Parity Violation Experiments at Jefferson Lab:

G^0 and HAPPEX

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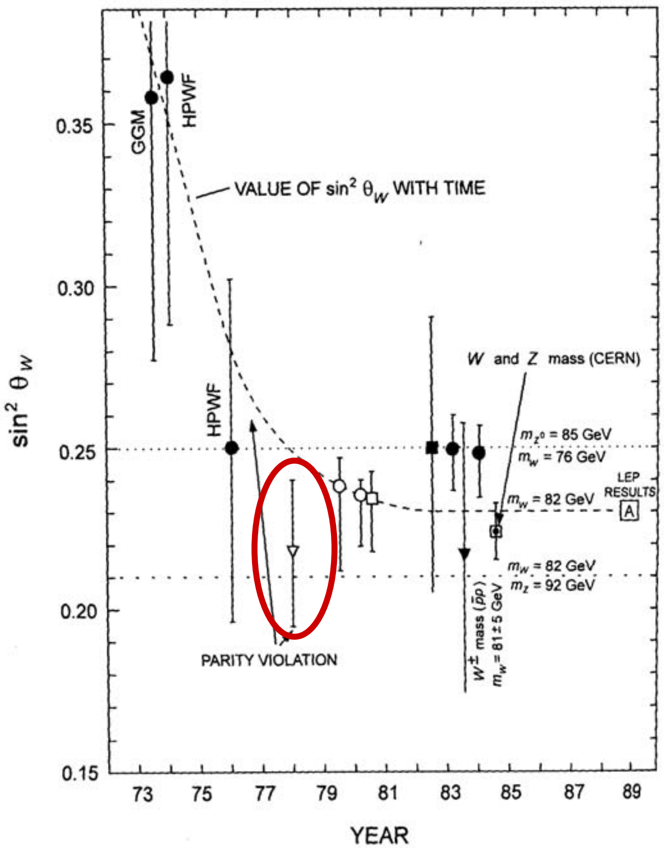
IPN-Orsay

Erice, 20 Sept 2004

Parity Violating Electron-Nucleon Scattering



70's: e + d (DIS) A ~ 100 ppm
SLAC E122
(Prescott et al)

Goal: **measure $\sin^2\theta_W = 0.22$ +/- .0.02**
most precise measurement at that time

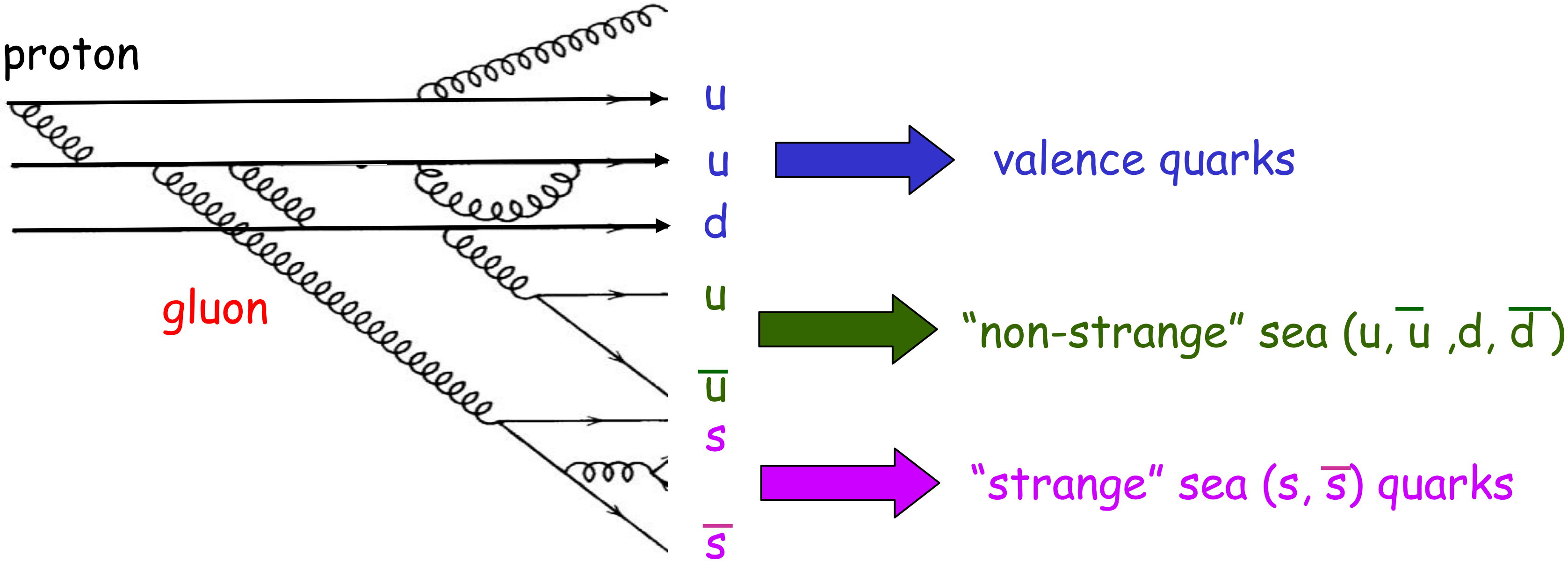
80's: e + ^{9}Be (QE) A ~ 10 ppm Mainz
e + ^{12}C (elastic) A ~ 1 ppm MIT-Bates

Goal: **Standard Model test**

90's: SAMPLE
HAPPEX e + p (elastic) A ~ 2 – 50 ppm
G^0 e + d (QE)
MAMI PV-A4

Goal: Assume Standard Model is correct, **measure strange form factors**

What role do strange quarks play in nucleon properties?



Momentum: $\int_0^1 x(s+\bar{s})dx \sim 2\text{-}4\%$ (DIS)

Spin: $<N|\bar{s}\gamma^5 s|N> \sim -10\%$ (polarized DIS)

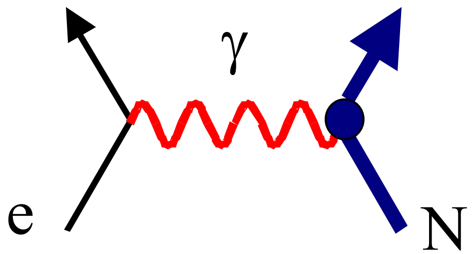
Mass: $<N|\bar{s}s|N> \sim 30\%$ (?) ($\pi N\ \sigma$ - term)

Charge and current: $<N|\bar{s}\ \gamma^\mu\ s|N> = ?? \rightarrow G_E^s\ G_M^s$

Nucleon form factors measured in elastic e-N scattering

Nucleon form factors

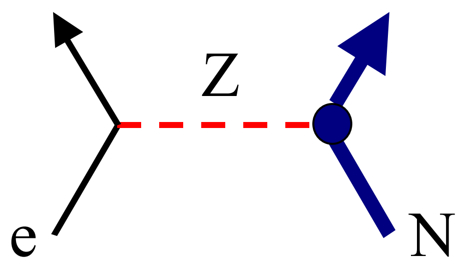
- well defined experimental observables
- provide an important benchmark for testing non-perturbative QCD structure of the nucleon



$$< N \,|\, J_\mu^\gamma \,|\, N > \quad \rightarrow \quad G_E^\gamma, G_M^\gamma$$

electromagnetic form factors

Precision of EM form factors in 0.1 - 1 GeV^2 Q^2 range ~ 2 - 4%



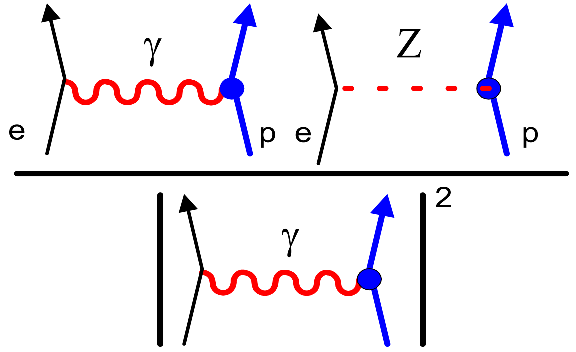
$$< N \,|\, J_\mu^Z \,|\, N > \quad \rightarrow \quad G_E^Z, G_M^Z$$

neutral weak form factors

Weak amplitude = 10^{-5} x Electromagnetic Amplitude

Parity Violating Electron Scattering
Probe of Neutral Weak Form Factors

polarized electrons, unpolarized target



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

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

$\rightarrow G_E^s$
$\rightarrow G_M^s$
$\rightarrow G_A^e$

Strange electric and magnetic form factors,
+ axial form factor

At a given Q² decomposition of $G^s{}_E$, $G^s{}_M$, $G^e{}_A$
Requires 3 measurements:

1. Forward angle e + p (elastic)
2. Backward angle e + p (elastic)
3. Backward angle e + d (quasi-elastic)
4. e+ He^4 elastic scattering (only $G^s{}_E$)

Parity Violating Electron-Nucleon Scattering

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1-4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^e}{\varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}$$

forward angles
HAPPEX, Mainz, G^0: sensitive to

G_E^s and G_M^s

backward angles
SAMPLE, G^0: sensitive to

G_M^s and G_A^e

axial-vector form factor

$$\tau = \frac{Q^2}{4M^2}$$

$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\left(\tfrac{\theta}{2}\right)\right]^{-1}$$

$$\varepsilon' = \sqrt{(1-\varepsilon^2)\tau(1+\tau)}$$

Overall goal of parity-violating electron scattering programs: determine G_E^s and G_M^s separately over a wide range (0.1 – 1.0) $(\mathrm{GeV}/c)^2$ of Q^2

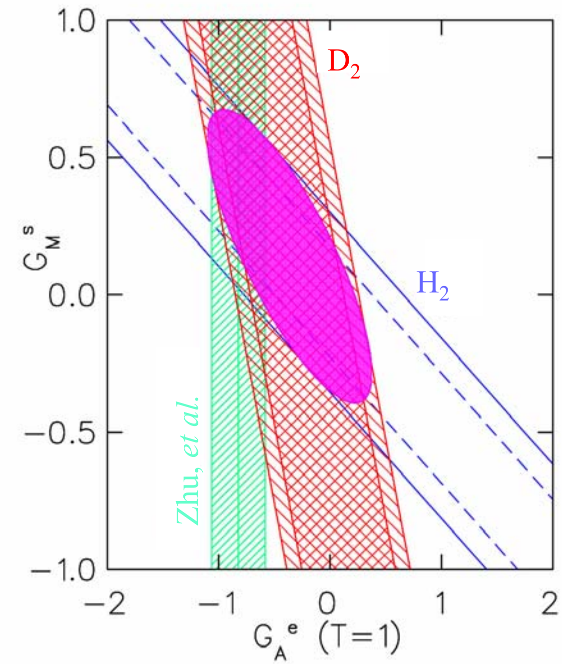
Strange form factors - published results

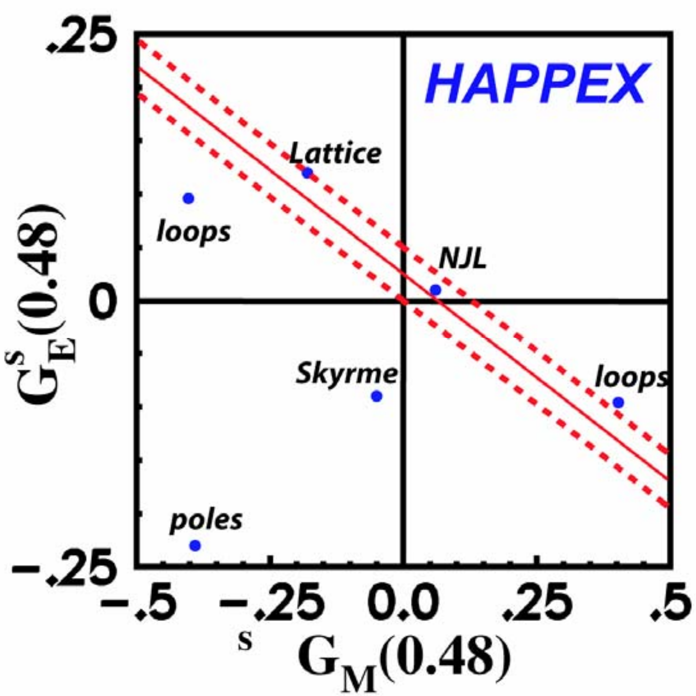
SAMPLE at MIT-Bates:

$\vec{e} + p$ elastic: $A_p = -4.92 \pm 0.61 \pm 0.73$ ppm

$\vec{e} + d$ quasielastic: $A_d = -7.55 \pm 0.70 \pm 0.60$ ppm

$$G_M^s(Q^2 = 0.1\,\mathrm{GeV}^2) = 0.14 \pm 0.35 \pm 0.40$$





HAPPEX I at Jefferson Lab:

$\vec{e} + p$ elastic: $A_p = -15.05 \pm 0.98 \pm 0.56$ ppm

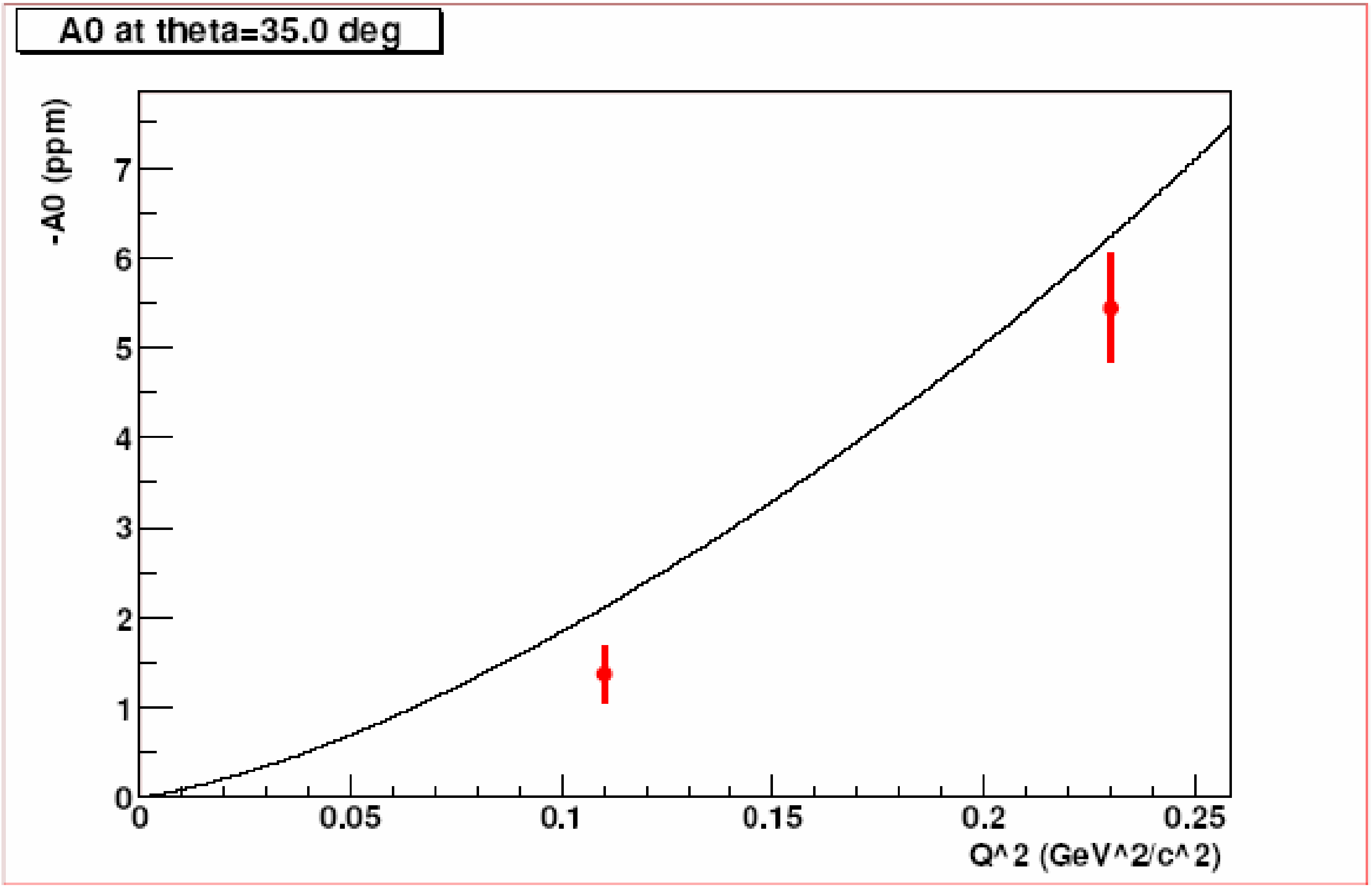
$$G_E^s + 0.39 G_M^s = 0.025 \pm 0.020 \pm 0.014$$

at $Q^2 = 0.48\,\mathrm{GeV}^2$

F. Maas

New Results from PV-A4

Note the Negative sign →

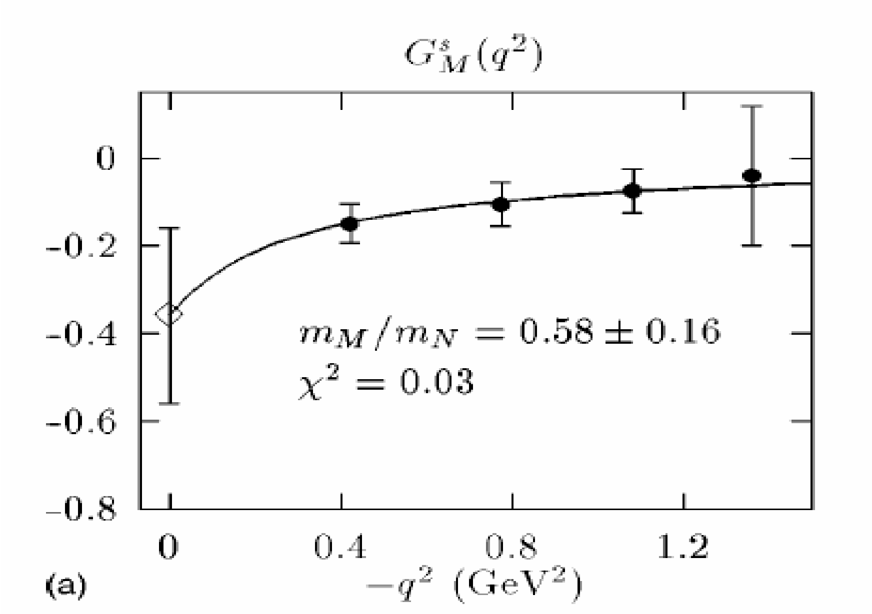


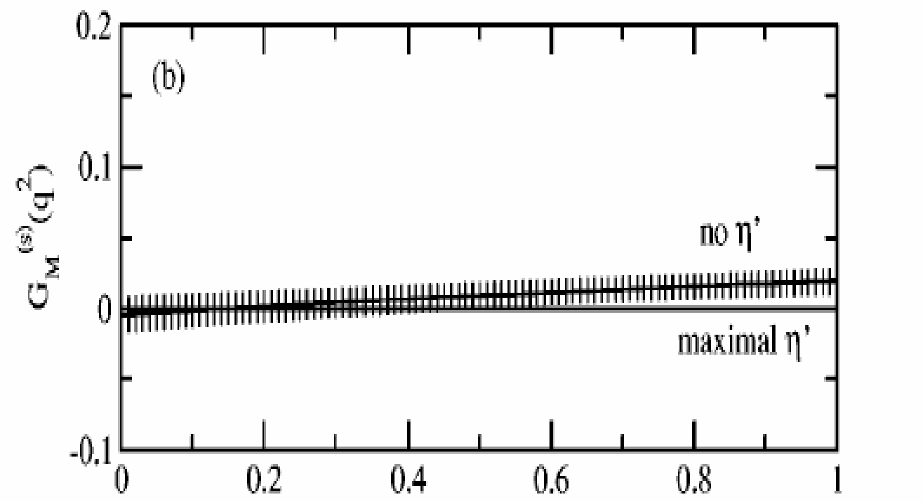
$$Q^2{=}0.23\ \mathrm{GeV}^2,\ G_E^s + 0.225 G_M^s = 0.039 \pm 0.034$$

$$Q^2{=}0.10\ \mathrm{GeV}^2,\ G_E^s + 0.106 G_M^s = 0.074 \pm 0.036$$

Lattice Computations

See also
Leinweber *et al*





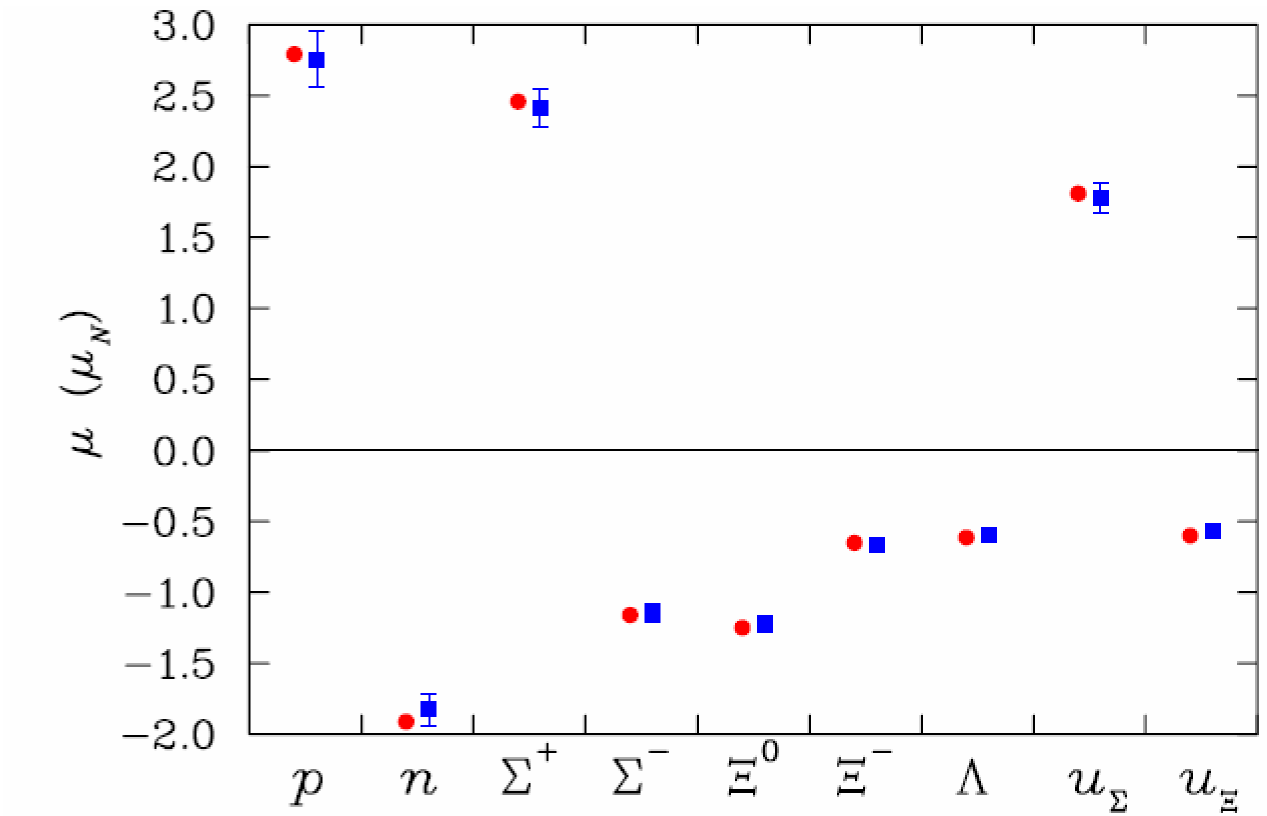
Dong, Liu, & Williams (1998)

- Quenched QCD
- Wilson fermions
- 100 gauge configurations
- 300-noise estimate/config

Lewis, Wilcox, Woloshyn (2003)

- Quenched QCD
- Wilson fermions
- 2000 gauge configurations
- 60-noise estimate/config

D. Leinweber, et al. (PAVI04)

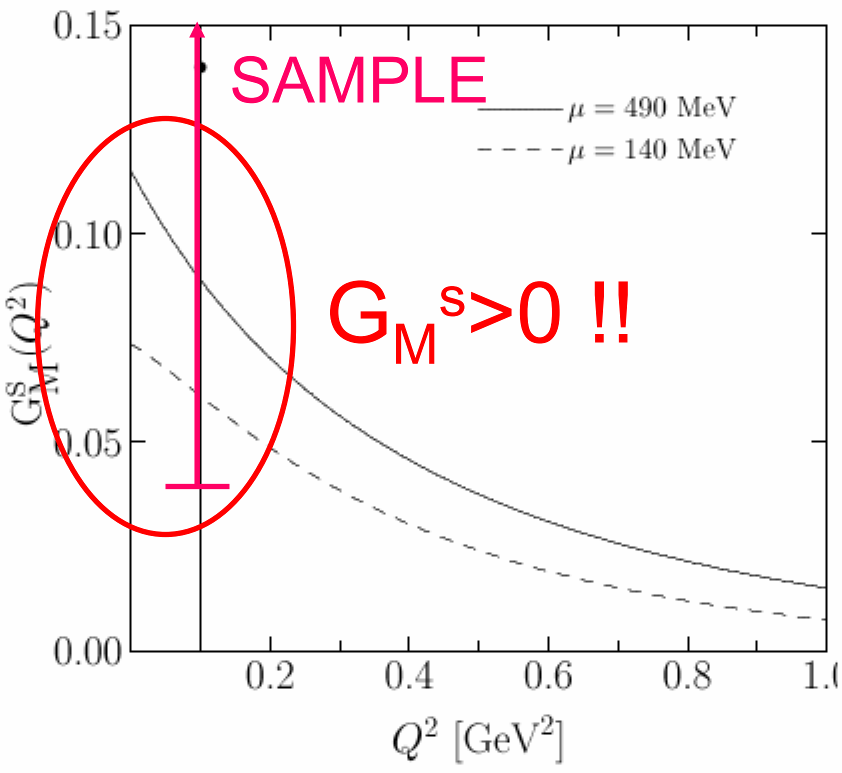


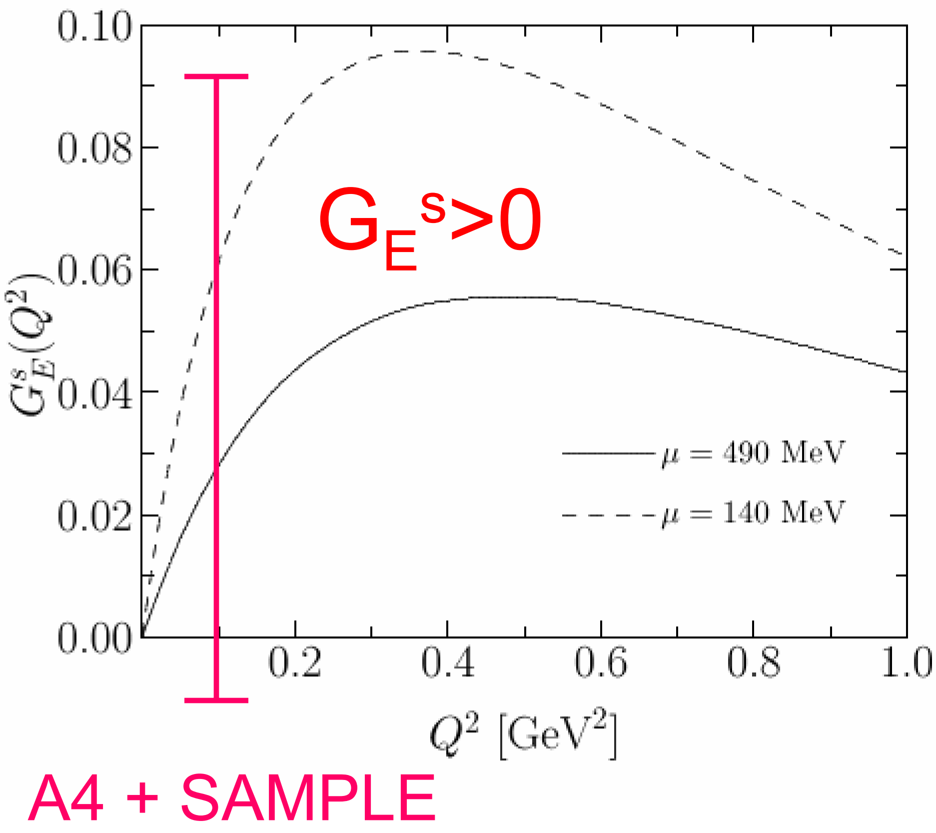
A PREDICTION OF LATTICE QCD

$$G_M^s = -0.051 \pm 0.021\ \mu_N$$

Chiral Soliton Model

A. Silva





Strange Quarks in the Nucleon: What have we learned ?

Effects in $\langle N | \bar{s}\gamma_\mu s | N \rangle$ are much less pronounced than in $\langle N | \bar{s} s | N \rangle$, $\langle N | \bar{s}\gamma_\mu\gamma_5 s | N \rangle$

Challenge to understand QCD at deep, detailed level

- Strange quarks don't appear in Quark Model picture of the nucleon
- Perturbation theory may not apply

$\Lambda_{QCD} / m_s \sim 1$ No HQET

Ramsey-Musolf, PAVI04

The G^0 Experiment at JLab

Caltech, Carnegie-Mellon, W&M, Hampton, IPN-Orsay, ISN-Grenoble, Kentucky, La.Tech, NMSU, Jlab, TRIUMF, Uconn, UIUC, UMan, UMd, UMass, UNBC, VPI, Yerevan

Goal: Determine contributions of strange quarks to charge and magnetization distributions of the nucleon within a few percent of G_{dipole} for Q^2 = 0.12-1.0 *(GeV/c)2*

- **Forward** and **backward** angle parity-violating e-p **elastic** and e-d **quasielastic** in Jefferson Lab Hall C
- **Kinematics**
  - **Forward** mode: detect recoil **protons**
  - **Backward** mode: detect **electrons**

Note that $G^0 = (G_u + G_d + G_s) / 3$ is the singlet form-factor

General Experimental Requirements

Want to measure A_{PV} ~ -3/-40 ppm with precision dA_{PV}/A_{PV} ~ 5%

Statistics (need 10^{13} - 10^{14} events):

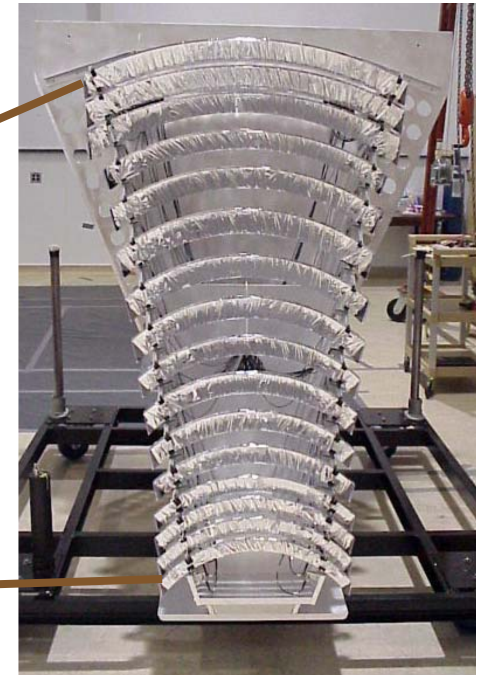
- **Reliable high polarization, high current polarized source**
- **High power H/D target**
- **Large acceptance detector**
- **High count rate capability detectors/electronics**

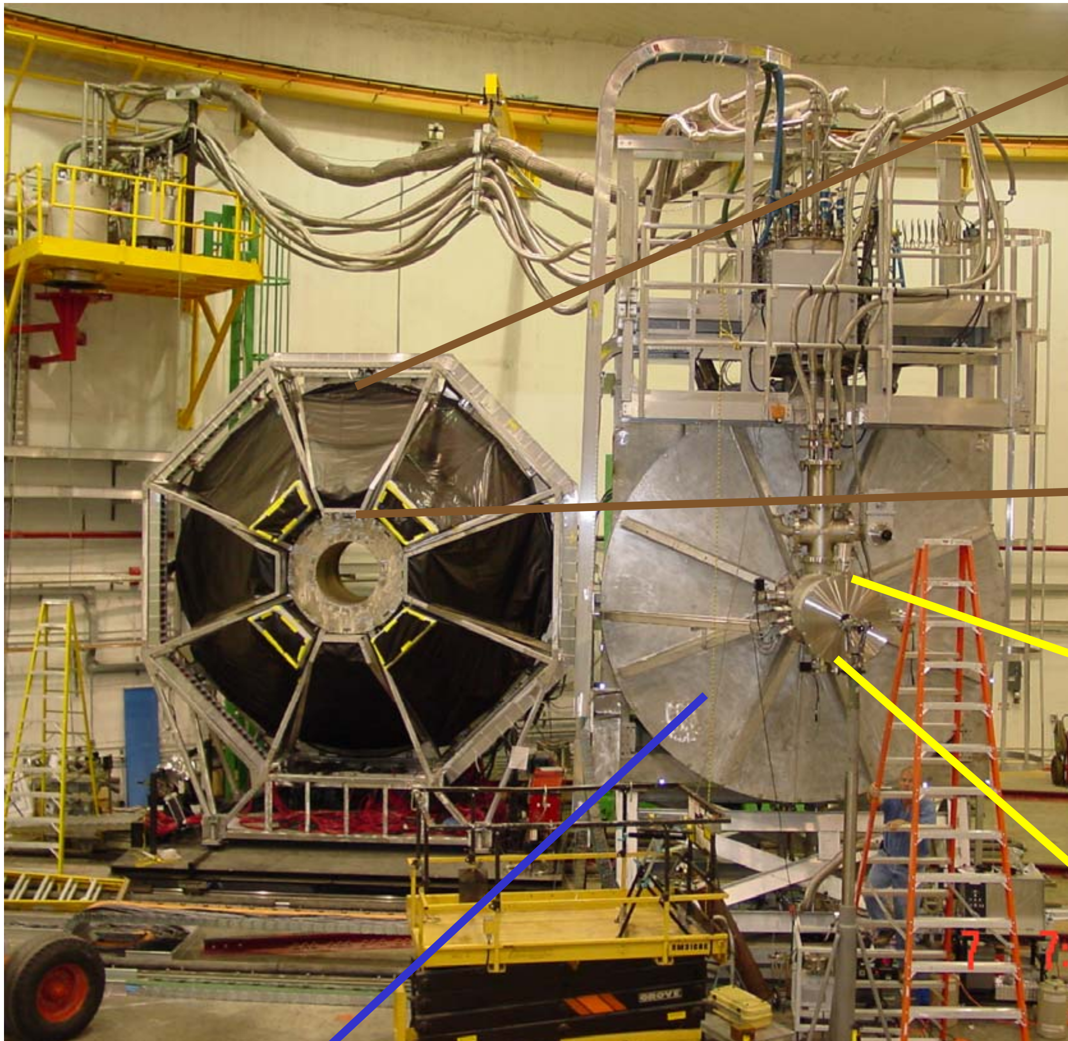
•Systematics (needed to reduce false asymmetries, accurately measure dilution factors):

- **Small helicity-correlated beam properties**
- **Capability to isolate elastic scattering from other processes**

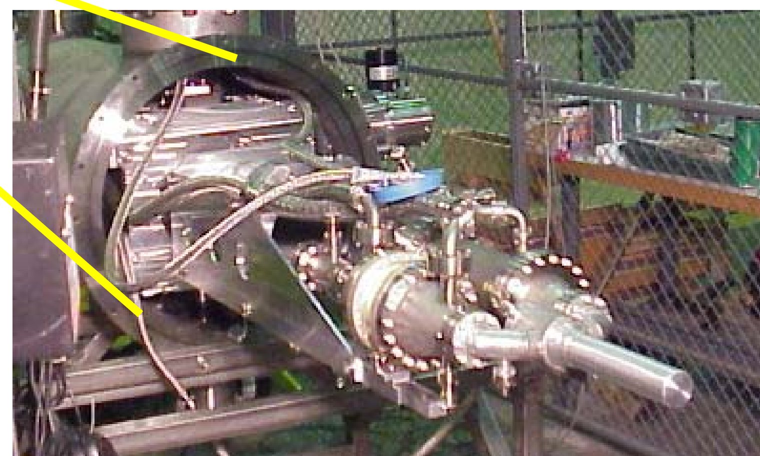
G^0 Apparatus

One octant scintillator array





20 cm LH_2 Target



SMS Magnet

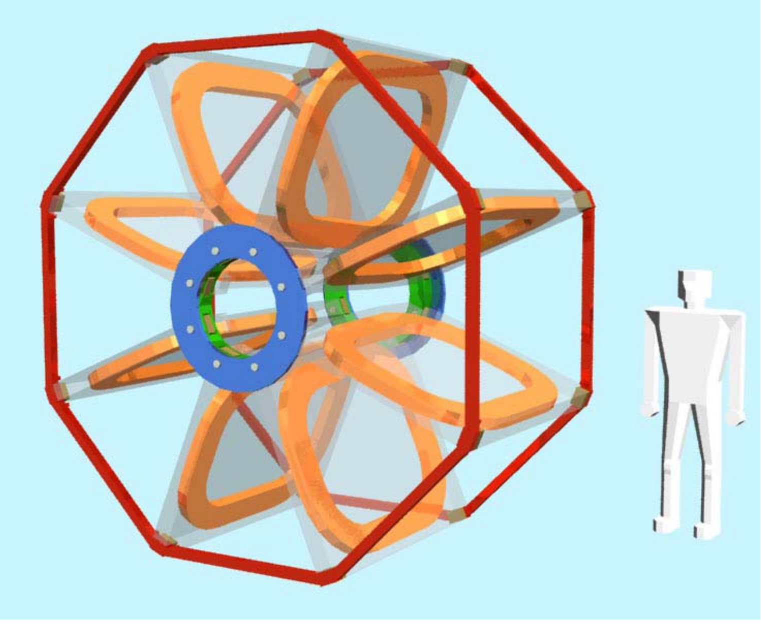
G^0 Superconducting Magnet System

Superconducting toroidal magnet:
8 coils

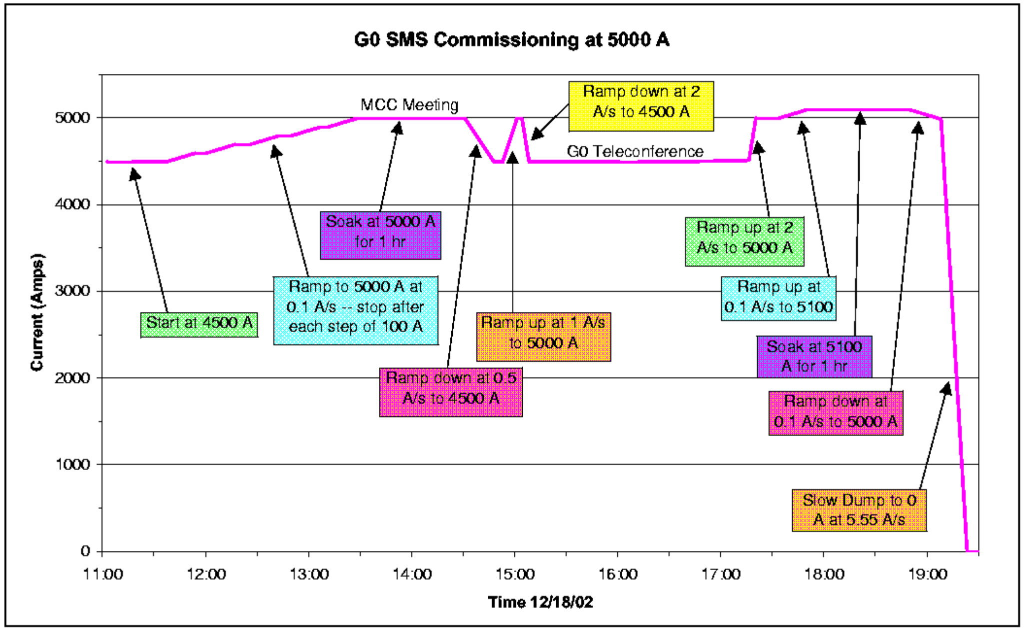
$$\int B \cdot dl = 1.6\ \text{Tm}$$

$$35^\circ < \theta_{bend} < 87^\circ$$

$$\phi\ \text{acceptance} \sim 0.44\,(2\pi)$$



- Initial manufacturing defects repaired in early 2002
- Ran at 4500 A initially (Aug. - Dec. 2002)
- Ran at full design current (5000 A) on Dec. 18, 2002
- Has operated satisfactorily up to 5100A since then

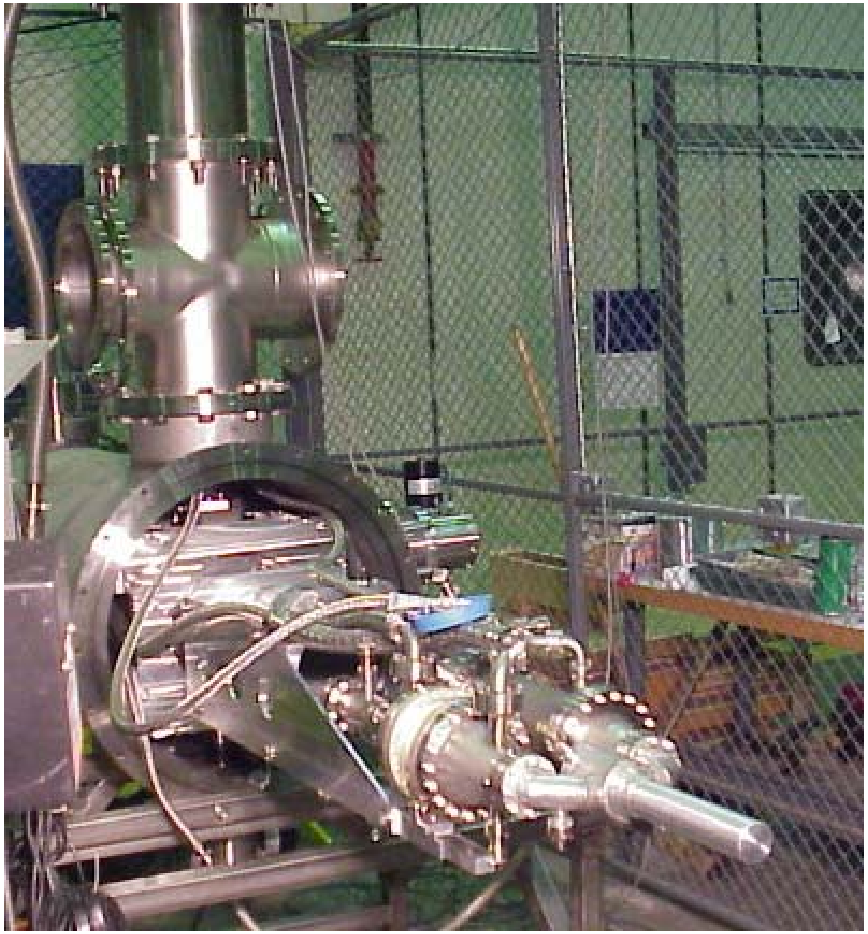


G0 Target

Designed and constructed at Caltech
(Controls system by U Md/JLab)

- **20 cm LH_2 cell**
- **High circulation rate to minimize target density fluctuations**
- **250 W heat load from beam**

Target performed excellently

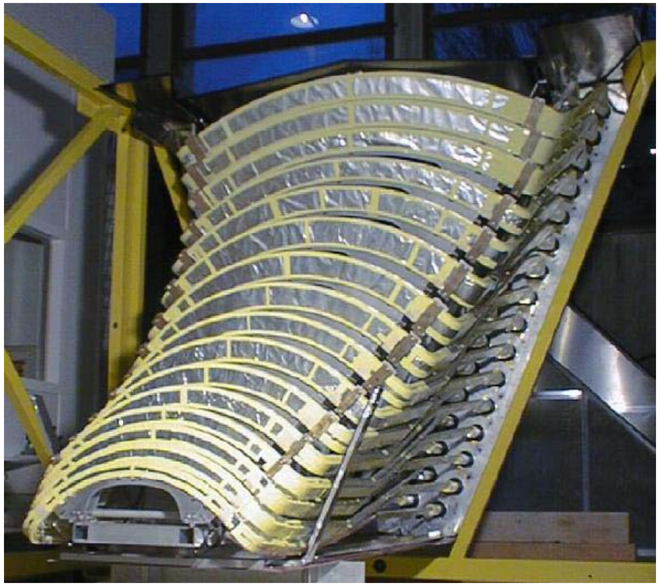


Target loop in Jlab Test Lab

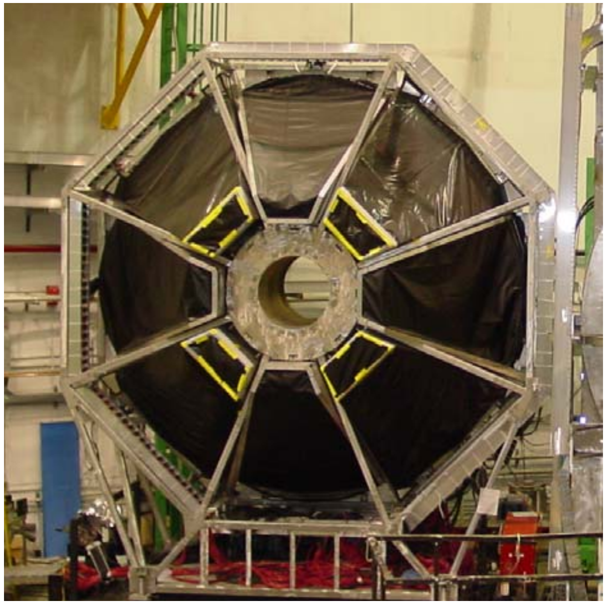
G^0 Focal Plane Detectors (FPD)

- 16 pairs of arc-shaped scintillators (iso-Q^2)
- F/B coincidences to eliminate neutrals
- 4 PMTs (one at each end of scintillators)
- Long light guides (PMT in low B field)

NA octant

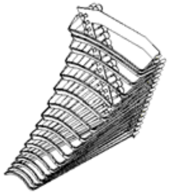


FR octant

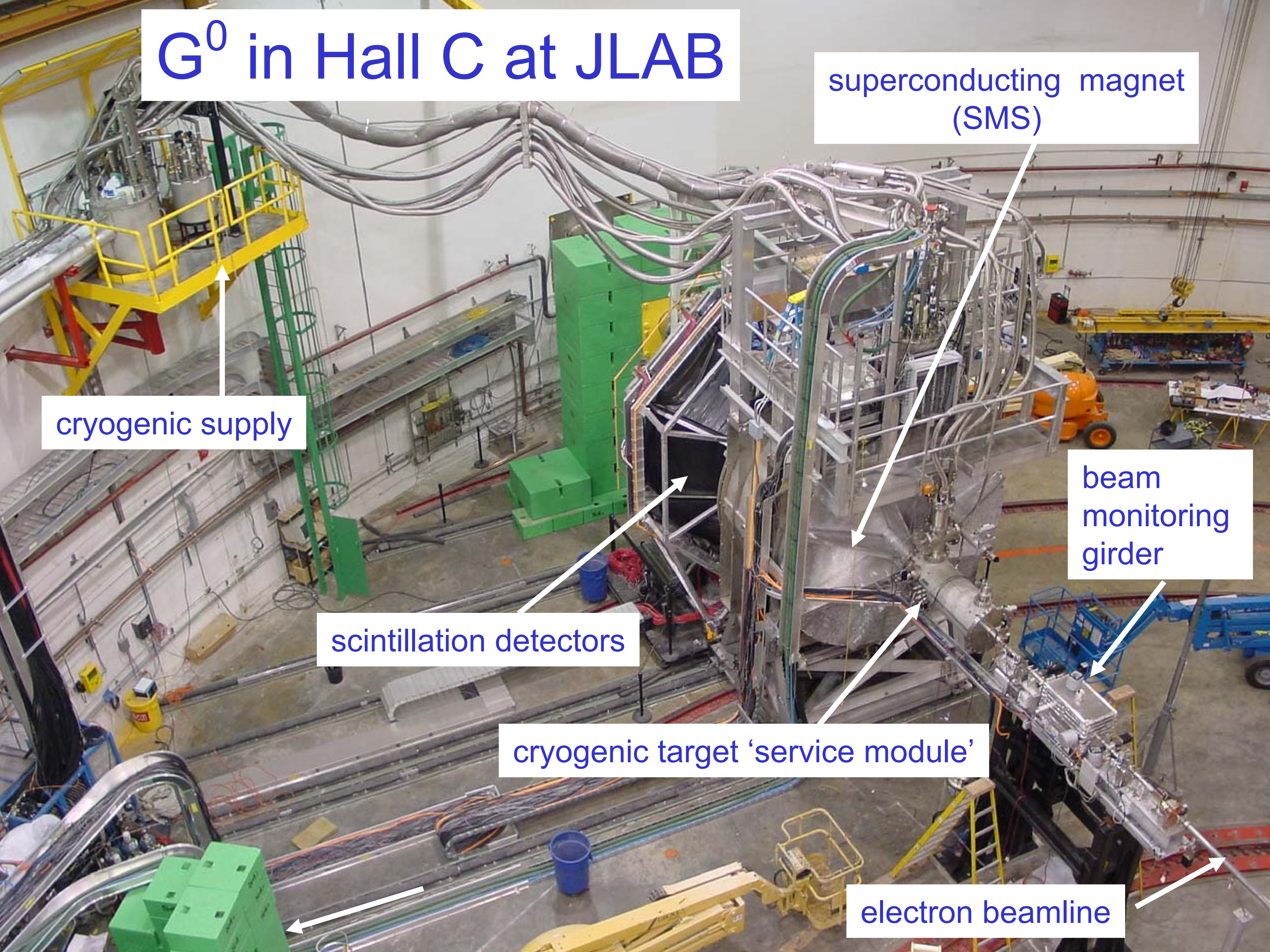


Detector
"Ferris wheel"

Detector Assembly

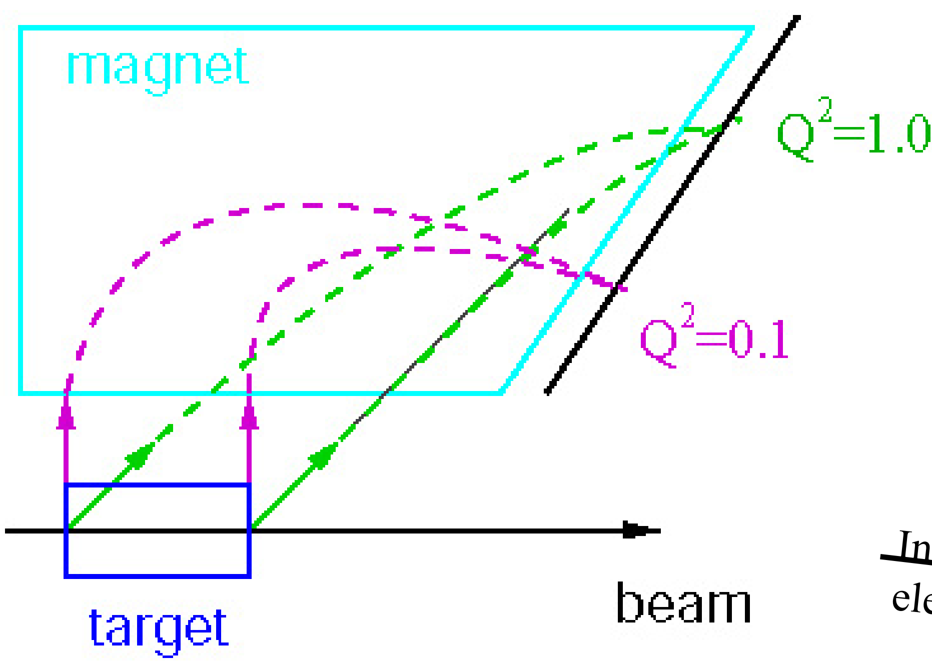


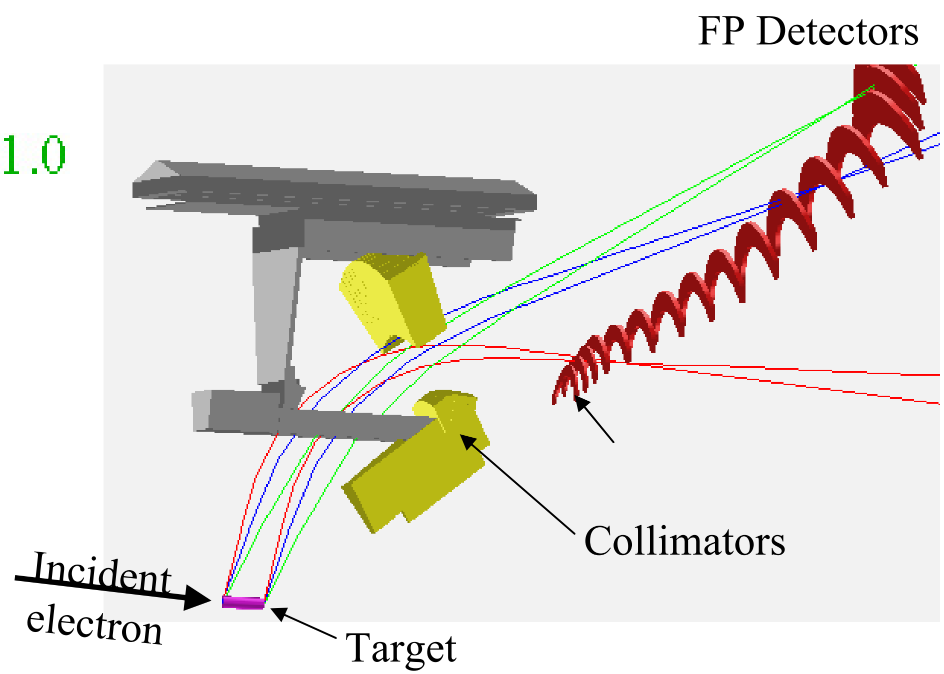
G^0 in Hall C at JLAB



G^0 Forward Angle Mode

- **Electron beam energy = 3 GeV on 20 cm LH_2 target**
- **Detect recoil protons ($\theta \sim 62$ - 78^o corresponding to 15 - 5^o electrons)**
- **Magnet sorts protons by Q^2 in focal plane detectors**
- **Full desired range of Q^2 (0.12 - 1.0 GeV^2) obtained in one setting**
- **Beam bunches 32 nsec apart (31.25 MHz = 499 MHz/16)**
- **Flight time separates p (about 20 ns) and π^+ (about 8 ns)**





Event Counting

Event rate up to 4 MHz for each detector (Front/Back coinc.)

16 x 8 detectors ⇒ up to 128 x 4 MHz = 512 MHz (total)

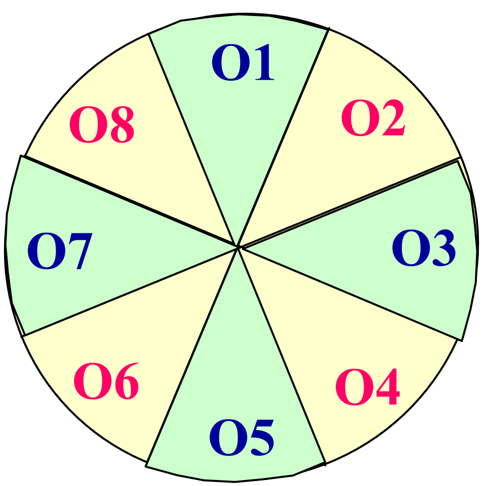
Data Flux

Forward angles measurements

Total Flux : ~ 2MB / s

1000h beam time (3.6 10^6 s) ⇒ **7 x 10^6 MB**

More than 20TB on disks!



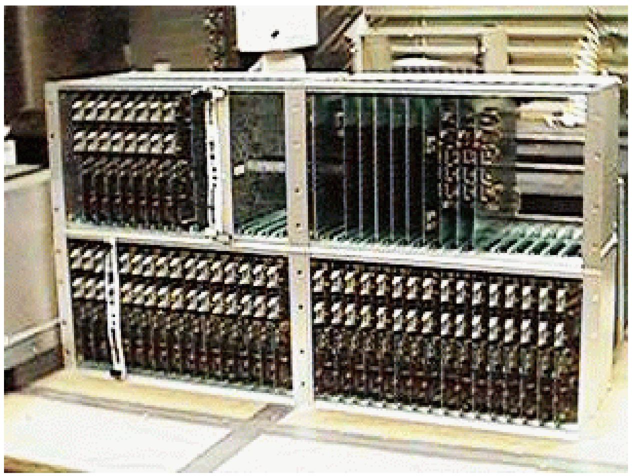
Odd Octant number **: " North American"**

Even Octant number **: " French"**

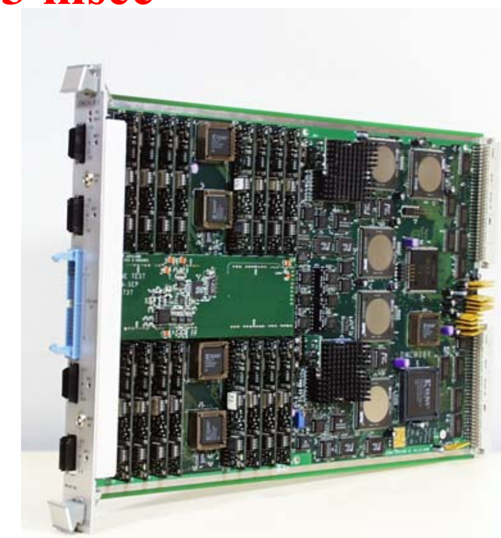
⇒ **2 different electronics designs**

G^0 Forward Angle Electronics

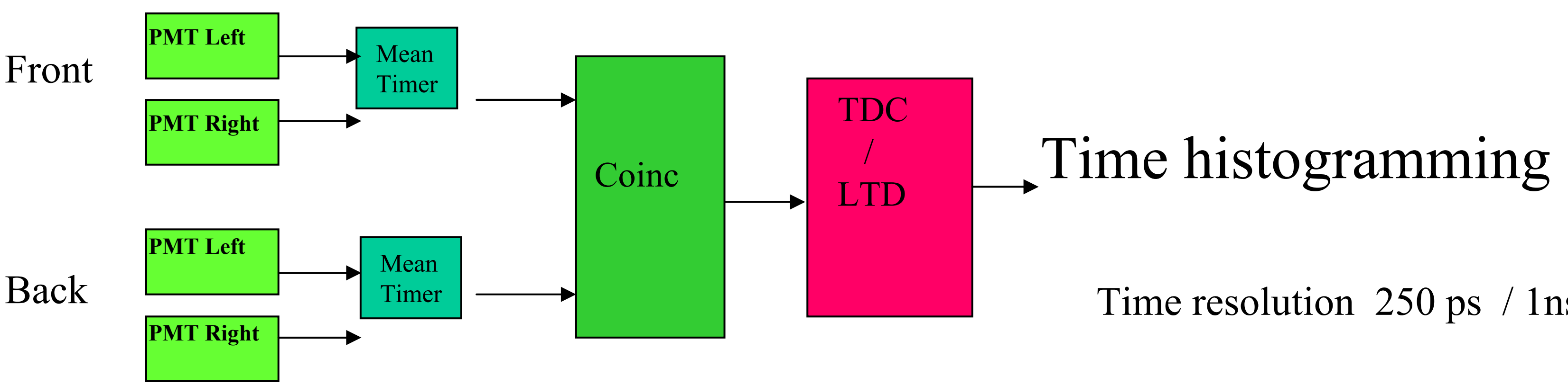
- **NA: mean timer → latching time digitizer → scalers (1 ns binning)**
- **French: mean timer → flash TDCs (0.25 ns binning) →Digital Signal Processors (DSPs)**
- **Time histograms read out by DAQ system every 33 msec**



NA LTD crate (1/2)



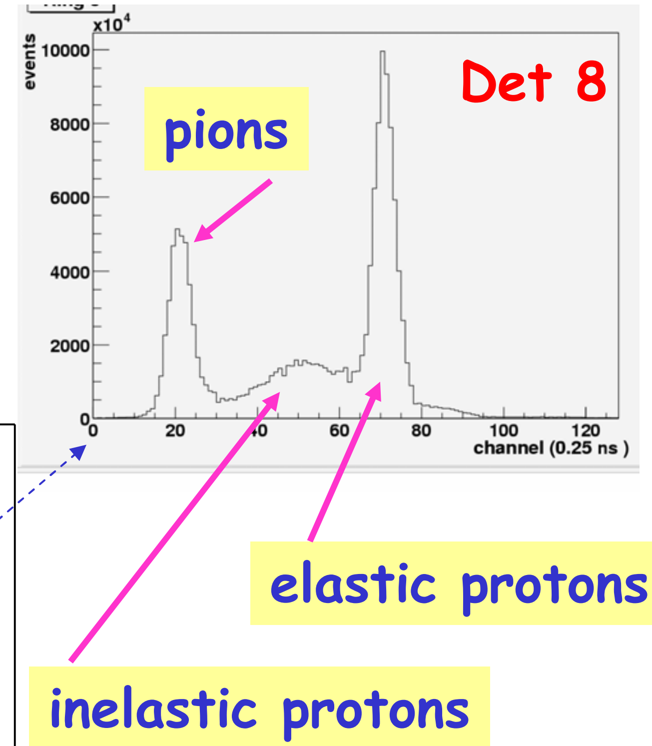
French DMCH16 Module 1/8



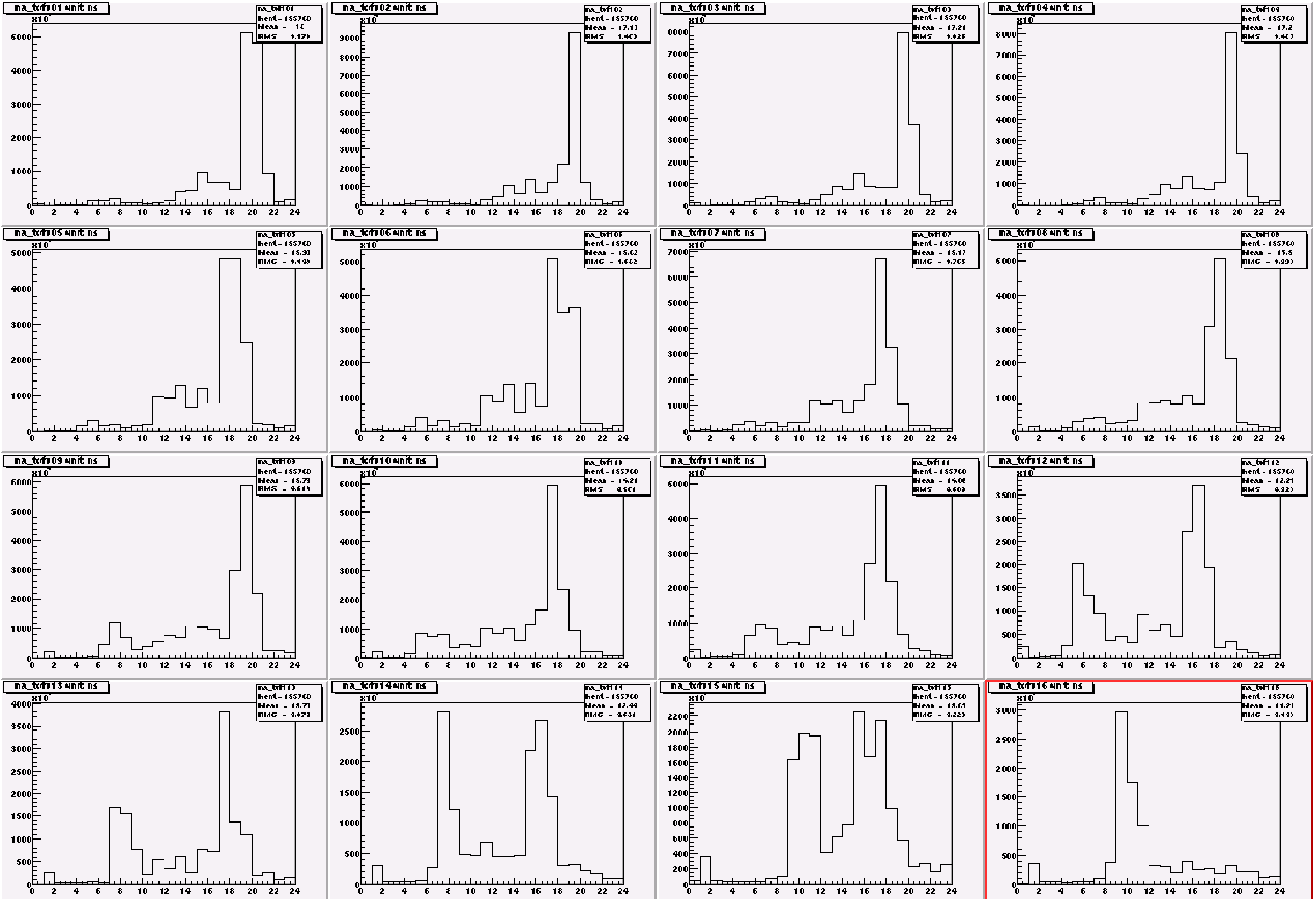
FR Time of Flight Spectra

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

1	2	3	4
5	6	7	8 3
9	10	11	12
13	14	15	16



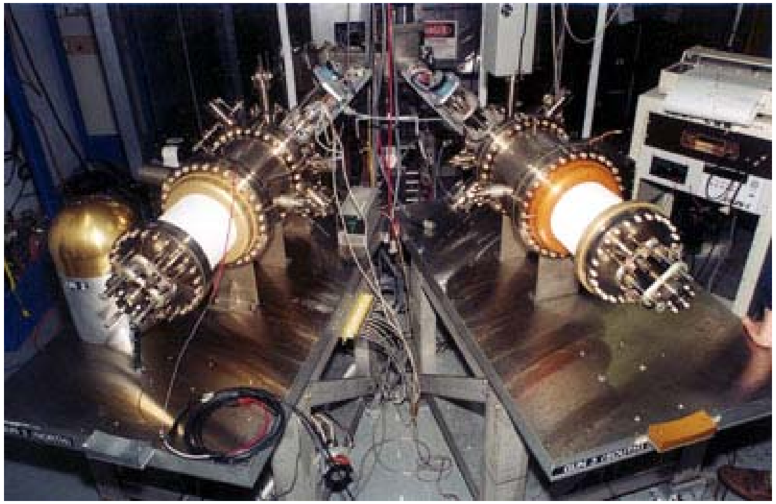
North American TOF spectra



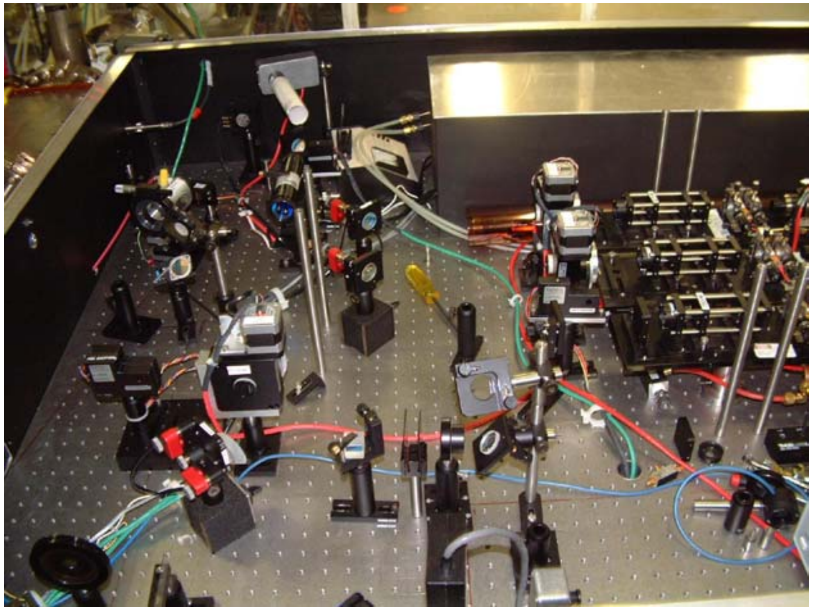
G^0 Beam

- G^0 beam requires unusual time structure: 31 MHz (32 nsec between pulses)
  1/16 of usual CEBAF time structure of 499 MHz (2 nsec between pulses)
- Required new Ti:Sapphire laser in polarized electron gun
- Higher charge per bunch (40 muA at 31 MHz is equivalent to 640 muA at 499 MHz)
  $\rightarrow$ space charge effects complicated beam transport in injector
- Beam with most desired properties delivered in Jan. 2003
  - Beam current 40 μA
  - Beam fluctuations at (30 Hz/4) ~ ΔX, ΔY < 20 μm ΔI/I < 2000 ppm

CEBAF polarized injector

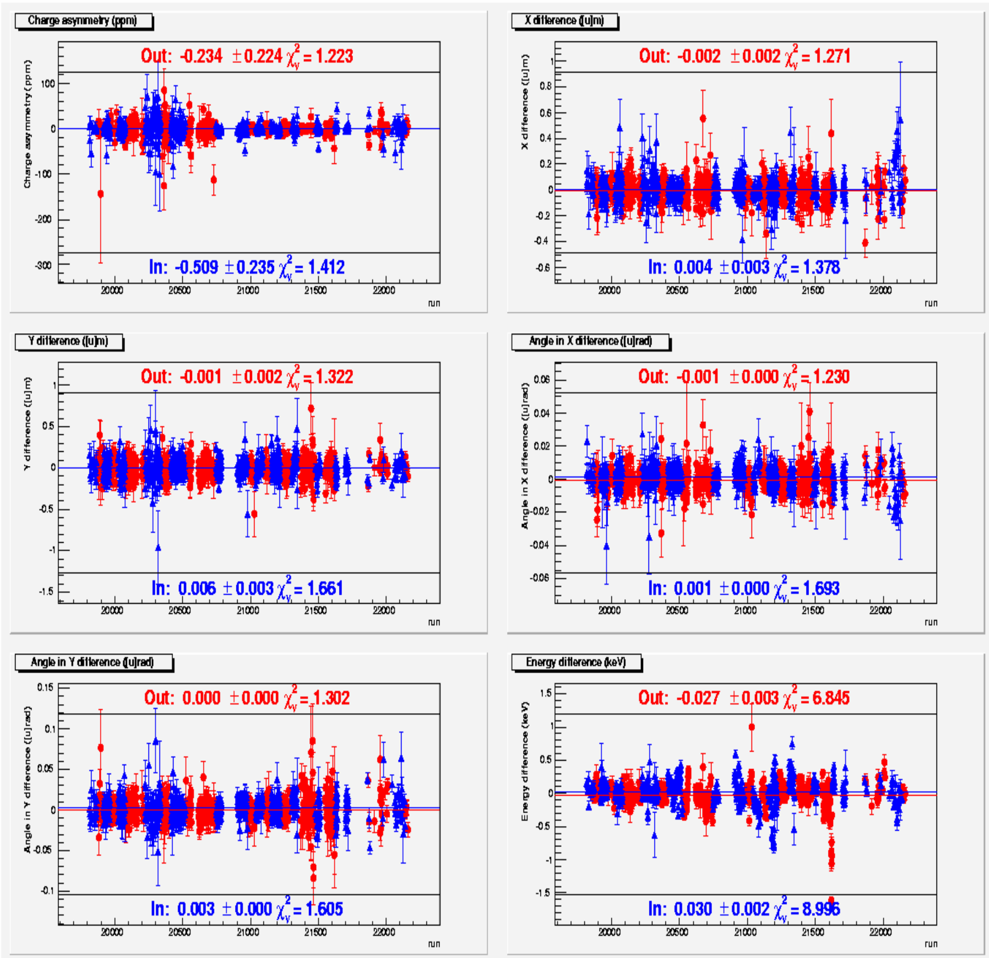


CEBAF polarized injector laser table



Parity Quality Beam

Total of 744 hours (103 Coulombs) of parity quality beam with a 4σ cut on parity quality.

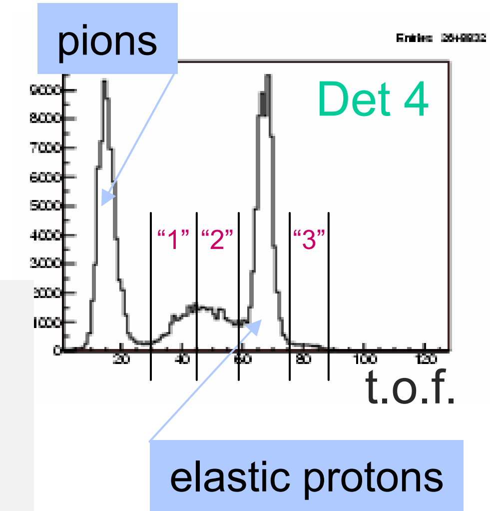


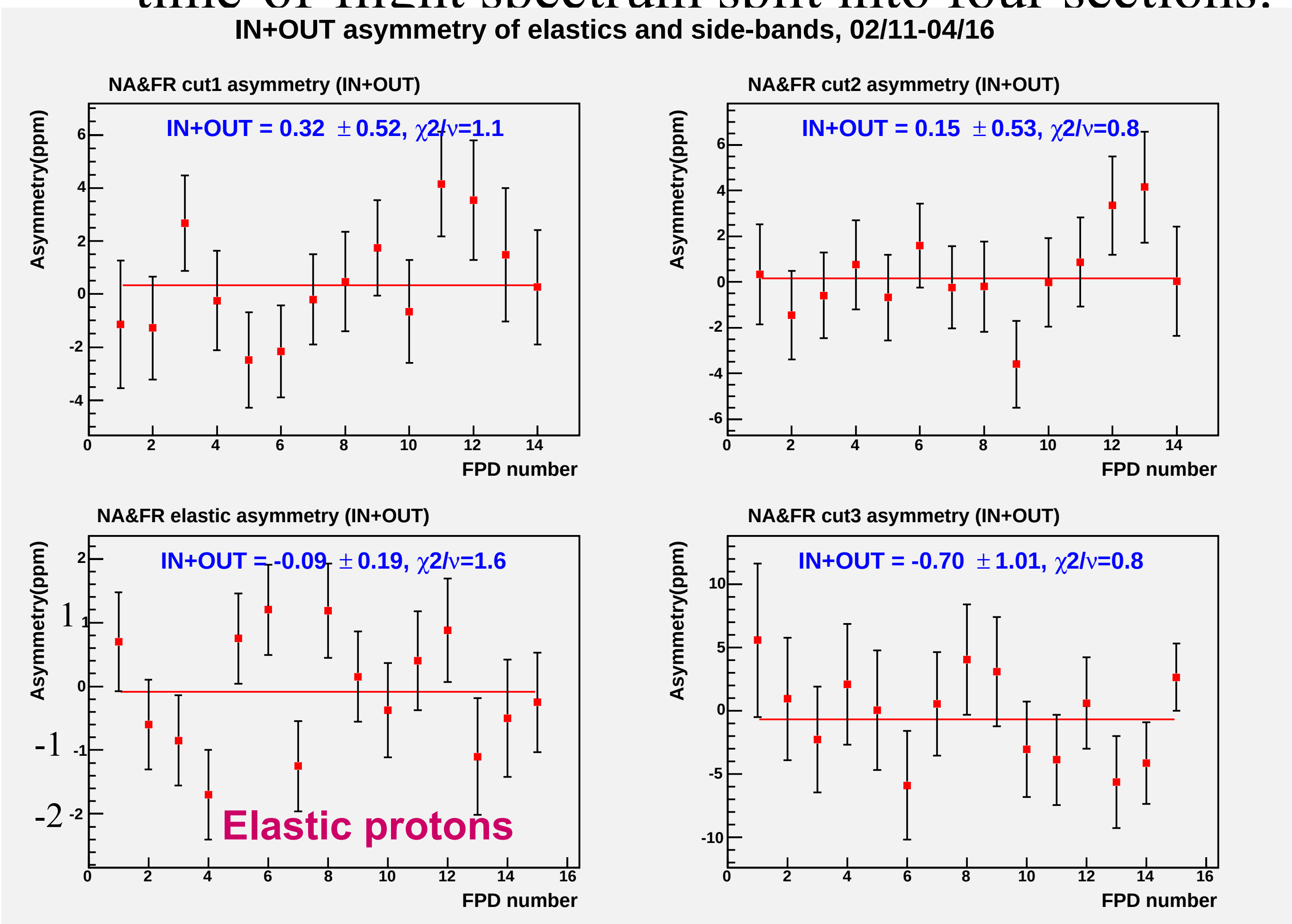
Beam Parameter	**Achieved**	**“Specs”**
Charge asymmetry	-0.14 ± 0.32 ppm	1 ppm
x position differences	3 ± 4 nm	20 nm
y position differences	4 ± 4 nm	20 nm
x angle differences	1 ± 1 nrad	2 nrad
y angle differences	1.5 ± 1 nrad	2 nrad
Energy differences	29 ± 4 eV	75 eV

All parity quality specs have been achieved!!

G0 Update: IN + OUT results

- Check for asymmetries in electronics
  - measure zero with uncertainty of ~ 0.2 ppm
  - time-of-flight spectrum split into four sections:





G0: Analysis Path

Start: Raw asymmetries

↓

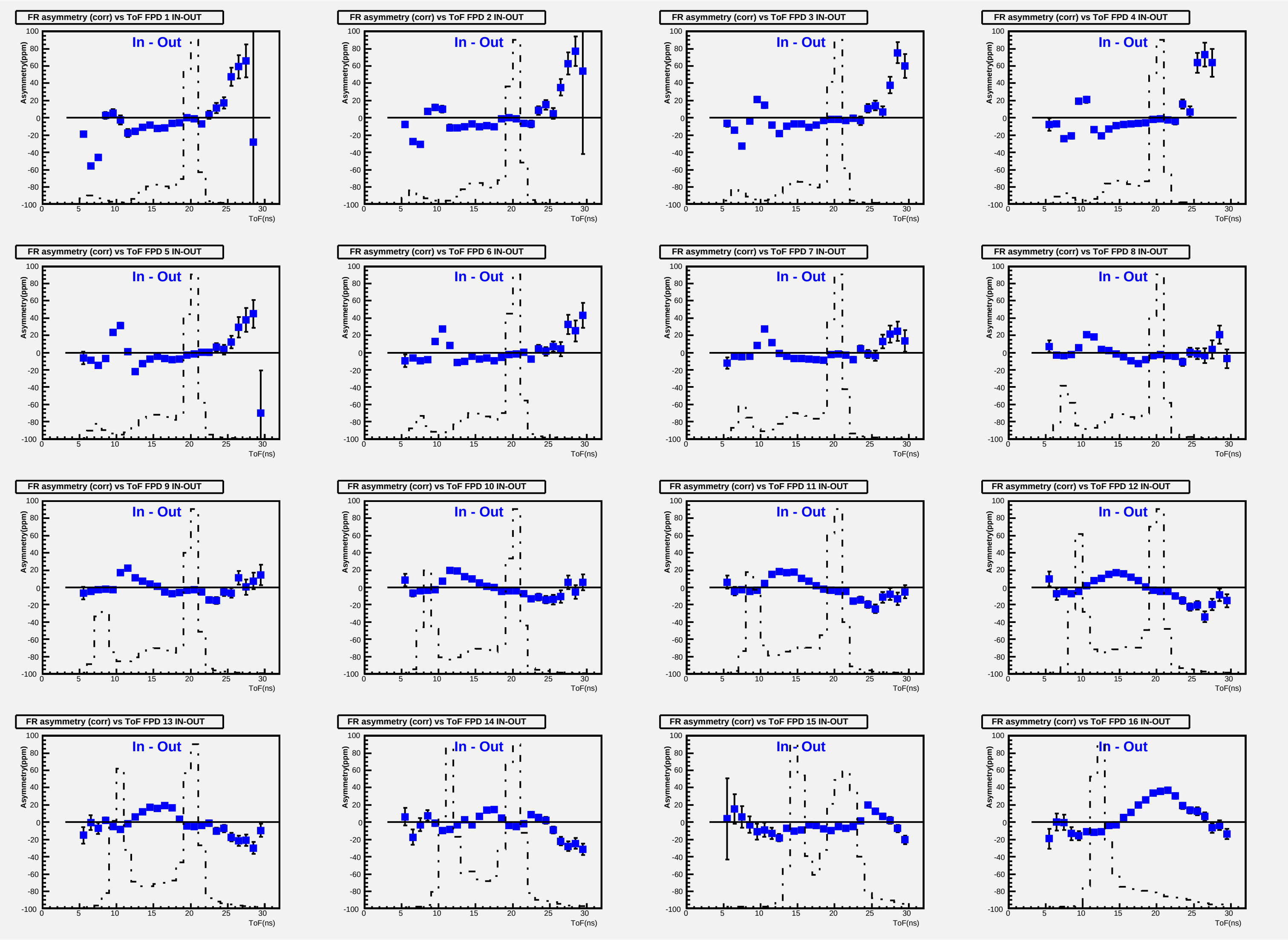
- Correct for deadtime — 1% error ✓
- False asymmetries (beam parameters) — 0.01 ppm ✓
- 'Leakage' correction — 0.10 ppm ✓
- Beam Polarization — 2% error ✓
- Background dilution & asymmetry — (under study)
- Bin in Q^2 — 1% error ✓
- Radiative Corrections, EM form factors — (to do)

↓

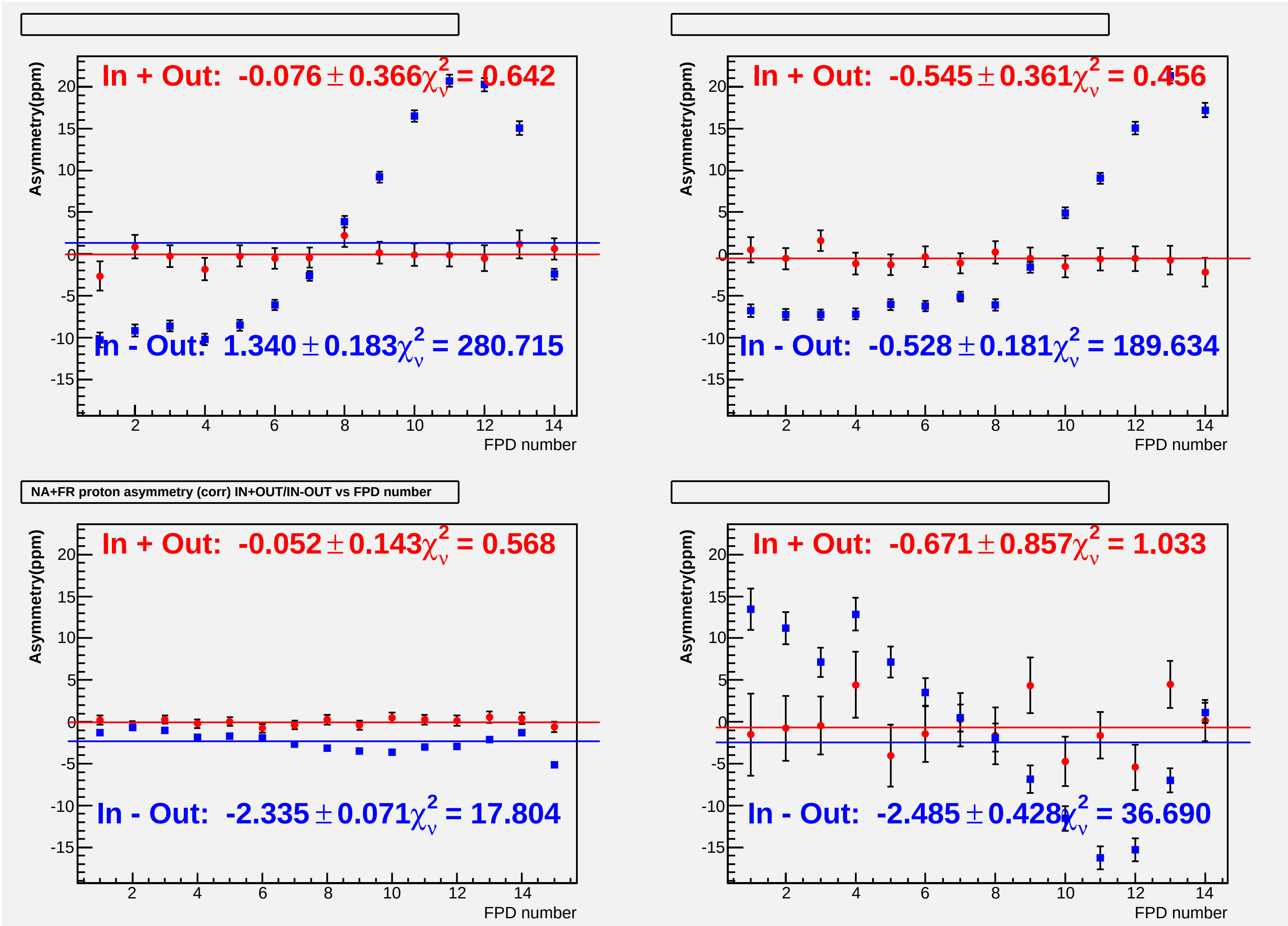
Result: $G_E^s + \alpha\, G_M^s$

errors likely dominated by backgrounds, esp. for large Q^2

Asymmetries in ToF spectra



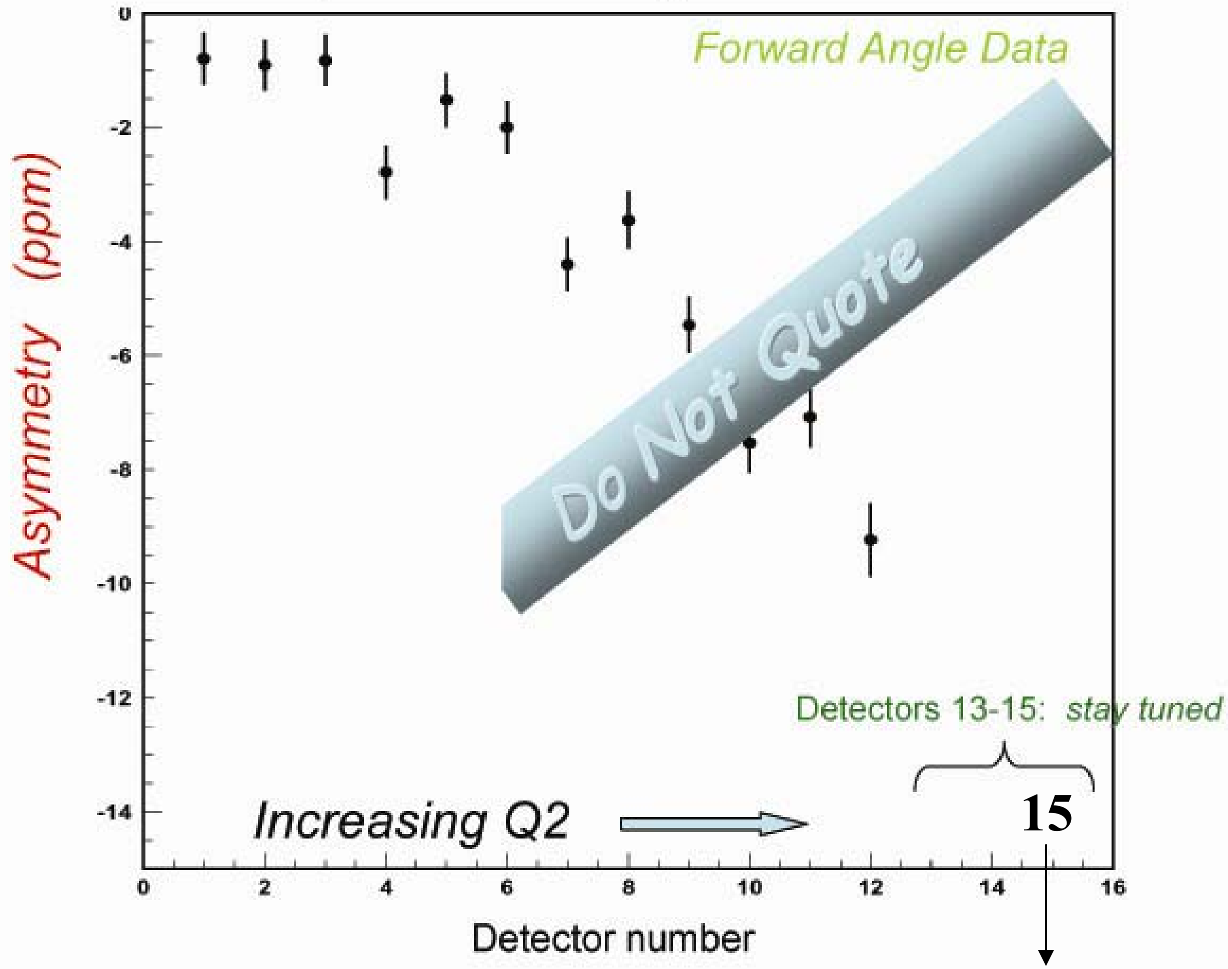
cut 1 | cut 2



elastic cut | cut 3

G0 Preliminary Result: Blinding Factor of 25%

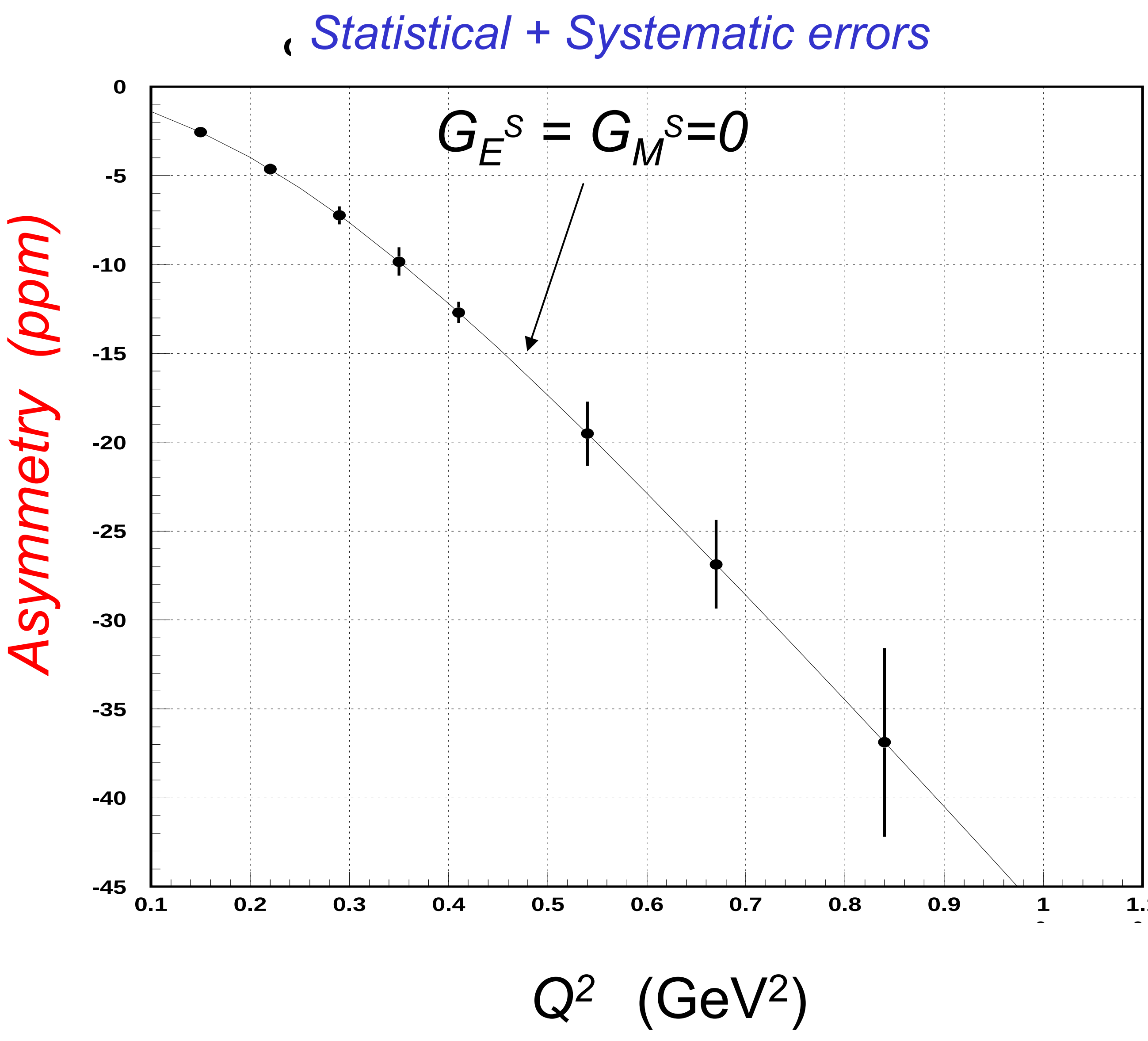
- Full statistics – present best background correction



0.5-1.0

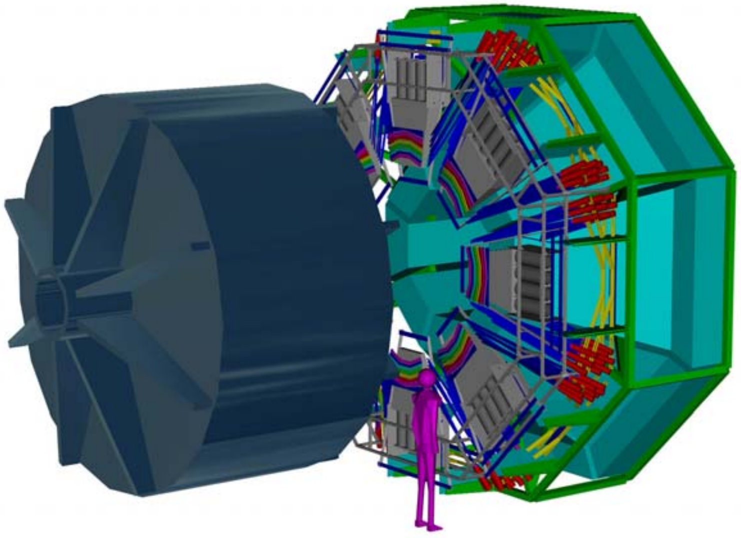
Q2 0.12 0.20 0.30 0.40

G0: Presently Estimated Final Precision



G0 Backward Angle Measurement

- Q^2= 0.8 $(GeV/c)^2$ approved by PAC Jul '01
- Turnaround done in Summer '04, installation and testing of new detectors Jan-May 05
- Installation in beam line: Sept-Nov 05 (?)
- Data taking late '05
- 2nd, 3rd Q^2 points at backward angles in 2006-7? (not yet approved by PAC)



The Second Generation HAPPEX Experiments

The HAPPEX Collaboration

California State University, Los Angeles - Syracuse University - DSM/DAPNIA/SPhN CEA Saclay - Thomas Jefferson National Accelerator Facility - INFN, Rome - INFN, Bari - Harvard - Indiana University - University of Virginia - University of Massachusetts - Florida International University - University of New Hampshire - Massachusetts Institute of Technology - College of William and Mary in Virginia

Parity Violation and Hadronic Structure / Grenoble, 9 Jun 2004

Courtesy of D. Armstrong, D. Lhuillier and R. Holmes

The HAPPEX Experiments

- ***HAPPEX I, e-p Q^2=0.5 $(GeV/c)^2$***
- ***HAPPEX-H: e-p, Q^2=0.1 $(GeV/c)^2$***
- ***HAPPEX-He: e-^{4}He, Q^2=0.1 $(GeV/c)^2$***
- ***PREX: e-Pb, Q^2=0.01 $(GeV/c)^2$***

HAPPEX-H (JLAB E99-115)

- Polarized e^- on ^1H
- $Q^2 = 0.1\ (GeV/c)^2$, 6□
- $A^{PV} = 1.6$ ppm

□ $\Delta A = 5\%$ (stat) + 2.5% (syst)

- Some preliminary data $\Delta A = 15\%$ (stat) taken

24 June- 26 July, 2004, results expected in October

- Remainder of statistics in Fall 2005

HAPPEX-He (JLAB E00-114)

- Polarized e^- on ^4He
- $Q^2 = 0.1\ (GeV/c)^2$, 6°
- $A^{PV} = 8.4$ ppm
- $\delta A = 2.2\%$ (stat) + 2.1% (syst)

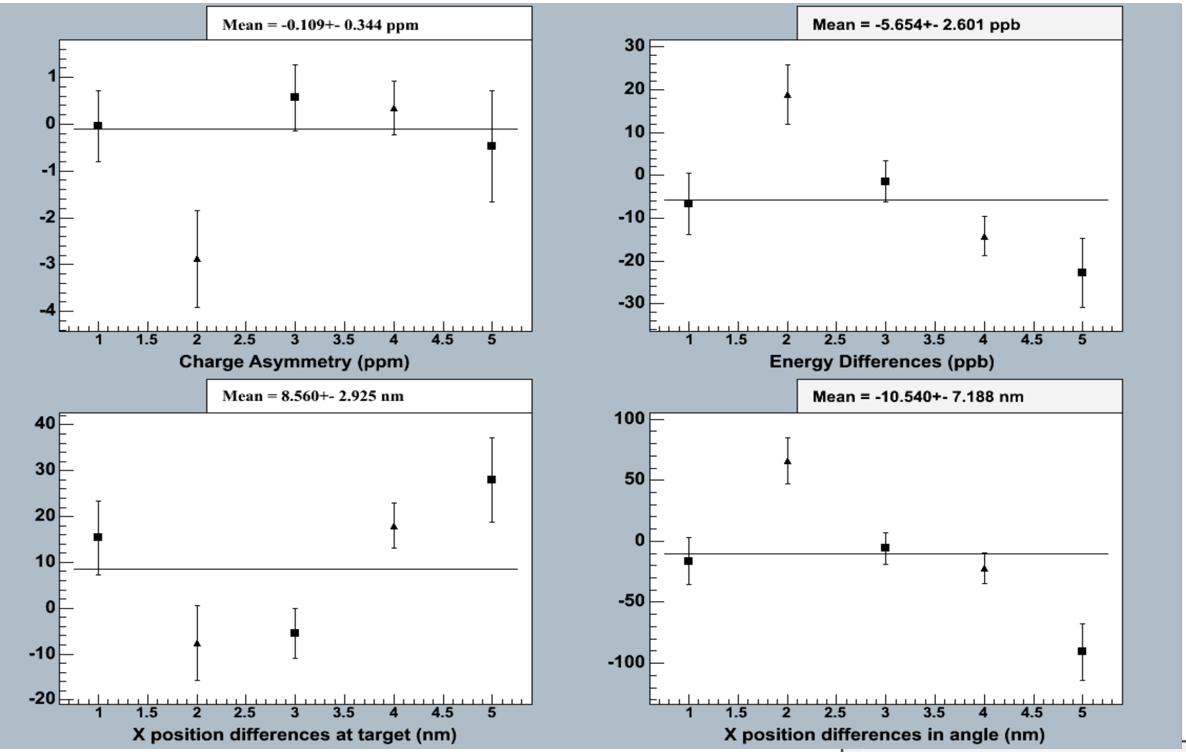
$$A^{PV} = -\frac{A_0}{2}\left(2\sin^2\theta_W + \frac{G_E^s}{G_E^{p\gamma} + G_E^{n\gamma}}\right)$$

For Helium => A^{PV} sensitive *only* to $G^s{}_E$

What's new at HAPPEX

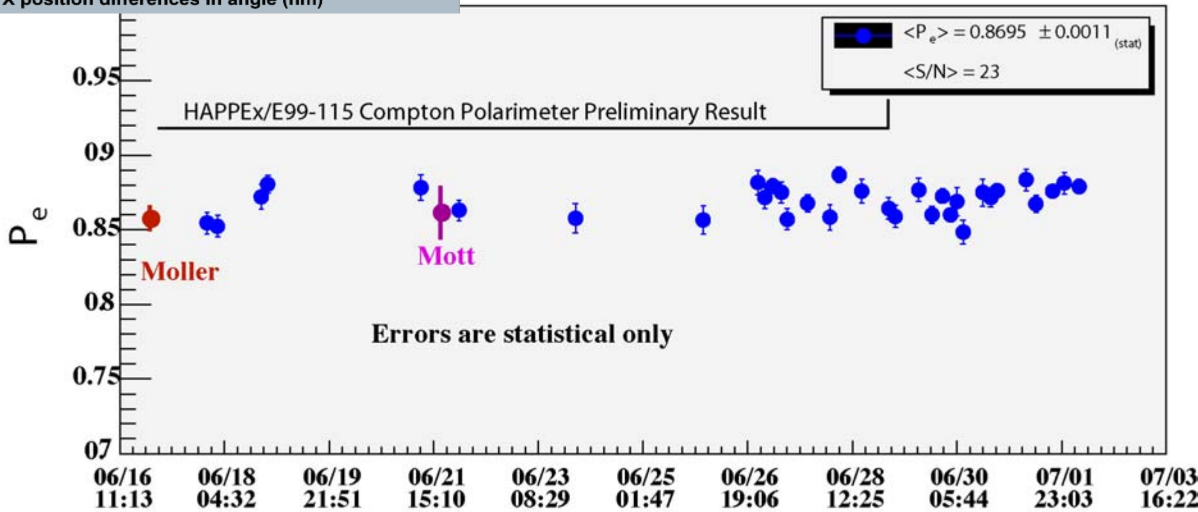
- New septum magnets
- New target cell
- Improved polarized source
- Improved polarimetry
- New Cerenkov detectors
- New luminosity monitors
- New profile scanners
- New beam monitors
- Improved DAQ

Highly Polarized Beam



- ^{4}He running used *superlattice photocathode*
- *5 λ/2 flips during run*
- *position differences controlled by careful alignment of polarized electron source optical elements*
- *no active position feedback*

Polarization monitored continuously with a Compton polarimeter: Average ~ 86%



HAPPEX-H & HAPPEX-He

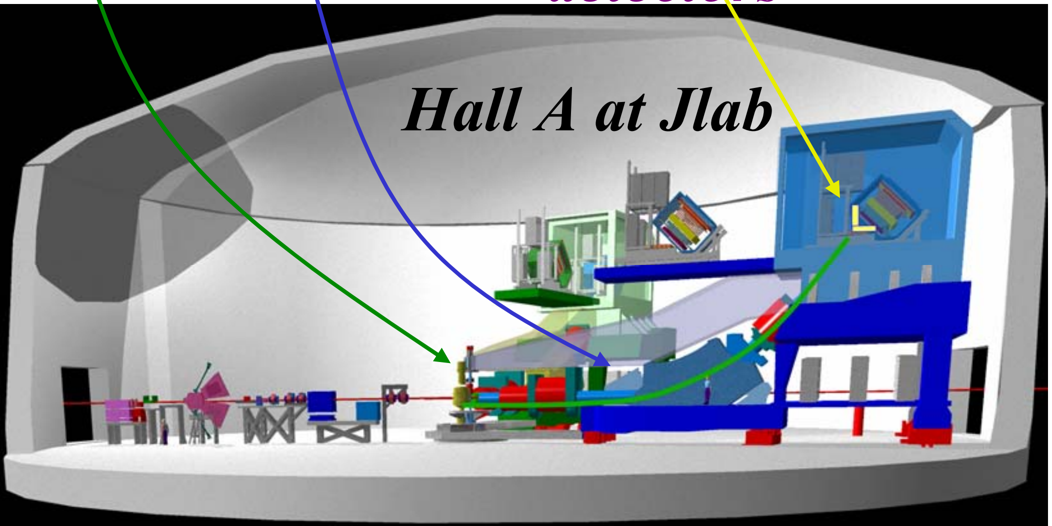
3 GeV beam in Hall A $\theta_{lab} \sim 6°$ $Q^2 \sim 0.1\ (GeV/c)^2$

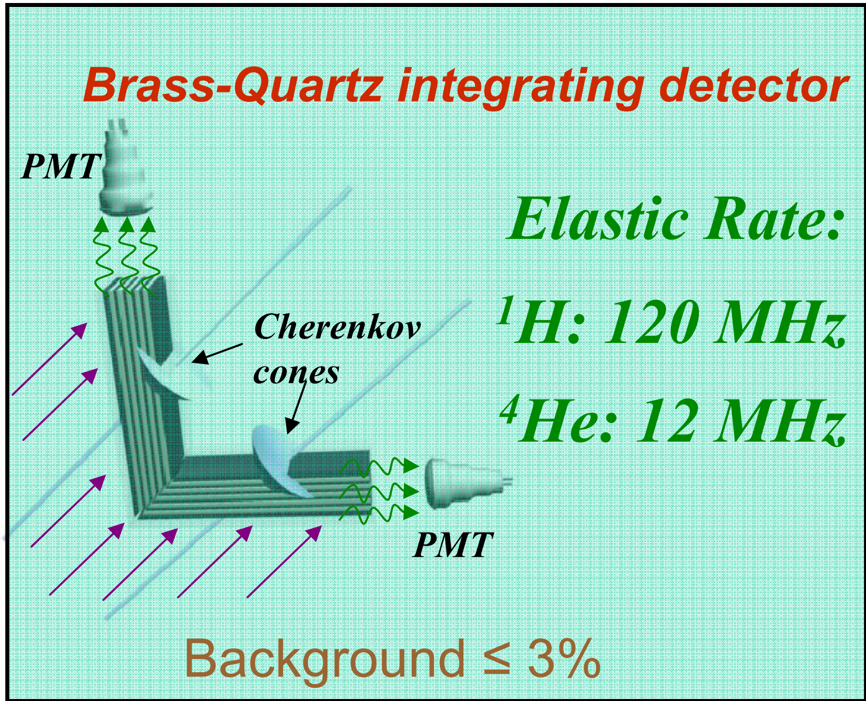
target	A_{PV} $G^s = 0$ (ppm)	Stat. Error (ppm)	Syst. Error (ppm)	sensitivity
^1H	-1.6	0.08	0.04	$\delta(G^s_E+0.08G^s_M) = 0.010$
^4He	+7.8	0.18	0.18	$\delta(G^s_E) = 0.015$

Septum magnets (not shown)

High Resolution Spectrometers

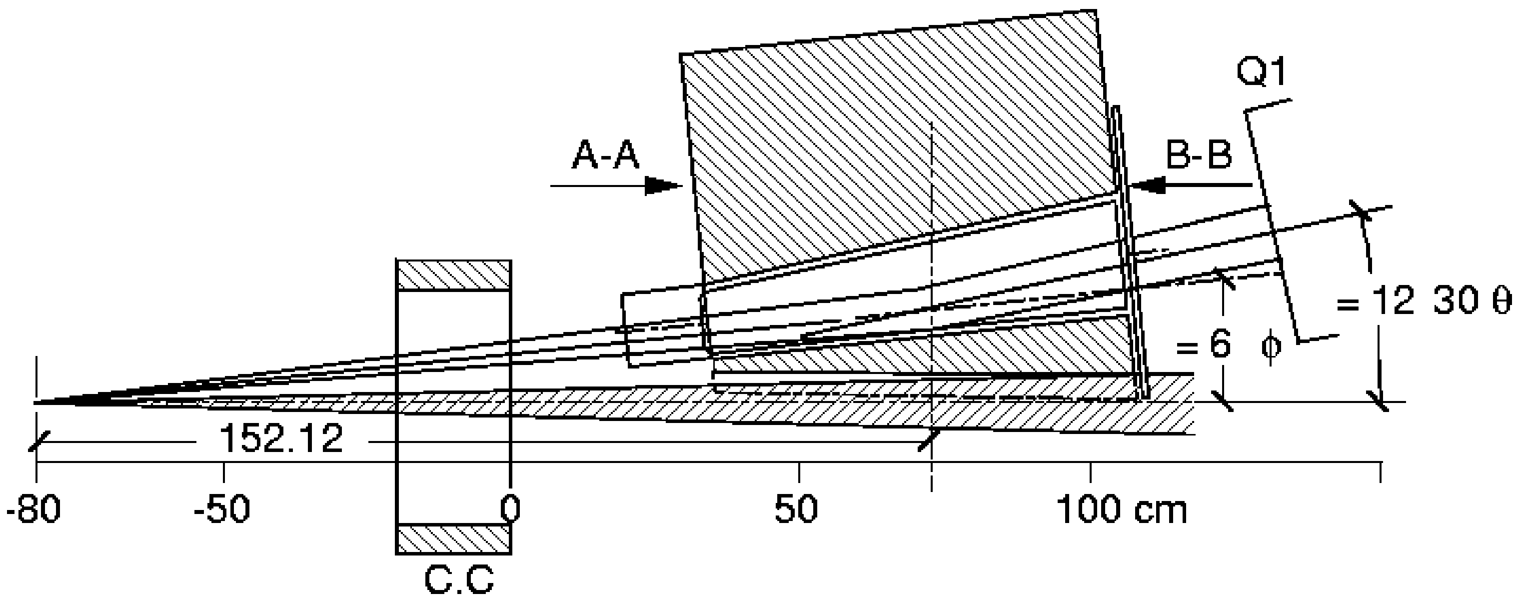
detectors





Septum magnets

- Minimum scattering angle 12.5° -> 6.0°
- Installed and commissioned 2003-2004



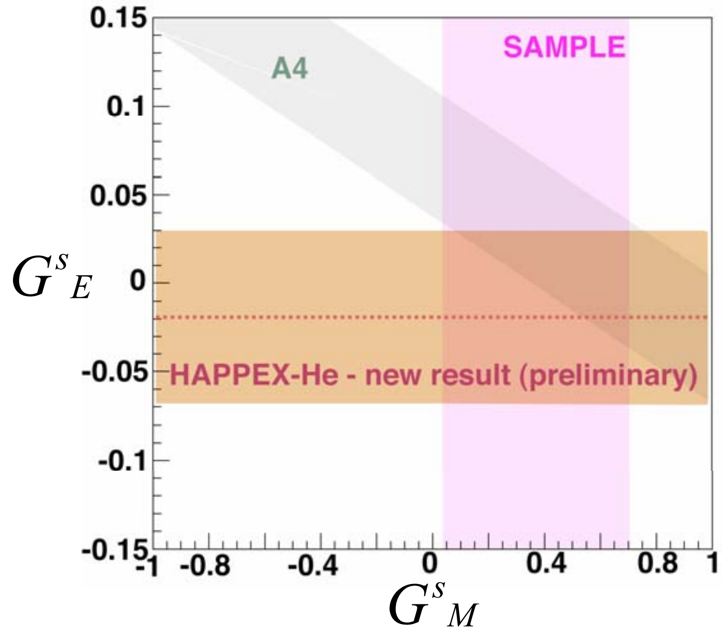
^{4}He Result & Future Prospects

A_{PV} (after all corrections):
+7.40 ± 0.89 (stat) ± 0.57 (syst) ppm

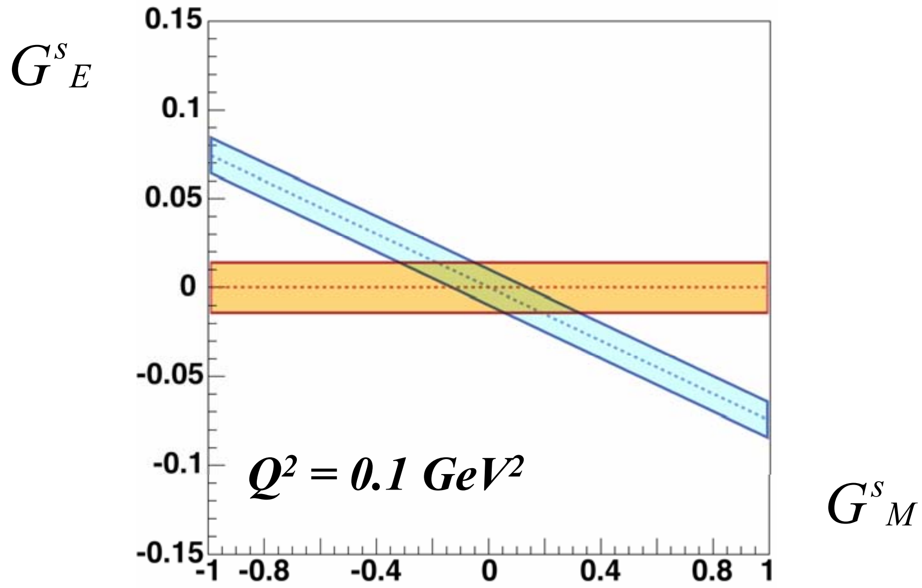
Preliminary!

Theory prediction (no strange quarks):
+7.82 ppm

G^s_E (Q^2 = 0.1 GeV^2) =
-0.019 ± 0.041 (stat) ± 0.026 (syst)



Anticipated results after final run (2005)



CONCLUSIONS

G^0 Forward

- Data taking completed May 17, 2004.
- Data under analysis. Unblinded results expected for Fall '04

G^0 Backward

- $Q^2 = 0.8\ (GeV/c)^2$ approved by PAC July 2001
- Turnaround started in Aug 2004, data taking late '05
- $Q^2 = 0.3 - 0.5\ (GeV/c)^2$ in 2006-7 if approved by PAC

HAPPEX

- First results on He
- Some data on Hydrogen at $Q^2 = 0.1$
- Full statistics in Fall 2005

Parity Violation Experiments at JLab are alive and going well

G^0 Backward Angle Measurement (1)

- **Detect scattered electrons at $\theta_e \sim 110^o$**
- **At back angles Q^2 only has small variation in G^0 acceptance**

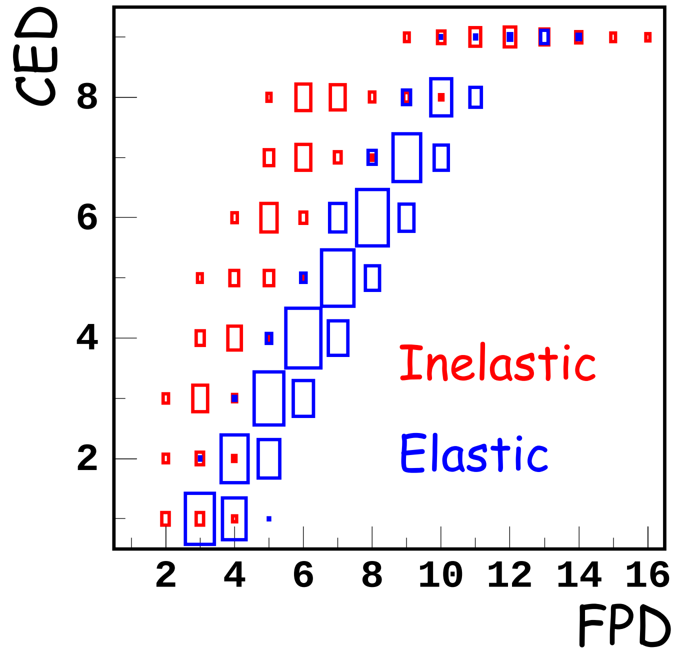
$\rightarrow$ Need separate runs at E = 424, 576, 799 MeV

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)

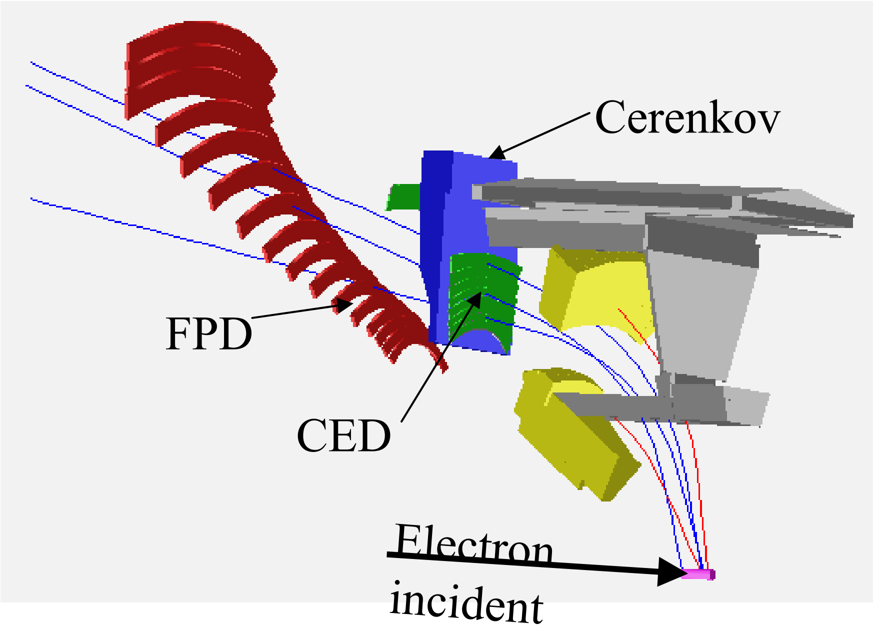
CED/FPD coincidences at Q^2 = 0.3 GeV^2



G0 Backward Angle Measurement (2)

Requires additional detectors: Cryostat Exit Detectors (CED) to separate elastic and inelastic electrons Cerenkov detector for pion rejection(primarily for LD2 target)

Ebeam	π/e ratio	
(MeV)	H	D
424	0.01	0.4
585	0.04	1.0
799	0.4	11.4



SMS Turnaround

- SMS turnaround took place Aug. 23

- Lockwood set up and performed the rotation (with Hall C support) in 4 days

- "Back" plate removed to help balance and achieve vertical lift -> a little extra Counterbalance weight Still needed

Ferris Wheel Turnaround

• FW turnaround was done on Aug. 11

• FW supported by 12 points (8 above, 4 below)

• Scales were used to carefully measure load at each point and ensure vertical lift