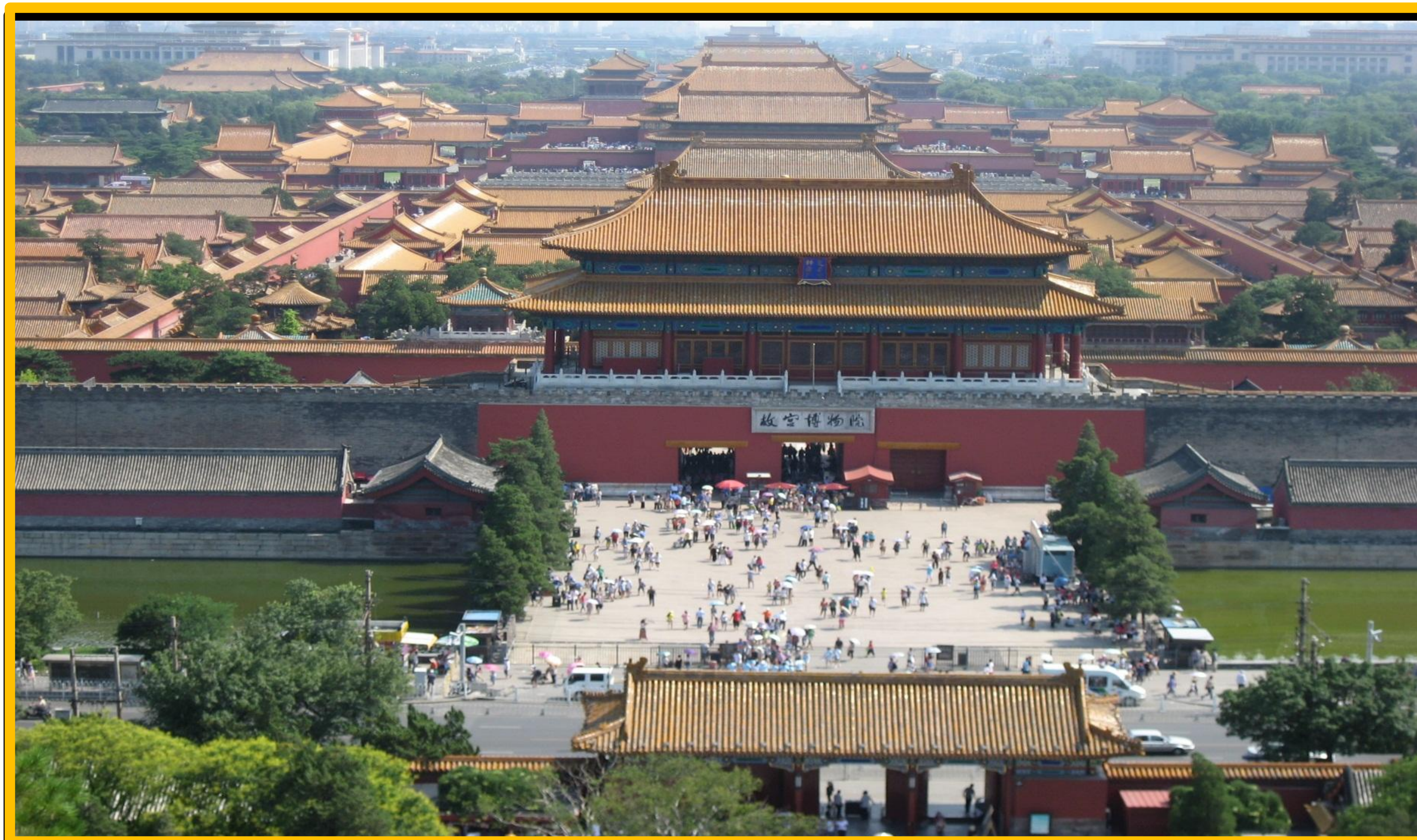
# Measuring the Weak Charge of the Proton – a Search for Physics Beyond the Standard Model



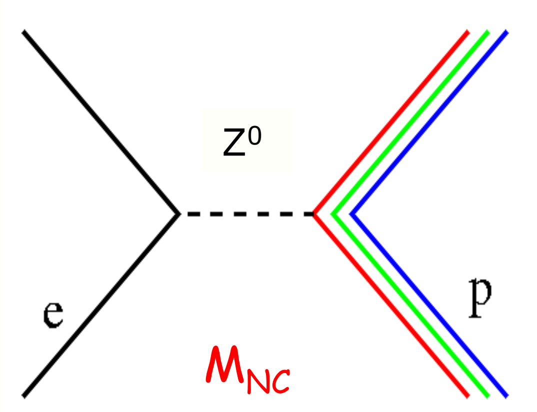
A.K. Opper from The George Washington University

**Fourth Workshop on Hadron Physics   July 2012**

# The Proton's Weak Charge, $\sin^2\theta_W$, and The $Q_{weak}$ Experiment

## $Q^p_{weak} = 1 - 4\sin^2\theta_w$

- characteristic like mass, elect charge, ….
- measure of proton's coupling to W and Z
- never been directly measured



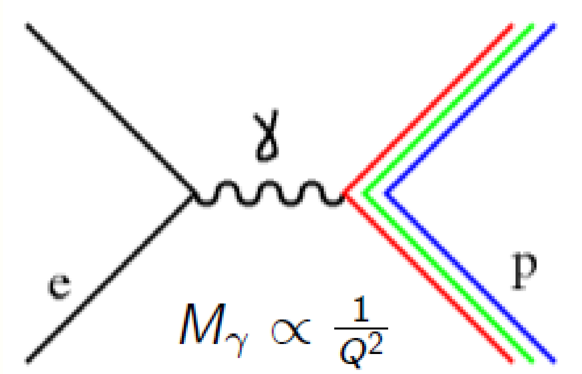

## $\sin^2\theta_w$

- mixing between EM and neutral weak interactions
- varies with energy (Q) – sensitive to possible extensions to the SM
- "well determined" near the $Z^0$-pole but no high precision low E expts

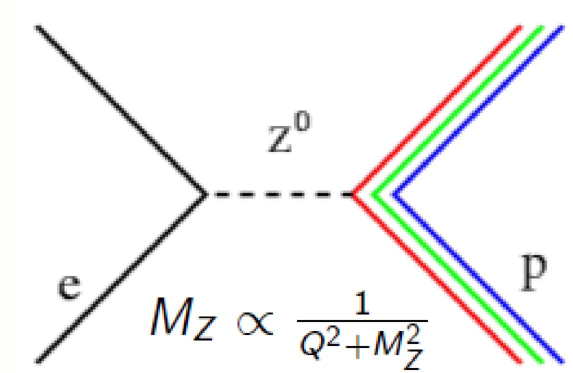
The $Q_{weak}$ experiment at JLab will precisely measure $\sin^2\theta_W$ at low Q
→ * test SM prediction of this running
* place limits on physics beyond the SM

# EM Charges

# Weak Charges




$$M_\gamma \approx 10^{-7} M_Z$$




parity conserving

measures $Q^p$ – proton's electric charge

parity violating

measures $Q^p_{weak}$ – proton's weak charge

| | $Q^\gamma$ |
|---|---|
| u | +2/3 |
| d | –1/3 |

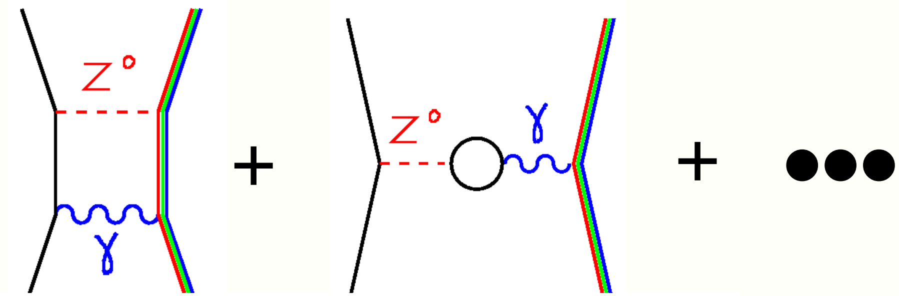
**Need to measure a parity violating observable!**

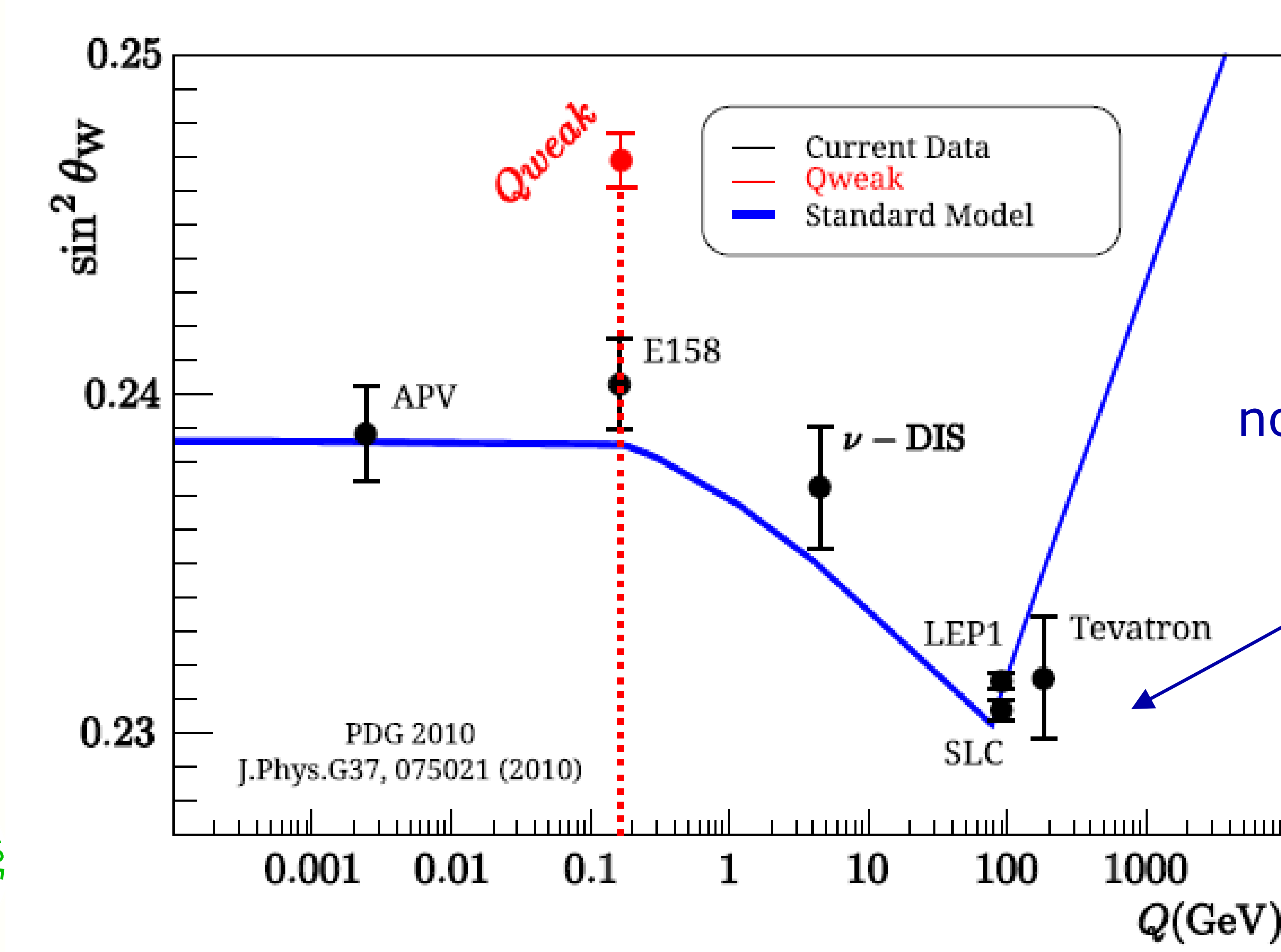
$$Q^p = 2\left(+\frac{2}{3}\right) + 1\left(-\frac{1}{3}\right) = +1$$

$$Q^p_{weak} = 2\left(1 - 8/3\sin^2\theta_W\right) + 1\left(-1 + 4/3\sin^2\theta_W\right)$$
$$= 1 - 4\sin^2\theta_W \approx 0.072$$

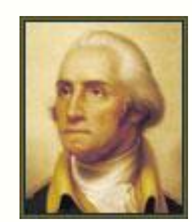
# "Running of $\sin^2\theta_W$" in the Electroweak Standard Model

- Electroweak radiative corrections
  → $\sin^2\theta_W$ varies with Q



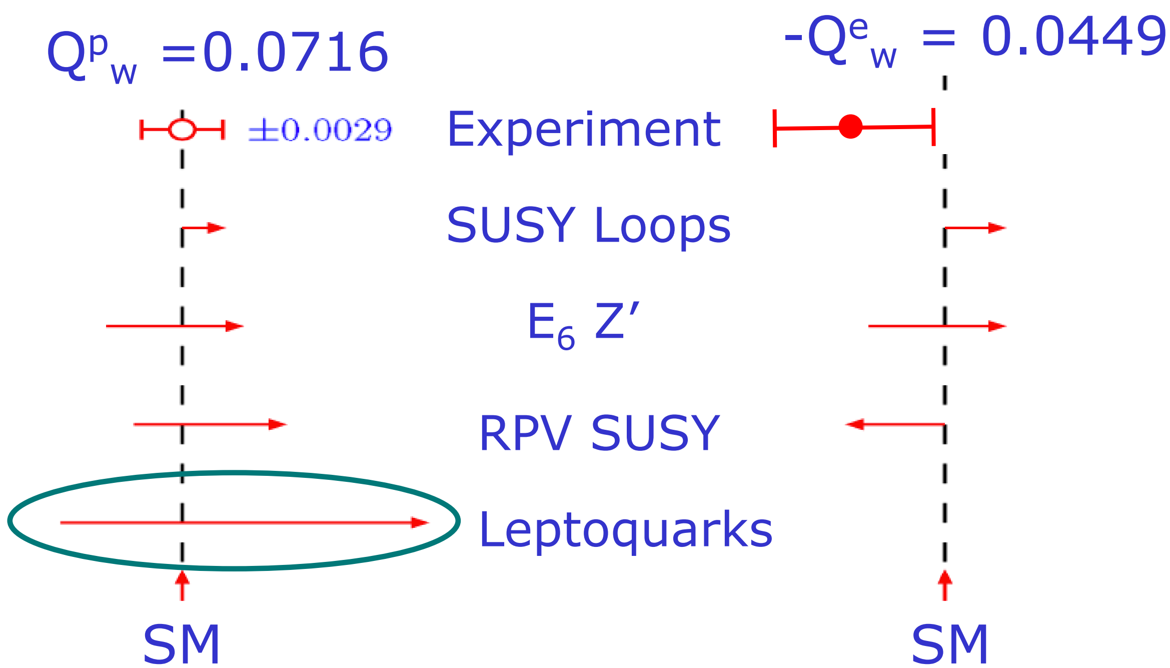




normalized to



# Comparison of $Q^p_w$ and $Q^e_w$ Sensitivities

JLab Qweak SLAC E158

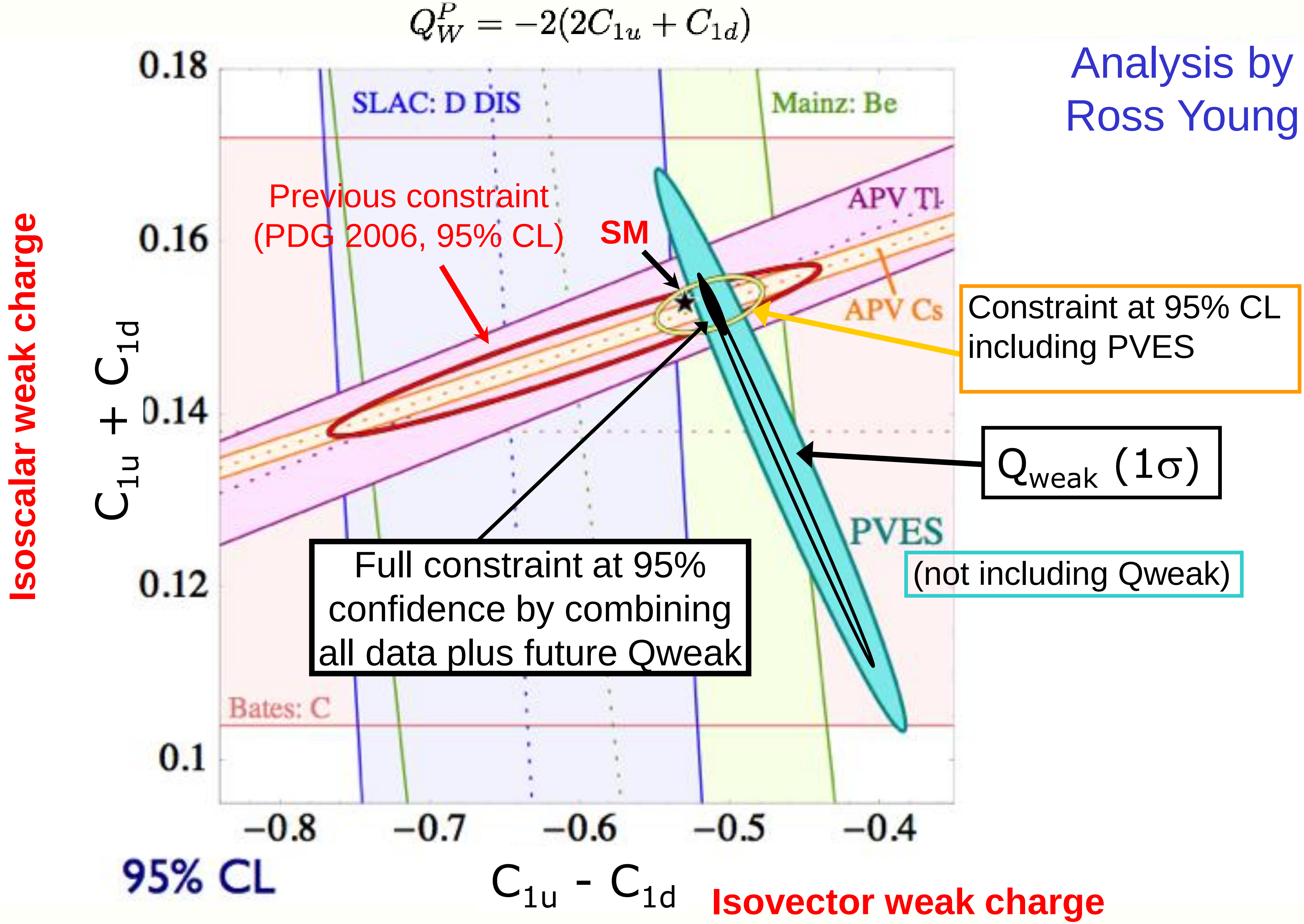


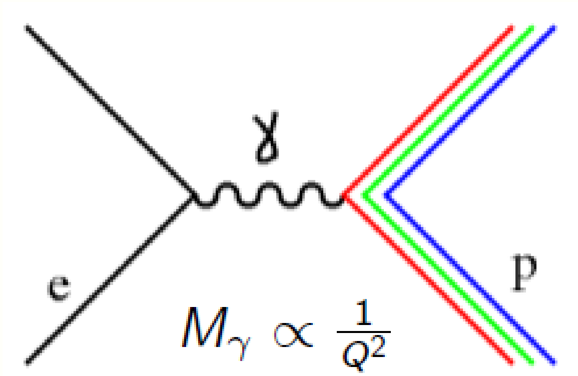

- $Q_{weak}$ → stringent constraint on lepto-quark based extensions to SM
- $Q_{weak}$ (semi-leptonic) and E158 (pure leptonic) → powerful program
- If SM and $Q_{weak}$ agree → most precise test of the running



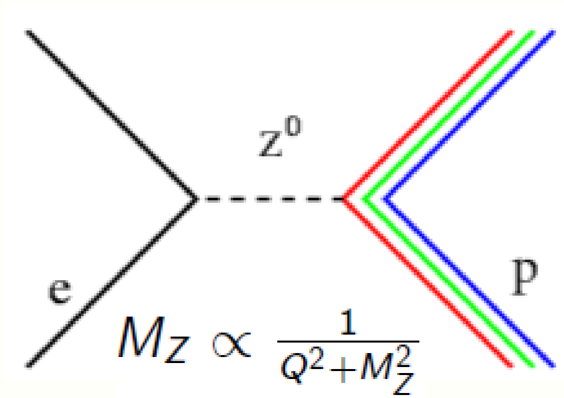
# Constraints on quark weak charges imposed by data

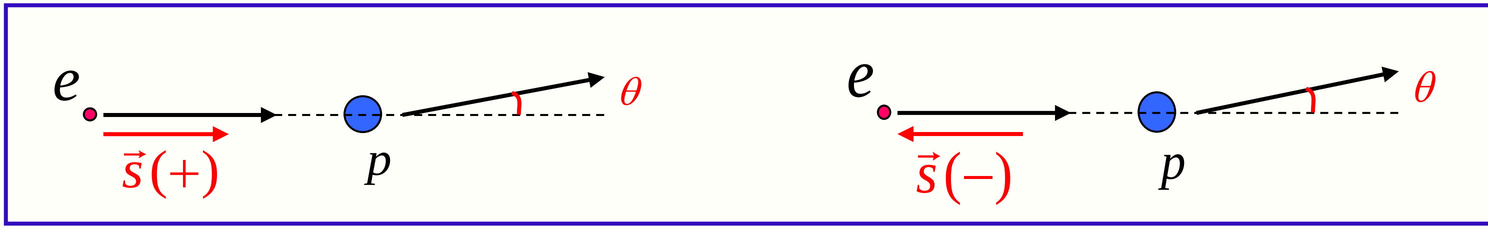
Analysis by Ross Young






← Interfere →




$$A \equiv \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} = \frac{2M_{NC}}{M_{EM}}$$

contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$ constrained by other expts

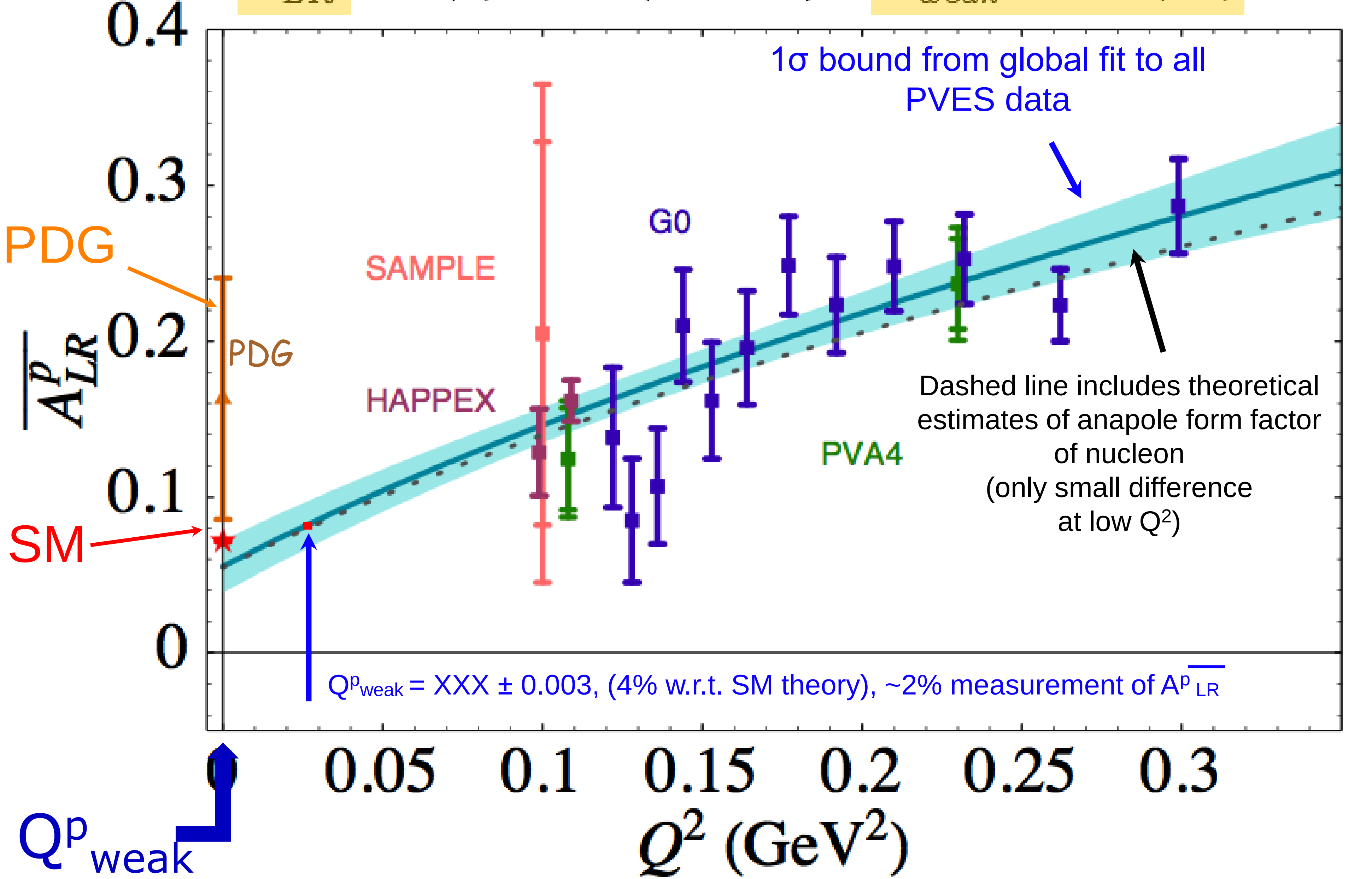
$$\xrightarrow[\theta \to 0]{Q^2 \to 0} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q^p_{weak} + Q^4 B(Q^2)\right] \sim -3(10)^{-7}$$

$Q^p_{weak} = 1 - 4\sin^2\theta_w \sim 0.072$ (at tree level)

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

(Ross Young et al.)

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




# Experimental Sensitivity: $Q^p_W = (1 - 4\sin^2\theta_W) \sim 0.072$

Precision measurement: $\delta A = \pm 2\% \;\; \Rightarrow \delta\, Q_W^p = \pm 4\%$

$$\Rightarrow \;\; \delta(\sin^2\theta_W) = \pm\; 0.3\%$$

Meas'd Asymmetry: $A(Q^2 \to 0) \; = \; -\frac{G_F}{4\pi\alpha\sqrt{2}}\left[\, Q^2\, Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$

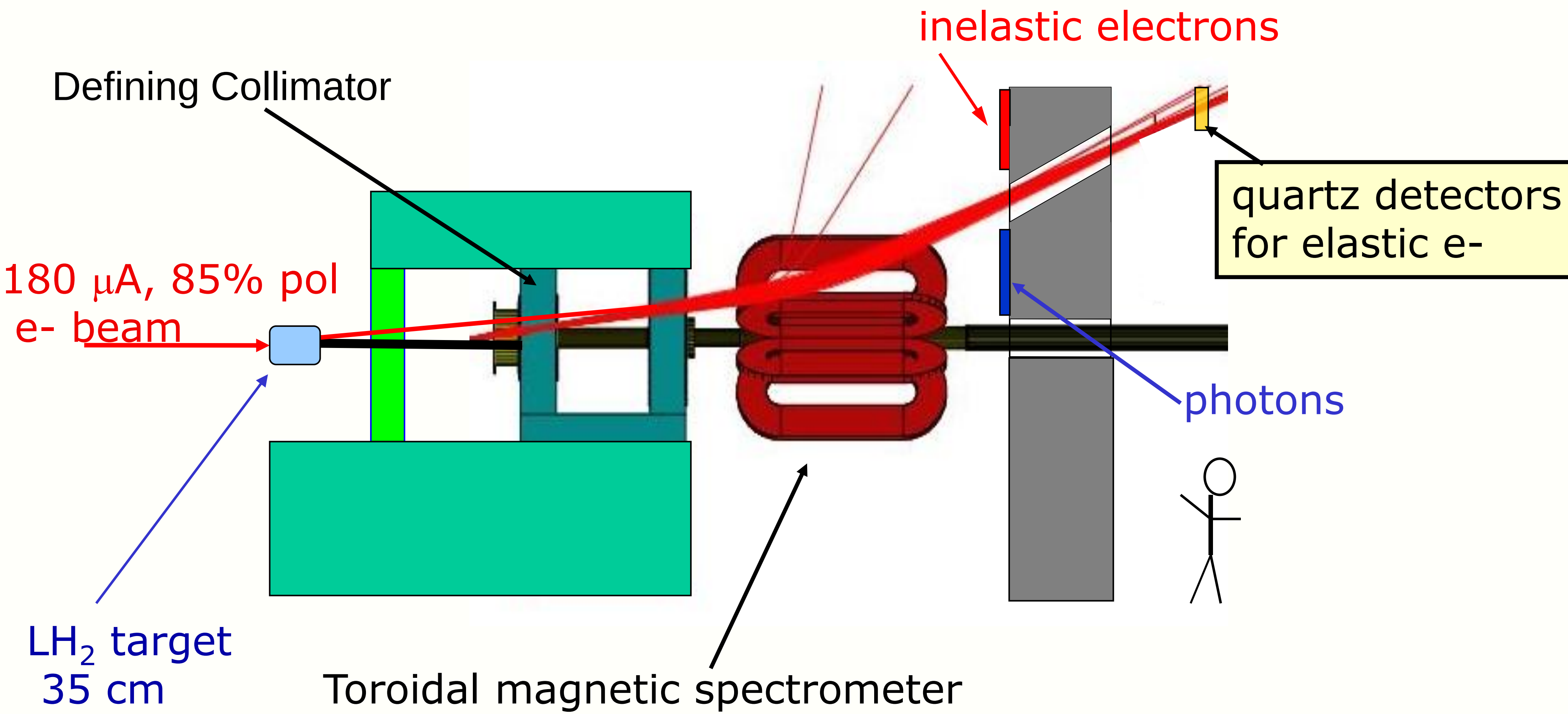
Expected value: $A\,(0.03\,\mathrm{GeV}^2) \; = \; A_{Q_W^p} \; + \; A_{B(Q^2)}$

$$= \; -.19\ \mathrm{ppm} \qquad -.10\ \mathrm{ppm}$$

Experimental considerations:

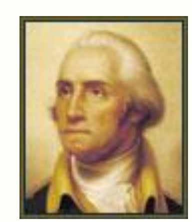
- need high statistics → integrating detector system
- measured asymmetry ~ P; → P must be large & well measured
- must know detector-response-weighted <Q$^2$> and <Q$^4$>
- helicity correlated systematic errors < 5 x $10^{-9}$
- need B(Q$^2$) so we can subtract it
- KISS ie **Keep It Simple, Stupid**!

# Main Apparatus



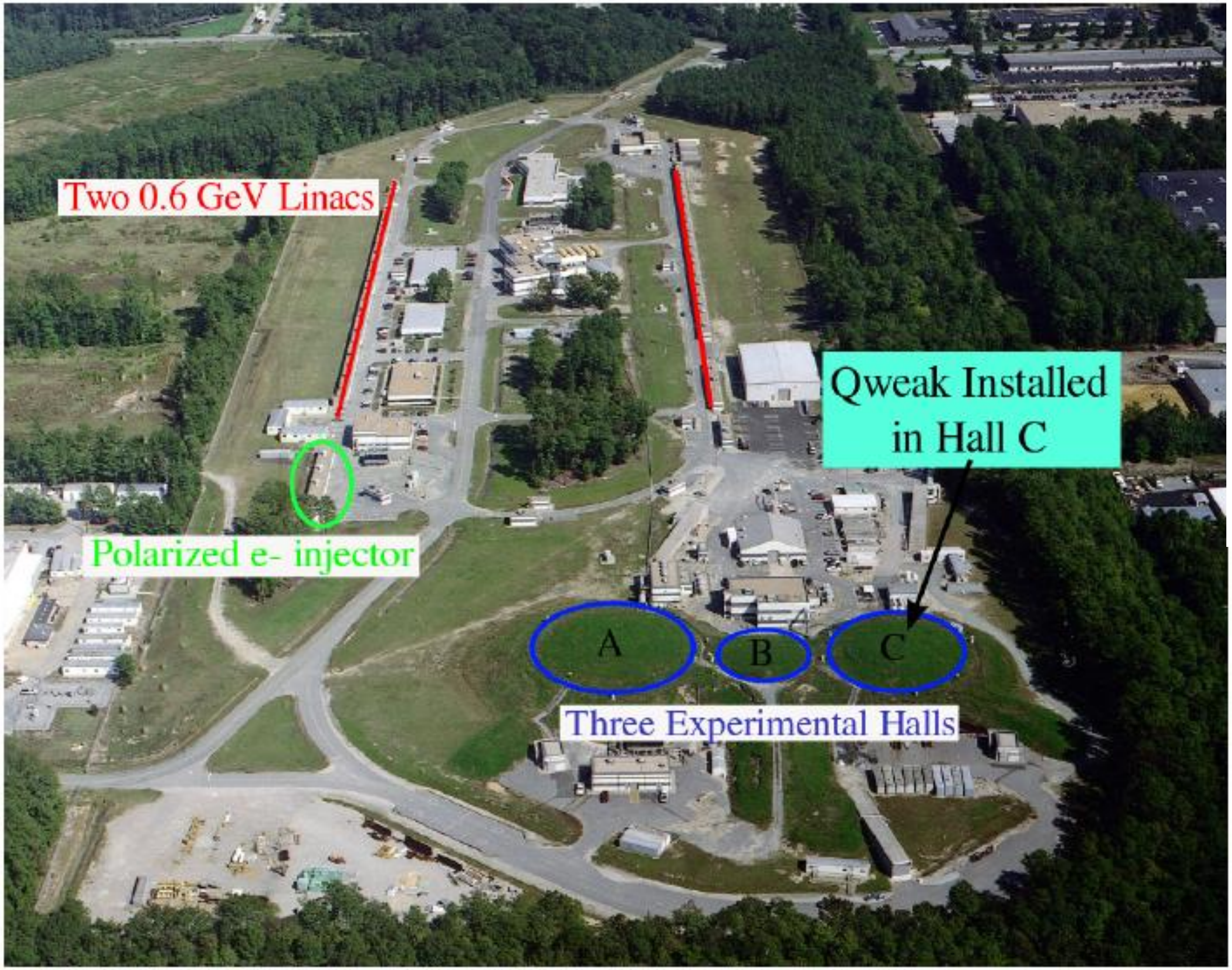

Toroidal magnetic spectrometer

- Bends elastically scattered e- away from the beamline
- Focuses e- onto detector
- $\int B \cdot dl \sim 0.7$ T-m



# The Qweak Experiment

Jefferson Lab Overview:

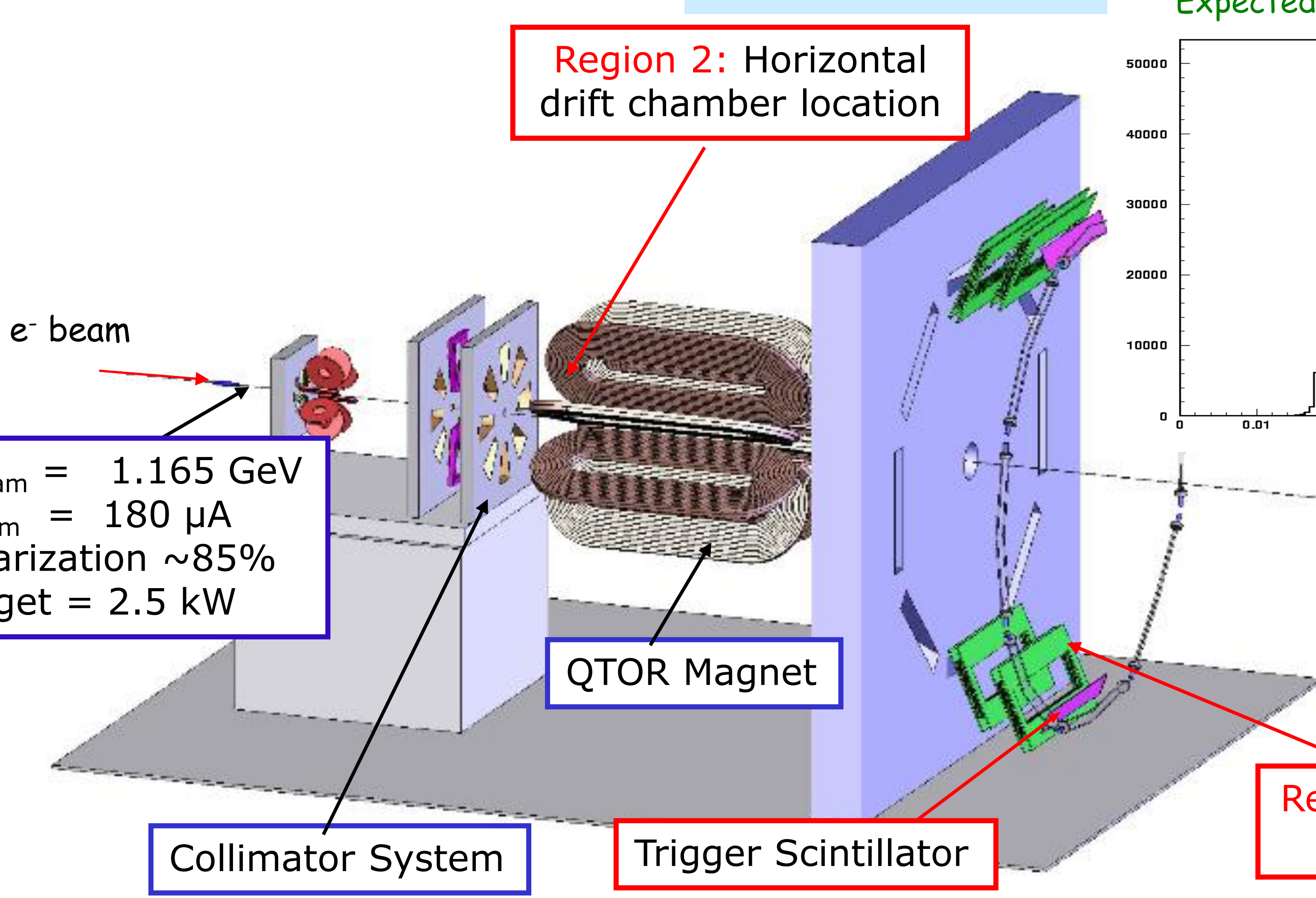



Qweak:
Typical Experiment Parameters

Beam Energy: 1.16 GeV
Beam Current: 170 $\mu$A
Beam Polarization: 88%
$LH_2$ Power: 2.5 kW
$\theta$ Acceptance: $7.9^\circ \pm 2^\circ$
$\phi$ Acceptance: 49% of $2\pi$
$\langle Q^2 \rangle$: 0.025 $GeV^2$
$\langle A_{ep} \rangle$: $-0.22$ ppm
$\langle A_{meas} \rangle$: $-0.15$ ppm
Integrated Rate: 6.5 GHz

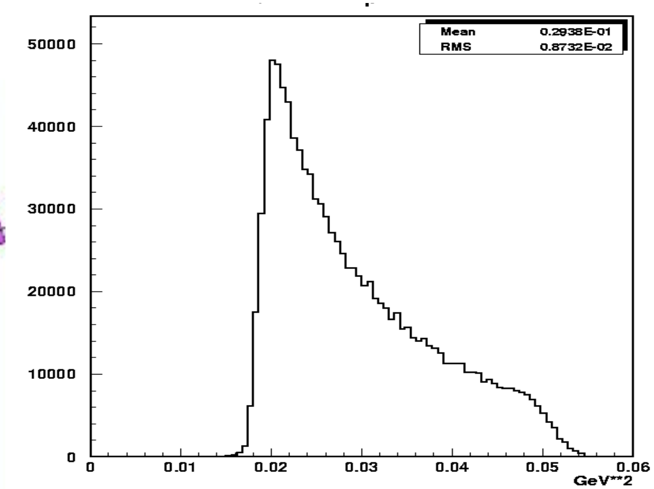
Commissioning:
July-Aug 2010
Oct-Dec 2010
Run I: Jan - May 2011
Run II: Nov 2011 - May 2012

## Layout drawing: main asymmetry plus tracking apparatus for $<Q^2>$, $<Q^4>$ (Ibeam ~ 100pA to 1 nA)




$E_{beam}$ = 1.165 GeV
$I_{beam}$ = 180 μA
Polarization ~85%
Target = 2.5 kW

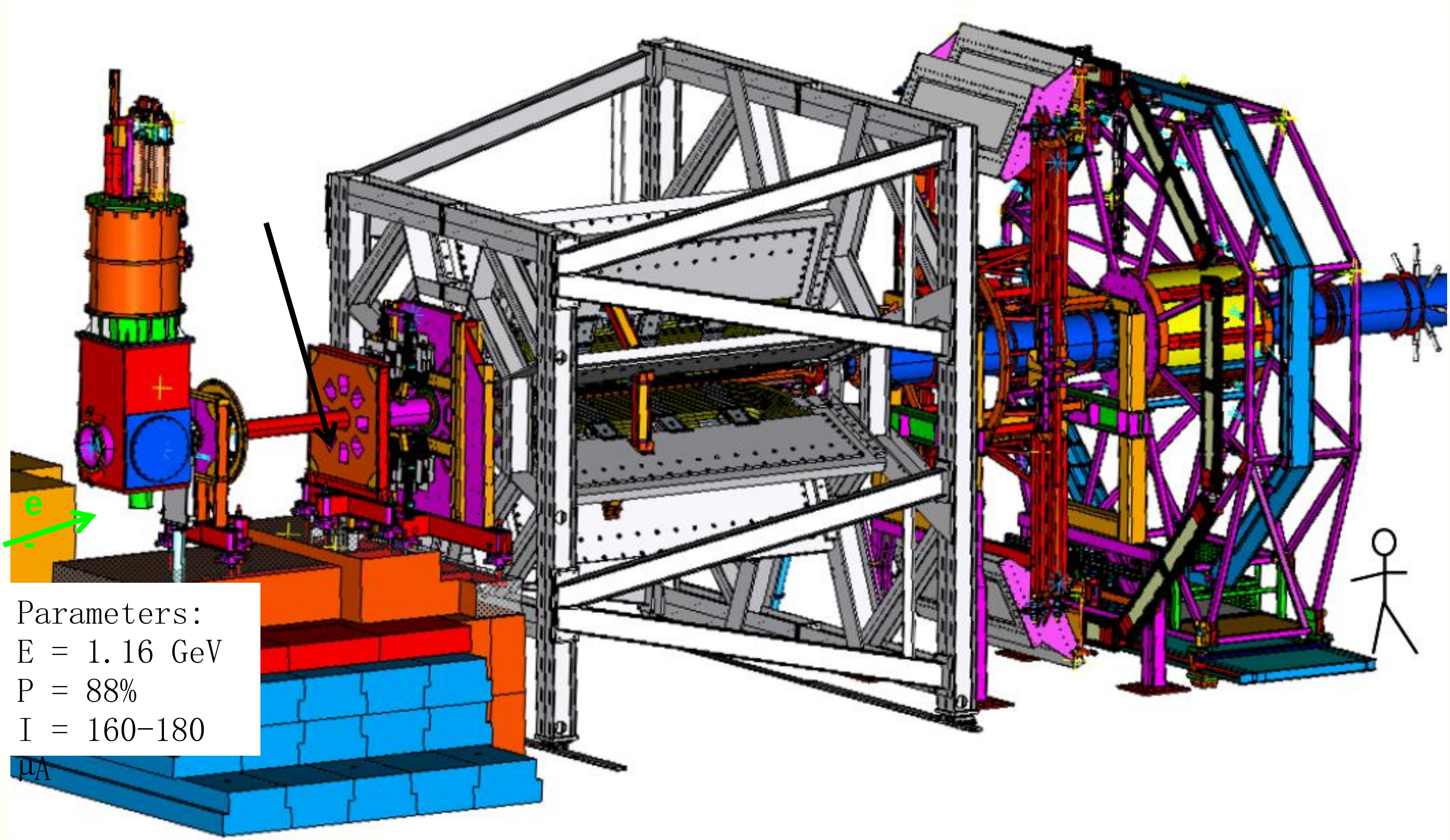
Expected $Q^2$ distribution




Region 2 chambers → Absolute $Q^2$ acceptance

Region 3 chamber → Efficiency map of quartz detectors

# The Qweak Experiment



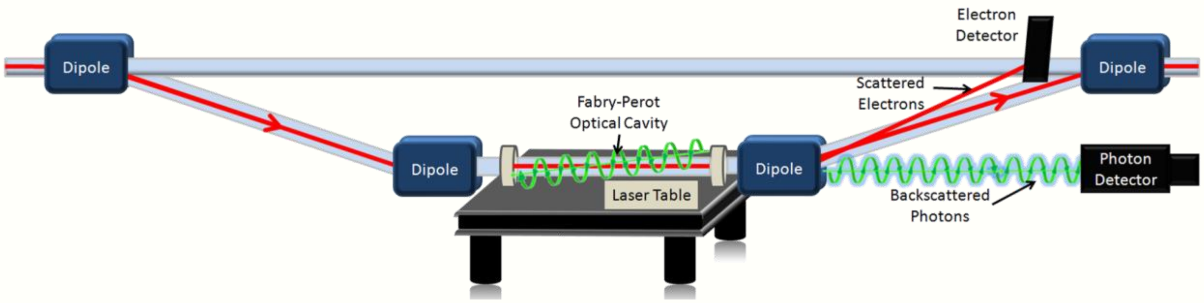

Parameters:
E = 1.16 GeV
P = 88%
I = 160-180 μA

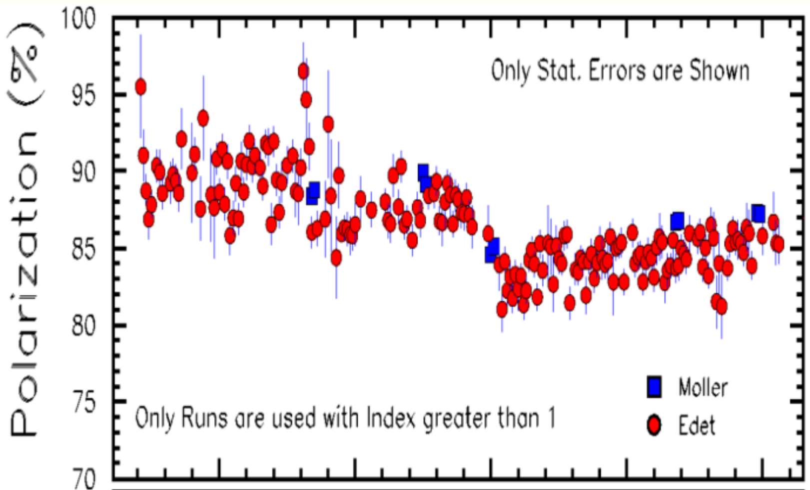


# Precision Polarimetry: 1% at 180 μA

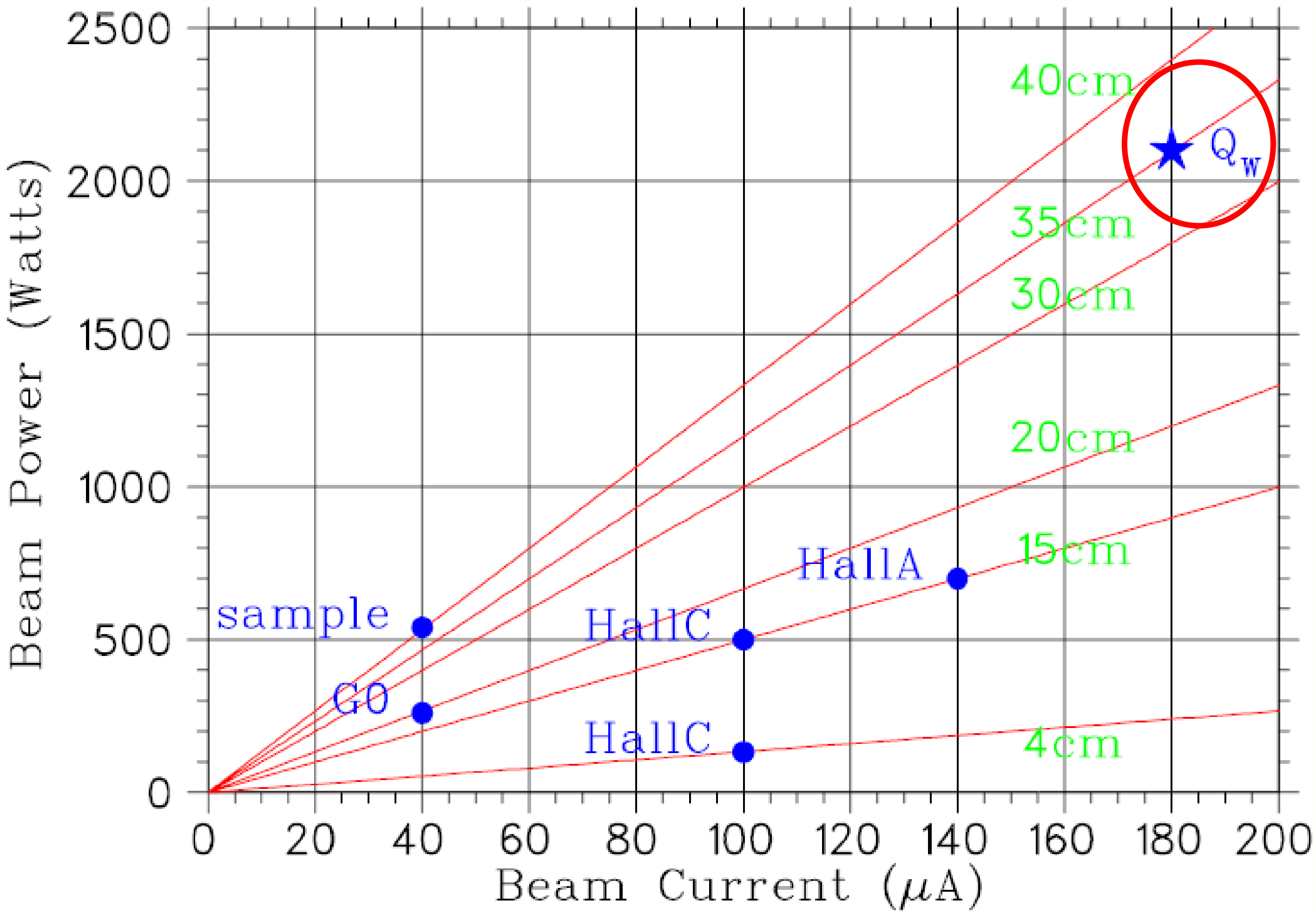
- Existing Hall C Moller polarimeter: 1% statistics in ~ minutes
  - $I_{Max}$ ~ 10 μA
  - Higher currents → Fe target depolarizes
  - Measurement is destructive

- New Hall C Compton polarimeter
  - Continuous, non-invasive monitor at full beam current
  - Two independent detectors of Compton scattering
  - 1 – 11 GeV
  - +/- 1% absolute accuracy



# $Q_{weak}$ $LH_2$ Target



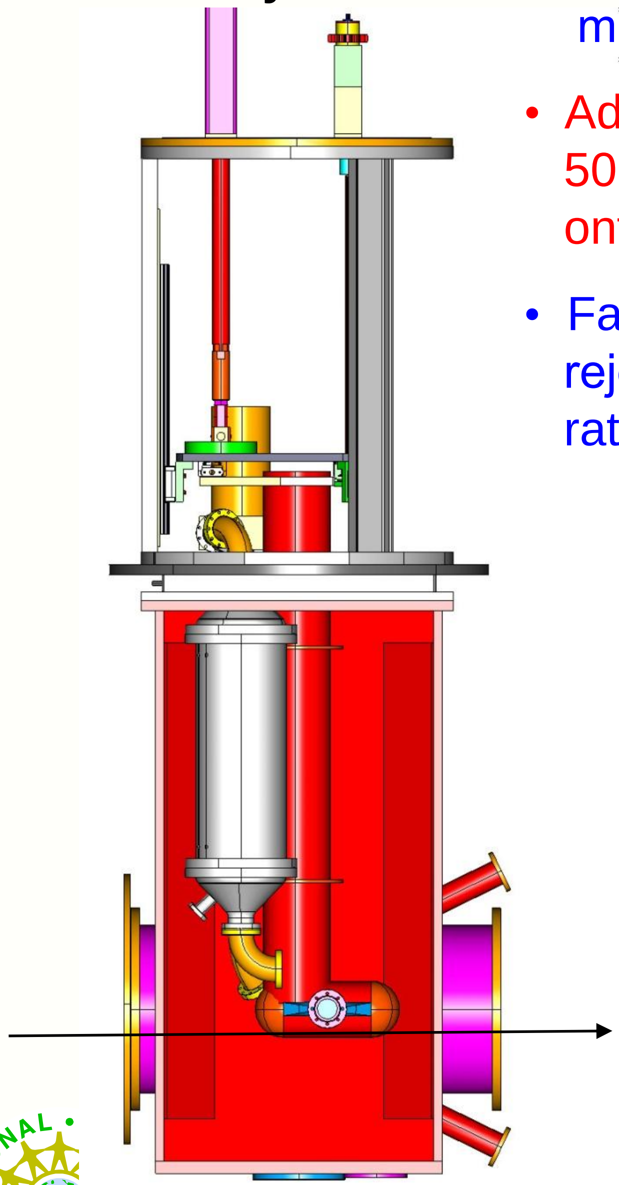

Requirements:

- 2500 W cooling power!
- raster size 4 x 4 mm²
- $\delta\rho/\rho$ < 10 ppm @ 30 Hz

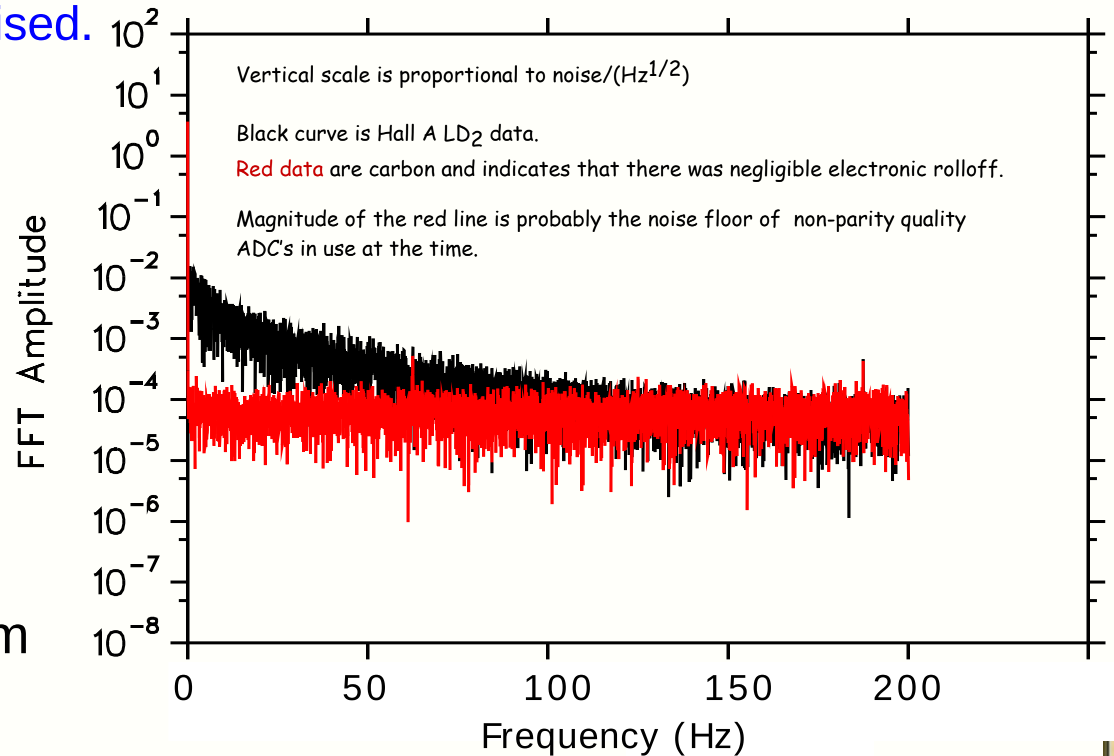
# 2.5 kW $LH_2$ Cryotarget

- Fluid dynamics simulation code used in the design effort to minimize "boiling noise" risk - in the liquid volume or at the windows.
- Additional safeguards: large raster size ~(4mm x 4mm) with new 50 kHz raster, faster pump speed, and more cooling directed onto windows....
- Faster helicity reversal 125 Hz up to 500 Hz. Common mode rejection of "boiling" noise increases as Helicity reversal/readout rate is raised.

**Layout**



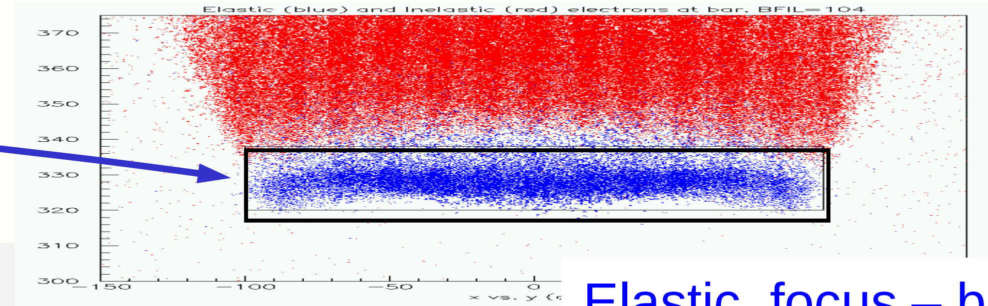
Beam



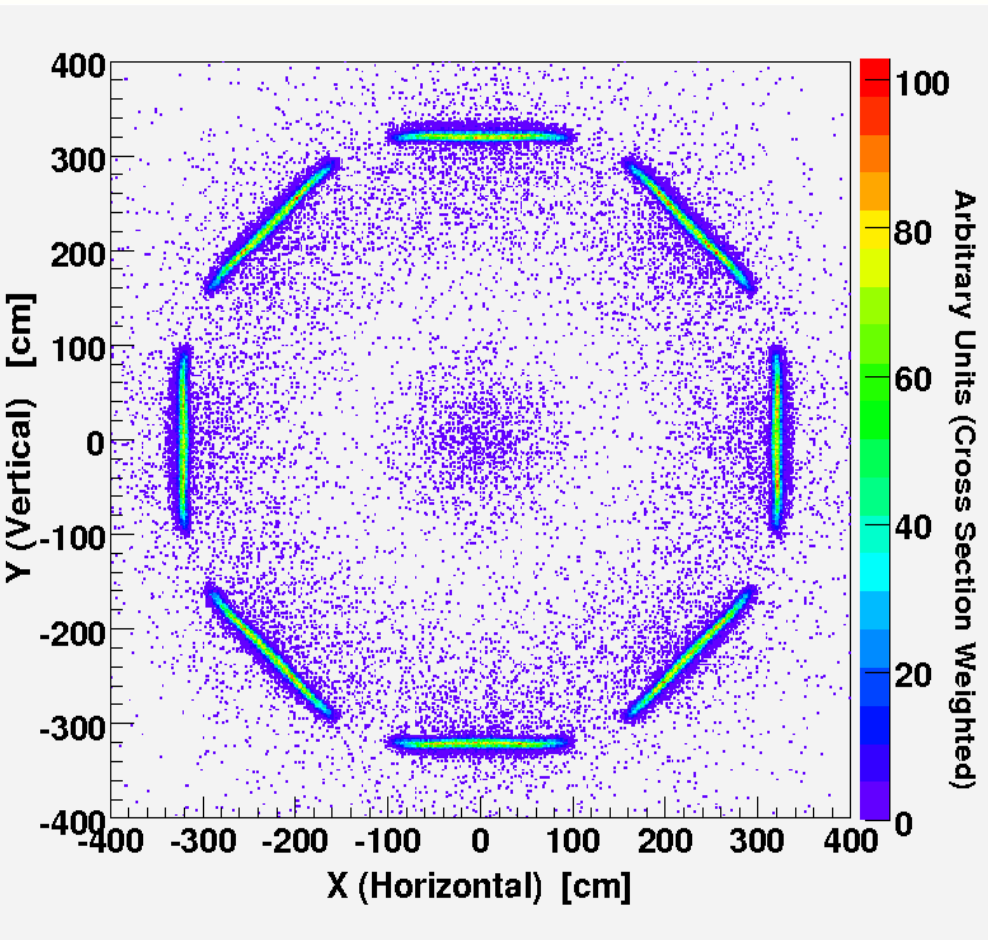

# Main Detector

8-fold symmetry

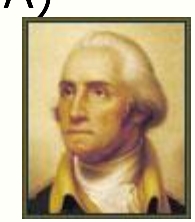
Inelastics - red




Elastic focus – blue




- 8 fused silica radiators
  200 cm x 18 cm x 1.25 cm
- Spectrosil 2000
  Rad-hard (expect > 300 kRad), low luminescence
- 900 MHz $e^-$ per bar
- $\theta_{Cerenkov}$=47°, $\theta_{TIR}$=43°, n = 1.47
- 5 Angstroms rms polish
- 5" PMTs with gain = 2000
- S20 photocathodes ($I_k$ = 3 nA)
- Current mode readout ($I_a$ = 6 μA)



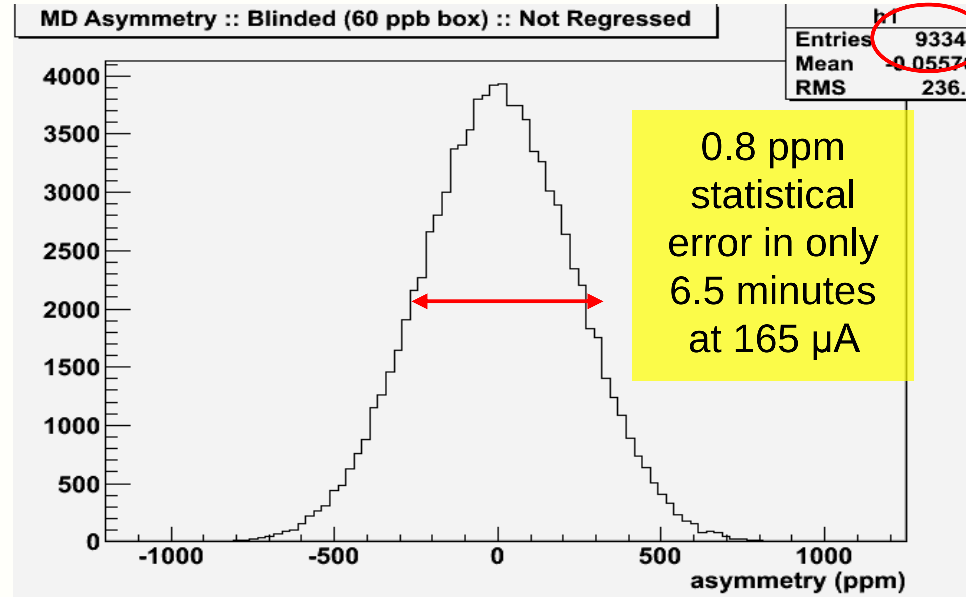
# $LH_2$ Data Quality (blinded asymm)

Convergence to mean ~rms/sqrt(N)
Width is a very important FOM!

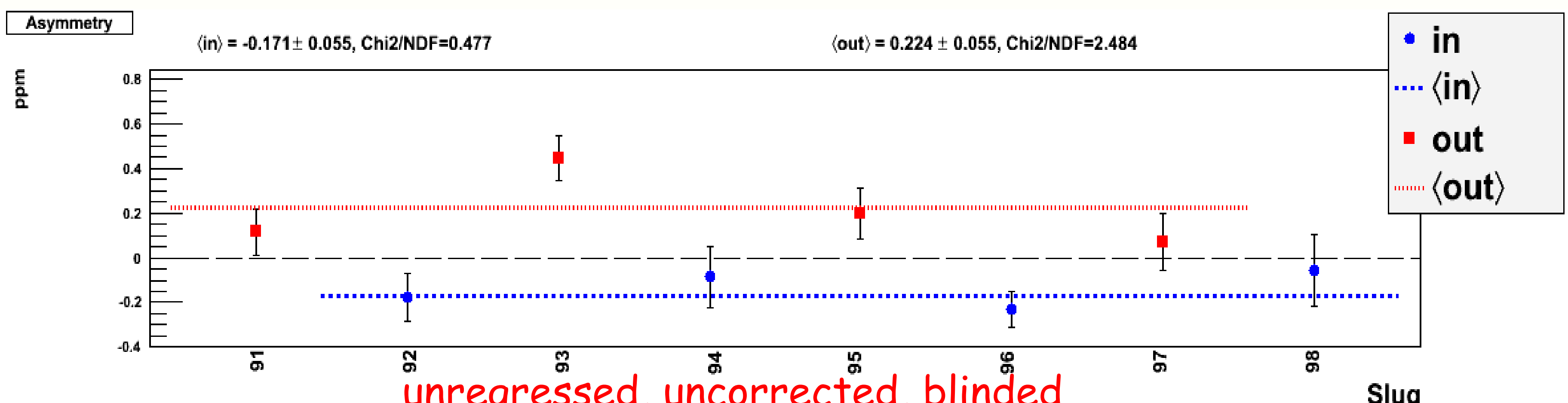
At 165 μA, total detected rate is 5.83 GHz.

| | |
|---|---|
| → Pure counting statistics: | 215 ppm |
| + detector shower fluctuations | 232 ppm |
| + current normalization and target | 235 ppm |

Width is understood and about 10% above c.s.




Electron helicity reversed every 1 msec by *electronic* means
Insertable Half Wave Plate (IHWP) → *optically* flips the helicity before every 8 hour "slug"
→ signal changes sign




unregressed, uncorrected, blinded

# Beam Property Requirements

| | | Achieved | |
|---|---|---|---|
| Beam value | Requirement | Run I | Run II |
| X-position at target [nm] | <2 | 3.6 +/- 0.39 | -0.95 +/- 0.06 |
| Y-position at target [nm] | <2 | -6.9 +/- 0.39 | -0.24 +/- 0.28 |
| X-angle at target [nrad] | <30 | -0.22 +/- 0.012 | -0.07 +/- 0.017 |
| Y-angle at target [nrad] | <30 | -0.18 +- 0.015 | -0.06 +/- 0.011 |
| Position at dispersion (3c12X)[nm] | - | -13.6 +/- 0.23 | -0.83 +/- 0.30 |
| Energy dE/E [ppb] | <1 | <3.8 +/- 0.06 | <0.23 +/- 0.08 |

# Regression: False asymmetry

- False asymmetry from helicity-correlated beam parameters

$$A_{reg} = A_{unreg} - \sum_i \left(\frac{\partial A}{\partial P_i}\right) \Delta P_i$$

Sensitivity　　HC parameter net size

P = (X, Y, X’, Y’, E, $A_Q$)

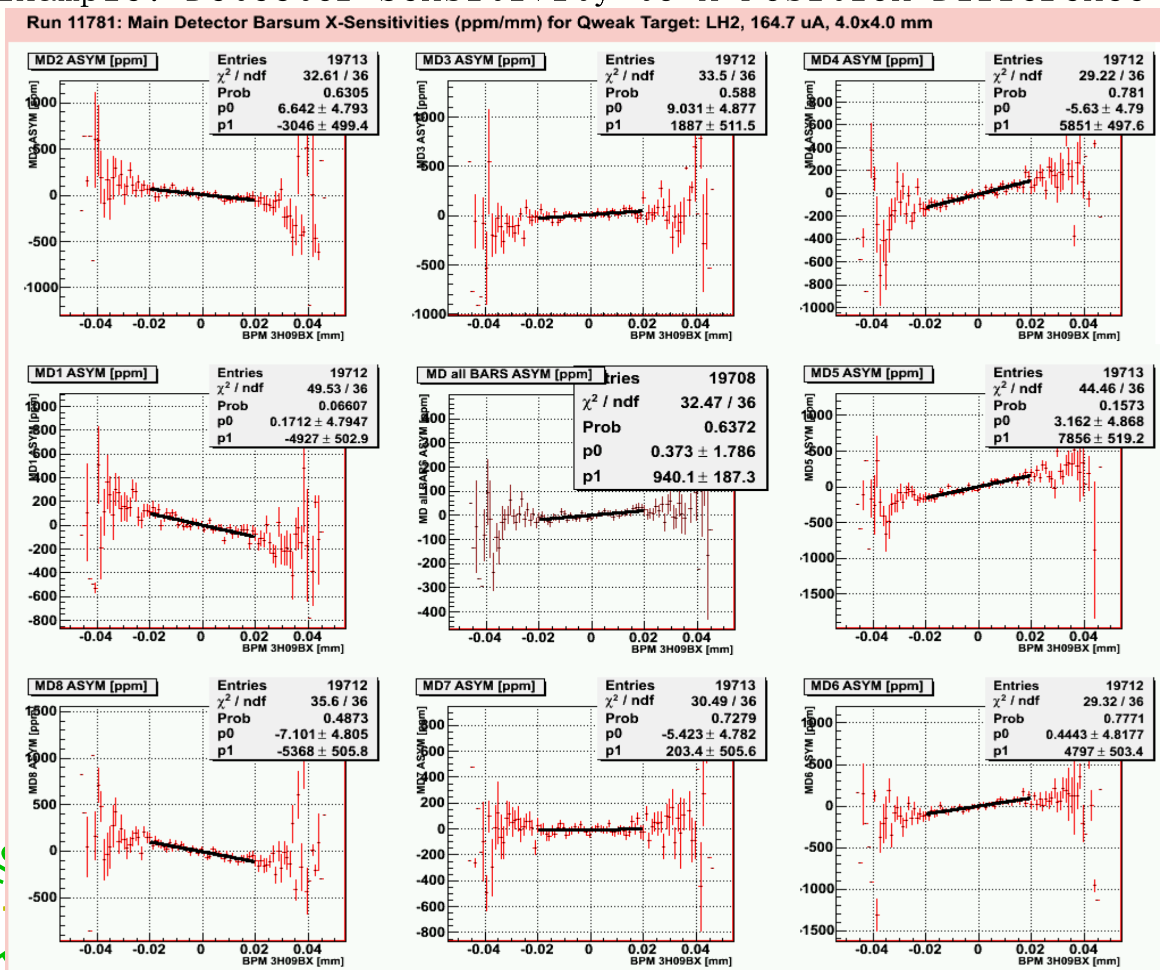
(X’,Y’,E): cross section effects

(X,Y): solid angle effects

($A_Q$): nonlinearity

→ Linear regression removes correlation between variables and calculates a correction

Example: Detector Sensitivity to X Position Difference

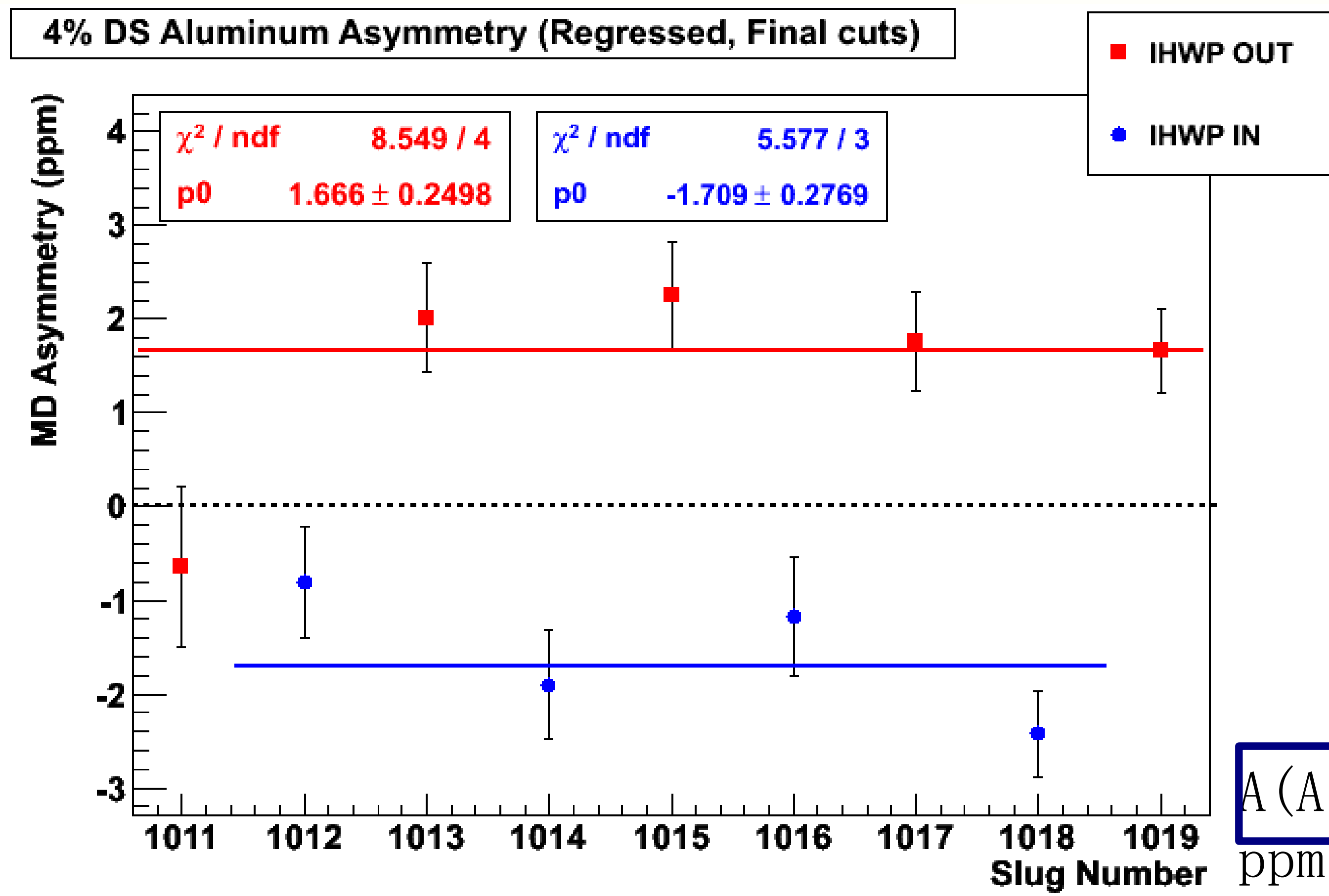



# Background Correction

$$A_{ep} = \frac{A_{meas}/P - \sum_i f^i_{bkgd} A^i_{bkgd}}{1 - f_{total}}$$

Need to know for each background:
- → background dilution
- → background asymmetry

Largest Background Correction: Aluminum target windows




Measure asymmetry on a thick dummy target

Regressed Asym: (ppm)

OUT: 1.67 +- 0.25
IN: -1.71 +- 0.28
**TOT: 1.67 +- 0.19**

(stat. errors)

w/ acceptance correction and systematic errors

**A(Al) = 1.52 +- 0.19 ppm**

# Anticipated Uncertainties

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

| Uncertainty | $\Delta A_z/A_z$ | $\Delta Q_w/Q_w$ |
|---|---|---|
| Statistical (2,544 hours at 180 μA) | 2.1% | 3.2% |
| Systematic: | | 2.7% |
| Hadronic structure uncertainties | --- | 1.5% |
| Beam polarimetry | 1.0% | 1.6% |
| Absolute $Q^2$ determination | 0.5% | 1.0% |
| Backgrounds | 0.7% | 1.0% |
| Helicity correlated beam properties | 0.5% | 0.8% |
| Regression | 0.4% | 0.6% |
| Total: | 2.6 % | 4.2% |



# Summary and $Q_{weak}$ Status

- Goals: $Q^p_w$ to ± 4% → $\sin^2\theta_w$ to ± 0.3% at low $Q^2$ via parity-violating elastic scattering at Jefferson Lab

- JLab schedule
  - installation began December 2010
  - engineering/commissioning run June – August 2010
  - Run I: Jan → May 2011
  - Run II: Nov 2011 → May 2012   ie ~ 2 years on the floor

- Successes
  - beam $P^2I$ exceeded proposal (150-180 μA, 86-88% polarization)
  - helicity correlated beam parameters acceptable
  - successful measurements of background asymmetries and dilutions
  - e-p at 3.36 GeV to check $\gamma Z$ box correction ($A_L$ ~ 8 ppm)
  - e-p inelastic analyzing power including to Δ(1232)
  - transverse spin analyzing power on p, Al and C



# The Qweak Collaboration

www.jlab.org/qweak

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[1]Spokespersons
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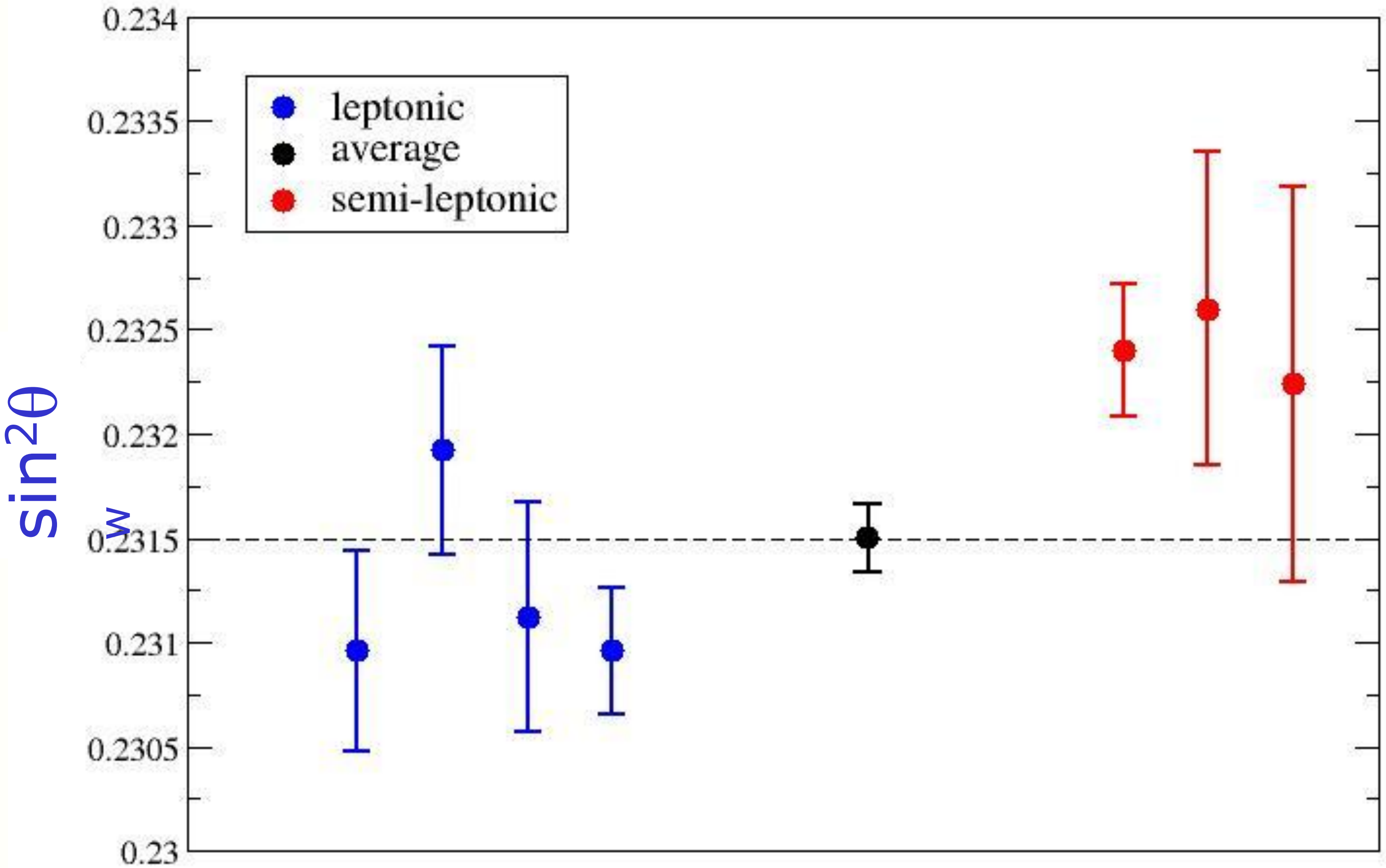
**Fourth Workshop on Hadron Physics July 2012**

# Extra Slides



# Weak Mixing Angle at the $Z^0$ Pole




$\delta(avg) = 0.00017$

~ $4\sigma$ between leptonic and semileptonic

Statistical?

Systematic
→
$\delta(avg)=0.0008$



# Energy Scale of the $Q_{weak}$ Experiment

(Erler et al. PRD 68, 016006 (2003)):

$$\mathcal{L}^{PV}_{e-q} = \mathcal{L}^{PV}_{SM} + \mathcal{L}^{PV}_{New}$$

$$= -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h^q_V \bar{q}\gamma^\mu q$$

$\Lambda$ = mass scale     g = coupling

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

Because $Q_W^p$ is a suppressed, weak-scale observable, our 4% measurement has TeV scale sensitivity.



# Energy scale of Indirect Search for New Physics

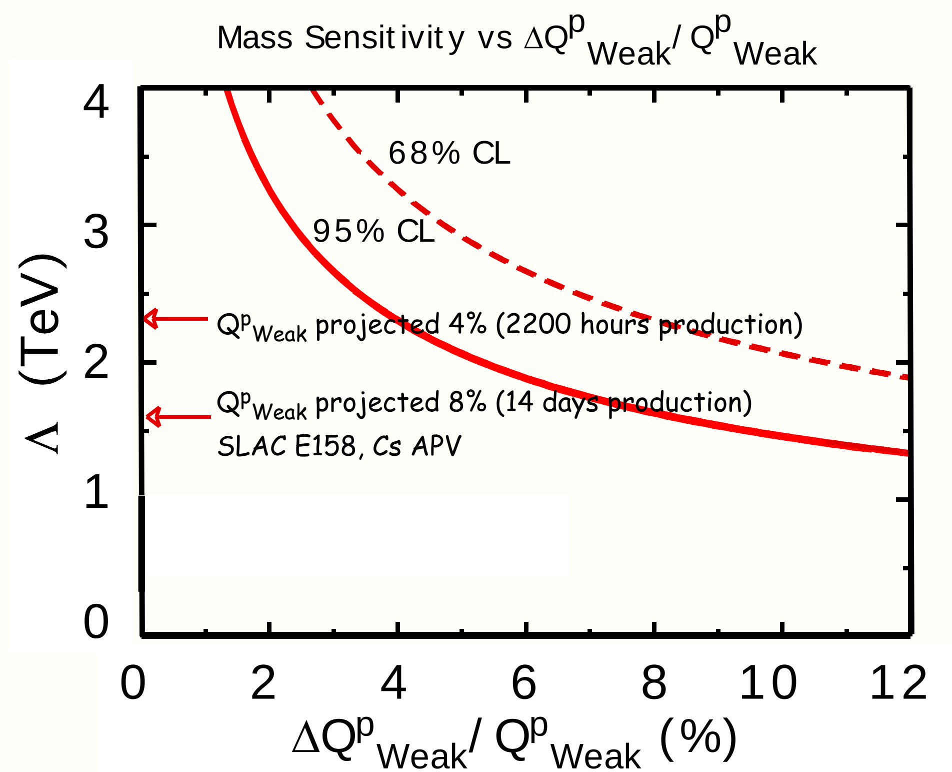
• Sensitivity to new physics Mass/Coupling ratios estimated by adding a new contact term to the *e-q* Lagrangian:

$$\mathrm{L}^{\mathrm{PV}}_{\mathrm{e\text{-}q}} = \mathrm{L}^{\mathrm{PV}}_{\mathrm{SM}} + \mathrm{L}^{\mathrm{PV}}_{\mathrm{NEW}} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e\sum_q C_{1q}\bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e\sum_q h_V^q\bar{q}\gamma^\mu q$$

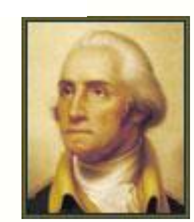
g: coupling, $\Lambda$: mass scale

• 4% $Q_{weak}$ measurement → 95% confidence level for new physics at energy scales to:

$$\frac{\Lambda}{g} \sim \frac{1}{2\sqrt{\sqrt{2}G_F\left|\Delta Q_W^p\right|}} \approx 2.3\ \mathrm{TeV}$$




• If LHC uncovers new physics first, precise low energy measurements will be need → charges, coupling constants, …



# Summary: State of Theoretical Corrections

| | |
|---|---|
| $Q^p_{Weak}$ Theoretical Value ($Q^2 = 0$) | 0.0713 ± 0.0008 |
| $Q^p_{Weak}$ Experimental Value (Young, et.al.) | 0.055 ± 0.017 |
| $Q^p_{Weak}$ (Anticipated this experiment) | 0.0XXX ± 0.003 |

| Source | $Q^p_{Weak}$ Uncertainty |
|---|---|
| $\Delta \sin \theta_W (M_Z)$ | ±0.0006 |
| $Z\gamma$ *box* | ±0.0005 |
| $\Delta \sin \theta_W (Q)_{hadronic}$ | ±0.0003 |
| *WW, ZZ box - pQCD* | ±0.0001 |
| *Charge symmetry* | 0 |
| Total | ±0.0008 |

Erler, Musolf, el.al.

| Estimates of Contribution to $A_{PV}$ at Qweak Kinematics | |
|---|---|
| TPEX (Blunden et.al.) | -0.05% |
| TBEX (Melnitchouk et.al.) | 0.58% ± 0.3%. |

**Our theory colleagues indicate that although some refinements and additional diagrams need to be calculated, they see no issues that should effect the interpretability of the measurement.**



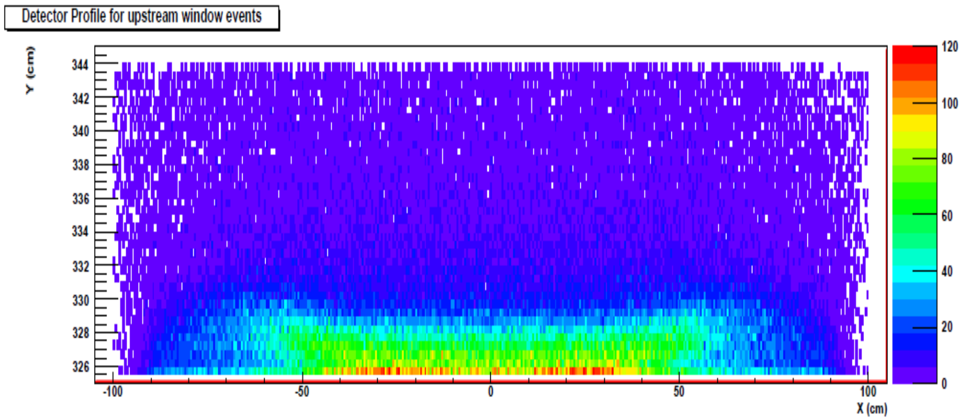
# Background Correction

## Aluminum Dilution:

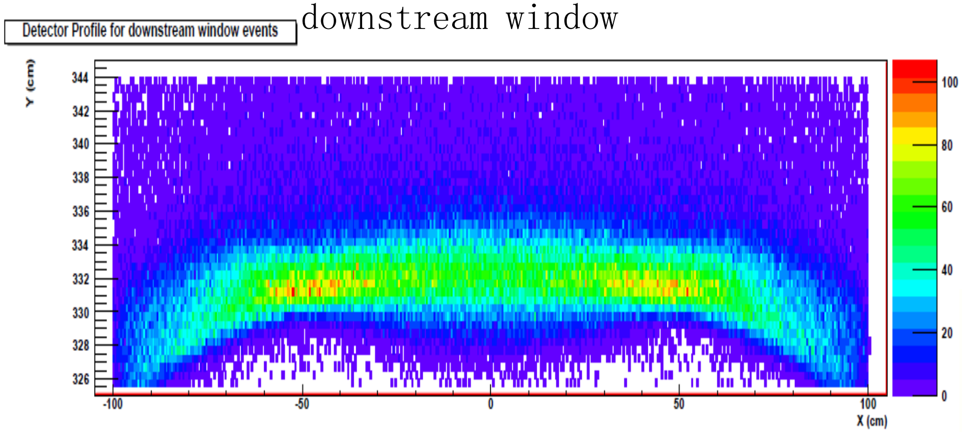
→ Directly measure window rates from evacuated target
→ Extraplation from cold gas measurements

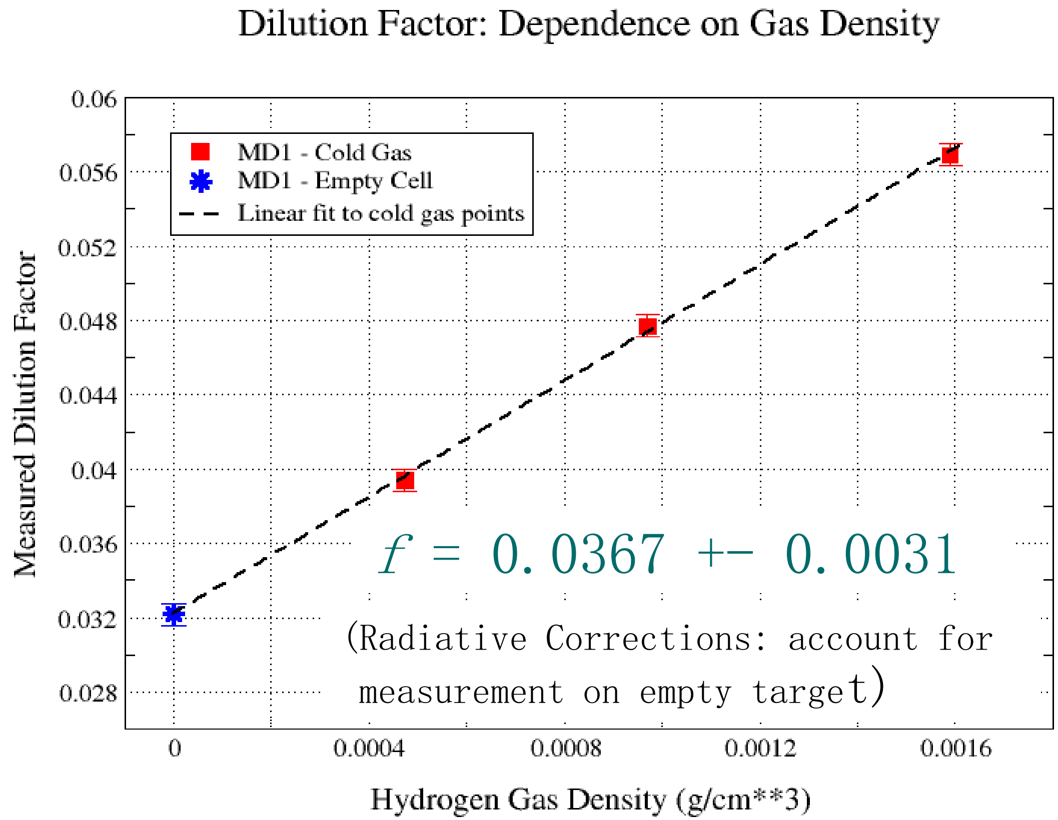
Simulated profile at detector (not to scale):

upstream window




downstream window




$f$ = 0.0367 +- 0.0031

(Radiative Corrections: account for measurement on empty target)

Other (smaller) background corrections:
*i.e.* Inelastics (N → Δ), Beamline bkgd