The Q_{WEAK} Experiment –

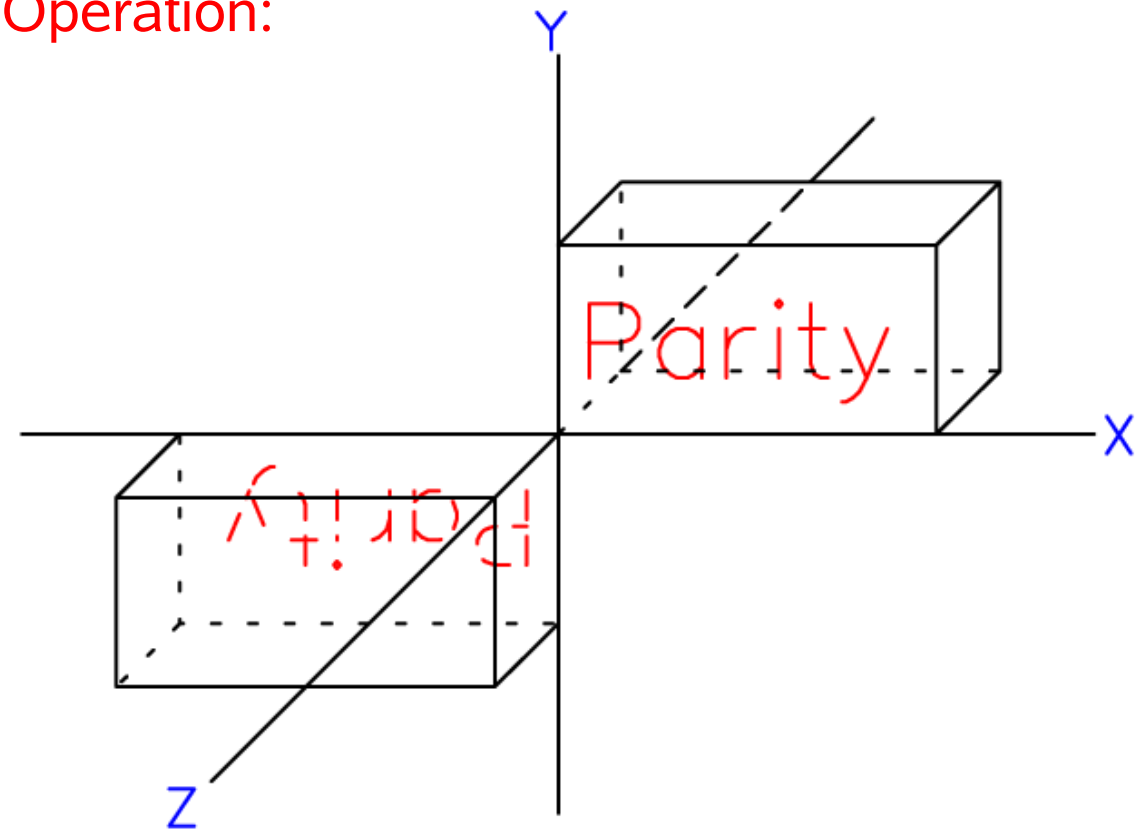
A search for new physics at the TeV scale by measurement of the Proton's weak charge.
Or
Measurement of Parity Violation in ep scattering

Des Ramsay
University of Manitoba/TRIUMF

- Qweak scatters longitudinally polarized electrons from liquid hydrogen
- We flip the electron spin and see how much the scattered fraction changes
- The difference is proportional to the weak charge of the proton

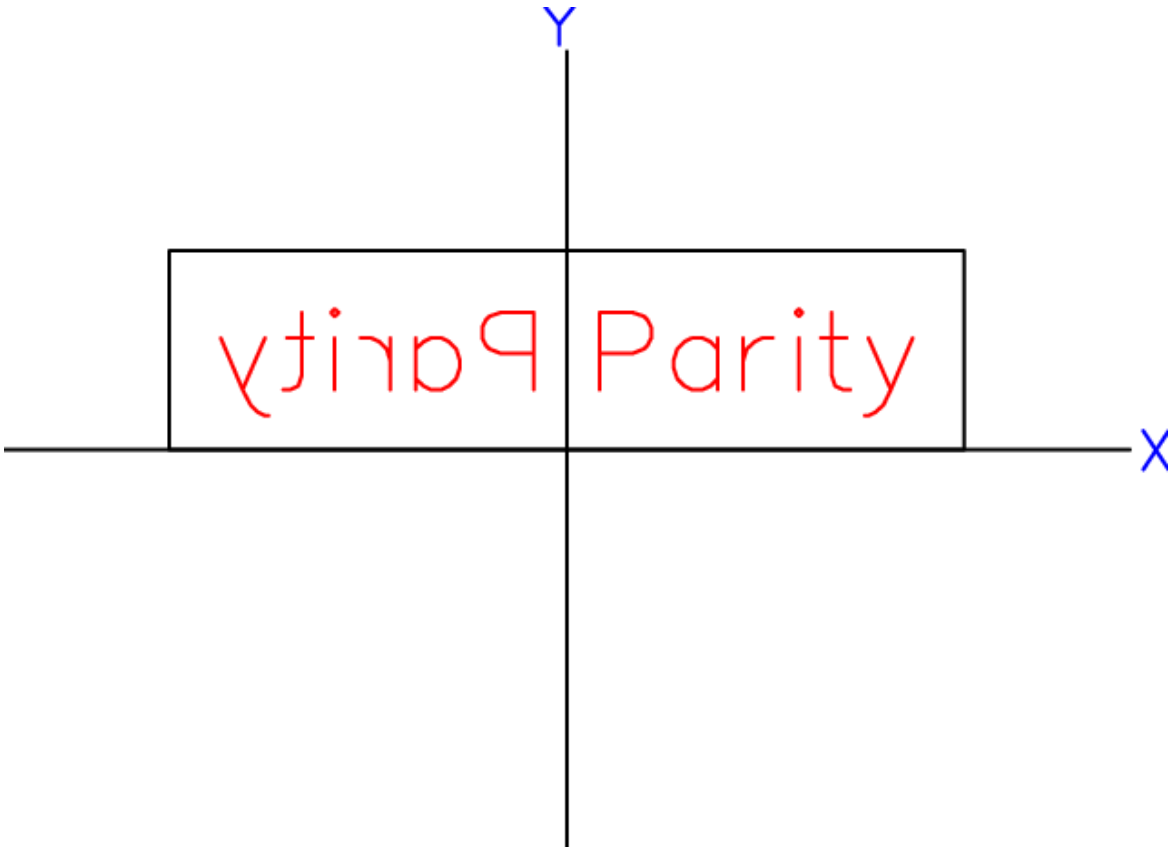
JLab, 18 April, 2008

The Parity Operation:

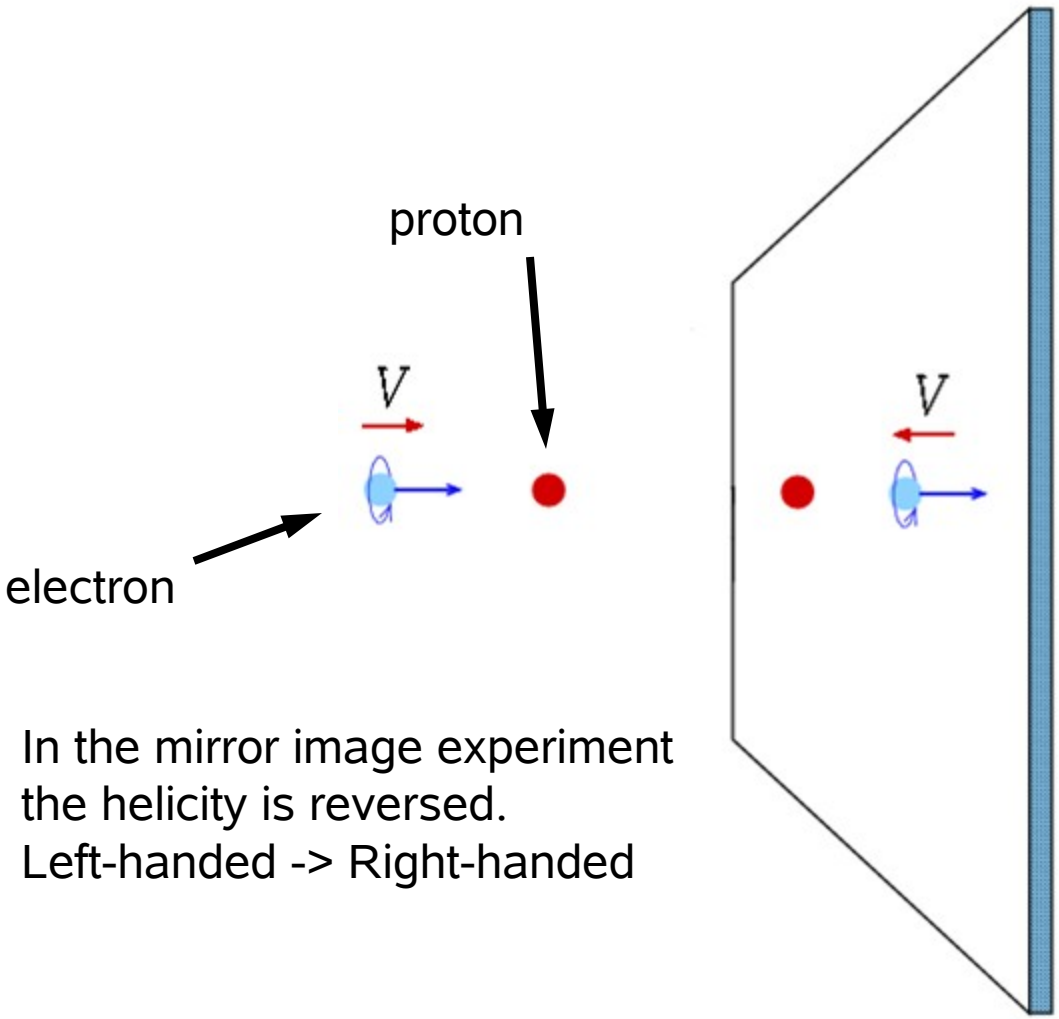


- Simultaneous reflection of all space coordinates through the origin
- Equivalent to reflection plus 180° rotation
- If we assume rotational invariance it is a mirror reflection

Parity operation plus 180 rotation:



parity violation experiments with longitudinally polarized beam

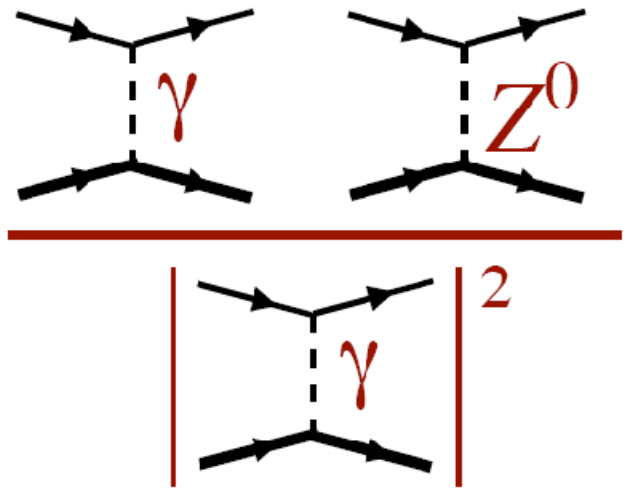


In the mirror image experiment
the helicity is reversed.
Left-handed -> Right-handed

If mirror experiment does not give same result – Parity Violation

Parity Violating Electron Scattering

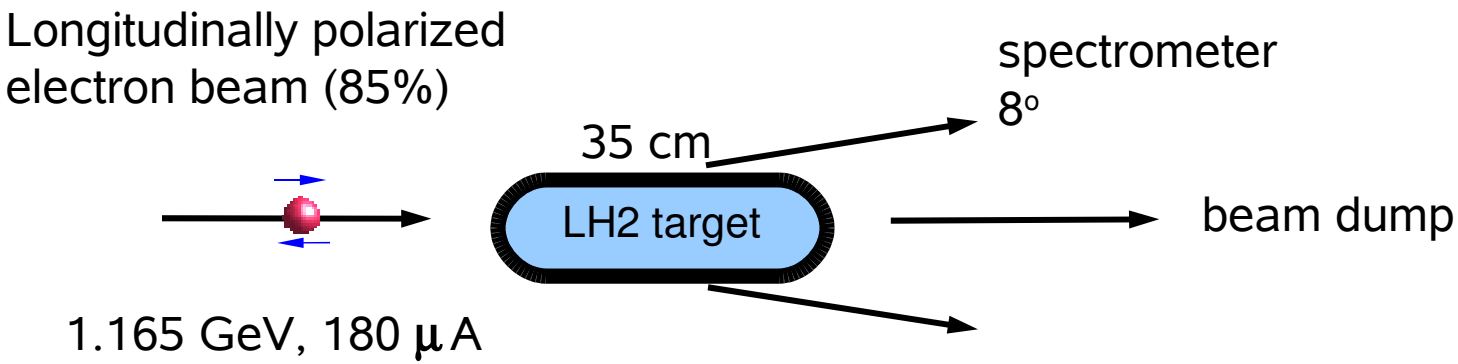
$$A_{\mathrm{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$



$$\sim \frac{Q^2}{M_Z^2}$$

- Difference between cross section for left and right handed electrons
- Measures interference between γ and Z^0 exchange.

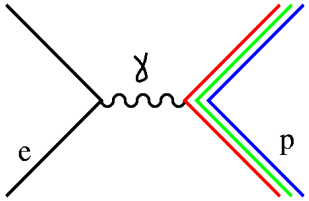
The Qweak Experiment
($\vec{e}p$ parity violation)



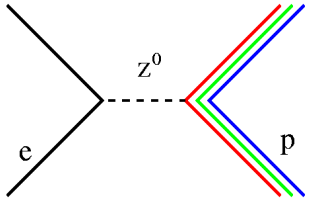
- we are slightly more likely to "hit a proton" if the electron is spinning to the left (parity violation)
- expect $A_z = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-) \approx -300$ ppb (-300×10^{-9})
- want ± 5 ppb statistics in 2500 hours
- use eight detectors at 800 MHz each
- run in **<u>current mode</u>**

Why measure parity violation?

- Parity *conserving* electron scattering measures the proton's *electric* charge. This is well measured; even the charge and current *distributions* are known.



- Parity *violating* electron scattering measures the proton's *weak* charge. This has not been measured yet.



Feynman diagrams: Dave Mack

Why measure the Proton's Weak Charge?

- From a distance (low momentum transfer) the charge is seen through the distorting effect of clouds of virtual particles.
- All particles, not only known ones, will contribute.
- If the measured weak charge does not agree with the calculations, then it may indicate new physics.
- $Q^p_{weak} = 1 - 4\sin^2\theta_W$, so Q^p_{weak} is a also a good stand-alone measure of the weak mixing angle, θ_w .

What we actually measure

- The parity violating longitudinal analyzing power, $A_Z = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-)$
- This experiment uses forward angles and low Q^2 , where

$$A_z = \frac{-G_F}{4\pi\alpha\sqrt{2}} \left(Q^2 Q^p_{weak} + Q^4 B\right)$$

$$= -90 \left(Q^2 Q^p_{weak} + Q^4 B\right)$$ (in ppm, with Q in GeV/c)

For point-like proton

Correction involving hadronic form factors

- The **lower** the momentum transfer, Q, the more the proton looks like a point and the less important are the form factor corrections.

How Low Should We Go in Q^2 ?

- low Q^2 reduces the hadronic correction, but also reduces A_z
- we will use $Q^2 = 0.03\ (\mathrm{Gev/c})^2$, $\theta = 8°$, where

$$A_Z = -194\ \text{ppb}\ -74\ \text{ppb} = -268\ \text{ppb}$$

Qweak term

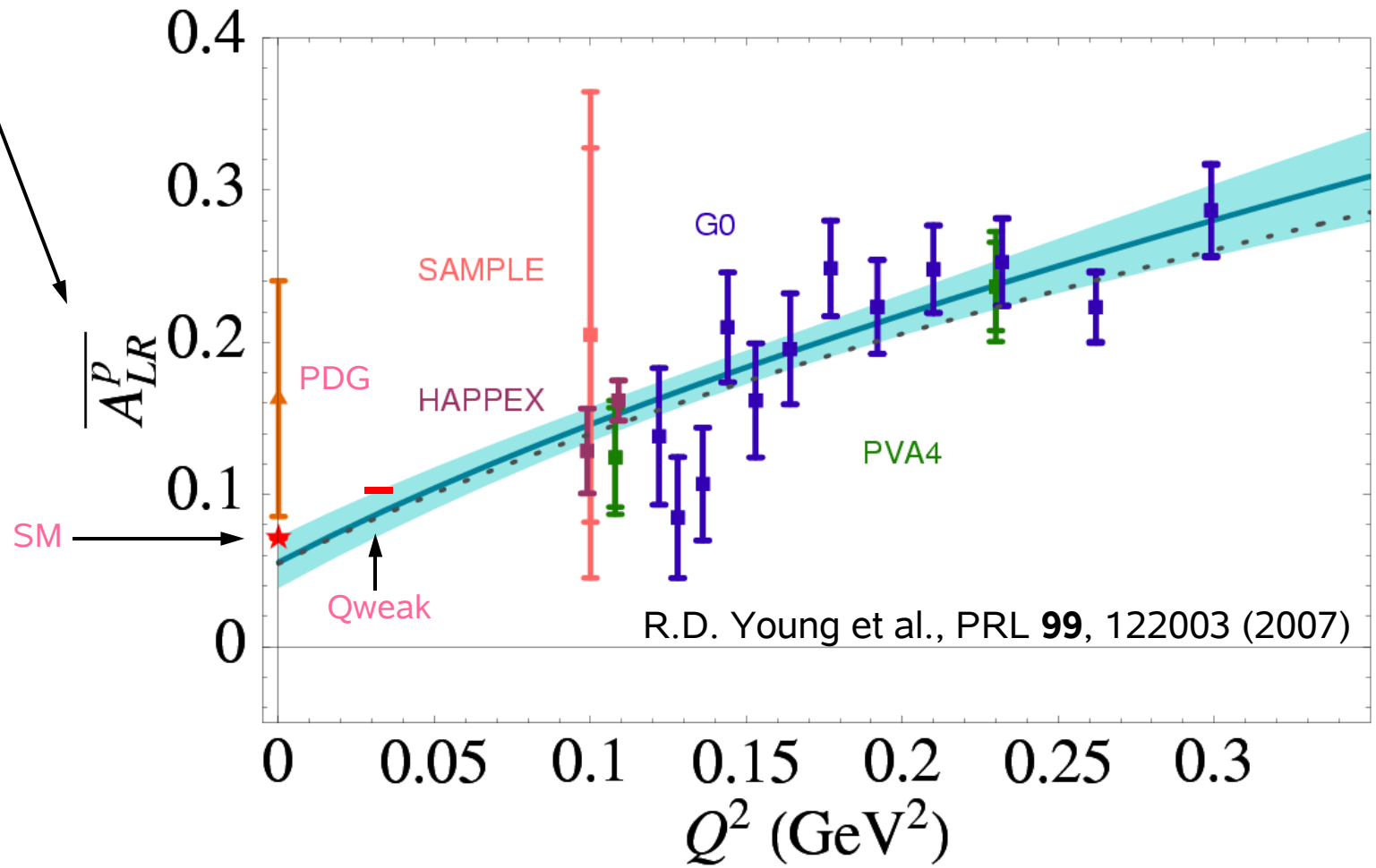
Hadronic correction constrained by Gzero, HAPPEX, PV-A4, SAMPLE

- The -300 ppb (-0.3 ppm) is technically manageable
- The hadronic corrections should introduce <2% error in Q_W

calculations Ross Young, JLab

Extrapolation to $Q^2 = 0$

$$\frac{A_z}{-90Q^2} = Q^p_{weak} + Q^2 B$$

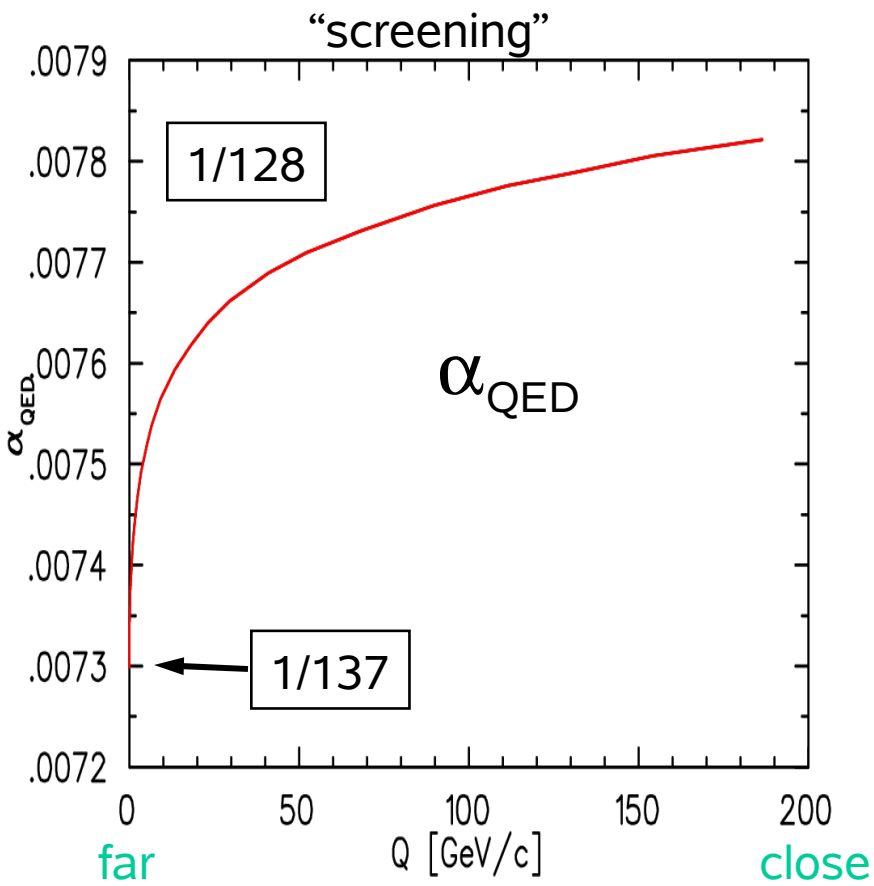


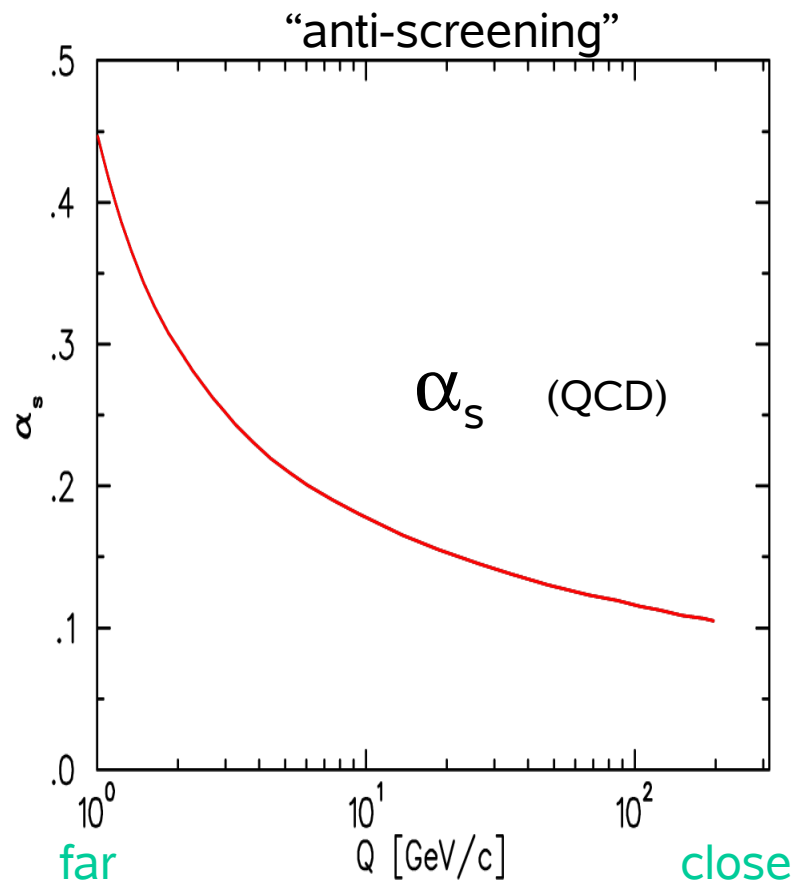
Measured Charges Depend on Distance

(running of the coupling constants)

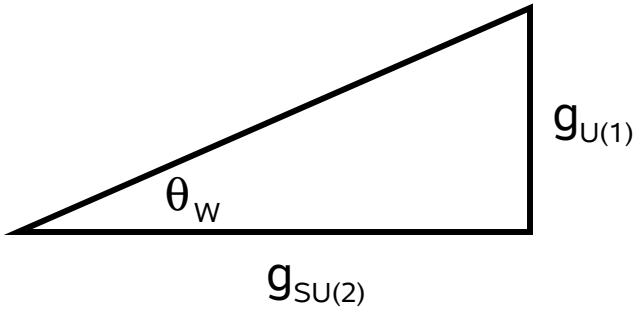
Electromagnetic coupling is *stronger* close to the bare charge

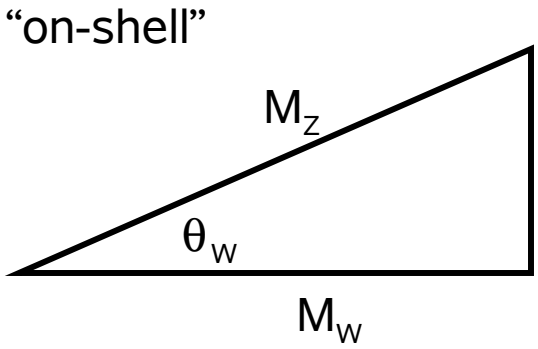
Strong coupling is *weaker* close to the bare charge





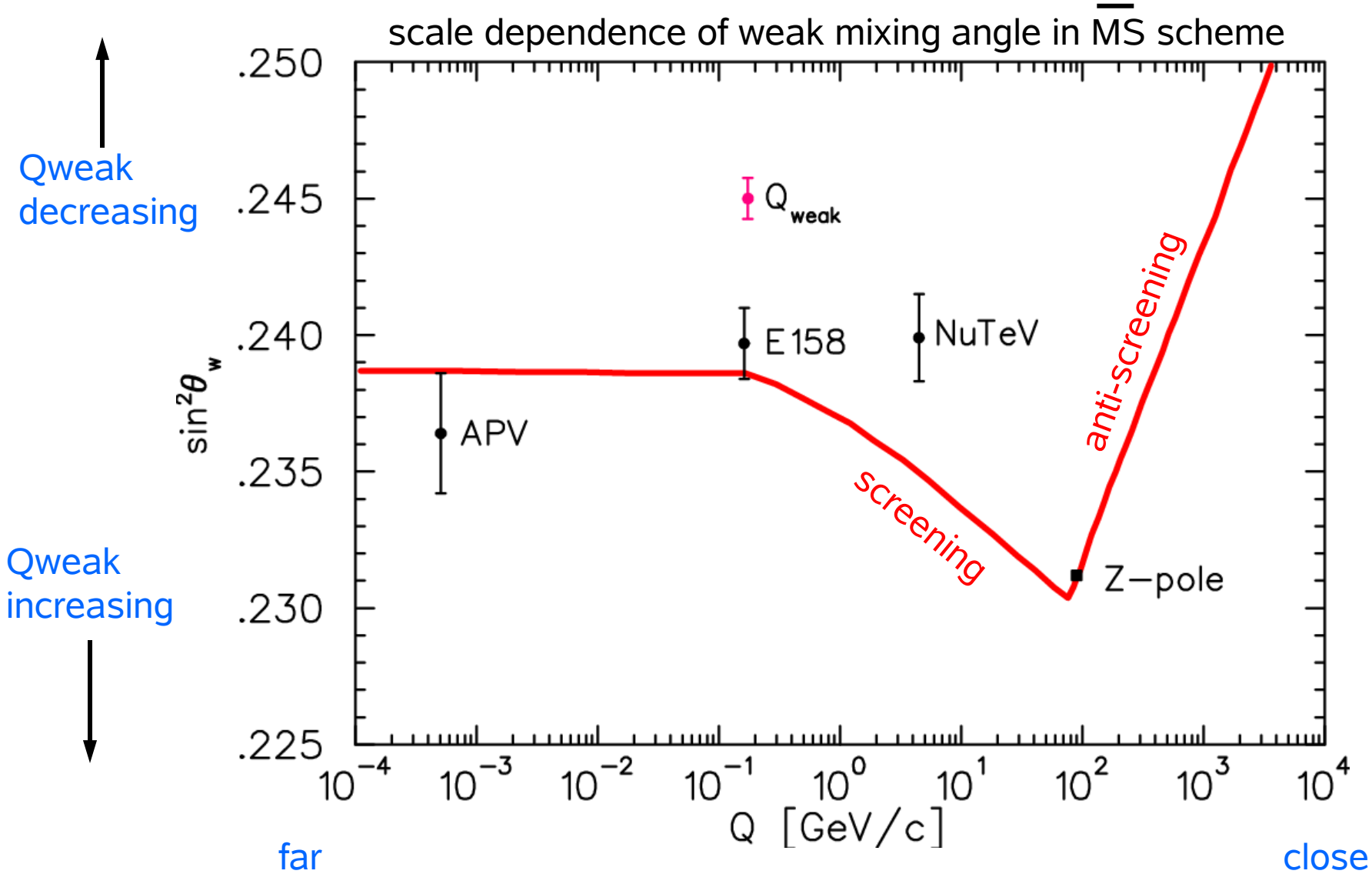
Weak charge of the proton depends on the Weak mixing angle, θ_W



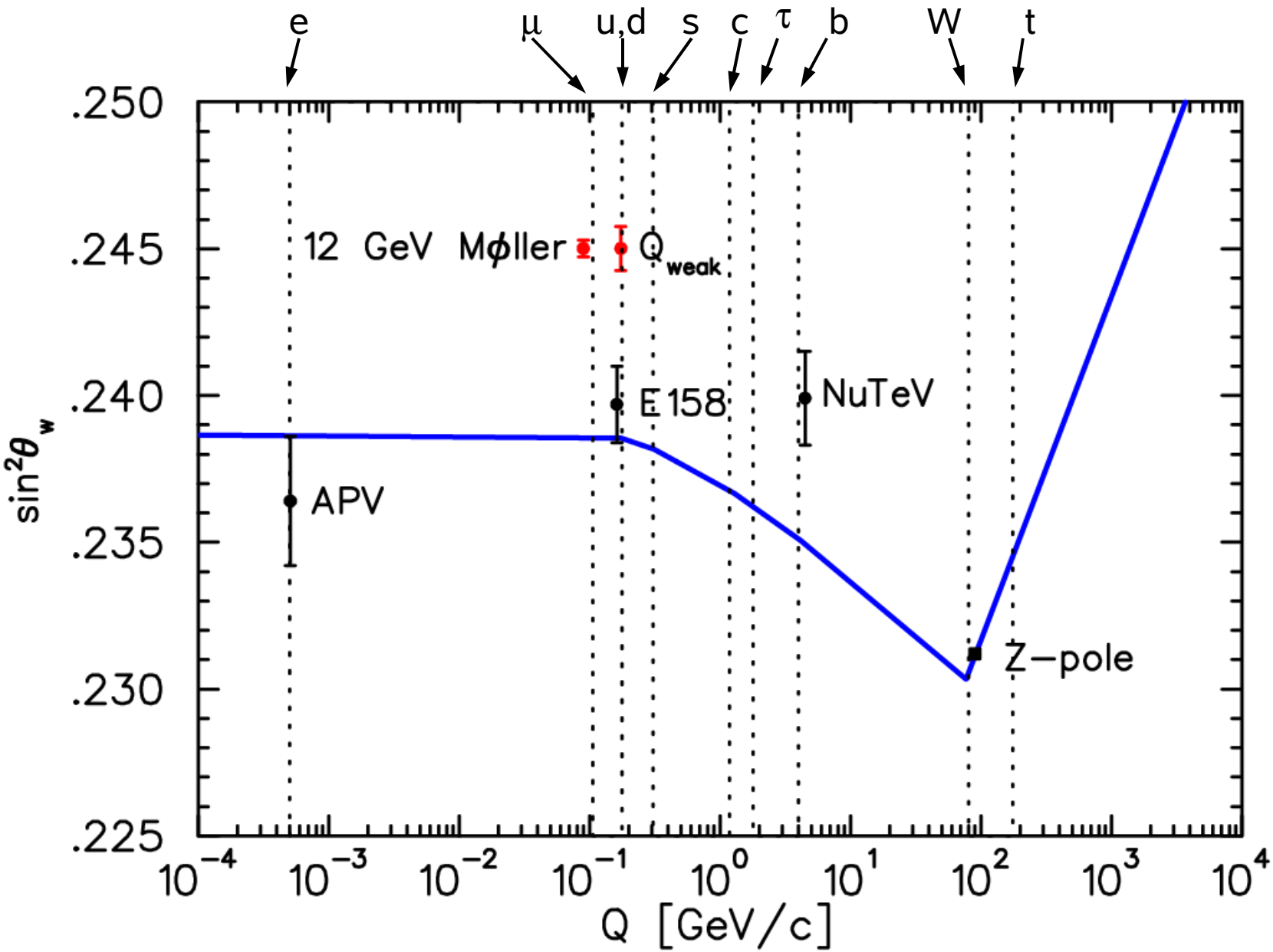


- $Q^p_{weak} = 1 - 4\sin^2\theta_W$ + corrections
- The exact value of the corrections depends on how much is included in the definition of $\sin^2\theta_W$ (normalization scheme).
- At the Z-pole, $\sin^2\theta_W$ = 0.23122 in the MSbar scheme, but is 0.22306 in the on-shell scheme
- You can take the value of $\sin^2\theta_W$ measured at the Z-pole and "run" it to other energies.

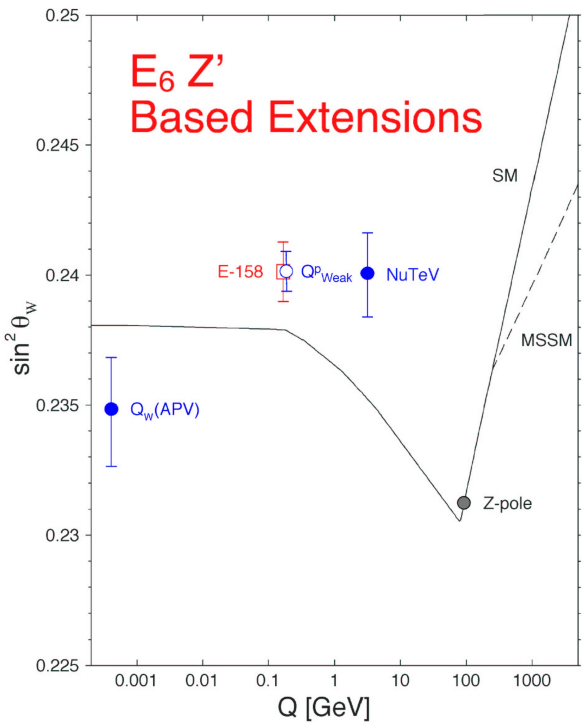
Running of $\sin^2\theta_w$

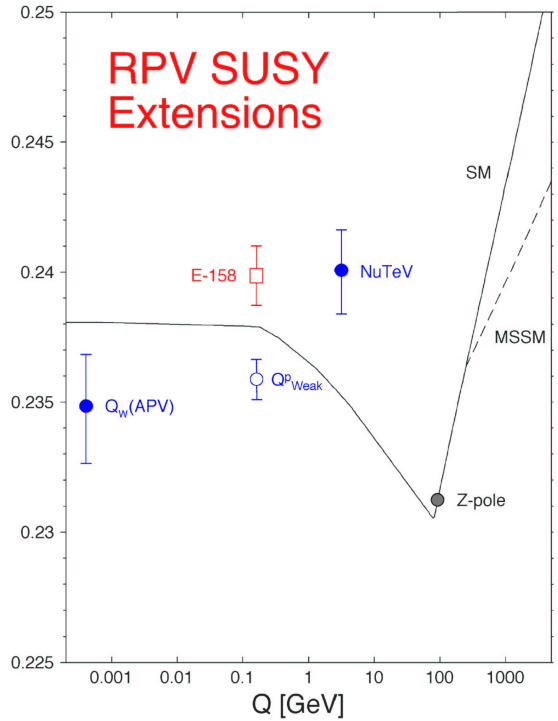


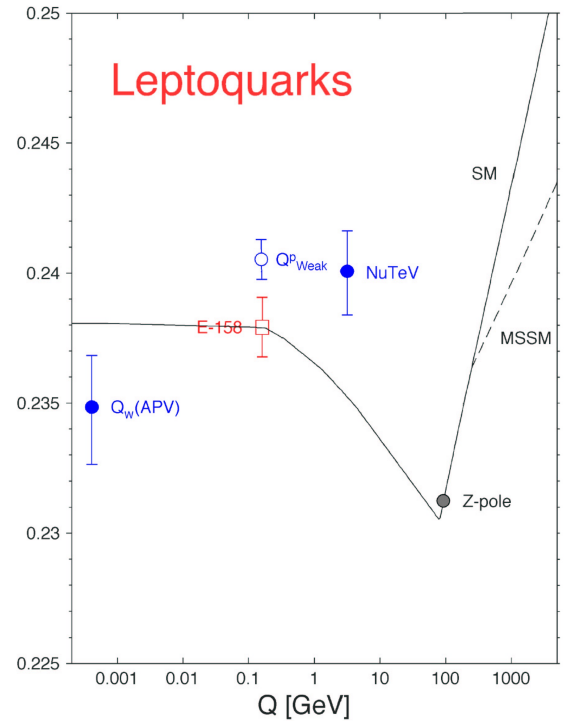
Red curve from Erler and Ramsey-Musolf, Phys.Rev. D 72, 073003 (2005)

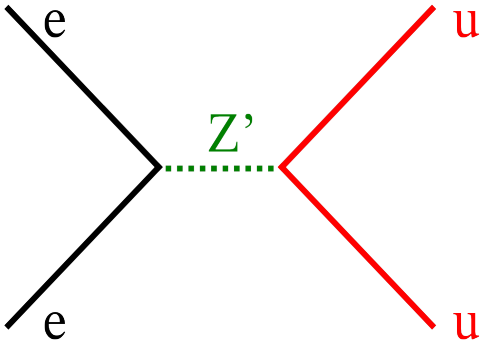

e
μ
u,d
s
c
τ
b
W
t
.250
.245
.240
.235
.230
.225
12 GeV Møller
Q weak
E158
NuTeV
APV
Z−pole
sin²θ w
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
10¹
10²
10³
10⁴
Q [GeV/c]

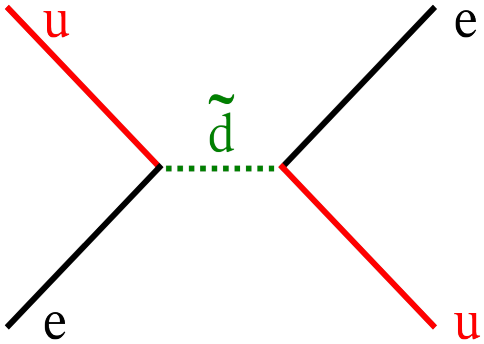
Both Proton and Electron Measurements Are Useful

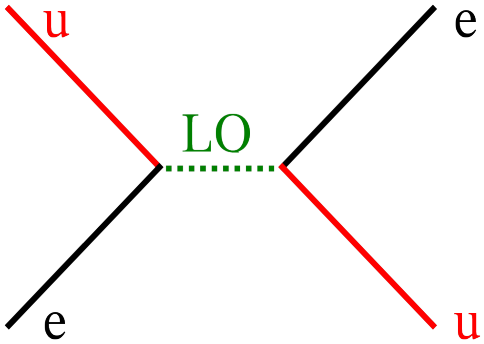




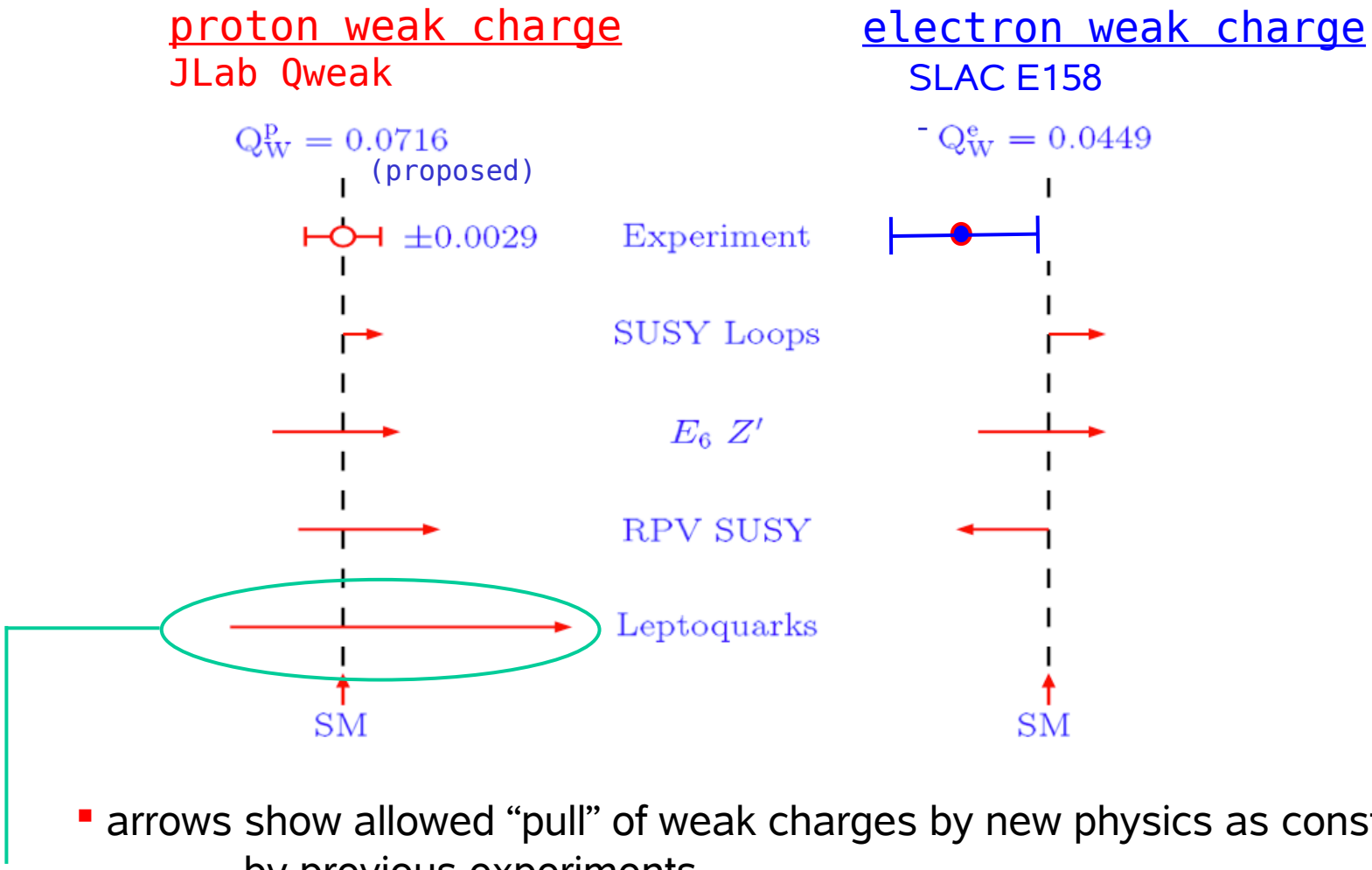








Both Proton and Electron Measurements are Important



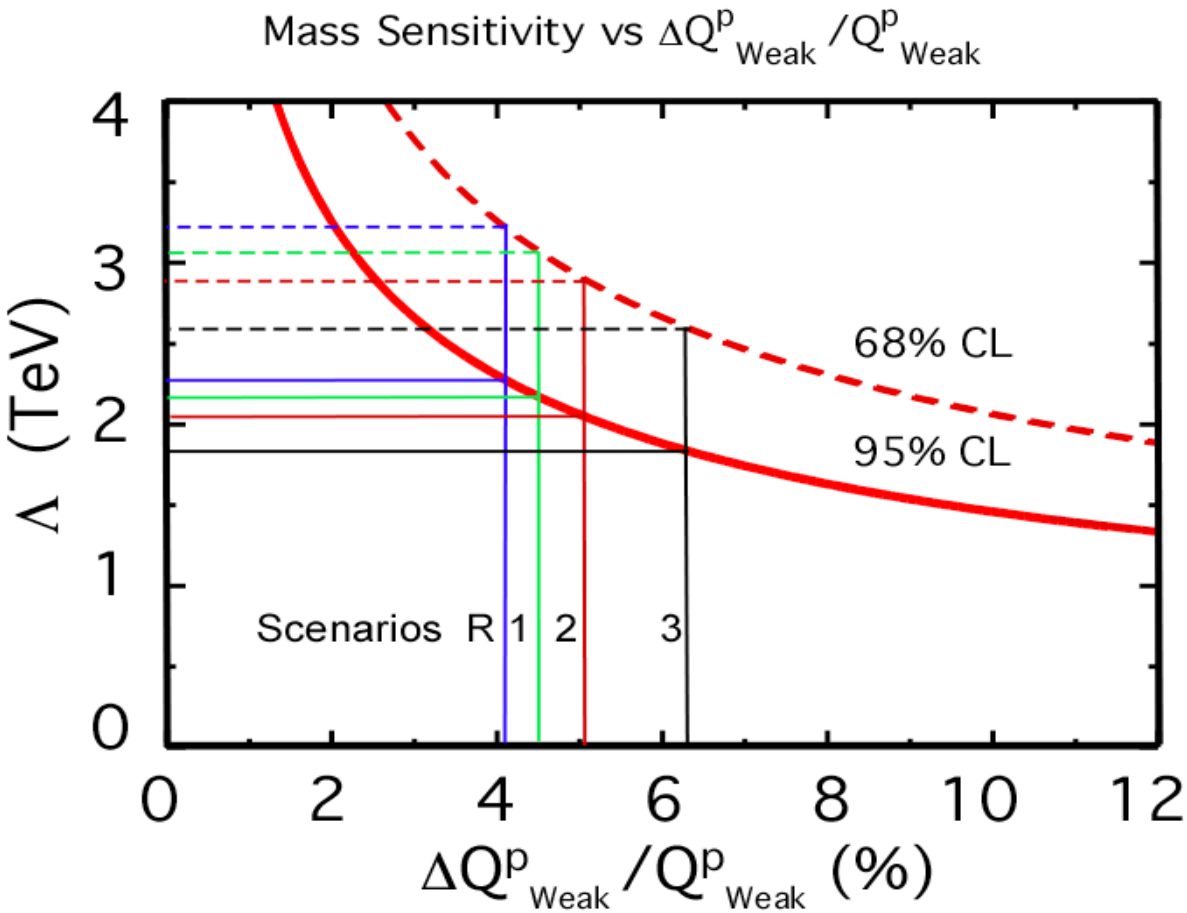
- arrows show allowed "pull" of weak charges by new physics as constrained by previous experiments
- electron and proton weak charge experiments are complementary

Charge of The Proton

	Electric charge	Weak charge
u	$+\frac{2}{3}$	$+1-\frac{8}{3}\sin^2\theta_W$
d	$-\frac{1}{3}$	$-1+\frac{4}{3}\sin^2\theta_W$
neutron = d d u	0	-1
proton = u u d	$+1$	$1-4\sin^2\theta_W \approx 0.07$

- The proton's weak charge is almost zero because $\sin^2\theta_W$ is so close to ¼ .
- The near cancellation of the proton's weak charge at tree level, makes it a sensitive measure of new physics.

What Energy Scale Are We Sensitive To?



- If LHC uncovers new physics, then precision low Q^2 measurements will be needed to determine charges, coupling constants, etc.

Roger Carlini

Technical details

$$A_z = \frac{1}{P_Z}\left(\frac{N^+ - N^-}{N^+ + N^-}\right) = -90\left(Q^2 Q^p_{weak} + Q^4 B\right)$$

We want: 2% on A_z ≈ 4% on Q_w ≈ 0.3% on $\sin^2\theta_W$

How do you do that?

➢ 5 x 10^{-9} statistics	Count for 2500 hr at 6.5 GHz.
➢ Beam polarization	New Hall-C Compton polarimeter.
➢ Absolute Q^2	Dedicated runs with full tracking. Accurate magnetic field map.
➢ hadronic correction	Theory and existing experiment
➢ Background fraction.	Dedicated runs with tracking and TOF
➢ Beam Properties.	Online measurement and correction.

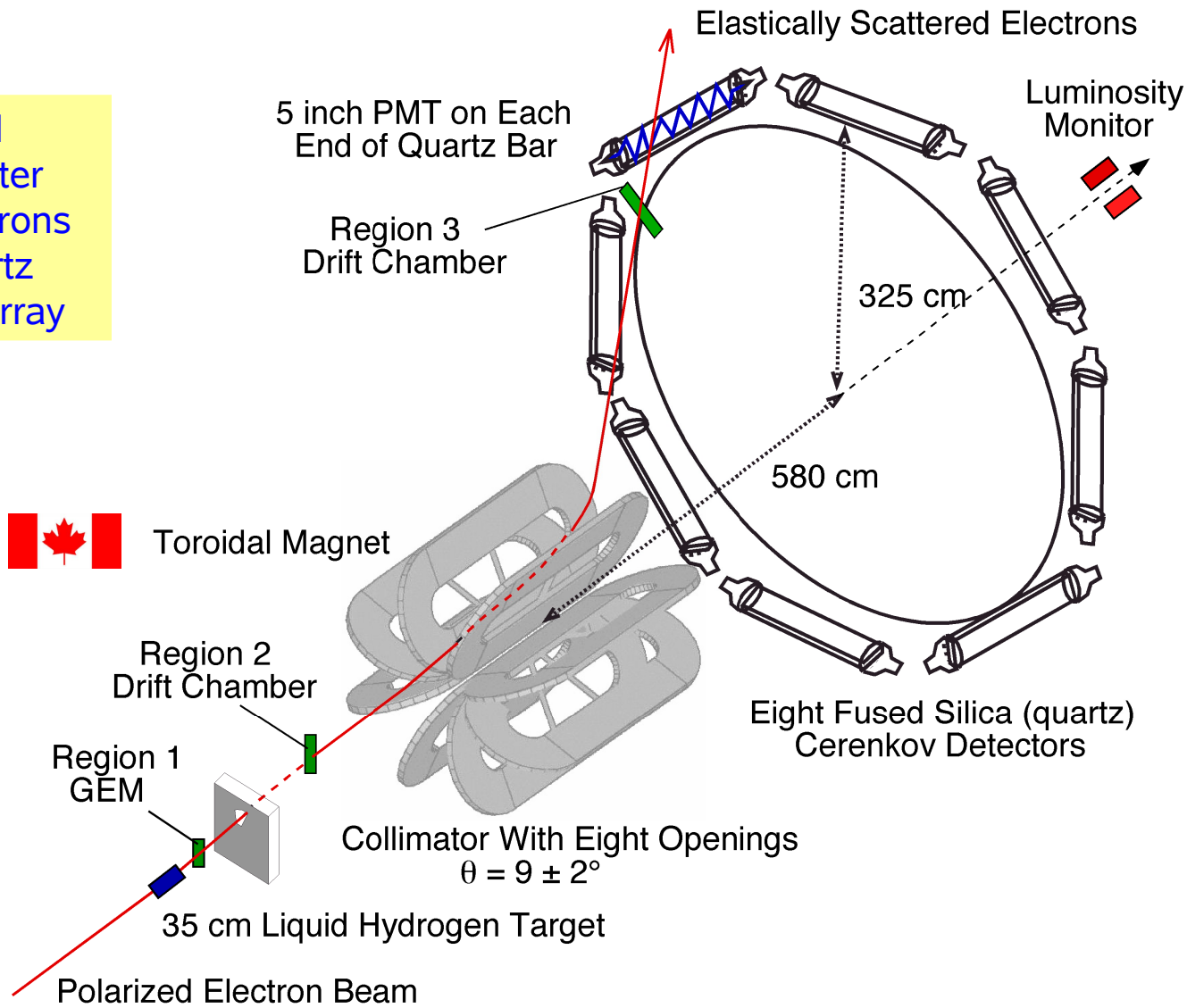
How hard is that?

Typical A_z uncertainties, adding statistical and systematic in quadrature. →

Gzero	500 ppb
HAPPEX 2	130 ppb
TRIUMF E497	35 ppb
Qweak	6 ppb

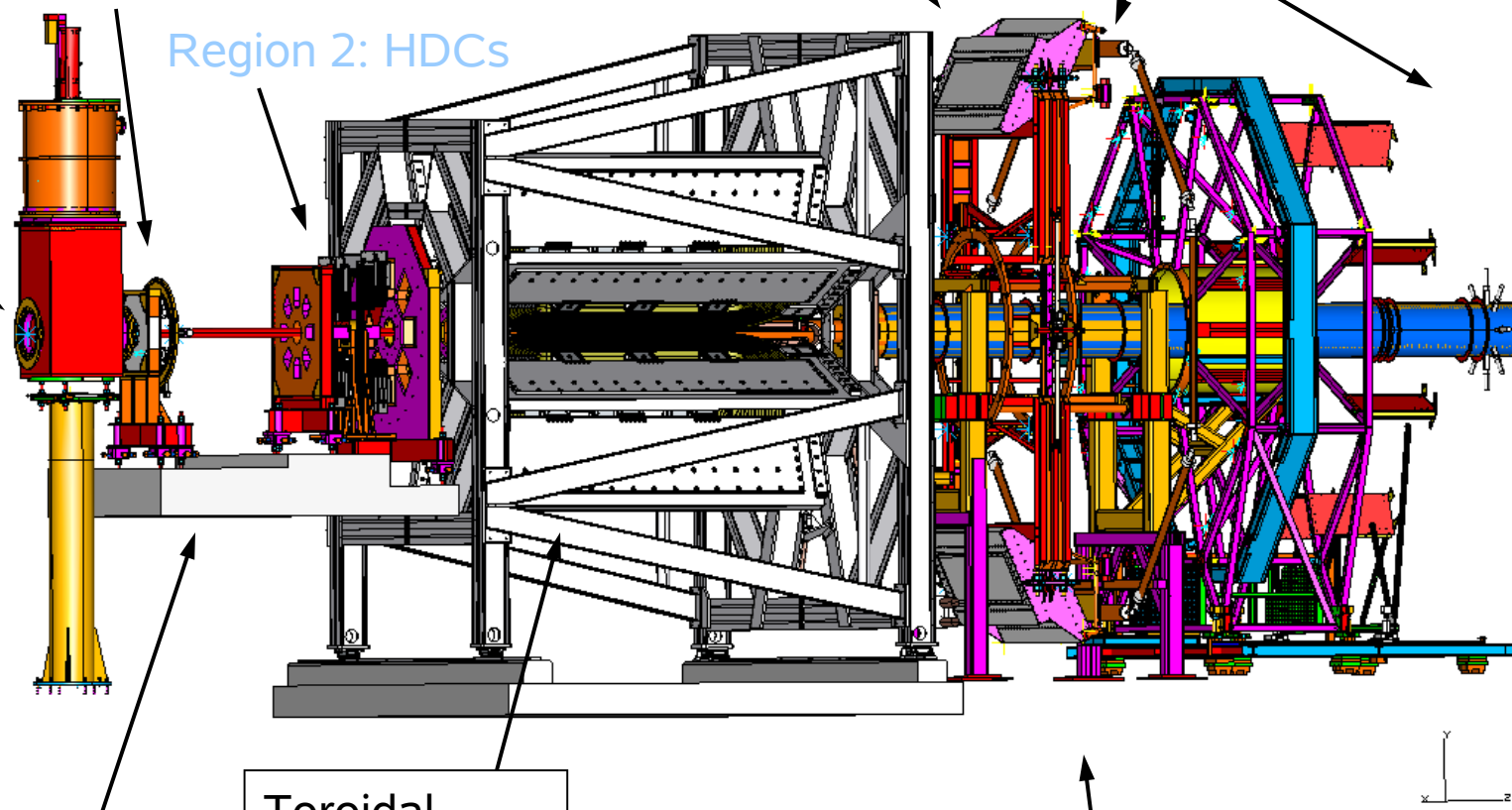
Qweak apparatus at JLab

- A resistive toroidal magnetic spectrometer focuses elastic electrons onto a rad-hard quartz Cerenkov detector array

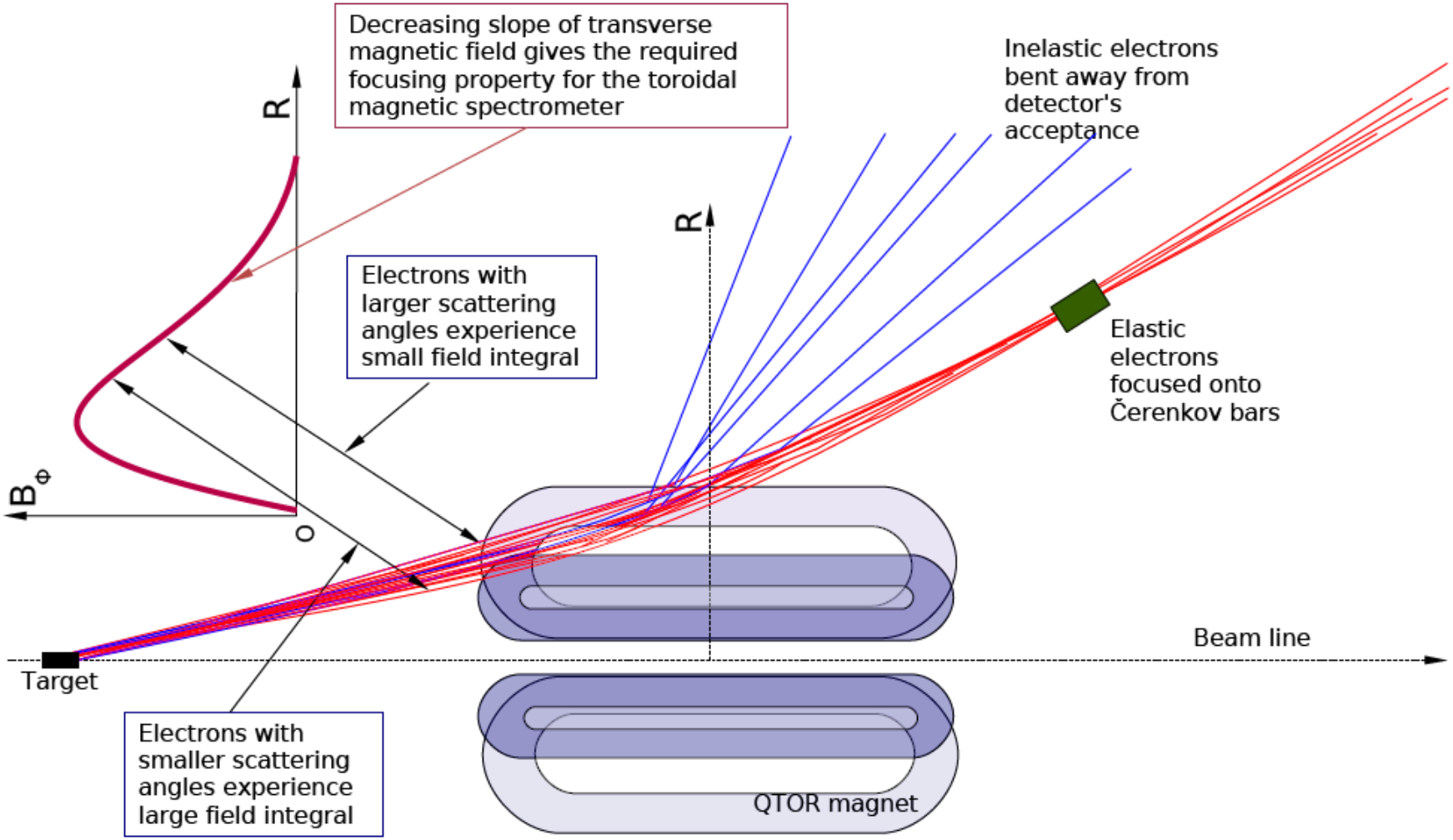


Principal Parts of the Qweak Experiment

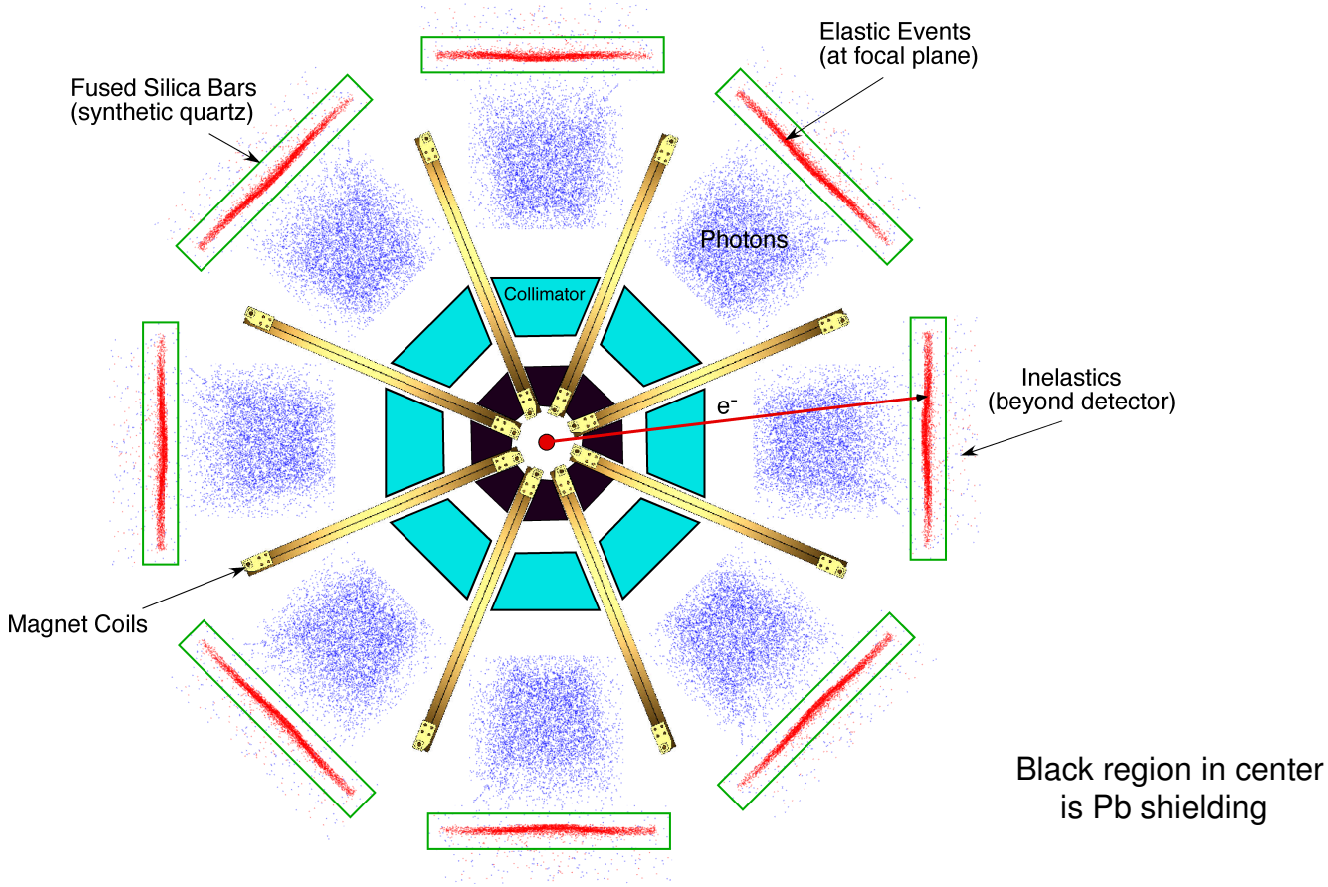
light blue = counting mode
black = current mode



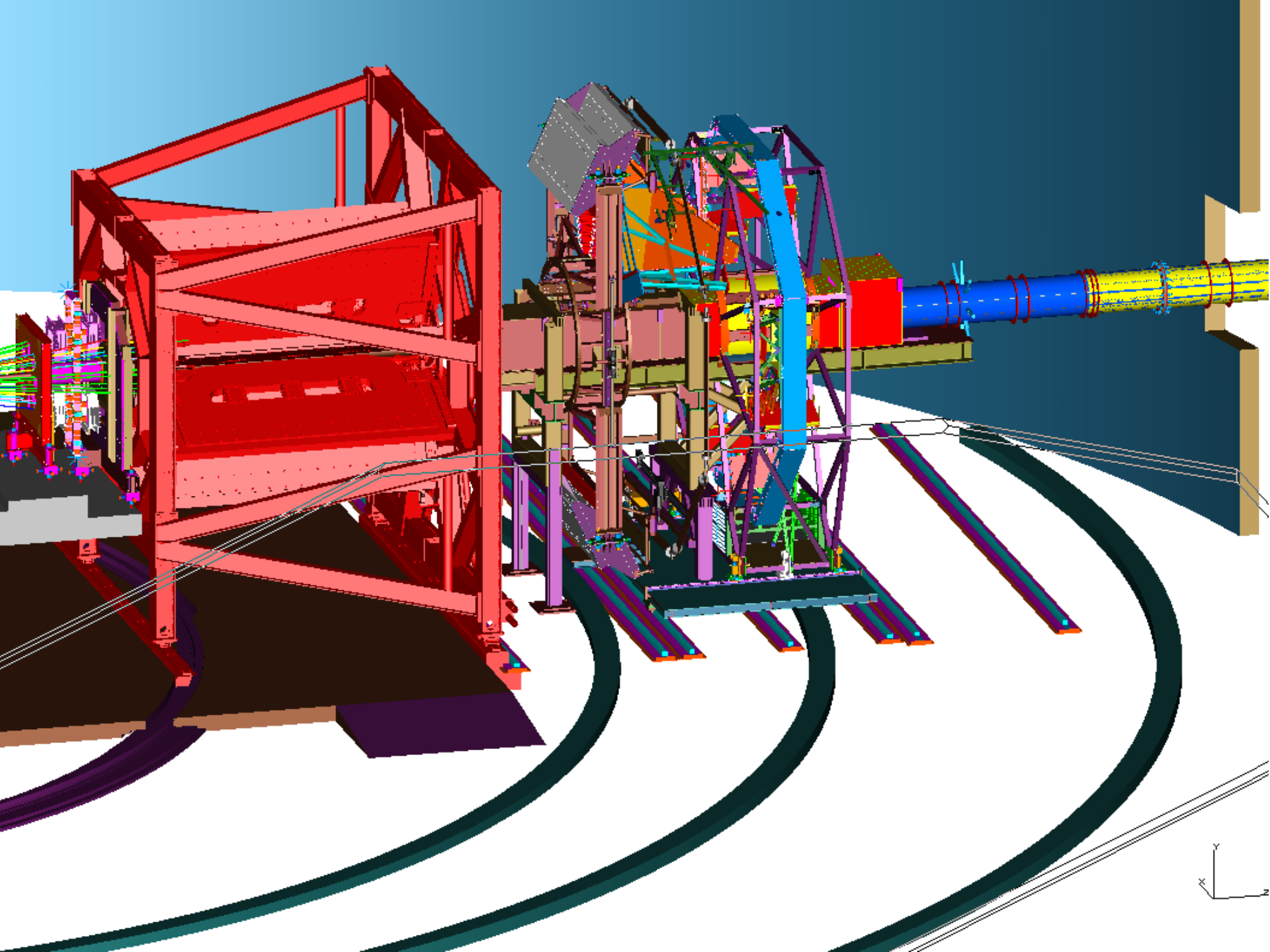
The QTOR Resistive spectrometer magnet:



Beam's Eye View with GEANT Simulated Events



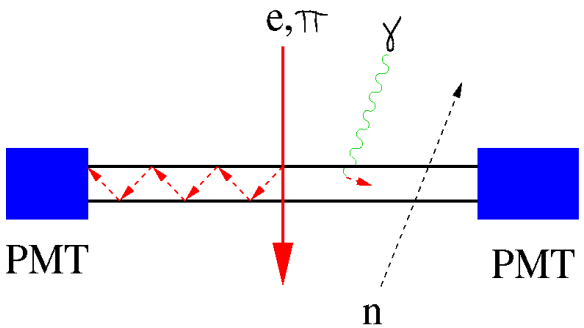
A small cm-sized scanning quartz detector (Winnipeg/TRIUMF)will map the event distribution at full beam current



Synthetic Quartz Čerenkov Detectors

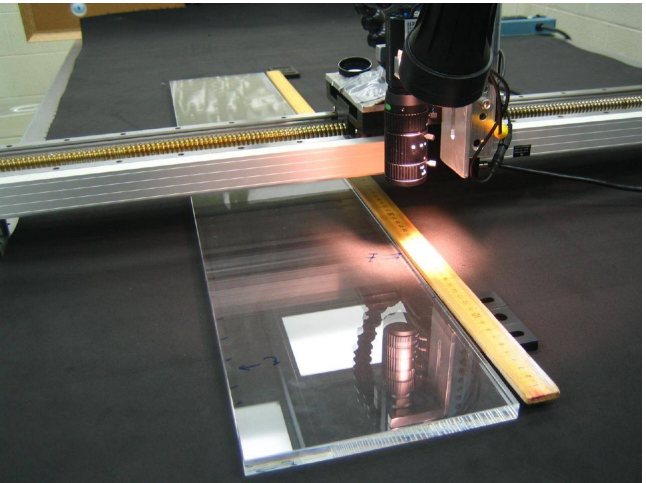
Focal plane detectors:

- 200 x 18 cm x 1.25 cm synthetic quartz bars
- Radiation hardness (expect > 300 kRad).
- Insensitivity to background γ, n, π.
- Operation at counting statistics.

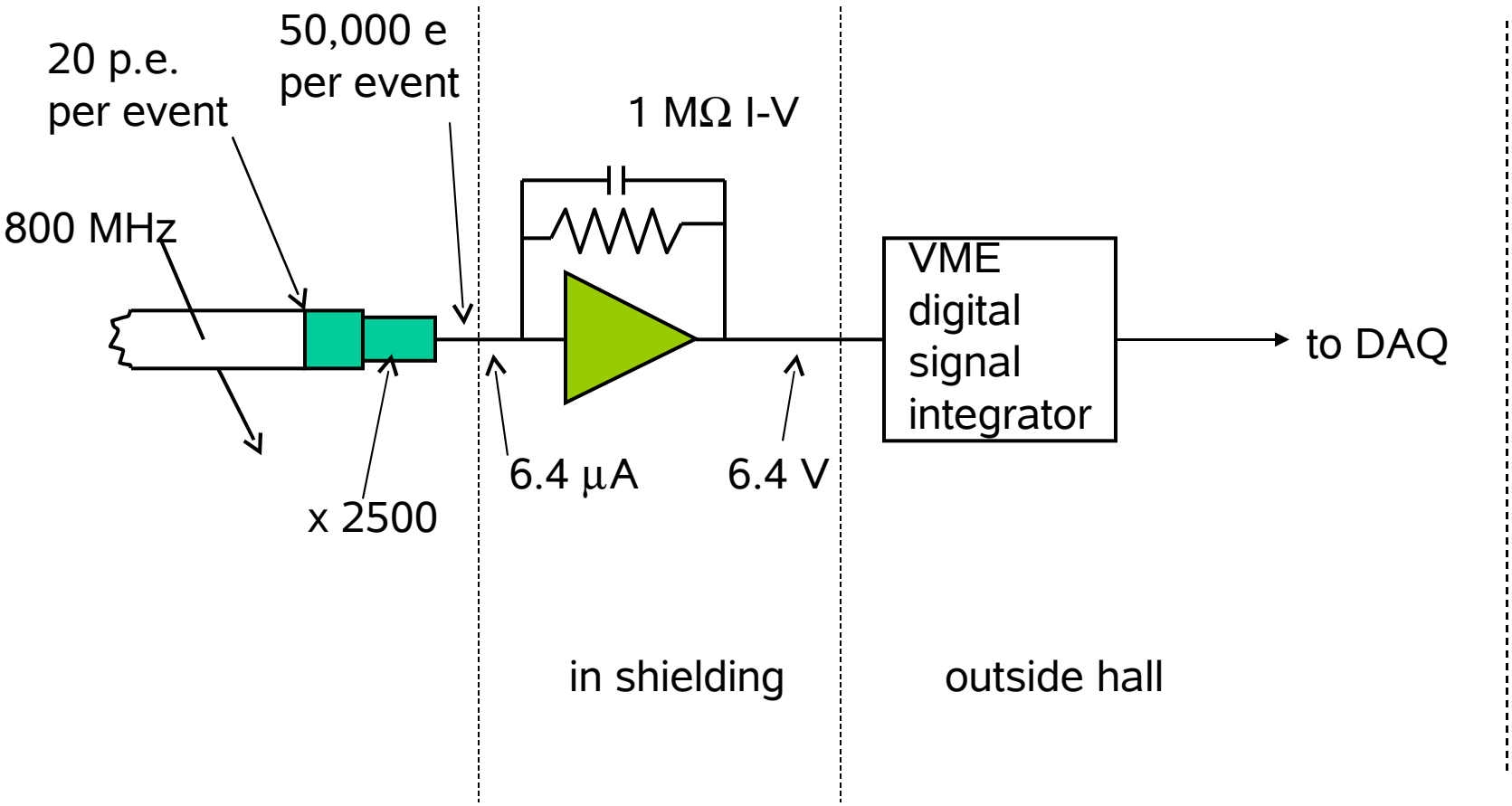


gluing

Quality control

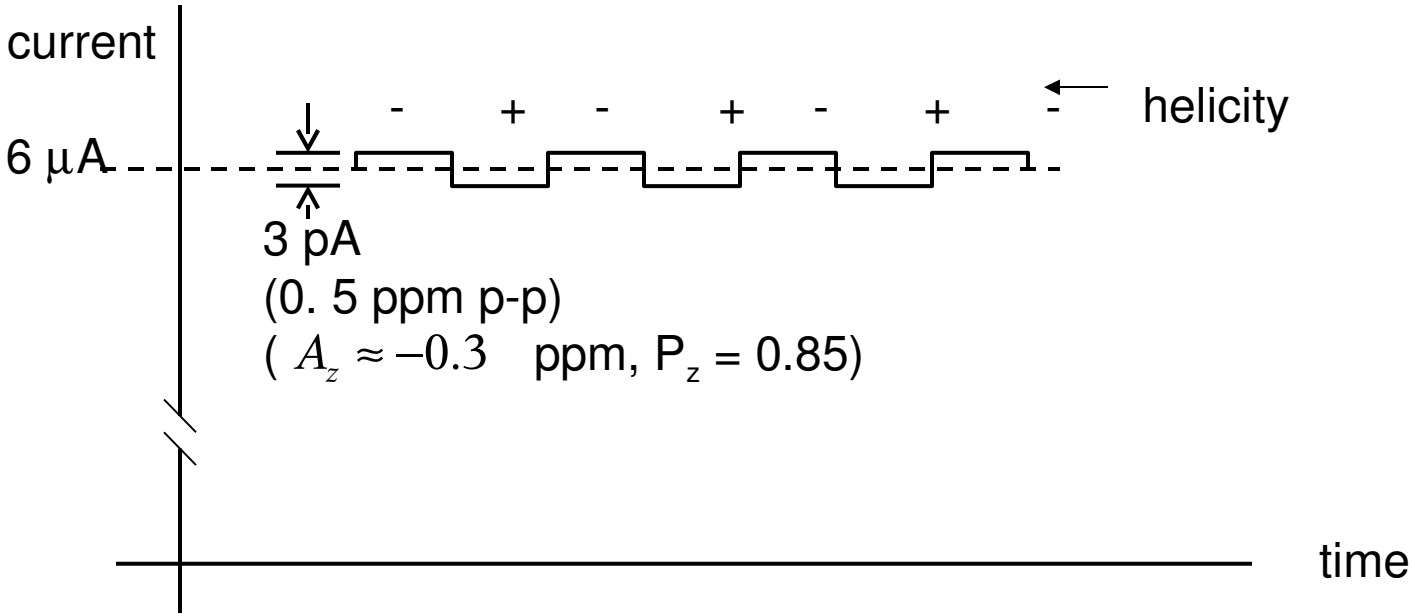


Nature of the Current Mode Signals



shot noise: $i_n^2 = 2QIB$

Size of Q_{weak} Signal



- figure shows regular spin flip; in practice may be some randomization
- for 50 kHz noise bandwidth, rms shot noise is 70 nA
- on a scope the noise band would be ≈ 100,000 x the signal !
- on printed page, origin is 6 km off bottom.

Shot Noise Numerical Example

equivalent noise bandwidth [Hz]

$\frac{1}{2T}$ or $f_{3db}(\frac{\pi}{2})$

one-sided shot noise, $$i_n^2 = 2QIB$$ [A²]

charge quantum [C]

current [A]

Example, 1 ms integration with beam on, assuming 800 MHz:

- Q = 50,000 e
- I = 6.4 μA (800 MHz x 50,000 e)
- B = 500 Hz
- i_n = 7.2 nA rms (7.2 mV with a 1 M Ω preamp)

Note that in 1 ms, N = 8 x 10^5 counts.

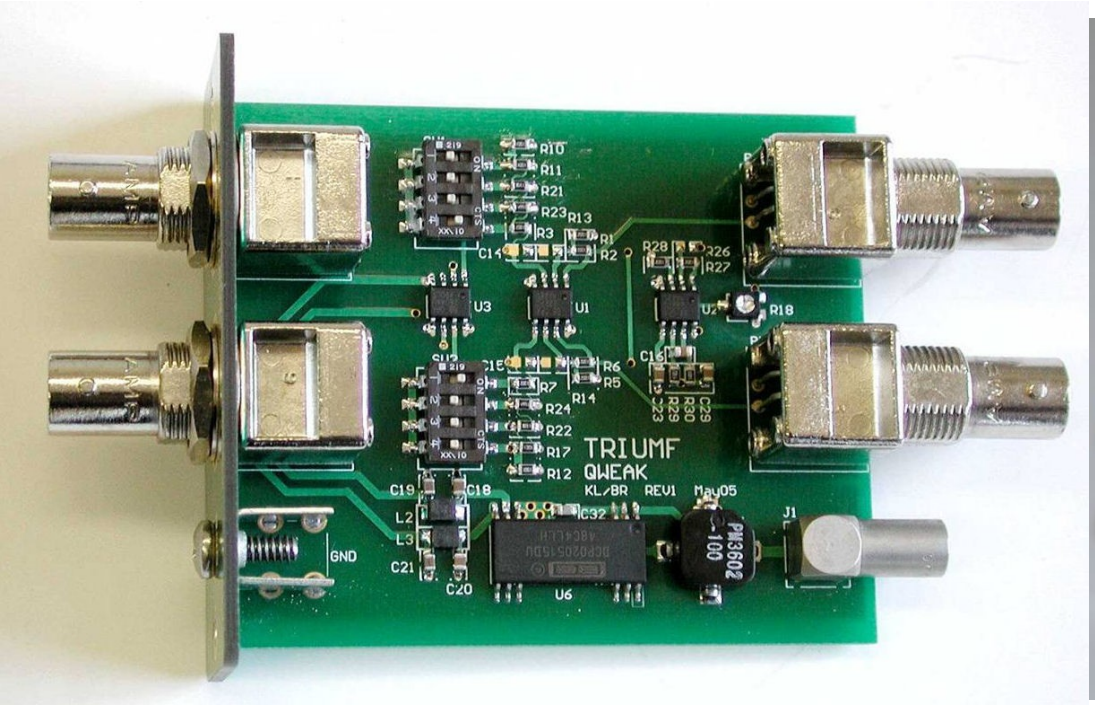
$1/\sqrt{N}$ = 1120 ppm, same as 7.2 nA/6.4 μA

Comparison of Different Noise Sources

rms noise on a 1 ms integral

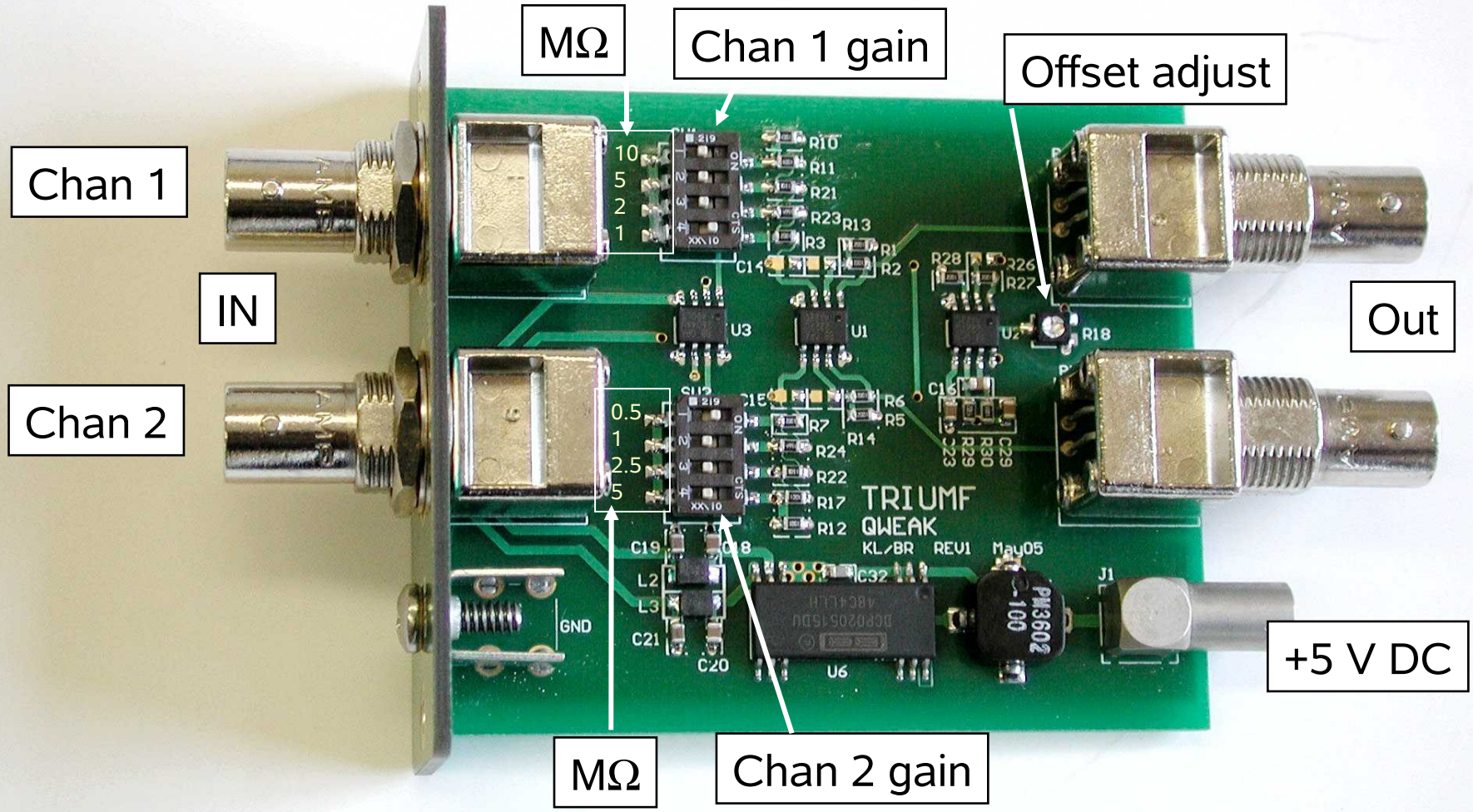
Condition	noise (ppm)
beam-ON shot noise	1120
shot noise during LED tests	160
shot noise during battery tests	5
preamplifier noise	2
digital integrator noise	1-2

Low Noise Current-Mode Preamplifier at TRIUMF



- Radiation hardness tested at JLab to 18 krad – no effect (spec. 1 krad)
- Small size to fit in shielding boxes on Qweak
- 28 modules now delivered to the Qweak collaboration.

TRIUMF Preamplifier

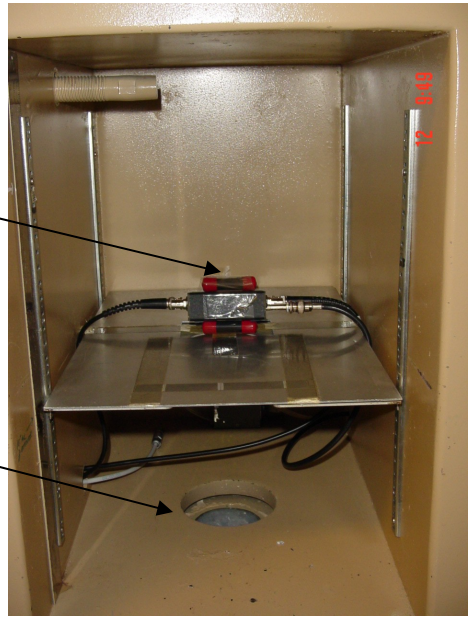


Preamp Irradiation Setup
37Cs 0.662 MeV gamma (85%) 86 Rads/hr

Preamplifier with signal cables and dosimetry

Battery

Gammas emitted from here



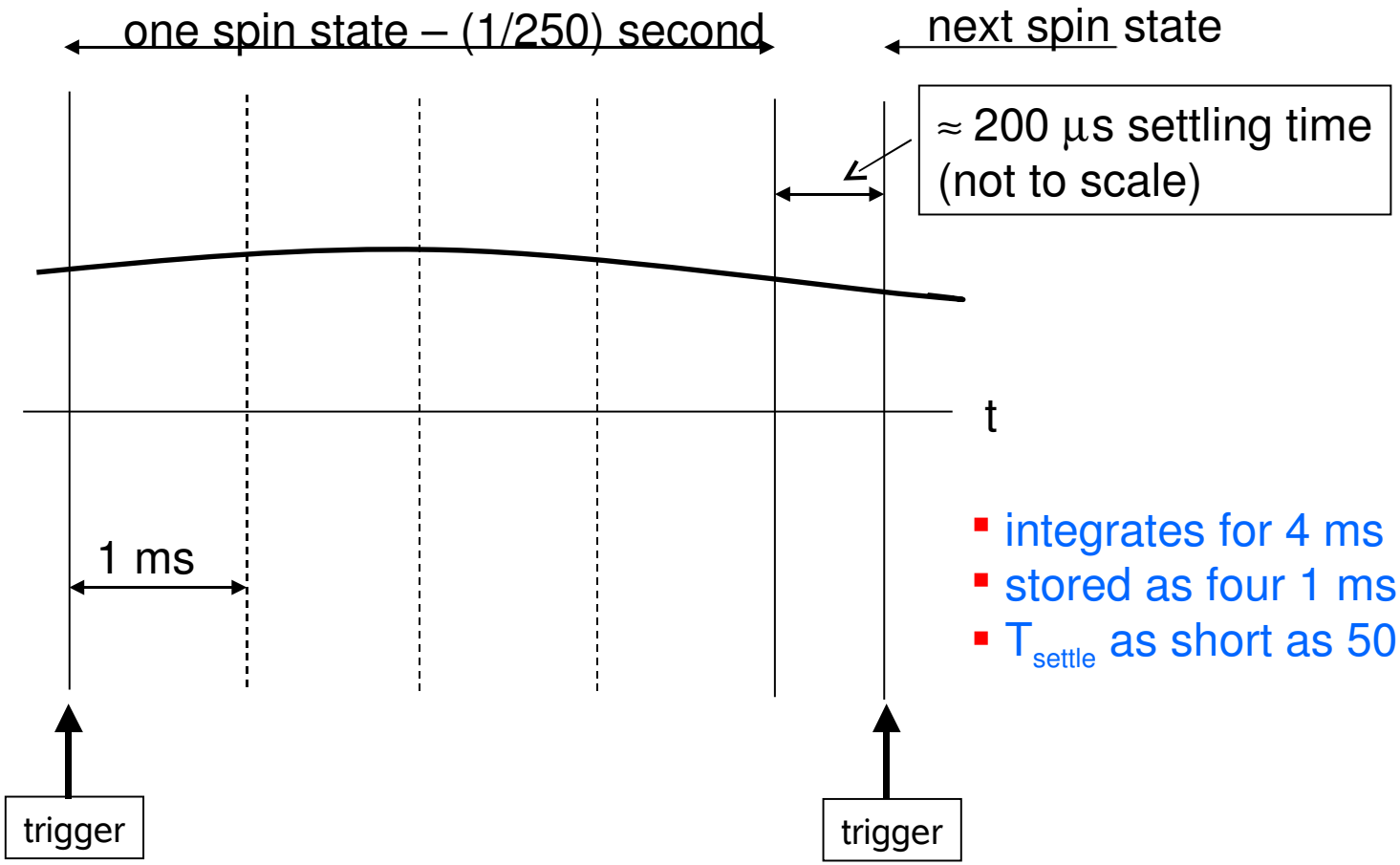
Preamp Setup:

- 3.6 microA input from battery (2' RG58)
- 1 MOhm transimpedance
- 4.7 V output (with 1 V offset)
- **Spectrum Analyzer Setup:**
- AC coupled, 0-400 Hz in 800 bins

No deterioration at 18 krad

Dave Mack

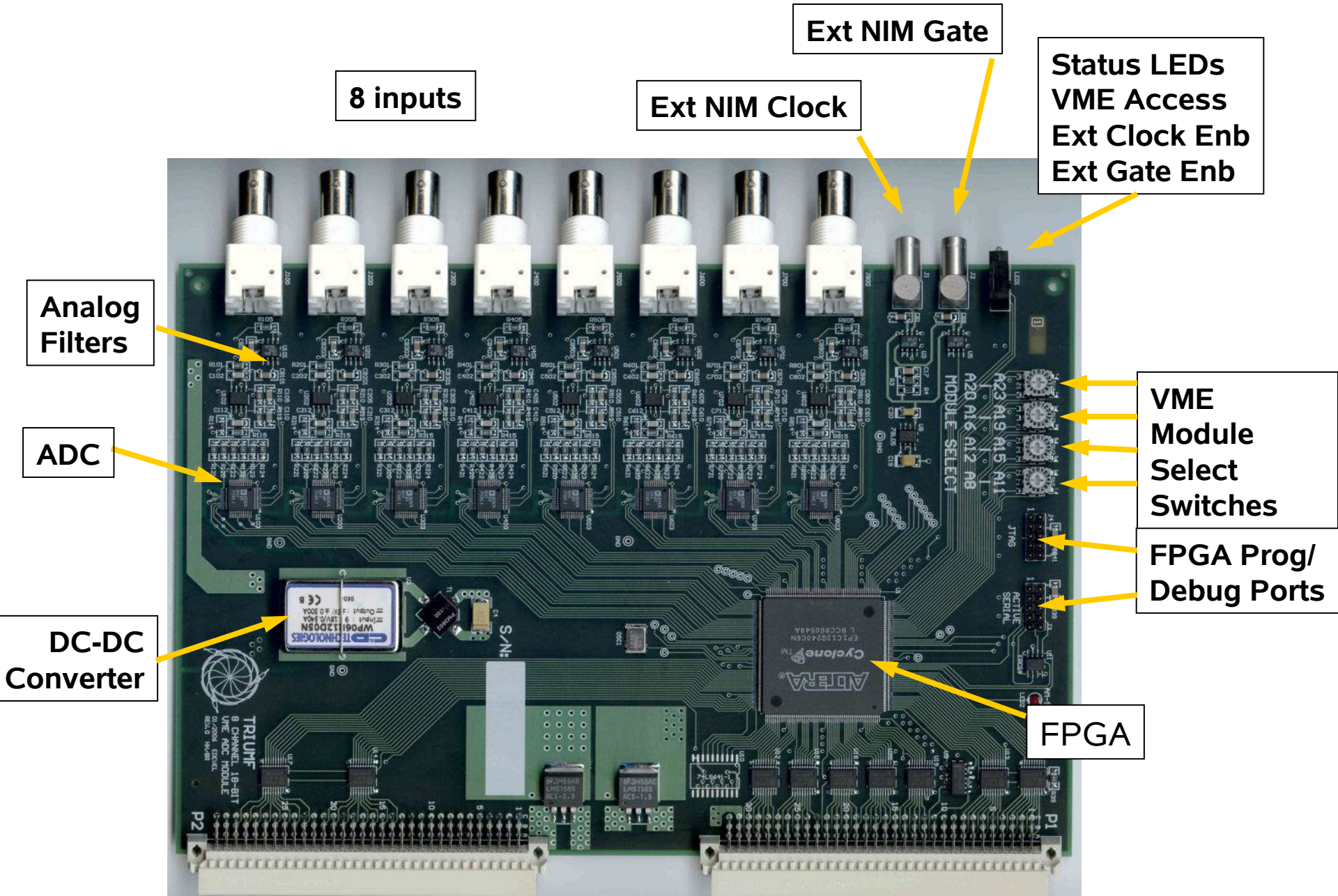
Possible DAQ pattern



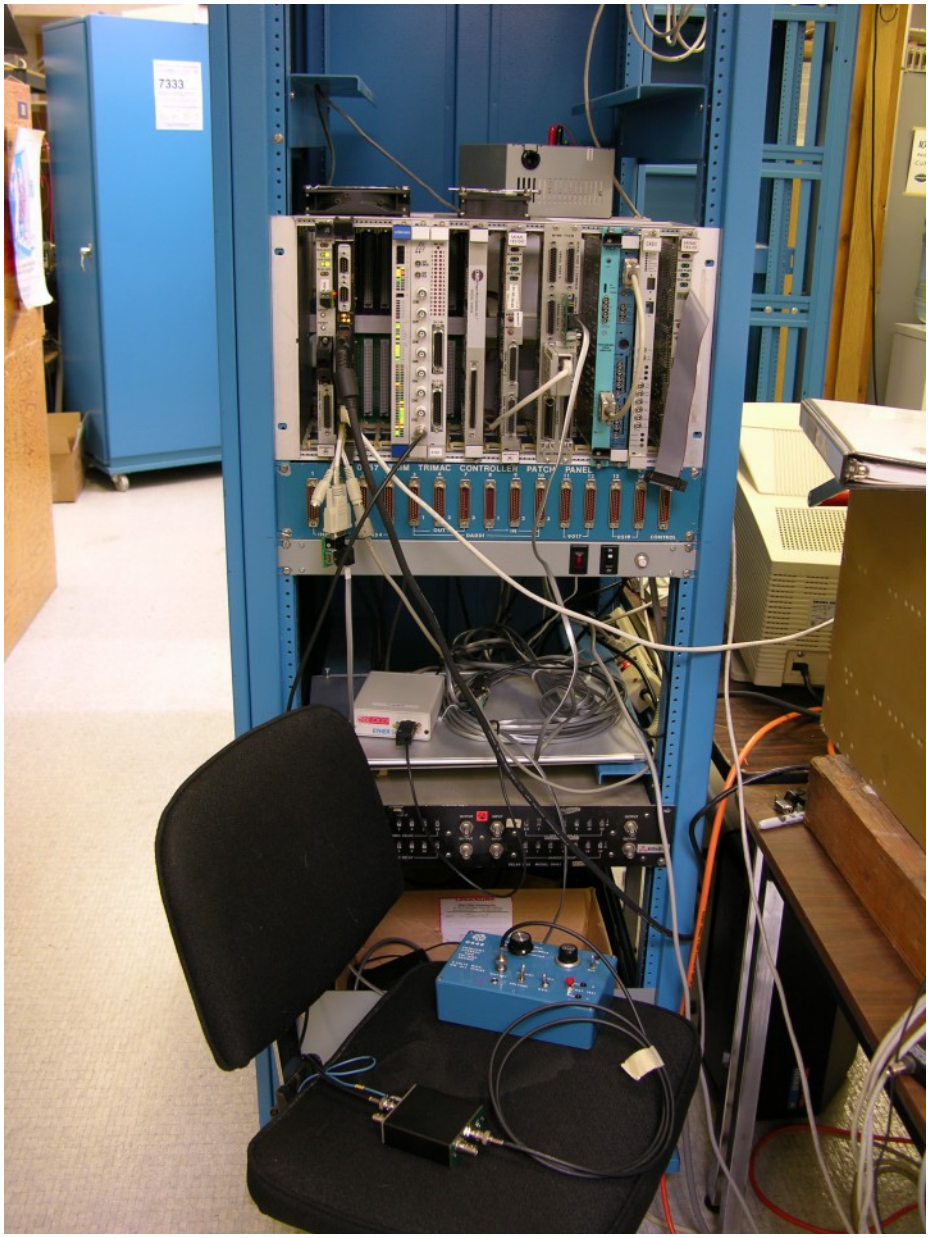
- integrates for 4 ms
- stored as four 1 ms integrals
- T_{settle} as short as 50 μs allowed

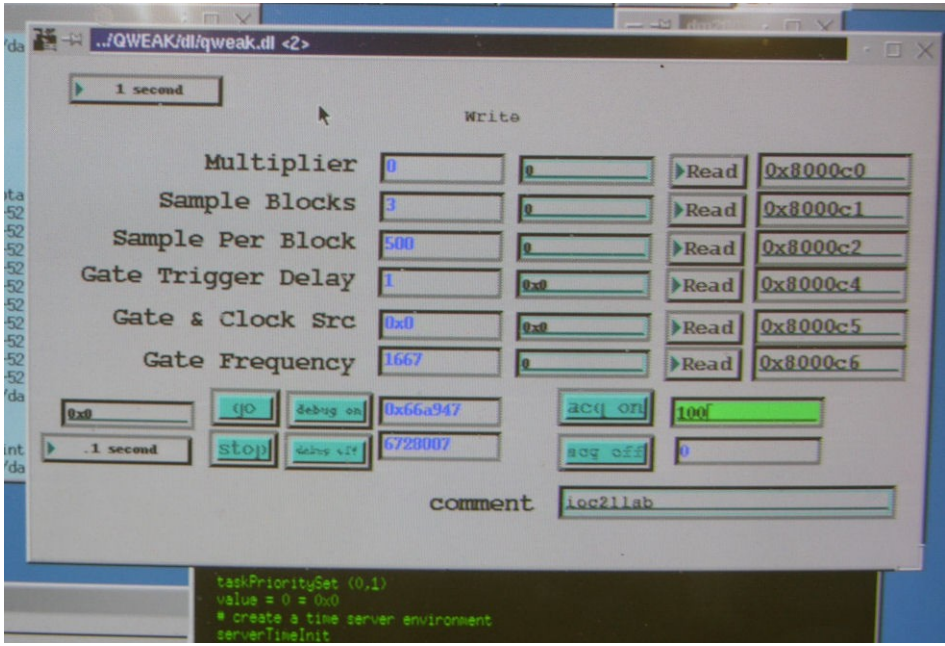
- Rapid spin flip reduces noise from target boiling
- Have capability to run as short at 1 ms per state

TRIUMF VME integrator details



VME integrator tests at TRIUMF

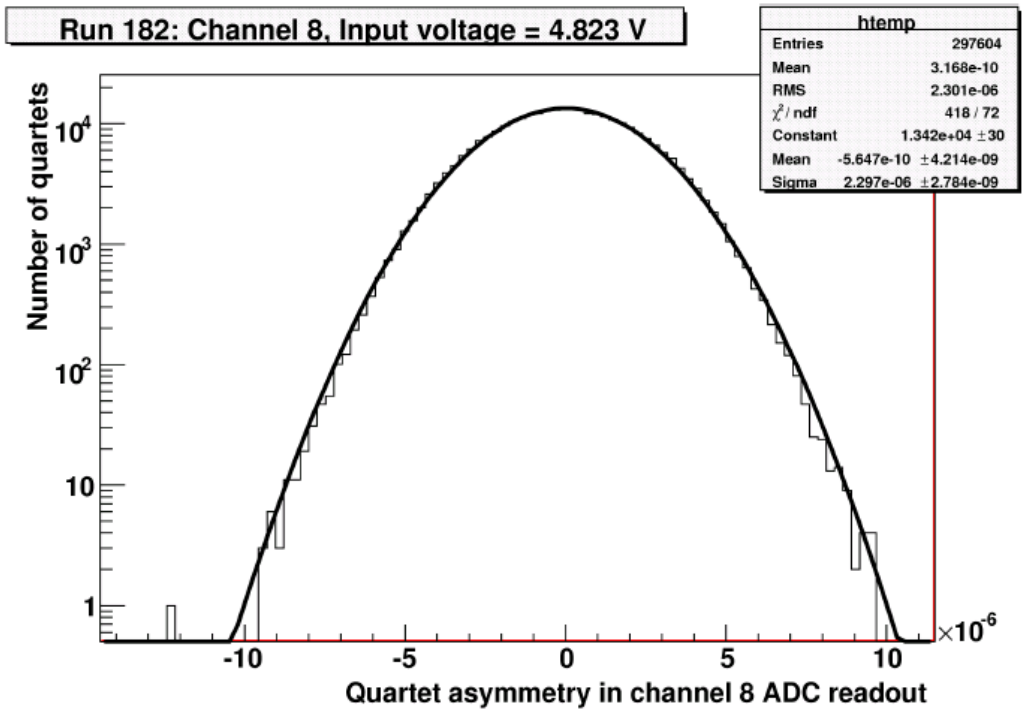




- Analog input range: -10 V to +10 V
- Front-end ADC: 500 ksps
- 4 ms integrals stored as 4 x 1ms blocks
- Shown here with 6μA current source and 200 pf cable.

Realistic VME Integrator Tests With Qweak DAQ at Ohio

- 6μA into 1 MΩ preamp: 6V above baseline
- 4 ms integration time; 4.2 ms gate period
- Quartets are +--+ ; QRT period is 16.4 ms



$$RMS_{asym} = 2.2\ ppm$$

$$\Delta V = 11.1\ \mu V$$

$$Noise \rightarrow 1.4\ \mu V / \sqrt{Hz}$$

Paul King

Null Asymmetry Check

Scaling to a 10 h run → $2.2\ ppm \times \sqrt{\frac{16.4\ ms}{10\ hr}} = 1.5 \times 10^{-9}$

- Preamp and integrator noise is low enough that we can perform a null asymmetry test in less than a day

Choice of Spin Sequence

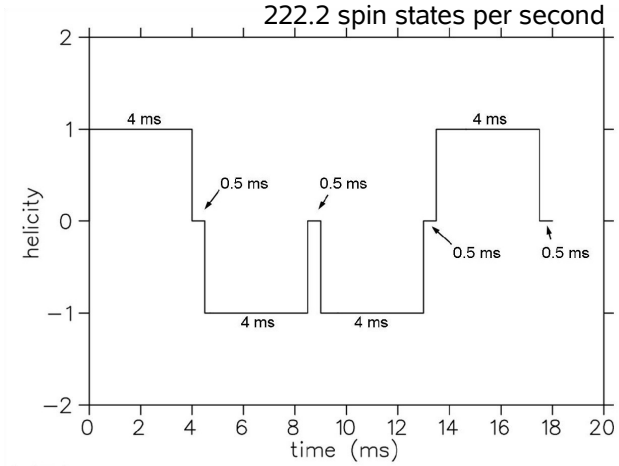
Some authorities prefer pairs $(+-)$ $(-+)$

Some prefer quartets $(+--+)$ $(-++-)$

Or even octets $(+--+-++-)$ $(-++-+--+)$

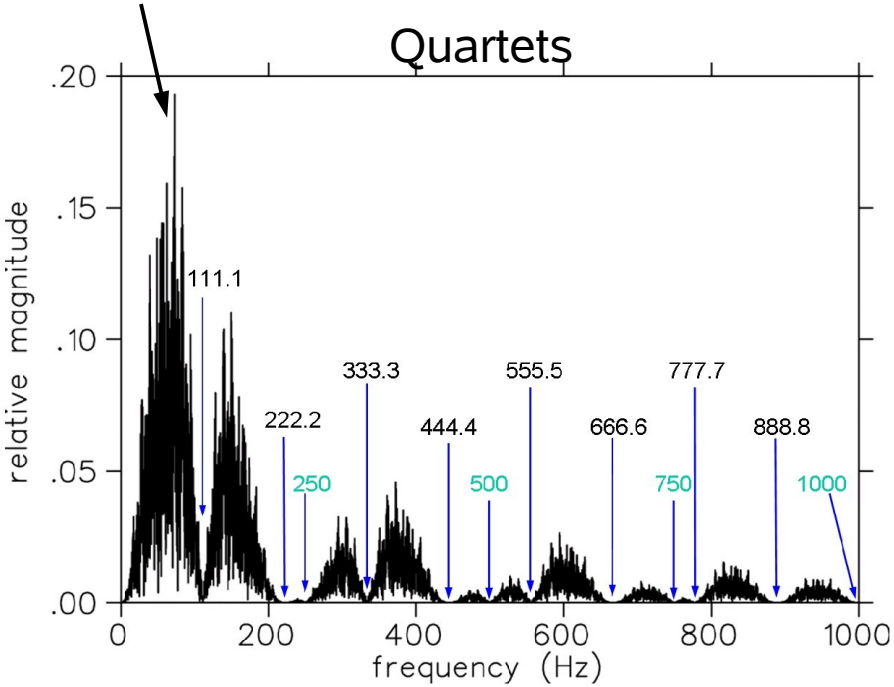
Linear drifts cancel over a quartet: +1-2-3+4=0
Quadratic drifts cancel over an octet: +1-4-9+16-25+36+49-64=0

Quartets or Doublets

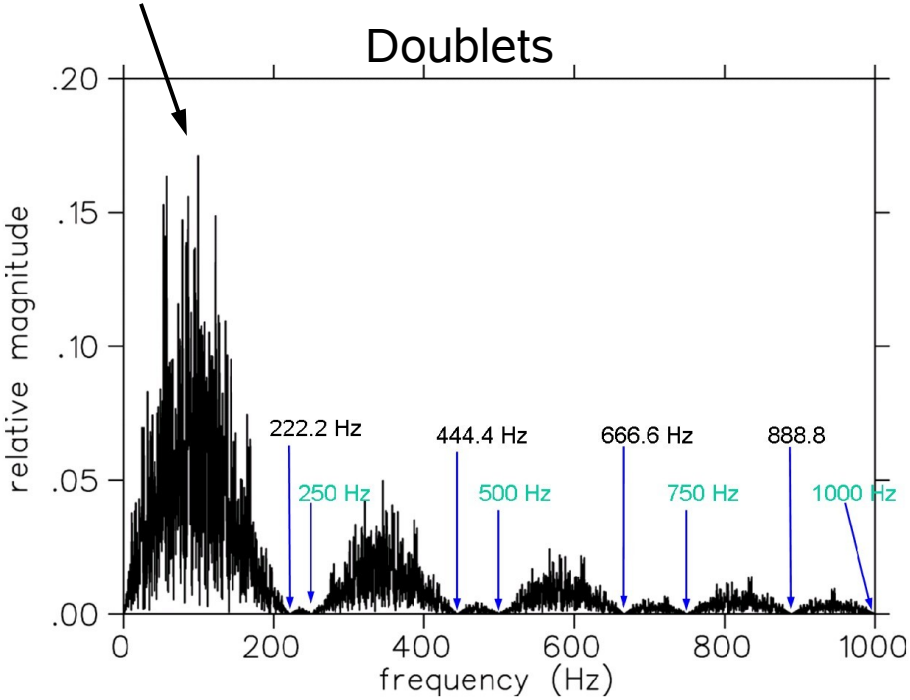


Quartets accept
more low frequencies

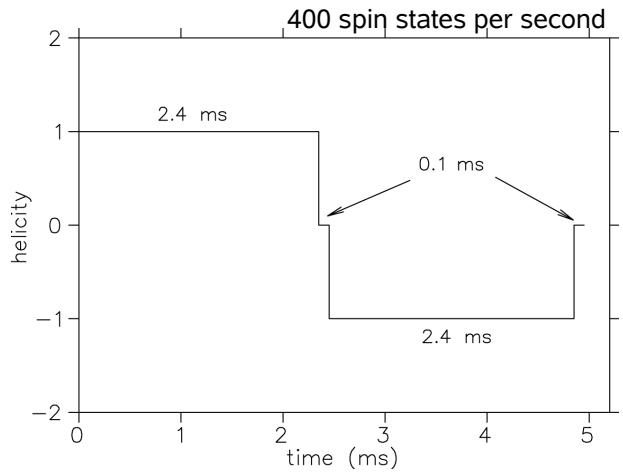
~50 Hz



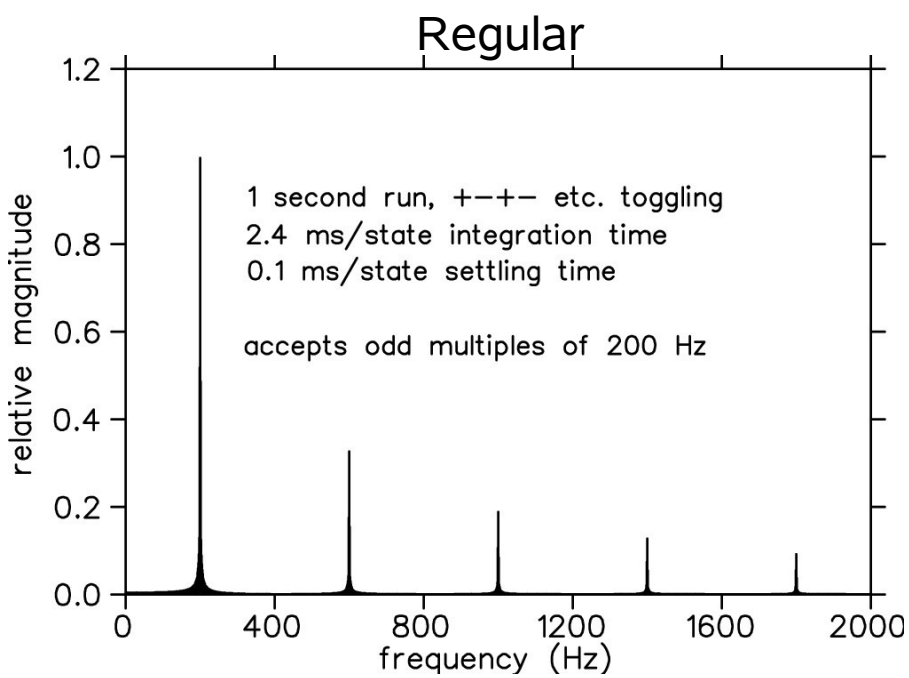
~100 Hz

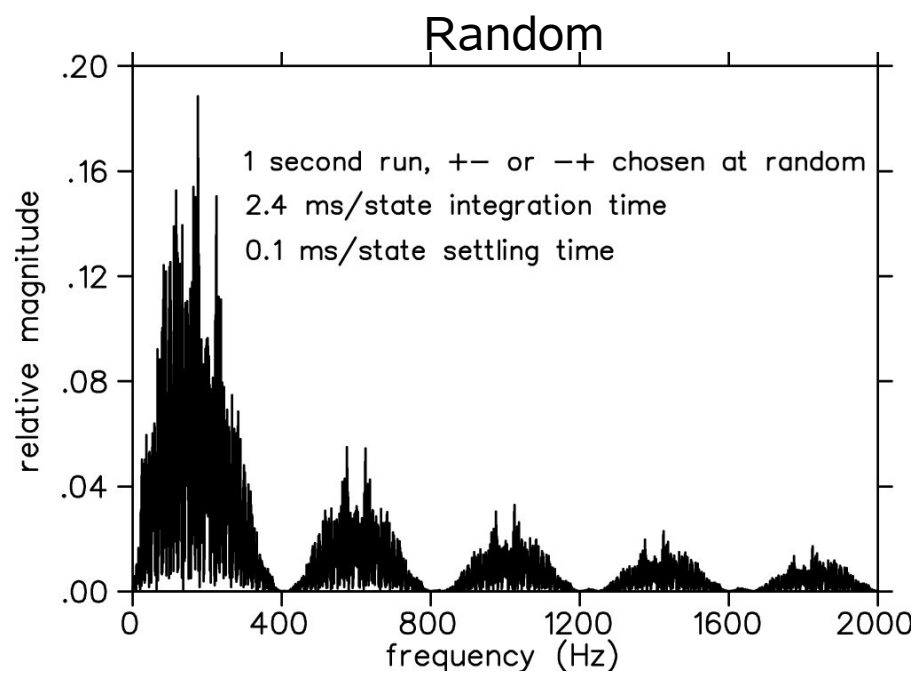


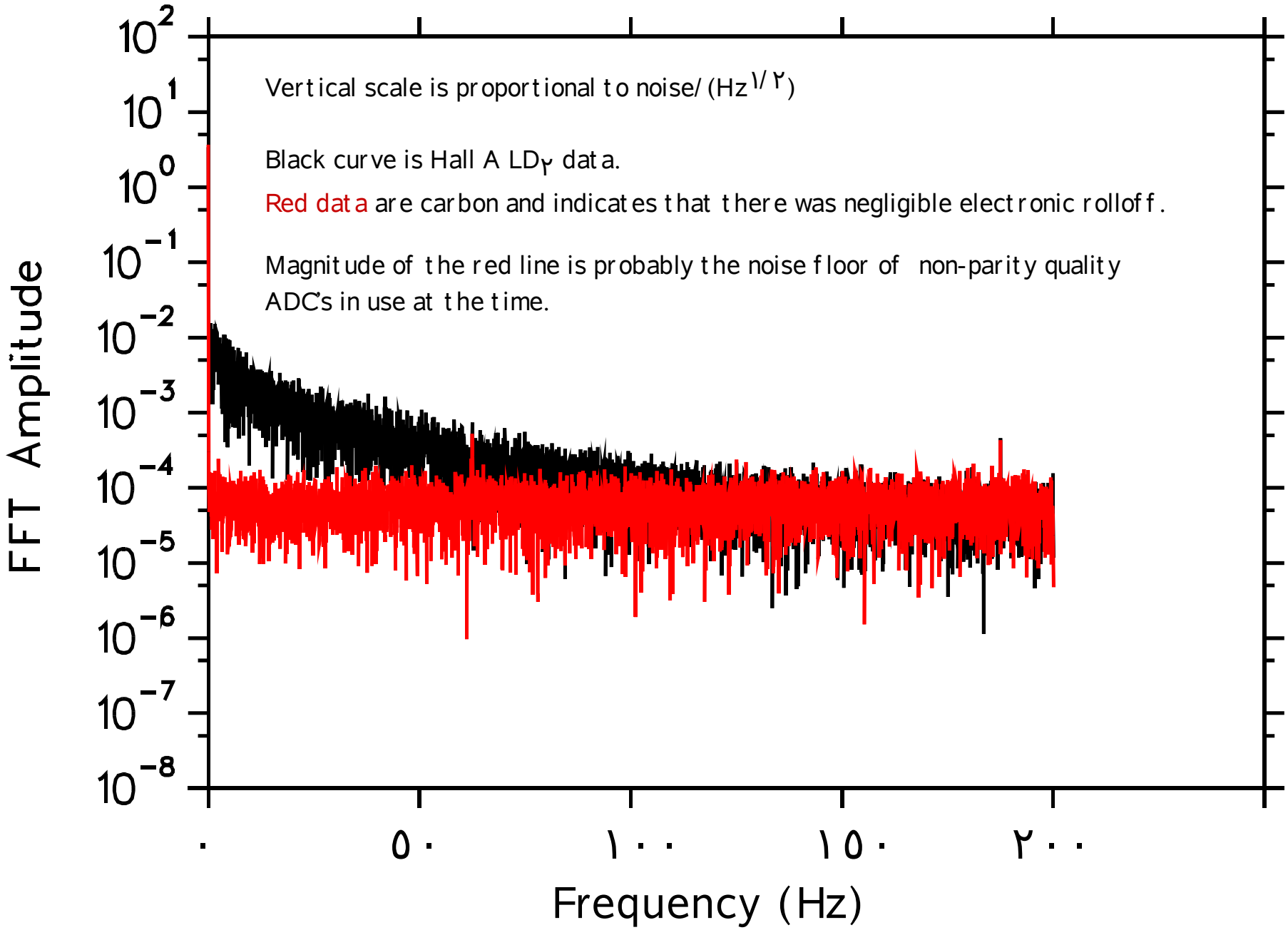
Regular or Random Doublets



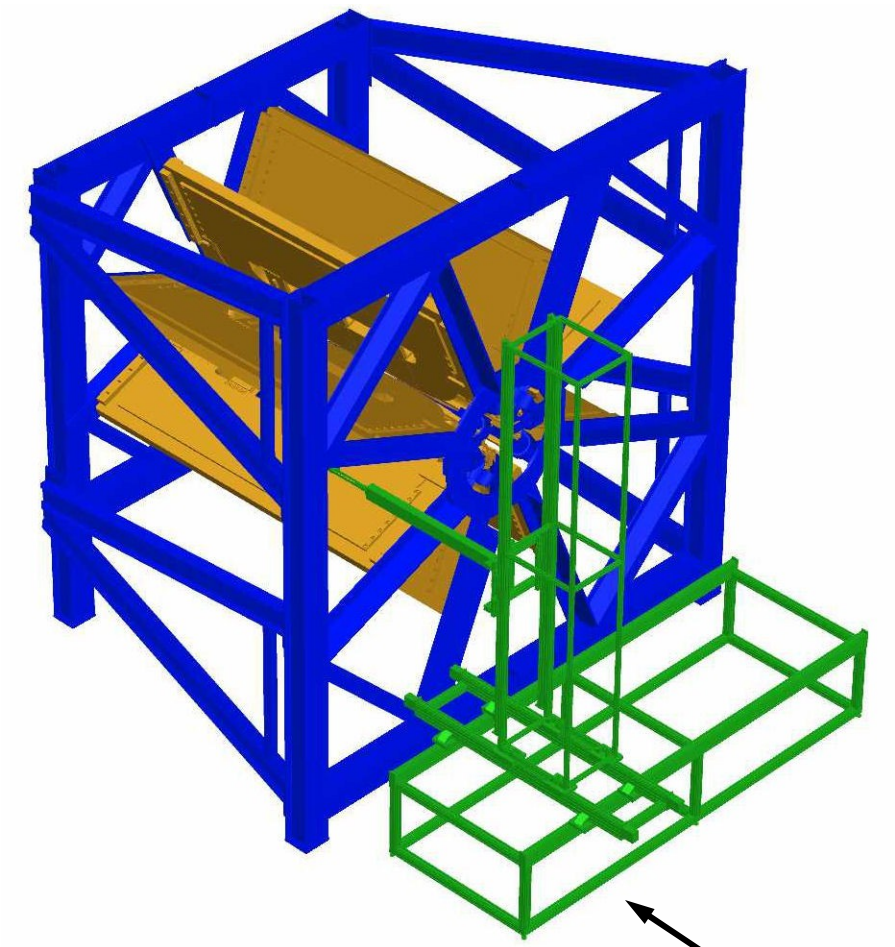
Non-random spin flip concentrates signal at spot frequencies






Vertical scale is proportional to noise/ (Hz$^{1/2}$)
Black curve is Hall A LD$_2$ data.
Red data are carbon and indicates that there was negligible electronic rolloff.
Magnitude of the red line is probably the noise floor of non-parity quality ADC's in use at the time.
FFT Amplitude
Frequency (Hz)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
۰
۵۰
۱۰۰
۱۵۰
۲۰۰

“QTOR” Spectrometer Magnet
U of M / TRIUMF / UNBC

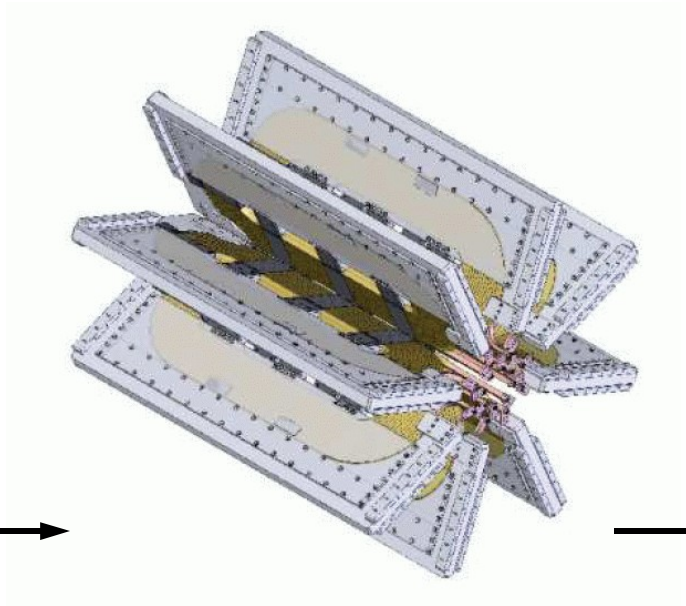


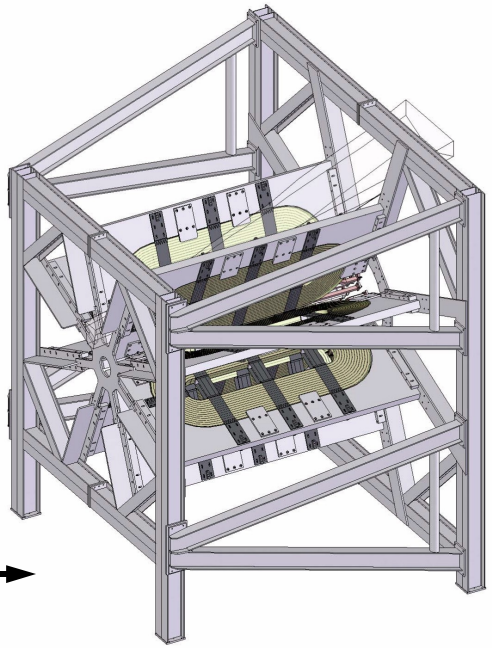
- 8 sector toroidal magnet
- water cooled copper coils
- 9500 A, 1.5 MW maximum
- 4.3 m long, 1.5 m wide coils, simple racetrack shape
- ~3300 kg per coil
- Field mapping with TRIUMF field mapping equipment.
- Contract management by TRIUMF engineers.
- ~$420k NSERC money

TRIUMF field mapper used on G zero

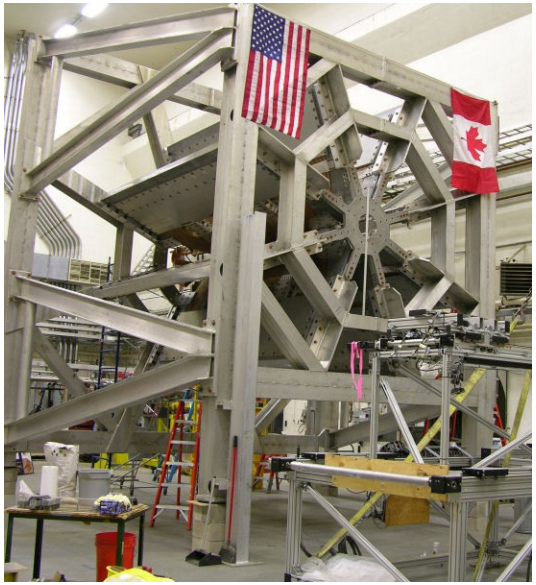
$$\int B \cdot dl = 0.89 \ \text{T.m}$$

All magnet and stand parts are now at MIT/ Bates

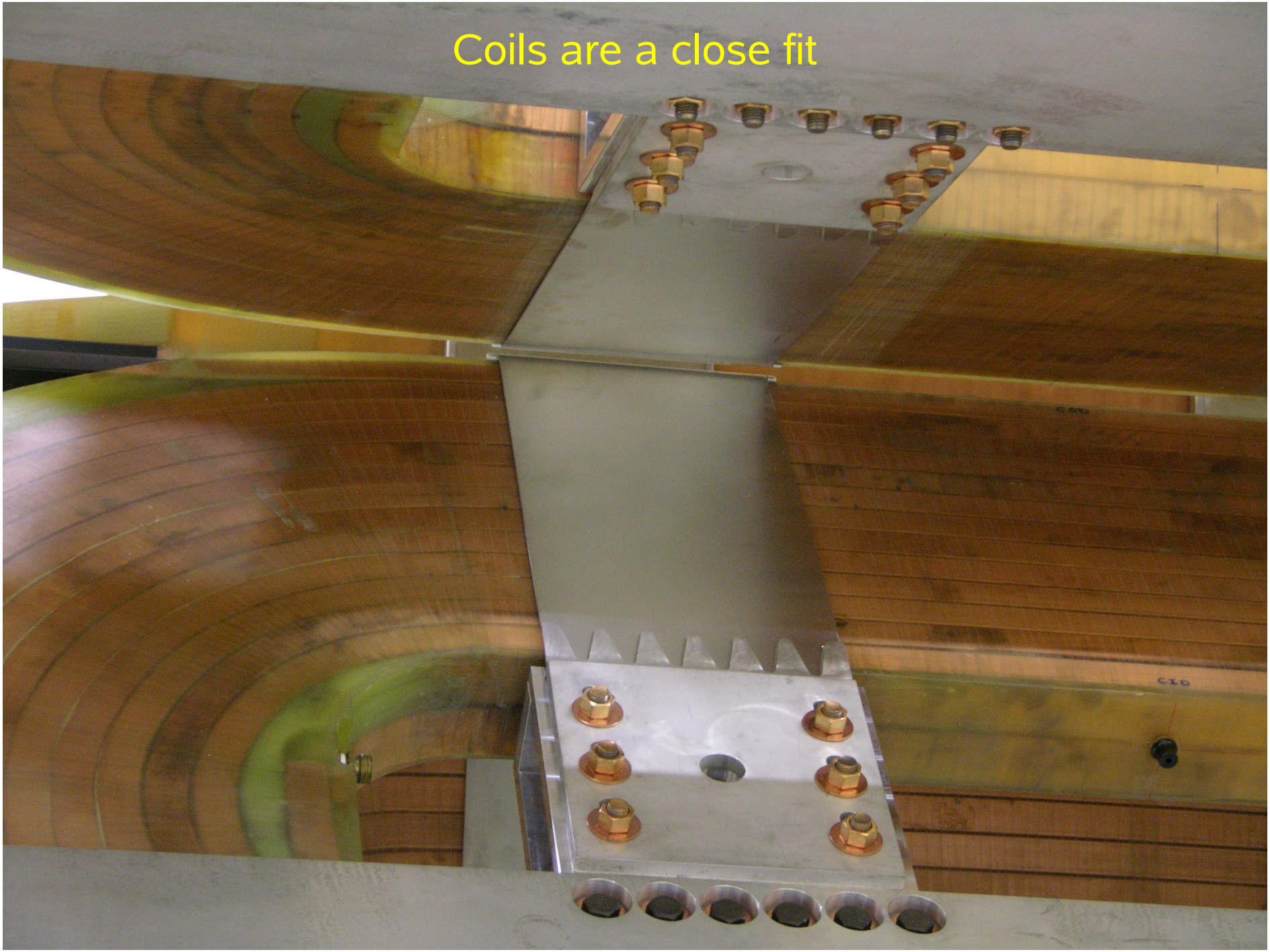




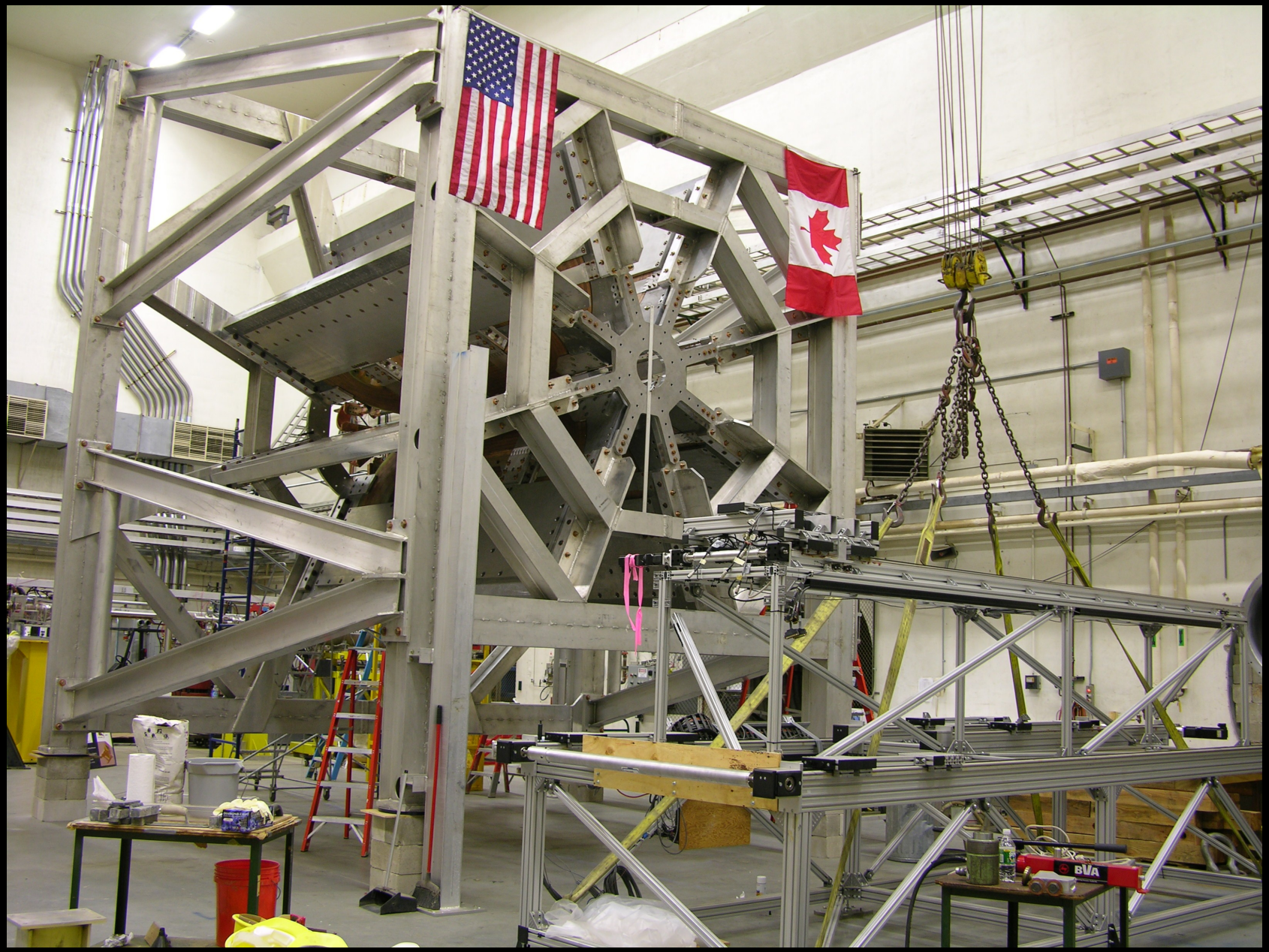
- ready to go at MIT
- full-power May 2008
- Field map May and September 2008
- to JLab April 2009



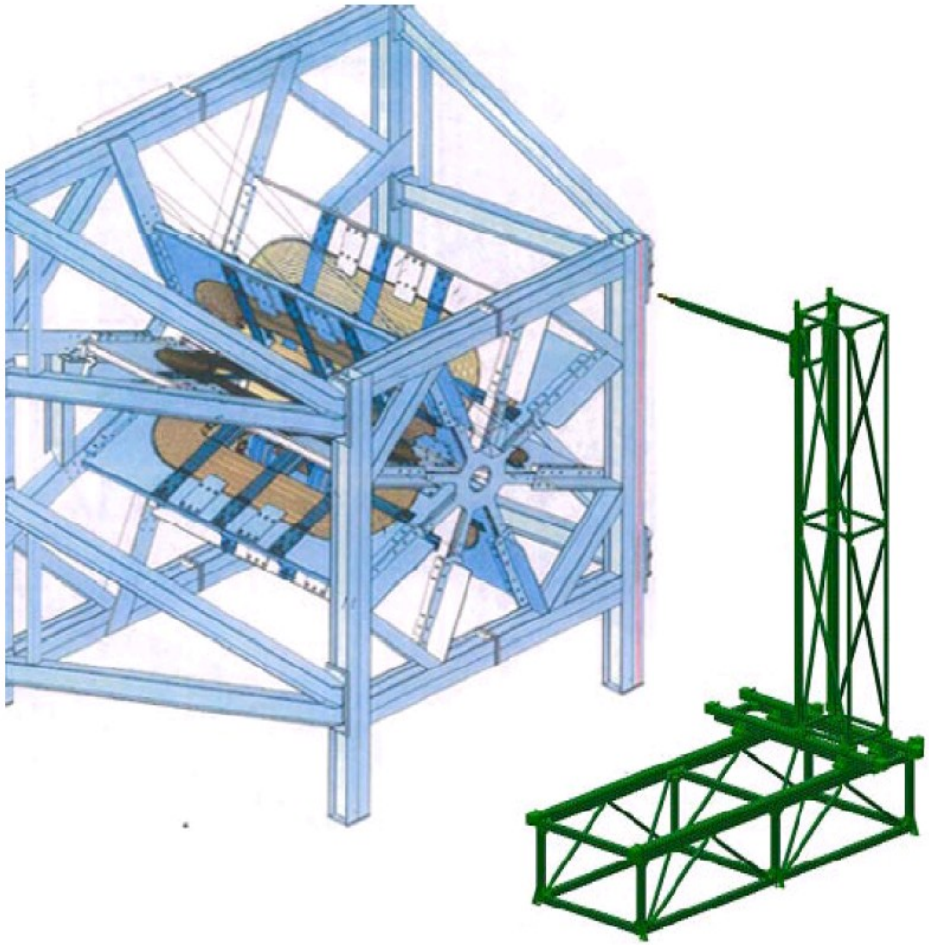
Coils are a close fit



Preparing the TRIUMF field mapper at MIT-Bates

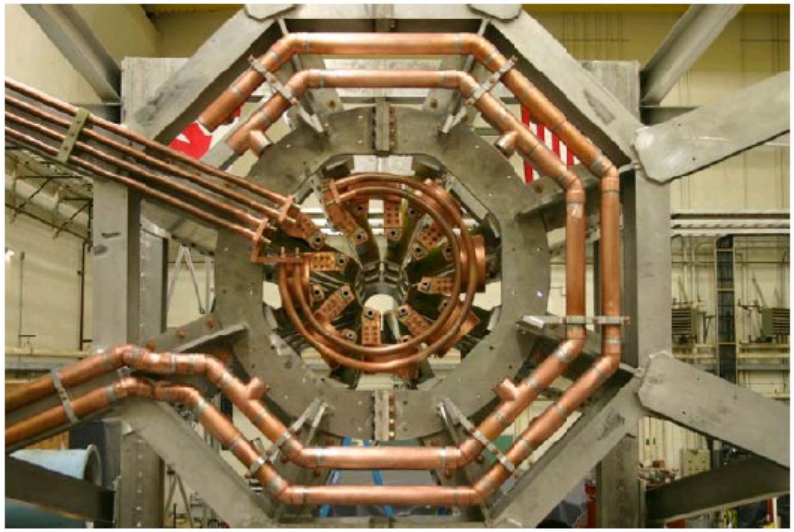


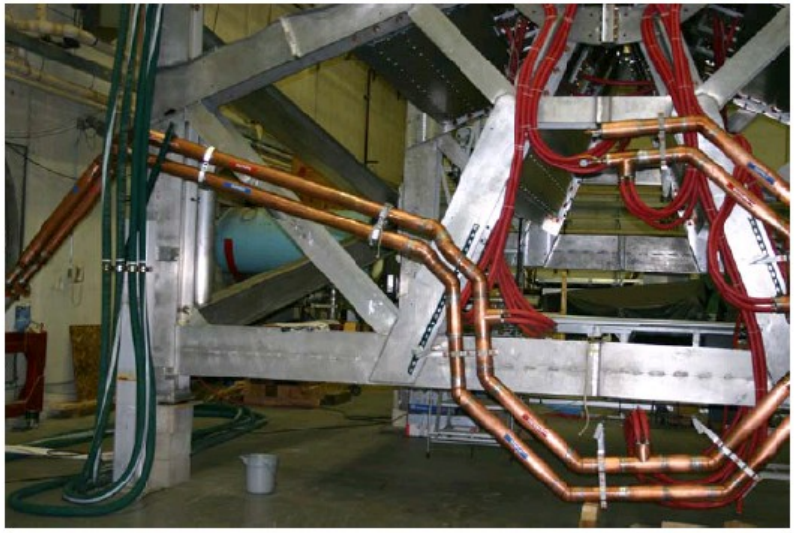
TRIUMF Magnetic Field Mapper

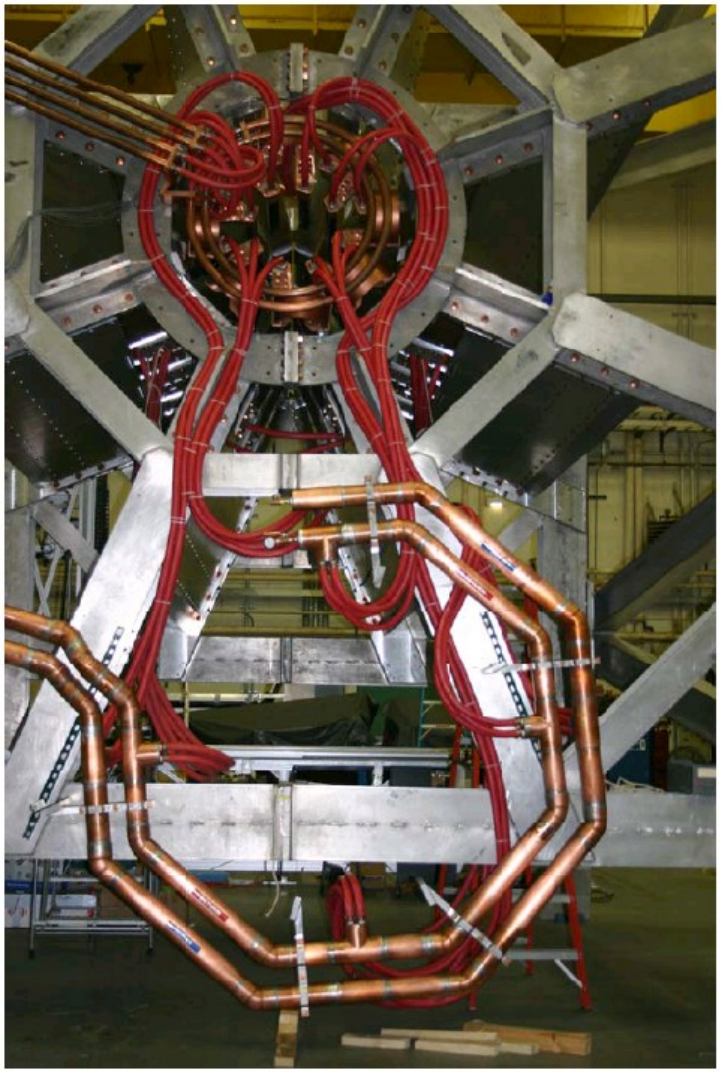


- used for Gzero
- Now at MIT-Bates
- Scans 4 m x 4 m x 2 m
- repeatability ~0.025 mm
- calibration ±0.2 mm
- ±0.2 gauss

Water Manifold Moved For Field Mapping

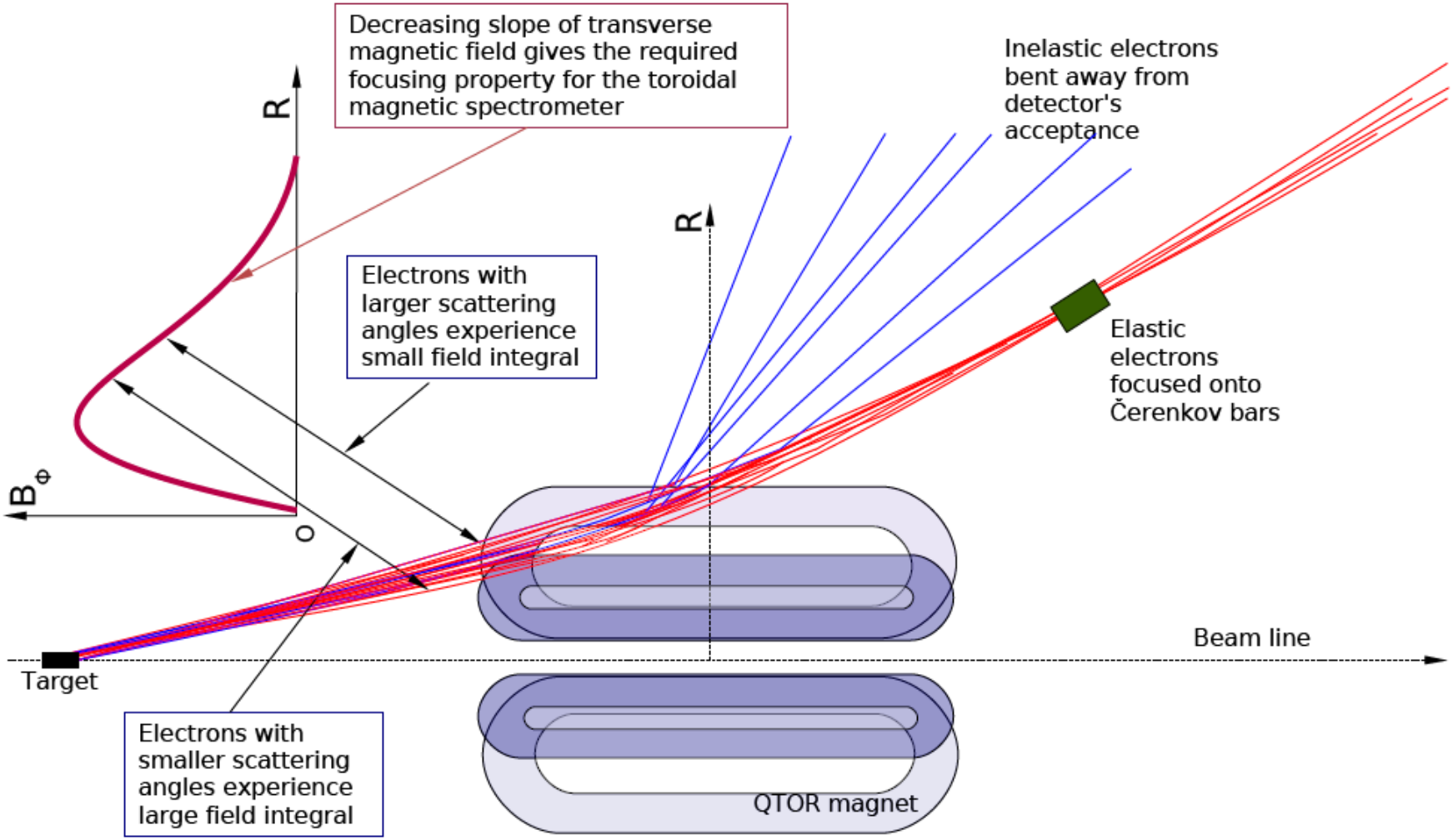




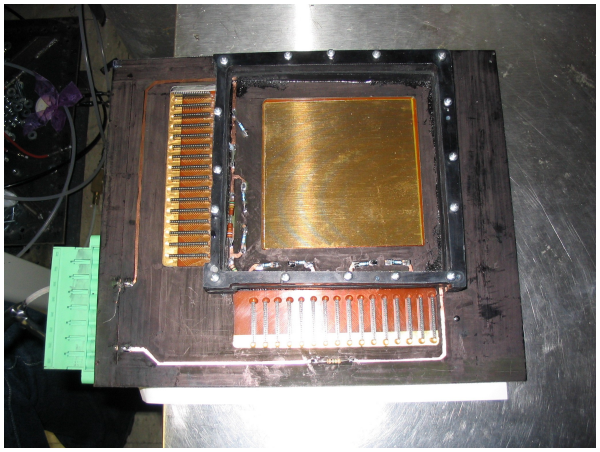


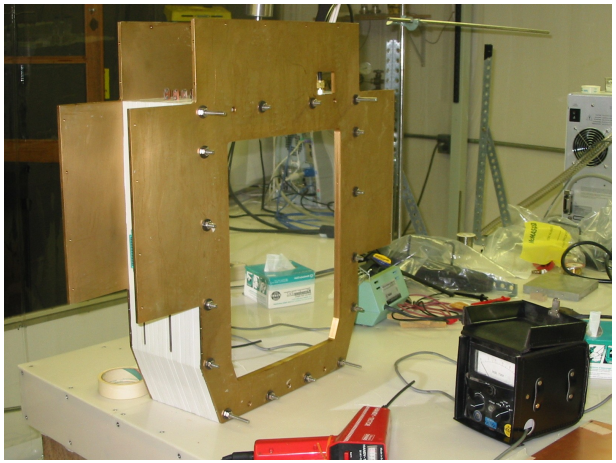
Karen Dow

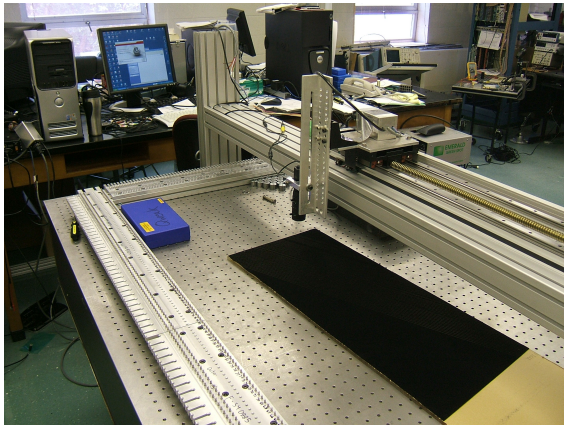
Features of the QTOR Resistive spectrometer magnet:



Tracking Systems (counting mode)



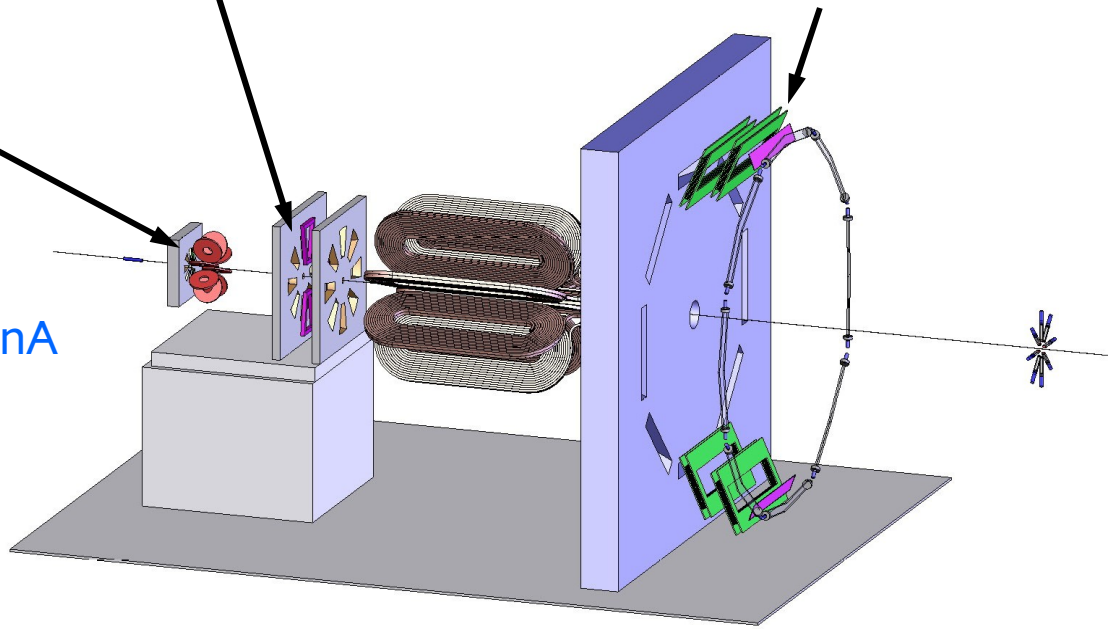




Region 1, GEMs
LaTech

Region 2, HDCs
VPI

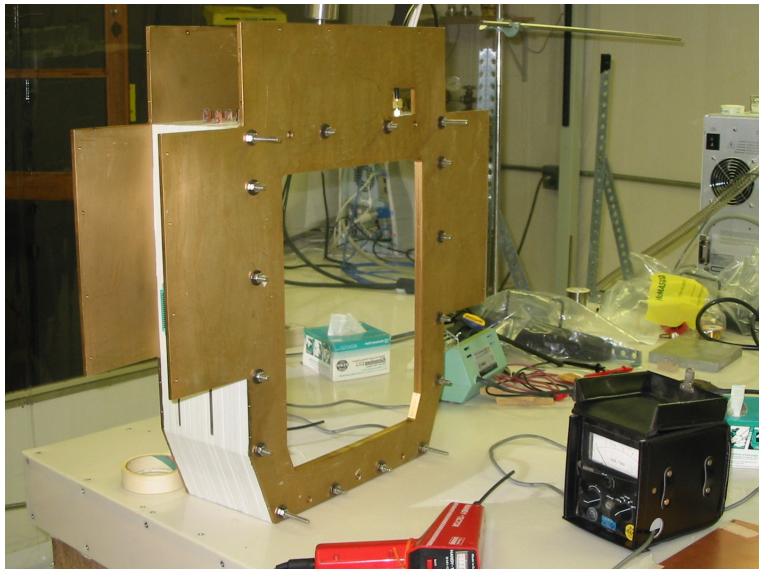
Region 3, VDCs
W&M

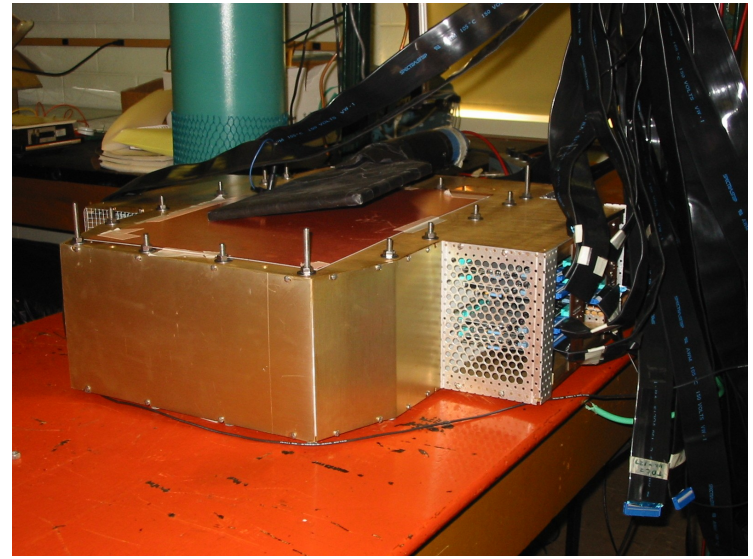


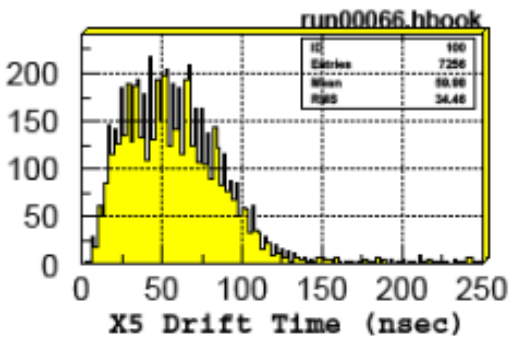
- Run in counting mode at 0.2 nA
- Determine Q^2 to 0.5 %
- Understand backgrounds

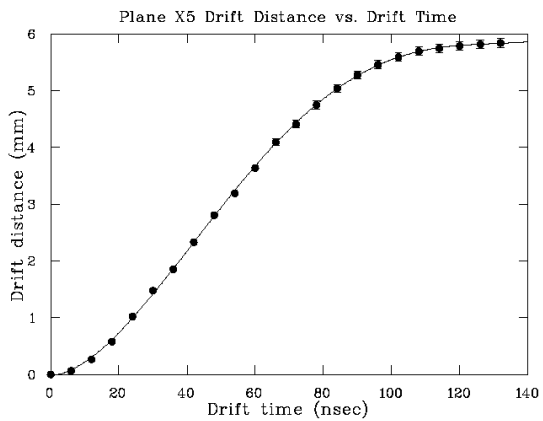
Region 2 First Production Chamber

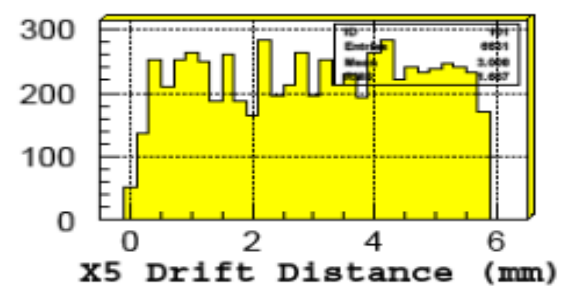
Region 2 chambers: horizontal drift chambers with 6 planes per chamber (xuvx'u'v')
active area 38 cm x 28 cm, wire pitch of 5.84 mm



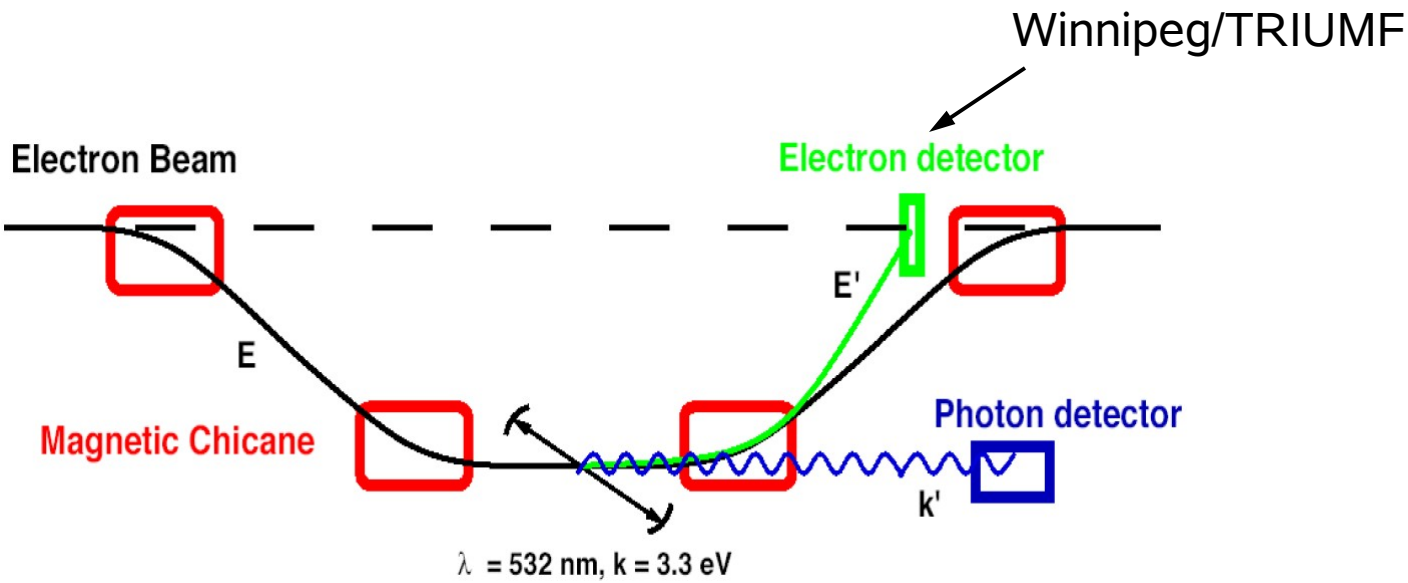




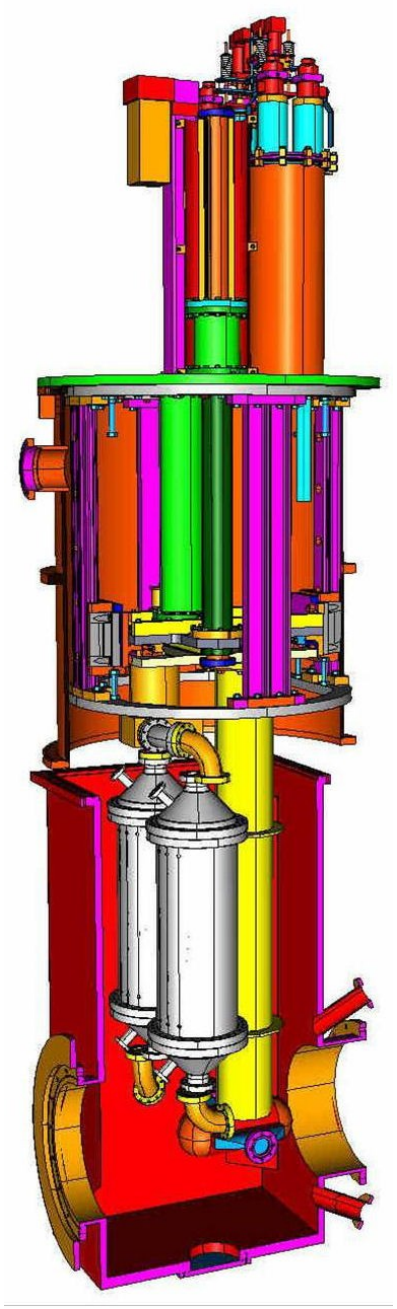




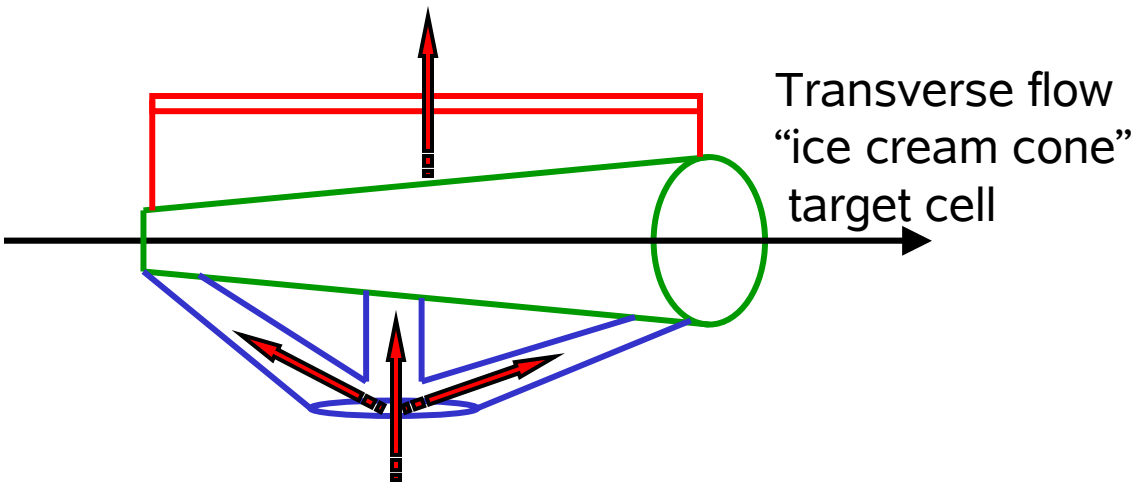
New Hall-C Compton Polarimeter



- Compton can run all the time (unlike the Møller).
- Photon and electron coincidences greatly reduce systematic uncertainties due to backgrounds.
- < 1% precision is guaranteed, cross-calibrate against existing Møller polarimeter.
- Hall C has calibrated ~1% Møller polarimeter based on magnetized foil in several Tesla field. It needs dedicated Møller runs.



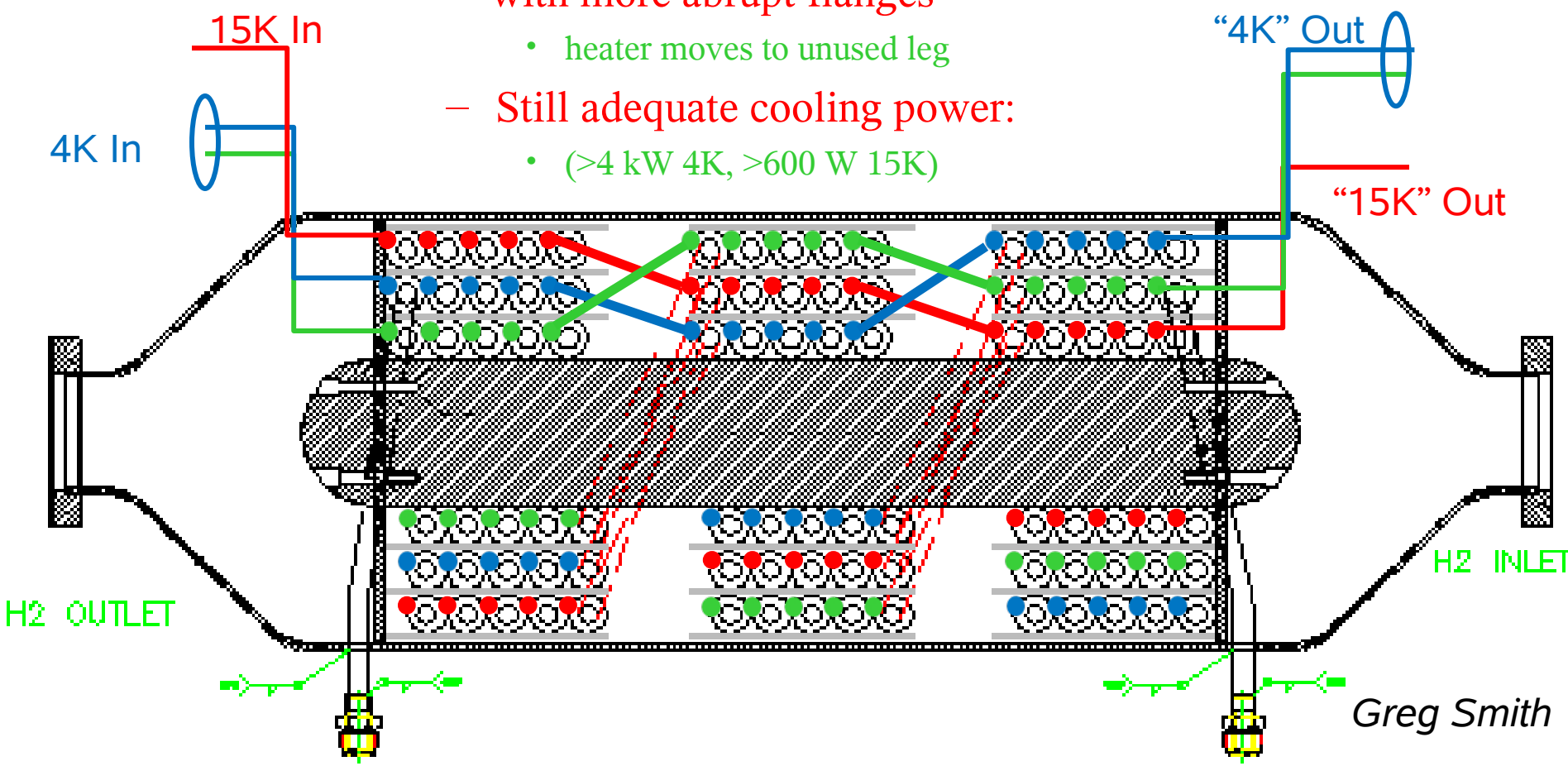
Cryotarget



- Highest power (2500 watt) cryotarget ever
- ~50 litre liquid hydrogen inventory
- 35 cm long, 2200 watt beam load
- High capacity combined 4K and 15K heat exchanger
- LN2 pump tests this summer
- cold helium gas tests at end 2008

Heat Exchanger

- Combine 4K & 15K HXs to reduce Volume
  - Retain balanced ΔP for each layer
  - Replace conical transition flanges with more abrupt flanges
    - heater moves to unused leg
  - Still adequate cooling power:
    - (>4 kW 4K, >600 W 15K)



Greg Smith

Helicity Correlated Beam Properties

- If a beam parameter changes with helicity, it can imitate parity violation.
- We must measure and, if necessary, correct for such modulation.

Errors from Helicity Correlated Beam Properties

Source	Conditions	Perfect array	Extra contribution from imperfections
Position modulation	x_0 = 1.0 mm δx = ±2 nm	4×10^{-10}	2×10^{-10}
Size modulation	4 mm x 4 mm raster $\delta_{\Delta x} = \delta_{\Delta y}$ = ±2 nm	5.3×10^{-10}	2.7×10^{-10}
Direction modulation	θ_0 = 60 μrad $\delta\theta$ = ±30 nrad	7×10^{-10}	47×10^{-10} Independent of θ_0
Transverse polarization and position	$P_y = 0.04$, $A_y = 10^{-5}$, x_0 = 1.0 mm	24×10^{-10}	-34×10^{-10} Independent of x_0
Transverse polarization and direction	$P_y = 0.04$, $A_y = 10^{-5}$, θ_0 = 60 μrad	3.7×10^{-10}	-38×10^{-10} Independent of θ_0
Energy Modulation	$\delta E/E = 10^{-9}$	$<6 \times 10^{-10}$	0

Jim Birchall

Errors from Helicity Correlated Beam Properties

Source of error	Conditions	Perfect array	Extra contribution from distorted array
Position modulation	x_0 = 1.0 mm, $\delta x = \pm 2$ nm	4×10^{-10}	2×10^{-10} independent of x_0
Size modulation	4 mm x 4 mm raster $\delta_{\Delta x} = \delta_{\Delta y} = \pm 2$ nm	5.3×10^{-10}	2.7×10^{-10}
Direction modulation	θ_0 = 60 μrad $\delta\theta = \pm 30$ nrad	7×10^{-10}	47×10^{-10} independent of θ_0
Transverse polarization and position	$P_y = 0.04$, $A_y = 10^{-5}$, x_0 = 1.0 mm	24×10^{-10}	-34×10^{-10} independent of x_0
Transverse polarization and direction	$P_y = 0.04$, $A_y = 10^{-5}$, θ_0 = 60 μrad	3.7×10^{-10}	-38×10^{-10} independent of θ_0
Energy	$\delta E/E = 10^{-9}$	$< 6 \times 10^{-10}$	0

Jim Birchall

Summary of Error Budget

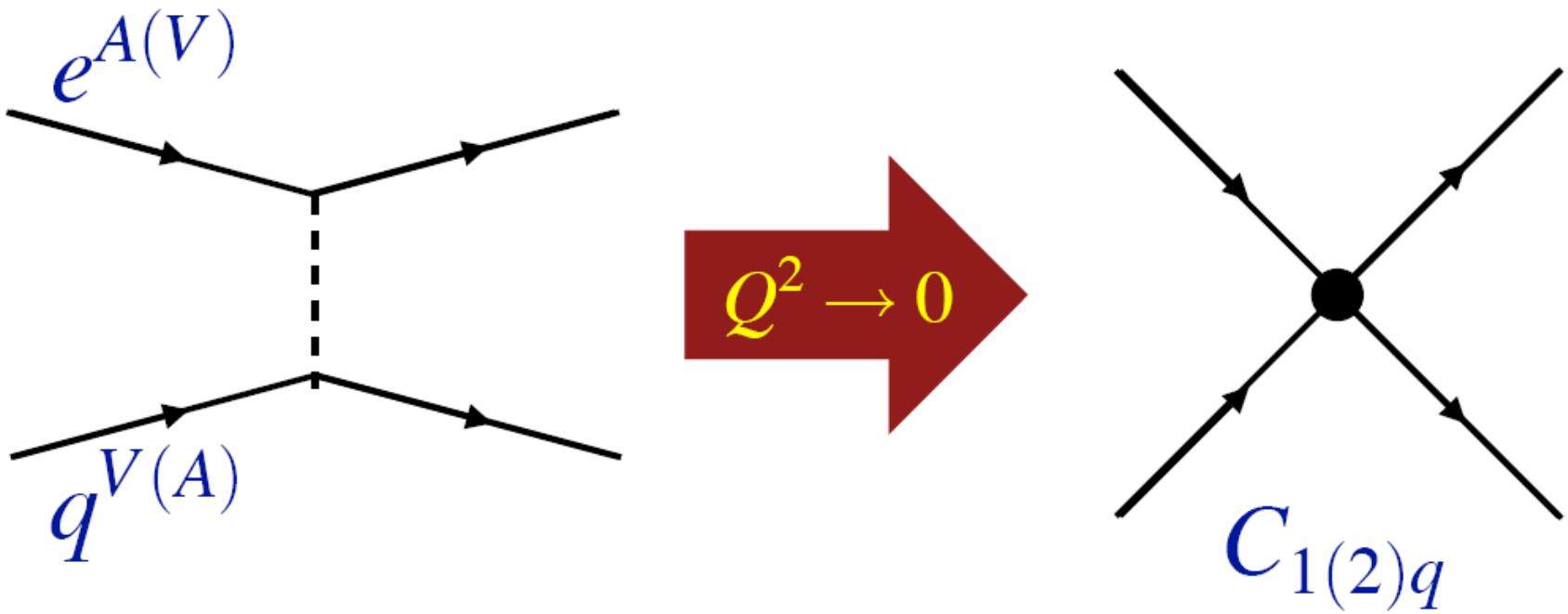
$$2\% \text{ on } A_z \approx 4\% \text{ on } Q_w \approx 0.3\% \text{ on } \sin^2\theta_W{}^{\blacklozenge}$$

	$\Delta A_z/A_z$	$\Delta Q_w/Q_w$
Statistical (2500 hours)	2.1%	3.2%
Systematic:		
Hadronic structure uncertainties	--	1.5%
Beam polarimetry	1.0%	1.5%
Absolute Q2 determination	0.5%	1.0%
Backgrounds	0.5%	0.7%
Helicity correlated beam properties	0.5%	0.7%
Total:	2.2%	4.1%

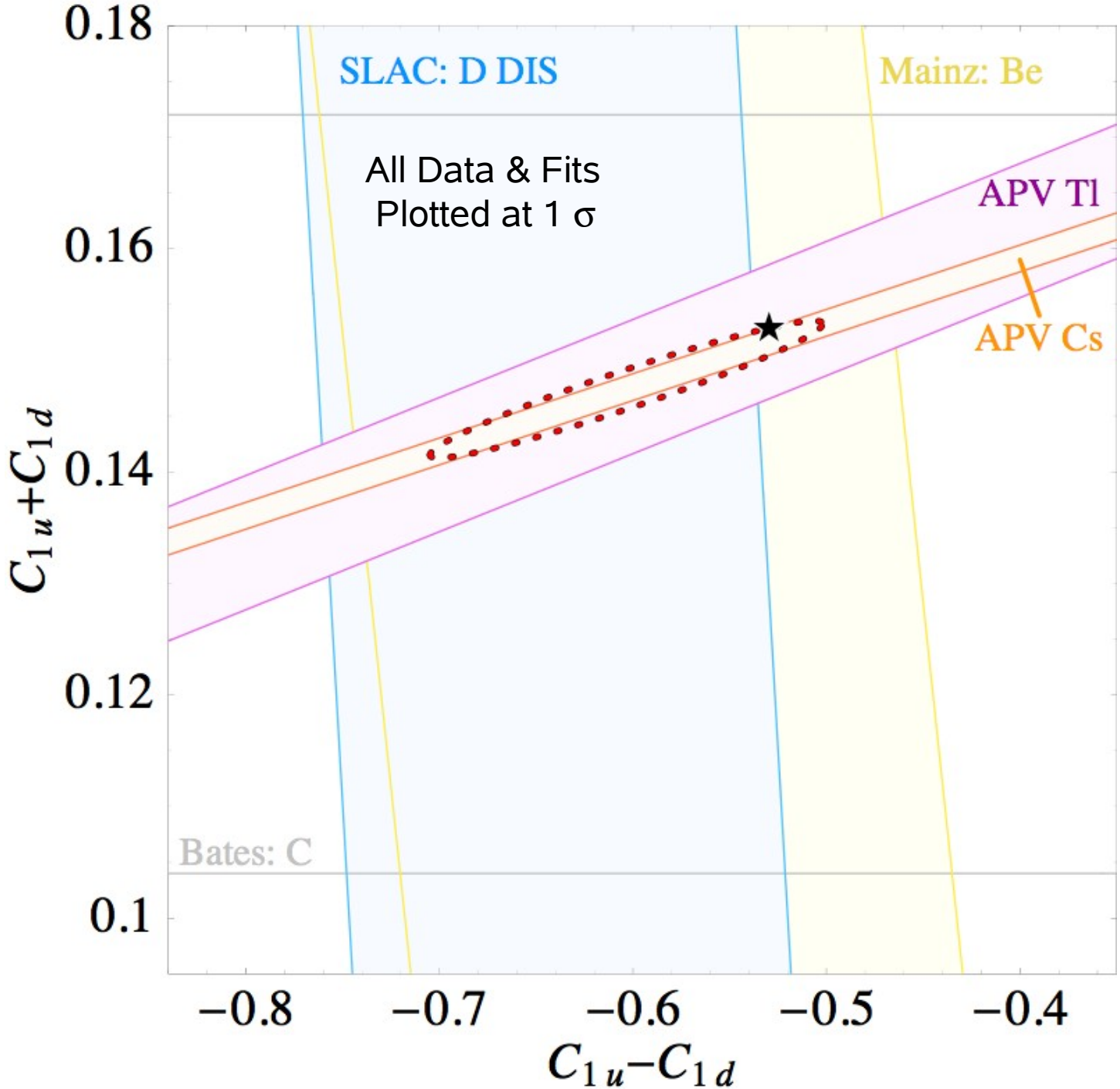
♦(An additional uncertainty associated with QCD corrections applied to the extraction of $\sin 2\theta W$: it raises $\Delta \sin 2\theta W$ / $\sin 2\theta W$ from 0.2% to 0.3%.)

What if we combine Qweak with other experiments with differing sensitivity to up and down quarks?

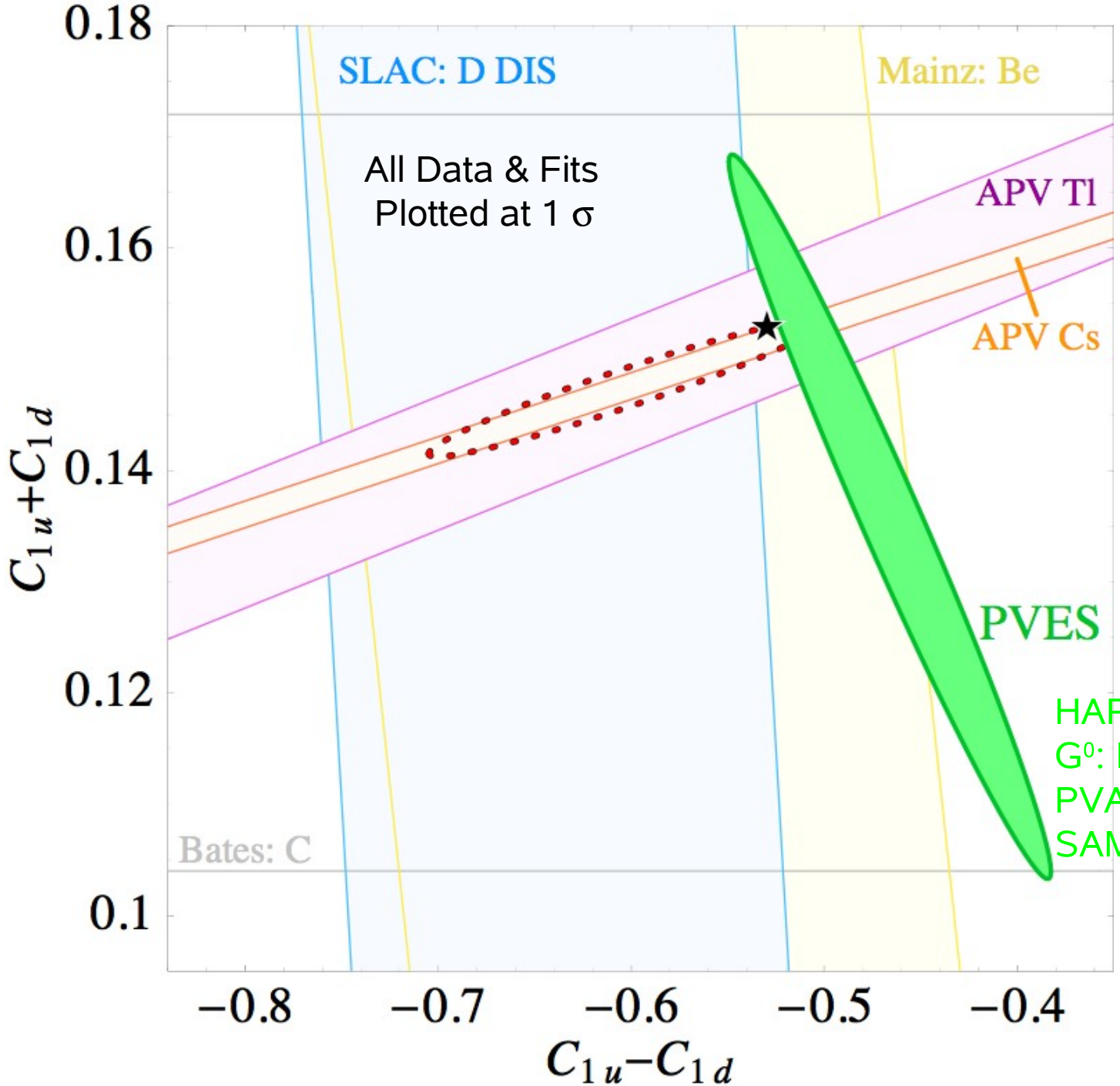
PV electron-quark couplings



- The C_1 coupling is half the quark "weak charge" I showed earlier
- For the proton (UUD), Qweak = $2(2C_{1u} + C_{1d})$

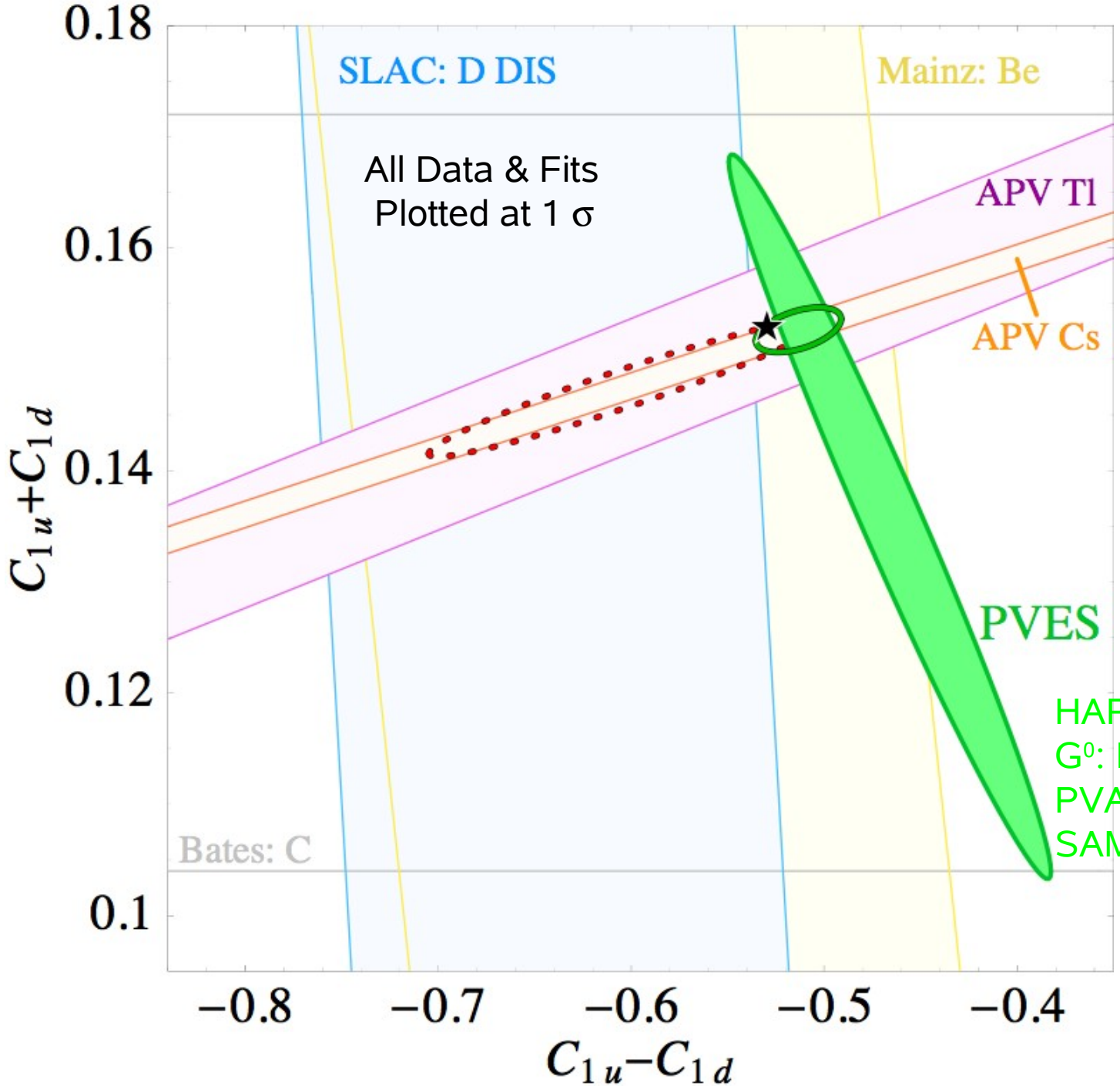


Latest from Ross Young



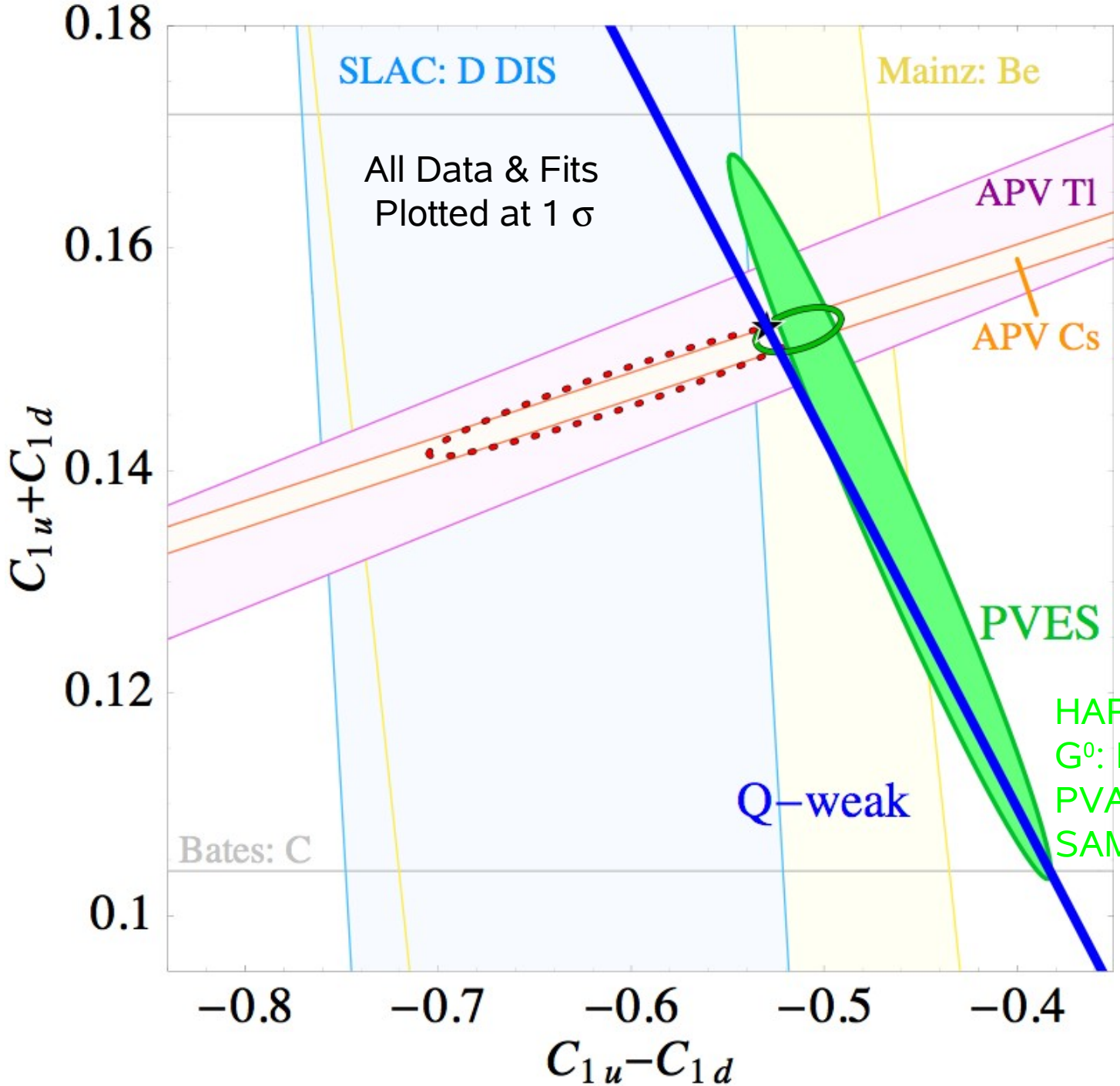
Latest from Ross Young

HAPPEx: H, He
G^0: H,
PVA4: H
SAMPLE: H, D



Latest from Ross Young

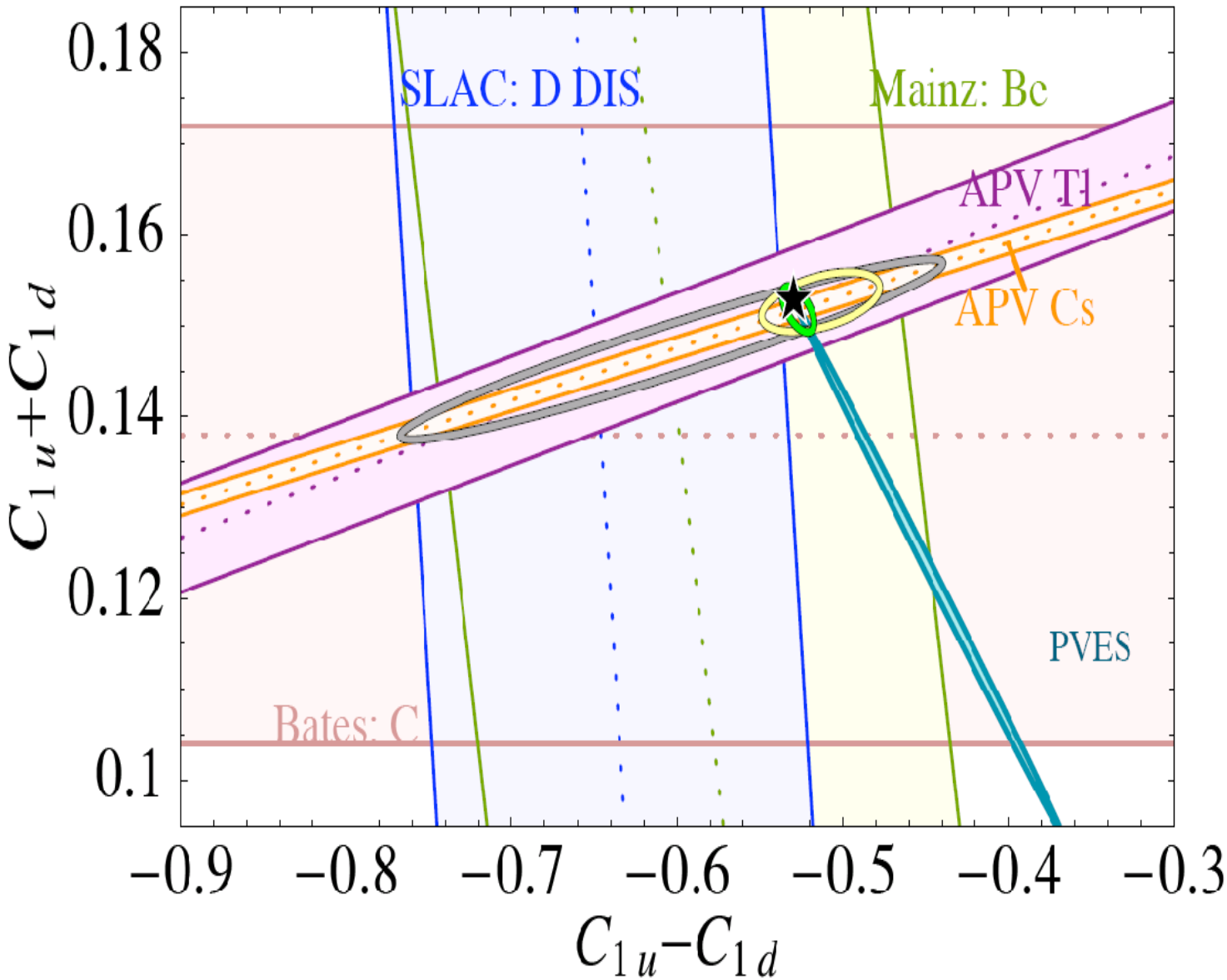
HAPPEx: H, He
G^0: H,
PVA4: H
SAMPLE: H, D



Latest from Ross Young

HAPPEx: H, He
G^0: H,
PVA4: H
SAMPLE: H, D

Final Impact of Qweak



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

Erler et al., PRD68(2003)

$$\mathcal{L}_{\rm NP}^{\rm PV} = \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

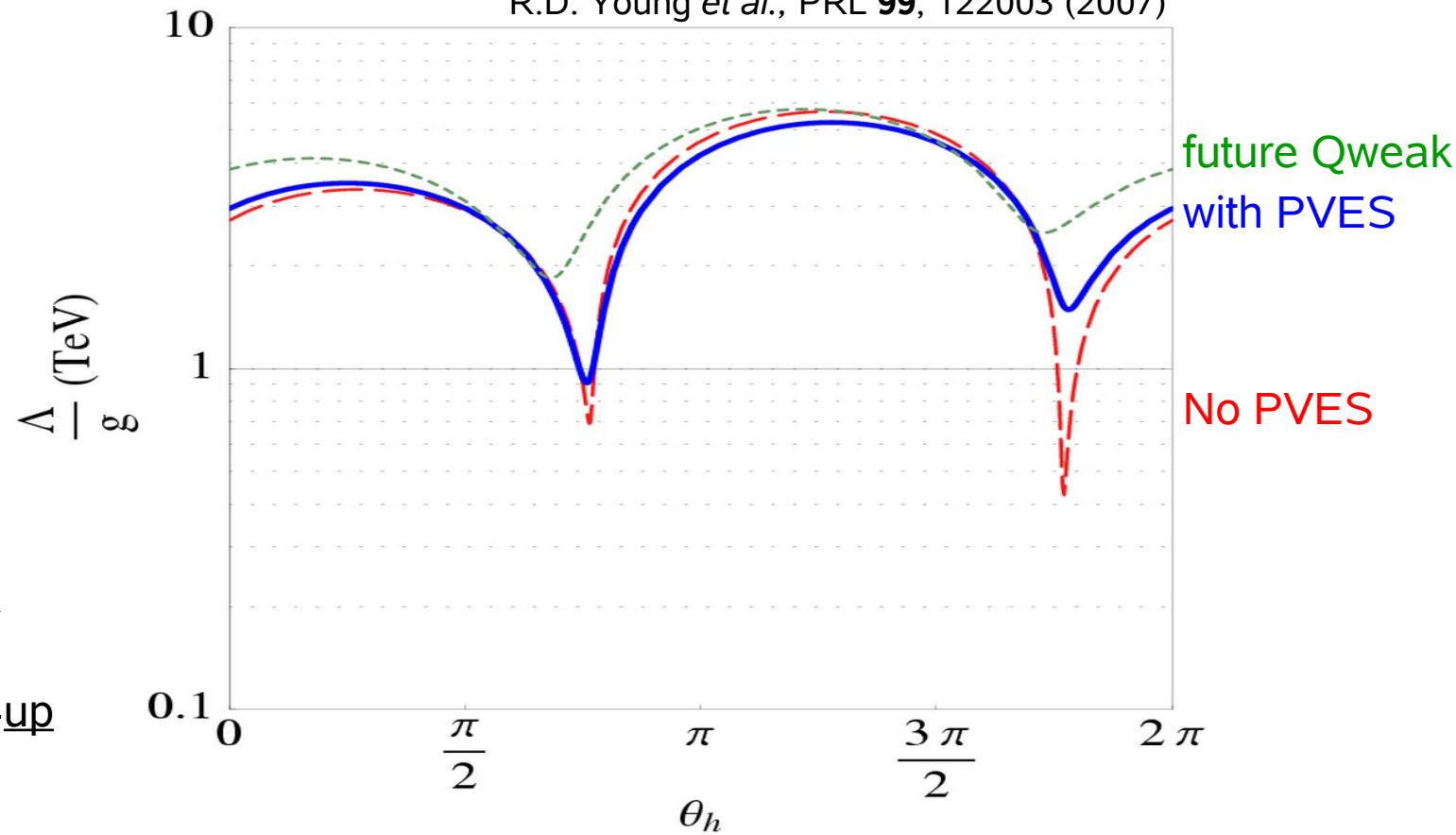
Full isospin coverage for limits on new physics!

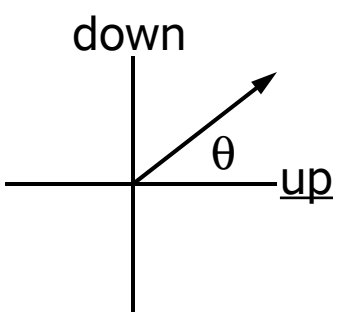
$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$

Data sets limits on $\frac{g^2}{\Lambda^2}$

Sensitivity to new physics depends on relative importance of the new up and down quark couplings

R.D. Young *et al.*, PRL **99**, 122003 (2007)





Qweak constrains new physics to beyond 2 TeV

Progress of Qweak -- Past

▪ May 2000	Collaboration formed
▪ July 2001	JLab Letter of Intent
▪ December 2001	JLab Proposal Submitted
▪ January 2002	JLab Proposal Approved with ‘A’ rating
▪ January 2003	Technical design review completed,
▪ 2003 - 2004	Funding approved by to DOE, NSF & NSERC
▪ January 2005	JLAB Jeopardy Proposal approved with ‘A’ rating
▪ March 2007	Two day engineering run (at end of G zero) Beam noise and target boiling studies.
▪ January 2008	PAC33 Jeopardy review. Qweak granted 198 PAC days as requested.

Progress of Qweak -- Present

As of April 2008:

- All QTOR magnet parts assembled and surveyed at MIT-Bates
- Power supply ready to go at MIT-Bates. Power-up 6 May 2008
- Field mapping with TRIUMF mapper to follow.
- All main preamplifiers delivered. TRIUMF VME modules ready later this summer.
- All silica (quartz) bars for main detectors are at JLab and being glued.
- LH2 target well under way. Expect LN2 pump tests this summer and cold helium gas tests later in year
- Hall C Compton proceeding. MIT chicane. Winnipeg electron detector.
- All Qweak geometry in incorporated in GEANT4 simulation.
- All tracking detectors designed and production started.
- Full 3D CAD model or experiment prepared at JLab. Designs proceeding on shield house, etc.
- JLab working on beamline instrumentation.

Progress of Qweak -- Future

Shutdown for JLab 12 GeV upgrade is scheduled for May 2012, so we must finish the full 4% measurement *before* then.

Possible schedule:

- April 2009 – Move magnet to JLab from MIT
- Oct 2009 start installation (6 months)
- Apr 2010 start engineering run (4 months)
- Aug 2010 start phase I (8%, 3 ½ months)
- Dec 2010 possible break then first part of phase II
- May 2011 start 6 month mini-shutdown
- Nov 2011 resume phase II running
- May 2012 beam off for 12 GeV upgrade; Qweak run ends.

The Qweak Collaboration

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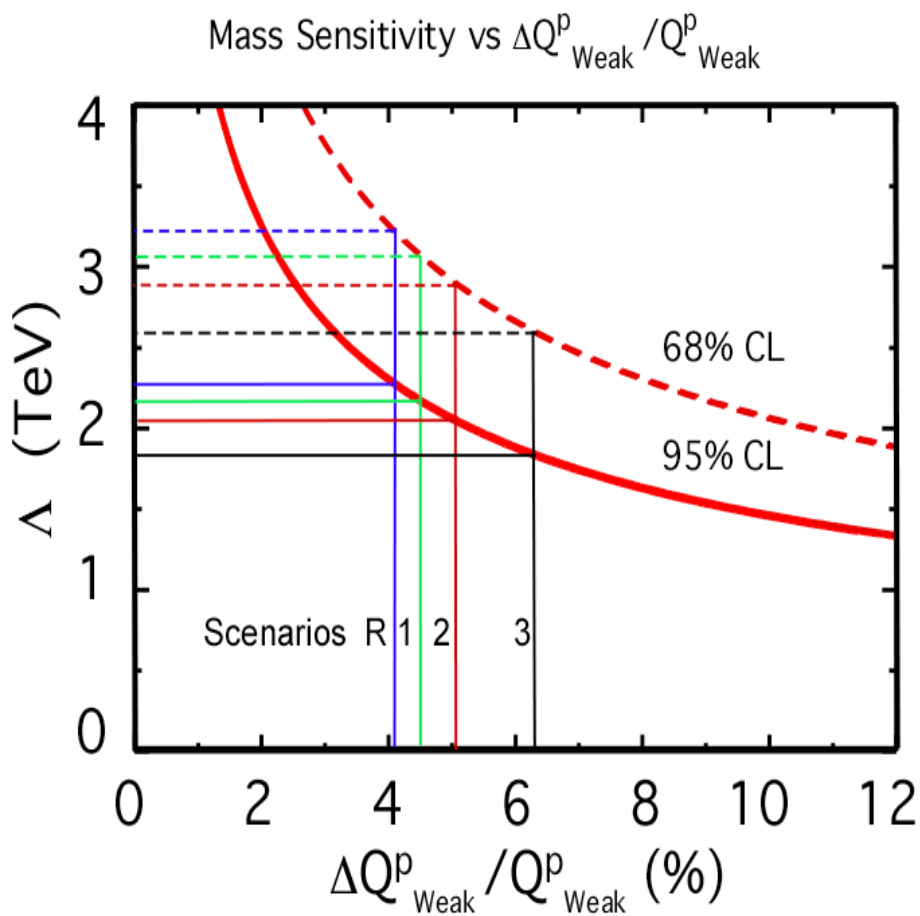
[1]Spokespersons [2]Project Manager

Institutions: 19 American, 4 Canadian, 1 Mexican, 1 British, 1 Armenian

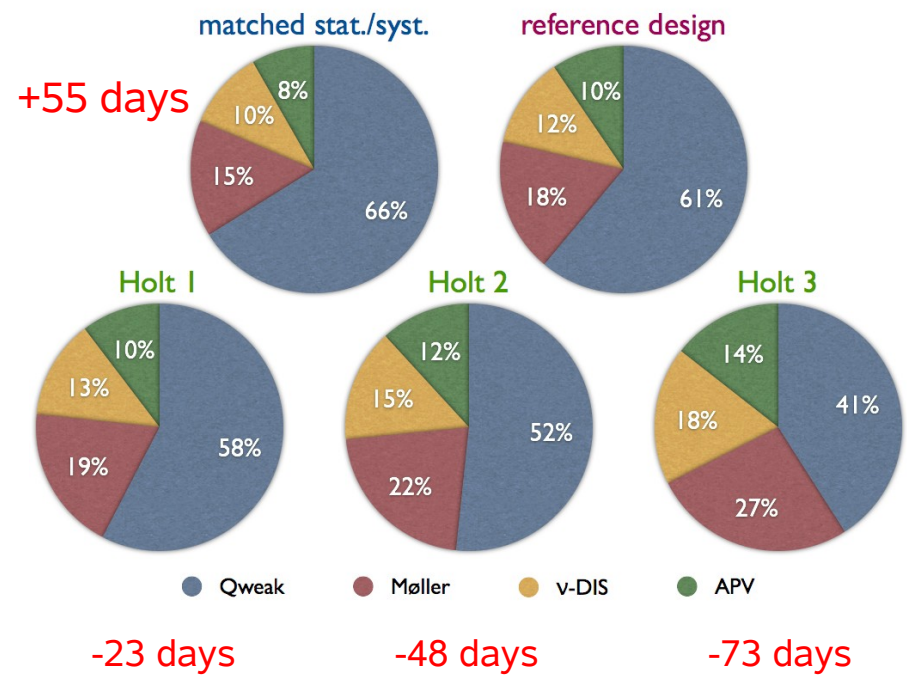
College of William and Mary, University of Connecticut, Instituto de Fisica, Universidad Nacional Autonoma de Mexico, University of Wisconsin, Hendrex College, Louisiana Tech University, University of Manitoba, Massachusetts Institute of Technology, Thomas Jefferson National Accelerator Facility, Virginia Polytechnic Institute & State University, TRIUMF, University of New Hampshire, Yerevan Physics Institute, Mississippi State University, University of Northern British Columbia, Cockroft Institute of Accelerator Science and Technology, Ohio University, Hampton University, University of Winnipeg, University of Virginia, George Washington University, Syracuse University, Idaho State University, University of Connecticut, Christopher Newport University

END

Energy Scale Sensitivity to Q^p_{Weak} Measurement Precision



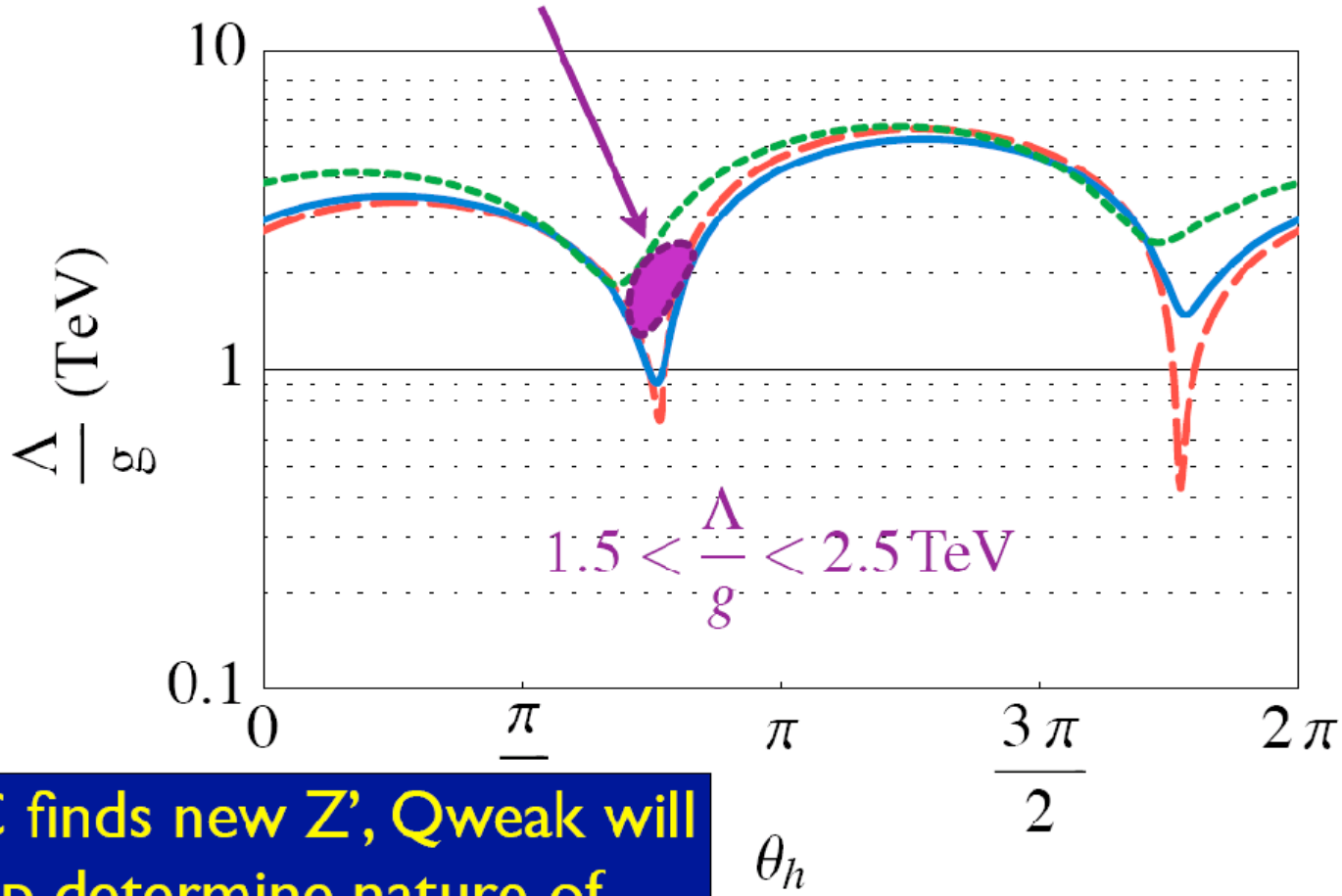
Relative contribution of Qweak to determination of $\sin^2\theta_w$ at low Q^2



- If LHC uncovers new physics, then precision low Q^2 measurements will be needed to determine charges, coupling constants, etc.

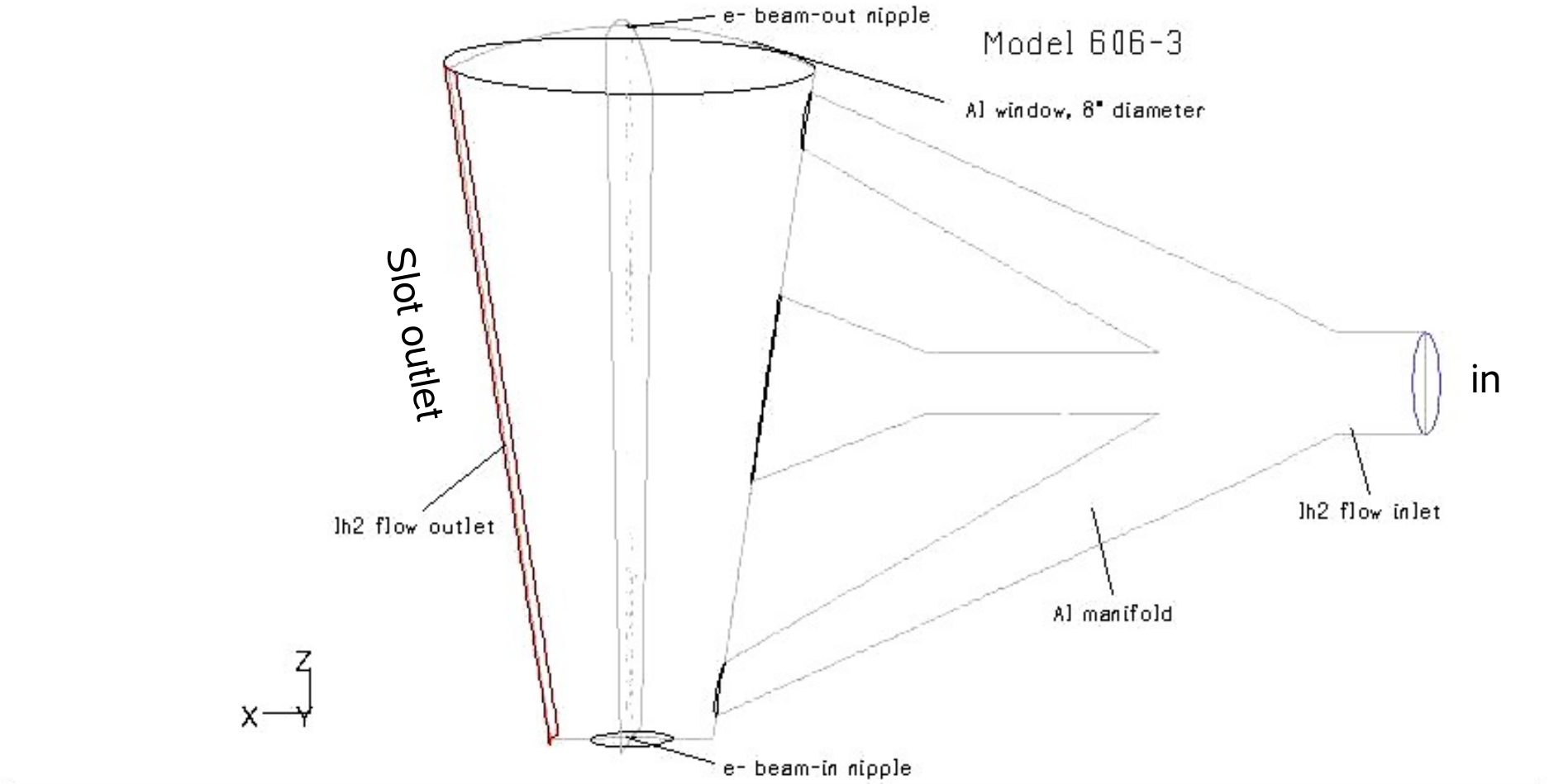
What about significant deviation from Standard Model?

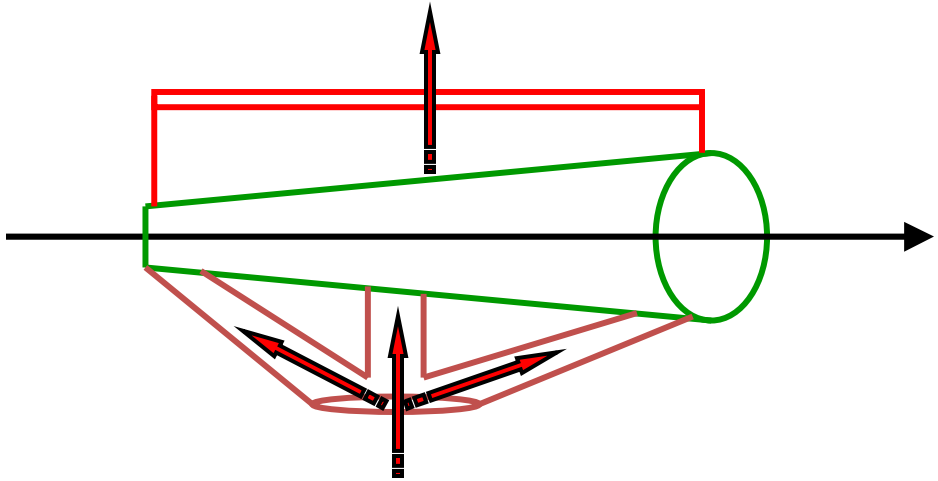
Assume Qweak takes central value of current measurements

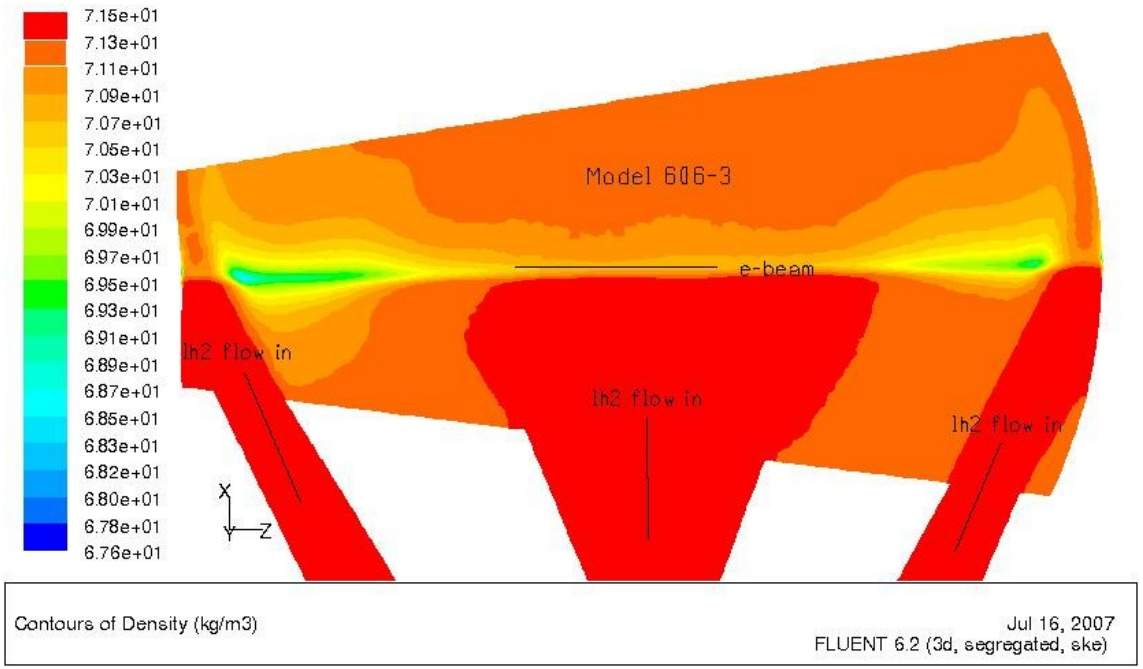


If LHC finds new Z', Qweak will help determine nature of interaction

Transverse Flow Model 606-3

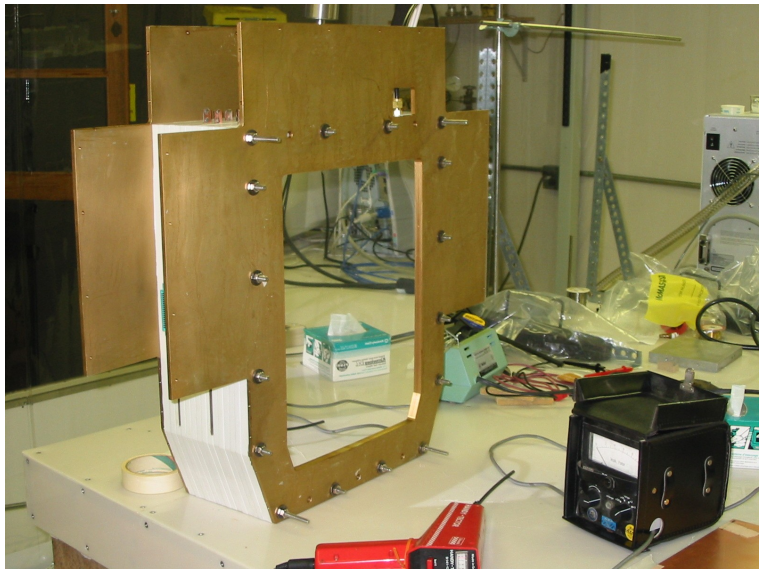


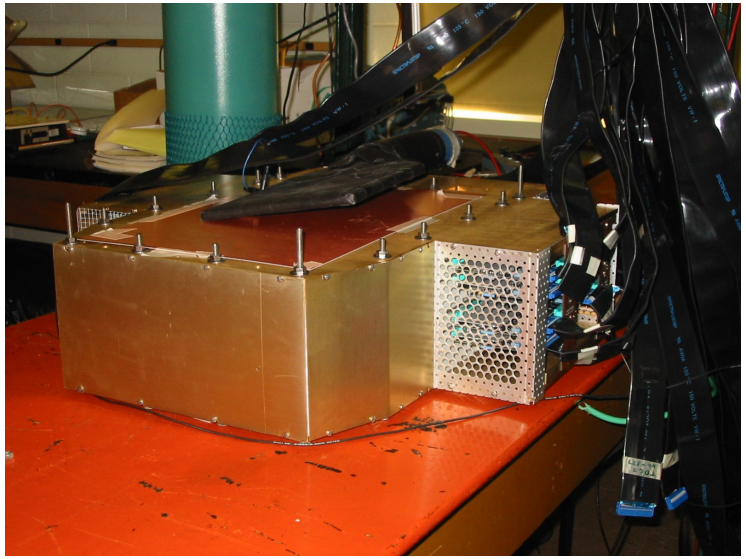


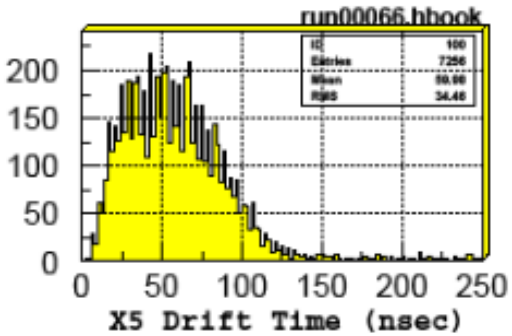

7.15e+01
7.13e+01
7.11e+01
7.09e+01
7.07e+01
7.05e+01
7.03e+01
7.01e+01
6.99e+01
6.97e+01
6.95e+01
6.93e+01
6.91e+01
6.89e+01
6.87e+01
6.85e+01
6.83e+01
6.82e+01
6.80e+01
6.78e+01
6.76e+01
Model 606-3
e-beam
lh2 flow in
lh2 flow in
lh2 flow in
X
Y
Z
Contours of Density (kg/m3)
Jul 16, 2007
FLUENT 6.2 (3d, segregated, ske)

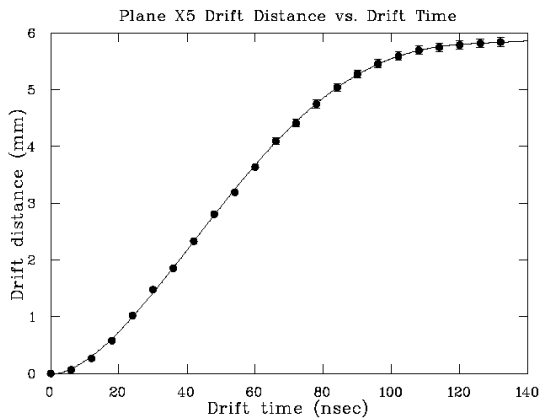
Region 2 First Production Chamber

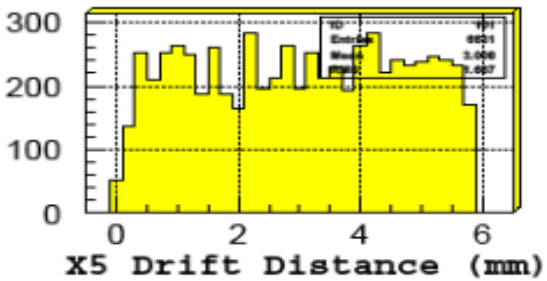
Region 2 chambers: horizontal drift chambers with 6 planes per chamber (xuvx'u'v')
active area 38 cm x 28 cm, wire pitch of 5.84 mm











Operational Parameters of the Q^p_{Weak} Experiment

Parameter	Value
Incident Beam Energy	1.165 GeV
Beam Polarization	85%
Beam Current	180 μA
LH_2 Target Length	35 cm (0.04 X_0)
Production Running Time	2544 hours
Nominal Scattering Angle	7.9 deg
Scattering Angle Acceptance	±3 deg
Acceptance	49% of 2π
Solid Angle	$\Delta\Omega$ = 37 msr
Acceptance Averaged Q^2	$< Q^2 > = 0.026$ (GeV / c)^2
Acceptance Averaged Physics Asymmetry	$< A > = -0.234$ ppm
Acceptance Averaged Expt'l Asymmetry	$< A > = -0.200$ ppm
Integrated Cross Section	4.0 μb
Integrated Rate (all sectors)	6.5 GHz (.81 GHz per sector)