

Precise Measurement of the Weak Charge of the Proton

- *The Q_{weak} Experiment*

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Outline

- Motivation and formalism
- Experimental apparatus and achievements
- Analysis and extraction of the proton's weak charge
- Implications of the new physics

The Standard Model

- Developed in 1960-70s.
- Local gauge invariance on $SU(3) \times SU(2) \times U(1)$ group.
- Symmetry breaking via Higgs mechanism to grant masses to W & Z bosons and fermions.
- Does not include gravity, matter-antimatter ratio, dark energy and dark matter.
- New physics to be found beyond the Standard Model.

	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 125.09 \text{ GeV}/c^2$
charge	2/3	2/3	2/3	0	0
spin	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	$\approx 4.7 \text{ MeV}/c^2$ -1/3 1/2	$\approx 96 \text{ MeV}/c^2$ -1/3 1/2	$\approx 4.18 \text{ GeV}/c^2$ -1/3 1/2	0 0 1	
	$\approx 0.511 \text{ MeV}/c^2$ -1 1/2	$\approx 105.66 \text{ MeV}/c^2$ -1 1/2	$\approx 1.7768 \text{ GeV}/c^2$ -1 1/2	$\approx 91.19 \text{ GeV}/c^2$ 0 1	
	$< 2.2 \text{ eV}/c^2$ 0 1/2	$< 1.7 \text{ MeV}/c^2$ 0 1/2	$< 15.5 \text{ MeV}/c^2$ 0 1/2	$\approx 80.39 \text{ GeV}/c^2$ ± 1 1	
QUARKS					SCALAR BOSONS
LEPTONS				GAUGE BOSONS	

Gauge bosons via local gauge invariance on $SU(2) \times U(1)$ group:

$$D_\mu = \partial_\mu + i\frac{g}{2}(\tau^1 W_\mu^1 + \tau^2 W_\mu^2 + \tau^3 W_\mu^3) + i\frac{g'}{2} B_\mu$$

Mixing between $SU(2)$ and $U(1)$ to include Z boson and photon:

$$\begin{cases} Z_\mu = \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu \\ A_\mu = \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu \end{cases}$$

Searching for “New Physics”

Two complementary approaches:

“Energy Frontier” – Like LHC

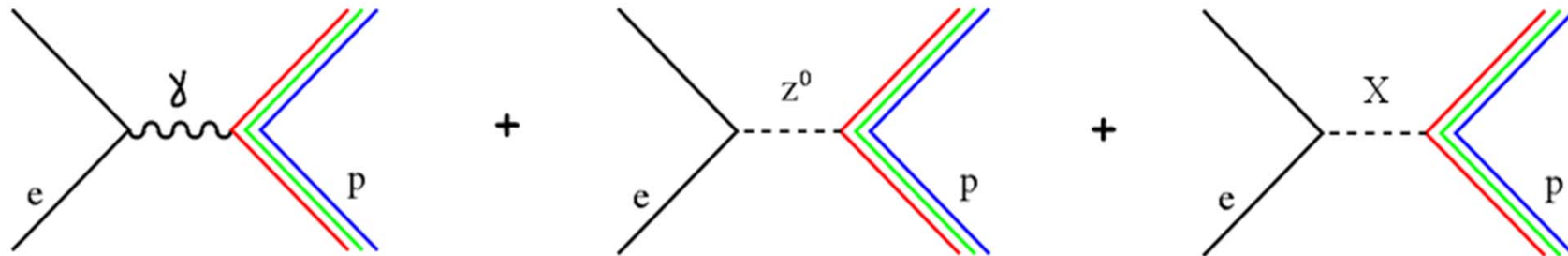
→ Make new particle “X” directly in high energy collisions



+

“Precision Frontier” – weak charge, etc

→ Measure indirect effects of new particle “X” made virtually in low energy processes

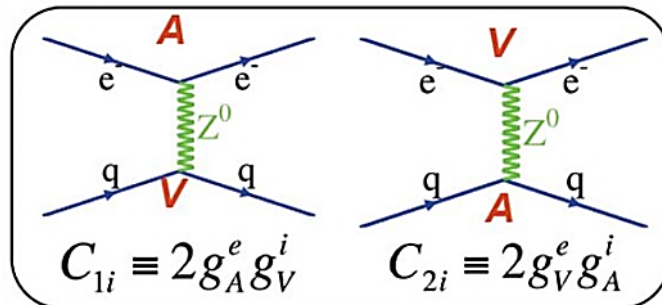


- If LHC sees “new physics”, precision measurements can help select among models
- If LHC sees no “new physics”, precision measurements are sensitive to some types of new physics unobservable at LHC

Weak Charge in the Standard Model

Particle	Electric charge	Weak vector charge ($\sin^2 \theta_W \approx \frac{1}{4}$)
e	-1	$Q_W^e = -1 + 4 \sin^2 \theta_W \approx 0$
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	$Q_W^p = 1 - 4 \sin^2 \theta_W \approx 0.07$
n(udd)	0	$Q_W^n = -1$

Accidental suppression of the proton's weak charge – sensitive to new physics beyond the Standard Model



$$Q_{\text{weak}}: \quad Q_w(p) = -2(2C_{1u} + C_{1d})$$

$$\text{APV: } Q_w(^{133}\text{Cs}) = -2(188C_{1u} + 211C_{1d})$$

Q_{weak} & APV:

$$C_{1u}, C_{1d}, Q_w(n) = -2(C_{1u} + 2C_{1d})$$

Parity Violating Asymmetry in Q_{weak} Experiment

The Q_{weak} experiment determines the proton's weak charge by measuring the parity-violating asymmetry in elastic scattering of longitudinally polarized electrons on proton.

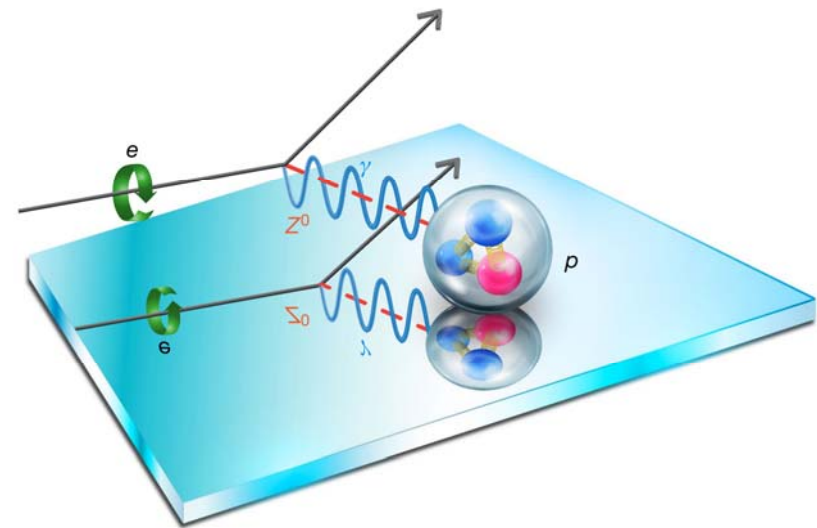
Asymmetry in Parity-Violating Electron-Proton scattering:

$$A_{ep} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{\epsilon G_E^{p\gamma} G_E^{pZ} + \tau G_M^{p\gamma} G_M^{pZ} - (1 - 4 \sin^2 \theta_w) \epsilon' G_M^{p\gamma} G_A^Z}{\epsilon (G_E^{p\gamma})^2 + \tau (G_M^{p\gamma})^2}$$

- EM, electroweak and axial form factors

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

- Both virtual photon and Z bosons can be exchanged.
- EM interaction is parity conserving but weak interaction is **Parity Violating**.
- Slight difference in scattering cross section under e spin flip defines **PV asymmetry**.



$Q_w(p)$ Determination

The weak charge of the proton:

$$A_{ep}/A_0 = [Q_w^p + Q^2 B(Q^2, \theta)], A_0 = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}$$

proton's weak charge:
 $Q_w^p = 1 - 4 \sin^2\theta_w$ at tree level

"Form factor" term due to finite proton size –
hadronic structure – determined well by existing
PVES higher Q^2 data

- Q_w^p as the intercept
- hadronic structure in $B(Q^2, \theta)$, can fit with global PVES data

By running at a small value of Q^2 (small beam energy, small scattering angle) we minimize sensitivity to the proton's detailed spatial structure. But this also brings a smaller asymmetry, which makes the experiment more challenging when asymmetry error can be bounded by experiment apparatus and techniques.

Q_{weak} Experiment History and Status

Q_{weak} **Experiment:** parity-violating e-p elastic scattering to measure proton's weak charge

- Initial organizational meeting 2000 **2000 – 2018: 18 Years**
- Proposal 2001
- Design/construction 2003 – 2010
- Data-taking 2010 – 2012 (~ 1 year total beam time)
- Last experiment in Hall C in “6 GeV era”
- First results on proton's weak charge (based on 4% of the dataset) published in **Phys. Rev. Lett. 111, 141803 (2013)**
- Apparatus described in **NIM A781, 105 (2015)**
- Final analysis and unblinding completed; final results first released at 21st Particles & Nuclei International Conference (PANIC) in Beijing, China by Roger Carlini on September 3, 2017
- Results published in **Nature 557, 207–211 (2018)**

Experimental Parameters

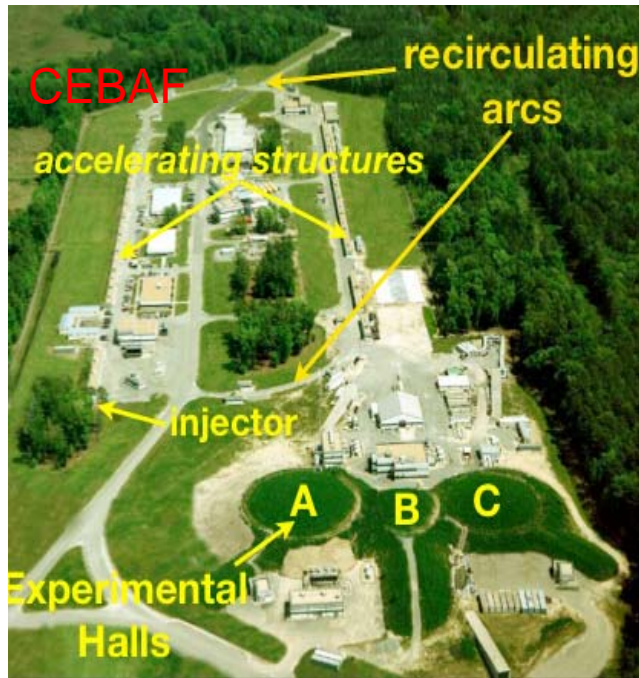
As the most precise PVES experiment to date, Q_{weak} experiment has pushed boundaries:

- Higher polarized beam intensity
- Faster beam-helicity reversal
- Better GeV-scale beam polarimetry precision
- Higher LH₂ target luminosity and cooling power
- Higher total detector rates

Main parameters of the experiment:

Central scattering angle:	$7.9^\circ \pm 3^\circ$
Phi Acceptance:	49% of 2π
Average Q^2 :	$0.026 \pm 0.0006 \text{ GeV}^2$
Beam Energy:	$1.155 \pm 0.003 \text{ GeV}$
Beam Current:	145 μA – 180 μA
Beam Polarization:	0.89 ± 0.018
Target Power:	2.5 kW
Luminosity:	$1.7 \times 10^{39} \text{ cm}^{-2} \text{ s}^{-1}$
Integrated Rate (per detector):	850 MHz (6.8 GHz total)

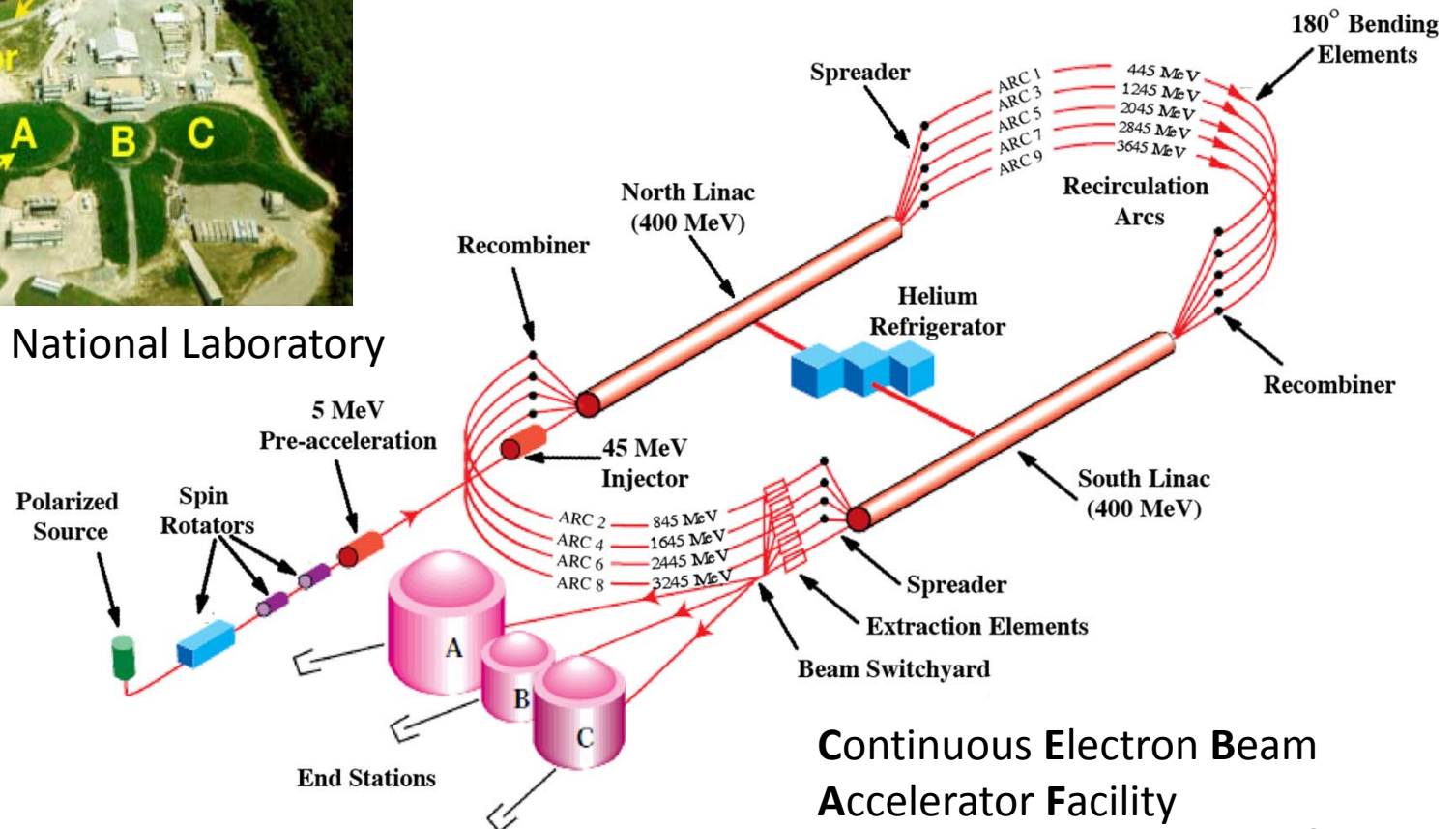
CEBAF at Jefferson Lab



Tomas Jefferson National Laboratory
Newport News
Virginia

Three Run periods of Q_{weak} Experiment:

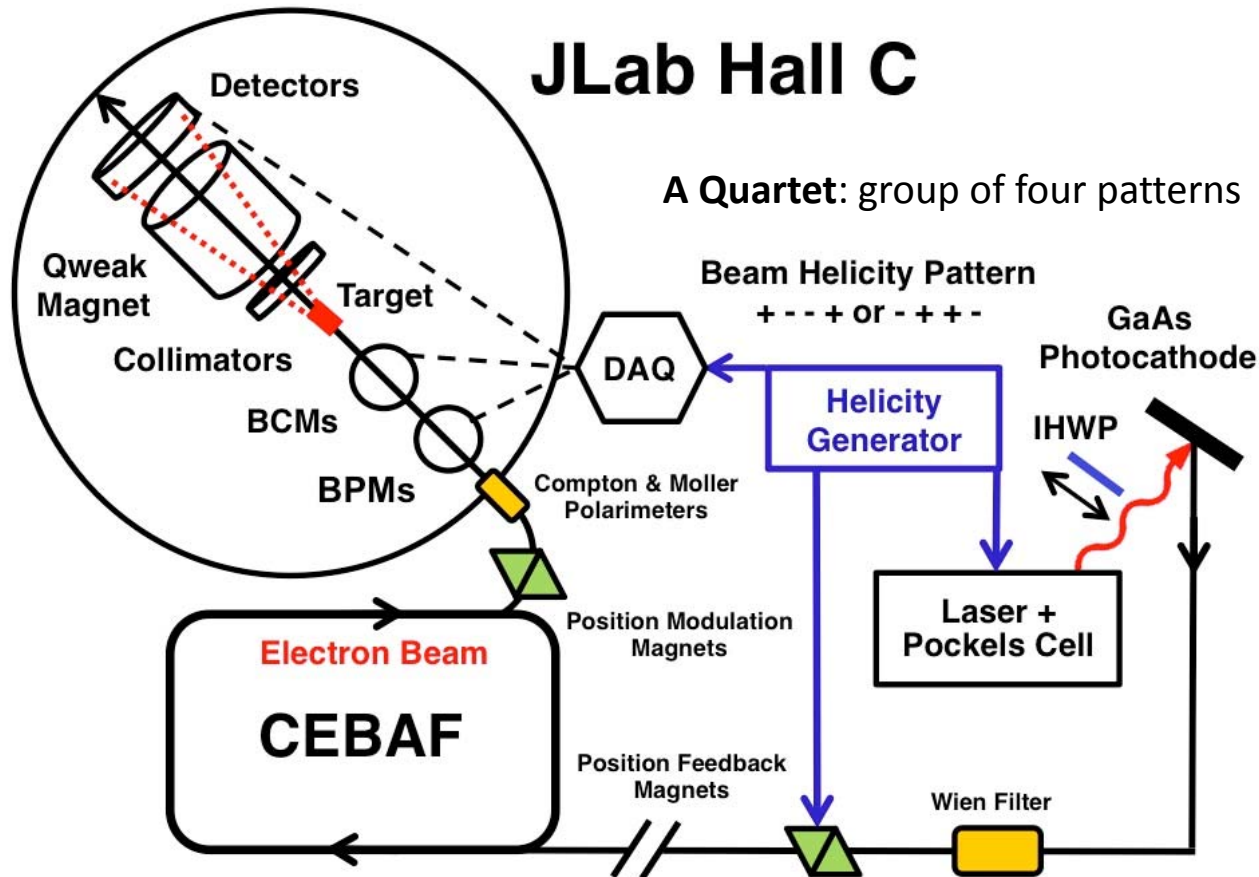
- Commissioning: February, 2011
- Run 1: February - May, 2011
- Run 2: November 2011 - May 2012



Continuous Electron Beam
Accelerator Facility

Experiment Overview

To change the helicity of the electron beam, three independent techniques:



Rapid pseudo-random reversal (960/sec).

IHWP at ~8-hour intervals:
 Mechanical action unable to induce electrical or magnetic induced false asymmetries.

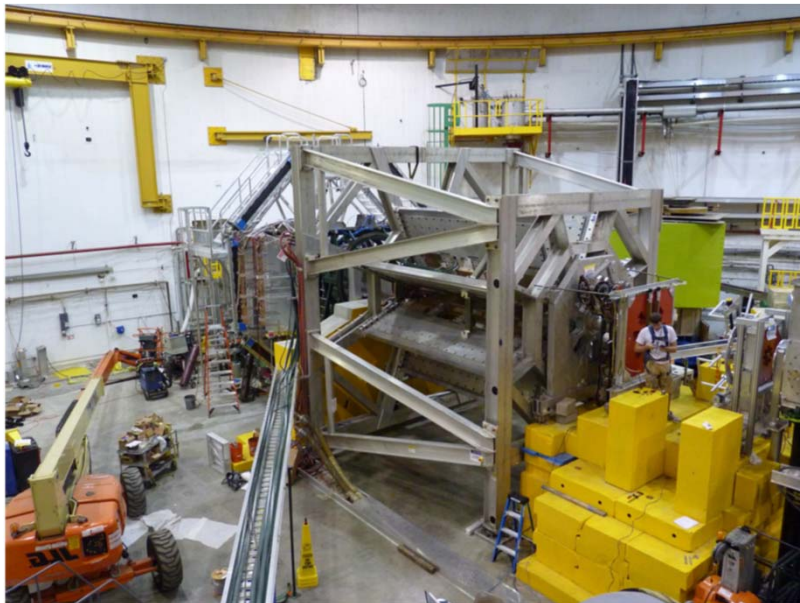
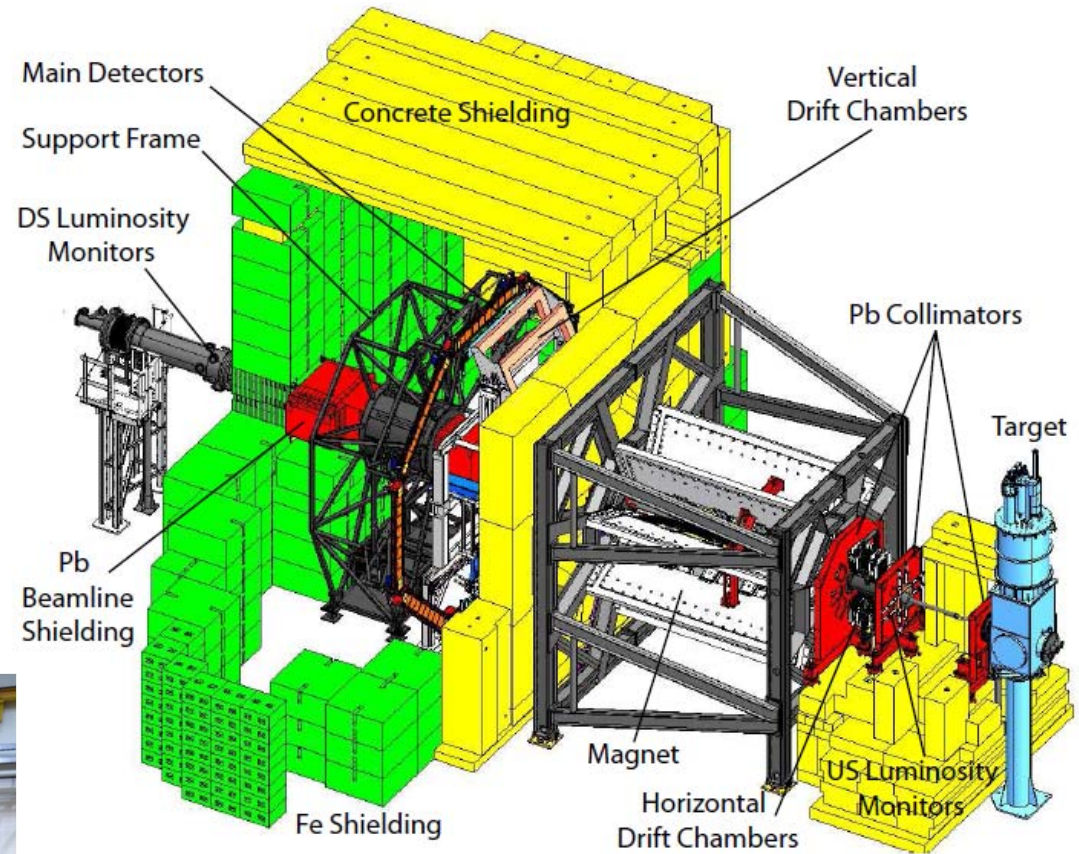
Wien filter at monthly intervals: Rejection of beam size (or focus) modulation induced false asymmetry and suppression of slow drifts in apparatus linearity.

1. Circularly polarized laser incident on a photocathode
2. Polarized electrons with corresponding helicity
3. Electrons accelerated via CEBAF to reach Hall C

$$A_{ep} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

Experimental Apparatus

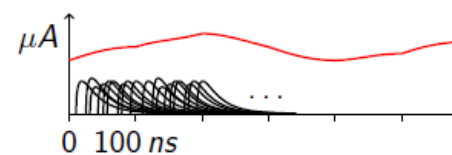
- Longitudinally polarized electron beam
- LH_2 target
- Three Pb collimator system
- Toroidal Spectrometer (QTOR)
- Eight quartz detector bar with two PMTs on each end
- Drift chambers for momentum transfer determination
- Background detectors



Integrating mode

180 μA

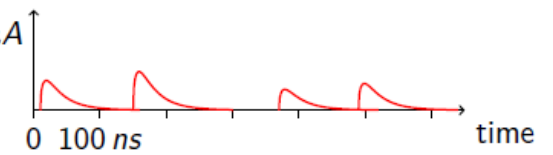
~ 800 MHz each detector



Tracking mode

50 pA

individual event



PV Asymmetry $A_{raw} \rightarrow A_{msr} \rightarrow A_{ep}$

From Raw Asymmetry to Measured Asymmetry:

- Different sources of false asymmetries are corrected for the raw asymmetry.
- The un-blinding factor are applied in the end.
- Each of the false asymmetry terms are associated with a systematic error.

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

(raw asymmetry) beam current position, angle, energy beamline background transverse leakage detector nonlinearity pre-radiator rescattering (un-blinding factor)

From Measured Asymmetry to Physics (ep scattering) Asymmetry:

$$A_{ep} = R_{det} R_{rc} R_{acc} R_{Q^2} \frac{\frac{A_{msr}}{P} - \sum_{i=1,3,4} f_i A_i}{1 - \sum_{i=1}^4 f_i}$$

- P: longitudinal polarization percentage
- A1, f1: Aluminum window asymmetry dilution
- f2: beamline background dilution
- A3, f3: neutral background dilution
- A4, f4: inelastic electron background
- R_{rc} : electromagnetic radiative correction
- R_{det} : detector analog response correction
- R_{acc} : acceptance correction
- R_{Q^2} : momentum transfer correction

Beam Current Asymmetry A_{BCM}

A_{BCM}

**Defined to be zero*

With rapid flipping of helicity states, the beam current fluctuates as well from state to state. This beam current asymmetry is the first step of false asymmetry removal, which is done by normalizing main detector signal to beam current measurement (180 uA).

Run Period	BCMs Utilized
Run 1	BCM5, BCM6
Run 2	BCM5, BCM6, BCM8

Take Run 2 for example:

- BCM5, BCM6 and BCM8 asymmetries are averaged.

$$A_{bcm} = \frac{A_{bcm5} + A_{bcm6} + A_{bcm8}}{3}$$

- Main detector is renormalized to the average of bcm5/6/8 at quartet level.

$$A_{MD}^{Renorm} = A_{MD} + A_{charge} - A_{bcm}$$

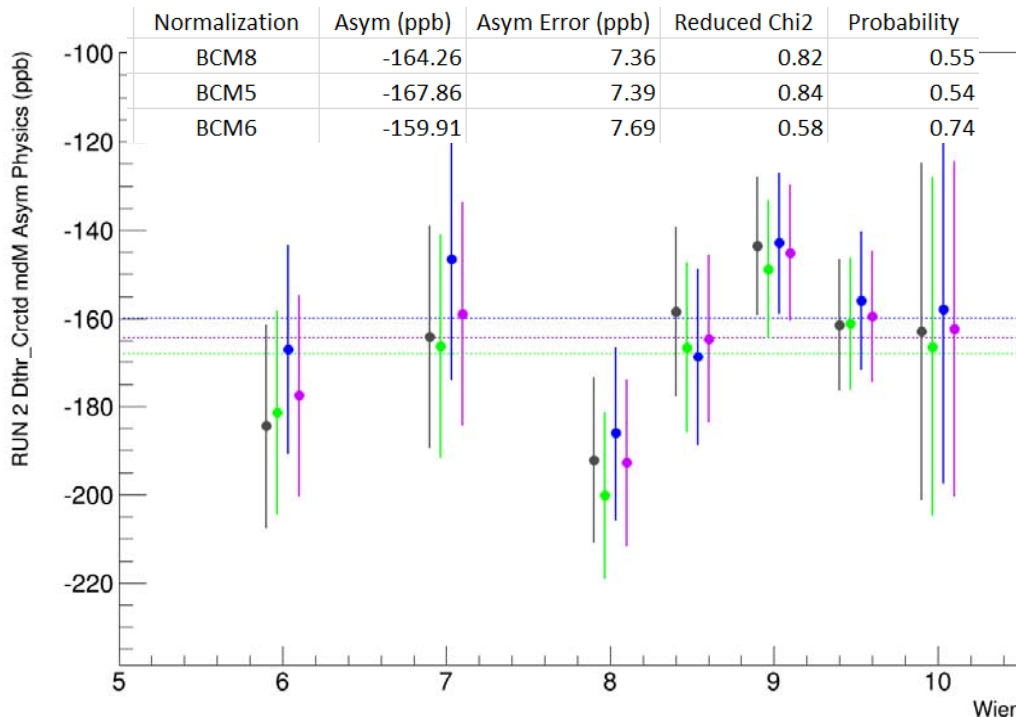
Beam Current Asymmetry Uncertainty dA_{BCM}

Assignment of BCM Systematic Error, dA_{BCM} . Introduced to cover the asymmetries from different BCMs.

$$\sigma_{syst}(A_{MD}^{Renorm}) = \frac{1}{\sqrt{n}} \sqrt{\frac{\sum (A_{MD}^{bcm} - A_{MD}^{Renorm})^2}{d}} - \sigma_{bcm}$$

- n , number of bcms.
- d , number of degrees of freedom.
- σ_{bcm} , BCM statistical noise.
- A_{MD}^{bcm} , MD asymmetries normalized to individual BCMs.
- A_{MD}^{Renorm} , MD asymmetry normalized to the average of BCMs.

Run 2 BCM Asymmetries vs Wien #



→ Different BCMs agree well in Run 2 of this experiment.

dA_{BCM} values:
Run 1 4.4 ppb
Run 2 2.1 ppb

Beam Correction A_{beam}

$$A_{beam} = - \sum_{i=1}^5 \left(\frac{\partial A}{\partial \chi_i} \right) \Delta \chi_i$$

Beam correction removes helicity correlated false asymmetries, including energy (E), position (X, Y) and angle (X', Y'), which are continuously measured by beam position monitors.

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

Helicity-correlated beam parameter differences for Run 1 and 2 and typical detector sensitivities.

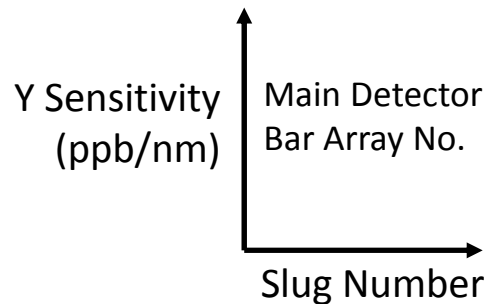
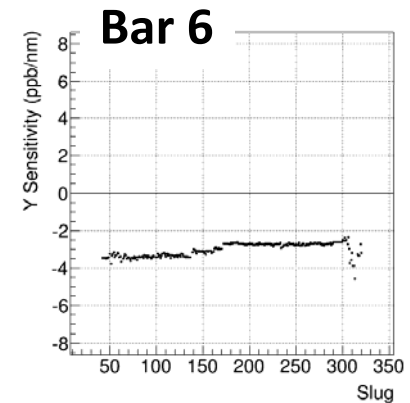
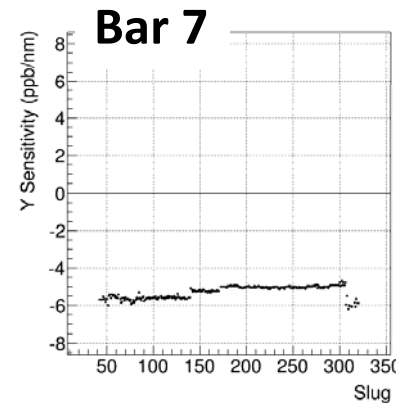
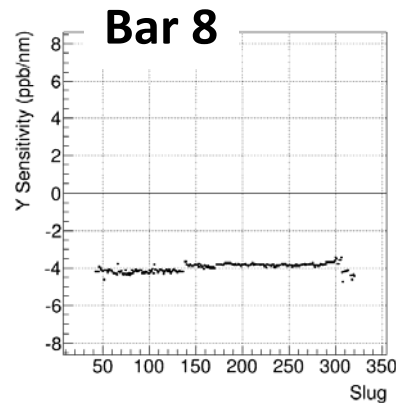
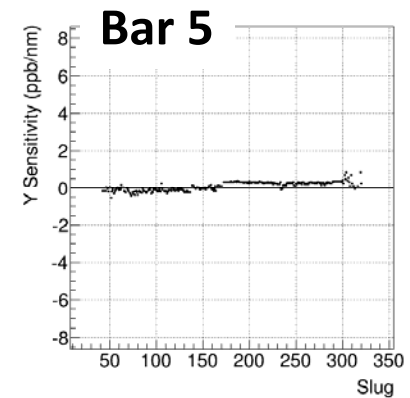
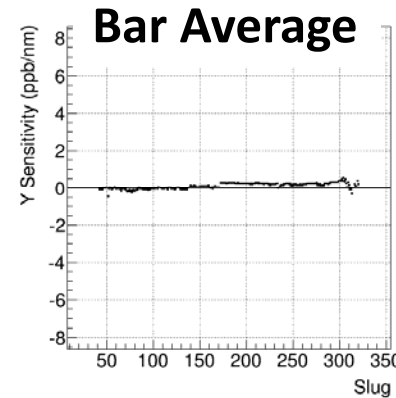
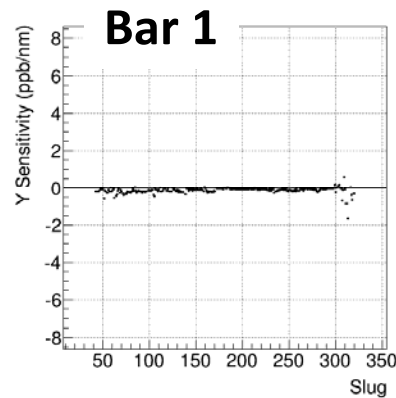
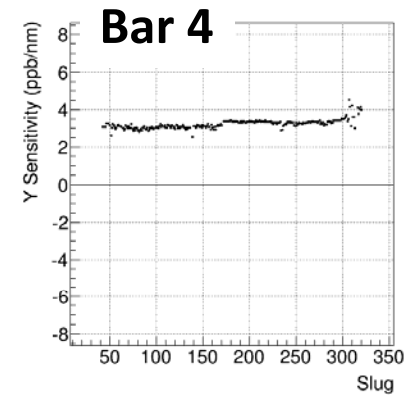
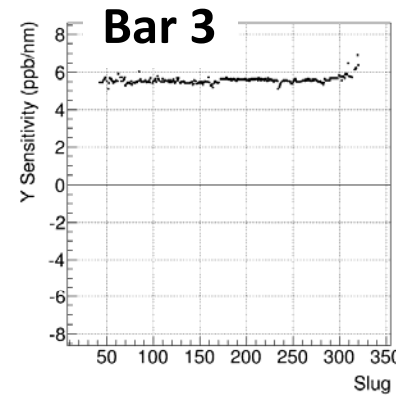
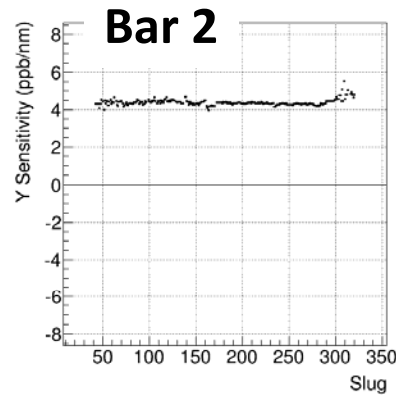
Detector sensitivity measurement:

- Deliberate, routine modulation of the beam parameters.
- A sinusoidal driving function at 125 Hz.
- Five independent modulation modes.

A_{beam} values:	
Run 1	18.5 ppb
Run 2	0.0 ppb

Detector Sensitivity

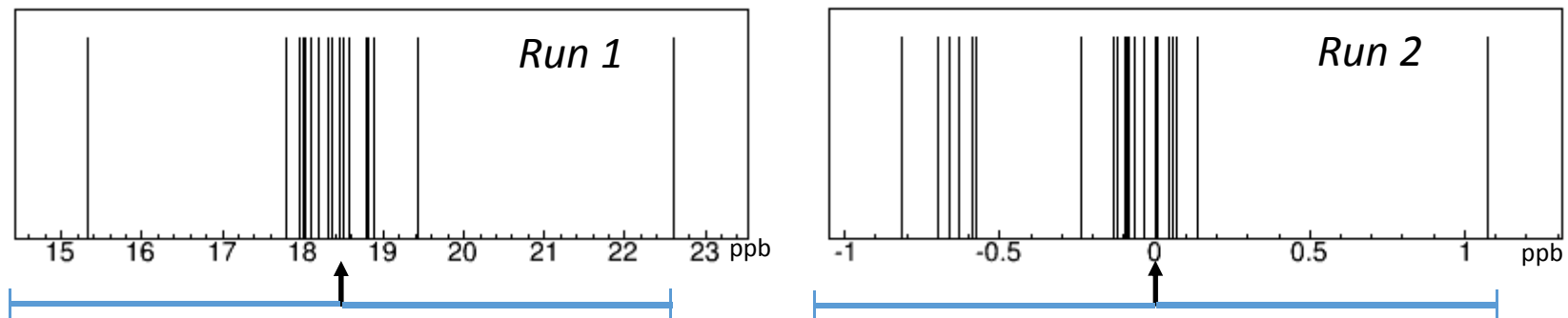
- Azimuthally symmetric detectors in eight directions.
- Directional sensitivity cancellation in detector average from opposite detector bars.
- Sensitivities are well measured – statistical uncertainty is negligible



Beam Correction Uncertainty dA_{beam}

- Beam stabilization feedback system interacted with beam modulation system.
- Result was additional modulation modes – a total of 11 different modes representing different combinations of the 5 beam parameters.
- Inconsistent results from this over-determined set of calibration data was taken as a measure of calibration uncertainty.

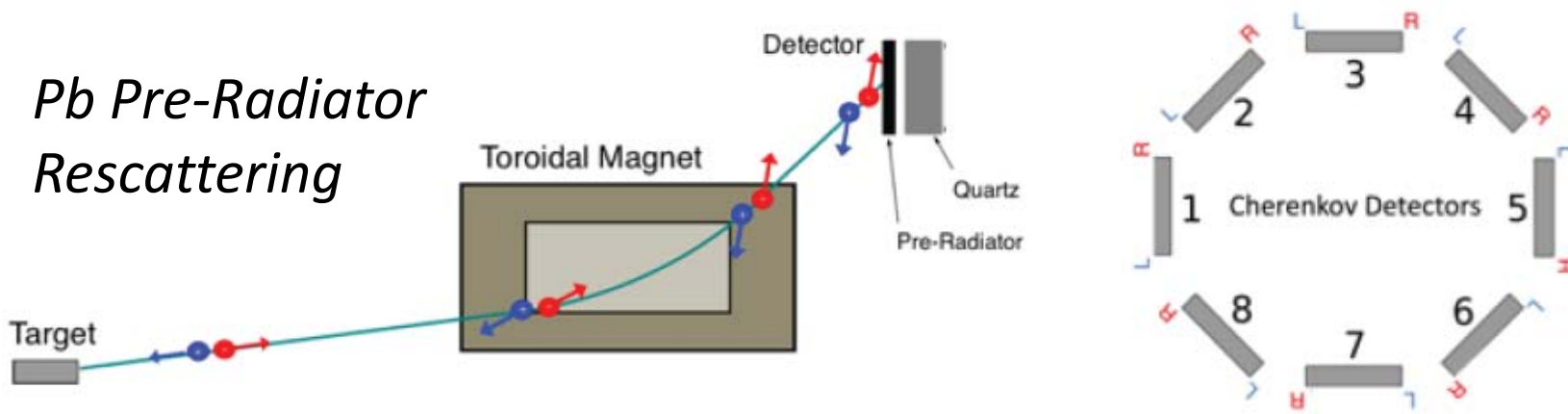
Various combination of calibration data find different net correction for beam parameters



This uncertainty in the calibration was the dominant component of the systematic uncertainty of corrections for helicity-correlated changes of beam parameters

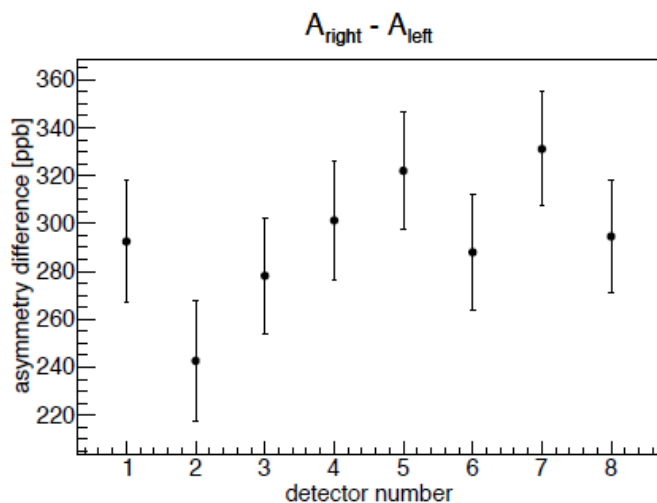
dA_{beam} values:
Run 1 4.1 ppb
Run 2 1.1 ppb

Rescattering Bias A_{bias}



- Spin precession of scattered electron in QTOR magnet
- Transverse polarization in front of Pb pre-radiator
- Rescattering in pre-radiator results in transverse asymmetry in detectors

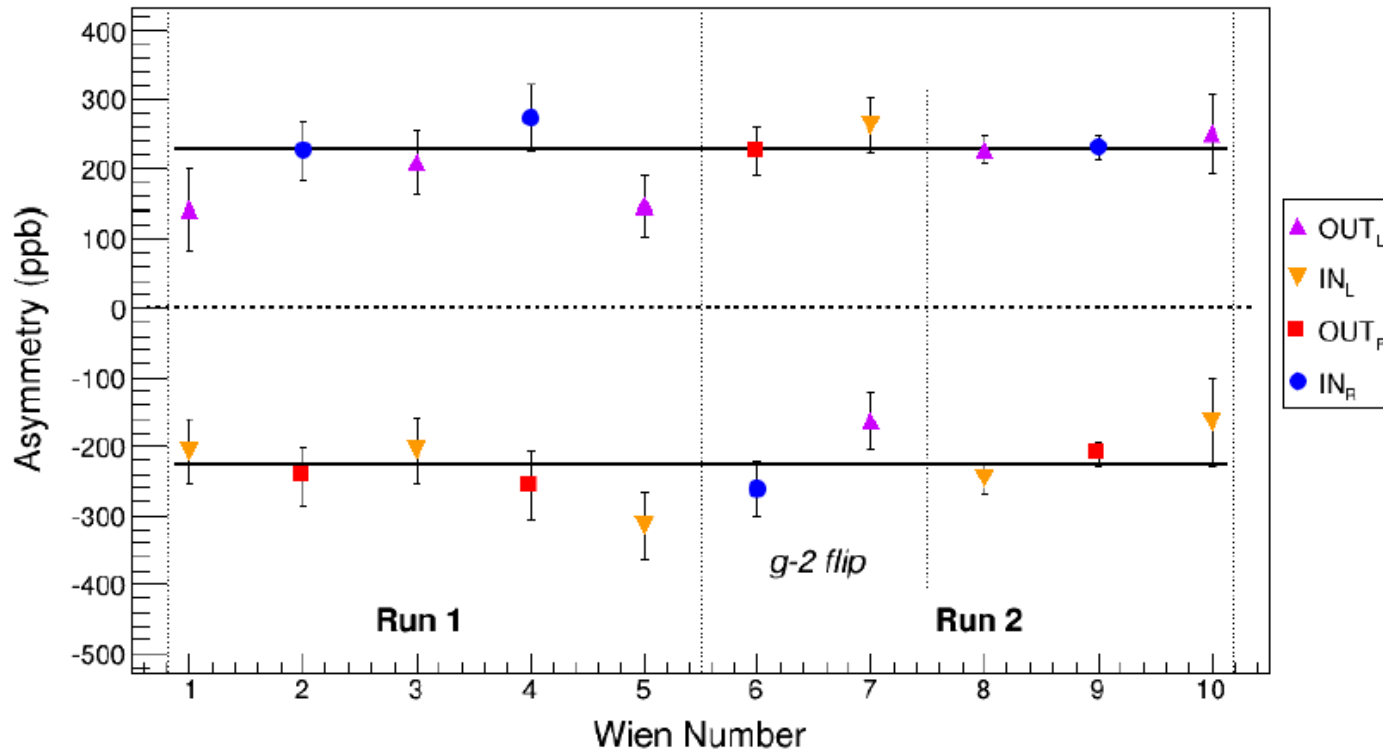
LH2 parity asymmetry + Pb transverse asymmetry → Different asymmetries in L and R PMTs



- To first order, this effect cancels
- Imperfect as-built apparatus lead to A_{bias} correction
- Uncertainty dominated by optical/mechanical imperfections.

A_{bias} values:
 4.3 ± 3.0 ppb

Asymmetry A_{ep} under Slow Reversals



- “IN or OUT” refer to status of HWP.
- Subscript denotes setting of Wien filter as “Left” or “Right”.
- Period of two pass accelerator running during g-2 spin flip configuration.

- The asymmetry flips sign under spin reversal of these techniques.
- Asymmetries are pretty constant from state to state. The error bar is statistical.
- The points with higher deviation can be accounted for with beam systematic errors.

NULL Asymmetry = -1.75 ± 6.51 ppb

→ consistent with zero. Good cancellation of asymmetries for different HWP+Wien states. Systematic false asymmetries suppressed under these techniques.

Most Significant Systematic Errors on the Asymmetry

Q_{weak} parity asymmetry. Statistical and systematic errors in Run 1 and Run 2:

Period	Stat. Unc. (ppb)	Syst. Unc. (ppb)	Tot. Uncertainty (ppb)
Run 1	15.0	10.1	18.0
Run 2	8.3	5.6	10.0

→ Run 1 and 2 were both statistics limited

The most significant systematic error contributions:

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	

→ Beam parameter related systematics are better controlled in Run 2 than Run 1.

As can happen when pushing the boundaries in precision:

Expected and planned for:

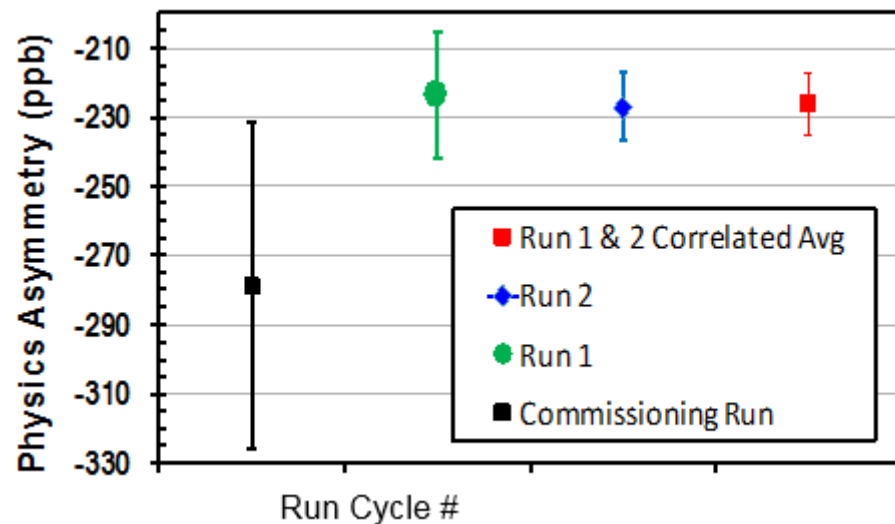
- Beam Asymmetries A_{beam}
- Aluminum target windows A_1

Unexpected but manageable

- Beamline background asymmetries A_{BB}
- Rescattering bias A_{bias}

Final Q_{weak} Asymmetry Results

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



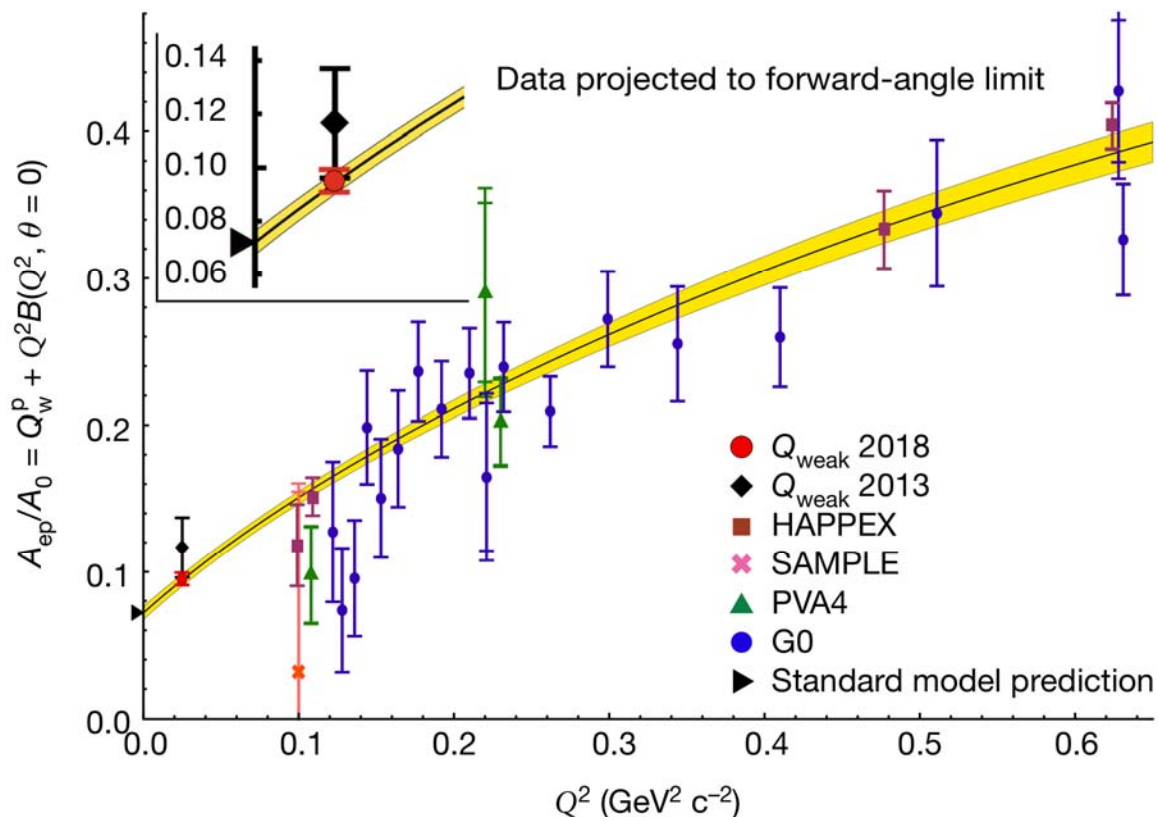
- Run 1 and Run 2 are combined with consideration of correlation between systematic errors of the two Run periods.
- Between Run 1 and Run 2, parts of the experiment were improved.
- Two Runs agree well, which gives confidence in the combined result.

Extraction of Q_{weak} from Parity Asymmetry

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

Global fit of world PVES data is done to extract the proton's weak charge, 33 entries in PVES database up to $Q^2 = 0.63 \text{ GeV}^2$

$$A_{ep} / A_0 = Q_w^p + Q^2 B(Q^2, \theta) \text{ with } A_0 = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}$$



- Q_{weak} + previous PVES data with higher Q^2 .
- Extrapolated to zero momentum transfer $Q^2=0$ to determine proton's weak charge Q_w^p .
- The Q_{weak} result has much smaller Q^2 and much higher, which dominates the near-zero fit and makes a good connection to Q_w^p .

Results Determined from $Q_{\text{weak}} A_{\text{ep}}$

	Quantity	Value	Error	Method
Global fit with Qweak & PVES	Q_W^p	0.0719	0.0045	$\left\{ \begin{array}{c} Q_{\text{weak}} A_{\text{ep}} \\ + \\ \text{PVES data base} \end{array} \right\}$
	$\sin^2\theta_W(Q=0.025)$	0.2382	0.0011	
	ρ_s	0.20	0.11	
	μ_s	-0.19	0.14	
	$G_A^{Z(T=1)}$	-0.64	0.30	

- World PVES data up to $Q^2=0.63 \text{ GeV}^2$
- Five free parameters, $C_{1u}, C_{1d}, \rho_s, \mu_s, G_A^{Z(T=1)}$
 - EM form factors (Arrington & Sick, PRC 76, 035201 (2007))
 - $G_A^{Z(T=0)}$ constrained by theory (Zhu, et al., PRD 62, 033008 (2000))
- All ep data corrected for E and Q^2 dependence of $\square_{\gamma Z}$
 - $\square_{\gamma Z}^V$: Hall et al., PLB753, 221 (2016). $\square_{\gamma Z}(Q)$: Gorchtein et al., PRC84, 015502 (2011).
 - $\square_{\gamma Z}^A$: Blunden et al., PRL107, 081801 (2011). $\Delta\square_{\gamma Z}^A$: Blunden et al., PRL109, 262301 (2012).

Results Determined from $Q_{\text{weak}} A_{\text{ep}}$

	Quantity	Value	Error	Method
Including ^{133}Cs APV result for neutron weak charge extraction & Separation of C_{1u} , C_{1d} quark couplings	Q_W^p	0.0719	0.0045	$\left\{ \begin{array}{c} Q_{\text{weak}} A_{\text{ep}} \\ + \\ \text{PVES data base} \end{array} \right\}$
	$\sin^2\theta_W(Q=0.025)$	0.2382	0.0011	
	ρ_s	0.20	0.11	
	μ_s	-0.19	0.14	
	$G_A^{Z(T=1)}$	-0.64	0.30	
	Q_W^p	0.0718	0.0044	$\left\{ \begin{array}{c} Q_{\text{weak}} A_{\text{ep}} \\ + \\ \text{PVES data base} \\ + \\ \text{APV } ^{133}\text{Cs} \end{array} \right\}$
	C_{1u}	-0.1874	0.0022	
	C_{1d}	0.3389	0.0025	
	Q_W^n	-0.9808	0.0063	
	C_1 correlation = -0.9318			

- $Q_W(^{133}\text{Cs}) = -72.62 \pm 0.43$ (PDG2016 EW Review)
 - ^{133}Cs experiment: Wood, et al., Science 275, 1759 (1997)
 - ^{133}Cs atomic corrections: Ginges & Flambaum, Phys. Rep. 397, 63 (2004)

Results Determined from $Q_{\text{weak}} A_{\text{ep}}$

Quantity	Value	Error	Method
Q_W^p	0.0719	0.0045	$\left\{ \begin{array}{l} \text{Qweak } A_{\text{ep}} \\ + \\ \text{PVES data base} \end{array} \right\}$
$\sin^2\theta_W(Q=0.025)$	0.2382	0.0011	
ρ_s	0.20	0.11	
μ_s	-0.19	0.14	
$G_A^{Z(T=1)}$	-0.64	0.30	
Q_W^p	0.0718	0.0044	$\left\{ \begin{array}{l} \text{Qweak } A_{\text{ep}} \\ + \\ \text{PVES data base} \\ + \\ \text{APV } ^{133}\text{Cs} \end{array} \right\}$
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Q_W^n	-0.9808	0.0063	
C_1 correlation	= -0.9318		
Q_W^p	0.0685	0.0038	$\left\{ \begin{array}{l} \text{Qweak } A_{\text{ep}} \\ + \\ \text{PVES data base} \\ + \\ \text{LQCD (strange)} \end{array} \right\}$
$\sin^2\theta_W(Q=0.025)$	0.2392	0.0009	

Strange quark constraints from Lattice QCD further improves the precision of Q_W^p & $\sin^2\theta_W$

LQCD: Green, et al., PRD **92**, 031501 (2015)

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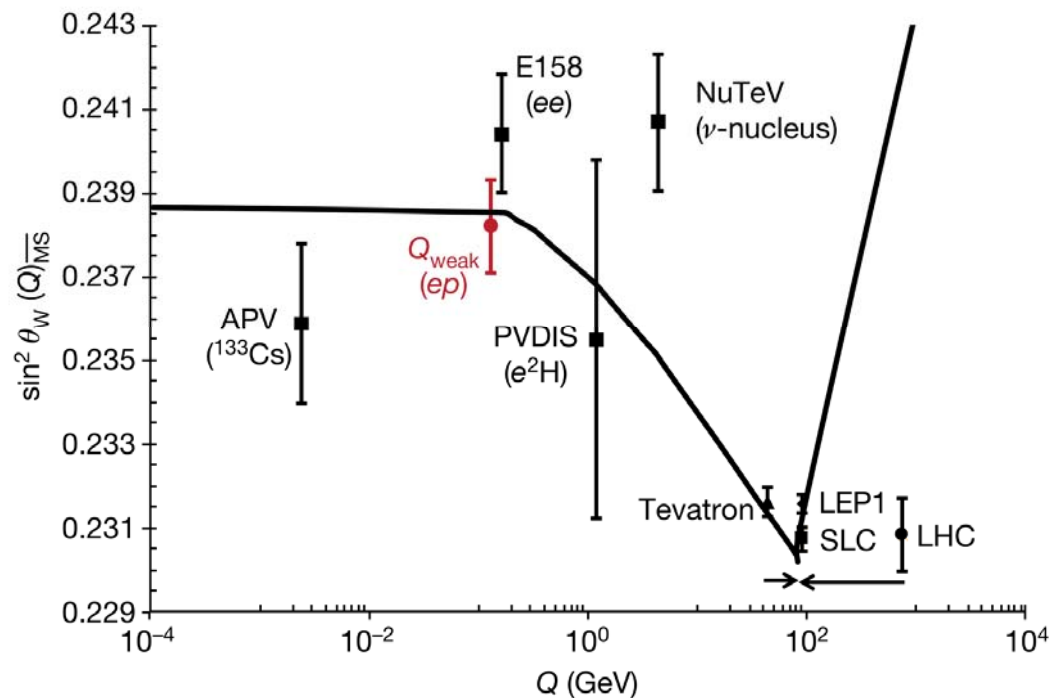
Alternate
"Standalone"
technique to extract
 Q_W^p

Q_W^p	0.0706	0.0047	$\left\{ \begin{array}{c} Q_{\text{weak}} A_{\text{ep}} \\ + \\ \text{EMFF's \& theory axial FF} \\ + \\ \text{LQCD (strange)} \end{array} \right\}$
EMFFs: Arrington & Sick, PRC 76, 035201 (2007) Axial FF: Liu McKeown & Ramsey-Musolf, PRC 76, 025202 (2007) Strange FF: Green, et al., PRD 92, 031501 (2015)			

Running of Weak Mixing Angle $\sin^2\theta_W$

The determination of Q_W^p can be used to test the weak mixing angle, a fundamental electroweak parameter of SM.

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



- The $Q_{\text{weak}}(ep)$ results lies about 1.2 sigma below E158 with Moller scattering (ee).
- Some new physics theories are suppressed at Z resonance, like the dark photon model which allows multi-hundred MeV dark Z mediator at low Q. LEP/SLC mass limits $\sim < \text{TeV}$, while low energy observables probe few TeV scale.

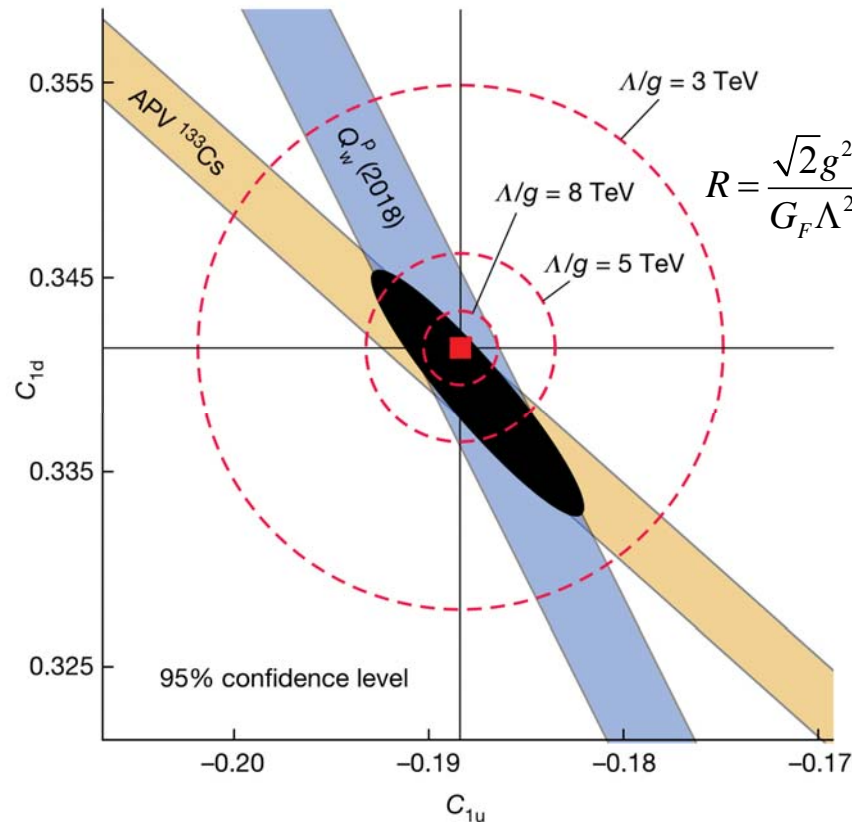
Limits on New Physics at TeV Scales

Standard Model of axial e and vector q neutral interaction + BSM Particle interaction:

$$\mathcal{L}_{\text{NC}}^{\text{eq}} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C_{1q} \bar{q} \gamma^\mu q + \mathcal{L}_{\text{NP}}^{\text{PV}} = -\frac{g^2}{\Lambda^2} \bar{e} \gamma_\mu \gamma_5 e \sum_q h_V^q \bar{q} \gamma^\mu q$$

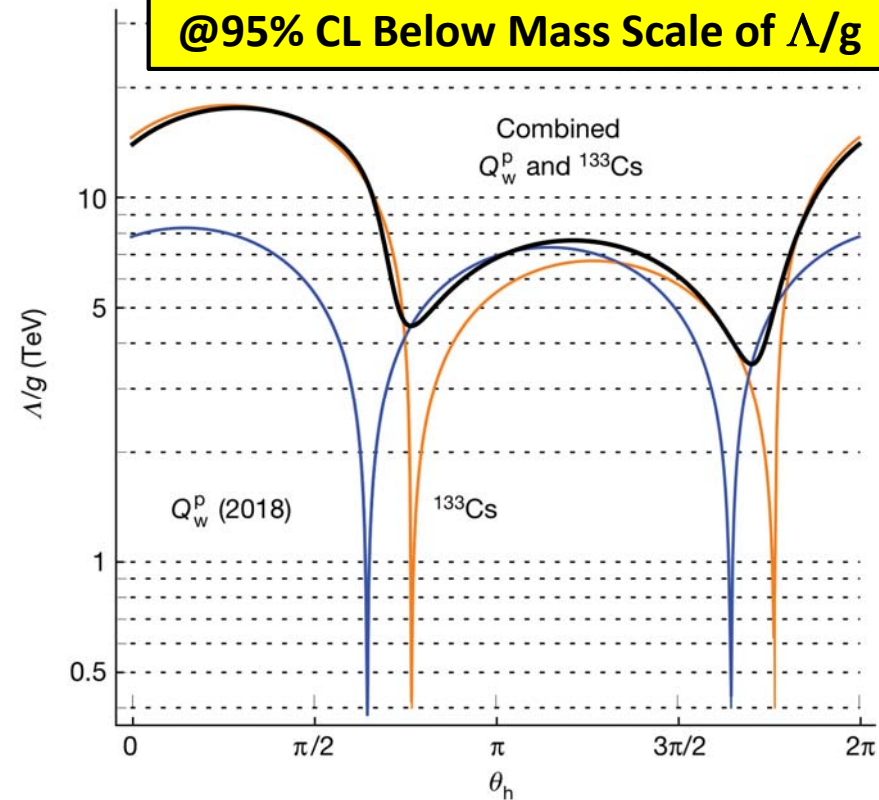
$$Q_W^{\text{P}} = -2(2C_{1u} + C_{1d})$$

$g = \text{coupling}$ $\Lambda = \text{mass scale}$ $h_V^u = \cos \theta_h$ $h_V^d = \sin \theta_h$



Standard model red square in the center.
Dashed contours indicate value of $\Lambda/g = 3, 5, \text{ and } 8 \text{ TeV}$.

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



θ_h is "flavor mixing angle" for new physics at value Λ/g mapped around experimental boundaries.

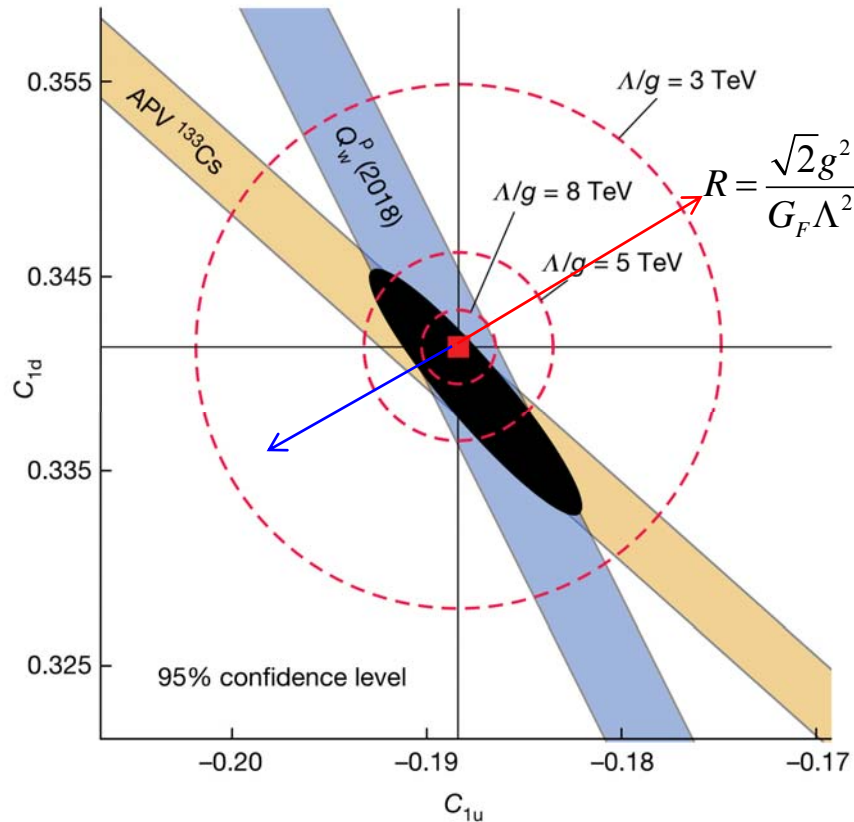
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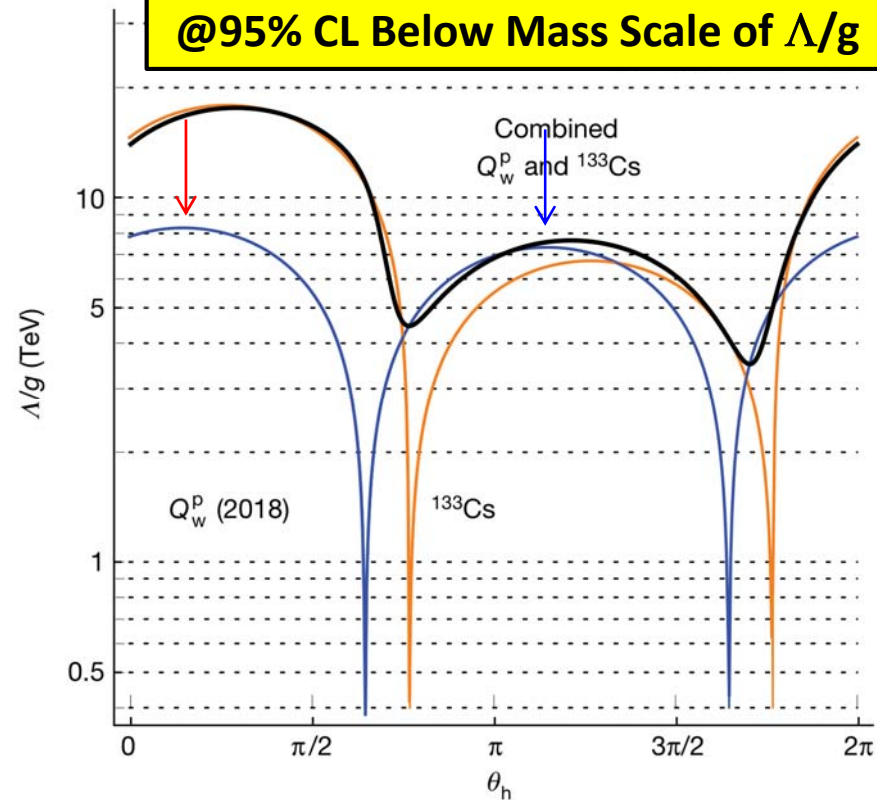
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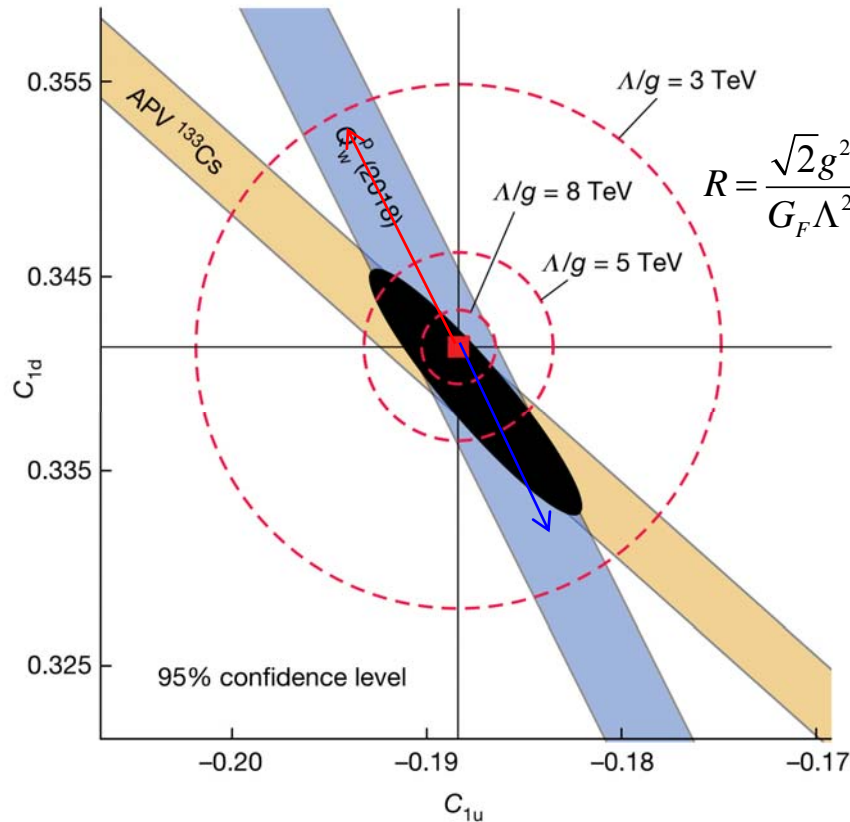
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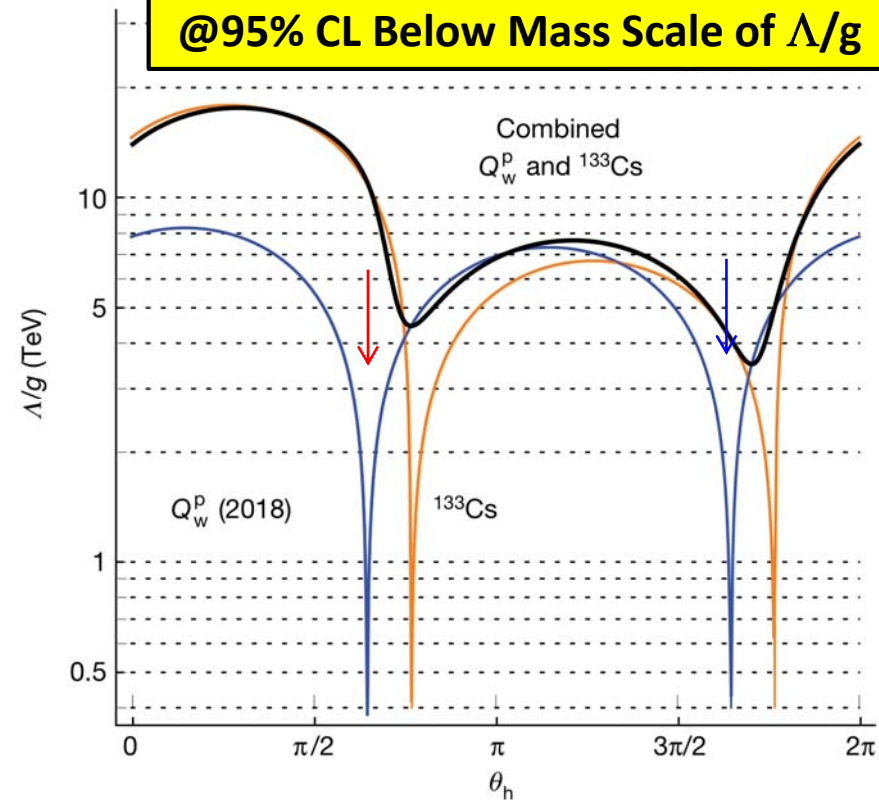
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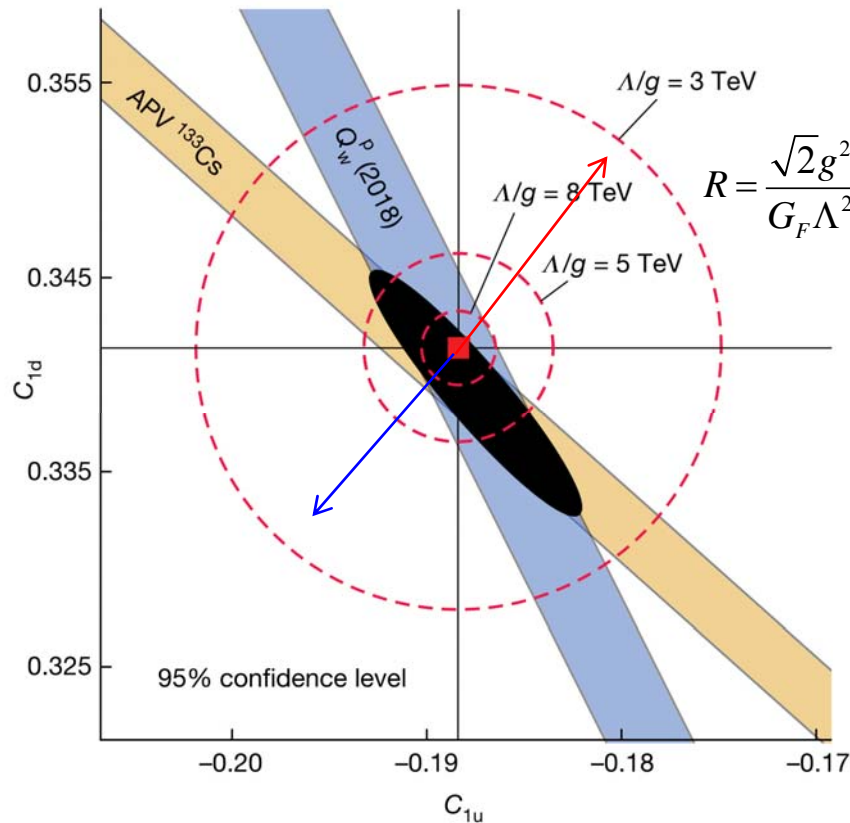
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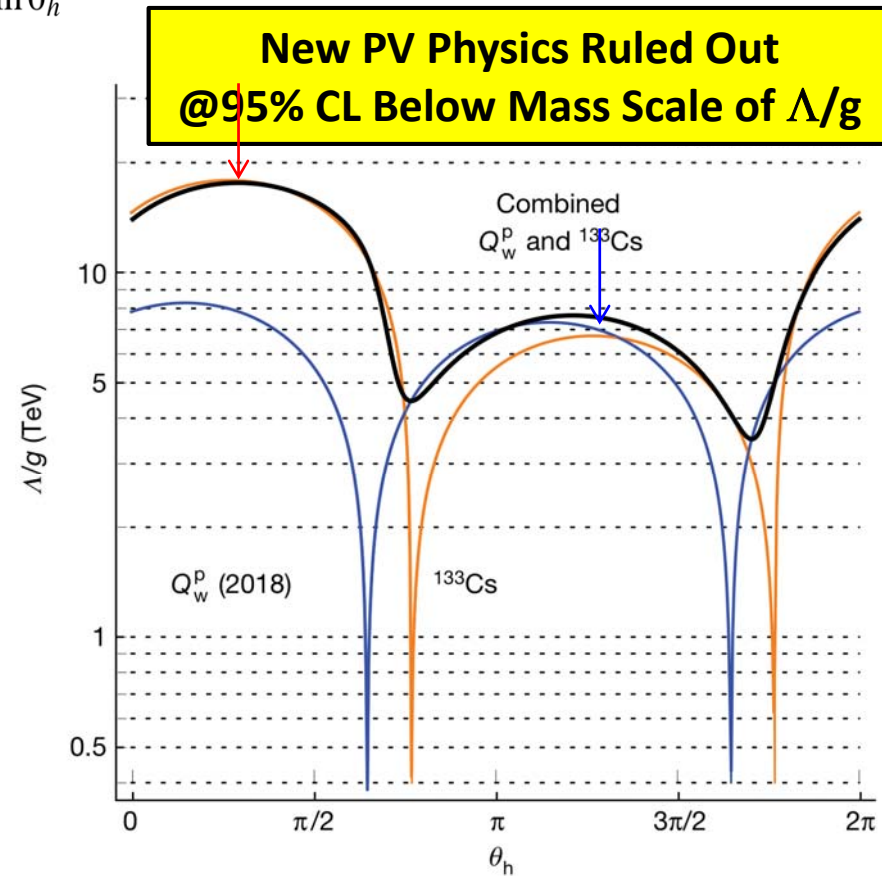
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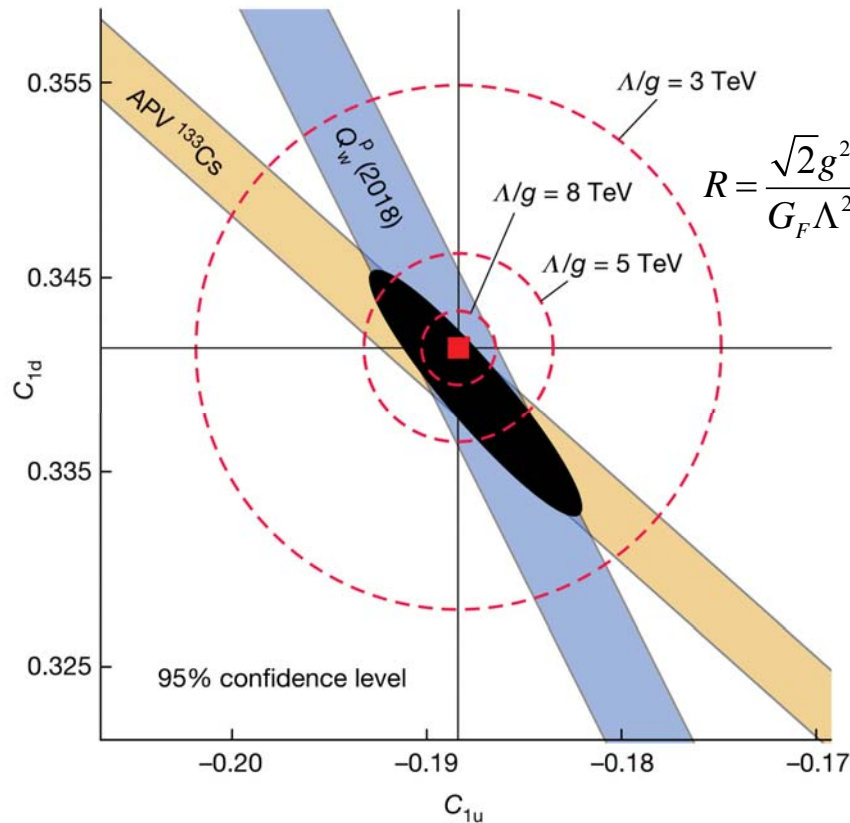
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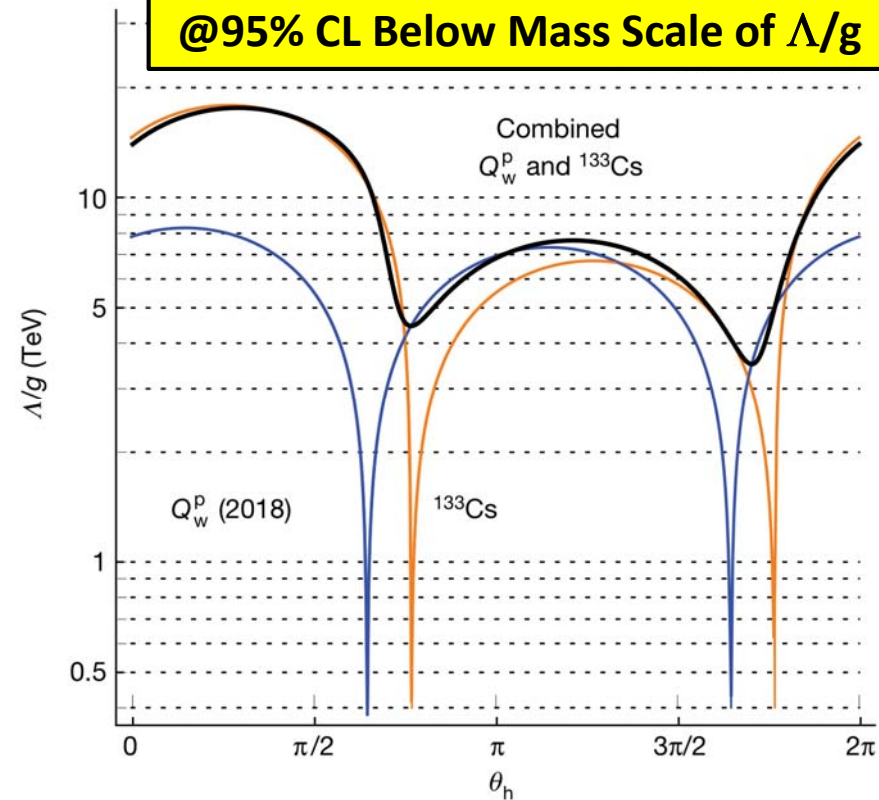
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@95% CL Below Mass Scale of Λ/g**



θ_h is "flavor mixing angle" for new physics at value Λ/g mapped around experimental boundaries.

Conclusion

Q_{weak} experiment measures the proton's weak charge via precision parity-violating e-p scattering.

$$A_{ep} = -226.5 \pm 7.3(\text{stat}) \pm 5.8(\text{syst}) \text{ ppb at } \langle Q^2 \rangle = 0.0249 \text{ (GeV/c)}^2$$
$$Q_W^p(\text{this expt.}) = 0.0719 \pm 0.0045 \quad Q_W^p(\text{SM}) = 0.0708 \pm 0.0003$$

- Total uncertainty achieved (9.3 ppb) sets a new level of precision for PVES from a nucleus.
- Measured proton weak charge agrees well with Standard Model.
- Bounds on new neutral current semi-leptonic PV physics:
 - mass/coupling scales of heavy new physics ruled out at $\Lambda/g < 7.5 \text{ TeV}$ at 95% CL.
 - Will play a role in future analyses of bounds (or discoveries) of a variety of new physics
- Pushed existing boundaries on many fronts and provides scientific and technical developments for next generation of measurements

The Qweak Collaboration

101 collaborators 26 grad students
11 post docs 27 institutions

Institutions:

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- 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
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Spokespersons Project Manager Grad Students

