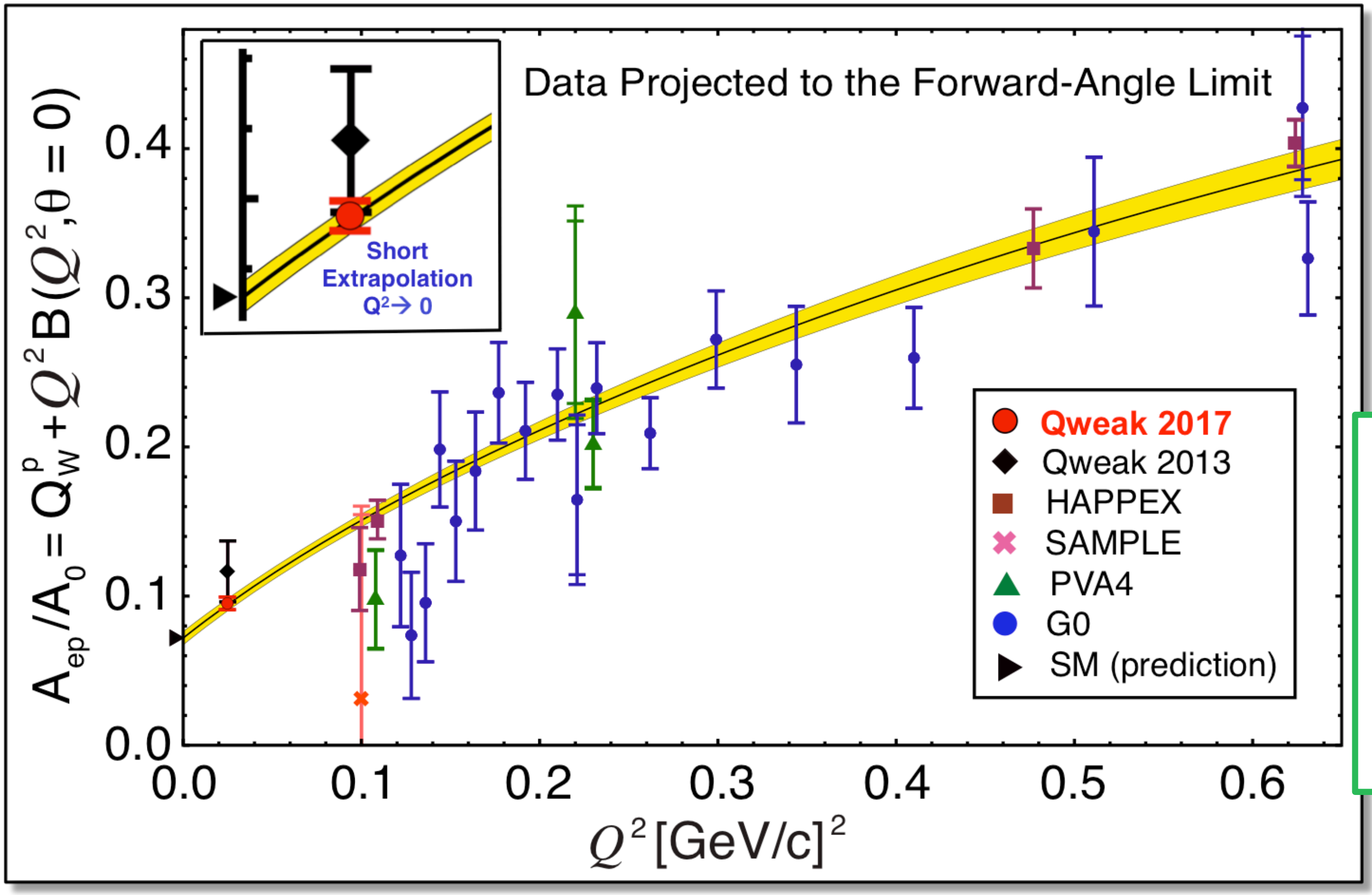
Calculation	$\Box_{\gamma Z}$ (vector) contribution to Q_W^p
Sibirtsev, Blunden, Melnitchouk & Thomas PRC **82**, 013011 (2010)	$0.0047^{+0.0011}_{-0.0004}$
Rislow & Carlson PRD **83**, 113007 (2011)	0.0057 ± 0.0009
Gorchtein, Horowitz & Ramsey-Musolf PRC **84**, 015502 (2011)	0.0054 ± 0.0020
Hall, Blunden, Melnitcouk, Thomas & Young Phys.Lett.B **753**, 221 (2016)	0.0052 ± 0.00043

Extracting Weak Charge from Asymmetry Result

$$\boxed{A_{ep} = -226.5 \pm 7.3(\mathrm{stat}) \pm 5.8(\mathrm{syst})\ \mathrm{ppb\ at}\ \left\langle Q^2 \right\rangle = 0.0249\ (\mathrm{GeV}/c)^2}$$

Global fit of world PVES data up to $Q^2 = 0.63\ \mathrm{GeV}^2$ to extract proton's weak charge:

$$A_{ep}/A_0 = Q_W^p + Q^2 B(Q^2, \theta), \qquad A_0 = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right].$$



33 entries in PVES (e-p, e-d, e-^{4}He) database

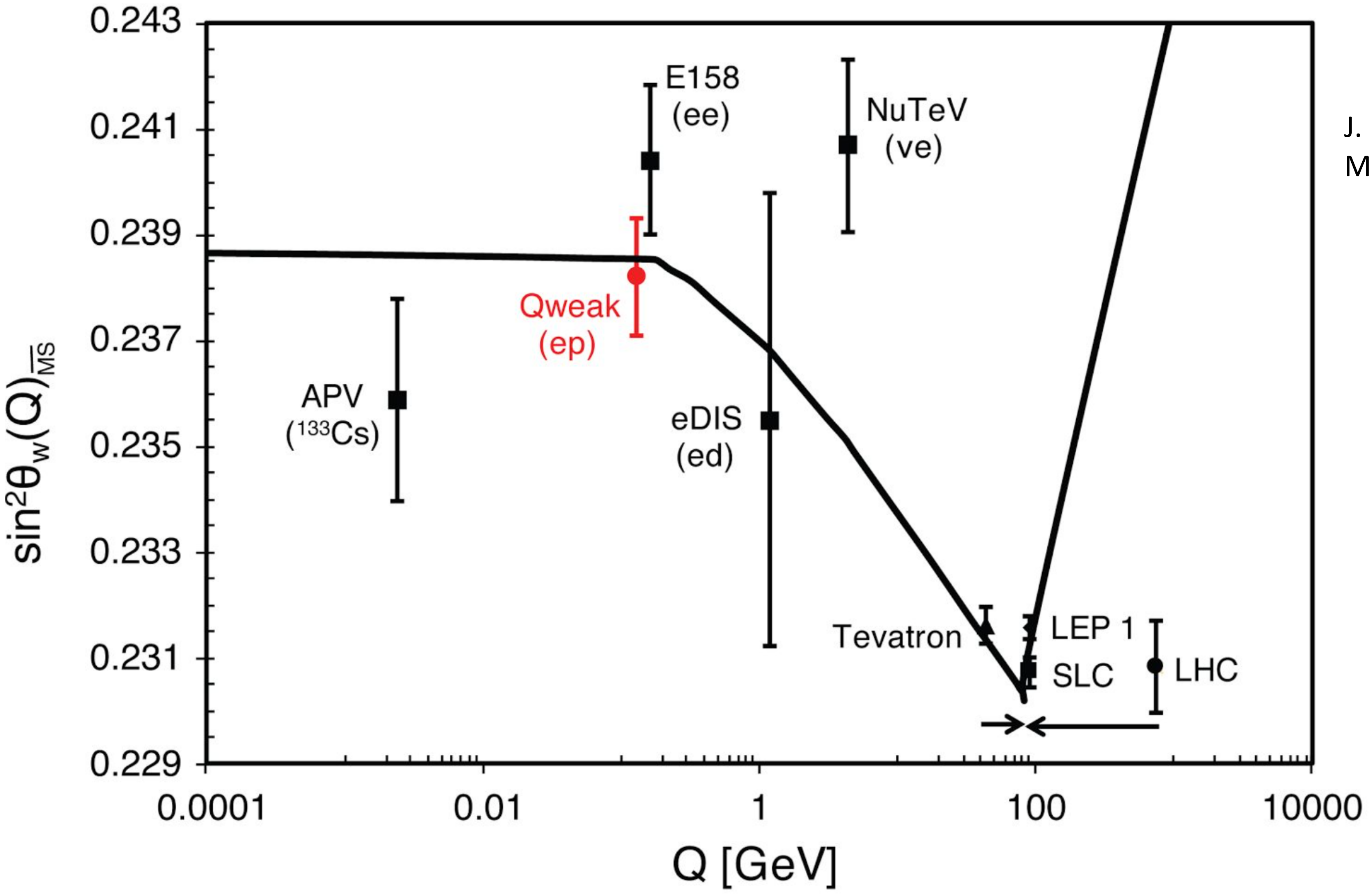
Standard Model:

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

Experiment:

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

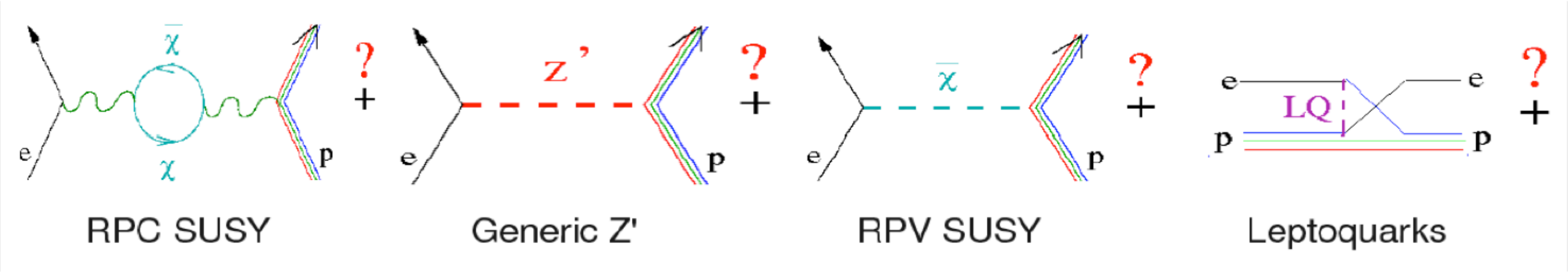
Running of the Weak Mixing angle $\sin^2\theta_W$



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

Note: interference effects of heavy new physics (*i.e.* Z', leptoquarks) suppressed at Z resonance → LEP/SLC mass limits ≤ TeV, while low energy observables probe few TeV scale

Sensitivity to New Physics at TeV scale



Parameterize generically by adding contact term to Lagrangian:

$$\mathcal{L}^{\mathrm{eq}}_{\mathrm{NC}} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e\sum_q C_{1q}\bar{q}\gamma^\mu q.$$

Standard Model term

$$\mathcal{L}^{\mathrm{PV}}_{\mathrm{NP}} = -\frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e\sum_q h^q_V\bar{q}\gamma^\mu q$$

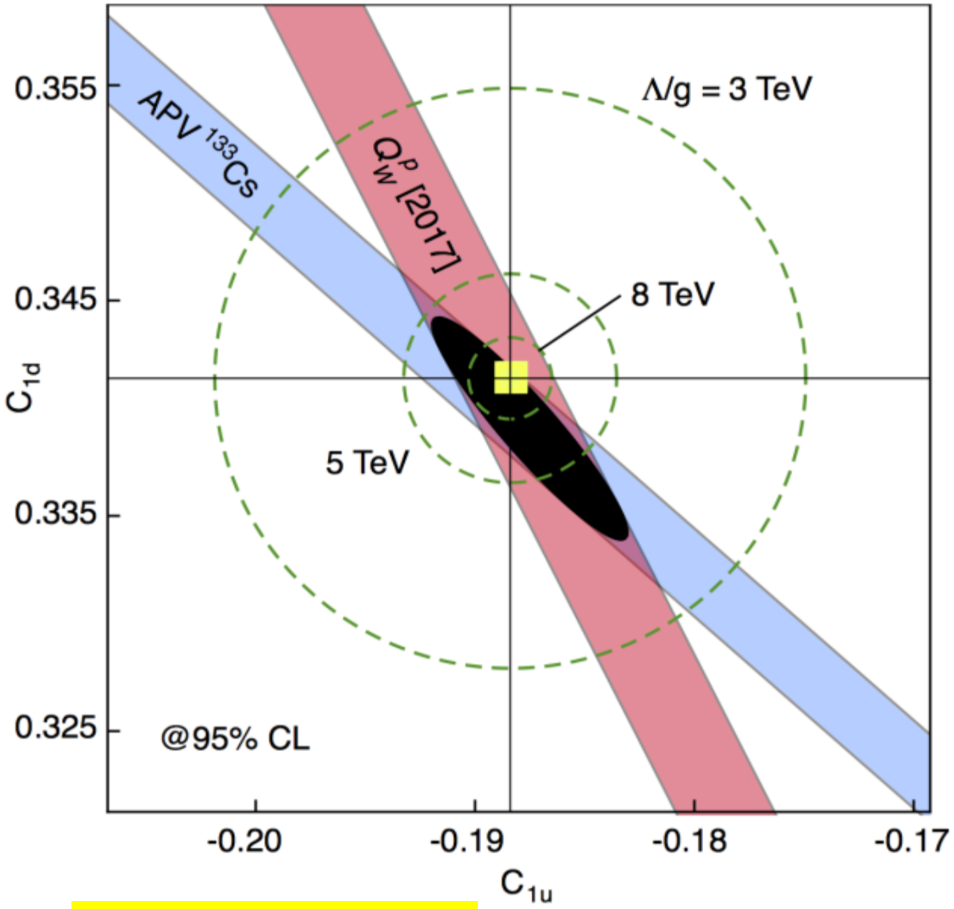
New Physics term

g=coupling
Λ=mass scale

Limits on Semi-Leptonic PV Physics beyond the SM

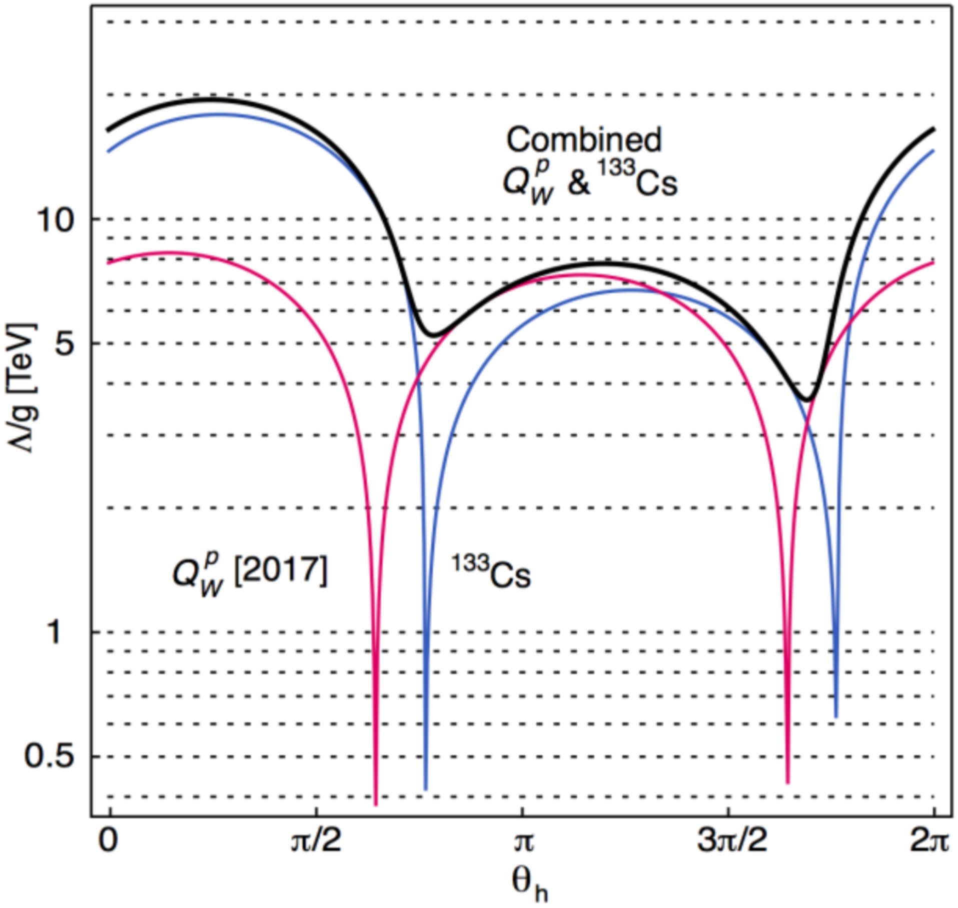
$$Q_W^p = -2(2C_{1u} + C_{1d})$$

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



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

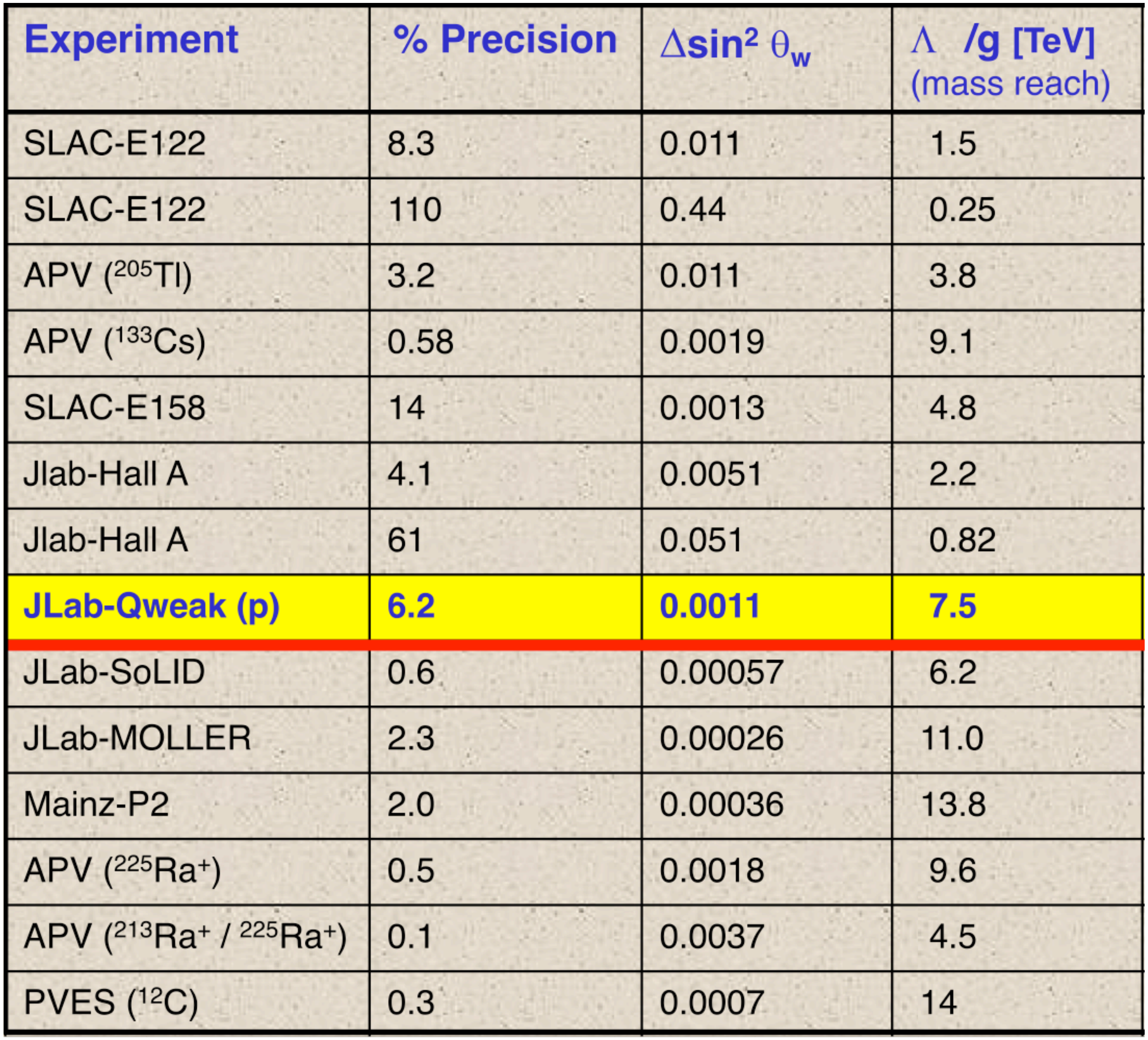
$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$



Yellow box: SM values

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

SM tests with Precision Low-Energy Parity Violation



Experiment	**% Precision**	**$\Delta\sin^2\theta_W$**	**Λ /g [TeV]** (mass reach)
SLAC-E122	8.3	0.011	1.5
SLAC-E122	110	0.44	0.25
APV (^{205}Tl)	3.2	0.011	3.8
APV (^{133}Cs)	0.58	0.0019	9.1
SLAC-E158	14	0.0013	4.8
Jlab-Hall A	4.1	0.0051	2.2
Jlab-Hall A	61	0.051	0.82
JLab-Qweak (p)	**6.2**	**0.0011**	**7.5**
JLab-SoLID	0.6	0.00057	6.2
JLab-MOLLER	2.3	0.00026	11.0
Mainz-P2	2.0	0.00036	13.8
APV (^{225}Ra$^+$)	0.5	0.0018	9.6
APV (^{213}Ra$^+$ / ^{225}Ra$^+$)	0.1	0.0037	4.5
PVES (^{12}C)	0.3	0.0007	14

Published

Planned

A suite of Auxiliary Measurements

Many ancillary measurements done to quantify various systematic effects:

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

Beam normal single-spin asymmetry* for elastic scattering on proton
Beam normal single-spin asymmetry for elastic scattering on ^{27}Al
PV asymmetry in the $N \rightarrow \Delta$ region.
Beam normal single-spin asymmetry in the $N \rightarrow \Delta$ region.
Beam normal single-spin asymmetry near W= 2.5 GeV
Beam normal single-spin asymmetry in pion photoproduction
PV asymmetry in inelastic region near W=2.5 GeV (related to γZ box diagrams)
PV asymmetry for elastic/quasielastic from ^{27}Al
PV asymmetry in pion photoproduction

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

The Qweak Collaboration

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A SEARCH FOR NEW PHYSICS
Qweak

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Summary

Precision measurement of proton’s weak charge: $\boxed{Q_W^p = 0.0719 \pm 0.0045}$

Excellent agreement with Standard Model prediction = 0.0708

Constrains generic new parity-violating “Beyond the Standard Model” physics
at TeV scale: Λ/g > 3.6 TeV (arbitrary u/d ratio of couplings)

Paper submitted for publication Oct 10.

Important addition to global electroweak fits to constrain many new physics scenarios