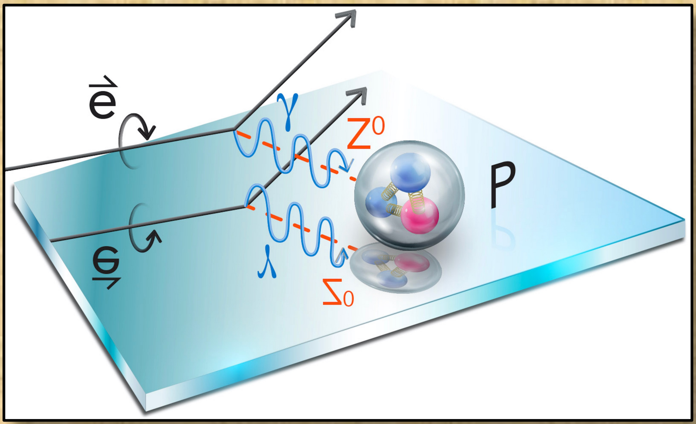
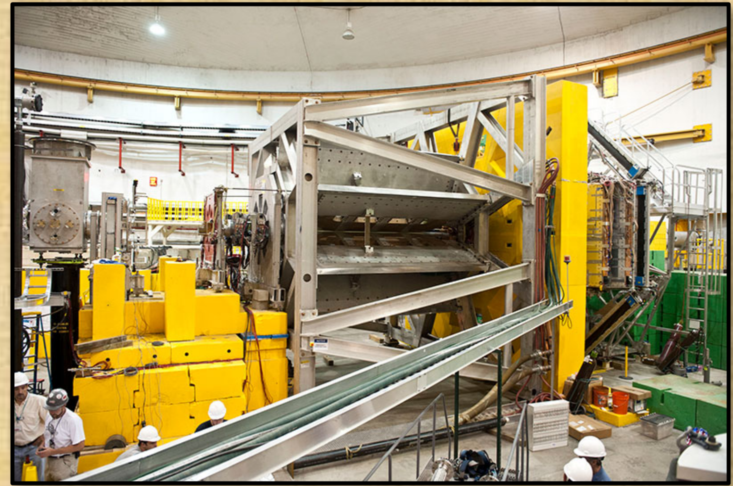
The Qweak Experiment at JLab

A search for parity violating new physics at the TeV scale by measurement of the Proton's weak charge.



Roger D. Carlini
Jefferson Laboratory
for the
Qweak Collaboration

101 collaborators
26 grad students
11 post docs
27 institutions



- Scatter longitudinally polarized electrons from liquid hydrogen.
- Flip the electron spin and see how much the scattered fraction changes.

"At the few ppb scale"

- This difference is proportional to weak charge of the proton, Q_W^p.
- From Q_W^p we can determine $\sin^2\theta_W$ at low Q^2.
- Running of $\sin^2\theta_W$ is sensitive to PV semi-leptonic physics beyond the SM.

NSERC CRSNG
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Thomas Jefferson National Accelerator Facility
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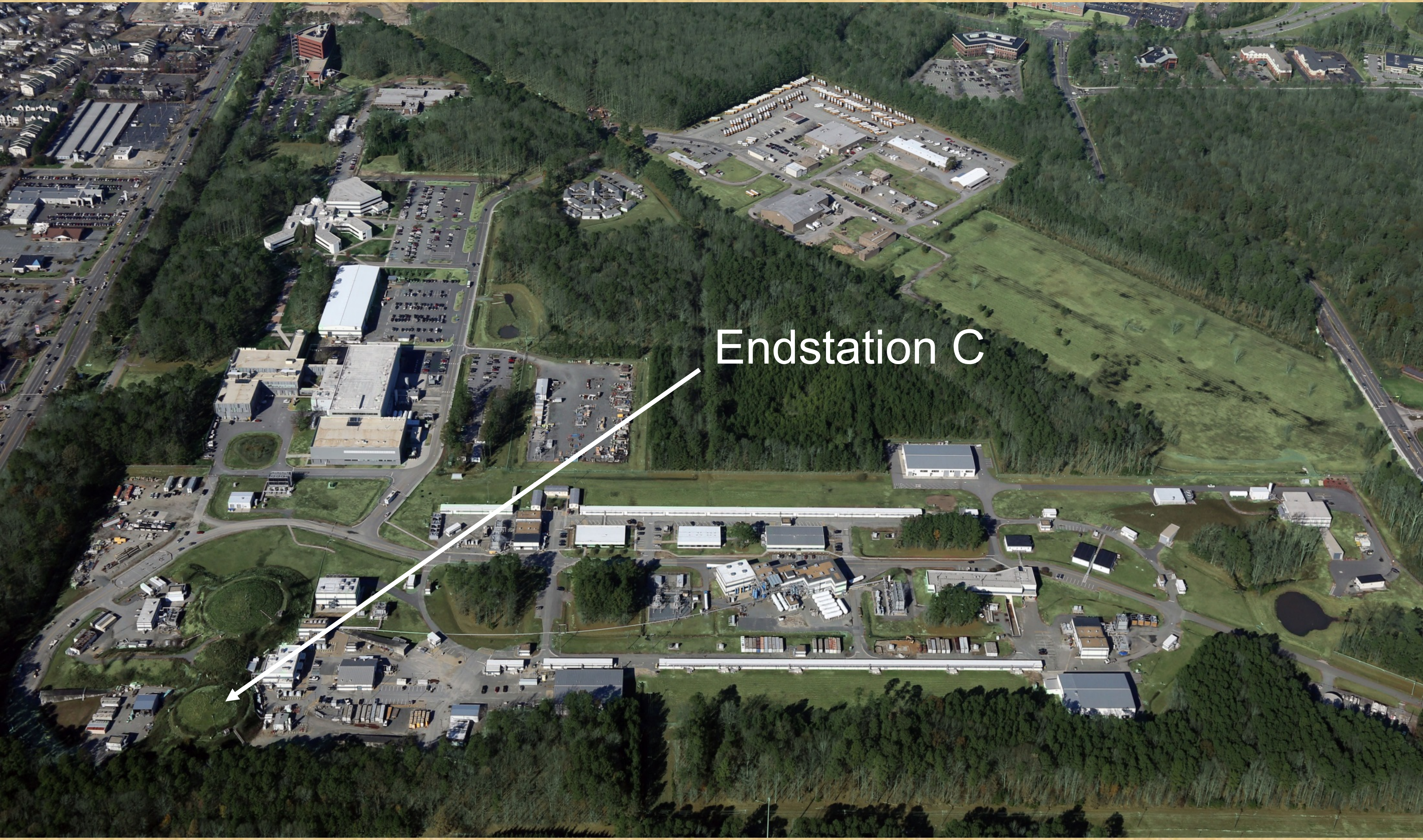
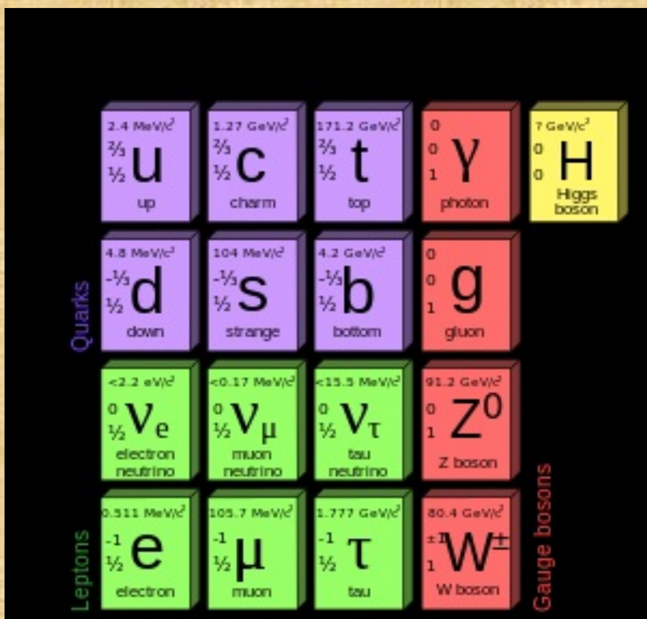
Jefferson Lab Complex



The Standard Model of Electroweak Interactions

Renormalizable GaugeTheory | Spontaneous Symmetry Breaking



Predicts

Massless γ , g, Higgs

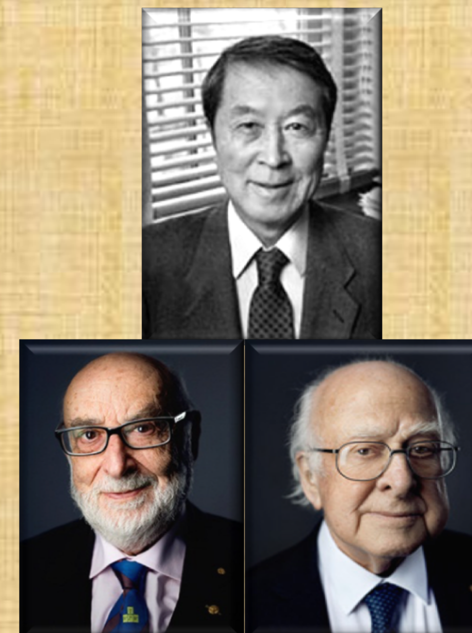
Massive W, Z

Fermion masses

Discovered

H, W, Z,

t,b,c,s,d,u,τ,μ,e,$\nu_{1,2,3}$



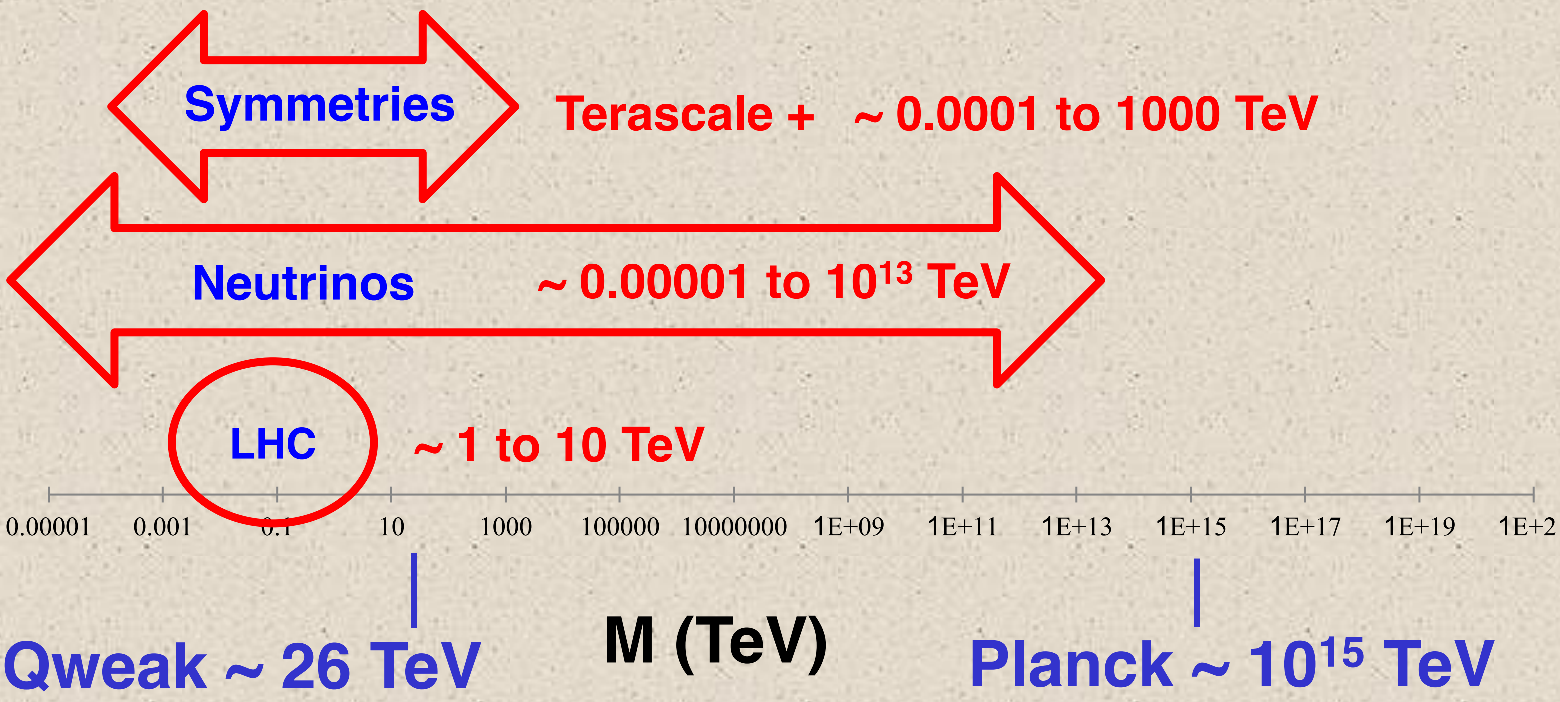
But: It‘s known to be incomplete

– so there is something more

Mass Scales

Terascale ~ 1 TeV,   Unification ~ 10^{13} TeV,   Planck ~ 10^{15} TeV

Precision experiments have potential to tell you something profound



Assuming strong contact interaction coupling of $g^2 = 4\pi$ and formalism of Erler, et.al.- arXiv:1401.6199v1 [hep-ph] 23 Jan 2014:

→ Qweak mass scale reach for new semi-leptonic PV physics ~26 TeV.

Precision Tests of the Standard Model

- Standard Model is known to be the effective low-energy theory of a more fundamental underlying structure.

- Finding new physics: Two complementary approaches:
  - **Energy Frontier (direct) :** ***eg*. ~~Tevatron~~, LHC**
  - **Precision Frontier (indirect) :** ***(a.k.a. Intensity Frontier)***
    - μ(g-2) , EDM, $\beta\beta$ decay, $\mu \to e\,\gamma$, $\mu A \to eA$, $K^+ \to \pi^+ \nu\nu$, *etc.*
    - *ν - oscillations*
    - *Atomic Parity violation*
    - *Parity-violating electron scattering*

Often at modest or low energy…

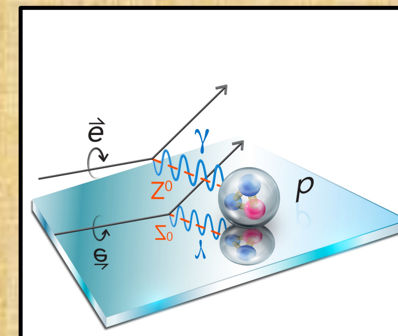
- **Hallmark of the Precision Frontier:** Choose observables that are "*precisely predicted*" or "*suppressed*" in Standard Model.

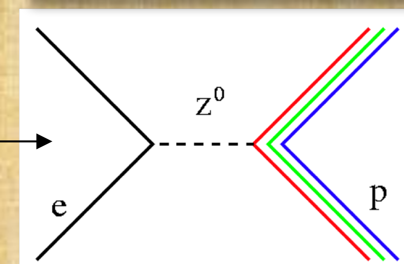
- If new physics is eventually found in direct measurements (LHC), precision measurements useful to determine e.g. couplings…

Weak Charges

Govern strength of neutral current interaction with fermion.

Charge / Particle	Electric	Weak (vector)
u	+2/3	$-2\,C_{1u} = +1 - 8/3\,\sin^2\theta_W$
d	-1/3	$-2\,C_{1d} = -1 + 4/3\,\sin^2\theta_W$
Proton uud	+1	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0.07$
Neutron udd	0	$Q_W^n = -1$

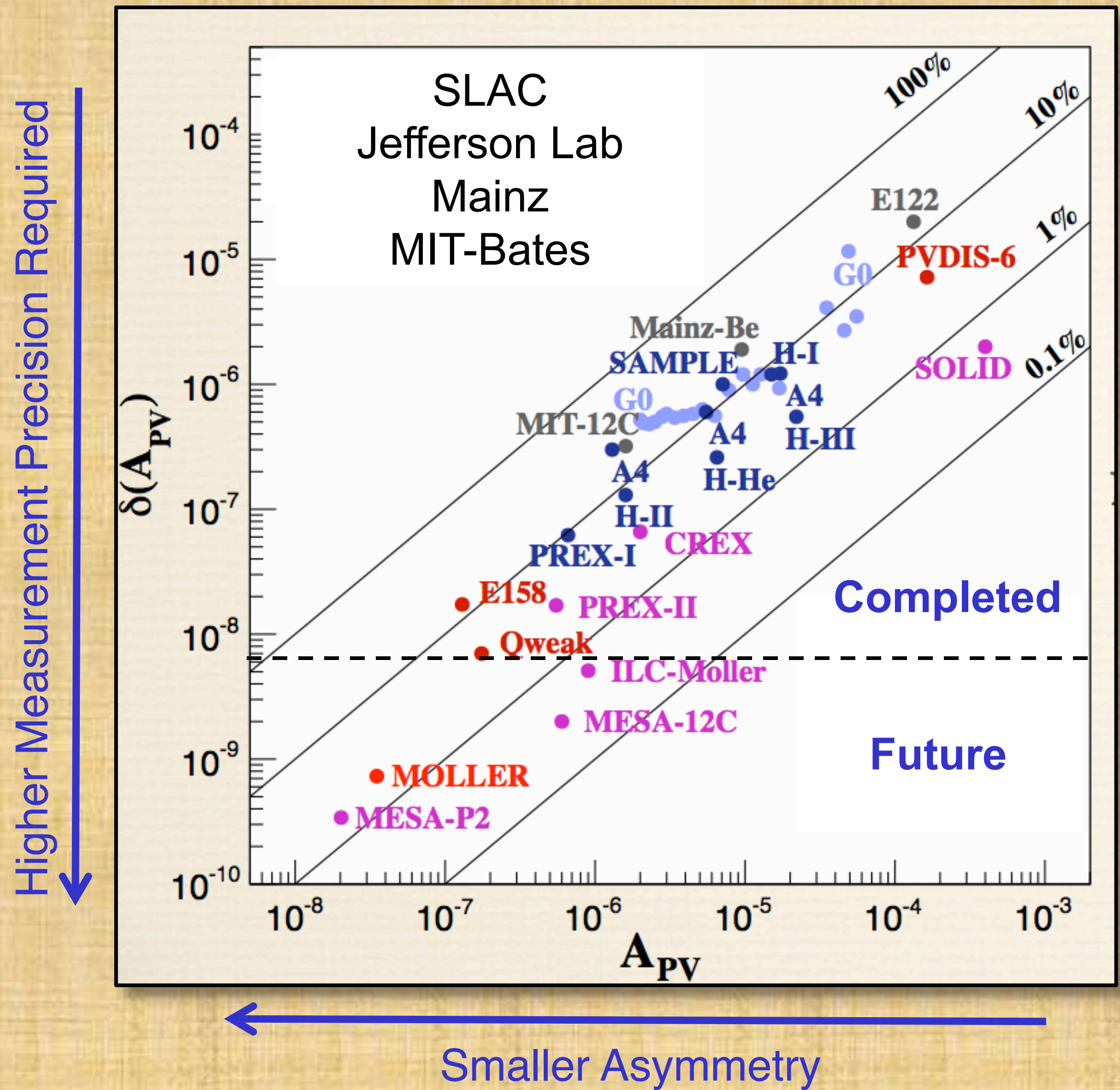




Note "accidental" suppression of Q_W^p $\rightarrow$ *sensitivity to new physics*

- Q_W^p is a well-defined experimental observable.
- Q_W^p has a definite prediction in the electroweak Standard Model.
- Q_W^e electron's weak charge was measured in PV Møller scattering (E158).

Parity-Violating Electron Scattering History & Relative Experimental Difficulty



Pioneering PVDIS (1978)
early SM test – Prescott *et al.*

SLAC E122: ΔA_{PV} = ±10 ppm

Strange FF Searches (98 – 09)
SAMPLE, G^0, A4, HAPPEX

ΔA_{PV} ~ 0.25 ppm – 2 ppm

High Precision SM Tests (2003 – 2017)

Note: Change of scale to ppb

SLAC E158: ΔA_{PV} ~ 17 ppb
JLab Qweak: ΔA_{PV} ~ 9 ppb

Future sub-ppb SM Tests

Jlab MOLLER: ΔA_{PV} ~ 0.8 ppb
Mainz P2: ΔA_{PV} ~ 0.34 ppb

PVES and Hadronic Structure Effects

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

Neutral-weak form factors **Axial form factor**

Assume charge symmetry

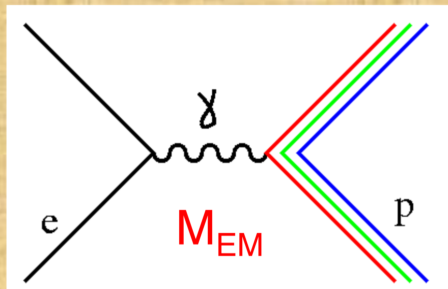
$$4G_{E,M}^{pZ} = (1 - 4\sin^2\theta_W) G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - G_{E,M}^{s}$$

Proton weak charge (tree level)

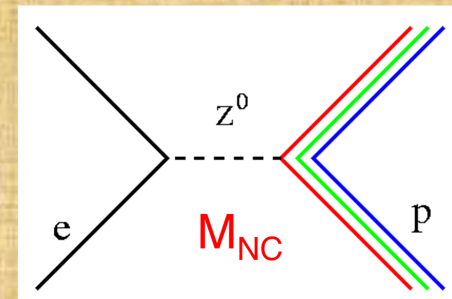
Strangeness (Now measured to be relatively small!)

Note: Parity-violating asymmetry is sensitive to weak charges *and* to hadron structure.

Extract Q_W^p from Parity-Violating Electron Scattering



As $Q^2 \rightarrow 0$



Measures Q^p – proton's electric charge

Measures Q_W^p – proton's weak charge

$$A = \frac{2M_{NC}}{M_{EM}} = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q^p_{weak} + F^p(Q^2,\theta)\right]$$

$$\xrightarrow[\theta \rightarrow 0]{Q^2 \rightarrow 0} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q^p_{weak} + Q^4 B(Q^2)\right]$$

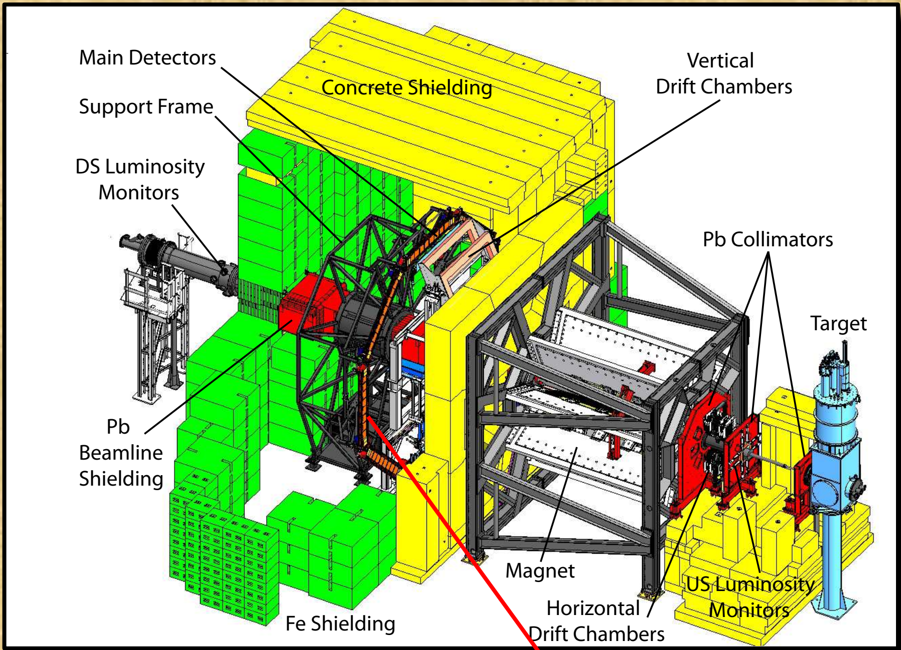
contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$

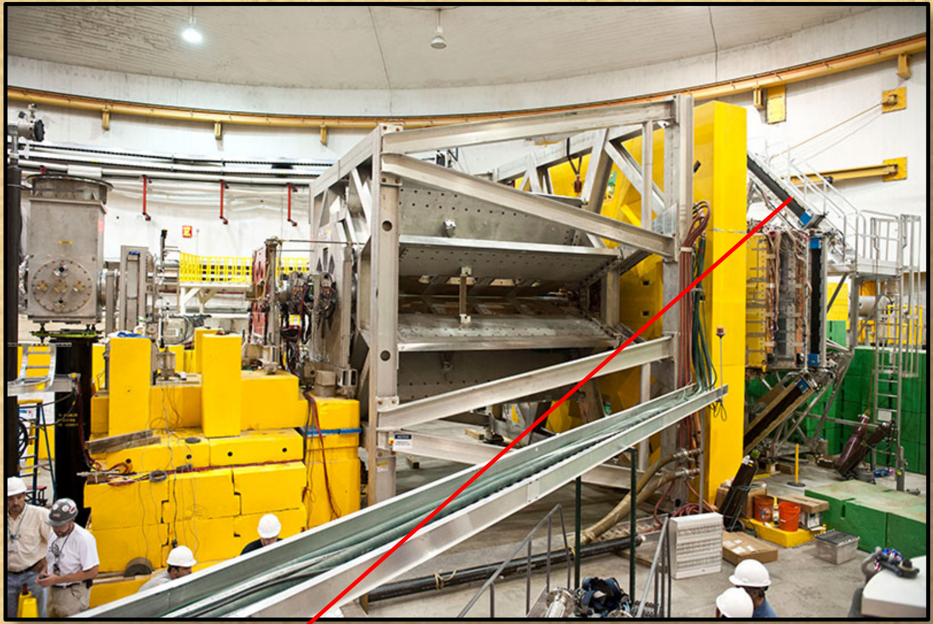
The **lower** the momentum transfer Q, the more the proton looks like a point and the less important are the hadronic form factor corrections *B(Q²)*.

B(Q²) determined using global analysis of published higher *Q²* PVES experiments.

→ **Therefore doesn't actually matter if $G^s_{E,M}$ is large or small.**

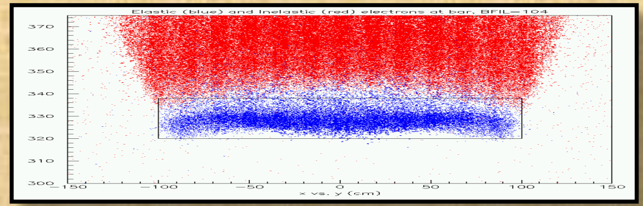
The Qweak Experiment in Hall C at JLab



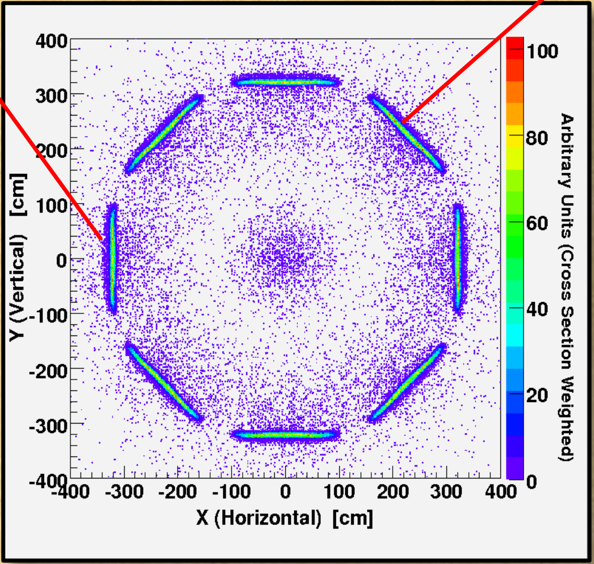


Toroidal Spectrometer Produces 8 Beam Spots

Each focus is ~2 meters long



Elastic focus – blue Inelastics - red



8 fused silica radiators:
200 cm x 18 cm x 1.25 cm
Spectrosil 2000
Rad-hard, low luminescence

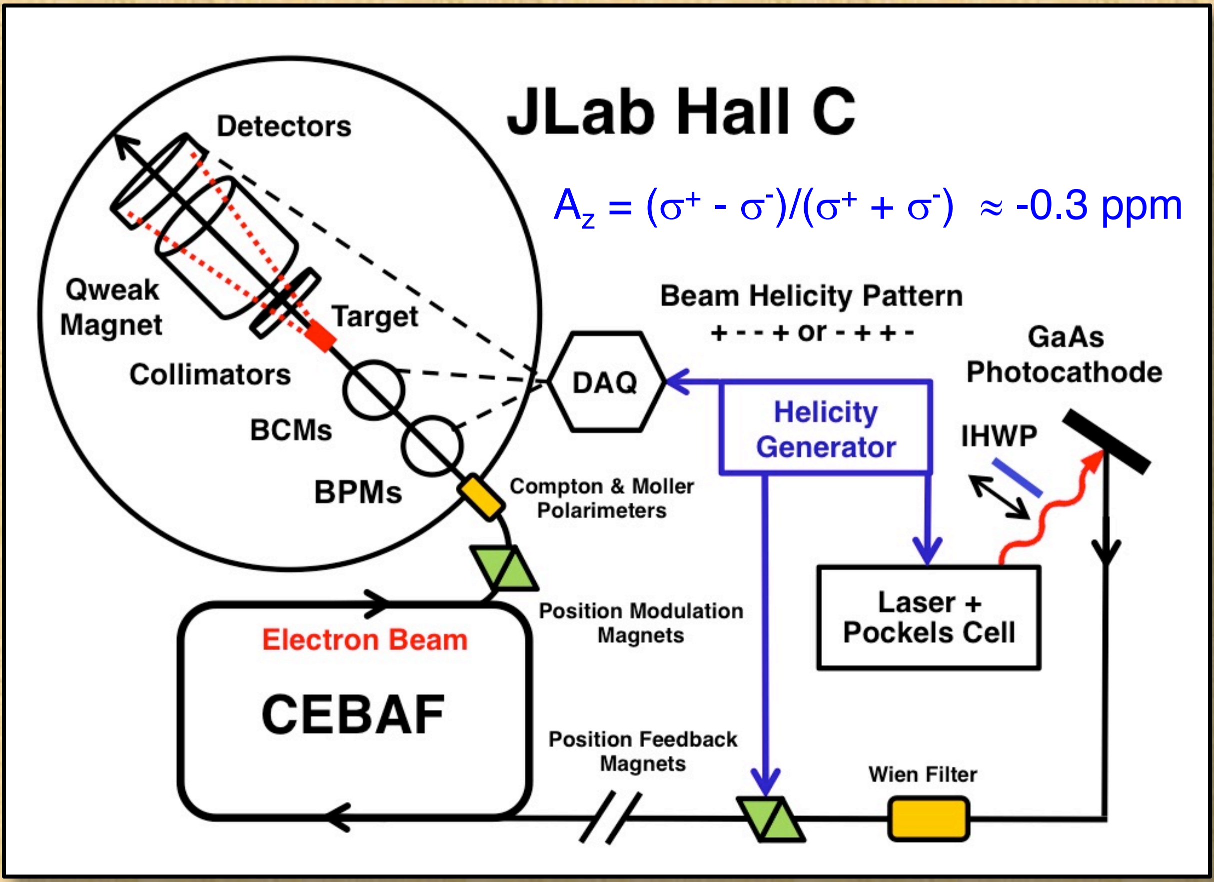
5 Angstroms rms polish
5" PMTs with gain = 2000
S20 photocathodes (I_k = 3 nA)

900 MHz e^- per bar

Current mode readout (I_a = 6 μA)

Experimental Technique to Isolate / Measure PV Signal

(The entire accelerator complex is our apparatus)



3 independent techniques for helicity reversal of longitudinally polarized 1.1 GeV e^- beam:

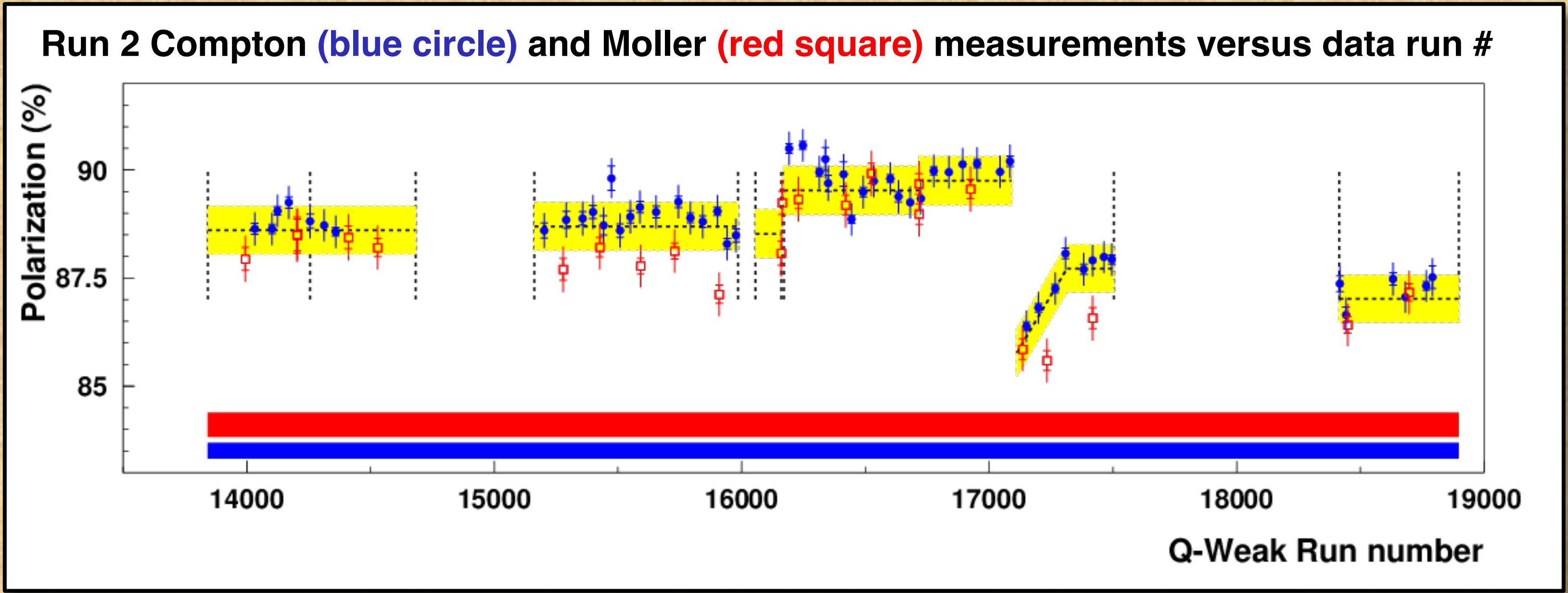
Rapid pseudo-random reversal (960/sec).
Rejects LH_2 target "boiling noise".

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.

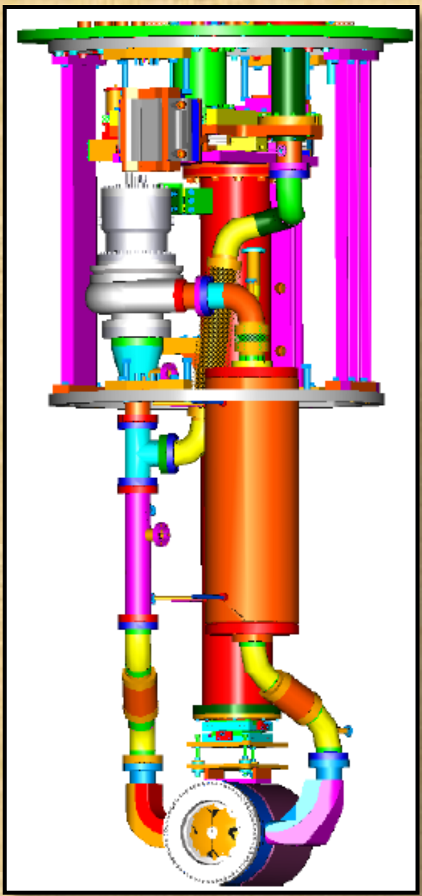
~0.6% Accuracy Achieved with Compton Polarimeter via Cross-calibrabration Against Saturated Fe Møller Polarimeter

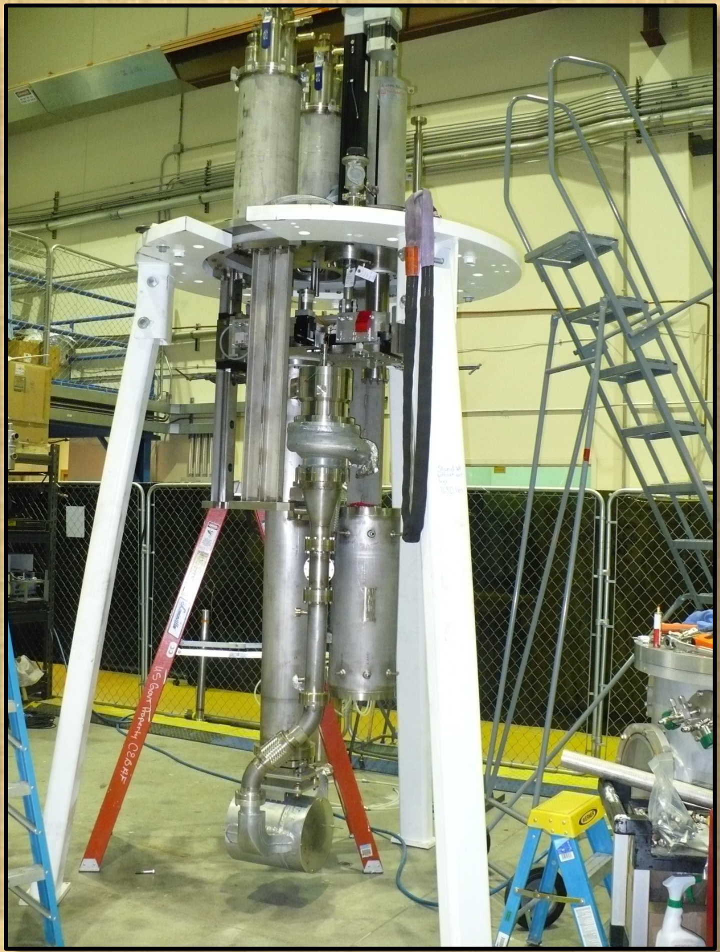


- Inner error bars statistical, outer error bars point-to-point systematic uncertainties added in quadrature with statistical uncertainties.
- Yellow band incorporates overall normalization uncertainties determining by weighted average and total uncertainty.
- Time dependence of reported polarization driven by continuous Compton measurements, with small scale correction (0.21%) determined from uncertainty-weighted global comparison of Compton and Møller polarimeters.

Qweak ~2.5 Kw LH_2 Cryo-target System

The highest power cryo-target ever built!
35 cm long liquid hydrogen (LH_2)





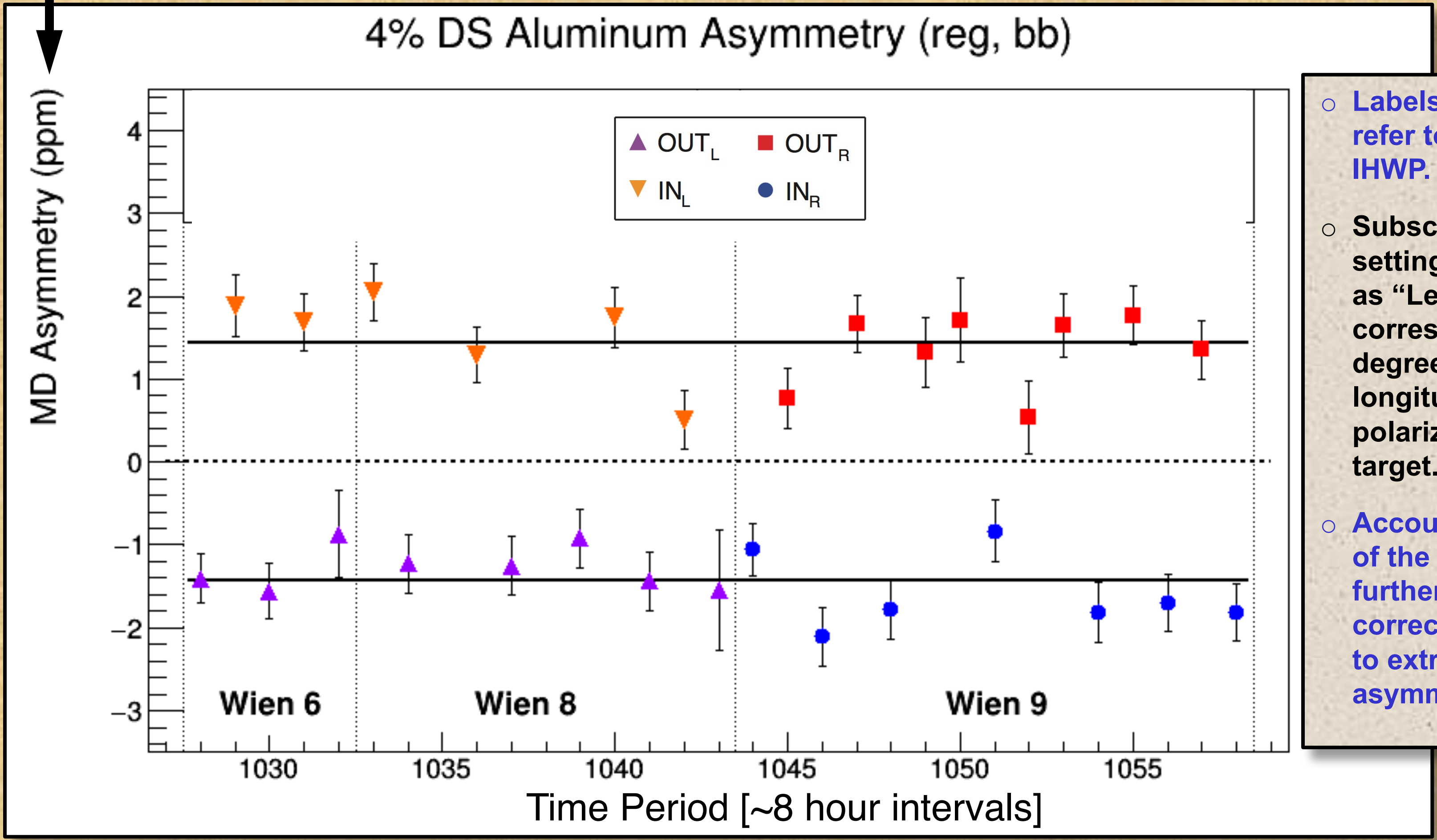
Target density fluctuations must be small compared to statistical uncertainty

This was achieved by:

- First use of fluid ***dynamics simulation*** in design to minimize "density changes", in liquid or at windows.
- ***Fast helicity reversal*** – up to ~1 ms flip rate allows common mode rejection "boiling" noise, line noise and undesired helicity correlated beam properties.
- ***Additional safeguards:*** large raster size ~(3mm x 3mm), faster pump speed, and more cooling directed onto windows....

Observed Al (LH_2 Target Windows) Asymmetry at ~8 hour intervals

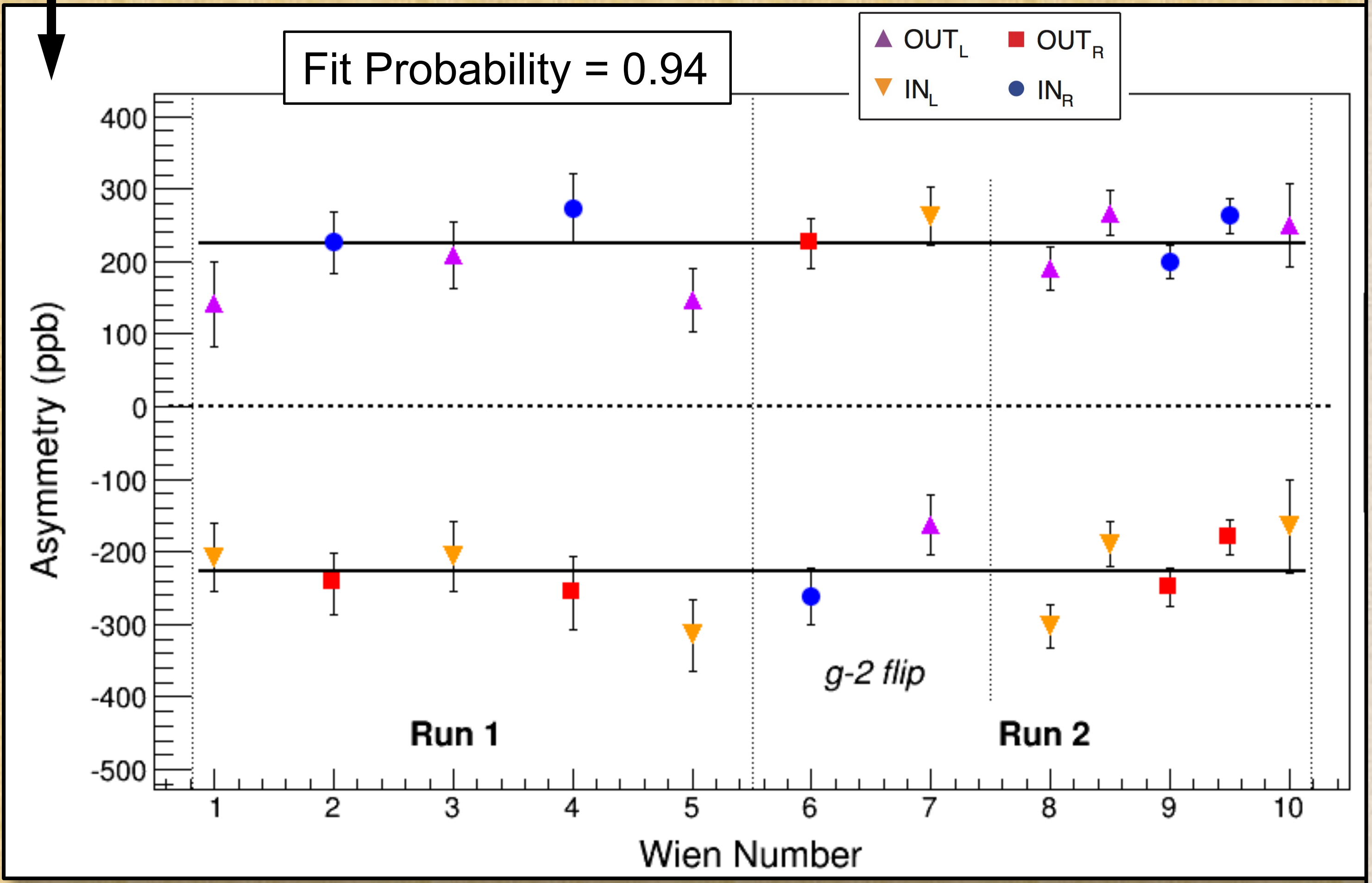
The **"easy part"** of the experiment – **[ppm]** asymmetry is **BIG**



- Labels "IN or OUT" refer to status of IHWP.
- Subscript denotes setting of Wien filter as "Left" or "Right" correspond to 180 degree rotation of longitudinally polarized beam at target.
- Accounting for sign of the Wien flips plus further systematic corrections required to extract physics asymmetry for Al

Observed A_{phy} Versus Wien Filter State

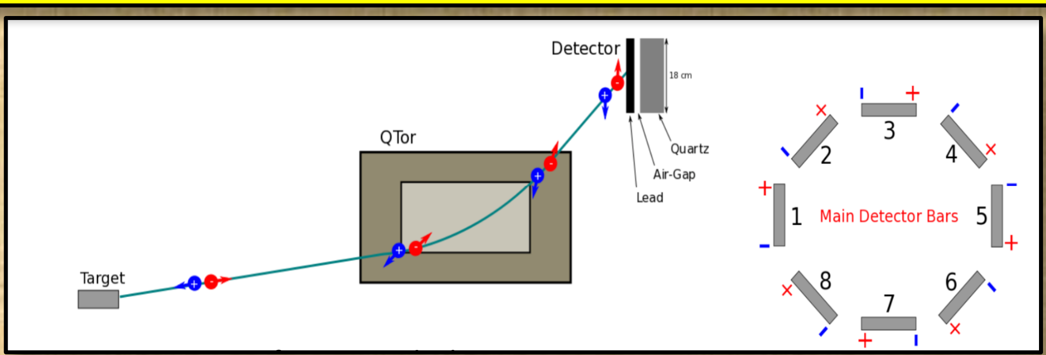
The **"hard part"** of the experiment – **[ppb]** asymmetry is **small**

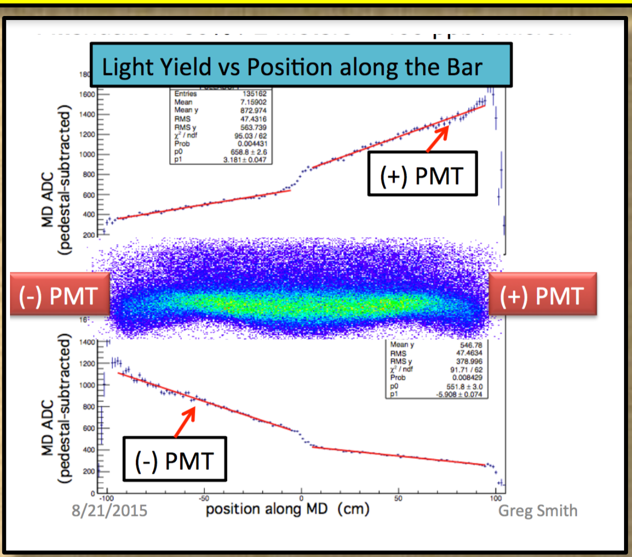


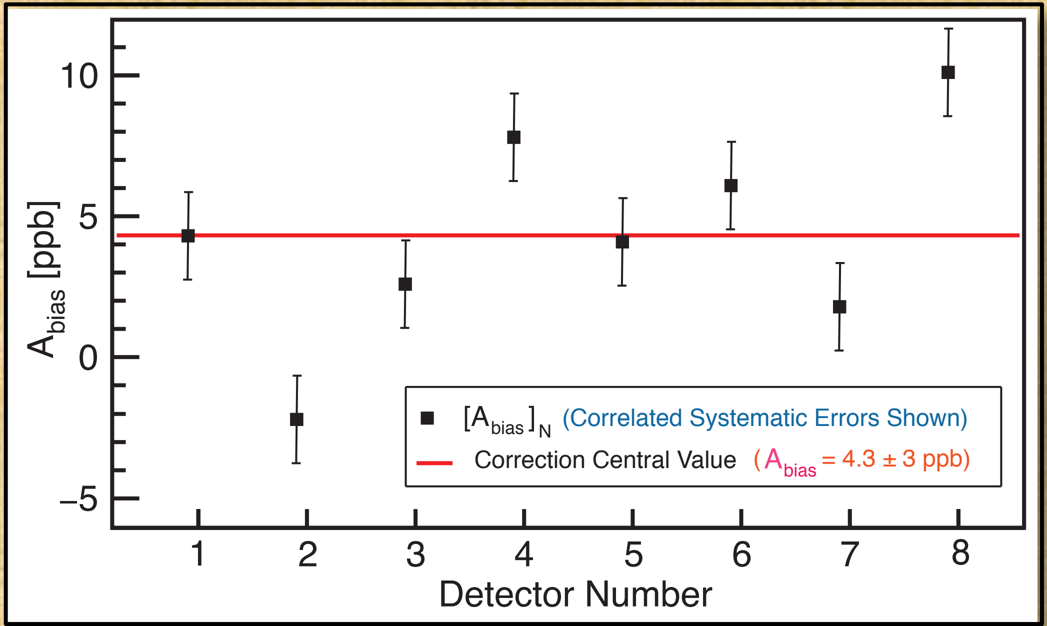
- Labels "IN or OUT" refer to status of IHWP.
- Subscript denotes setting of Wien filter as "Left" or "Right" correspond to 180 degree rotation of longitudinally polarized beam at target.
- Plot is sign corrected for period of two pass accelerator running during g-2 spin flip configuration.
- Accounting for sign of the Wien flips plus further systematic corrections required to extract physics asymmetry A_{ep}

Detector Optical Imperfections: A_{bias} Systematic

- Small residual non-cancellation of L / R transverse scattering from Pb pre-radiator in front of quartz bars.
- GEANT4 simulation & models tied to our data determine effect dominated by optical & mechanical imperfections and **NOT** details of transverse scattering cross-section in Pb.
- **Unnecessary to have precise theoretical calculation of cross-section!**







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**

Very Conservative

Asymmetries (A_{ep}) & Systematic Errors

Fractional quadrature contributions $(\sigma_i / \sigma_{total})^2$ to systematic uncertainty on A_{ep} for Runs 1 & 2. Only errors with fractional contributions ≥ 5% are shown.
Note: Contribution from Al target windows has already been removed.

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

Quantity	Run 1 error (ppb)	Run 1 fractional	Run 2 error (ppb)	Run 2 fractional
BCM Normalization: $A_{\rm BCM}$	5.1	25%	2.3	17%
Beamline Background: $A_{\rm BB}$	5.1	25%	1.2	5%
Beam Asymmetries: $A_{\rm beam}$	4.7	22%	1.2	5%
Rescattering bias: $A_{\rm bias}$	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	

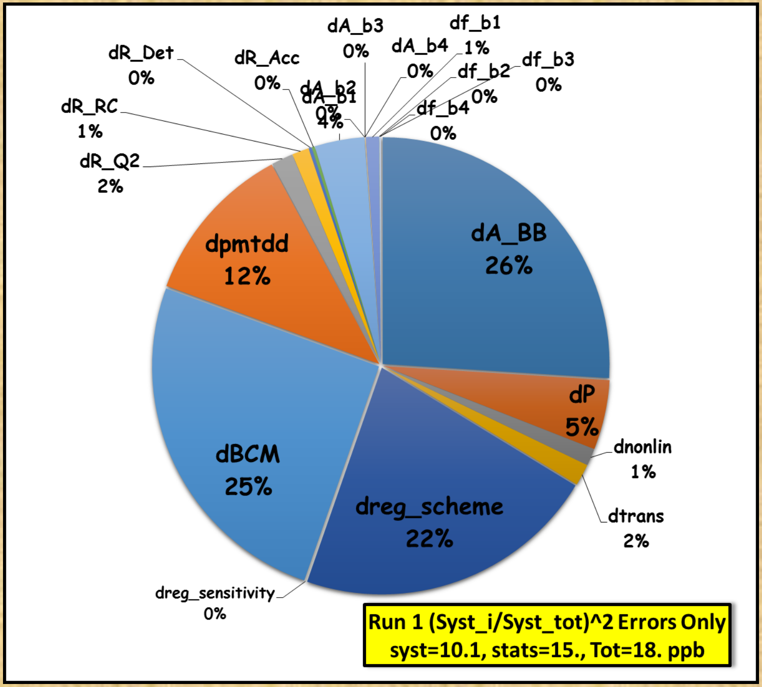
$$A_{ep} = R_{\rm tot} \frac{A_{\rm msr}/P - \sum_{i=1,3,4} f_i A_i}{1 - \sum_{i=1}^{4} f_i}$$

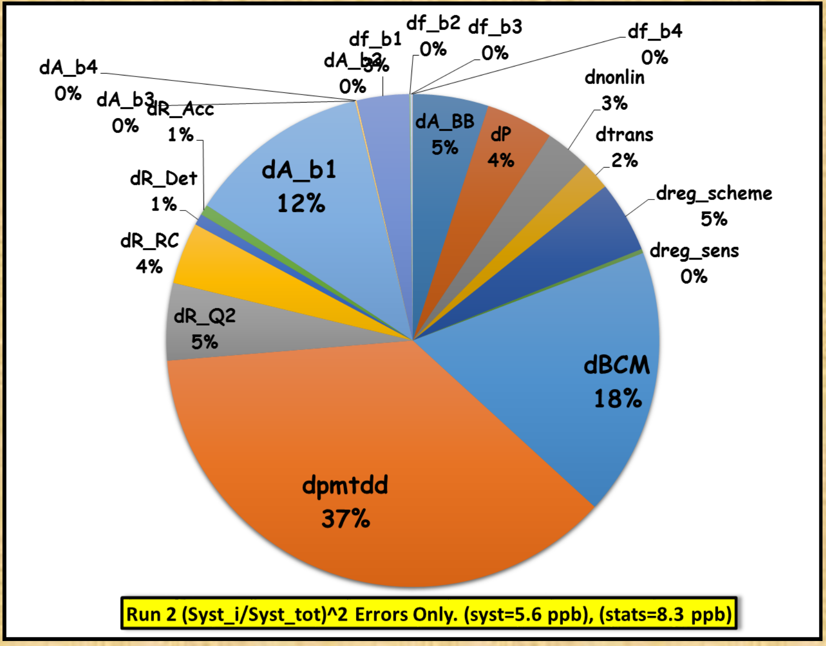
where $R_{\rm tot} = R_{\rm RC} R_{\rm Det} R_{\rm Acc} R_{Q^2}$.

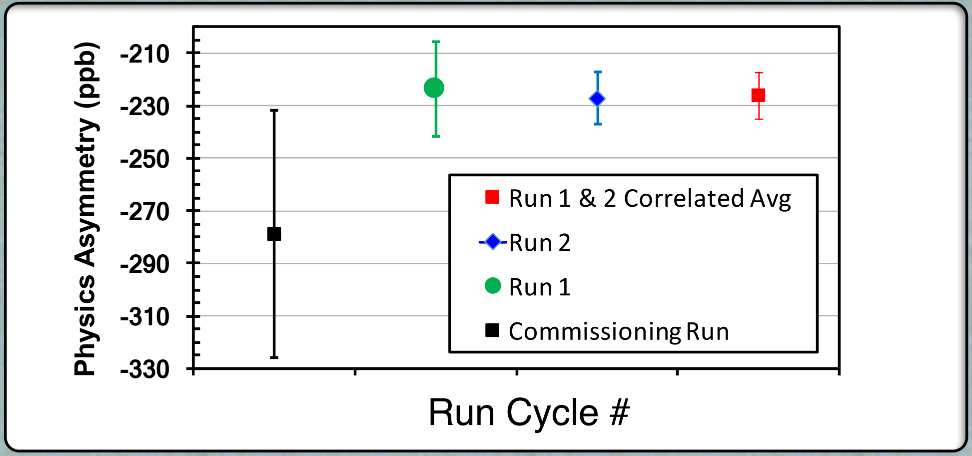
$$A_{\rm msr} = A_{\rm raw} + A_T + A_L + A_{\rm BCM} + A_{\rm BB} + A_{\rm beam} + A_{\rm bias}$$

A_T = Residual transverse pol, A_L = Linearity

Relative Systematic Error Contributions & NULL







Very different relative systematic contributions:

→ **Target setup, beamline instrumentation upgrades & injector / accelerator tunes, etc.**

Un-blinded asymmetries agree well:

→ **Evidence all significant systematic effects are accounted for and corrected.**

Experiment NULL Asymmetry

(Slow Helicity Reversals Out-of-Phase)

Weighted Avg: -1.75 +/- 6.51 ppb

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
$Z\gamma$ 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).

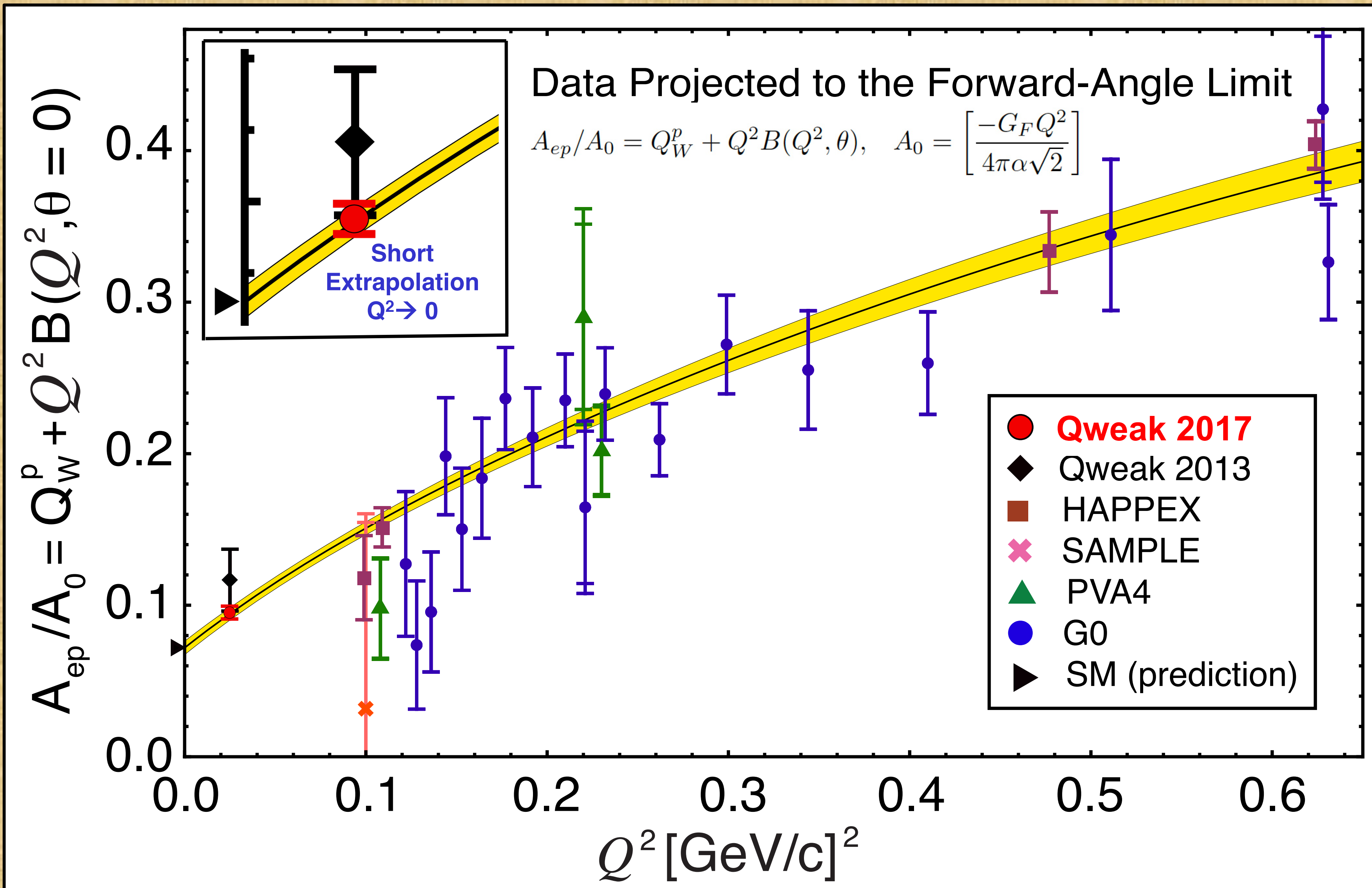
Axial Vector γZ correction:

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).

Qweak Parity-Violating Asymmetry Extrapolated to $Q^2 = 0$



Summary of Results Determined from Qweak A_{ep}

Addition of *Lattice QCD* constraint on strange quarks further improves precision of Q_W^p & $\sin^2\theta_W$

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	
ρ_s	0.19	0.11	
μ_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^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)

Summary of 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 →

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	
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$\sin^2\theta_W$	0.2392	0.0009	
Q_W^p	0.0706	0.0047	Qweak A_{ep} + EMFF's & theory axial + LQCD (strange)

Summary of Results Determined from Qweak A_{ep}

*Precision of A_{ep} **dominates** determination of Q_W^p*

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**	
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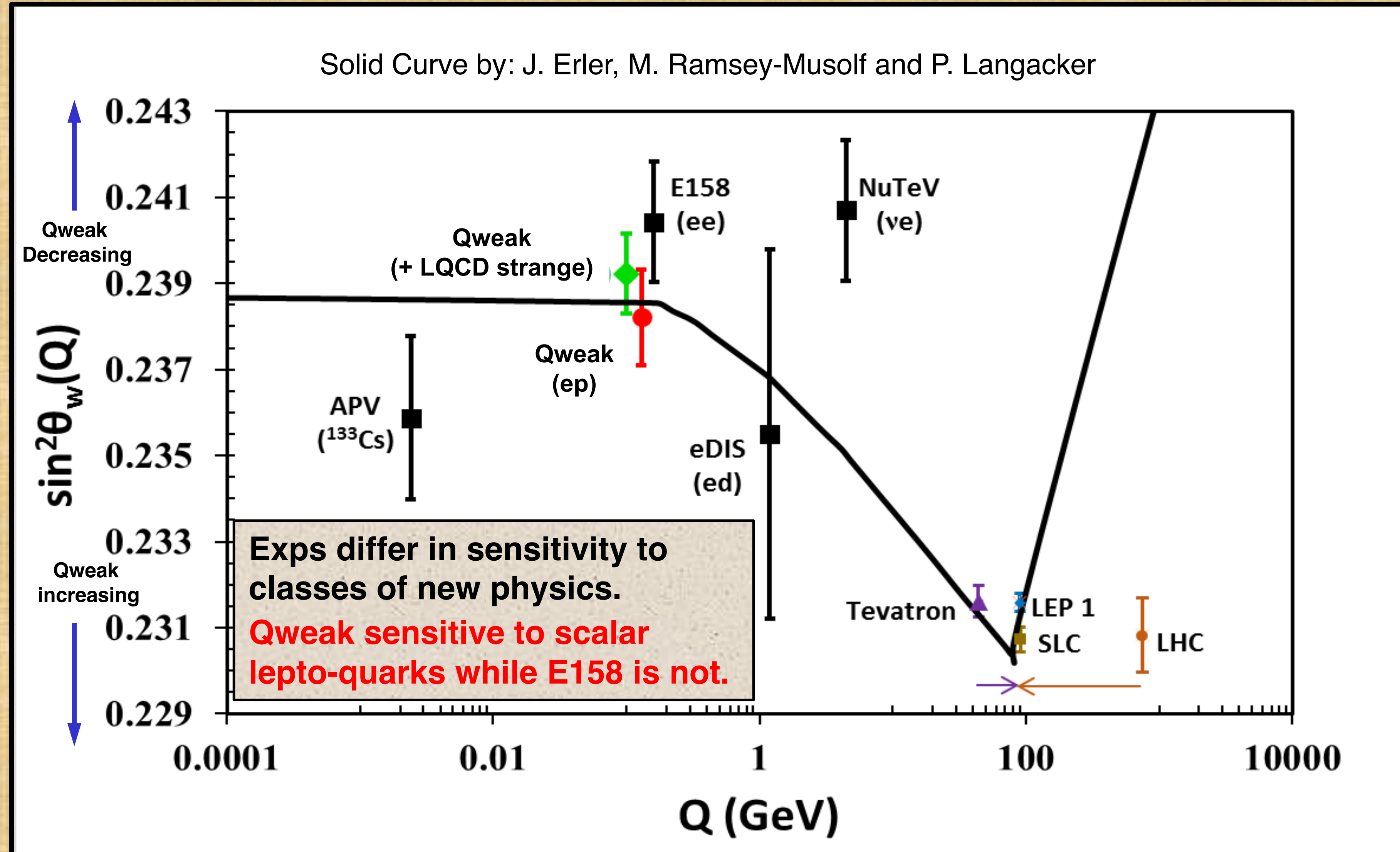
Q_W^p	**0.0706**	**0.0047**	Qweak A_{ep} + EMFF's & theory axial + LQCD (strange)

*Alternate **"Standalone"** technique to extract Q_W^p does **NOT** depend on other PV measurements*

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



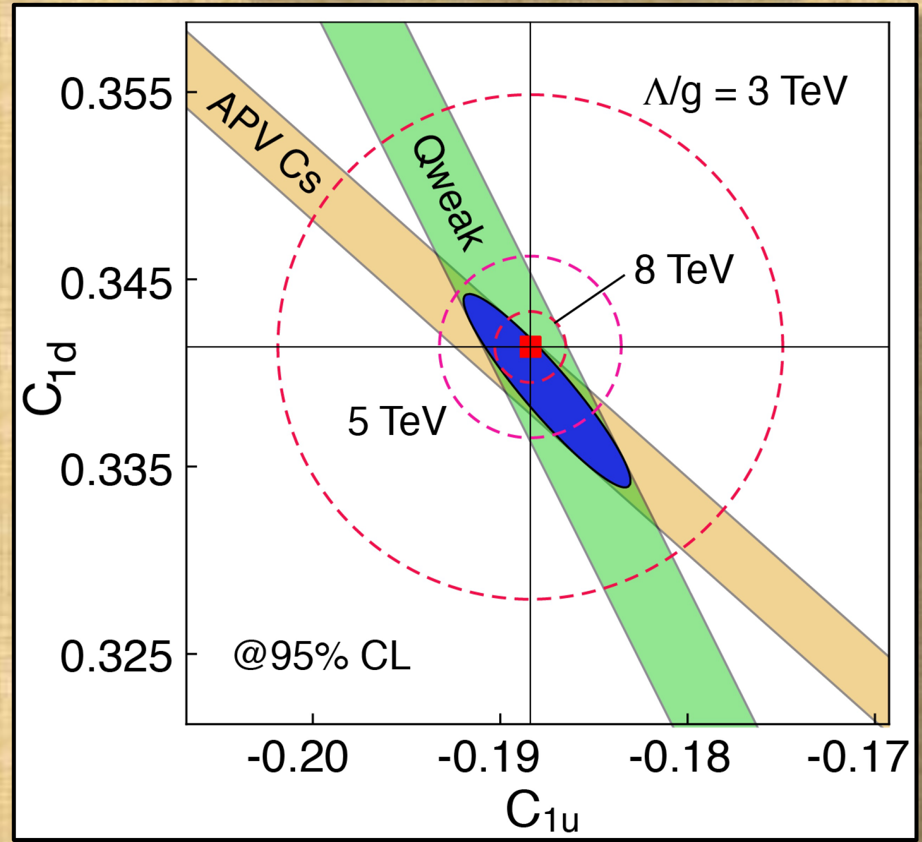
Limits on Semi-Leptonic PV Physics Beyond SM

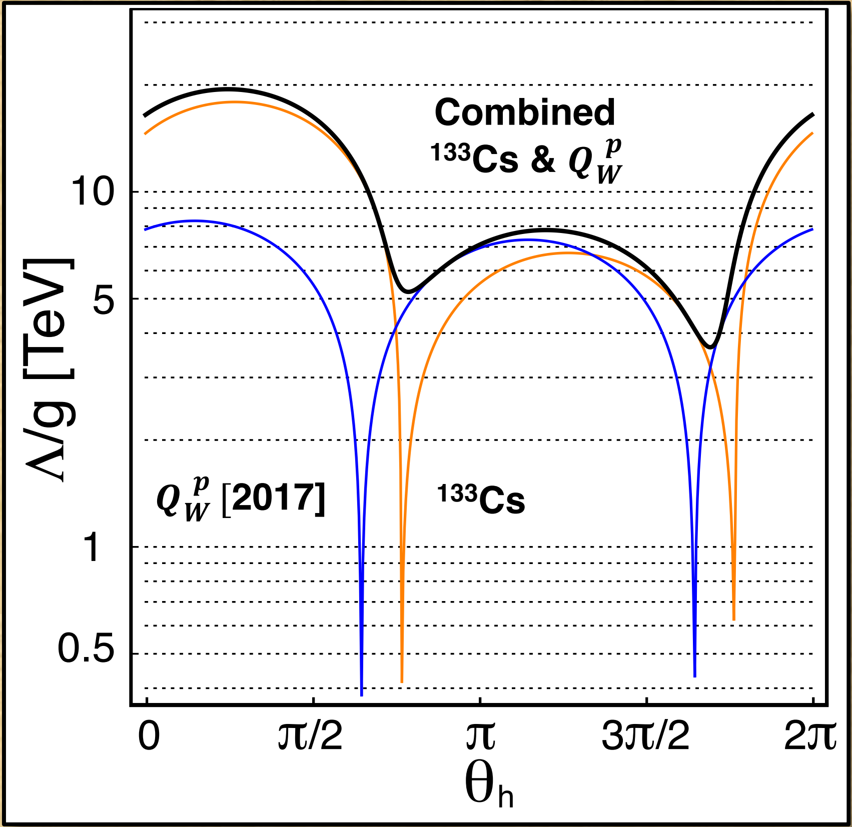
$$\mathcal{L}_{NP}^{PV} = -\frac{g^2}{\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

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

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

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



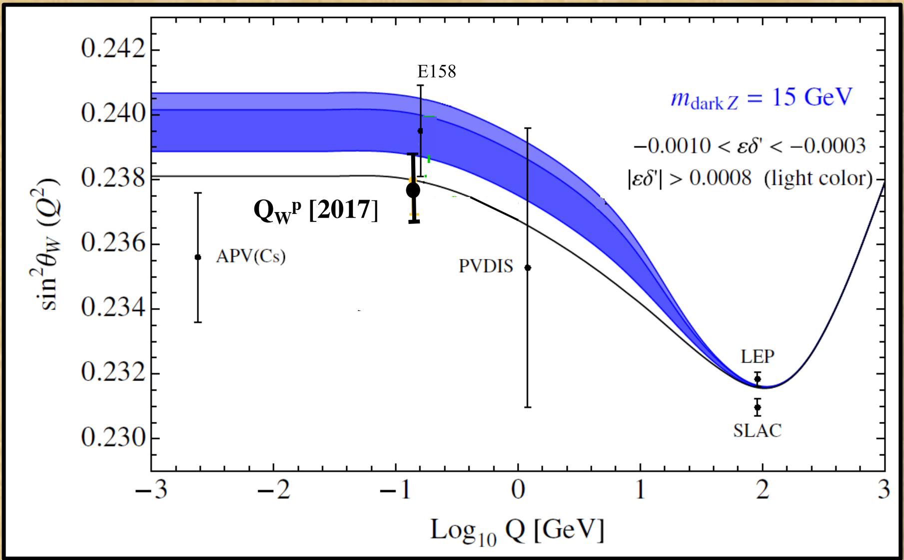


SM is red square. Dashed contours indicate value of Λ/g = 3, 5, and 8 TeV.
(^{133}Cs APV, from PDG – Flambaum)

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

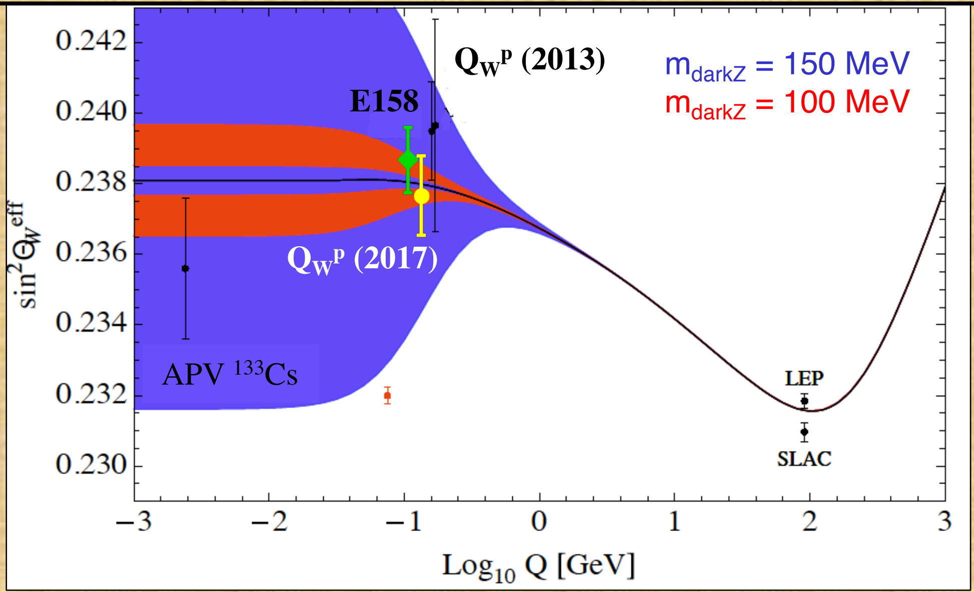
Implications for "Dark Parity Violation"

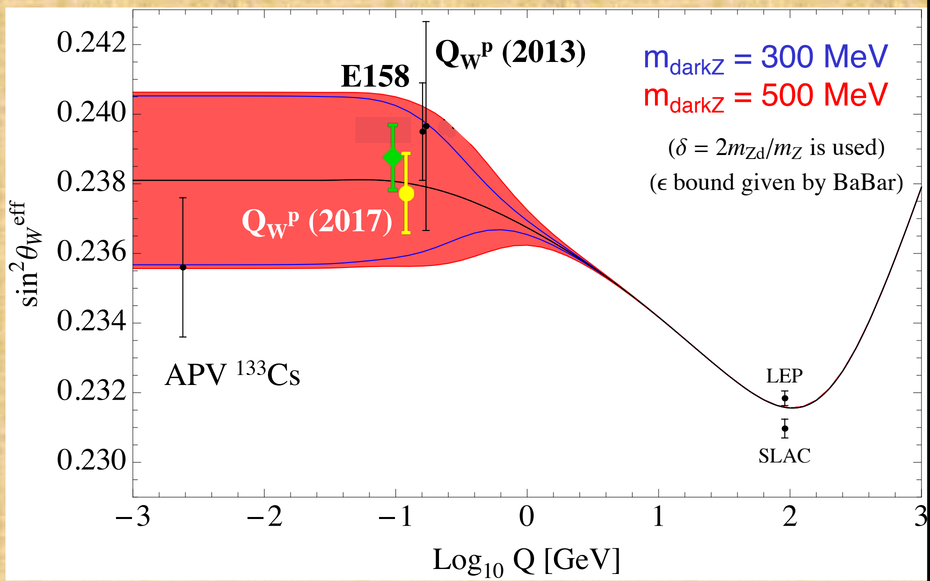
"Dark photon" – possible portal for new force to communicate with SM?



(Davoudiasl, Lee, Marciano, arXiv 1402.3620)

- Astrophysical motivation: observed excess in positron data.
- Introduces new source of low energy parity violation through mass mixing between Z and Z_d with observable consequences.
- Complementary to direct searches for heavy dark photons.





SM Tests: Past & Future Precision Low Energy Parity Violation Measurements

$\Lambda / g_{new\ physics}$ @ 95% CL using formalism of
Erler, et.al.- arXiv:1401.6199v1 [hep-ph] 23 Jan 2014

Experiment	% Precision	$\Delta\sin^2\theta_W$	Λ /g [TeV] (mass reach)		Status
SLAC-E122	8.3	0.011	1.5		published
SLAC-E122	110	0.44	0.25		published
APV (^{205}Tl)	3.2	0.011	3.8		published
APV (^{133}Cs)	0.58	0.0019	9.1		published
SLAC-E158	14	0.0013	4.8		published
Jlab-Hall A	4.1	0.0051	2.2		published
Jlab-Hall A	61	0.051	0.82		published
JLab-Qweak (p)	**6.2**	**0.0011**	**7.5**		**2017**
JLab-SoLID	0.6	0.00057	6.2		conceptual
JLab-MOLLER	2.3	0.00026	11.0		seeking funding
Mainz-P2	2.0	0.00036	13.8		funded (>2020)
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		

Summary

- Because Q_W^p is suppressed in the SM, an accurate determination provides a sensitive measure of $sin^2\theta_W$ and thus a precision test of the **SM**.
- Interpretable measurement of proton's weak charge in the simplest system.
  - ⇨ Most hadronic structure effects determined from global PVES data.
  - ⇨ Other theoretical uncertainties calculated to be small.
- ***Assuming strong contact interaction coupling → $g^2 = 4\pi$ and formalism of Erler, et.al.- arXiv:1401.6199v1 [hep-ph] 23 Jan 2014:***

  → No evidence of new semi-leptonic PV physics to mass scale ~26 TeV.

- If the LHC eventually observes a new neutral boson with mass Λ, our results could help identify it by constraining the magnitude and sign of the coupling-to-mass ratio $g_{e\text{-}p}/\Lambda$
- This experiment builds the scientific and technical foundation for a next generation of measurements.

The Qweak Collaboration

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