# The Qweak Experiment

*A Search for New PV Physics at the TeV Scale*
*via High Precision Measurement of the Proton's Weak Charge*

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(for the Qweak Collaboration)

# Overview

- Qweak determines $Q^p_W$ and $\sin^2\theta_W$ to high precision via measuring parity-violation asymmetry (~300 ppb) in e-p elastic scattering at low $Q^2$ (0.0248 $GeV^2$)

*Deviations from Standard Model predictions would be sensitive to PV semi-leptonic physics beyond the SM*

- Qweak Ran in Hall C with two run periods during 2010 - 2012

- Commissioning data (~4% of total dataset) was published in **PRL 111, 141803 (2013)**

- Data were unblinded last March

- Results out of full analysis were released last September

*This will lead to a publication soon!*

# Search for Physics beyond the Standard Model

- The Standard Model (SM)

  - A successful low energy effective theory of more fundamental physics, yet incomplete

- Two complimentary approaches in testing SM and searching for new physics

  - Direct searches for new particles at high energy (e.g. LHC)
  - Indirect searches to test the SM via precision measurements at low energy (e.g. PVES, including Qweak)

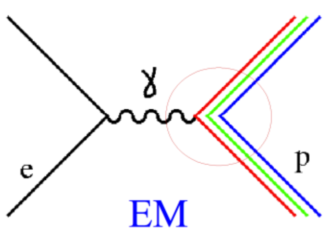
**The Qweak Experiment**
- Elastic scattering of electron beam from proton target ($\vec{e}+p \rightarrow \vec{e}+p$)
- Measure significantly suppressed SM observable ($Q_W(p)$) to high precision
- Sensitive search for new physics at TeV mass scale

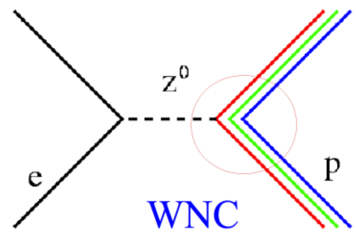
# Proton's Weak Charge in the Standard Model

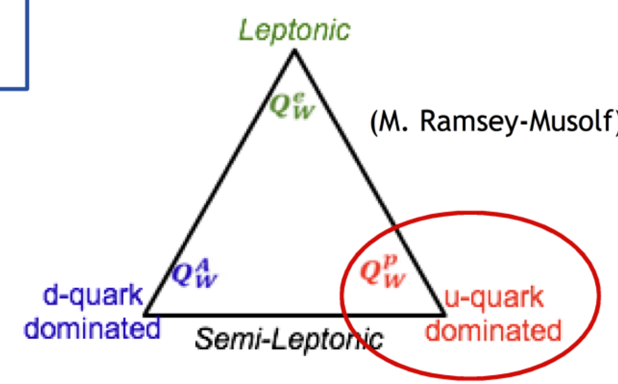
Weak charges - neutral current analog to the electric charges

| 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) | $0$ | $Q_W^n = -1$ |

*The accidental suppression of $Q^p_W$ and $Q^e_W$ in the SM makes them sensitive to new physics!*



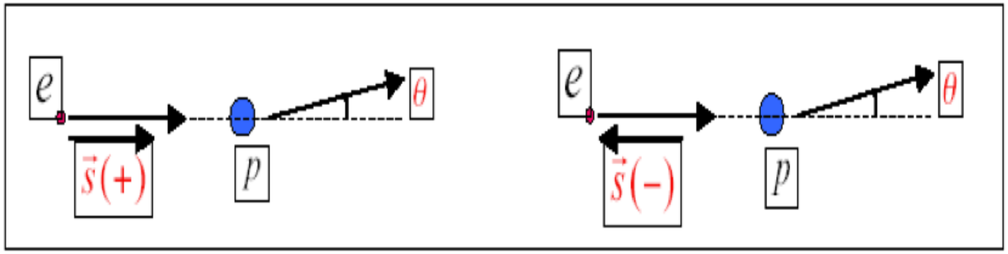

$$Q_W^p = -2(2C_{1u} + C_{1d})$$
$$Q_W^n = -2(C_{1u} + 2C_{1d})$$

- Qweak completes the low $Q^2$ "weak charge triad" by adding a precision measurement of $Q^p_W$ to APV and Møller

- At tree level, $Q^p_W = 1 - 4\sin^2\theta_W$ ( $\theta_W$ - weak mixing angle); Qweak can lead to a high precision test of $\sin^2\theta_W$ at low energy

# Parity Violating Electron Scattering

- Scatter electrons of opposite helicity from an unpolarized target




right-handed e⁻ beam    left-handed e⁻ beam

- The scattering process: EM + WNC


Electromagnetic (PC) + Neutral-weak (PV)

$$\sigma \propto |\mathcal{M}^{EM}|^2 + 2\,\mathcal{M}^{EM}\mathcal{M}^{NC}_{PV} + \left|\mathcal{M}^{NC}_{PV}\right|^2$$

- The interference term gives rise to a parity-violating asymmetry

$$A_{PV}(p) = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{\mathcal{M}^{NC}_{PV}}{\mathcal{M}^{EM}} \propto \frac{Q^2}{M_Z^2} \quad \text{when } Q^2 \ll M_Z^2$$

~ -200 ppb

# Extraction of the Proton's Weak Charge

The PV asymmetry in e-p elastic scattering:

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

At Qweak kinematics ($Q^2 \rightarrow 0$ and $\theta \rightarrow 0$):

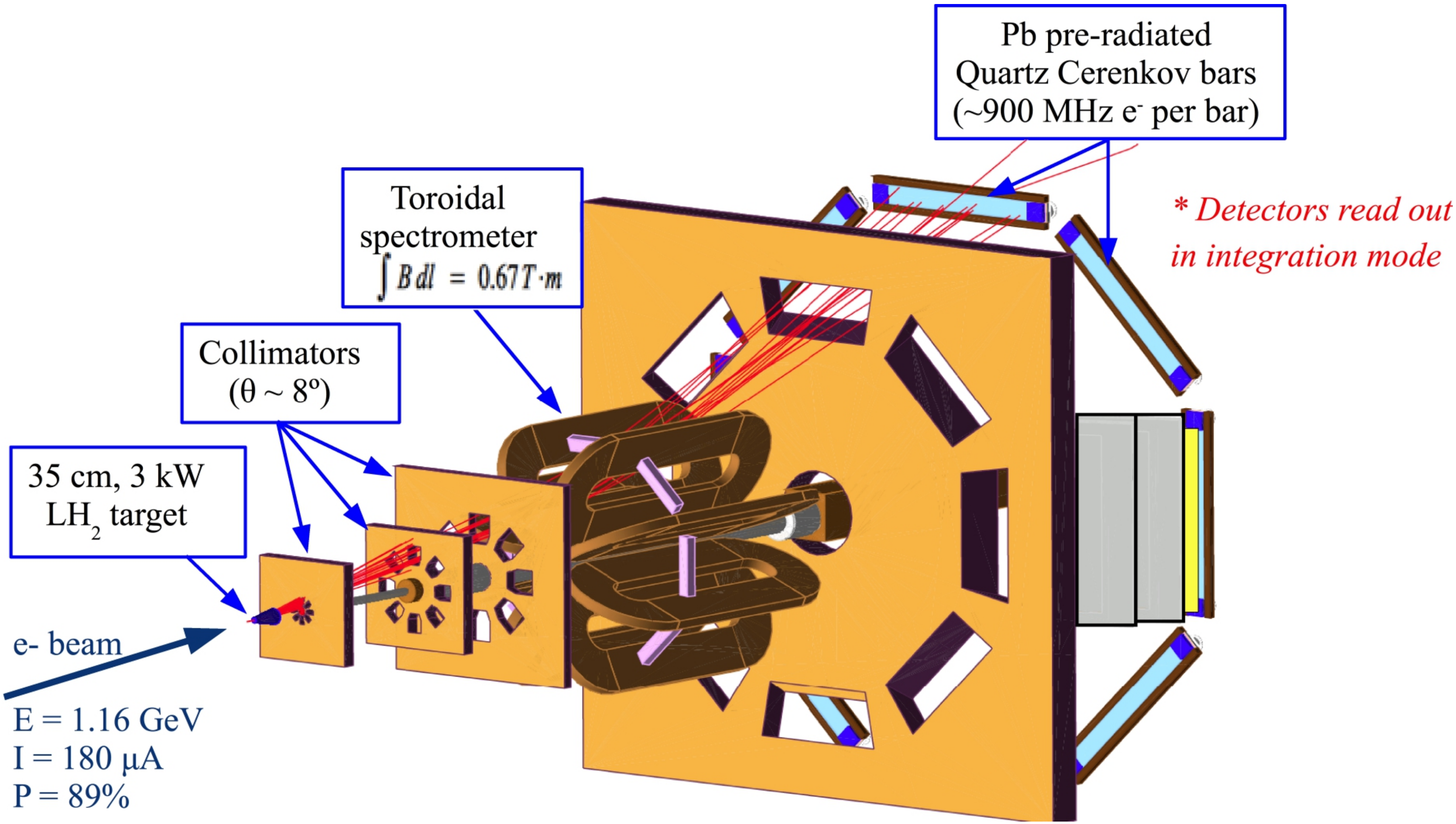
*The $Q^p_W$ term dominates the total asymmetry (~2/3)*

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

Proton's weak charge
($Q^p_W = 1 - 4\sin^2\theta_W$ at tree level)

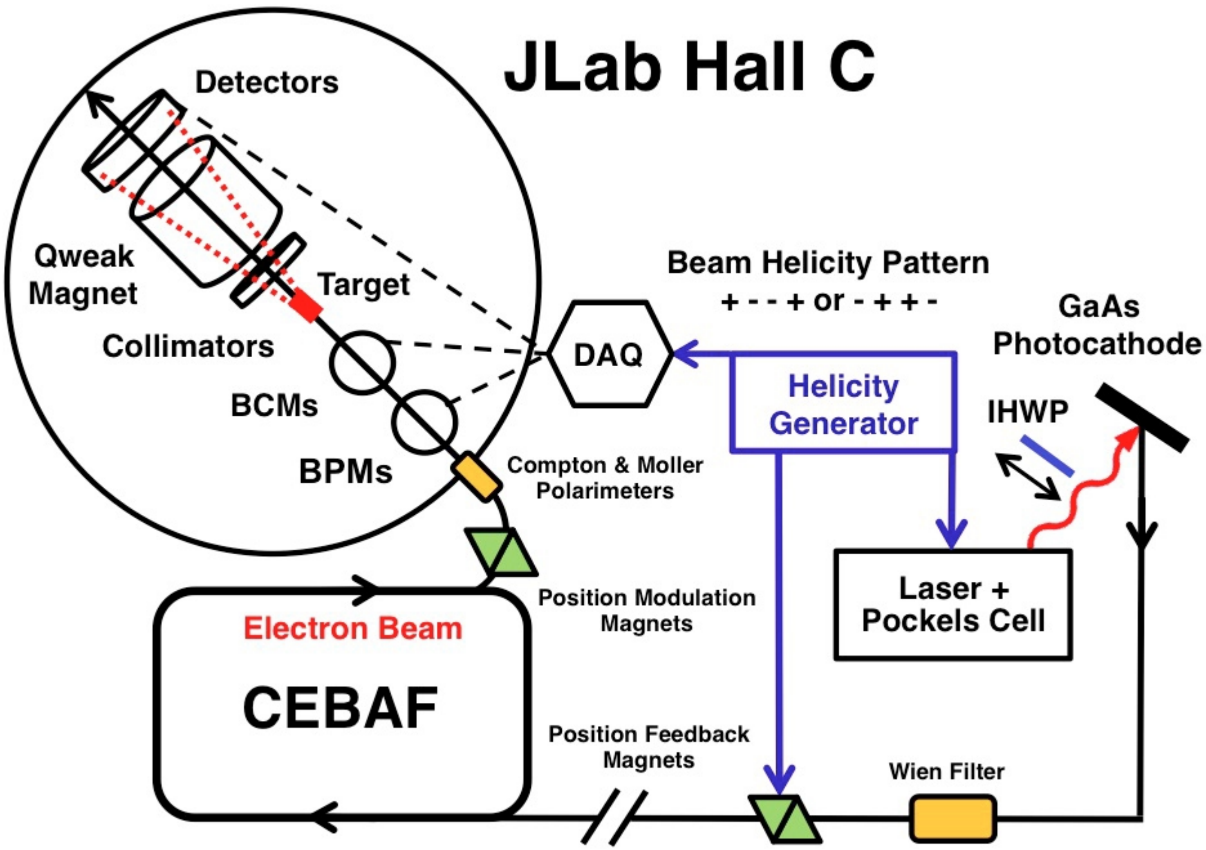
Hadronic structure - contains $G^\gamma_{EM}$ & $G^Z_{EM}$ form factors, well determined by existing higher $Q^2$ PVES data

# Qweak Apparatus




[T. Allison et al. Nuclear Instruments and Methods in Physics Research A 781 (2015) 105-133]

# Multiple Helicity Reversals




**Three independent techniques for helicity reversal of $e^-$ beam:**

**Rapid pseudo-random reversal (960/sec):**
Rejects $LH_2$ target "boiling noise".

**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.

**Also as check construct NULL:**
"out-of-phase" quantity from the two slow reversal techniques to bound unaccounted for false asymmetries.

# From Raw Asymmetry to Physics Asymmetry

**STEP 1: Measure $A_{raw}$**

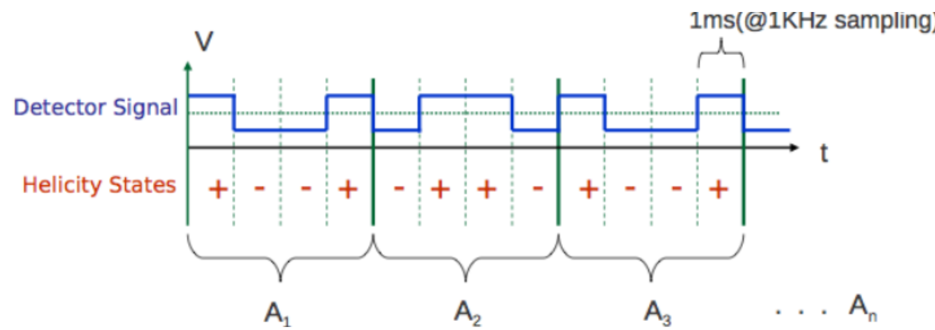
- Integrate detector signal (S) over each helicity state and normalized to beam charge (Q)

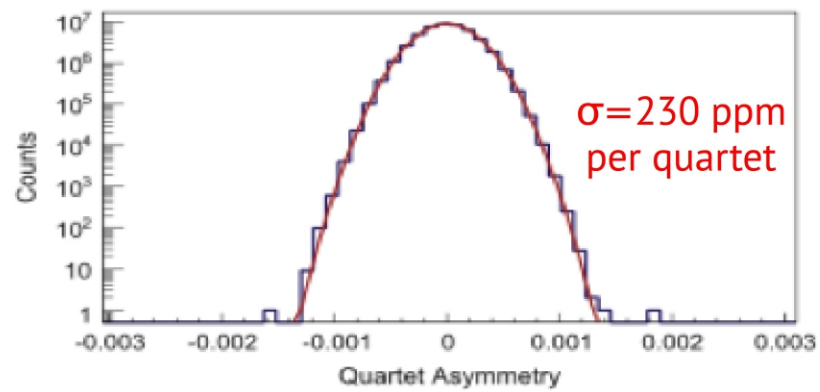
$$Y = S / Q$$

- Calculate asymmetries for each quartet pattern

$$A_{raw} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

*(Blinding analysis applied)*




**STEP 2: Correct $A_{raw}$ for measured false asymmetries**

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

**STEP 3: Correct $A_{msr}$ for polarization, backgrounds, acceptance, etc**

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

where $R_{\rm tot} = R_{\rm RC} R_{\rm Det} R_{\rm Acc} R_{Q^2}$.

- Largest correction is from Al target windows
- $A_{bias}$ contribute large error to $A_{ep}$

# Aluminum Target Window Backgrounds

Dilution fraction ($f_{Al}$)

- Directly measured with empty target

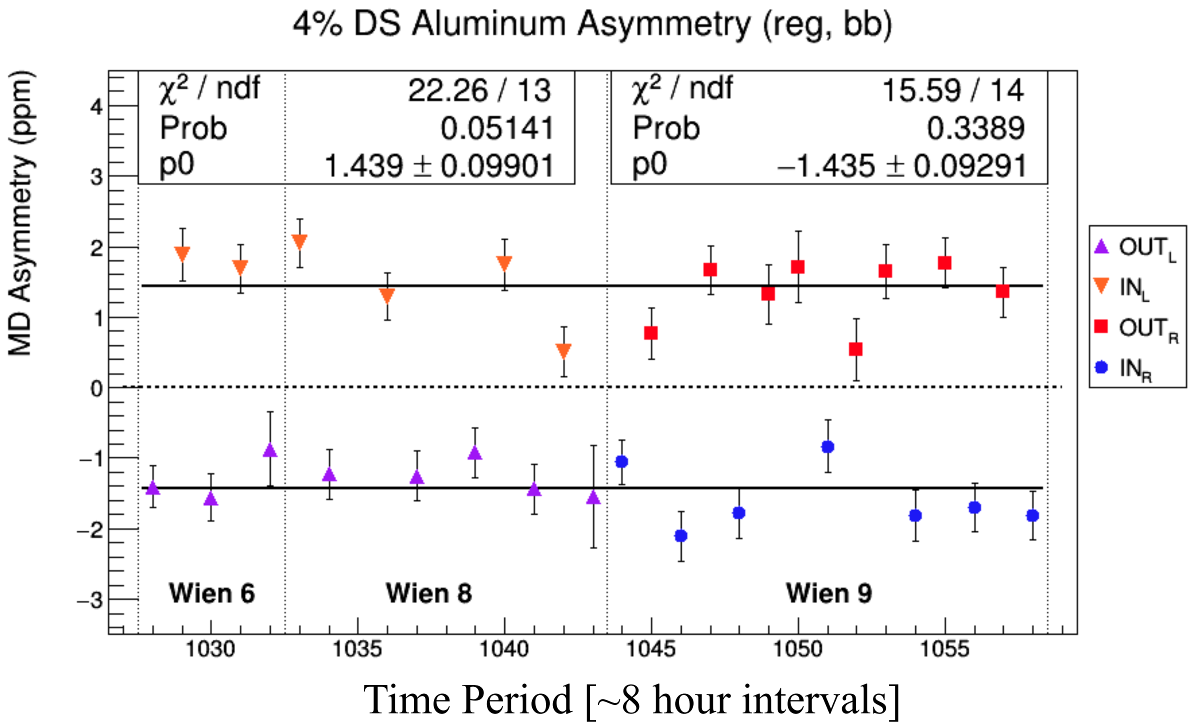
Asymmetry ($A_{Al}$)

- Directly measured from thick Al "dummy" target

(Corrections for effects of $H_2$ made using simulation and data driven models of elastic and quasi-elastic scattering)

**IHWP – IN or OUT**
**Wien Filter – L or R**

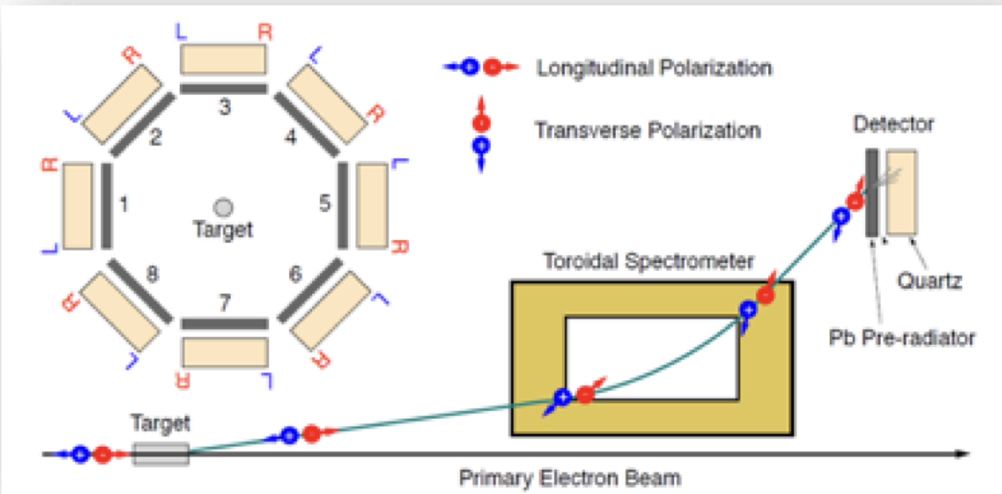
*Sign correction for slow reversals and further systematic corrections are needed to extract physics asymmetry for Al*

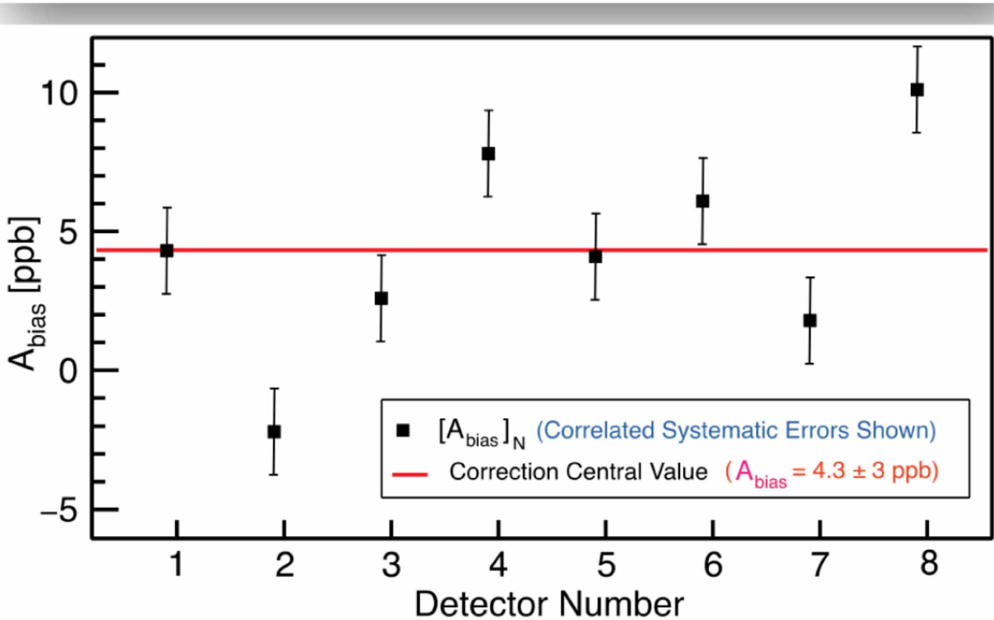



$f_{Al} \sim 2.5\%$ $A_{Al} = 1515 \pm 77$ ppb

Resulting in a -38 ppb correction to the hydrogen asymmetry (20%)

# Detector Optical Imperfections: $A_{bias}$ Systematic



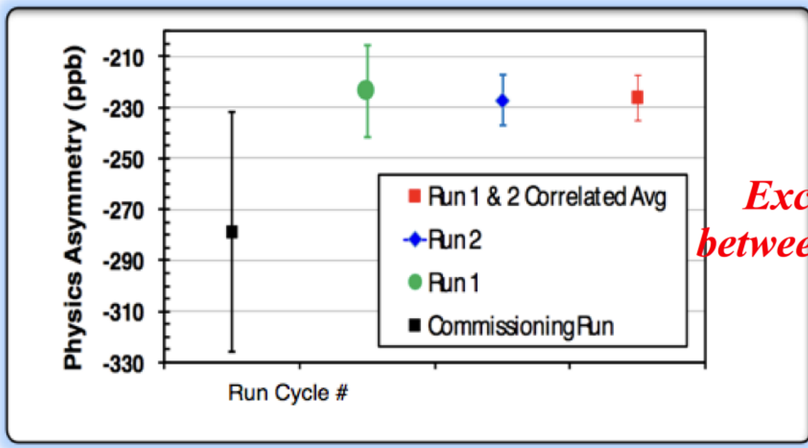




- Small residual non-cancellation of L/R transverse scattering from Pb pre-radiators in front of quartz bars
- The effect is dominated by optical & mechanical imperfection of the as-built apparatus, not details of the Pb analyzing power
- GEANT simulations and models tied to our asymmetry and light yield data were used to determine $A_{bias}$

| **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** |

# Final $A_{ep}$ & Uncertainty Contributions

| 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 |




*Excellent agreement between Run 1 and Run 2*

- Run 1 & Run 2 are both statistics limited

- Systematic contributions for Run 1 & Run 2 are different due to different run conditions; Run 2 shows much better systematics

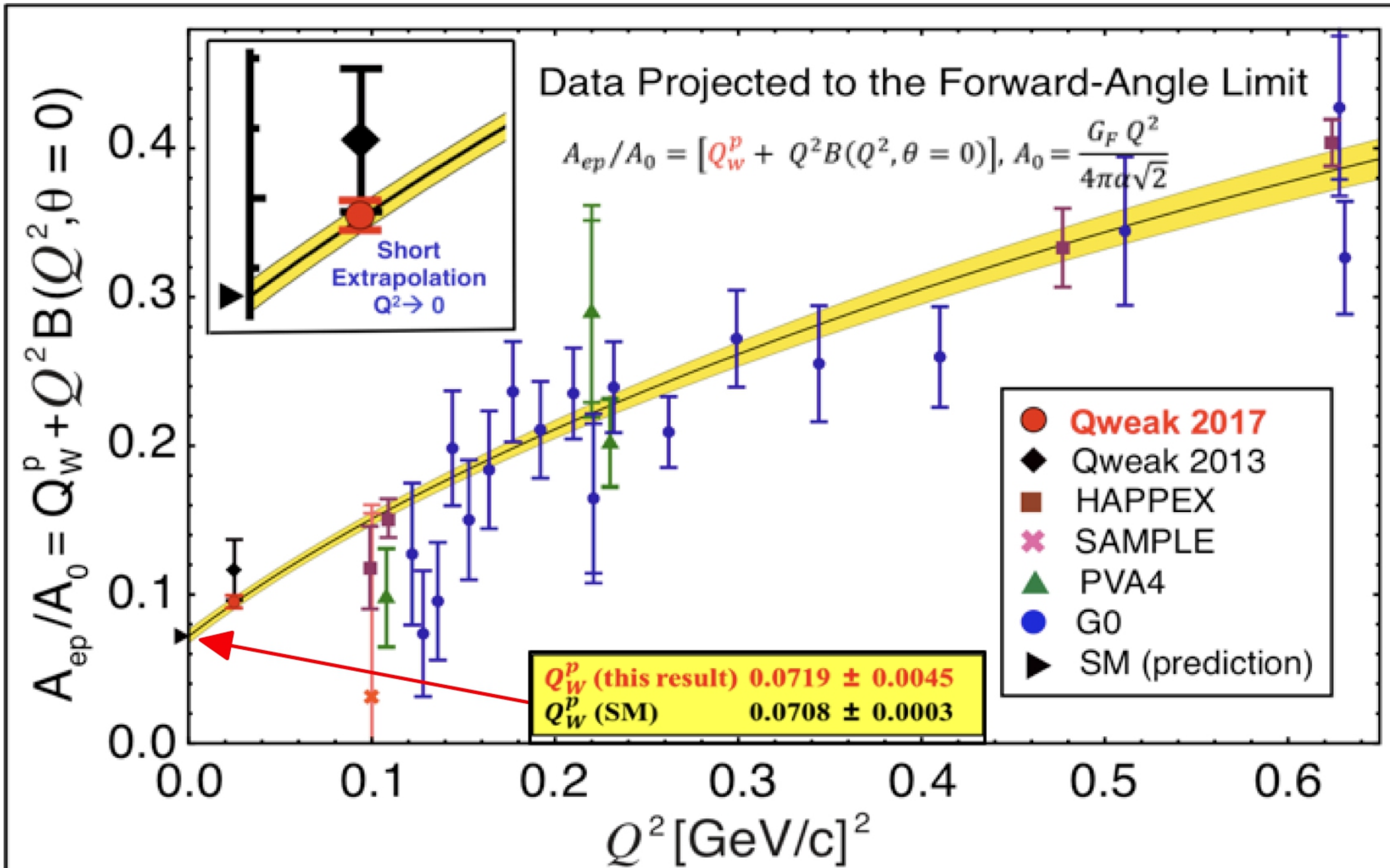
- All significant systematic effects are accounted for and corrected

| 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 | |

**Experiment NULL Asymmetry**
(slow helicity reversals out-of-phase)
**Weighted Avg = -1.75 ± 6.51 ppb**

# $Q^p_W$ Determination

**Method - global fit of PVES data extrapolated to $Q^2 = 0$** [R.D. Young et al. PRL 99, 122003]



# Results Determined from Qweak $A_{ep}$

***Provide data-driven constraint on $B(Q^2)$ term***

| Quantity | Value | Error | Method |
|---|---|---|---|
| $Q_W^p$ | 0.0719 | 0.0045 | |
| $\sin^2\theta_W$ | 0.2382 | 0.0011 | Qweak $A_{ep}$ + PVES data base |
| $\rho_s$ | 0.19 | 0.11 | |
| $\mu_s$ | -0.18 | 0.15 | |
| $G_A^{Z(T=1)}$ | -0.67 | 0.33 | |

- Use world PVES data up to $Q^2 = 0.63\ (\text{GeV}/c)^2$
- Use five free parameters: $C_{1u}$, $C_{1d}$, $\rho_s$, $\mu_s$ & $G_A^{Z(T=1)}$
  - EM form factors from [Arrington & Sick, PRC 76, 035201 (2007)]
  - $G_E^S$, $G_M^S$ and $G_A^{Z(T=1)}$ use a dipole form: $(1-Q^2/\lambda^2)^{-2}$, with $\lambda = 1$ GeV/c
  - $G_A^{Z(T=0)}$ is small, constrained by theory [Zhu, et al., PRD 62, 033008 (2000)]
- All e-p data points were corrected for E & $Q^2$ dependence of γZ-box contributions
  - $□^V_{\gamma Z}$: Hall et al., PLB753, 221 (2016); - $□_{\gamma Z}(Q)$: Gorchtein et al., PRC84, 015502 (2011);
  - $□^A_{\gamma Z}$: Blunden et al., PRL107, 081801 (2011); - $\Delta□^A_{\gamma Z}$: Blunden et al., PRL109, 262301 (2012).
  - The $□_{\gamma Z}$ RC for Qweak is 6.4% ± 0.6%.

# Results Determined from Qweak $A_{ep}$

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

**$Q_w(p) = -2(2C_{1u} + C_{1d})$**
**$Q_w(^{133}Cs) = -2(188C_{1u} + 211C_{1d})$**

| Quantity | Value | Error | Method |
|---|---|---|---|
| $Q_W^p$ | **0.0719** | **0.0045** | Qweak $A_{ep}$ + PVES data base |
| $\sin^2\theta_W$ | **0.2382** | **0.0011** | |
| $\rho_s$ | 0.19 | 0.11 | |
| $\mu_s$ | -0.18 | 0.15 | |
| $G_A^{Z(T=1)}$ | -0.67 | 0.33 | |
| $Q_W^p$ | **0.0718** | **0.0045** | Qweak $A_{ep}$ + PVES data base + APV $^{133}$Cs |
| $Q_W^n$ | **-0.9808** | **0.0063** | |
| $C_{1u}$ | -0.1874 | 0.0022 | |
| $C_{1d}$ | 0.3389 | 0.0025 | |

$C_1$ correlation = -0.9317

$Q_W(^{133}Cs) = -72.62 \pm 0.43$ [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 Qweak $A_{ep}$

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| $Q_W^p$ | 0.0719 | 0.0045 | Qweak $A_{ep}$ + PVES data base |
| $\sin^2\theta_W$ | 0.2382 | 0.0011 | |
| $\rho_s$ | 0.19 | 0.11 | |
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| $C_{1u}$ | -0.1874 | 0.0022 | |
| $C_{1d}$ | 0.3389 | 0.0025 | |
| $C_1$ correlation = -0.9317 | | | |
| $Q_W^p$ | 0.0684 | 0.0039 | Qweak $A_{ep}$ + PVES data base + LQCD (strange) |
| $\sin^2\theta_W$ | 0.2392 | 0.0009 | |

***Addition of Lattice QCD constraint on strange quarks further improves precision of $Q^p_W$ & $Sin^2\theta_W$***

- High-precision calculation of strange form factors using LQCD: [Green, et al., PRD **92**, 031501 (2015)]

# Results Determined from Qweak $A_{ep}$

*Precision of $A_{ep}$ dominates determination of $Q^p_W$*

| Quantity | Value | Error | Method |
|---|---|---|---|
| $Q_W^p$ | **0.0719** | **0.0045** | |
| $\sin^2\theta_W$ | **0.2382** | **0.0011** | Qweak $A_{ep}$ + PVES data base |
| $\rho_s$ | 0.19 | 0.11 | |
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| $G_A^{Z(T=1)}$ | -0.67 | 0.33 | |
| $Q_W^p$ | **0.0718** | **0.0045** | |
| $Q_W^n$ | **-0.9808** | **0.0063** | Qweak $A_{ep}$ + PVES data base + APV $^{133}$Cs |
| $C_{1u}$ | -0.1874 | 0.0022 | |
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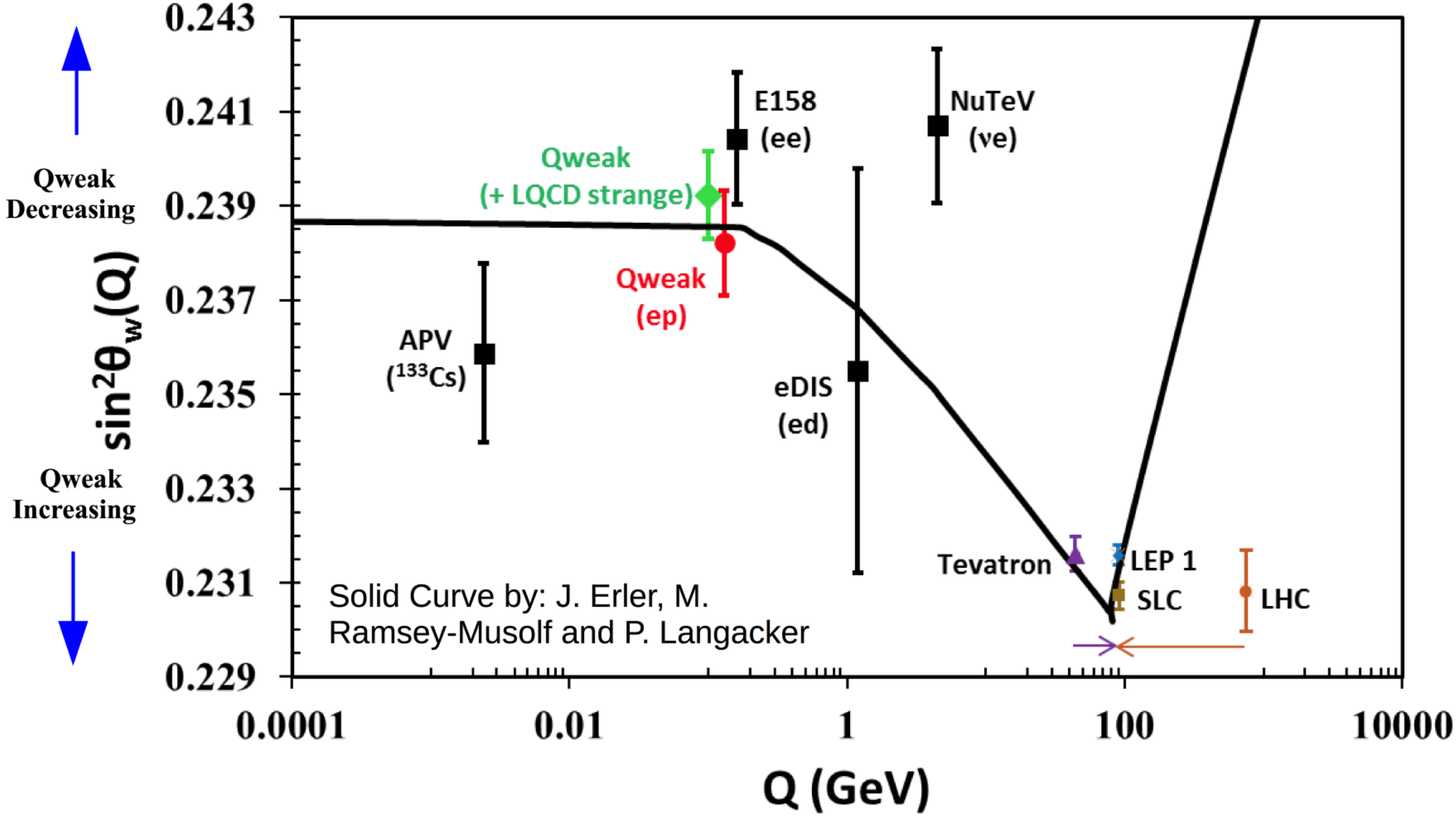
| $C_1$ correlation = -0.9317 | | | |
| $Q_W^p$ | **0.0684** | **0.0039** | Qweak $A_{ep}$ + PVES data base + LQCD (strange) |
| $\sin^2\theta_W$ | **0.2392** | **0.0009** | |
| $Q_W^p$ | **0.0706** | **0.0047** | Qweak $A_{ep}$ + EMFF's & theory axial + LQCD (strange) |

*Alternate "Standalone" technique to extract $Q^p_W$ does NOT depend on other PVES measurements*

- EMFFs: [Arrington & Sick, PRC 76, 035201 (2007)]
- Axial FF: [Liu, Mckeown & Ramsey-Musolf, PRC 76, 025202 (2007)]
- Strange FF (LQCD): [Green, et al., PRD 92, 031501 (2015)]

# Running of $Sin^2\theta_W$

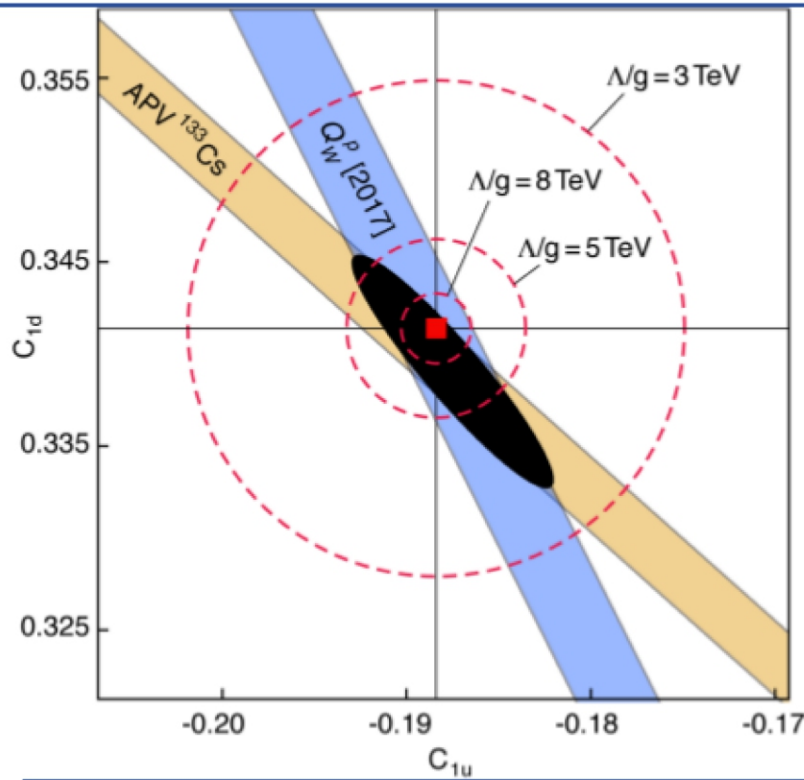
$$Q_W^p = [\rho_{NC} + \Delta_e][1 - 4\sin^2\hat{\theta}_W(0) + \Delta'_e] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$



# Sensitivity to New Physics

$$\mathcal{L}^{PV}_{NC+NP} = \frac{-G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma^5 e\sum_q\left(C_{1q} - \frac{\sqrt{2}\,g^2}{G_F\,\Lambda^2}h^q_V\right)\bar{q}\gamma^\mu q$$

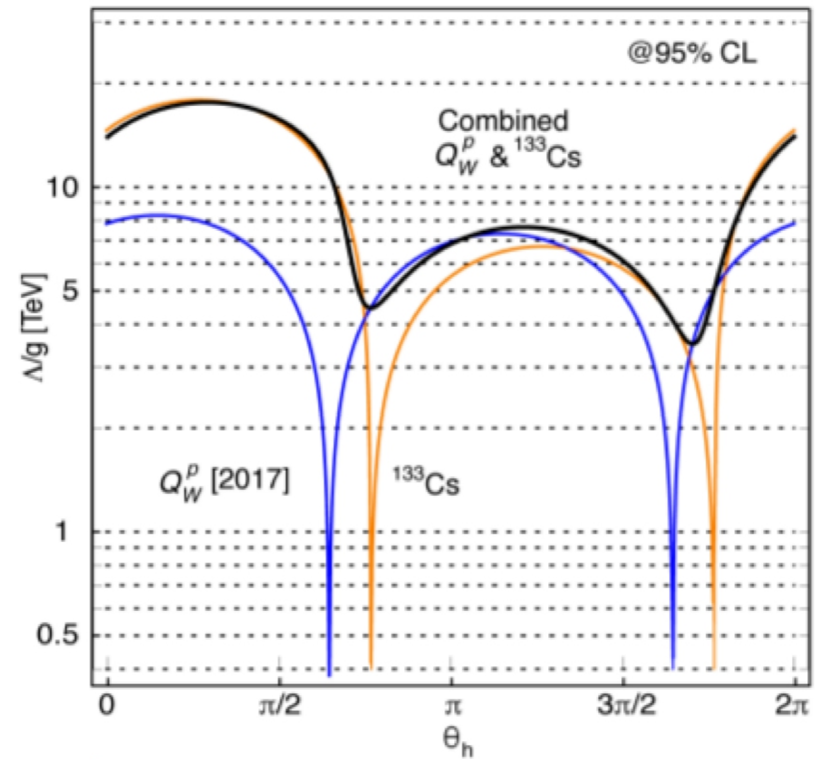
$$h^u_V = \cos\theta_h \qquad h^d_V = \sin\theta_h$$




SM values indicated by the red square. Dashed contours indicate value of $\Lambda/g$ = 3, 5, and 8TeV. (133Cs APV, from PDG – Flambaum)

$$Q^p_W = -2(2C_{1u} + C_{1d})$$

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

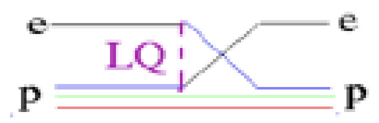



$\theta_h$ is "flavor mixing angle" in Lagrangian $\mathcal{L}^{PV}_{NP}$ for new physics at value $\Lambda/g$ mapped around boundary of experimental limits.

# Leptoquarks

**Impact of $Q^p_W$ on leptoquarks:**

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



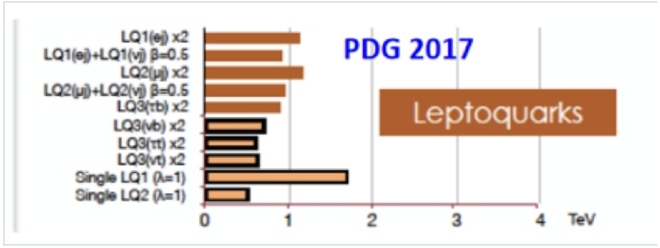

Leptoquarks

Included HERA, LEP and APV data in analysis [Aaron, et al. Phys. Lett. B **705**, 52 (2011)]

*New Qweak data has sensitivity to distinguish among LQ types @ 95% CL*

**Scalar Leptoquarks** | **Vector Leptoquarks**

| LQ | Consistency | $\Delta Q_W(p)/Q_W(p)$ | LQ | Consistency | $\Delta Q_W(p)/Q_W(p)$ |
|---|---|---|---|---|---|
| $S_1^L$ | 0.57 | 9% | $U_{1\mu}^L$ | 0.26 | −8% |
| $S_1^R$ | 0.01 | −6% | $U_{1\mu}^R$ | 0.56 | 6% |
| $\tilde{S}_1^R$ | 0.44 | −6% | $\tilde{U}_{1\mu}^R$ | 0.99 | 25% |
| $S_3$ | 0.76 | 10% | $U_{3\mu}$ | 0.31 | −4% |
| $R_2^L$ | 0.44 | −13% | $V_{2\mu}^L$ | 0.87 | 9% |
| $R_2^R$ | 0.89 | 15% | $V_{2\mu}^R$ | 0.11 | −7% |
| $\tilde{R}_2^L$ | 0.13 | −4% | $\tilde{V}_{2\mu}^L$ | 0.56 | 14% |



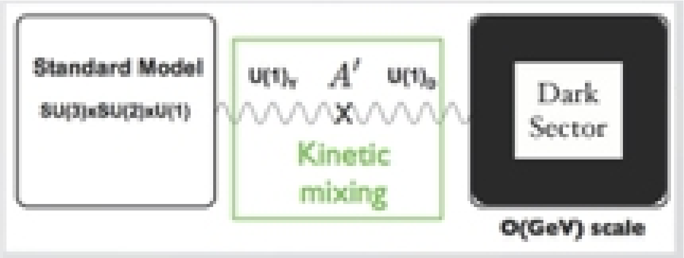

*New Qweak data rule out leptoquark masses limit ~ 2.3 TeV for $g^2 = 4\pi\alpha$*
*(The current LHC limits at ~1 TeV)*

# Implications for "Dark Parity Violation"

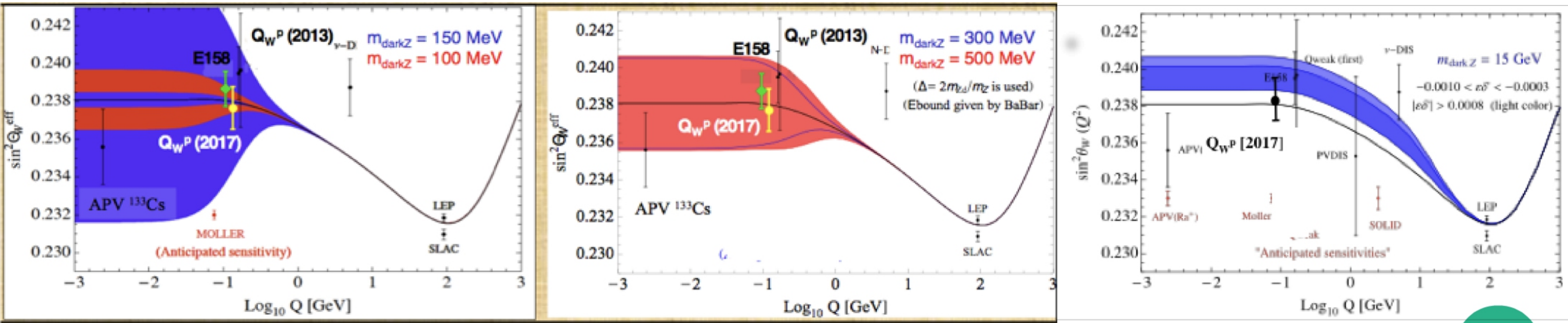
## "Dark Photon" - possible portal for new force to communicate with SM?

"Dark parity violation"
[Davoudiasl, Lee, Marciano, Phys. Rev. D**89**, 095006 (2014)]
[Davoudiasl, Lee, Marciano, Phys. Rev. D**92**, 055005 (2015)]

- New source of low energy PV through mass mixing between $Z_0$ and $Z_d$
- Complementary to direct searches for heavy dark photons




*New Qweak point rules out some of the allowed region*



# Summary

- Qweak precisely measured $Q^p_W$, in good agreement with SM

  $A_{ep}$ = -226.5 ± 7.3 (stat) ± 5.8 (syst) ppb
  $Q_W^p$ (this exp.) = 0.0719 ± 0.0045 [$Q_W^p$ (SM) = 0.0708 ± 0.0003]

- Lead to a very sensitive measurement of $\sin^2\theta_W$ at low Q for BSM test
  ~ 0.46% in precision

- Mass reach for new neutral current semi-leptonic PV physics ruled out @ 95% CL:
  - $\Lambda/g$ < 7.4 TeV (<3.5 TeV for arbitrary flavor ratios)
  - Quark flavor dependent mass reach limit $\Lambda \sim 26$ TeV (assume $g^2 = 4\pi$)

- Will play a role in future analyses of bounds (or discoveries) of a variety of new physics

- Builds scientific and technical foundation for next generation of measurements

# The Qweak Collaboration

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

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*Thank you!*