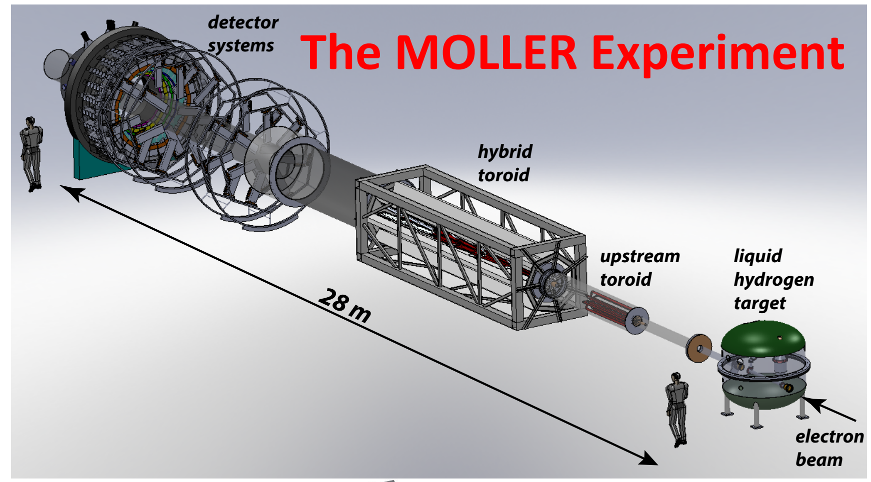
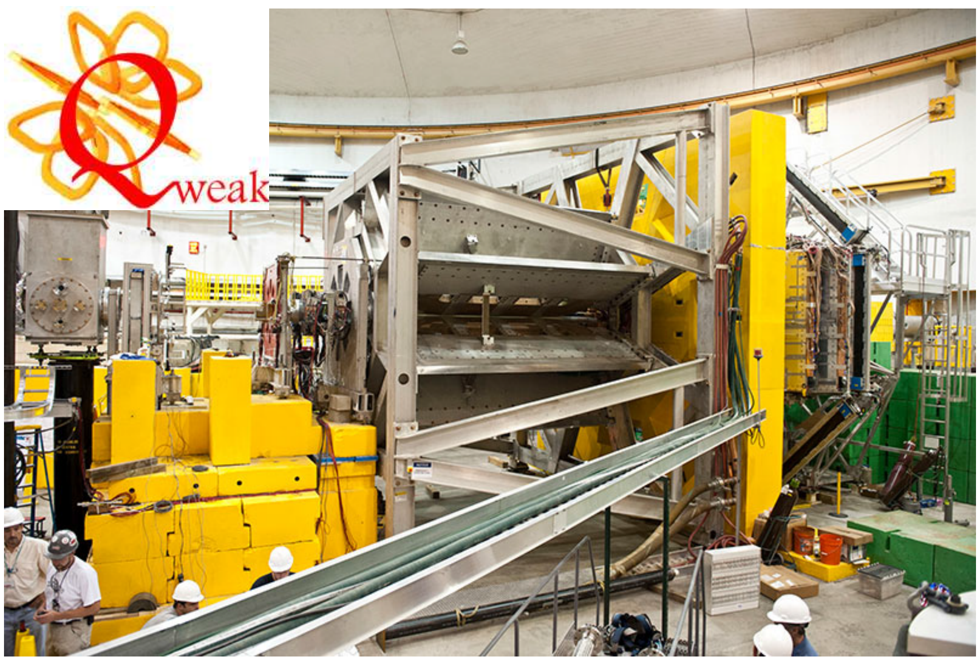
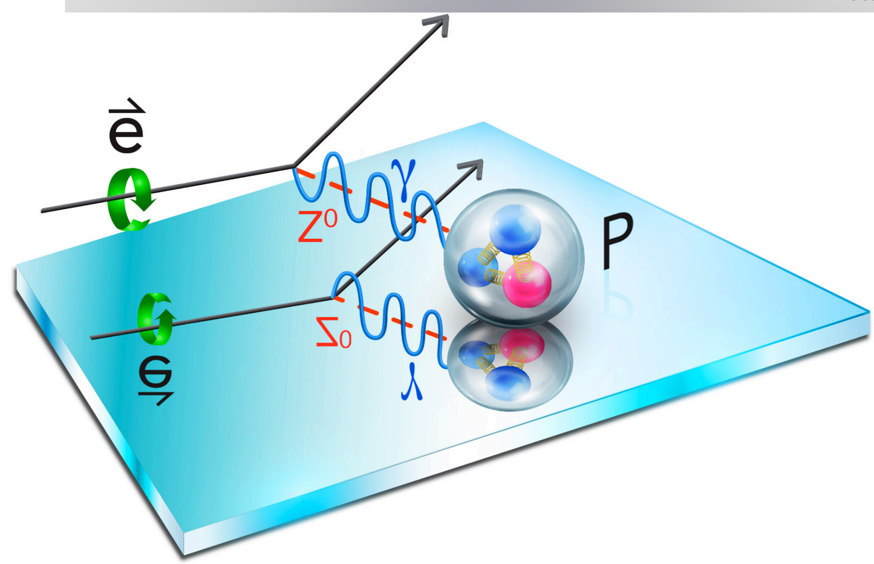
Parity-Violating Electron Scattering – Recent Results and Future Prospects

Mark Pitt, Virginia Tech



Virginia Tech Center for Neutrino Physics Research Day





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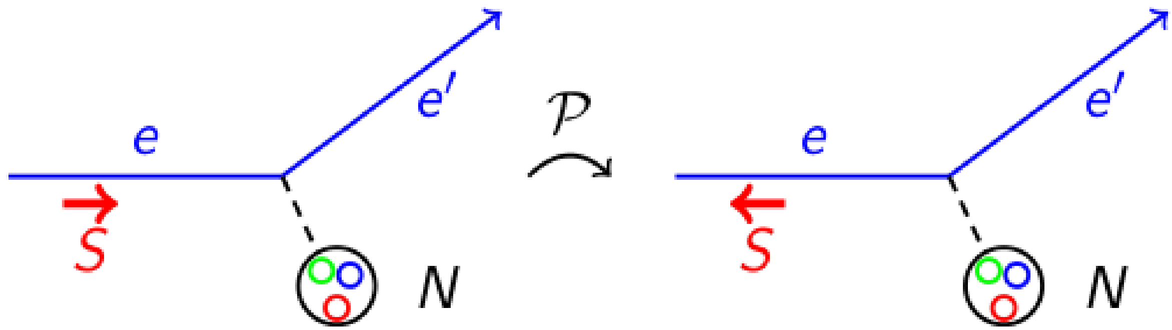
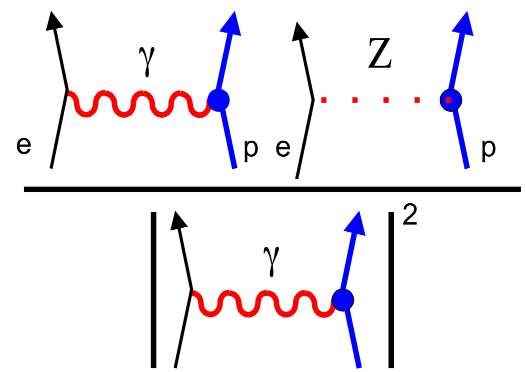
Parity-Violating Electron Scattering – The Basics



$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto$$

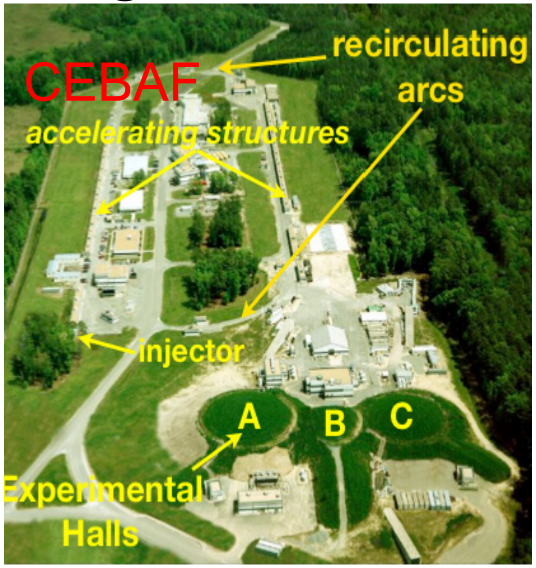


- Longitudinally polarized electrons on unpolarized targets –
  e, **p**, d, ^{4}He, ^{9}Be, ^{12}C, ^{208}Pb
- Measure small parity-violating cross section asymmetry
  (~ 20 ppb – 100 ppm)
- **Elastic** and deep inelastic kinematics
- **Neutral weak current** – **Standard Model test** and select hadronic physics topics

Q_{weak} Experiment at Jefferson Lab

Q_{weak} Collaboration: 101 collaborators, 26 graduate students, 11 postdocs, 27 institutions

Qweak Experiment: parity-violating e-p elastic scattering to measure proton's weak charge



- Initial organizational meeting 2000
- 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 results from the full Q_{weak} dataset published last month: **Nature 557, 207 - 211 (2018)**

The Hunt for New Physics

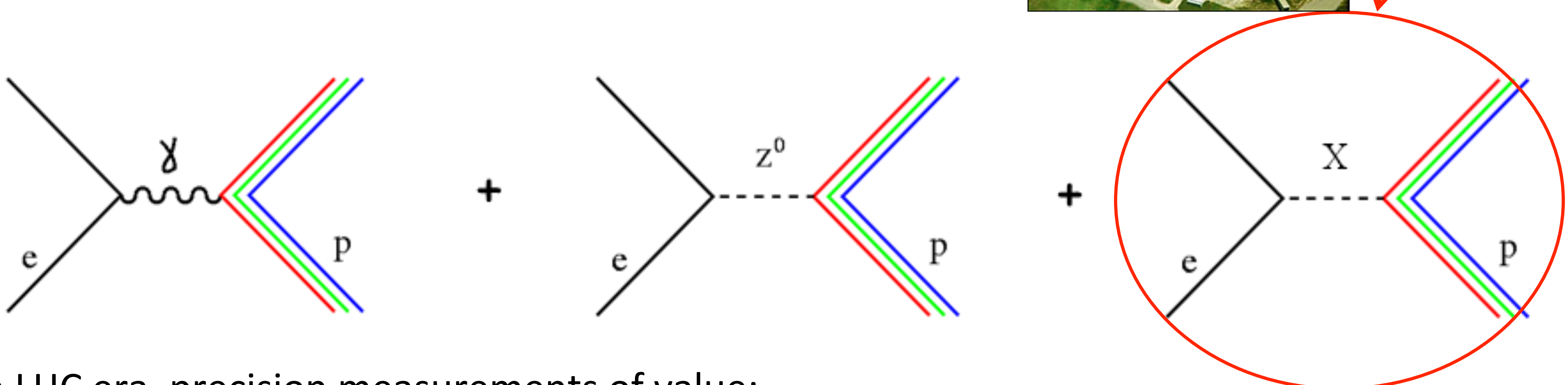
Two complementary approaches to searching for "New Physics"

"Energy frontier" - like LHC

→ Make new particles ("X") directly in high energy collisions

"Precision frontier" – weak charge, g-2(μ), etc.

→ Measure indirect effects of new particles ("X") made virtually in low energy processes



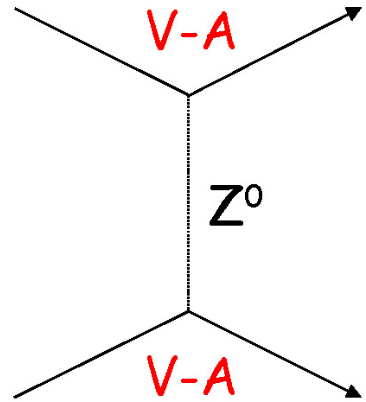
In LHC era, precision measurements of value:

- 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

Standard Model Weak Neutral Current Couplings

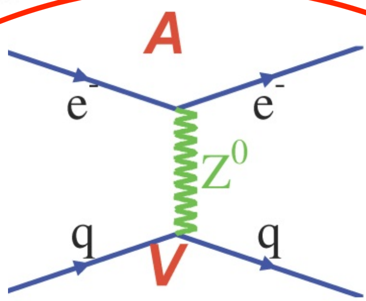
The Standard Model prescribes the couplings of the fundamental fermions to the Z boson:

fermions	$g_A^f = I_3$	$g_V^f = I_3 - 2Q\sin^2\theta_W$
ν_e, ν_μ	$\frac{1}{2}$	$\frac{1}{2}$
$e-, \mu-$	$-\frac{1}{2}$	$-\frac{1}{2} + 2\sin^2\theta_W$
u, c	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$
d, s	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$



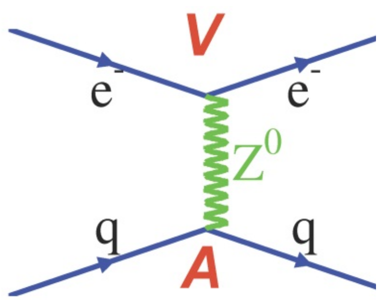
For low energy electroweak tests ($Q^2 << M^2_Z$), restrict to parity-violating e-q and e-e four-fermion contact interaction:

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}\left[\bar{e}\gamma^\mu\gamma_5 e\left(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d\right) + \bar{e}\gamma^\mu e\left(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d} d\gamma_\mu\gamma_5 d\right) + C_{ee}\bar{e}\gamma^\mu\gamma_5 e\left(\bar{e}\gamma_\mu e\right)\right]$$



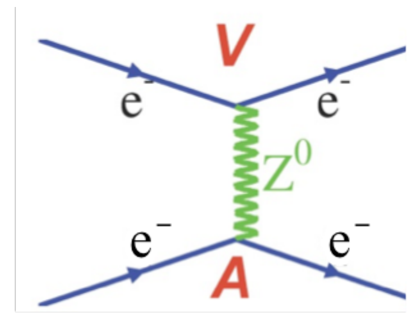
$$C_{1i} \equiv 2g_A^e g_V^i$$

quark vector: C_{1u}, C_{1d}



$$C_{2i} \equiv 2g_V^e g_A^i$$

quark axial-vector: C_{2u}, C_{2d}



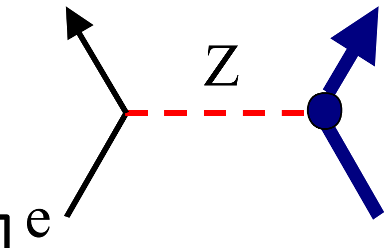
$$C_{ee} \equiv 2g_V^e g_A^e$$

electron: C_{ee}

C_{1u}, C_{1d}, C_{ee} : "Weak Charges": neutral current analog to the electric charges

“Weak Charges” in Low Energy Neutral Current Tests

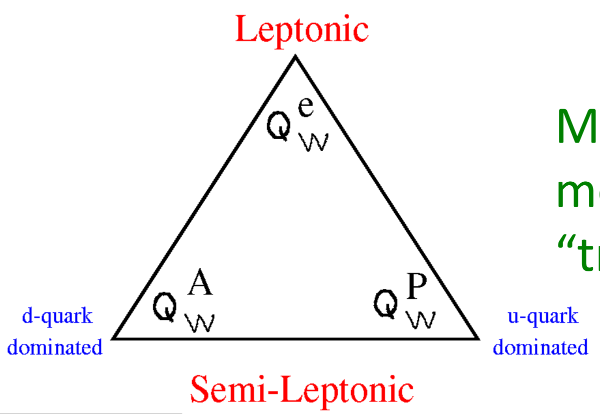
C_{1u}, C_{1d}, C_{ee} : “Weak Charges”: neutral current analog to the electric charges



Electron’s weak charge: $Q_W^e \equiv -2C_{ee} = -(1-4\sin^2\theta_W)$

parity-violating Møller scattering $\vec{e} + e \rightarrow e + e$

- **published: SLAC E158 ~ 13% on Q^e_W**



Most precise low energy measurements define a weak charge “triad” (M. Ramsey-Musolf)

“Neutron’s weak charge”:

$$Q^A_W(Z,N) \equiv -2\left[C_{1u}(2Z+N) + C_{1d}(Z+2N)\right]$$
$$\approx Z\left(1-4\sin^2\theta_W\right) \text{-} N(1) \approx \text{-}N$$

Atomic parity violation

- **published: ^{133}Cs ~ 0.6% on Q^A_W**

Proton’s weak charge:

$$Q_W^p \equiv -2\left[2C_{1u} + C_{1d}\right] = \left(1-4\sin^2\theta_W\right)$$

parity-violating elastic ep scattering

$\vec{e} + p \rightarrow e + p$

- **published: JLab Qweak ~ 6% on Q^p_W**

Q^e_W and Q^p_W are suppressed in Standard Model → increased sensitivity to new physics.

ie. 6% on Q^p_W=0.0708 sensitive to **new neutral current amplitudes as weak as ~ 4×10^{-3} G_F**

Parity-Violating Electron Scattering Experiments – A Brief History

Pioneering (1978) early SM test

SLAC E122 PVDIS – Prescott *et al.*

A = -152 ppm

Bates: ^{12}C, Mainz: ^{9}Be

Strange Form Factors

(1998 – 2009)

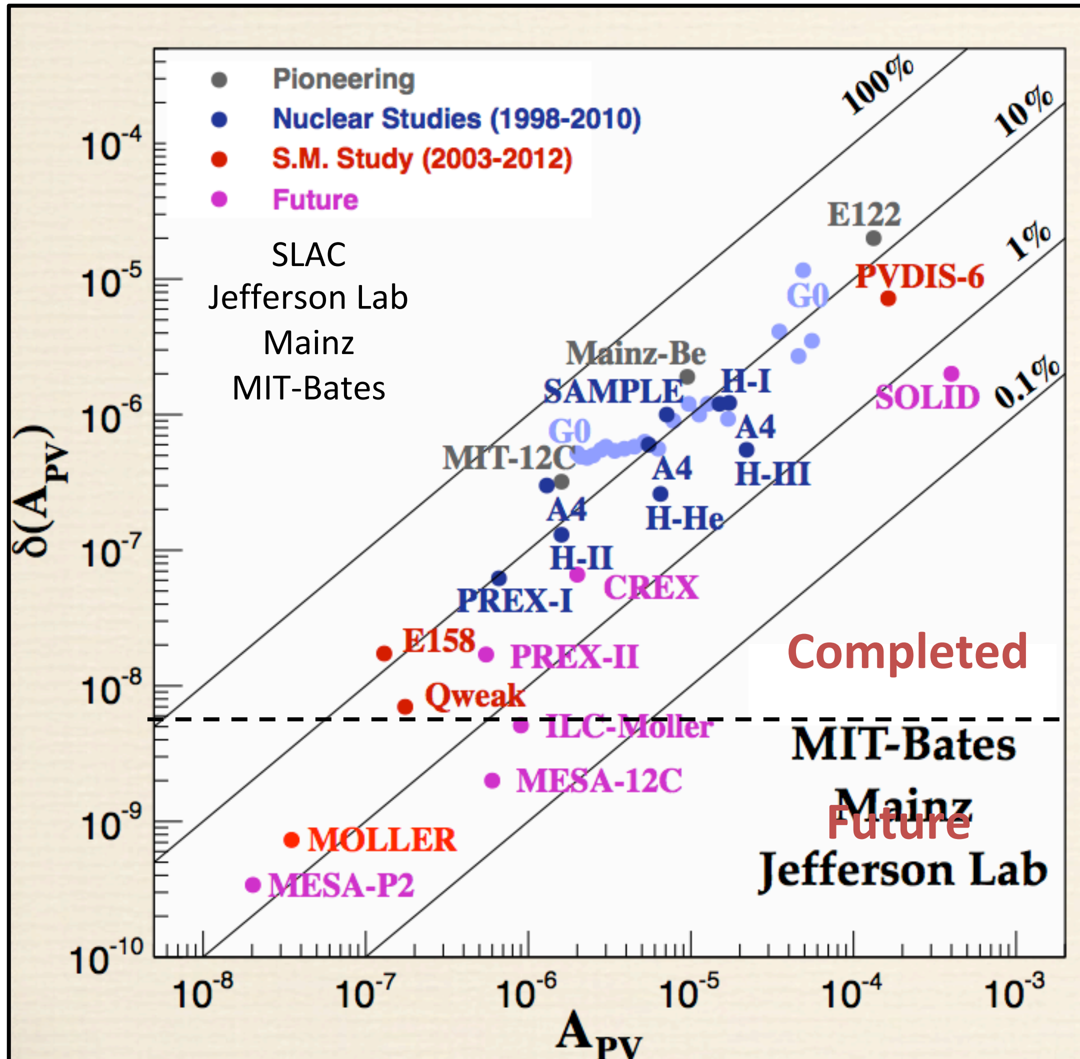
SAMPLE, G0, A4, HAPPEX

A ~ 1 – 50 ppm

Standard Model Tests

(2003 – present)

SLAC E158 Moller: A = - 131 ppb



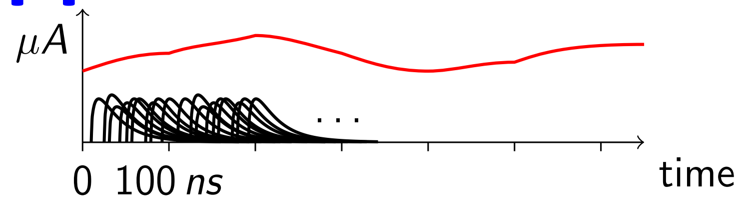
JLAB Q_{weak}: A ~ -230 ppb, ΔA = 9 ppb,

ΔA/A = 4%　　MOLLER -33 ppb, ΔA =0.8 ppb,　ΔA/A = 2.4%

Qweak Experimental Apparatus

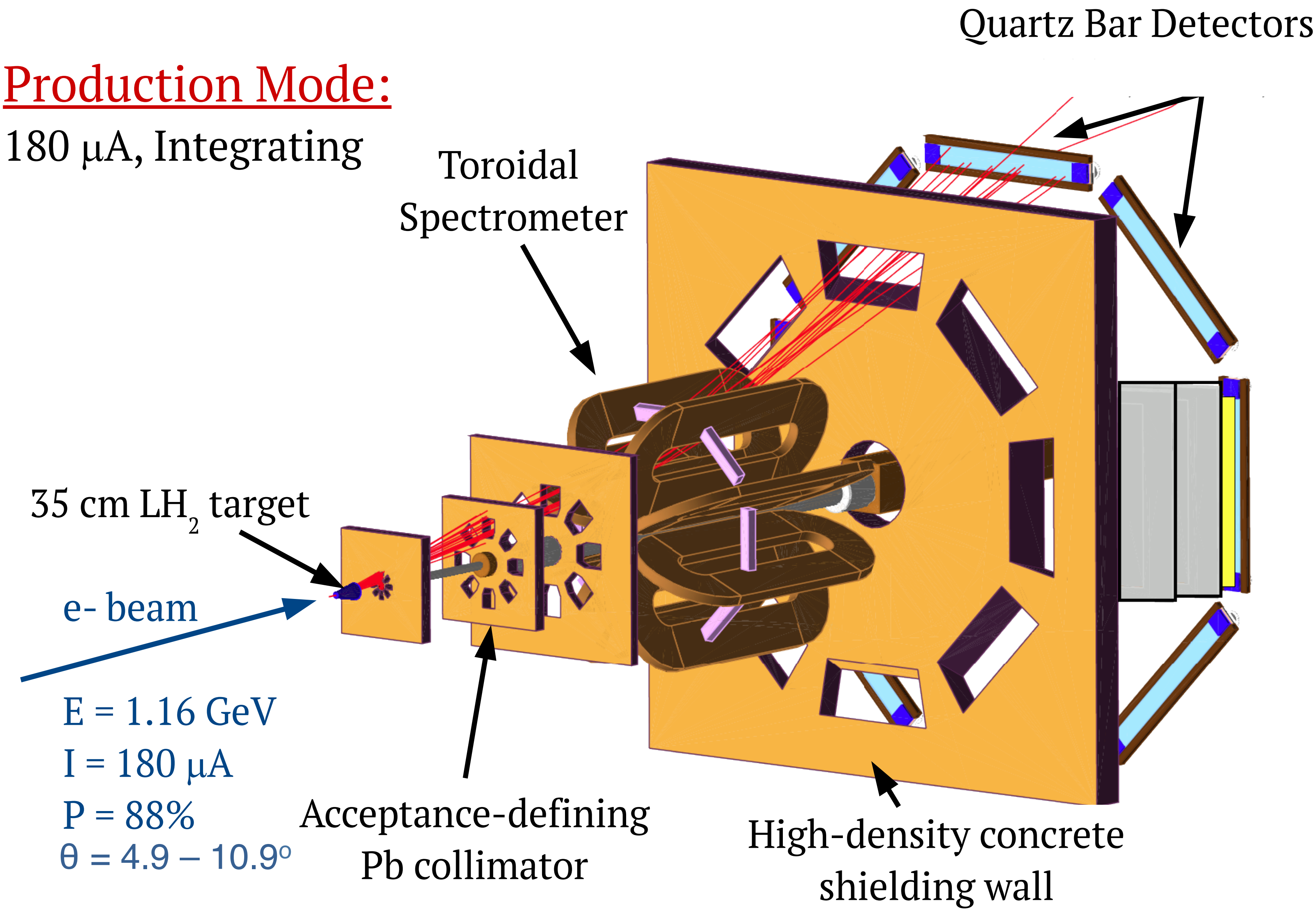
Production: ~ 800 MHz rates

must integrate PMT current

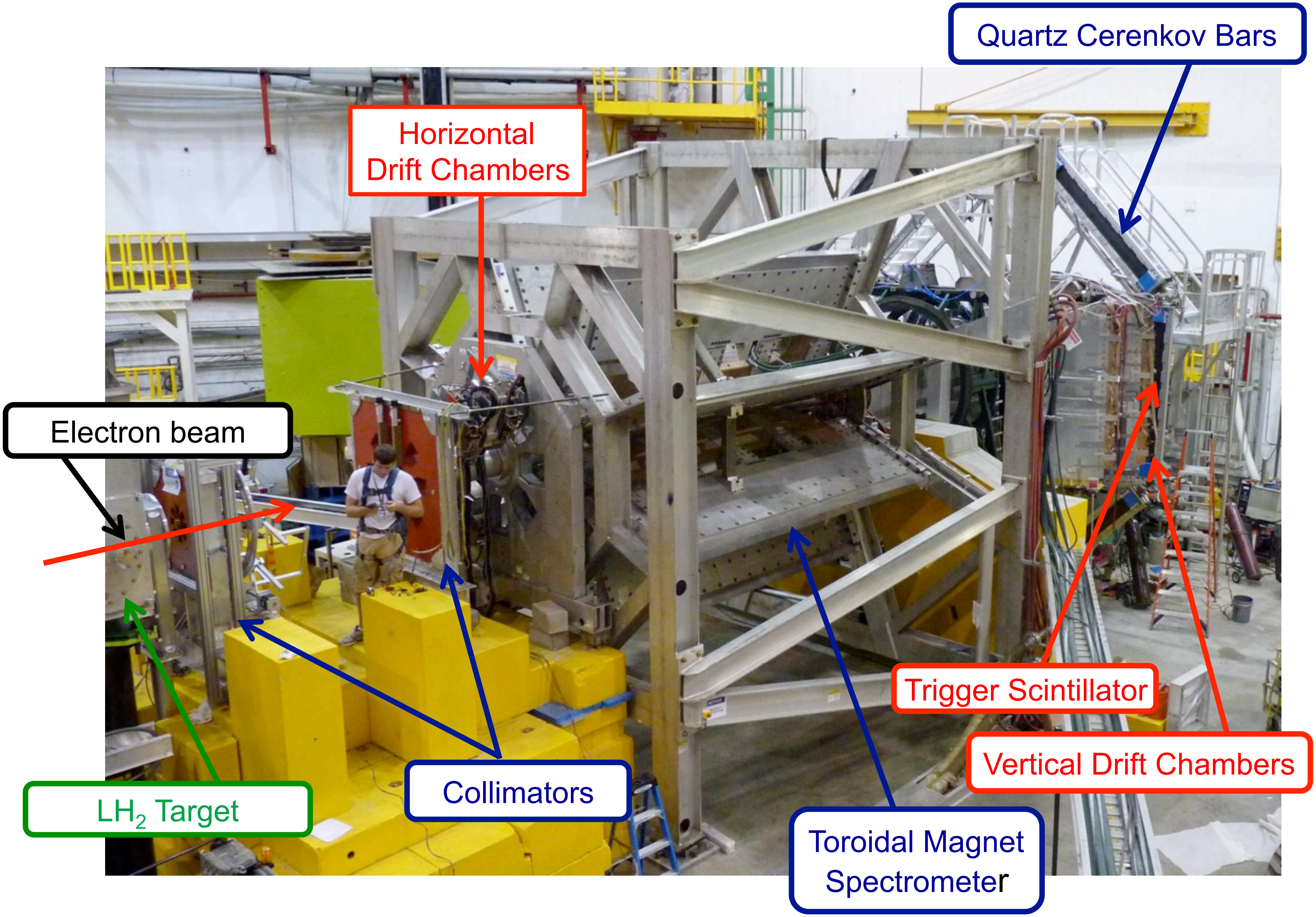


Production Mode:

180 μA, Integrating



Qweak Apparatus During Installation



From Measured Asymmetry to Physics Asymmetry

Correct **raw** asymmetry for measured false asymmetry effects to get **measured** asymmetry

$$A_{raw} = \frac{Y^+ - Y^-}{Y^+ + Y^-}$$

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

Correct **measured** asymmetry for polarization, backgrounds, acceptance, etc. to get **ep physics** asymmetry

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

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

Quantity	Run 1	Run 2
$A_{\rm raw}$	-192.7 ± 13.2 ppb	-170.7 ± 7.3 ppb
$A_{\rm T}$	0 ± 1.1 ppb	0 ± 0.7 ppb
$A_{\rm L}$	1.3 ± 1.0 ppb	1.2 ± 0.9 ppb
$A_{\rm BCM}$	0 ± 4.4 ppb	0 ± 2.1 ppb
$A_{\rm BB}$	3.9 ± 4.5 ppb	-2.4 ± 1.1 ppb
$A_{\rm beam}$	18.5 ± 4.1 ppb	0.0 ± 1.1 ppb
$A_{\rm bias}$	4.3 ± 3.0 ppb	4.3 ± 3.0 ppb
$A_{\rm msr}$	-164.6 ± 15.5 ppb	-167.5 ± 8.4 ppb
P	87.66 ± 1.05 %	88.71 ± 0.55 %
f_1	2.471 ± 0.056 %	2.516 ± 0.059 %
A_1	1.514 ± 0.077 ppm	1.515 ± 0.077 ppm
f_2	0.193 ± 0.064 %	0.193 ± 0.064 %
f_3	0.12 ± 0.20 %	0.06 ± 0.12 %
A_3	-0.39 ± 0.16 ppm	-0.39 ± 0.16ppm
f_4	0.018 ± 0.004 %	0.018 ± 0.004 %
A_4	-3.0 ± 1.0 ppm	-3.0 ± 1.0ppm
$R_{\rm RC}$	1.010 ± 0.005	1.010 ± 0.005
$R_{\rm Det}$	0.9895 ± 0.0021	0.9895 ± 0.0021
$R_{\rm Acc}$	0.977 ± 0.002	0.977 ± 0.002
R_{Q^2}	0.9928 ± 0.0055	1.0 ± 0.0055
$R_{\rm tot}$	0.9693 ± 0.0080	0.9764 ± 0.0080
$\sum f_i$	2.80 ± 0.22 %	2.78 ± 0.15 %

→ Run 1 and 2 were statistics limited

Dominant systematic errors were both expected and unexpected (as can happen when pushing the boundaries in precision):

Expected and planned for:

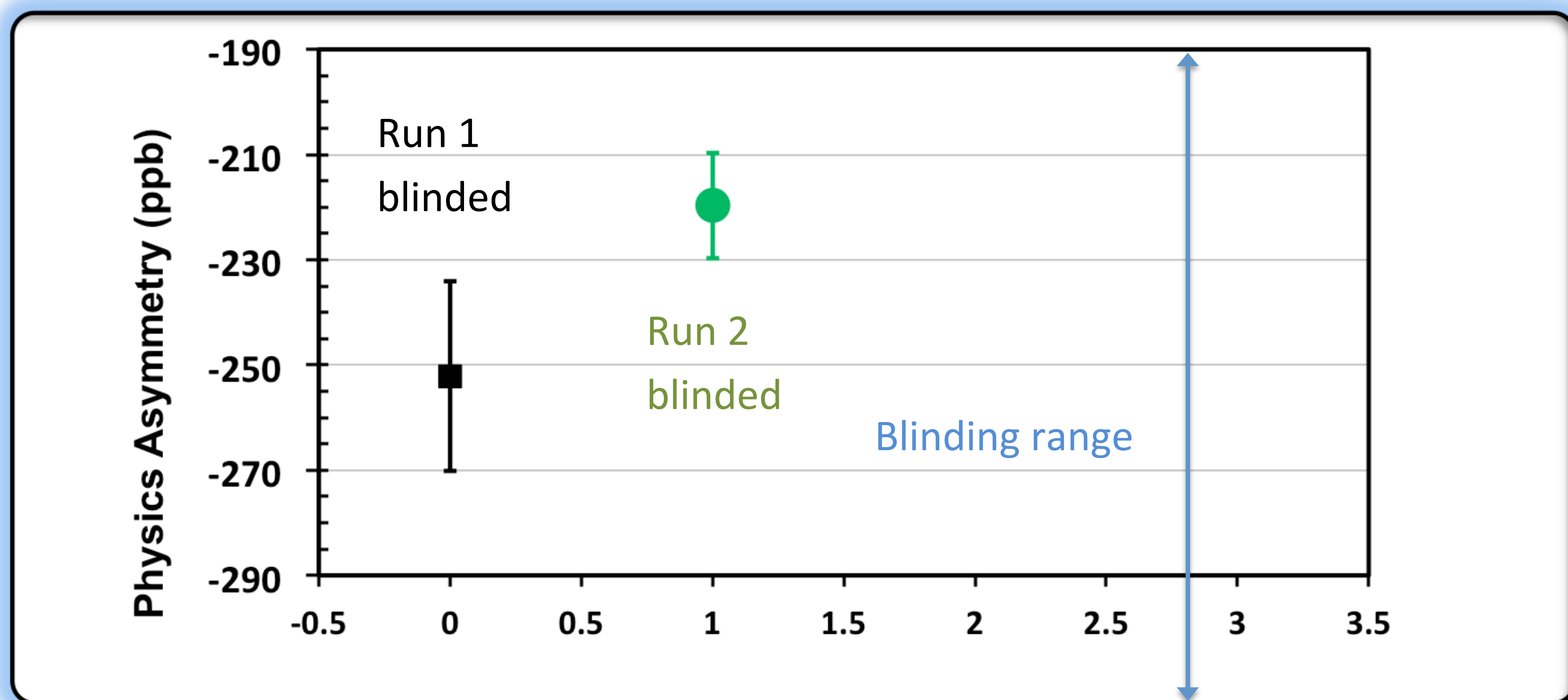
- Beam Asymmetries A_{beam}
- Aluminum target windows A_1

Unexpected but symmetry and auxiliary background detectors made them manageable

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

Blinded analysis

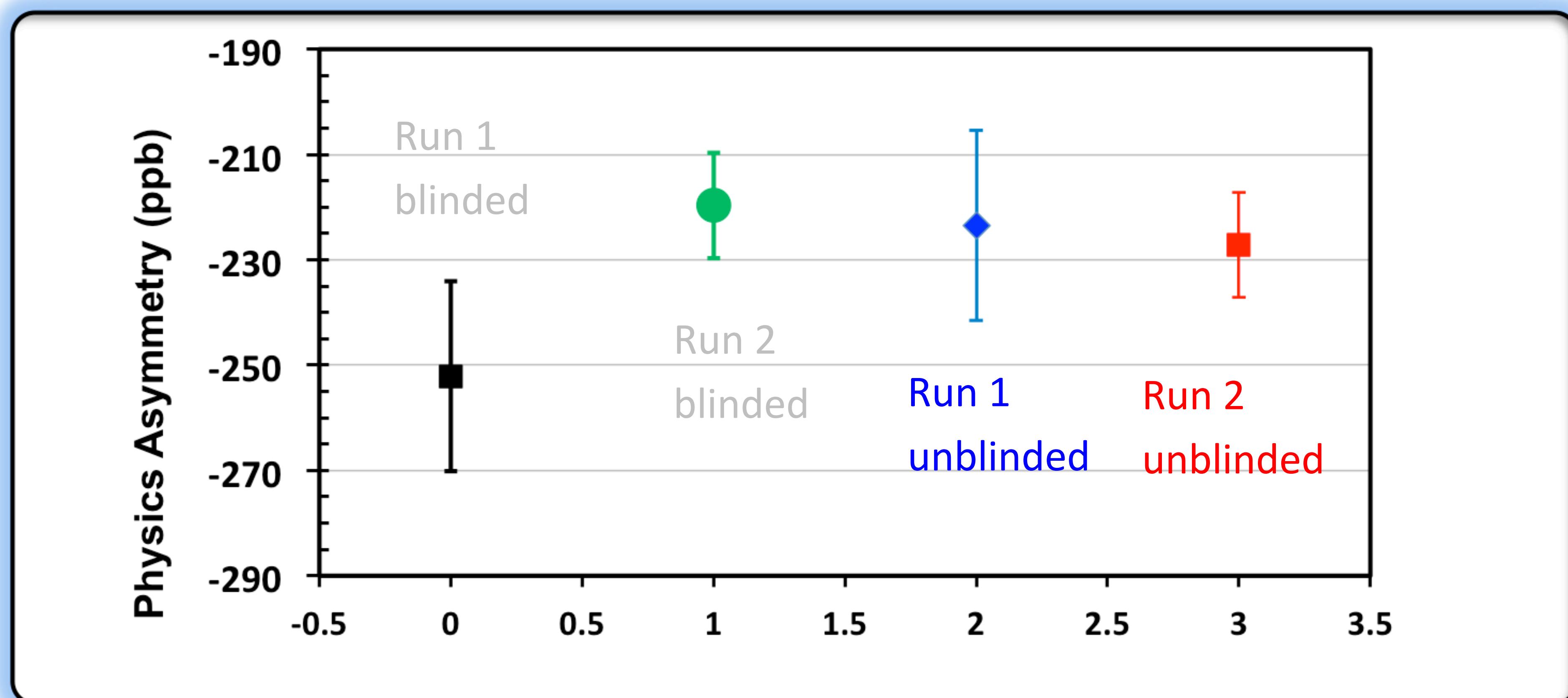
Run 1 and 2 each had its own independent "blinding factor" (additive offset in range ±60 ppb) to avoid analysis bias.



Un-Blinded Analysis

Excellent agreement between the two runs

(several systematic corrections rather different between 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

Un-Blinded Analysis

Excellent agreemen

(several systematic ... two runs)

It didn't happen if you don't tweet about it!

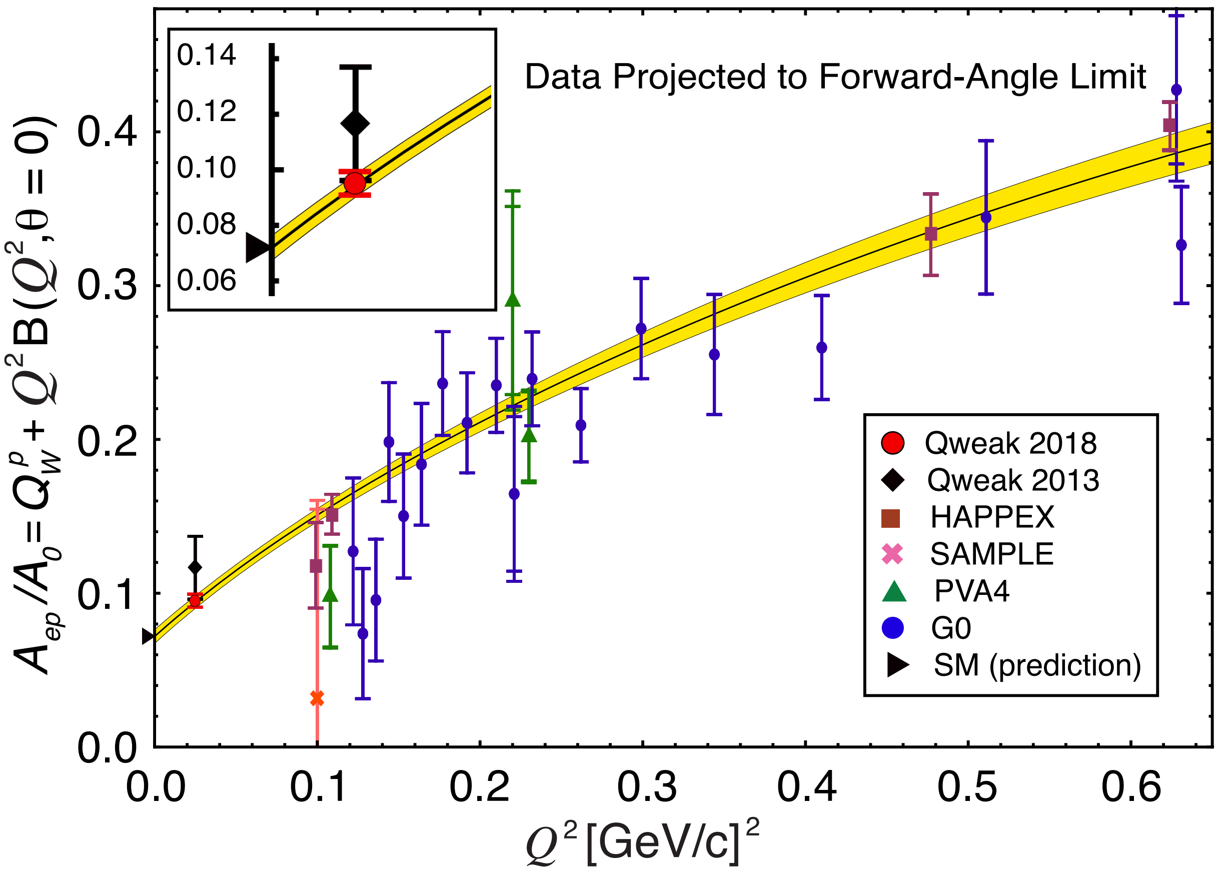
Extraction of Q_{weak} From e-p Asymmetry

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

Global fit of world PVES data up to $Q^2 = 0.63$ GeV^2 is done to extract the proton's weak charge

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

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



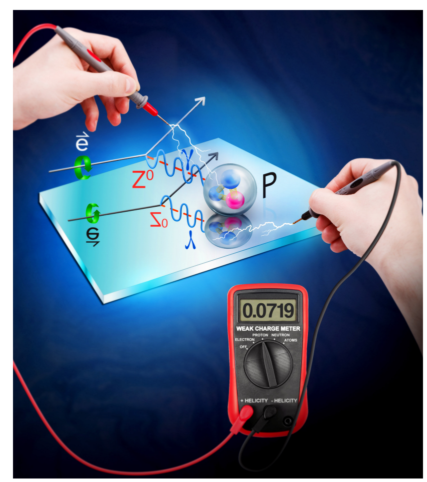
Standard Model:

$Q_W^p = 0.0708 \pm 0.0003$

Experiment:

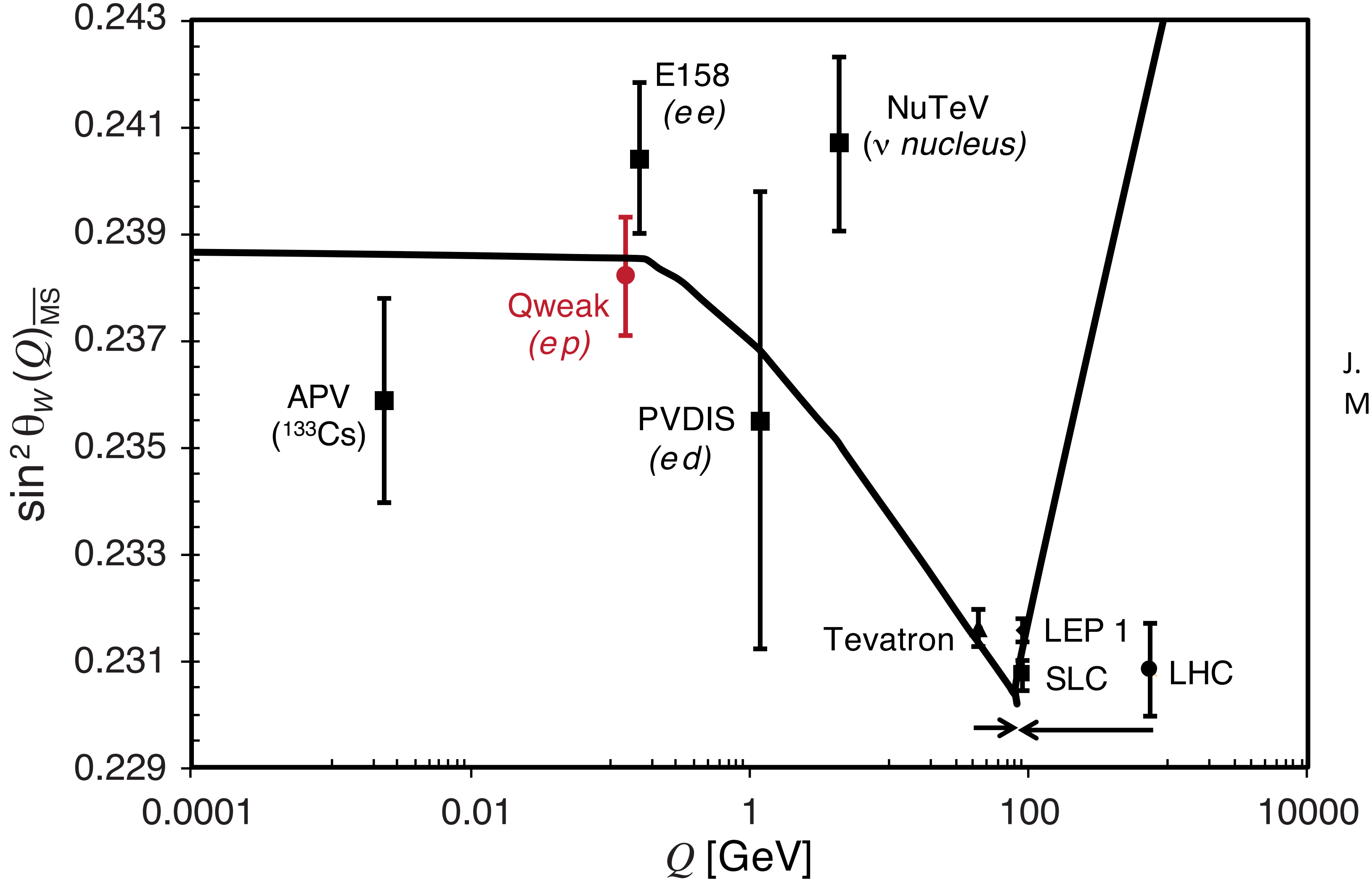
$Q_W^p = 0.0719 \pm 0.0045$

Nature 557, 207 - 211 (2018)



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

Q_{weak} completes the low Q^2 "weak charge triad" by adding a precision measurement of the proton's weak charge.



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

Note: interference effects of heavy new physics (ie. Z', leptoquarks) is suppressed at Z resonance so LEP/SLC mass limits ~<TeV, while low energy observables probe few TeV scale

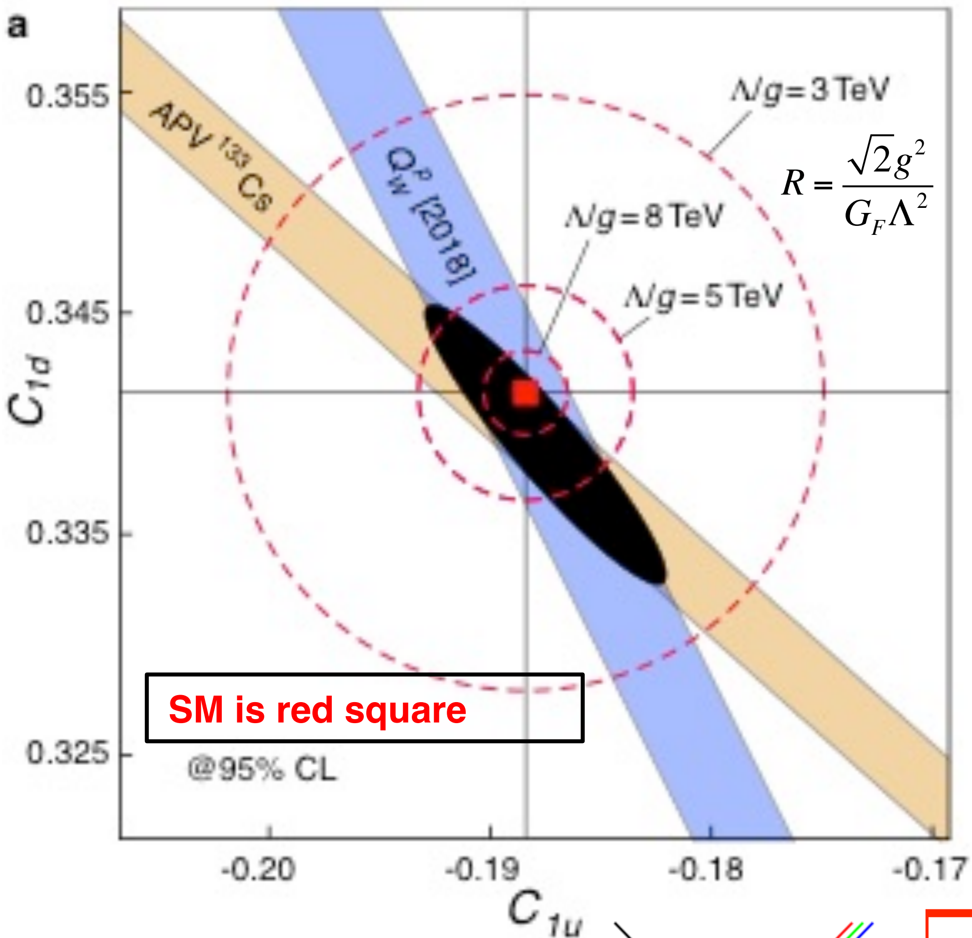
Limits on Semi-Leptonic PV Physics Beyond the SM

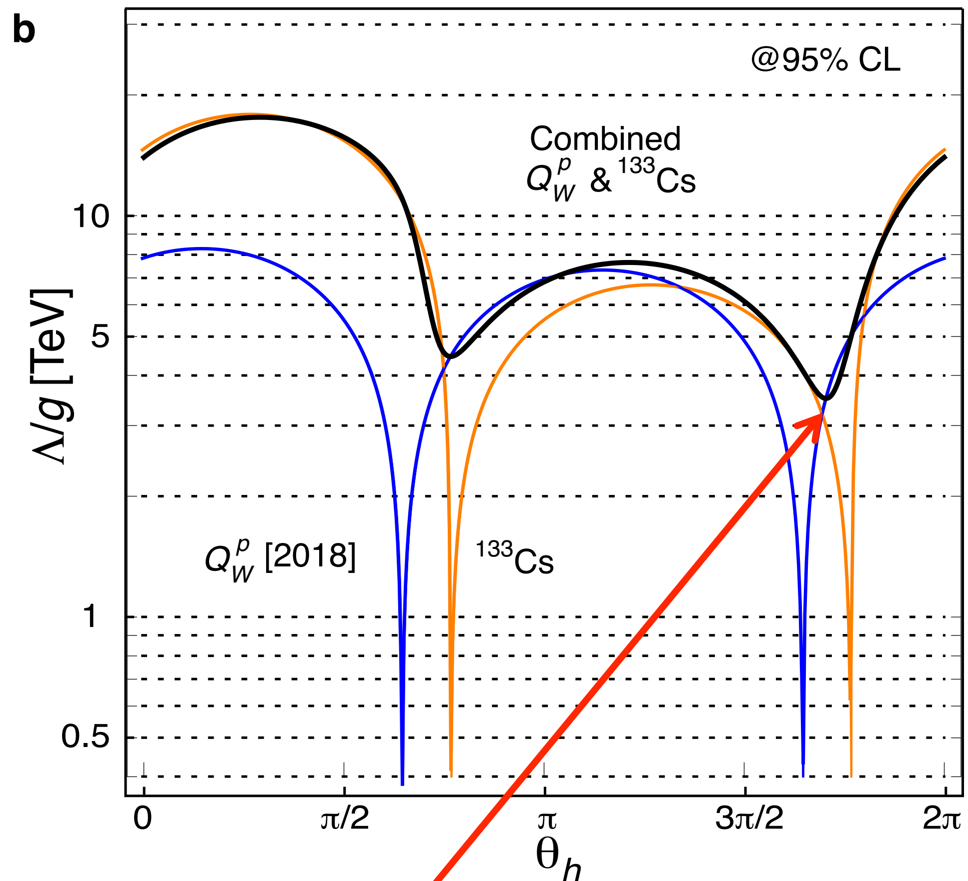
$$\mathcal{L}_{\rm NP}^{\rm PV} = -\frac{g^2}{\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

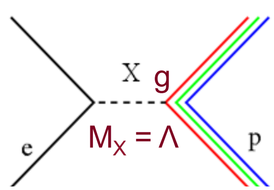
$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$

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

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







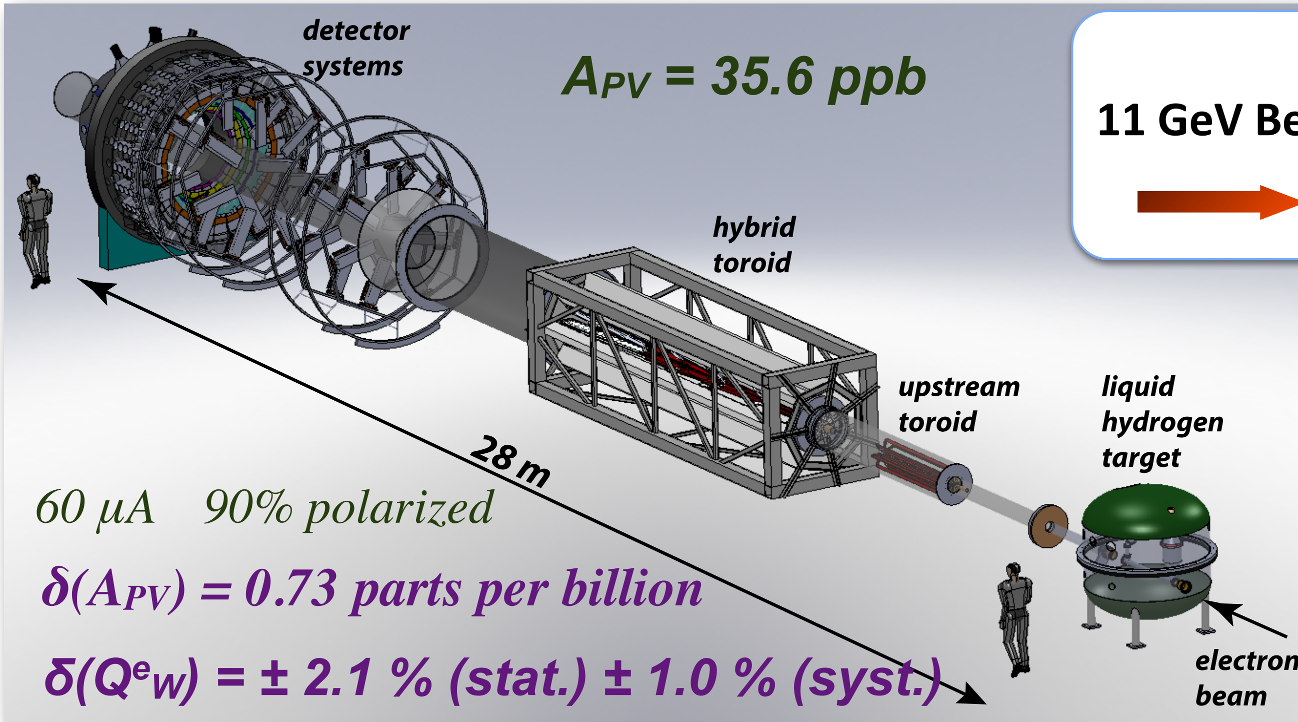
g=coupling strength
Λ=mass scale

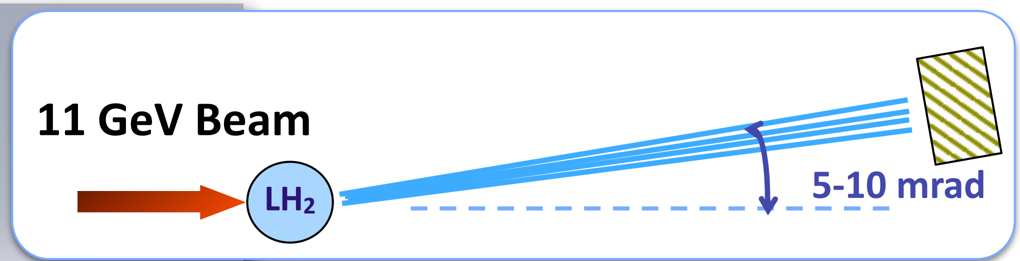
$$\theta_h \text{ independent limit: } \frac{\Lambda}{g} > 3.5\text{ TeV @95\% CL}$$

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

Future: MOLLER Experiment at 11 GeV JLab

An ultra-precise measurement of the weak mixing angle using Møller scattering



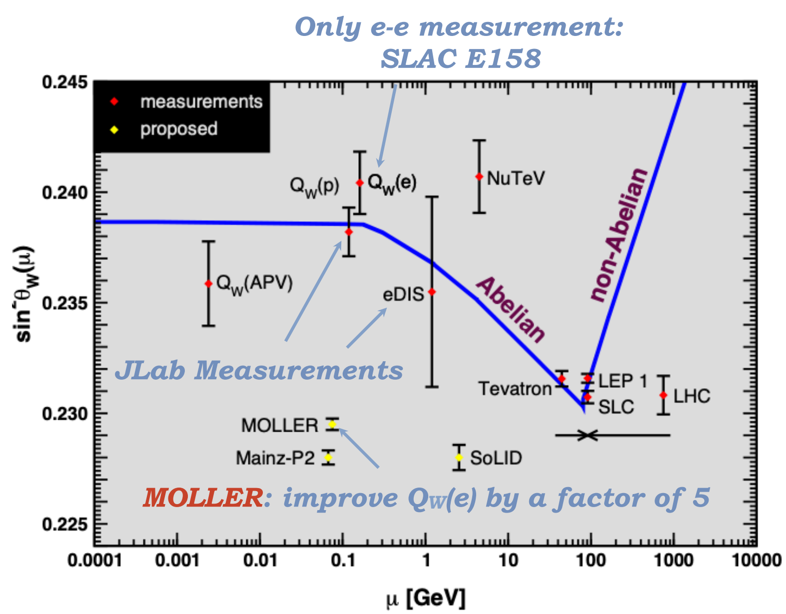


Parity-violating Møller scattering

$$\vec{e} + e \rightarrow e' + e'$$

$$Q_W^e \equiv -2C_{ee} = -(1 - 4\sin^2\theta_W)$$

- Precision goal – 2.4% on electron's weak charge
  - factor of 5 improvement over E158
- 0.1% precision on $\sin^2\theta_W$ at low Q^2 – comparable to best collider determinations



Status:

- 120 collaborators, 30 institutions
- \$30-35M MIE Proposal
- Achieved DOE "CD0" status
- Moving towards "CD1" status
- Hoped for data-taking in 2024

Physics Potential of Precision Electron Weak Charge Measurement from MOLLER

The MOLLER experiment provides:

- **Excellent sensitivity to Beyond Standard Model (BSM) physics**

  High precision measurement $\delta(Q_W^e)/Q_W^e \sim \pm 2.4\%$

  of suppressed SM observable $Q_W^e = -\left(1 - 4\sin^2\theta_W\right) \sim -.046$

  $\longrightarrow$ **sensitive to new neutral current amplitudes as weak as ~ 10^{-3} G_F**

  Most sensitive probe of new flavor and CP-conserving neutral current interactions over next decade

  - new TeV scale dynamics (Z', supersymmetry, doubly charged scalars,…)
  - weakly coupled MeV – GeV scale mediators (dark photons, …)

- **High precision benchmark point within the Standard Model**

  $\delta(\sin^2\theta_W) \sim \pm 0.00024\,(\text{stat.}) \pm 0.00013\,(\text{syst.})$

  ~ 0.1% precision, comparable to sensitivity of best collider determinations

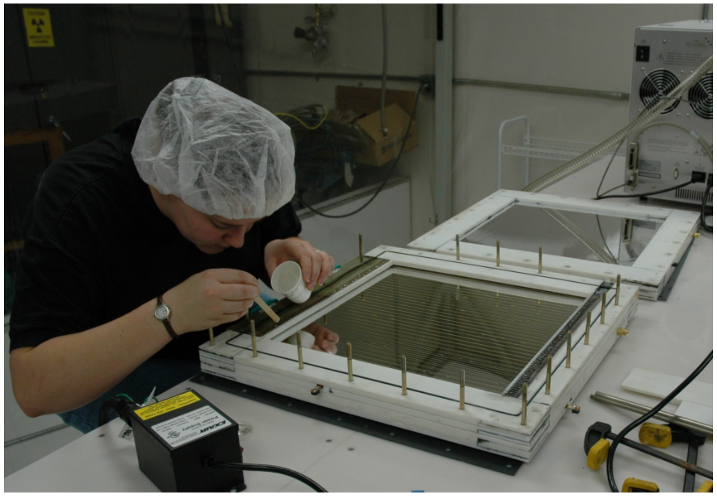
Other measurements on same timescale	$\delta(\sin^2\theta_W)$
Mainz MESA P2	~ ±0.00034
Final Tevatron	~ ±0.00041
LHC 14 TeV, 300 fb^{-1}	~ ±0.00036

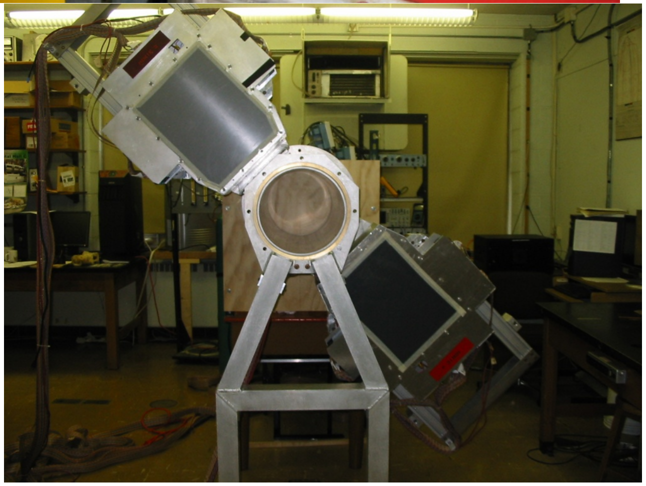
MOLLER Complementarity to LHC

- **If LHC sees ANY anomaly in Runs 2 or 3 (~2022)**
  - **The unique discovery space provided by MOLLER will become a pressing need, like other sensitive probes (eg. *g-2* anomaly)**
- **If LHC observes no anomaly in next decade, MOLLER sensitive to discovery scenarios beyond LHC signatures**
  - **Hidden weak scale scenarios (eg. compressed supersymmetry)**
  - **Lepton number violating amplitudes**
  - **Light dark matter mediators**
  - **…**

Most sensitive discovery reach over the next decade for CP-/ flavor- conserving or lepton number violating scattering amplitudes

Virginia Tech Contributions and Personnel




- VT contributions: luminosity monitors, drift chambers, halo monitors, simulations, analysis
- Undergraduates: Kevin Finelli, Jim Dowd, Elizabeth Bonnell, Jackson Walters, John Echols, Jon Hoffman, Jonathan Baker, Bevin Huang, Kyle Stewart, Alex Nikrant, Alejandro Sosa, Carlos Segovia-Bustamante, Danny Vowell, Cheyenne Neff, Chris Wollbrink
- Graduates: Juliette Mammei, John Leacock, Wade Duvall, Anna Lee
- Postdoc: Riad Suleiman
- Senior staff: Norman Morgan

Summary

- Parity-violating electron scattering provides stringent low energy tests of the Standard Model

- **Qweak Experiment:** Parity-violating elastic e-p scattering

  - Final result: Nature 557, 207 − 211 (2018)

  - precision determination of proton's weak charge

$$Q_W^p(\mathrm{PVES}) = 0.0719 \pm 0.0045 \qquad Q_W^p(\mathrm{SM}) = 0.0708 \pm 0.0003$$

  - Constrains generic new parity-violating "Beyond the Standard Model Physics" at TeV scale: ruled out at $\Lambda/g < 3.5$ TeV at 95% CL

- **MOLLER Experiment:** Parity-violating elastic e-e scattering

  - new initiative being developed for Jlab

  - anticipated 0.1% precision on weak mixing angle

  - sensitive down to 10^{-3} G_F ; mass scales to Λ/g ~ 7.5 TeV

  - best discovery reach for flavor and CP conserving process over next decade