# The $Q^p_{weak}$ Experiment at Jefferson Lab

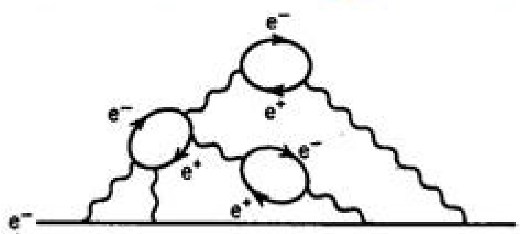
Mark Pitt Virginia Tech

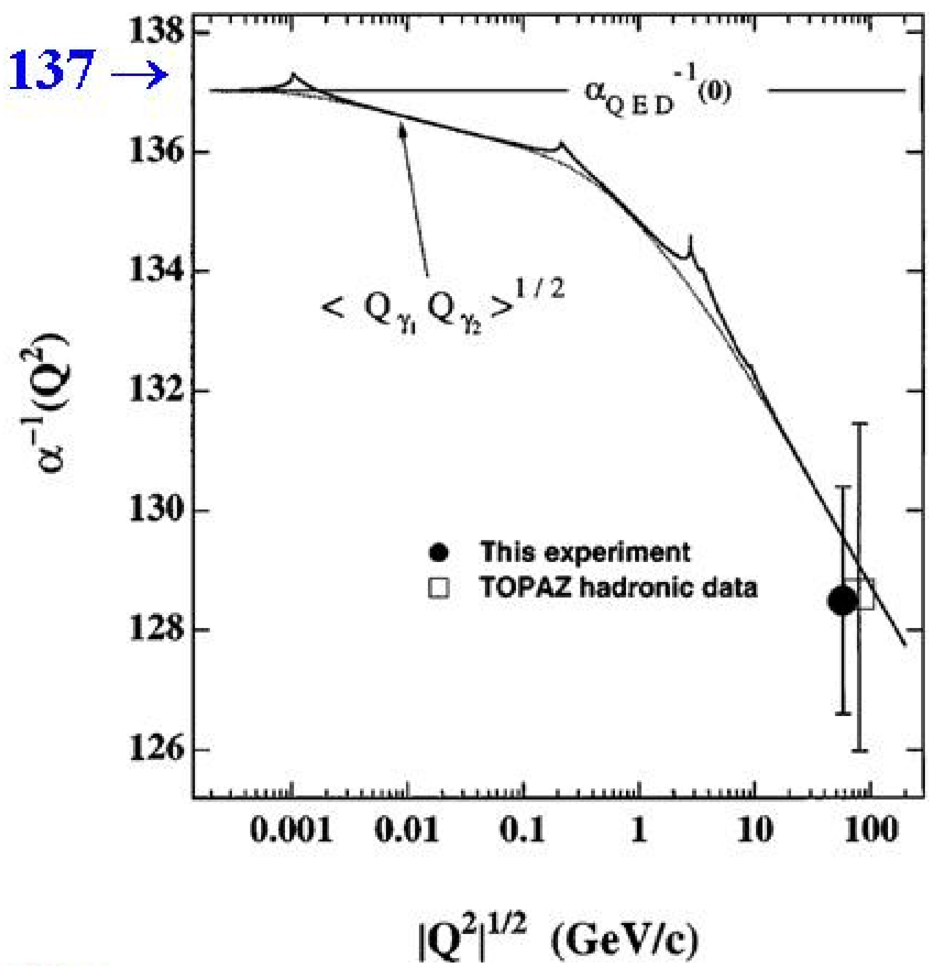
Precision Electroweak Interactions Workshop 2005

- Motivations for low energy Standard Model tests
- Overview and status report of an approved JLAB Standard Model test – The $Q^p_{weak}$ Experiment

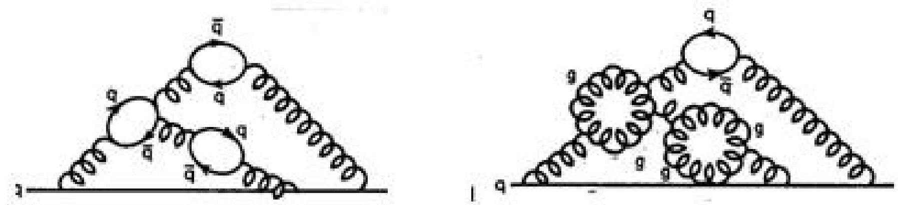
# Running coupling constants in QED and QCD

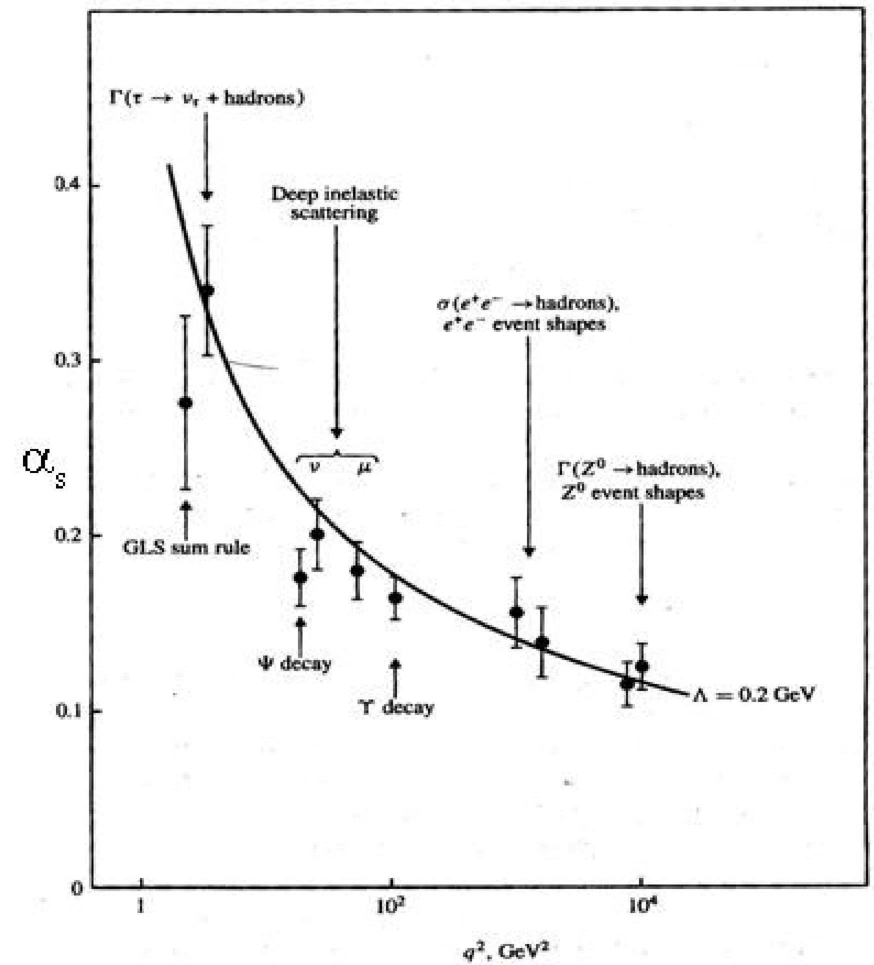
## QED (running of $\alpha$)




## QCD(running of $\alpha_s$)



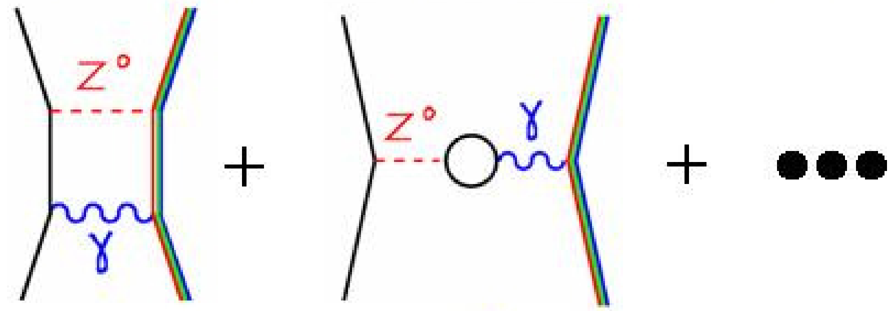



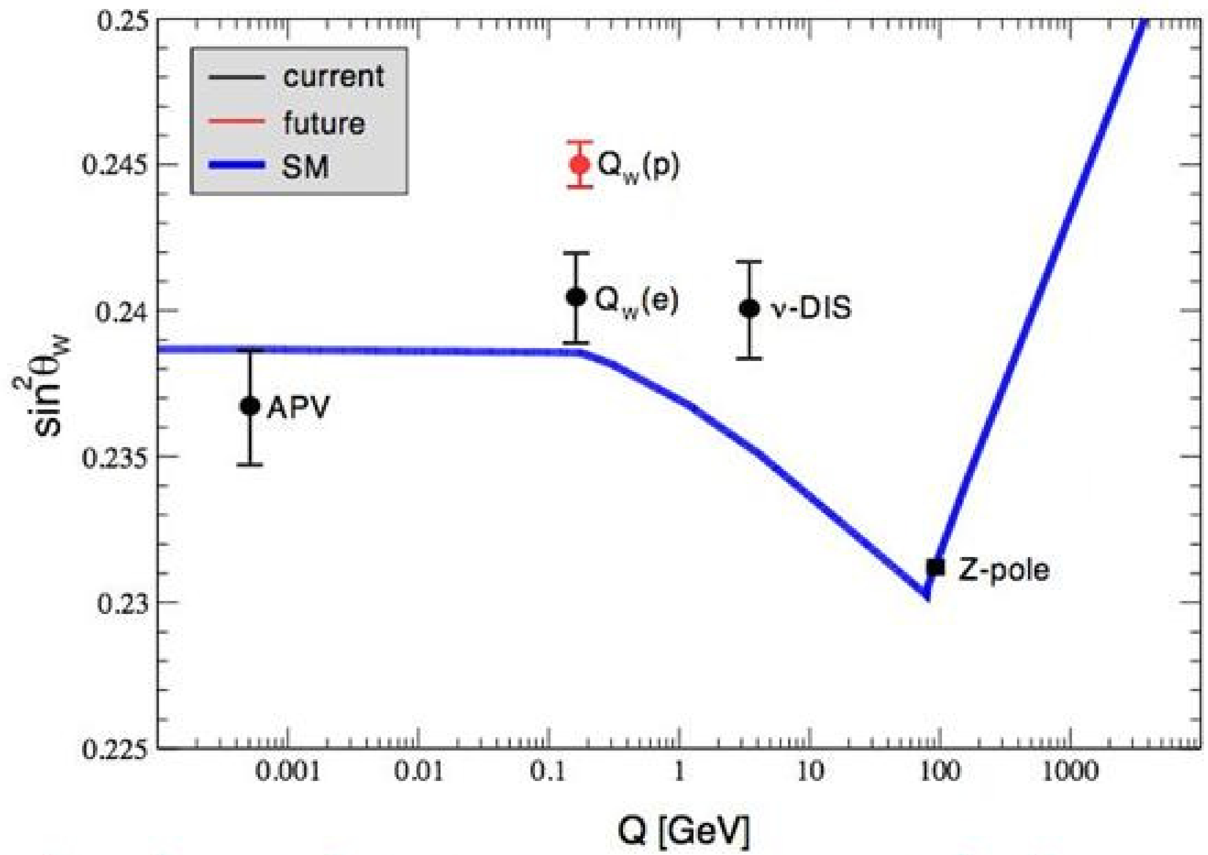

What about the running of $\sin^2\theta_W$?

M. Pitt, Virginia Tech
Prec. EW Workshop,

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

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

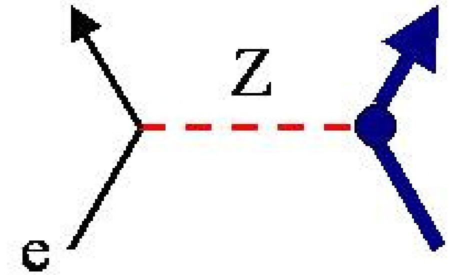


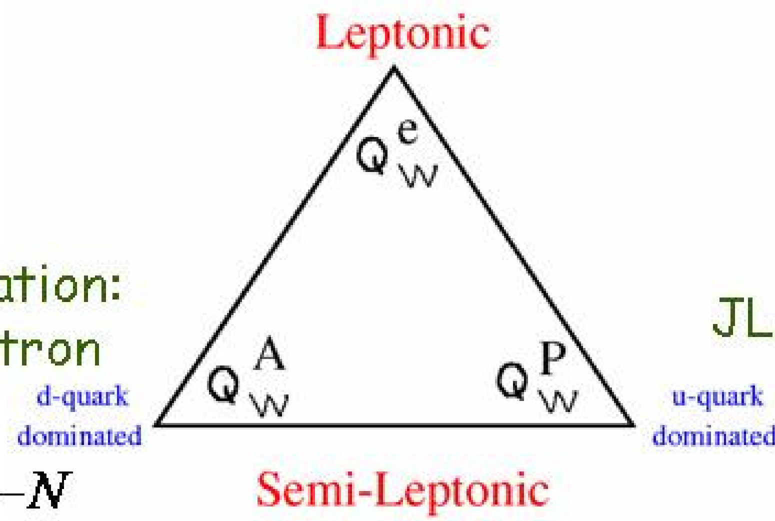

- All "extracted" values of $\sin^2\theta_W$ must agree with the Standard Model prediction or new physics is indicated.

# Low Energy Weak Neutral Current Standard Model Tests

Low energy
weak charge "triad" (M. Ramsey-Musolf)
probed in weak neutral current experiments




SLAC E158: parity-violating
Moller scattering
$\vec{e} + e \rightarrow e + e \quad Q_W^e \approx -(1 - 4\sin^2\theta_W)$



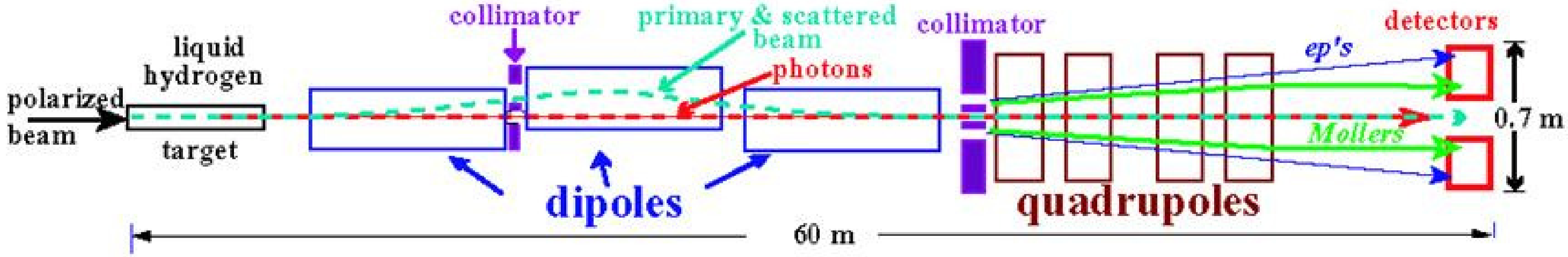

Cesium Atomic Parity Violation:
primarily sensitive to neutron
weak charge

$Q_W^A \approx -N + Z(1 - 4\sin^2\theta_W) \approx -N$

JLAB $Q^p_{weak}$: parity-violating
$\vec{e}$-p elastic scattering
$\vec{e} + p \rightarrow e + p$
$Q_W^p \approx 1 - 4\sin^2\theta_W$

These three types of experiments are a complementary set for exploring new physics possibilities well below the Z pole.

# $Q^e_{weak}$ : Electron Weak Charge - SLAC E158 Experiment




$\vec{e} + e \rightarrow e + e$

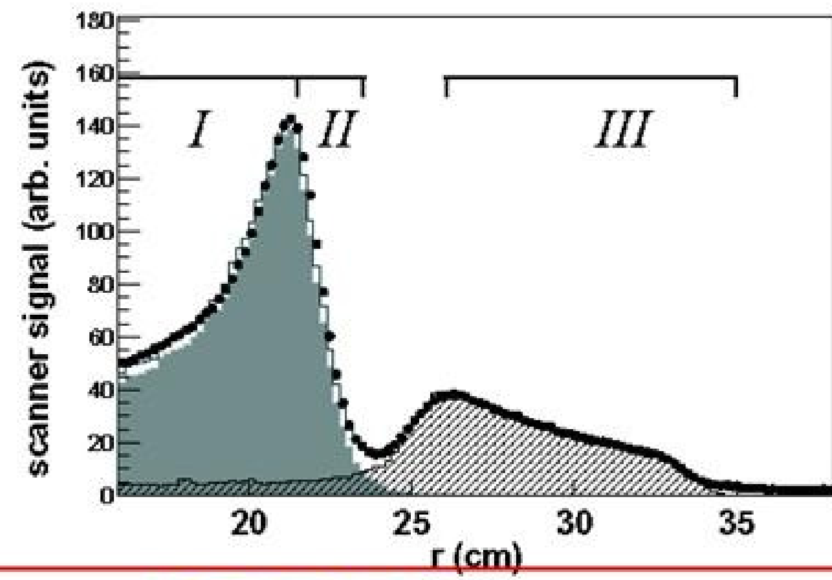
Parity-violating *Moller scattering*

$Q^2 \sim .026$ *GeV*$^2$

$\theta \sim 4 - 7$ mrad

E ~ 48 *GeV*

at SLAC End Station A



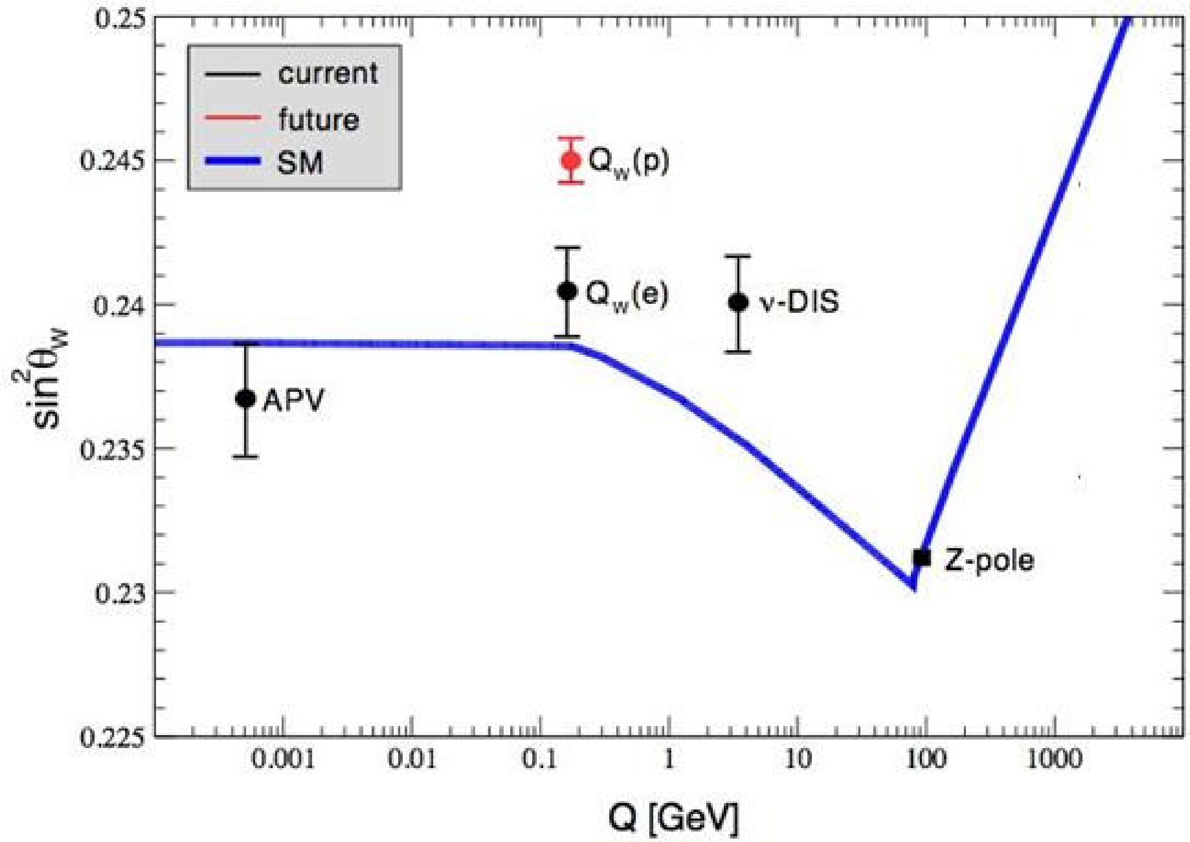

Final results: hep-ex/0504049

$A_{PV}$ = -131 ± 14 (stat) ± 10 (syst) ppb

$\sin^2\theta_{eff}(Q^2=0.026\ GeV^2) = 0.2397 \pm 0.0010 \pm 0.0008$

Running of $\sin^2\theta_{eff}$ established at $6\sigma$ level in pure leptonic sector

# "Running of $\sin^2\theta_W$" : Current Status and Future Prospects




present:

"d-quark dominated" : Cesium APV ($Q^A_W$): SM running verified at ~ 4σ level

"pure lepton": SLAC E158 ($Q^e_W$): SM running verified at ~ 6σ level

future:

"u-quark dominated" : $Q_{weak}$ ($Q^p_W$): projected to test SM running at ~ 10σ level

# The $Q^p_{Weak}$ Experiment JLAB E02-020:

"A Search for new physics beyond the Standard Model at the TeV Scale"

## The Institutions

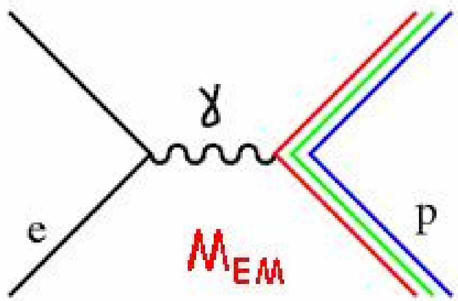
*JLab, LANL, MIT, TRIUMF, William & Mary, Univ. of Manitoba, Virginia Tech, Louisiana Tech, Univ. of Connecticut, Univ. Nacional Autonoma de Mexico,* Univ. of Northern British Columbia, *Univ. of New Hampshire, Ohio Univ., Mississippi State, Hampton Univ., Yerevan Physics Institute*

## The Collaboration

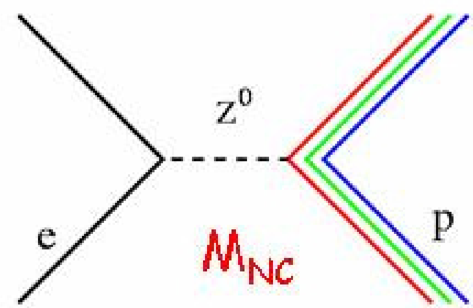
D. Armstrong, T. Averett, J. Birchall, T. Botto, J. D. Bowman, P. Bosted, A. Bruell, R. Carlini (PI), S. Chattopadhay, C. Davis, J. Doornbos, K. Dow, J. Dunne, R. Ent, J. Erler, W. Falk, M. Farkhondeh, J.M. Finn, T. Forest, W. Franklin, D. Gaskell, K. Grimm, F. W. Hersman, M. Holtrop, K. Johnston, R. Jones, K. Joo, C. Keppel, M. Khol, E. Korkmaz, S. Kowalski, L. Lee, Y. Liang, A. Lung, D. Mack, S. Majewski, J. Martin, J. Mammei, R. Mammei, G. Mitchell, H. Mkrtchyan, N. Morgan, A. Opper, S.A. Page, S. Penttila, M. Pitt, B. (Matt) Poelker, T. Porcelli, W. Ramsay, M. Ramsey-Musolf, J. Roche, N. Simicevic, G. Smith (PM),
T. Smith, R. Suleiman, S. Taylor, E. Tsentalovich, W.T.H. van Oers, S. Wells, W.S. Wilburn, S. Wood, H. Zhu, C. Zorn, T. Zwart

| | |
|---|---|
| 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 |

# $Q^p_{weak}$: Extract from Parity-Violating Electron Scattering




As $Q^2 \to 0$




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

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

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

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

contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$

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

- $Q^p_{weak}$ is a well-defined experimental observable
- $Q^p_{weak}$ has a definite prediction in the electroweak Standard Model

# Energy Scale of an "Indirect" Search for New Physics

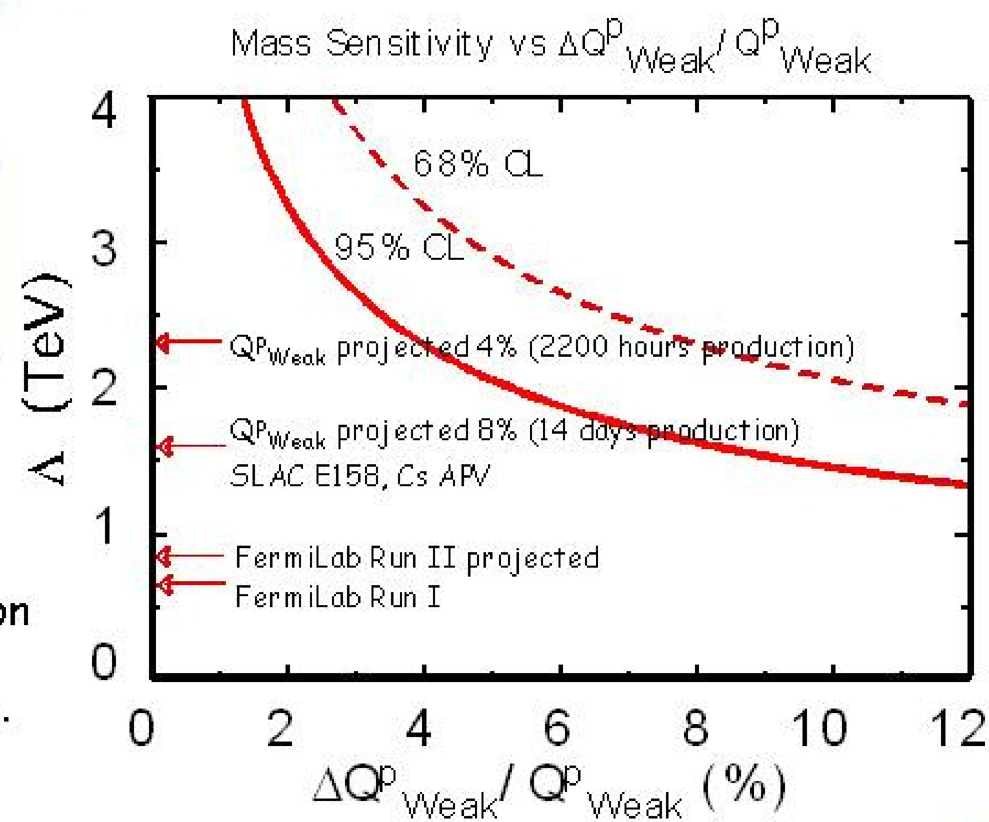
- Parameterize **New Physics** contributions in electron-quark Lagrangian

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

g: coupling constant, $\Lambda$: mass scale

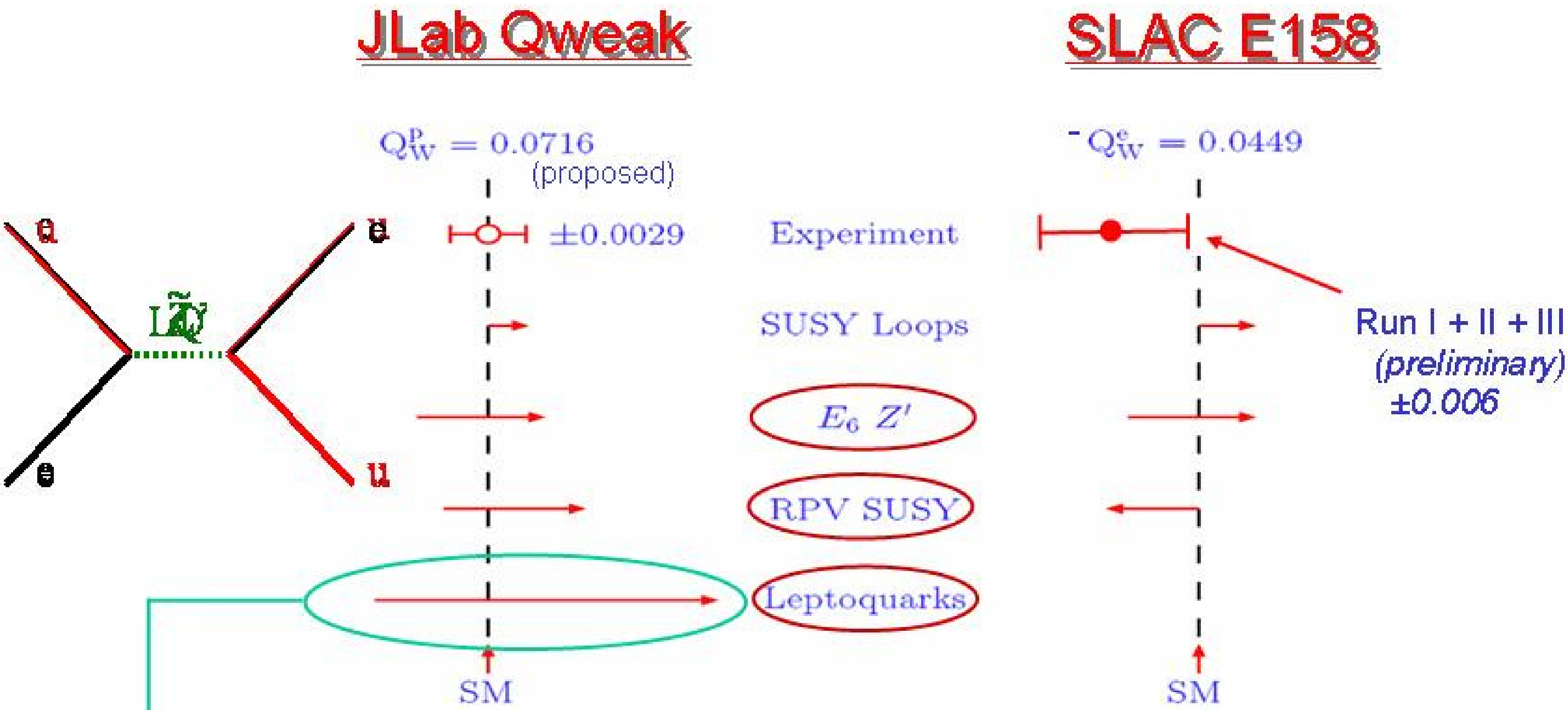
- A 4% $Q^p_{Weak}$ measurement probes with 95% confidence level for new physics at energy scales to:

$$\frac{\Lambda}{g} \sim \frac{1}{2\sqrt{\sqrt{2}G_F\left|\Delta Q^p_W\right|}} \approx 2.3\ \text{TeV}$$




- The TeV discovery potential of weak charge measurements will be unmatched until LHC turns on.
- If LHC uncovers new physics, then precision low $Q^2$ measurements will be needed to determine charges, coupling constants, etc.

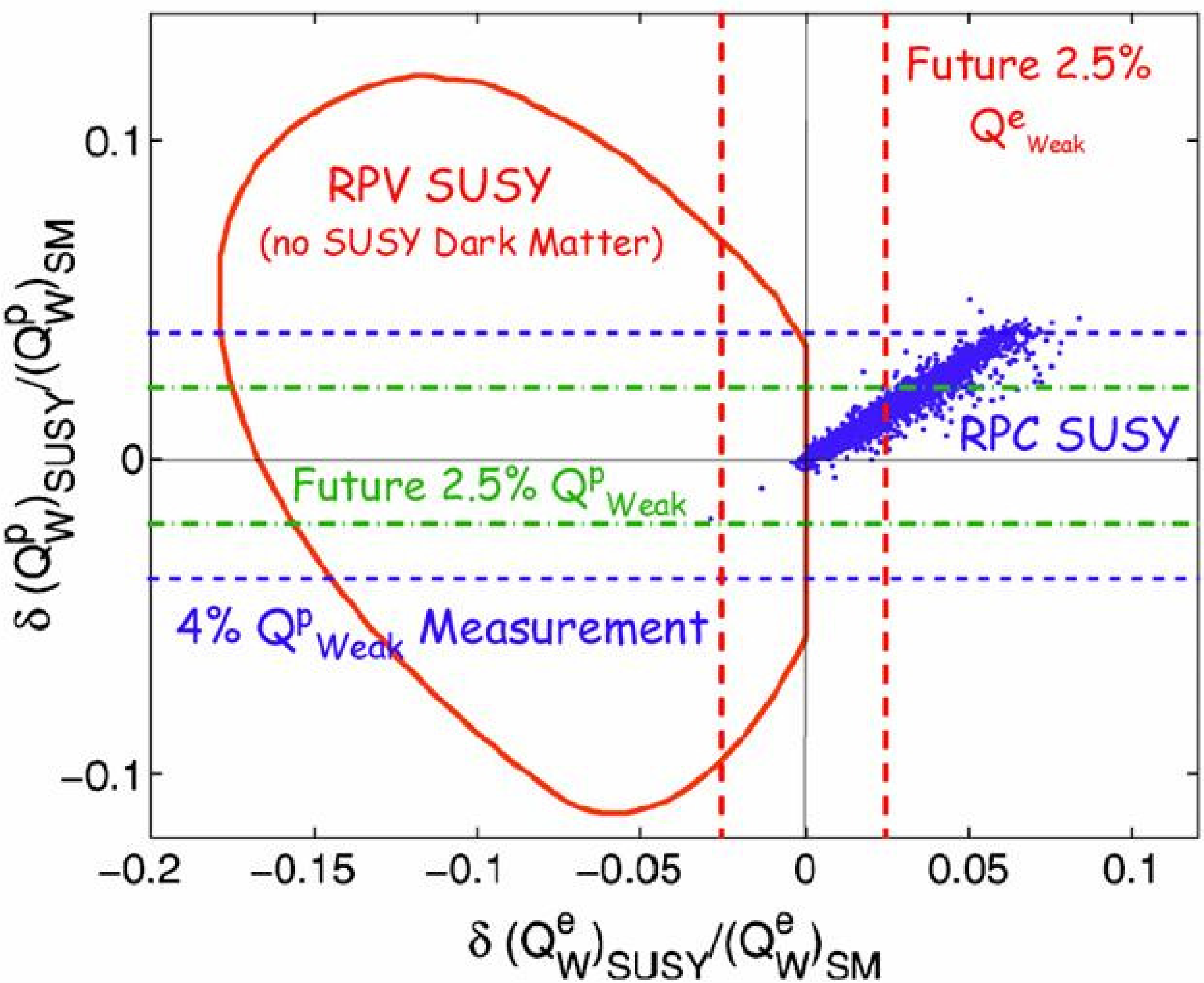
# $Q^p_{weak}$ & $Q^e_{weak}$ - Complementary Diagnostics for New Physics




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

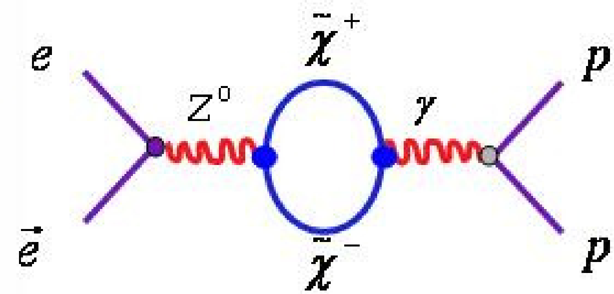
- Qweak measurement will provide a stringent stand alone constraint on Lepto-quark based extensions to the SM.
- $Q^p_{weak}$ (semi-leptonic) and E158 (pure leptonic) together make a powerful program to search for and identify new physics.

# Relative Shifts in Proton and Electron Weak Charges due to SUSY Effects

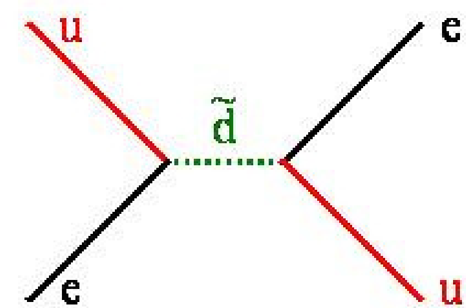



R parity (B-L conservation)

RPC SUSY occurs only at loop level

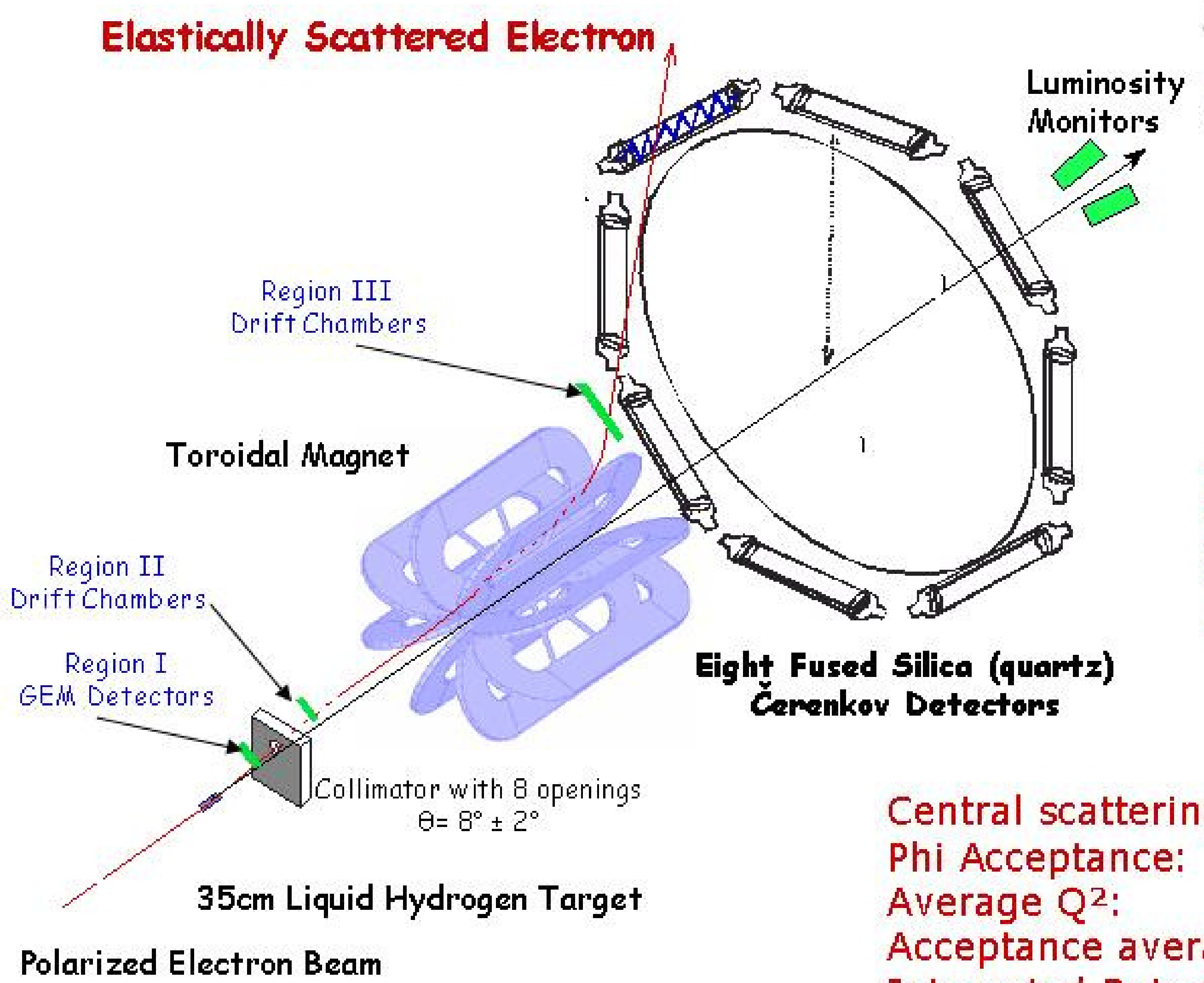


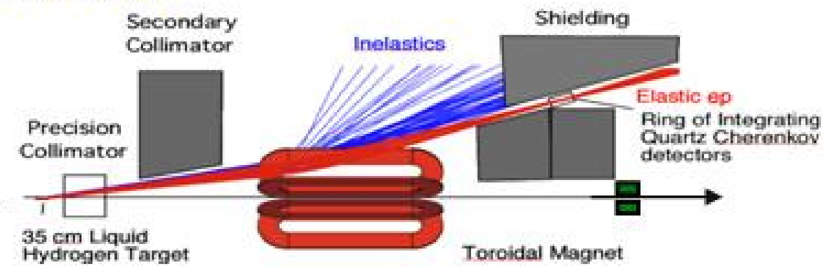

RPV SUSY occurs at tree level




Erler, Ramsey-Musolf, Su hep-ph/0303026

# Overview of the $Q^p_{Weak}$ Experiment




## Experiment Parameters (integration mode)

| | |
|---|---|
| Incident beam energy: | 1.165 GeV |
| Beam Current: | 180 μA |
| Beam Polarization: | 85% |
| $LH_2$ target power: | 2.5 KW |

| | |
|---|---|
| Central scattering angle: | 8.4° ± 3° |
| Phi Acceptance: | 53% of 2π |
| Average $Q^2$: | 0.030 $GeV^2$ |
| Acceptance averaged asymmetry: | –0.29 ppm |
| Integrated Rate (all sectors): | 6.4 GHz |
| Integrated Rate (per detector): | 800 MHz |

# Anticipated $Q^p_{Weak}$ Uncertainties

| | $\Delta A_{phys} / A_{phys}$ | $\Delta Q^p_{weak} / Q^p_{weak}$ |
|---|---|---|
| **Statistical (2200 hours production)** | 1.8% | 2.9% |
| **Systematic:** | | |
| Hadronic structure uncertainties | -- | 1.9% |
| Beam polarimetry | 1.0% | 1.6% |
| Absolute $Q^2$ determination | 0.5% | 1.1% |
| Backgrounds | 0.5% | 0.8% |
| Helicity-correlated Beam Properties | 0.5% | 0.8% |
| **Total** | **2.2%** | **4.1%** |

4% error on $Q^p_W$ corresponds to ~0.3% precision on $\sin^2\theta_W$ at $Q^2$ ~ 0.03 $GeV^2$

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

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

$Q^p_W = 0.0716 \pm 0.0006$ theoretically

0.8% error comes from QCD uncertainties in box graphs, etc.

# Nucleon Structure Contributions to the Asymmetry

$A = A_{Q_W^p} + A_{hadronic} + A_{axial}$

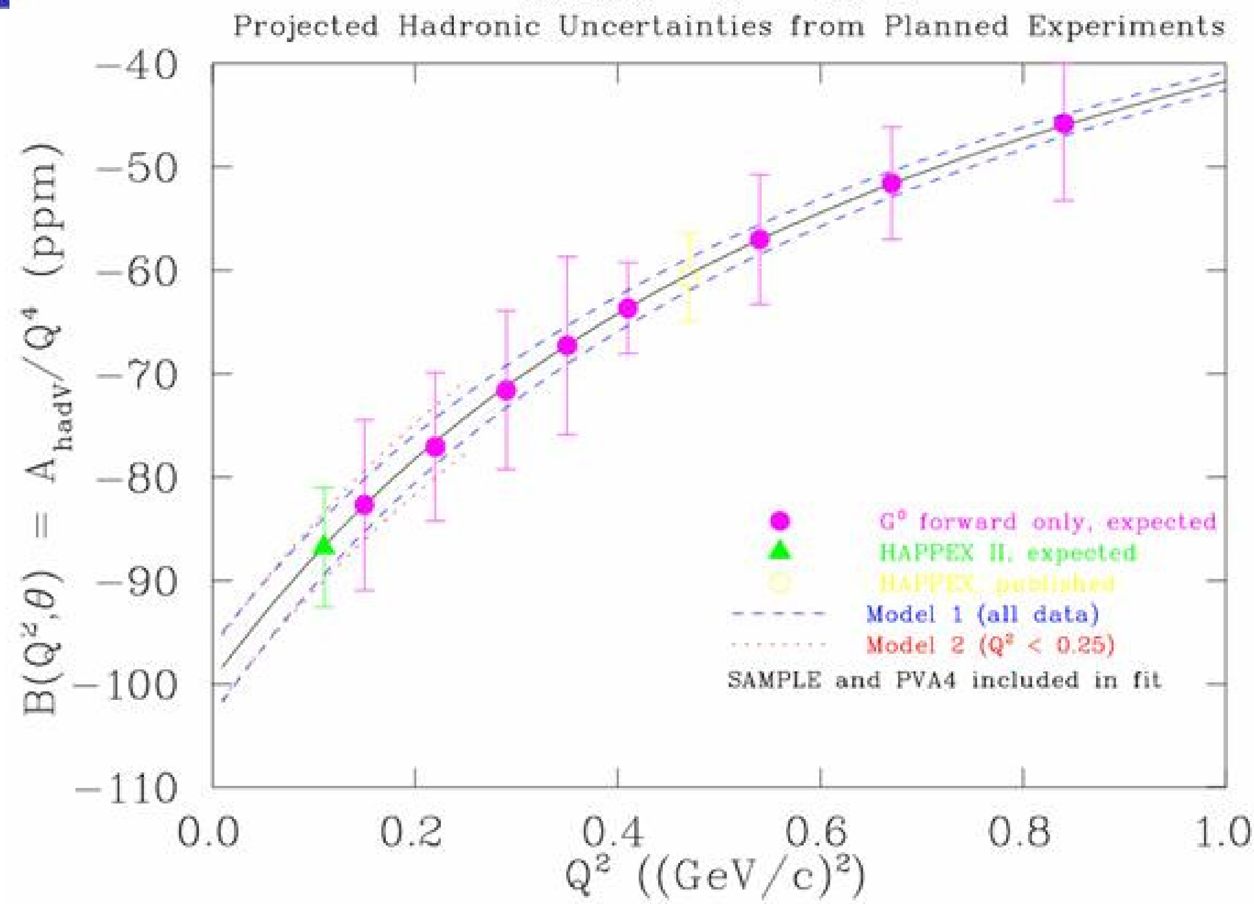
$= -.19\ \text{ppm} \quad -.09\ \text{ppm} \quad -.01\ \text{ppm}$

**hadronic:**
(31% of asymmetry)
- contains $G^{\gamma}_{E,M}$, $G^{Z}_{E,M}$
Constrained by
HAPPEX, $G^0$, MAMI PVA4

**axial:**
(4% of asymmetry) -
contains $G^{e}_{A}$,
has large electroweak radiative corrections.
Constrained by
$G^0$ and SAMPLE

Constraints on $A_{hadronic}$ from other Measurements

$$A_{hadronic} = Q^4 B(Q^2)$$




**Quadrature sum of expected $\Delta A_{hadronic}$ = 1.5% and $\Delta A_{axial}$ = 1.2% errors contribute ~1.9% to error on $Q^p_W$**

# "Contamination" from Transverse Polarization Effects

For the primary measurement, the "beam normal" asymmetry will cause a small "contamination" to the desired parity-violating asymmetry.

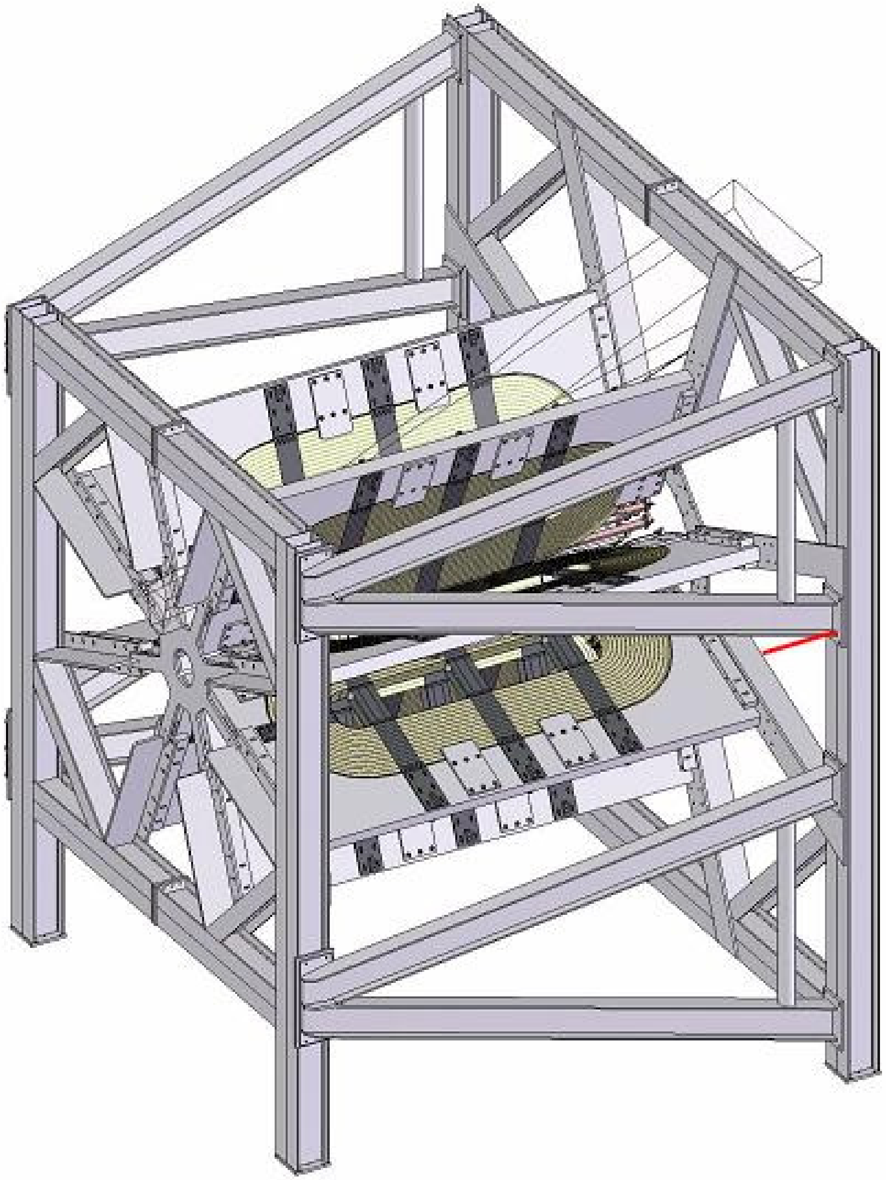
Estimate of effect:

- From Pasquini and Vanderhaeghen (hep-ph/0405303) we estimate $A_{normal} \sim -3$ ppm

- Assuming ~ 5% residual transverse polarization in beam and acceptance matching of the $Q_{weak}$ focal plane detectors to 1% yields a value of 0.0015 ppm (< 1% of the expected PV asymmetry of 0.29 ppm)

- We will run a few hours with transversely polarized beam to measure the actual size of the beam normal asymmetry at these kinematics.

# $Q^p_{Weak}$ Toroidal Magnet - QTOR

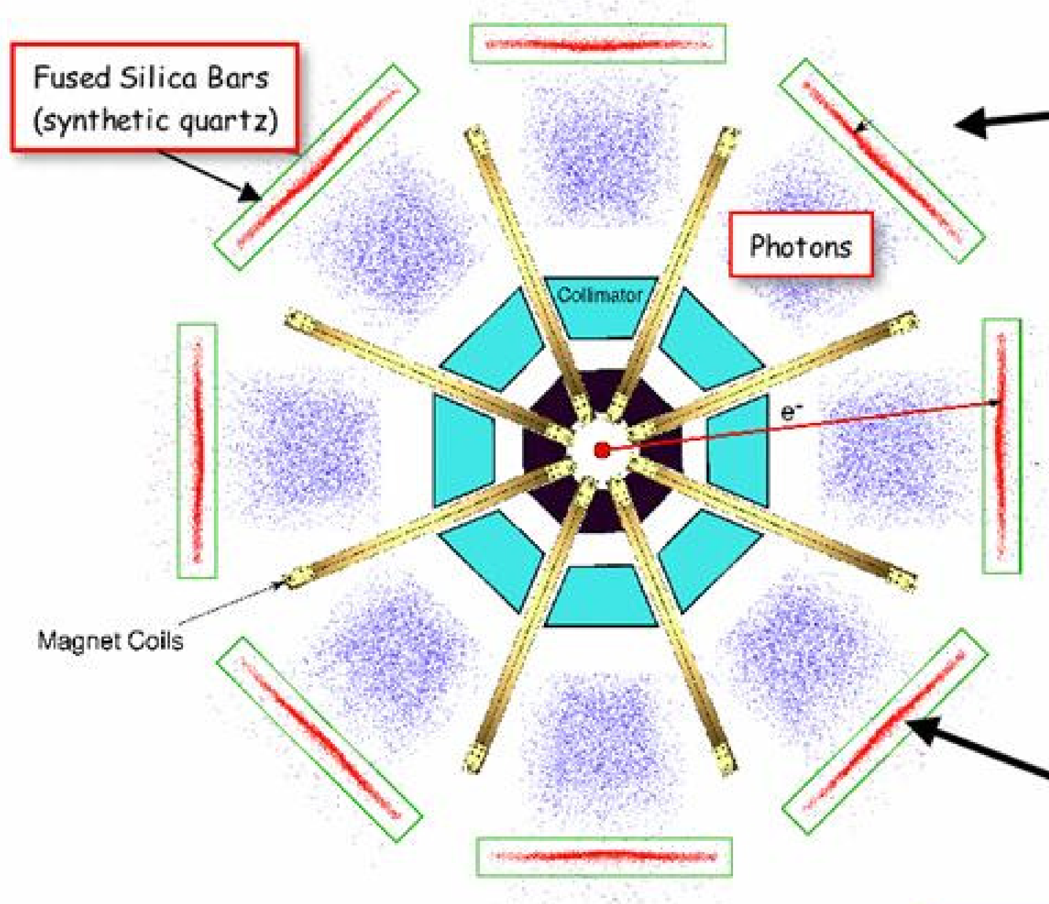


- 8 toroidal coils, 4.5m long along beam
- Resistive, similar to BLAST magnet
- Pb shielding between coils
- Coil holders & frame all Al
- $\int B \cdot dl \sim 0.7$ T-m
- bends elastic electrons ~ 10°
- current ~ 9500 A

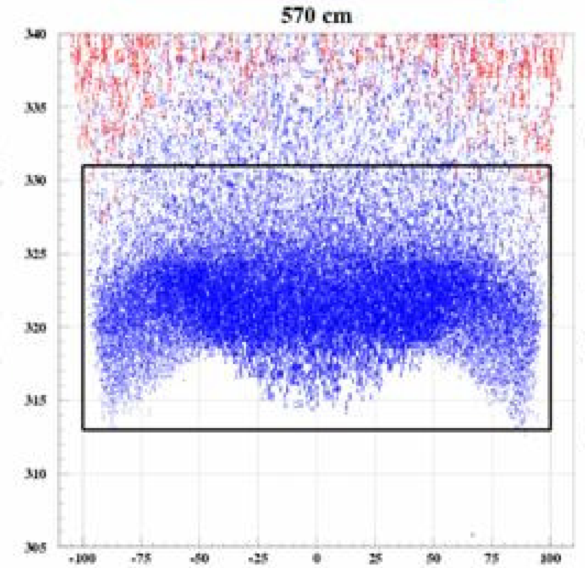
Status:
- coils being wound in France
- support stand designed, out for bid

# Inelastic/Elastic Separation in $Q^p_{Weak}$

## View Along Beamline of $Q^p_{Weak}$ Apparatus - Simulated Events



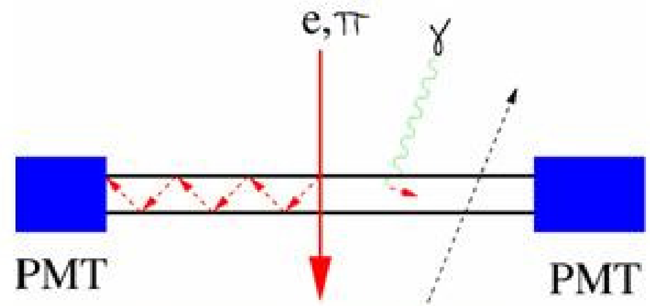

Black region in center is Pb shielding




Very clean elastic separation!

| | |
|---|---|
| Central scattering angle: | ~8° ± 2 |
| Phi Acceptance: | > 50% of $2\pi$ |
| Average $Q^2$: | 0.030 $GeV^2$ |
| Acceptance averaged asymmetry: | -0.29 ppm |
| Integrated Rate (per detector): | ~801 MHz |
| Inelastic/Elastic ratio: | ~0.026% |

# The $Q^p_{Weak}$ Detector and Electronics System




Focal plane detector requirements:

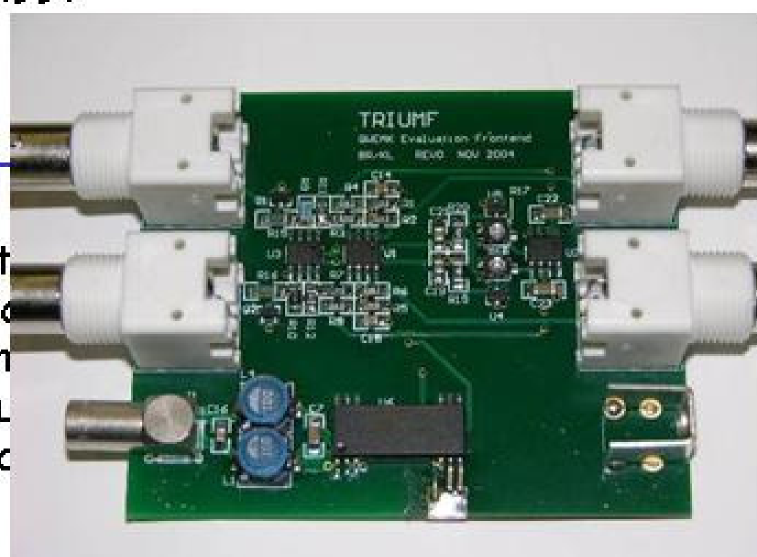
- Insensitivity to background $\gamma$, n, $\pi$.
- Radiation hardness (expect > 300 kRad).
- Operation at counting statistics.

Fused Silica (synthetic quartz) Cerenkov detector.

- Plan to use 18 cm x 200 cm x 1.25 cm quartz
- bars read out at both ends by 5 inch S20
- photocathode PMTs (expect ~ 100 pe/event)
- n =1.47, $\theta_{Cerenkov}$=47°, total internal reflection $\theta_{tir}$=43°
- reflectivity = 0.997

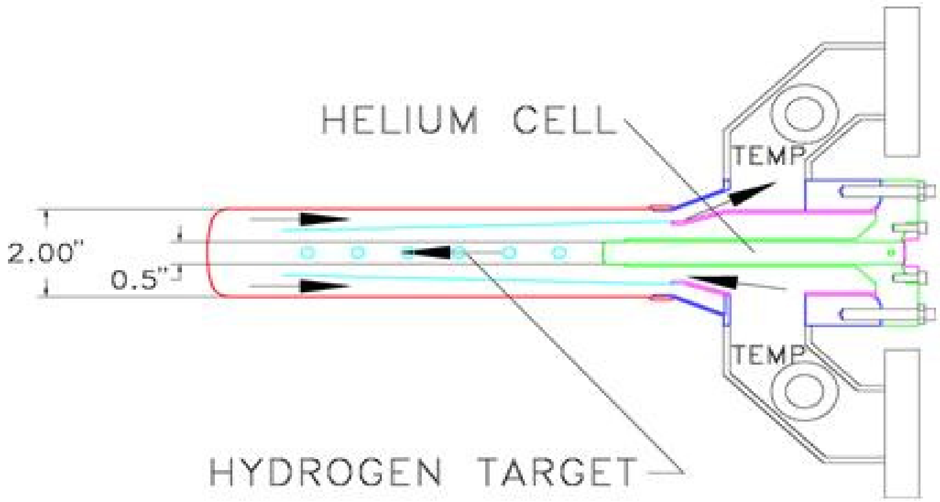
Electronics (LANL/T

- Normally operat
- Will have connec
- Low electronic n
  compared to cou
- 18 bit ADC will c



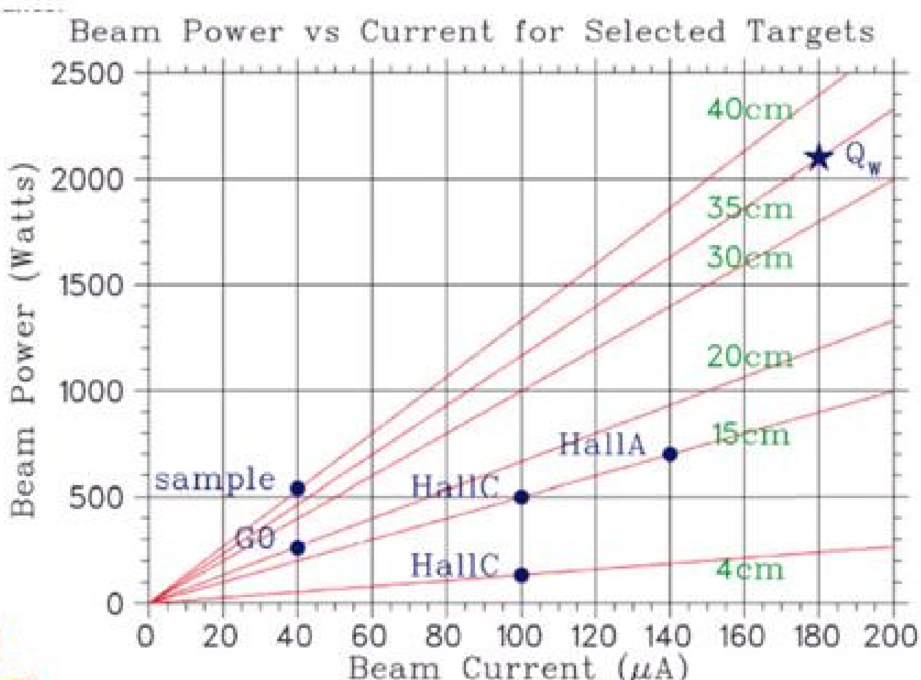

HV in mode in

# The $Q^p_{Weak}$ Liquid Hydrogen Target




**Target Concept:**

- Similar in design to SAMPLE and $G^0$ targets
  - → longitudinal liquid flow
  - → high stream velocity achieved with perforated, tapered "windsock"




**$Q^p_{Weak}$ Target parameters/requirements:**

- Length = 35 cm
- Beam current = 180 μA
- Power = 2200 W beam + 300 W heater
- Raster size ~4 mm x ~4 mm square
- Flow velocity > 700 cm/s
- Density fluctuations (at 15 Hz) < $5\times10^{-5}$

# Limiting the Target "boiling noise" Contribution

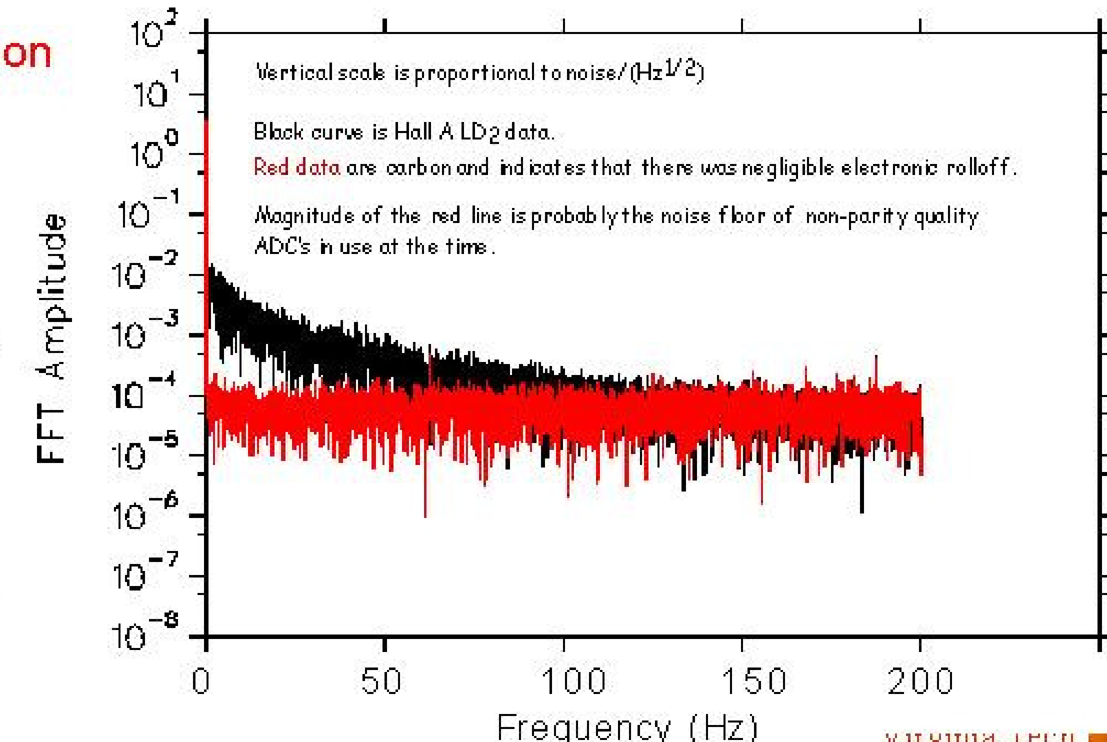
$$\sigma_{random} = \sqrt{\sigma^2_{counting} + \left(\frac{\Delta t}{t}\right)^2}$$

- Construct target that does not "boil" at a level << 50ppm/pulse pair level (assuming a 30Hz helicity reversal). Options: large raster size, faster pump speed, better cooled windows....
- Use Luminosity monitors to normalize experiment instead of beam current.
- Assume "boiling" is not a resonant phenomena and "noise" is the result of small "bubbles" formed along the target length being ejected from the beam region.

Decrease relative contribution of "boiling" by increasing the reversal/data readout rate.

noise/pulse pair decreases as the reversal/readout frequency is raised.

- Target starts to appear as "solid" w.r.t. any single asymmetry calculation.

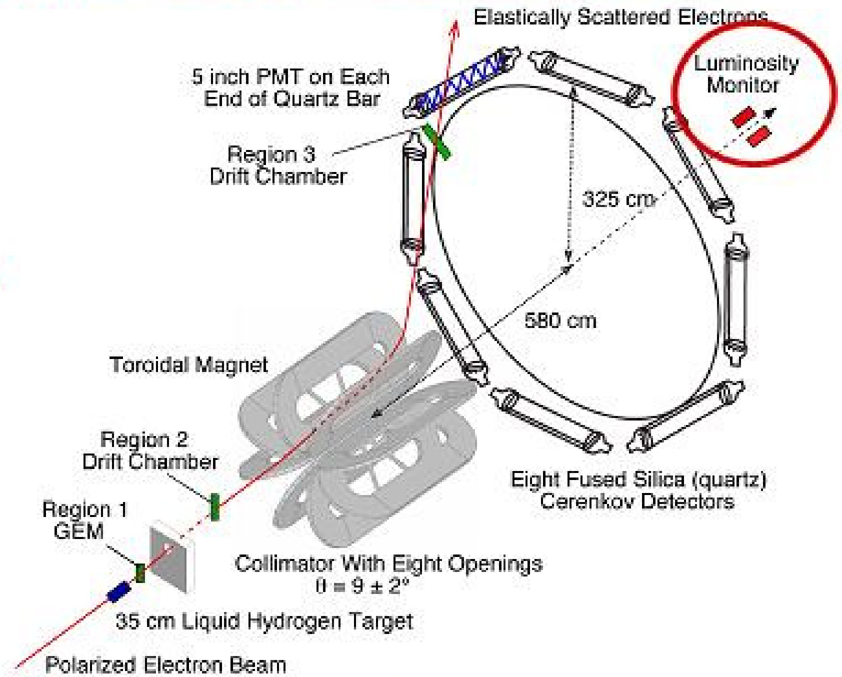


# The $Q^{p}_{Weak}$ Luminosity Monitor

- Luminosity monitor → Symmetric array of 8 quartz Cerenkov detectors instrumented with rad hard PMTs operated in "vacuum photodiode mode" & integrating readout at small θ (~ 0.8°). Low $Q^2$, high rates ~29 GHz/octant.

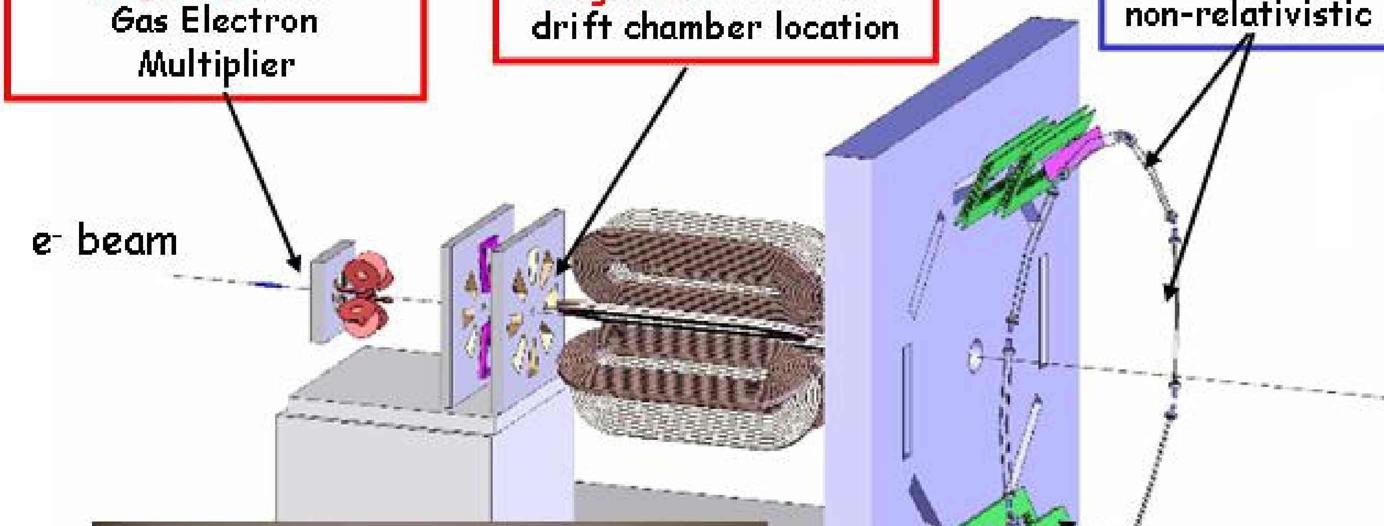
- Expected signal components: 12 GHz e-e Moeller, 11 GHz e-p elastic, EM showers 6 GHz.
- Expected lumi monitor asymmetry ‹‹ main detector asymmetry.
- Expected lumi monitor statistical error ~ (1/6) main detector statistical error.

- Useful for:
  - Sensitive check on helicity-correlated beam parameter corrections procedure.
  - Regress out target density fluctuations.

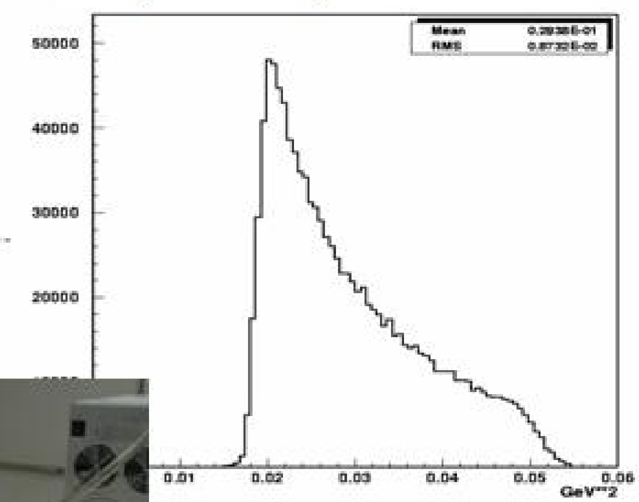


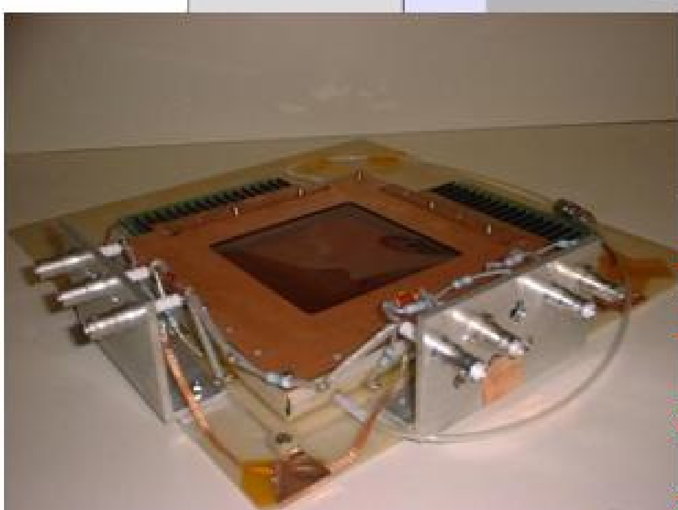
# $Q^2$ Determination

Use low beam current (~ few nA) to run in "pulse counting" mode with a tracking system to determine the "light-weighted" $Q^2$ distribution.




Expected $Q^2$ distribution



GEM prototype

HDC prototype

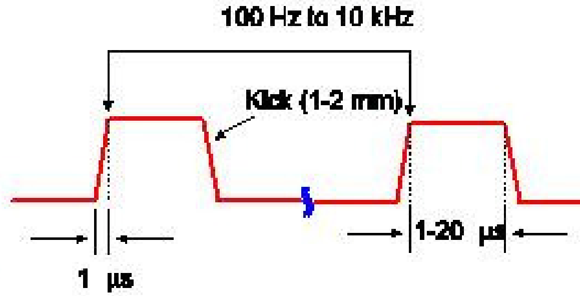
# Precision Polarimetry

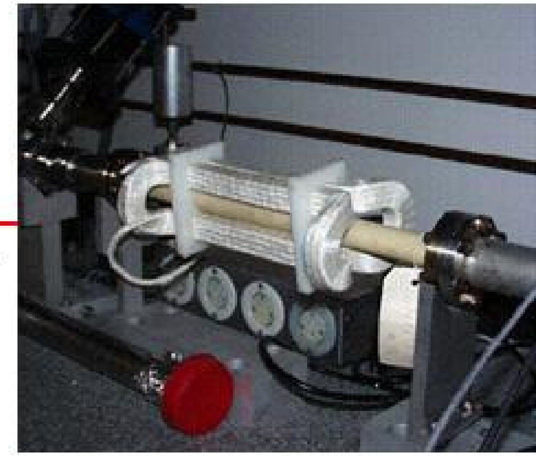
Hall C has existing ~1% precision Moller polarimater

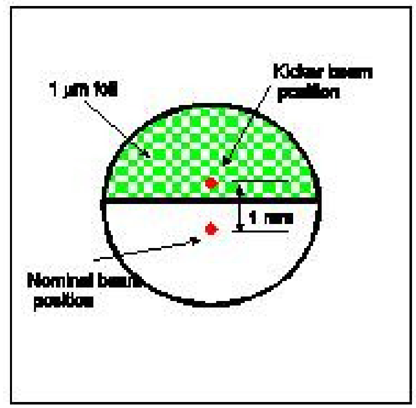
- Present limitations:
  - $I_{Max}$ ~ 10 μA.
  - At higher currents the Fe target depolarizes.
  - Measurement is destructive

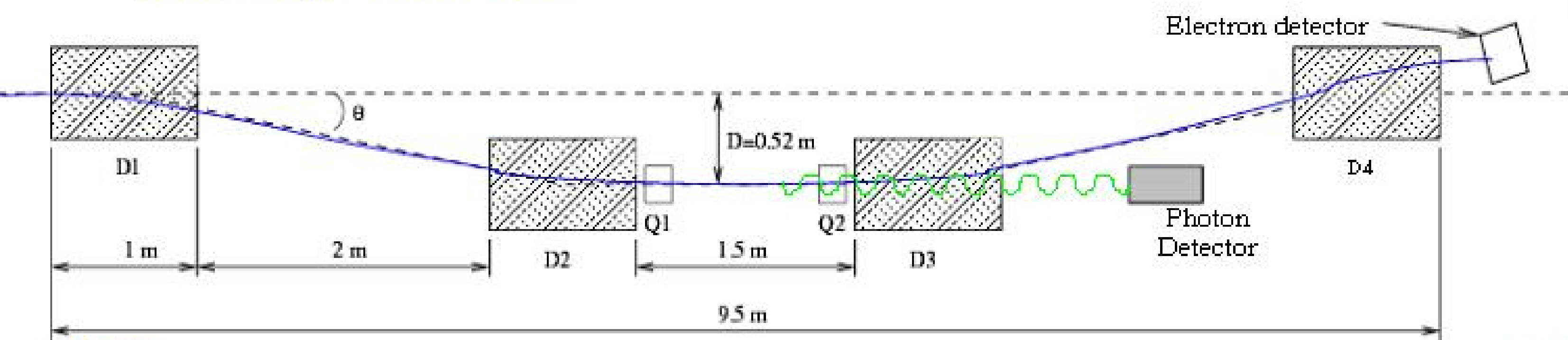
- Plan to upgrading Møller:
  - Measure $P_{beam}$ at 100 μA or higher, quasi-continuously
  - Trick: kicker + strip or wire target (early tests look promising – tested up to 40 μA so far)

- Schematic of planned new Hall C Compton polarimeter.





# Summary

- Completed low energy Standard Model tests are consistent with Standard Model "running of $\sin^2\theta_W$"

  SLAC E158 (running verified at ~ 6σ level) - leptonic
  Cs APV (running verified at ~ 4σ level) – semi-leptonic, "d-quark dominated"

- Upcoming $Q^p_W$ Experiment
  - Precision measurement of the proton's weak charge in the simplest system.
  - Sensitive search for new physics with CL of 95% at the ~ 2.3 TeV scale.
  - Fundamental 10 σ measurement of the running of $\sin^2\theta_W$ at low energy.
  - Currently in process of 3 year construction cycle; goal is to have multiple runs in 2008 – 2009 timeframe

weak charge triad →
(Ramsey-Musolf)