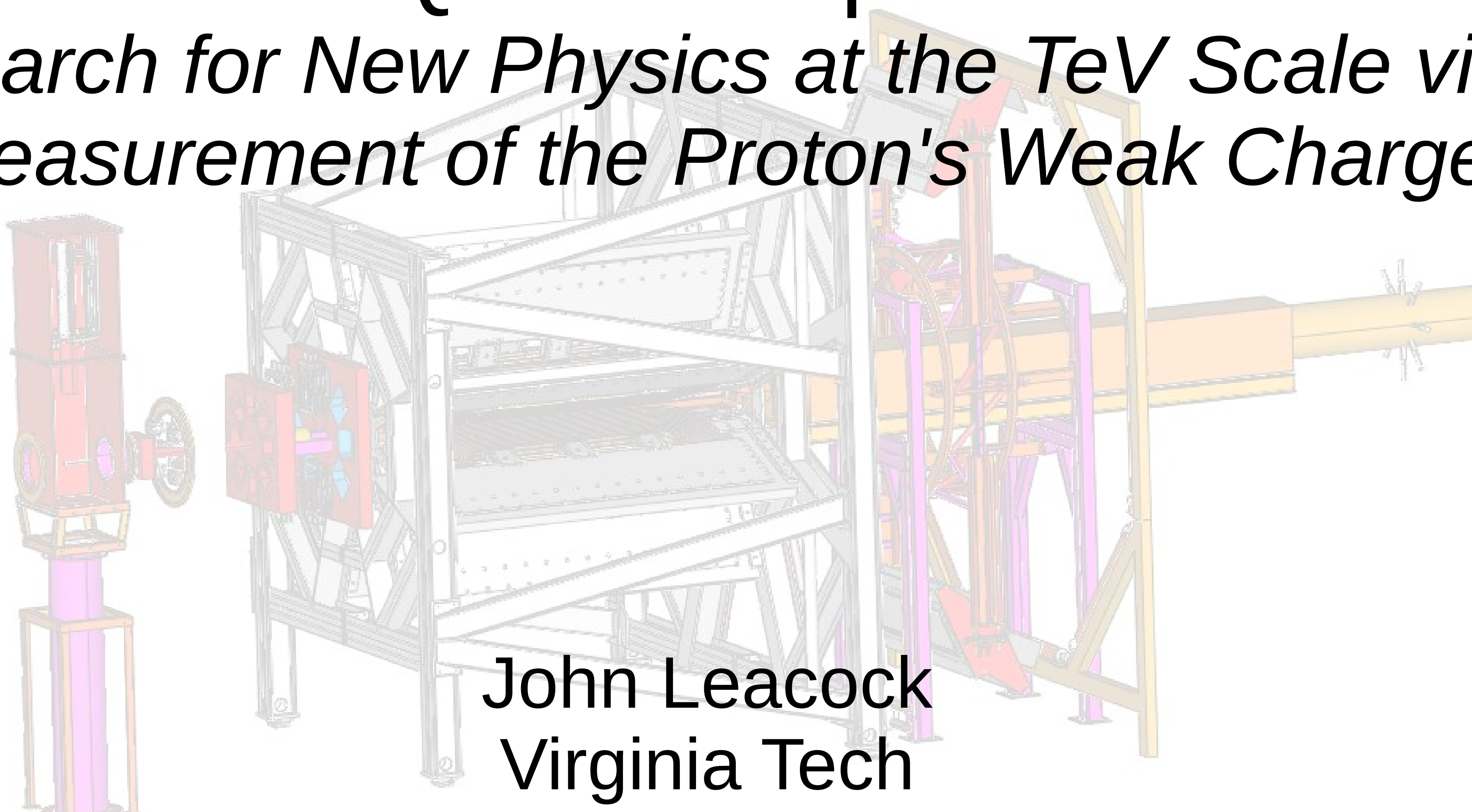
The Qweak Experiment

A Search for New Physics at the TeV Scale via a Measurement of the Proton's Weak Charge



John Leacock
Virginia Tech

2011 JLab User's Group Meeting
Jefferson Lab, Newport News, Virginia

Outline

Introduction to Qweak physics

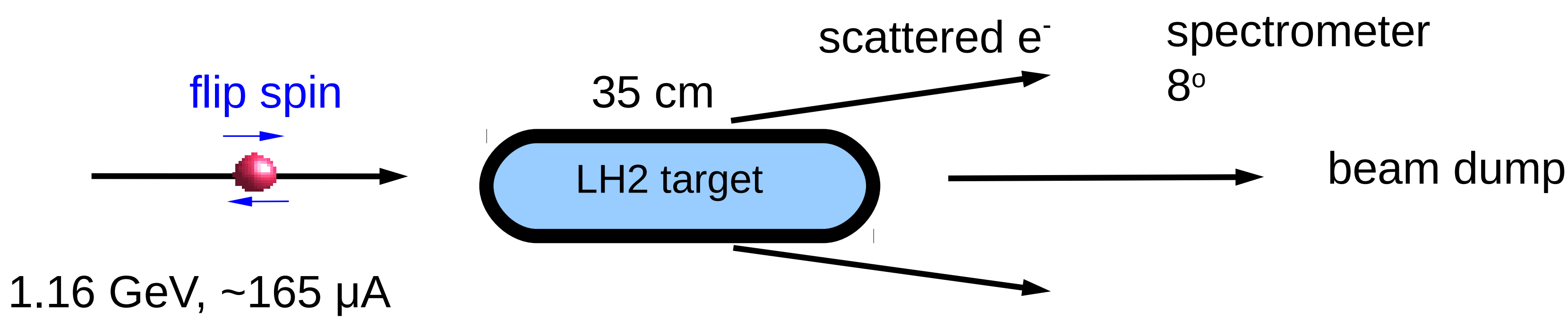
Overview and Performance of Qweak subsystems

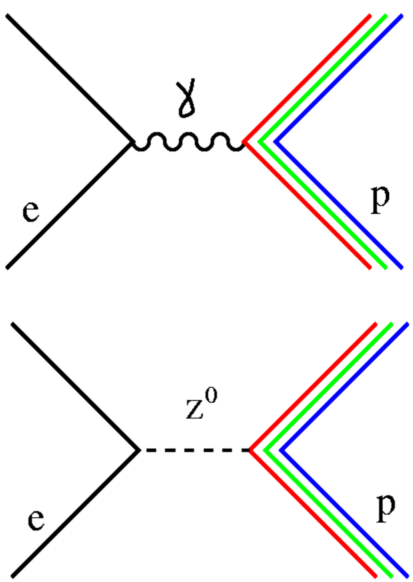
Expected Quality of the Results

Introduction to Qweak

$\vec{e}^{-} + \color{red}{p} \rightarrow e^{-} + \color{red}{p}$

The Qweak experiment is the measurement of elastically scattered longitudinally polarized electrons at forward angles.





	Q^{γ}	Q^{Z}	
u	$+2/3$	$1 - 8/3\sin^2\theta_W$	
d	$-1/3$	$-1 + 4/3\sin^2\theta_W$	
p(uud)	$+1$	$1 - 4\sin^2\theta_W$	≈ 0.07
n(udd)	0	-1	

suppressed

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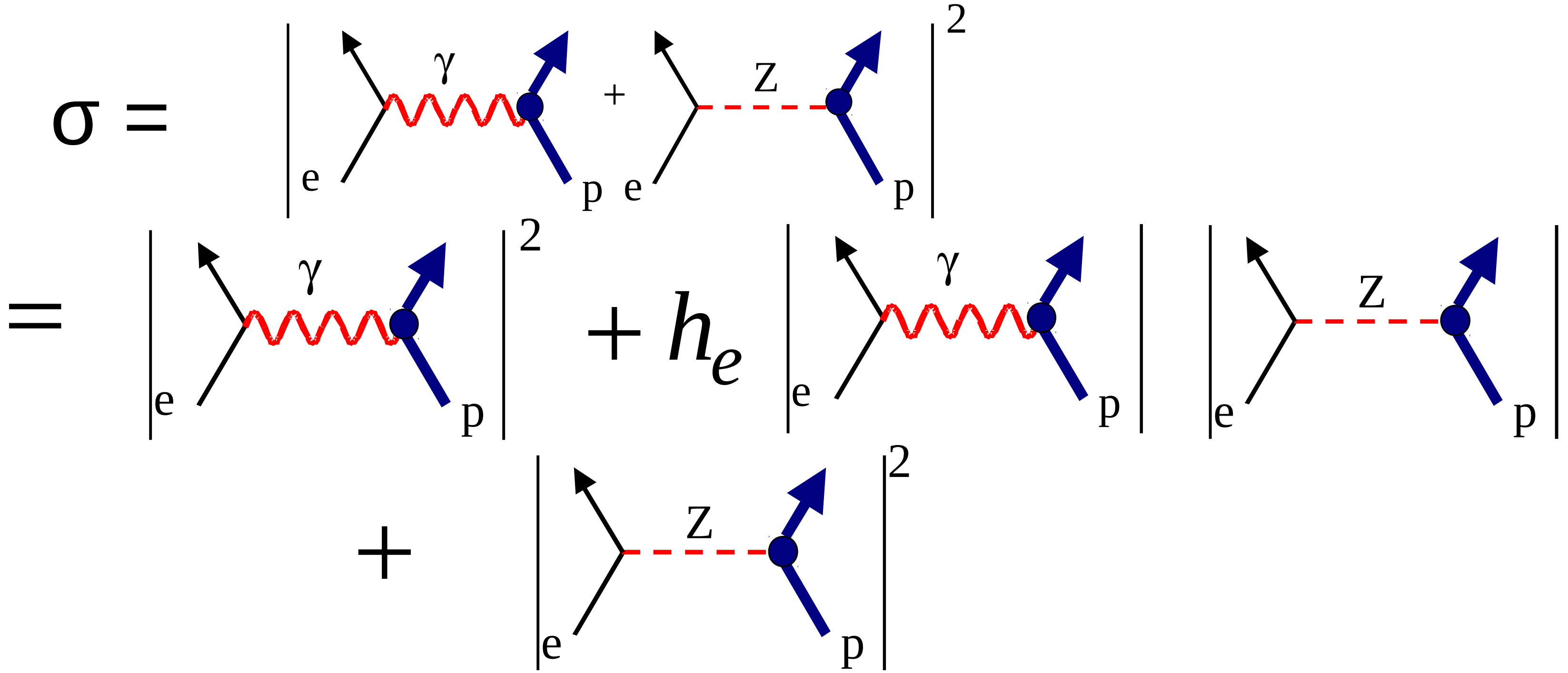
Exploiting Parity Violation

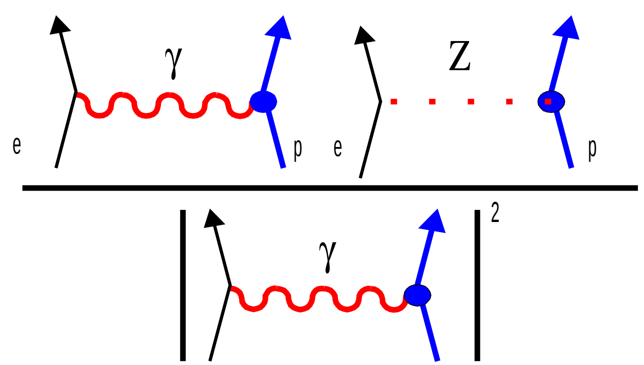
To access the weak interaction:

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

$\sigma =$



$A = \dfrac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$



$\sim$ -2.3 x 10^{-7}

or -0.23 ppm

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Asymmetry and the Weak Charge

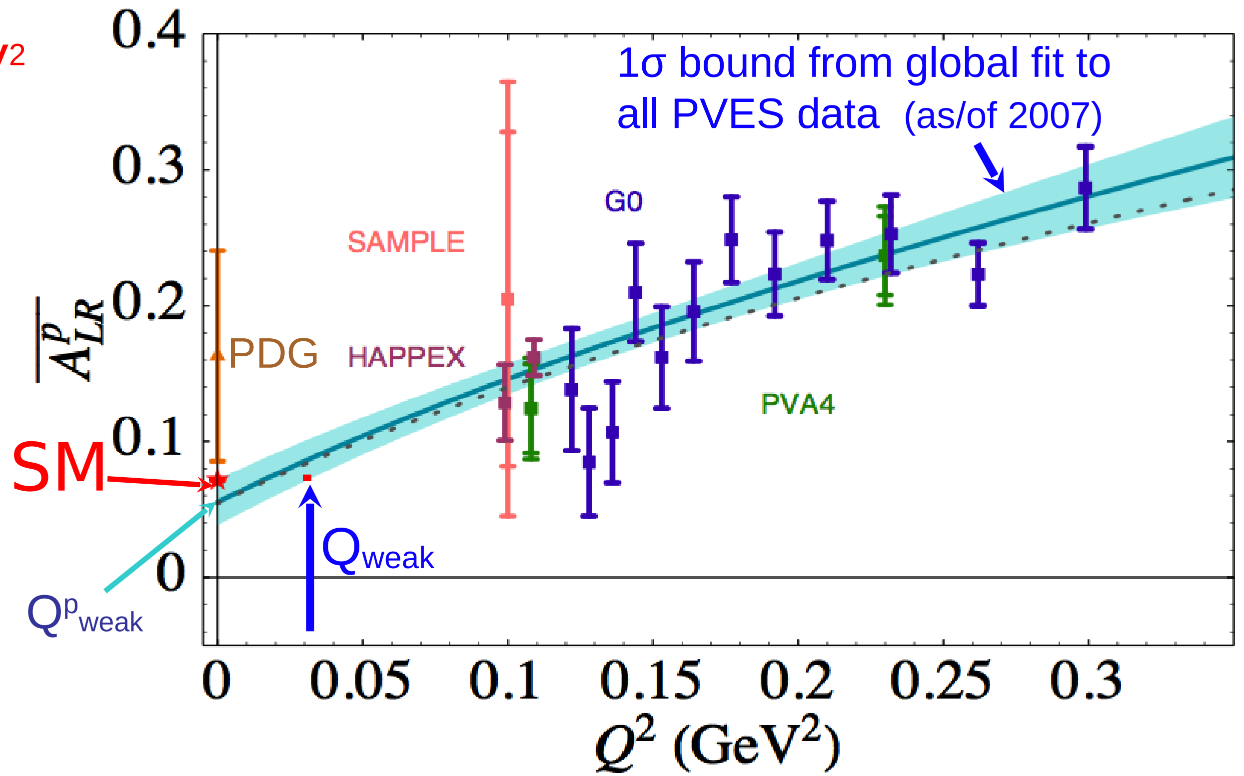
$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{2M_{NC}}{M_{EM}} = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q^p_{weak} + F^p(Q^2,\Theta)\right]$$

Qweak experiment $Q^2 \sim 0.026\ GeV^2$

Because the momentum transfer is small the Qweak experiment is relatively less sensitive to the internal structure of the proton.

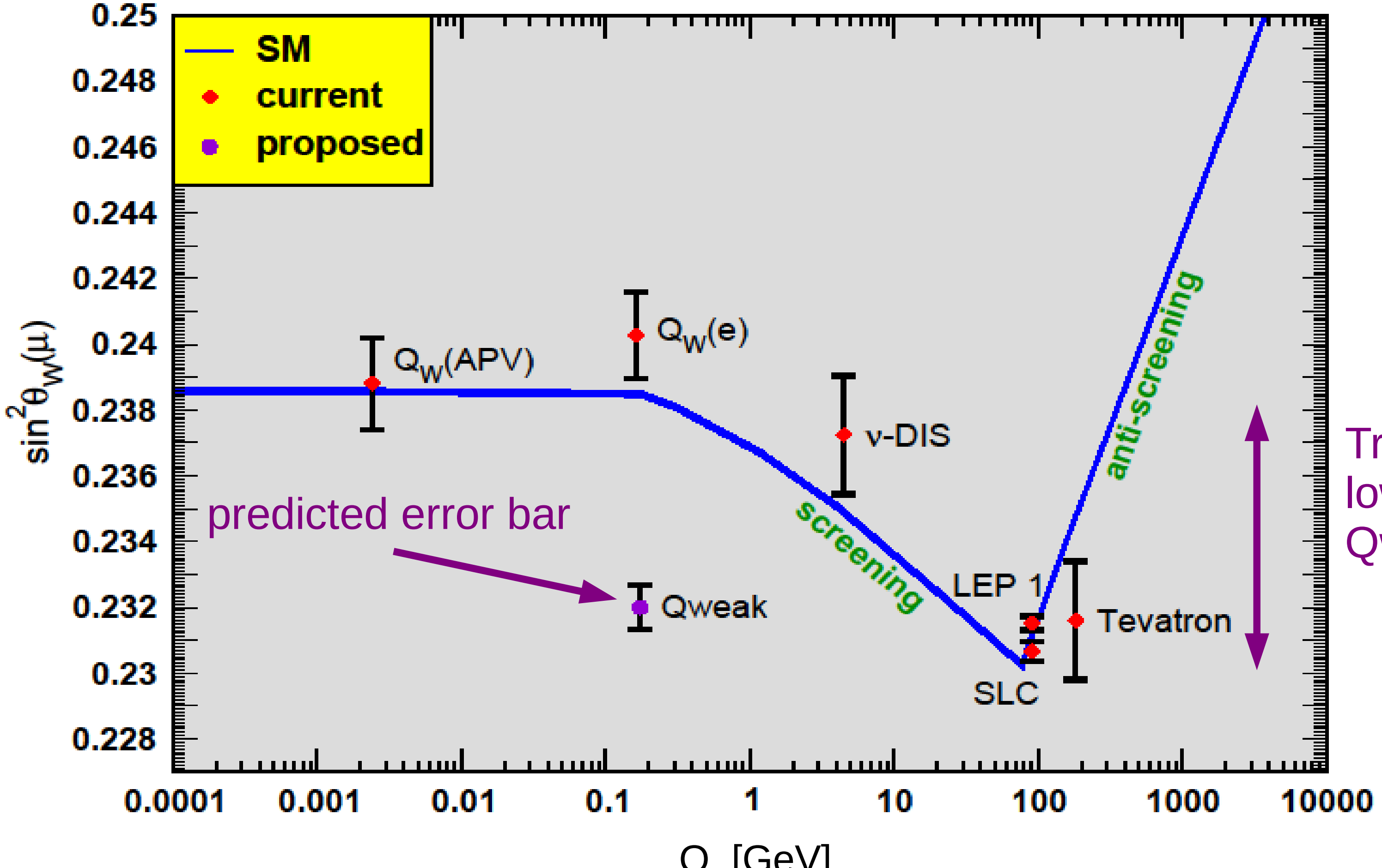
Hadronic contributions constrained by previous experiments.

as $Q^2 \rightarrow 0.026$ and $\Theta \rightarrow 8^o$



$$A = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q^p_{weak} + Q^4 B(Q^2,\Theta)\right] \sim -0.23\ ppm$$

Standard Model predicts $\sin^2\theta_W$ "runs" with Momentum Transfer



Transition from Z-pole to low Q is a 10 σ effect for Qweak

SM curve by: J. Erler, M. Ramsey-Musolf and P. Langacker

Any deviation from SM would signal "new physics"

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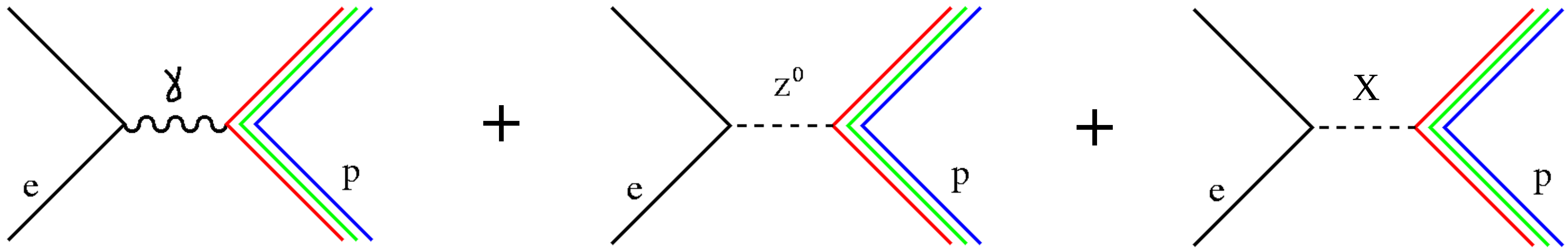
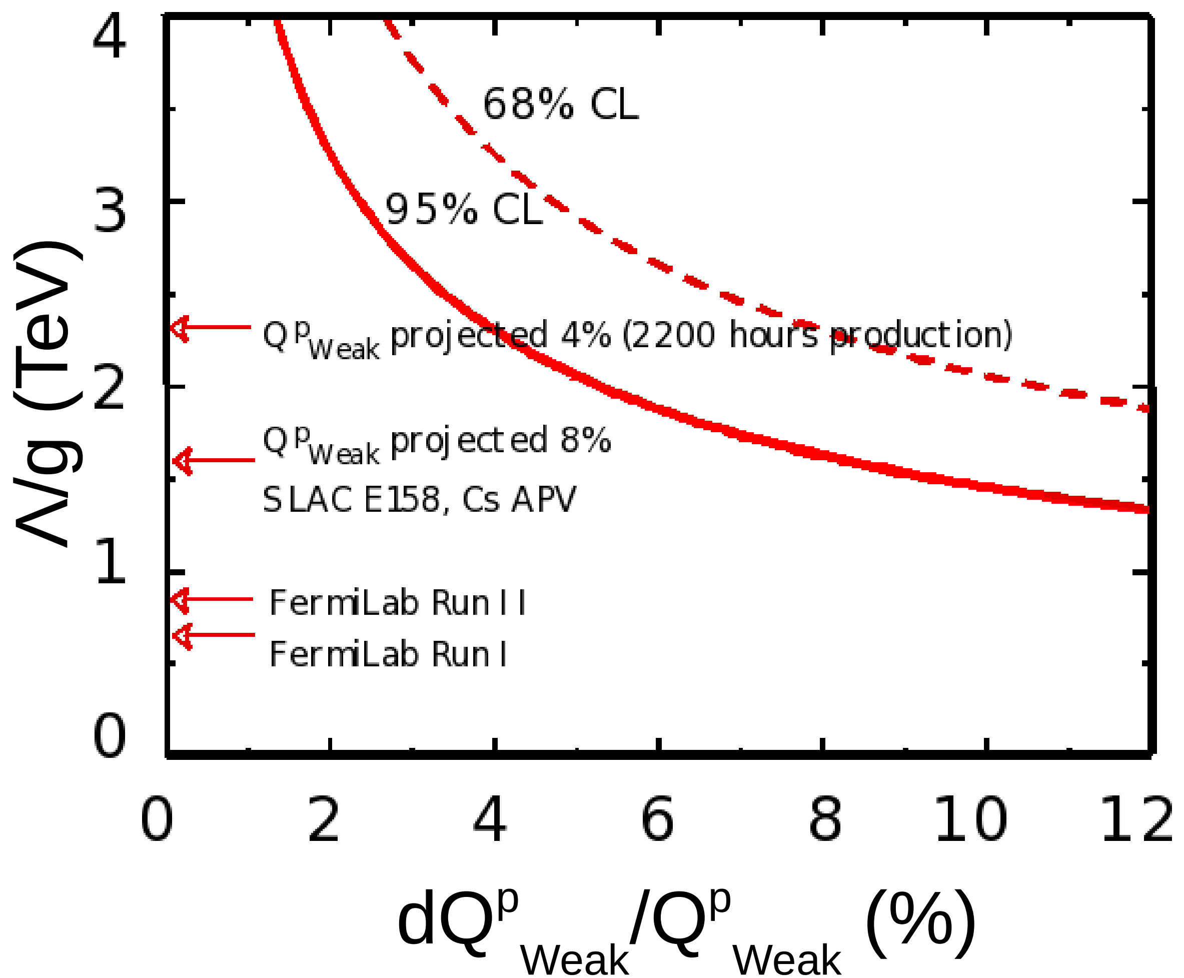
Indirect Probe of New Physics



A 4% Q^p_{Weak} measurement probes with 95% confidence level for new physics at energy scales to:

$$\frac{\Lambda}{g} \sim \frac{1}{2\sqrt{\sqrt{2}G_F|dQ_W^p|}} \sim 2.3\,TeV$$

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



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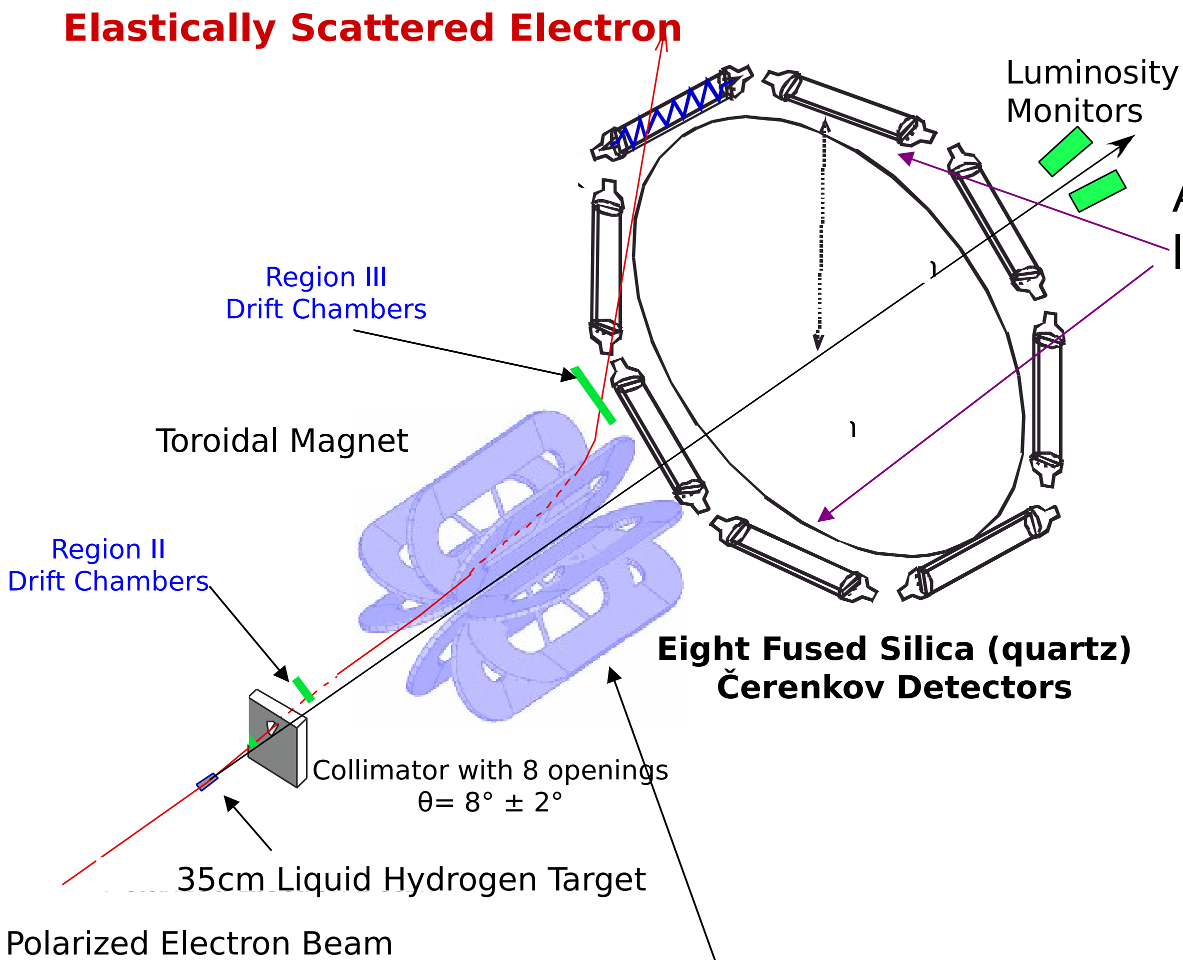
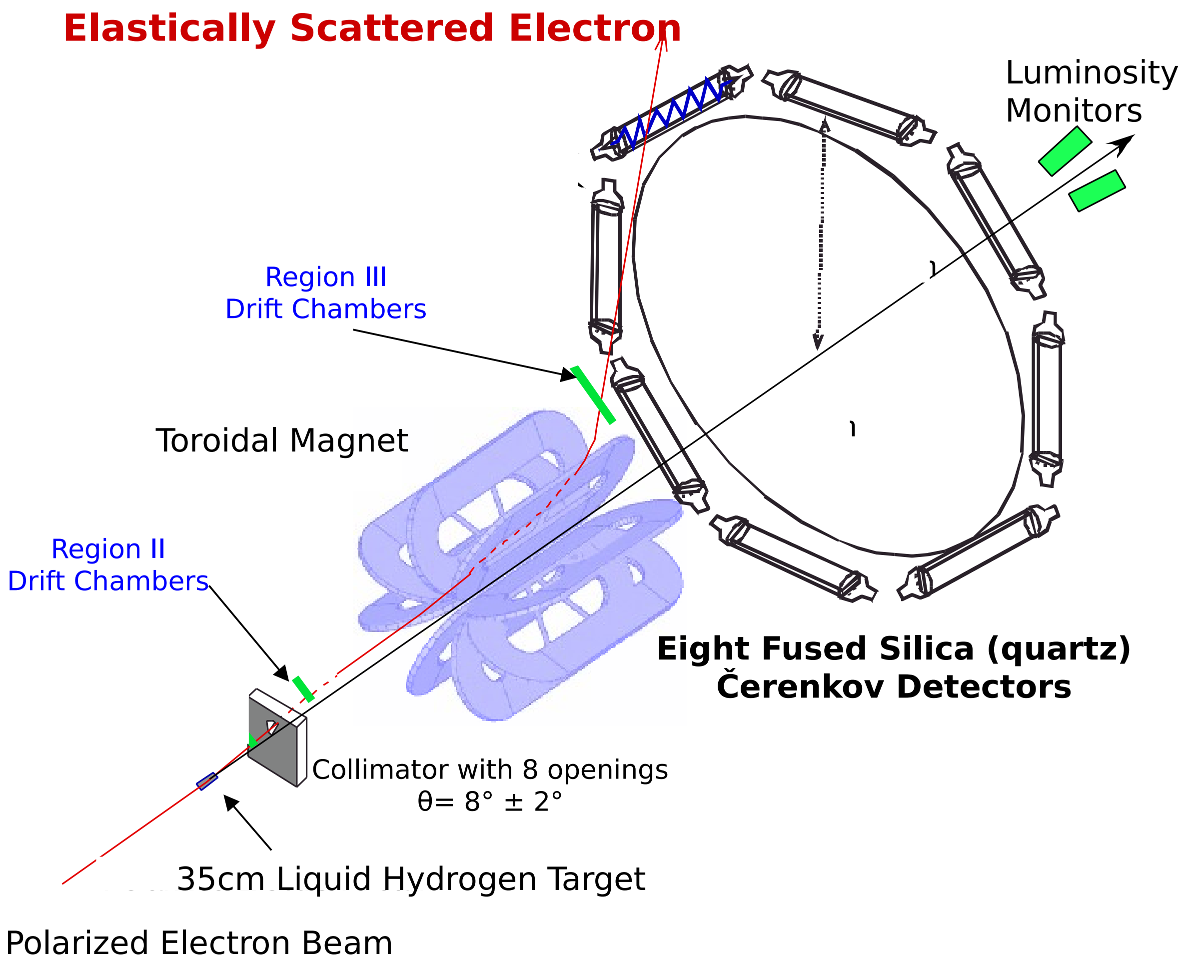
Qweak Overview



Azimuthally symmetric to limit false asymmetries.

Need to be sensitive to elastic scattering only: Magnet focuses elastics to detector and bends inelastics away

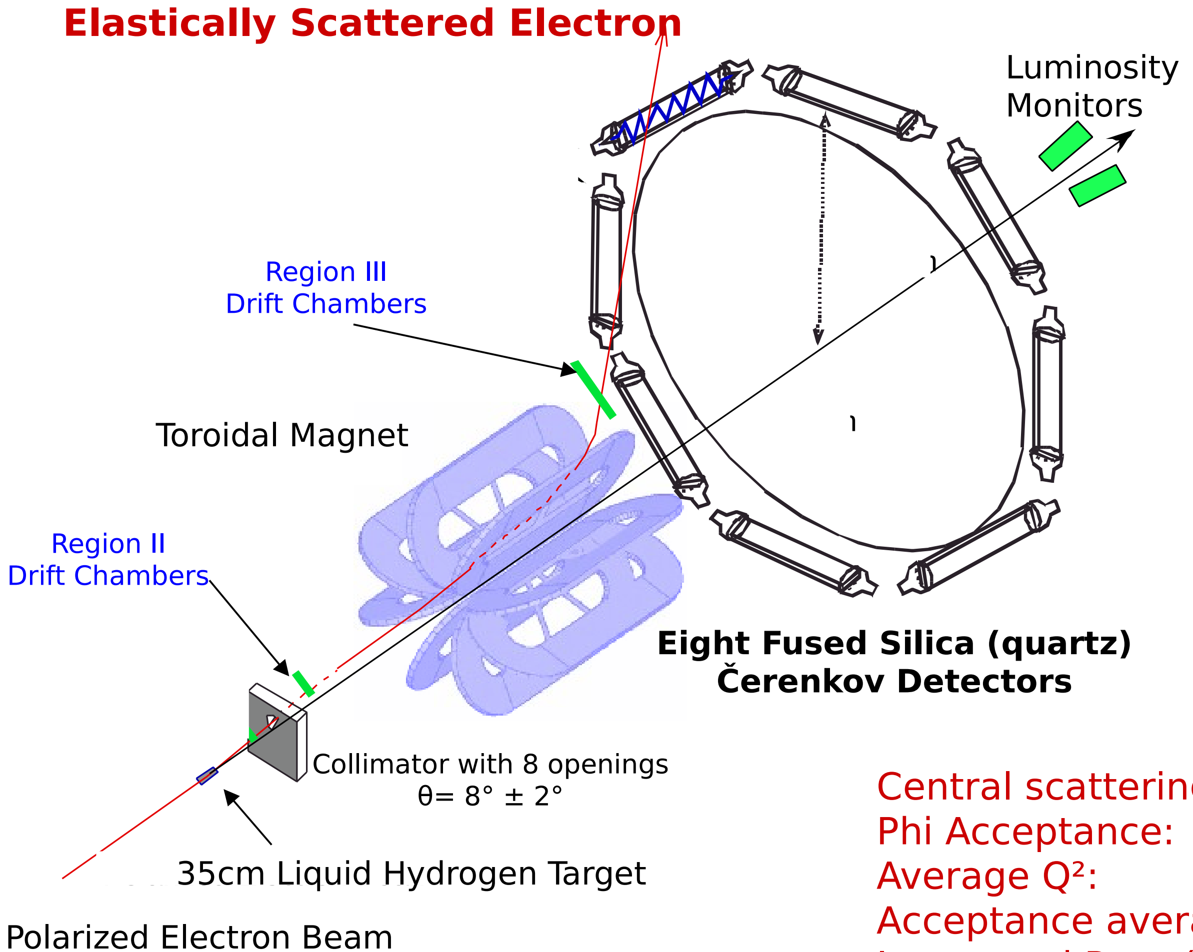
Qweak Overview



Experiment Parameters
(integration mode)

Incident beam energy:	1.16 GeV
Beam Current:	~165 μA
Beam Polarization:	89%
LH_2 target power:	2.5 kW

Qweak Overview



Experiment Parameters (integration mode)

Incident beam energy:	1.16 GeV
Beam Current:	~165 μA
Beam Polarization:	89%
LH_2 target power:	2.5 kW

Central scattering angle:	8° ± 2°
Phi Acceptance:	~50% of 2π
Average Q^2:	0.026 GeV^2
Acceptance averaged asymmetry:	–0.23 ppm
Integrated Rate (all sectors):	5.8 GHz
Integrated Rate (per detector):	730 MHz

Technical Requirement Drivers

Statistics: $$A_{meas} = P_e(1-f)A_{phys}(Q^2) + fA_{back} + A_{false}$$

- Small counting statistics error (Γ_{count}) (~10^{17} events): $\rightarrow$ $\Gamma_{count} \propto \frac{1}{\sqrt{N}}$
  - reliable high polarization, high current polarized source
  - high power cryogenic LH_2 target
  - large acceptance and high count rate

While minimizing contributions of random noise from

$$\Gamma_{total} = \sqrt{\Gamma^2_{count} + \Gamma^2_{electronics} + \Gamma^2_{target}}$$

- target density fluctuations (Γ_{target})
- electronics noise (in integrating mode) ($\Gamma_{electronics}$)

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Technical Requirement Drivers

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While minimizing contributions of random noise from

- target density fluctuations (Γ_{target})
- electronics noise (in integrating mode) ($\Gamma_{electronics}$)

$$\Gamma_{total} = \sqrt{\Gamma_{count}^2 + \Gamma_{electronics}^2 + \Gamma_{target}^2}$$

Systematics:

- High precision electron beam polarimetry (P_e)
- Precision Q^2 determination ($A_{phys} \propto Q^2$)
- To measure dilution due to backgrounds and background asymmetry (fA_{back})
- To minimize helicity-correlated beam properties (A_{false})

Source of error	Contribution to $\Delta A_{phys}/A_{phys}$	Contribution to $\Delta Q_w^p / Q_W^p$
Counting Statistics	2.1%	3.2%
Hadronic structure	—	1.5%
Beam polarimetry	1.0%	1.5%
Absolute Q^2	0.5%	1.0%
Backgrounds	0.5%	0.7%
Helicity-correlated beam properties	0.5%	0.7%
TOTAL:	2.5%	4.1%

Q weak

NSF

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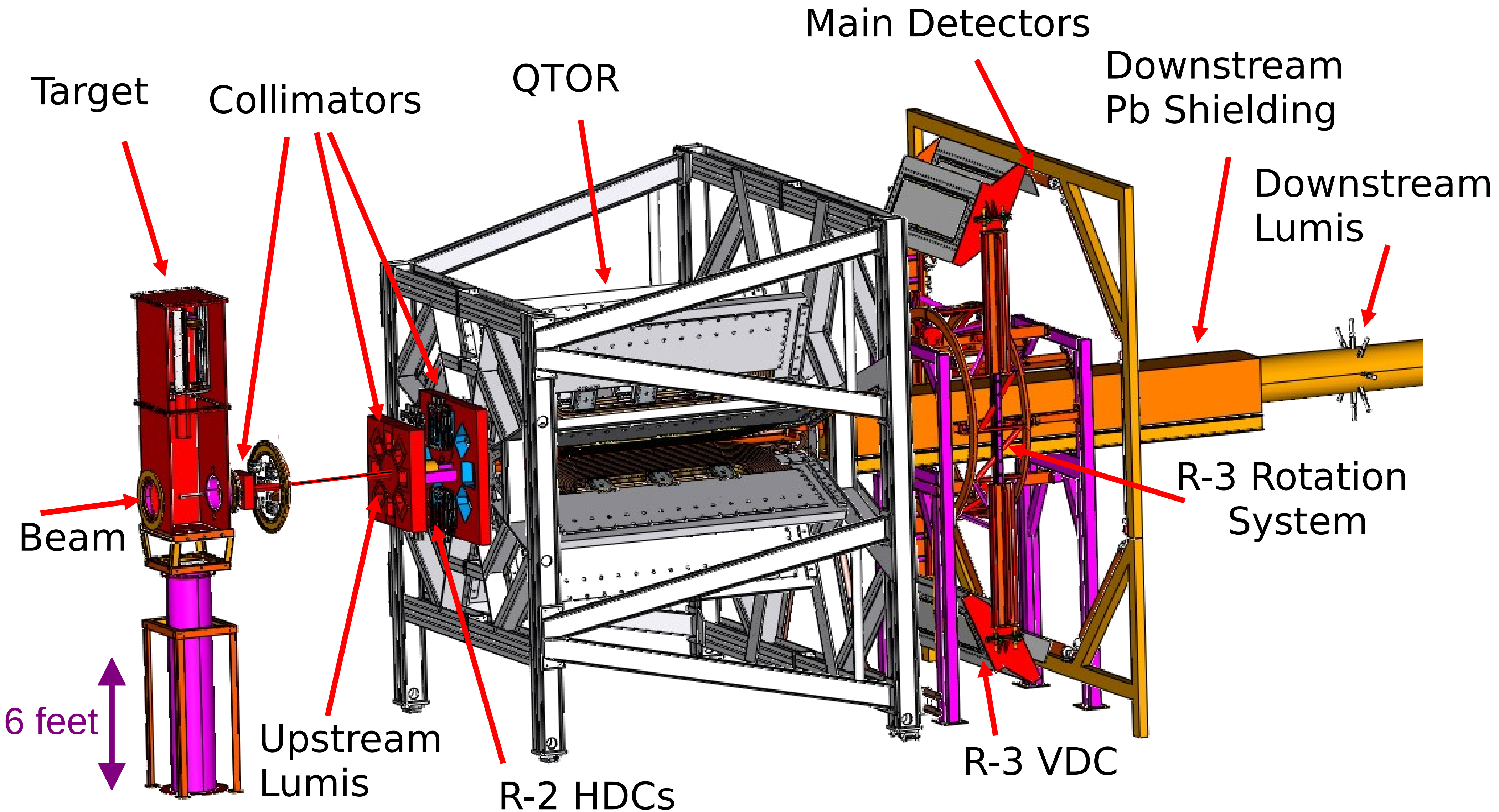
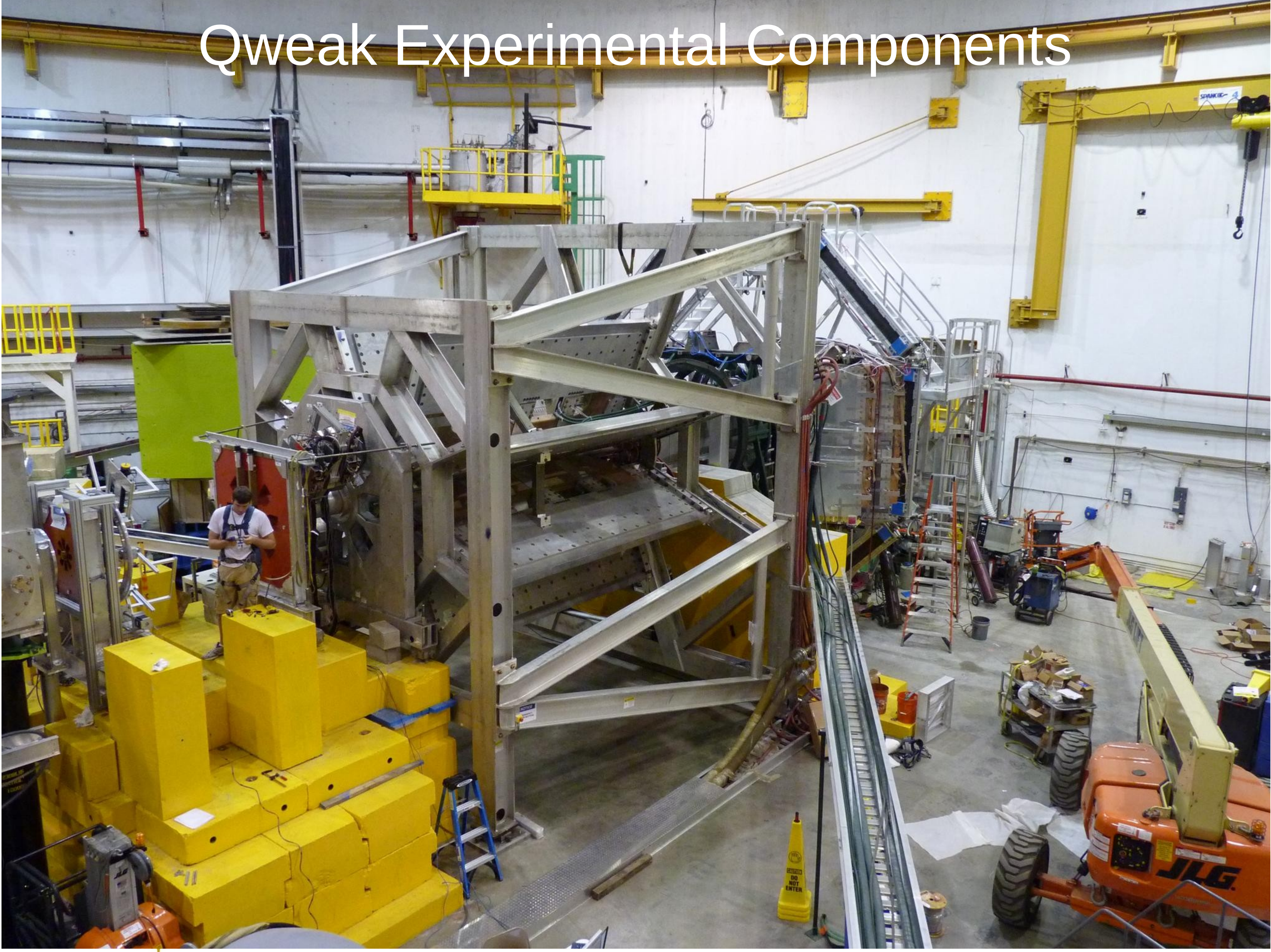
Qweak Experimental Components



"Current Mode": ~165 µA, integrate detector signals for ~1 ms
"Event Mode": 50 pA – 100 nA, insert tracking system, count individual pulses

Qweak Experimental Components



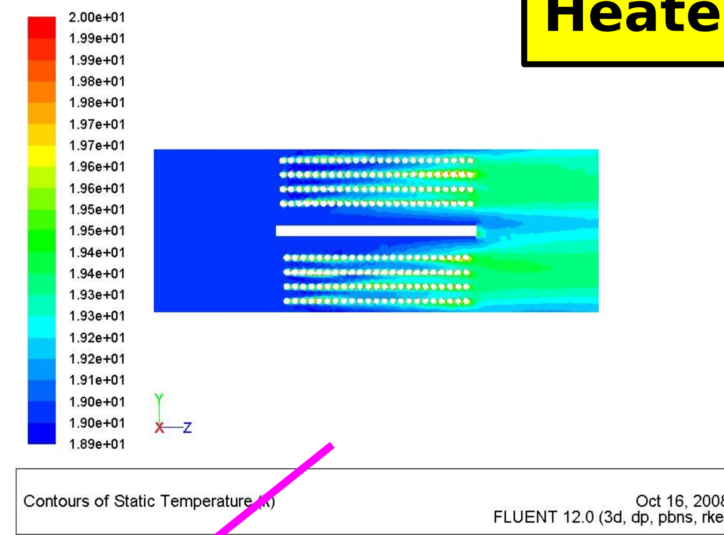
Qweak Target

World's highest power cryotarget
2500 W

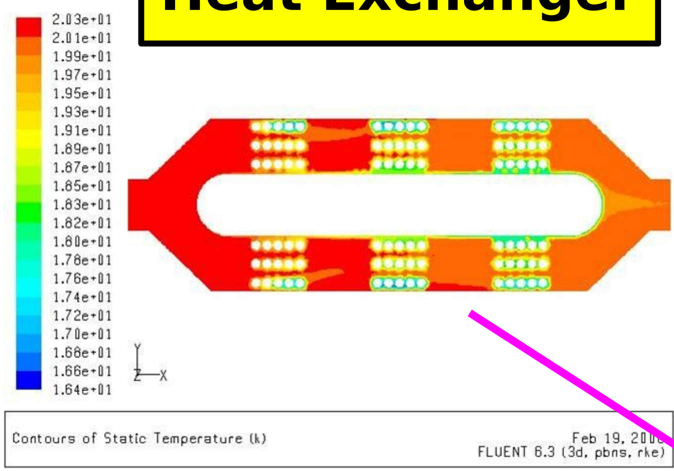
Density fluctuations small

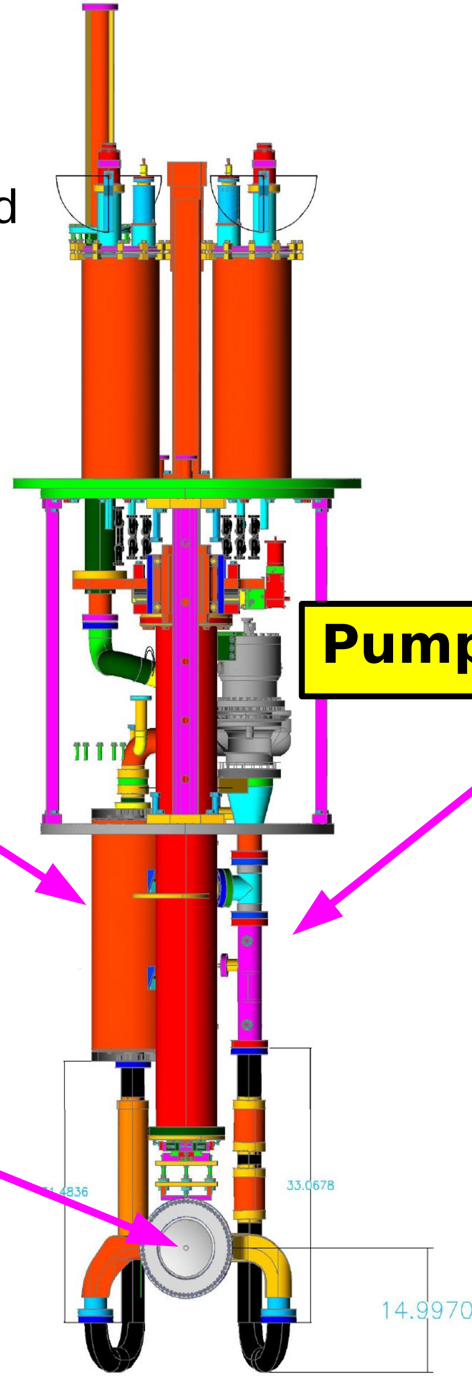
Designed using Computational Fluid Dynamics (CFD by Silviu Covrig)

Heater

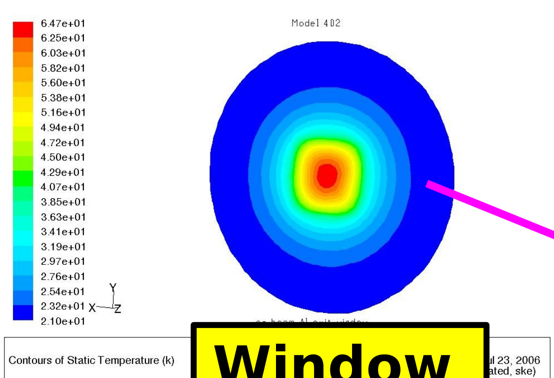


Heat Exchanger





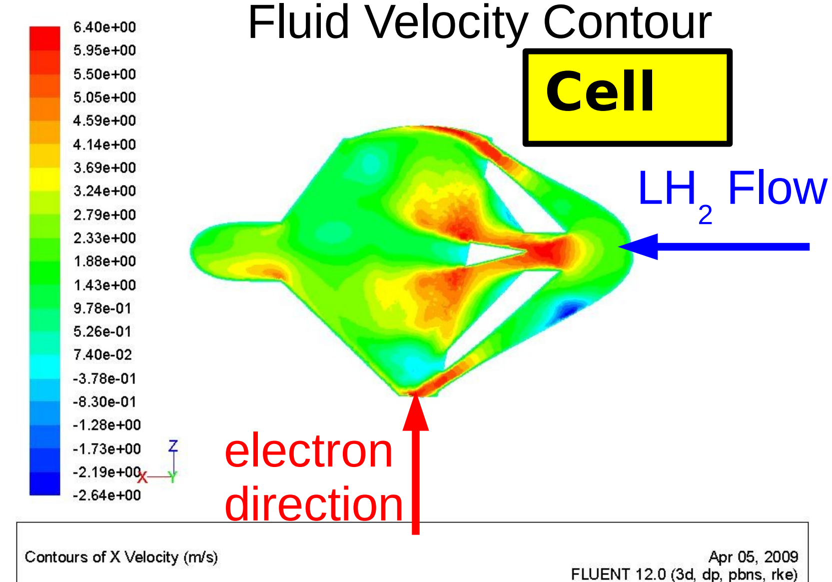
Pump



Window

Fluid Velocity Contour

Cell



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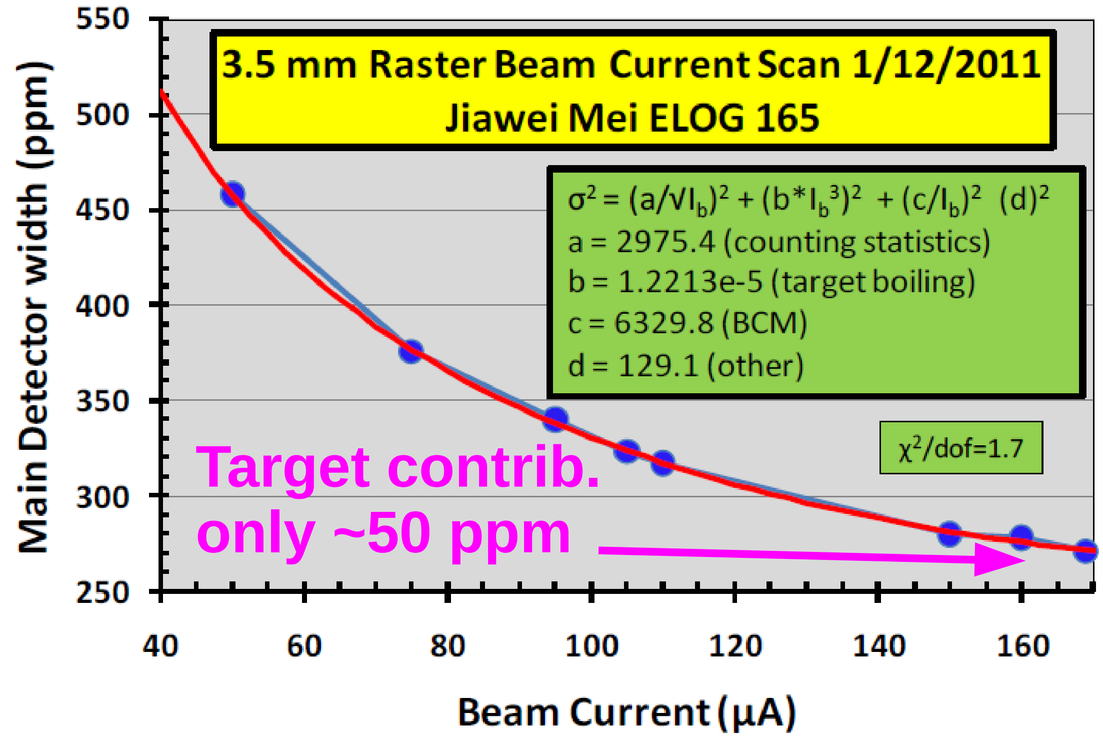
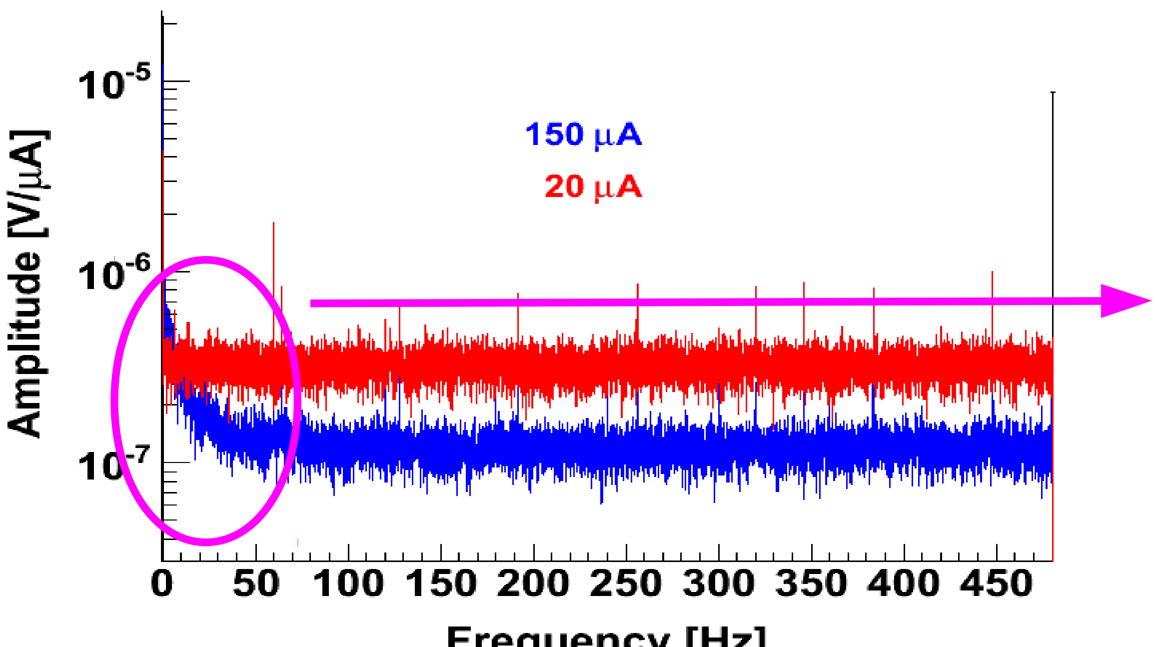
Target Density Studies

If the Main Detector asymmetry RMS or "width" is dominated by particle counting statistics then:

$$\sigma \propto \frac{1}{\sqrt{I}}$$

If not, then there is likely significant noise coming from another source, such as target density fluctuations.



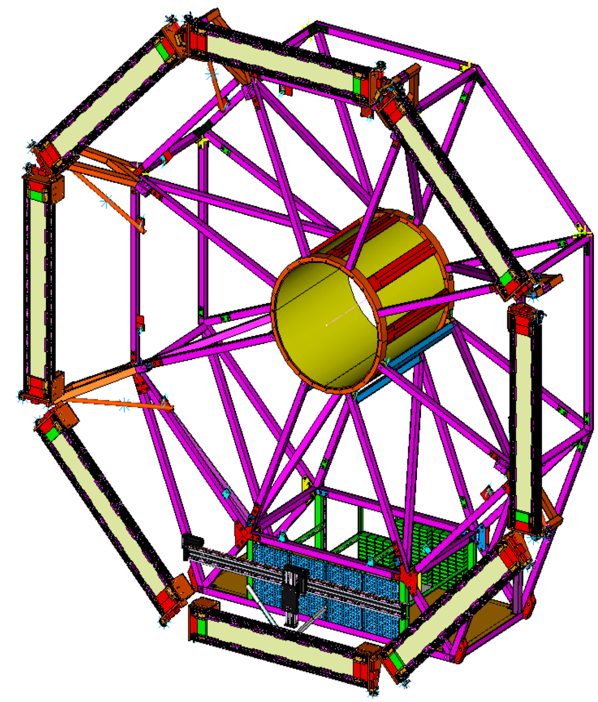


- density fluctuations are seen at high currents
- but the frequency of the fluctuations is much lower than our data taking rate (960 Hz)
- only a small contribution to total width
- width is dominated by counting (good)

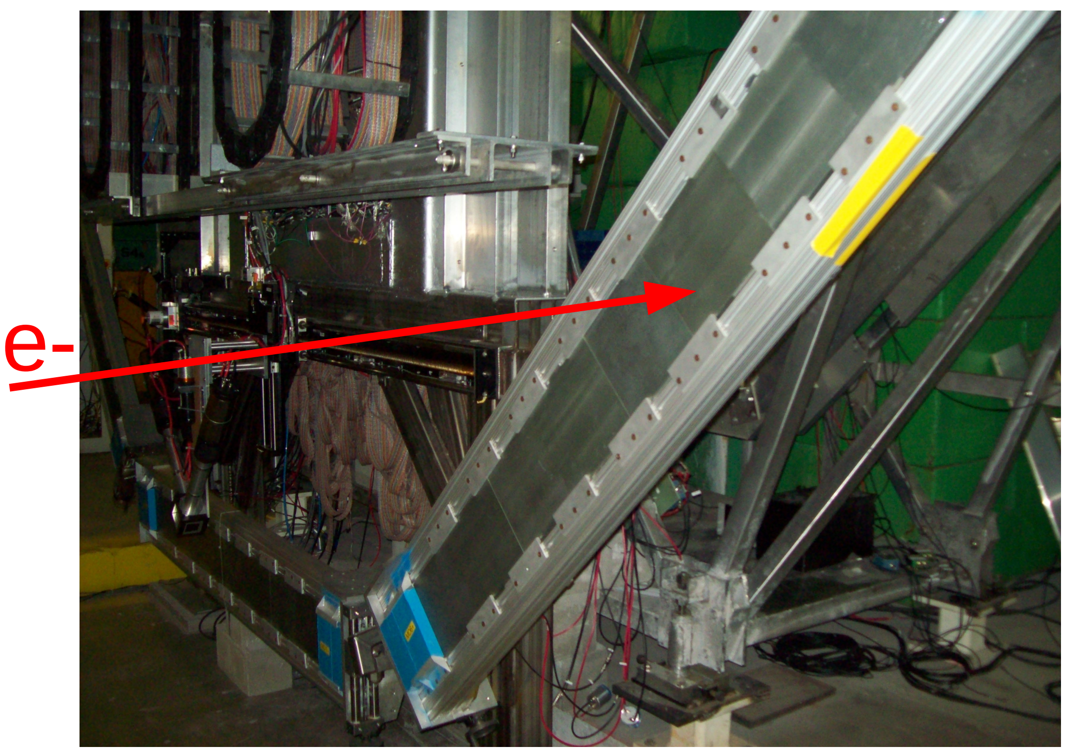
Main Detectors

Eight fused silica bars with dimensions 200 x 18 x 1.25 cm

- Cerenkov radiator
- low noise electronics; high precision ADCs
- radiation hard
- background insensitive
- preradiated to boost signal and kill backgrounds

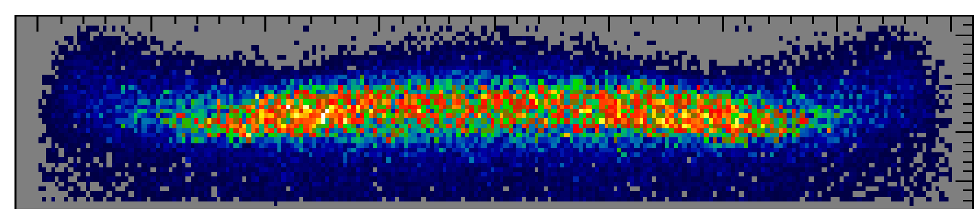


QTOR focuses the elastically scattered electrons onto each bar

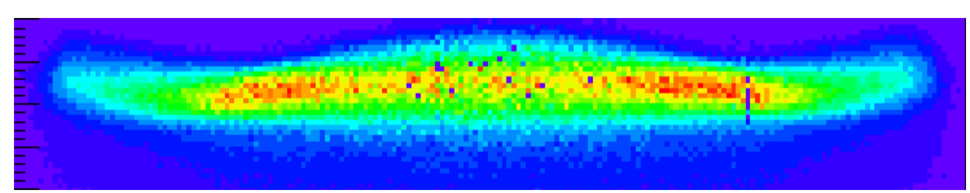


Scanner Rate map on MD face

Simulated



As measured



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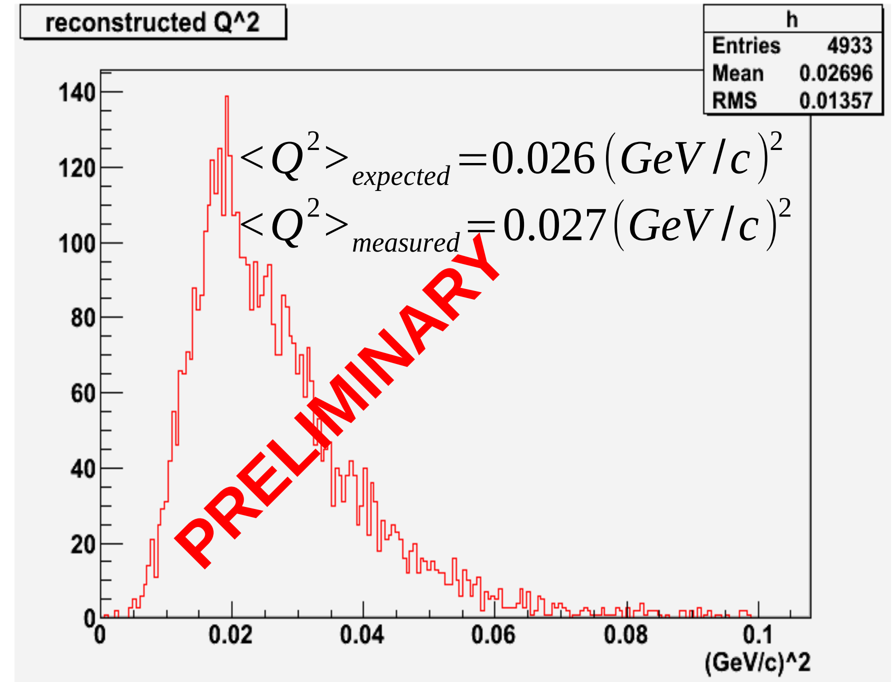
Qweak Particle Tracking System

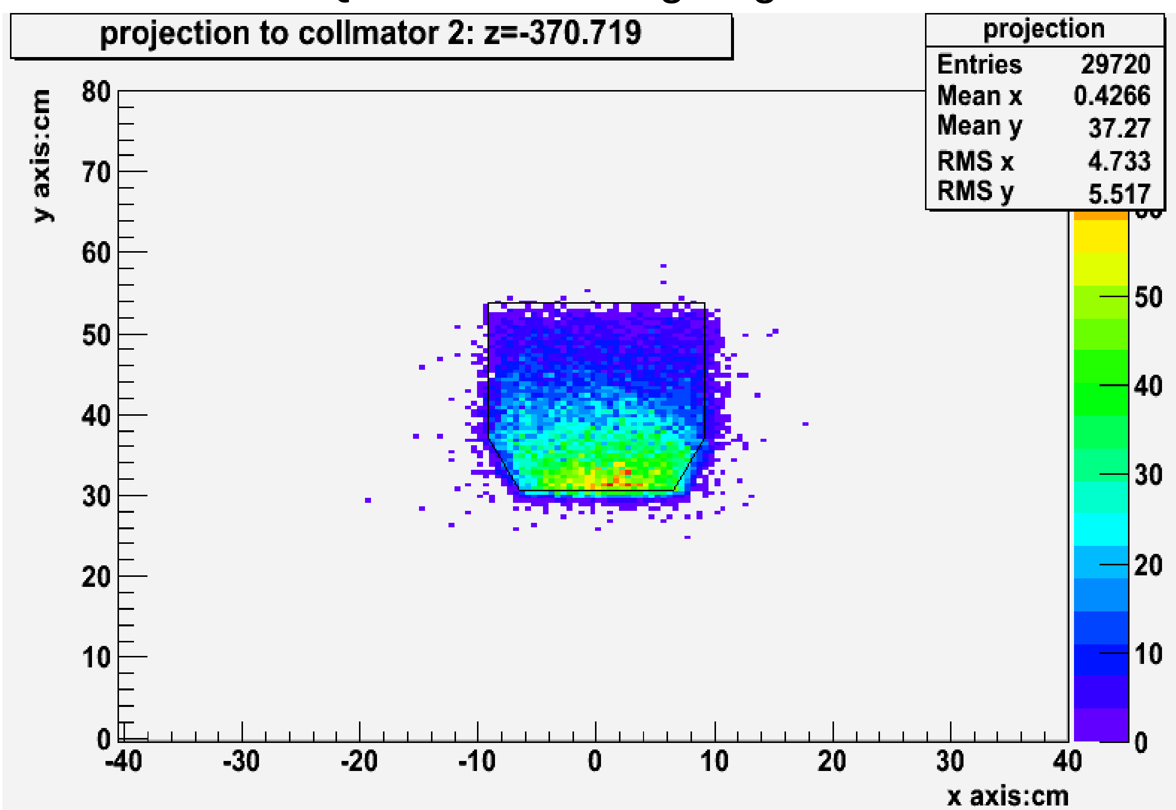
Motivation:
Need 0.5% determination of Q^2

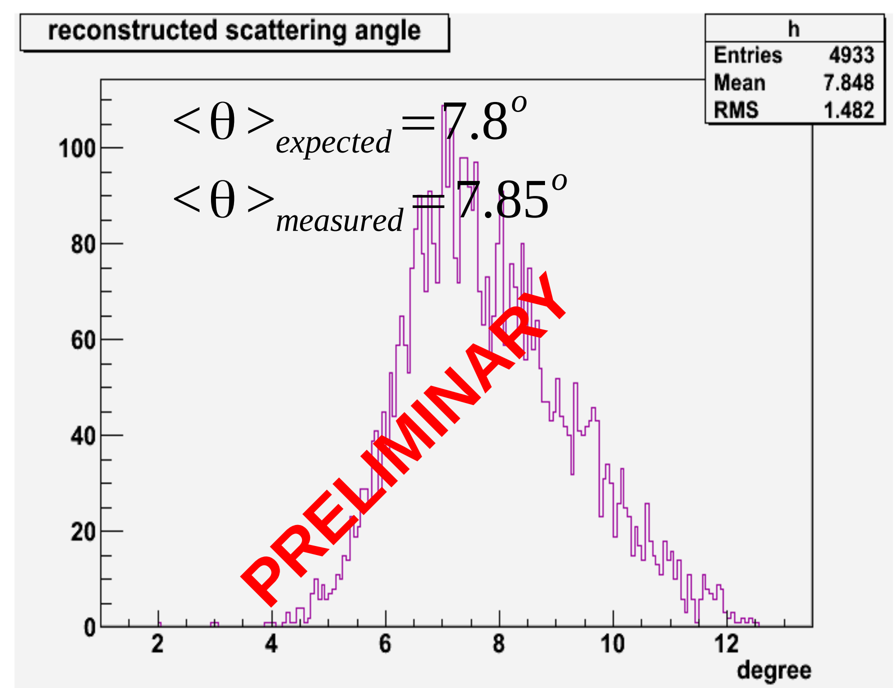
as the electron flies

1^{st} collimator
2^{nd} collimator
horizontal drift chambers (partial tracks)
QTOR
vertical drift chambers (partial tracks)

use the partial tracks and magnetic field to reconstruct Q^2 and scattering angle



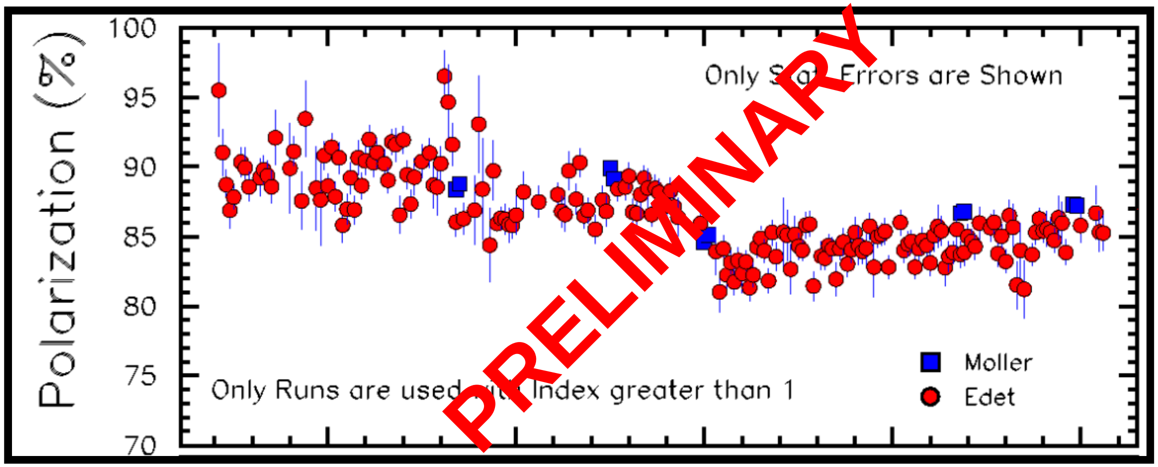


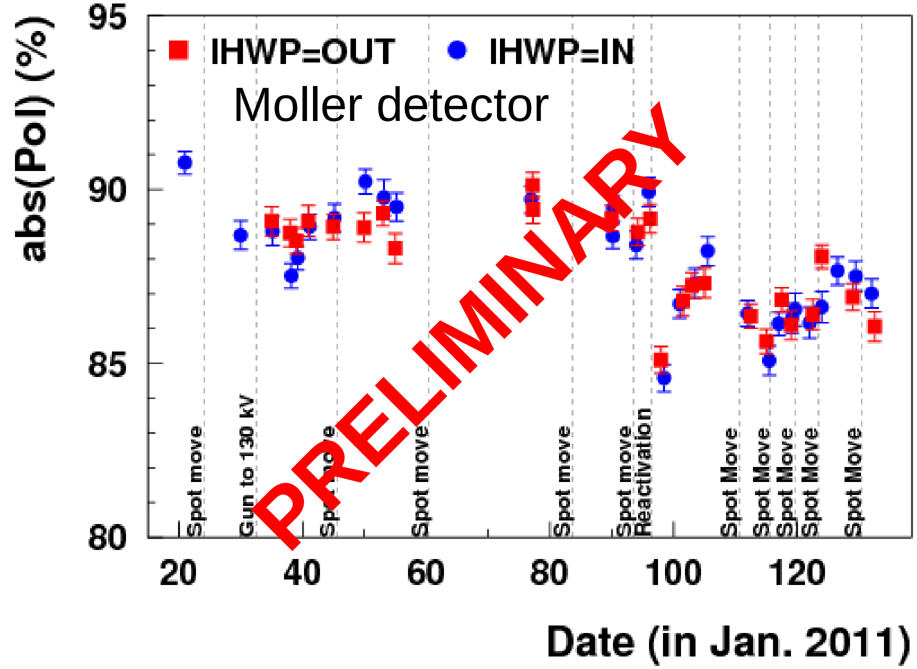


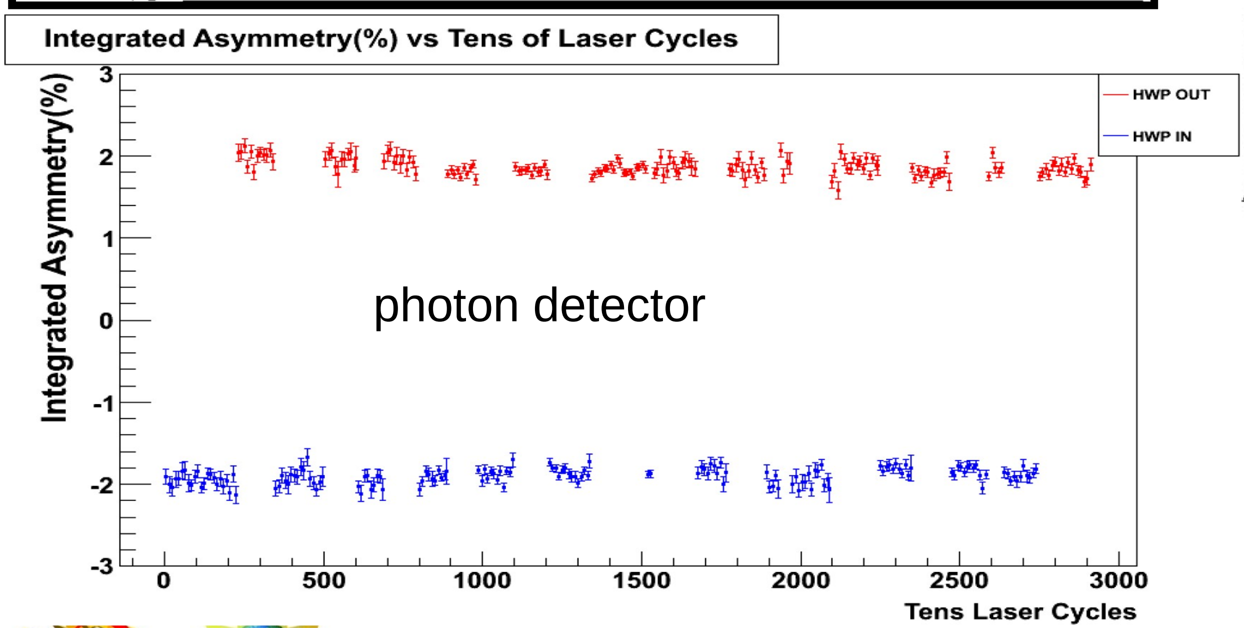
Polarimetry

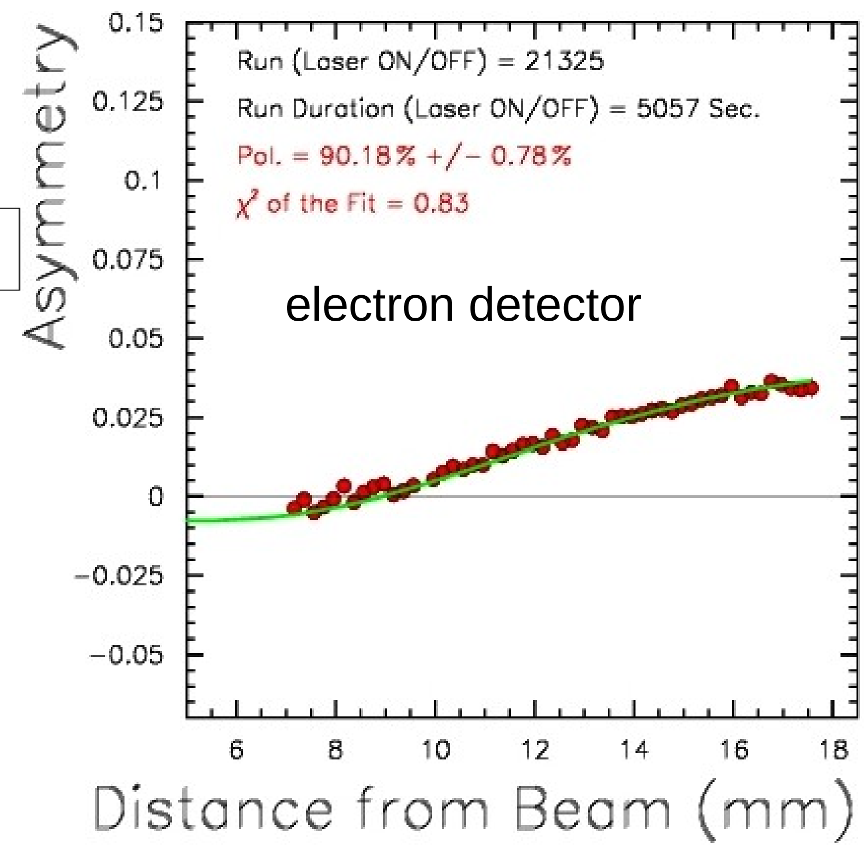
Motivation:
1% measurement of polarization

Moller (invasive)
Compton Photon (noninvasive)
Compton Electron (noninvasive)









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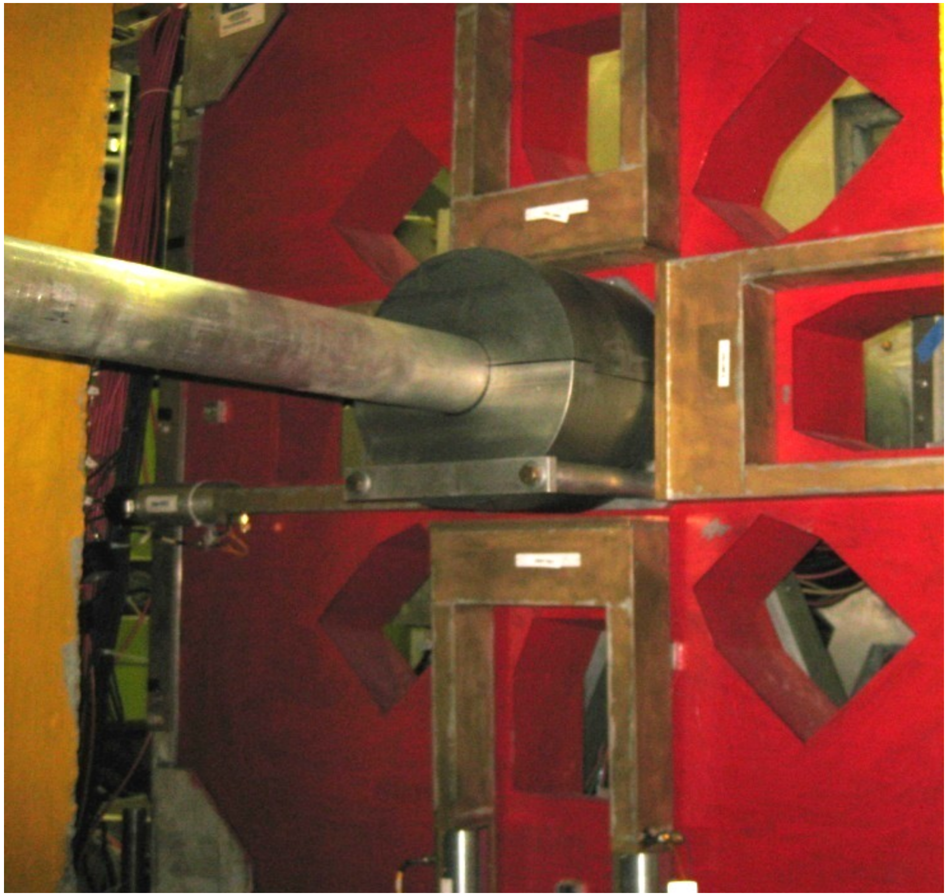
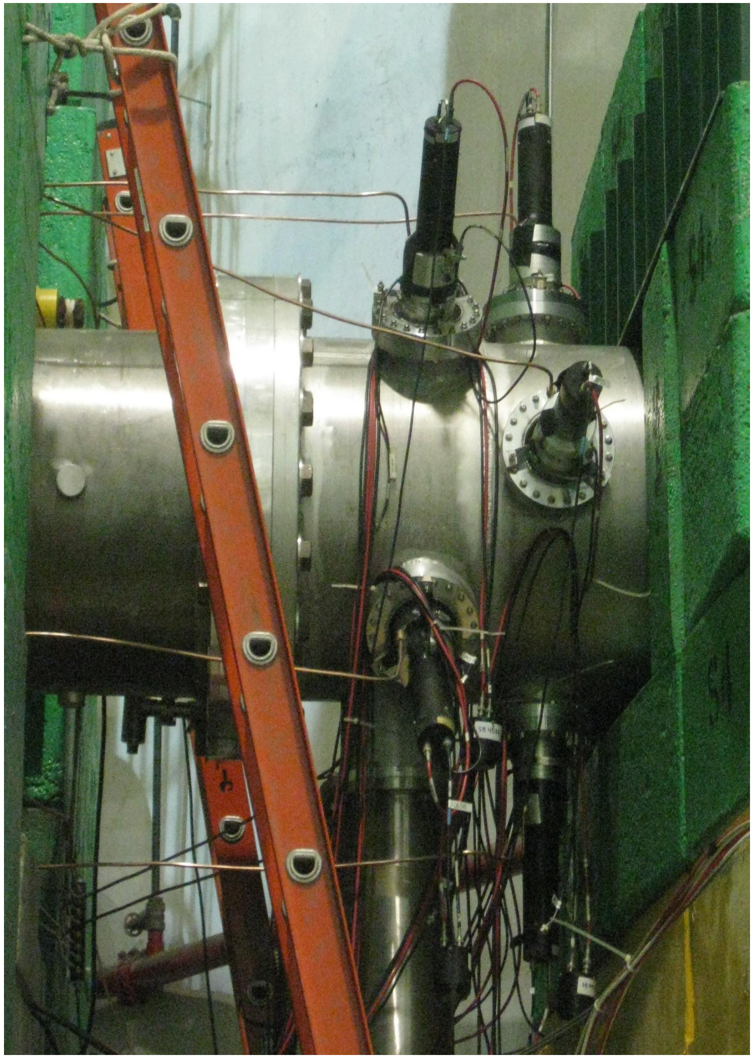
Qweak Luminosity Monitors



upstream lumis:
4 detectors at ~5 degrees
100 GHz / detector
signal dominated by Mollers

designed to be:
a target density monitor
a sensitive beam diagnostic



downstream lumis:
8 detectors at ~0.5 degrees
100 GHz / detector
signal split between Mollers and elastics

designed to be:
a null asymmetry monitor
a sensitive beam diagnostic

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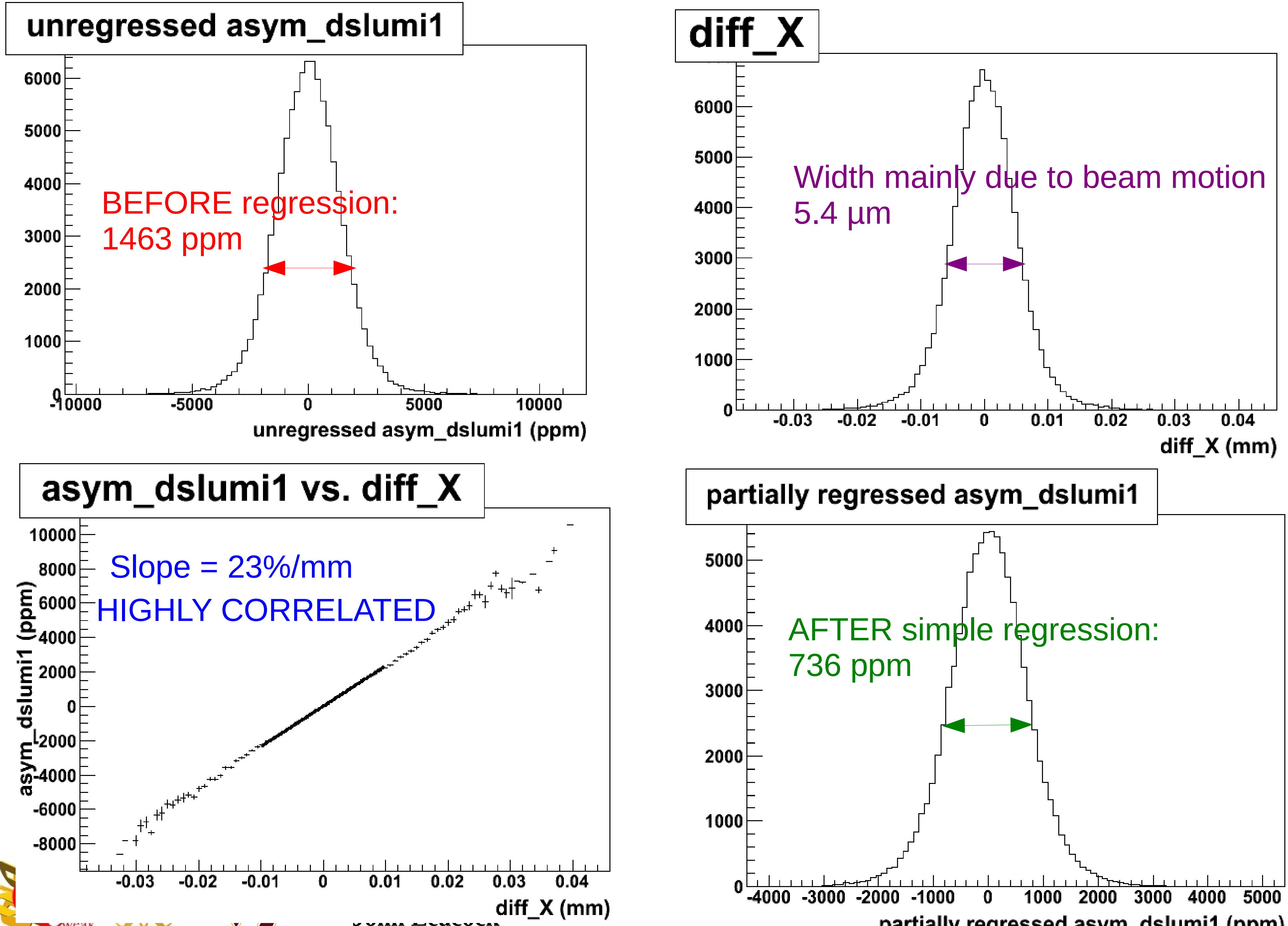
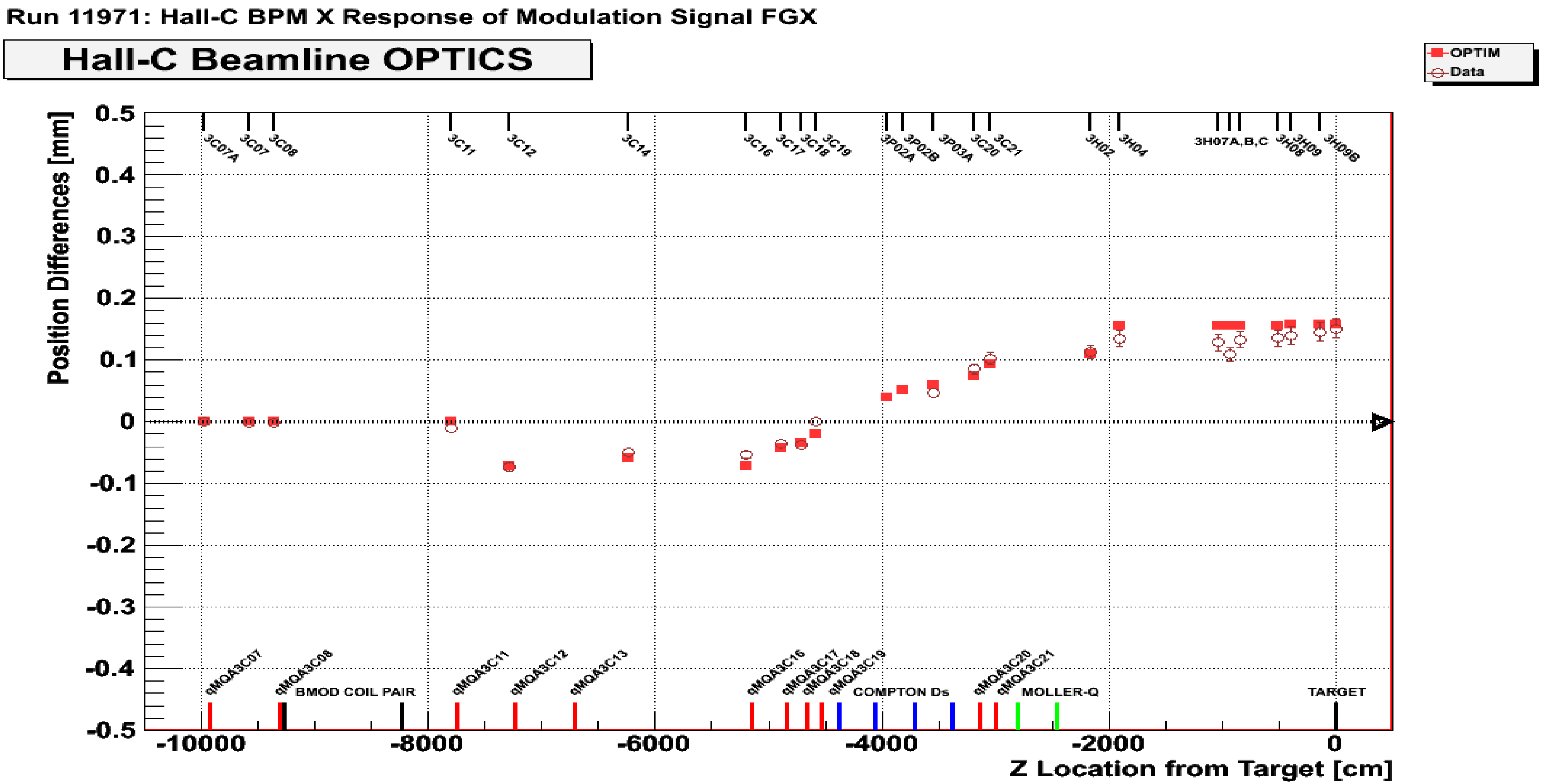
Luminosity Monitor Simplified Regression



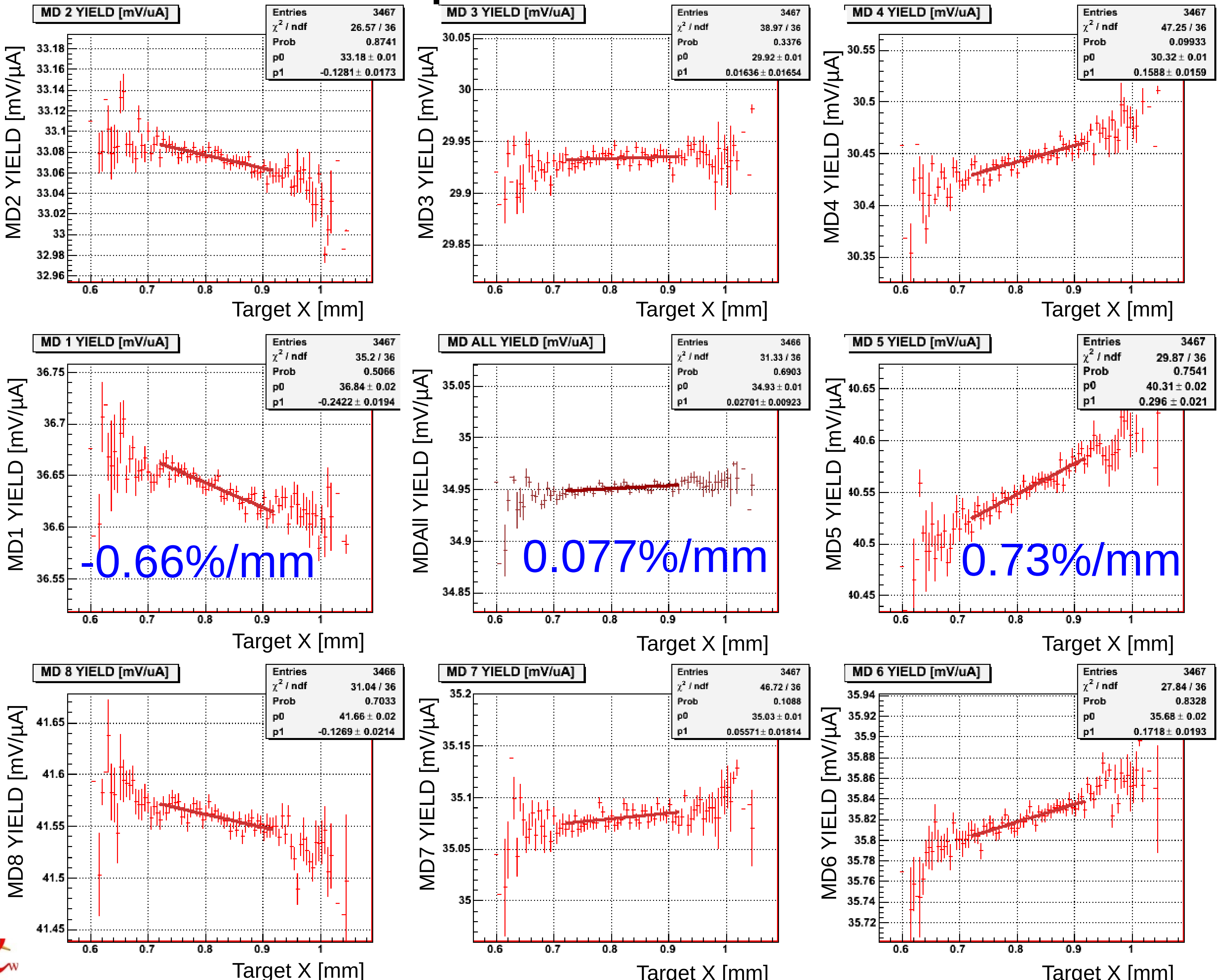
Beam Modulation

Used to remove false asymmetries

Beam is moved by a set of magnets to extract decoupled detector position, angle, and energy sensitivities



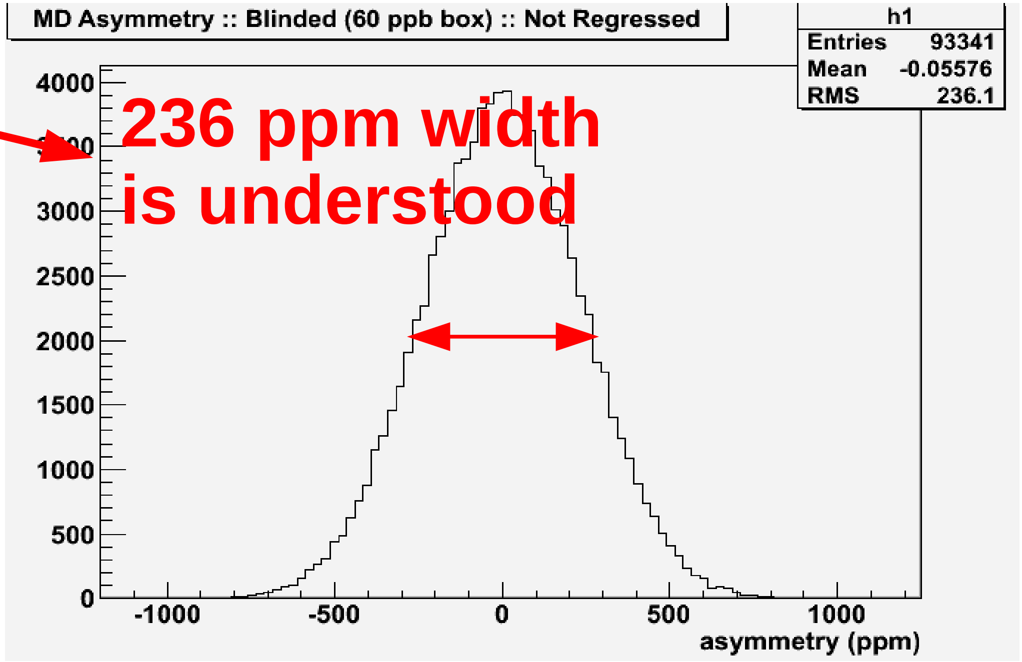
MD X position sensitivities



LH_2 Data Quality

asymmetry width is very important

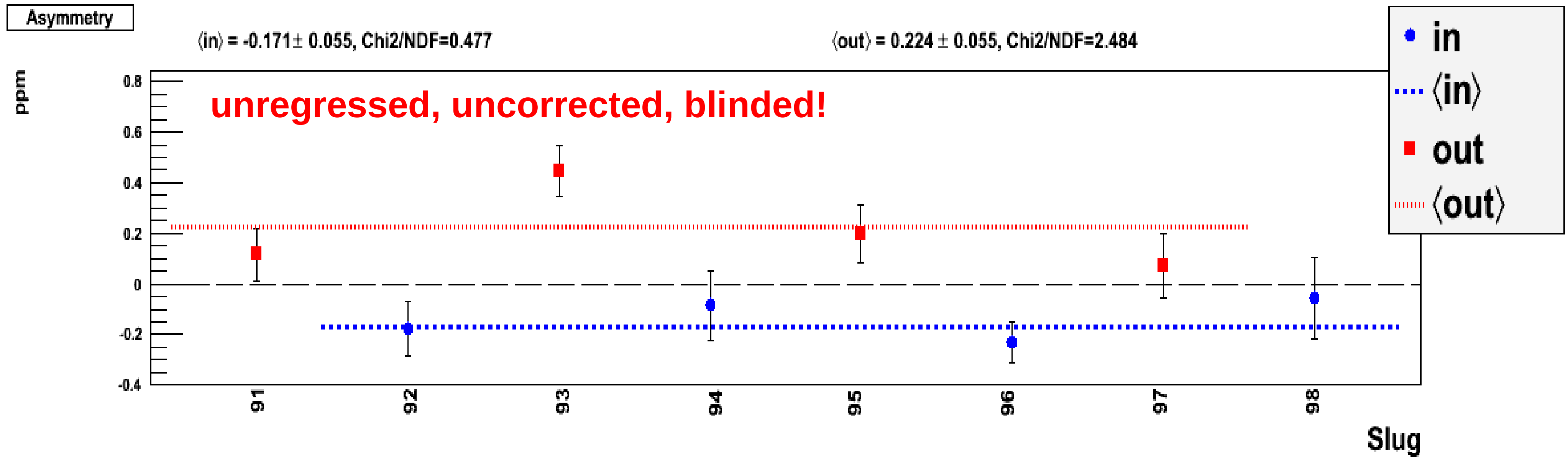
uncertainty of measurement ~ $\frac{\sigma}{\sqrt{N_q}}$



each slug is approx. 8 hours of data

Insertable Half Wave Plate (IHWP) flips the polarity of the incident electrons (IN/OUT)

Should not change other properties of the beam and is used as a check of systematics



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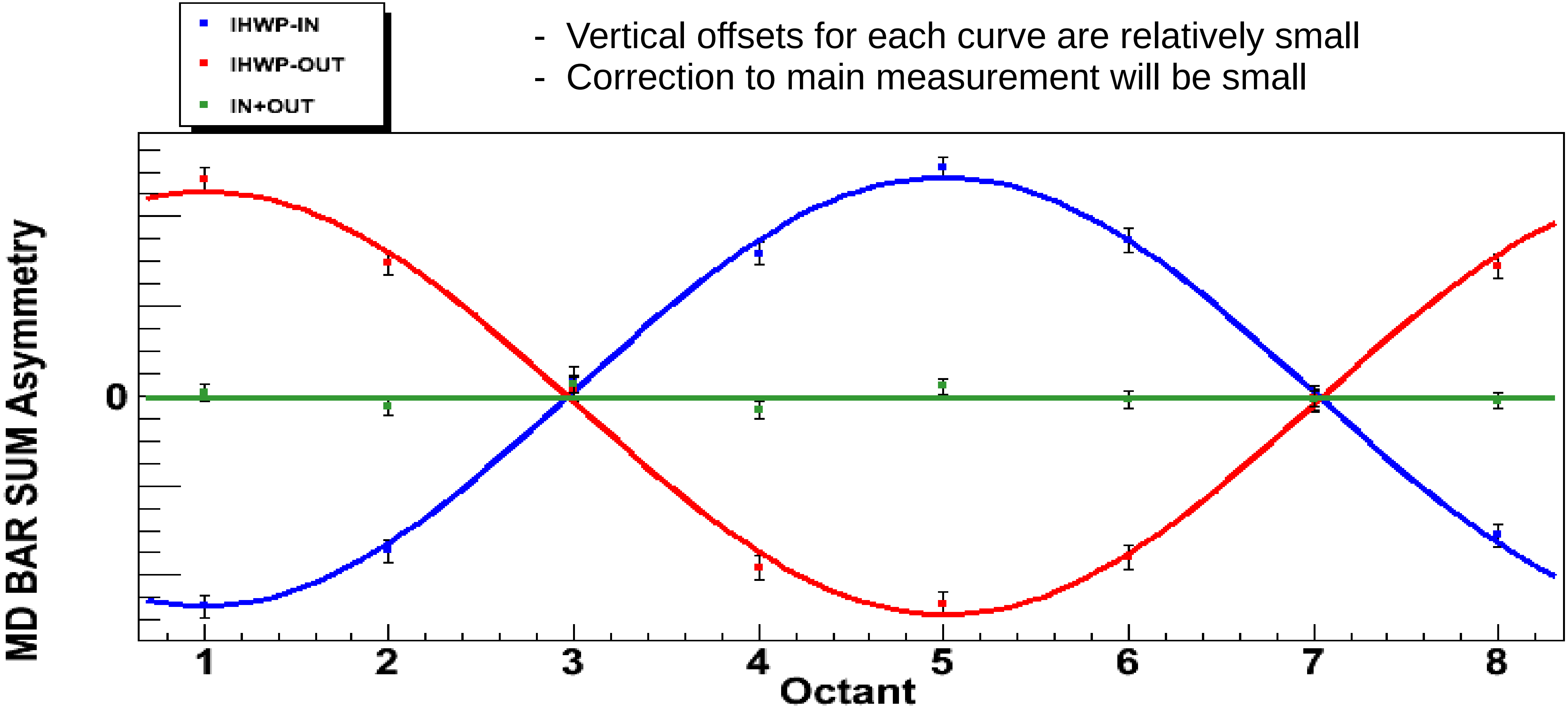
Transverse Asymmetry Data Quality

Motivation:

- During normal running the beam is ~89% longitudinally polarized.
- Some large parity conserving transverse asymmetries may leak into the experimental PV asymmetry through broken azimuthal symmetries
- The product of residual P_T and A_N is continuously measured

To help disentangle the residual P_T and A_N, and bound the azimuthal symmetry breaking, we temporarily changed the beam polarity to purely transverse.

- Vertical offsets for each curve are relatively small
- Correction to main measurement will be small

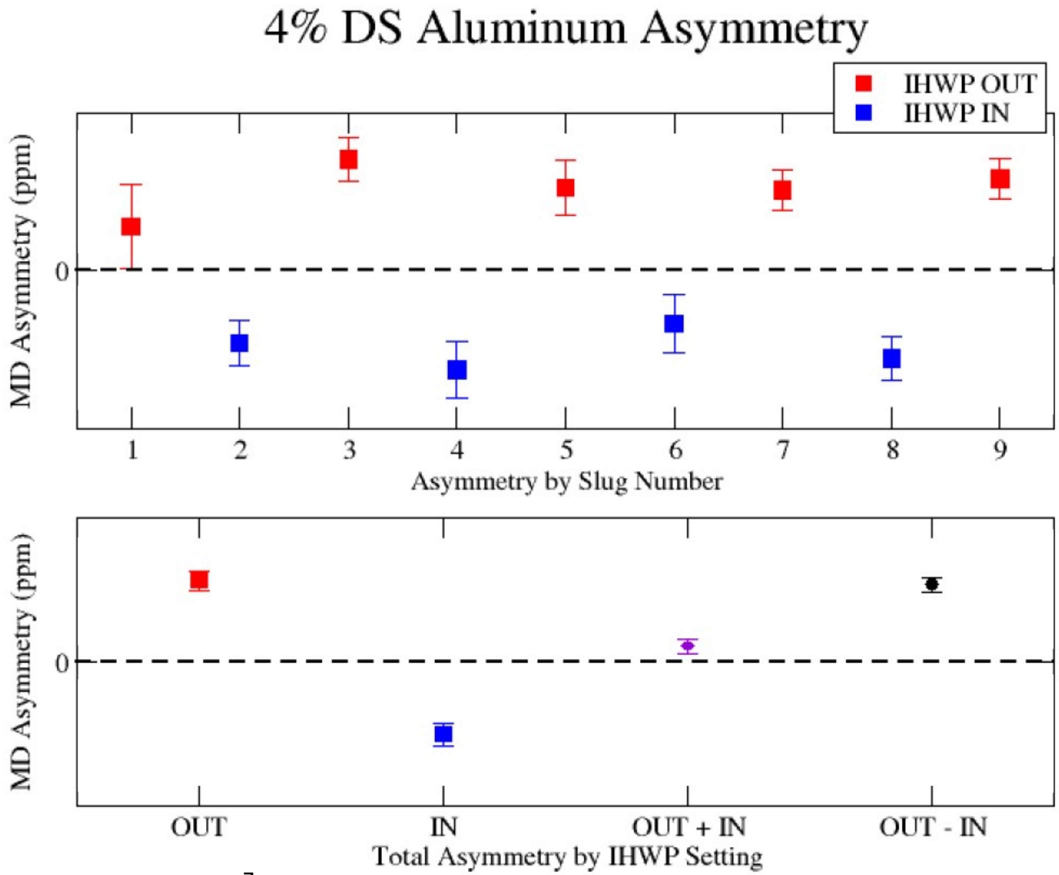


Aluminum Background Data Quality

Motivation:

- Aluminum windows on target
- elastic and quasielastic e- + Al interactions in acceptance, ~1% of signal
- relatively large asymmetry (~A_{ep} x 10)
- ~10% correction

- first direct measurement of Al elastic asymmetry



$$\frac{A_m}{P} = (1-f) A_{ep} + f A_{bkgd} \rightarrow A_{ep} = \frac{1}{1-f} [A_m / P - f A_{bkgd}]$$

A_m = measured asymmetry
A_{bkgd} = background asymmetry (aluminum, inelastic, etc.)
A_{ep} = elastically scattered electron proton asymmetry
P = electron beam polarization
f = dilution factor

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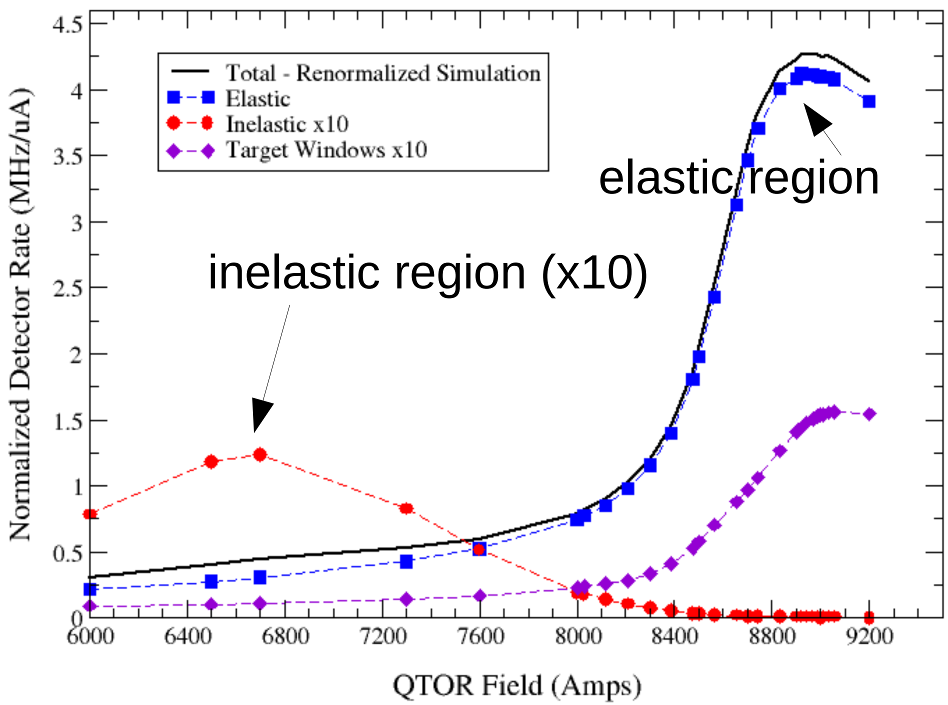
Inelastic Background Data Quality

LH2 QTOR Scan: Simulated Rate versus Field

(no secondary backgrounds included)



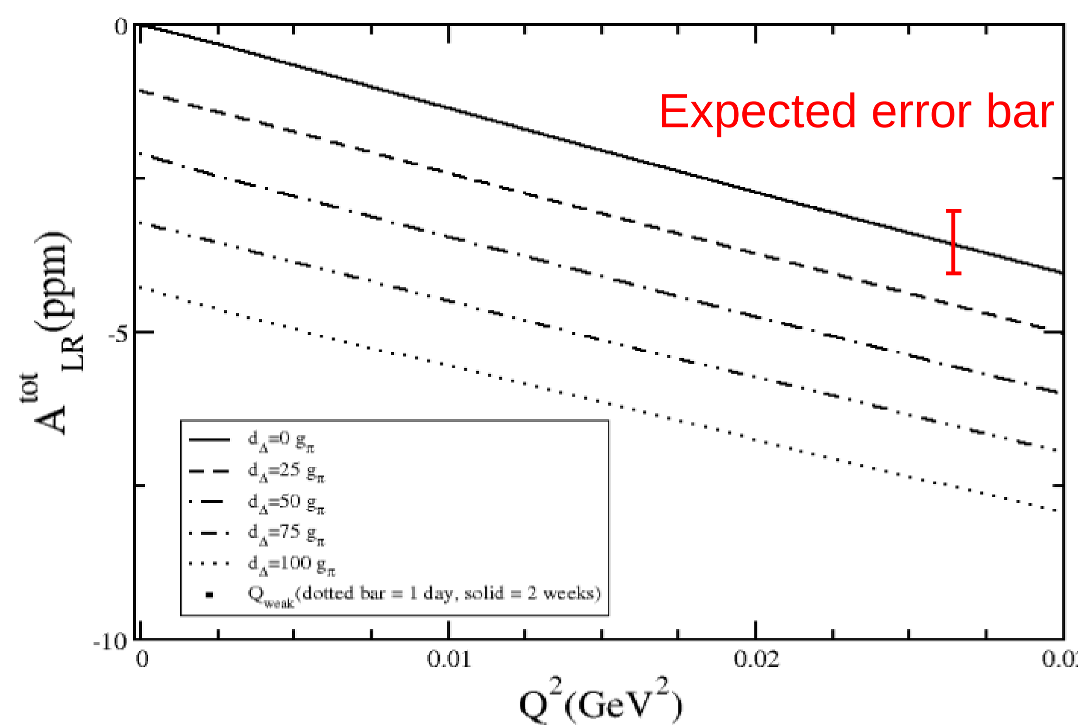
Motivation:

- $N \rightarrow \Delta$ asymmetry
- e- + p inelastic 0.1% of signal
- relatively large asymmetry (~A_{ep} x 10)
- ~1% correction to Qweak

- compelling standalone measurement

Does not go to zero

$$A_{meas} = \frac{-G_F}{\sqrt{2}} \frac{Q^2}{4\pi\alpha} [\Delta_{(1)}^{\pi} + \Delta_{(2)}^{\pi} + \Delta_{(3)}^{\pi,'}] + A_{Sieg}$$



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Qweak Status

- First commissioning beam   July 2010
- Commissioning   Fall 2010
- “Run I”   Jan - May 2011
- “Run II”   Nov 2011 - May 2012

Beam: routine data-taking at 165 μA , tests up to 180 μA (scheduled for 150 μA)
: ≈ 86-89% polarization
: helicity-correlated properties acceptable

Some teething pains: Target pump, Toroid power supply, beam dump vacuum,…

At present: have “in hand” ≈ 1/4 of proposed statistics

Initial Auxiliary measurements done:

- A_{PV} for Aluminum   (target windows)
- A_{PV} for $N \rightarrow \Delta$
- Parity-conserving transverse asymmetry

(each valuable and competitive measurements on their own)

Summary

- Precision measurement of the proton's weak charge in the simplest system.
  - ⇨ hadronic structure corrections largely determined from previous experiments
  - ⇨ Other theoretical uncertainties calculated to be small.
  - ⇨ **theoretically clean measurement**
- Q^p_{weak} has "accidental" suppression ⟹ quite sensitive to $\sin^2\theta_W$
  ~10 σ test of the running.
- Search for parity-violating new physics up to the ~ 2 TeV scale
- Experiment well underway, data-taking ends May 2012
- No show-stoppers found, can accomplish proposed 4% precision on Q^p_{weak}

The Collaboration

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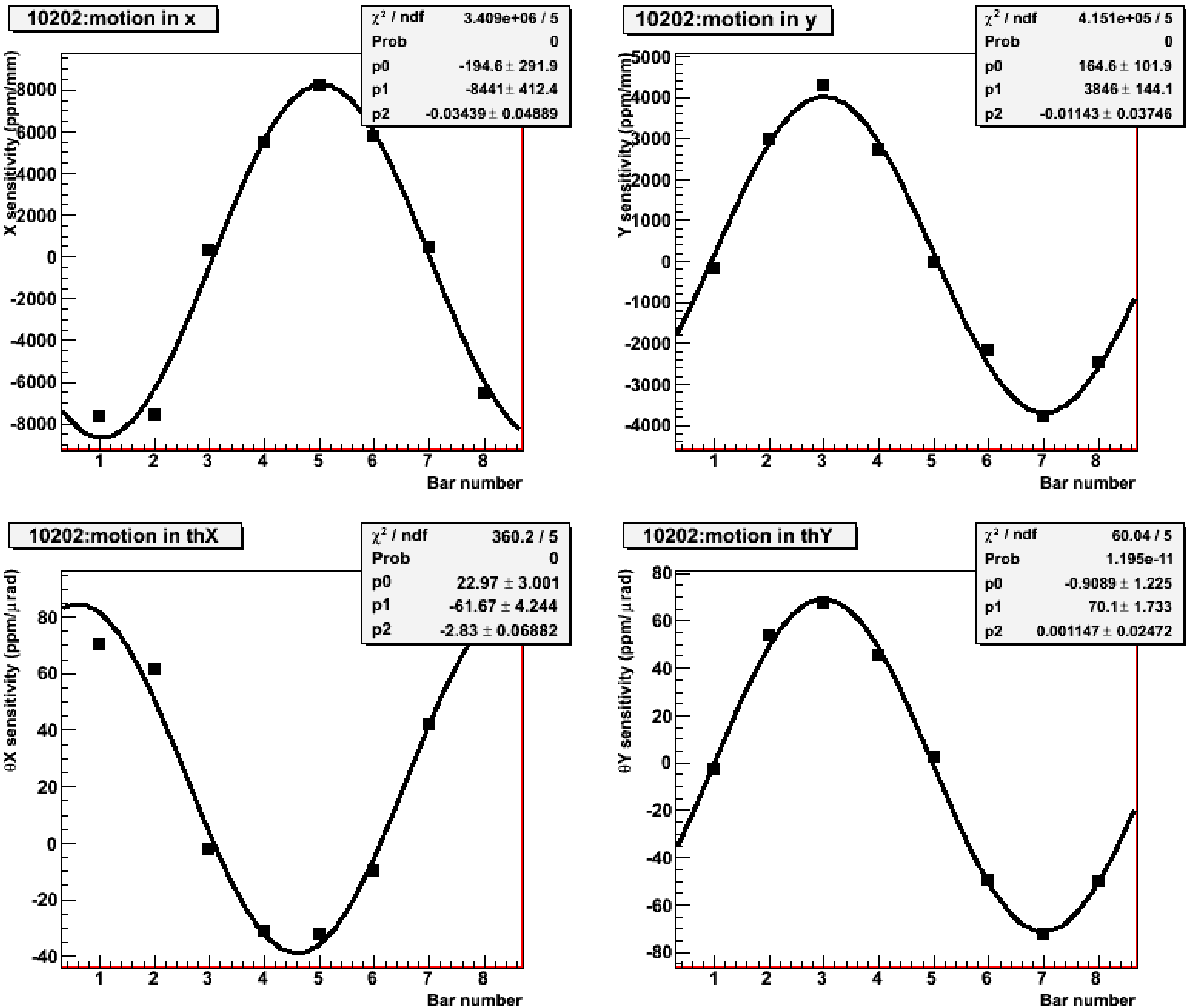
[1]Spokespersons *deceased [2]Project Manager

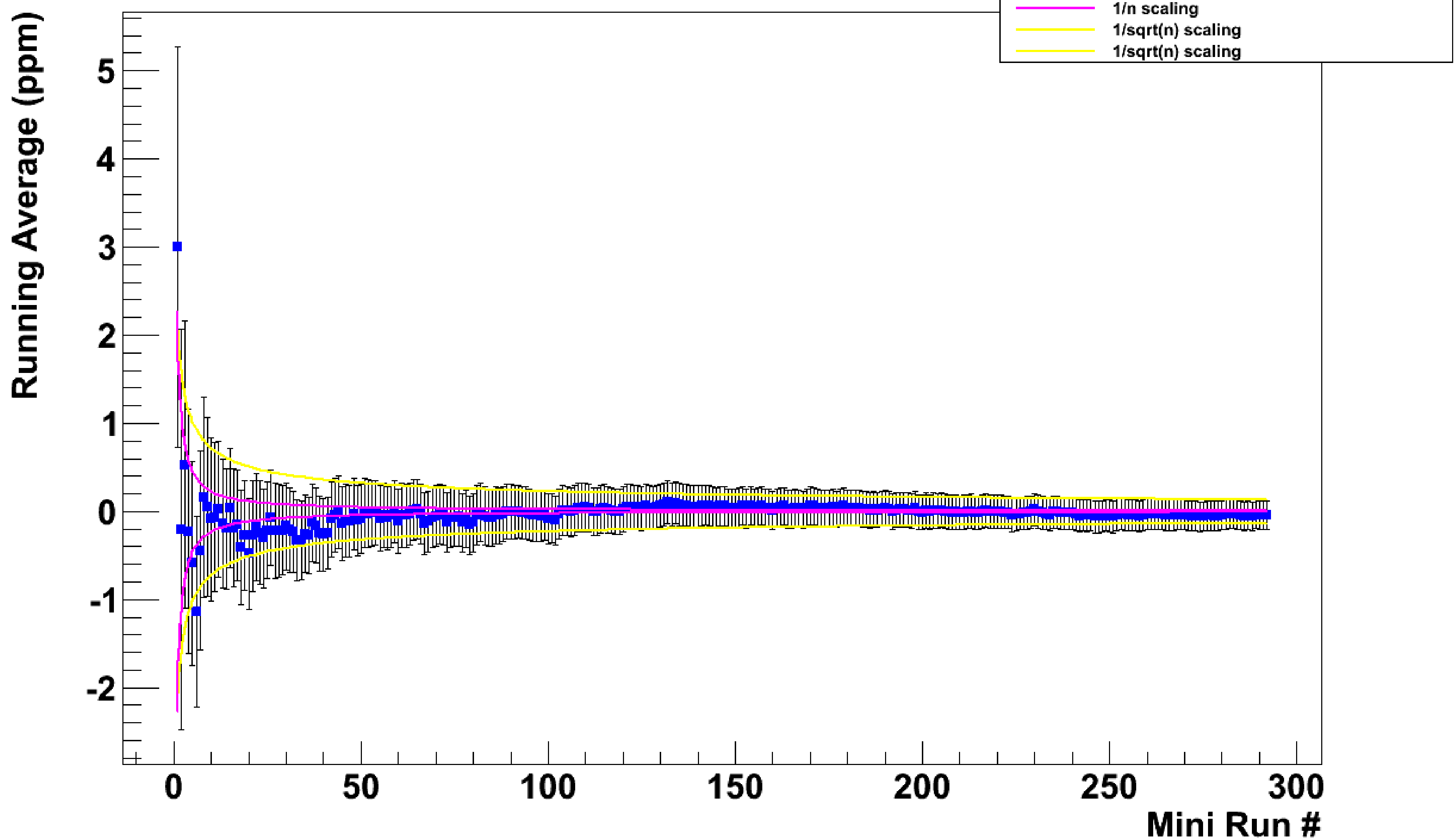
Funded by DOE, NSF, NSERC

Extra Slides



10202:motion in x
χ^2 / ndf 3.409e+06 / 5
Prob 0
p0 -194.6 ± 291.9
p1 -8441 ± 412.4
p2 -0.03439 ± 0.04889
X sensitivity (ppm/mm)
Bar number
10202:motion in y
χ^2 / ndf 4.151e+05 / 5
Prob 0
p0 164.6 ± 101.9
p1 3846 ± 144.1
p2 -0.01143 ± 0.03746
Y sensitivity (ppm/mm)
Bar number
10202:motion in thX
χ^2 / ndf 360.2 / 5
Prob 0
p0 22.97 ± 3.001
p1 -61.67 ± 4.244
p2 -2.83 ± 0.06882
θX sensitivity (ppm/μrad)
Bar number
10202:motion in thY
χ^2 / ndf 60.04 / 5
Prob 1.195e-11
p0 -0.9089 ± 1.225
p1 70.1 ± 1.733
p2 0.001147 ± 0.02472
θY sensitivity (ppm/μrad)
Bar number

Charge Asymmetry (BCM1) Convergence

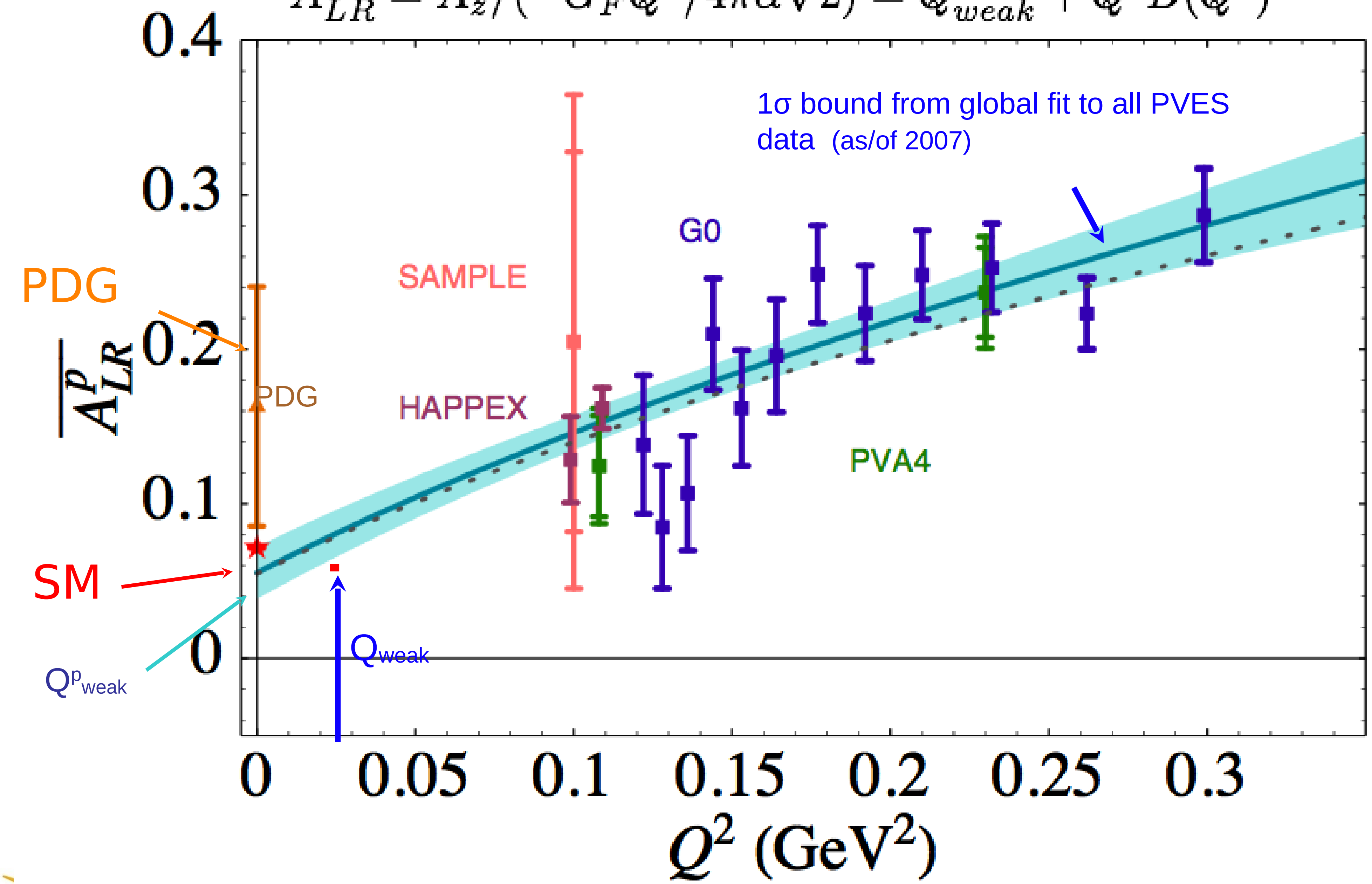


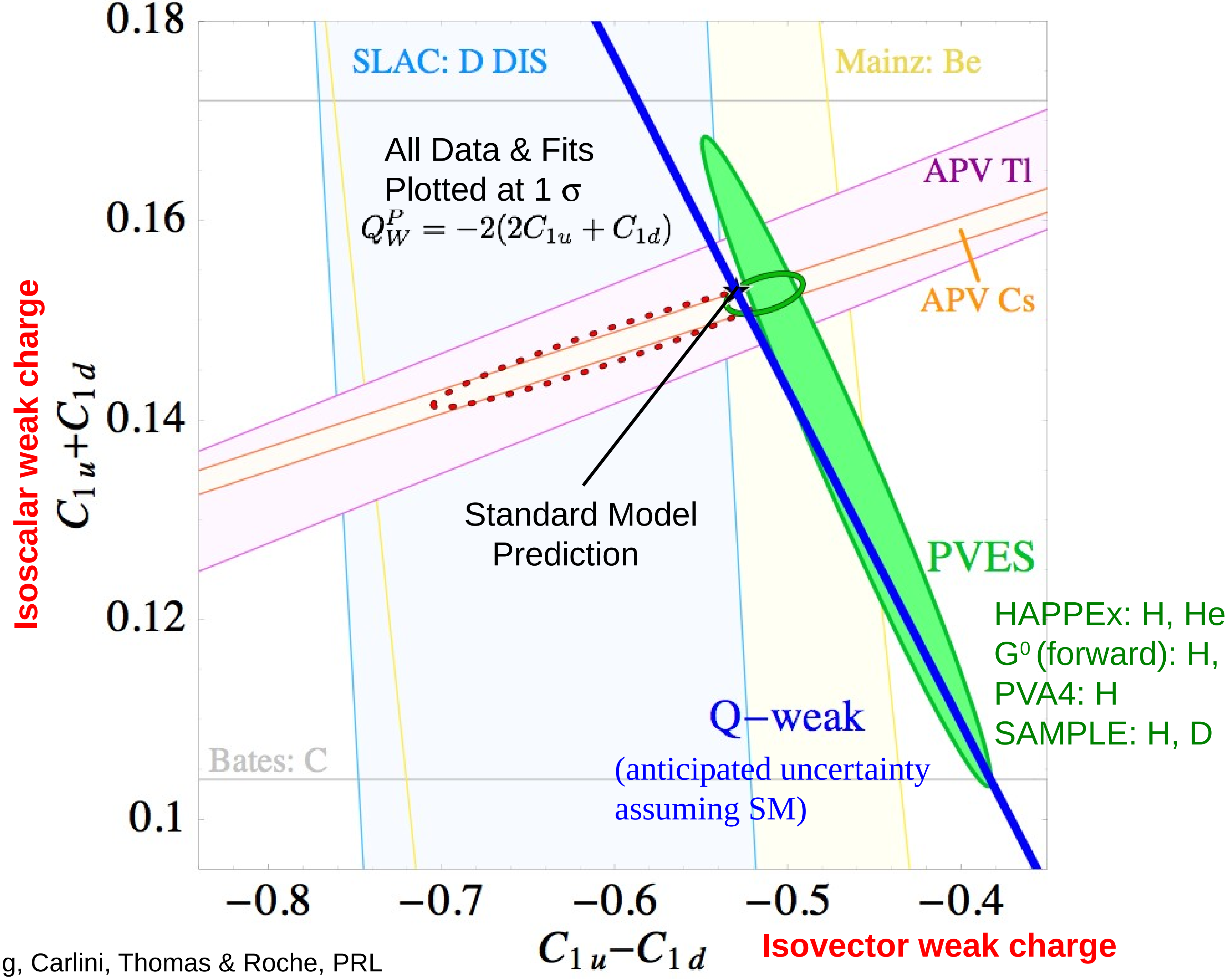
John Leacock

Parity-Violating Asymmetry Extrapolated to $Q^2 = 0$

(Young, Carlini, Thomas & Roche, PRL 99, 122003 (2007))

$$\overline{A^p_{LR}} = A_z/(-G_F Q^2/4\pi\alpha\sqrt{2}) = Q^p_{weak} + Q^2 B(Q^2)$$





Young, Carlini, Thomas & Roche, PRL

Electroweak Radiative Corrections

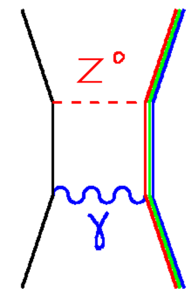
Source	Q^p_{Weak} Uncertainty
$\Delta \sin \theta_W (M_Z)$	±0.0006
$Z\gamma$ box	
$\Delta \sin \theta_W (Q)_{hadronic}$	±0.0003
WW, ZZ box - pQCD	±0.0001
Charge symmetry	0
Total	±0.0008

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

Erler, Kurylov, Ramsey-Musolf
PRD 68(2003)016006.

(c.f. $Q^p_{weak} \approx 0.07$)

Estimates of $Z\gamma$ box diagram on Q^p_{weak} (at our kinematics)



Gorchtein & Horowitz **~ 7%**

Phys. Rev. Lett. 102, 091806 (2009)

Sibirtsev, Blunden, Melnitchouk, Thomas **$6.6^{+1.5\%}_{-0.6\%}$**

Phys. Rev. D 82, 013001 (2010)

Rislow and Carlson **8.0 ± 1.3%**

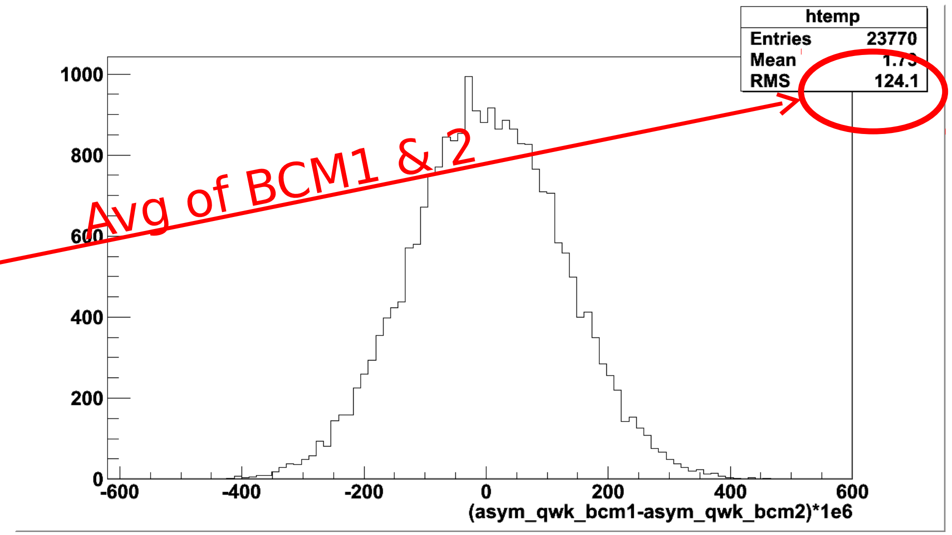
arXiv:1011.2397

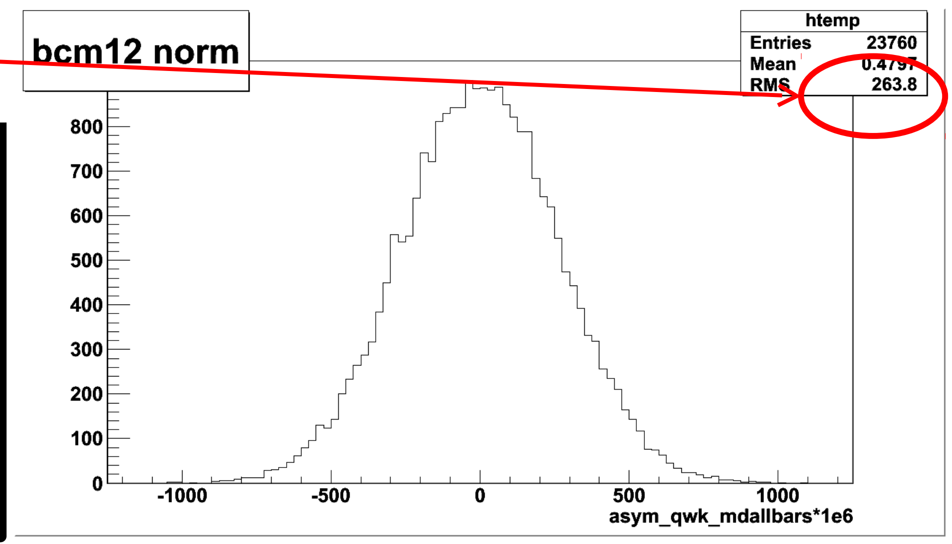
Gorchtein, Horowitz, Ramsey-Musolf **7.6 ± 2.8%**

arXiv:1102:3910

Target Boiling

Simulation:	5.3	GHz total for	150 uA
Actual beam	150	uA	3.5 mm raster
Flip rate	960	Hz	
Stat width	213	ppm	per quartet
T_settle	70	us	
Flip livetime	93%		
Corrected width	220	ppm	
Main detector resolution	10%		
Corrected width	242	ppm	
BCM width	62	ppm	
Expected total width	250	ppm	
Target boiling	41.2	ppm	
Expected total width	254	ppm	
Measured width	264	ppm	
excess width	74	ppm	





Extra beamtime required due to tgt noise = $(41/250)^2$ = 2.7%.

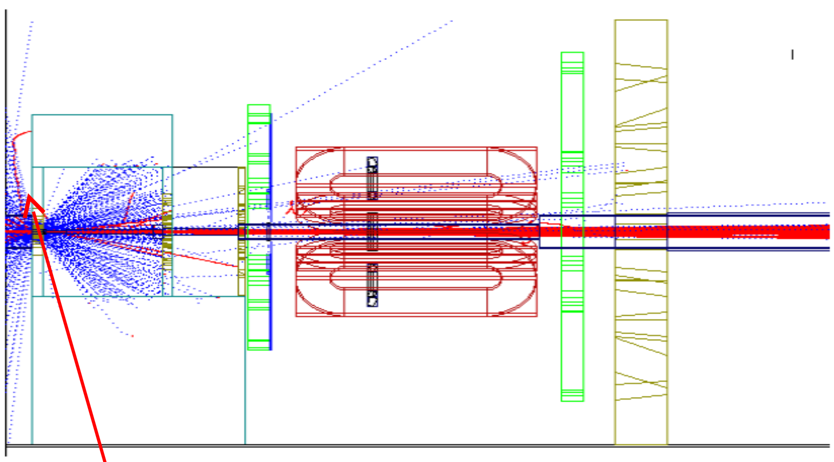
Our goal was < 5%.

Mission Accomplished!

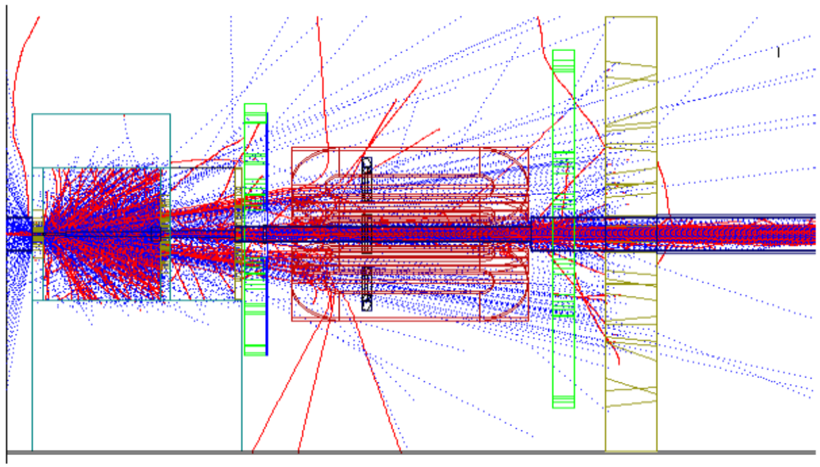
What is the Tungsten Beam Collimator?

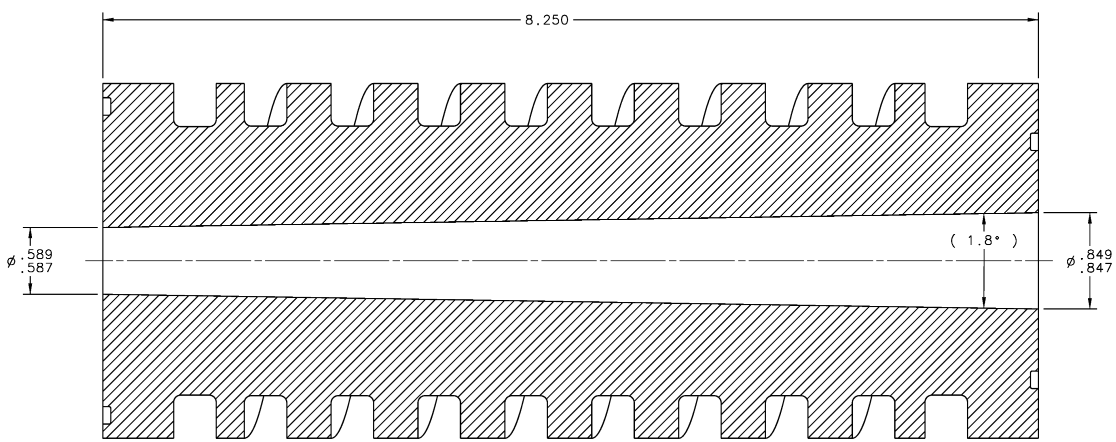
The role of the tungsten beam collimator is to collimate the scattered electron beam so that it cleanly passes through the narrow diameter beampipe in the QTOR region without creating backgrounds in the beampipe that the main detector may detect.

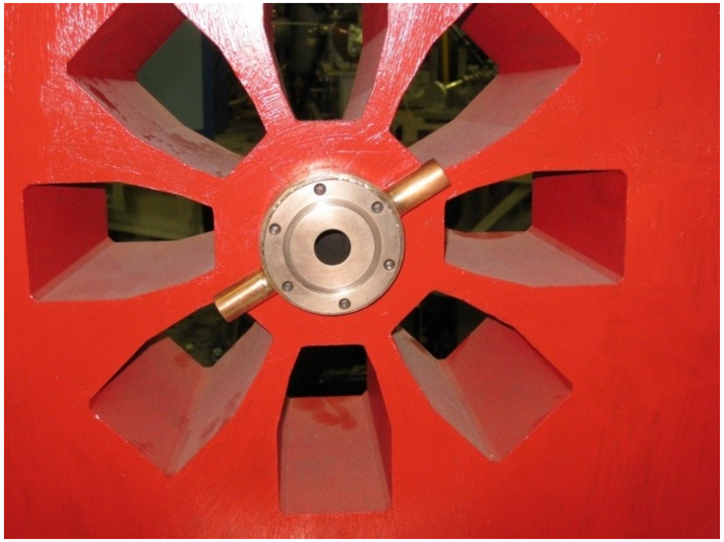
with plug: 1.4% background



without plug: 9.5% background





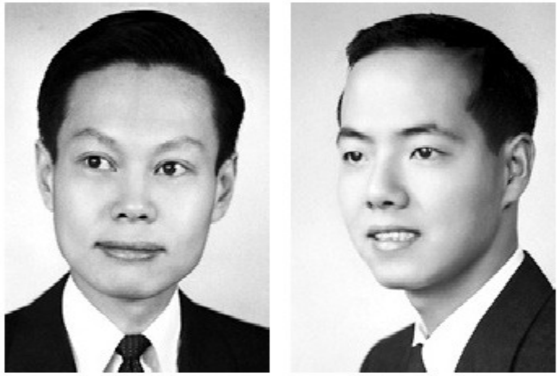


John Leacock

Parity Violation of Weak Interaction

The Nobel Prize in Physics 1957

"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"



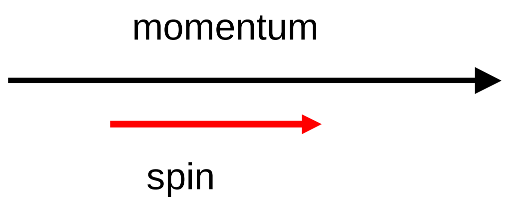
Chen Ning Yang	Tsung-Dao Lee
1/2 of the prize	1/2 of the prize
China	China
Institute for Advanced Study Princeton, NJ, USA	Columbia University New York, NY, USA
b. 1922	b. 1926

Parity Violation (parity operator: $\vec{r} \rightarrow -\vec{r}$)

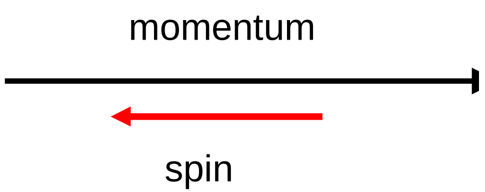
T.D. Lee, C.N. Yang; suggested based on various particle decays (1956)

C.S. Wu – first experimental determination polarized ^{60}Co beta decay (1957)

Right-handed fermion



Left-handed fermion



Left-handed fermions are more likely to interact via the weak force than right-handed fermions

The Weak Mixing Angle θ_W

Electromagnetic and Weak interactions are manifestations of the same fundamental interaction, Electroweak.

The photon and the Z boson are combinations of the same two massless states. This unifies the electromagnetic and weak interactions

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W^{(3)}_\mu \\ B_\mu \end{pmatrix}$$

A_μ ~ photon, Z_μ ~ Z boson

θ_W is the weak mixing angle between the two neutral currents in the model

Coupling constants are same order of magnitude: $e = g^* \sin\theta_W \sim g/2$

Weak Neutral Current **Electromagnetic**

$$M_{NC} \sim \frac{g^2}{-Q^2 + M_Z^2} \qquad M_\gamma \sim \frac{e^2}{-Q^2}$$

$Q^2 \rightarrow 0$

$$M_{NC} \sim \frac{g^2}{M_Z^2}$$

Q^2 is 4 momentum transfer

$Q^2 = 4EE' \sin^2\theta/2$

Outline

Introduction:
- Qweak overview
- Qweak physics
  - Standard Model test
  - New Physics

Subsystem Overview and Performance:
- target
- MD
- tracking system
- polarimetry
  - moller
  - electron detector
  - photon detector
- luminosity monitors
- beam modulation

Results:
- hydrogen
- transverse
- Aluminum
- N->Delta