Qweak: Measuring the Weak Charge of the Proton With Parity Violation in Electron Scattering

Lepton-Nucleus Scattering XIV

Marciana Marina, Isola d'Elba
June 27-July 1, 2016

Kent Paschke

UNIVERSITY *of* VIRGINIA

Thanks to Mark Pitt, Paul King, Dave Mack, Kurtis Bartlett, and Wouter Deconinck for figures

Parity-Violating Electron Scattering

Low Q^2 offers complementary probes of new physics at multi-TeV scales

$0\nu\beta\beta$ *decay,* β *decay, EDM, DM, LFV, weak decays,* g_μ*-2…*

Parity-Violating Electron Scattering: *Low energy weak neutral current couplings, precision weak mixing angle (SLAC, Jefferson Lab, Mainz)*

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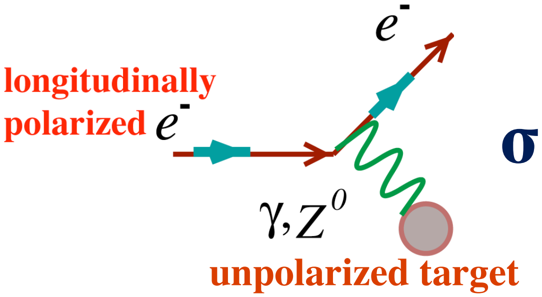

$$\sigma \propto |A_\gamma + A_{weak}|^2$$

$$\sim |A_\gamma|^2 + 2A_\gamma(A_{weak})^* + \ldots$$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim 10^{-4} Q^2$$

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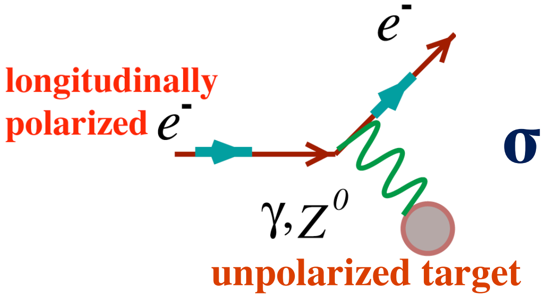

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Many new physics models give rise to new neutral current interactions

$$\mathcal{L} = \mathcal{L}_{\mathtt{SM}} + \mathcal{L}_{\mathtt{new}}$$

Heavy Z's and neutrinos, technicolor,
compositeness, extra dimensions, SUSY…

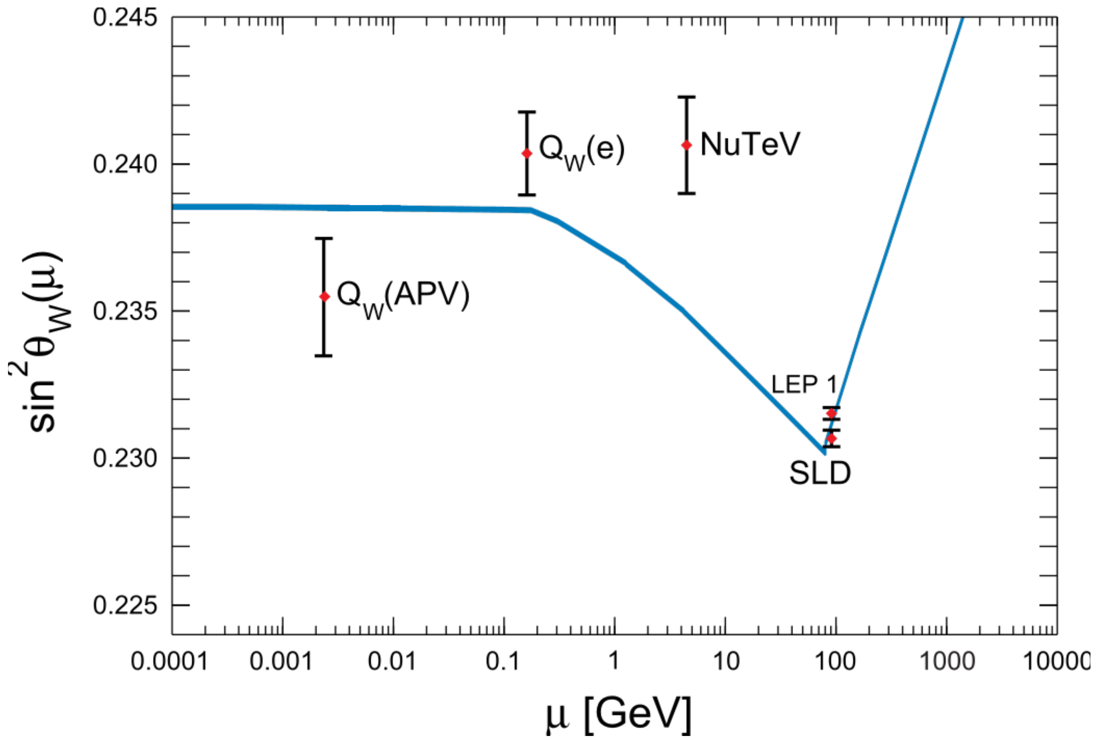
Electromagnetic amplitude interferes with Z-exchange as well as any new physics

$$\left|\mathbf{A}_\gamma + \mathbf{A}_\mathbf{Z} + \mathbf{A}_{\mathrm{new}}\right|^{\mathbf{2}} \rightarrow \mathbf{A}_\gamma^{\mathbf{2}}\left[\mathbf{1} + \mathbf{2}\left(\frac{\mathbf{A}_\mathbf{Z}}{\mathbf{A}_\gamma}\right) + \mathbf{2}\left(\frac{\mathbf{A}_{\mathrm{new}}}{\mathbf{A}_\gamma}\right)\right]$$

SLAC E122 (1978): First measurement of PVES, central to establishing $SU(2)_L \times U(1)_Y$

Weak Neutral Current Vector Charge

	EM Charge	WNC Vector Charge
u	$+\frac{2}{3}$	$1-\frac{8}{3}\sin^2\theta_W$
d	$-\frac{1}{3}$	$-1+\frac{4}{3}\sin^2\theta_W$
$p=2u+d$	$+1$	$1-4\sin^2\theta_W$
$n=u+2d$	0	-1
e	-1	$-(1-4\sin^2\theta_W)$



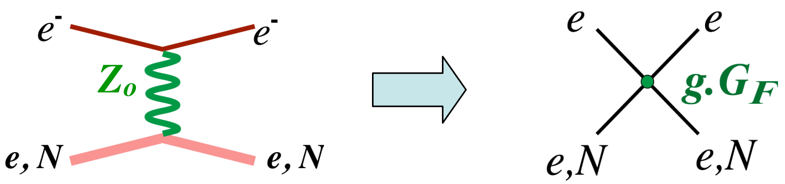
$$Q_W^p = 1-4\sin^2\theta_W \qquad \sin^2\theta_W \sim \frac{1}{4}$$

Suppression of Standard Model WNC vector coupling to the proton enhances the sensitivity of parity-violating interactions with the proton for new physics

Search for, or study, new neutral currents

Low energy WNC interactions ($Q^2 << M_Z^2$)

Heavy mediators = contact interactions



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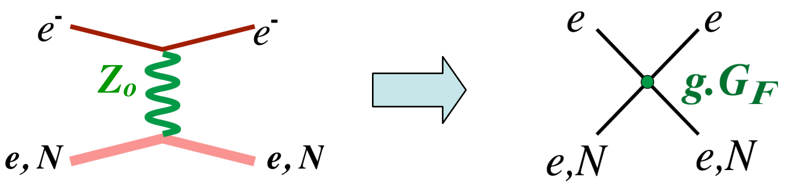
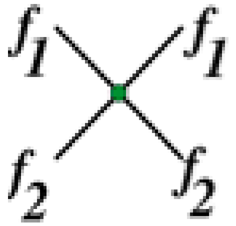


Consider $f_1 f_1 \to f_2 f_2$ **or** $f_1 f_2 \to f_1 f_2$



$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g^{12}_{i\,j})^2}{\Lambda^2_{ij}} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$

Eichten, Lane and Peskin, PRL50 (1983)

mass scale Λ, coupling g **for each fermion and handedness combination**

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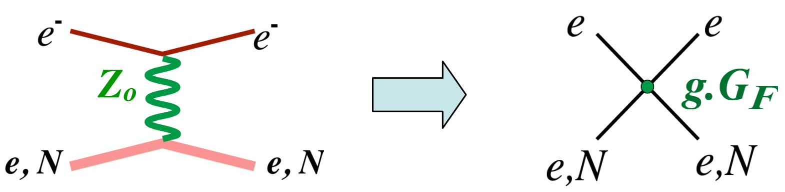

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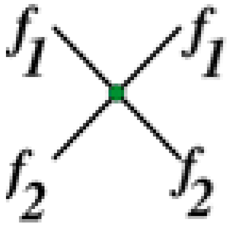

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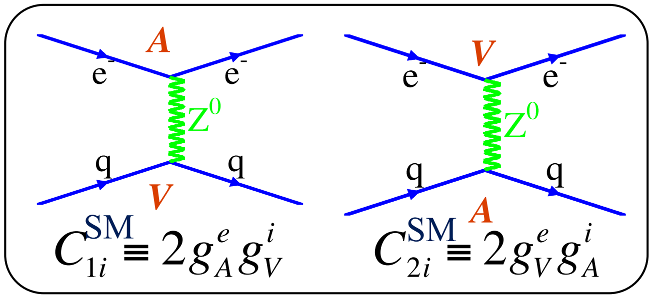
Example:
Standard model
e-q couplings



$C^{\mathrm{SM}}_{1i} \equiv 2 g^e_A g^i_V$ $C^{\mathrm{SM}}_{2i} \equiv 2 g^e_V g^i_A$

precision measurement to test for new possible couplings

$$C_{1q} = (g^{eq}_{RR})^2 + (g^{eq}_{RL})^2 - (g^{eq}_{LR})^2 - (g^{eq}_{LL})^2$$

$$C_{2q} = (g^{eq}_{RR})^2 - (g^{eq}_{RL})^2 + (g^{eq}_{LR})^2 - (g^{eq}_{LL})^2$$

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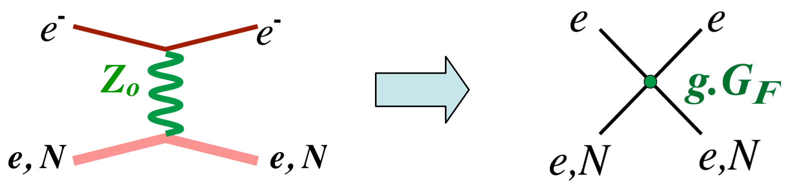

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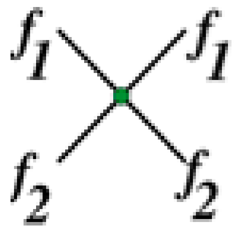

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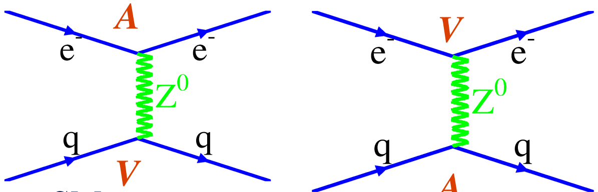

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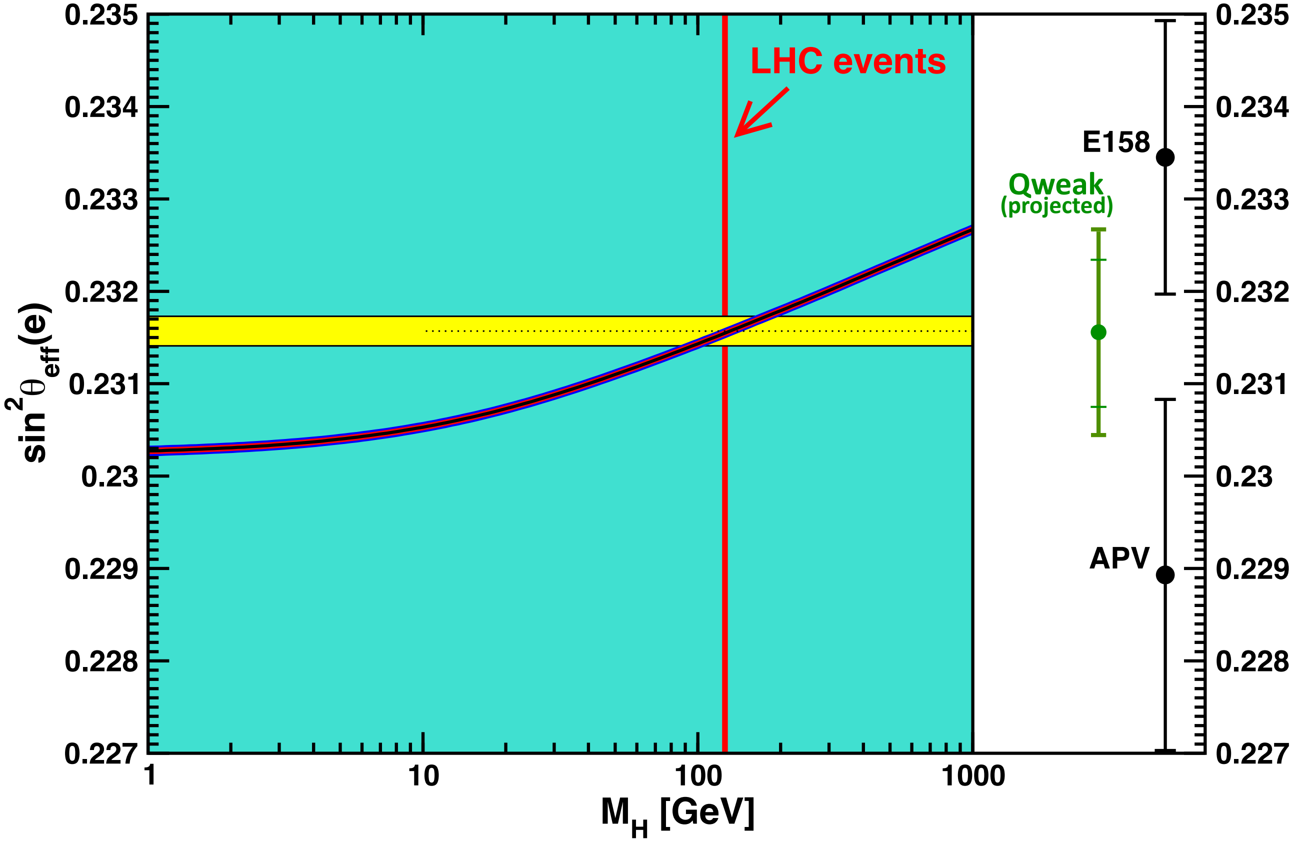
Conventional "mass limits" in precision measurements are defined using a compositeness scale $g^2=4\pi$.

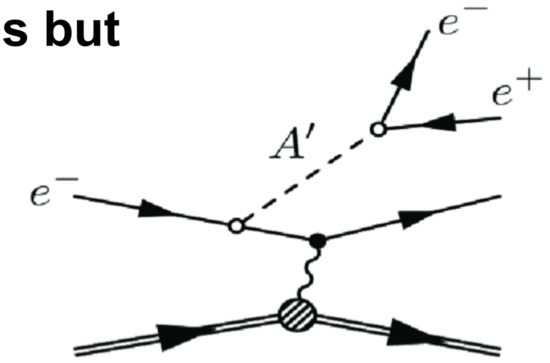
Following the conventions of Erler *et al.* (arXiv1401.6199): a 4% measurement of $Q_W^p = 2C_{1u} + C_{1d}$ corresponds to a mass limit of 33 TeV .

Mixing Angle in Higgs Era



Can there be light new physics?

Dark photon, couples to Dark Sector massive particles but with small E&M couplings to known matter



Hypothesis could explain $(g\text{-}2)_\mu$ discrepancy, 511keV line in galactic core, Pamela high energy positron excess

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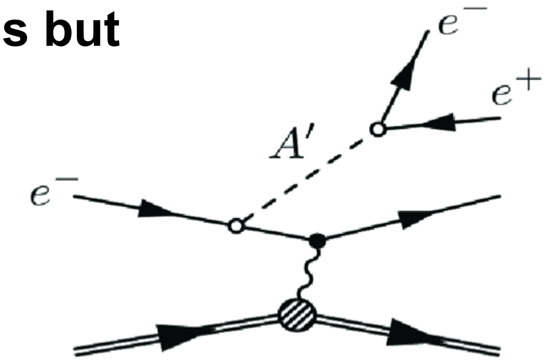

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Beyond kinetic mixing: introduce mass mixing with Z^0

The Z mass eigenstates is mostly Z^o, but with a little bit Z_d^0

The propagator no longer reduces to the contact interaction for low E PVES, due to light component in the Z^0 coupling

Davoudiasl, Lee, Marciano
Phys.Rev.Lett. 109 (2012) 031802
Phys.Rev. D85 (2012) 115019

Requires $\delta <\sim 10^{-3}$ to have remained hidden at the Z-pole and in meson decay

Complementary to direct heavy photon searches:

Lifetime/branching ratio/decay-mode model dependence vs mass mixing assumption

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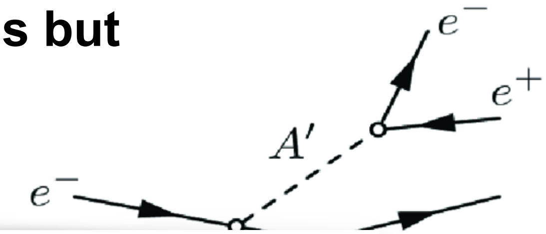

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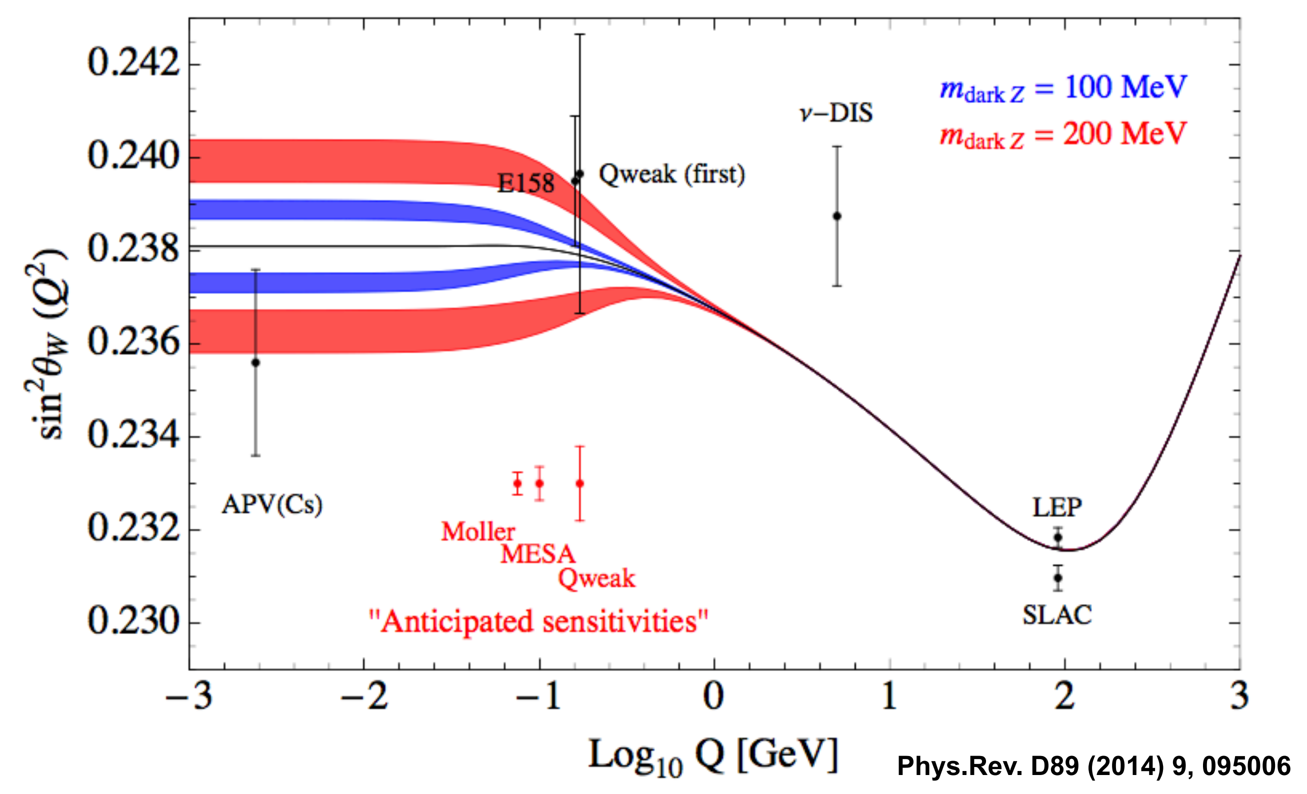

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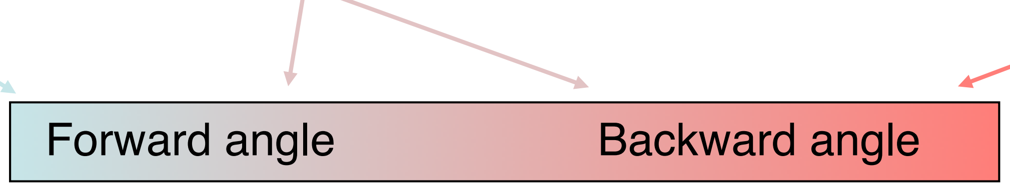
Accessing Q_W^P with PVES

Axial-electron / Vector Quark coupling dominates at forward angle, with nucleon structure increasing in importance with increasing momentum-transfer Q^2

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{A_E + A_M + A_A}{\sigma_p}$$

$$A_E = \epsilon\, G_E^p G_E^Z \qquad A_M = \tau\, G_M^p G_M^Z \qquad A_A = (1-4\sin^2\theta_W)\epsilon'\, G_M^p \tilde{G}_A^p$$



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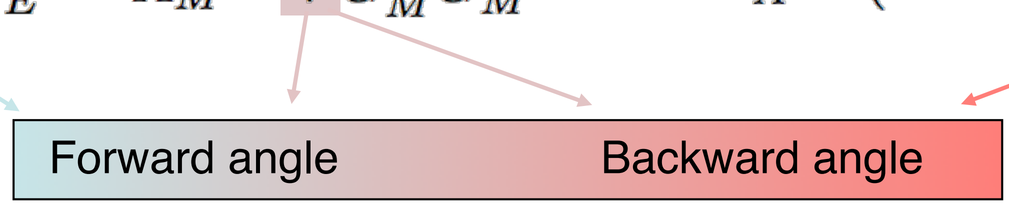

Forward angle

Backward angle

At small angle and low Q^2, form-factor and other contributions are small:

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

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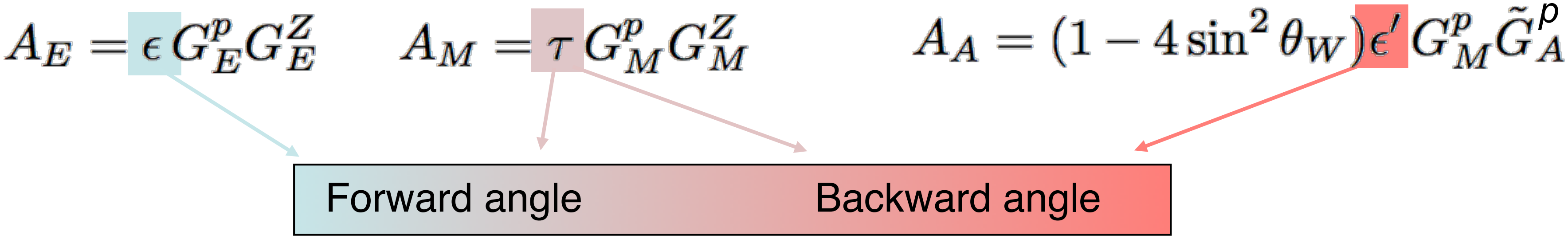

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Qweak

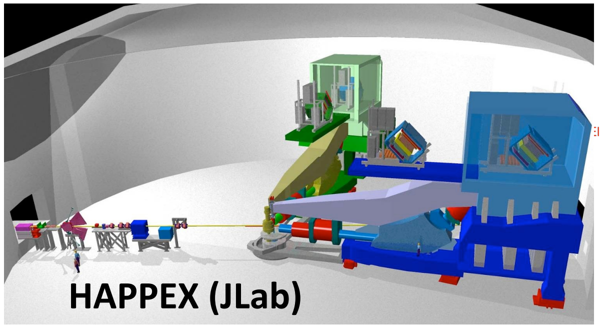
Q^2: 0.025 GeV^2
Beam Energy: 1.16 GeV
θ Acceptance: 5.8°-11.6°

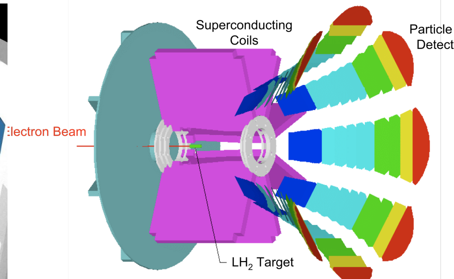
$$A_{PV} \sim -230 \text{ ppb}$$
$$\delta(A_{PV}) \sim 5 \text{ ppb}$$

Proton structure $B(\theta,Q^2)$ contributes ~30% to A_{PV}

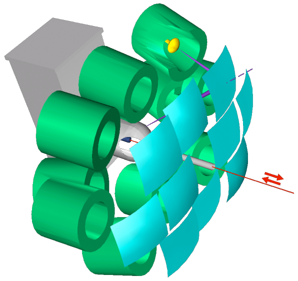
$$\boxed{\delta Q_W^p = \pm 4\%} \qquad \boxed{\delta(\sin^2\theta_W) = \pm\ 0.3\%}$$

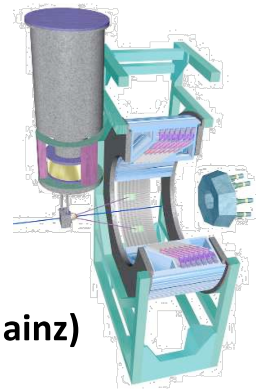
Weak Vector Form Factors at low Q^2


HAPPEX (JLab)



G0 (JLab)

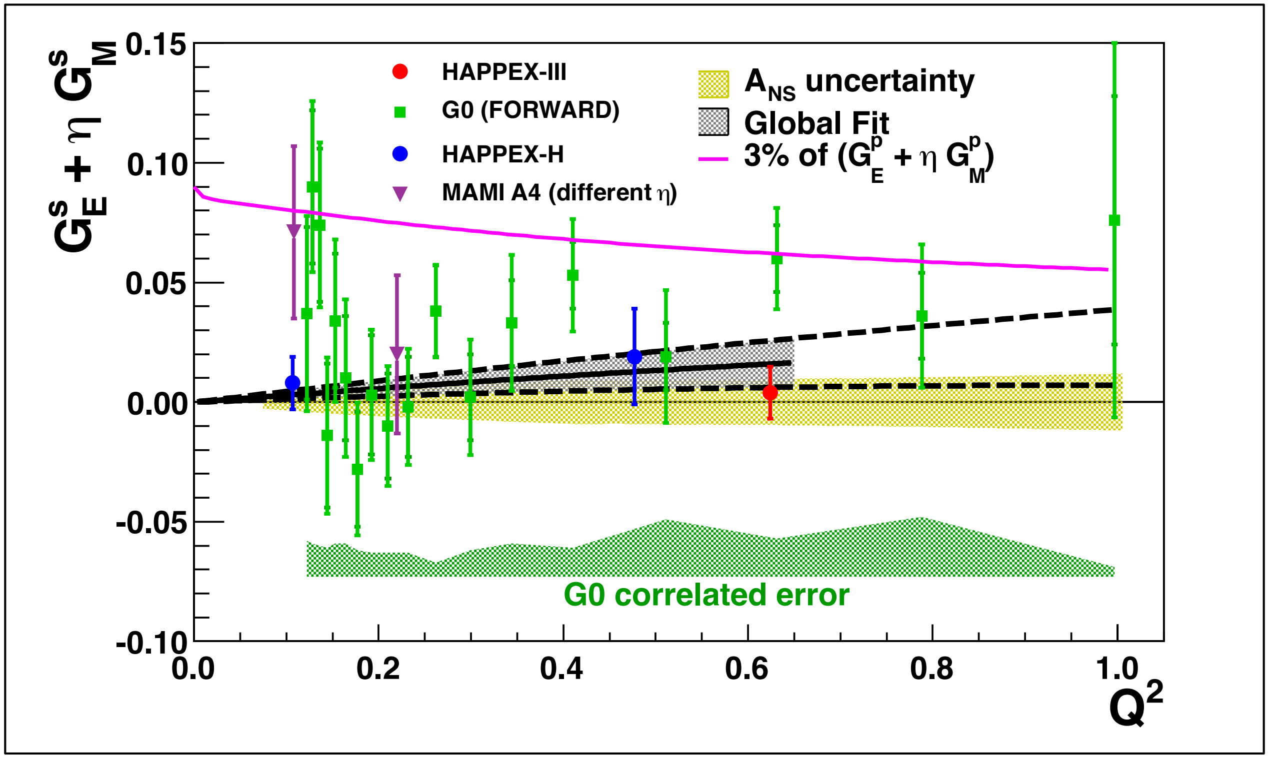

SAMPLE (Bates)


A4 (Mainz)

WNC elastic form-factors have been well studied in search of intrinsic nucleonic strangeness

$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p} - \frac{1}{3}\boxed{G_E^s}$$

$$G_M^p = \frac{2}{3}G_M^{u,p} - \frac{1}{3}G_M^{d,p} - \frac{1}{3}\boxed{G_M^s}$$



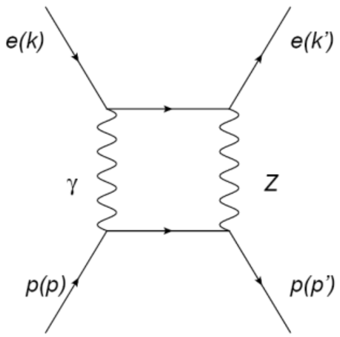
Probing over a range of low-Q^2, strange effects are small (<3%) and consistent with zero.

Whatever the cause - proton structure effects in A_{PV} must go to zero at $Q^2 = 0$

Electroweak Corrections

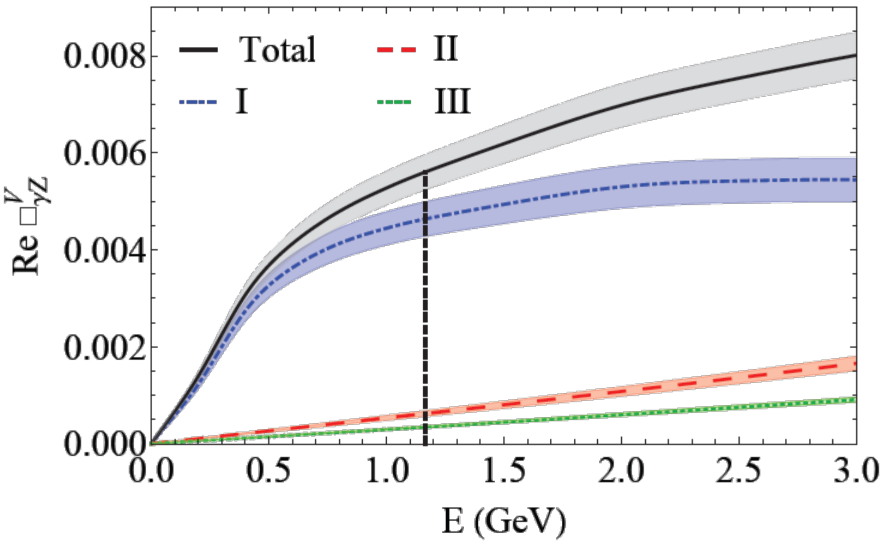
$$Q_W^p = [\rho_{NC} + \Delta_e]\left[1 - 4\sin^2\hat{\theta}_W(0) + \Delta'_e\right] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

new (energy dependent) γZ box corrections must be considered



Authors	**Vector Y-Z rad. corr. for Q_W_p**
Gorchtein & Horowitz, PRL **102**, 091806 (2009)	0.0026±0.0026
Rislow & Carlson, PRD **83**, 113007 (2011)	0.0057±0.0009
Gorchtein, Horowitz, Ramsey-Musolf, PRC 84, 015502 (2011)	0.0054±0.0020
Hall, Blunden, Melnitchouk, Thomas, Young, arXiv:1504.0397	0.0054±0.0004

Significant theoretical work, converging on precise calculation



γZ - box is E & Q^2 dependent

~7% correction at Qweak kinematics, but now well estimated

Similar corrections are required for all data in the fit

Apparatus

Measuring A_{PV}

Measure fractional rate difference between opposition helicity states

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

A_{measured} ~ -200 ppb
with 2% precision

N ~ 1×10^{17} electrons!

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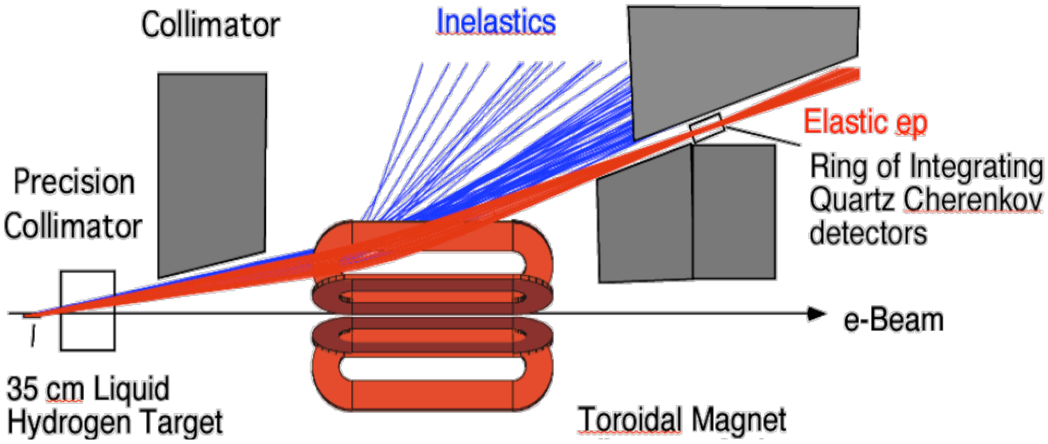
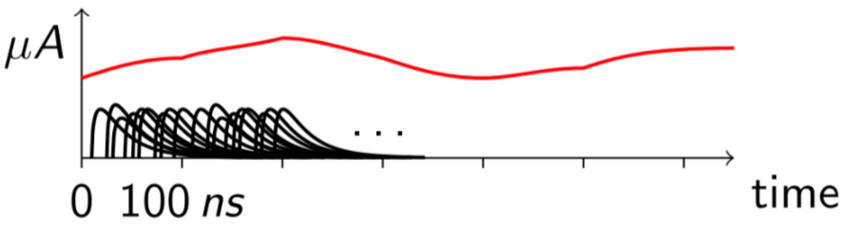
Elastic signal focused on detector



Analog integration of detector current



~6 GHz total rate

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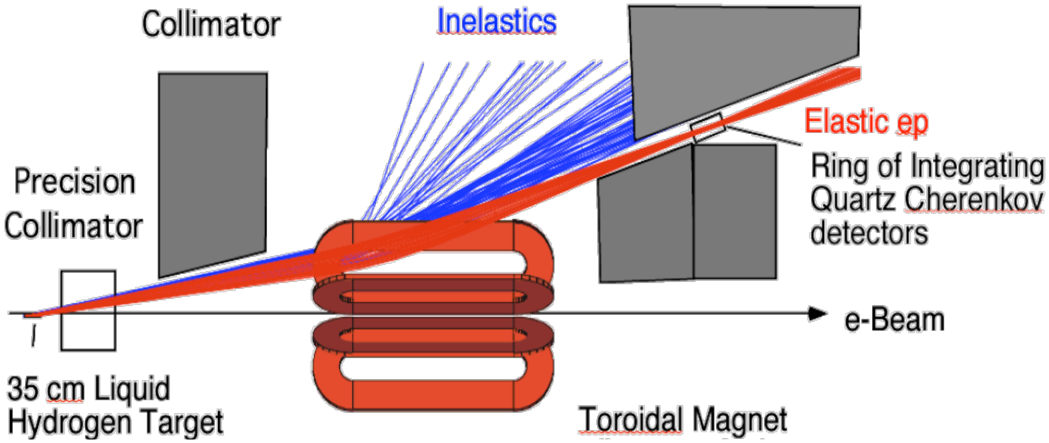

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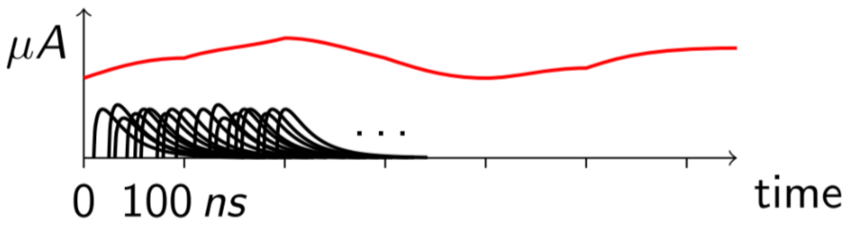
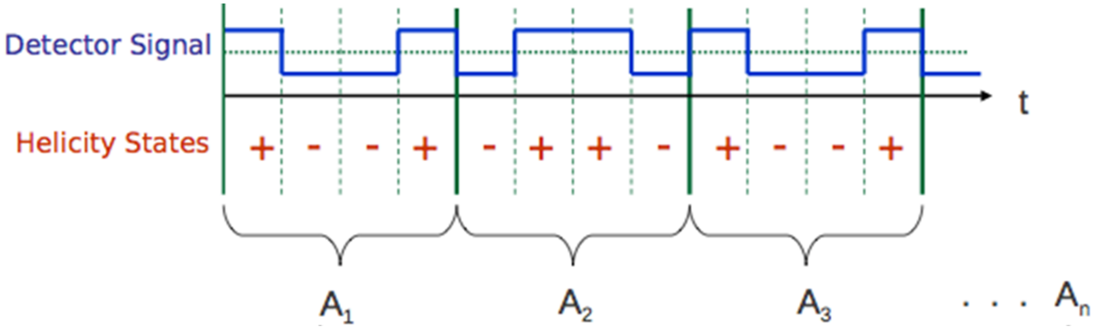
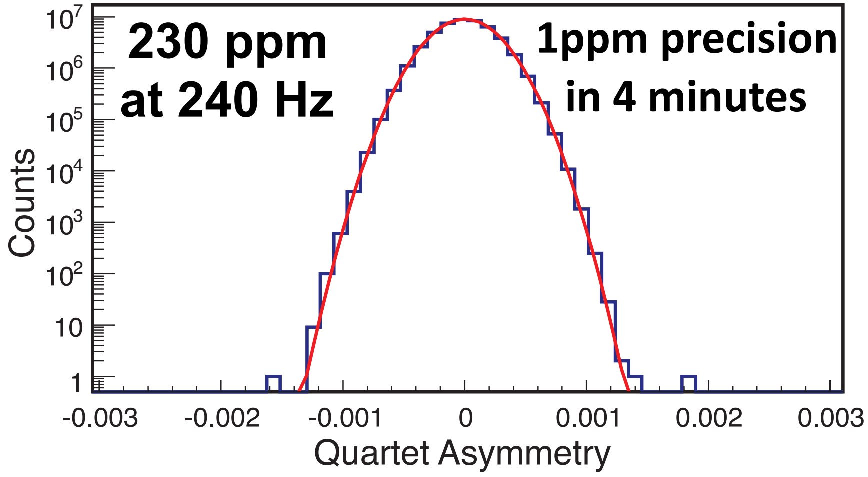


~6 GHz total rate

Rapid (1kHz) measurement over helicity reversals to cancel noise
"lock-in amplifier"



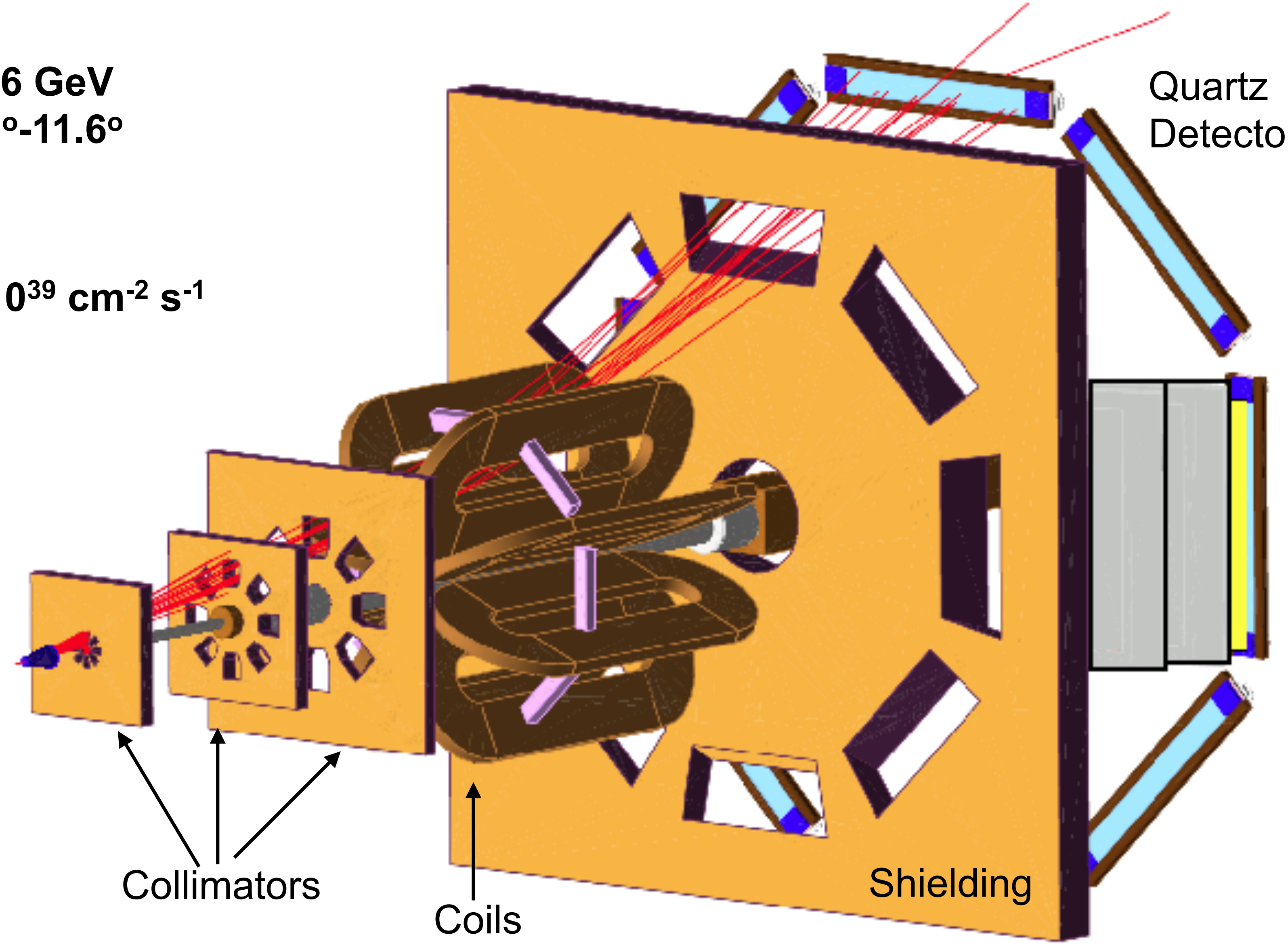


QTor Spectrometer

Goal: Isolate small-angle *ep* scattered events with large acceptance

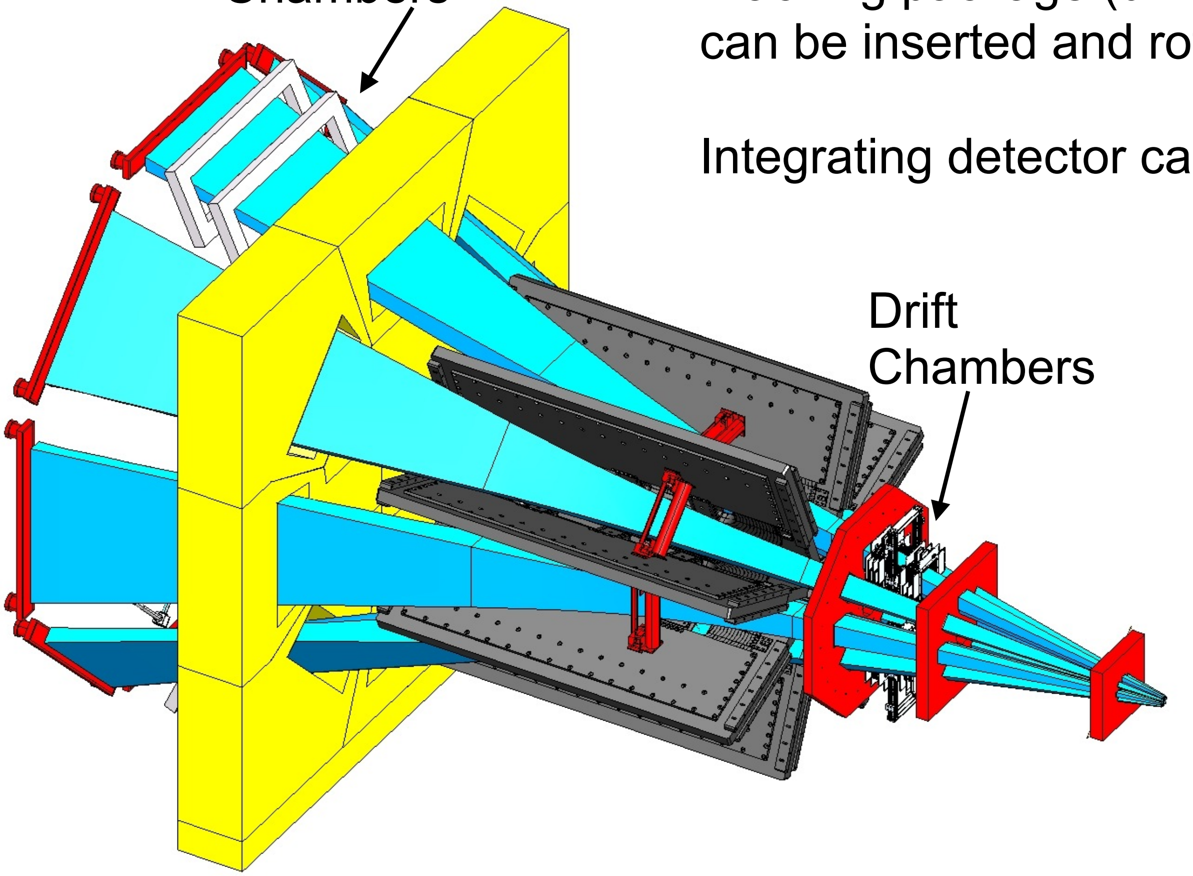
Q^2: 0.025 GeV^2
Beam Energy: 1.16 GeV
θ Acceptance: 5.8°-11.6°

Polarization: 89%
Current: 180 μA
Luminosity: 1.7×10^{39} cm^{-2} s^{-1}



Tracking System for Calibration

Used to verify understanding of kinematics, measure backgrounds



Vertical Drift Chambers

Drift Chambers

Tracking package (drift chambers plus trigger scintillators) can be inserted and rotated to any octant

Integrating detector can be converted to counting mode

- Beam current about 50 pA
- position/intensity monitored with low-angle scattering detectors

- Spectrometer optics calibrated using field maps, survey positions.
- Poor momentum resolution

Tracking Calibration

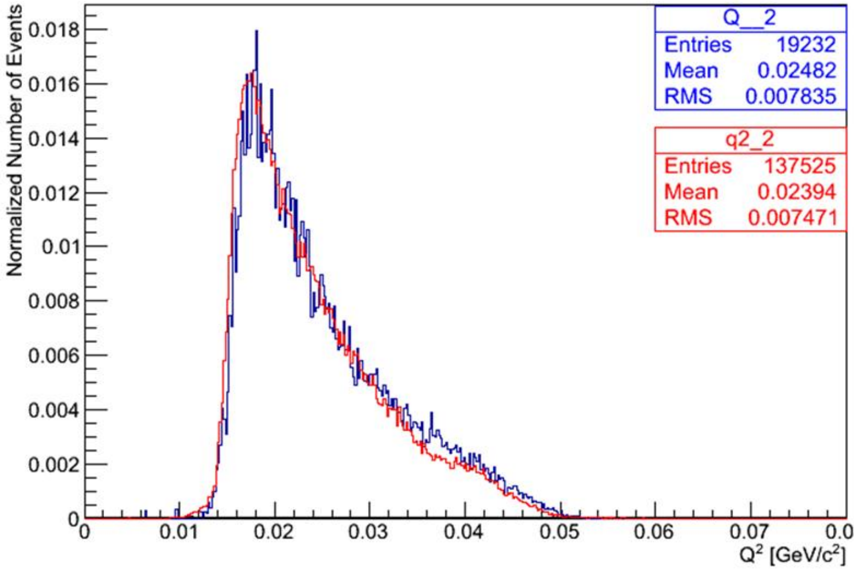
$\langle A(Q^2)\rangle$ is measured

$A(\langle Q^2\rangle)$ is reported

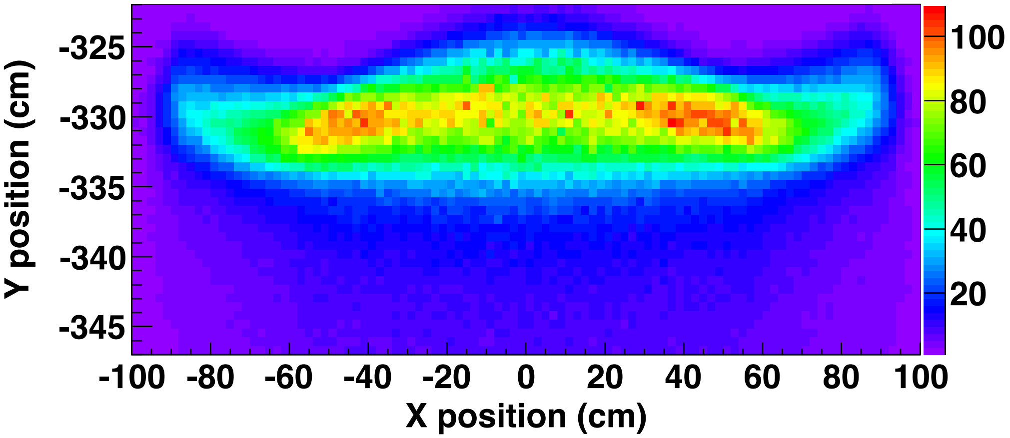
Simulation (using survey, field map) estimates the Q^2 distribution.

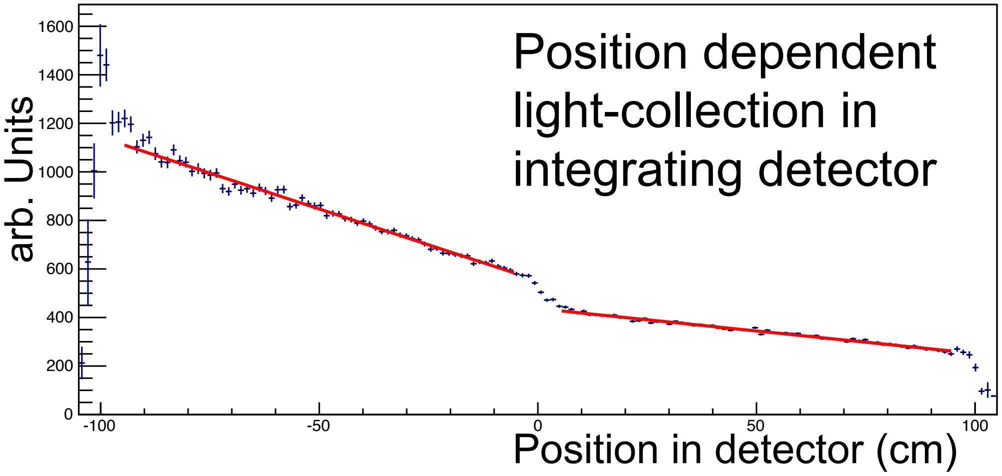
Spatial distributions are verified against tracking distributions

Q^2 distribution (simulation & data)



Hit distribution in quartz bar





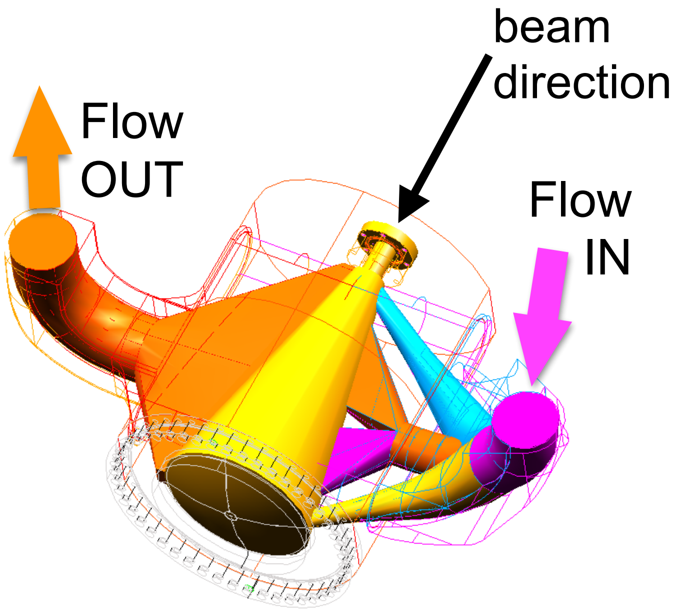
Position dependent light-collection in integrating detector

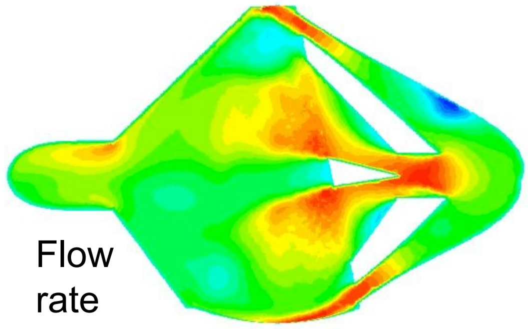
Qweak Experimental Target

World’s highest power and lowest noise cryogenic target

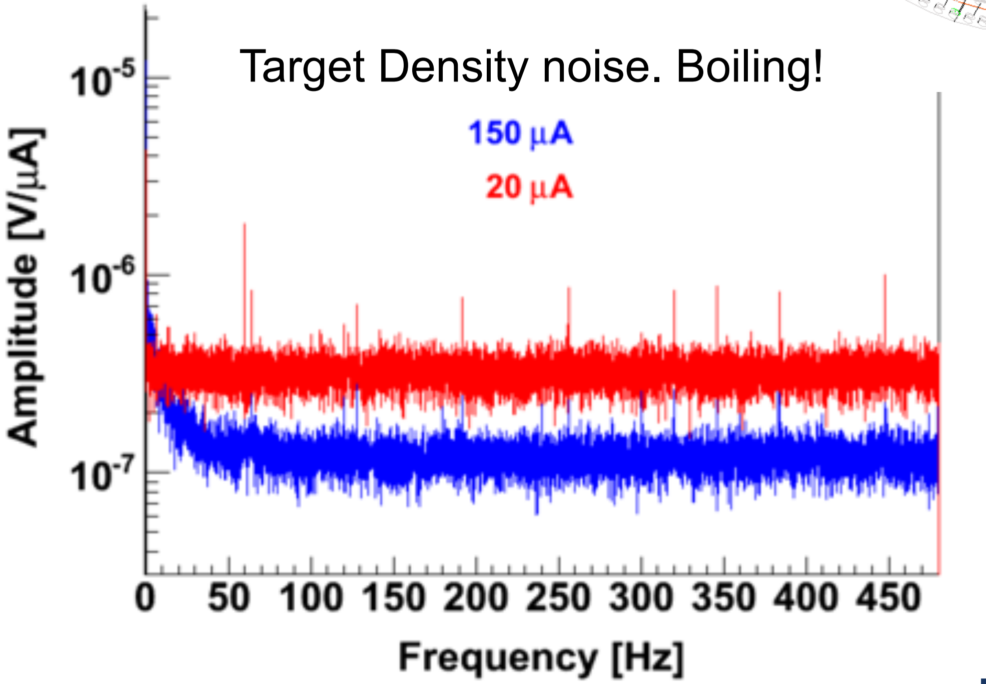
Length: 35 cm (4% X_0)

Beam Current: 180 µA
Power Deposited: 2.2 kW
A_{spot}: 4x4 mm^2





Designed with CFD simulation


Target Density noise. Boiling!

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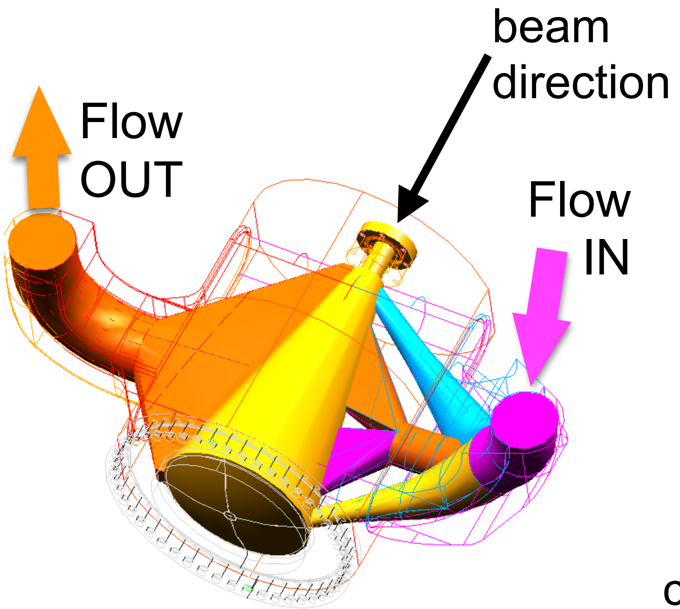

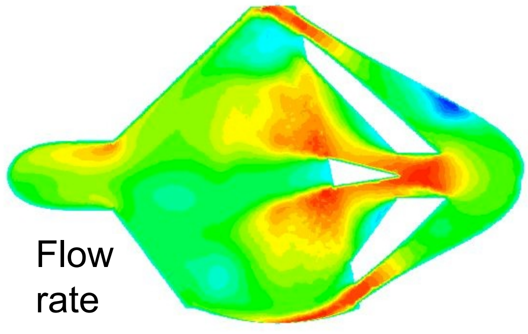

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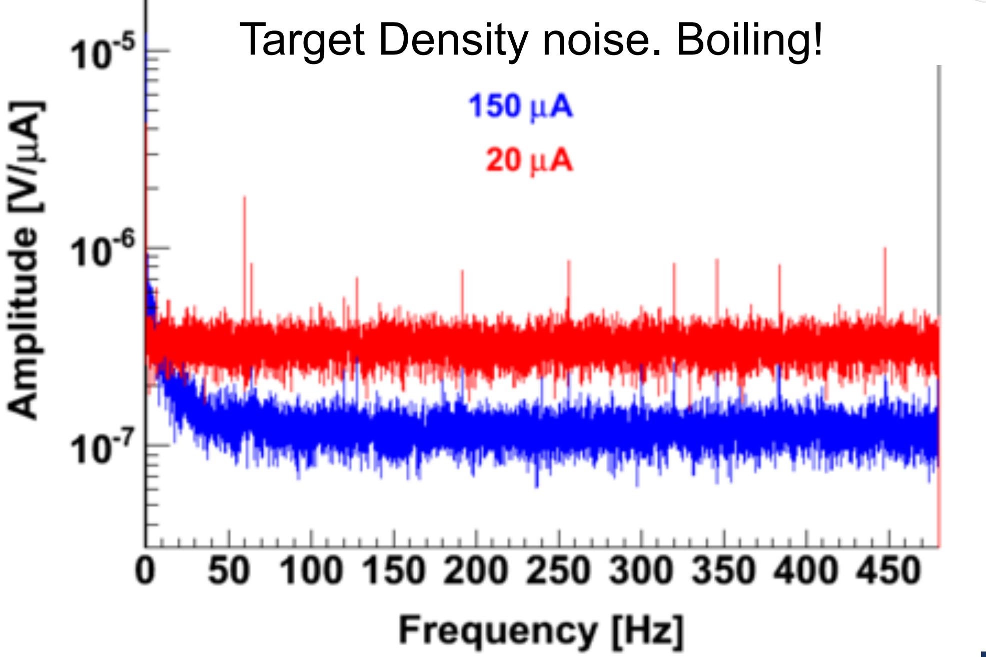
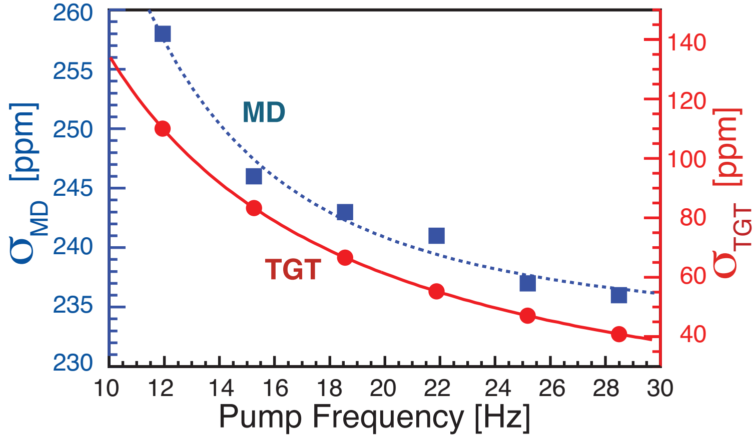

Target Density noise. Boiling!

Fast helicity reversal (1 ms)
cancelled density fluctuations

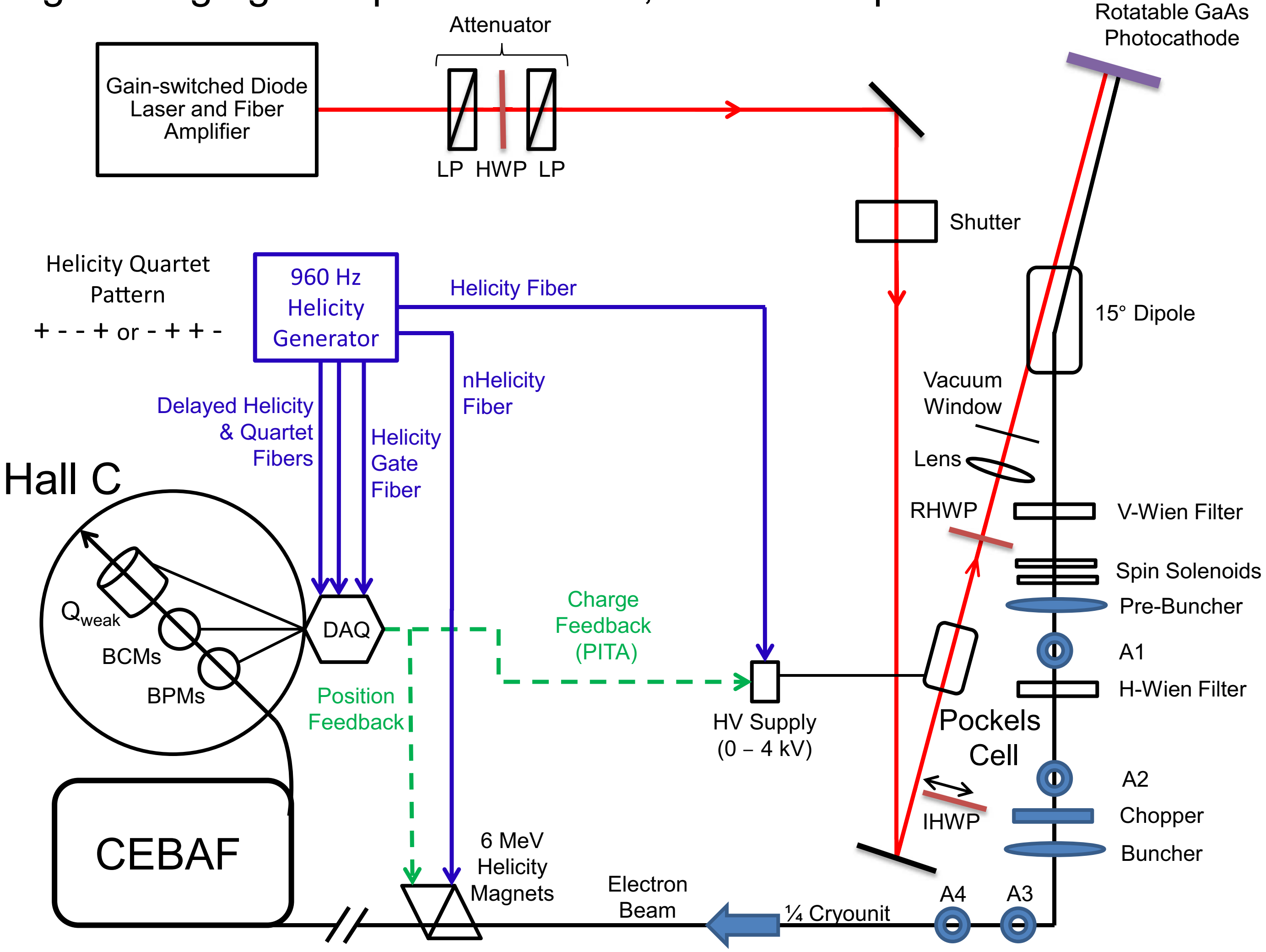


**Density Variation: ~50 ppm
over 4 ms at 180 μA**

Source and HCBA

High polarization, high power, long lifetime

- Photoemission from GaAs cathode
- Rapid Helcity reversal: polarization flips at 1 kHz
- Helicity-correlated beam asymmetry: stable at 50 nm under sign flip
- high-voltage gun improved lifetime, beam transport



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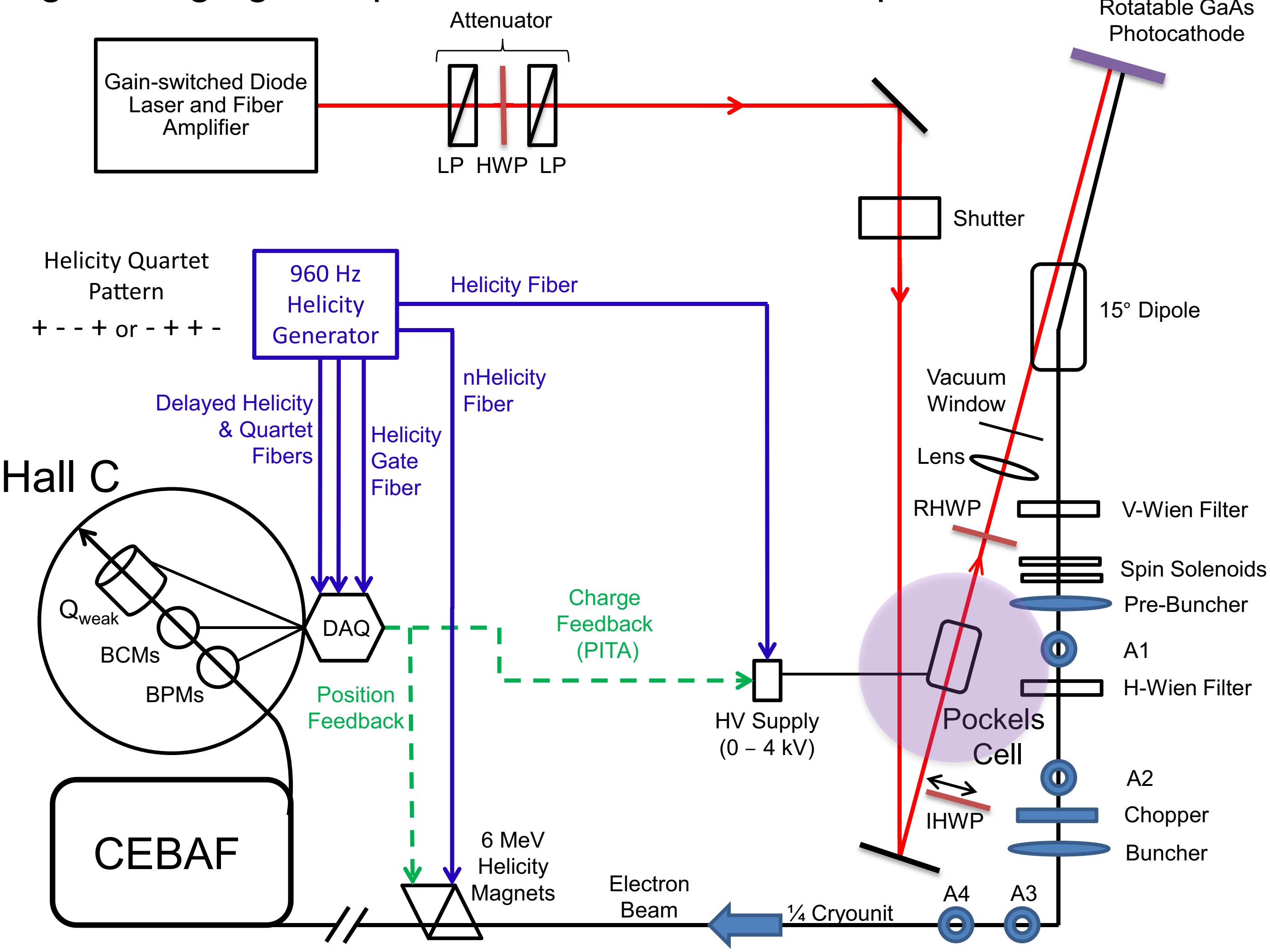

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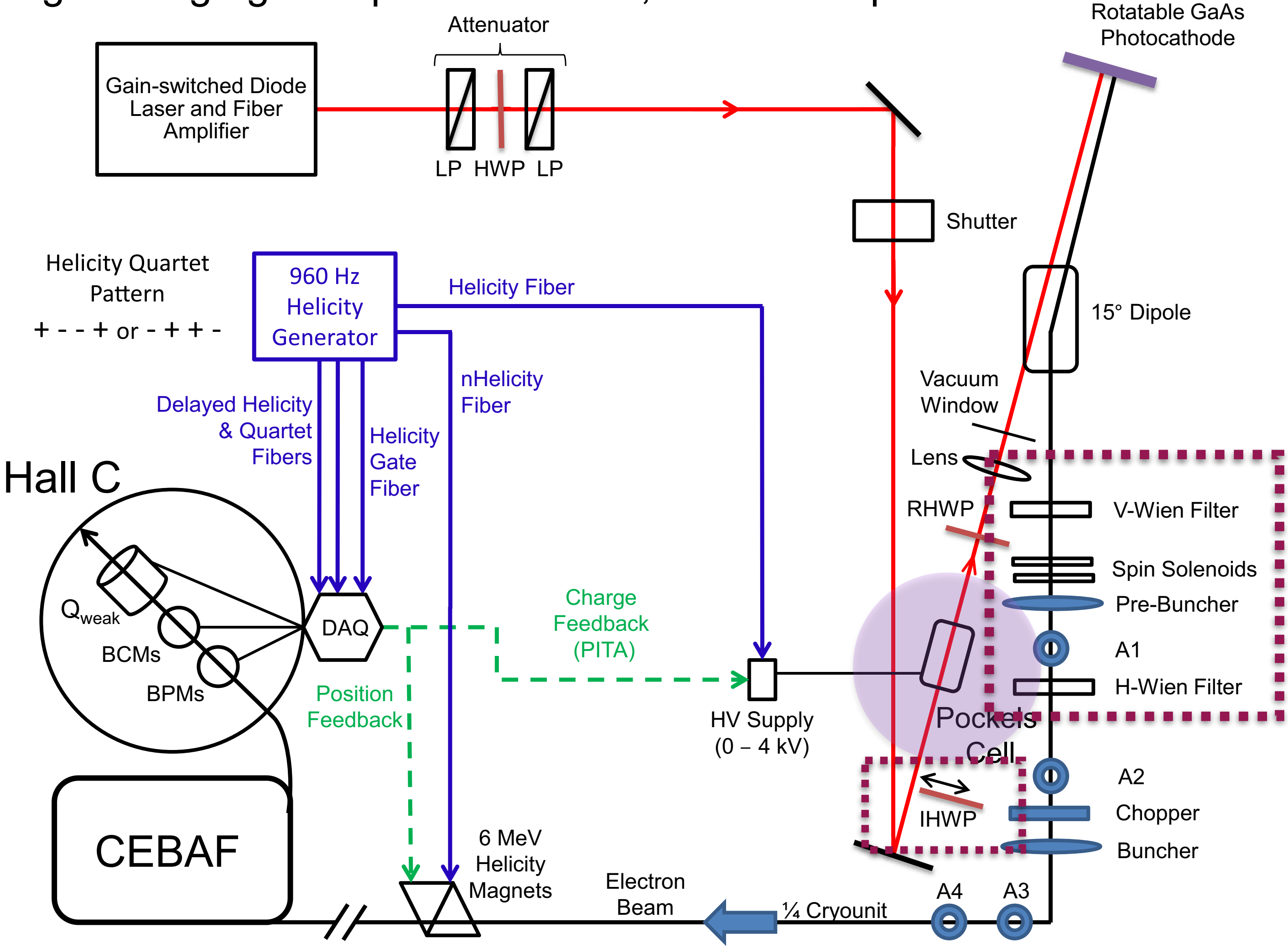
- **Rapid:** Pockels cell (1 kHz)
- **Insertable waveplate** (8 hours)
- **Injector spin manipulation** (monthly)



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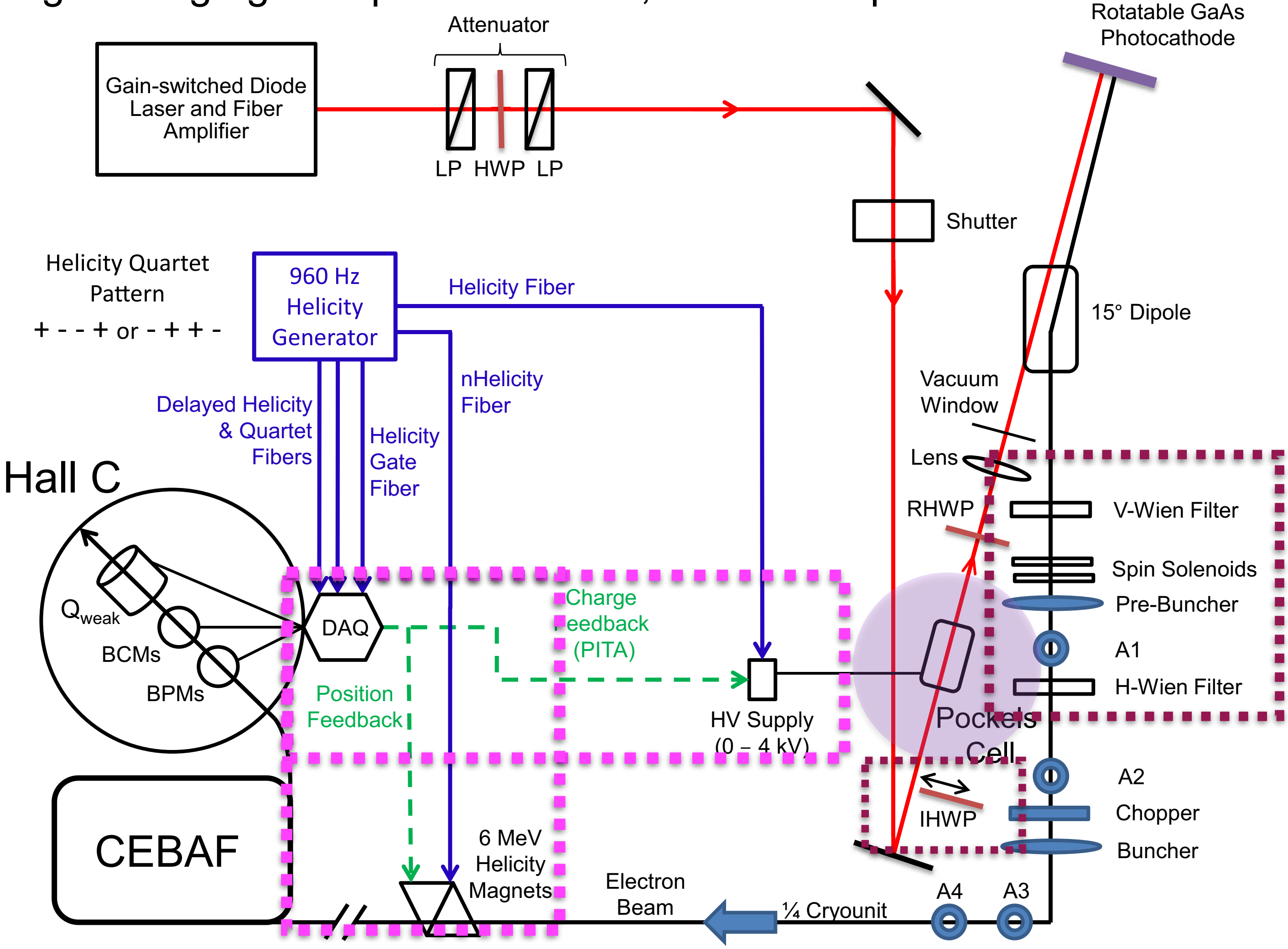

Feedback

Intensity asymmetries feedback adjusted the Pockels cell voltage setpoint (~ 10 ppb)

Position differences adjusted with air-core dipole magnets in the injector

Source and HCBA

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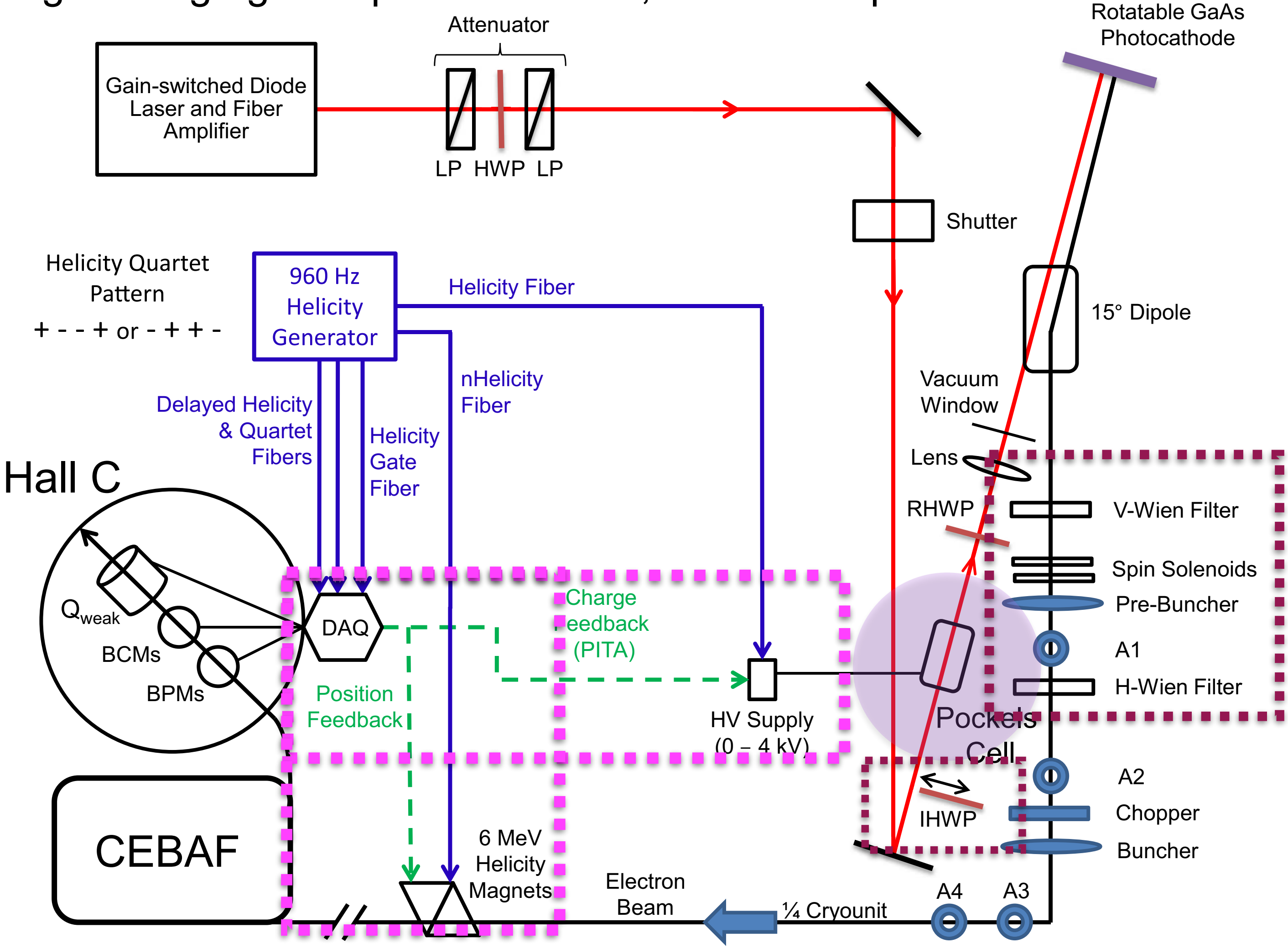

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Position differences adjusted with air-core dipole magnets in the injector

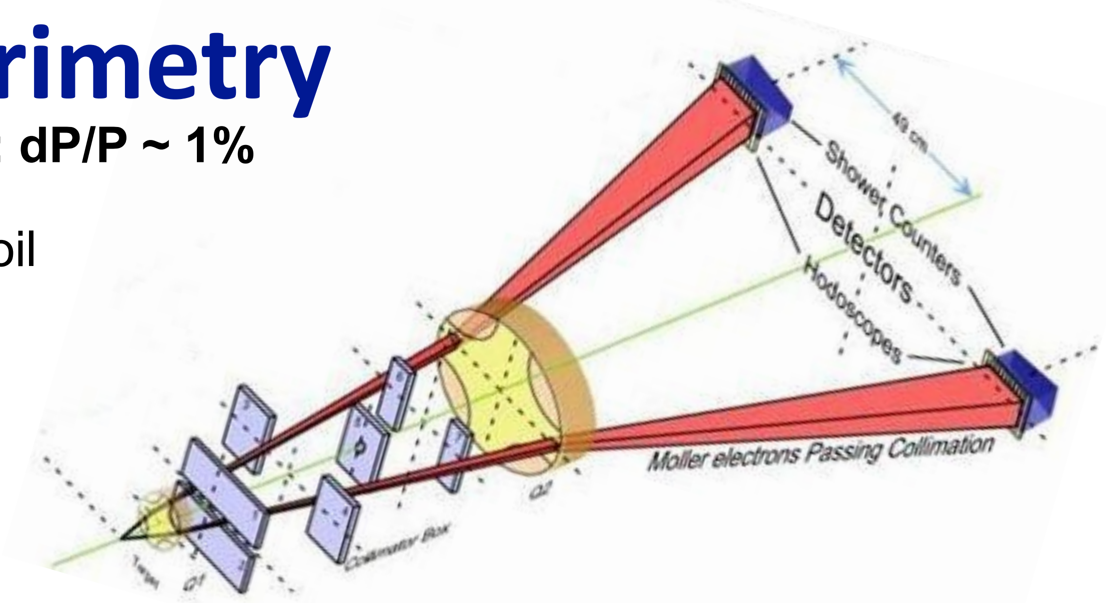
Results

- Injector: ~50 nm
- Hall: ~100 nm
- reversals: ~10 nm
- Feedback: ~1-2 nm

Polarimetry

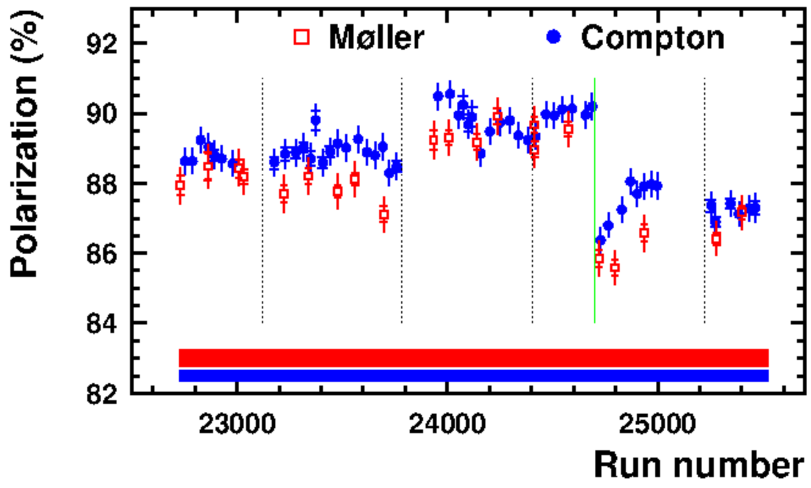
Goal: dP/P ~ 1%

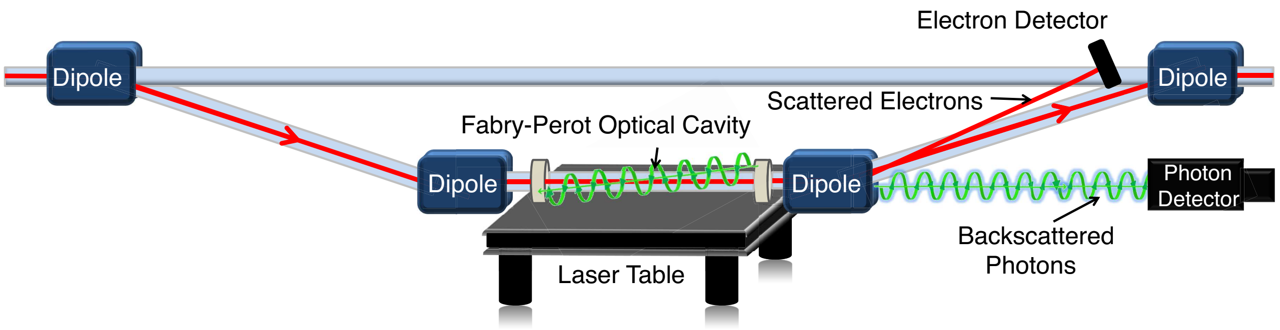
Moller: *ee* scattering off polarized iron foil
- saturated iron
- experience with ~1% precision in Hall C
- modified spectrometer for 1 GeV
- invasive, low current only



Compton: $e\gamma$ scattering with polarized green laser light
- new polarimeter
- low E_{beam}: low analyzing power, low scattering energies
- diamond microstrip detector
- *per mille* control of laser polarization inside cavity

Comparison of independent polarimeters





Important milestone for high precision polarimetry needed for future program

Physical Review X6 (2016) no.1, 011013

First Results

Qweak had ~ 1 calendar year of beam split into 3 running periods

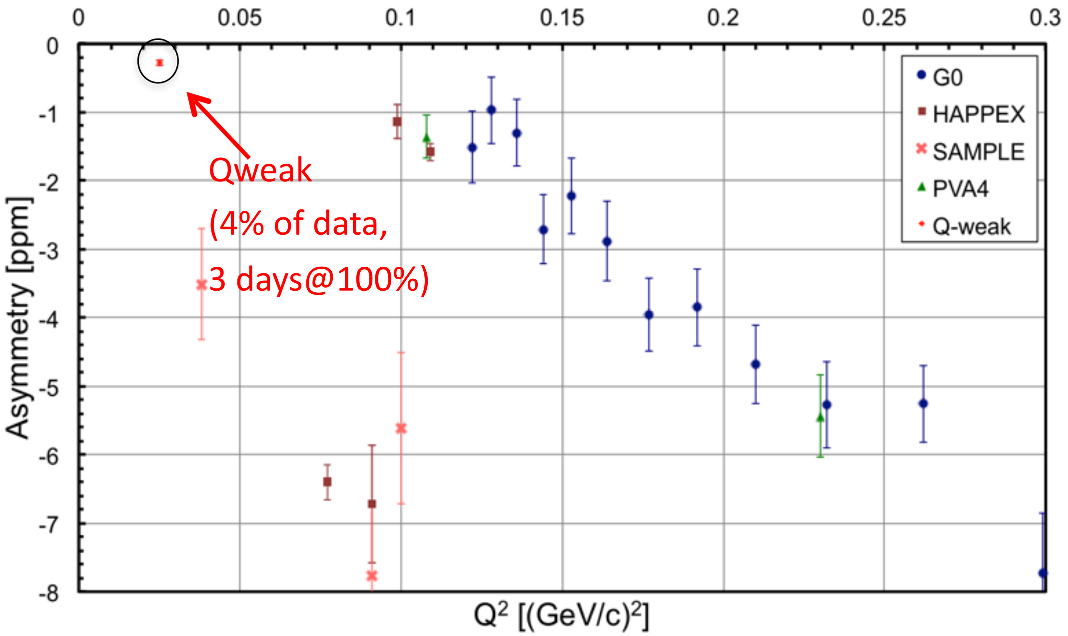
Each period had its own “blinding factor” for unbiased analysis

- Run 0: January – February 2011 (commissioning data)
- Run 1: February – May 2011
- Run 2: November 2011 – May 2012

“Run 0” results (about 1/25 of data set) were published in PRL in Oct. 2013

A_{PV} = -279 (35)(31) ppm

$Q^2 = 0.0250 \pm 0.0006\ (\mathrm{GeV}/c)^2$



Qweak
(4% of data,
3 days@100%)

Significant corrections:

- Aluminum background (3% fraction, but 10x the asymmetry.)
- Transverse polarization

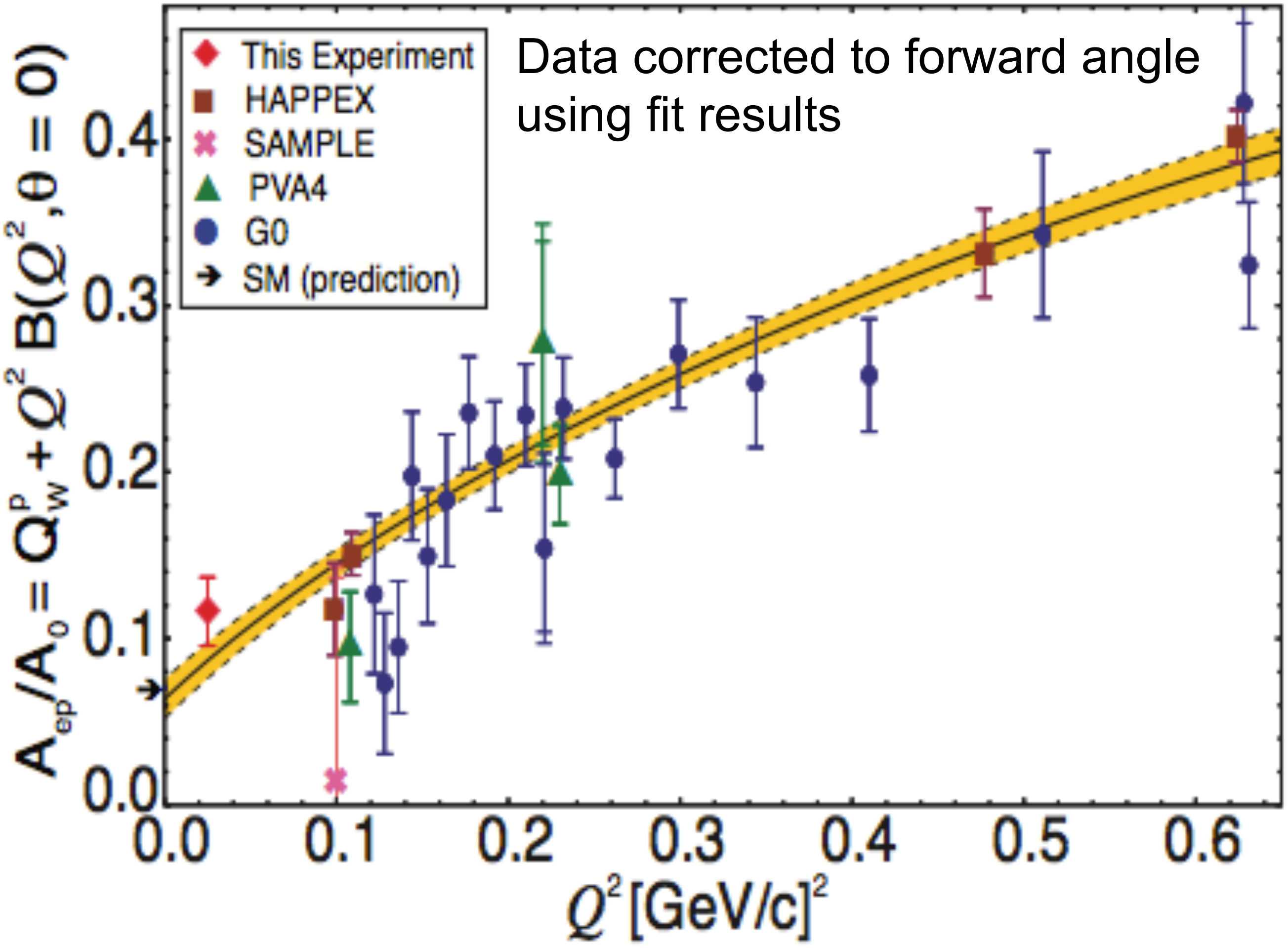
These (and other ancillary measurements) are themselves valuable physics results

- Beam asymmetries
- Beamline background

Required significant work to improve

All systematic errors reduced in final data set

Extraction of Q_W^P



Data corrected to forward angle using fit results

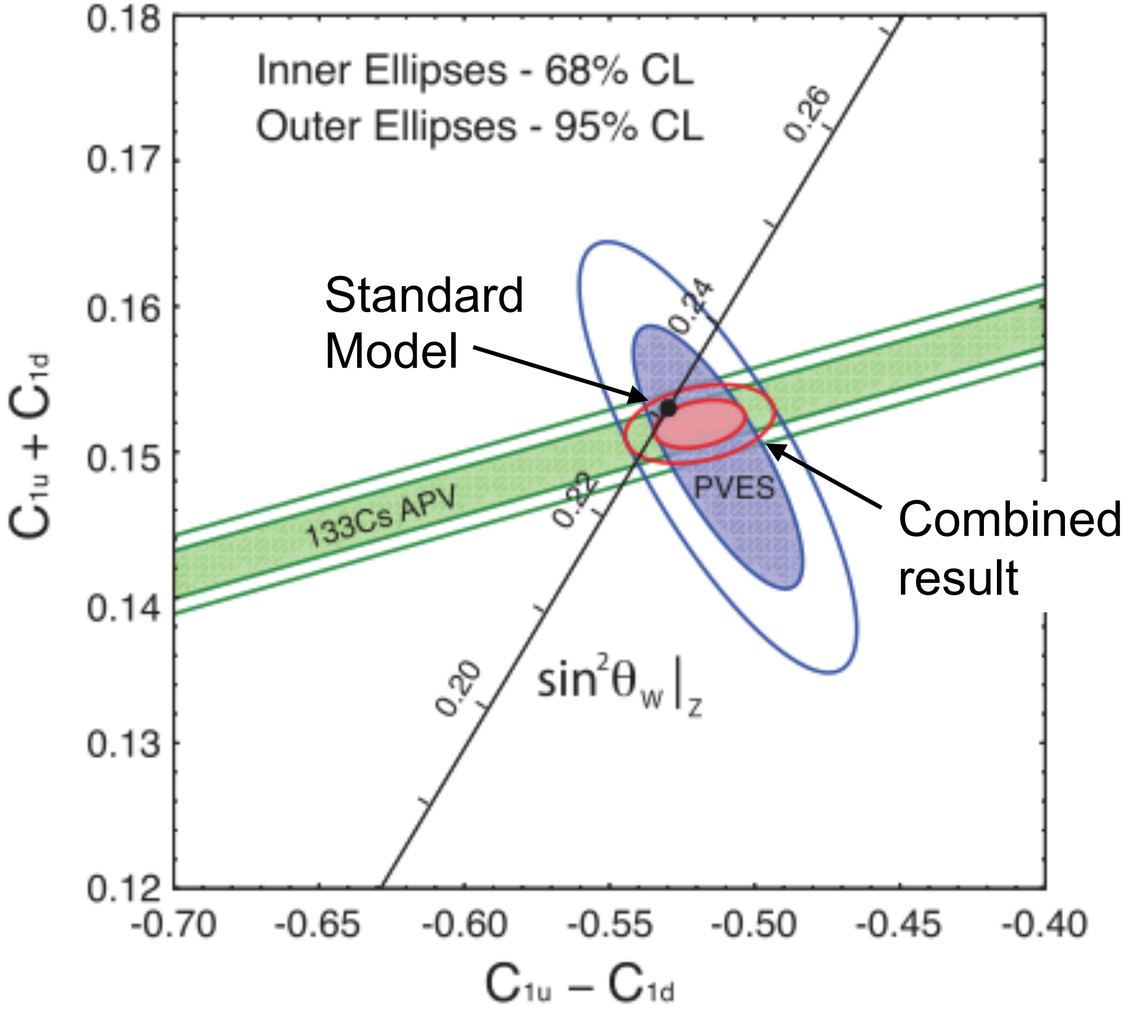
Global fit to provide results on Q_w^p

- All nuclear PVES data (hydrogen, deuterium, helium). Uses E&M form-factors.
- 5 parameters (C_{1u}, C_{1d}, isovector axial FF, ρ_s, μ_s)
- Illustration shown here at forward angle.

C_{1u}/C_{1d} result

Combined with ^{133}Cs atomic PNC result

First independent extraction of Q_W^n

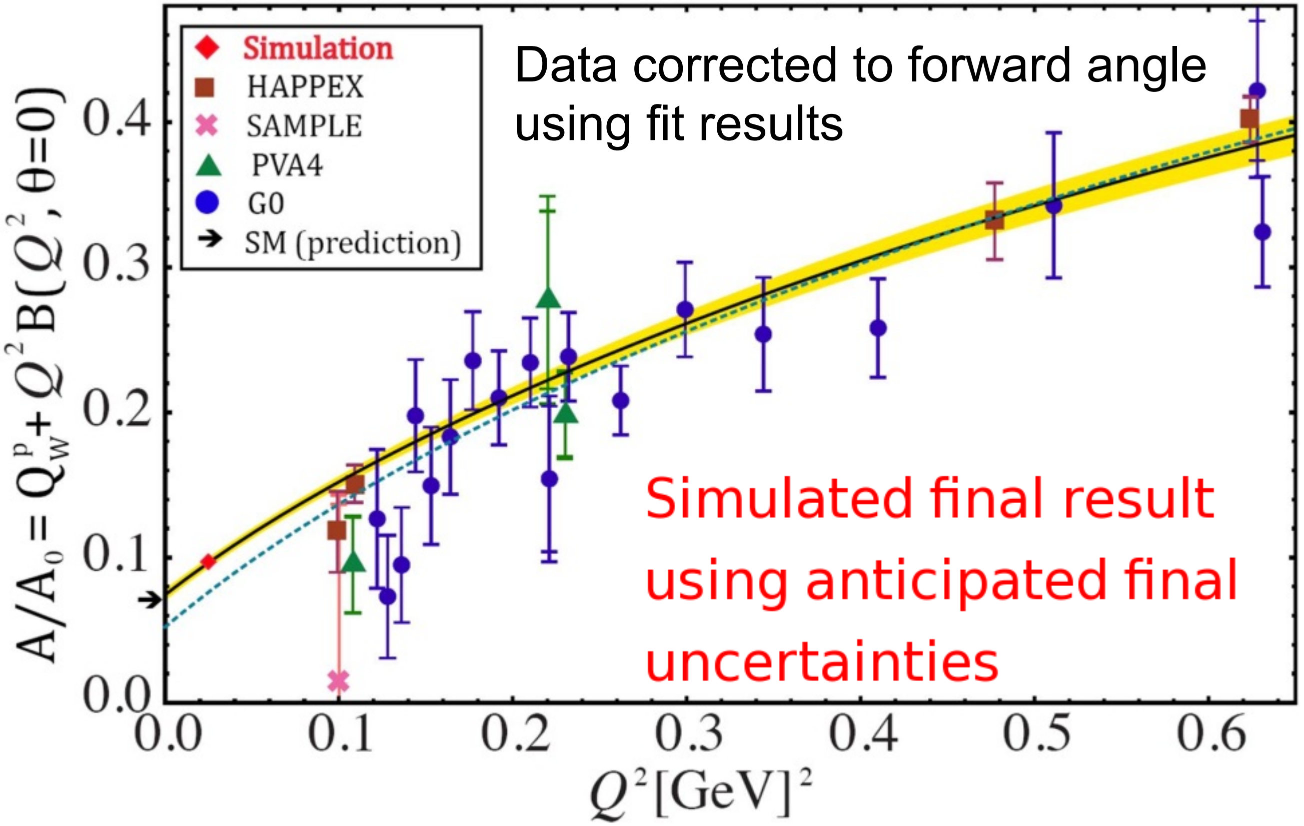


$$Q_W^p = 0.063 \pm 0.012$$
$$Q_W^n = -0.975 \pm 0.010$$

$$Q_W^p(SM) = 0.0710 \pm 0.0007$$
$$Q_W^n(SM) = -0.9890 \pm 0.0007$$

Future precision

Ultimately, the Qweak precision will greatly improve the precision of the fit

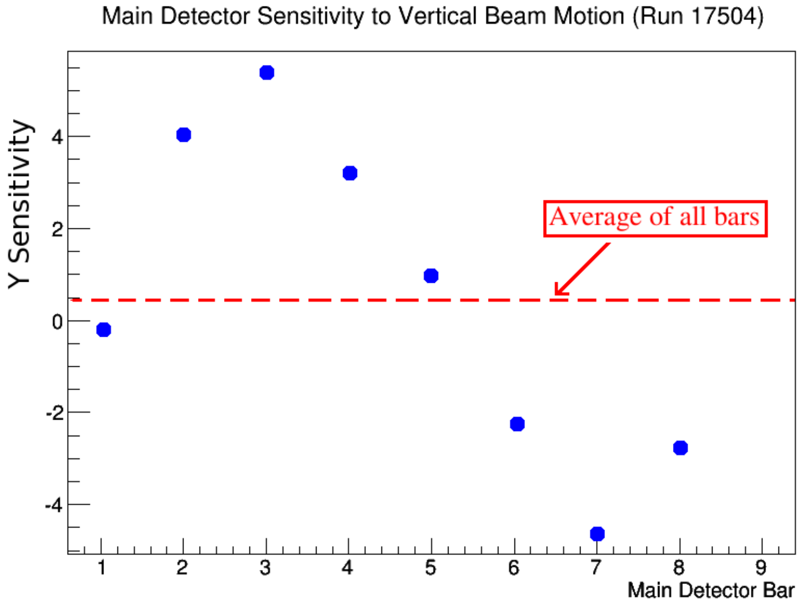


Data corrected to forward angle using fit results

Simulated final result using anticipated final uncertainties

Current Analysis Status

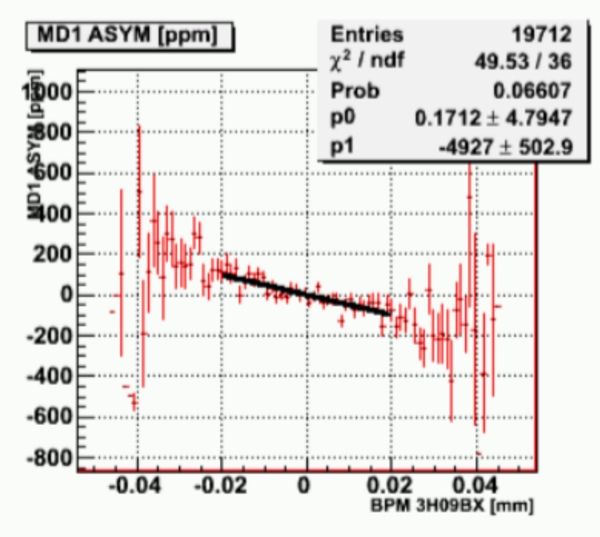
Beam Corrections



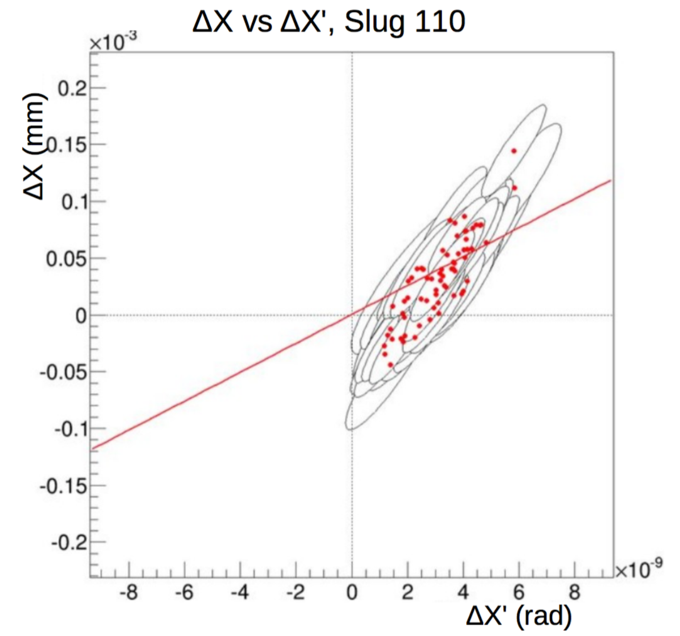
$$A_c = A_r - \sum \alpha_i \Delta x_i - \beta A_E$$

Measurement of the sensitivity of the Main Detector elements to beam motion. The spectrometer provides a high degree of cancellation for beam motion effects.

Regression: remove correlation of main detector with beam position "jitter", *i.e.* minimize noise due to beam jitter



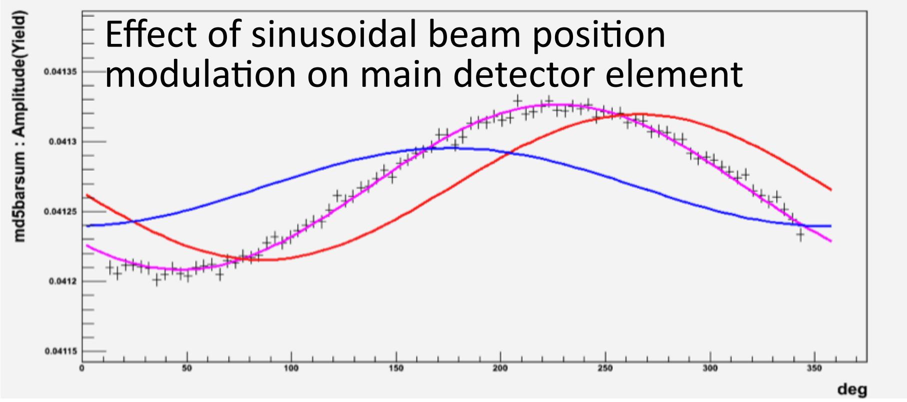
But if noise and the systematic offset look different, this is potentially misleading



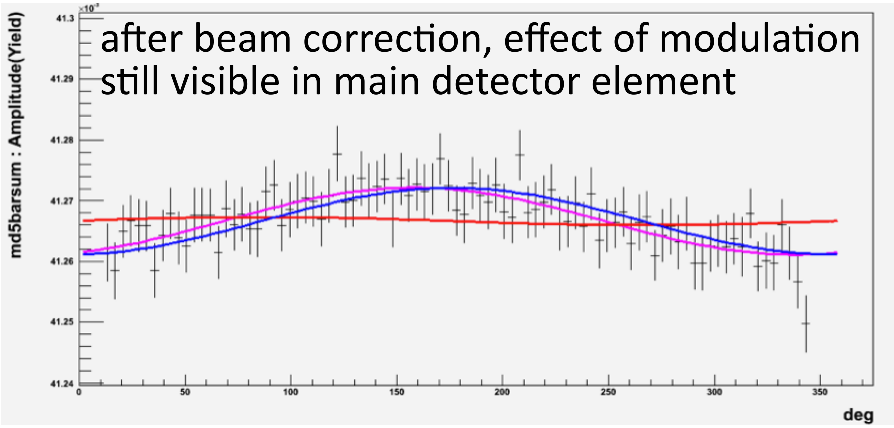
Calibrated Beam Corrections

Modulation: calibrate response matrix to controlled beam excursions

- Periodically run calibration routine, with sinusoidal modulation of the beam using dipole magnets
- Independently calibrate each degree of freedom


Effect of sinusoidal beam position modulation on main detector element

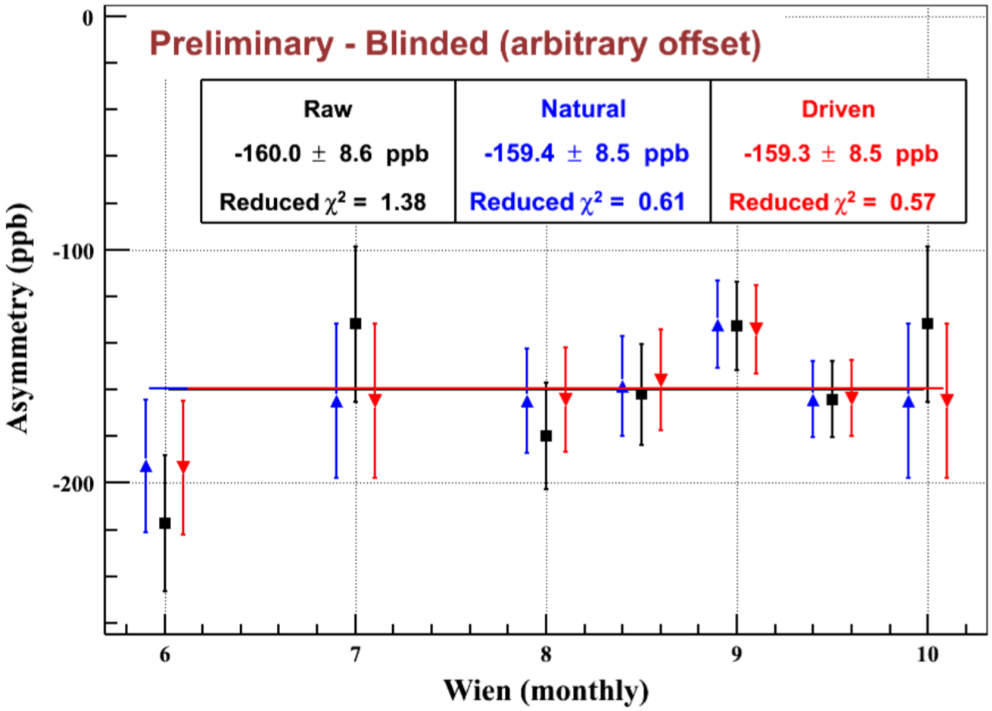
But, imperfect implementation led to inconsistent calibration information


after beam correction, effect of modulation still visible in main detector element

In the end:

- gross inconsistencies removed from calibration
- small inconsistencies were shown to be harmless
- corrections were small, agreed between techniques

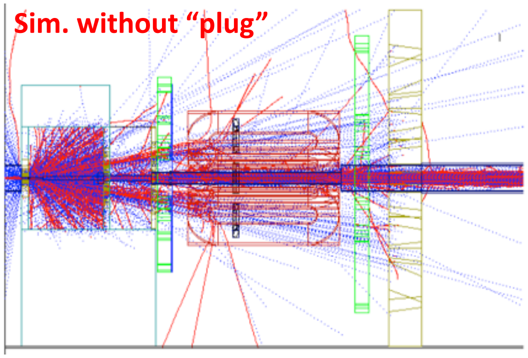
Run2 measured asymmetry

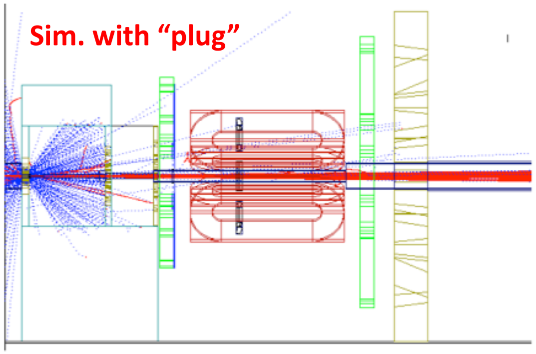

Preliminary - Blinded (arbitrary offset)

Raw	Natural	Driven
-160.0 ± 8.6 ppb	-159.4 ± 8.5 ppb	-159.3 ± 8.5 ppb
Reduced χ^2 = 1.38	Reduced χ^2 = 0.61	Reduced χ^2 = 0.57

Beamline Background

Scattering from the beampipe was recognized
as a possible source of background





- But collimation didn't fully solve the problem.
- Radiators were added to the main detector to enhance hard scatters and cut soft backgrounds

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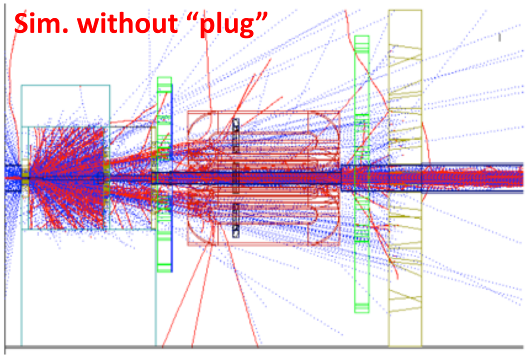

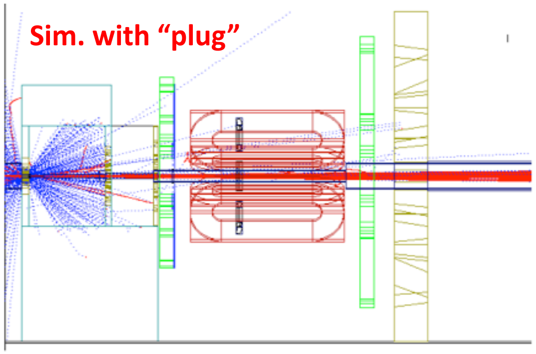

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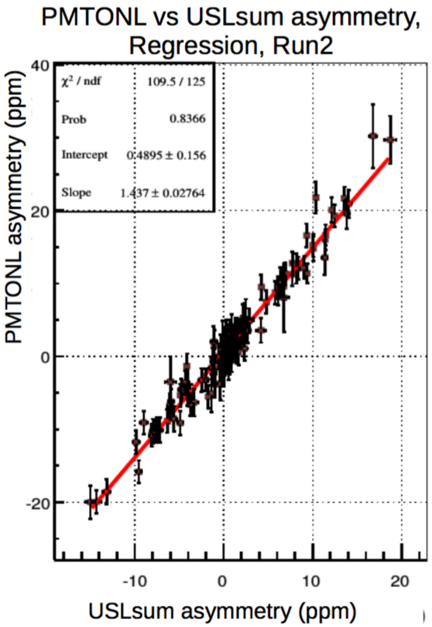
But then: large asymmetries seen in both small angle monitors and background monitors

Correlations with MD


PMTONL vs USLsum asymmetry, Regression, Run2

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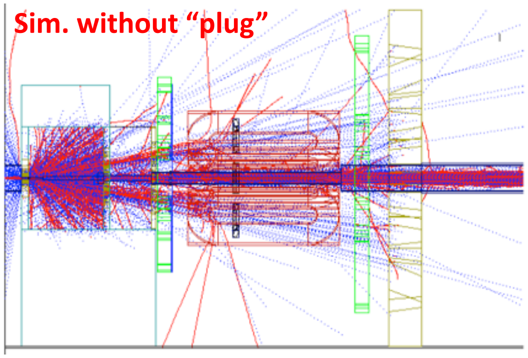
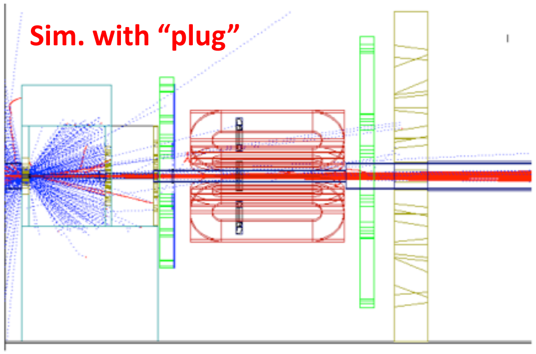
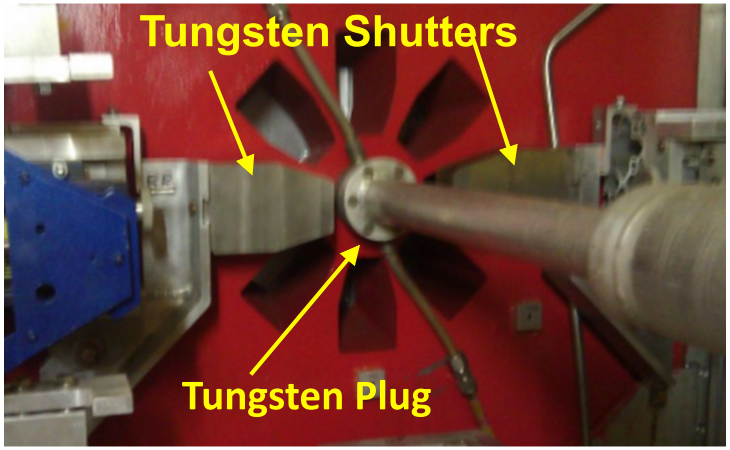




- But collimation didn't fully solve the problem.
- Radiators were added to the main detector to enhance hard scatters and cut soft backgrounds

Studies (included blocking octants):

- beamline background $f \sim 0.2\%$ in MD
- asymmetry due to beam halo
- asymmetry well measured by background detectors



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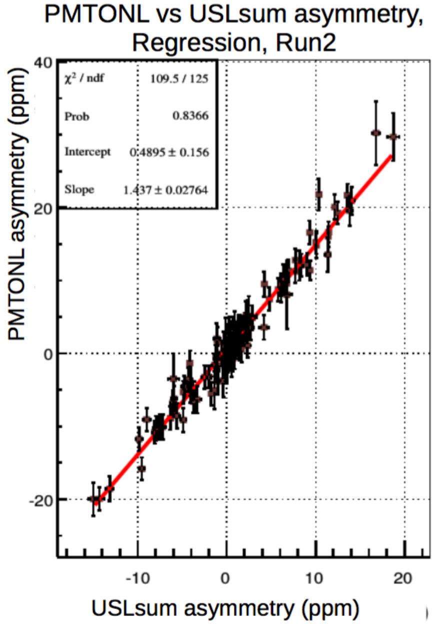
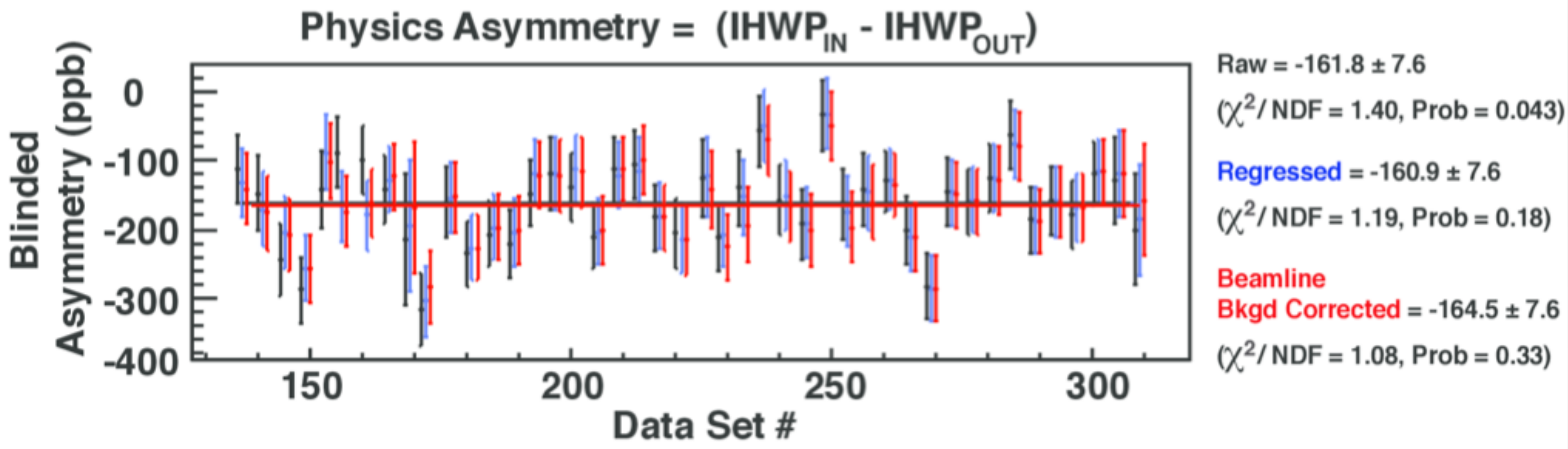

PMTONL vs USLsum asymmetry, Regression, Run2

Scaling of backgrounds over the course of the run, and correlation with main detectors, were stable.

Correction: ~3.5 ppb, ~50% precision

Qweak - Blinded Asymmetries (Run 2)

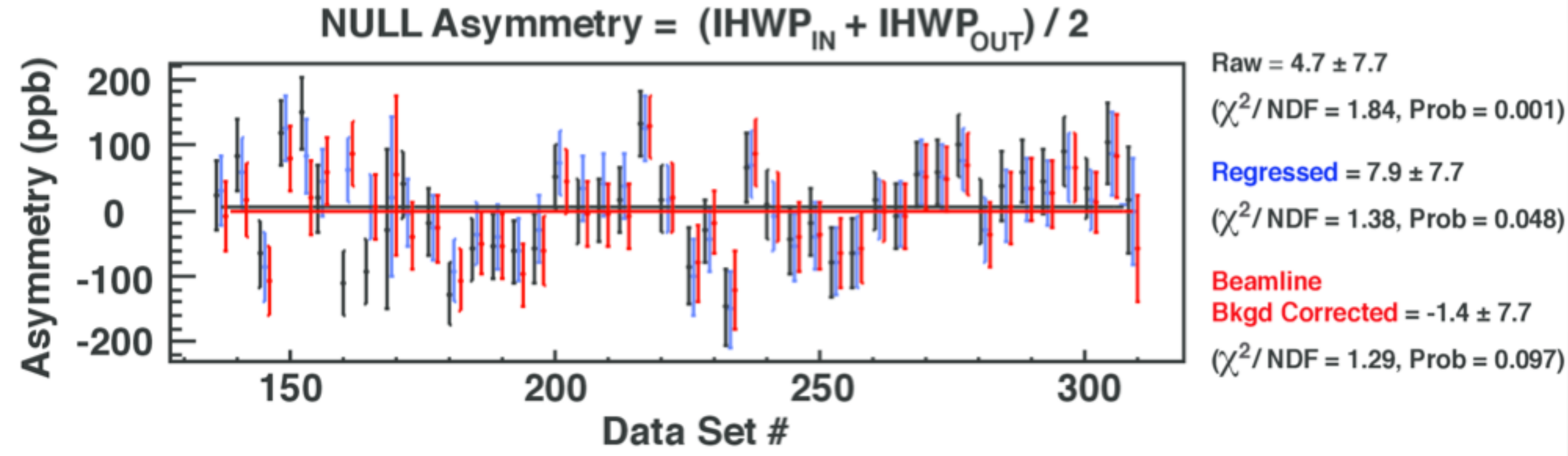
Measured asymmetry,Statistical uncertainty only.
Not scale corrected (P_{beam}, backgrounds, etc.)



Raw = -161.8 ± 7.6
(χ^2/ NDF = 1.40, Prob = 0.043)

Regressed = -160.9 ± 7.6
(χ^2/ NDF = 1.19, Prob = 0.18)

Beamline
Bkgd Corrected = -164.5 ± 7.6
(χ^2/ NDF = 1.08, Prob = 0.33)



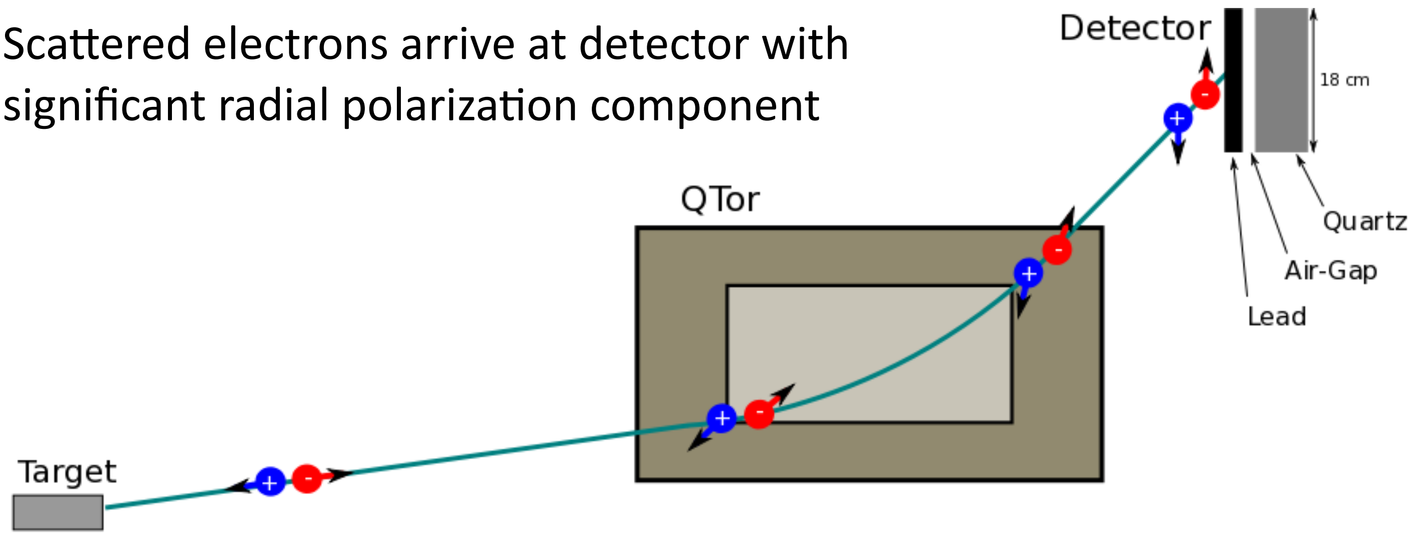
Raw = 4.7 ± 7.7
(χ^2/ NDF = 1.84, Prob = 0.001)

Regressed = 7.9 ± 7.7
(χ^2/ NDF = 1.38, Prob = 0.048)

Beamline
Bkgd Corrected = -1.4 ± 7.7
(χ^2/ NDF = 1.29, Prob = 0.097)

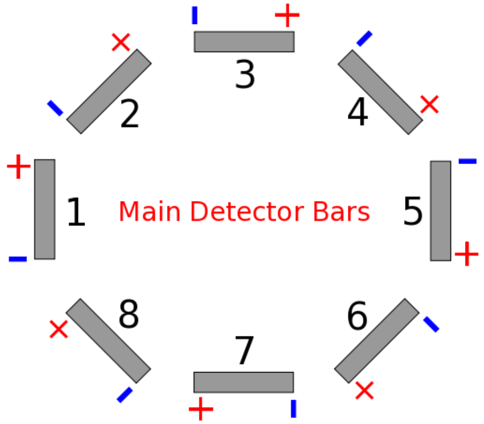
Polarization sensitive detector

Scattered electrons arrive at detector with significant radial polarization component



Apparent polarization analyzing effect, so that PMTs on opposite ends of each detector bar see opposite sign asymmetry shifts

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

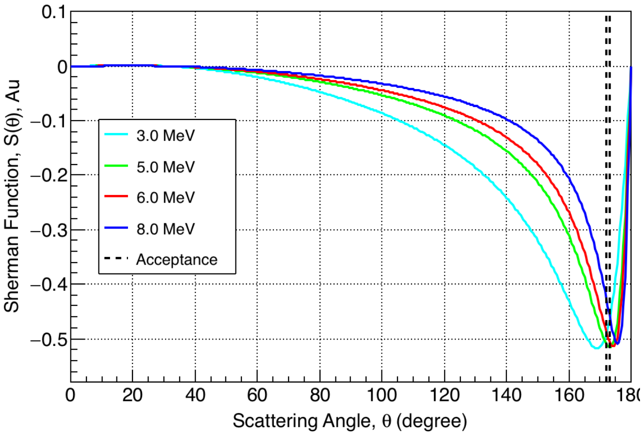


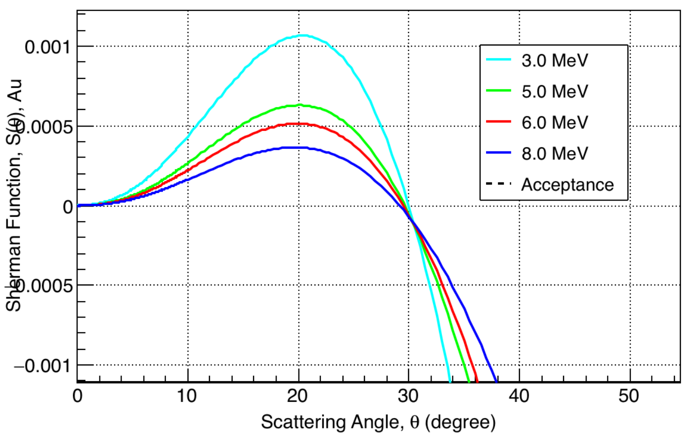
At first order, this cancels, since we measure an average of the two PMTs

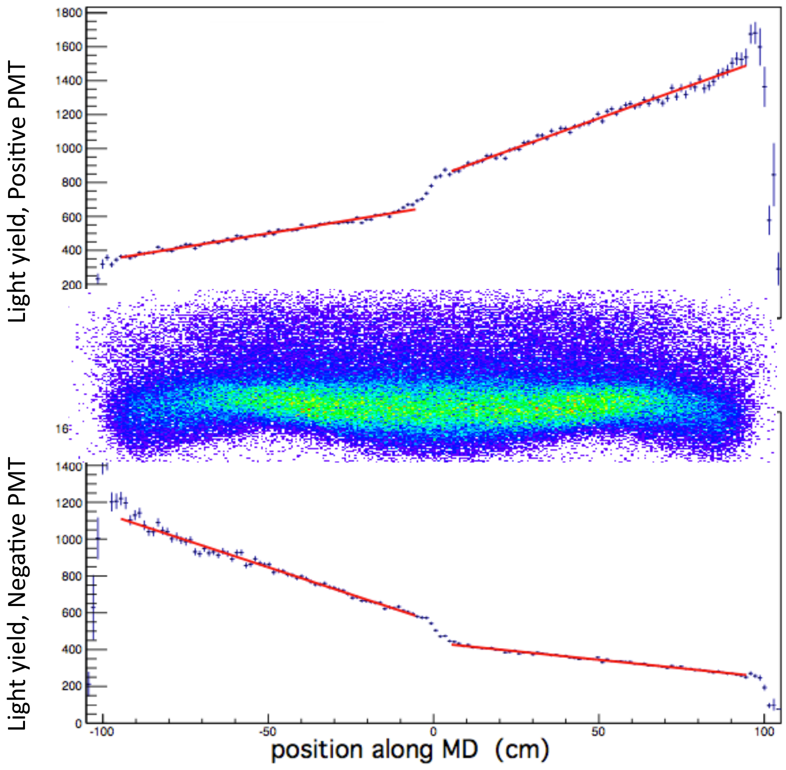
$$A_{PV} = (A_{-} + A_{+})/2$$

Polarization sensitive detector

Mott scattering has asymmetry at low energy, so shower through radiator can become polarization-dependent







- Imperfect cancellation depends on imperfections in the bar light collection and alignment
- MC simulation is being used to investigate how precisely we know this cancellation

Last significant systematic uncertainty before result is complete

Future Measurements

Beyond Qweak: MESA/P2 at Mainz

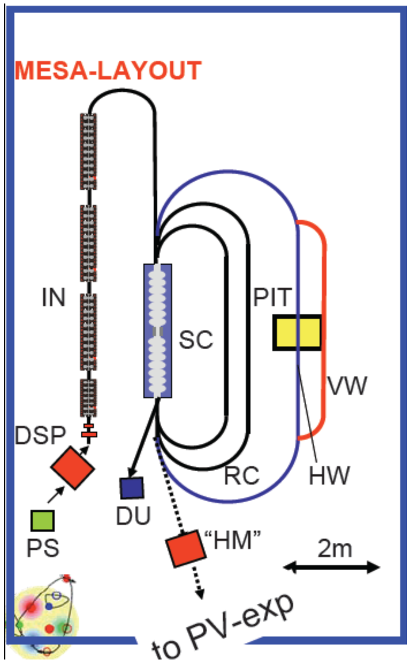
$$A_{PV} = -\frac{Q^2 G_F}{4\sqrt{2}\pi\alpha}\left[Q_W^p + F(\theta, Q^2)\right]$$

Qweak: proton structure F contributes ~30% to asymmetry, ~2% to $\delta(Q_W^p)/Q_W^p$

Negligible for significantly lower Q^2

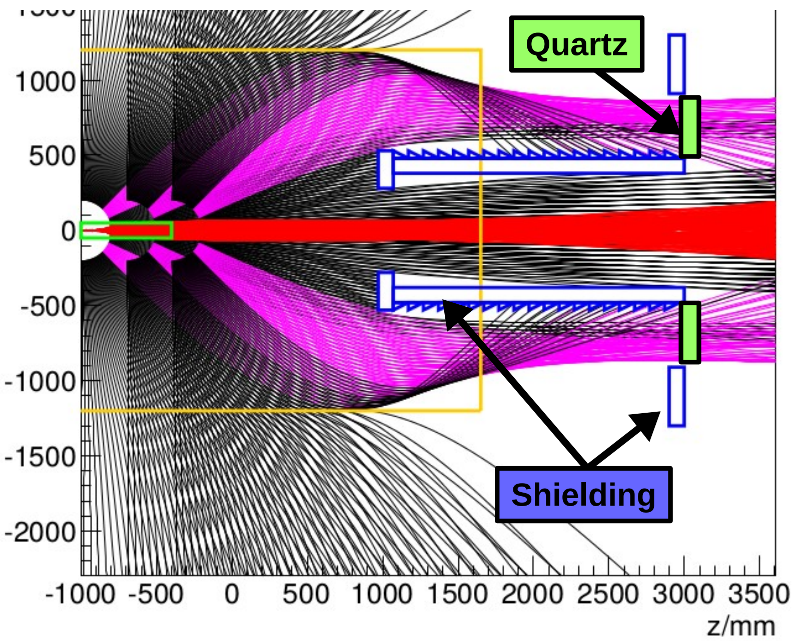
- rate up 100x, Q^2 down 10x: same FOM of A_{pv} and 2x FOM on Q^2
- reduced sensitivity to radiative corrections and proton structure

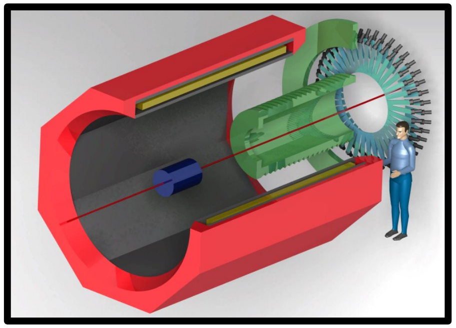
MESA: New research machine based on ERL will also support a high-current extracted beam at 100-200 MeV suitable for a PV experiment



Development underway

Funding approved by DFG





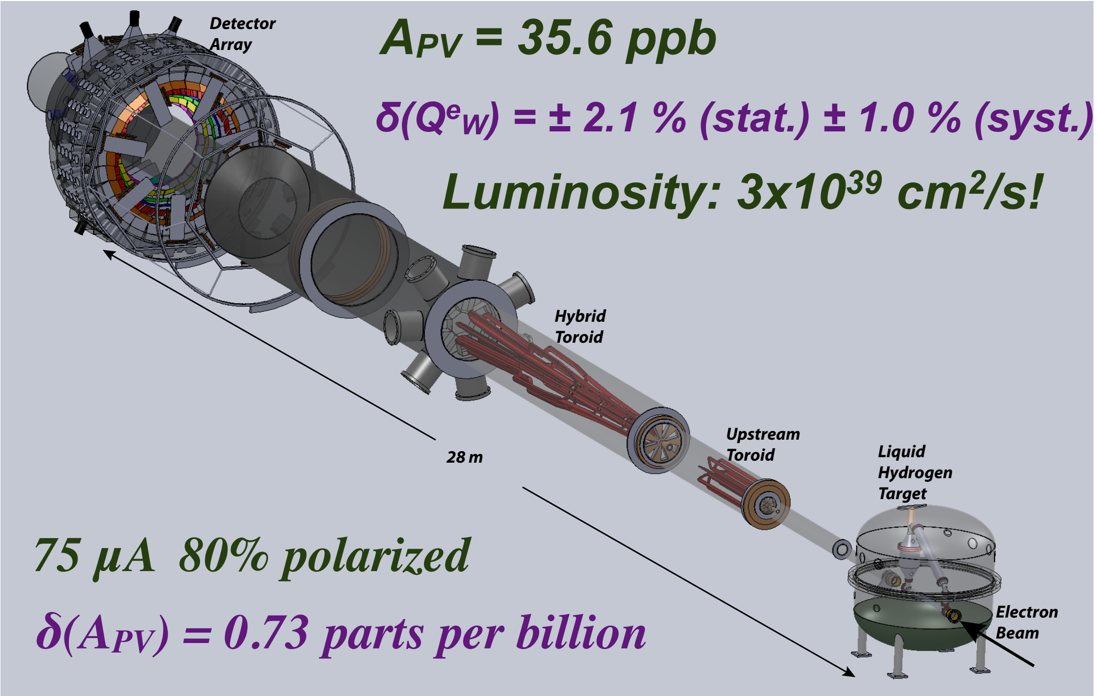
- E_{beam} = 155 MeV, 25-45°
- Q^2 = 0.0045 GeV^2
- 60 cm target, 150 uA, 10^4 hours, 85% polarization
- A_{PV} = -28 ppb to 1.5% (0.4ppb)
- $\delta(\sin^2\theta_W)$ = 0.13%

MOLLER at 11 GeV JLab

At 11 GeV, JLab luminosity and stability makes large improvement in Q_W^e possible

$$\delta(\sin^2\theta_W) = \pm 0.00028\ (\mathrm{stat}) \pm 0.00012\ (\mathrm{syst})$$

Matches best collider (Z-pole) measurement



A_{PV} = 35.6 ppb

$\delta(Q^e_W) = \pm 2.1\ \%\ (\mathrm{stat.}) \pm 1.0\ \%\ (\mathrm{syst.})$

Luminosity: $3\mathrm{x}10^{39}\ \mathrm{cm}^2/\mathrm{s}$!

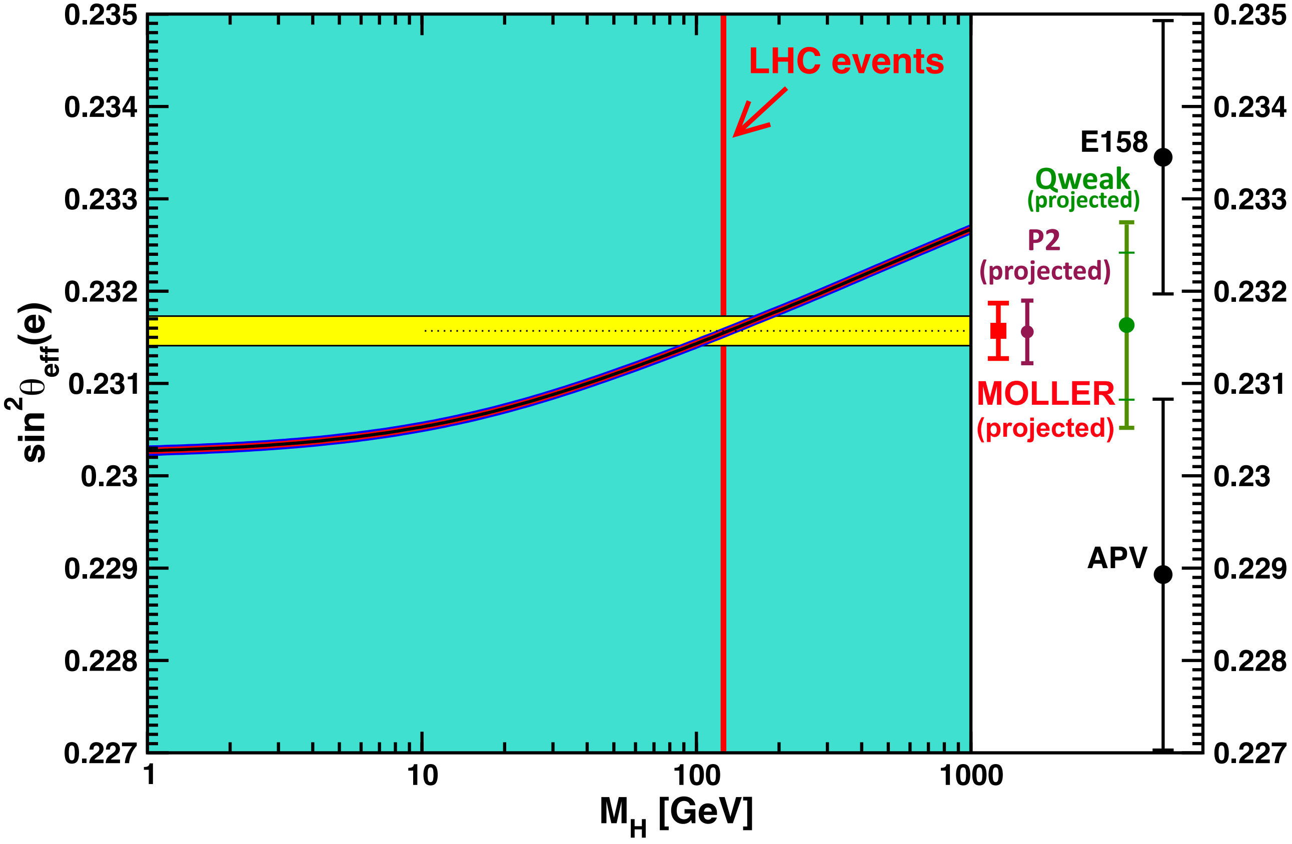
75 μA 80% polarized

$\delta(A_{PV})$ = 0.73 parts per billion

Best contact interaction reach for leptons at low OR high energy

To do better for a 4-lepton contact interaction would require:
Giga-Z factory, linear collider, neutrino factory or muon collider

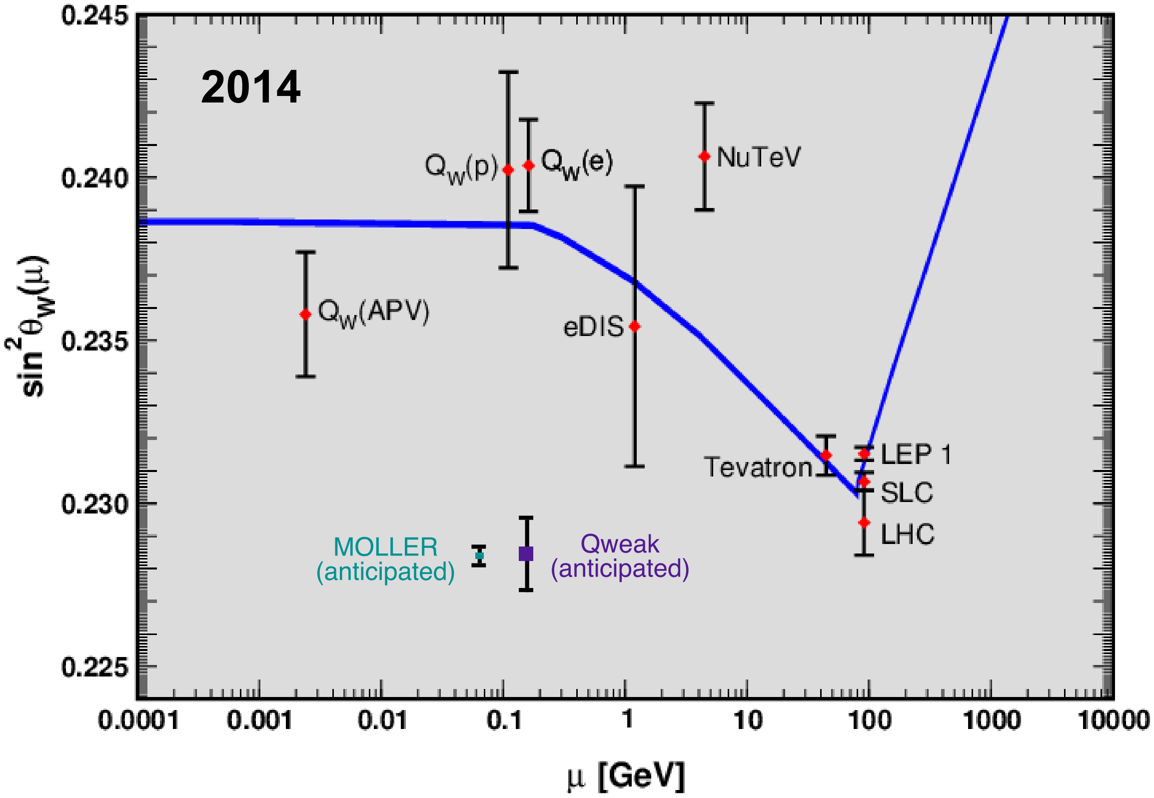
Precision Mixing Angle at Low Q^2



Summary

- The investigation of parity-violation in electron scattering is a powerful tool in the hunt for signatures of physics beyond the Standard Model with a reach into 10's of TeV
- Qweak aims at the most precise measurement of an electron scattering asymmetry ever made.
- A first publication provided an improved measure of the proton weak charge, based on the broad program of weak form-factor measurements

- The final Qweak result is close to complete, work continuing to pin down uncertainty for systematic uncertainties
- Future measurements will continue to add to the reach of this experiments

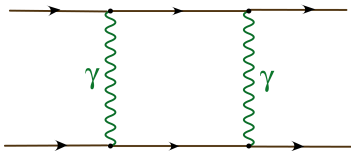


Backup

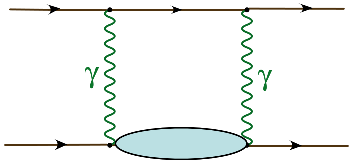
Transverse Asymmetry

Beam-Normal Asymmetry in elastic electron scattering

Electron beam polarized transverse to beam direction



"elastic"



"inelastic"

Interference between one- and two-photon exchange

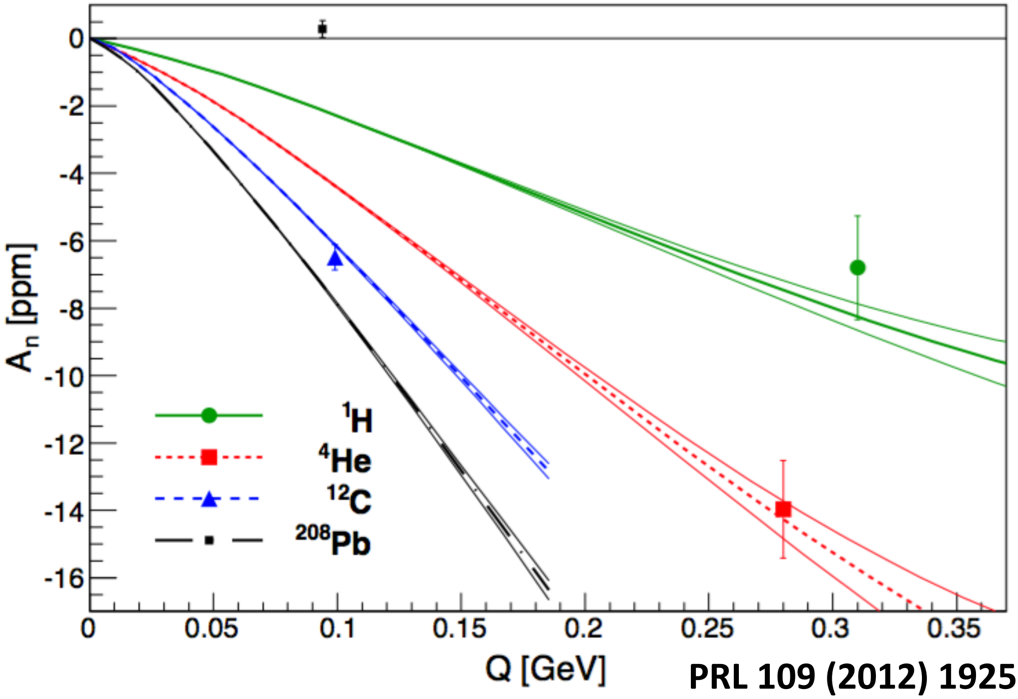
- Inelastic intermediate states enhance this asymmetry
- measured for several nuclei
- ~4ppm for Qweak
- Potential systematic error if poorly cancelled
- Well bounded by polarimetry, check on geometric averaging
- Measured also by Qweak, on hydrogen and Aluminum

$$A_T \equiv \frac{2\pi}{\sigma^{\uparrow}+\sigma^{\downarrow}}\frac{d(\sigma^{\uparrow}-\sigma^{\downarrow})}{d\phi} \propto \vec{S}_e \bullet (\vec{k}_e \times \vec{k}'_e)$$

$$A_T \propto \frac{\alpha m_e}{\sqrt{s}}$$

Effect suppressed by

- **α**
- **Lorentz boost**



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