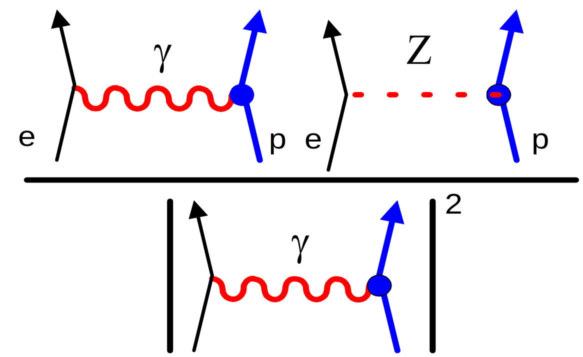
Lecture 2

Parity Violating Electron Scattering - Probe of Neutral Weak Form Factors

polarized electrons, unpolarized target

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



$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{A_E + A_M + A_A}{2\sigma_{unpol}}$$

$$A_E = \varepsilon(\theta) G_E^Z(Q^2) G_E^\gamma(Q^2)$$
$$A_M = \tau(Q^2) G_M^Z(Q^2) G_M^\gamma(Q^2)$$
$$A_A = -(1 - 4\sin^2\theta_W)\varepsilon' G_A^e(Q^2) G_M^\gamma(Q^2)$$

$\rightarrow G_E^s$

$\rightarrow G_M^s$

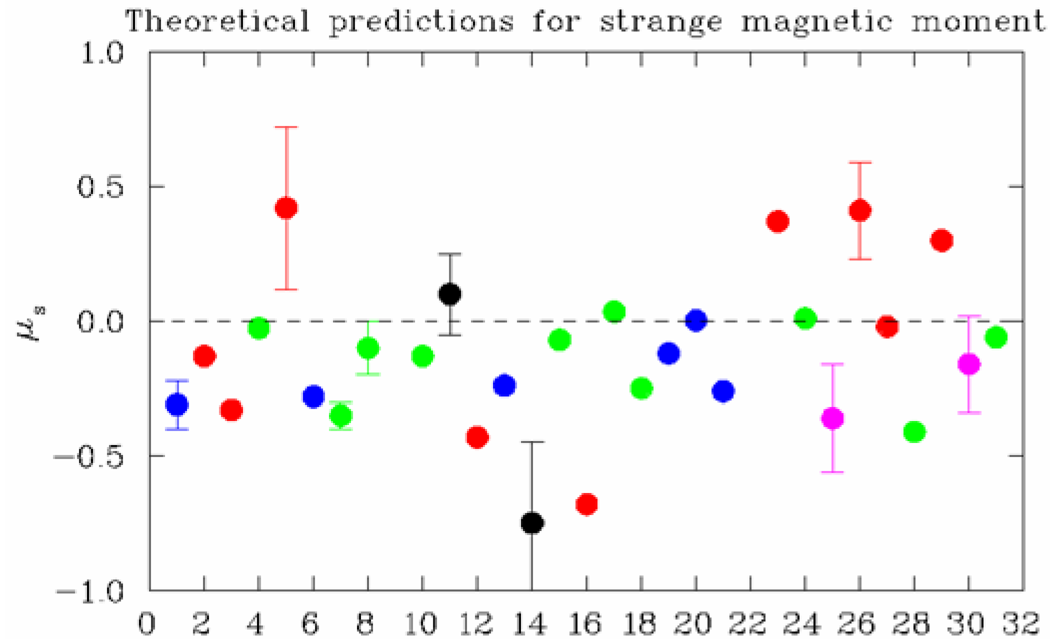
$\rightarrow G_A^e$

Strange electric and magnetic form factors, + axial form factor

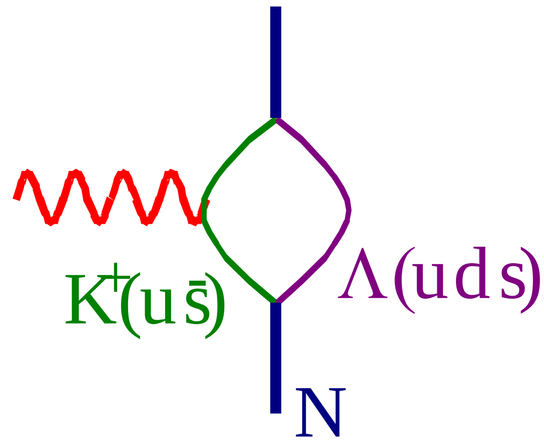
At a given Q^2 decomposition of G^s_E, G^s_M, G^e_A
Requires 3 measurements for full decomposition:

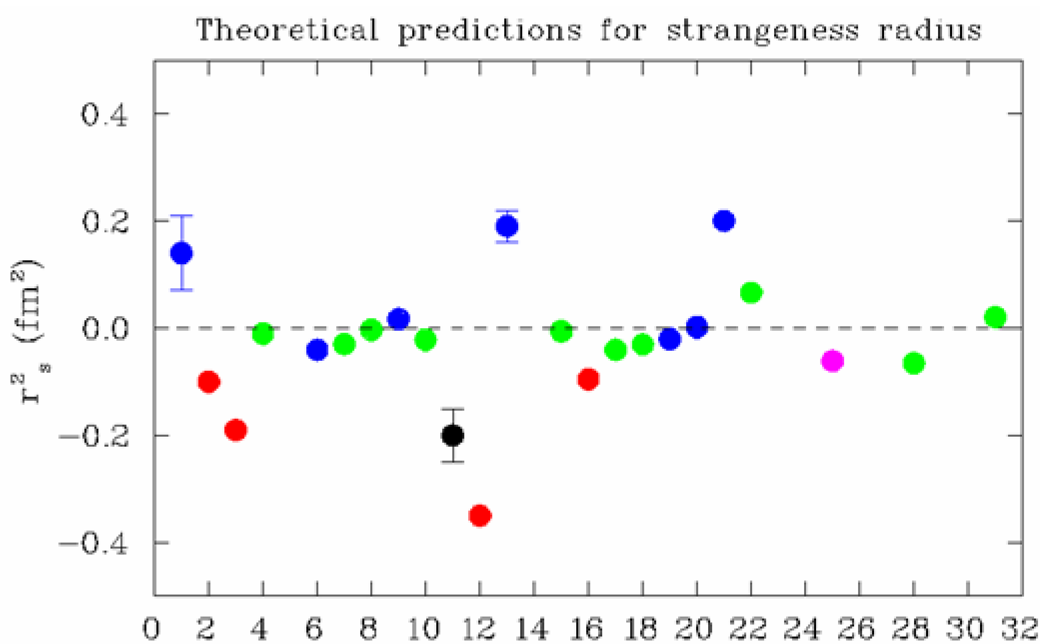
Forward angle $\vec{e}$ + p (elastic)
Backward angle $\vec{e}$ + p (elastic)
Backward angle $\vec{e}$ + d (quasi-elastic)

Theoretical predictions at $Q^2 = 0$ for strange form factors



$$\mu_s \equiv G_M^s(Q^2 = 0)$$





$$r_s^2 \equiv -6\left[\frac{dG_E^s}{dQ^2}\right]_{Q^2=0}$$

"Textbook physics" - SLAC E122 Experiment, 1978-79

Charles Prescott and collaborators:

$\vec{e}^- + d \rightarrow e^- + X$, deep inelastic scattering at SLAC

first result in 1978: $A/Q^2 = -(95 \pm 16) \times 10^{-6}\ (\text{GeV}/c)^{-2}$

$\rightarrow$ first measurement of parity-violation in the neutral weak current

From D.H. Perkins,
Intro. to High Energy Physics

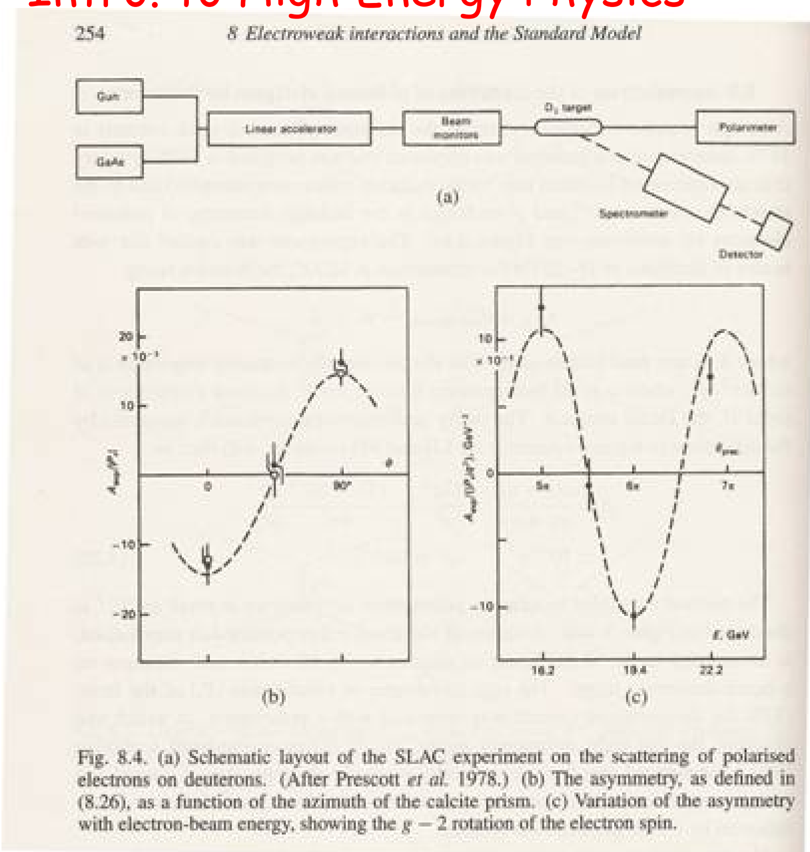
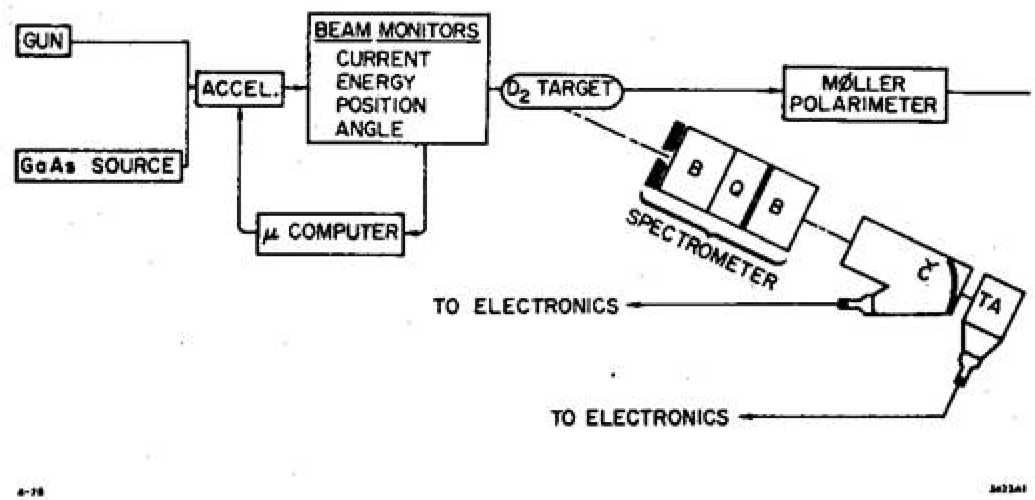


Fig. 8.4. (a) Schematic layout of the SLAC experiment on the scattering of polarised electrons on deuterons. (After Prescott et al. 1978.) (b) The asymmetry, as defined in (8.26), as a function of the azimuth of the calcite prism. (c) Variation of the asymmetry with electron-beam energy, showing the $g - 2$ rotation of the electron spin.

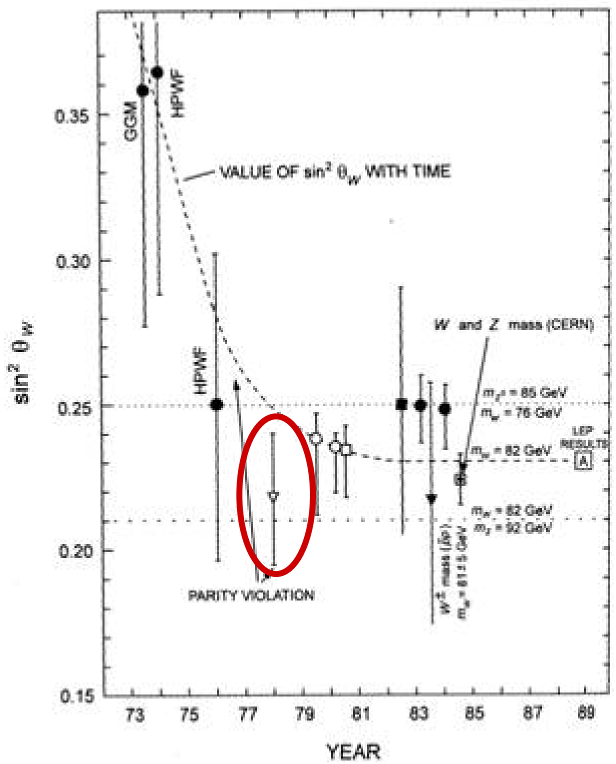
Experiment had most features of modern PV:

- GaAs polarized source, rapid helicity reversal
- accurate measurement and control of beam properties
- integrating particle detectors/electronics



"Textbook physics" - SLAC E122 Experiment, 1978-79, continued

"Finally, parity-violation in the neutral currents was discovered at the expected level in electron-nucleon scattering at SLAC in 1978, and after that most physicists took it for granted that the electroweak theory is essentially correct."



Steven Weinberg
"The Making of the Standard Model"
on the occasion of the CERN
30th anniversary celebration of discovey
of neutral currents AND
20th anniversary celebration of
discovery of W/Z bosons
hep-ph/0401010

World Program of Parity-Violating Electron Scattering Expts.

Lab/Expt	target	Q^2 $(GeV/c)^2$	A_{phys} (ppm)	Measures	Status
MIT-Bates					
- SAMPLE	H_2	0.10	7.0	$G^s_M + 0.4G^e_A$	published
- SAMPLE II	D_2	0.10	8.0	$G^s_M + 2.2G^e_A$	published
- SAMPLE III	D_2	0.04	3.0	$G^s_M + 3.4G^e_A$	published
JLAB Hall A					
- HAPPEX	H_2	0.47	15.0	$G^s_E + 0.4G^s_M$	published
- HAPPEX II	H_2	0.11	1.5	$G^s_E + 0.1G^s_M$	2004/2005
- Helium 4	^4He	0.11	10.0	G^s_E	2004/2005
- Lead 208	^{208}Pb	0.01	0.5	neutron skin	2005
JLAB Hall C					
- G^0	H_2, D_2	0.1-1.0	1.0-30.0	G^s_E, G^s_M, G^e_A	2004-2007
- Q_{weak}	H_2	0.03	0.3	Q^p_W	2007
Mainz MAMI					
- A4	H_2, D_2	0.1-0.25	1.0-10.0	G^s_E , G^s_M	published/ running
SLAC					
- E158	H_2, D_2	0.02	0.2	Q^e_W	published/ analyzing

General Experimental Requirements

Statistical considerations require:

- High current (40 - 100 μA), highly polarized (80%) electron beam
- High power (200 - 500 W) liquid H_2/D_2 targets
- High count rate capability
  - integrate signals: SAMPLE, HAPPEX, Q_{weak}, E158
  - specialized particle counting: G^0 , Mainz A4

Systematic considerations (mainly reduction of false asymmetries)

- Helicity reversal
  - rapid: random pattern, 600 Hz (Bates)   30 Hz (JLAB)
  - slow: manual, every few days
- Continuous beam property monitoring; position, angle, energy, intensity
- Active feedback to minimize helicity-correlated beam properties
- High precision electron beam polarimetry
- Elastic/inelastic separation: only interested in elastic scattering

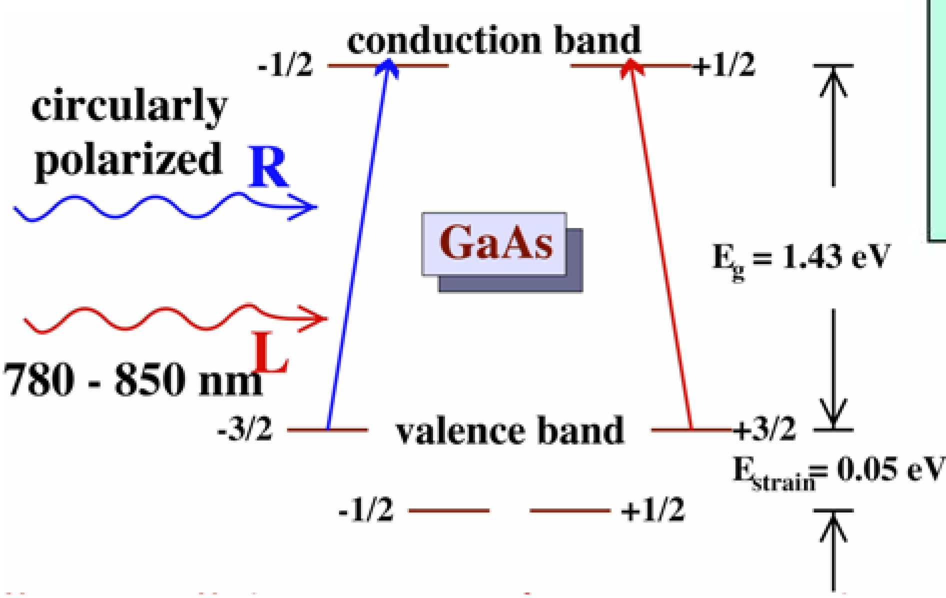
Polarized Electron Sources

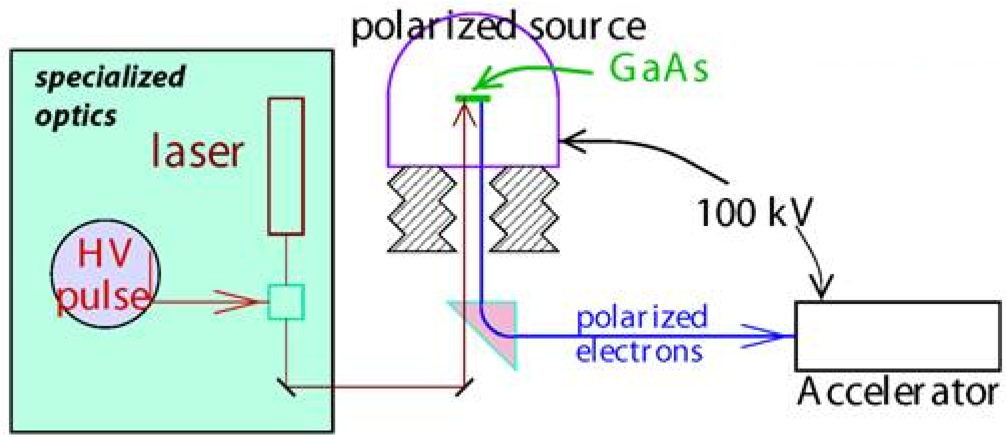
Polarized electron sources are based on photoemission of electrons from GaAs; circularly polarized incident light leads to polarized electrons

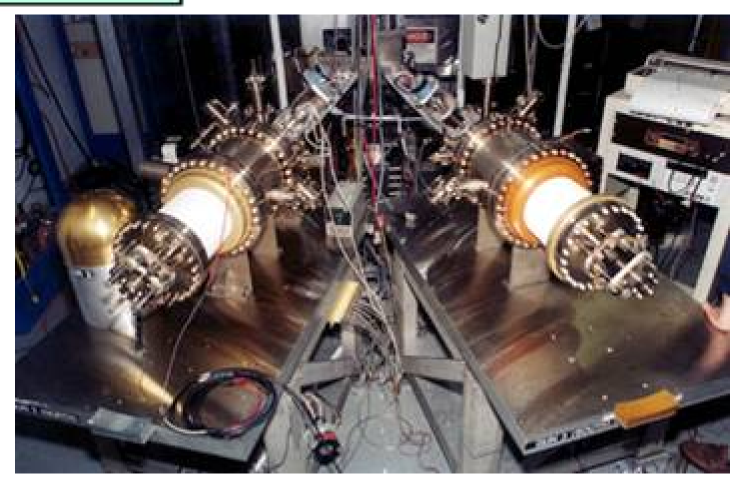
→ "Bulk" GaAs; theoretical maximum P_e = 50%; typical ~ 37%

→ "Strained" GaAs; theoretical maximum P_e = 100%; typical ~ 70-80%

note: "Figure of Merit" in these experiments $\propto I\, P_e^2$

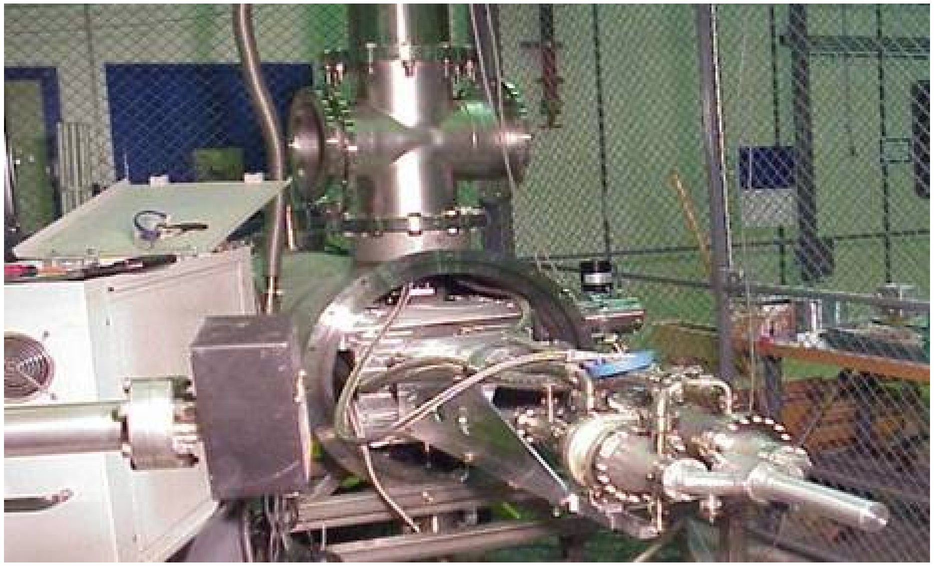


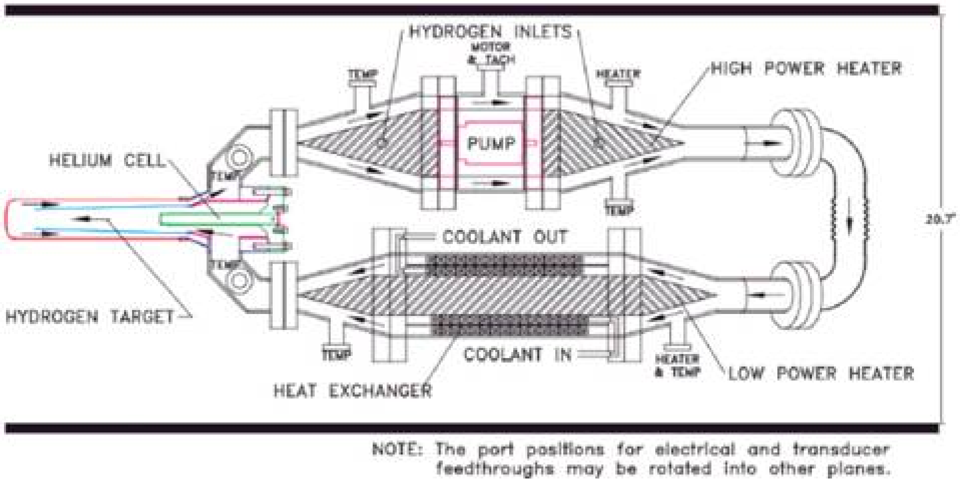


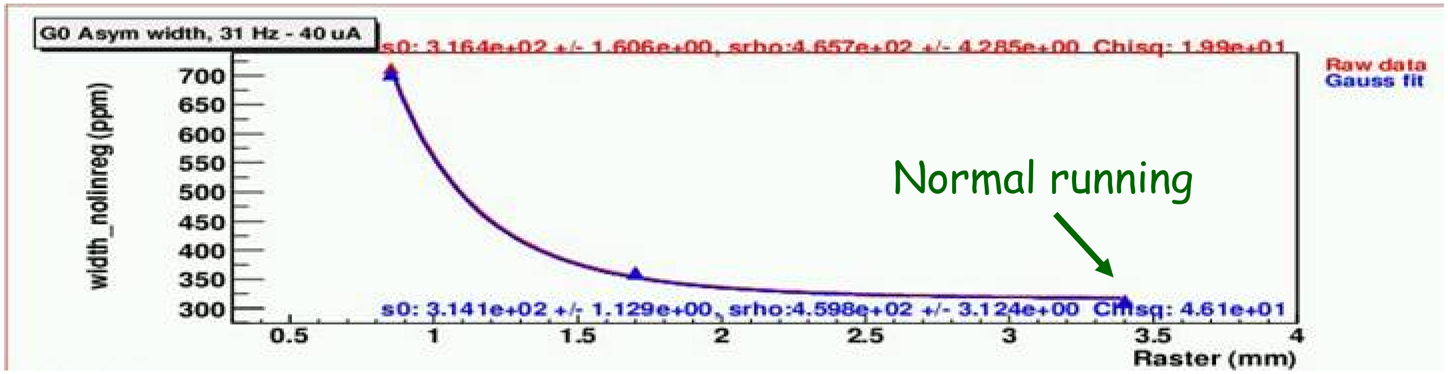


Example of High Power Cryogenic Target: G^0 target

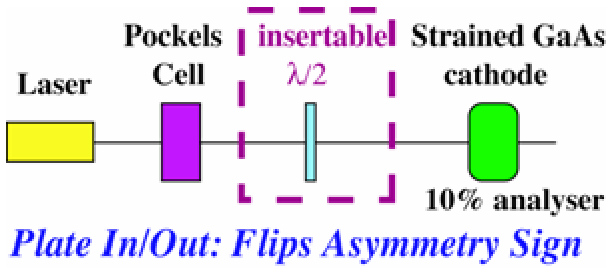
- 20 cm LH_2 cell, 250 W heat load from beam at 40 μA
- High flow rate to minimize target density fluctuations
- Observed target density fluctuations at 40 μA negligible





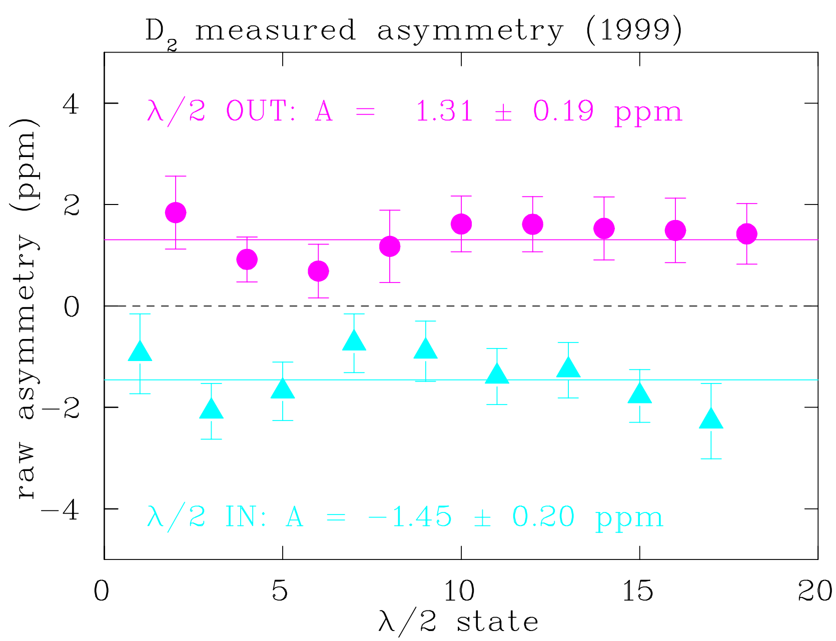


Slow Helicity Reversal

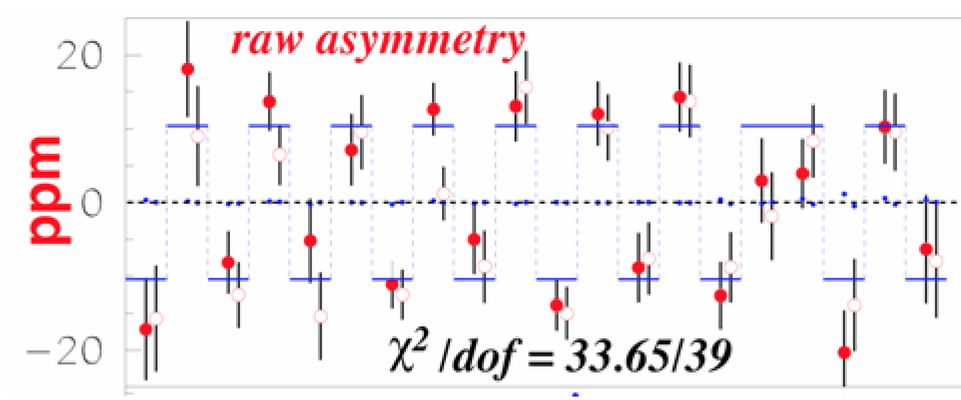


Reverse sign of electron helicity without changing anything else
- insertion of half-wave plate
- if it is a real physics asymmetry, the sign should flip

SAMPLE

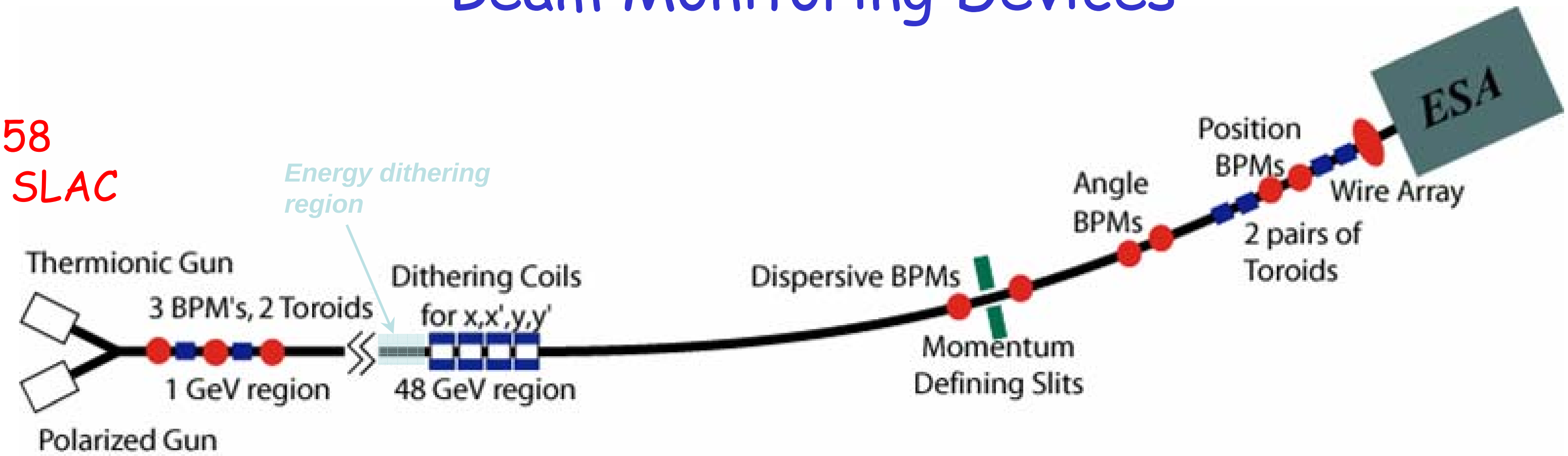


HAPPEX

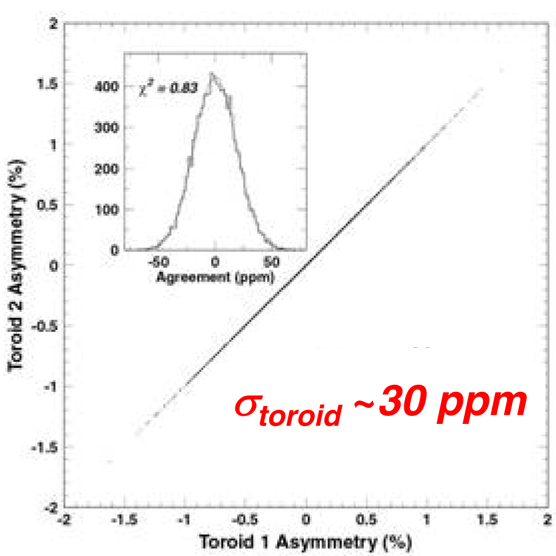


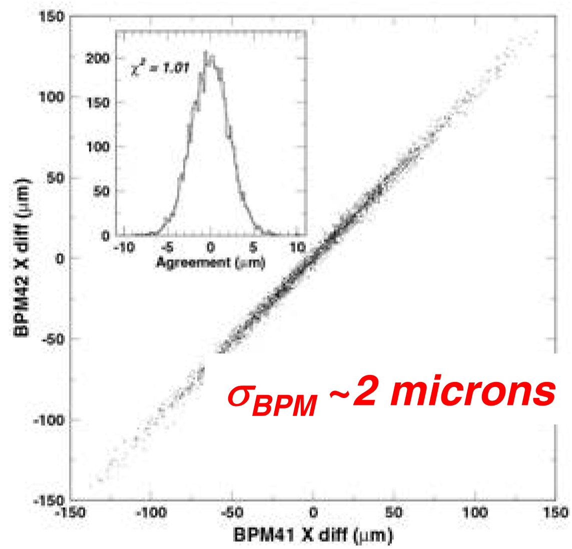
Beam Monitoring Devices

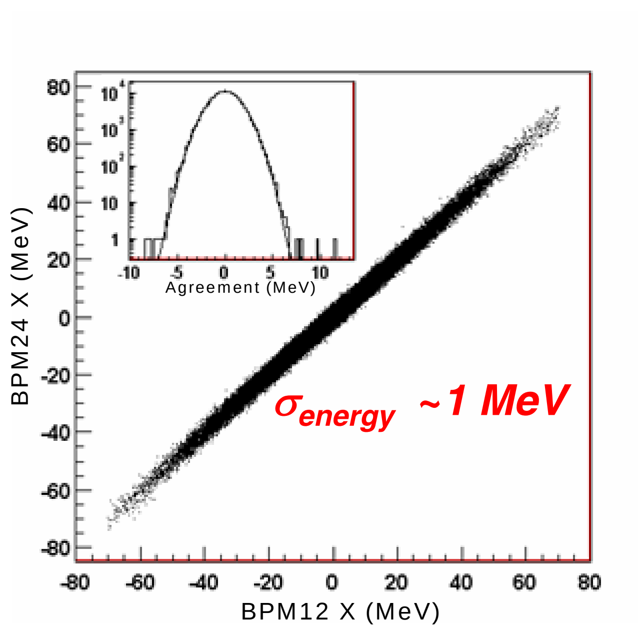
E158
at SLAC



Can compare measurements of neighboring devices to determine the precision of the measurement.







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

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

Typical goals for run-averaged beam properties

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

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

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

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

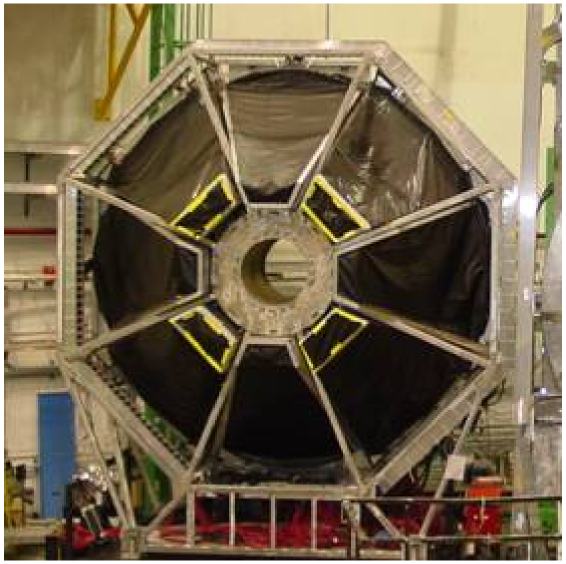
Helicity - Correlated Beam Properties - Sensitivity

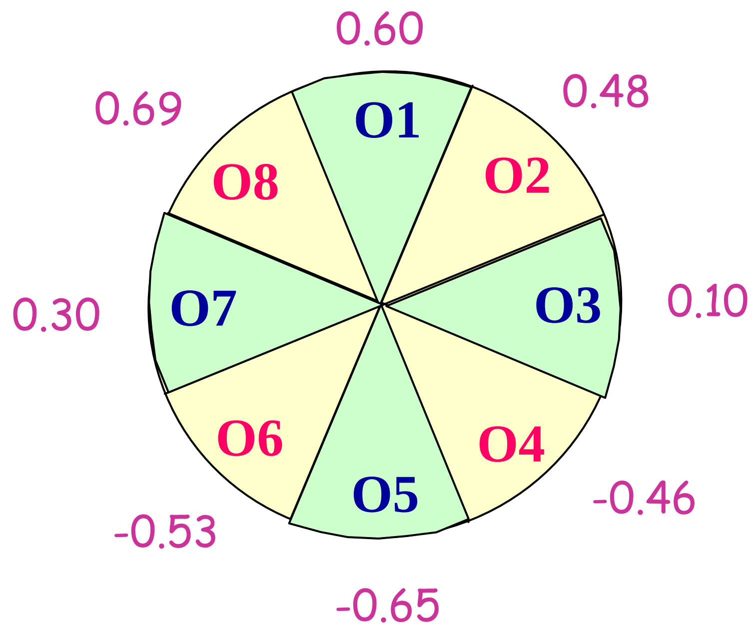
Symmetry of apparatus
→ reduces sensitivity to some helicity-correlated beam properties

Example: Sensitivity to vertical beam motion (y direction)

Measured yield slopes (1/Y) dY/dy (%/mm)

G^0

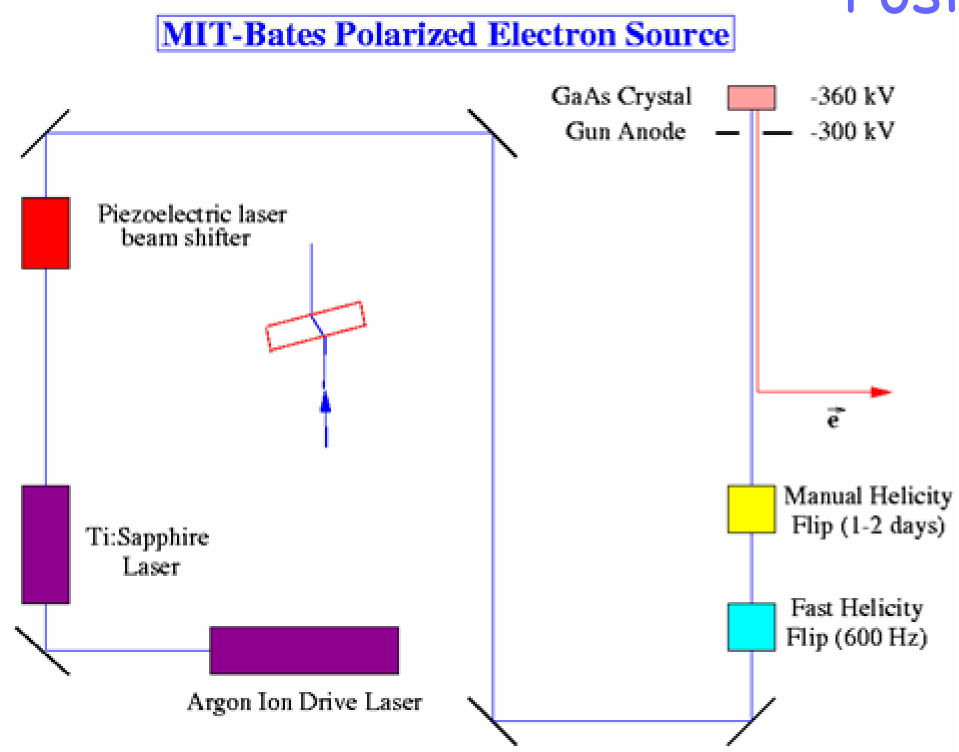




$$\text{Averaging} \rightarrow \frac{dY}{dy} \sim .07\% / \text{mm}$$

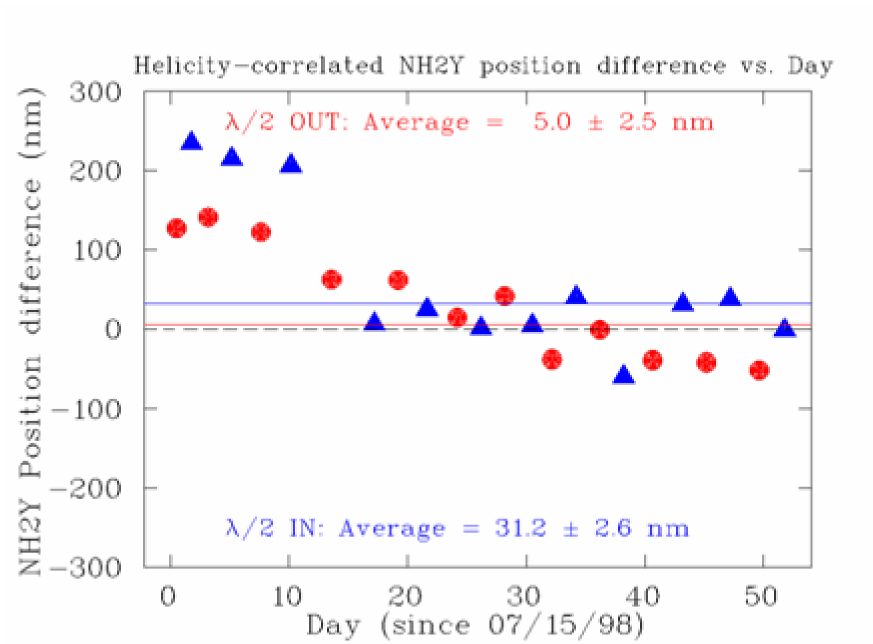
$$A_{corr} = \frac{1}{2Y}\frac{dY}{dy}\Delta y \ \sim \ .01\,\text{ppm} \ \ \text{for desired } \Delta y = 20\text{ nm}$$

Example of Feedback to Reduce Helicity-Correlated Beam Position



Beam position feedback system

Averett et al., NIM **A438**, 246 (1999)



Beam position differences
In the experimental hall

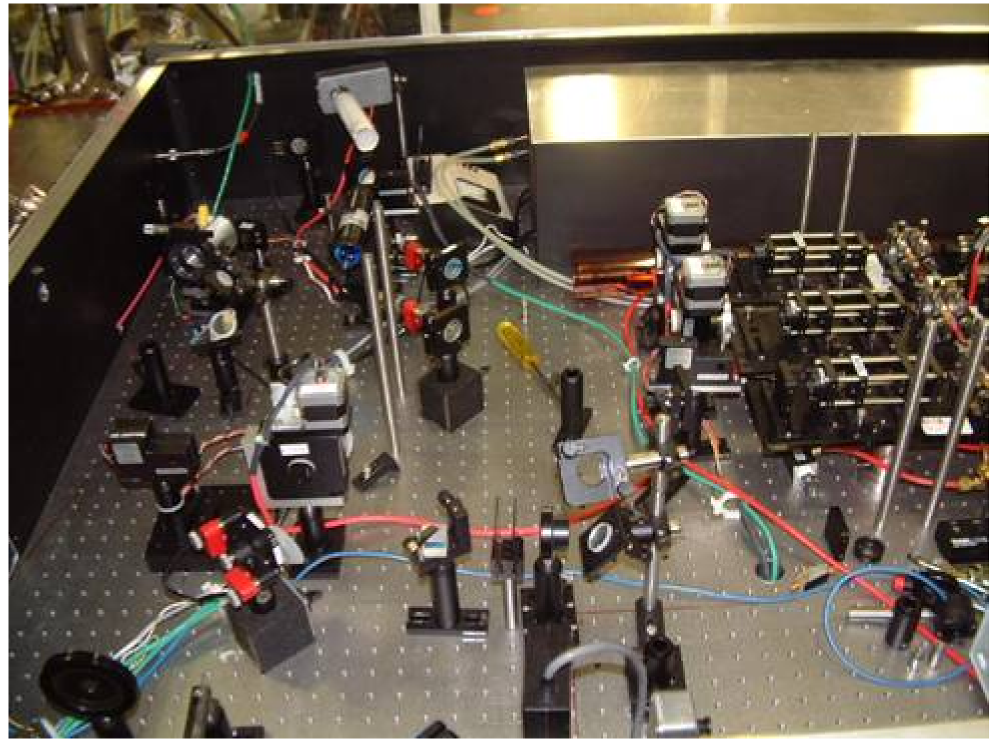
SAMPLE-98

$$A_{corr} = A_{meas} - \frac{1}{2\langle Y \rangle} \sum_{x,\theta,y,\phi,E,I} \frac{\partial Y}{\partial P_i} \Delta P_i$$

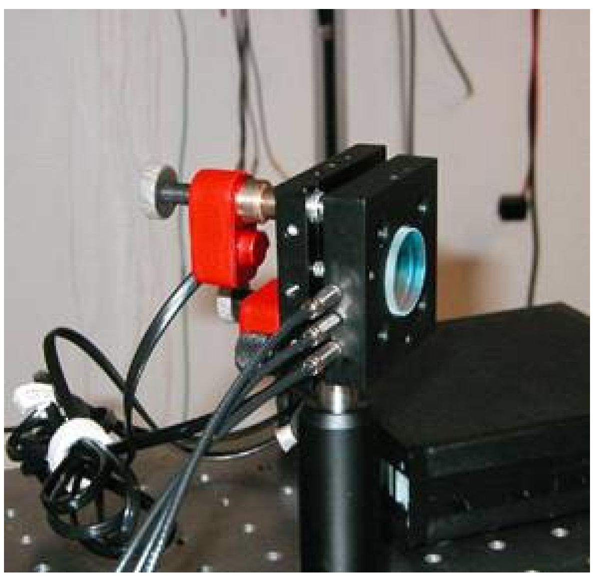
$$-1.14 \pm 0.14 = (-1.08 \pm 0.14) - (0.06 \pm 0.06)\ ppm$$

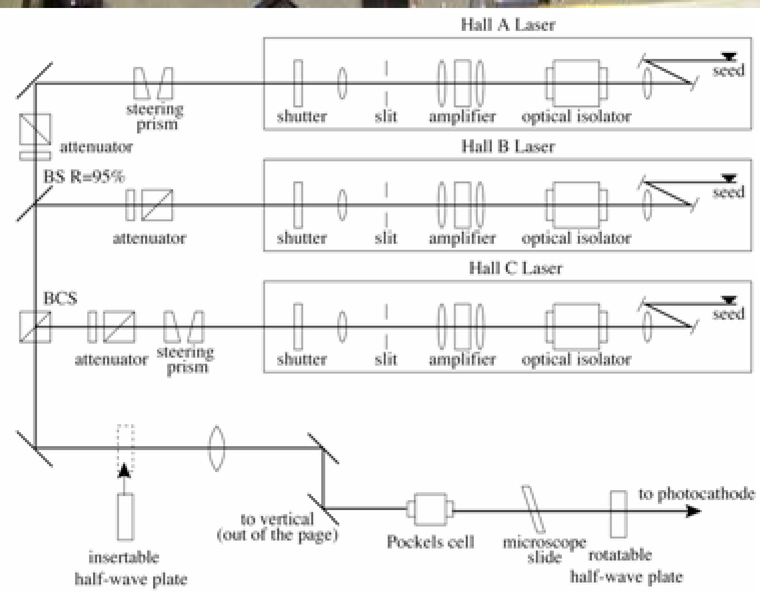
Typical Polarized Source Laser Configuration

Jefferson Lab polarized source laser table



Piezo-electric mirror mount for position feedback





Systematics: From raw asymmetry to physics results

Form raw measured asymmetry from the detector yields:

$$A_{meas} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

Correct for false asymmetries from helicity-correlated beam properties:

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

$$\text{where } \Delta P_i = P_+ - P_-$$

- helicity-correlated beam properties
- deadtime corrections

Correct for background and its asymmetry:

$$A_{sig} = \frac{A_{corr} - A_{back}\ f_{back}}{f_{sig}}$$

- background dilution factor correction

Correct for beam polarization and radiative corrections:

$$A_{phys} = \frac{A_{corr}}{P_{beam}\ R_{rad}}$$

- electron beam polarization
- electromagnetic radiative corrections

Correct for measured Q^2 and EM form factors:

$$A_{phys} \propto Q^2\ f(G_E^\gamma, G_M^\gamma, G_E^s, G_M^s)$$

- $\langle Q^2 \rangle$ determination
- electromagnetic form factors

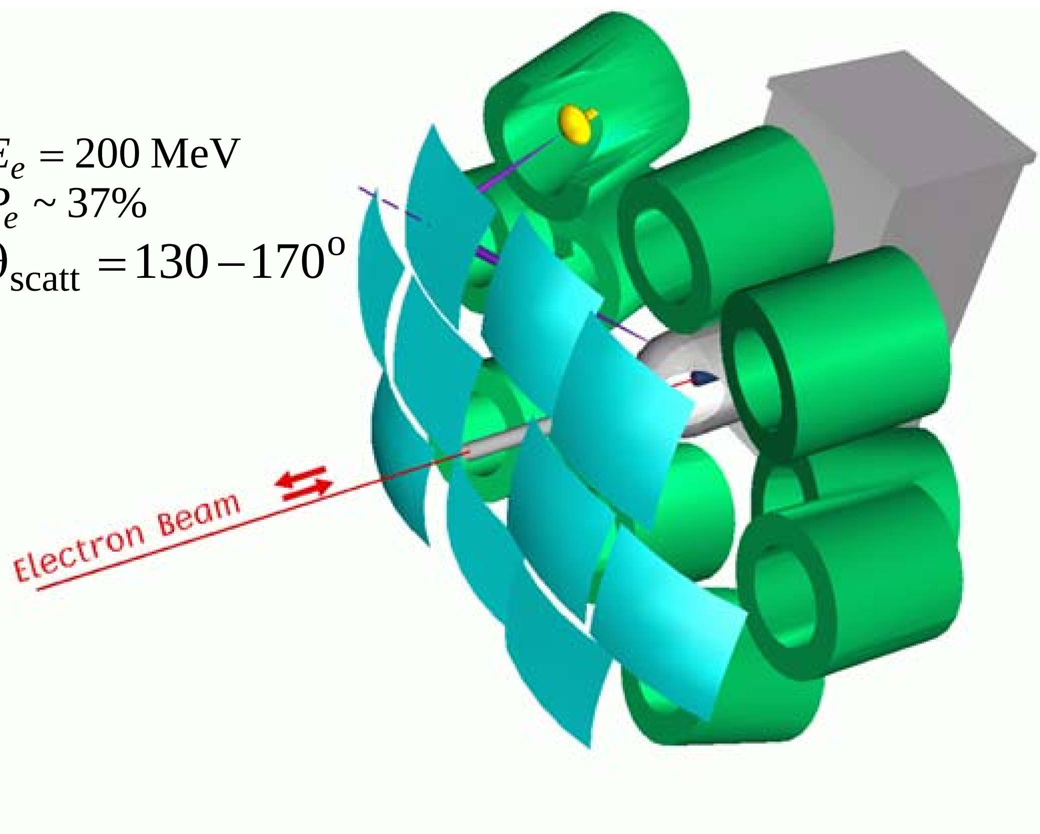
The SAMPLE Experiment:
at MIT-Bates LinearAccelerator Center in Middleton, MA
up to 1 GeV pulsed electron beams

The SAMPLE Experiment at MIT-Bates Linac

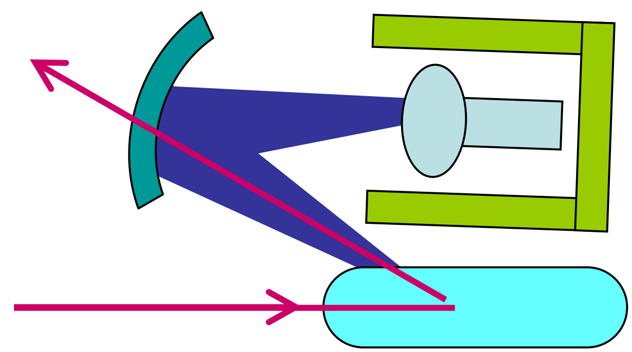
Determines G_M^s and G_A^e at low Q^2 = 0.04, 0.1 $(GeV/c)^2$

Back angles: $\vec{e} + p$ (elastic) $\vec{e} + d$ (quasielastic)

$E_e = 200$ MeV
$P_e \sim 37\%$
$\theta_{scatt} = 130 - 170^o$

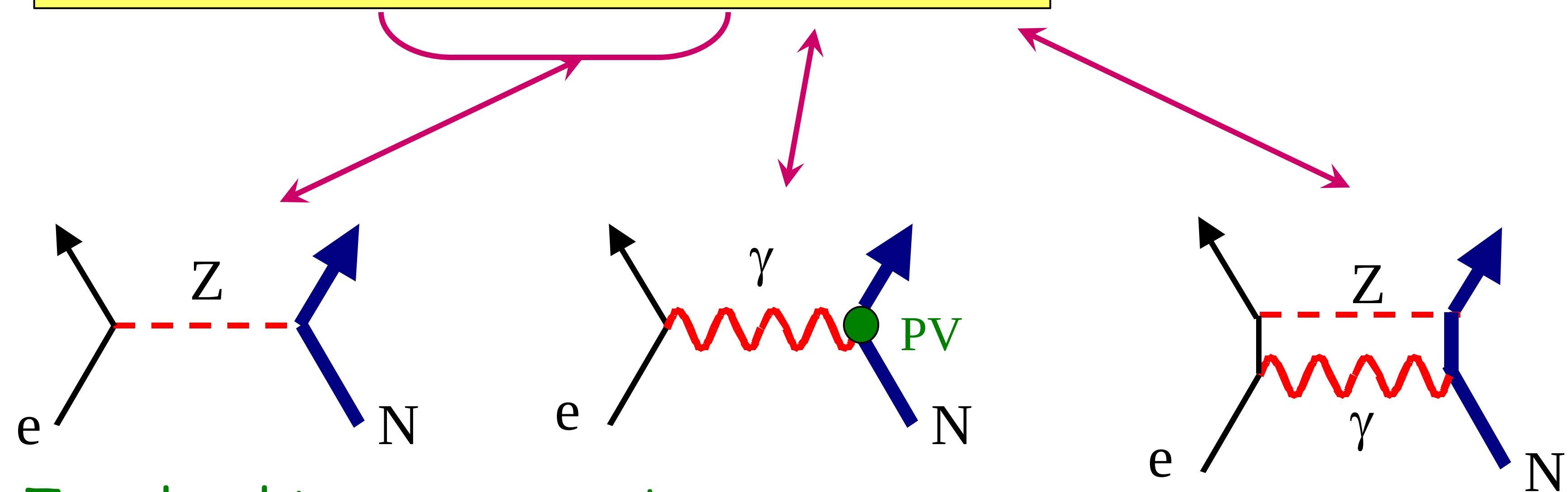


- Large solid angle (1.4 sR) air Cerenkov detector
- 40 cm liquid hydrogen/deuterium target
- Beam time structure: 25 μsec width at 600 Hz
- Signals in phototubes are integrated over the 25 μsec beam pulse



Axial Form Factor and Anapole Moment

$$G_A^e(Q^2) = -G_A(Q^2) + \Delta s + \eta F_A + R^e$$



Tree level term:
multiplied by
$g^V_e = 1 - 4\sin^2\theta_W$

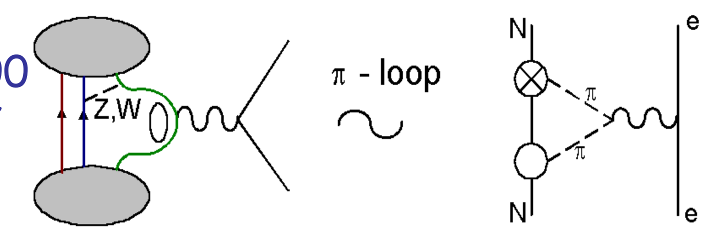
Anapole term:
PV electromagnetic moment, arises from weak interaction between quarks

Electroweak radiative correction

Calculations of G_A^e or anapole moment

Musolf, Holstein Phys. Lett. B **242**, 461 (1990)
Zhu, Puglia, Holstein, Ramsey-Musolf PRD **62**, 033008 (2000
Maekawa, Veiga, and van Kolck, Phys. Lett. **B488** (2000) 167
D. Riska, Nucl. Phys. A**678**, 79 (2000)

example of contribution to anapole:



SAMPLE Experiment Summary

In quasi-static approximation for deuterium quasi-elastic scattering:

$$A_d = \frac{\sigma_p A_p + \sigma_n A_n}{\sigma_d}$$

(1998) SAMPLE I: $\vec{e}$-p at 200 MeV [Q^2 = 0.1 $(GeV/c)^2$]

$$A_p = -5.56 + 3.37 G_M^s + 1.54 G_A^{e\,(T=1)} \quad ppm$$

(1999) SAMPLE II: quasielastic $\vec{e}$-d at 200 MeV

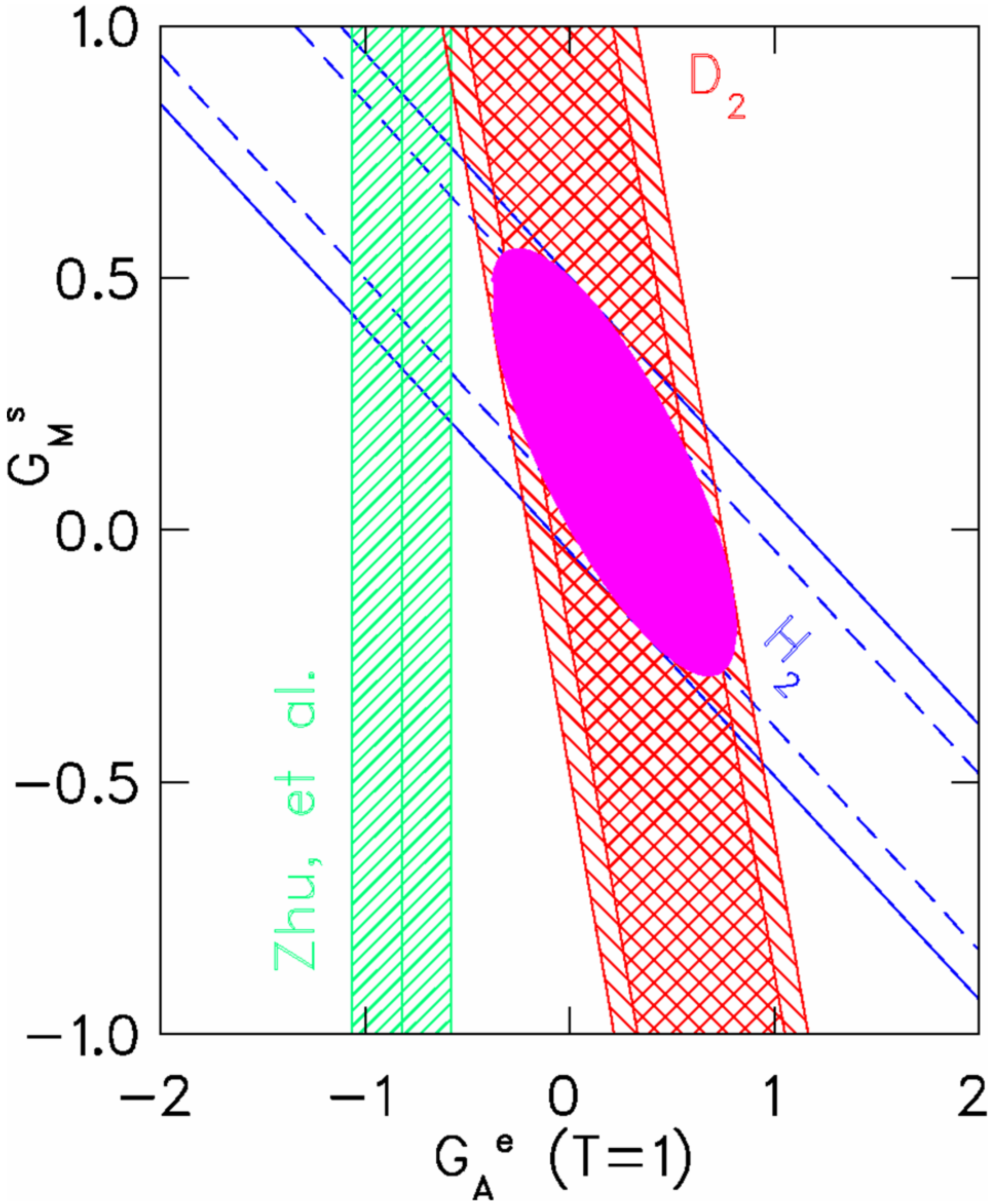
$$A_d = -7.06 + 0.72 G_M^s + 1.66 G_A^{e\,(T=1)} \quad ppm$$

(2001) SAMPLE III: QE $\vec{e}$-d at 120 MeV [Q^2 = 0.03 $(GeV/c)^2$]

$$A_d = -2.14 + 0.27 G_M^s + 0.76 G_A^{e\,(T=1)} \quad ppm$$

"Old" SAMPLE Results

R. Hasty et al., Science 290, 2117 (2000).



at Q^2=0.1 (GeV/c)^2

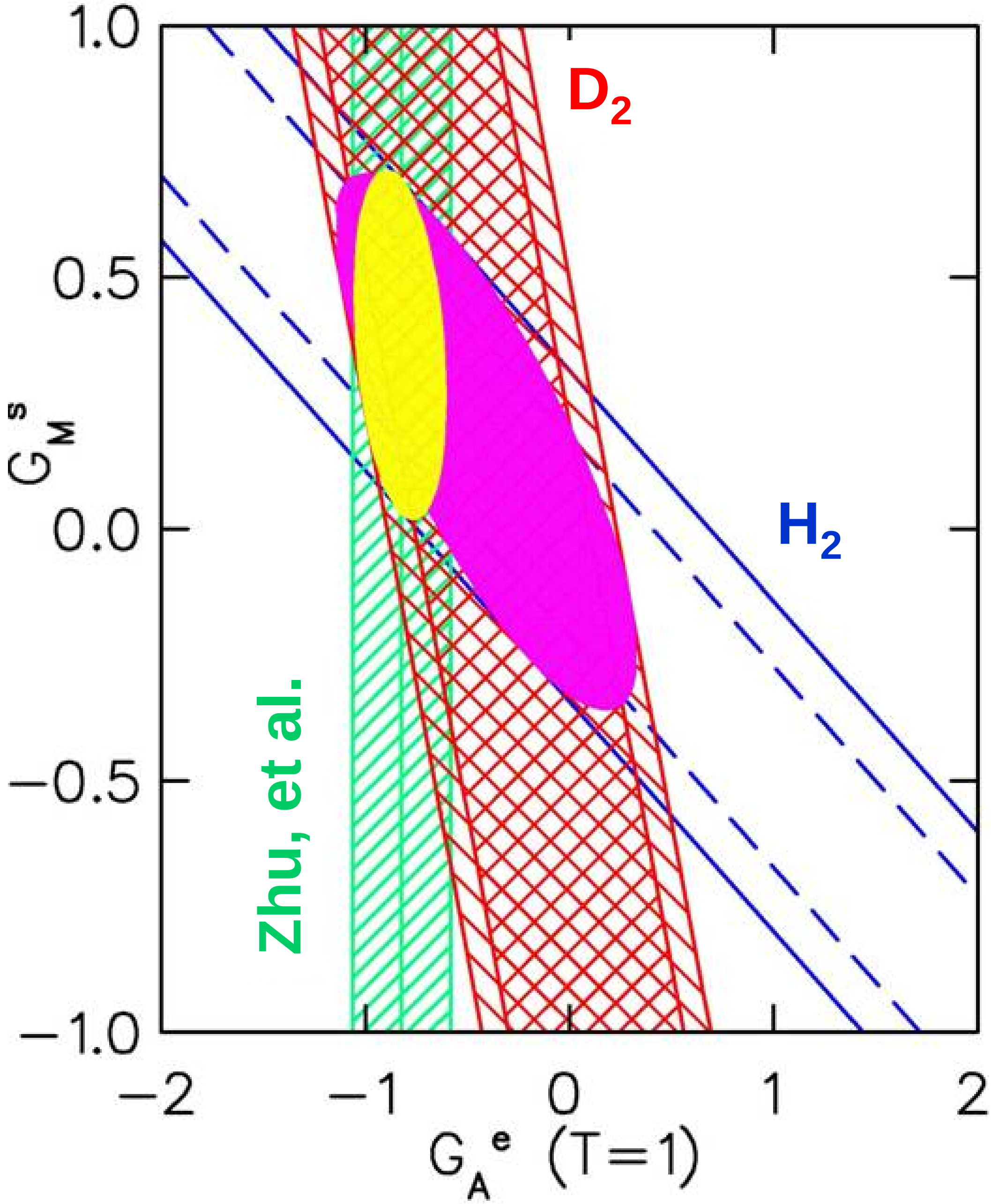
- *s*-quarks contribute less than 5% (1σ) to the proton's magnetic moment.
- Apparent discrepancy between theory and experiment for G_A^e

BUT further work ocurred:

200 MeV update 2003:
Improved EM radiative corr.
Improved acceptance model
Correction for π background

125 MeV (Q^2=0.03 GeV^2):
no π background
similar sensitivity to G_A^e(T=1)

Summary of Results from 200 MeV data



Using Zhu et al. for $G_A^e(T=1)$

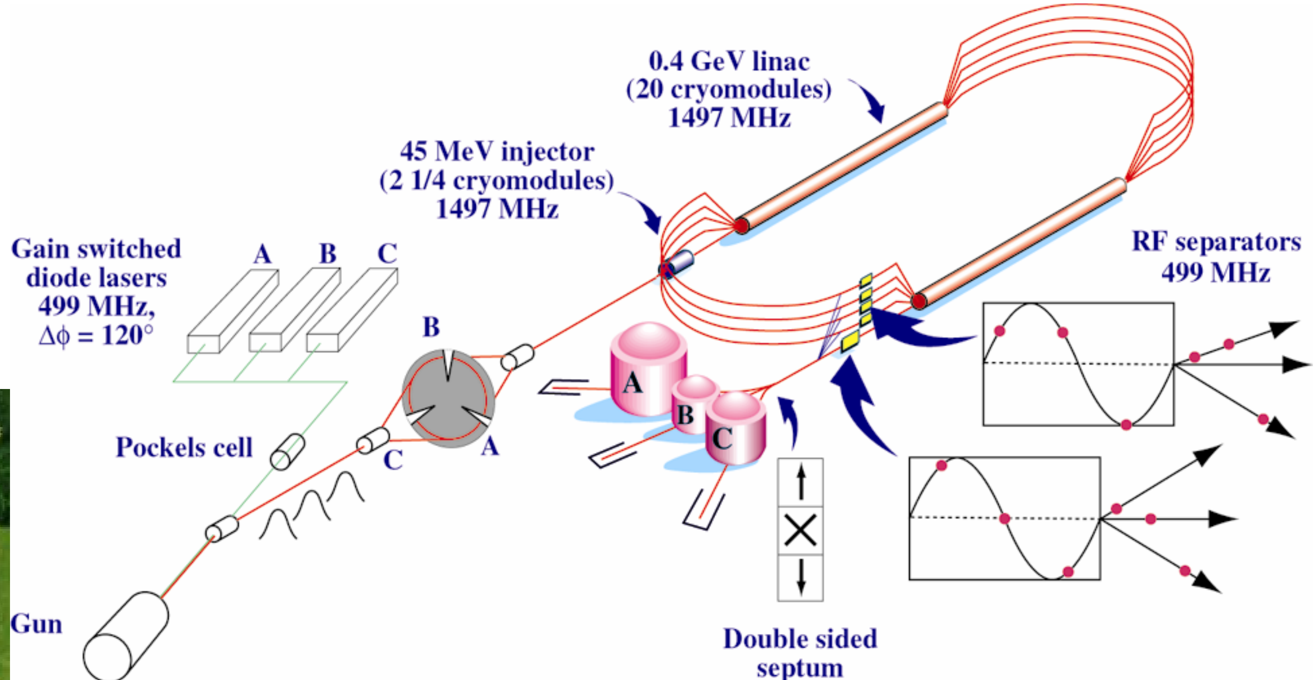
$$G_M^s = 0.37 \pm 0.20 \pm 0.26 \pm 0.07$$

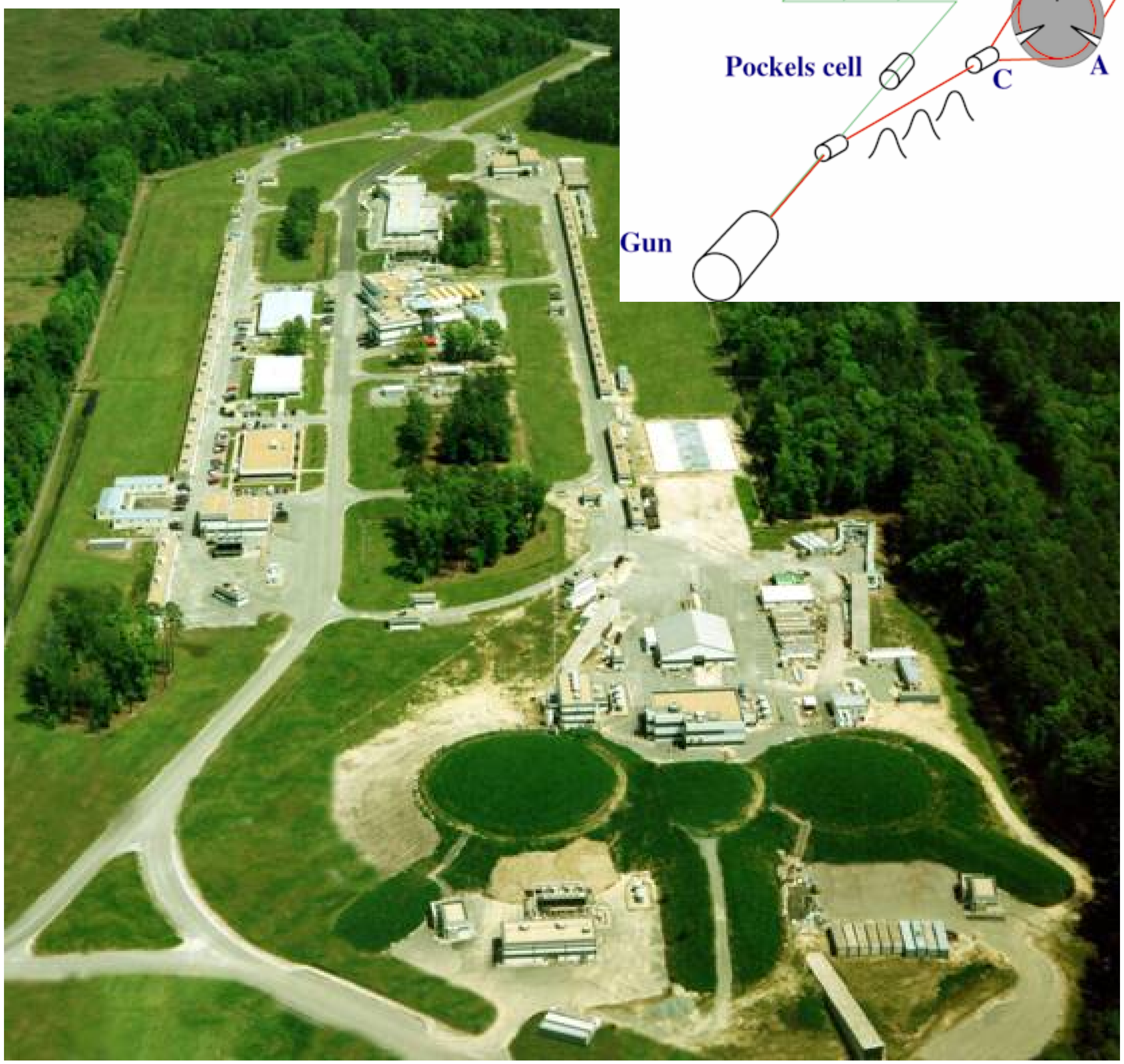
Combined D_2/H_2 at 200 MeV

$$G_M^s = 0.23 \pm 0.36 \pm 0.40$$

$$G_A^e(T=1) = -0.53 \pm 0.57 \pm 0.50$$

D.T. Spayde *etal*, PLB 583 (2004) 79



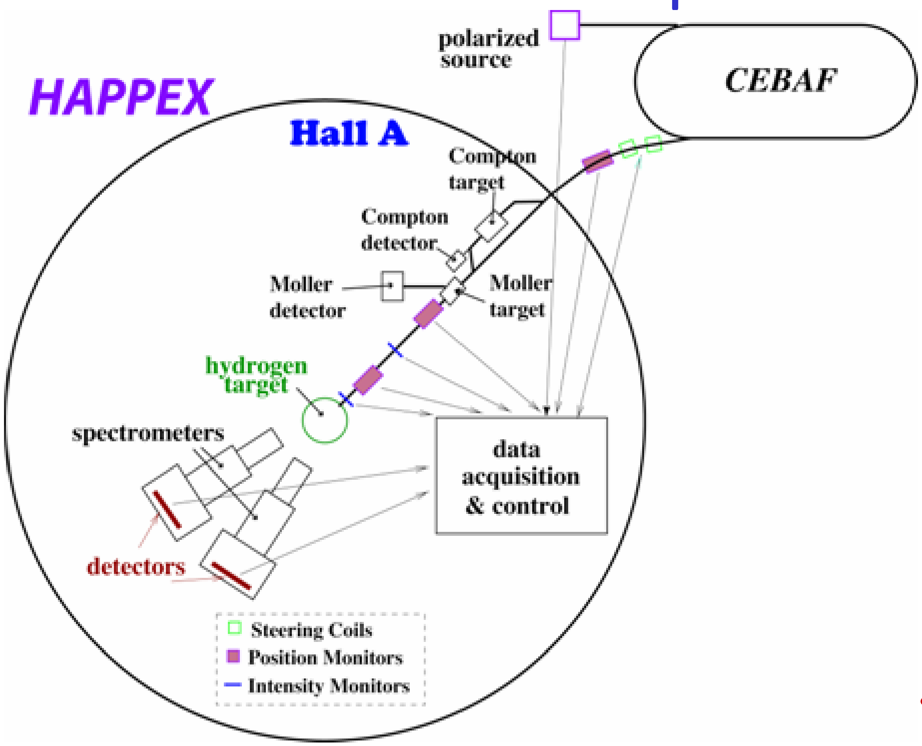


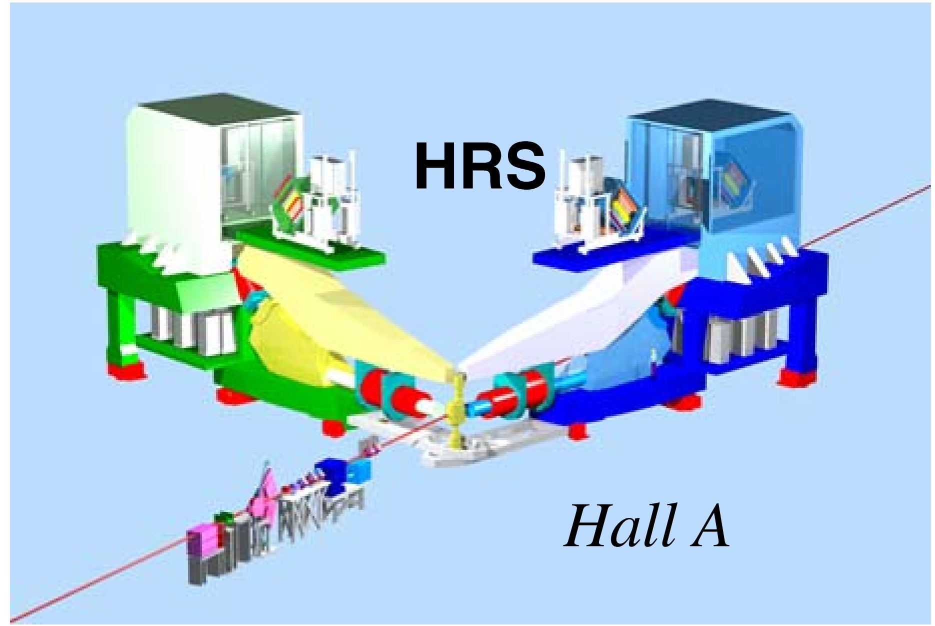
Jefferson Lab in Newport News, Virginia

CEBAF: CW electron accelerator, energies up to 6 GeV

HAPPEX, G^0

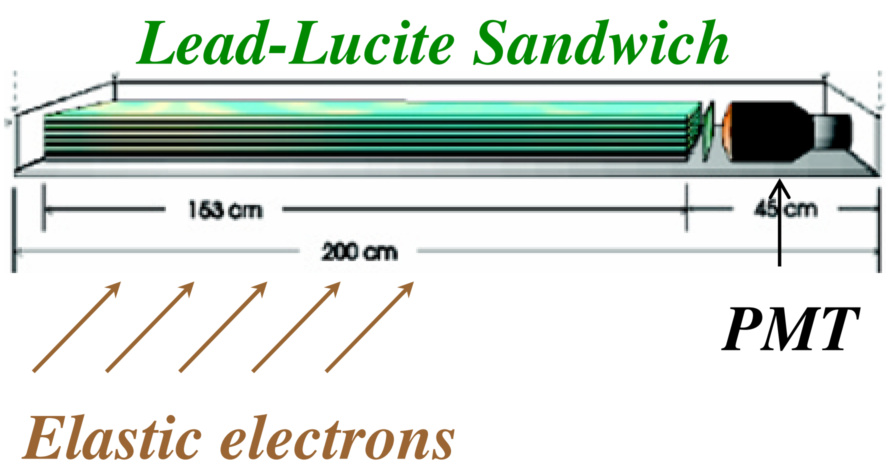
The HAPPEX Experiment in Hall A at Jefferson Lab





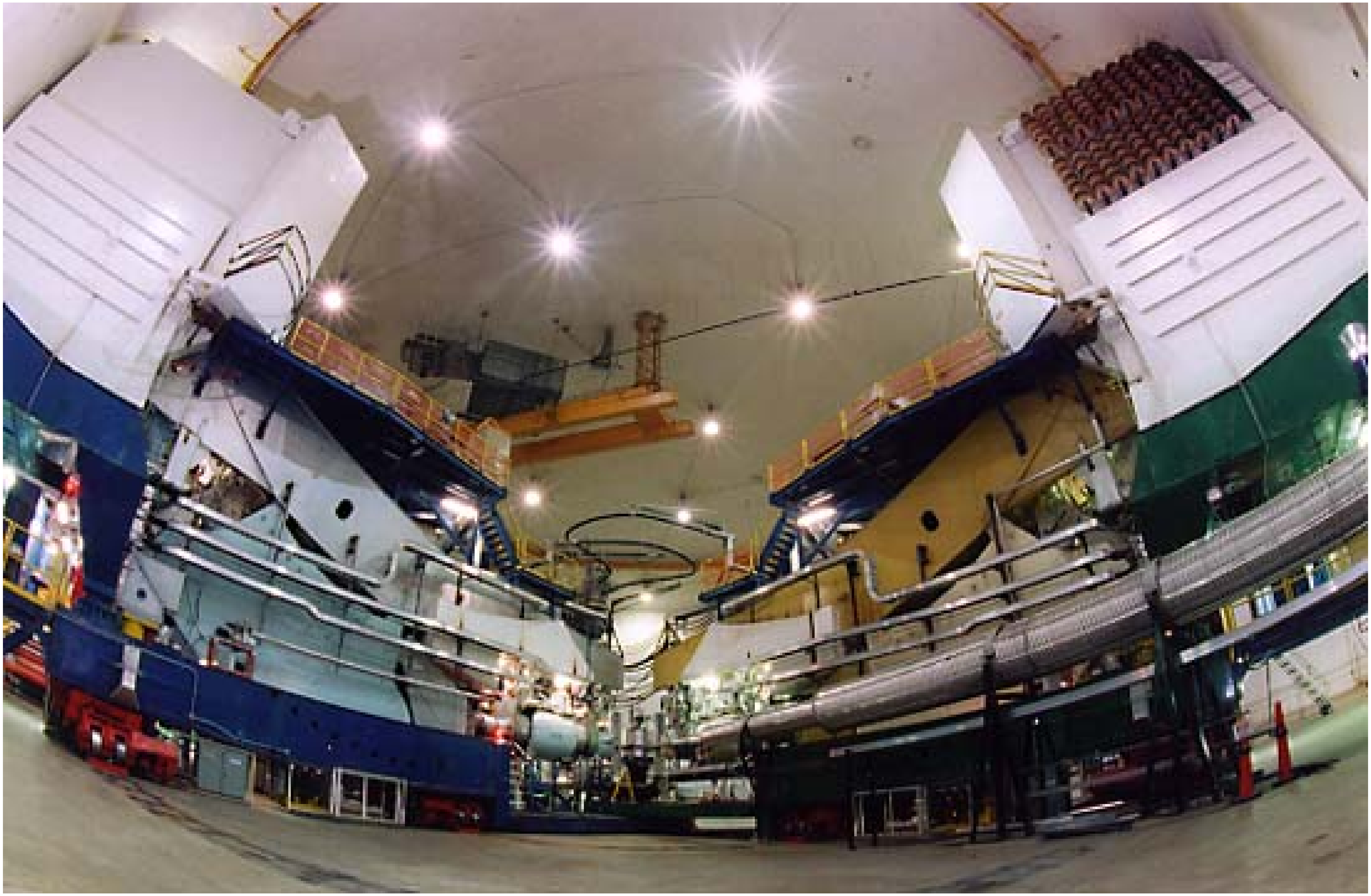
- Forward angle $\vec{e}$ - p elastic scattering
- E = 3.335 GeV (θ_{lab} = 12.5°) Q^2 = 0.47 (GeV/c)^2
- Strangeness form factor combination measured:

$$G_E^s + 0.39 G_M^s \quad \text{at } Q^2 = 0.47\ (\text{GeV/c})^2$$

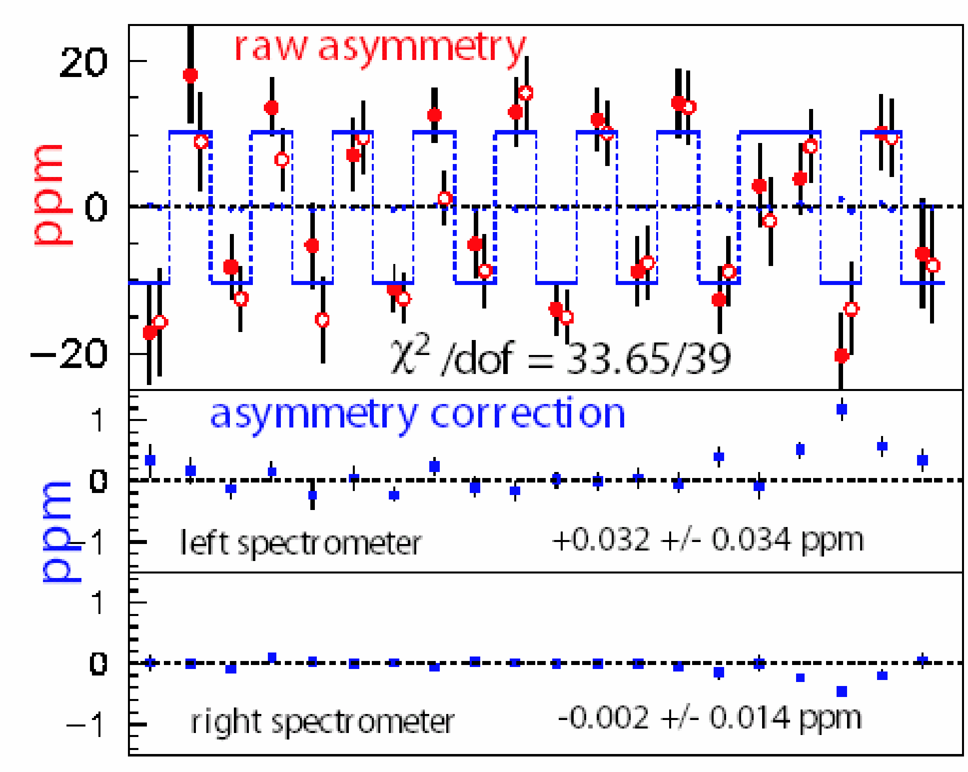


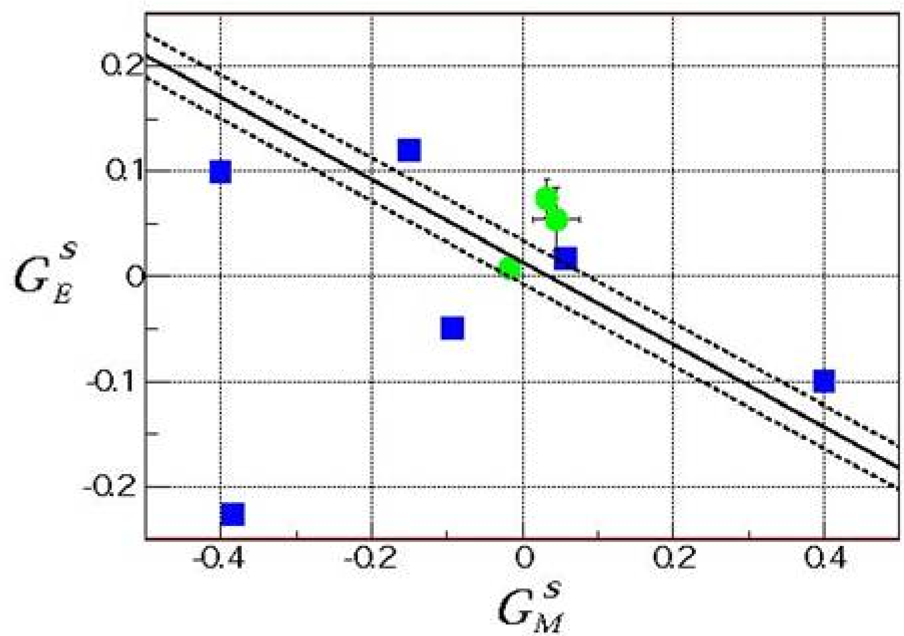
- Detection: integrate signal in special focal plane calorimeter of Hall A high resolution spectrometers
- 1998 run: I ~ 100 uA P ~ 40% (bulk GaAs)
- 1999 run: I ~ 40 uA P ~ 70% (strained GaAs)

Hall A High Resolution Spectrometers



HAPPEX I Results





HAPPEX requires that G_E^s and G_M^s have opposite sign

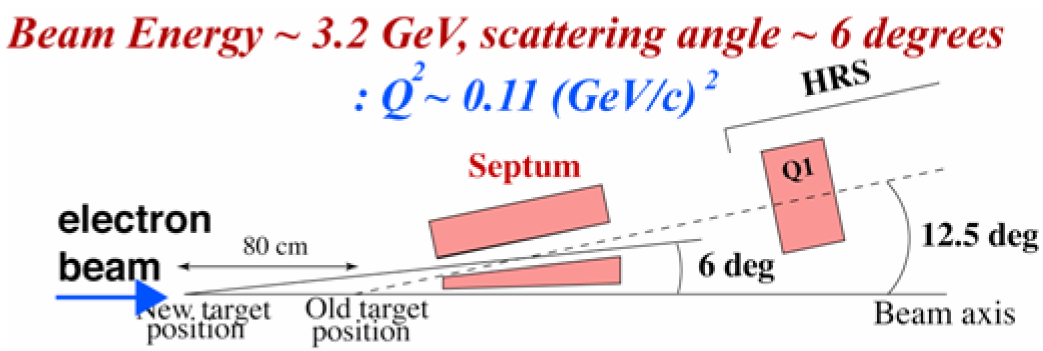
$$A_p = -14.92 \pm 0.98 \pm 0.56 \text{ ppm}$$

$$G_E^s + 0.39 G_M^s = 0.014 \pm 0.020 \pm 0.010$$

$$Q^2 = 0.47 \, (\text{GeV/c})^2$$

K. Aniol, PRL 82 (1999), ibid, PLB509 (2001) 211, & submitted to PRC 2004, nucl-ex/0402004

What's next? → HAPPEX II and ^{4}He



→ New Hall A septum magnets allow access to scattered electrons at 6°

HAPPEX II: JLAB Experiment 99-115 (Kumar, Lhullier)

- Elastic $\vec{e}$ - p at E = 3.2 GeV $\theta_{lab} = 6°$ $Q^2 = 0.11\ (GeV/c)^2$
- A = -1.7 ppm
- Will determine the linear combination:

$$G_E^s + 0.09\, G_M^s$$

HAPPEX ^{4}He: JLAB Experiment 00-114 (Armstrong, Michaels)

- Elastic $\vec{e}$ - ^{4}He at E = 3.2 GeV $\theta_{lab} = 6°$ Q^2 =0.11 (GeV/c)2
- A = 8.4 ppm
- Determines: G_E^s since $A_{PV} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[4\sin^2\theta_W + \frac{2G_E^s}{(G_E^p + G_E^n)}\right]$ for ^{4}He

The G^0 Experiment at Jefferson Lab

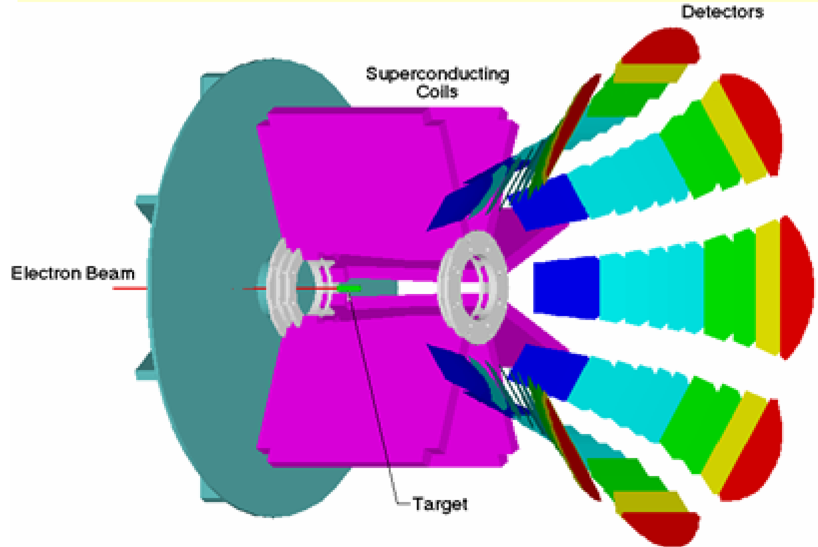
- Forward and backward angle PV $\vec{e}$-p elastic and $\vec{e}$-d (quasielastic) in JLab Hall C

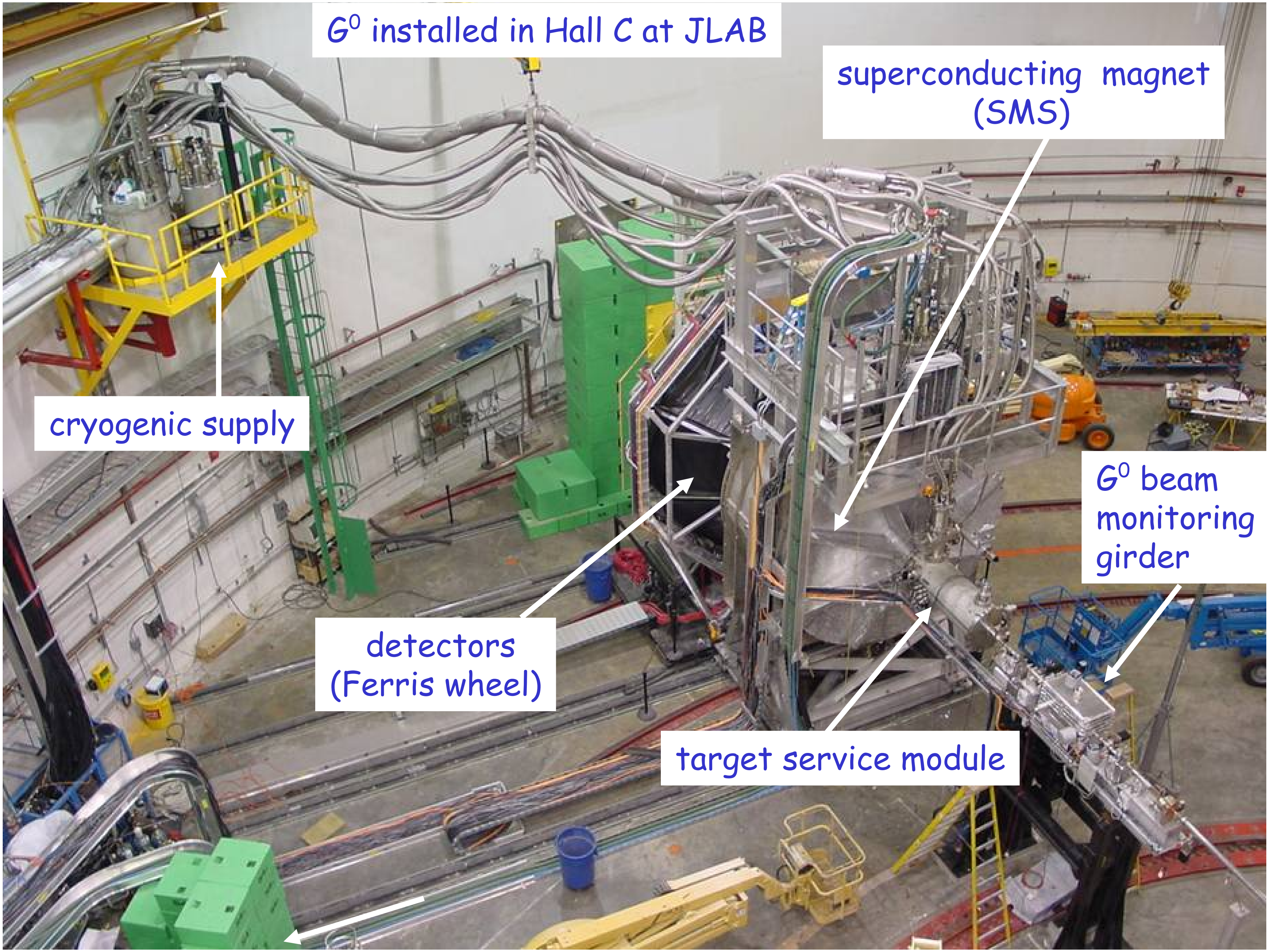
- superconducting toroidal magnet

- scattered particles detected in segmented scintillator arrays in spectrometer focal plane

- custom electronics count and process scattered particles at > 1 MHz

G_E^s, G_M^s and G_A^e separated over range $Q^2 \sim 0.1 - 1.0$ (GeV/c)^2




G0 installed in Hall C at JLAB
superconducting magnet (SMS)
cryogenic supply
G0 beam monitoring girder
detectors (Ferris wheel)
target service module

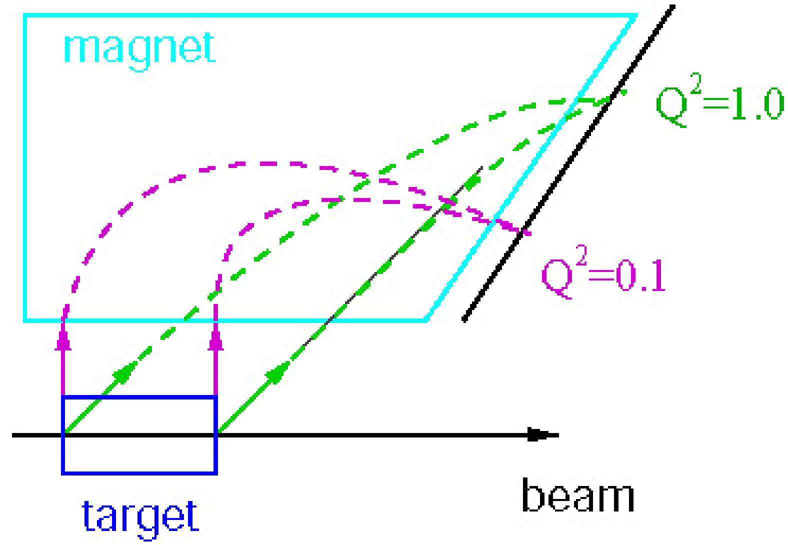
G0 Forward Angle Detection Scheme

Detect scattered Protons:

Magnet sorts protons by Q^2 at one setting

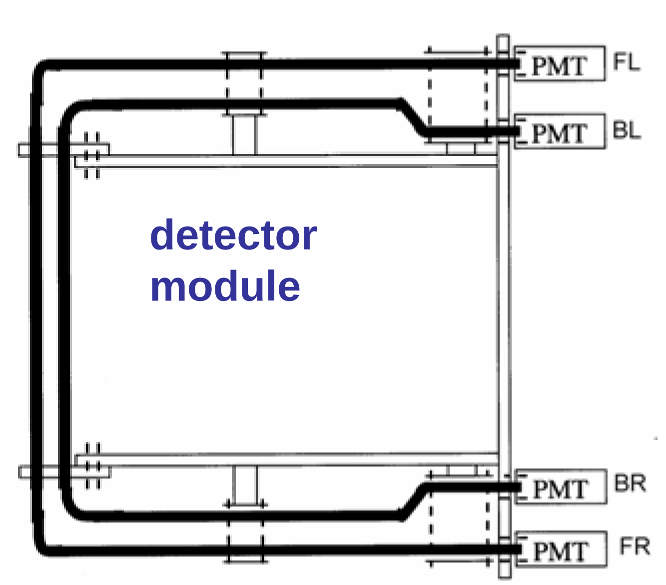
Beam bunches 32 nsec apart

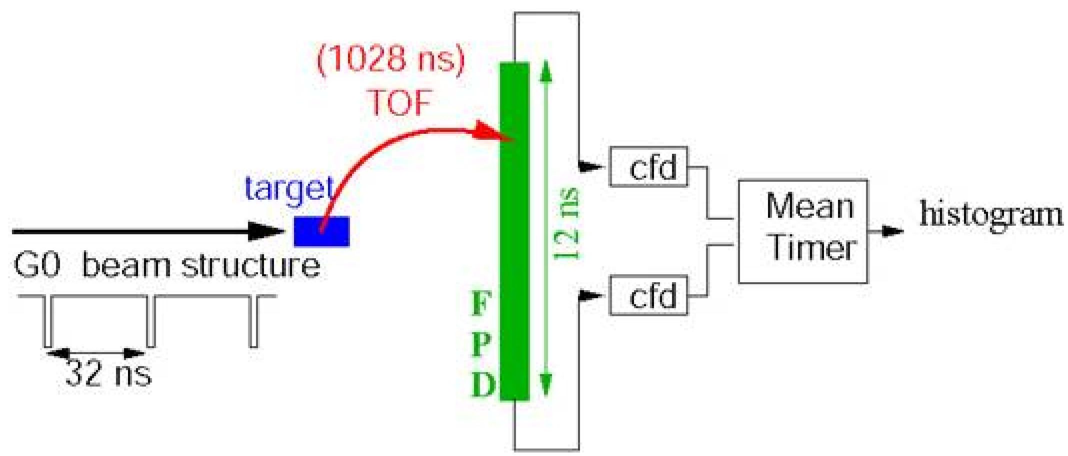
Flight time separates p and π^+



Beam spin flipped every 30 ms: $+ - - +$

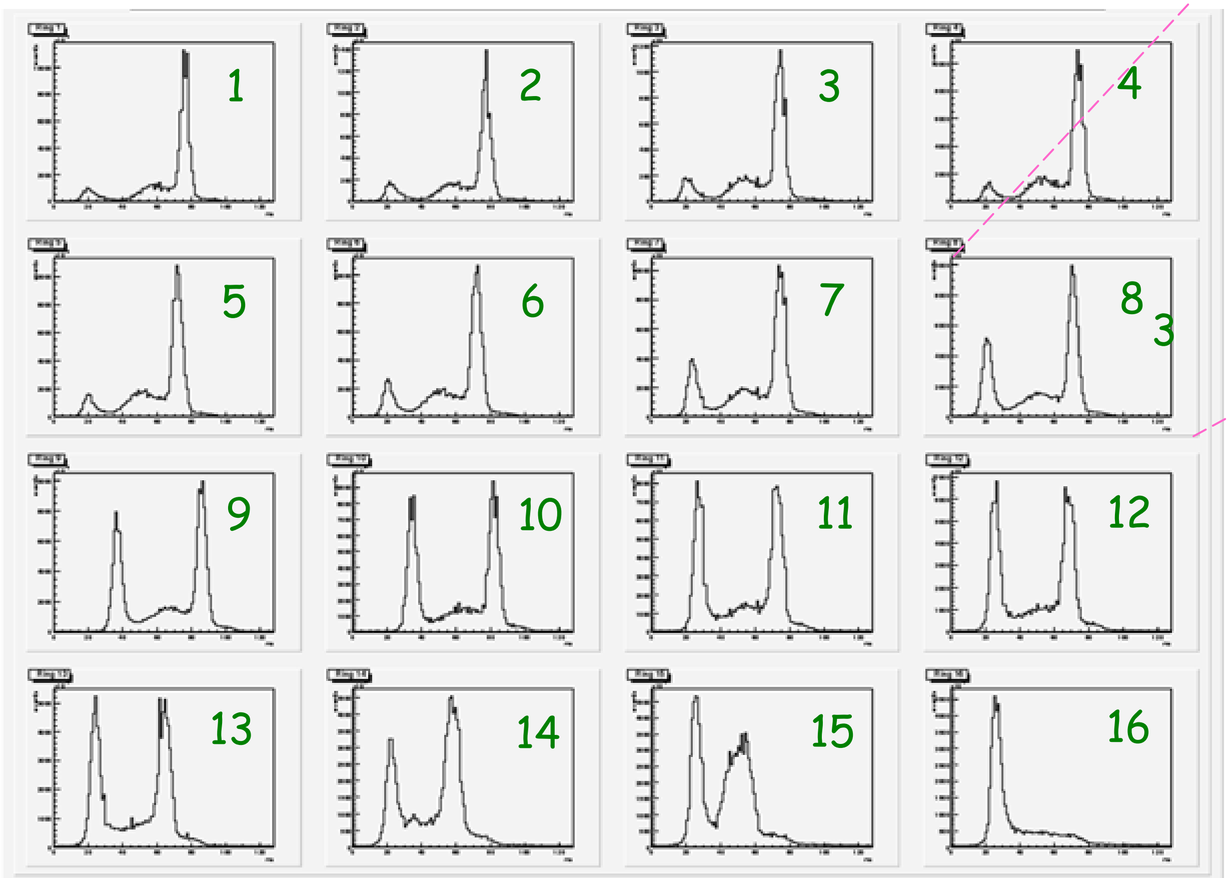
$$A = \frac{Y_1 + Y_4 - Y_2 - Y_3}{\sum Y_i}$$

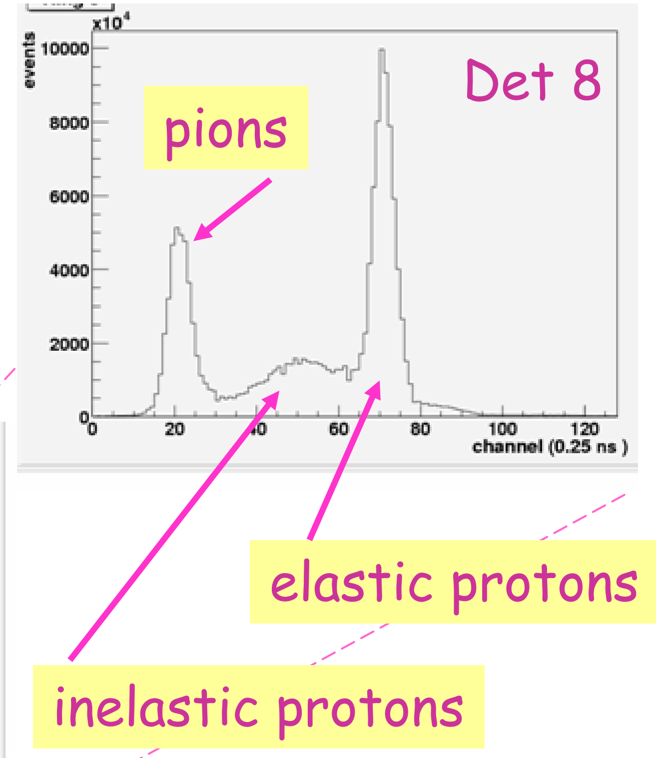




Time of Flight Spectra from G^0 Commissioning Run

Time of flight spectra for all
16 detectors of a single octant
- recorded every 33 msec





G^0 Backward Angle Measurement

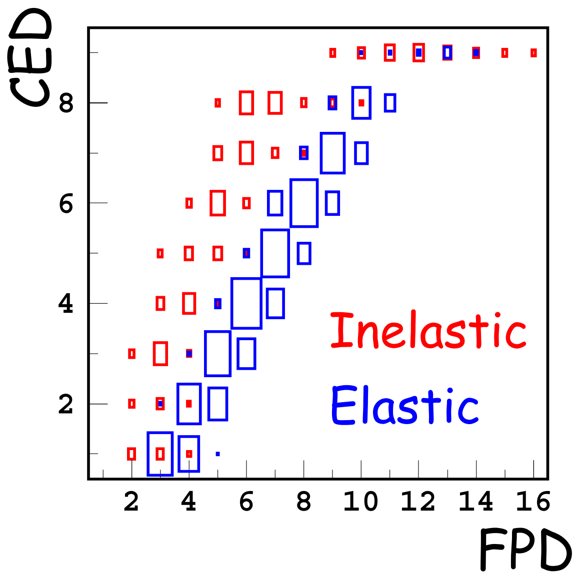
- Detect scattered electrons at θ_e ~ 110°
- At back angles Q^2 only has small variation in G^0 acceptance

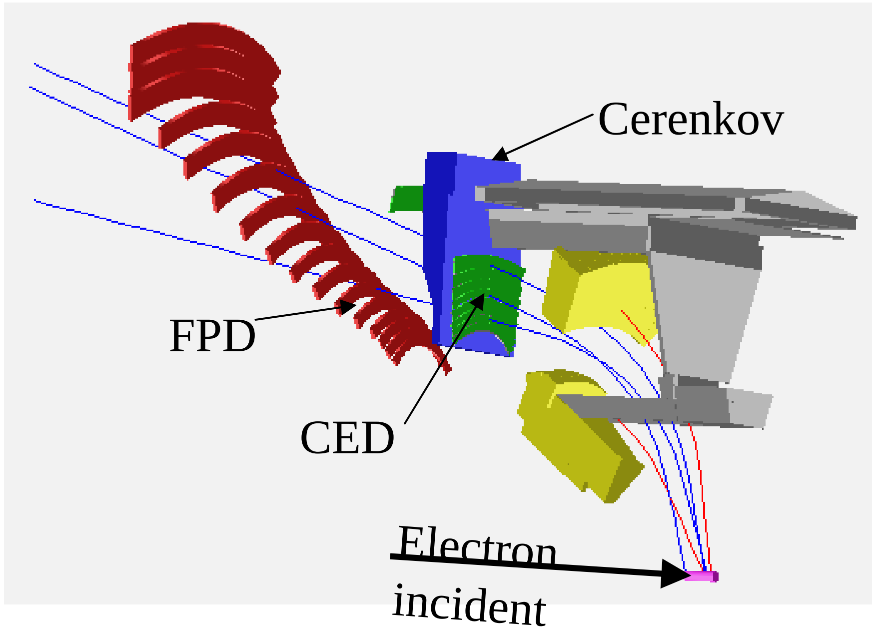
→ Need separate runs at E = 424, 576, 799 MeV
for Q^2 = 0.3, 0.5, 0.8 $(GeV/c)^2$
for both LH_2 and LD_2 targets
(total of 6 runs x 700 hours)

Requires additional detectors:

- Cryostat Exit Detectors (CED) to separate elastic and inelastic electrons
- Cerenkov detector for pion rejection (primarily for LD_2 target)

CED/FPD coincidences at Q^2 = 0.3 GeV^2 →

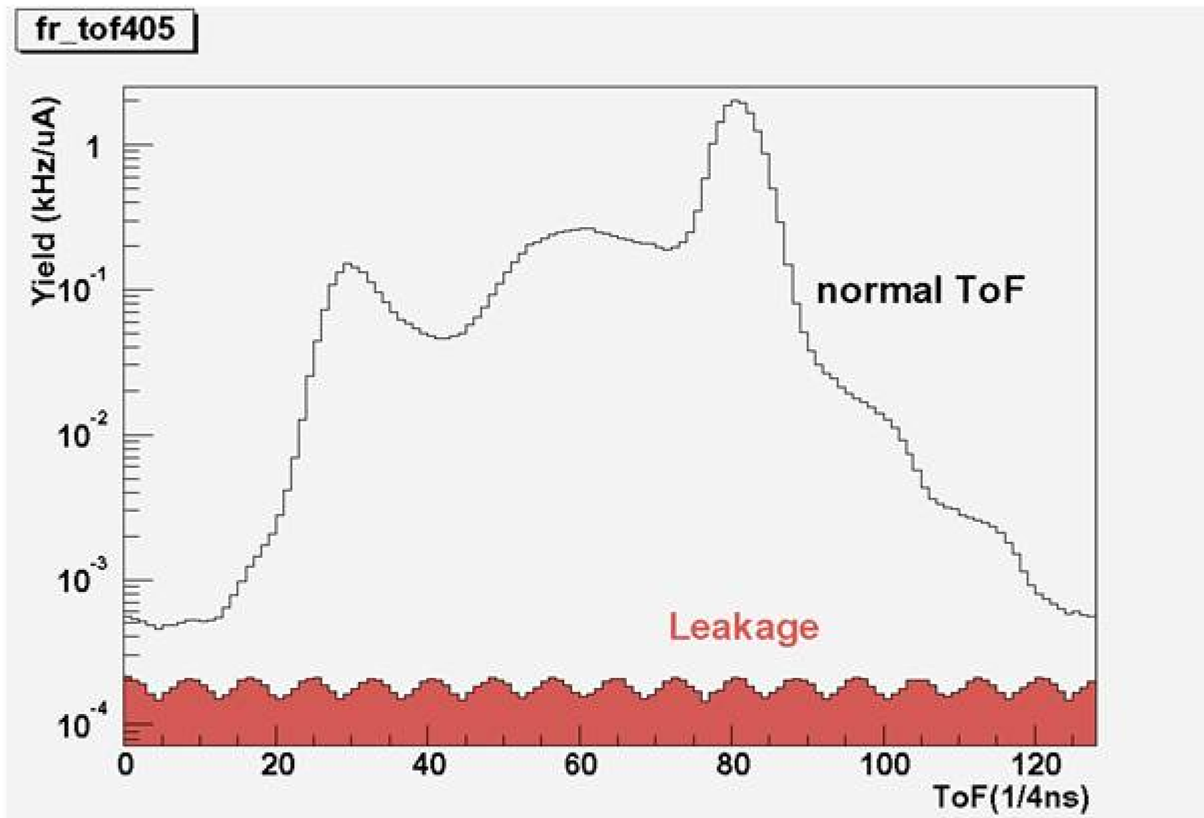




What could go wrong? go wrong? go wrong? go wrong?

During our G^0 run, we observed "leakage beam" from the other two halls lasers (which had a repetition rate of 2 nsec in instead of the 32 nsec G^0 repetition rate.)

Problem: the leakage beam had ~ 5000 ppm charge asymmetry!
Solution: correct using the data in TOF regions where there are few G^0 events.



go wrong? go wrong? go wrong? go wrong?

Mainz PVA4 Program

PbF_2 scintillating Calorimeter

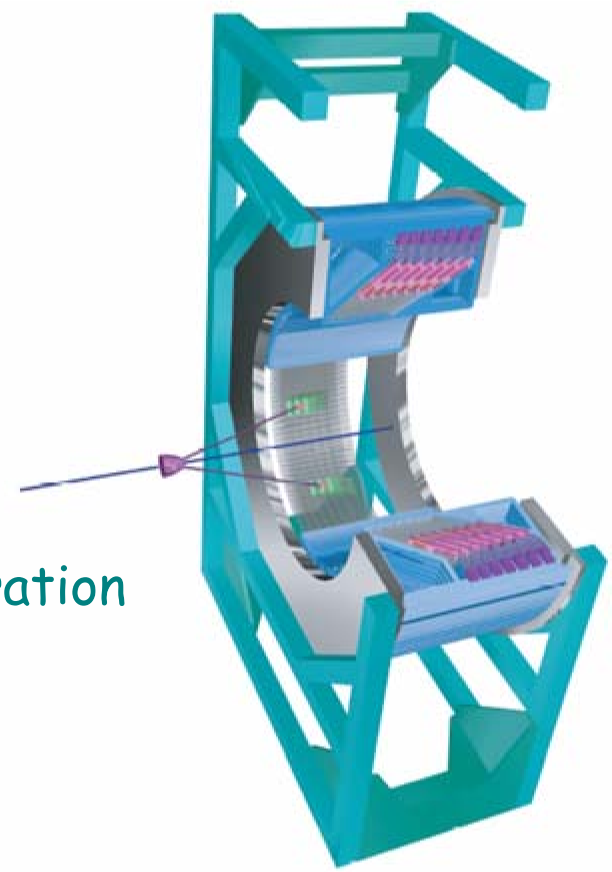
I=20 μA, 80% pol'n.

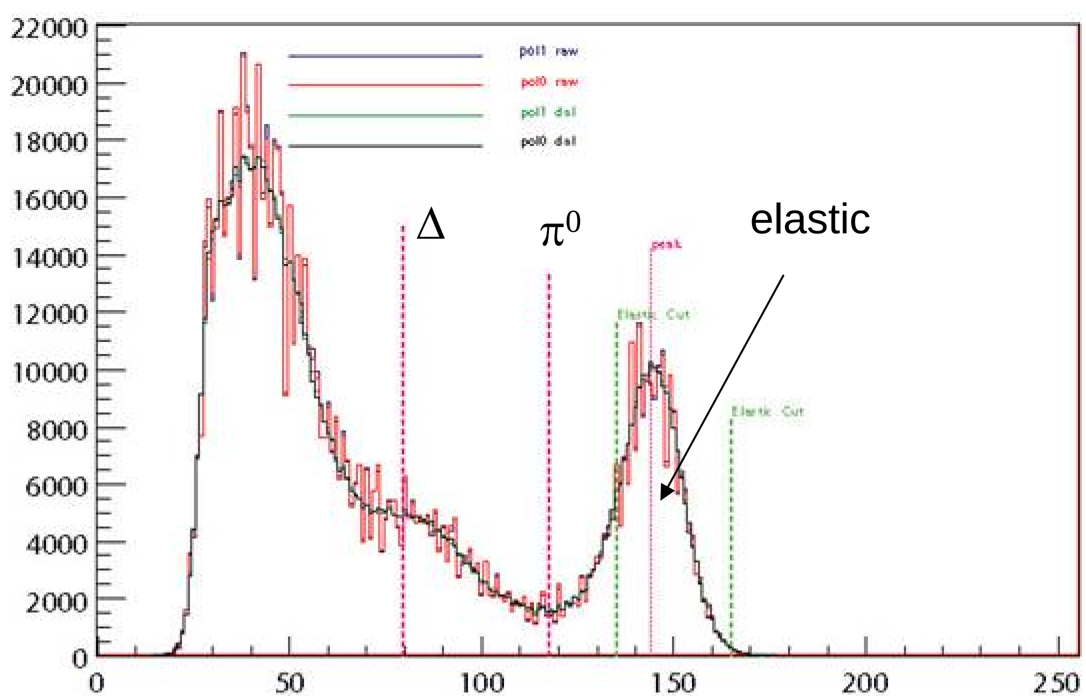
10 cm LH2 target

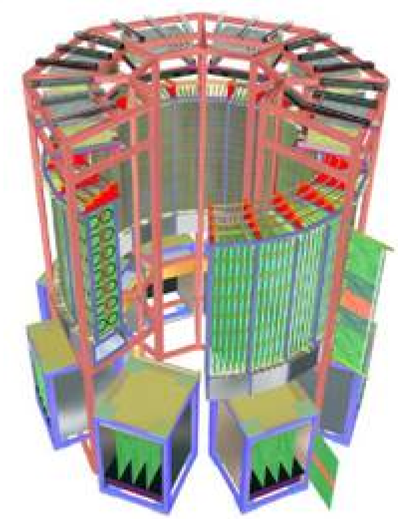
Count scattered electrons

elastic rate 10 MHz, inelastic 90 MHz

histogramming electronics for real-time separation







Mainz PVA4 Measurements

Run I: 600 hours at 854 MeV

$Q^2 = 0.230\ (GeV/c)^2$, $\theta = 35°$

sensitive to $G_E^s + 0.21\ G_M^s$

Run II: 400 hours at 570 MeV

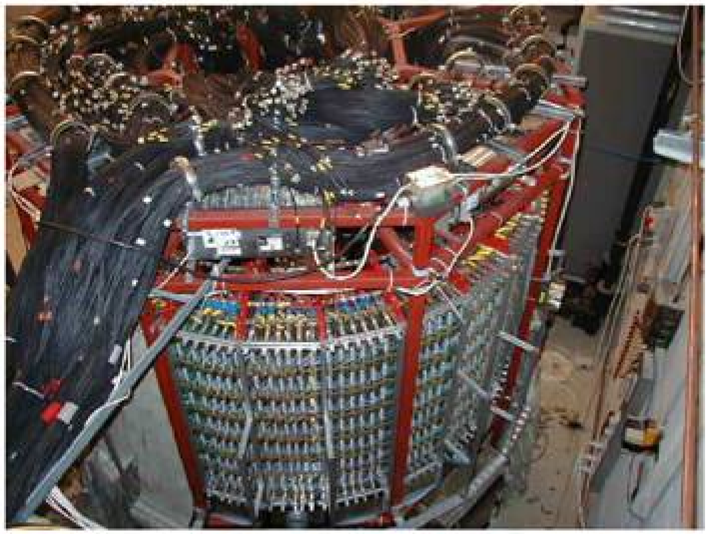
$Q^2 = 0.10\ (GeV/c)^2$, $\theta = 35°$

sensitive to $G_E^s + 0.11\ G_M^s$

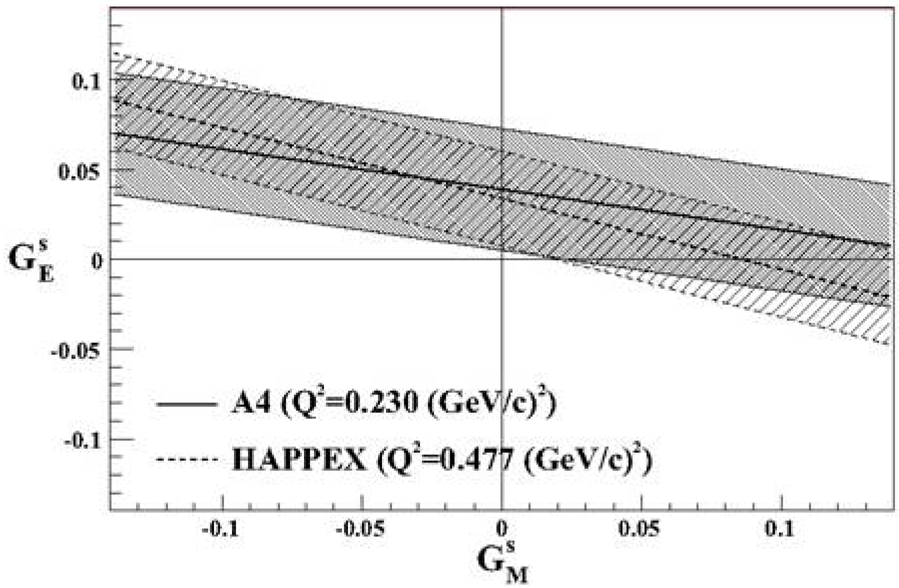
Future Program: $\theta = 145°$

$Q^2 = 0.23$ and $0.45\ (GeV/c)^2$

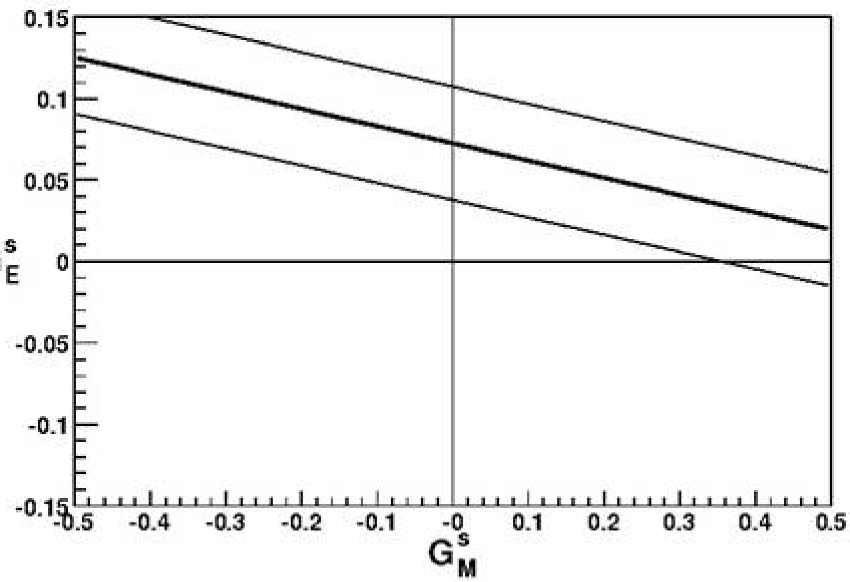
combine with Run I and w/ HAPPEX



Mainz A4: Results from Runs I and II



$$A = -5.44 \pm .54 \pm .26 \quad \text{ppm}$$
$$Q^2 = .23\,(\text{GeV/c})^2$$
$$G_E^s + 0.23 G_M^s = 0.039 \pm 0.034$$



$$A = -1.37 \pm .29 \pm .11 \quad \text{ppm}$$
$$Q^2 = .10\,(\text{GeV/c})^2$$
$$G_E^s + 0.11 G_M^s = 0.074 \pm 0.036$$

Strange Form Factor Measurement Summary (Summer 2004)

SAMPLE: $Q^2 = 0.1\ (GeV/c)^2$

$$G_M^s = 0.37 \pm 0.34$$

HAPPEX I: $Q^2 = 0.48\ (GeV/c)^2$

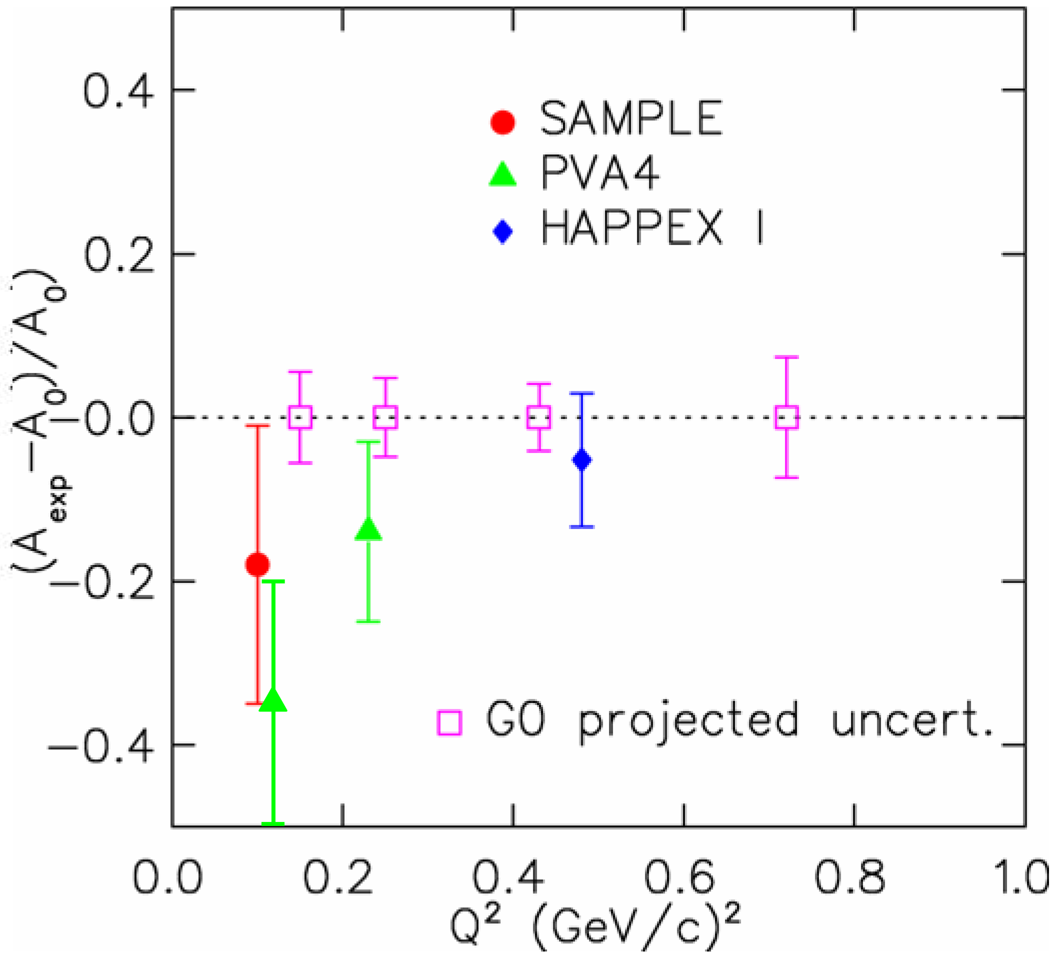
$$G_E^s + 0.39\, G_M^s = 0.014 \pm 0.020$$

PVA4 I: $Q^2 = 0.24\ (GeV/c)^2$

$$G_E^s + 0.23\, G_M^s = 0.039 \pm 0.034$$

PVA4 II: $Q^2 = 0.1\ (GeV/c)^2$

$$G_E^s + 0.11\, G_M^s = 0.074 \pm 0.036$$

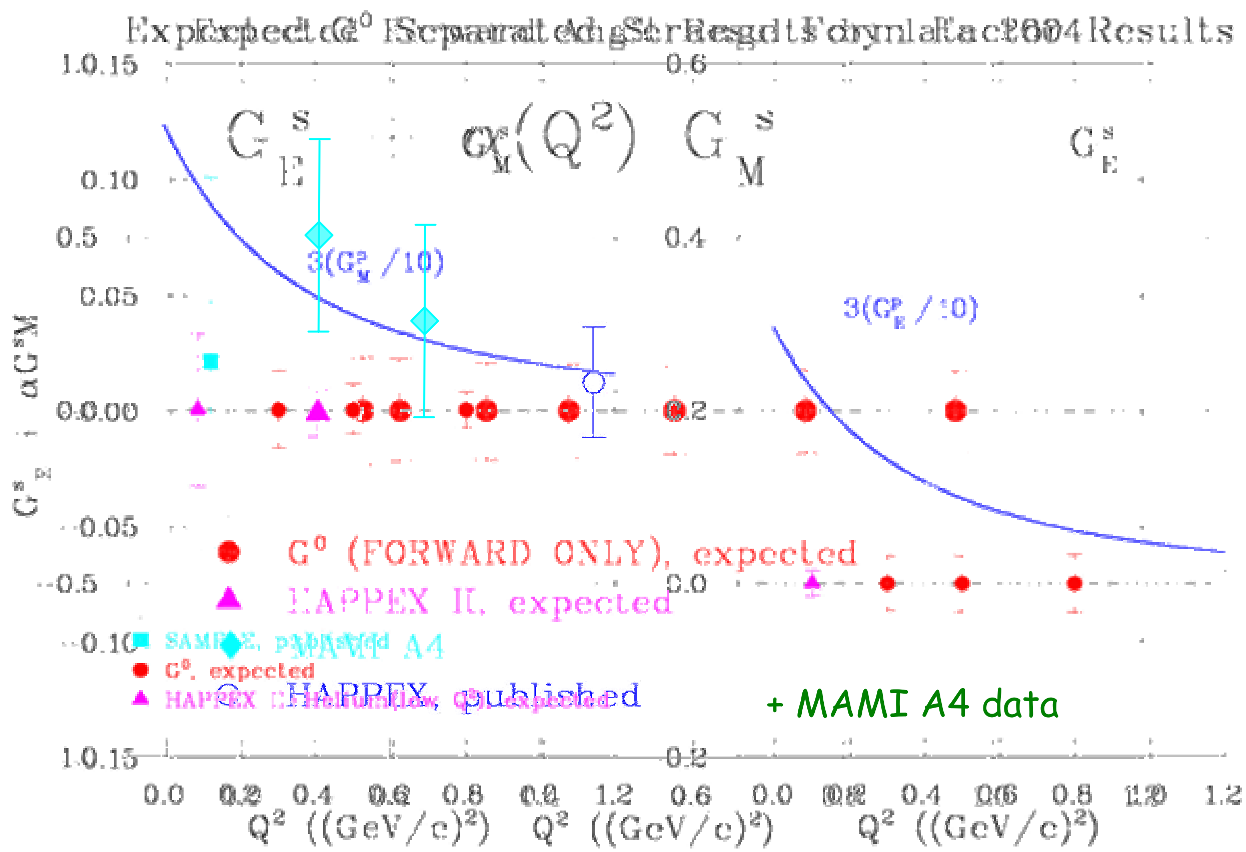


Outlook for Strange Form Factors

- Possibly non-zero strangeness value from Mainz at $Q^2 \sim 0.1\ GeV^2$
- G^0 forward angle data-taking complete
- Happex II data-taking in progress
- Back angle running for G^0 and A4 expected in 2004 - 2007

And by late 2004 we can present a wide range of forward angle data:

Hopefully by 2006 we can present complete world's separated form factors:

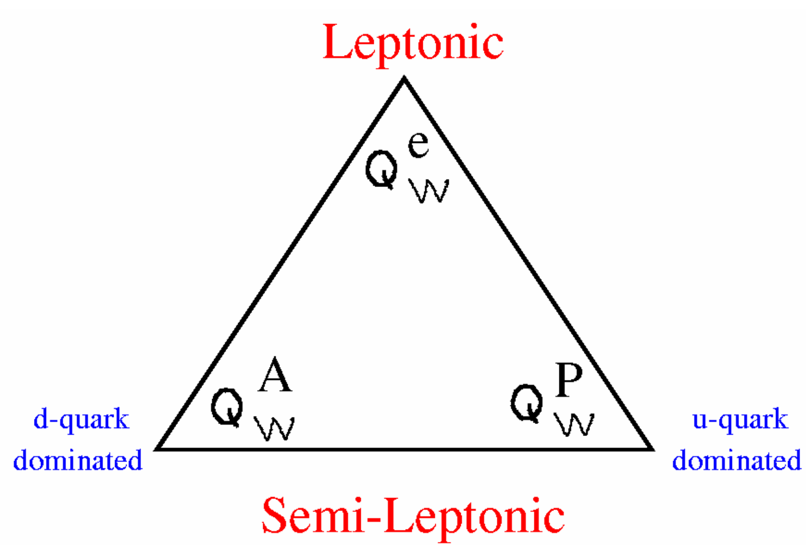


Standard Model Tests using Low Energy Precision Measurements

The weak charges (the charge probed by Z boson exchange) can be measured in low Q^2 processes:

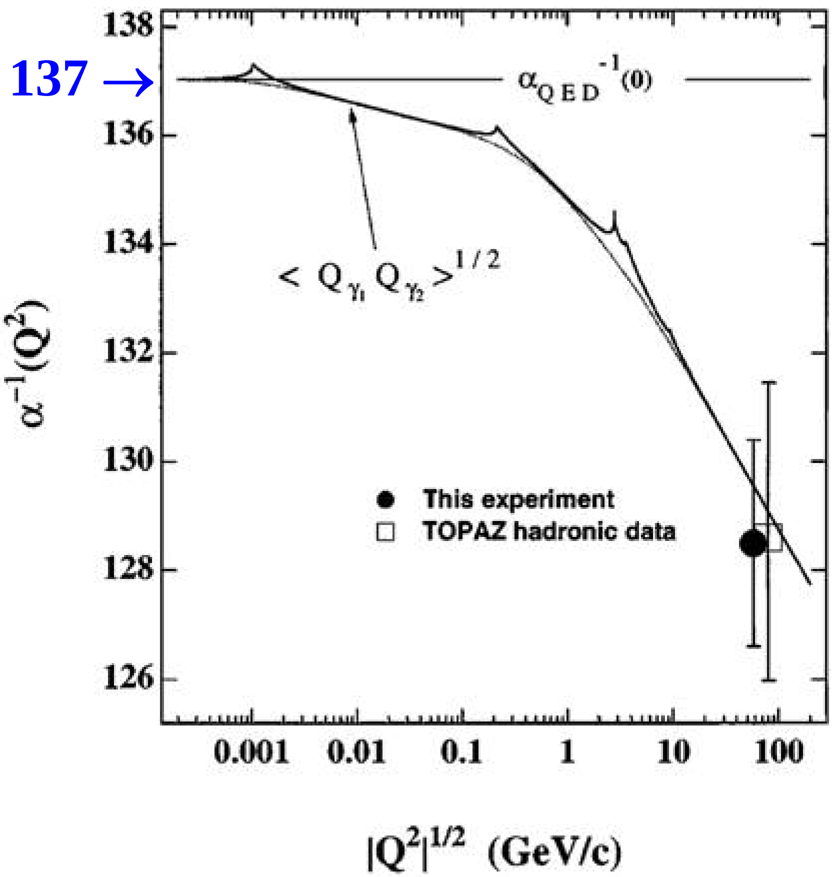
• Moller scattering	$\vec{e} + e \rightarrow e + e$	Q_W^e
• e-p elastic scattering	$\vec{e} + p \rightarrow e + p$	Q_W^p
• Atomic parity violation		Q_W^A

weak charge triad→



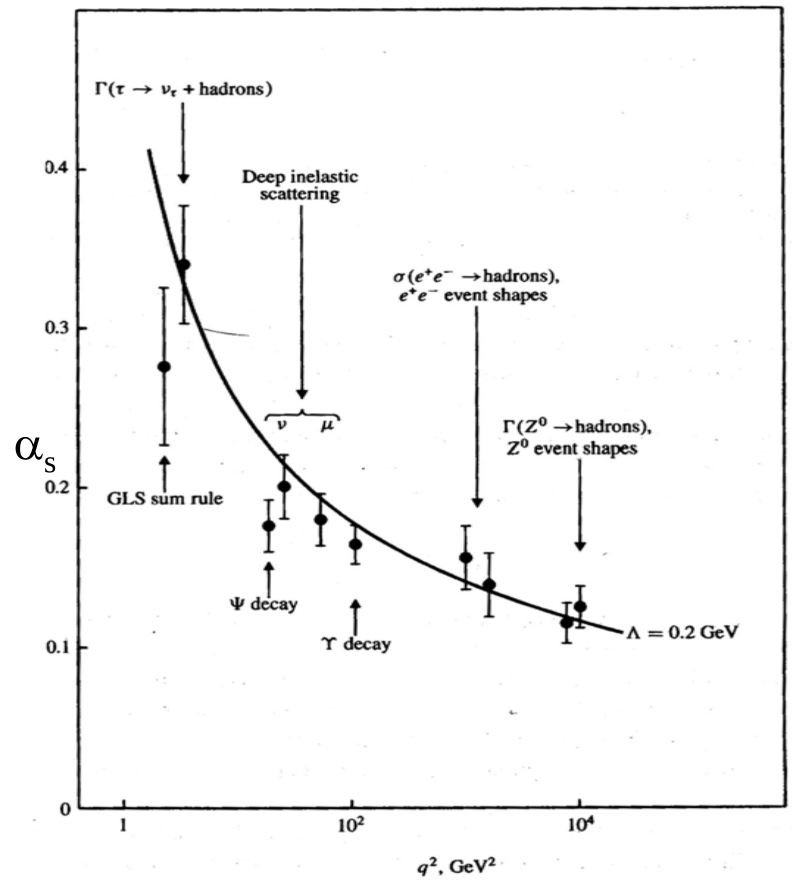
Running coupling constants in QED and QCD: recent data

QED (running of α)



TOPAZ collaboration at KEK TRISTAN:
I. Levine *et al.* Phys. Rev. Lett. **78**, 424 (1997)

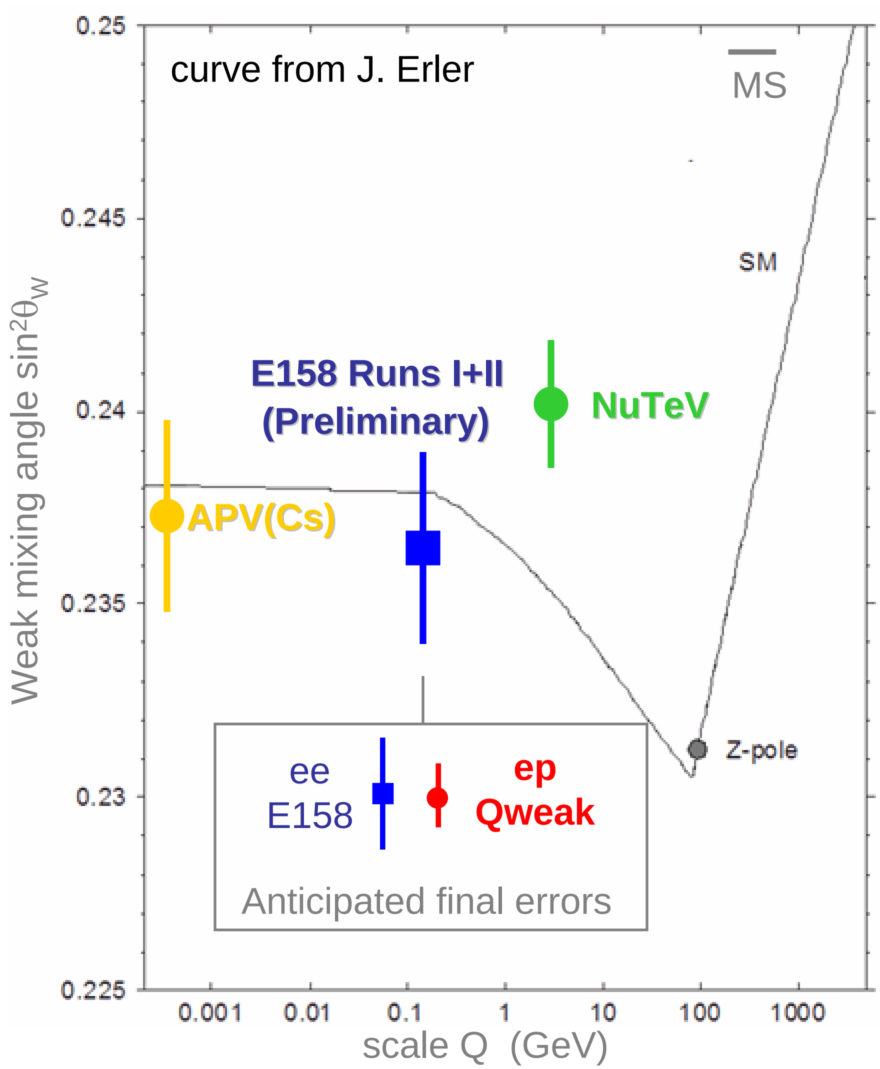
QCD(running of α_s)



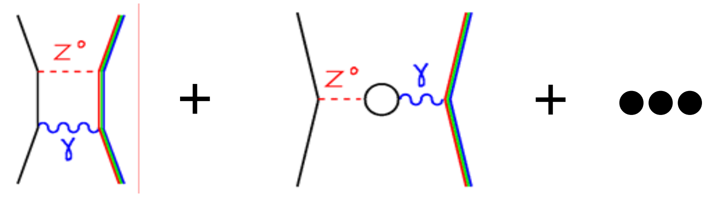
D. Perkins, **Introduction to High Energy Physics**, 4th Edition, 2000

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

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



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



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

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

- Q^p_{weak} (semi-leptonic) and E158 (pure leptonic) together make a powerful program to search for and identify new physics.

E158

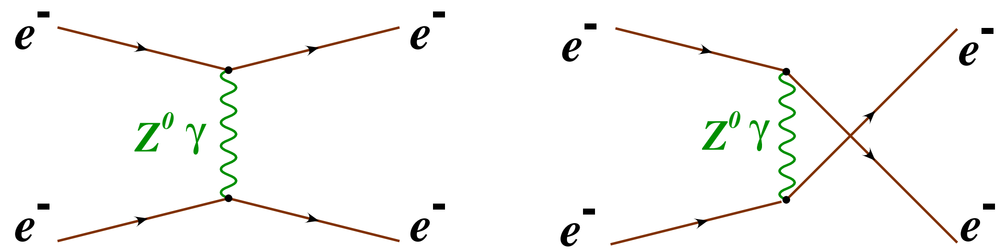
A precision measurement of the Weak Mixing Angle
in Møller Scattering

at SLAC

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

Møller scattering :

- Sensitive to: e, Q_w



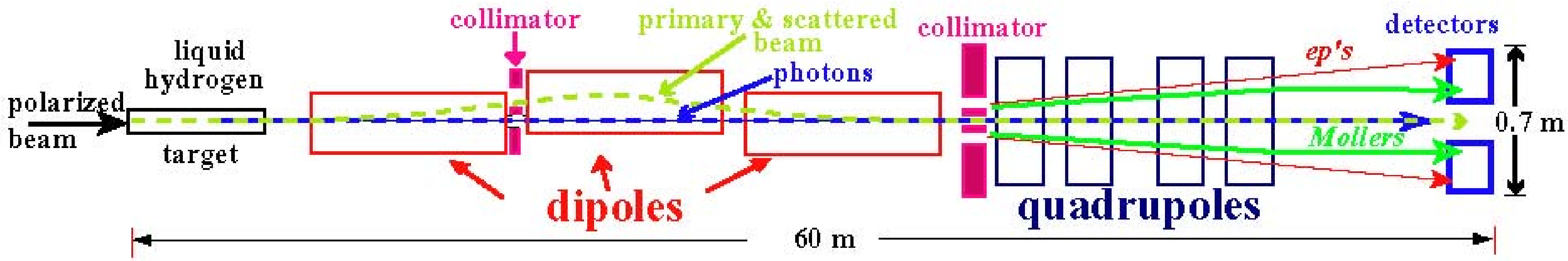
Parity violation asymmetry : $A_{PV} = \dfrac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \dfrac{M_\gamma M_Z}{M_\gamma^2}$

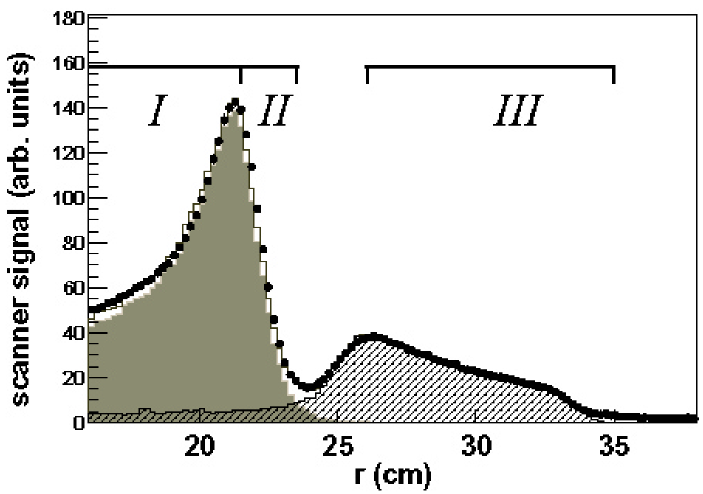
Tree level Moller asymmetry : $A_{ee} = mE \dfrac{G_F}{\sqrt{2}\pi\alpha} \dfrac{16 \sin^2\theta}{(3+\cos^2\theta)^2} \left(\dfrac{1}{4} - \sin^2\theta_W\right)$

Q_w

$$A_{ee}(Q^2 = 0.03) \approx 3.2 \times 10^{-7} \quad (320\ ppb)$$

E158 Experimental Layout at SLAC





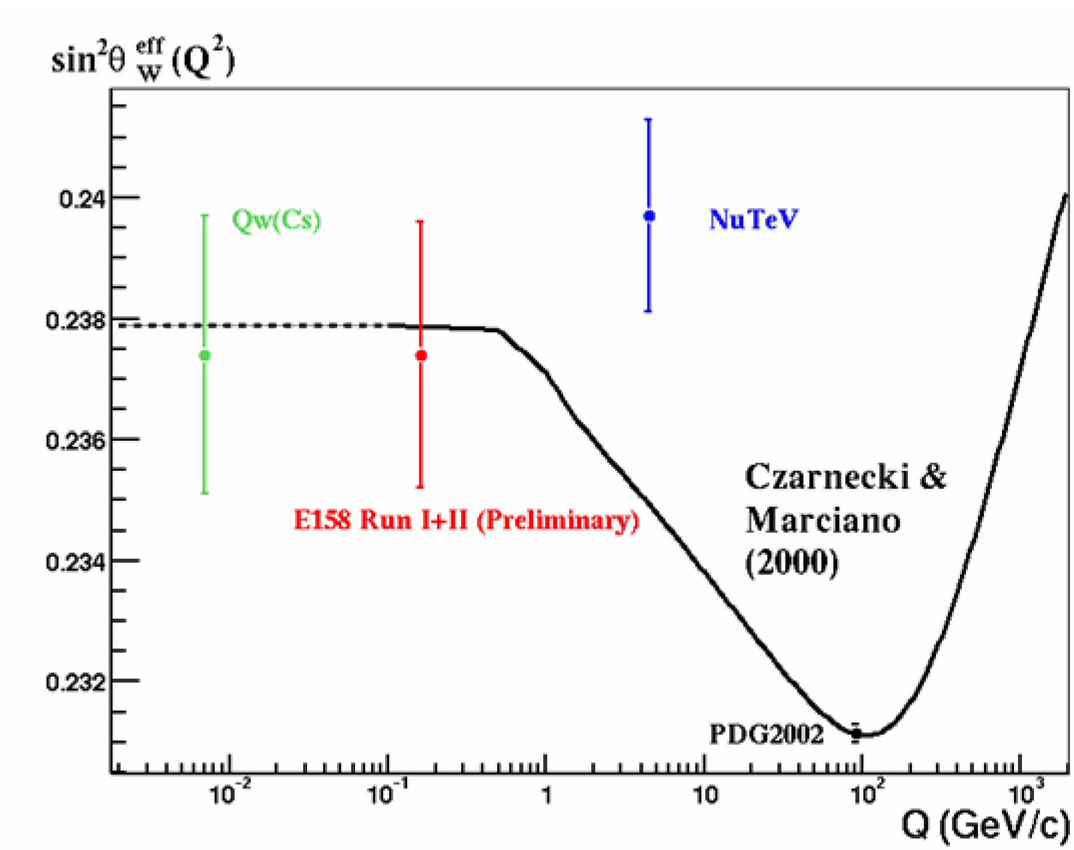
E158 results

A_{PV} = -161 ± 21 (stat) ± 17 (syst) ppb

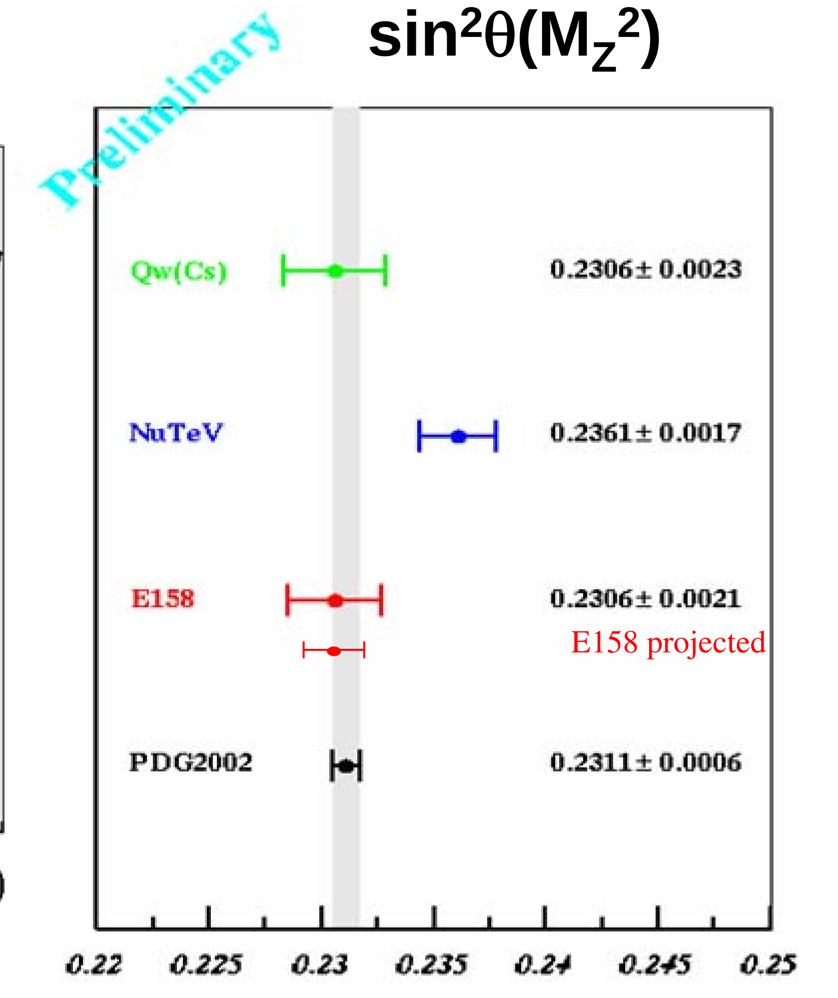
Run I + II (preliminary)

$\sin^2\theta_{eff}(Q^2=0.026\ GeV^2)$ = 0.2379 ± 0.0016 ±0.0013

(Run I + II, preliminary) (stat) (syst)



$\sin^2\theta(M_Z^2)$



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

Recall: Weak mixing angle $\sin^2\theta_W$ is the key parameter of the electroweak Standard Model theory; all existing experimental observables can be described in terms of it

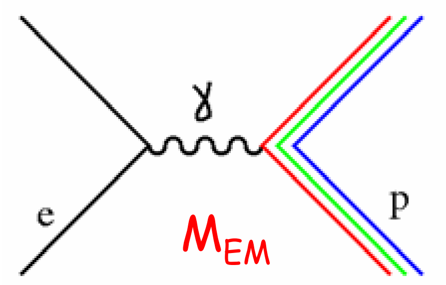
Measure: Parity-violating asymmetry in $\vec{e}$ + p elastic scattering at $Q^2 \sim 0.03$ GeV^2 to ~4% relative accuracy at JLab

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

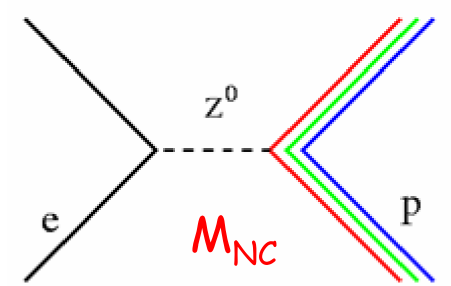
⇒ tests "running of $\sin^2\theta_W$" from M^2_Z to low Q^2

⇒ sensitive to new TeV scale physics

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

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

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

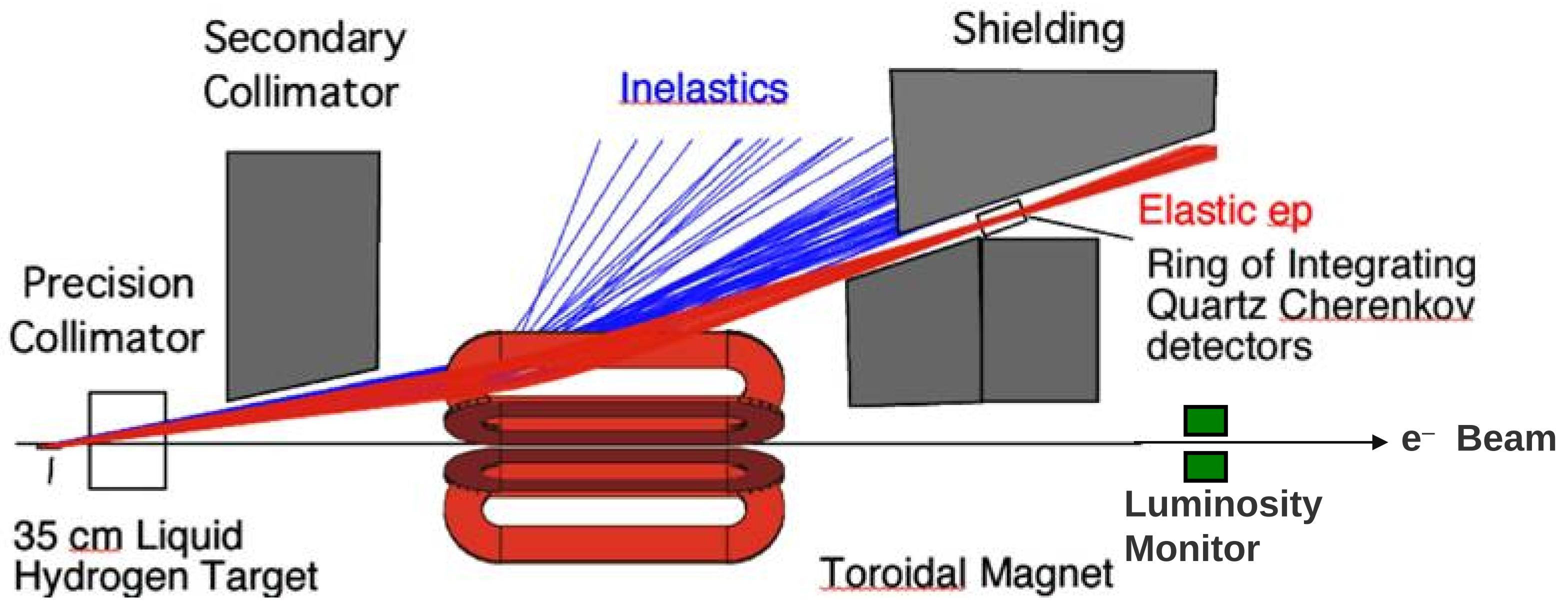
contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$

$Q^p_{weak} = 1 - 4\sin^2\theta_W \sim 0.072$ (at tree level, see Erler, Musolf hep-ph/0302149)

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

Q^e_{weak} : electron's weak charge is measured in PV Moller scattering (E158)

The Q^p_{weak} Experimental Apparatus

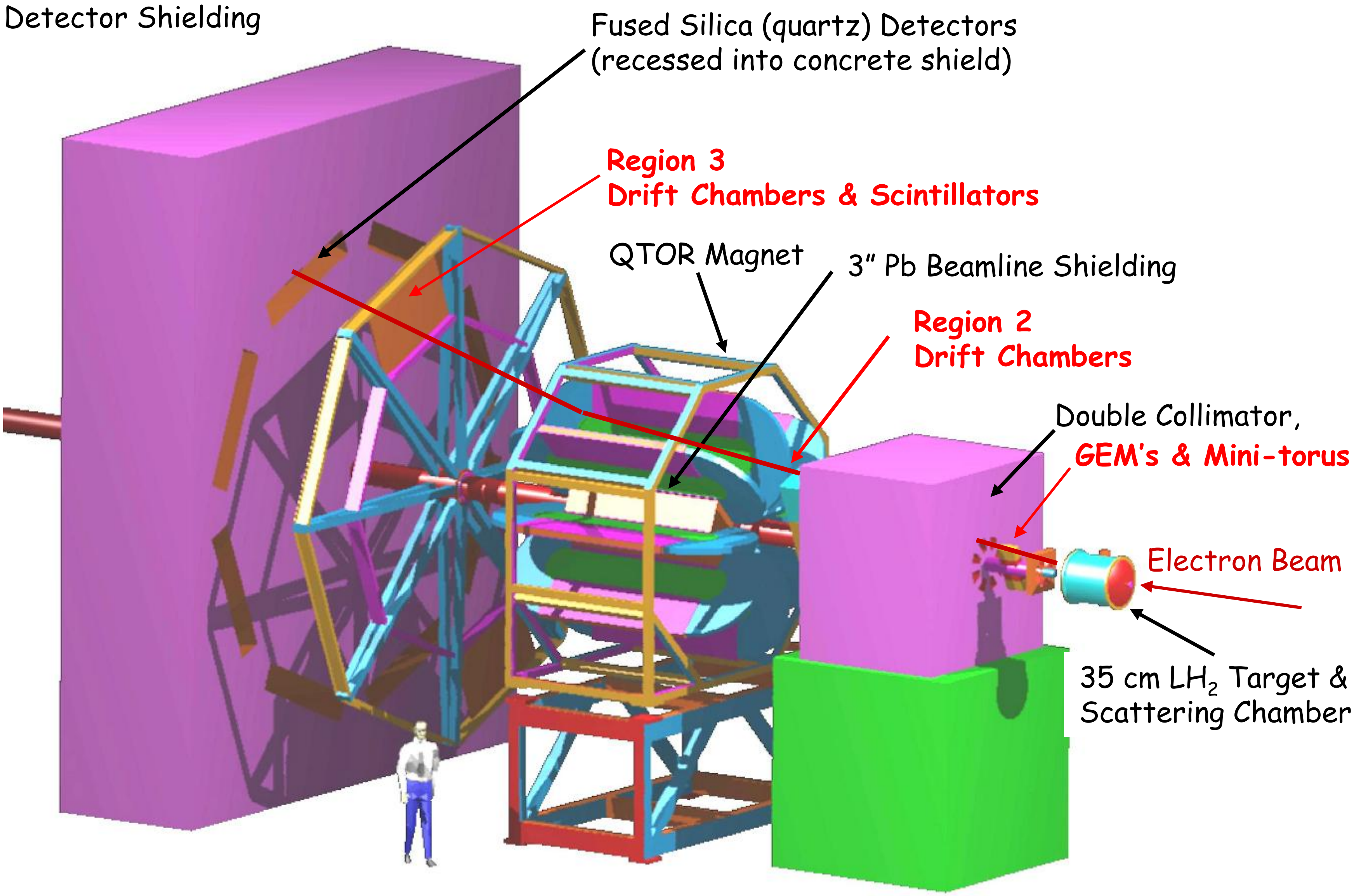


Experimental parameters

Incident beam energy	1.165 GeV
Beam Current	180 μA
Beam Polarization	80%
Running Time	Run I 23 days
	Run II 93 days

Central scattering angle	9°
Scattering angle acceptance	± 2°
Phi Acceptance	67% of 2π
Solid angle	46 msr
Average Q^2	0.03 GeV^2
Integrated Rate (all sectors)	6.1 GHz
Integrated Rate (per detector)	0.8 GHz
Acceptance averaged asymmetry	–0.3 ppm
Statistical error per pulse pair	5×10^{-5}

CAD Illustration of Q^p_{Weak} Experiment

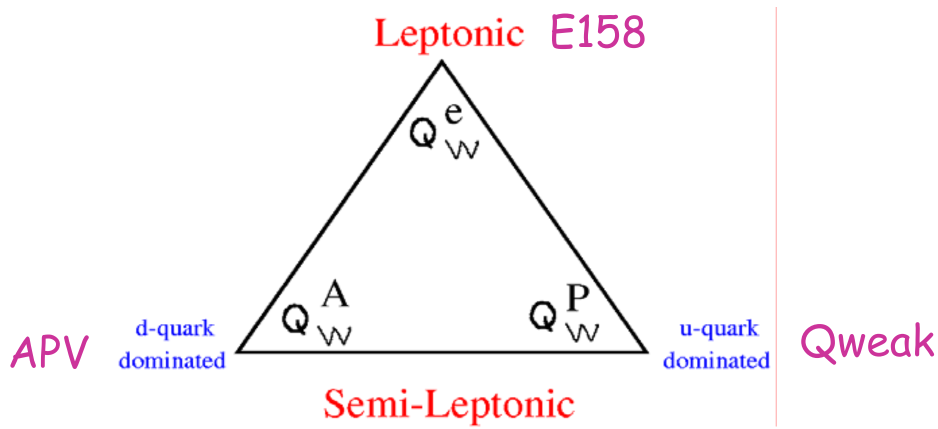


Conclusions

Parity-violating electron scattering is currently primarily used as an experimental tool for two purposes:

1. Measurement of strange form factors
   - First hints of non-zero strange form factors perhaps seen from Mainz A4 experiment
   - More data to come in 2004-2007 including separated (E and M) strange form factors

2. Low energy Standard Model tests   weak charge triad→



Thanks to Betsy Beise, Damon Spayde, Krishna Kumar, Frank Maas for contributions.
Thanks to NSF and DOE for financial support for the experiments listed here.