The Q^p_{weak} Experiment: A Search for New TeV Scale Physics via a Measurement of the Proton's Weak Charge

Measure: Parity-violating asymmetry in
$\vec{e}$ + p elastic scattering at $Q^2 \sim 0.03$ GeV^2
to ~4% relative accuracy at JLab

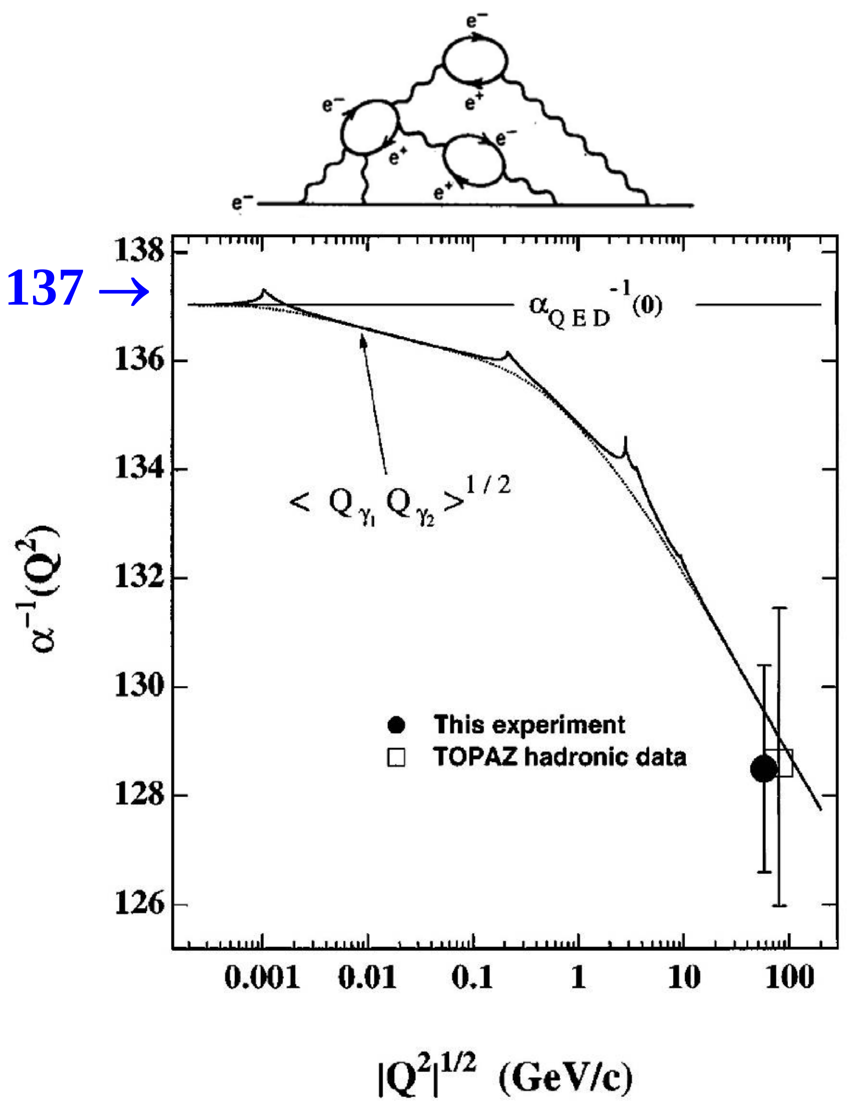
Extract: Proton's weak charge $Q^p_{weak} \sim 1 - 4 \sin^2\theta_W$
to get ~0.3% on $\sin^2\theta_W$ at $Q^2 \sim 0.03$ GeV^2

⇒ tests "running of $\sin^2\theta_W$" from M^2_Z to low Q^2
⇒ sensitive to new TeV scale physics

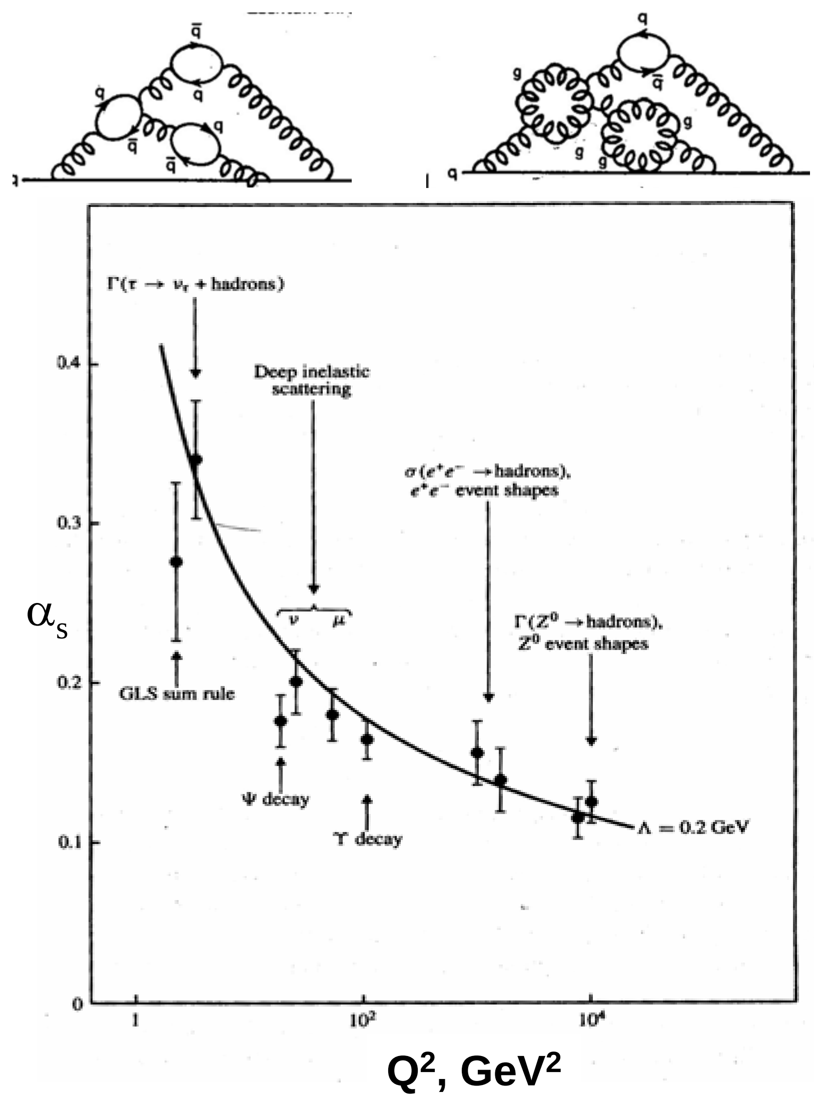
W.T.H. van Oers *(Hall C Users Meeting 2006)*

Running coupling constants in QED and QCD

QED (running of α)



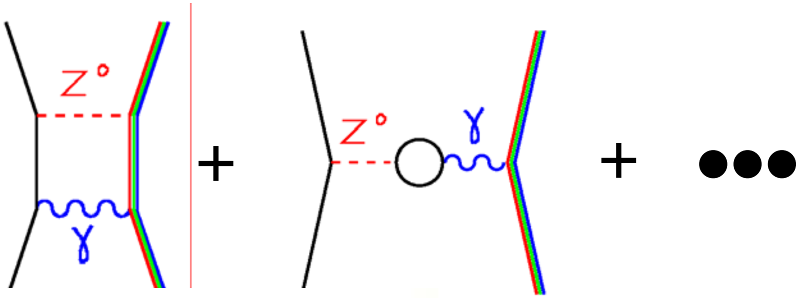
QCD(running of α_s)

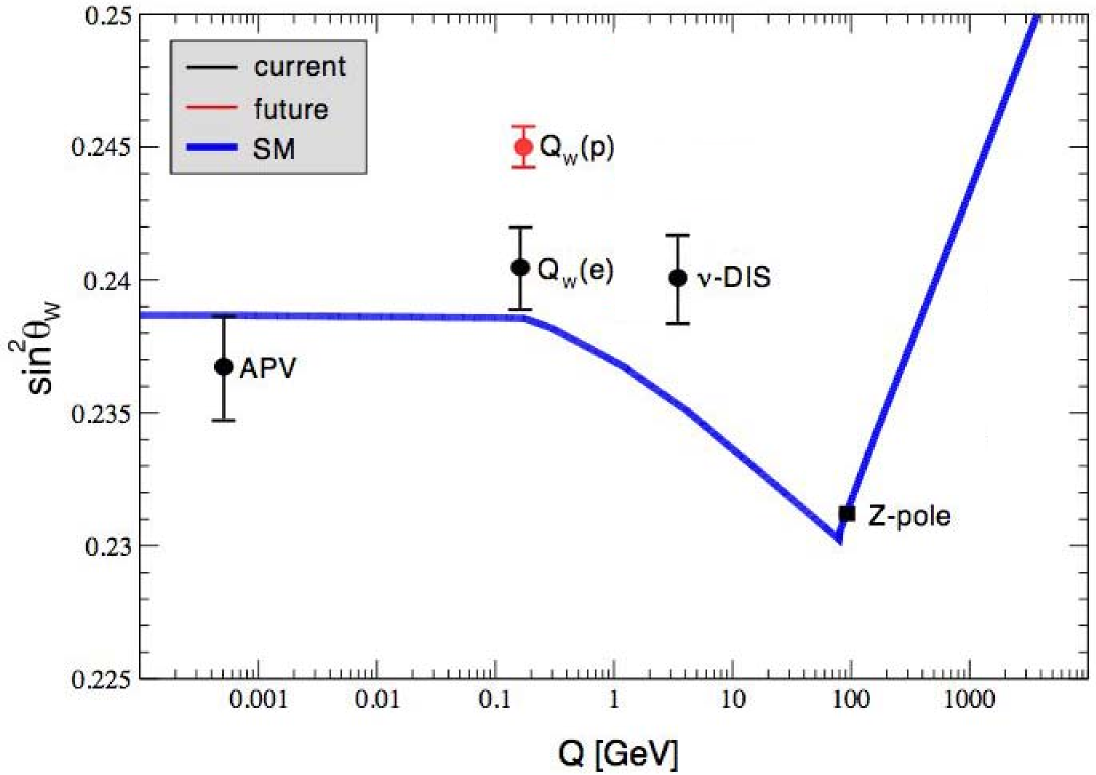


What about the running of $\sin^2\theta_W$?

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

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

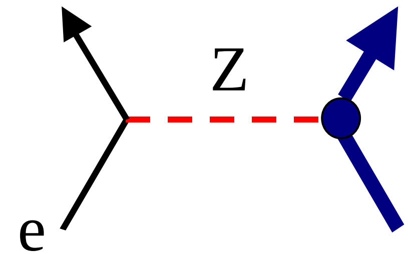




- All "extracted" values of $\sin^2\theta_W$ must agree with the Standard Model prediction or new physics is indicated.

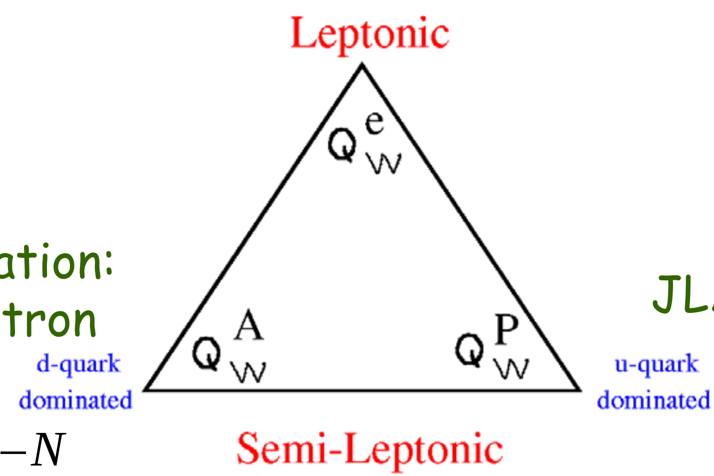
Low Energy Weak Neutral Current Standard Model Tests

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

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

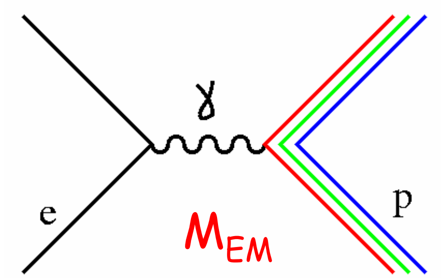
JLAB Q^p_{weak}: parity-violating
$\vec{e}$-p elastic scattering

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

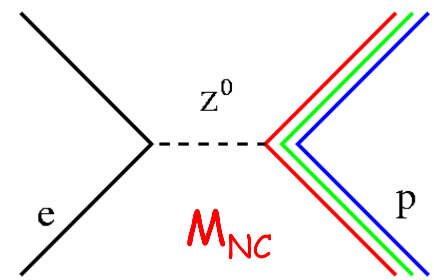
$Q_W^p \approx 1 - 4\sin^2\theta_W$

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

Q^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

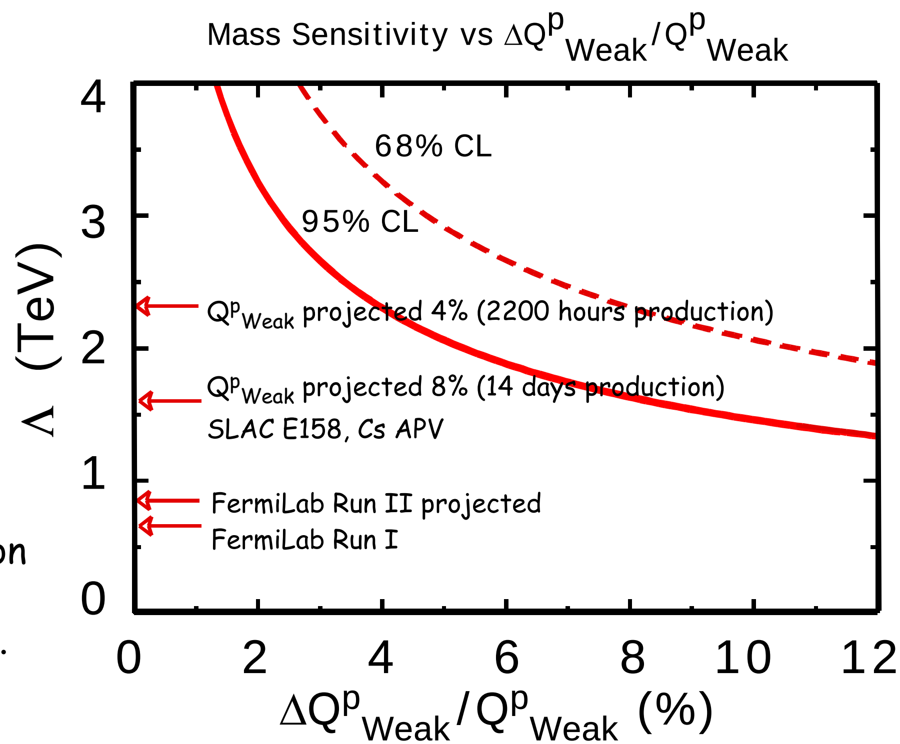
- Parameterize New Physics contributions in electron-quark Lagrangian

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

g: coupling constant, Λ: mass scale

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

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

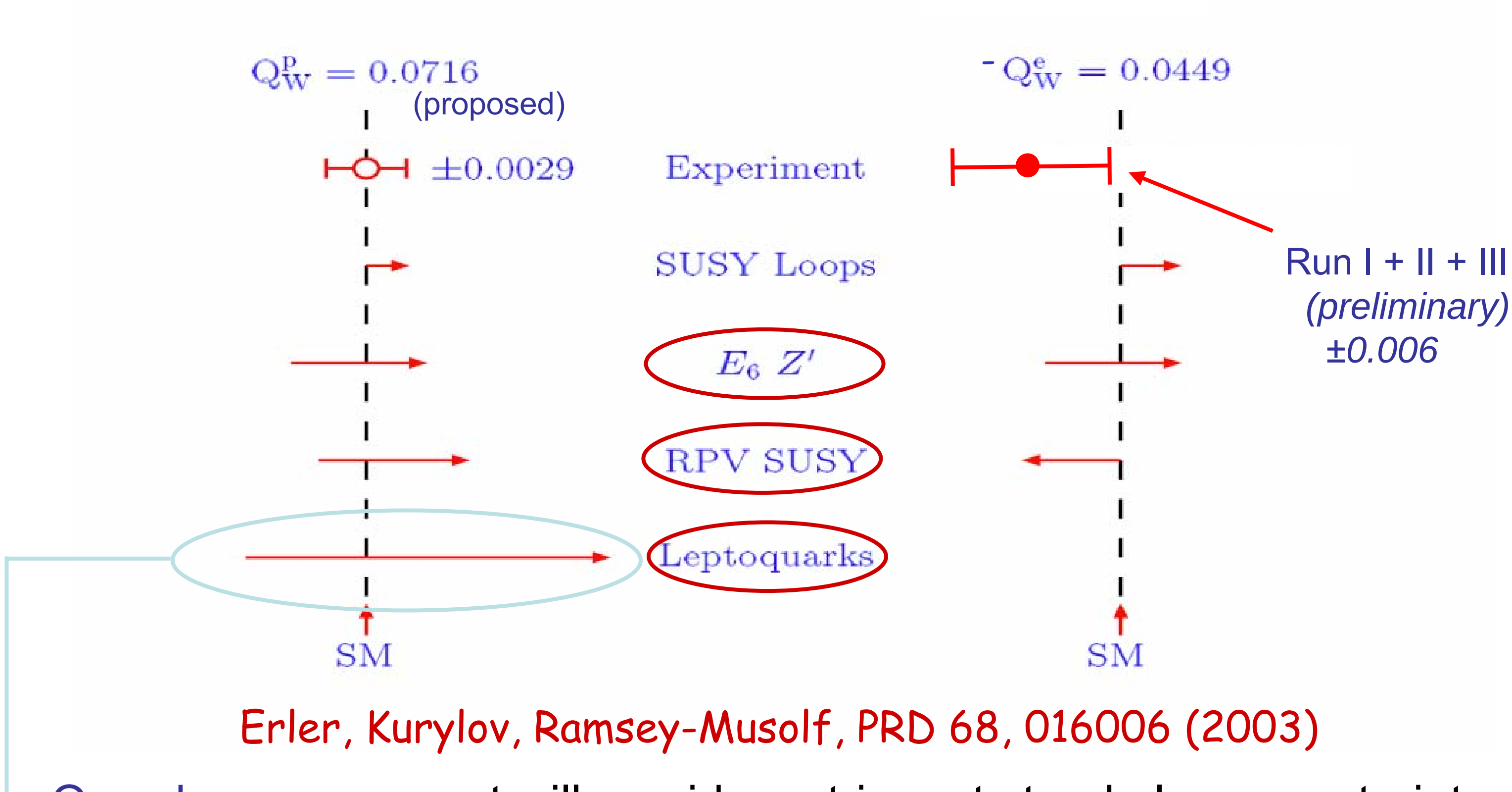


- The TeV discovery potential of weak charge measurements will be unmatched until LHC turns on.
- If LHC uncovers new physics, then precision low Q^2 measurements will be needed to determine charges, coupling constants, etc.

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

JLab Qweak

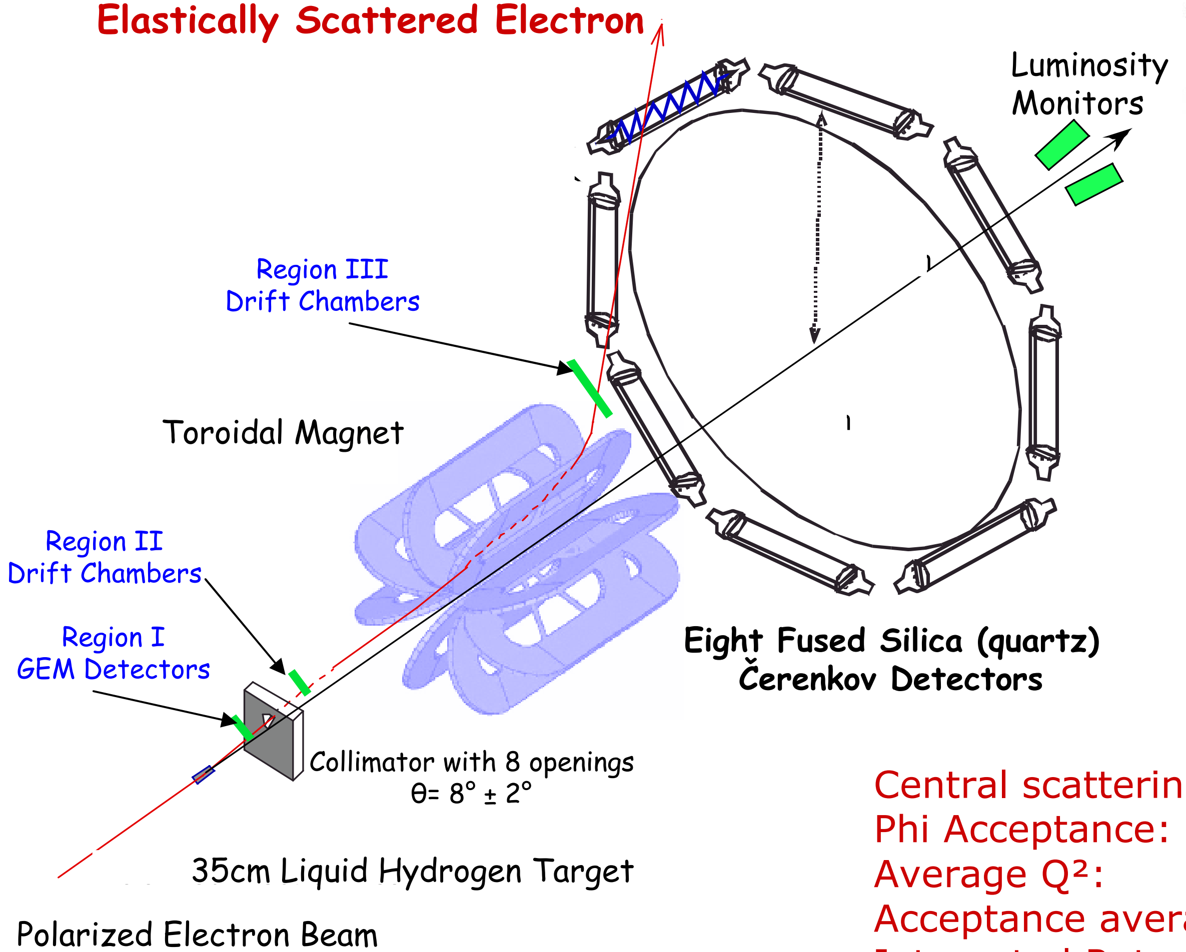
SLAC E158

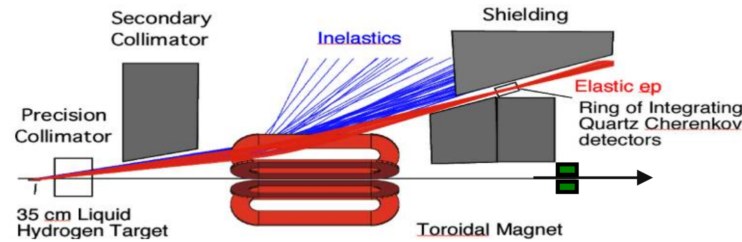


Erler, Kurylov, Ramsey-Musolf, PRD 68, 016006 (2003)

- 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.

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

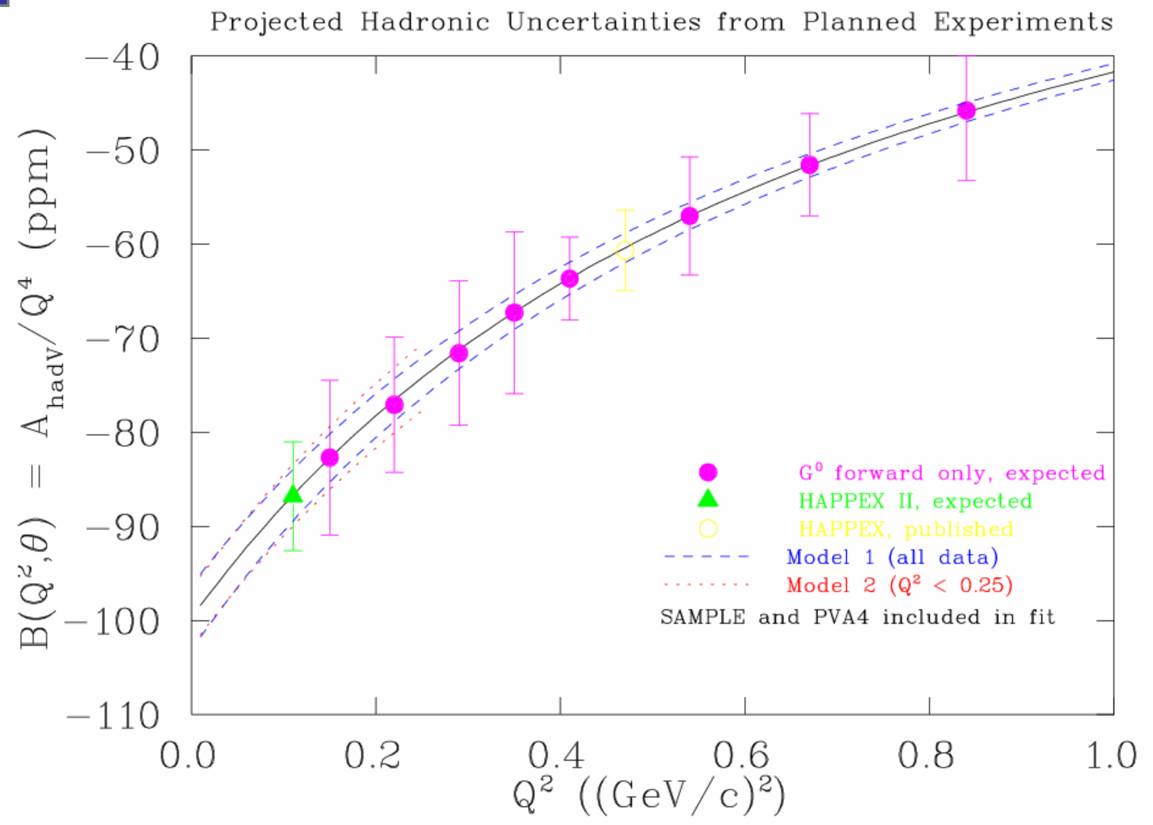
$$A = A_{Q_W^p} + A_{hadronic} + A_{axial}$$
$$= -.19 \text{ ppm} \quad -.09 \text{ ppm} \quad -.01 \text{ ppm}$$

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

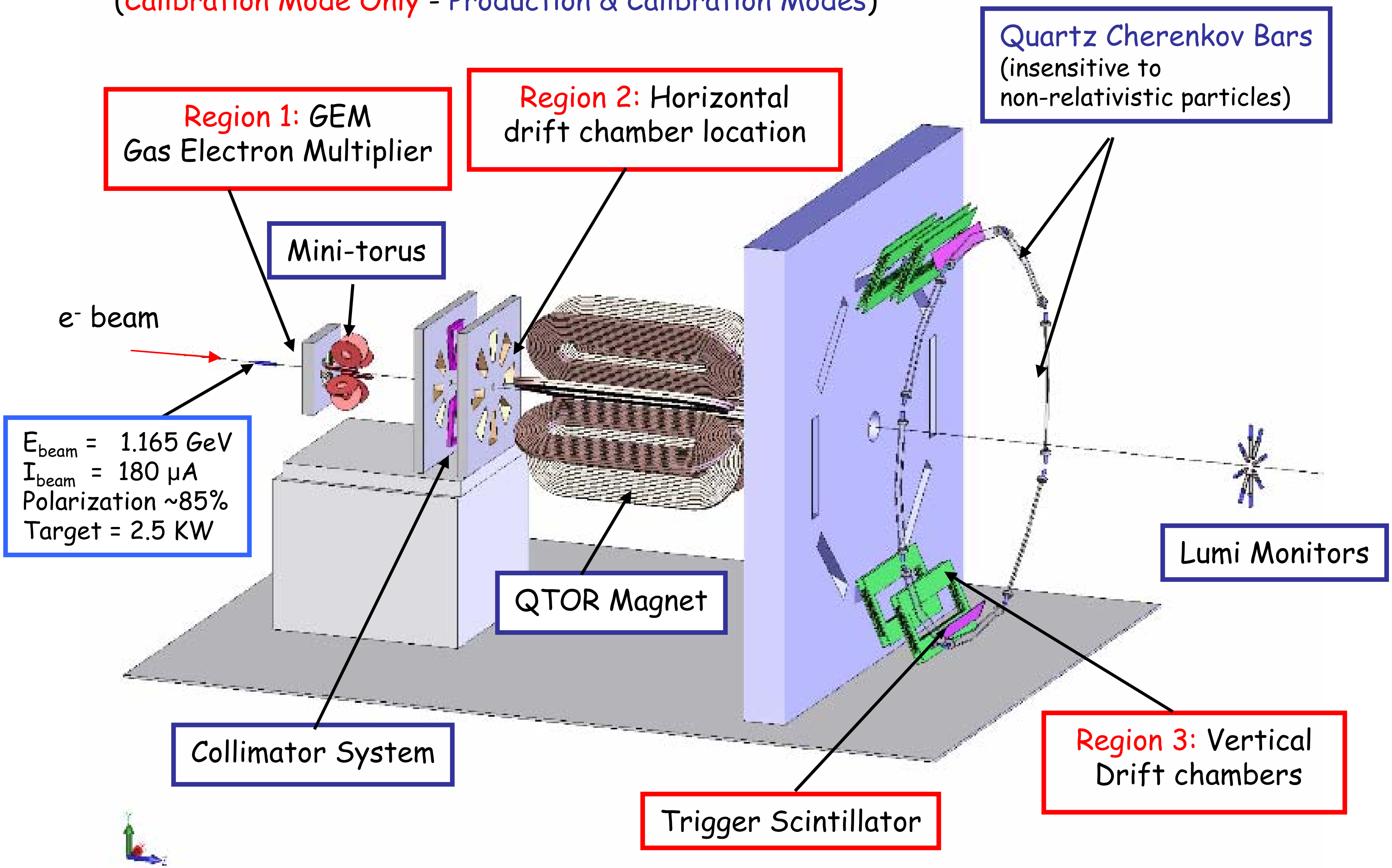
$$A_{hadronic} = Q^4 B(Q^2)$$



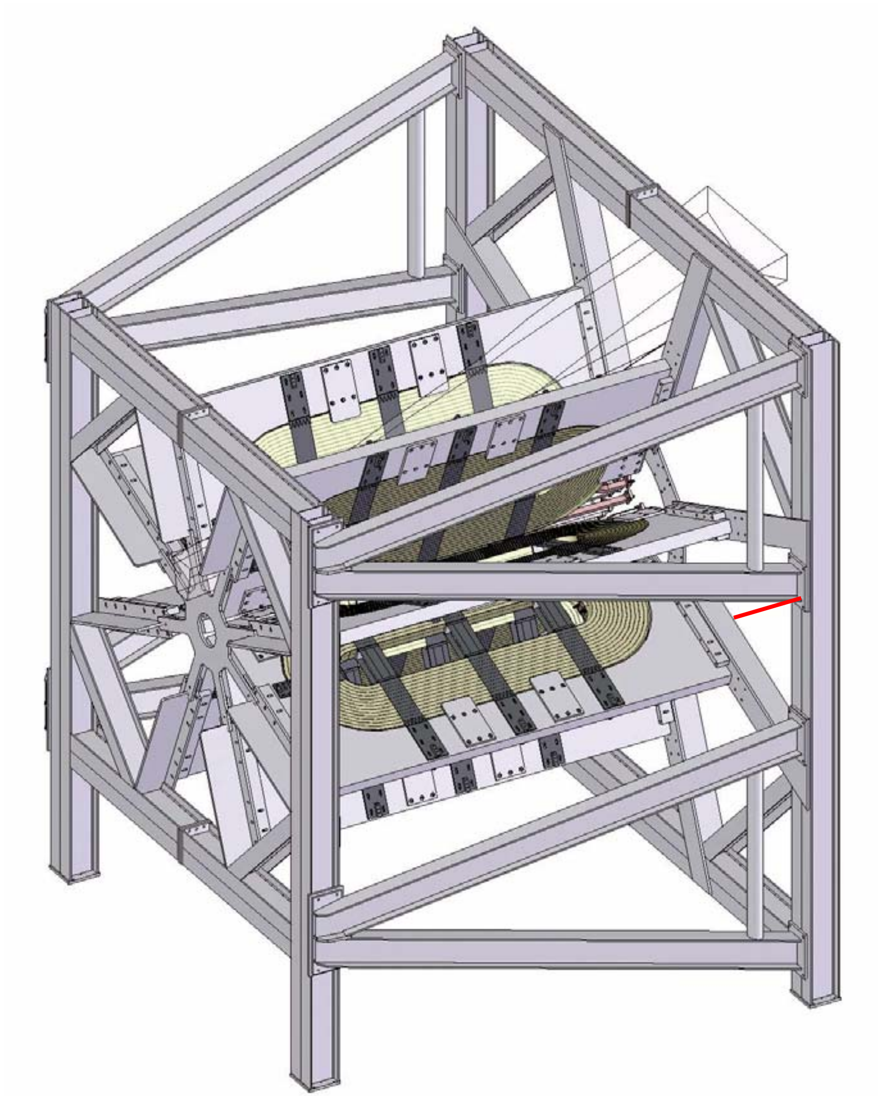
Quadrature sum of expected
$\Delta A_{hadronic}$ = 1.5% and ΔA_{axial} = 1.2% errors
contribute ~1.9% to error on Q^p_W

The Qweak Apparatus

(Calibration Mode Only - Production & Calibration Modes)



Q^p_{Weak} Toroidal Magnet - QTOR

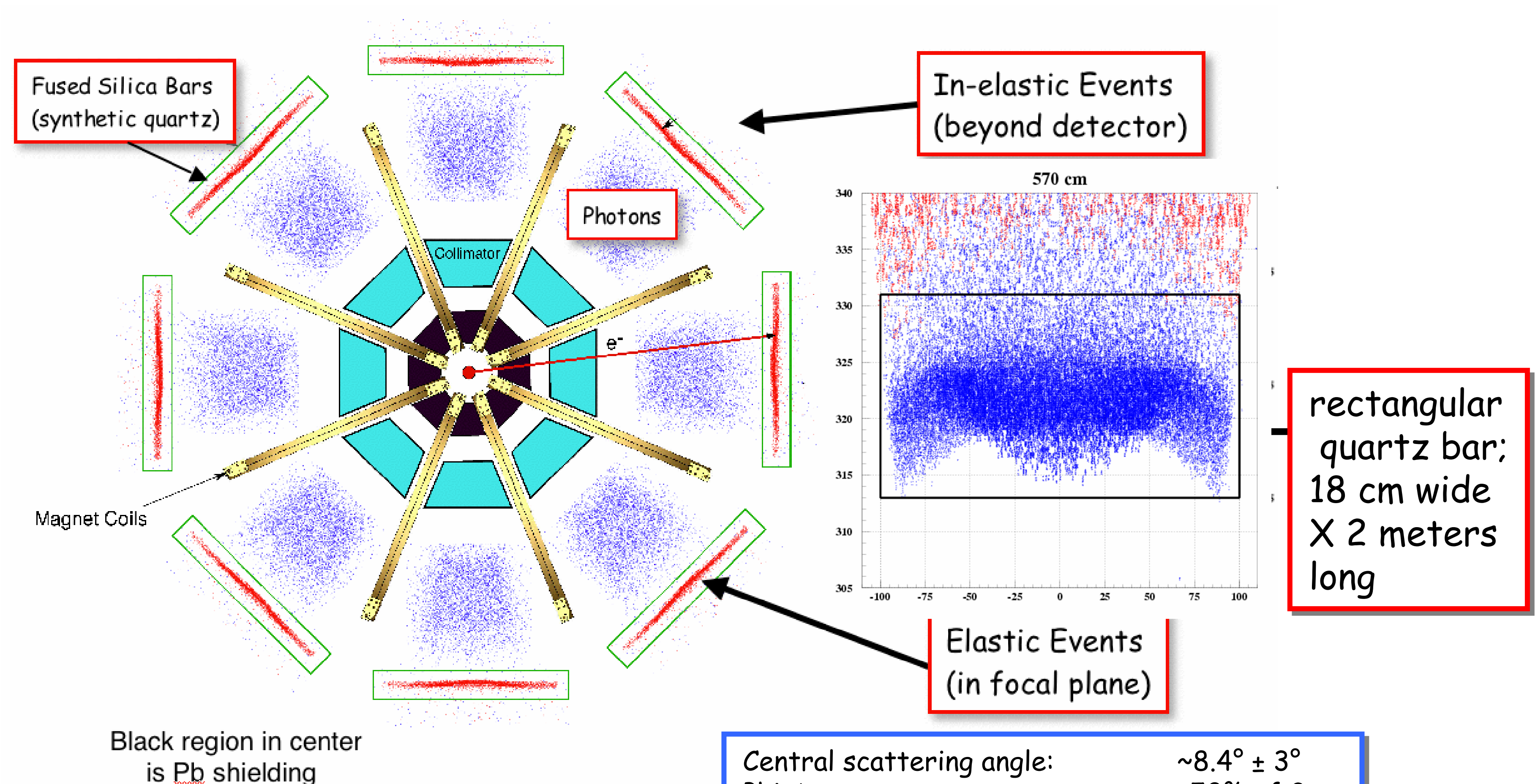


- 8 toroidal coils, 4.5m long along beam
- Resistive, similar to BLAST magnet
- Pb shielding between coils
- Coil holders & frame all Al
- $\int B \cdot dl \sim 0.7$ T-m
- bends elastic electrons ~ 10°
- current ~ 9500 A

Status:
- coils wound in France
- support stand under construction

Inelastic/Elastic Separation in Q^p_{Weak}

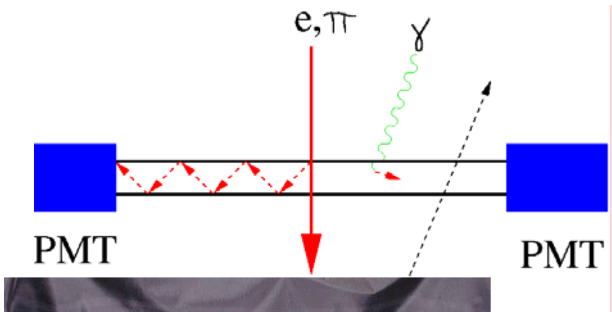
View Along Beamline of Q^p_{Weak} Apparatus - Simulated Events



Very clean elastic separation!

Central scattering angle:	~8.4° ± 3°
Phi Acceptance:	> 50% of 2π
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:

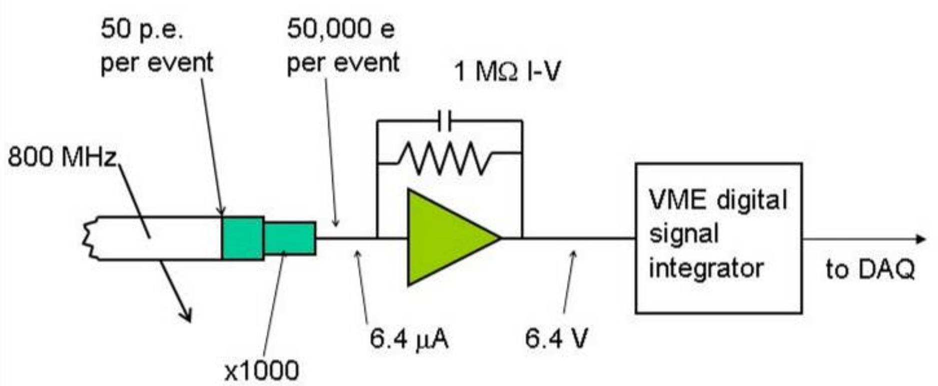
- Insensitivity to background γ, n, π.
- Radiation hardness (expect > 300 kRad).
- Operation at counting statistics.

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 θ_{tir}=43°
- reflectivity = 0.997

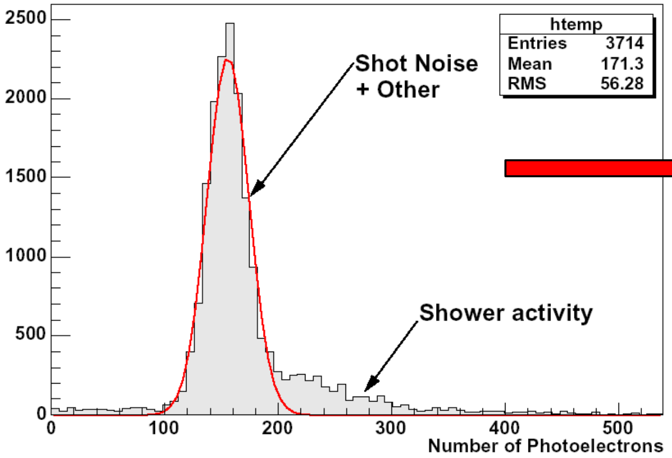
Electronics (LANL/TRIUMF design):

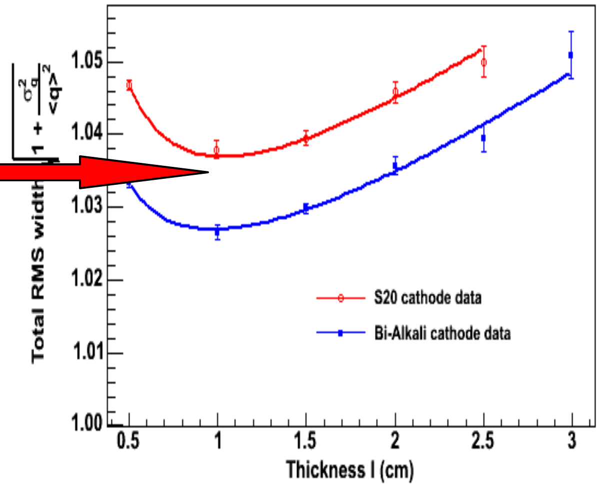
- Normally operates in integration mode.
- Will have connection for pulse mode.
- Low electronic noise contribution. compared to counting statistics.
- 18 bit ADC will allow for 4X over sampling.



Main Detector Response Optimization

Detector noise is due to photoelectrons statistics and shower fluctuations.

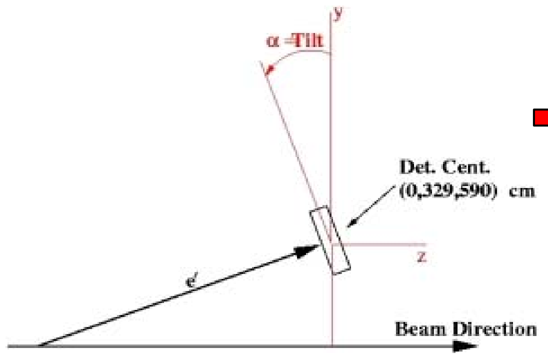


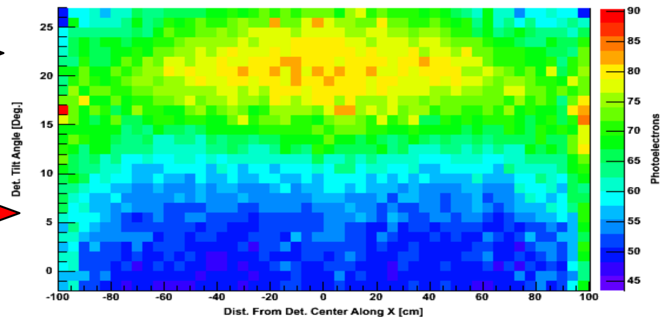


1.25 cm thickness

→ **4% increase in statistical error**

Tilt angle of the TIR radiator nontrivially affects pe number and collection uniformity.





Jury's still out on the tilt angle:

Sys. vs Stat. trade-off

TRIUMF MK2 I-V Preamplifier

Gain: V_{out}/I_{in} = 1 MΩ with option of up to 10 MΩ. Set by switches on board.

Output: 0 to +10V. Adjustable ±2V offset. Drives 130 m RG-213

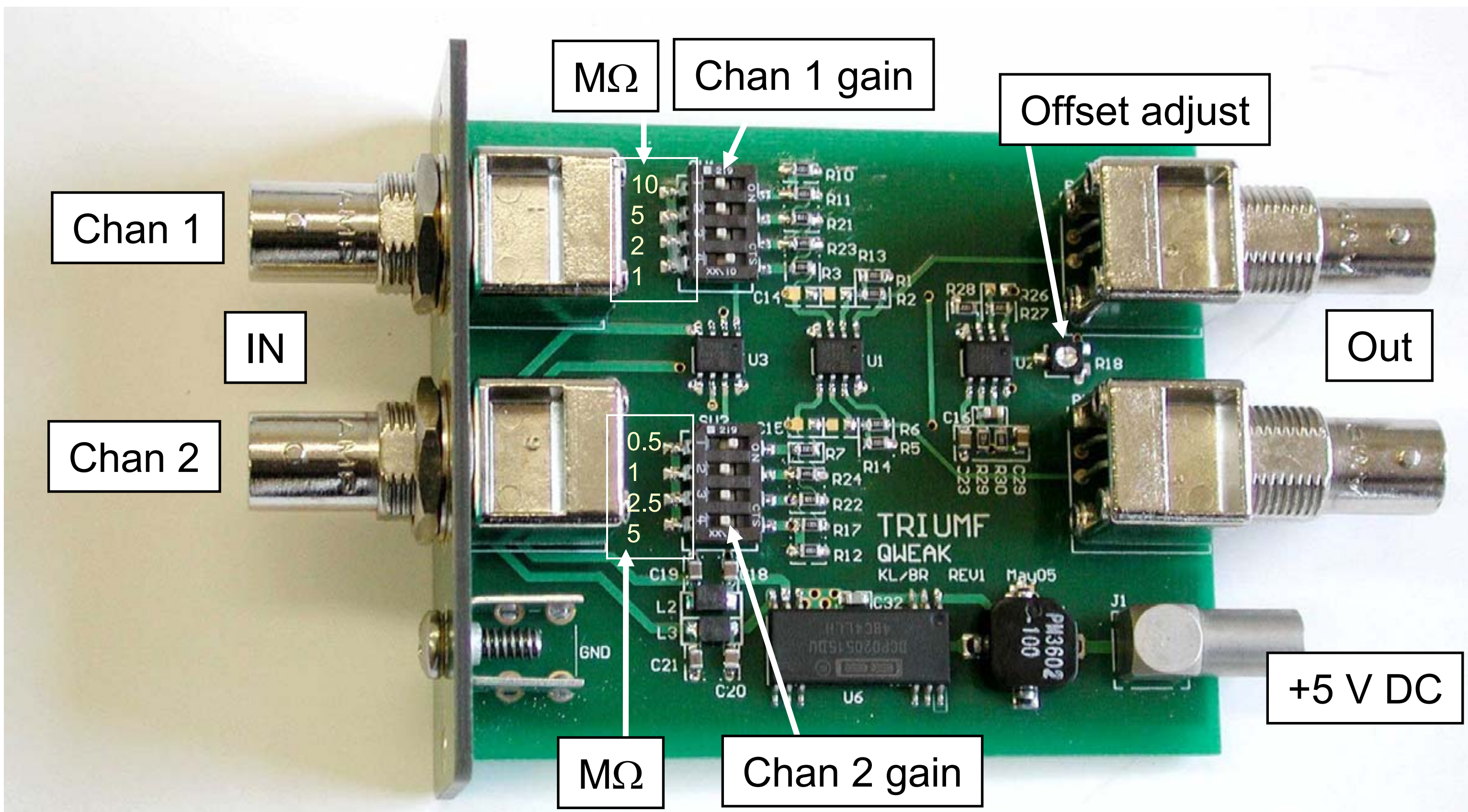
Input: 10 μA range. (e.g. +1 μA to -9 μA with +1V offset.). Tolerates 5m of RG-62 on input. (Noise set mainly by input cable length.)

Bandwidth: f_{3db} =30 kHz (settles to <10^{-4} in 50 μs)

Density: two amplifiers per module (one per detector bar).

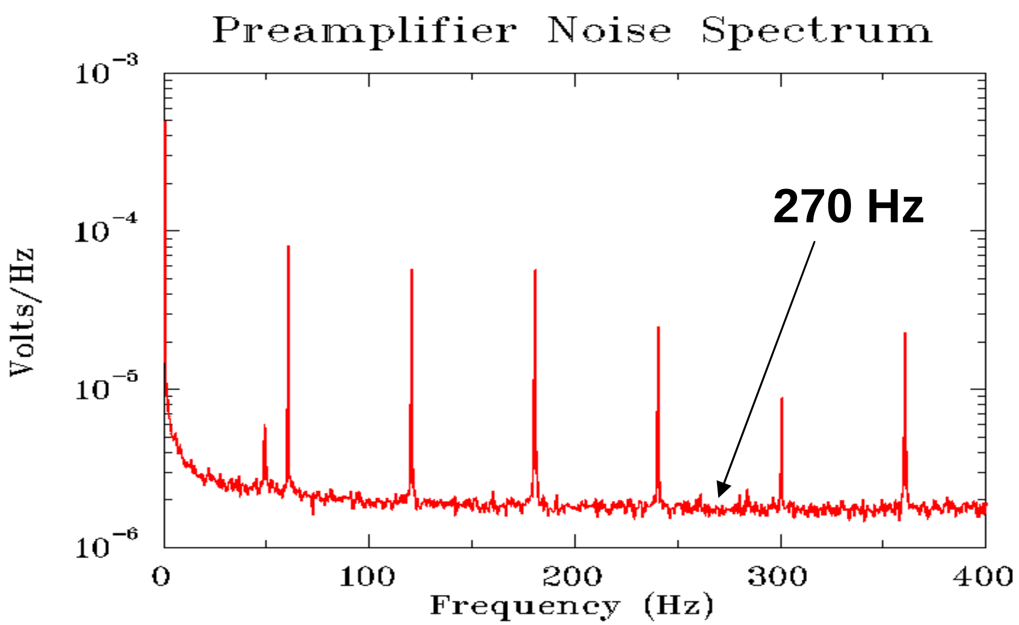
Uses 5 V DC Supply. Ground fully isolated by internal DC-DC converter. BNC connectors. Center conductor negative on input.

Small size for ease of shielding.



Preamp Irradiation Results

Total dose was 18 kRad, or about 0.2 Joules/gram (Specification is 10 kRad.)



- **No observable changes in noise level during or after irradiation**

  (Encouraging since shot noise for 3.5 μA input is much smaller than Qweak counting statistics.)
- **More sensitive, post-irradiation measurements at TRIUMF find no long term damage.**

Post 18.6 krad irradiation Noise Measurements

(rms noise in 50 kHz band)

MK2 -- 745 pf

Gain (MΩ)	Noise (μV_{rms})
Channel 1	
1 no cap.	47
1	170
2	325
5	755
10	1240

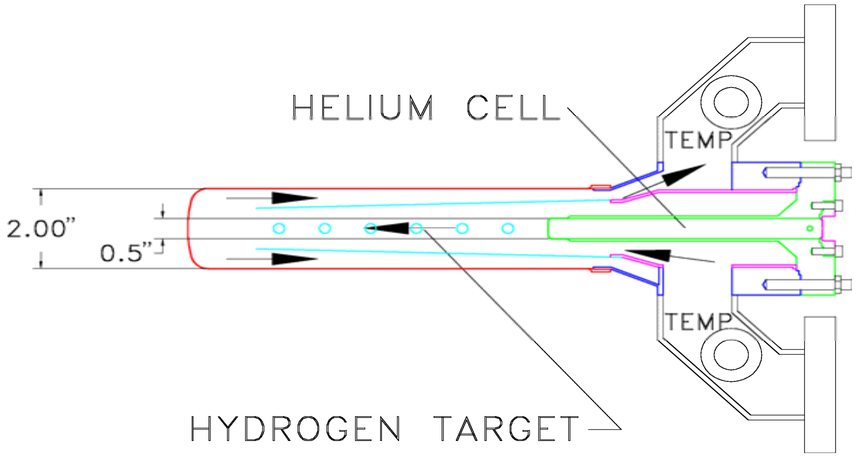
MK2 -- 745 pf

Gain (MΩ)	Noise (μV_{rms})
Channel 2	
0.5 no cap.	26
0.5	95
1	190
2.5	420
5	800

Compare to similar, but un-irradiated amp. with 745 pf

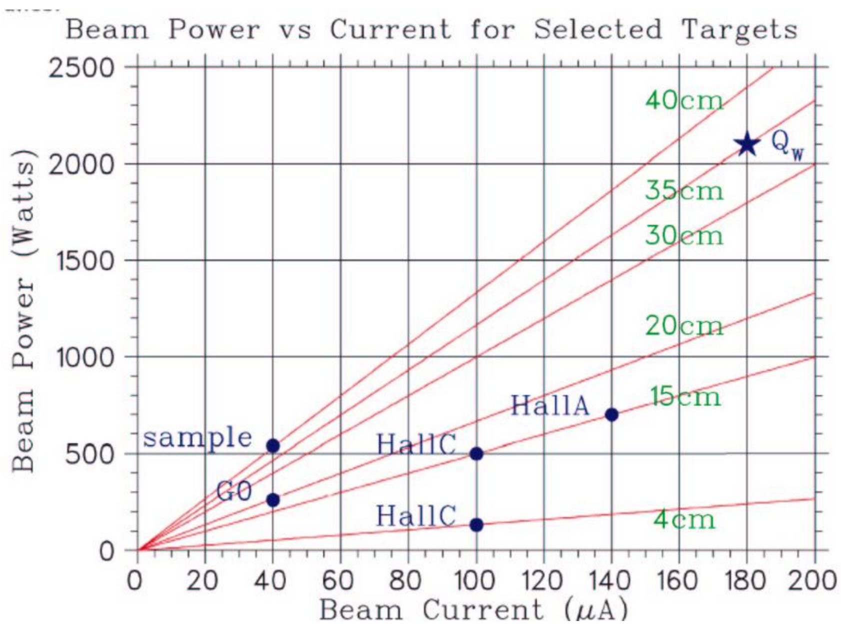
Gain (MΩ)	Noise (μV_{rms})
1	180
2	350
5	775
10	1300
10 no cap.	340

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) < 5×10^{-5}
- Use reversal rate of 270 Hz

Helicity Correlated Beam Properties: False Asymmetry Corrections

$$A_{meas} = A_{phys} + \sum_{i=1}^{N} \frac{1}{2Y}\left(\frac{\partial Y}{\partial P_i}\right)\Delta P_i$$

$\Delta P = P_+ - P_-$

Y = Detector yield

(P = beam parameter
~energy, position, angle, intensity)

Example: $\frac{1}{2Y}\left(\frac{\partial Y}{\partial x}\right) \sim 1.0\ \%/\mathrm{mm}\ ,\ \Delta x = 100\ \mathrm{nm}$

$$A_{\mathrm{false}} = \frac{1}{2Y}\left(\frac{\partial Y}{\partial x}\right)\Delta x \sim 10^{-6} = 1\ \mathrm{ppm}$$

Typical goals for run-averaged beam properties

Intensity: $A_I = \frac{I_+ - I_-}{I_+ + I_-} < 1\ \mathrm{ppm}$

Position: $\Delta x, \Delta y < 2 - 20\ \mathrm{nm}$

$\Delta P = P_+ - P_-$ → keep small with feedback and careful setup

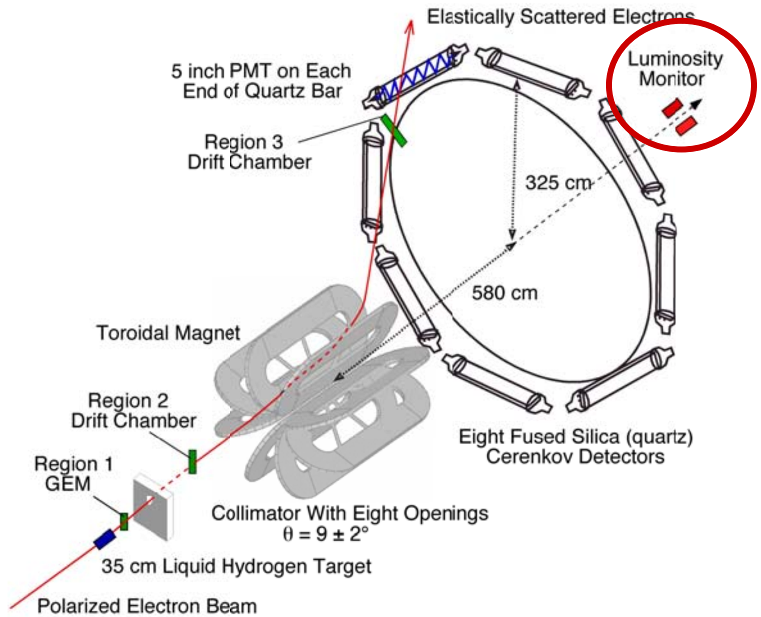
$\frac{1}{2Y}\left(\frac{\partial Y}{\partial P}\right)$ → keep small with symmetrical detector setup

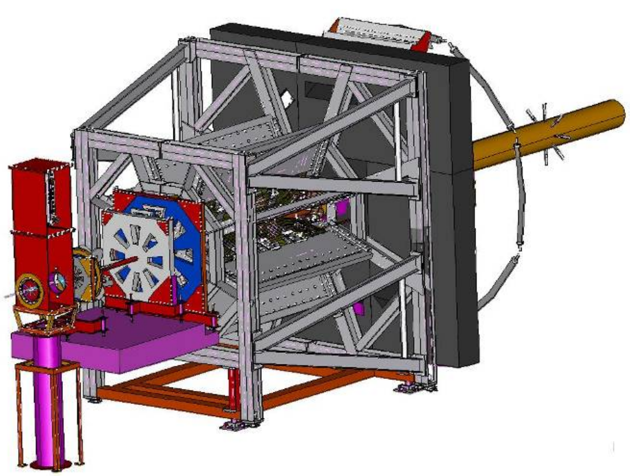
The Q^p_{Weak} Luminosity Monitor

- 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.

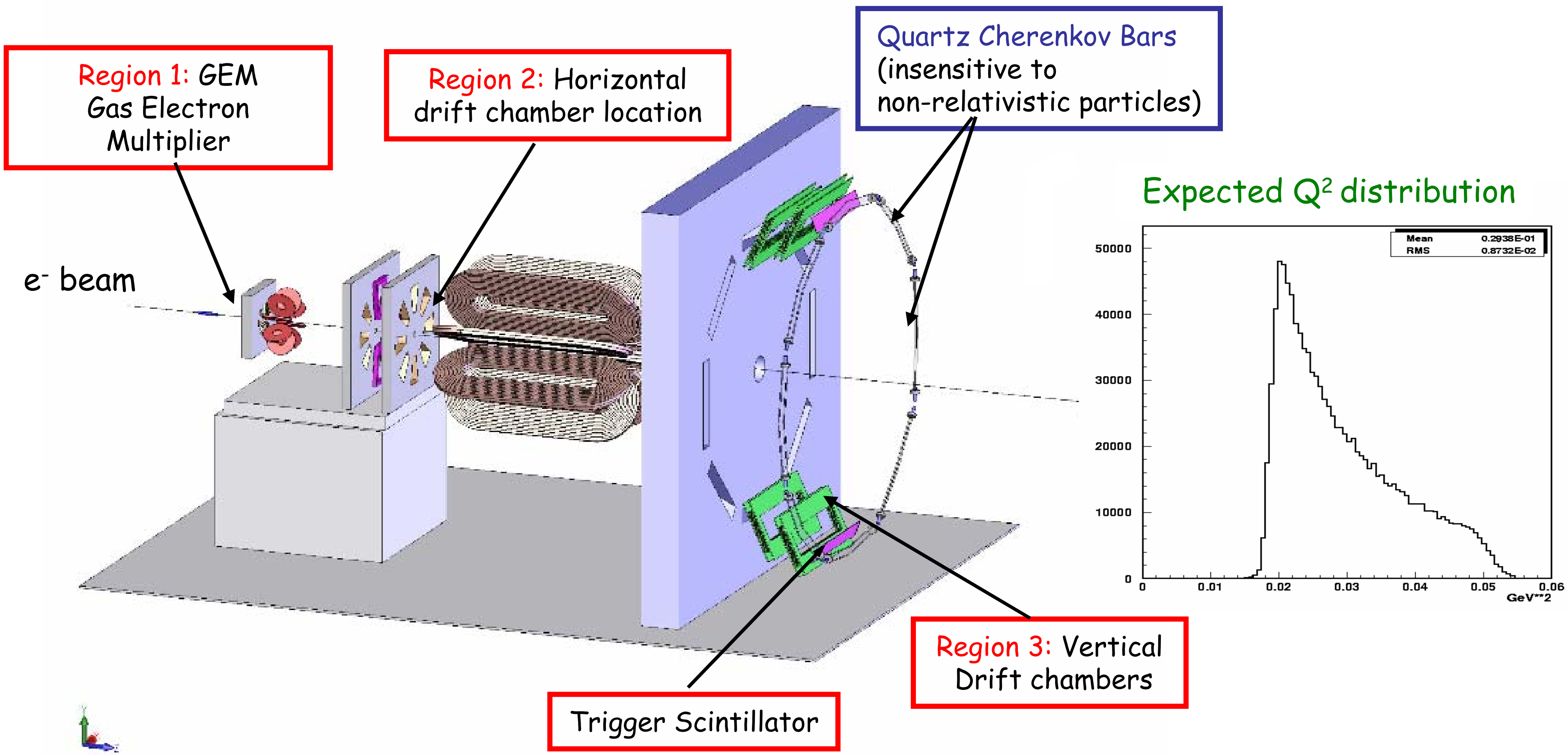
- Useful for:
  - Sensitive check on helicity-correlated beam parameter corrections procedure.
  - Regress out target density fluctuations.





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.

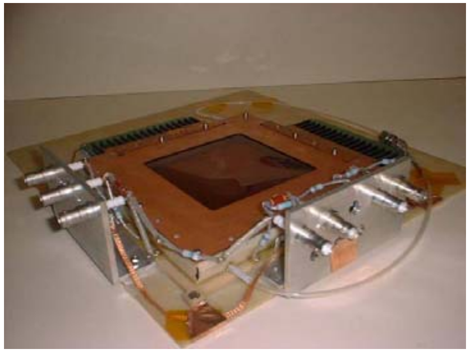


Region 1 + 2 chambers --> determine value of Q^2

Region 3 chamber --> efficiency map of quartz detectors

Tracking Systems

LaTech

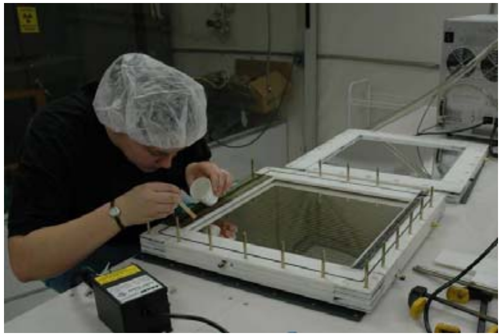


Major Construction effort by university collaborators.

Critical for :

- Checking optics and alignment
- Understanding backgrounds that leave tracks
- Determination of Q^2

VPI

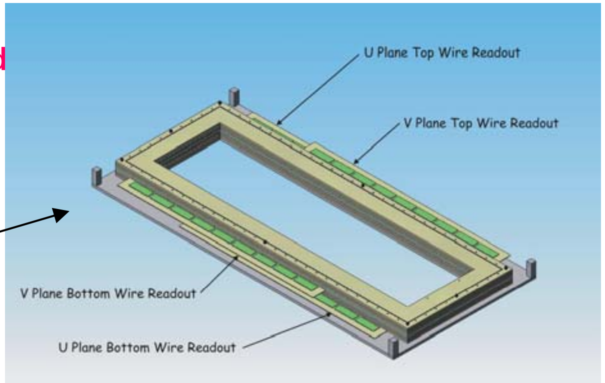


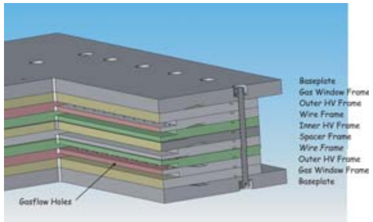
Tracking detector status:

- **Region I (small GEM):**
  reading out half-size prototype

- **Region II (medium size pair of HDC's)**
  single-plane prototype now understood
  final design phase

- **Region III (2.5 m long VDC)**
  design complete,
  ordering frames and electronics



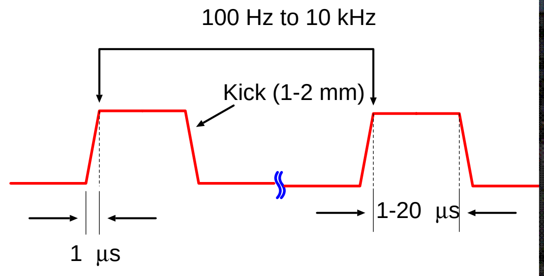


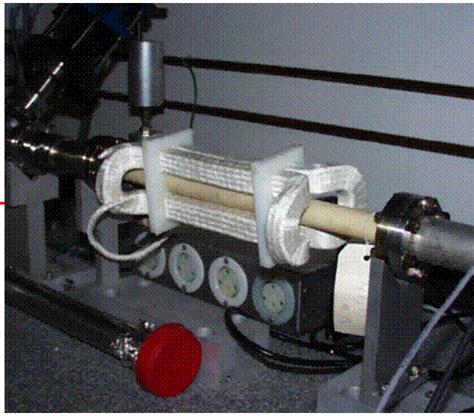
W&M

Precision Polarimetry

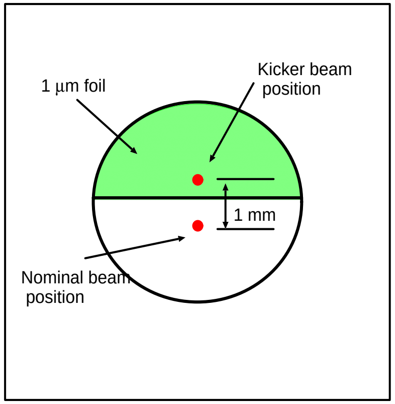
Hall C has existing ~1% precision Moller polarimeter

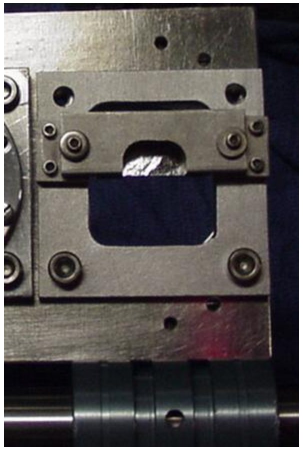
- Present limitations:
  - I_{Max} ~ 10 μA.
  - At higher currents the Fe target depolarizes.
  - Measurement is destructive



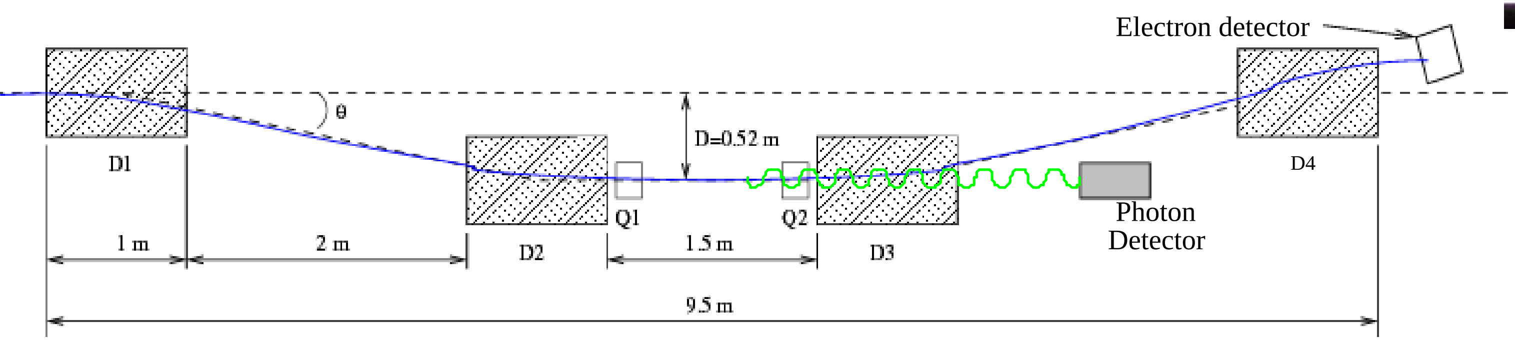


- Plan to upgrading Møller:
  - Measure P_{beam} at 100 μA or higher, quasi-continuously
  - Trick: kicker + strip or wire target (early tests look promising – tested up to 40 μA so far)





- 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

- Possible 12 GeV Parity-Violating Moller Experiment at JLAB

  - Conceptual design indicates reduction of E158 error by ~5 may be possible at 12 GeV JLAB.

weak charge triad →
(Ramsey-Musolf)