



## The $Q_{\text{weak}}$ Experiment at JLab

Roger D. Carlini  
Jefferson Laboratory

# The $Q^P_{Weak}$ Experiment:

"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. Chattopadhyay, 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. 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

December 2001

January 2002

January 2003

2003 - 2004

2007 -2009

Collaboration formed

JLab Proposal Submitted

JLab Proposal Approved with 'A' rating

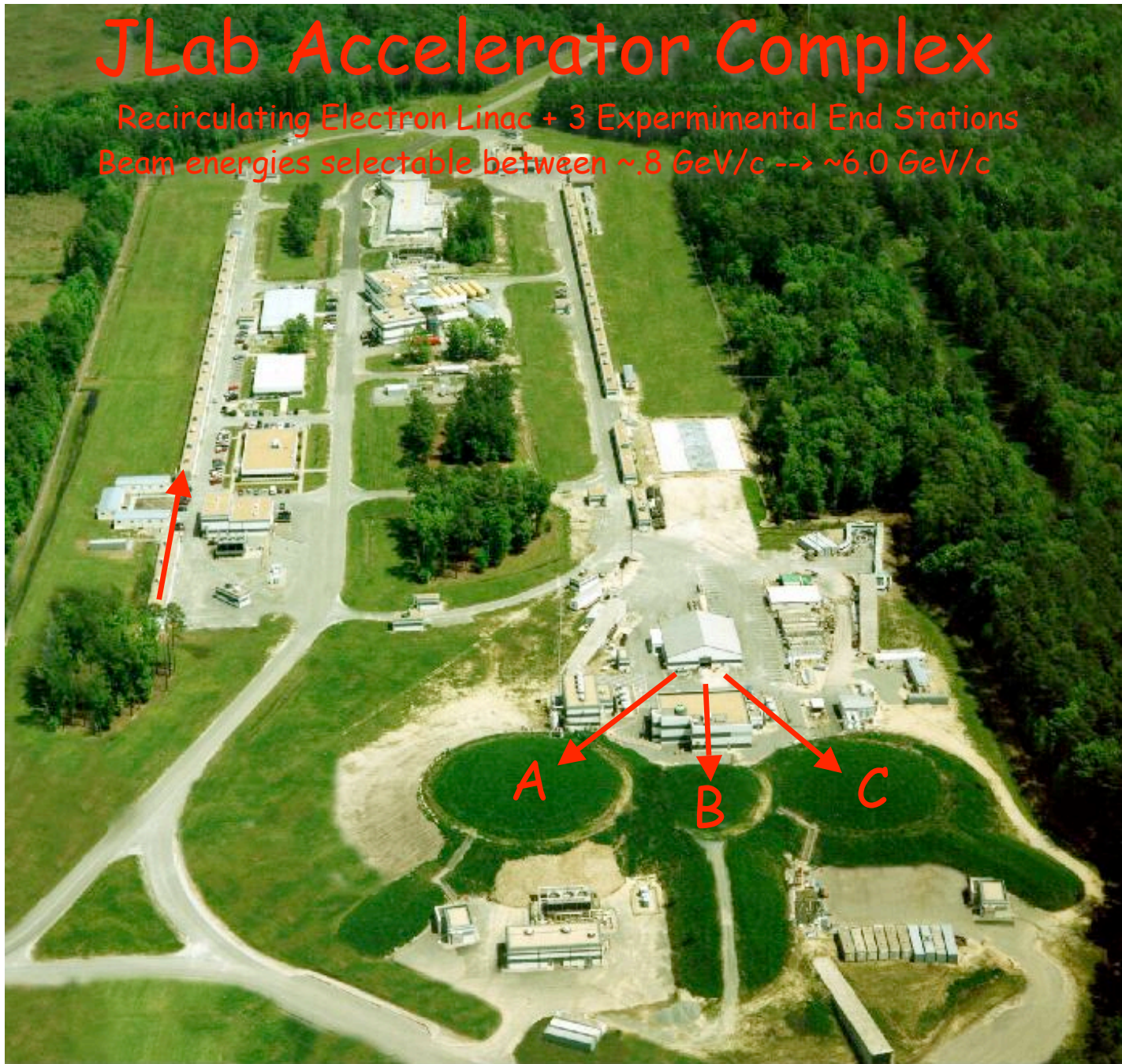
Technical design review completed,

Funding approved by DOE, NSF & NSERC

Production Running

# JLab Accelerator Complex

Recirculating Electron Linac + 3 Experimental End Stations  
Beam energies selectable between  $\sim 0.8 \text{ GeV}/c \rightarrow \sim 6.0 \text{ GeV}/c$



# The Basic Idea

- 1<sup>st</sup> measurement of  $Q_{\text{Weak}}^{\text{P}} = 1 - 4\sin^2 \theta_{\text{W}}$ 
  - 1<sup>st</sup> SM test at JLab
- SM makes firm prediction for  $Q_{\text{W}}^{\text{P}}$ 
  - based on running of  $\sin^2 \theta_{\text{W}}$  from  $Z^0$  pole
    - a  $10 \sigma$  effect in our expt.
  - deviation from SM prediction  $\rightarrow$  new physics
    - even sensitive to which SM extension
    - agreement would constrain SM extensions
  - precise measurement possible
    - hadronic corrections small, & measured

# NC expts as indirect probes of new physics

SM is a low energy approximation of a more fundamental theory

NC exp: ① consistency check of SM  
② complementary to direct new physics searches  
③ distinguish various new physics

- SUSY: minimal Supersymmetric extension of SM (MSSM)

each SM particle  $\longleftrightarrow$  spins differ by  $\frac{1}{2}$  superpartner

- with R-parity : loop corrections
- without R-parity: tree-level contribution

- extra  $Z'$

- exists in extension of SM
- constraints from Z-pole observable (mix with Z)

- leptoquark

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

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

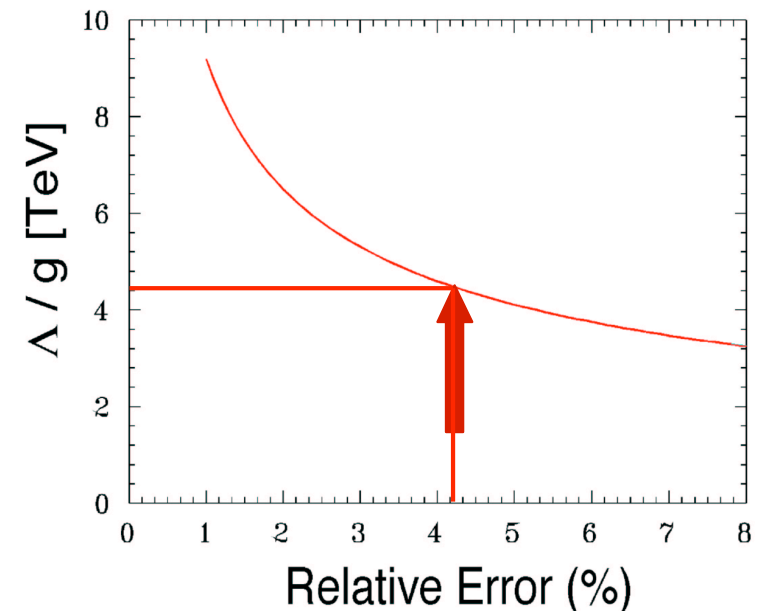
$$\mathcal{L}_{e-q}^{\text{PV}} = \mathcal{L}_{\text{SM}}^{\text{PV}} + \mathcal{L}_{\text{NEW}}^{\text{PV}} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C_{1q} \bar{q} \gamma^\mu q + \frac{g^2}{4\Lambda^2} \bar{e} \gamma_\mu \gamma_5 e \sum_q h_V^q \bar{q} \gamma^\mu q$$

g: coupling constant  
 $\Lambda$ : mass scale

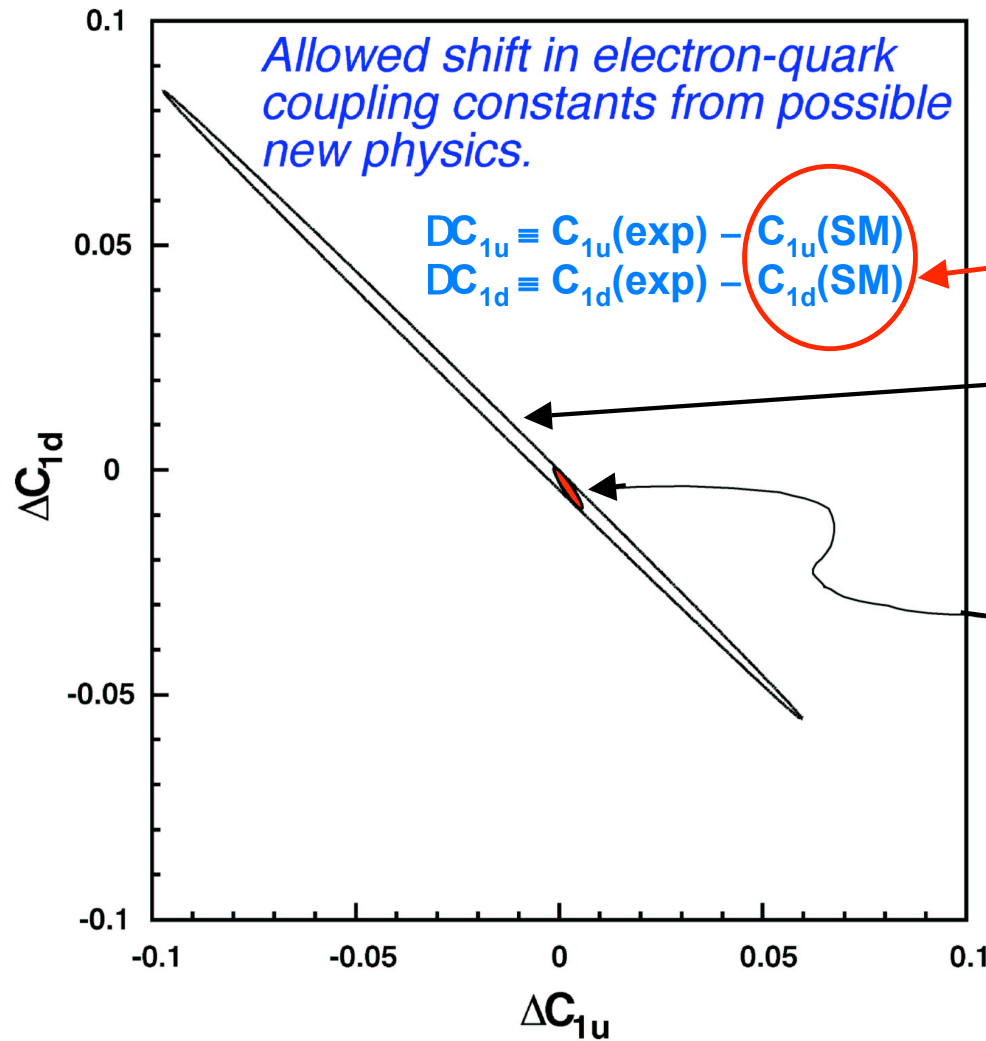
- A 4%  $Q_{\text{Weak}}^p$  measurement probes for new physics at energy scales to:

$$\frac{\Lambda}{g} \sim \frac{1}{\sqrt{\sqrt{2} G_F |\Delta Q_W^p|}} \approx 4.6 \text{ TeV}$$

- 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.



# Impact of $Q_{Weak}^P$ "Model-independent Semi-Leptonic Analysis"



Effective electron-quark neutral current Lagrangian:

$$L_{e-q}^{PV} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C_{1q} \bar{q} \gamma^\mu q$$

→ A(e) x V(q)

Large ellipse (existing data):  
 SLAC e-D (DIS)  
 MIT-Bates  $^{12}C$  (elastic)  
 Cesium APV

Red ellipse:  
 Impact of  $Q_{Weak}^P$  measurement  
 (centroid assumes agreement with SM)

Why so much better?  
 (precision & complementarity of  $Q_{Weak}^P$  measurement)

# Electroweak Unification

- **Right** handed fermions form iso-spin singlets
- **Left** handed fermions form iso-spin doublets
- EW **gauge interaction**:
  - Vector singlet field B
  - Vector triplet field  $W^i$
- 3 of the four fields develop mass by the **Higgs mechanism**

$$(e)_R$$

$$\begin{pmatrix} e \\ \nu \end{pmatrix}_L$$

$$SU(2)_L \otimes U(1)$$

Vector bosons		Mass	charge
$W^\pm$	$W^\pm = \frac{1}{\sqrt{2}}(W^1 \mp W^2)$	80 GeV	$\pm 1$
Z	$Z = -B \sin \theta_w + W^3 \cos \theta_w$	91 GeV	0
A	$A = B \cos \theta_w + W^3 \sin \theta_w$	0 (long-ranged EM field)	0

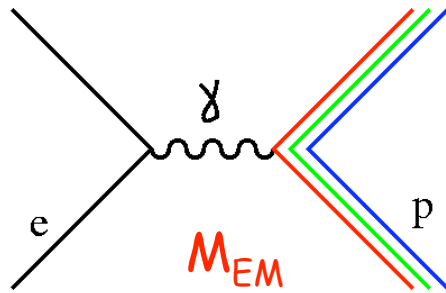
- Where the **weak mixing angle**  $\theta_w$  is the fundamental parameter of the theory

$$Q_{EM}^P = 1 \quad Q_{Weak}^P = 1 - 4 \sin^2 \theta_w$$

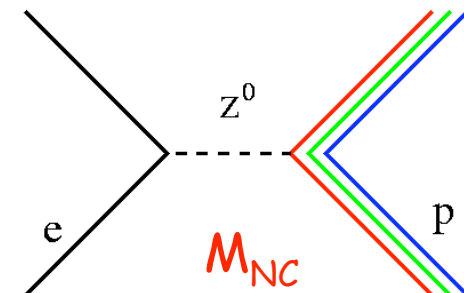


**Measure this!**

## $Q_{Weak}^P$ : Extract from Parity-Violating Electron Scattering



As  $Q^2 \rightarrow 0$



measures  $Q^P$  - proton's electric charge

measures  $Q_{Weak}^P$  - proton's weak charge

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

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

contains  $G_{E,M}^Y$  and  $G_{E,M}^Z$

$$Q_{weak}^P = 1 - 4 \sin^2 \theta_W \sim 0.072 \quad (\text{at tree level})$$

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

$Q_{weak}^e$  : electron's weak charge is measured in PV Moller scattering (E158)

# Nucleon Structure Contributions to the Asymmetry

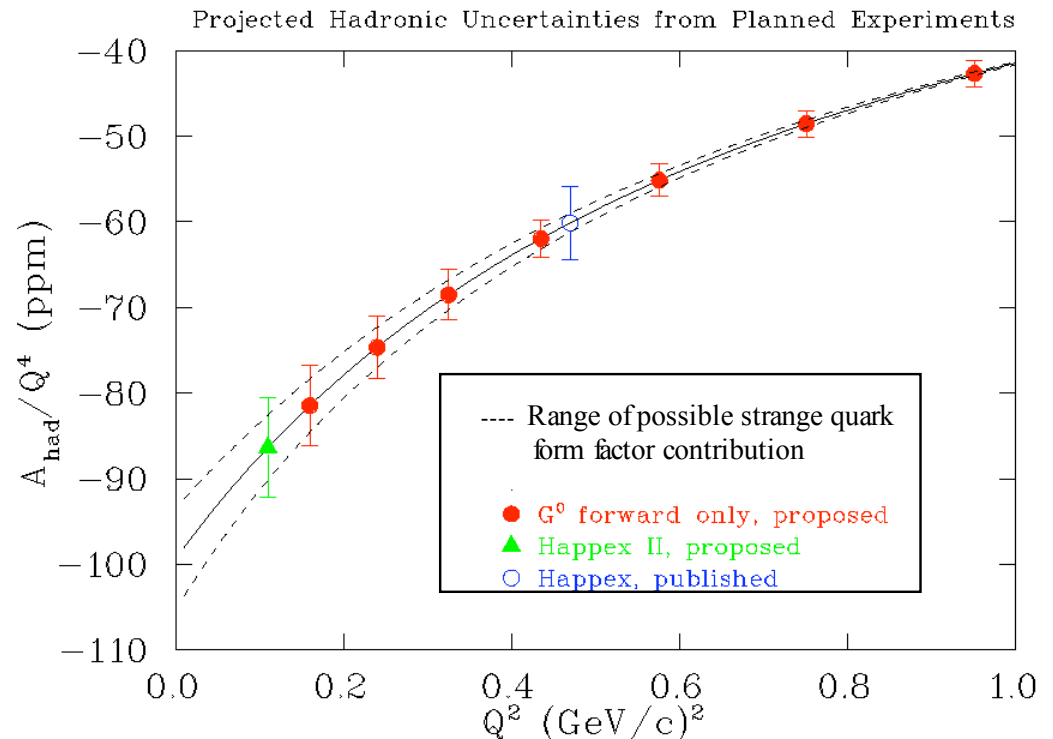
$$\begin{aligned}
 A &= A_{Q_W^p} + A_{hadronic} + A_{axial} \\
 &= -.19 \text{ ppm} - .09 \text{ ppm} - .01 \text{ ppm}
 \end{aligned}$$

hadronic: (31% of asymmetry)  
 - contains  $G_{E,M}^Y$   $G_{E,M}^Z$   
 Will be constrained  
 by HAPPEX,  $G^0$ , MAMI PVA4

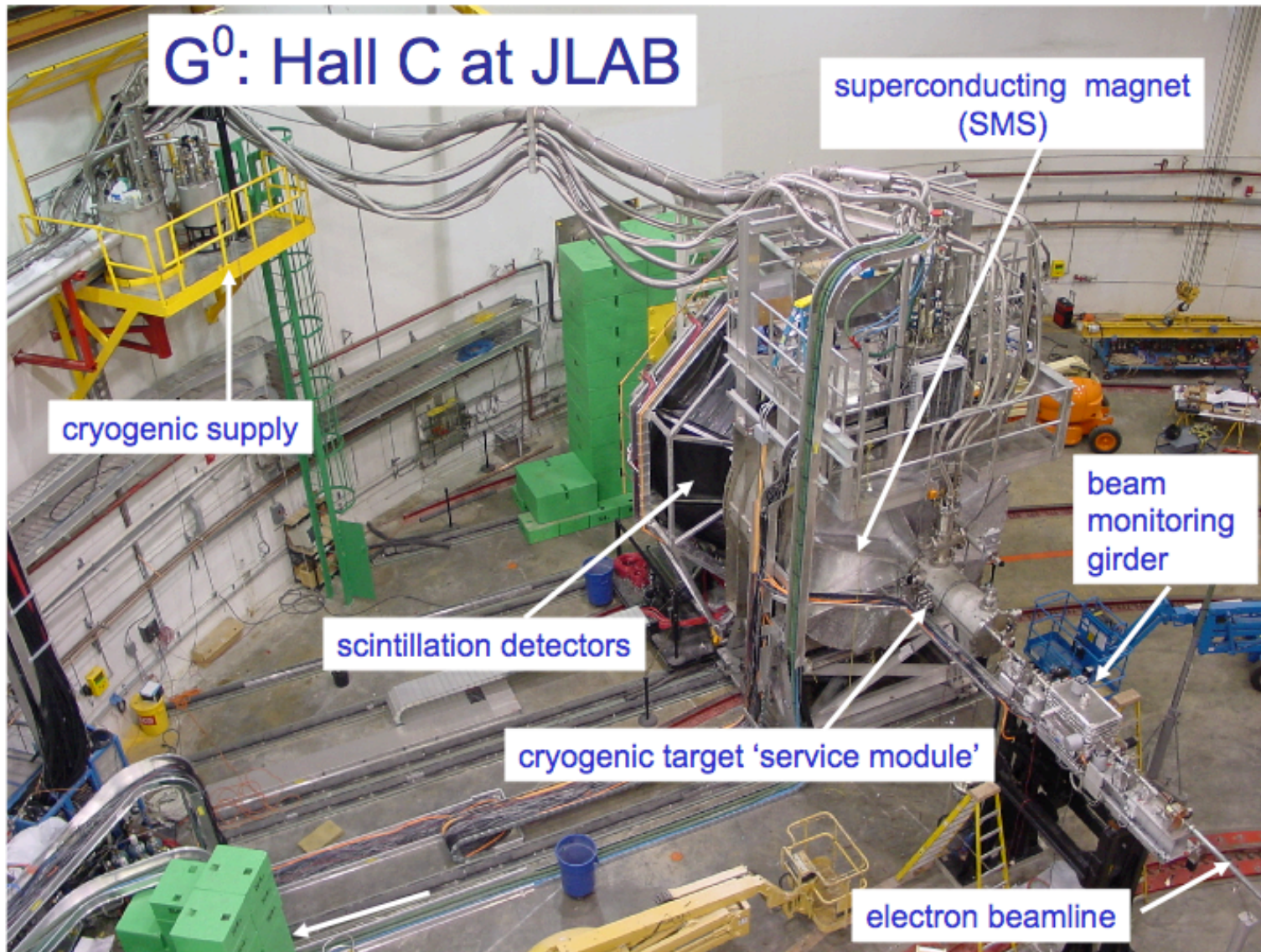
axial: (4% of asymmetry) - contains  $G_{A'}^e$ ,  
 has large electroweak radiative corrections.  
 Will be constrained by  $G^0$  and SAMPLE

Quadrature sum of expected  
 $A_{hadronic}$  and  $A_{axial}$  errors  
 contributes ~2% to error on  $Q_W^p$

Expected constraints  
 on  $A_{hadronic}$  from  
 currently running experiments



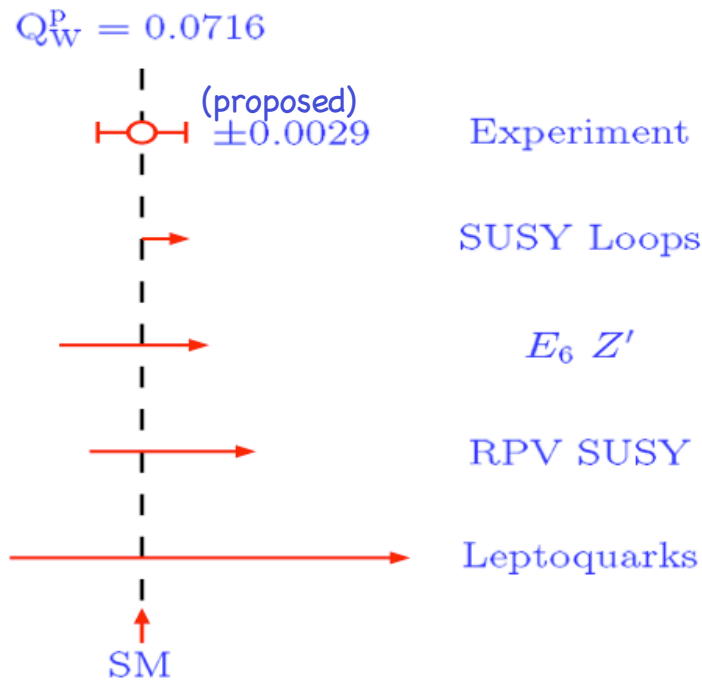
# Qweak Hadronic Background Measurement Apparatus!



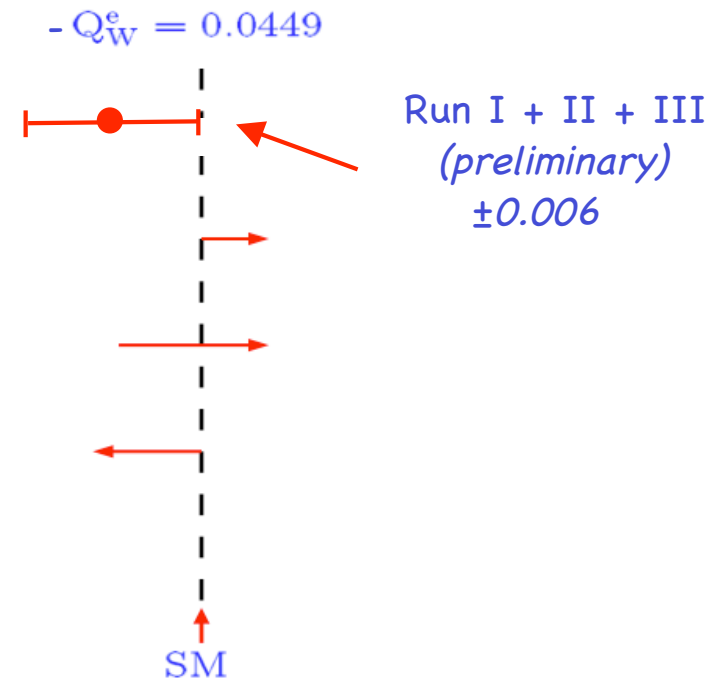
## Other Relevant Experiments

- **SLAC E158 (Moeller, purely leptonic):**
  - similar  $Q^2$ , complementary measurement
    - combined with  $Q_W^p$  can isolate new physics
    - ~consistent with SM but with larger than originally proposed uncertainties
- **NuTeV ( $\nu A$  @  $\sim 10$  (GeV/c) $^2$ ):**
  - higher  $Q^2$ ,  $3\sigma$  discrepancy (hard to explain)
- **APV -  $Q_W$  of Cs atom:**
  - moving theoretical corrections (atomic structure)
  - at present, consistent with SM
  - a 13% measurement of  $Q_W^p$

## JLab Qweak



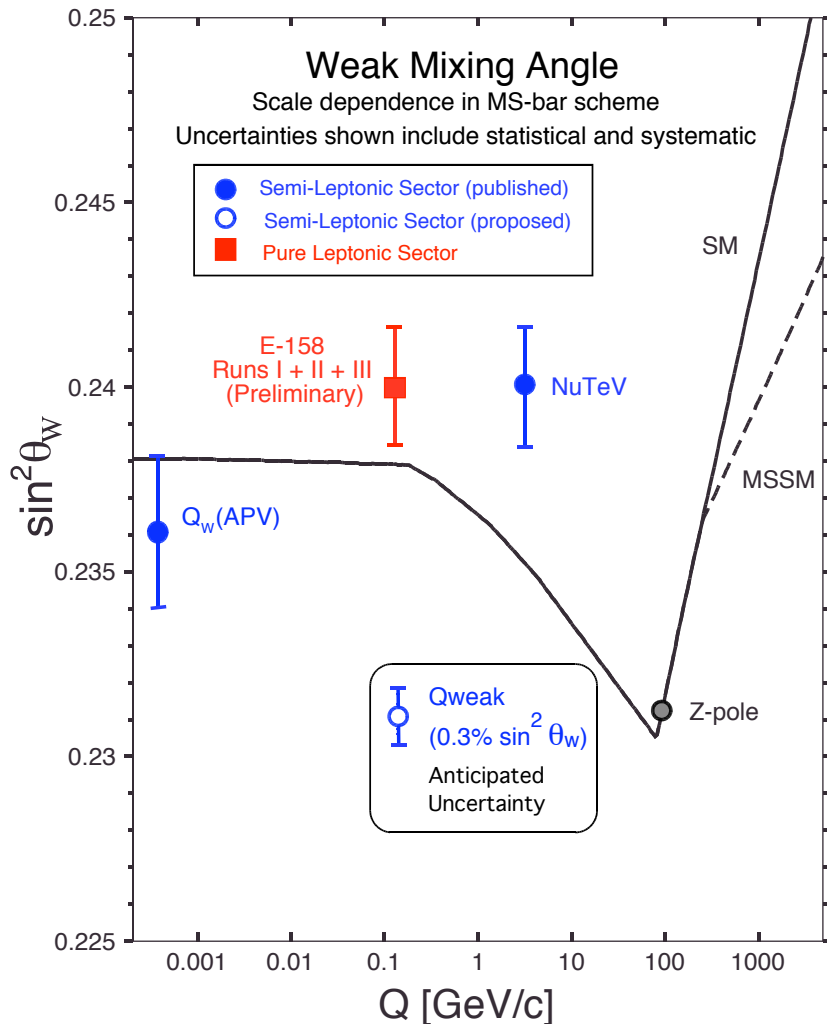
## SLAC E158



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

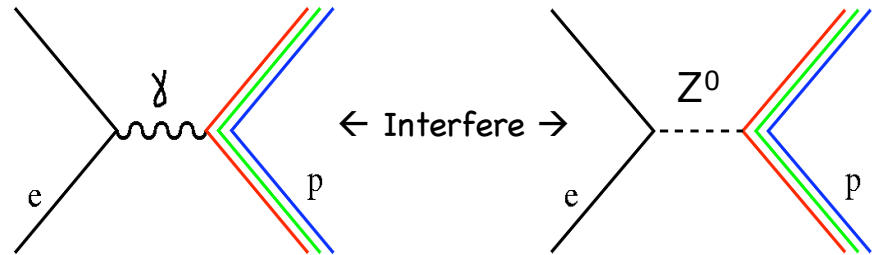
# The $Q_{Weak}^P$ Experiment

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



- Extracted values of  $\sin^2 \theta_W$  must agree with Standard Model or new physics is indicated.

$$Q_{weak}^p = 1 - 4 \sin^2 \theta_W \sim 0.072$$



- A 4%  $Q_{Weak}^P$  measurement probes for new physics at energy scales to:

$$\frac{\Lambda}{g} \sim \frac{1}{\sqrt{\sqrt{2}G_F |\Delta Q_W^p|}} \approx 4.6 \text{ TeV}$$

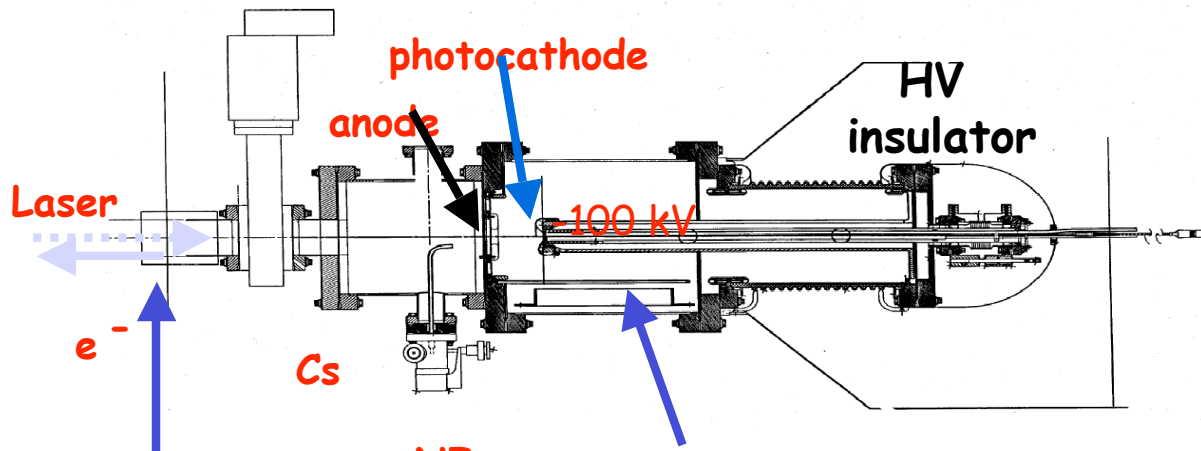
Qweak will provide a stringent stand alone constraint on Lepto-quark based SM extensions.

With APV and SLAC E158 results Qweak will constrain SM extensions based on extra Z's.

## The Basic Apparatus:

- Keep it simple (precision)!
- Build on JLab expertise with parity quality polarized beams
- Moeller & Compton polarimetry
- Use (resistive) magnet to isolate the elastics
  - from inelastics & neutral bkg
- Use quartz Cerenkov detectors
  - 8 \* 2m x 16cm x 2cm bars, 5" PMTs
  - integrating readout
    - counting mode for  $Q^2$  calibrations

## Polarized Electron Guns at JLab



Photoemission from GaAs semiconductor

NEG-coated  
Beamline

$\text{NF}_3$

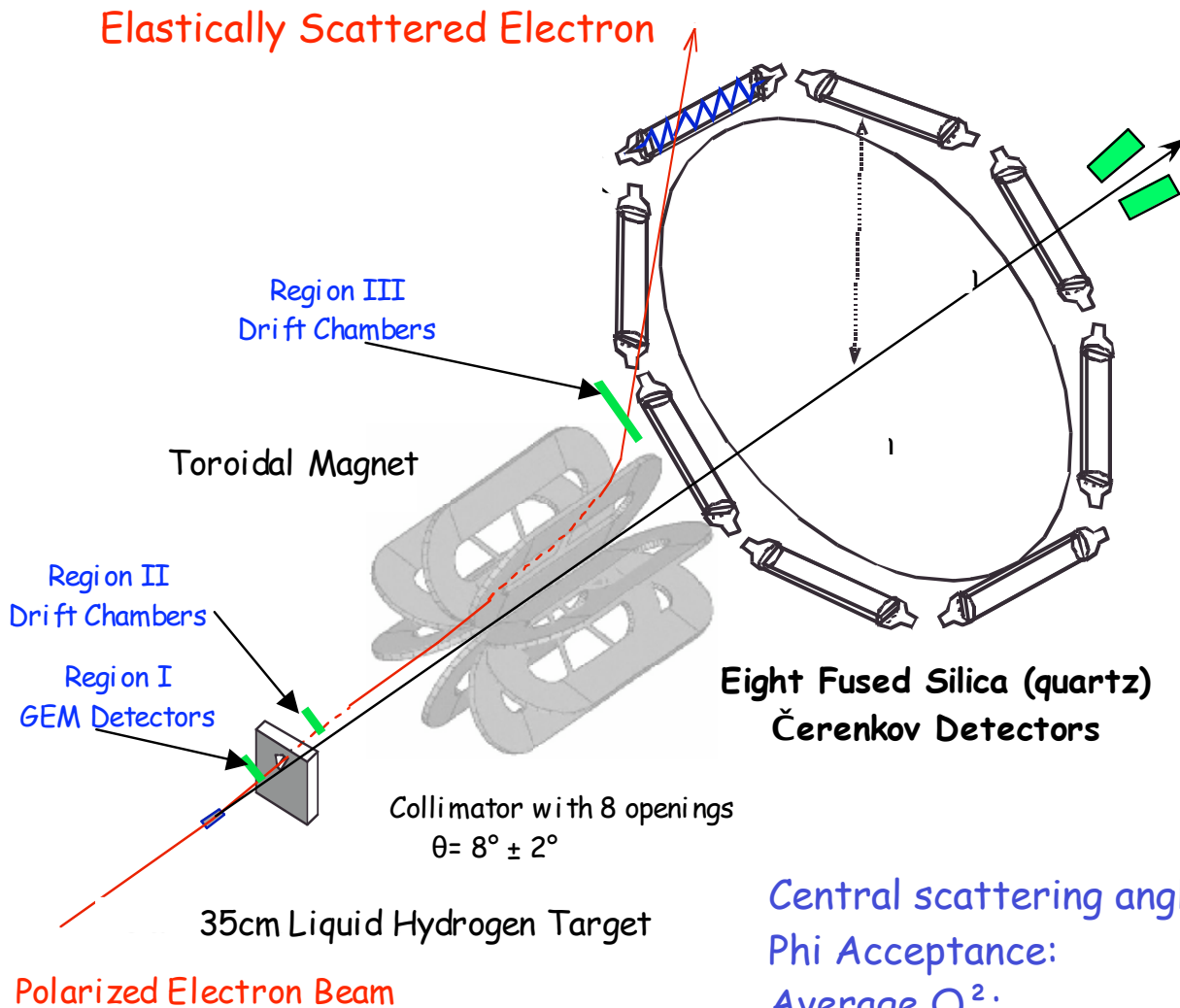
NEG  
pumps

Strained GaAs in Gun2  
("old" material)  
~ 75% Polarized

Strained-superlattice GaAs  
In Gun3 ("new" material)  
~ 85% Polarized



# Illustration of the $Q^P_{Weak}$ Experiment

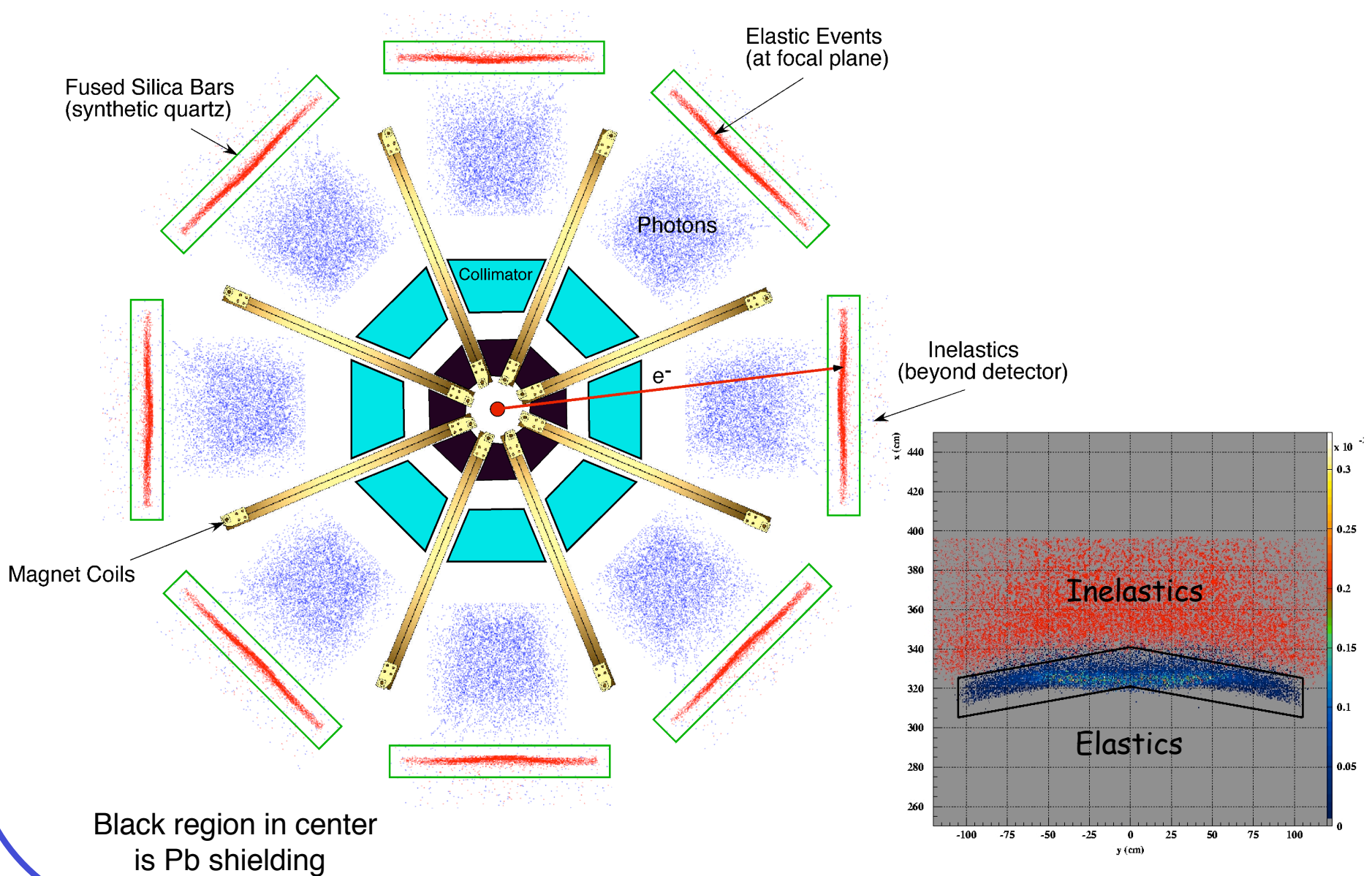


## Experiment Parameters (integration mode)

Incident beam energy: 1.165 GeV  
 Beam Current: 180  $\mu$ A  
 Beam Polarization: ~80%  
 LH<sub>2</sub> target power: 2.5 KW

Central scattering angle:  $8^\circ \pm 2$   
 Phi Acceptance: >50% of  $2\pi$   
 Average  $Q^2$ : 0.028 GeV<sup>2</sup>  
 Acceptance averaged asymmetry: -0.28 ppm  
 Integrated Rate (all sectors): ~6 GHz  
 Integrated Rate (per detector): ~750 MHz

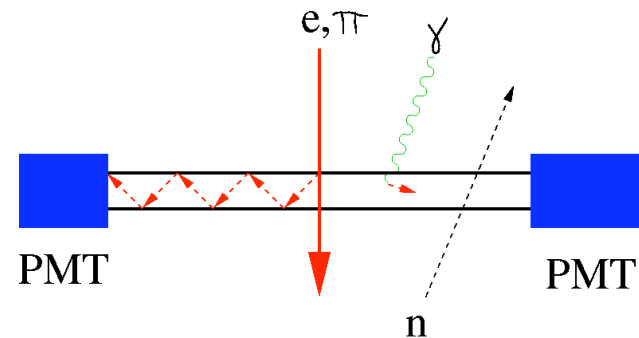
# View Along Beamline of $Q^P_{Weak}$ Apparatus with Simulated Events



# The $Q^P_{\text{weak}}$ Detector and Electronics System

## Focal plane detector requirements:

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



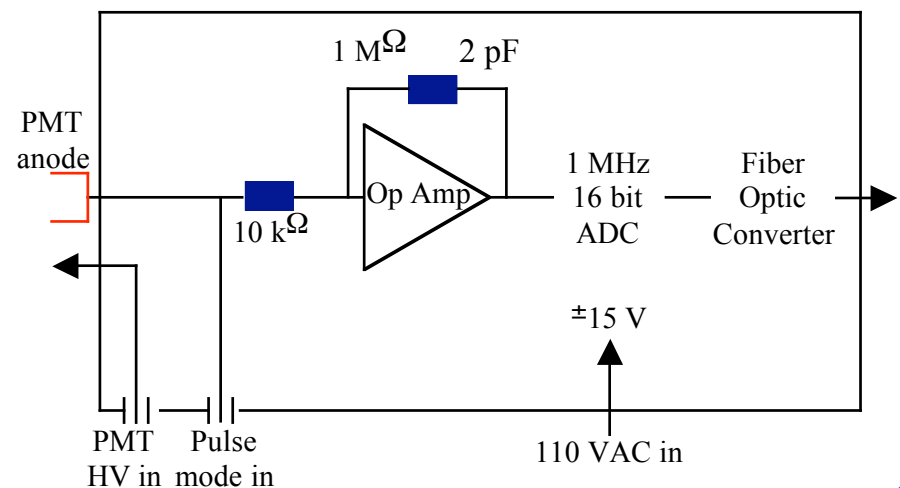
## → Fused Silica (synthetic quartz) Cerenkov detector.

- Plan to use 15 cm x 200 cm x 2.5 cm quartz
- bars read out at both ends by S20
- photocathode PMTs (expect  $\sim 100$  pe/event)
- $n = 1.47$ ,  $\theta_{\text{Cerenkov}} = 47^\circ$ , total internal reflection  $\theta_{\text{tir}} = 43^\circ$
- reflectivity = 0.997



## Electronics (LANL/TRIUMF design):

- Normally operates in integration mode.
- Will have connection for pulse mode.
- Low electronic noise contribution. compared to counting statistics.
- 1 MHz 16 bit ADC will allow for over sampling.



# Collimator Design

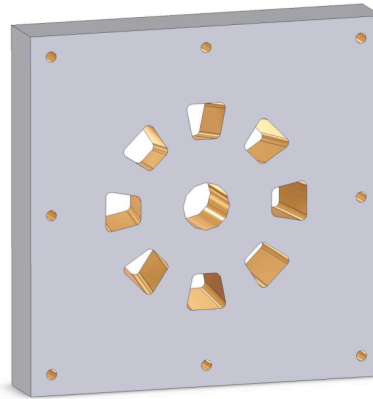
Kinematical acceptance:

$$\theta = 8^\circ \pm 2^\circ \text{ (azimutal)}$$

$$\varphi = \pm 11^\circ \text{ (polar, per octant)}$$

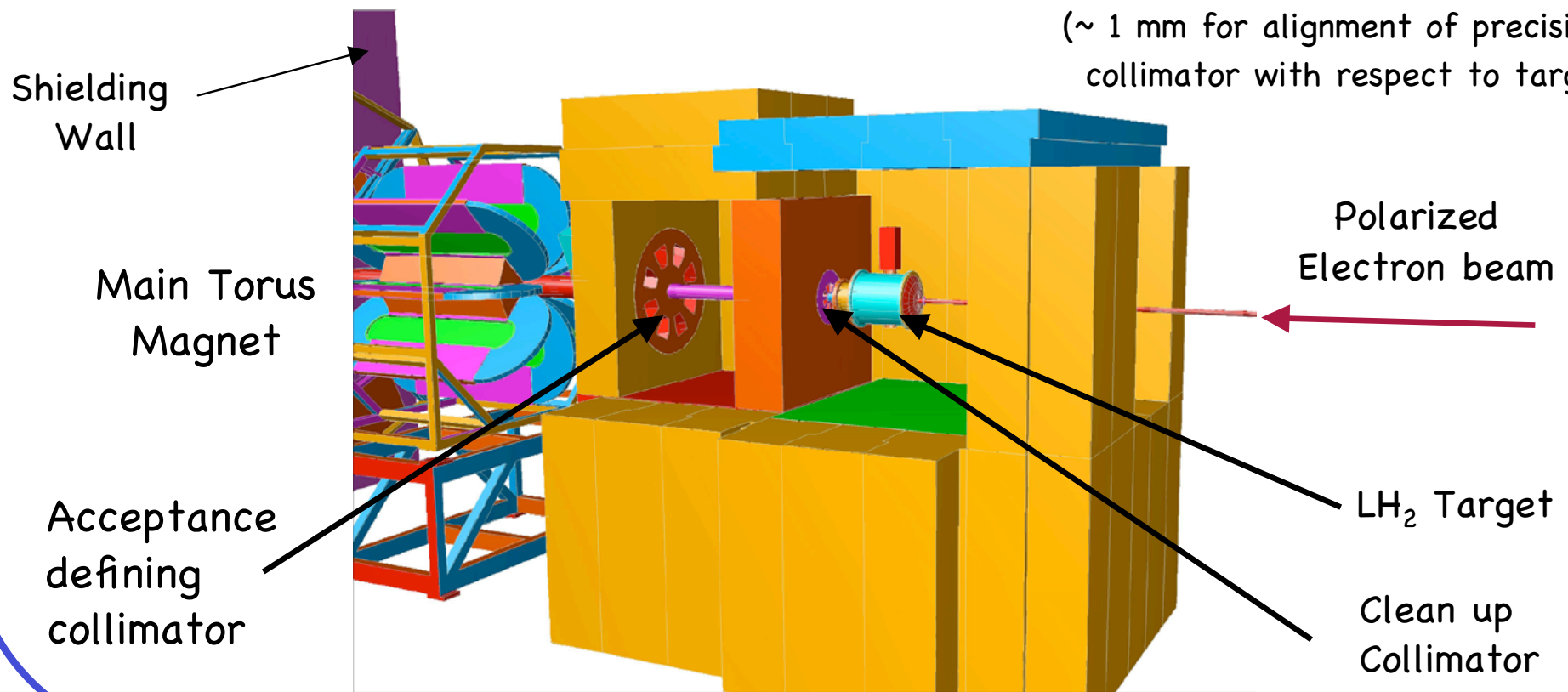
$$Q^2 = 0.028 \text{ GeV}^2$$

$$\text{Rate} = 750 \text{ MHz/octant}$$

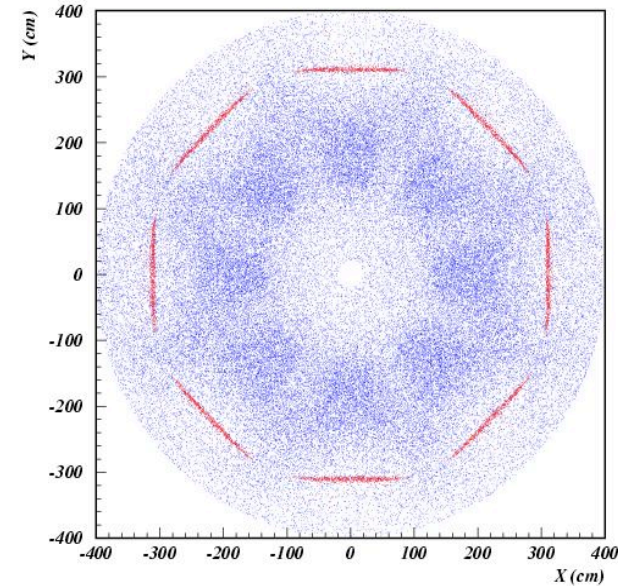
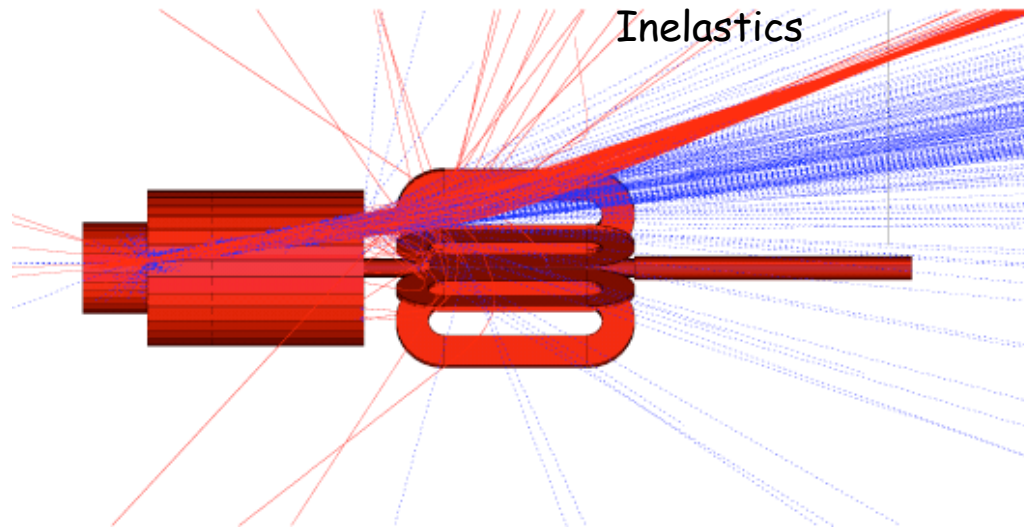


Material: leaded brass  
(25% lead, 70% Cu, 5% Sn)

required survey accuracy:  $\sim 1 \text{ mrad}$   
( $\sim 1 \text{ mm}$  for alignment of precision  
collimator with respect to target)



# Estimate of the Inelastic & Photon Background



At Detector:  
(with Cerenkov cut)

Elastic e-p rate = 763 MHz / octant

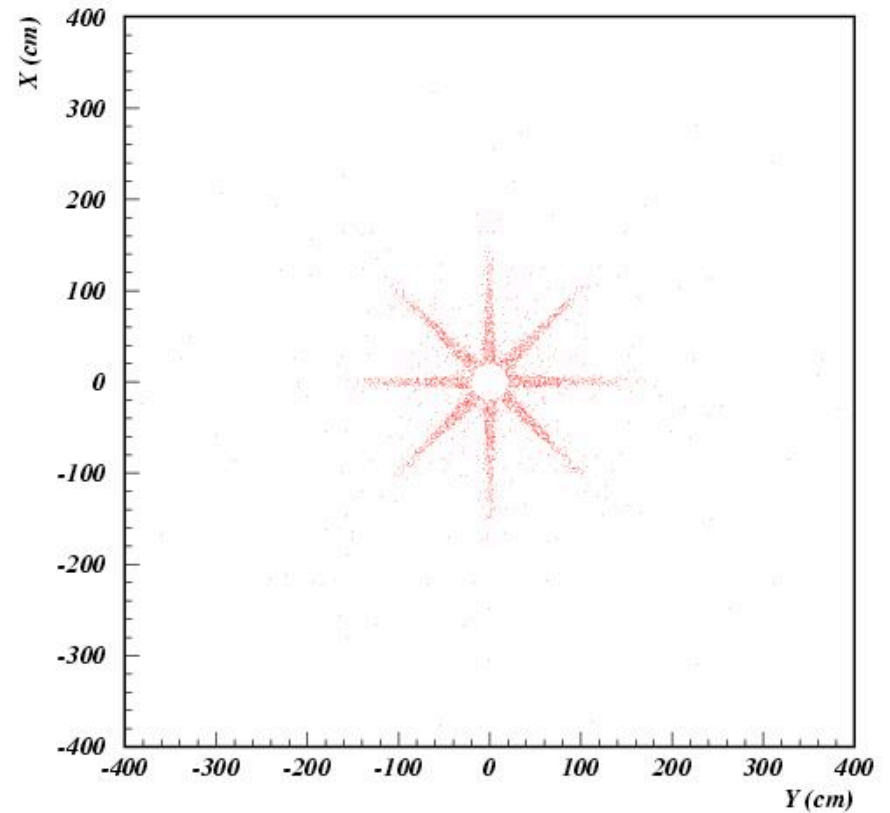
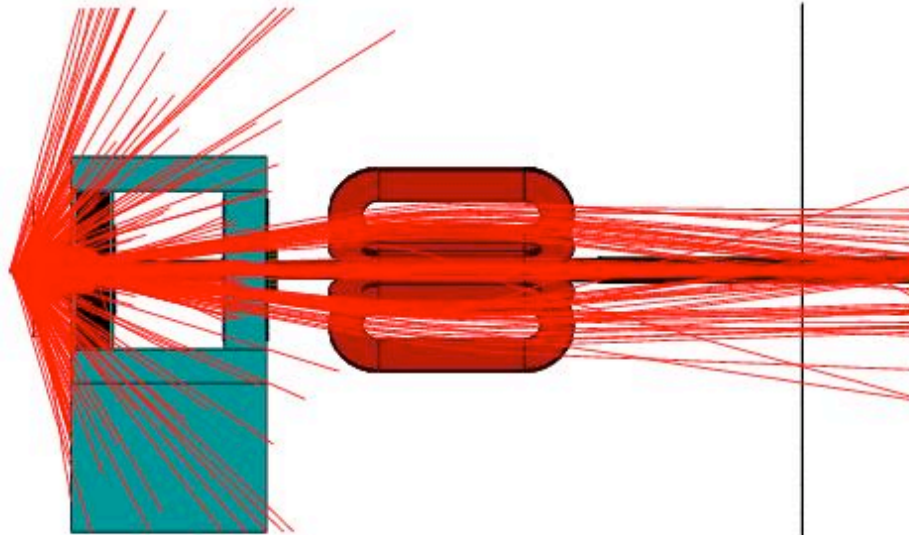
Inelastic rate = 35 KHz → Inelastic contamination ~ 0.005%

Photon rate ~ 50 KHz → Photon contamination ~ 0.007%

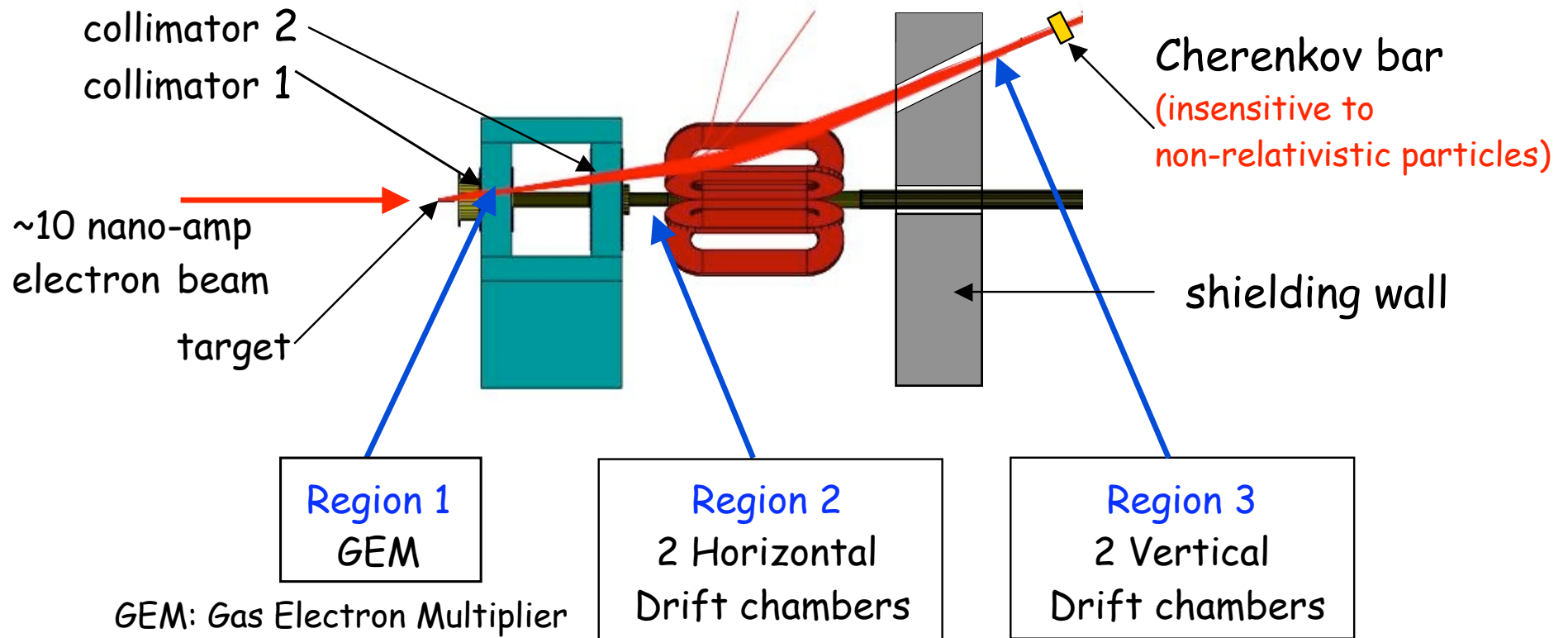
N -  $\Delta$  asymmetry  $A \propto 4 \sin^2\theta_w \sim 4 \times 10^{-6}$  (factor of 10 more than e-p elastic)  
so the contribution of inelastic asymmetry to the elastic asymmetry ~ 0.1%

→ We will also directly measure this asymmetry by running with magnet adjusted to put inelastic events on focal plane detector

## Background from Protons & Positively Charged Particles



# Calibration Technique (nA's $I_{beam}$ )



Region 1+2 chambers provides:

$Q^2$  Acceptance determination

Region 3 chamber provides:

Efficiency map of quartz detectors

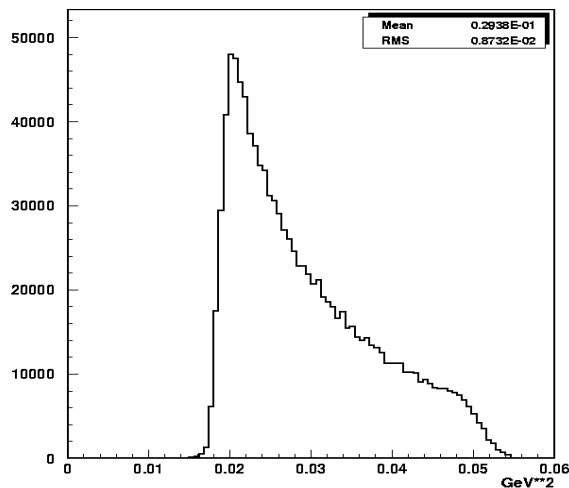
# Measurement of the $\langle Q^2 \rangle$ & Dilution Factor

Tolerances  $\sim \pm 1\text{mm}, \pm 1\text{mrad}, 0.7\%$  in  $\langle Q^2 \rangle$

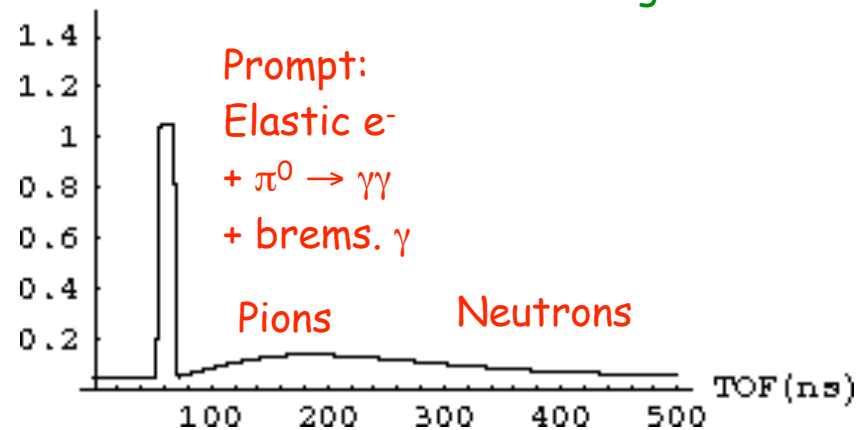
Auxiliary measurements (at low beam current) will be made with set of 3 chambers & scint.'s to:

- Measure shape of focal plane distribution.
- Measure position-dependent detector efficiency.
- Determine dilution with detectors in "pulse" mode
- Compare measured  $Q^2$  distribution to MC.

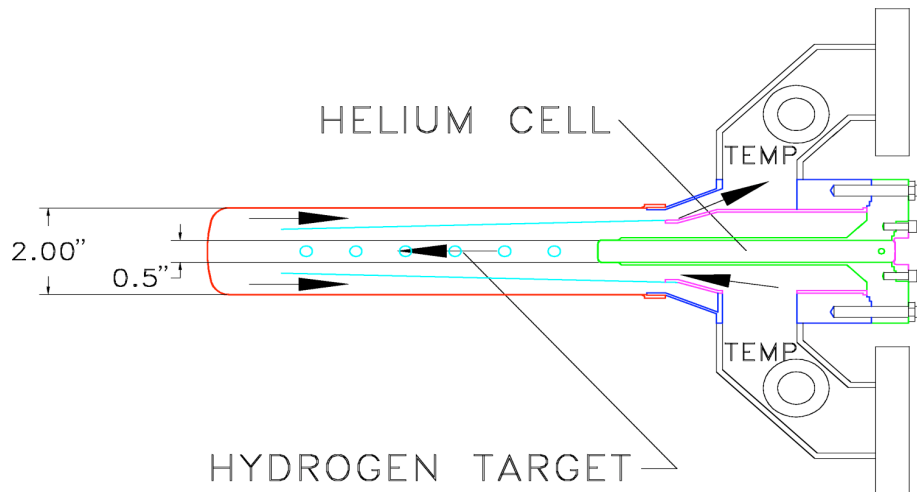
Expected  $Q^2$  distribution



PMT Anode  $\rightarrow$   
1 GHz 8 bit transient digitizer

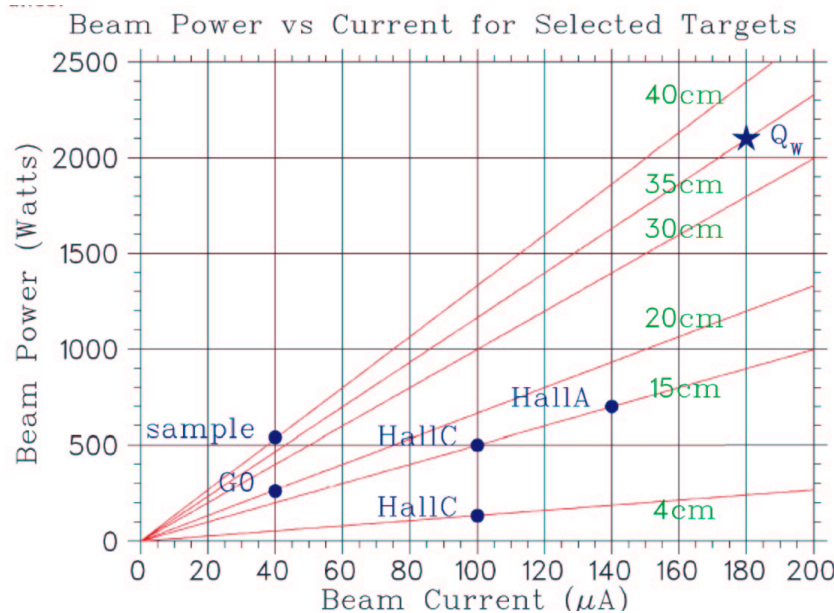


# The $Q^P_{weak}$ Liquid Hydrogen Target



## Target:

- 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  $\mu A$
- Beam power = 2200 W
- Raster size  $\sim 4$  mm  $\times$   $\sim 4$  mm square
- Flow velocity  $> 700$  cm/s
- Density fluctuations (at 15 Hz)  $< 5 \times 10^{-5}$

## Reducing the target "boiling" noise contribution

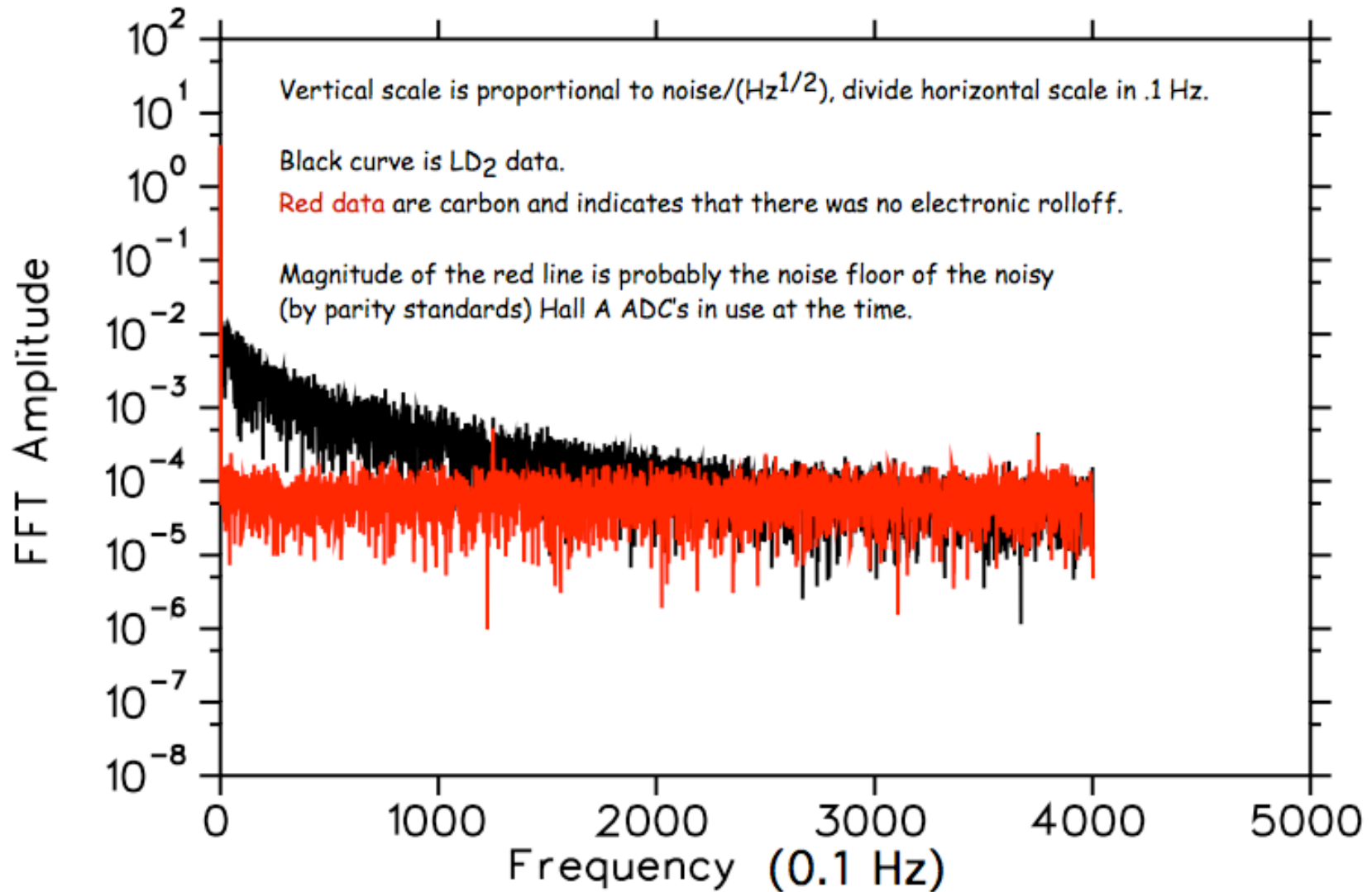
- 1) Make a target that simply does not "boil" or at least only to a level that is small with respect to  $\sim 50\text{ppm/pulse pair}$ . Options: large raster size, faster pump speed, better cooled windows....
- 2) Use Luminosity monitors to normalize the experiment rather than the beam current.
- 3) Take a lesson from "Slow motion photography" - Increase the frame rate!

Assume the simple model - "boiling" is not a resonant phenomena  
- "boiling" noise is the result of "bubbles" formed along the length of the target that are ejected from the beam region by rapidly flowing  $\text{LH}_2$ .

Then the associated noise/pulse pair should decrease as the reversal/readout frequency is raised.

If one goes high enough in frequency even a boiling target would appear effectively as a "solid" w.r.t. any single "helicity reversal pair" asymmetry calculation.

Fourier Transform of old Hall A data (>100 microamps on LD<sub>2</sub> and C) from 2003



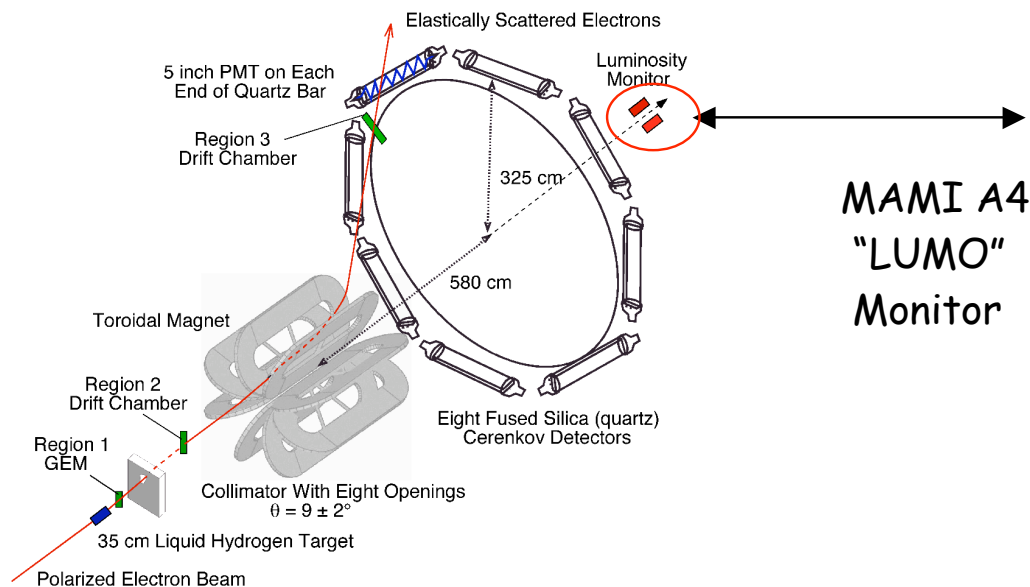
## The $Q^P_{weak}$ Luminosity Monitor

Luminosity monitor → Symmetric array of 8 quartz Cerenkov detectors instrument with vacuum photo diodes & integrating readout at small  $\theta$  ( $\sim 1.2^\circ$ ). Low  $Q^2$ , high rates  $\sim 28$  GHz/octant.

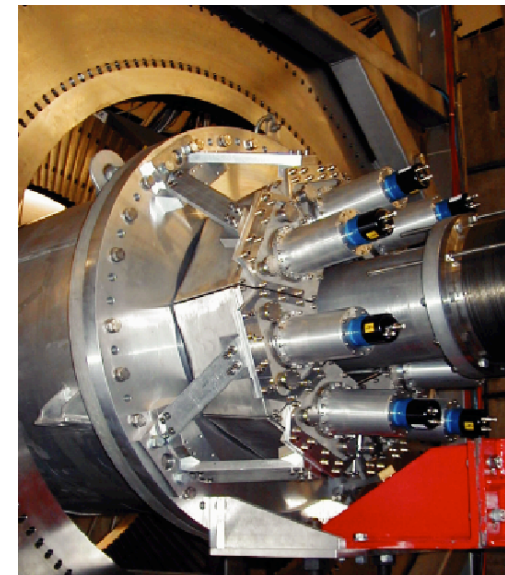
Expected signal components: 52% e-e Moeller, 42% e-p elastic, 5% e- $^{27}\text{Al}$  elastic.  
 Expected lumi monitor asymmetry  $\ll$  main detector asymmetry.  
 Expected lumi monitor statistical error  $\sim (1/6)$  main detector statistical error.

Useful for:

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

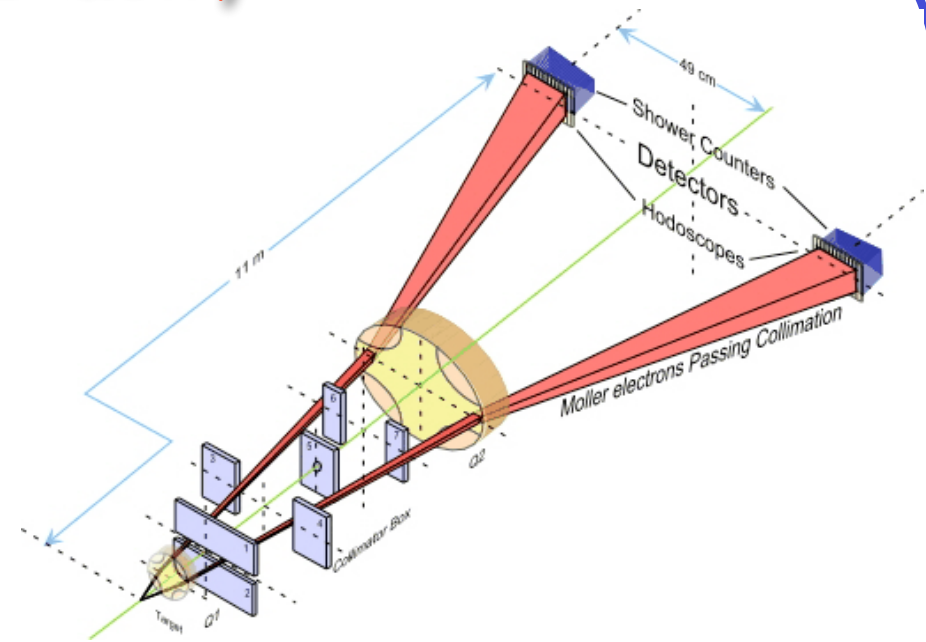


MAMI A4  
"LUMO"  
Monitor

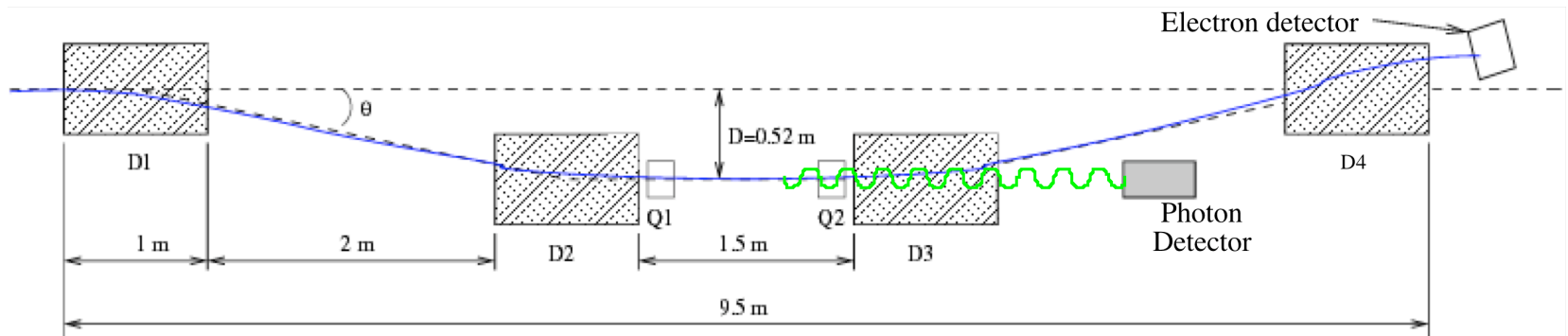


# Precision Polarimetry

- Present limitations:
  - $I_{Max} \sim 10 \mu A$ .
  - At higher currents the Fe target depolarizes.
  - Measurement is destructive
- Plan to upgrading Møller:
  - Measure  $P_{beam}$  at  $100 \mu A$  or higher, quasi-continuously
  - Trick: kicker + strip or wire target (looks promising)
- Schematic of planned new [Hall C Compton](#) polarimeter.



Existing Hall C Møller can do 1% (stat) in a few minutes



## Anticipated $Q^p_{Weak}$ Uncertainties

	<u><math>\Delta Q^p_{weak} / Q^p_{weak}</math></u>
<b>Statistical (2200 hours)</b>	<b>2.8%</b>
<b>Systematic:</b>	
Beam polarization	1.4%
Average $Q^2$ determination	1.0%
Helicity-correlated Beam Properties	0.6%
Uncertainty in Inelastic contamination	0.2%
Target window Background	<1.0%
Hadronic structure uncertainties (measured)	2.0%
Radiative correction uncertainties in $Q^p_{Weak}$	<1%
<b>Total Systematic</b>	<b>2.9%</b>
<hr/> <b>Total</b>	<hr/> <b>~4.0%</b>

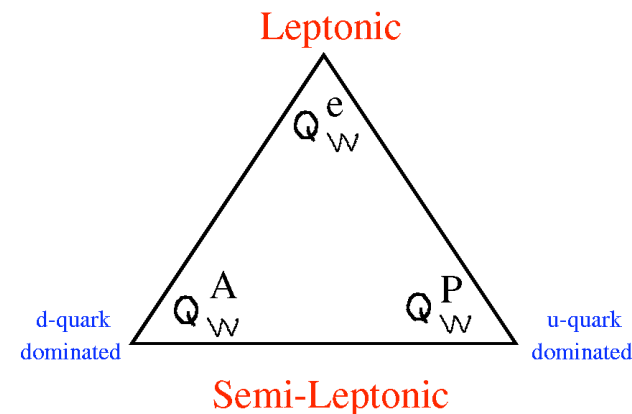
An additional uncertainty associated with QCD corrections applies to the extraction of  $\sin^2\theta_W$  : it raises  $\Delta\sin^2\theta_W / \sin^2\theta_W$  from 0.2% to 0.3%.

# Summary

## Potential of the $Q_{\text{weak}}^{\text{P}}$ Experiment :

- Precision measurement of the proton's weak charge in the simplest system.
- Sensitive search for new physics at the  $\sim 4.6$  TeV scale.
- Fundamental  $10 \sigma$  measurement of the running of  $\sin^2\theta_W$  at low energy.
- As emphasized by Ramsey-Musolf,  $Q_{\text{Weak}}^{\text{P}}$  is part of the low energy

weak charge triad  $\rightarrow$



- Collaboration with strong credentials in precision measurements.
- Aggressive physics goal & conservative technology - no "inventions"!
- Anticipate  $\sim 3$  years to construct full experiment.
- Goal: Multiple runs during 2007 - 2009 timeframe.

END