# Measurement of the weak charge of the proton with Qweak

Ciprian Gal
University of Virginia

# The Qweak Collaboration

101 collaborators 26 grad students
11 post docs 27 institutions

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[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 Univers
[13] Virginia Polytechnic Instit
[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

A SEARCH FOR NEW PHYSICS

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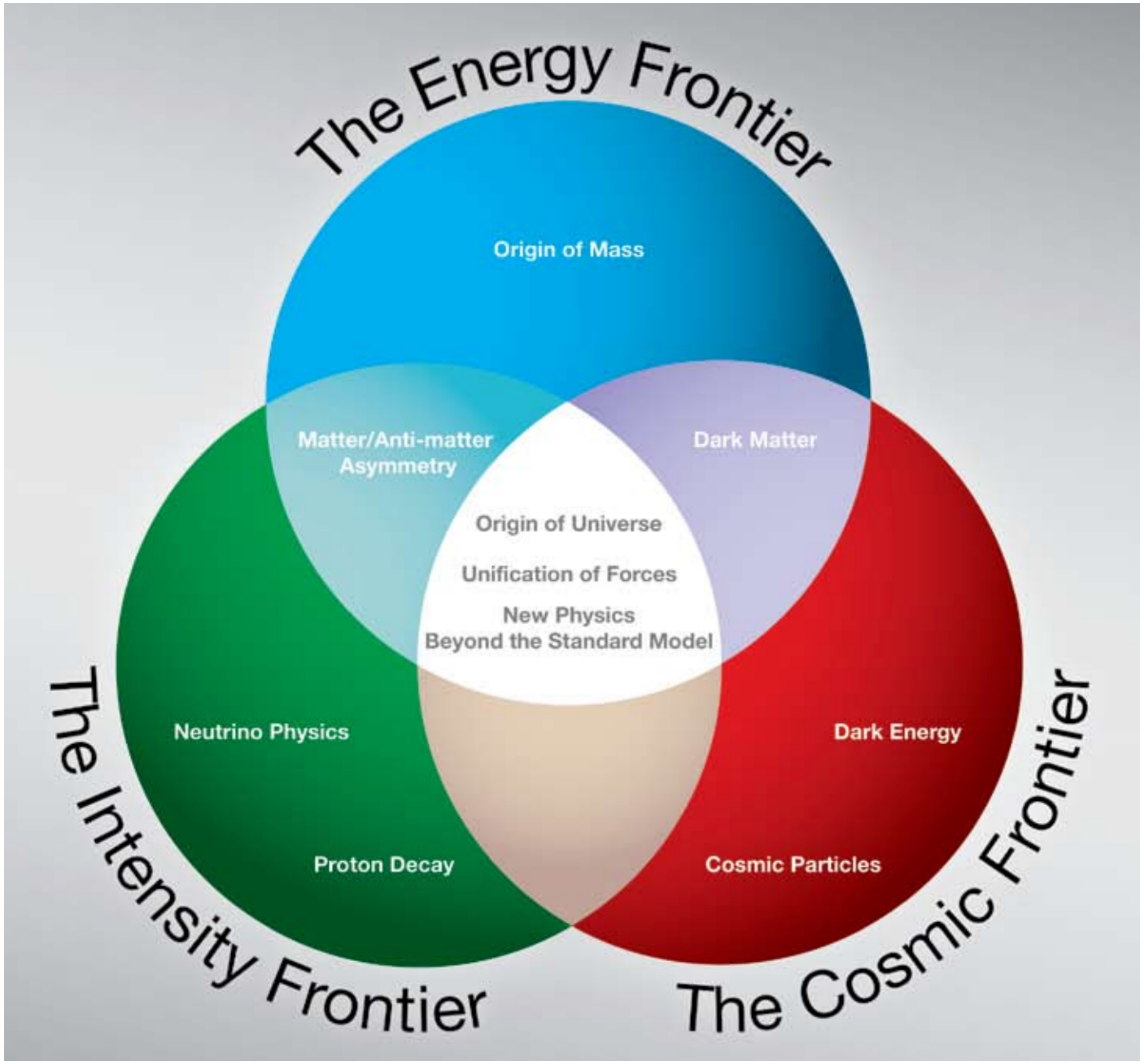
Jefferson Lab

Spokespersons Project Manager Grad Students *deceased

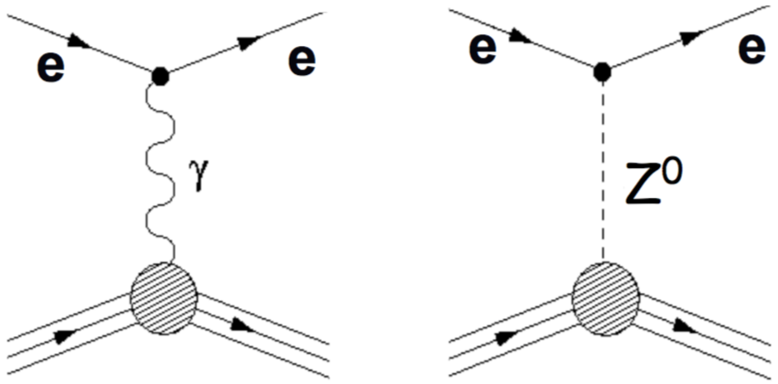
# The path to discovery



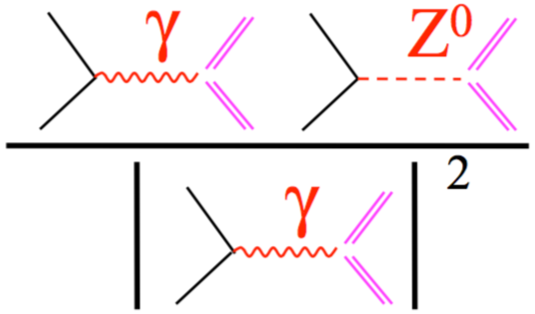
https://science.energy.gov/~/media/hep/pdf/files/pdfs/p5_report_06022008.pdf

- In order to reveal the way nature works a multi-pronged approach is needed
- From astronomical observations (cosmic frontier) to direct measurements (energy frontier) to indirect measurements (intensity frontier)
    - some of our most tantalizing results have come from indirect searches where we get hints at what could lie ahead
- Each of these paths comes with their own pros and cons

# Particle physicists' intro to PVES



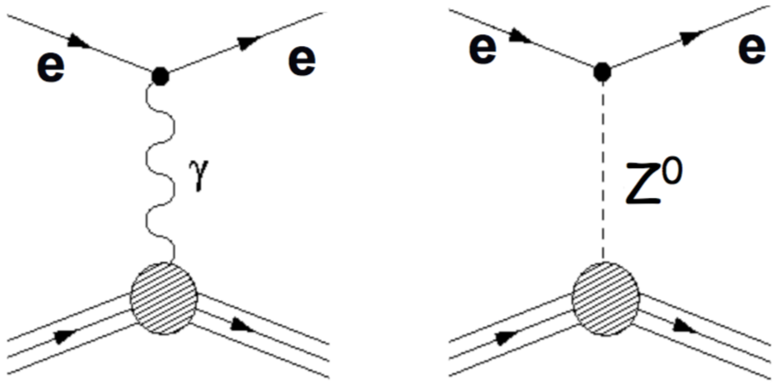
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$

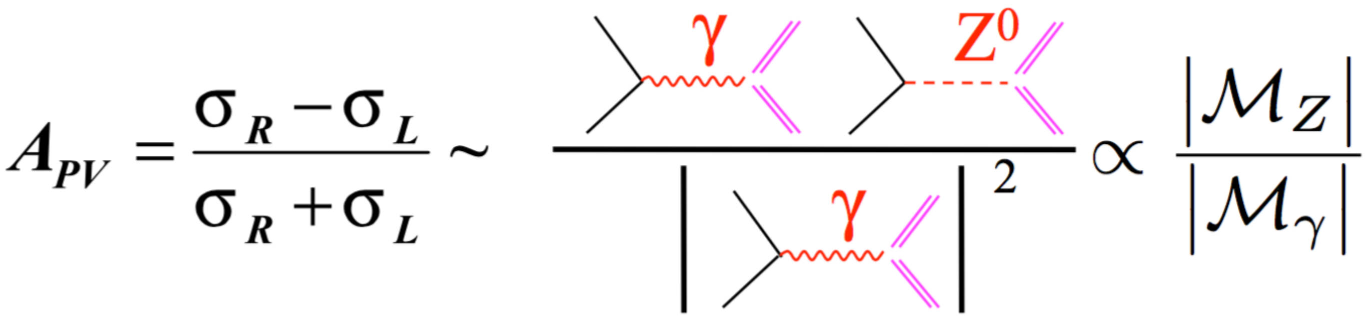


$$\propto \frac{|\mathcal{M}_Z|}{|\mathcal{M}_\gamma|}$$

- uses longitudinally polarized electron beams
- measures asymmetries that are generally on the level of ppm or less

# Particle physicists' intro to PVES





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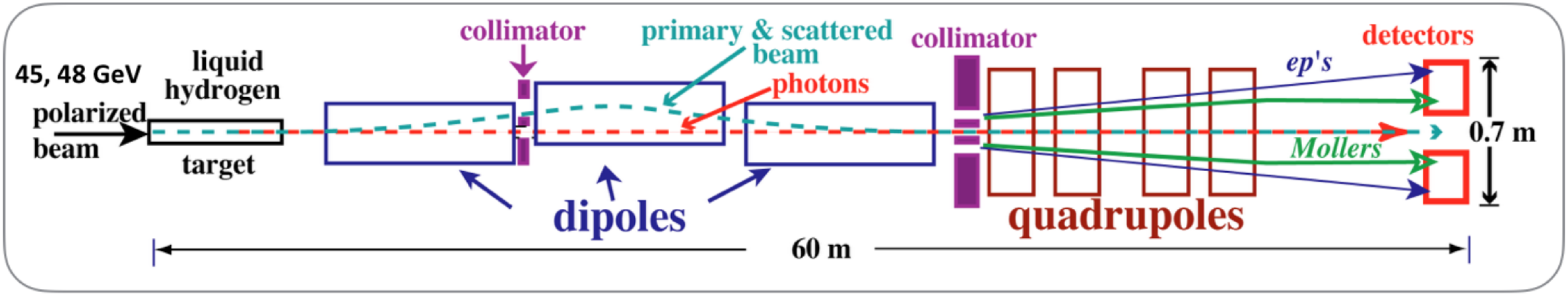

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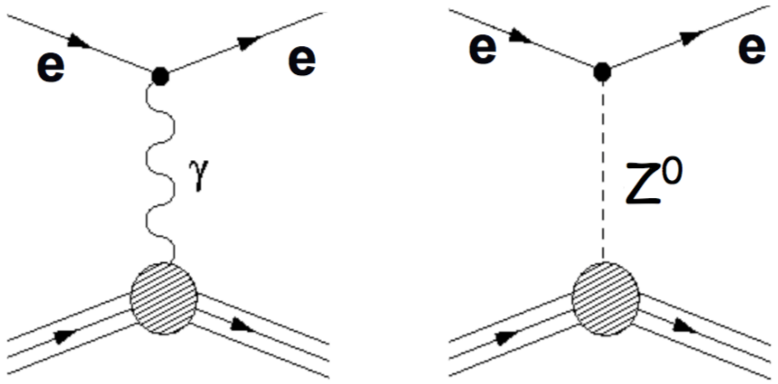

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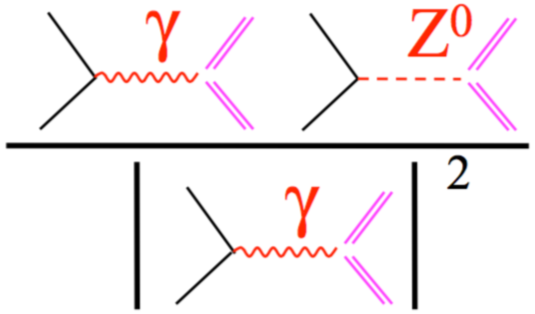

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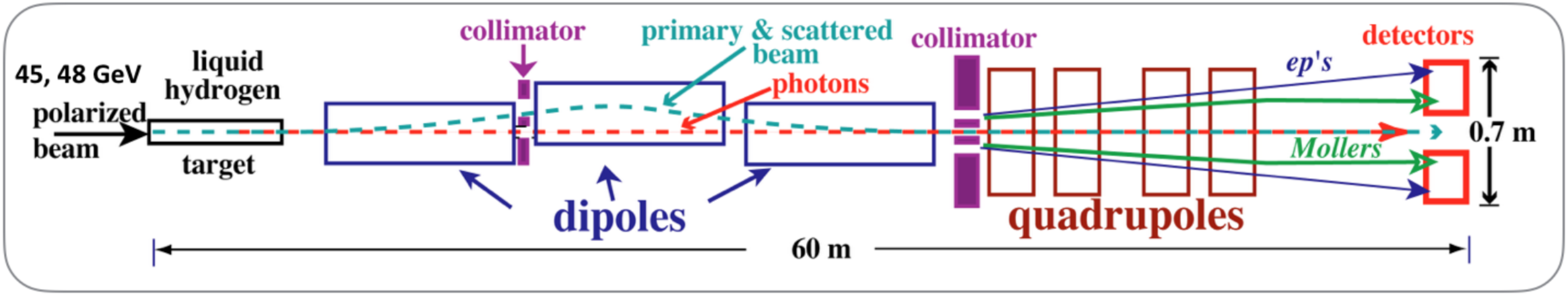
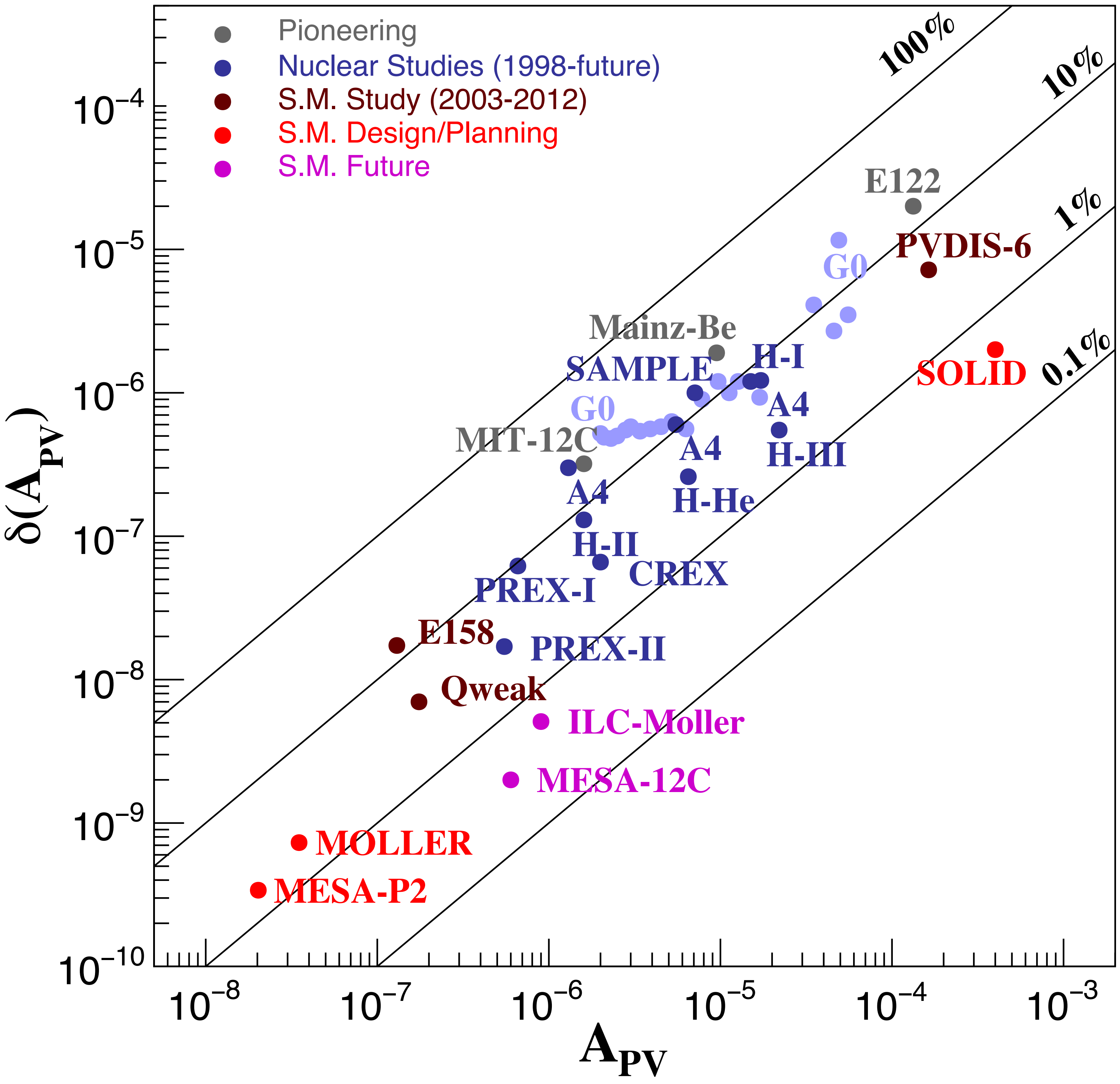


Allows for the collection of large amounts of data (100s of MHz) needed to resolve small asymmetries:

**E158:**

$A_{PV} = (-131 \pm 14 \pm 10)$ ppb

# History of PVES



- PVES has a long history of pushing the limits of precision and discovery
  - E122: (ΔA=10 ppm)
  - G0, A4, HAPPEX (ΔA=0.25 to 2 ppm)
  - E158 (ΔA=17 ppb)
  - Qweak (ΔA=9 ppb)

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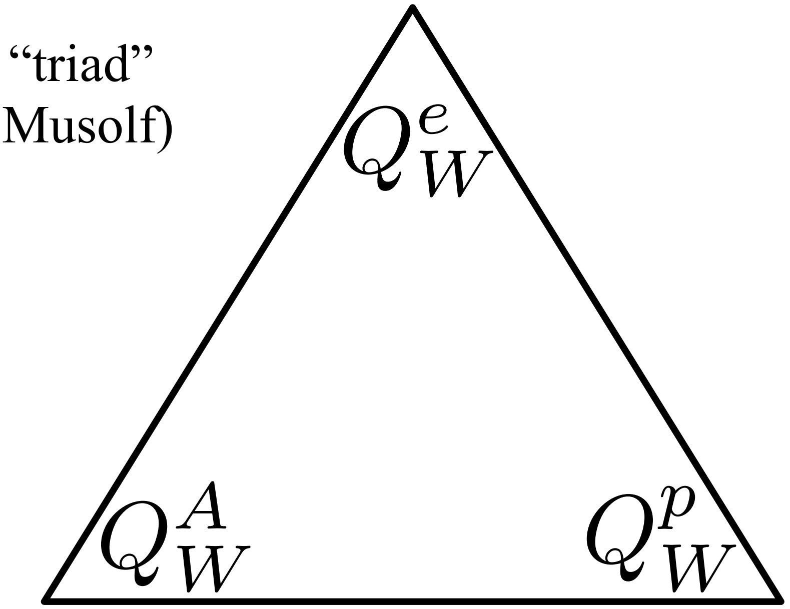
  - Moller (ΔA=0.8 ppb)
  - P2 (ΔA=0.34 ppb)

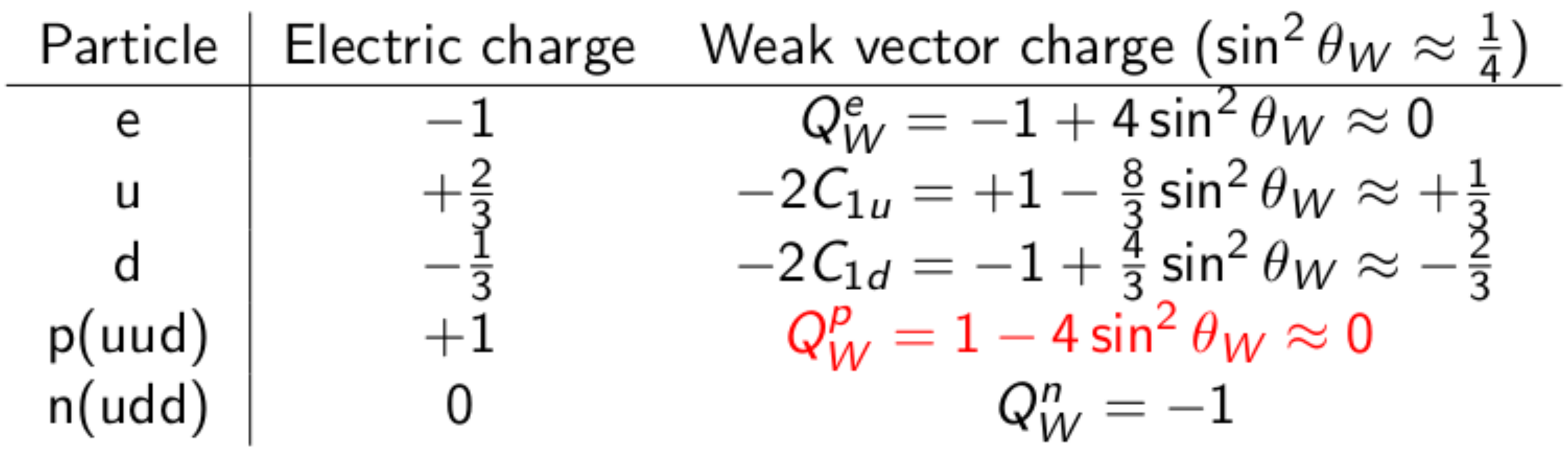
# Electroweak measurements



Weak charge “triad”
(M. Ramsey-Musolf)

- In the early 2000s E158 made the first measurement of electron weak charge $Q^e_W$
- Atomic Parity Violation measurements on $^{133}$Cs gave unique insights into d-quark weak vector charge
- Finally Qweak directly measures the proton weak vector charge $Q^p_W$

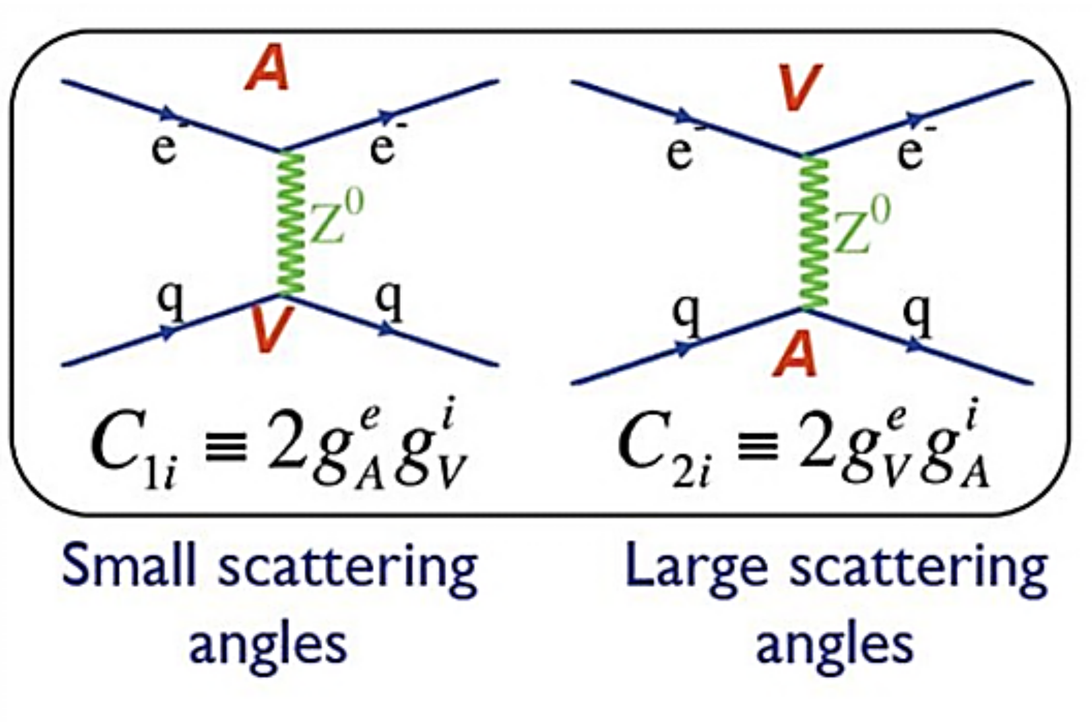
- Weak charge is the analog to the electric charge:
  - also defined as $Q^2$->0 (intrinsic property of particle)
  - proton and electron have nearly 0 weak charge
  - combined with the very well defined SM prediction makes it a good place to look for deviations (and new physics)



| 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) | $+1$ | $Q_W^p = 1 - 4\sin^2\theta_W \approx 0$ |
| n(udd) | 0 | $Q_W^n = -1$ |

# Quark Vector couplings ~ contact interaction

$$\mathcal{L}_{eq}^{PV} = -\frac{G_F}{\sqrt{2}}\sum_i \left[C_{1i}\bar{e}\gamma_\mu\gamma_5 e\bar{q}\gamma^\mu q + C_{2q}\bar{e}\gamma_\mu e\bar{q}\gamma^\mu\gamma^5 q\right] + \mathcal{L}_{new}^{PV}$$



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

Small scattering angles

Large scattering angles

- At low $Q^2$ ($Q^2 << M_Z$) the SM Lagrangian is effectively a 4-fermion contact interaction

- Qweak is sensitive to quark vector couplings $C_{1u}$ and $C_{1d}$

# Tree-level Qweak asymmetry

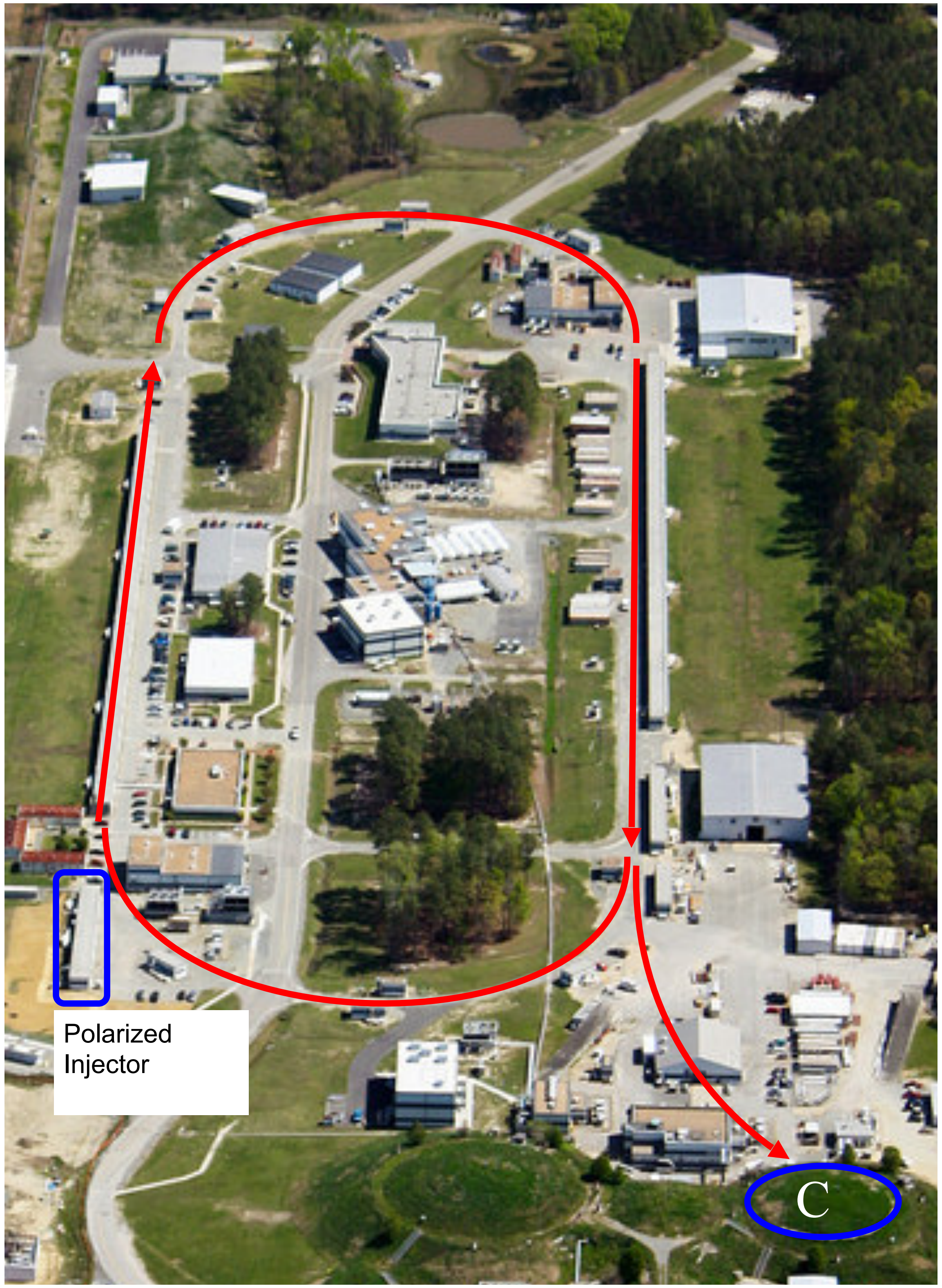
$$A_{PV} = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[ \frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1 - 4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^e}{\varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2} \right]$$

At forward scattering angles and low 4-momentum transfer ($Q^2$):

$$A_{PV} = \frac{-G_F Q^2}{\underbrace{4\pi\alpha\sqrt{2}}_{A_0}} [Q_W^p + Q^2 B(Q^2, \theta)]$$

- Unlike measurements on $Q^e_W$, Qweak asymmetry needs to take care of the hadronic part of the interaction
  - small $Q^2$ makes the contributions smaller compared to previous experiments (proton looks like a point particle)
- The hadronic contributions can be determined from the previous PVES experiments

# Qweak experimental setup



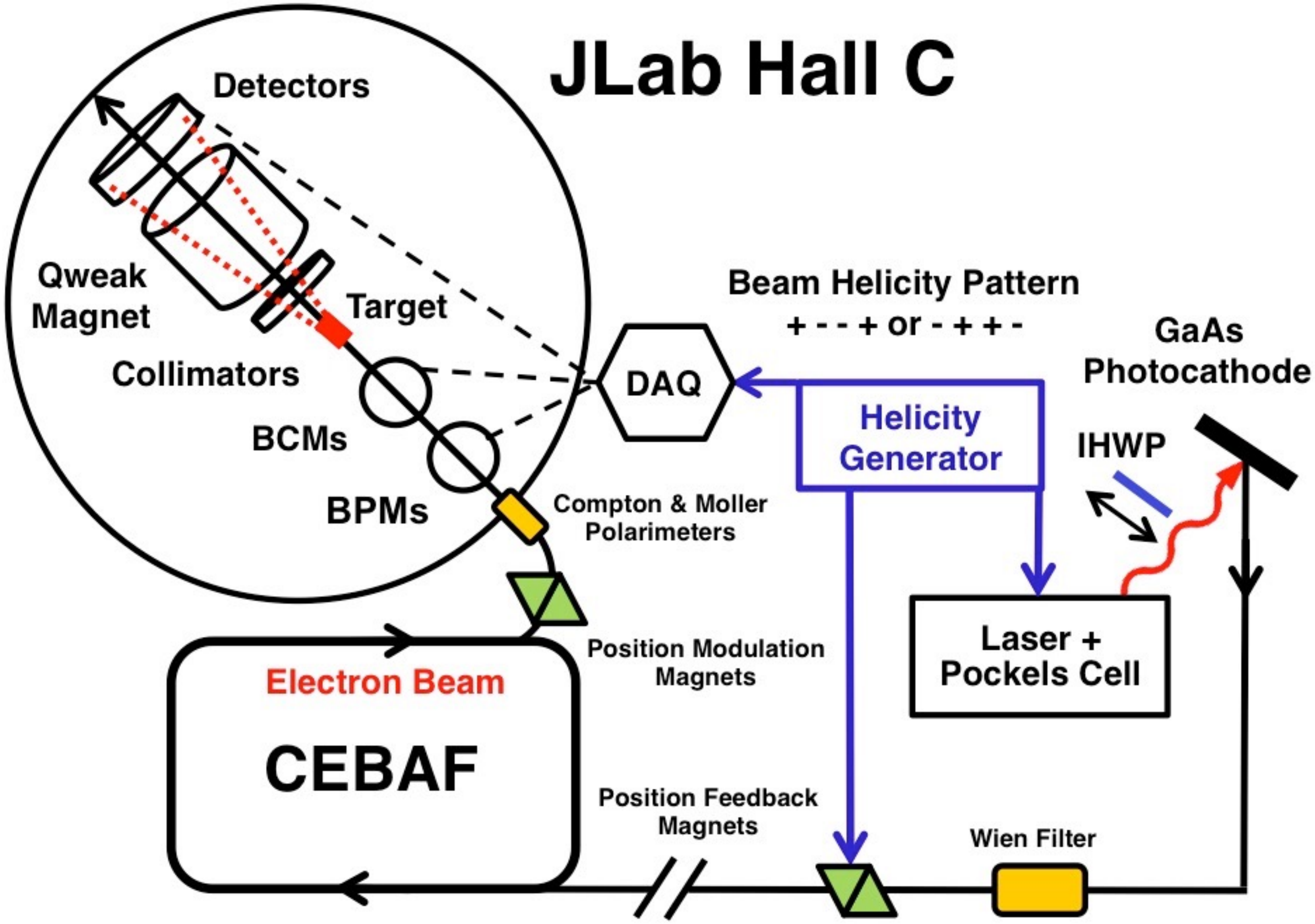
- Ran in three periods between 2010 and 2012 at the Continuous Electron Beam Accelerating facility at DOE's Jefferson Lab
  - Commissioning data published in **PRL 111, 141803 (2013)**

$$Q_w^p(SM) = 0.0708 \pm 0.0003$$

**initial result:** $Q_w^p(PVES) = 0.064 \pm 0.012$

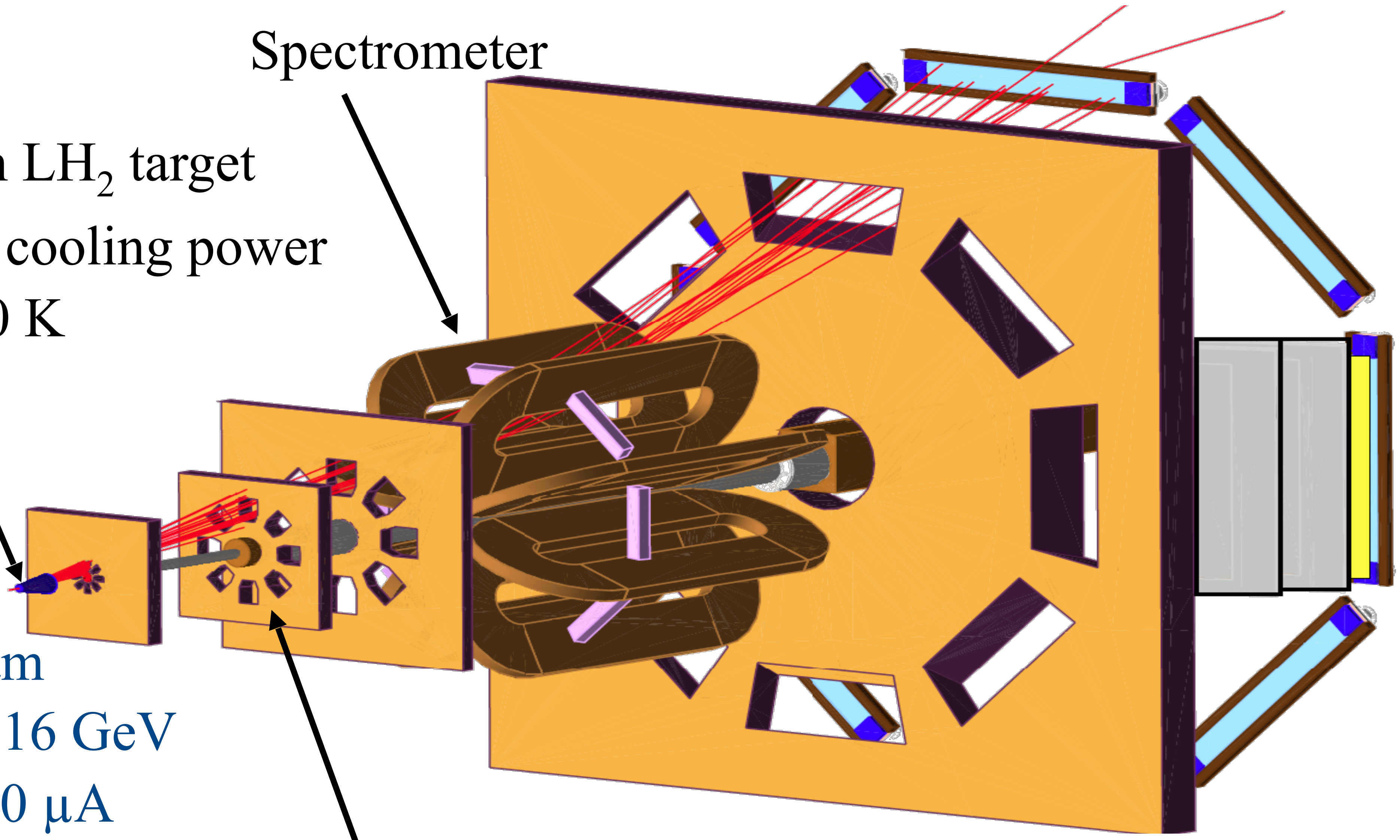
**final result:** $Q_w^p(PVES) = \qquad \pm 0.0045$

# Qweak experimental setup



- Careful preparation of the entire machine (from injector all the way to the experiment) has to be made
  - The injector was setup to have a fast helicity reversal at 1kHz
  - High polarization of the electron beam had to be maintained
  - Special care was taken to avoid helicity correlated beam asymmetries (intensity, beam positions)
  - Checks were done throughout the machine until the target to make sure beam quality was maintained

# Qweak experimental setup



Toroidal
Spectrometer

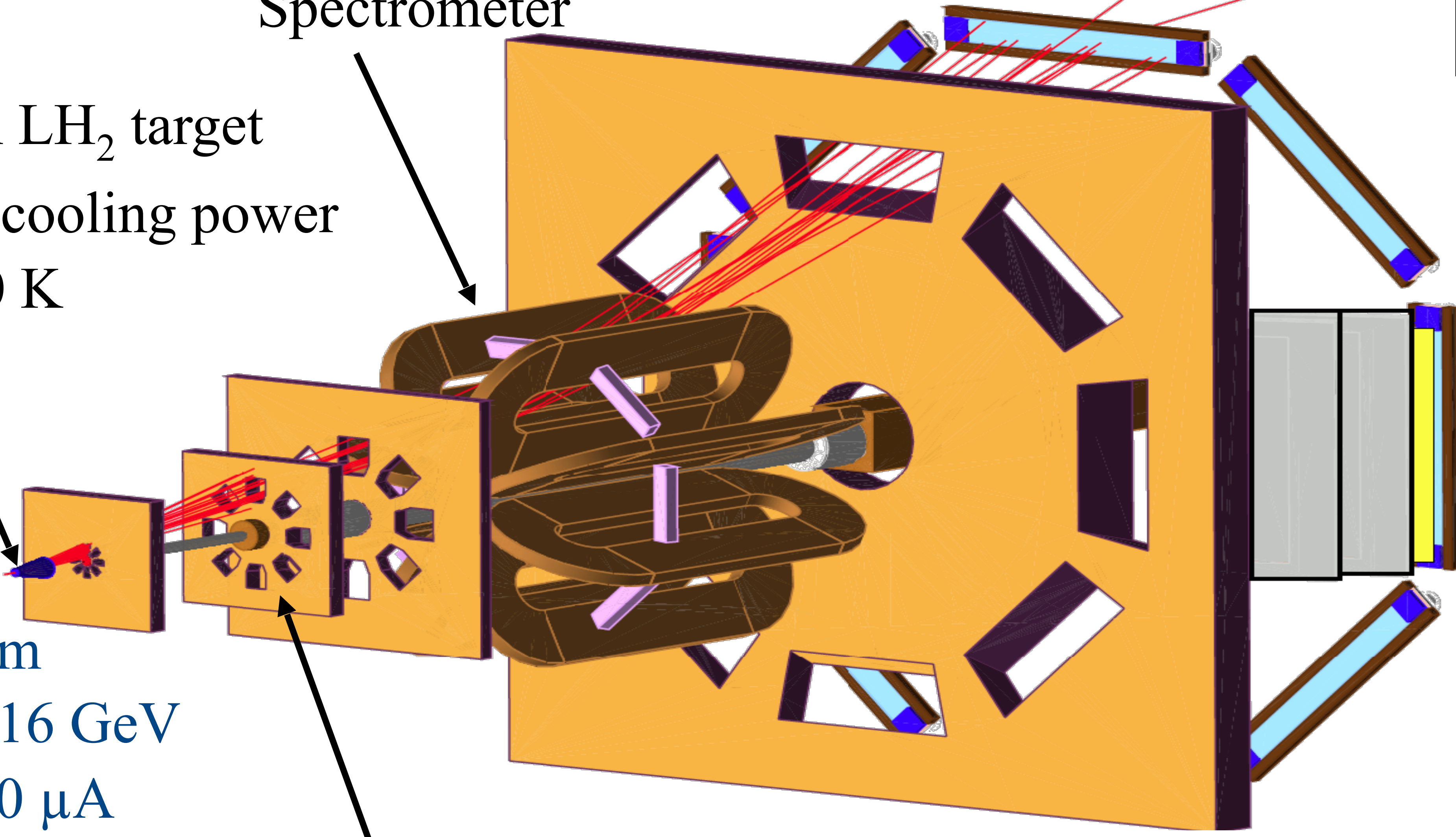
35 cm $LH_2$ target
3 kW cooling power
at ~20 K

e- beam
E = 1.16 GeV
I = 180 μA
P = 89%

Acceptance defining
Pb collimator

$$5.8^o \leq \theta \leq 11.6^o$$

# Qweak experimental setup



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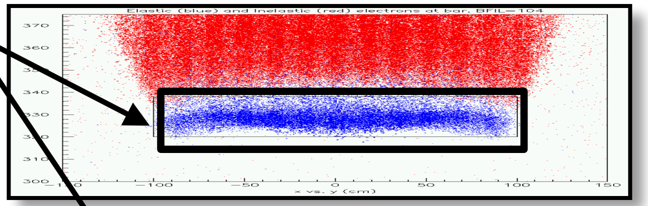
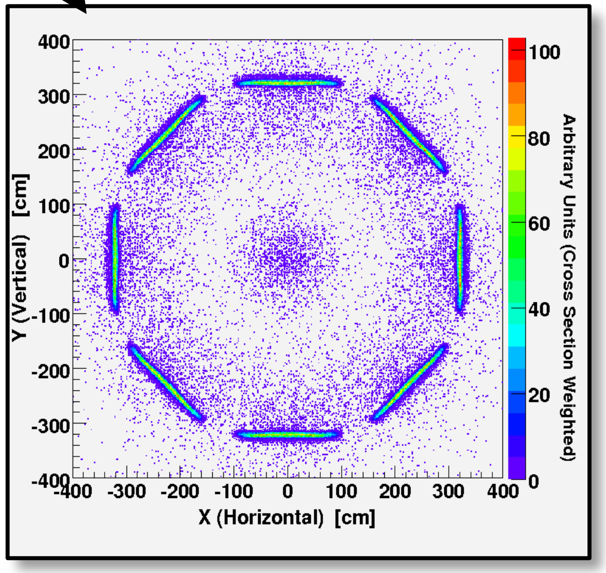
**select elastic peak**





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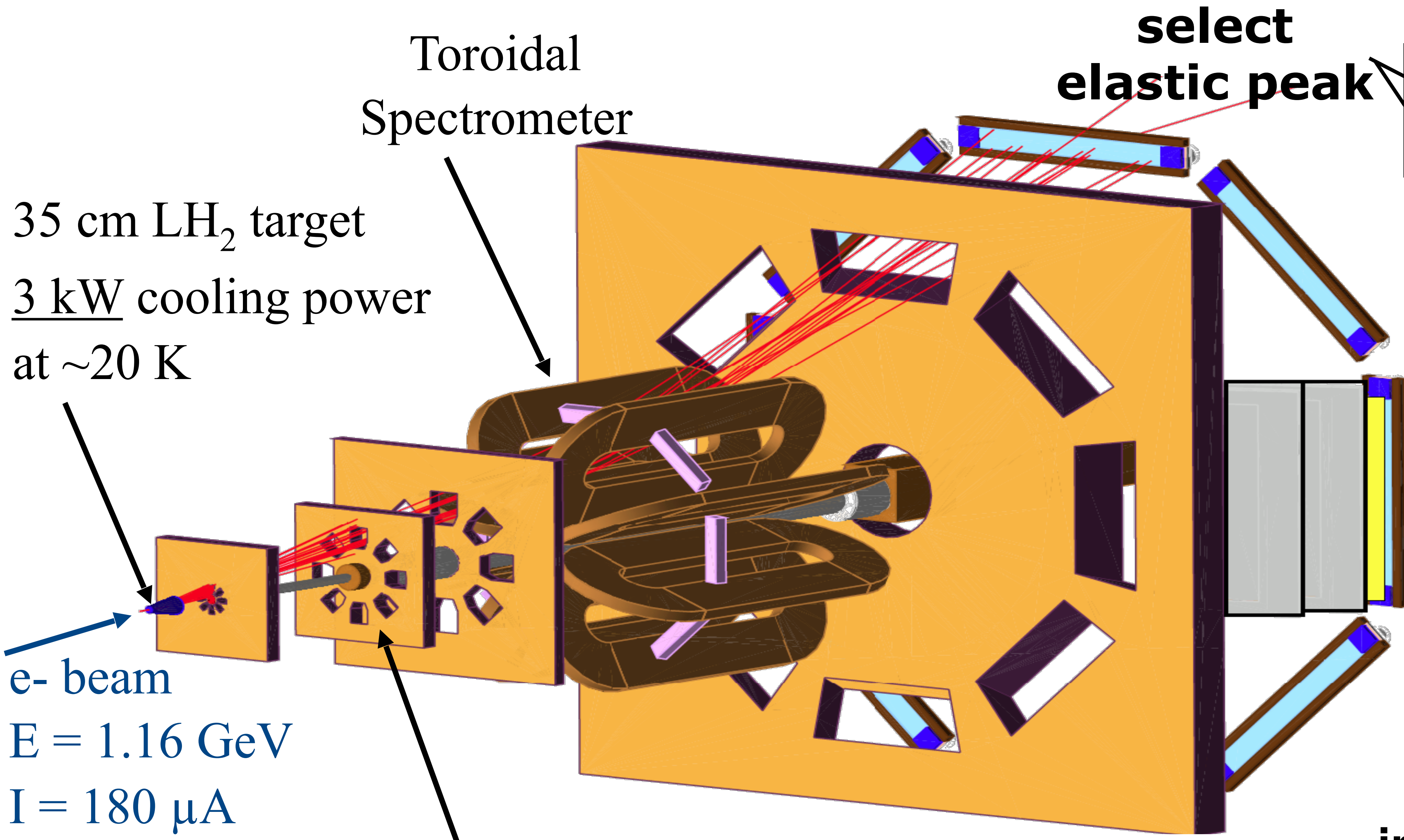

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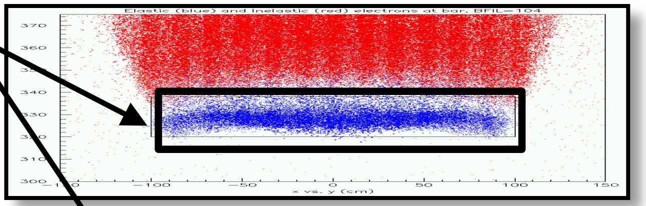
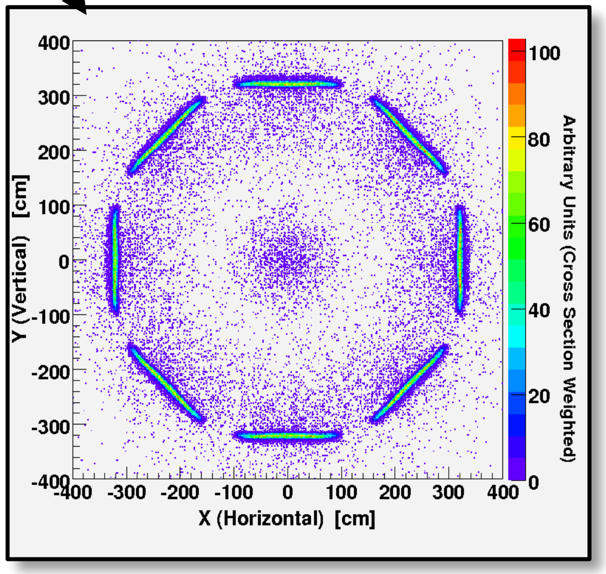
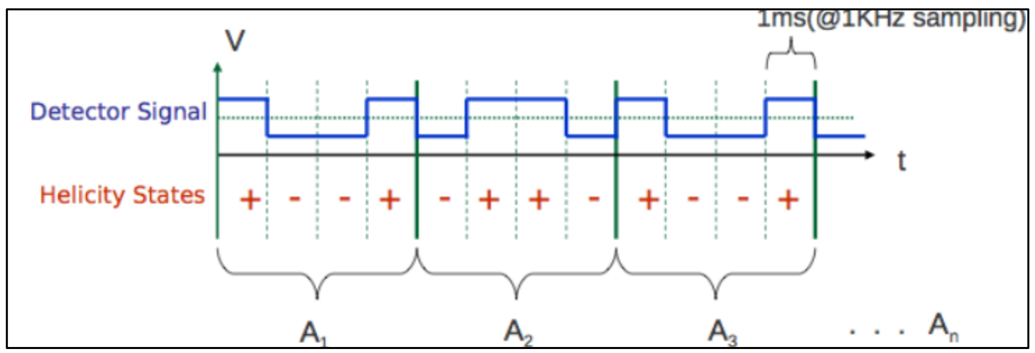


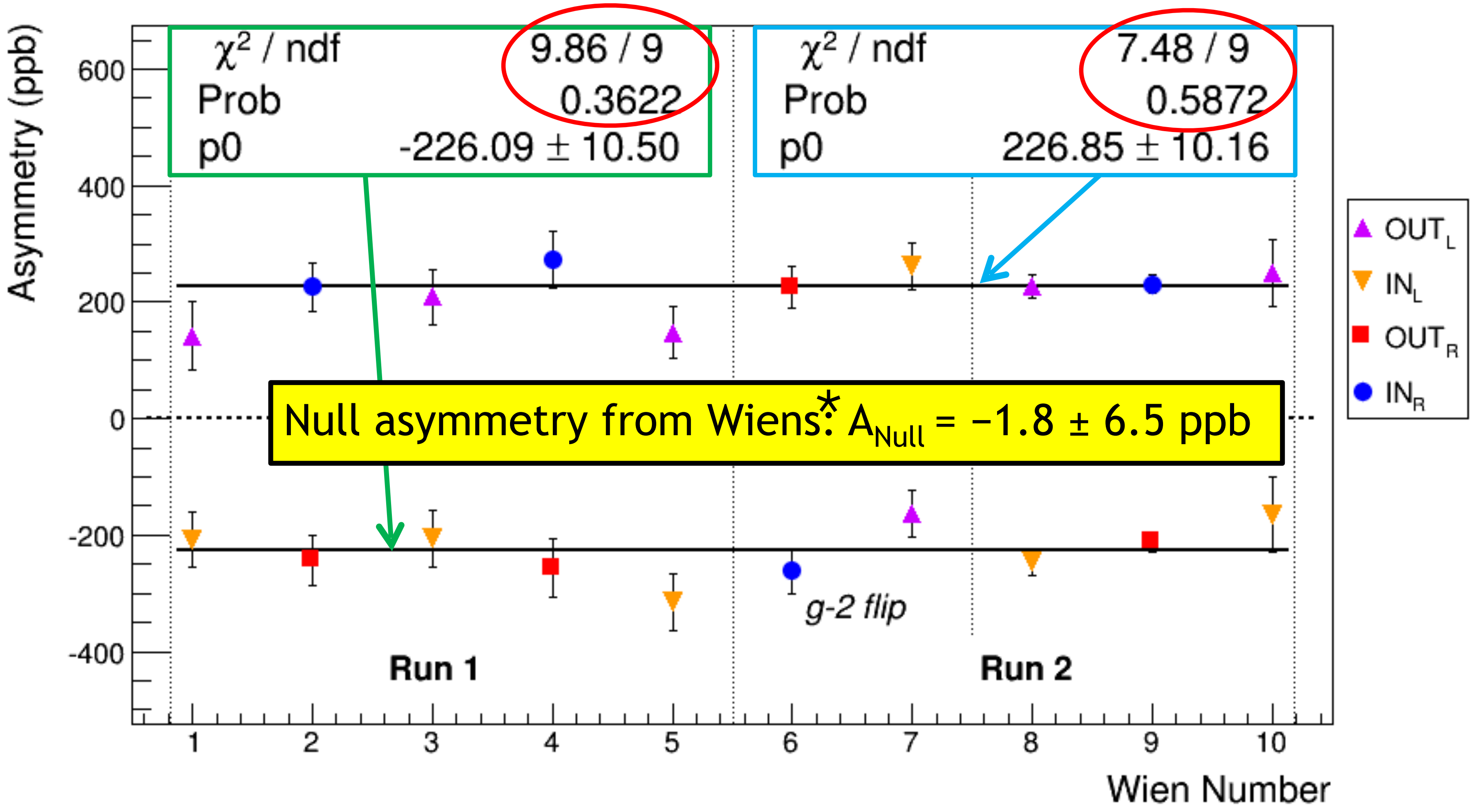


**integrate for ~1msec**



**calculate asymmetry from 4 windows**

# NULL asymmetry



Null asymmetry from Wiens*: $A_{Null}$ = −1.8 ± 6.5 ppb

*1 wien ~ 2-6 weeks of data

- insertable laser optics flip the polarization of the laser and electron beam
- magnetic spin manipulation (Wein filter) allowed for direct electron beam polarization flip
- Energy variation through the accelerator (g-2 flip)

- The physics asymmetry was consistent through these slow spin reversals

# Corrections and systematics

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

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

- Correct the raw asymmetry for measured experimental factors (detector non-linearity, beam asymmetries)

- Apply additional corrections (polarization, acceptance, backgrounds)

# Corrections and systematics

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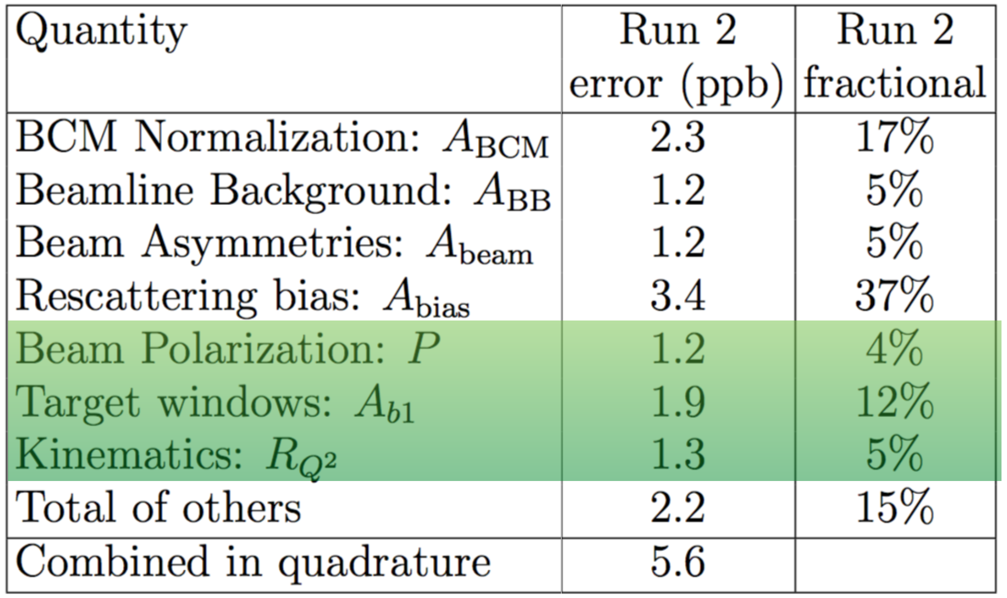

| Quantity | Run 2 error (ppb) | Run 2 fractional |
|---|---|---|
| BCM Normalization: $A_{\mathrm{BCM}}$ | 2.3 | 17% |
| Beamline Background: $A_{\mathrm{BB}}$ | 1.2 | 5% |
| Beam Asymmetries: $A_{\mathrm{beam}}$ | 1.2 | 5% |
| Rescattering bias: $A_{\mathrm{bias}}$ | 3.4 | 37% |
| Beam Polarization: $P$ | 1.2 | 4% |
| Target windows: $A_{b1}$ | 1.9 | 12% |
| Kinematics: $R_{Q^2}$ | 1.3 | 5% |
| Total of others | 2.2 | 15% |
| Combined in quadrature | 5.6 | |

- The polarization measurement used both Compton and MOLLER measurements to reach σP of 1.05/0.73% (Run1/Run2)
- Target Al windows caused the largest correction (~38 ppb)
- Using vertical drift chambers we benchmarked detailed $Q^2$ simulations with data

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- Cross checks between redundant sets of high precision beam monitoring systems allowed us to obtain a small uncertainty for our determination of beam properties (charge, position)

- Using these monitors we could determine remaining asymmetry in beam properties under the fast helicity flip

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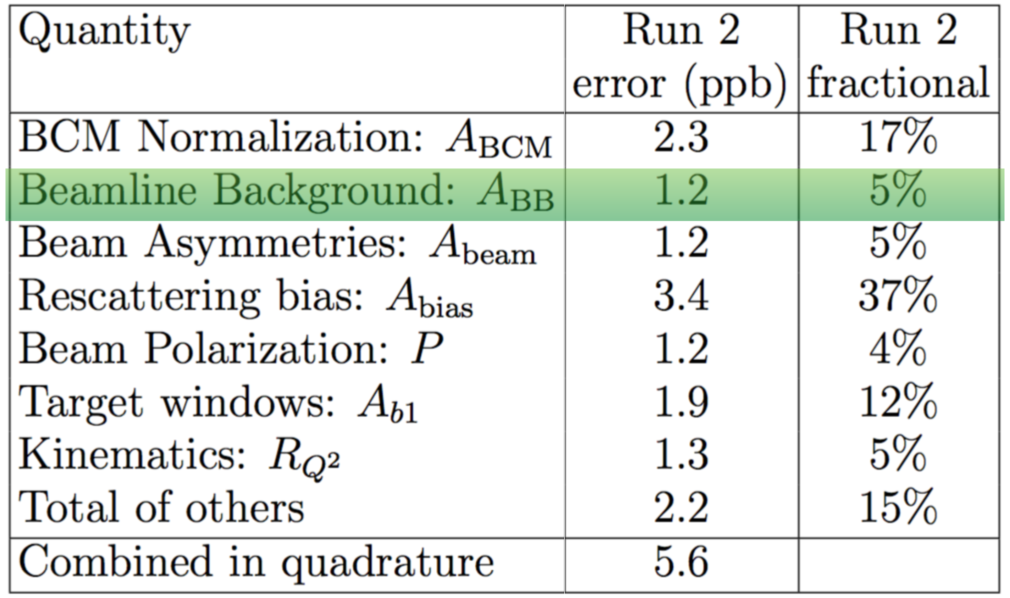

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- In the early stages of the experiment we observed a large amount of background coming from beam line elements
  - We introduced a tungsten plug to reduce this background (not fully taken care of)
- A small contribution to the total signal (0.19%) remained after the introduction of the W-plug
- Further studies were done to determine and correct this background contribution
  - background detectors were used to account for possible helicity correlated asymmetries from this background

# Corrections and systematics

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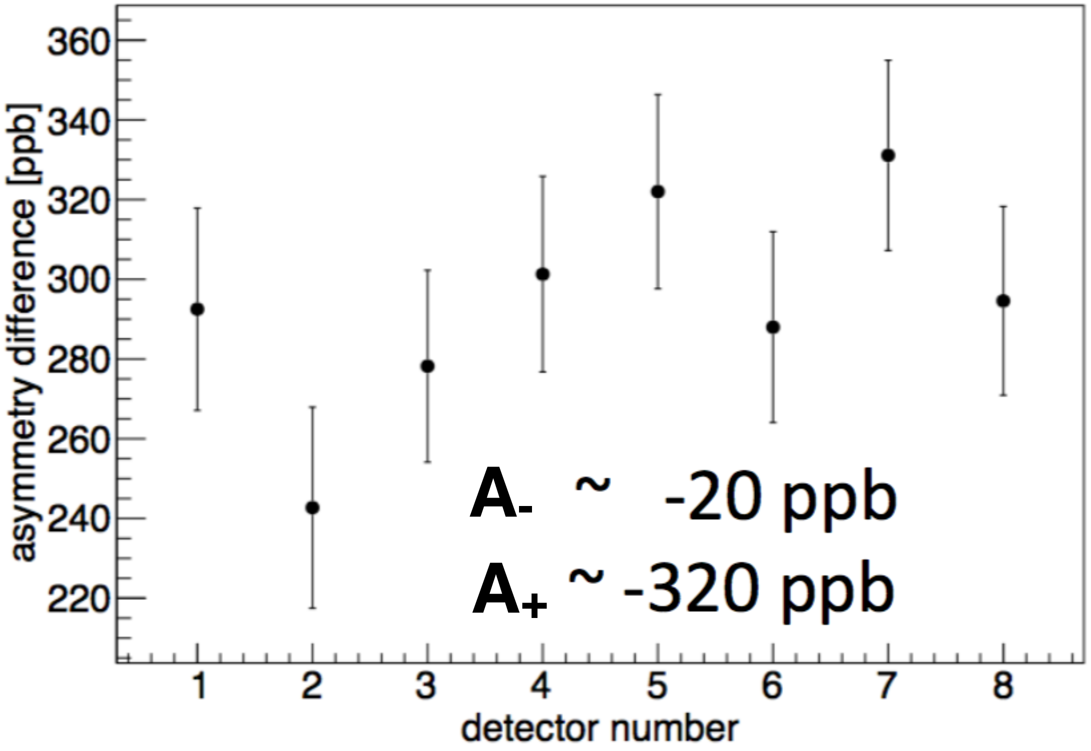
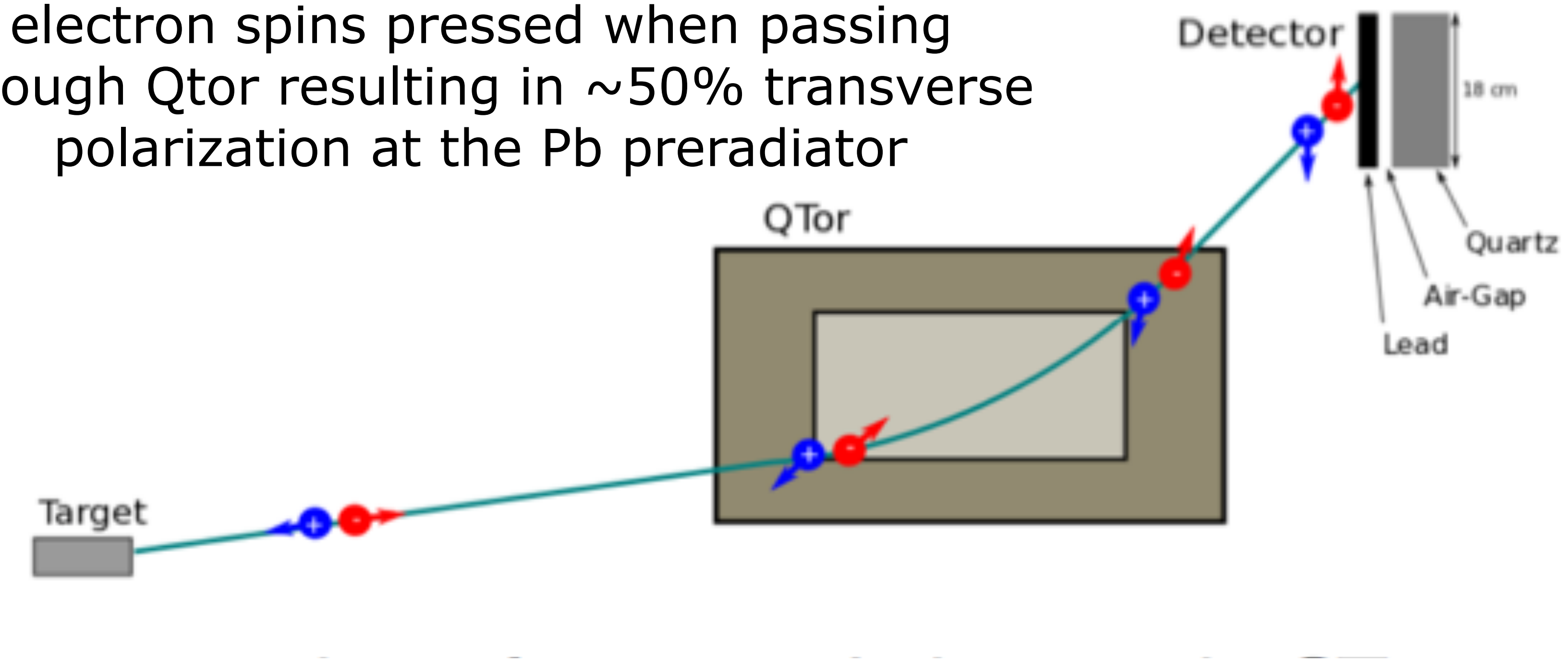
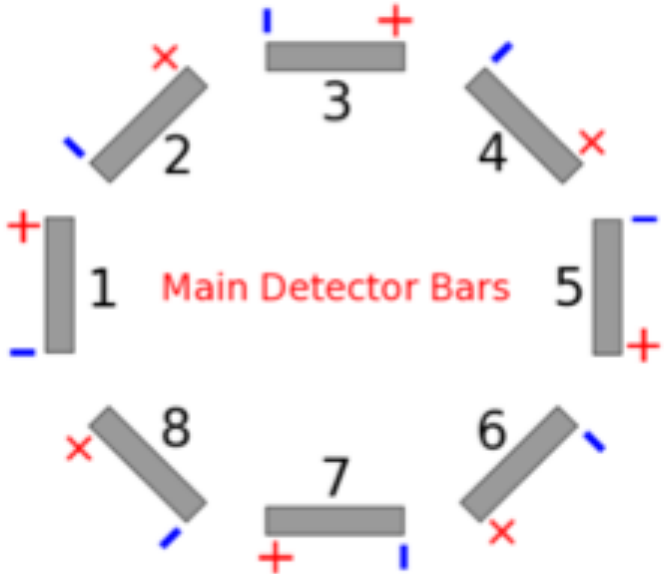
- During the analysis we observed a systematic difference between the asymmetries measured with the positive and negative PMTs



# Polarized scattering in preradiator

electron spins pressed when passing through Qtor resulting in ~50% transverse polarization at the Pb preradiator





produced significant asymmetry difference between + and - PMTs

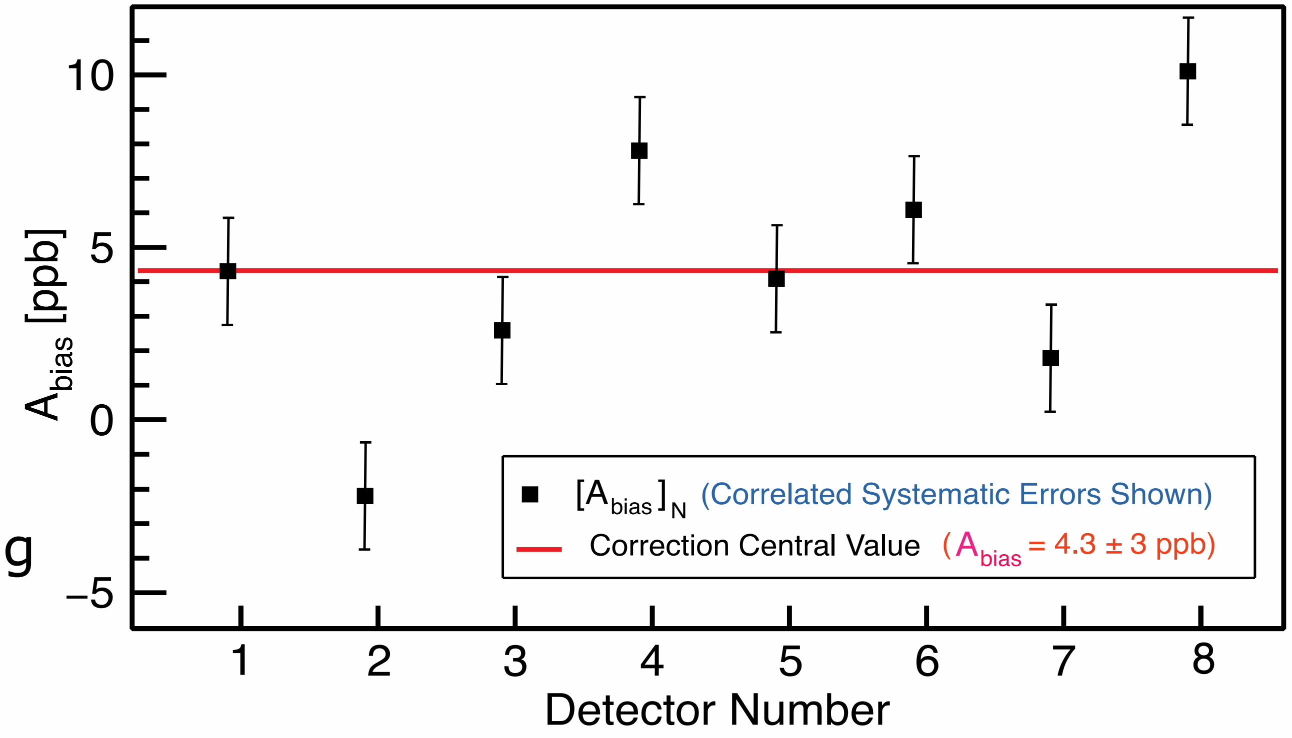
$$A_{PMTDD} = A_{-} - A_{+}$$

this effect cancels at first order for our measurement

$$A_{PV} = (A_{-} + A_{+})/2$$

Effect was evaluated using several MCs implementing low energy (few MeV) Mott Scattering and optical properties of the Quartz bars.

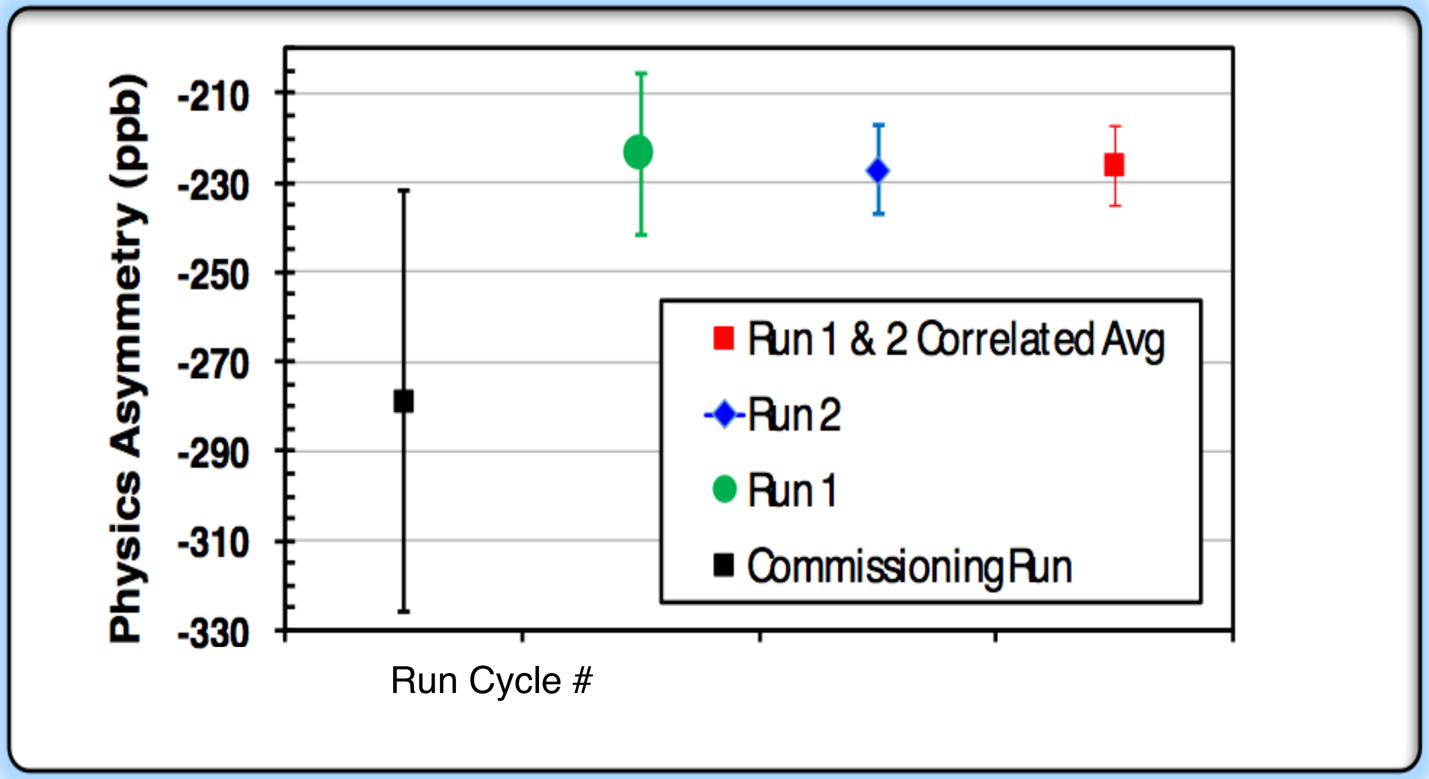
Corrected asymmetries were due to imperfections in quartz bar construction



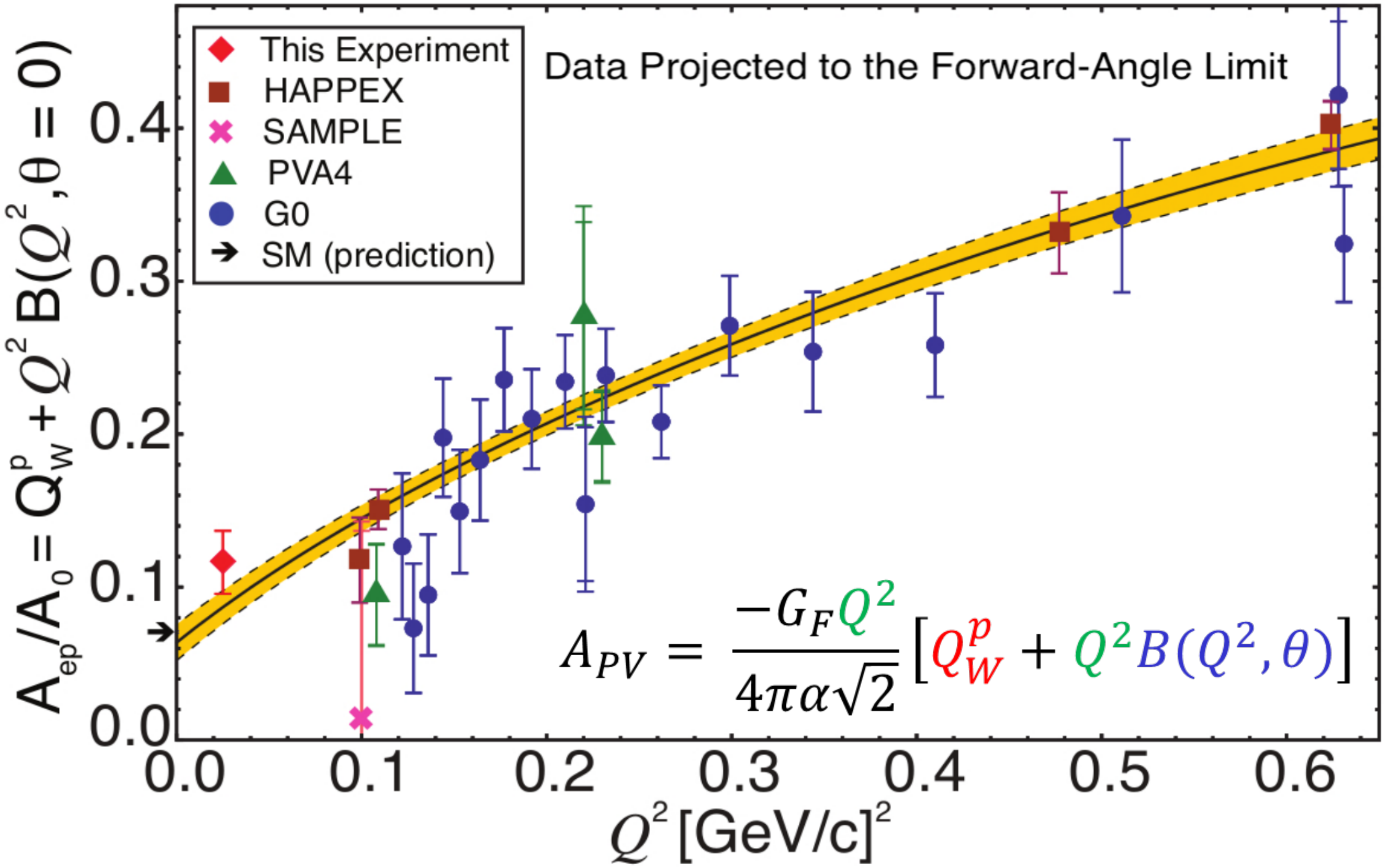
# Corrections and systematics

| 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 |

- Our final result is still statistically limited and dominated by the results from our second running period

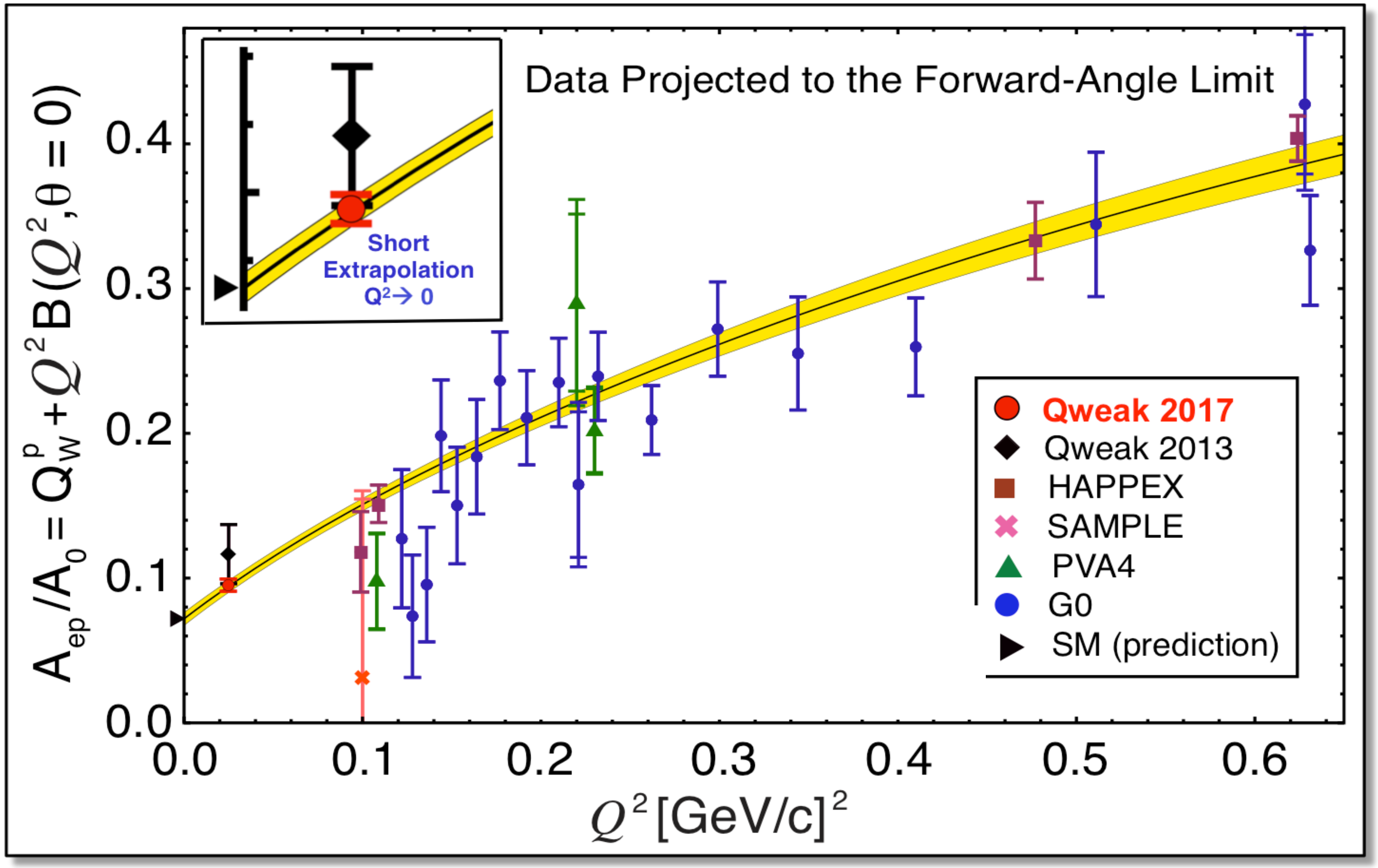


# Determining $Q^p_w$



- Global fit:
  - 5 parameters: $C_{1u}$, $C_{1d}$, $\boldsymbol{\rho}_s$, $\boldsymbol{\mu}_s$ and $G^Z_A$
- Using all PVES data up to $Q^2 = 0.63$ GeV$^2$

# Determining $Q^p_w$



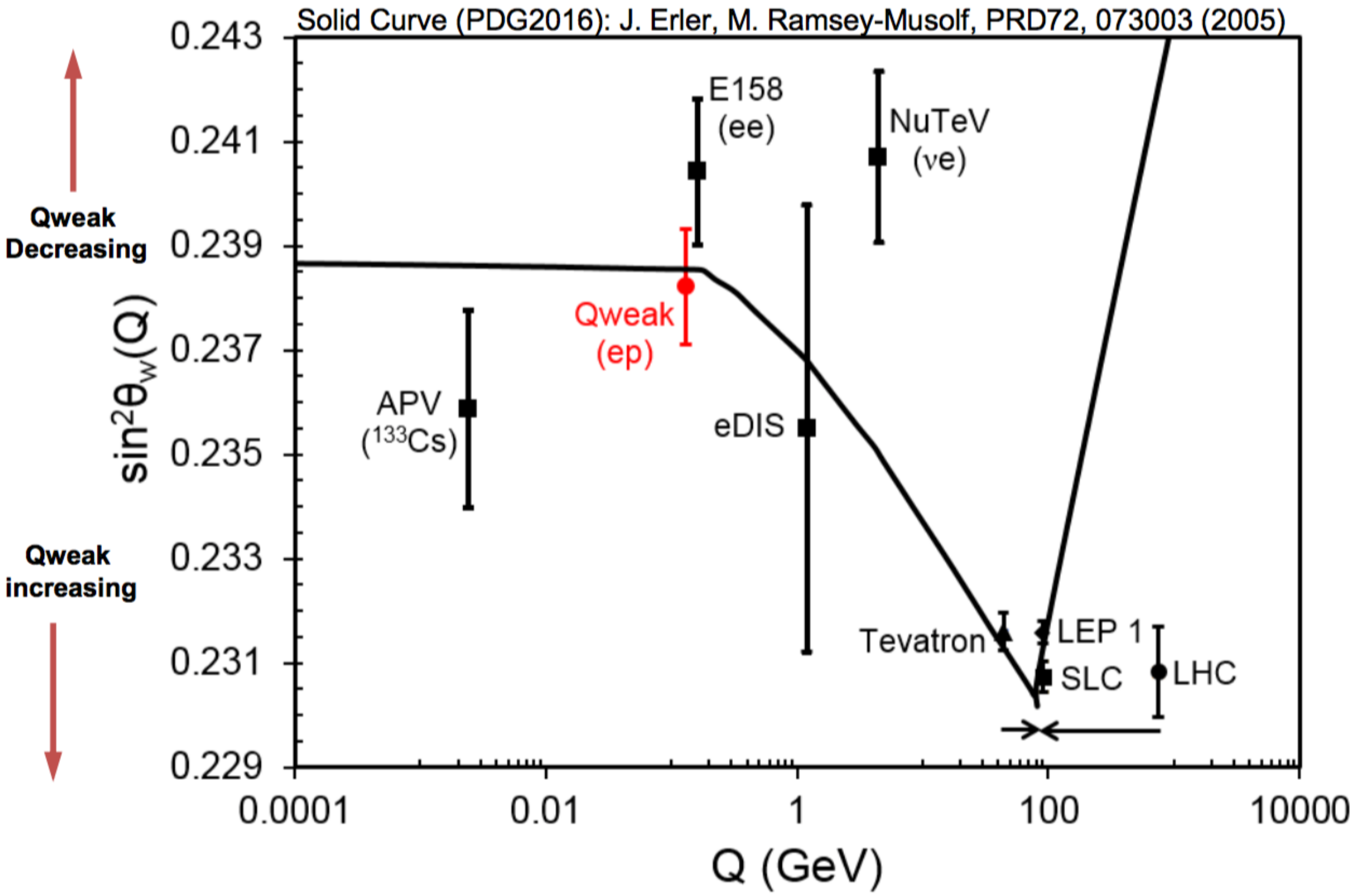
- Global fit:
  - 5 parameters: $C_{1u}$, $C_{1d}$, $\boldsymbol{\rho}_s$, $\boldsymbol{\mu}_s$ and $G^Z_A$
- Using all PVES data up to $Q^2 = 0.63$ GeV$^2$

- $Q^p_W$ is determined from a global fit of PVES data
  - our measurement is the closest to the extrapolation point and anchors the fit while the rest of the data determine the hadronic contributions

$$Q^p_w(SM) = 0.0708 \pm 0.0003$$

$$Q^p_w(PVES) = 0.0719 \pm 0.0045$$

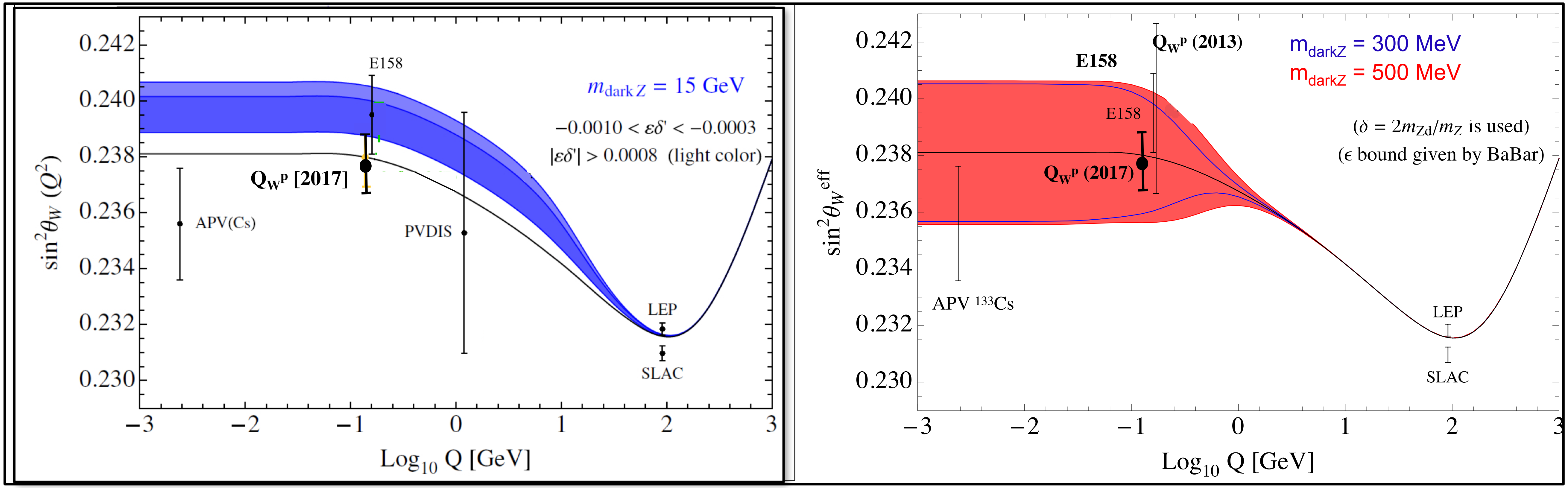
# Weak mixing angle



- E158 and Qweak are sensitive to different types of new physics
  - strong consistency with SM for Qweak should put a stronger limit on scalar lepto-quarks (E158 insensitive)

# Dark photon/“Z”

(Davoudiasl, Lee, Marciano, Phys. Rev. D**89**, 095006 (2014), & Marciano (private communication))



- Some models point to a heavy dark photon ($Z_d$) could be detected at low Q through it’s mixing with between $Z_0$ and $Z_d$

- Complementary with direct searches
  - in this scenario the $Z_d$ would not have any coupling with SM

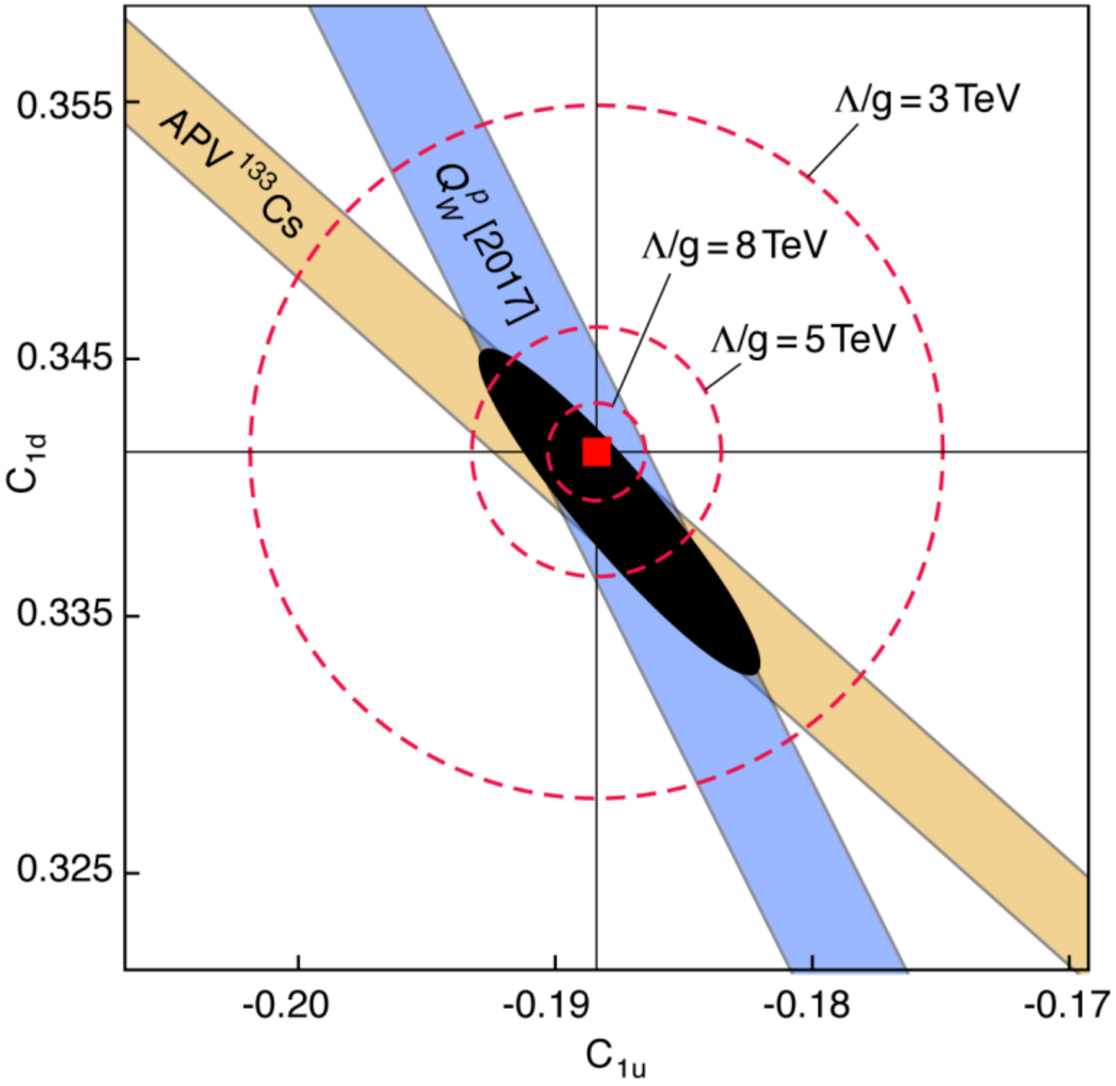
# Semi-leptonic PV Physics

Following prescription for new physics from contact interactions in **PhysRevD.68.016006:**

$$\mathcal{L} = \mathcal{L}^{\mathrm{PV}}_{\mathrm{SM}} + \mathcal{L}^{\mathrm{PV}}_{\mathrm{NEW}}$$

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

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

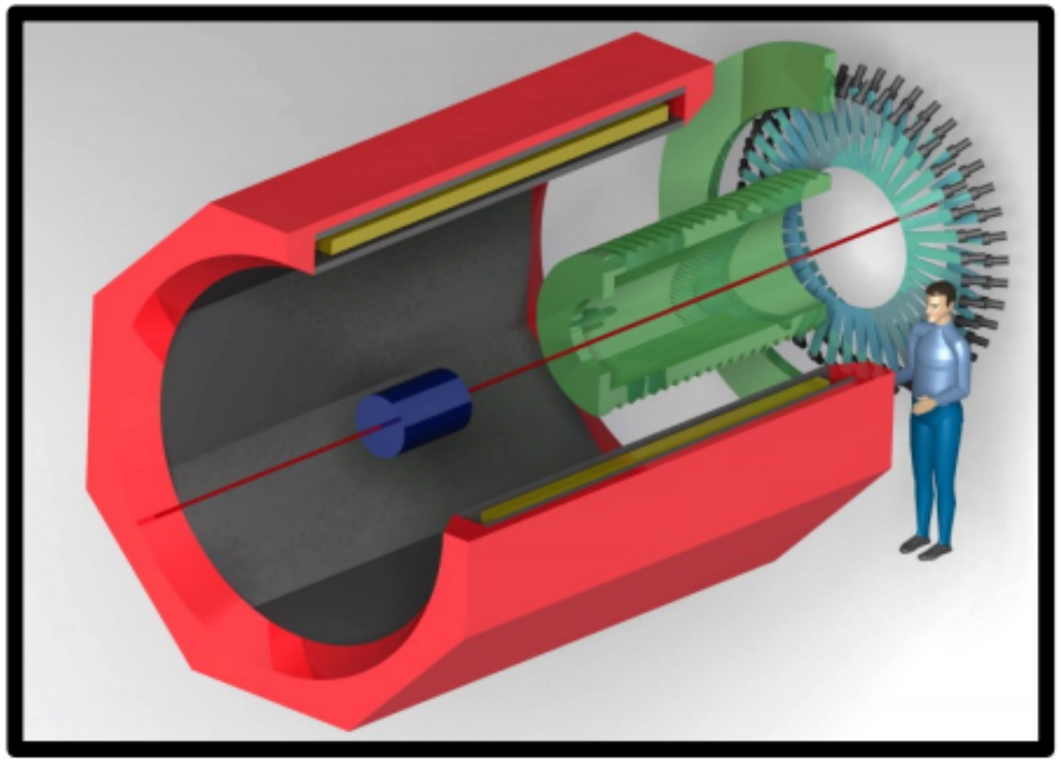


- Our measurement of vector-proton weak neutral current charge constraints new physics which are comparable with current limits from LHC

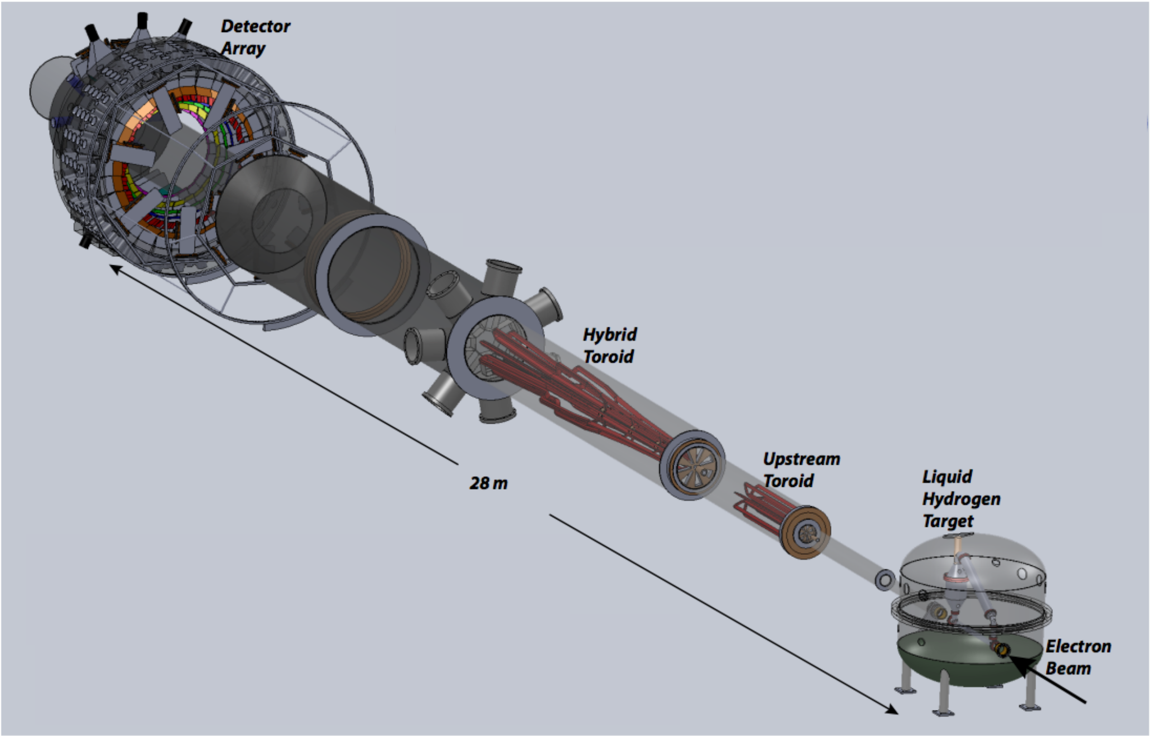
$$g^2 = 4\pi \text{ limit is } 26.3 \text{ TeV}$$

# Future PVES experiments

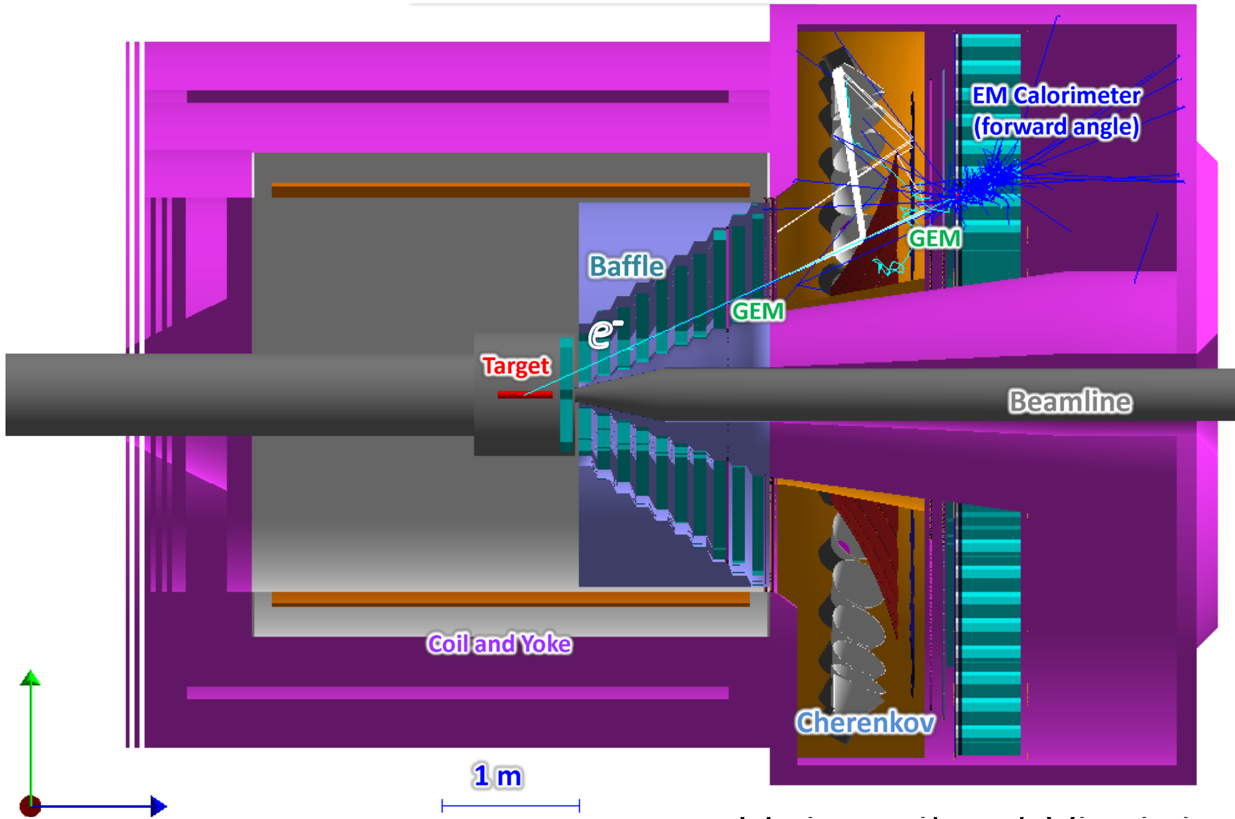
## MESA/P2 at Mainz



## MOLLER at JLab



## PVDIS SOLID at JLab

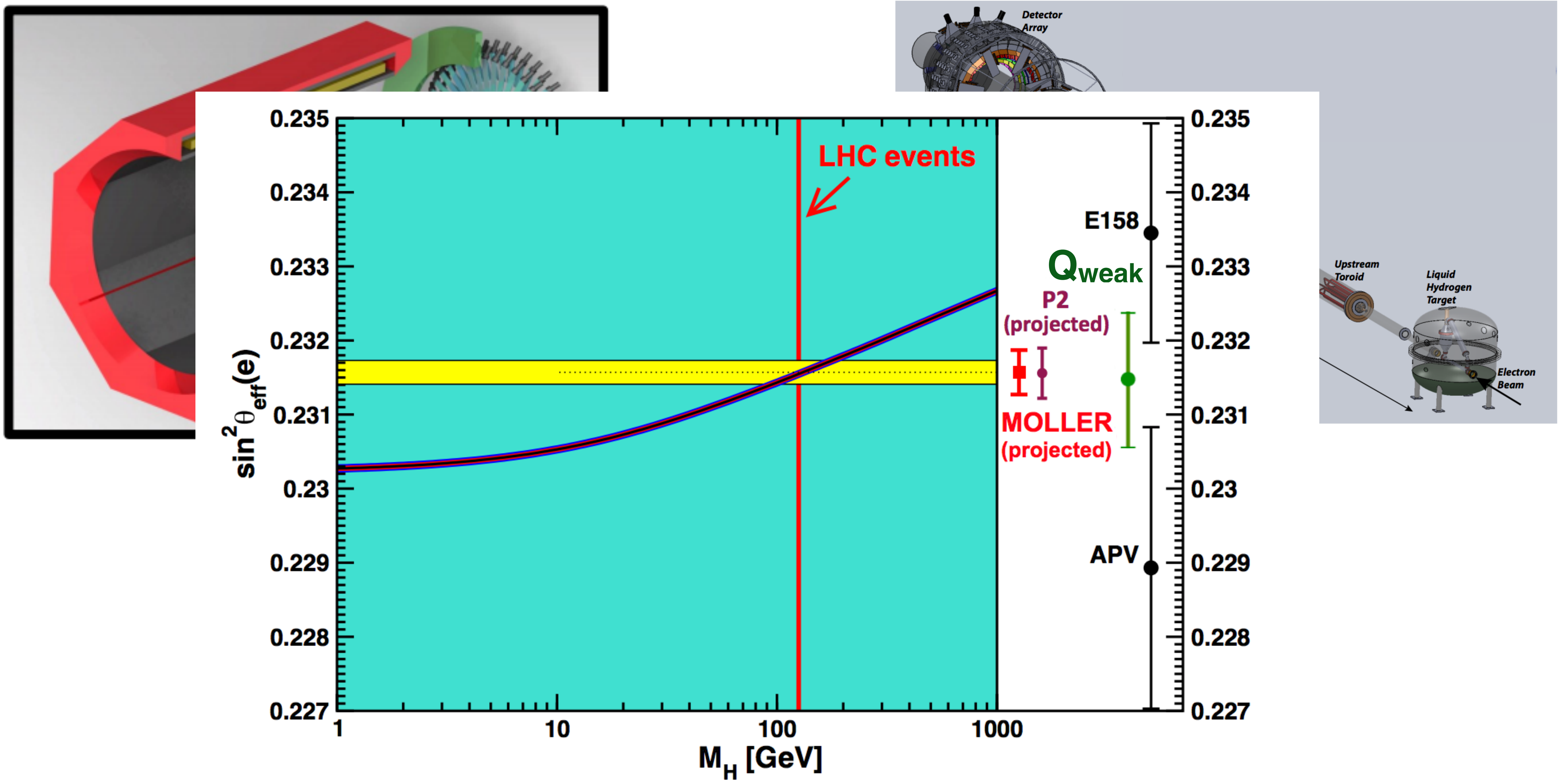


- P2 will improve on the weak charge of the proton
- MOLLER will improve on the weak charge of the electron
- SOLID will make measurement over a wide kinematic range that will include test SM prediction for the axial proton weak charge

# Future PVES experiments

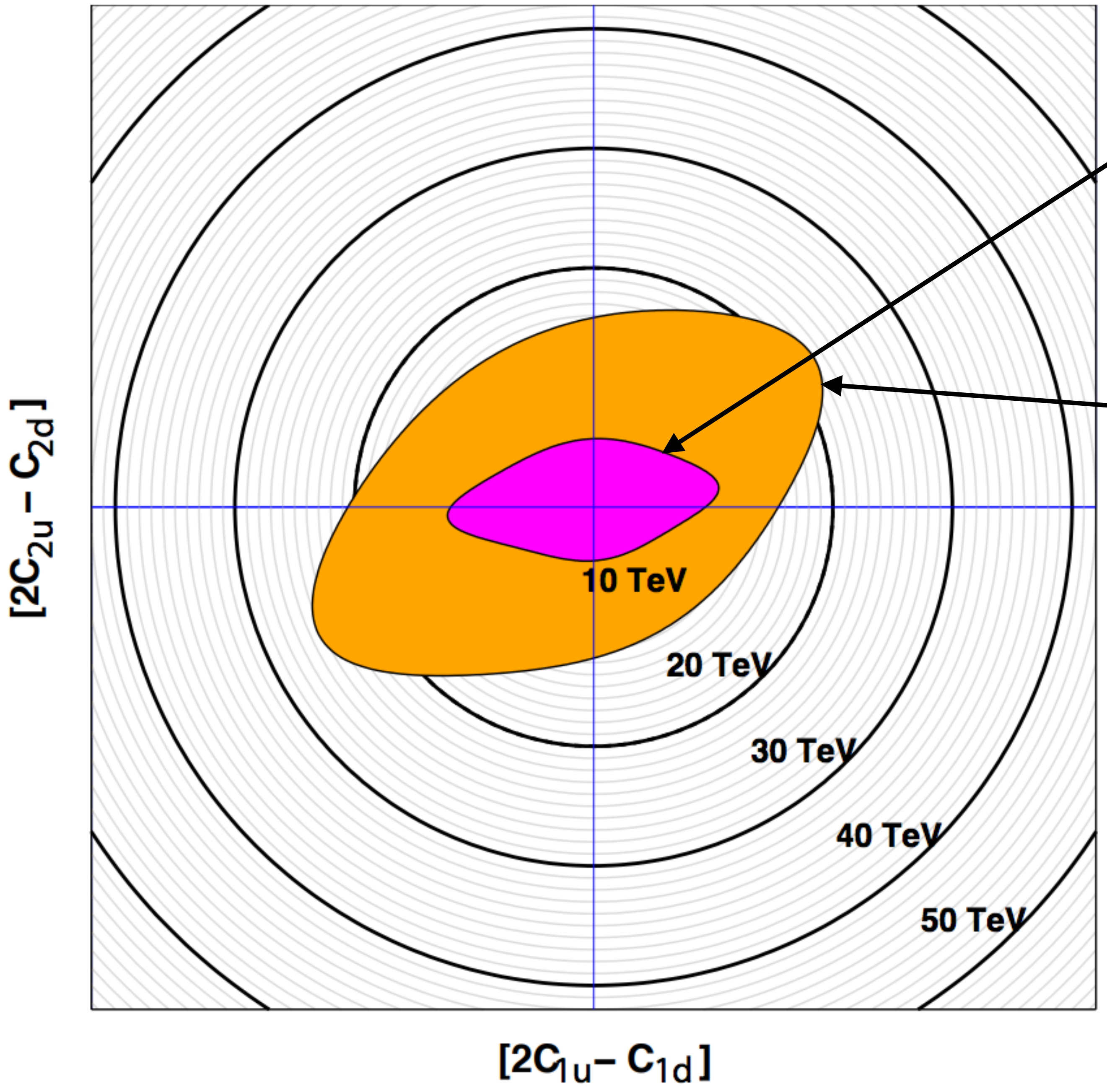
**MESA/P2 at Mainz**

**MOLLER at JLab**



- P2 and MOLLER will have weak mixing angle determinations as precise as Z-pole measurement but at very low $Q^2$

# Future PVES experiments

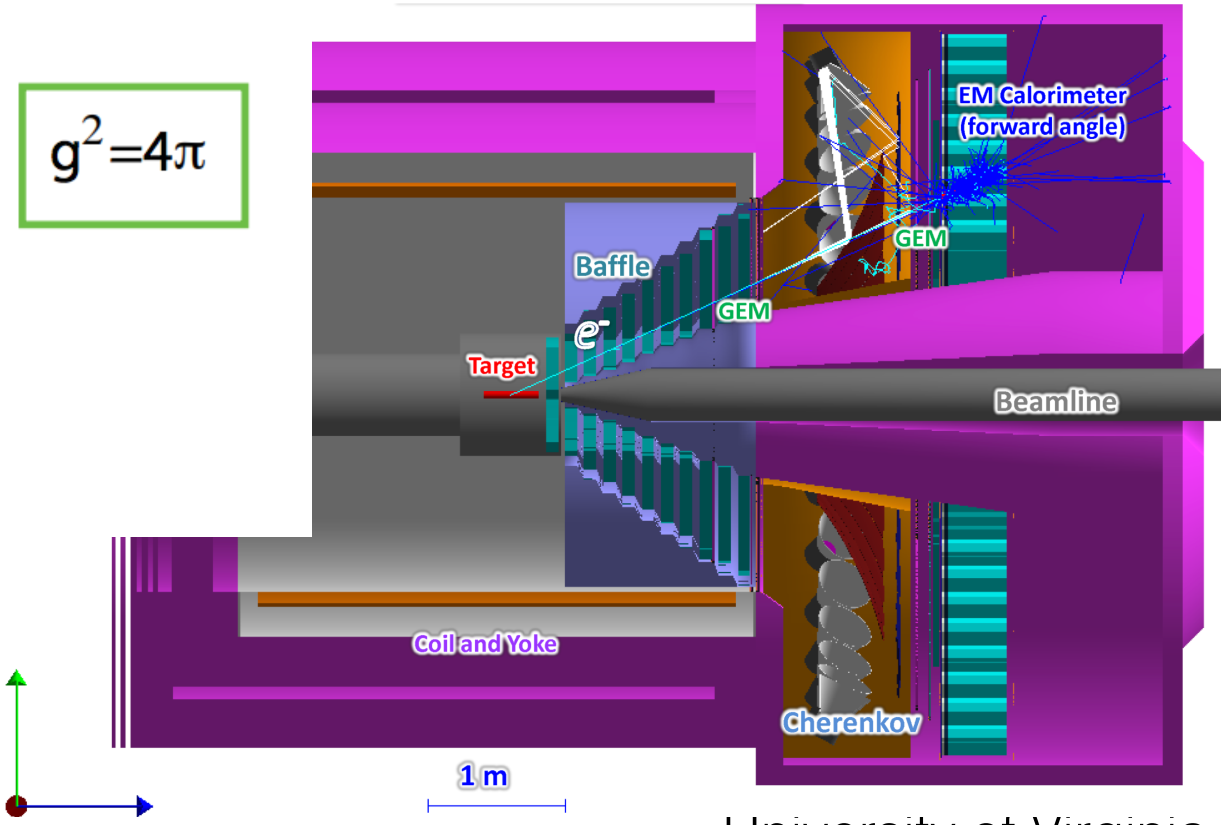


**Currently published constraints (6GeV PVDIS, Qweak, APV)**

**Constraints after SOLID comparable with future LHC running.**

$g^2=4\pi$

**PVDIS SOLID at JLab**



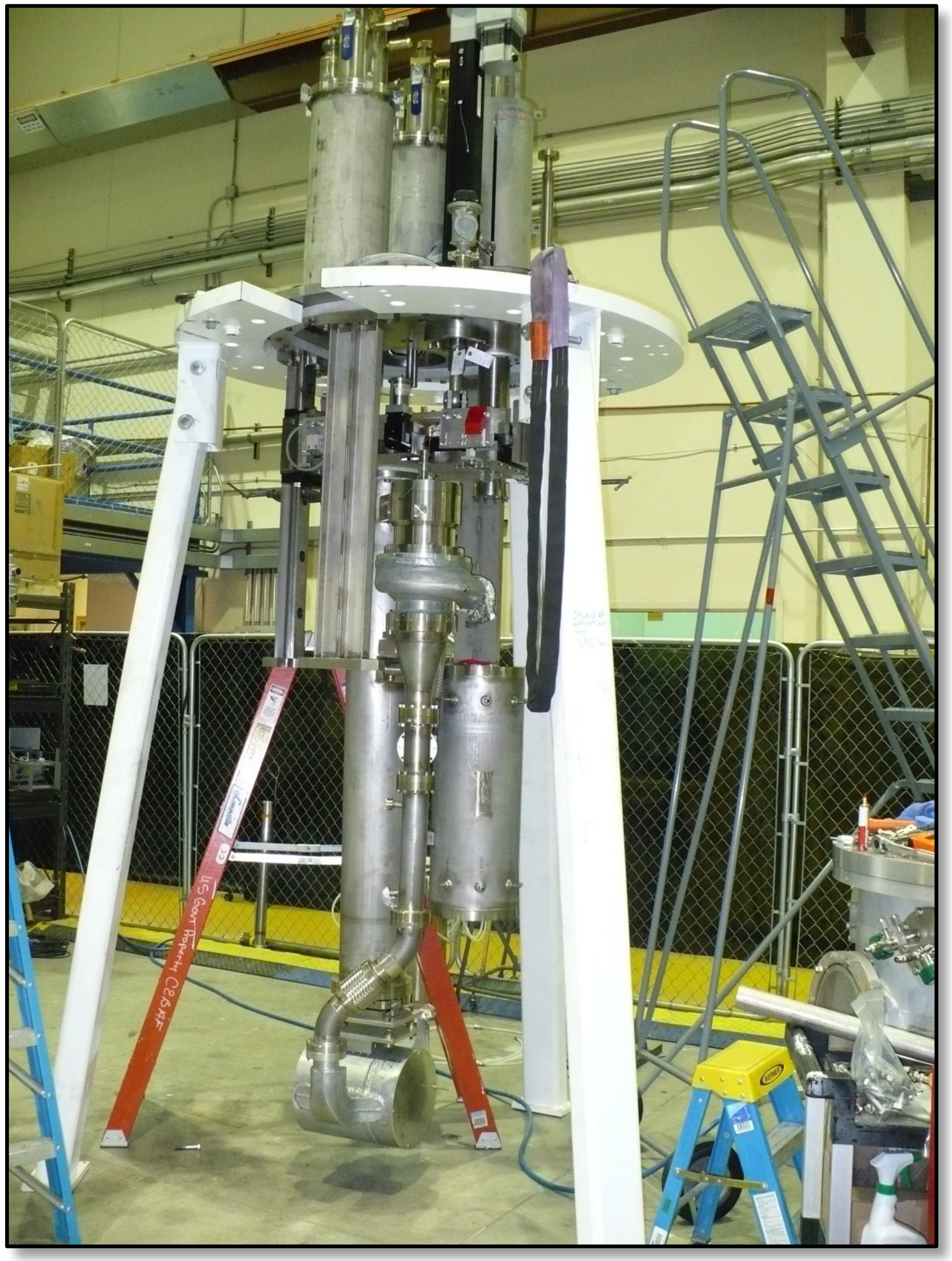
# Summary

- Qweak has obtained the most precise determination of a PVES asymmetry and extracted the vector weak charge of the proton $Q^p_w$
- Sensitive measurement of weak mixing angle limits the phase space of dark Zs
- Consistency with SM further constrains semi-leptonic PV physics above 26.3 TeV
- Future PVES experiments will bring us even closer to the answers we all seek

# Backup

# Qweak ~2.5 kW $LH_2$ Target

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

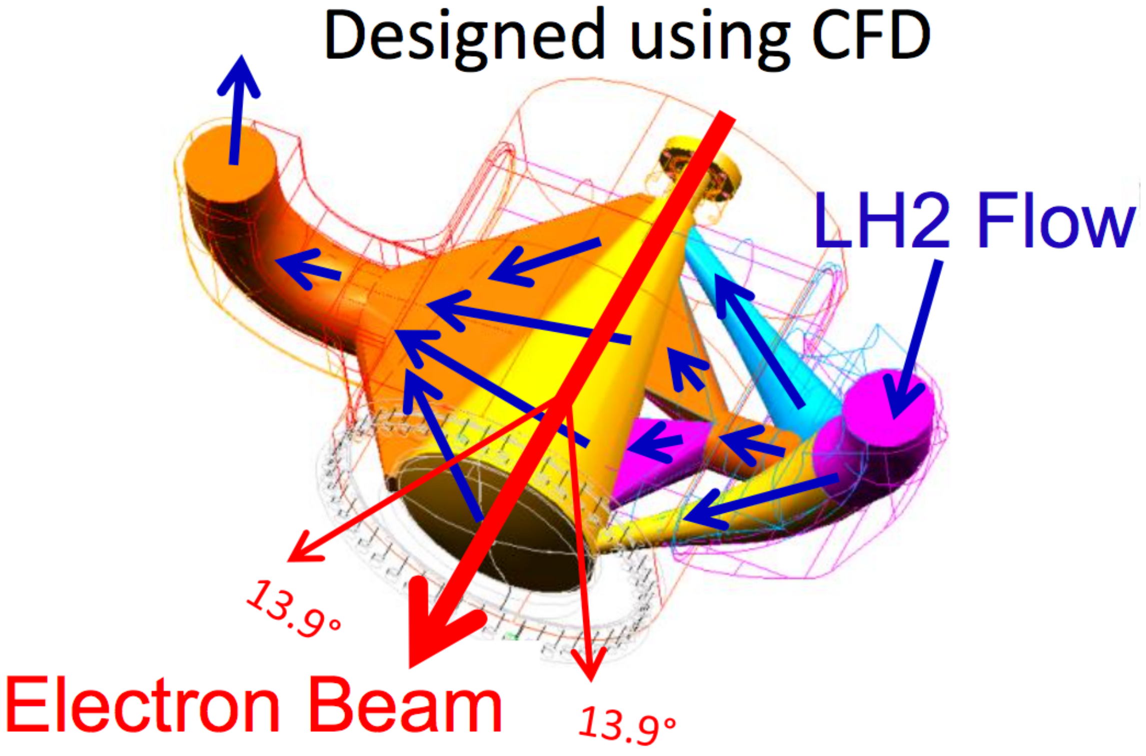


***courtesy of R. Carlini**

**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....



# Corrections and systematics

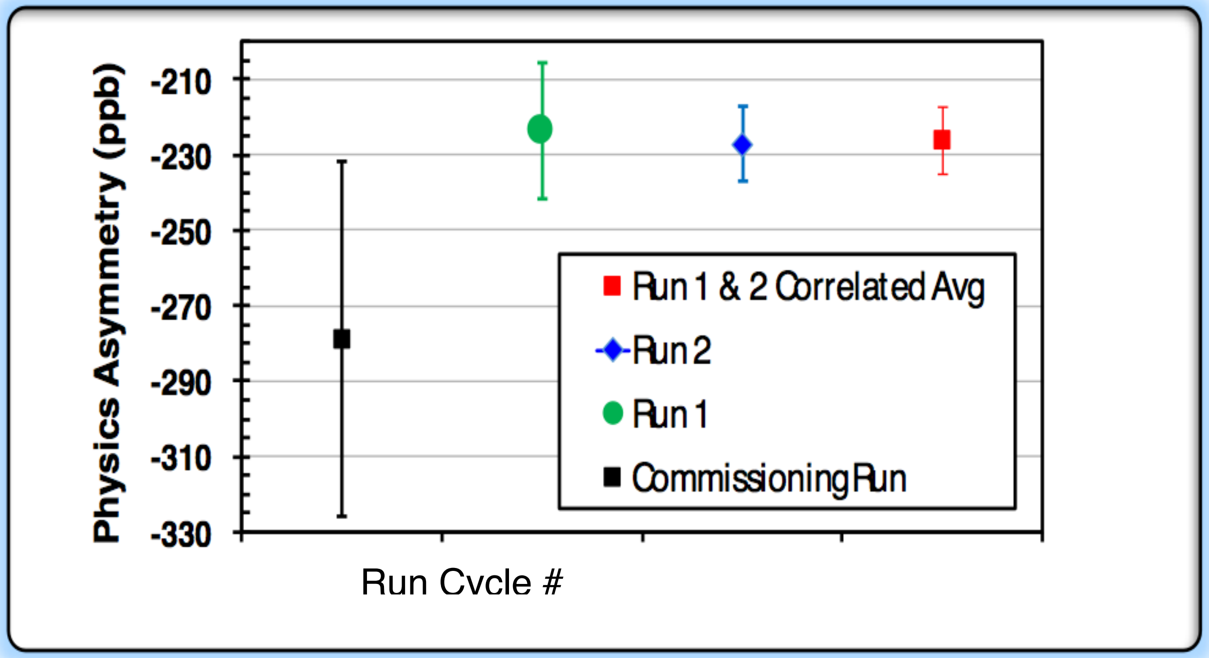
$$A_{\text{msr}} = A_{\text{raw}} + A_T + A_L + A_{\text{BCM}} + A_{\text{BB}} + A_{\text{beam}} + A_{\text{bias}}$$

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

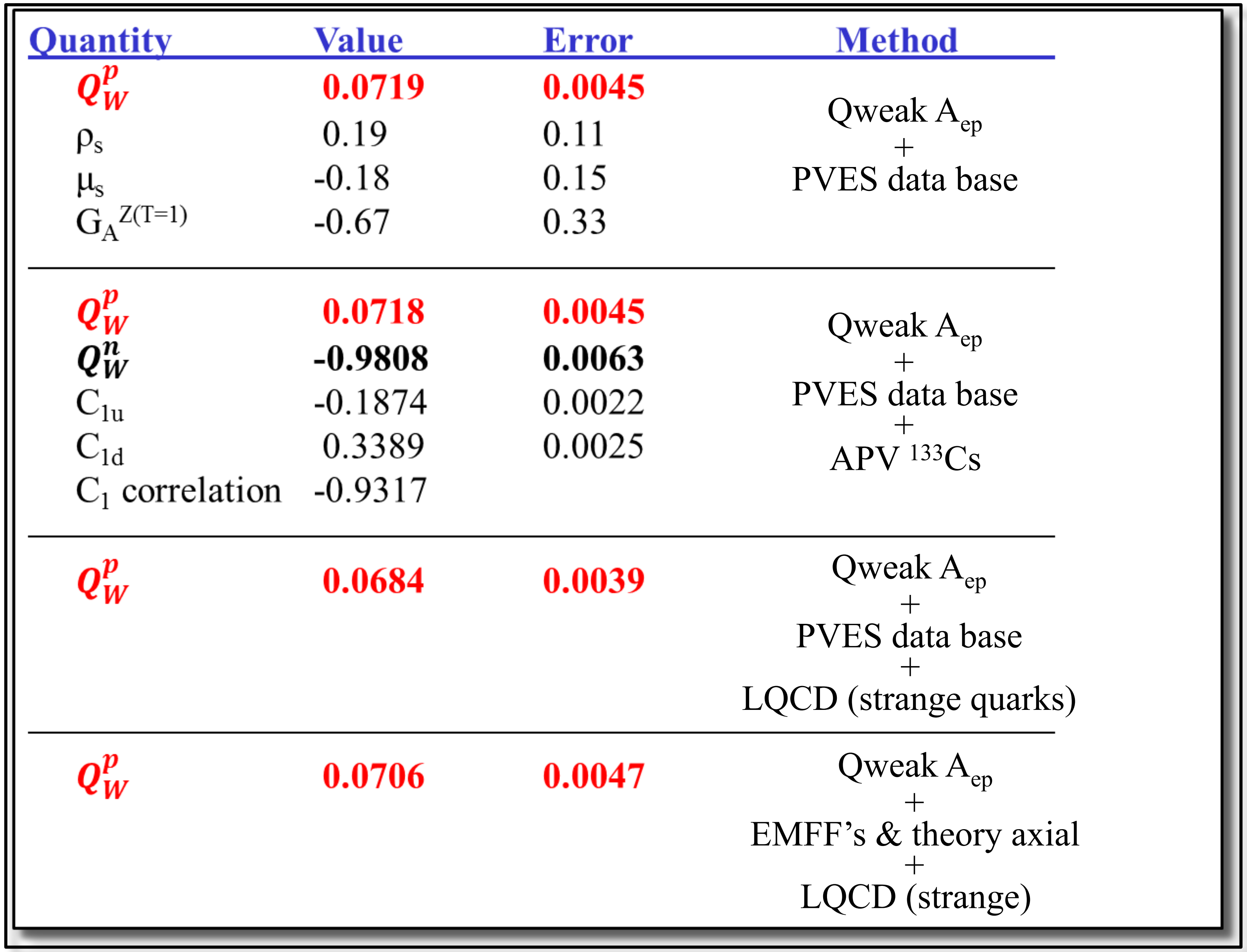
| Quantity | Run 1 error (ppb) | Run 1 fractional | Run 2 error (ppb) | Run 2 fractional |
|---|---|---|---|---|
| BCM Normalization: $A_{\text{BCM}}$ | 5.1 | 25% | 2.3 | 17% |
| Beamline Background: $A_{\text{BB}}$ | 5.1 | 25% | 1.2 | 5% |
| Beam Asymmetries: $A_{\text{beam}}$ | 4.7 | 22% | 1.2 | 5%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

- Our final result is still statistically limited

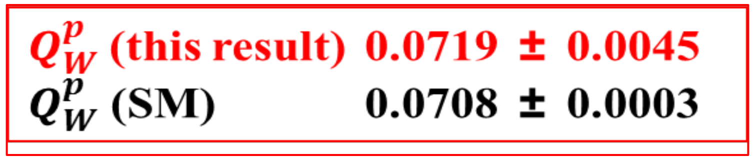
| Period | Asymmetry (ppb) | Stat. Unc. (ppb) | Syst. Unc. (ppb) | Tot. Uncertainty (ppb) |
|---|---|---|---|---|
| Run 1 | -223.5 | 15.0 | 10.1 | 18.0 |
| Run 2 | -227.2 | 8.3 | 5.6 | 10.0 |
| Run 1 and 2 combined with correlations | -226.5 | 7.3 | 5.8 | 9.3 |



# Result stability



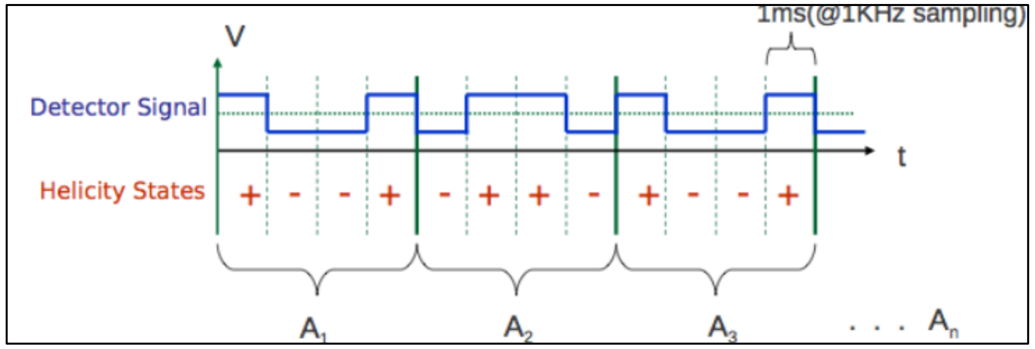
| Quantity | Value | Error | Method |
|---|---|---|---|
| $Q^p_W$ | **0.0719** | **0.0045** | Qweak $A_{ep}$ + PVES data base |
| $\rho_s$ | 0.19 | 0.11 | |
| $\mu_s$ | -0.18 | 0.15 | |
| $G_A^{Z(T=1)}$ | -0.67 | 0.33 | |
| $Q^p_W$ | **0.0718** | **0.0045** | Qweak $A_{ep}$ + PVES data base + APV $^{133}$Cs |
| $Q^n_W$ | **-0.9808** | **0.0063** | |
| $C_{1u}$ | -0.1874 | 0.0022 | |
| $C_{1d}$ | 0.3389 | 0.0025 | |
| $C_1$ correlation | -0.9317 | | |
| $Q^p_W$ | **0.0684** | **0.0039** | Qweak $A_{ep}$ + PVES data base + LQCD (strange quarks) |
| $Q^p_W$ | **0.0706** | **0.0047** | Qweak $A_{ep}$ + EMFF's & theory axial + LQCD (strange) |

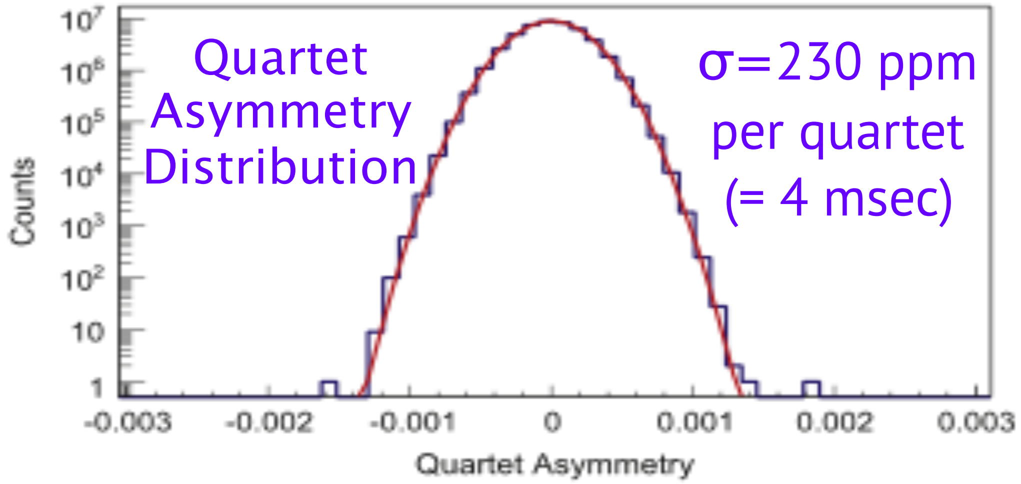


| | | |
|---|---|---|
| $Q^p_W$ (this result) | 0.0719 | ± 0.0045 |
| $Q^p_W$ (SM) | 0.0708 | ± 0.0003 |

- Including the APV data gives discrimination power for C1u and C1d which leads to $Q^n_W$
- The addition of LQCD data add additional constraints on the $Q^p_W$ determination
- A determination without the rest of the PVES data (but with some ansatz for the form factors) shows the power of the Qweak experiment

# PV Measurement





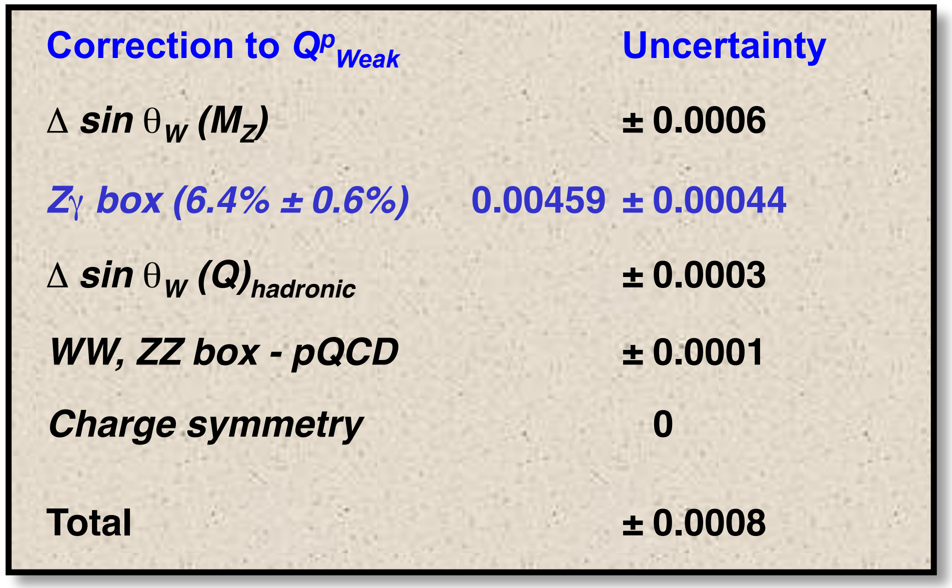
LH2 statistical width (per quartet):

- Counting statistics: 200 ppm
- Main detector resolution: 92 ppm
- Target noise/boiling: 55 ppm
- BCM Resolution: 43 ppm
- Electronic noise: 3 ppm

- Integrate light signal for ~1 msec
- Calculate asymmetry for 4 adjacent data samples and add a blinding factor
- Analyzed ~$10^9$ quartets which is equivalent to ~$10^{17}$ detected electrons

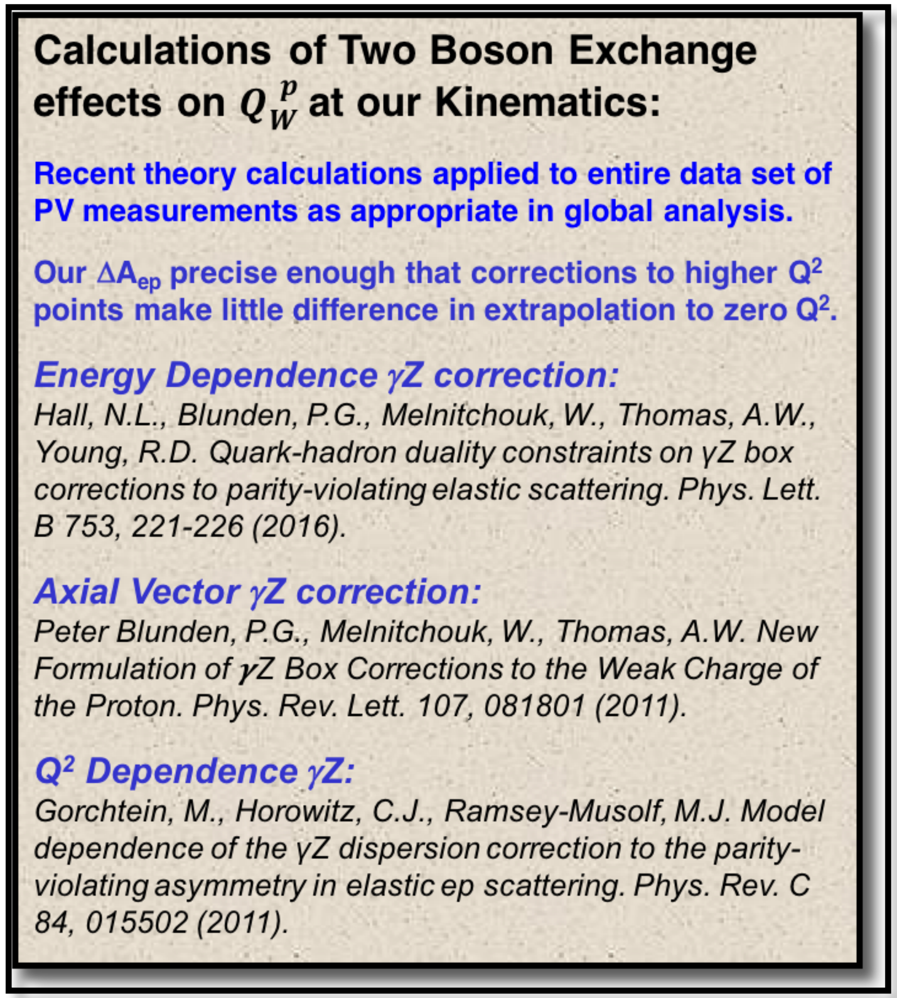
# Electroweak radiative corrections

$$Q^p_W = [1 + \Delta\rho + \Delta_e]\left[(1 - 4\sin^2\theta_W(0)) + \Delta_{e'}\right] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$



| 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 $Q^p_W$ at our Kinematics:**

**Recent theory calculations applied to entire data set of PV measurements as appropriate in global analysis.**

**Our $\Delta A_{ep}$ precise enough that corrections to higher $Q^2$ points make little difference in extrapolation to zero $Q^2$.**

***Energy Dependence $\gamma Z$ 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 $\gamma Z$ correction:***

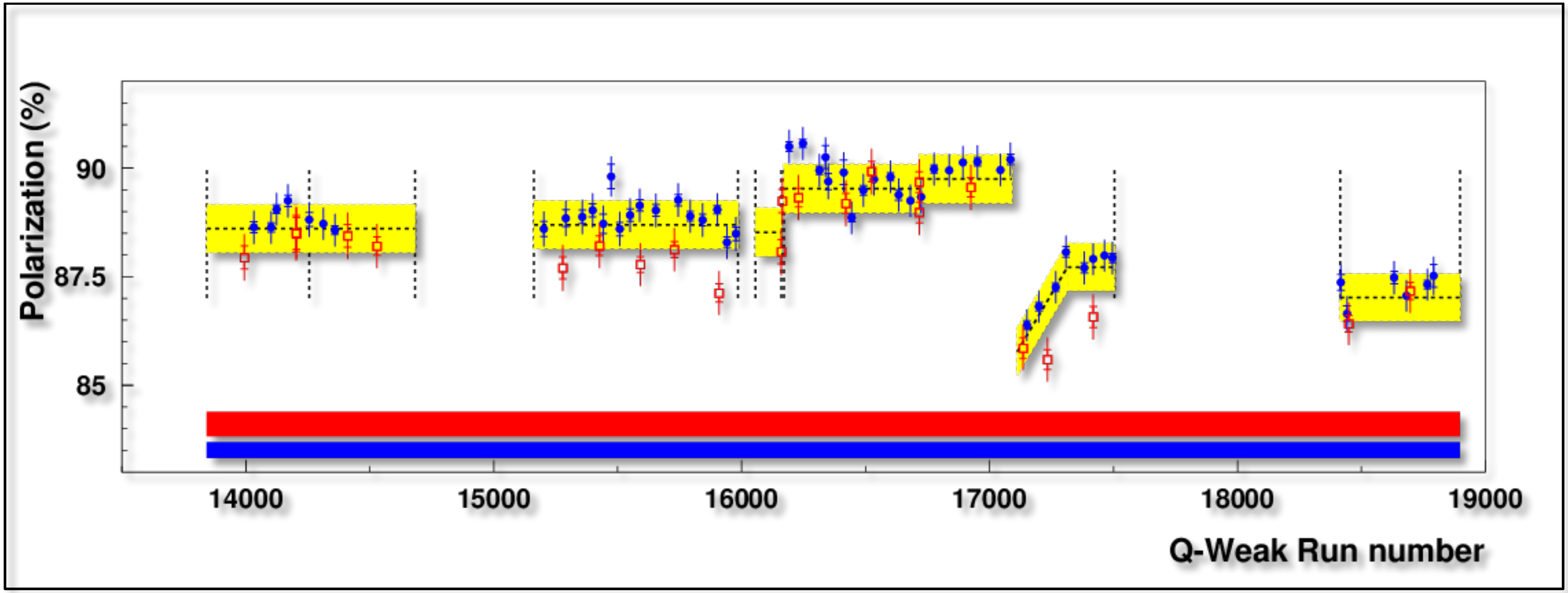
*Peter Blunden, P.G., Melnitchouk, W., Thomas, A.W. New Formulation of γZ Box Corrections to the Weak Charge of the Proton. Phys. Rev. Lett. 107, 081801 (2011).*

***$Q^2$ Dependence $\gamma Z$:***

*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).*

***courtesy of R. Carlini**

# Polarization measurement



- 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.

***courtesy of R. Carlini**