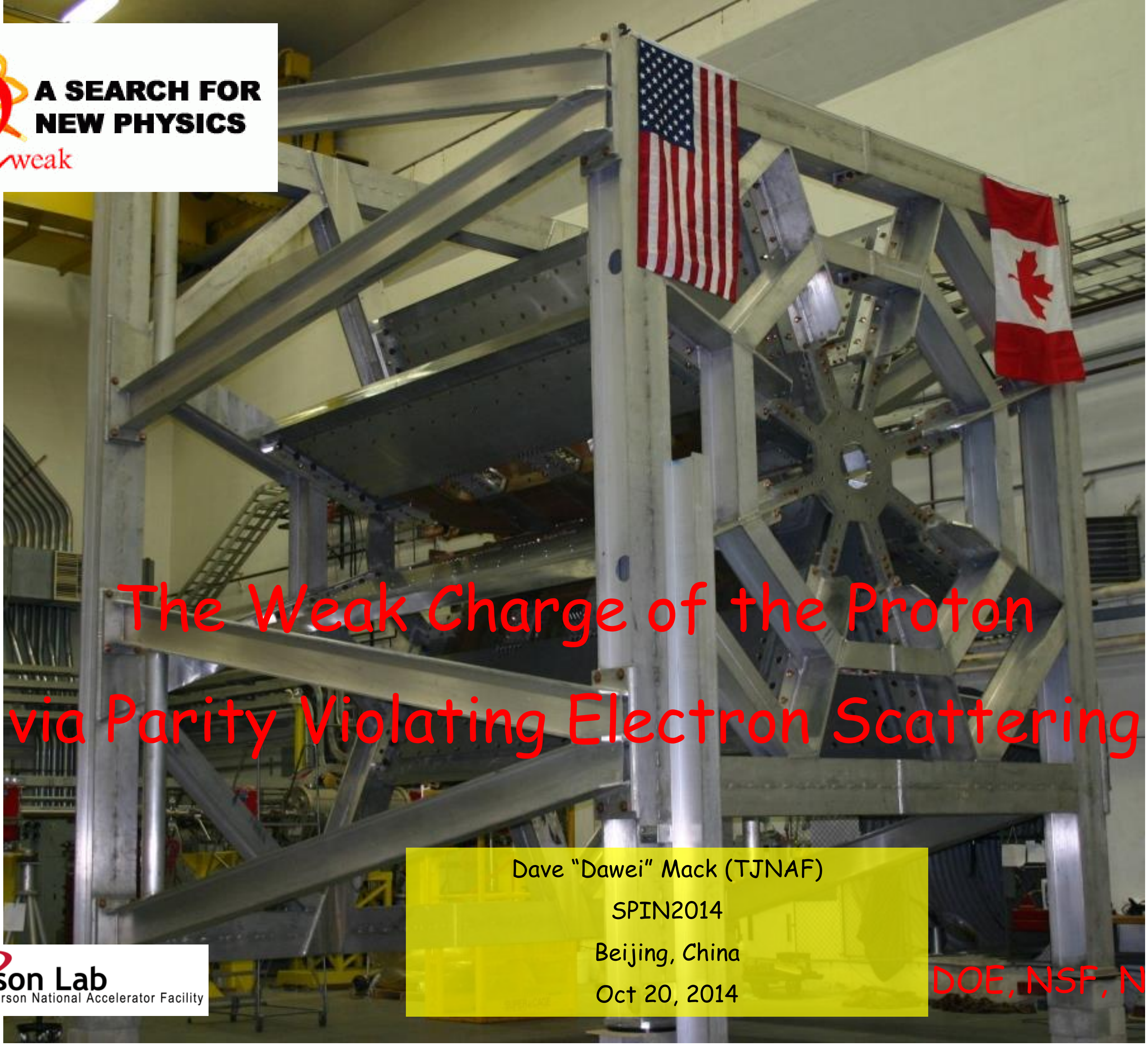
Qweak

A SEARCH FOR NEW PHYSICS



The Weak Charge of the Proton via Parity Violating Electron Scattering

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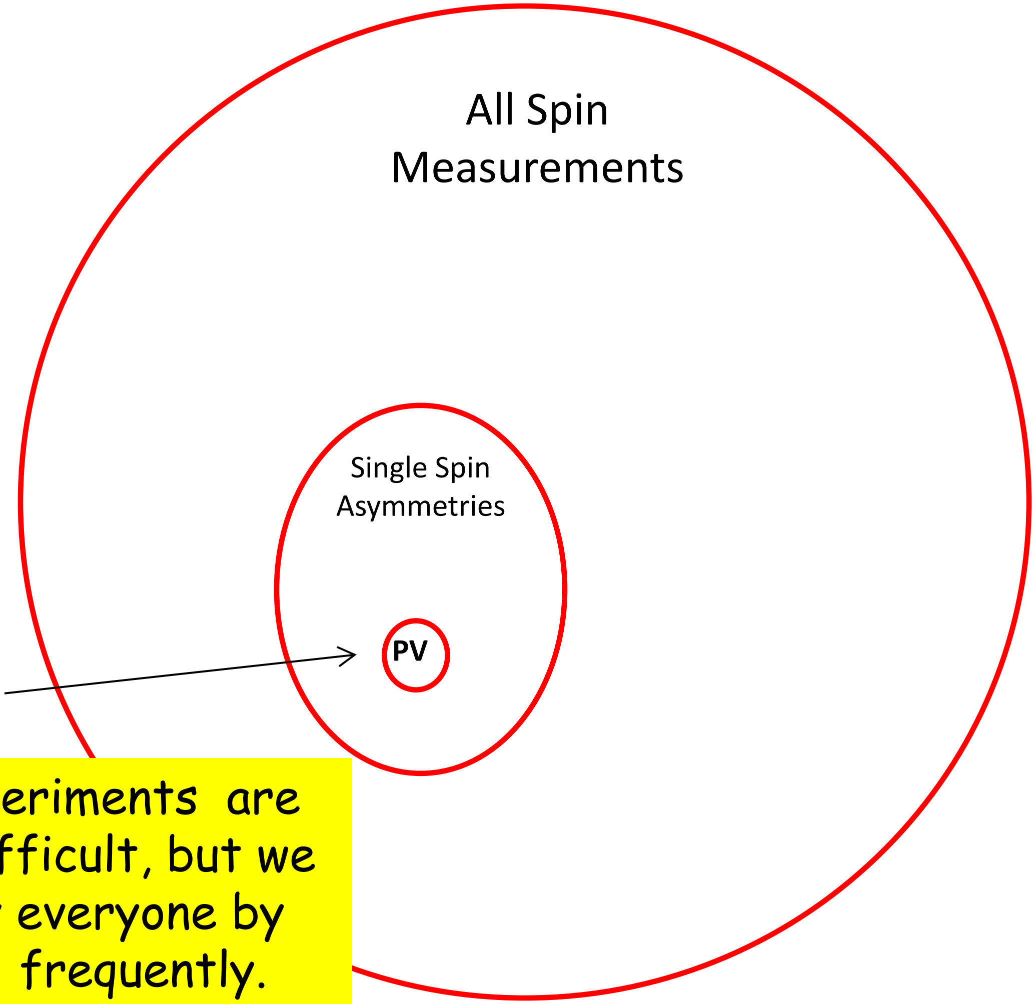


All Spin
Measurements

Single Spin
Asymmetries

PV

You are here …

… where experiments are unusually difficult, but we don’t annoy everyone by publishing frequently.

Motivation

The Standard Model

(a great achievement, but not a theory of everything)

Too many free parameters (masses, mixing angles, etc.).

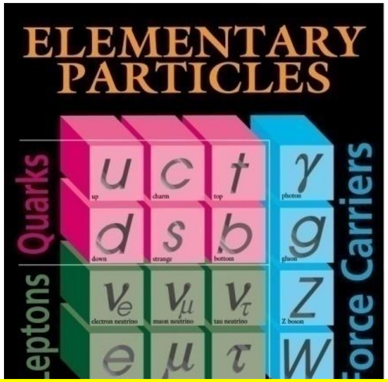
No explanation for the 3 generations of leptons, etc.

Not enough CP violation to get from the Big Bang to today's world

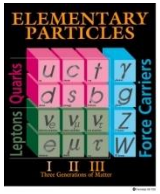
No gravity. (dominates dynamics at planetary scales)

No dark matter. (essential for understanding galactic-scale dynamics)

No dark energy. (essential for understanding expansion of the universe)



What we call the SM is only part of a larger model.



+gravity

+dark matter

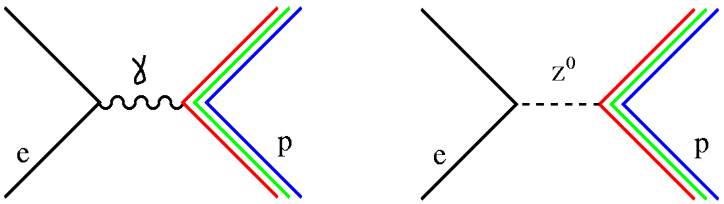
+dark energy

The astrophysical observations are compelling, but only hint at the nature of dark matter and energy.

We can look but not touch!

To extend the SM, we need more BSM evidence (or tight constraints) <u>from controlled experiments</u>.

The Quark Weak Vector Charges



	EM Charge	Weak Charge
q^{up}	$+2/3$	$1 - \frac{8}{3}\sin^2\theta_W \approx 1/3$
q^{down}	$-1/3$	$-1 + \frac{4}{3}\sin^2\theta_W \approx -2/3$
$Q^p = 2q^{up} + 1q^{down}$	$+1$	$1 - 4\sin^2\theta_W = -.048$
$Q^n = 1q^{up} + 2q^{down}$	0	-1

Q_w^p is the neutral-weak analog of the proton's electric charge

Note the traditional roles of the proton and neutron are almost reversed:

ie, neutron weak charge is dominant, proton weak charge is almost zero.

This suppression of the proton weak charge in the SM makes it a sensitive way to:

- measure $\sin^2\theta_W$ at low energies, and
- search for evidence of new PV interactions between electrons and light quarks.

Running of $\sin^2\theta_W$

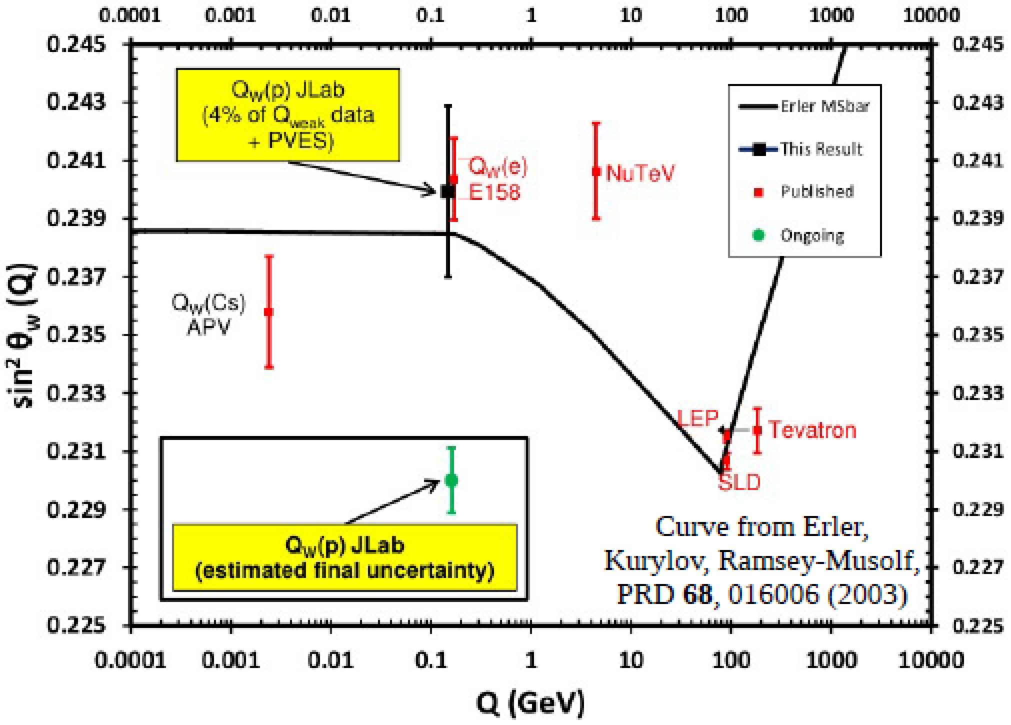
But $\sin^2\theta_W$ is determined much better at the Z pole. What's the point of a precise-but-admittedly-not-as-great low energy measurement?

The value of $\sin^2\theta_W$ may be a free parameter in the SM, but the <u>running</u> of $\sin^2\theta_W$ in the SM is precisely calculable.

Comparing the low energy $\sin^2\theta_W$ with the Z pole result can indicate whether there are new interactions.

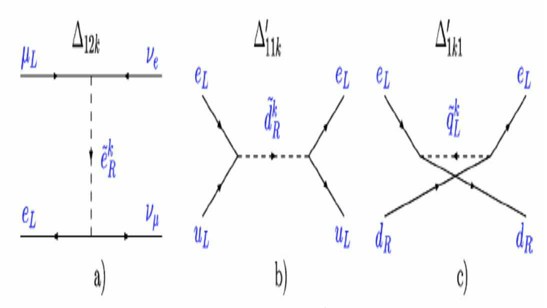
In the context of the SM, we need <u>one</u> precise $\sin^2\theta_W$ measurement.

For new physics searches, measurements on Cs, proton, e+e (Moeller) , B quarks, etc, are <u>complementary.</u>



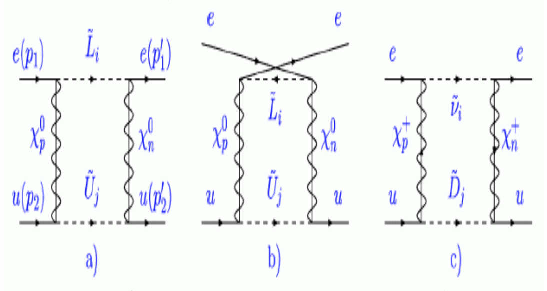
SUSY Sensitivities

R-parity Violating
(tree-level) SUSY:

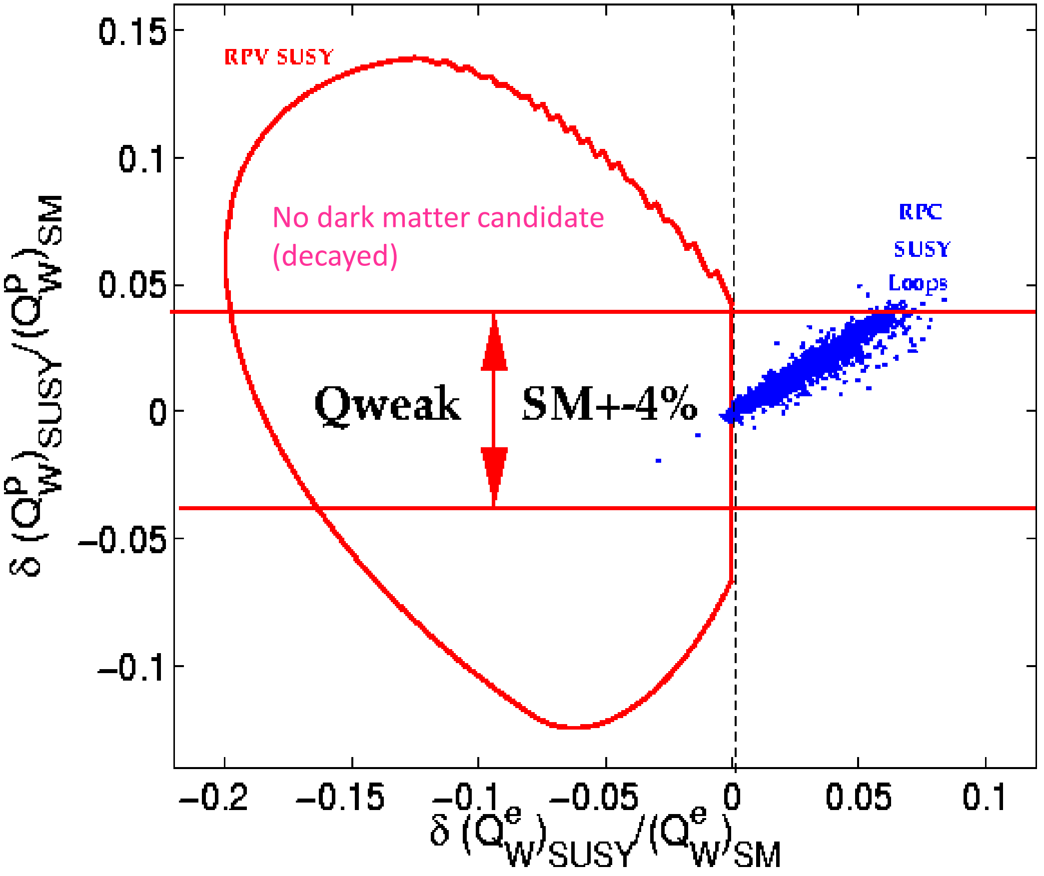


No obvious dark matter.
("New" particles would decay to normal matter.)

R-parity Conserving
(loop-level) SUSY:



Dark matter may be the lightest SUSY particle.
(It got "stuck" carrying the R quantum number.)



Contour 95% CL

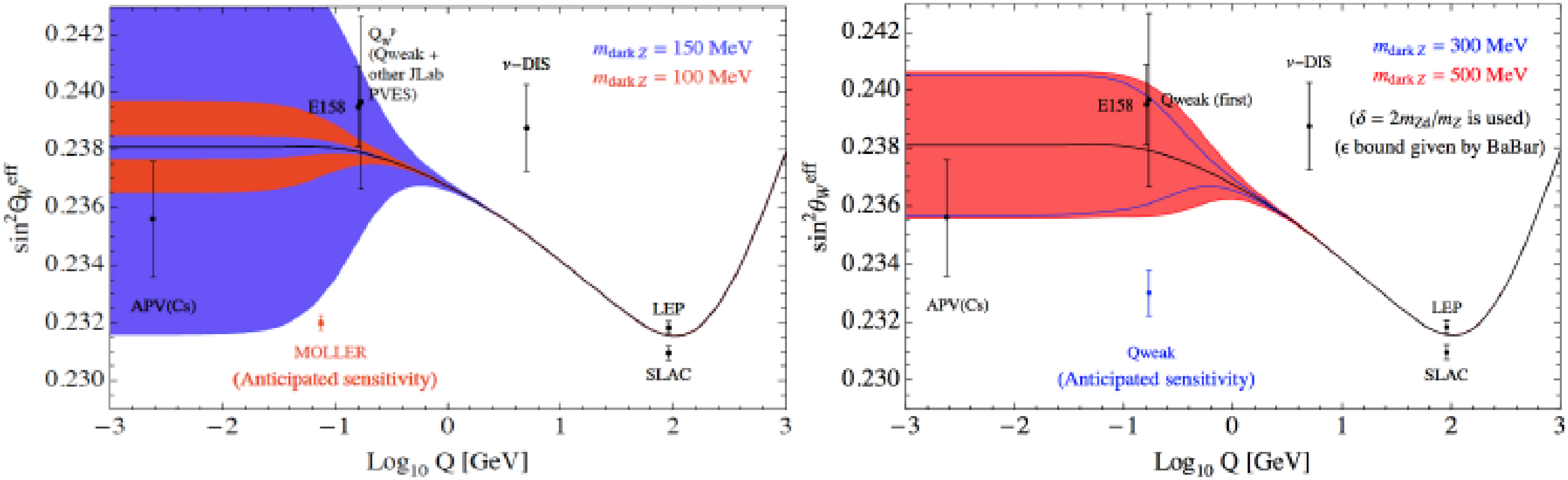
A. Kurylov et al., PRD 68, (2003) 035008

contour courtesy of Shufang Su

New Physics Example - Dark Z

"Dark parity violation" (Davoudiasl, Lee, Marciano, arXiv 1402.3620)

- Introduces a 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.



Low-E experiments most sensitive to deviations from SM due to Dark Z

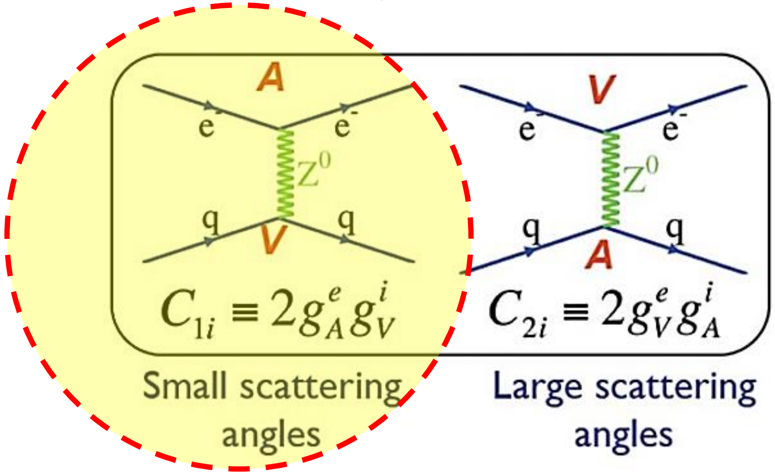
PVES and Accessing Q_W^p

Accessing Q_w^p from PV Electron Scattering

Parity violation in electron scattering arises from V x A couplings of the Z.

We isolate the small EM x WEAK interference term, normalized to $|EM|^2$, thru the PV asymmetry.

By varying the angle, momentum Xfer, and target one can extract Qw^p, Qw^e, axial couplings, etc.



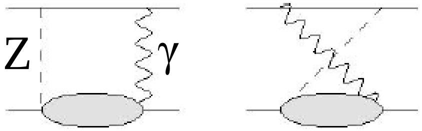
We wanted A(e) x V(q) to dominate.

In the limit of low momentum transfer and forward kinematics, the leading order term for elastic scattering contains the weak charge:

- Recast $A_{ep} = \frac{G_F\, Q^2}{4\pi\alpha\sqrt{2}}\left[Q_w^p + Q^2 B(Q^2,\theta)\right]$ (-200 ppb)
  - So in a plot of $A_{ep}/\left[\frac{G_F\, Q^2}{4\pi\alpha\sqrt{2}}\right]$ vs Q^2:
    - Q_w^p **is the *intercept*** (anchored by precise data near Q^2=0)
    - $B(Q^2,\theta)$ is the ***slope*** (determined from higher Q^2 PVES data)

At our chosen kinematics, Q_w^p dominates the asymmetry (~2/3).

Electroweak Corrections

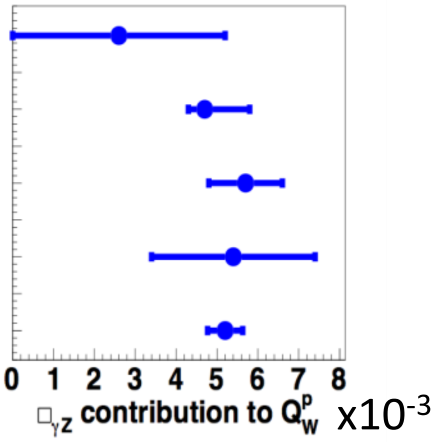


$$Q_W^p = [\rho_{\mathrm{NC}} + \Delta_e][1 - 4\sin^2\hat{\theta}_W(0) + \Delta'_e] + \Box_{WW} + \Box_{ZZ} + \boxed{\Box_{\gamma Z}}$$

~7% correction

Table 1: $\Box^V_{\gamma Z}$ contribution to Q^p_W (Qweak kinetmatics)

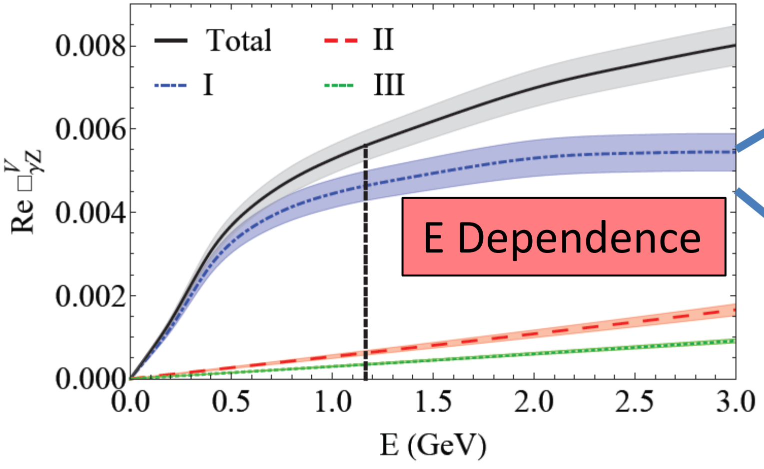
Gorchtein & Horowitz Phys. Rev. Lett. **102**, 091806 (2009)	**0.0026 ± 0.0026**
Sibirtsev, Blunden, Melnitchouk, & Thomas Phys. Rev. D **82**, 013011 (2010)	**$0.0047^{+0.0011}_{-0.0004}$**
Rislow & Carlson Phys. Rev. D **83**, 113007 (2007)	**0.0057 ± 0.0009**
Gorchtein, Horowitz, & Ramsey-Musolf Phys. Rev. C **84**, 015502 (2011)	**0.0054 ± 0.0020**
Hall, Blunden, Melnitchouk, Thomas, & Young Phys. Rev. D **88**, 013011 (2013)	**0.00557 ± 0.00036**



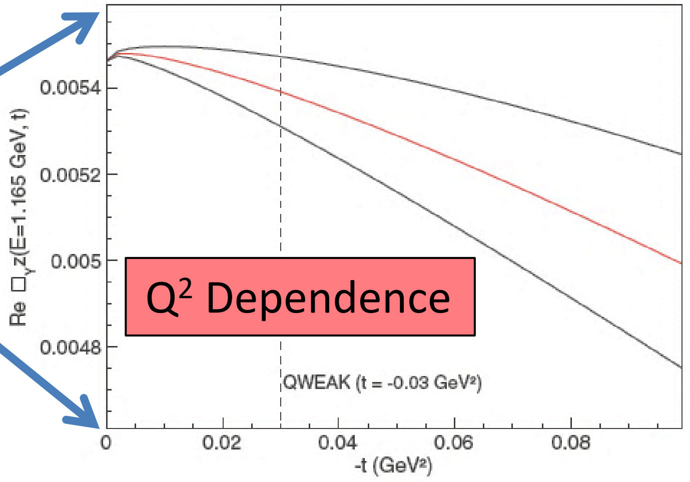
The $\Box_{\gamma Z}$ is the only E & Q^2 dependent EW correction.

→ Correct the PVES data for this E & Q^2 dependence.

- Calculations are primarily dispersion theory type
  - error estimates can be firmed up with data!



E Dependence



Q^2 Dependence

Energy Scale of a Q_w^p Measurement

The sensitivity to new physics Mass/Coupling ratios of the Q-weak experiment can be estimated by adding a new PV contact term to the electron-quark Lagrangian (Erler et al. PRD 68, 016006 (2003)):

$$\begin{aligned}\mathcal{L}^{PV}_{e-q} &= \mathcal{L}^{PV}_{SM} + \mathcal{L}^{PV}_{New} \\ &= -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q\end{aligned}$$

where Λ is the mass and g is the coupling.

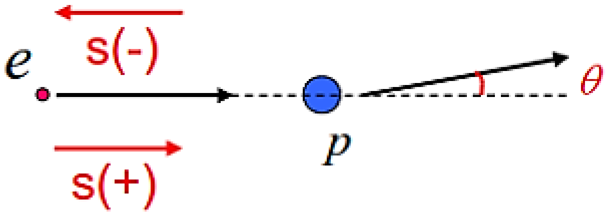
A new physics "pull" on the proton weak charge, ΔQ_w^p, can then be related to the mass to coupling ratio:

$$\frac{\Lambda}{g} = \frac{1}{\sqrt{\sqrt{2}G_F}} \cdot \frac{1}{\sqrt{\Delta Q_W(p)}}$$

- Because $\Delta Q_w^p = 4\% \times Q_w^p$ in our case, and Q_w^p is suppressed, our measurement has TeV scale sensitivity assuming g ~ 1.
- The measurement is "broad band" however: one can be as sensitive to a 200 MeV new particle with small couplings as to a 20 TeV particle with large couplings.

Methodology

We flip the longitudinal beam polarization up to 1000 times per second, with a brief pause for the beam polarization and intensity to stabilize. (That's as fast as we can manage without excessive dead-time.)



With an electron scattered into each detector every nsec, the signal must be integrated.

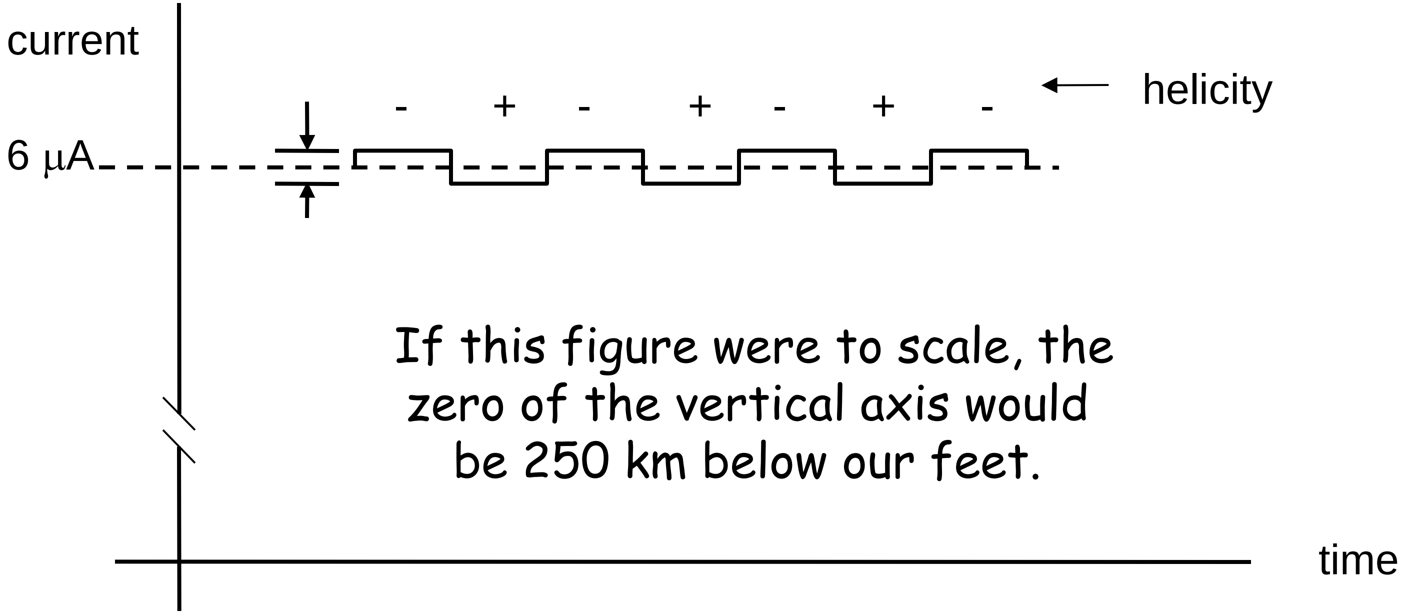
$$A_{PV} = \frac{1}{P}\frac{Y^{+} - Y^{-}}{Y^{+} + Y^{-}} = \frac{1}{P}\frac{\frac{N^{+}}{Q^{+}} - \frac{N^{-}}{Q^{-}}}{\frac{N^{+}}{Q^{+}} + \frac{N^{-}}{Q^{-}}}$$

(-200 ppb)

The experiment also requires:

- Noise from target density fluctuations and electronics must be << 1/√N.
- Minimal beam parameter changes on spin flip (ie, << wavelength of visible light)
- Corrections for remaining small false asymmetries that *do* occur on spin flip
- Precise measurements of Q^2, beam polarization, and backgrounds.

How Small is the 200 ppb Q-weak PV Signal?



If this figure were to scale, the zero of the vertical axis would be 250 km below our feet.

It is like the thickness of a coat of paint on top of the 325m Eiffel Tower.

And we have to measure it to a few percent!

Statistical Facts of Life for Very Small Asymmetries

How long would it take to measure a 200 ppb asymmetry to 1% if one were tracking particles at Rate = 10 MHz (eg, 10 detectors each with 1 MHz rate)?

$\Delta A = 1/\sqrt{N}$

$N = 1/\Delta A^2 = 1/(0.01 * 200\times10^{-9})^2 = 2.5\times10^{17}$ events

Time = N/Rate = 2.5×10^{10} sec

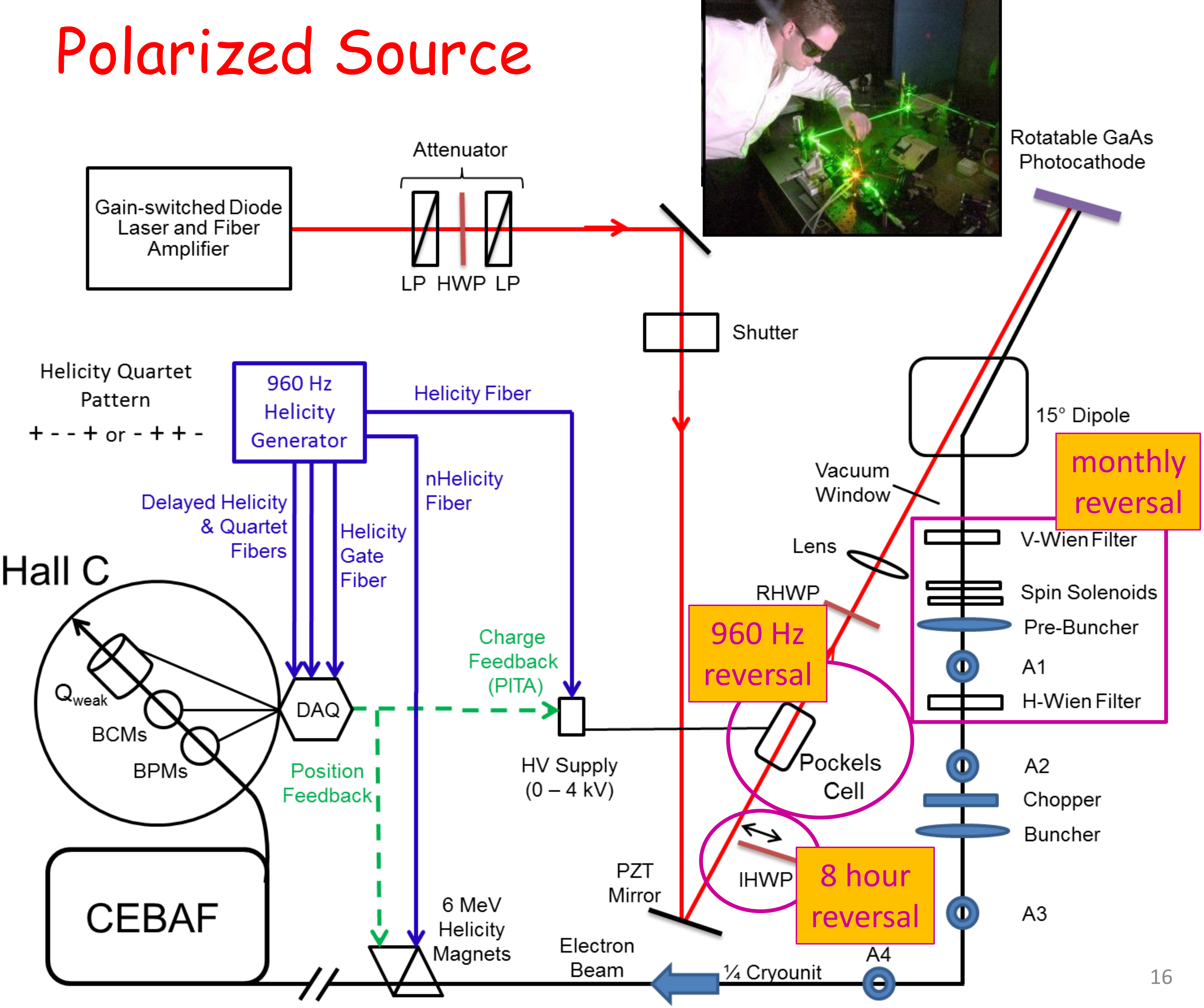
1 year = 3.2×10^{7} sec (ie, " $\pi \times 10^7$ sec ")

T = 793 years

For $\Delta A < 10$ ppb, experiments cannot be done in event- or tracking-mode.
The only choice is to design a low-background experiment and <u>integrate</u>.
(SAMPLE, E158, HAPPEx, etc.)

For $\Delta A > 100$ ppb, event mode can be used. Tracking allows powerful background suppression, but the downside is that dead-time and randoms must be controlled.
(G0, PVDIS, etc.)

Polarized Source



Gain-switched Diode Laser and Fiber Amplifier

Attenuator

LP HWP LP

Shutter

Rotatable GaAs Photocathode

Helicity Quartet Pattern

\+ - - + or - + + -

960 Hz Helicity Generator

Helicity Fiber

Delayed Helicity & Quartet Fibers

Helicity Gate Fiber

nHelicity Fiber

Hall C

Q_{weak}

BCMs

BPMs

DAQ

Charge Feedback (PITA)

Position Feedback

HV Supply (0 – 4 kV)

CEBAF

6 MeV Helicity Magnets

Electron Beam

¼ Cryounit

PZT Mirror

IHWP

8 hour reversal

Pockels Cell

960 Hz reversal

RHWP

Lens

Vacuum Window

15° Dipole

monthly reversal

V-Wien Filter

Spin Solenoids

Pre-Buncher

A1

H-Wien Filter

A2

Chopper

Buncher

A3

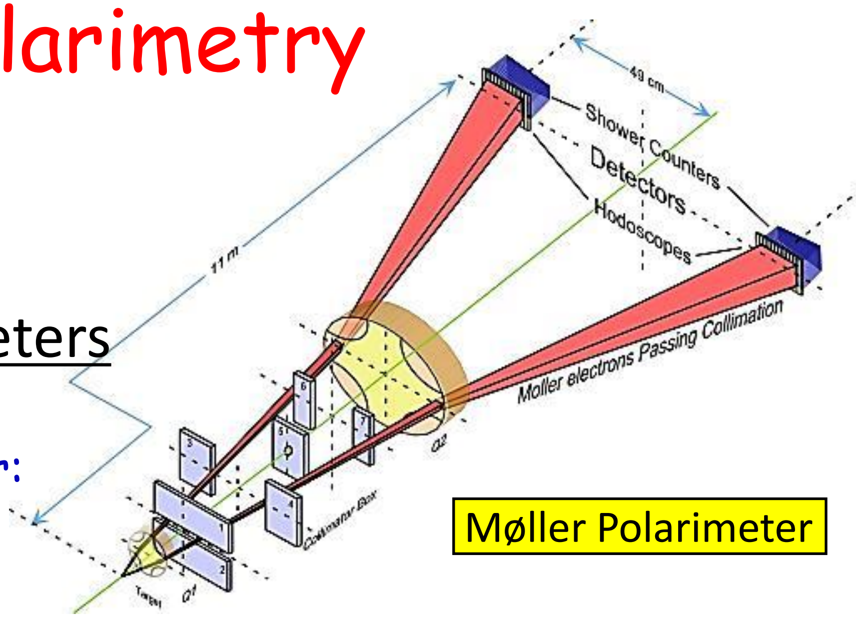
A4

Precision Polarimetry

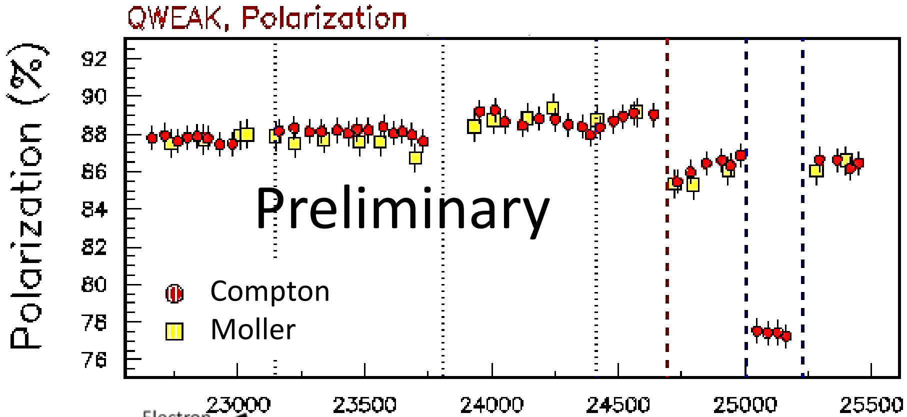
Qweak requires ΔP/P ≤ 1%

Strategy: use 2 independent polarimeters

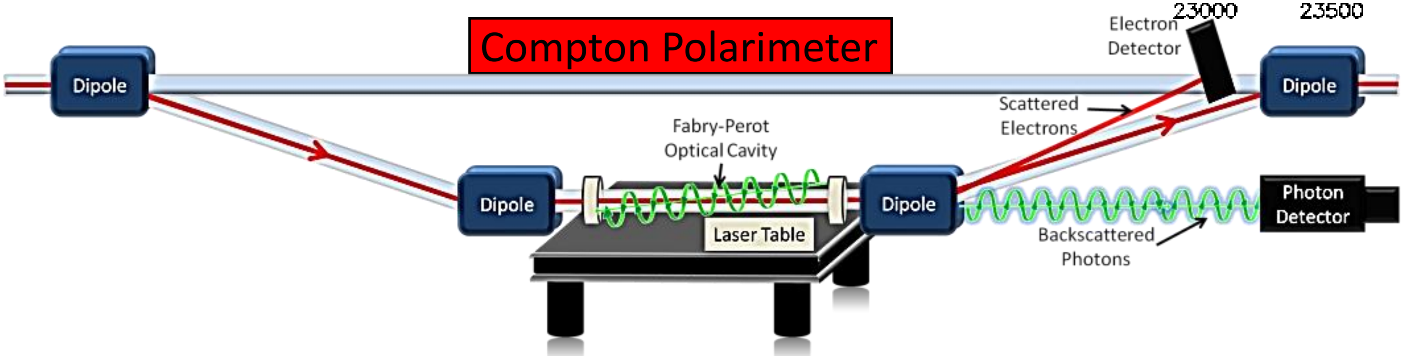
- Use existing <1% Hall C Møller polarimeter:
  - Low beam currents, invasive
  - Known analyzing power provided by polarized Fe foil in a 3.5 T field.
- Use new Compton polarimeter (1%/h)
  - High I_{beam}, non-invasive
  - Known analyzing power provided by circularly-polarized laser



Møller Polarimeter



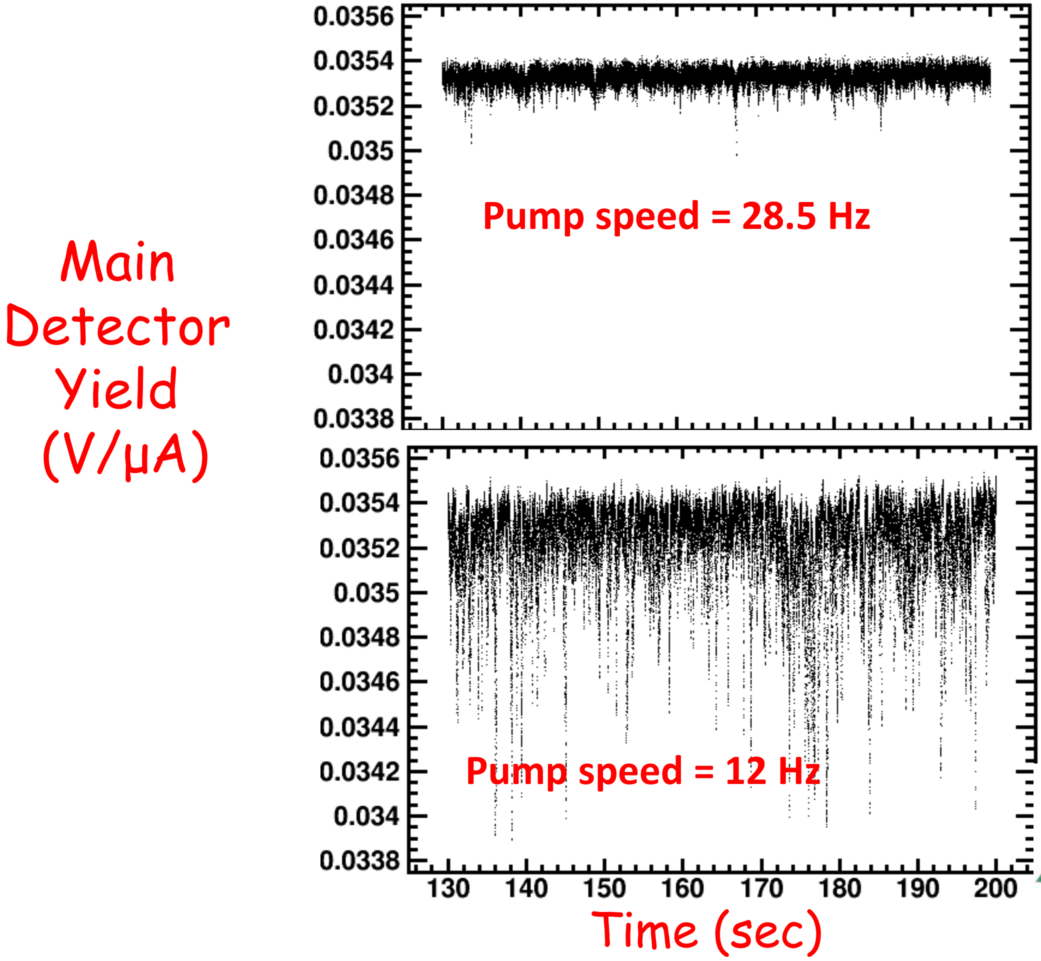
Compton Polarimeter



Target Bubble-ology

Changes in column density between + and – helicity samples are a source of noise. The main source is bubble/vapor layer formation on the Al windows.

Reversing helicity every 1 msec was critical to make the fluctuations appear negligible.



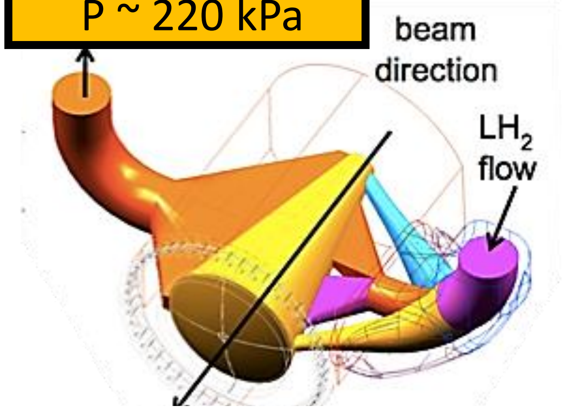
The target under nominal running conditions.

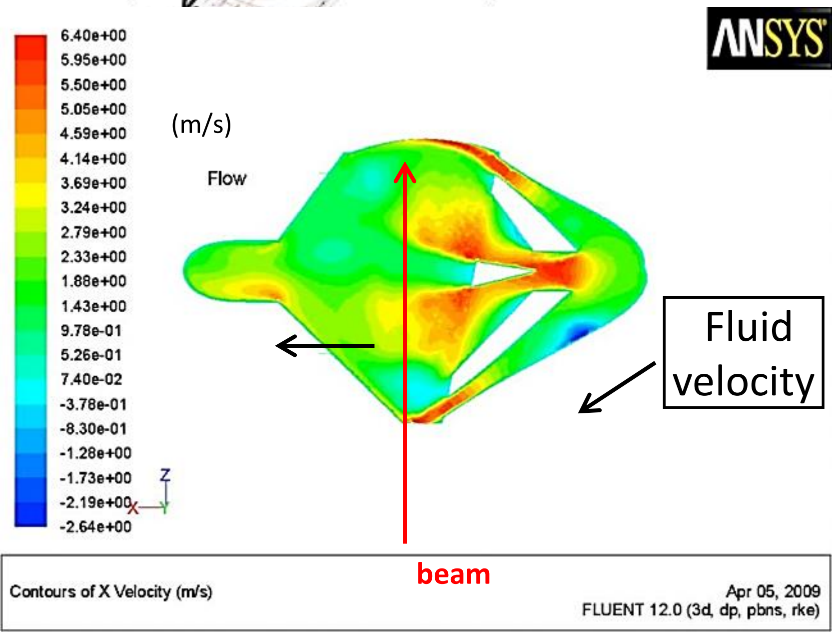
The target during a stress test.

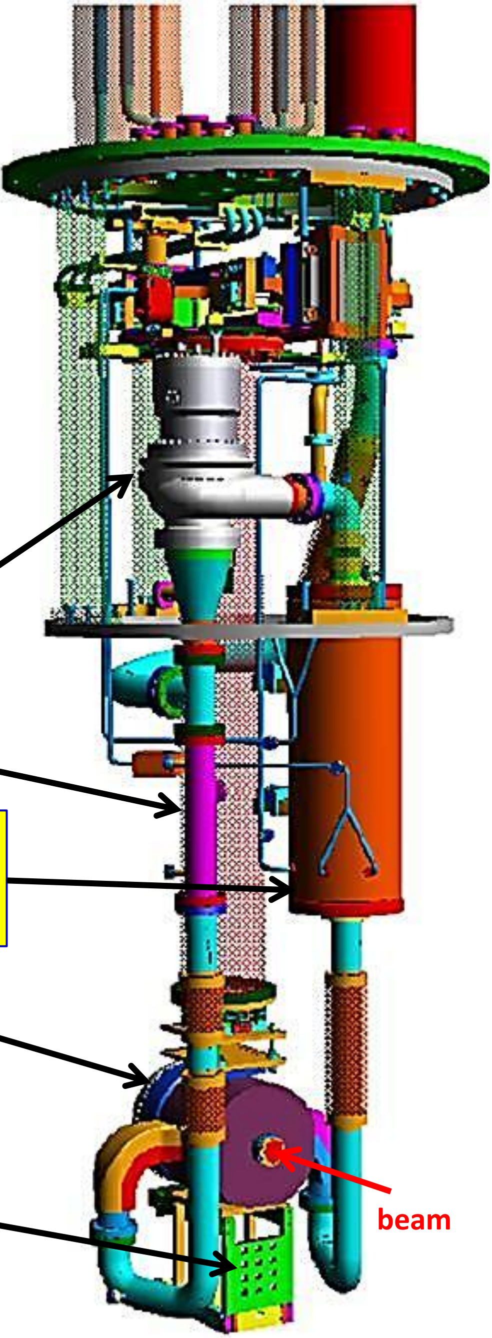
LH_2 Cryotarget Design

I_{Beam} = 180 uA
L = 35 cm (4% X_0)
P_{beam} = 2.2 kW
A_{spot} = 4x4 mm^2
V = 57 liters
T = 20.00 K
P ~ 220 kPa

World's highest power *and lowest noise* cryogenic target ~3 kW







Centrifugal pump (17 l/s, 7.6 kPa)

3 kW Heater

3 kW HX utilizing 4K & 14K He coolant

35 cm cell (beam interaction volume)

Solid Tgts

Q-weak Spectrometer (schematic)

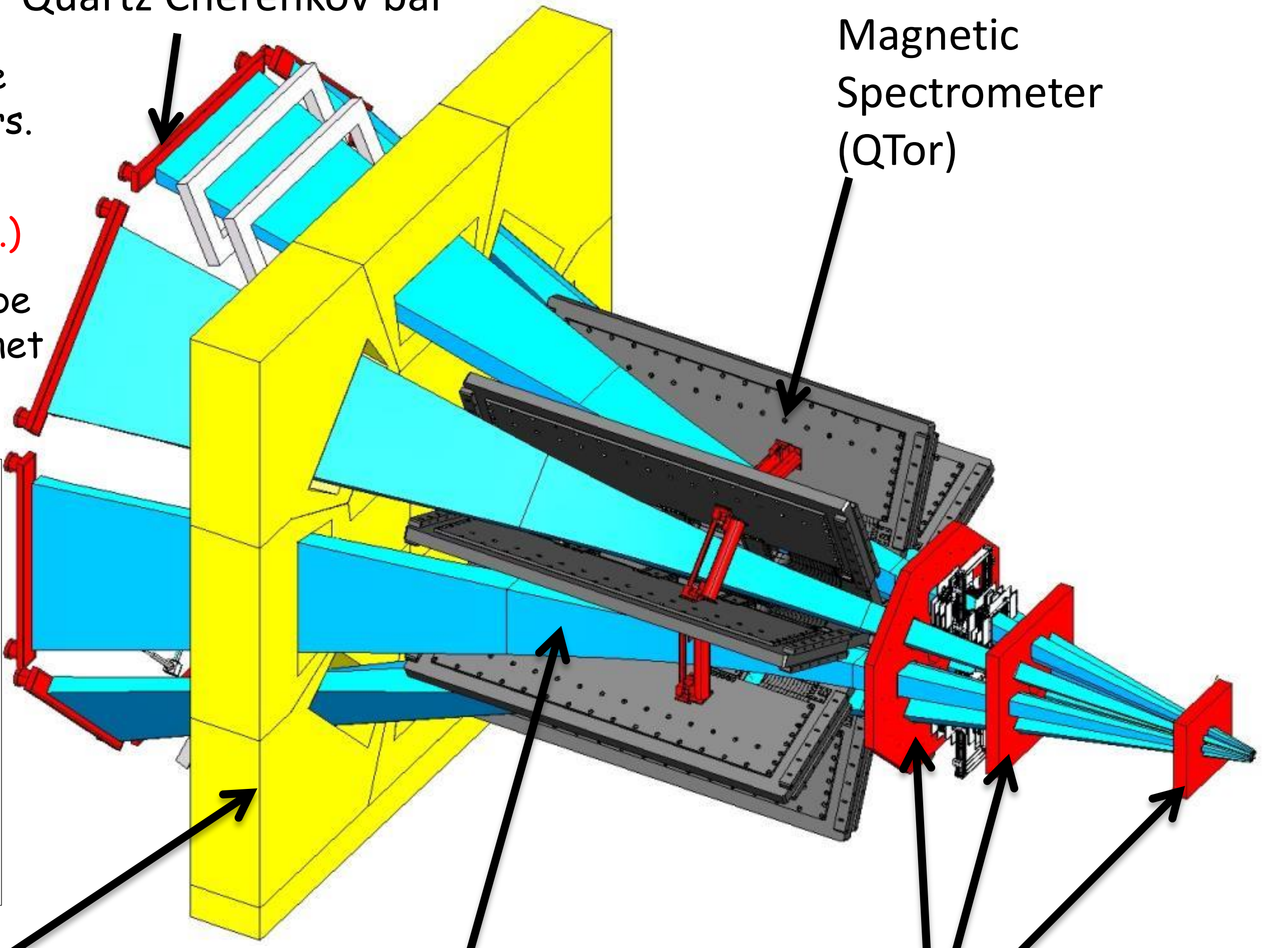
The Qweak spectrometer had to isolate elastic e+p events at small angles, with the largest acceptance possible, without tracking detectors.

(A new particle traverses each detector approximately every nsec.)

No ferromagnetic materials could be used, so a brute-force electromagnet was required.

Parameters:

E_{beam}= 1.16 GeV
Luminosity = 1.7 x 10^{39} $cm^{-2}s^{-1}$
$\theta = 6° - 12°$
$Q^2 = 0.025\ (GeV/c)^2$
Integrated Rate = 6.4 GHz



Quartz Cherenkov bar

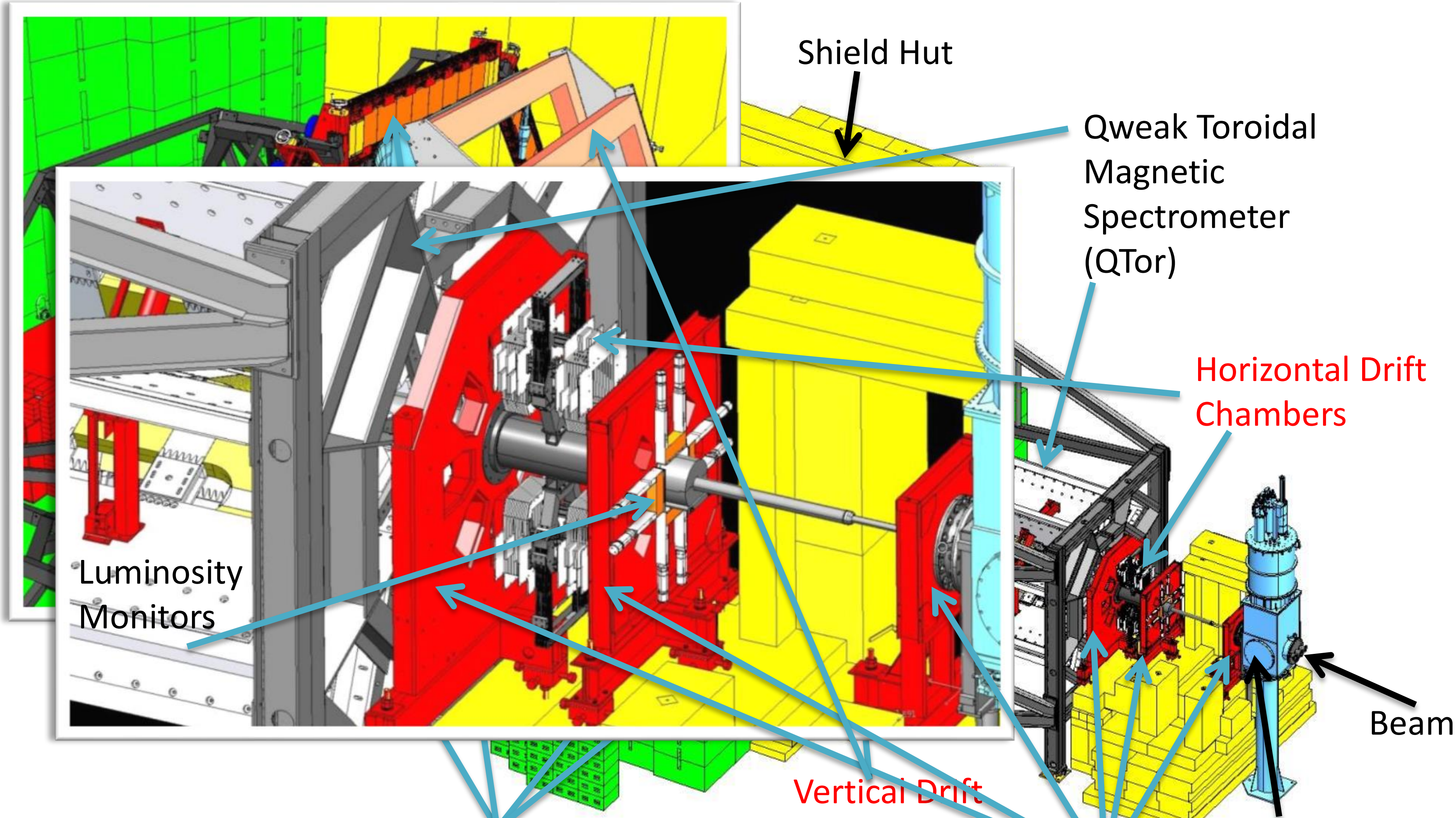
Qweak Toroidal Magnetic Spectrometer (QTor)

High density concrete shield wall

Scattered electron beam

Collimators

Q-weak Spectrometer (detail)



Shield Hut

Qweak Toroidal Magnetic Spectrometer (QTor)

Horizontal Drift Chambers

Luminosity Monitors

Beam

Vertical Drift Chambers

LH2 target

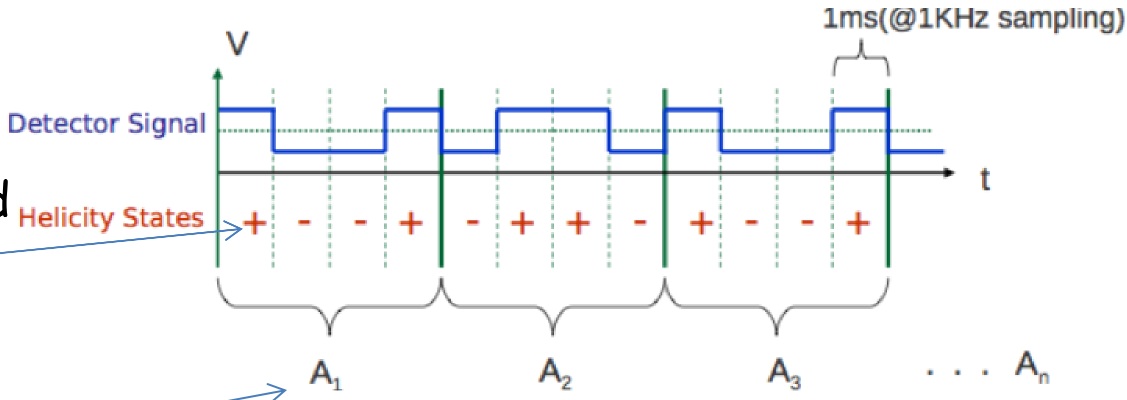
Quartz Cherenkov bars

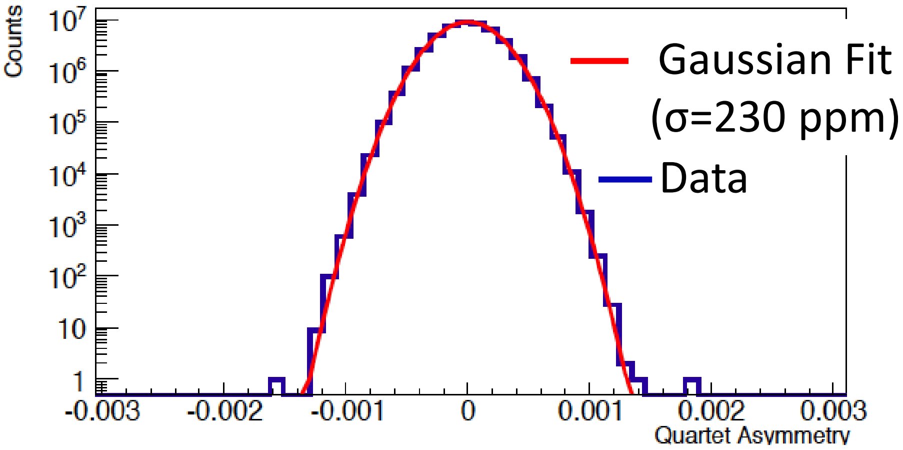
Collimators

Used only during low current tracking mode operation

Signal Manipulation

- Helicity flip every 1/960 sec
- PMT anode current integrated for each helicity state, normalized to beam charge
- Quartet asymmetries calculated (cancels linear drifts)
- Asymmetry width ~230 ppm at 180 μA is dominated by √N
- Additive "blinding factor" applied.





(Quartet Asymmetries over several days)

Status and Results
(in hand and anticipated)

Status

- The Qweak Experiment finished successfully
  - 2 years in situ, ~1 year of beam
  - Commissioning run analyzed
    - ~ 4% of total data collected
    - Results presented here:
      - 1st Determination of $Q_w(p)$, C_{1u}, C_{1d}, & $Q_w(n)$

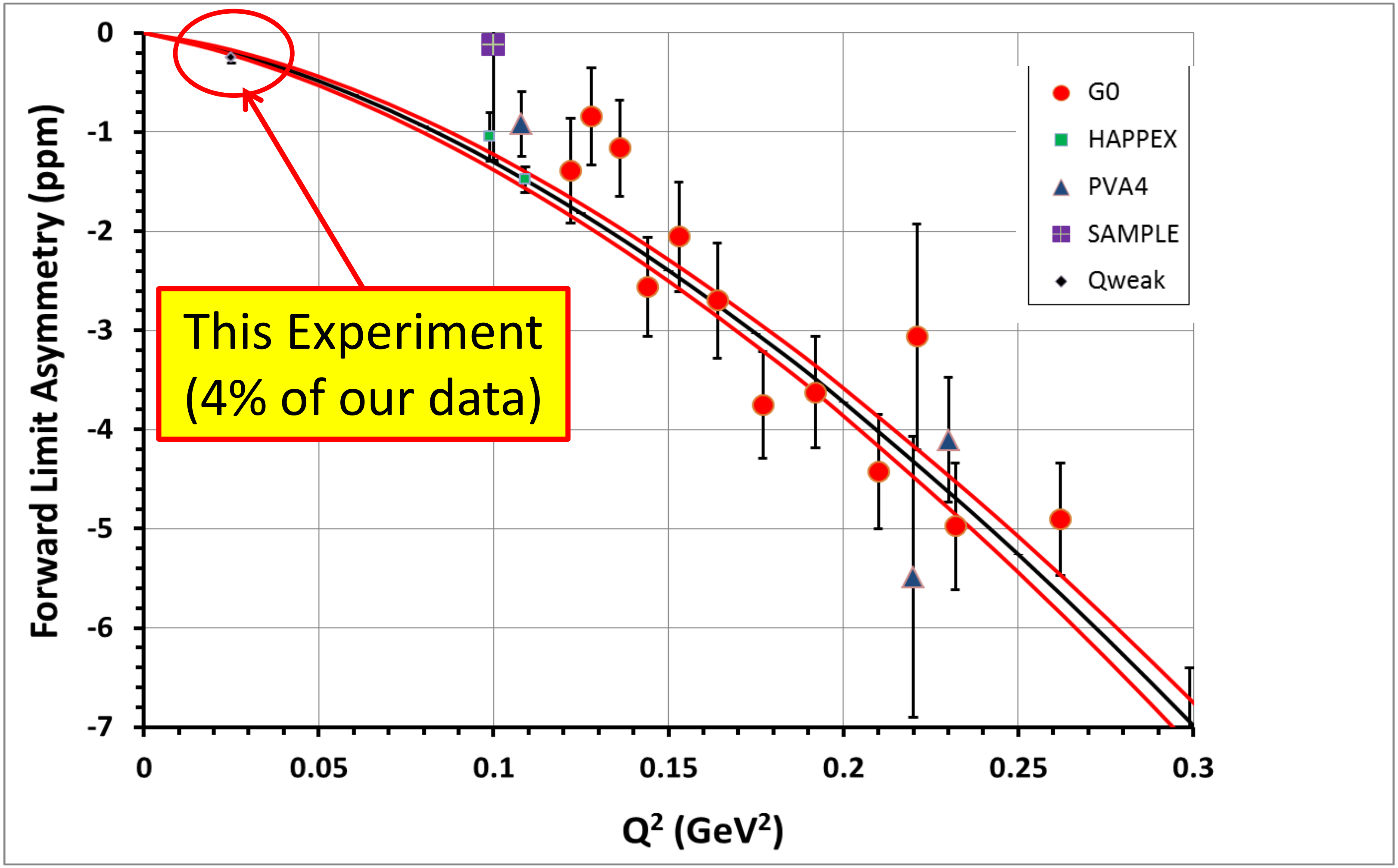
  - Remainder of experiment still being analyzed
    - Expect final result Spring 2015 (-ish)
    - Expect final result will have ~5x better precision
    - Should come close to proposed goal (4% msr of $Q_w(p)$)

Msrd Asymmetry (rotated to Θ=0°)

A_{PV} = -279 ± 35 (statistics) ± 31 (systematics) ppb

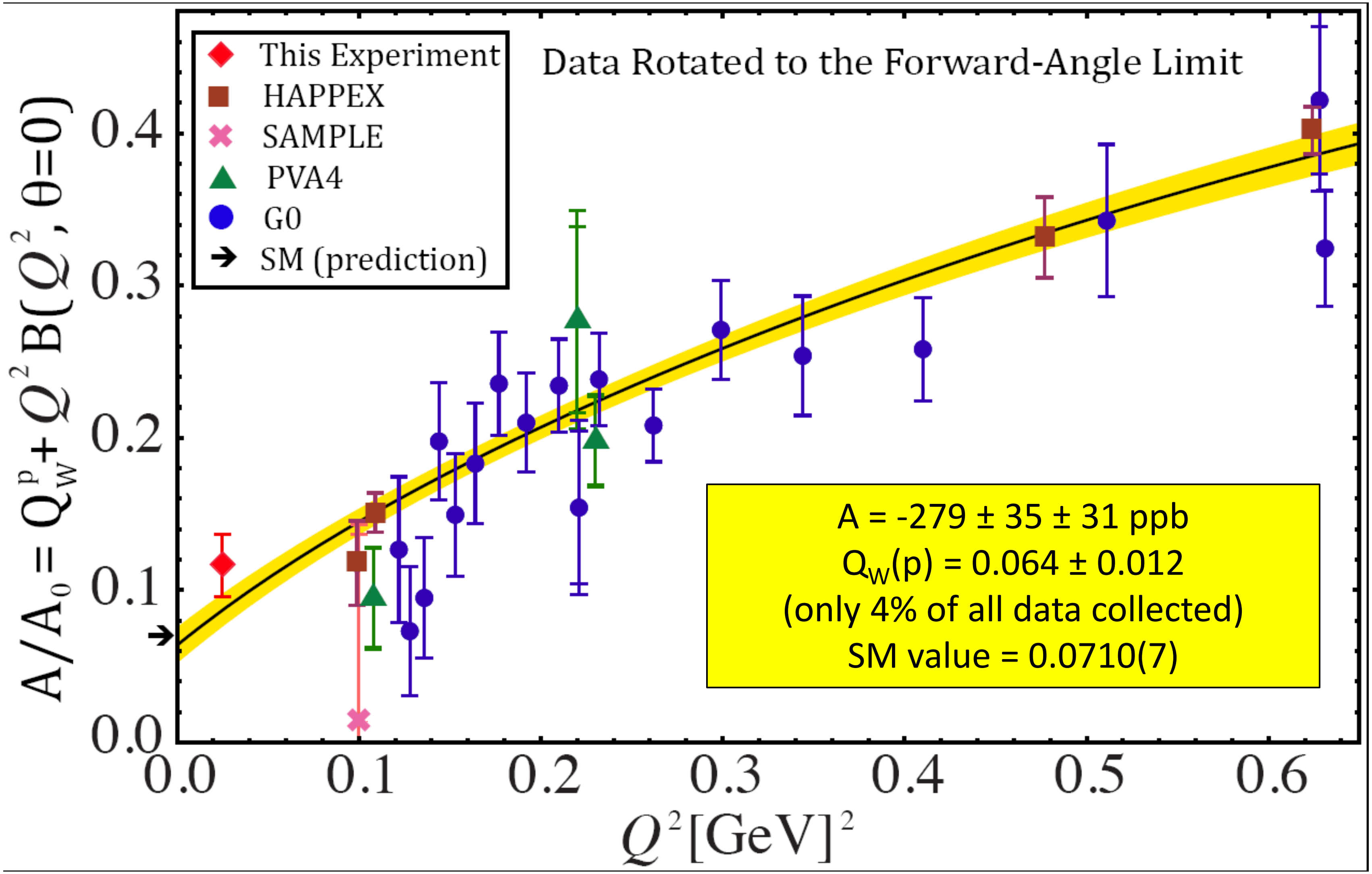
$\langle Q^2 \rangle = 0.0250 \pm 0.0006\ (\text{GeV}/c)^2$

<E> = 1.155 ± 0.003 GeV



This Experiment (4% of our data)

Global fit of PV Electron Scattering Data



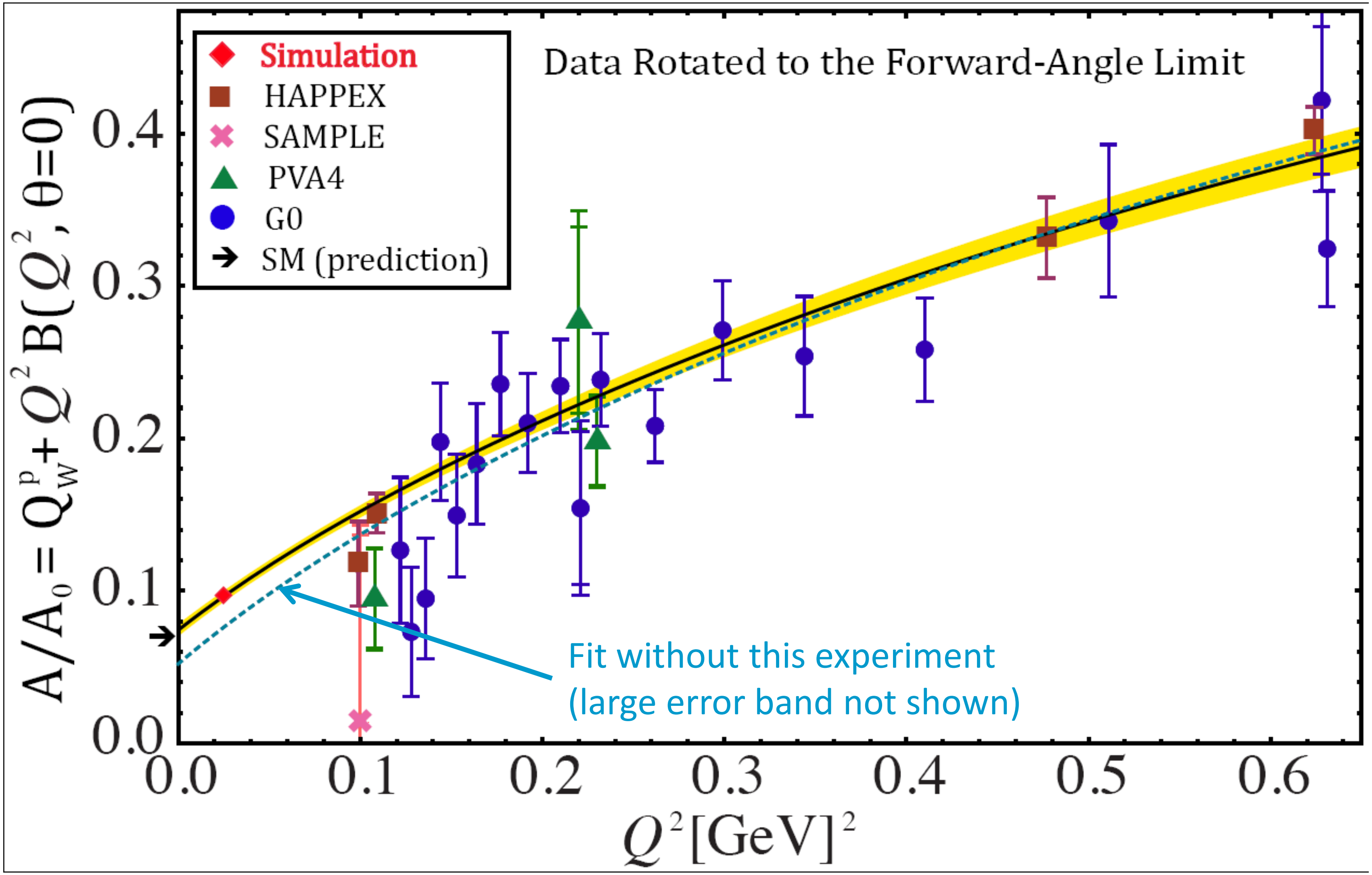
A = -279 ± 35 ± 31 ppb

$Q_W(p) = 0.064 \pm 0.012$

(only 4% of all data collected)

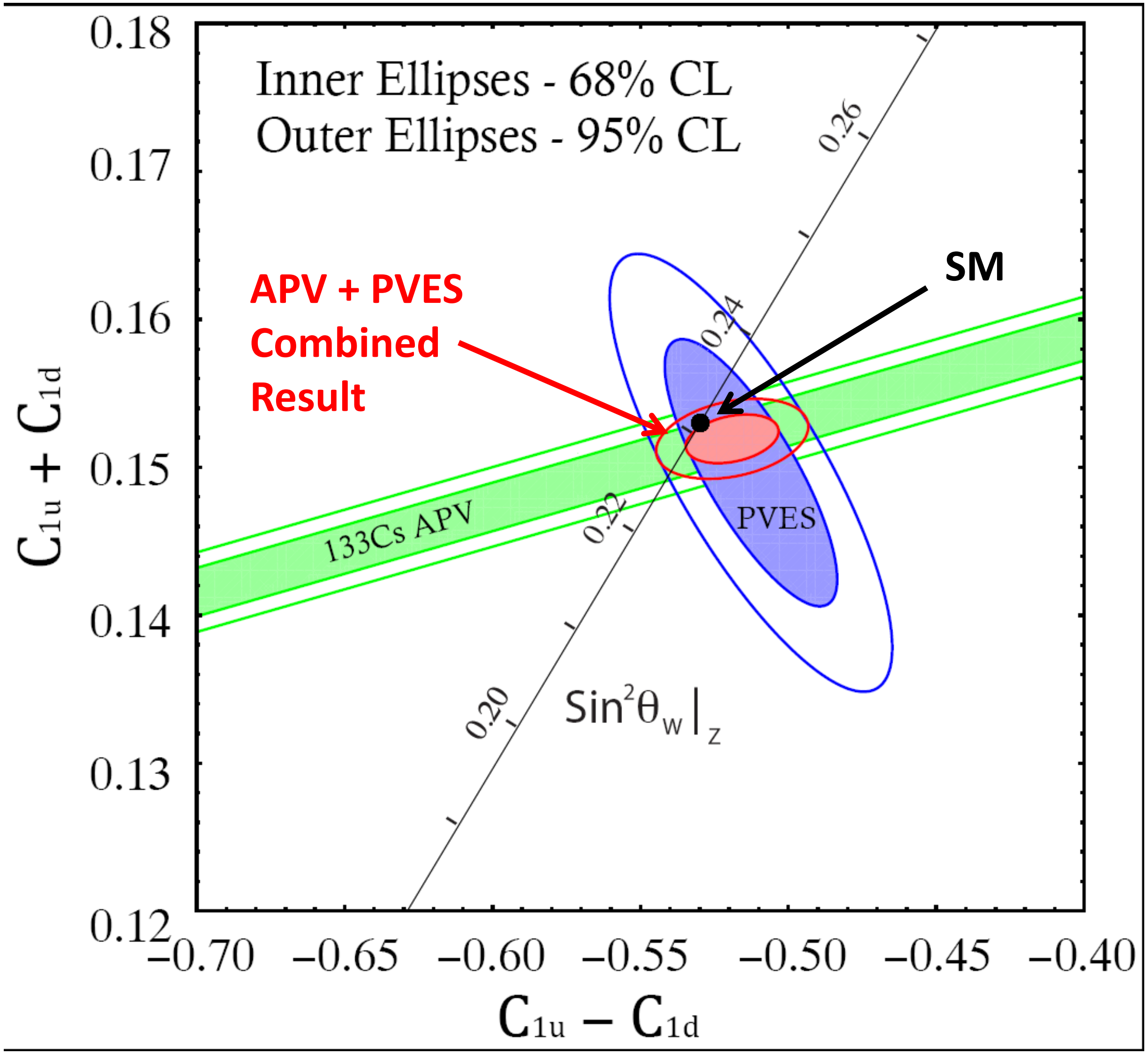
SM value = 0.0710(7)

Estimated Fit Uncertainties with Final Result (Assuming SM Value)



Fit without this experiment
(large error band not shown)

PV Electron Scattering & Atomic PV Combined Result



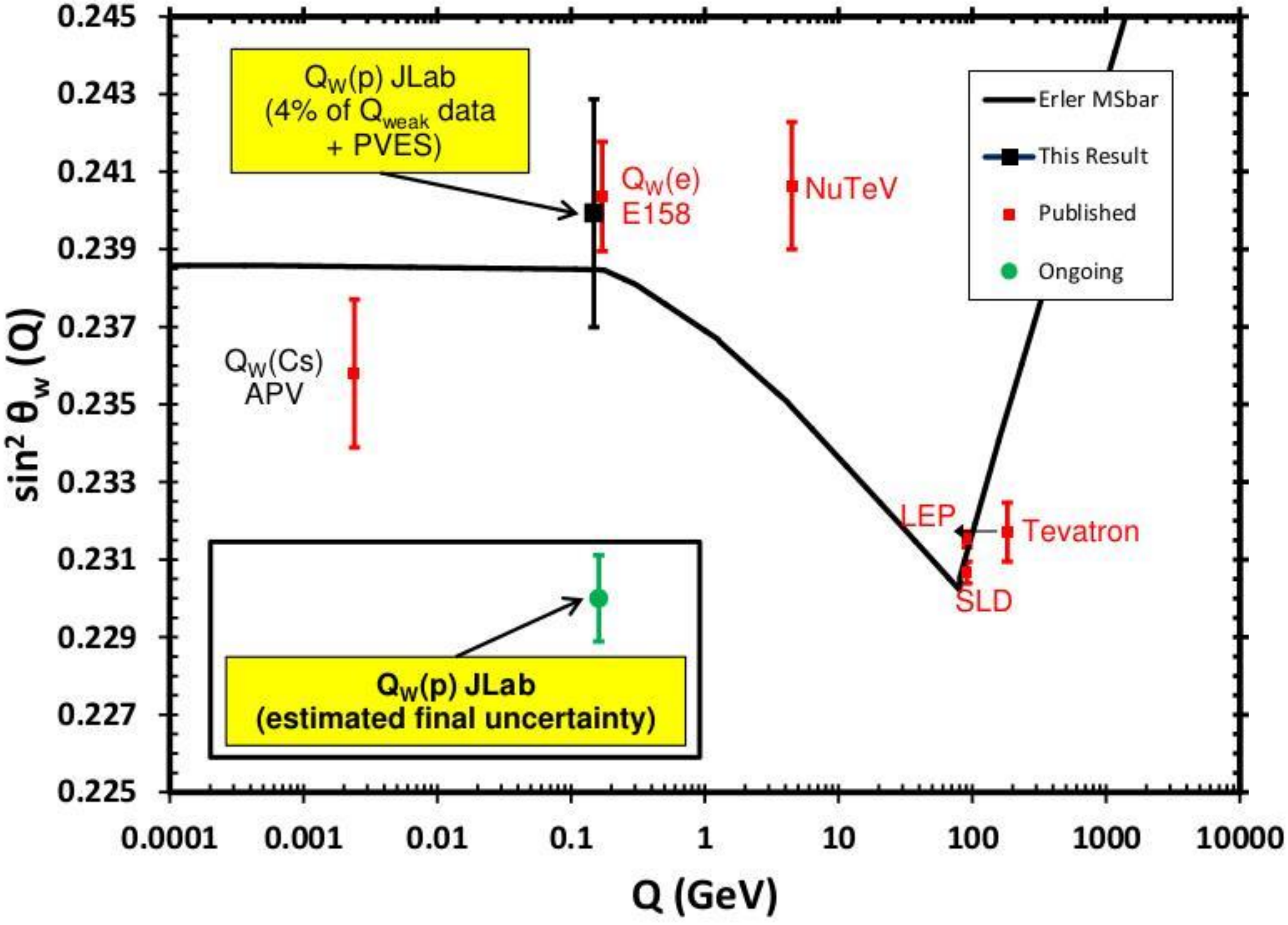
$Q_W(p) = -2(2C_{1u} + C_{1d})$
$= 0.064 \pm 0.012$
(only 4% of data)
SM value = 0.0710(7)

$C_{1u} = -0.184 \pm 0.005$
$C_{1d} = 0.336 \pm 0.005$
(only 4% of data)

$Q_W(n) = -2(C_{1u} + 2C_{1d})$
$= -0.975 \pm 0.010$
(only 4% of data)
SM value = -0.9890(7)

First Results: Weak Mixing Angle

$$\sin^2\theta_w = \frac{1}{4}\left\{1+\Delta'_e - \frac{Q_w(p) - \Box_{WW} - \Box_{ZZ} - \Box_{\gamma Z}}{\rho_{NC}+\Delta_e}\right\}$$



Piece	Value
ρ_{NC}	1.00833
Δ_e	-0.00116
Δ'_e	-0.00142
$\hat{\alpha}$	1/127.944
$\hat{s}^2$	0.23116
$\Box_{WW}$	0.01832
$\Box_{ZZ}$	0.00193
$\Box_{\gamma Z}$	0.00440

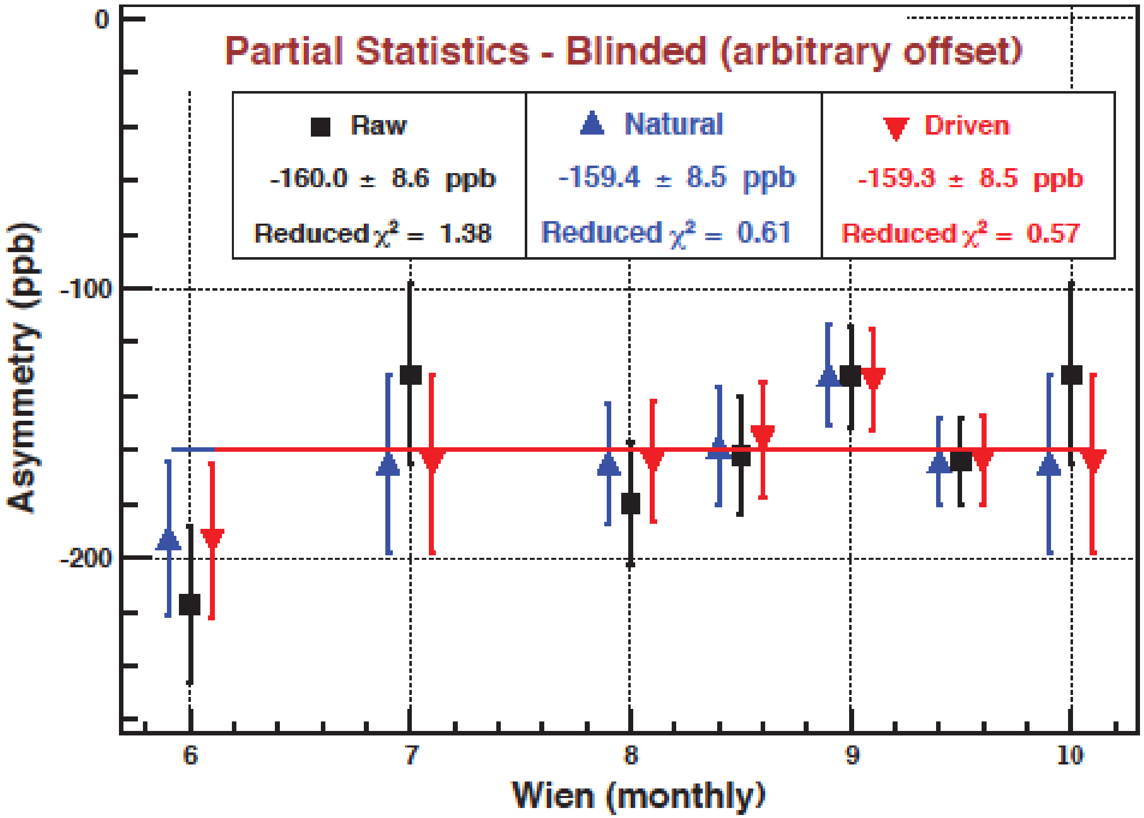
Curve from
Erler, Kurylov, Ramsey-Musolf,
PRD**68**, 016006 (2003)

Towards the Final Result

Two ways to determine sensitivity of the detector asymmetries to beam parameter variations

Corrections based on the two methods are in excellent agreement for this subset of our data where both are available

Run 2 measured asymmetry



- ○ About 77% of the Run2 data-set
- ○ Asymmetries have no corrections other than beam parameter correction

Summary

- PV electron scattering allows us to determine the weak vector charge of the proton.
- Q_w^p is $1\text{-}4\sin^2\theta_W$ suppressed, hence a good way to measure $\sin^2\theta_W$ at low energies and search for new PV interactions between electrons and light quarks.
- We measured the smallest & most precise e+p asymmetry ever.
- First determination of $Q_W(p)$: 0.063 ± 0.012 (from only 4% of data)
    - New physics reach $\Lambda/g = \frac{1}{2}(\sqrt{2}\, G_F\, \Delta Q_W)^{-1/2} = 1.1$ TeV
- Combining our result with Cs APV, we sharpen C1u, C1d, and hence Q_w^n.
- Expect to report results with ~5 times smaller uncertainties
    - Expected physics reach of ~ 2.3 TeV.
    - SM test, sensitive to Z's and LQs

The Q-weak Collaboration

W&M meeting

A. Almasalha, D. Androic, D.S. Armstrong, A. Asaturyan, T. Averett, J. Balewski, R. Beminiwattha, J. Benesch, F. Benmokhtar, J. Birchall, **R.D. Carlini^1 (Principal Investigator)**, G. Cates, J.C. Cornejo, S. Covrig, M. Dalton, C. A. Davis, W. Deconinck, J. Diefenbach, K. Dow, J. Dowd, J. Dunne, D. Dutta, R. Ent, J. Erler, W. Falk, **J.M. Finn^{1*}**, T.A. Forest, M. Furic, D. Gaskell, M. Gericke, J. Grames, K. Grimm, D. Higinbotham, M. Holtrop, J.R. Hoskins, E. Ihloff, K. Johnston, D. Jones, M. Jones, R. Jones, K. Joo, E. Kargiantoulakis, J. Kelsey, C. Keppel, M. Kohl, P. King, E. Korkmaz, **S. Kowalski1**, J. Leacock, J.P. Leckey, A. Lee, J.H. Lee, L. Lee, N. Luwani, S. MacEwan, D. Mack, J. Magee, R. Mahurin, J. Mammei, J. Martin, M. McHugh, D. Meekins, J. Mei, R. Michaels, A. Micherdzinska, A. Mkrtchyan, H. Mkrtchyan, N. Morgan, K.E. Myers, A. Narayan, Nuruzzaman, A.K. Opper, **S.A. Page^1**, J. Pan, K. Paschke, S.K. Phillips, M. Pitt, B.M. Poelker, J.F. Rajotte, W.D. Ramsay, M. Ramsey-Musolf, J. Roche, B. Sawatzky, T. Seva, R. Silwal, N. Simicevic, **G. Smith^2**, T. Smith, P. Solvignon, P. Souder, D. Spayde, A. Subedi, R. Subedi, R. Suleiman, E. Tsentalovich, V. Tvaskis, W.T.H. van Oers, B. Waidyawansa, P. Wang, S. Wells, S.A. Wood, S. Yang, R.D. Young, S. Zhamkochyan, D. Zou

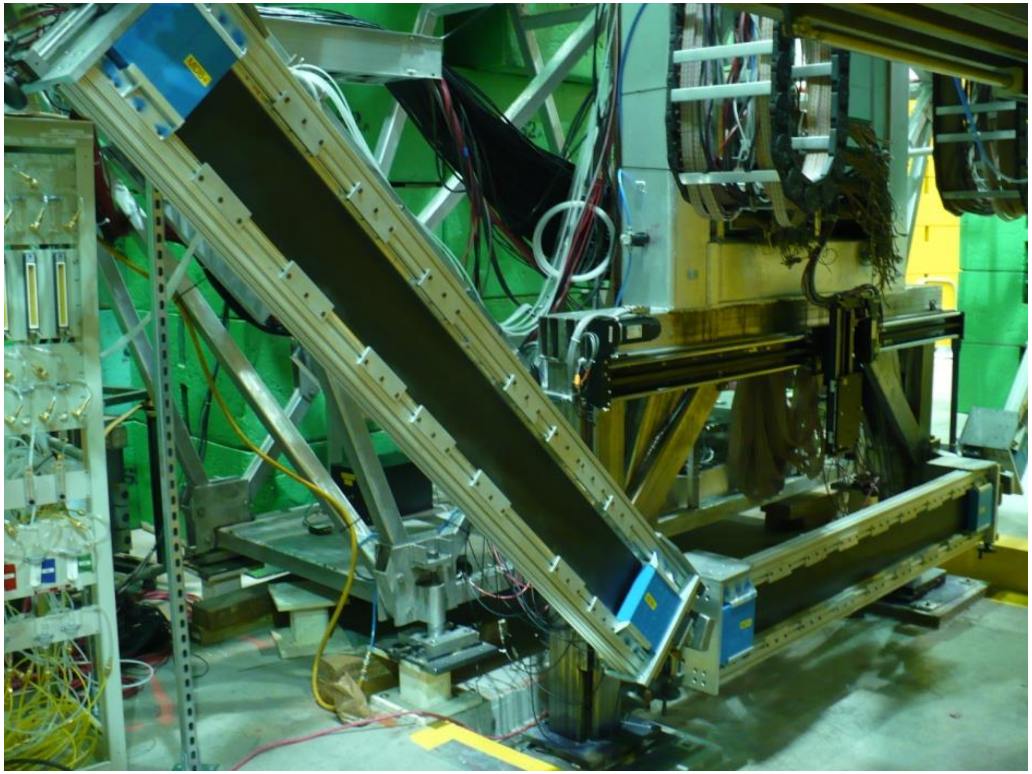
^{1}Spokespersons *deceased ^{2}Project Manager

Extras

Jlab Exo-Skeletons

Manitoba radiator modules (physicist responsibility) were installed in a strong, stiff Jlab exo-skeleton suitable for carrying Pb shielding and pre-radiators (engineering and safety responsibility).

Each module carries 200 lbs (90 kg) of Pb bricks to provide limited shielding for PMTs. (Pre-radiators would double that.)



Corrections and Uncertainties: First Result

UNITS: parts per billion (ppb)

$$A_{msr} = A_{raw} + A_T + A_L - A_{reg}$$

$$A_{msr} = -204 \quad \pm 31\,(stat) \quad \pm 13\,(sys)$$

$$\left.\begin{aligned} A_T &= 0 \pm 4 \\ A_L &= 0 \pm 3 \\ A_{reg} &= -35 \pm 11 \end{aligned}\right\}$$

~ 1σ correction to A_{raw}

$$A_{ep} = \left(\frac{R_{tot}}{P\,(1 - f_{tot})} \right) \times \left(A_{msr} - P \sum_{i=1}^{4} f_i\, A_i \right)$$

f_i : fraction of light from background i

$f_{tot} = \Sigma f_i = 3.6\%$

R: product of factors ~ unity:

(Rad. corr, kinematics, detector response)

$$A_{ep} = -279 \quad \pm 35\,(stat) \quad \pm 31\,(sys)$$

← Published commissioning result from 4% of total data collected

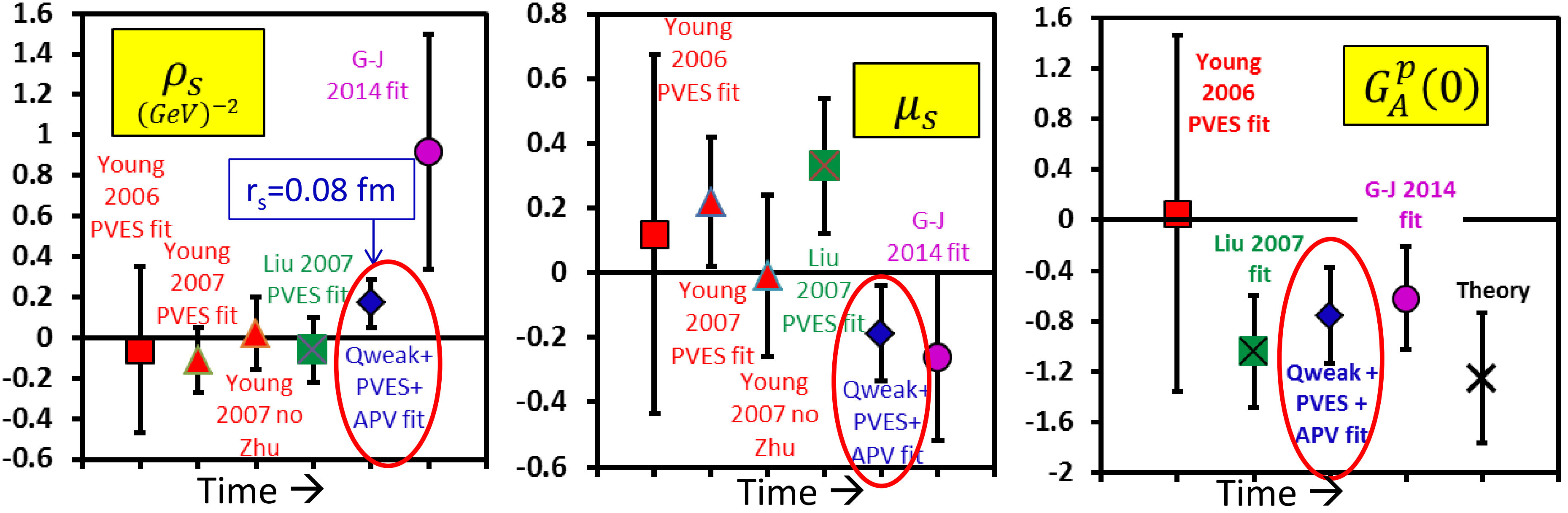
$$R_{TOT} / (P(1 - f_{tot})) = 1.139$$

$$\left. P\, f_i\, A_i = -51 + 11 + 0 + 1 = -39 \right\}$$

~ 1σ correction

(Al windows + beamline bgd. + soft neutrals + inelastic)

Global fit results for ρ_s, μ_s, & G_A



- Consistency of our fitted ρ_s, μ_s, & G_A^p with other fits gives us confidence in our published $Q_W(p)$ result.
- Physics statements about ρ_s, μ_s, & G_A^p will be made after careful systematic studies of our fit with the final $Q_W(p)$ data point included.

Q_{weak} +PVES fit: Androic, et al, PRL 111, 141803 (2013)
(only 4% of expt's total data)
G-J 2014 fit: Gonzalez-Jimenez, et al, PRD 90, 033002 (2014)

Young 2006 fit: Young, et al, PRL 97, 102002 (2006)
Young 2007 fit: Young, et al, PRL 99, 122003 (2007)
Liu fit: Liu, et al, PRC76, 025202 (2007)

Theory: See ref's in 2006 Young paper: $$G_A^p = \frac{\xi_A^{T=1} G_A \tau_3 + \xi_A^{T=0} a_8 + \xi_A^0 a_s + A_{ana}^{T=1}\tau_3 + A_{ana}^{T=0}}{\left(1+{Q^2}/{\lambda^2}\right)^2}$$

Usually fixed to Zhu, et al, PRD62, 033008 (2000)

Constrained by other expt's

Always floated in the fits

Spin -off: Beam Normal Single Spin Asymmetry in e+p elastic scattering

It was helpful to measure the Parity Conserving asymmetry in e+p elastic scattering to high accuracy to constrain potential leakage into the PV asymmetry.

Arises from 2-photon exchange.

Figure of Apv + Apc for all octants. Then same with broken azimuthal symmetry.

The PC contamination leakage turned out to be very small, but because of the relatively large (~5 ppm) asymmetry, the ability to operate the LH2 target at the full beam current of 180 muA, and the need for both Px and Py polarization states to probe azimuthal symmetry breaking in the detector, we ended up with by far the most precise measurement of the BNSSA (2%?).

Figure of Buddhini’s result vs theory.

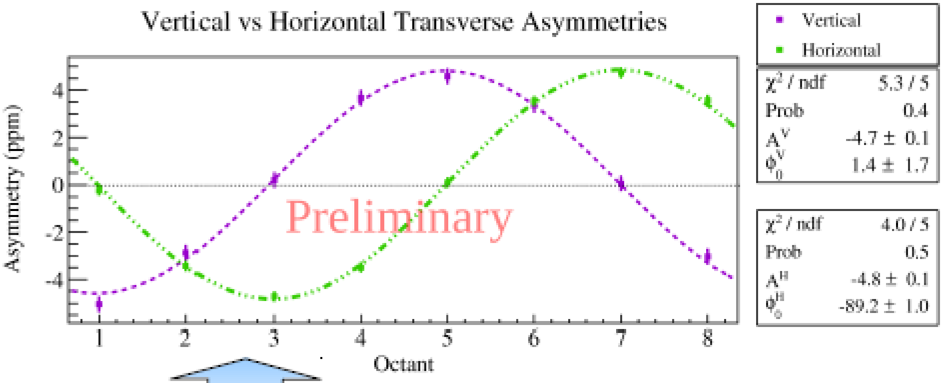
(Also a 10% N to Delta result.)

Transverse Asymmetry Leakage

Generated by residual transverse polarization in the beam ~ 2%

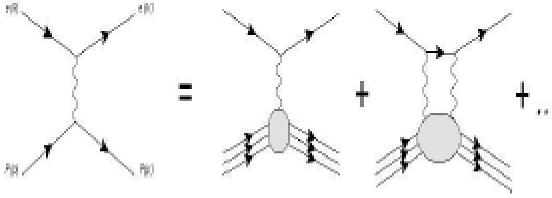
For the commissioning data set:

A_T = 0 ± 4 ppb

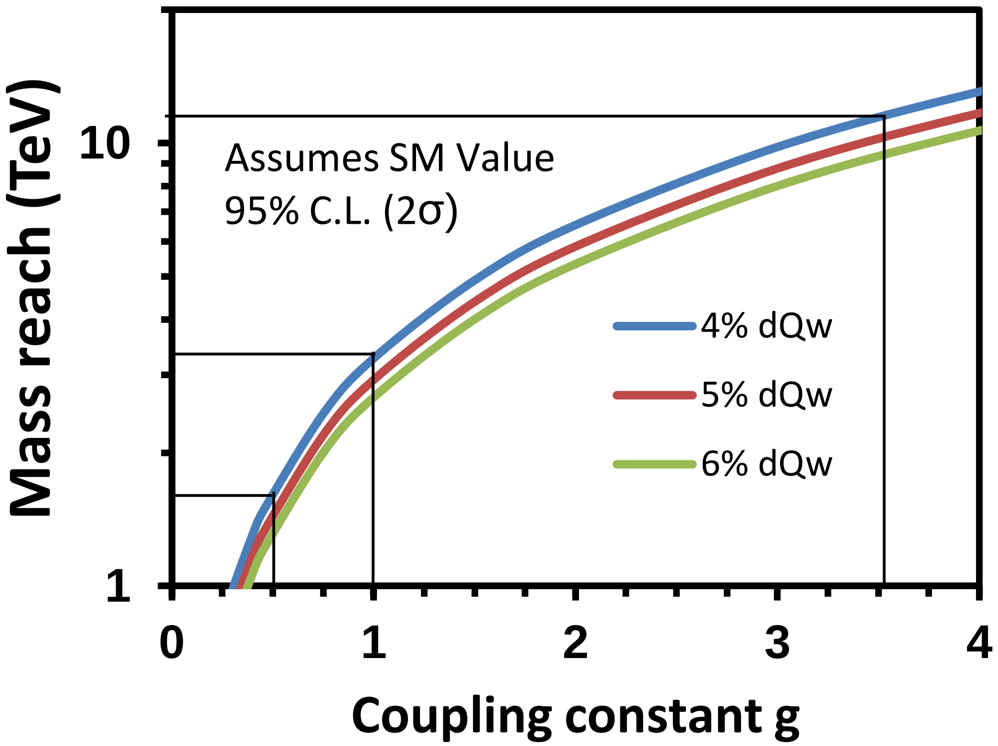


Determined from dedicated measurements with a fully transversely polarized beam

- In its own a valuable physics result!
- Carries information on 2-photon exchange
- an integral test of all allowed virtual excitations of the proton up to E_{cm} = 1.7 GeV



Sensitivity to New Physics



Expected Final Result with:

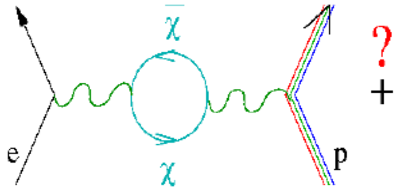
- **proposal $\Delta Q_w/Q_w = 4.2\%$**
- **95% C.L.**
- **Q_w = SM = 0.0710**

Λ / g ~ 3.2 TeV

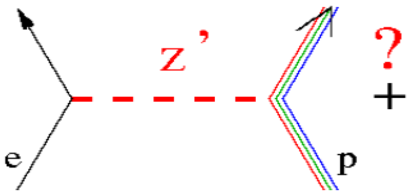
g depends on the PV "new physics" Lagrangian

$$\frac{\lambda}{g} = \frac{1}{\sqrt{2\sqrt{2}G_F|\Delta Q_w(p)|}}$$

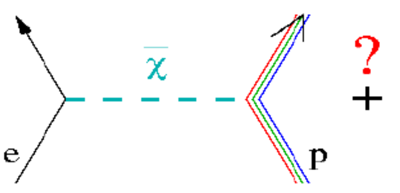
Erler, Kurylov, and Ramsey-Musolf
Phys. Rev D 68, 016006 (2003)



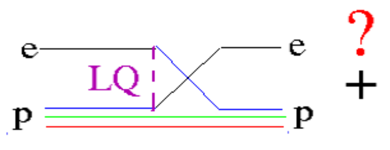
RPC SUSY



Generic Z'



RPV SUSY



Leptoquarks

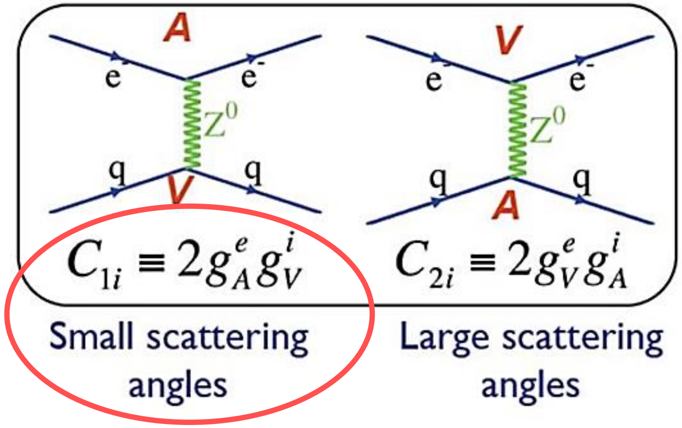
The Weak Charges

$Q_w(p)$ is the neutral-weak analog of the proton's electric charge

The Standard Model makes a firm prediction of Q_W^p:

	Q_{EM}	Weak Vector Charge
u quark	2/3	$-2C_{1u} = 1 - \frac{8}{3}\sin^2\theta_W \approx 1/3$
d quark	-1/3	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_W \approx -2/3$
p (uud)	+1	$1 - 4\sin^2\theta_W \approx 0.07$
n (udd)	0	≈ -1

Q-weak is particularly sensitive to the quark vector couplings C_{1u} & C_{1d}



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

Small scattering angles

Large scattering angles

- **General: $Q_w(Z,N) = -2\{C_{1u}(2Z + N) + C_{1d}(Z + 2N)\}$**
  - **Ex: $Q_w(p) = -2(2C_{1u} + C_{1d})$ (this experiment)**
    - **Uses higher Q^2 PVES data to constrain hadronic corrections (about 20%)**
  - **Ex: $Q_w(^{133}Cs) = -2(188C_{1u} + 211C_{1d})$ (APV)**
    - **Latest atomic corrections from PRL 109, 203003 (2012)**
- **Combining $Q_w(p)$ and $Q_w(^{133}Cs)$ → C_{1u} & C_{1d} , $Q_w(n)$**

Low Energy PV and the Tevatron Top A_{FB} Anomaly

Tevatron CF and D0 collaborations saw an excess in the t-tbar forward-backward asymmetry, A_{FB}.

(Precision measurements can also be made at the energy frontier!)

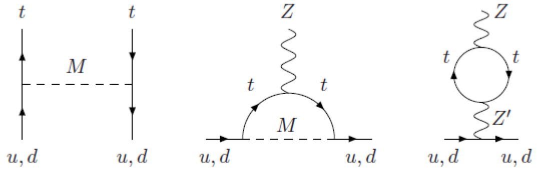


FIG. 1: *A_{FB} from t-channel exchange of M (left). Anomalous coupling of Z to u, d at one-loop is generated by M (center) and by flavor-conserving Z' associated with certain vector M models.*

A possible explanation which avoided known constraints was a new, not-too-massive, scalar or vector particle.

M. Gresham et al., arXiv:1203.1320v1 [hep-ph] 6 Mar 2012

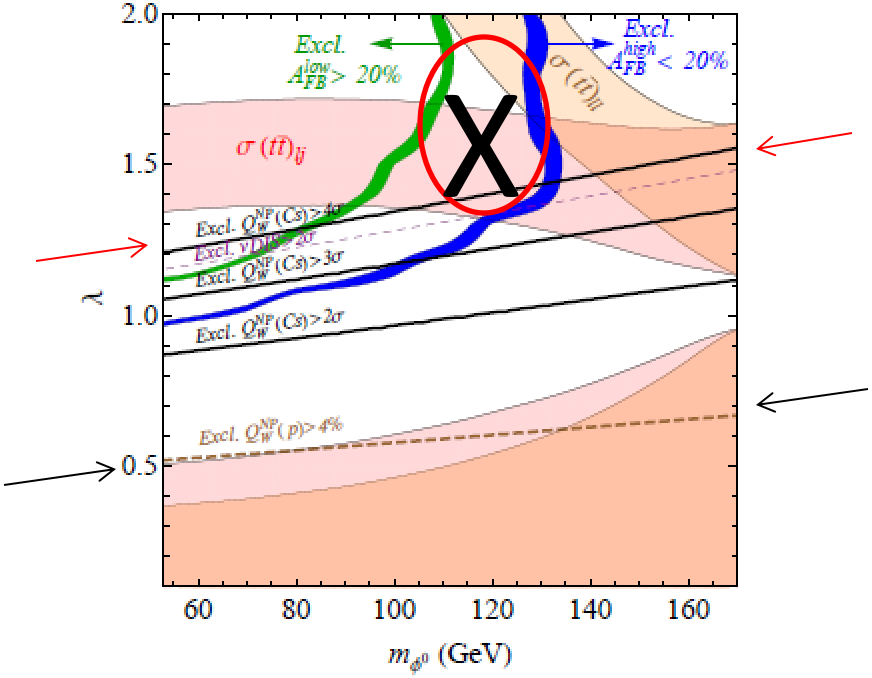
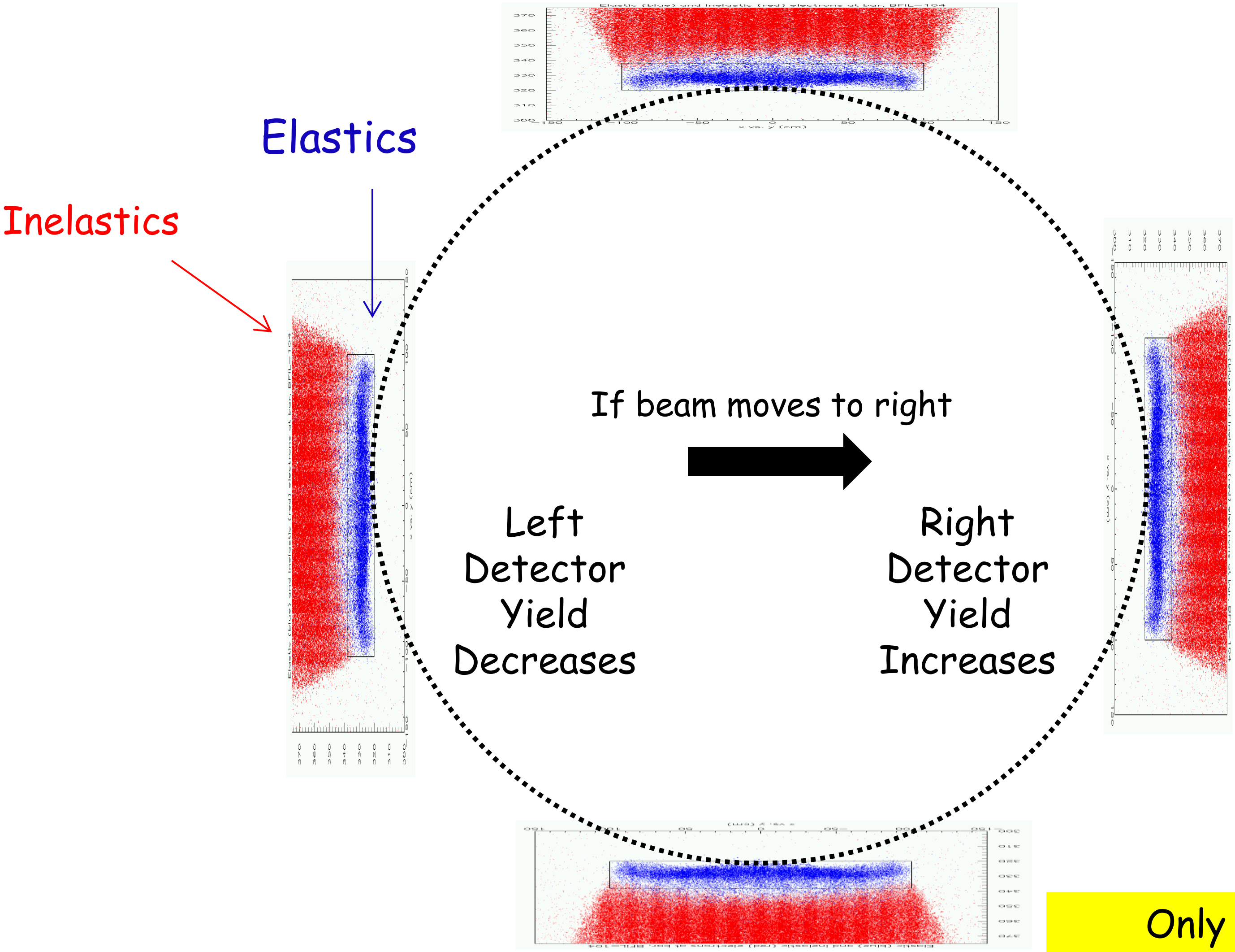


FIG. 2: *Exclusion plot for weak doublet (ϕ) model. Pink and tan shaded regions are consistent with $\sigma(t\bar{t})_{\ell j}$ and $\sigma(t\bar{t})_{\ell\ell}$, respectively. Mass-dependent-A_{FB}-favored region is within the blue and green curves, marking $A_{FB}^{\text{high}} > 20\%$ and $A_{FB}^{\text{low}} < 20\%$, respectively. Constraints from $Q_W(\text{Cs})$, νDIS, and future $Q_W(\text{p})$ measurements shown by black solid, purple dashed, and brown dashed lines, respectively.*

Sufficiently precise low energy PV experiments can constrain new physics models.

Azimuthal Symmetry Helps Suppress False Asymmetries



Elastics

Inelastics

If beam moves to right

Left
Detector
Yield
Decreases

Right
Detector
Yield
Increases

Azimuthal symmetry means the "whole detector" false asymmetries from changes in beam position or angle are much smaller than those in an individual detector.

Only 4 detectors illustrated. There are 8.

Apv in e+Al elastic scattering

A few percent measurement of Apv in e+Al elastic scattering was <u>essential</u> due to the window background. This is one of our largest corrections.

Despite the relatively large (~ 5 ppm) asymmetry, the 4% Al alloy target was limited to ~60 muA. We devoted 10% of our running time to this.

Although non-trivial to interpret due to the complex alloy, QF backgrounds, etc, *this is one of a handful of neutral current observables that have ever been measured to such high accuracy.*

Gorchtein reference and figure,

simulation of asymmetry-weighted xsect vs theta???

Kamyer’s prelim result

(Also a 10% N to Delta result which constrains the PV E1? transition.)
Musolf reference, G0 reference

Beam Parameter Differences Most Likely to Cause False Asymmetries

The yield of events scattered into a detector is proportional to

$$Y \sim d\sigma/d\Omega * \Delta\Omega(x_0,y_0)$$

where (x_0,y_0) represents the beam position on the target. A good approximation for small angle e+p elastic scattering is the Rutherford cross section. Then

$$Y \sim \alpha^2/(4E^2\sin^4(\theta/2)) * \Delta\Omega(x_0,y_0)$$

Small changes in the highlighted beam parameters on polarization reversal lead to **false asymmetries** in $(Y^+ - Y^-)/(Y^+ + Y^-)$. <u>These differences have to be measured and corrected using linear regression.</u>

In a Transport-like notation, the 5 beam parameters most likely to be important IVs (Independent Variables) for linear regression are therefore beam energy, position, and angle:

$$E,\ X_0,\ Y_0,\ X',\ Y'$$

Complications like curvature of the target windows changes the details, but not the conclusion that these are the most important IV's.

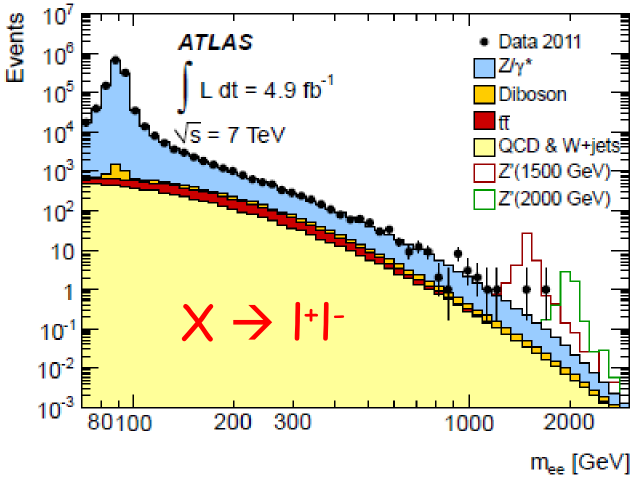
New Physics Search Technique – Creating non-SM Particles

Often thought of as the Energy Frontier .

Advantages: If you see a non-SM particle, it's revolutionary.

Disadvantages: masses could be beyond the reach of human accelerators
(e.g., pairs of R parity conserving supersymmetric particles might be too heavy)

arXiv: 1209.2535v1 [hep-ex] 12Sep2012



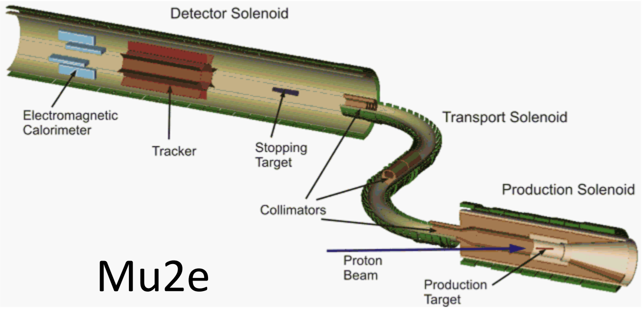
$X \to l^+l^-$

LHC

New Physics Search Technique –
Measuring the Effects of non-SM Virtual Particles

Often thought of as Low Energy Experiments.

- “Forbidden” processes – highly suppressed SM observables which may be enhanced orders of magnitude by new physics
  (electron EDM, lepton flavor violation, new sources of CP violation, rare K and B decays)

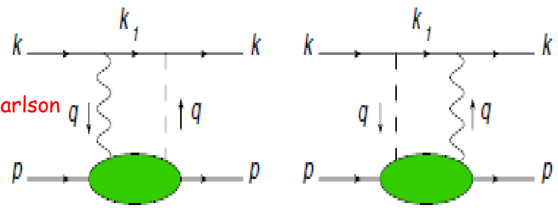


- Precision Measurements - a precise measurement of a quantity may reveal a significant discrepancy with the SM
  (muon g-2, weak charge of proton or electron, etc.)

A SEARCH FOR NEW PHYSICS
Qweak

γZ Box Corrections near 1.16 GeV

Rislow and Carlson



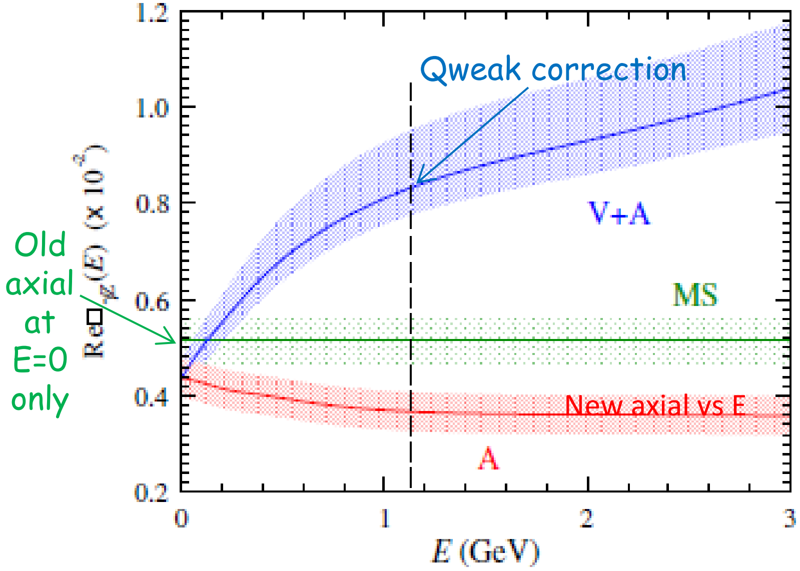
In 2009, Gorchtein and Horowitz showed the vector hadronic contribution to be significant and energy dependent.

This soon led to more refined calculations with corrections of ~8% and error bars ranging from +-1.1% to +-2.8%.

It will probably also spark a refit of the global PVES database used to constrain G_E^s, G_M^s, G_A.

PV Amplitude	Authors	Correction* @ E=1.165 (GeV)
$A^e x V^p$ (vanishes as E→0)	MS	-
	GH	0.0026
	SBMT	$0.0047^{+0.0011}_{-0.0004}$
	RC	0.0057+-0.0009
	GHR-M	0.0054+-0.0020
$V^e x A^p$ (finite as E→0)	EKR-M	0.0052+-0.0005**
	BMT	0.0037+-0.0004

BMT and references
(V and A are hadronic couplings)



Qweak correction

Old axial at E=0 only

New axial vs E

*This does not include a small contribution from the elastic.
**Included in Q_w^p. For reference, Q_W^p =0.0713(8).

After significant theoretical effort, the correction is under control. Now theorists have to agree about the uncertainty.

Determining Q_w(p)

EM (PC) + neutral-weak (PV)

- $A_{ep} = \left[\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right] \sim \frac{|M^{PV}_{weak}|}{|M_{EM}|}$ where σ± is $\vec{e}$p x-sec for e's of helicity ±1
- $A_{ep} = \left[\frac{G_F\,Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{\epsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1-4\sin^2\theta_W)\epsilon' G_M^\gamma G_A^Z}{\varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}$
  - where $\varepsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}$, $\varepsilon' = \sqrt{\tau(1+\tau)(1-\varepsilon^2)}$,
    $\tau = Q^2/4M^2$, $G^\gamma_{E,M}$ are EM FFs, $G^Z_{E,M}$ & G^Z_A are strange & axial FFs,
    and $\sin^2\theta_W = 1 - (M_W / M_Z)^2$ = weak mixing angle
- Recast $A_{ep} = \frac{G_F\,Q^2}{4\pi\alpha\sqrt{2}}\left[Q^p_w + Q^2 B(Q^2,\theta)\right]$
  - So in a plot of $A_{ep}/\left[\frac{G_F\,Q^2}{4\pi\alpha\sqrt{2}}\right]$ vs Q^2:
    - Q^p_w **is the *intercept*** (anchored by precise data near Q^2=0)
    - $B(Q^2,\theta)$ is the ***slope*** (determined from higher Q^2 PVES data)

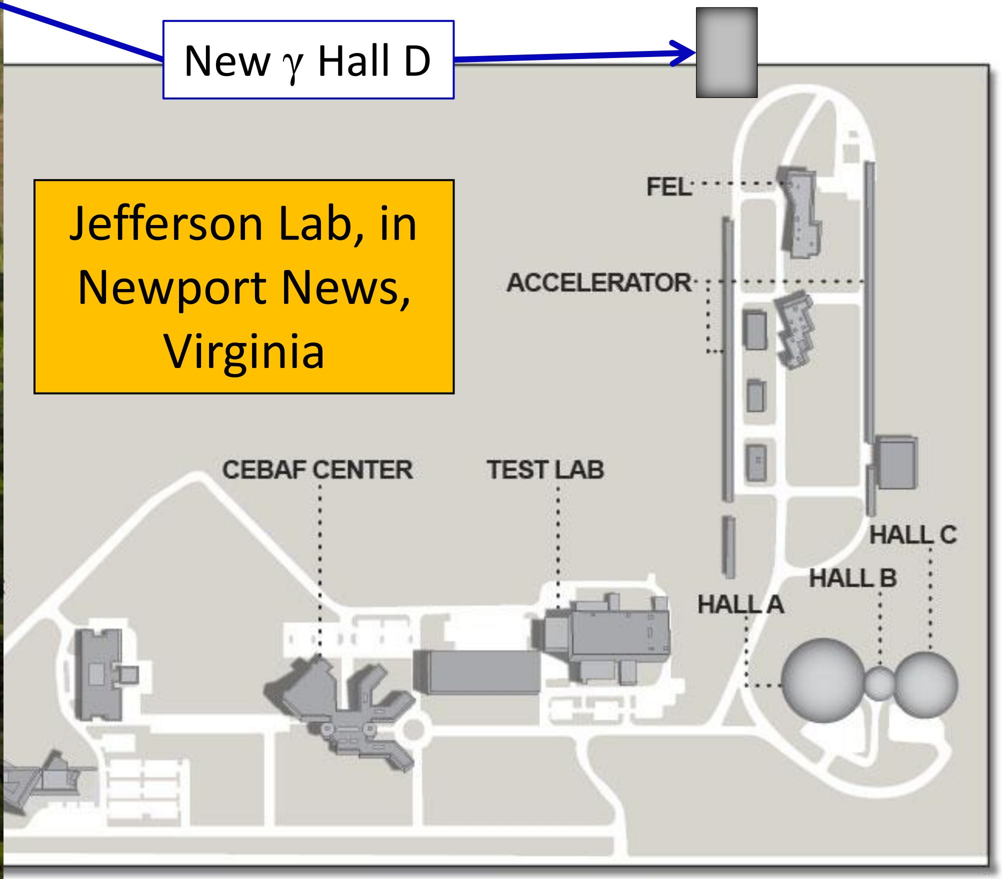
This Experiment

CEBAF Accelerator at JLab

- Superconducting RF accelerators
- Continuous e- beam (499 MHz)
- **4** experimental halls
- 12 GeV upgrade essentially complete

Q_{weak} in Hall C

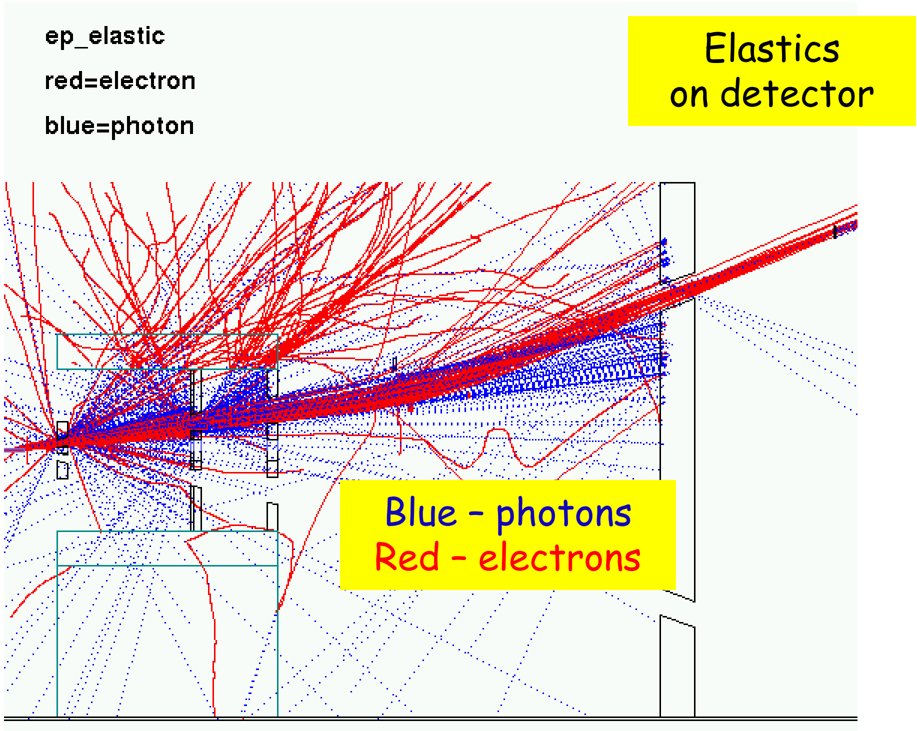
New γ Hall D



Jefferson Lab, in Newport News, Virginia

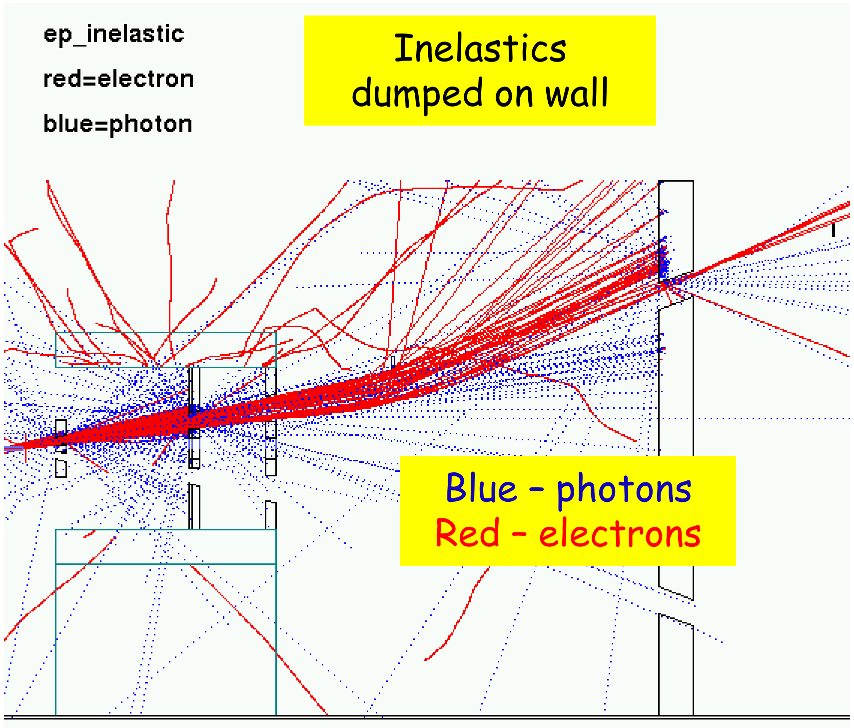
Front Shield Wall for Background Reduction

- Safely dump gamma rays and inelastic electrons before they enter the detector hut.
- Reduce the solid angle for accepting the "glow" from the Hall and beamline.



Elastics on detector

Blue – photons
Red – electrons



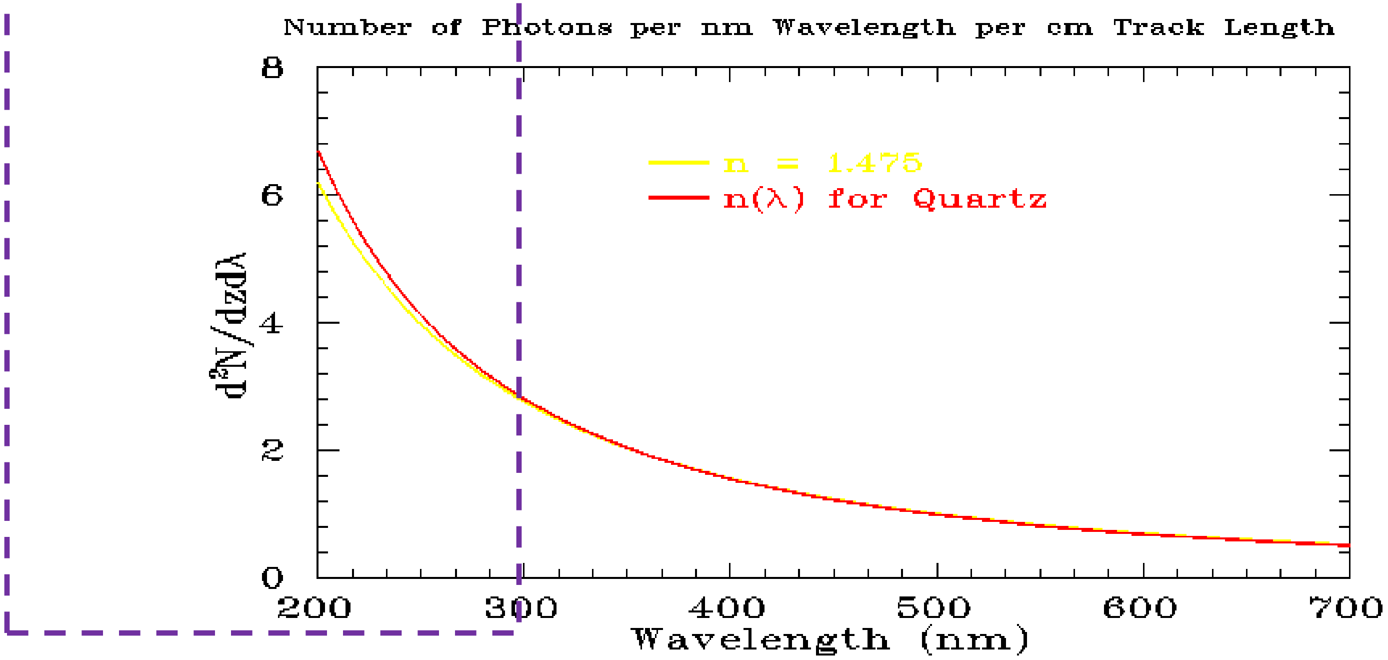
Inelastics dumped on wall

Blue – photons
Red – electrons

Cerenkov Radiation

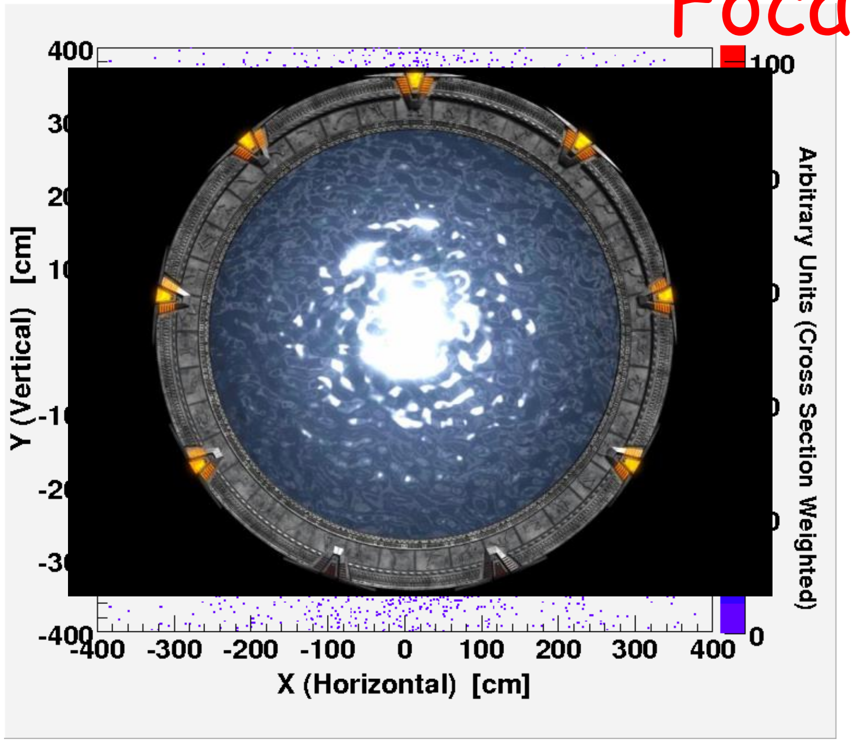
The number of Cerenkov photons emitted per cm is

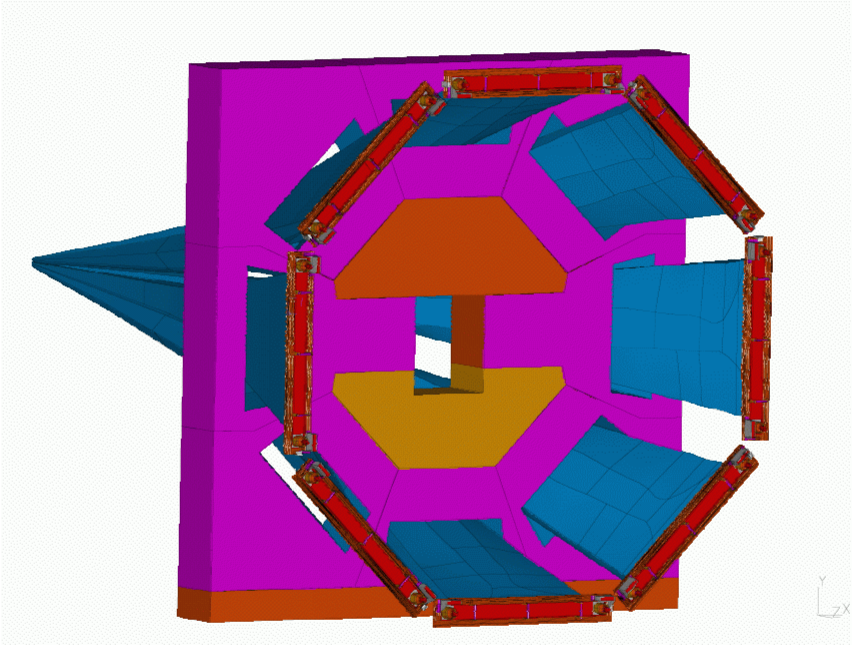
$$\frac{dN}{d\lambda} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n(\lambda)^2}\right)$$



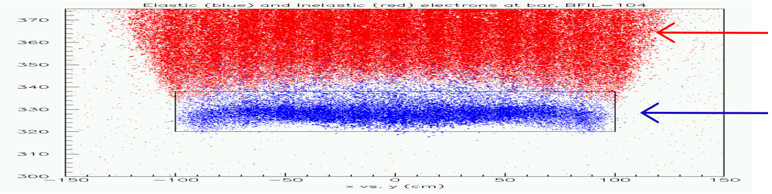
Most of the potential photons are UV i.e. , below 300 nm.

Focal Plane





Our azimuthal acceptance is about 50%.
It appears larger here because
azimuthal defocusing enlarges the beam
spots to 2m length.



Inelastics

Elastics

Separation of elastics from
inelastics is excellent.

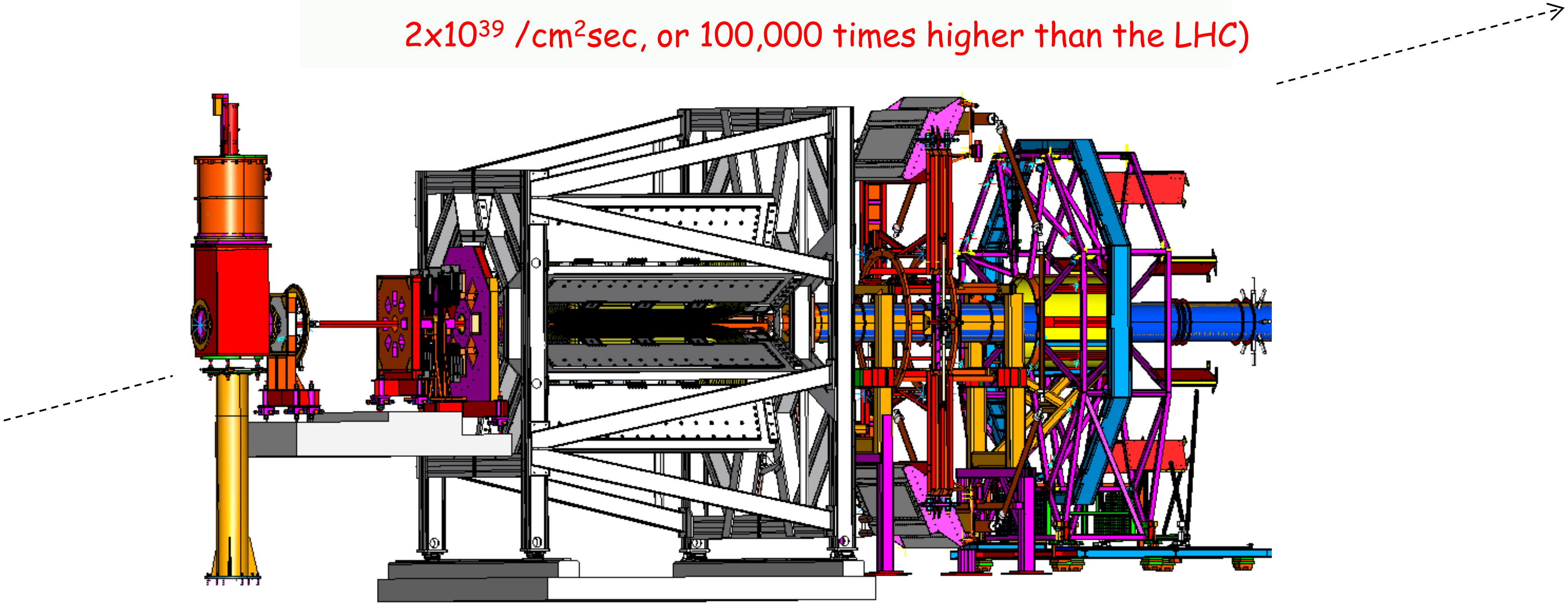
Spectrometer Implementation

A resistive toroidal spectrometer driven at 9,000 amps was used:

- good azimuthal acceptance (~50%),
- the approximate 1/R field brings a range of scattering angles to a focus, and
- although the 15 degree average bend is modest, it's just enough to keep the detectors from direct view of the target or brightly glowing collimators,
- lower cost, shorter lead-time, higher reliability than a superconducting magnet

(our luminosity is high even by the standards of fixed target experiments:

2×10^{39} /cm^2sec, or 100,000 times higher than the LHC)



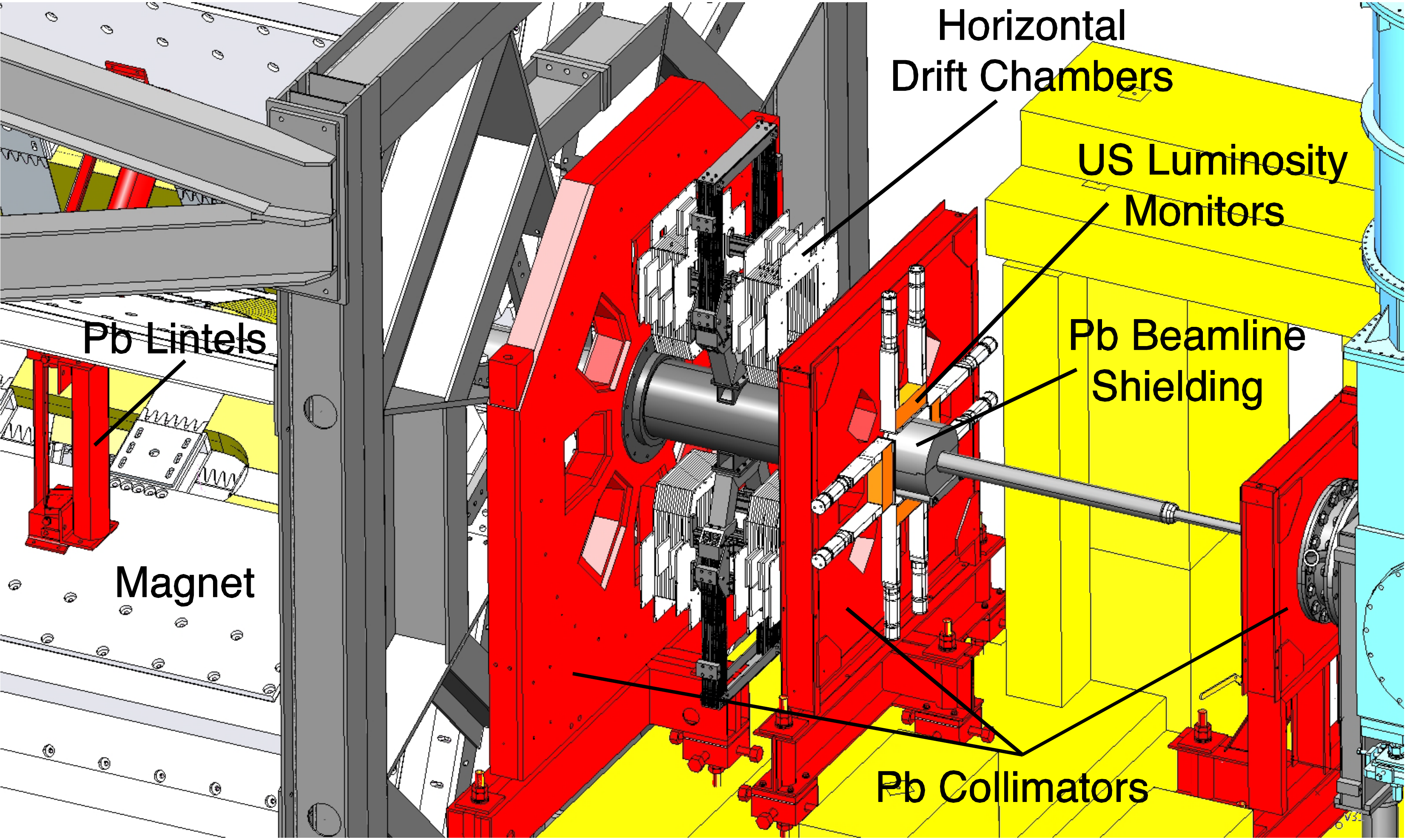
Uncertainty Goals

2% on A_z $\approx$ 4% on Q_w $\approx$ 0.3% on $sin^2\theta_W$

Source of error	**Contribution to** $\Delta A_{phys}/A_{phys}$	**Contribution to** $\Delta Q^p_w\ /Q^p_W$
Counting Statistics	2.1%	3.2%
Hadronic structure	—	1.5%
Beam polarimetry	1.0%	1.5%
Absolute Q^2	0.5%	1.0%
Backgrounds	0.7%	1.0%
Helicity-correlated beam properties	0.5%	0.8%
TOTAL:	2.5%	4.2%

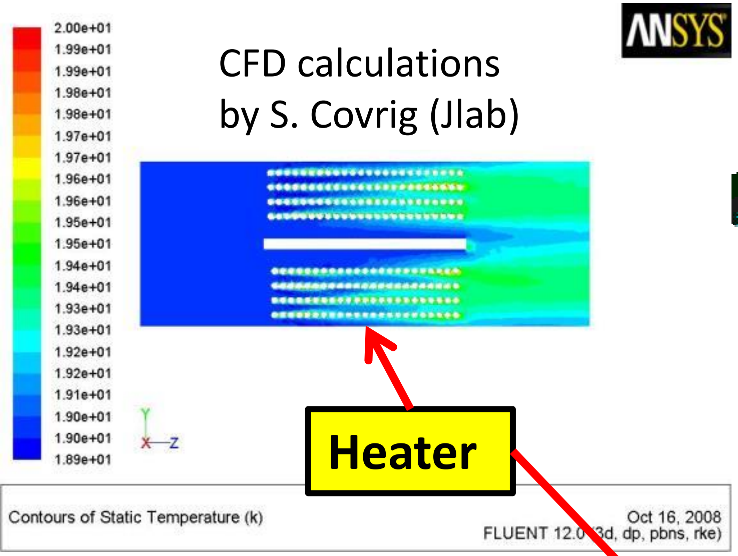
Hadronic contributions to A_{PV} magnify the error in going from A_{PV} to Q^p_W

Collimation



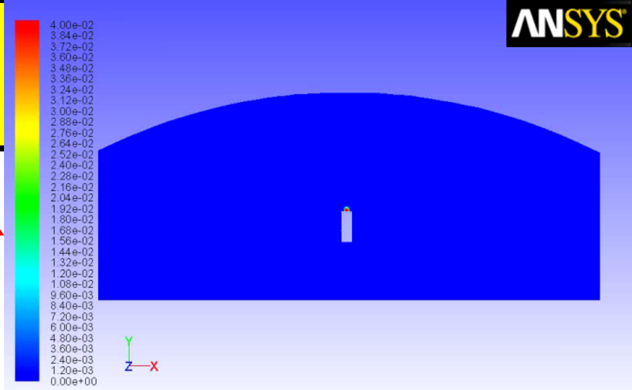
Design by CFD

CFD calculations
by S. Covrig (Jlab)

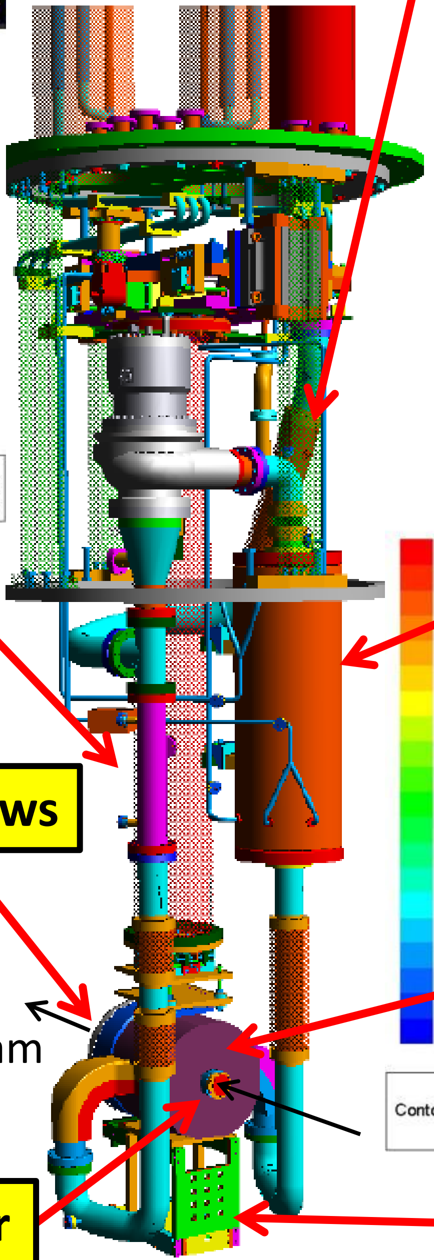


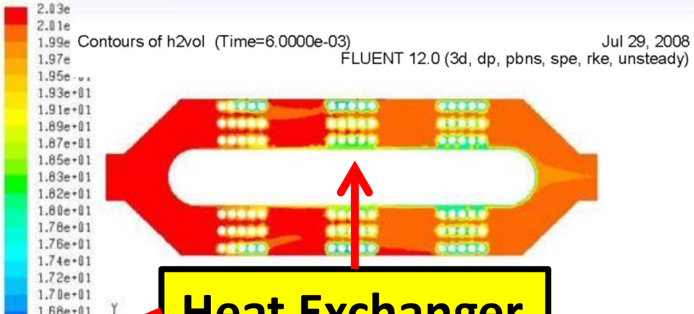
Contours of Static Temperature (k) Oct 16, 2008
FLUENT 12.0 (3d, dp, pbns, rke)

Heater



H2 Release/ Safety

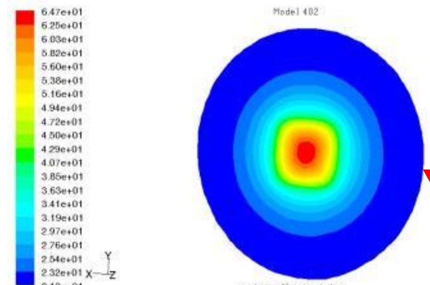




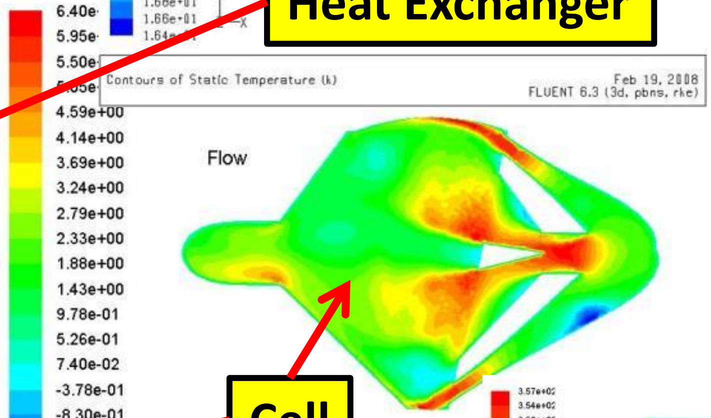
Contours of h2vol (Time=6.0000e-03) Jul 29, 2008
FLUENT 12.0 (3d, dp, pbns, spe, rke, unsteady)

Contours of Static Temperature (k) Feb 19, 2008
FLUENT 6.3 (3d, pbns, rke)

Heat Exchanger



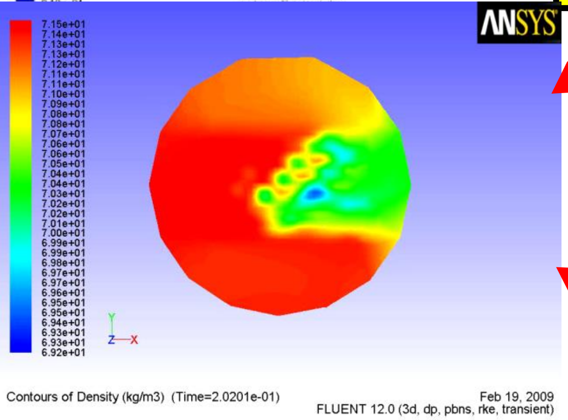
Windows



-1.28e+00
-1.73e+00
-2.19e+00
-2.64e+00

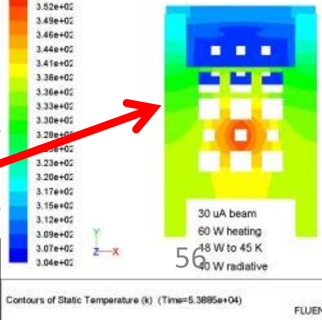
Contours of X Velocity (m/s)

Cell



Contours of Density (kg/m3) (Time=2.0201e-01) Feb 19, 2009
FLUENT 12.0 (3d, dp, pbns, rke, transient)

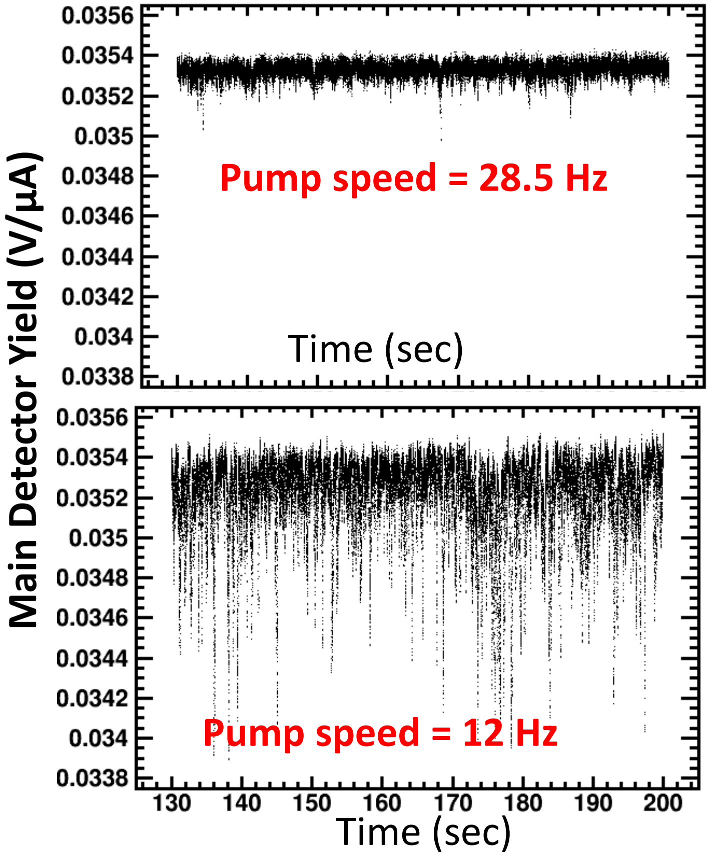
Raster

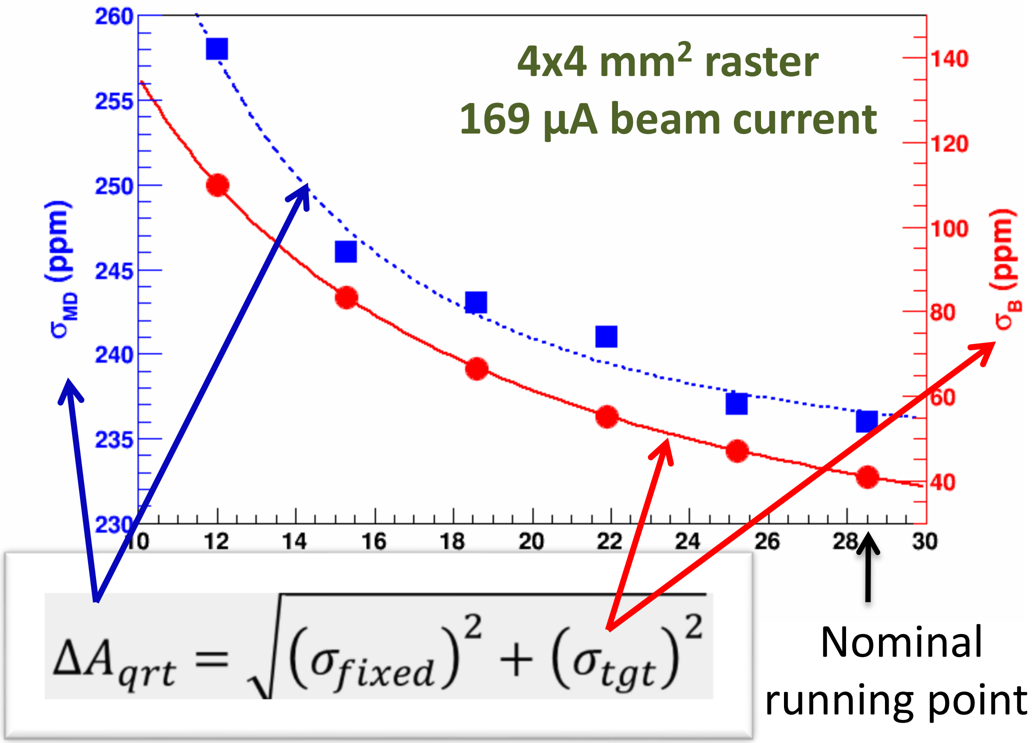


Contours of Static Temperature (k) (Time=5.3885e+04)

Dummy/Bkg Tgts

Target Performance

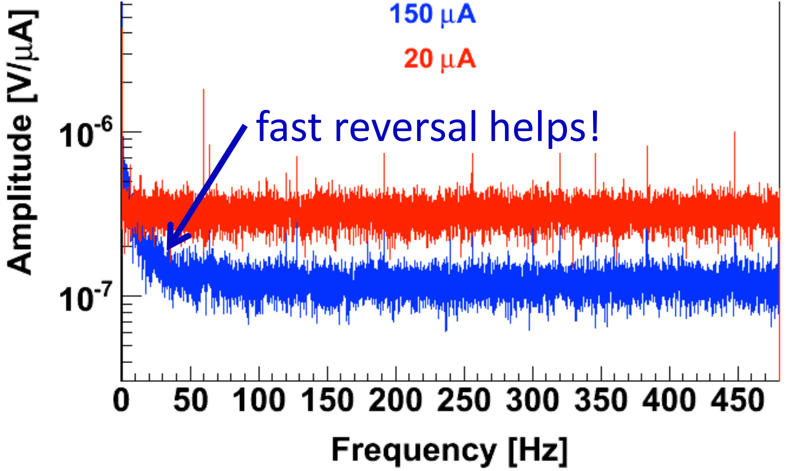




$$\Delta A_{qrt} = \sqrt{(\sigma_{fixed})^2 + (\sigma_{tgt})^2}$$

Nominal running point

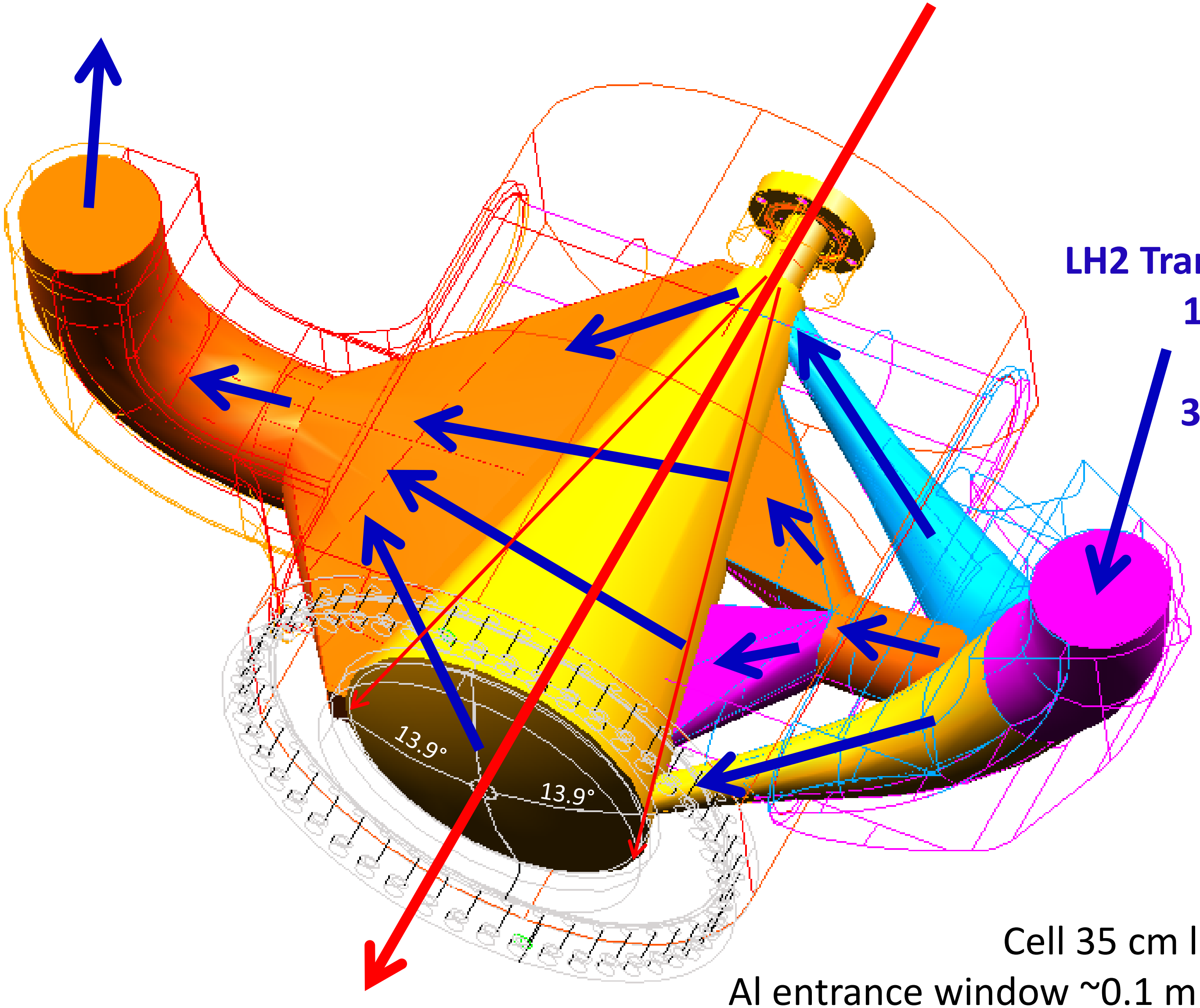
FFT of noise spectrum



- **From 3 independent ways, tgt. noise at 960 Hz reversal rate, 180 μA beam, 4x4 mm² raster <50 ppm**

- **Very small contribution to the total measured quartet asymmetry (230 ppm @ 180 μA)**

Cell



LH2 Transverse Flow:
1.1 kg/s
15 L/s
3-7 m/s

Electron Beam
180 μA, 4x4 mm²

Cell 35 cm long
Al entrance window ~0.1 mm thick, 22.2 mm Φ
Al exit window ~0.125 mm thick over 15 mm Φ,
0.635 mm thick over 173.5 mm
Scattered electron acceptance ±13.9°