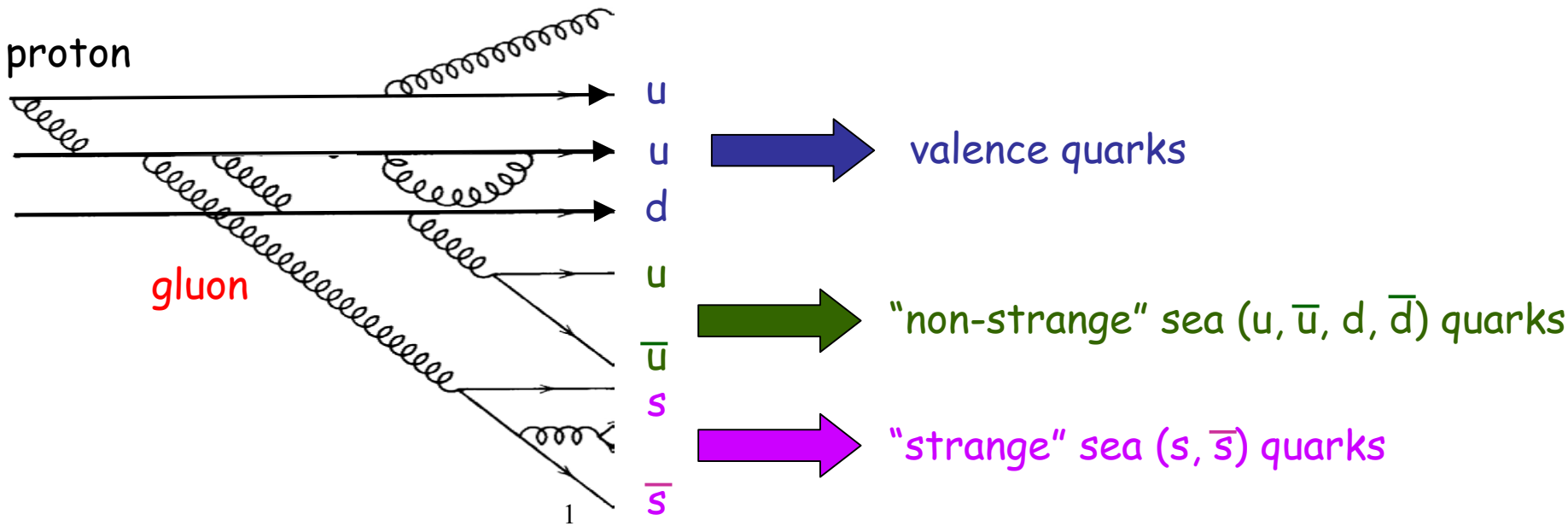
Proud member of the

What role do strange quarks play in nucleon properties?



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

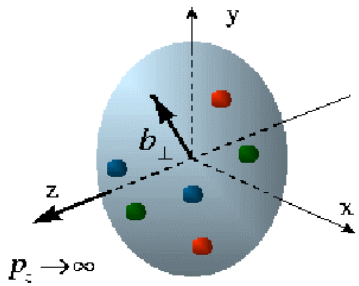
Spin: $< N | \bar{s}\gamma^5 s | N > \sim -10\%$ (polarized DIS)

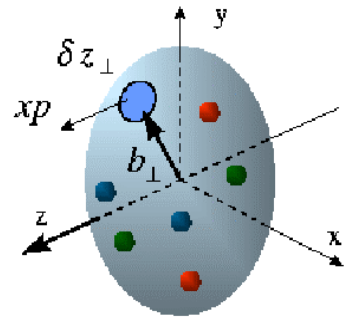
Mass: $< N | \bar{s}s | N > \sim 30\%$ (πN σ - term)

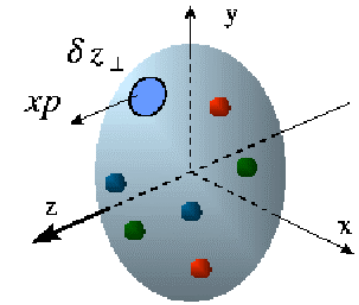
Charge and current: $< N | \bar{s}\ \gamma^\mu\ s | N > = ?? \rightarrow G_E^s\ G_M^s$

Main goal of G^0 : To determine the contributions of the strange quark sea (s s) to the electromagnetic properties of the nucleon ("strange form factors").

The complete nucleon landscape - unified description







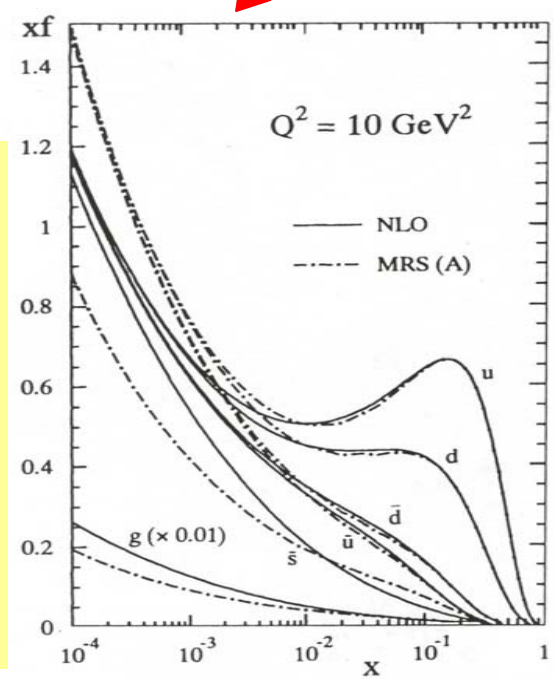
Elastic scattering:
transverse quark distribution
in coordinate space

Deep exclusive scattering (DES):
Generalized parton dist. (GPD):
fully-correlated quark distribution
in coordinate and momentum space

Deep inelastic scattering (DIS):
longitudinal quark distribution
in momentum space

Electric and magnetic form
factors well - measured
$G_E \quad G_M$ for p, n
BUT quark flavor decomposition
of these form factors is not yet known
$G^u_{E,M} \qquad G^d_{E,M} \qquad G^s_{E,M}$

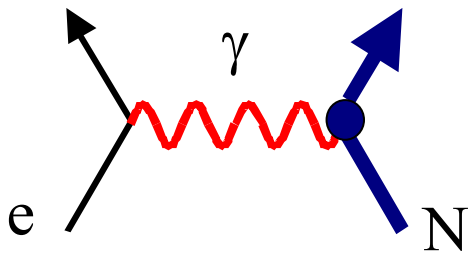
Measured nucleon
momentum fractions
$(Q^2 = 2\,\mathrm{GeV}^2)$:
$\varepsilon_{u+\bar{u}} \sim 37\%$
$\varepsilon_{d+\bar{d}} \sim 20\%$
$\varepsilon_{s+\bar{s}} \sim 4\%$
$\varepsilon_{glue} \sim 39\%$



Nucleon form factors measured in elastic e-N scattering

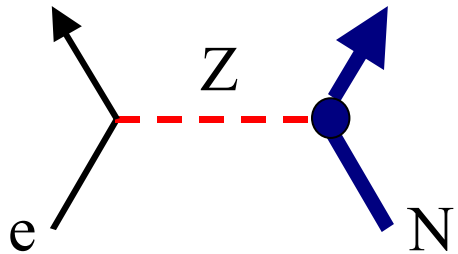
Nucleon form factors

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



$$< N | J^{\gamma}_{\mu} | N > \quad \rightarrow \quad G^{\gamma}_{E}, G^{\gamma}_{M}$$

electromagnetic form factors



$$< N | J^{Z}_{\mu} | N > \quad \rightarrow \quad G^{Z}_{E}, G^{Z}_{M}$$

neutral weak form factors

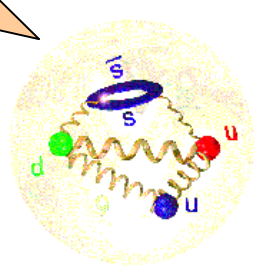
- Measured precision of EM form factors in 0.1 - 1 GeV^2 Q^2 range ~ 2 - 4%
- Projected precision of NW form factors in 0.1 - 1 GeV^2 Q^2 range ~ 10% from the current generation of experiments (for magnetic)

Neutral weak form factors → strange form factors

STANDARD MODEL COUPLINGS

	Q^γ	Q^Z
u	+2/3	$1 - 8/3 \sin^2\theta_W$
d	−1/3	$-1 + 4/3 \sin^2\theta_W$
s	−1/3	$-1 + 4/3 \sin^2\theta_W$

$\sin^2\theta_W = 0.2312 \pm 0.0002$
weak mixing angle
key parameter of Standard Model



$= \sum_i$

A SEARCH FOR NEW PHYSICS

Qweak

E158

A precision measurement of the Weak Mixing Angle in Møller Scattering

Flavor decomposition of nucleon E/M form factors:

$$< p \,|\, J^\gamma_\mu \,|\, p >: \quad G^{\gamma,p}_{E,M} = \frac{2}{3} G^{u,p}_{E,M} - \frac{1}{3} G^{d,p}_{E,M} - \frac{1}{3} G^{s,p}_{E,M}$$

$$< n \,|\, J^\gamma_\mu \,|\, n >: \quad G^{\gamma,n}_{E,M} = \frac{2}{3} G^{u,n}_{E,M} - \frac{1}{3} G^{d,n}_{E,M} - \frac{1}{3} G^{s,n}_{E,M}$$

$$< p \,|\, J^Z_\mu \,|\, p >: \quad G^{Z,p}_{E,M} = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G^{u,p}_{E,M} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right) G^{d,p}_{E,M} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right) G^{s,p}_{E,M}$$

Invoke proton/neutron charge symmetry → 3 equations, 3 unknowns

$$\left(G^{\gamma,p}_{E,M}, G^{\gamma,n}_{E,M}, G^{Z,p}_{E,M}\right) \Leftrightarrow \left(G^{u}_{E,M}, G^{d}_{E,M}, G^{s}_{E,M}\right)$$

Validity of charge symmetry breaking assumption

$$u \leftrightarrow d$$

$$G_{E,M}^{u,p} = G_{E,M}^{d,n} \qquad G_{E,M}^{d,p} = G_{E,M}^{u,n} \qquad G_{E,M}^{s,p} = G_{E,M}^{s,n}$$

Size of charge symmetry breaking effects in some n,p observables:

- n - p mass difference $\rightarrow (m_n - m_p)/m_n \sim 0.14\%$
- polarized elastic scattering $\vec{n} + p$, $\vec{p} + n$ $\Delta A = A_n - A_p = (33 \pm 6) \times 10^{-4}$
  Vigdor et al, PRC 46, 410 (1992)
- Forward backward asymmetry $n + p \rightarrow d + \pi^0$ $A_{fb} \sim (17 \pm 10) \times 10^{-4}$
  Opper et al., nucl-ex 0306027 (2003)

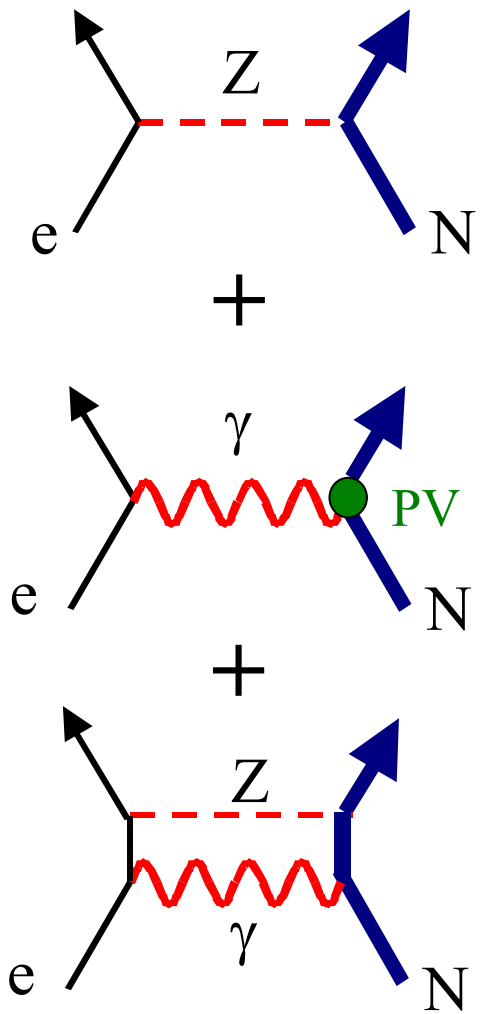
$\rightarrow$ For vector form factors theoretical CSB estimates indicate < 1% violations (unobservable with currently anticipated uncertainties)

(Miller PRC 57, 1492 (1998) Lewis and Mobed, PRD 59, 073002(1999)

The Nucleon's e-N Axial Form Factor G_A^e

Z^0 has axial, as well as vector couplings → we measure axial FF too

$$G_A^e = G_A^Z + \eta F_A + R^e$$



G_A^Z: neutral weak axial form factor, determined from neutron β decay and neutrino scattering

→ multiplied by $g_e^v = 1 - 4\sin^2\theta_W \sim 0.074$

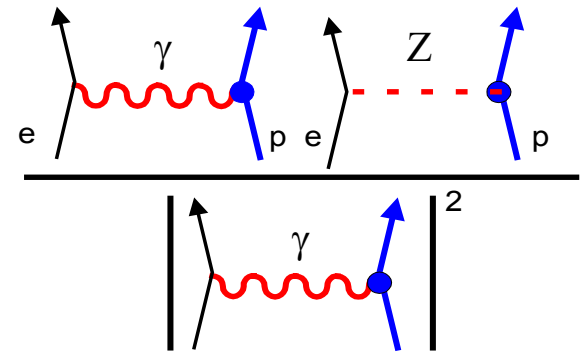
F_A: nucleon's anapole moment - parity-violating electromagnetic moment

R^e: electroweak radiative corrections to e-N scattering

Parity Violating Electron Scattering - Probe of Neutral Weak Form Factors

polarized electrons, unpolarized target

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



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

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

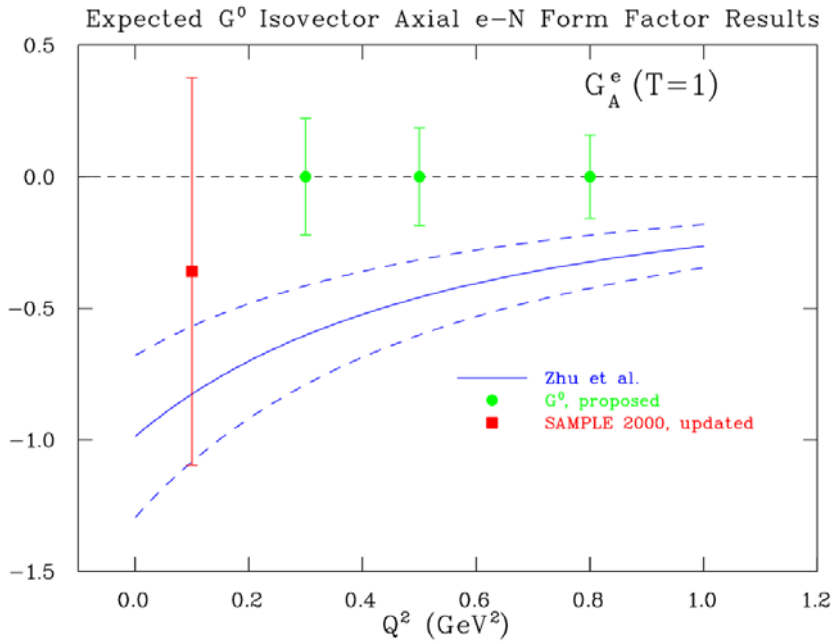
Strange electric and magnetic form factors,
+ axial form factor

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

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

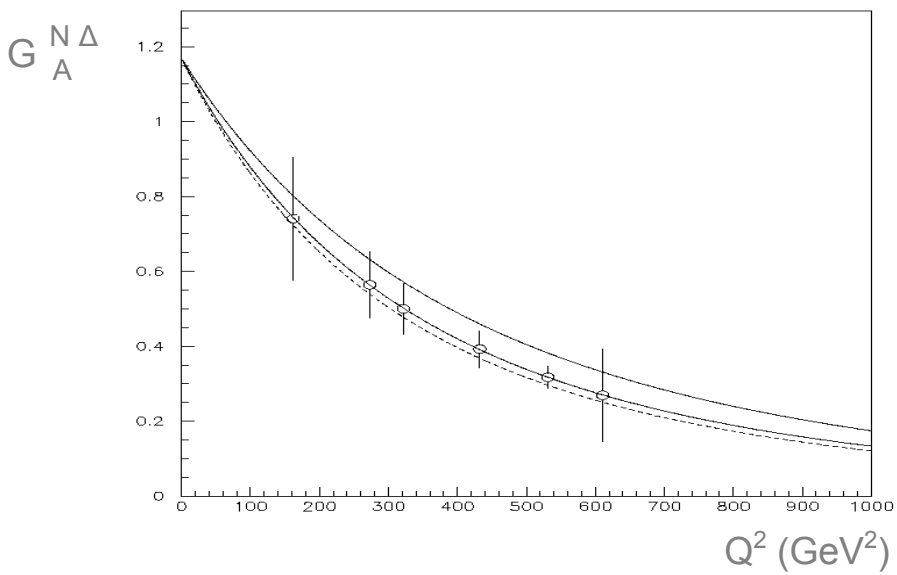
G^0 will perform all three measurements at three different Q^2 values - 0.3, 0.5, 0.8 GeV

Other Aspects of G^0 Physics Program



$G_A^e(Q^2)$ - e-N axial form factor

$\vec{e}$ + d quasielastic measurements at back angles will map out e - N axial form factor G_A^e as a function of Q^2



$N \rightarrow \Delta$ Axial Transition Form Factor

data taken concurrently with back angle $\vec{e}$ + p elastic data-taking

- First measurement in neutral current process
- sensitive to hadronic radiative corrections

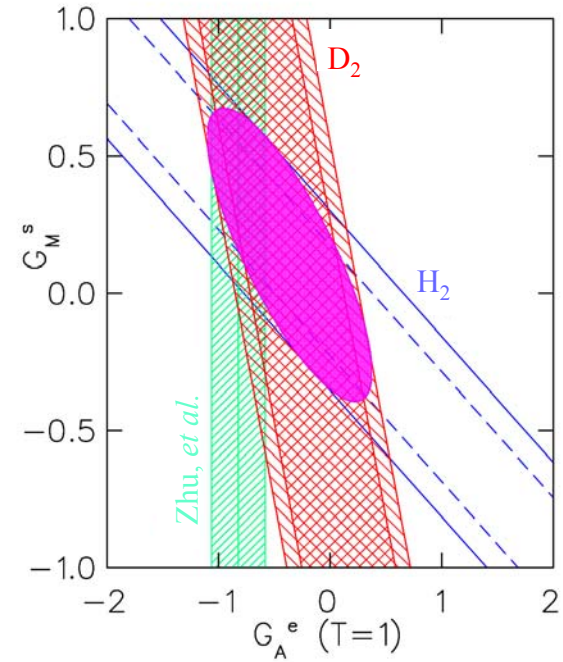
Strange form factors - published results

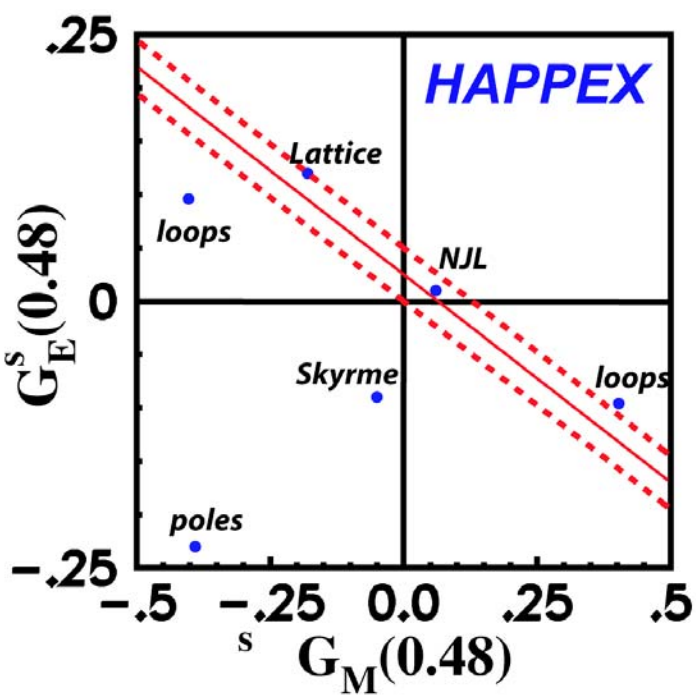
SAMPLE at MIT-Bates:

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

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

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





HAPPEX at Jefferson Lab:

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

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

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

Judging the Size of the Strange Form Factors

Strange momentum fraction: fraction of total proton momentum ~ 4%

fraction of total quark contribution ~ 7%

Strange spin content: fraction of total proton spin ΔS ~ -10%

fraction of quark contribution (Σ = 30%) ~ 33%

Note: strange form factors only contribute to ISOSCALAR form factors

$$G^{T=1} \equiv \frac{G^p - G^n}{2} = \frac{G^u - G^d}{2} \qquad G^{T=0} \equiv \frac{G^p + G^n}{2} = \frac{G^u + G^d - G^s}{3}$$

SAMPLE: $G_M^s < .67$ at 1σ at $Q^2 = .1$ GeV^2

compare to G_M^p, fractional strange contribution $(G_M^s/3)/G_M^p <$ 10%

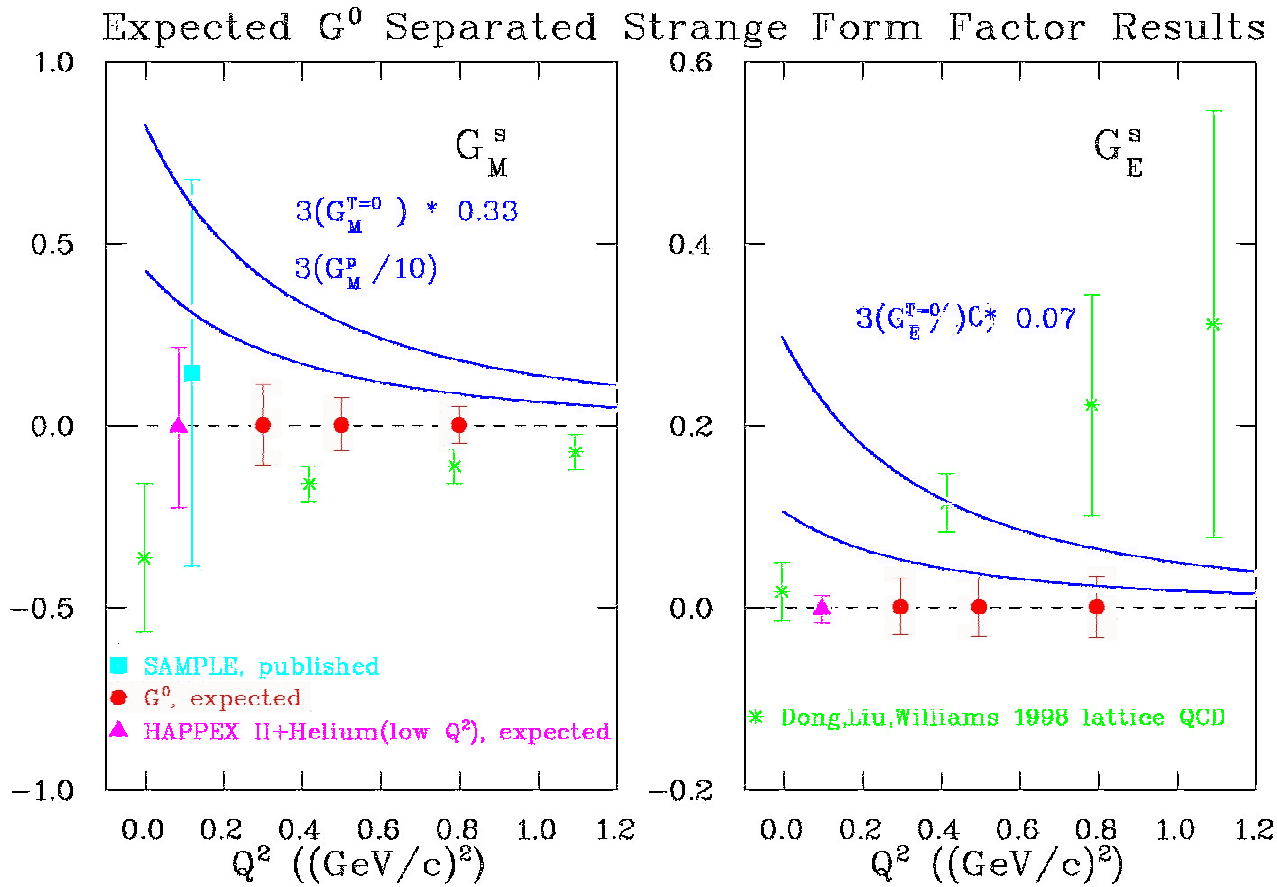
compare to $G_M^{T=0}$, fractional strange contribution $(G_M^s/3)/G_M^{T=0} <$ 66%

HAPPEX: $(G_E^s + .39\, G_M^s) < .049$ at 1σ at $Q^2 = .47$ GeV^2

compare to $(G_E^p + .39\, G_M^p)$, fractional strange contribution < 2%

compare to $(G_E^p + .39\, G_M^p)^{T=0}$, fractional strange contribution < 6%

Strange Form Factors - Expected G^0 Results



G^0 experiment will provide:

- separated form factors G^s_E and G^s_M
- ultimate precision ~<3% of G^p_E and G^p_M

in the next few years

General Experimental Requirements

Want to measure A_{PV} ~ -3 to -40 ppm with precision $\delta A_{PV} / A_{PV}$ ~ 5% AND separate G_E^s and G_M^s

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

- Reliable high polarization, high current polarized electron source
- Large acceptance detector
- High count rate capability detectors/electronics

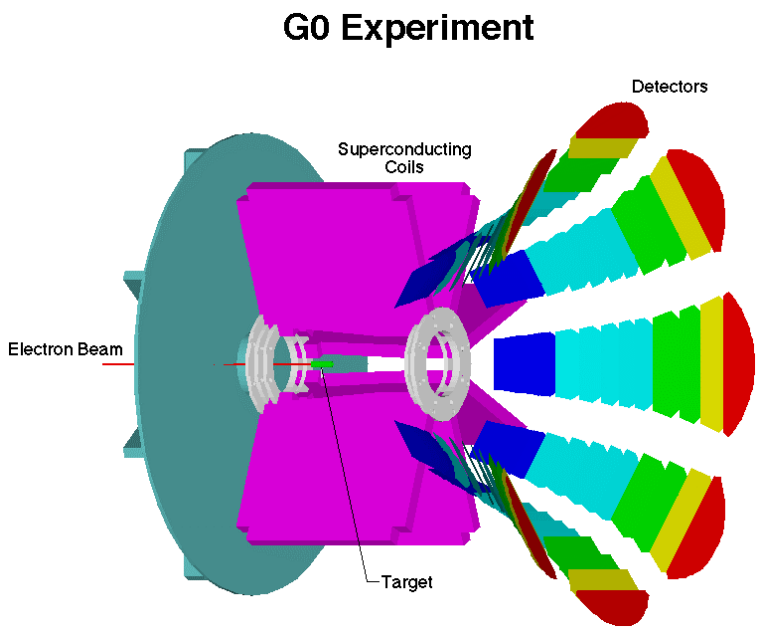
Systematics (need to reduce false asymmetries, accurately measure dilution factors):

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

The G^0 Experiment in Jefferson Lab Hall C

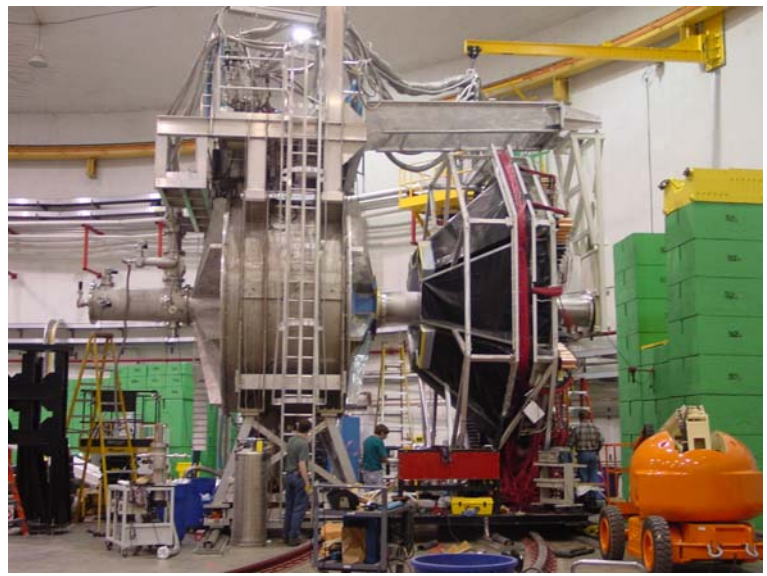
Main components:

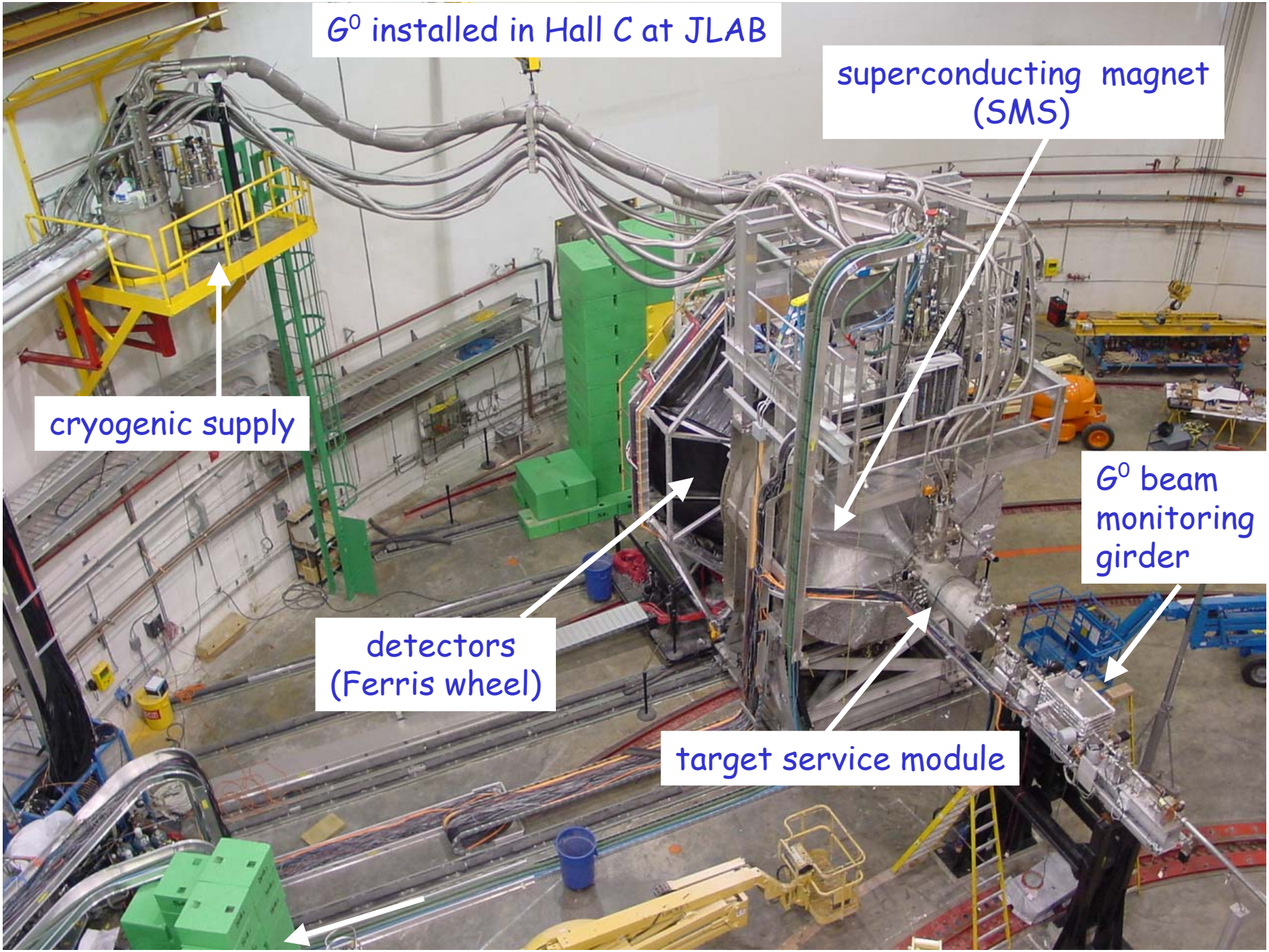
- Superconducting toroidal magnet
- Jefferson Lab polarized source
- High power H_2 /D_2 target
- Large acceptance scintillation detector array
- Custom high count rate electronics



History:

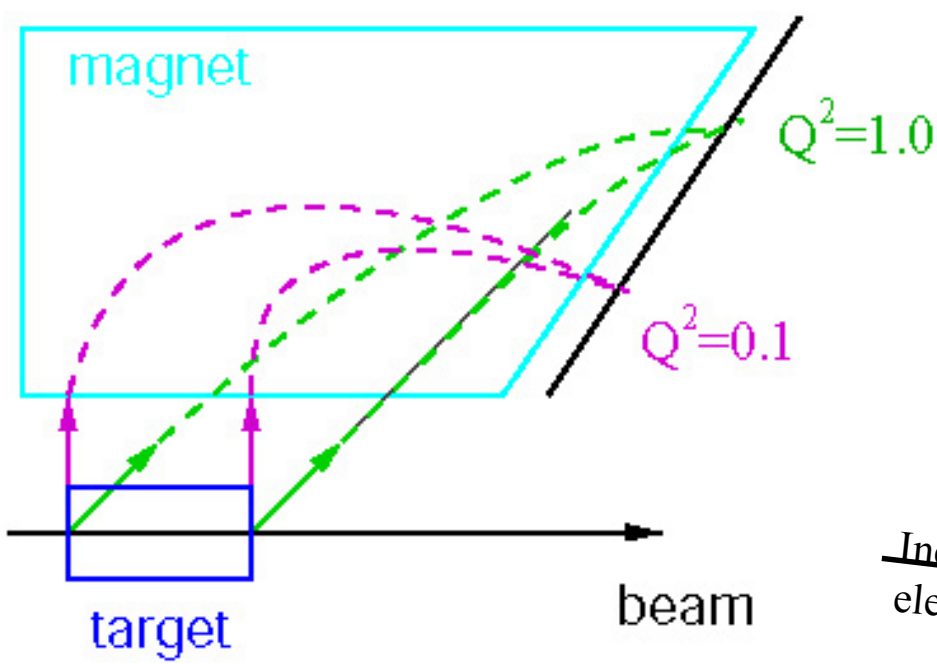
- Design and construction (1993 - 2001)
- Commissioning run (fall 2002/winter 2003)
- Finish commissioning run (fall 2003)
- Forward angle production run (winter 2004)
- Back angle production runs (2004 - 2006)

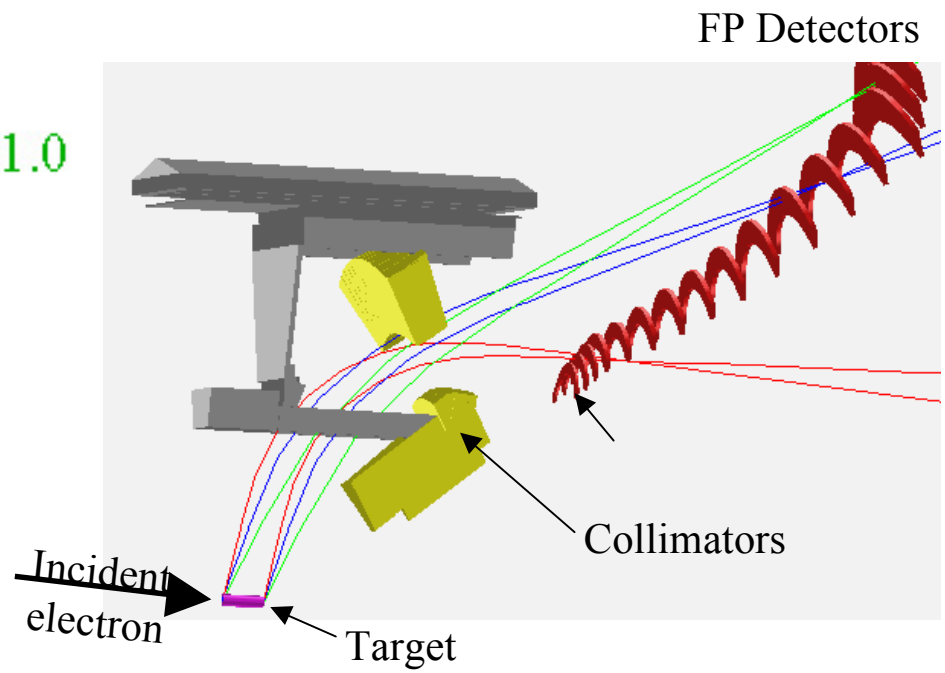



G0 installed in Hall C at JLAB
superconducting magnet (SMS)
cryogenic supply
G0 beam monitoring girder
detectors (Ferris wheel)
target service module

G^0 Forward Angle Mode

- Electron beam energy = 3 GeV on 20 cm LH_2 target
- Detect recoil protons (θ ~ 62 - 78° corresponding to 15 - 5° electrons)
- Magnet sorts protons by Q^2 in focal plane detectors
- Full desired range of Q^2 (0.16 - 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)





Data-taking and polarization flip sequence

Data readout interval = (1 / 30 Hz) = 33 msec

→ detector TOF histograms recorded

integrated values of beam monitors (charge and position) recorded

electron beam polarizaton flip sequence (pseudo - random pattern)

$$\underbrace{+\ -\ -\ +}_{1\,\text{quartet}}\ \underbrace{-\ +\ +\ -}\ \underbrace{-\ +\ +\ -}\ \underbrace{+\ -\ -\ +}$$

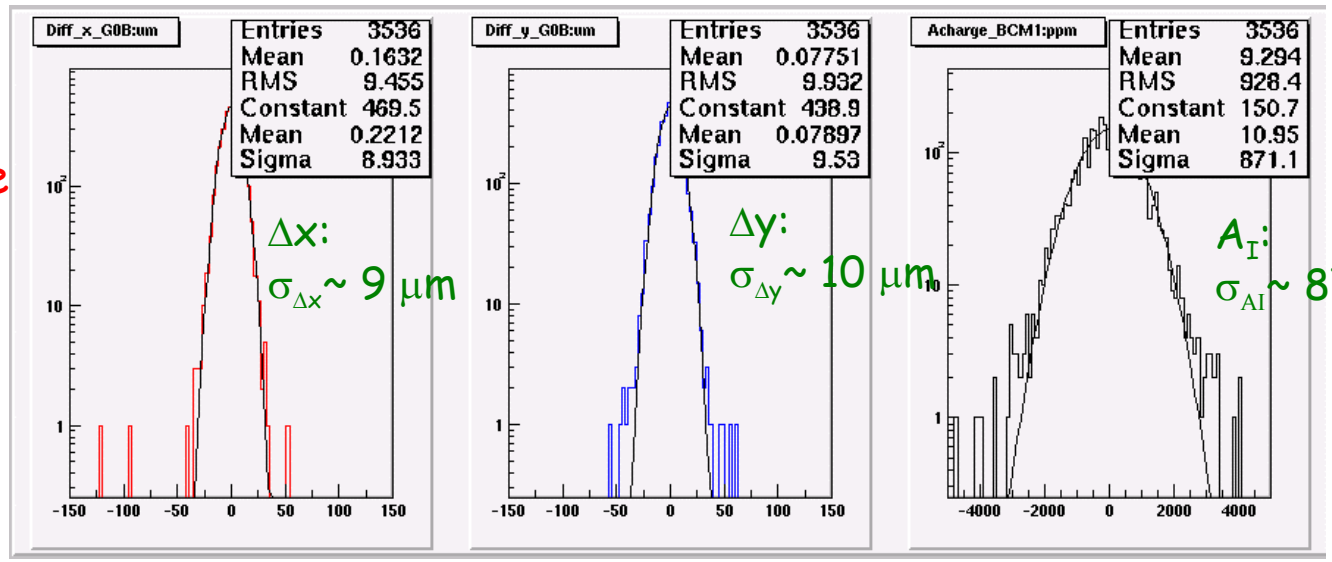
asymmetry (detector yield or intensity):

$$A = \frac{Y_{1+} + Y_{2+} - Y_{1-} - Y_{2-}}{Y_{1+} + Y_{2+} + Y_{1-} + Y_{2-}}$$

differences (beam position differences)

$$\Delta x = X_{1+} + X_{2+} - X_{1-} - X_{2-}$$

Typical difference and asymmetry histograms



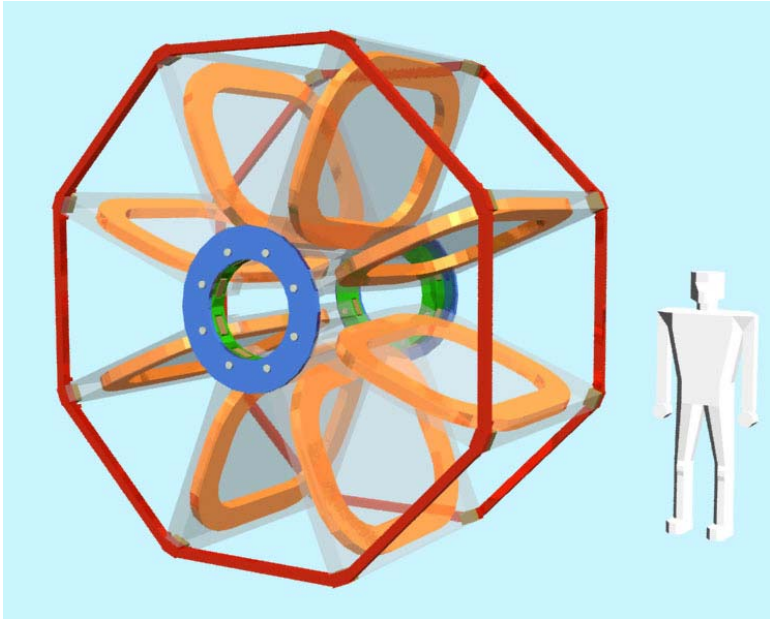
G^0 Superconducting Magnet System

Superconducting toroidal magnet:
8 coils

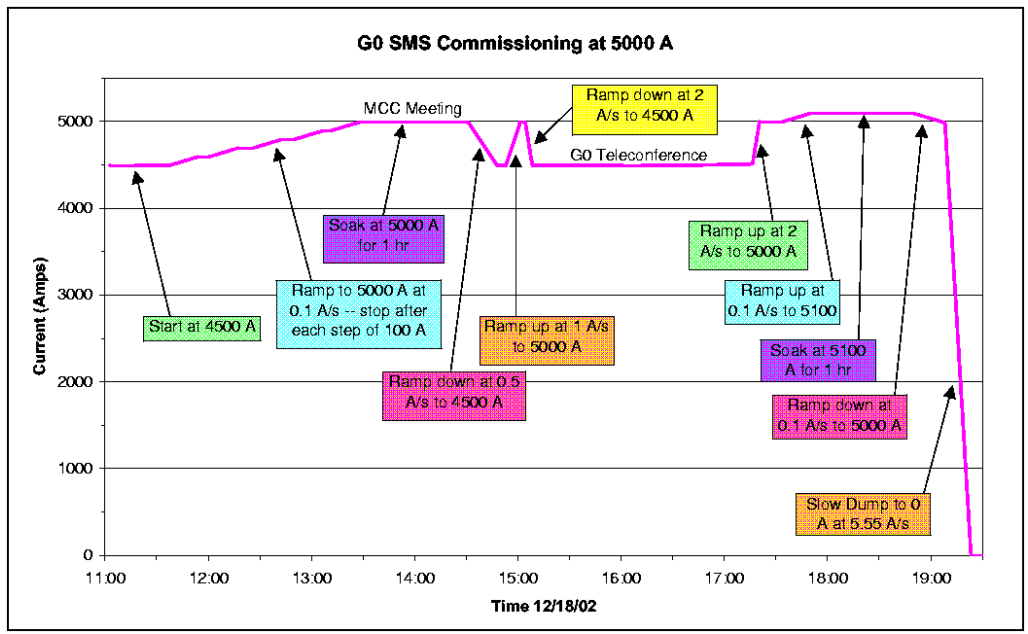
$$\int B \cdot dl = 1.6 \text{ Tm}$$

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

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

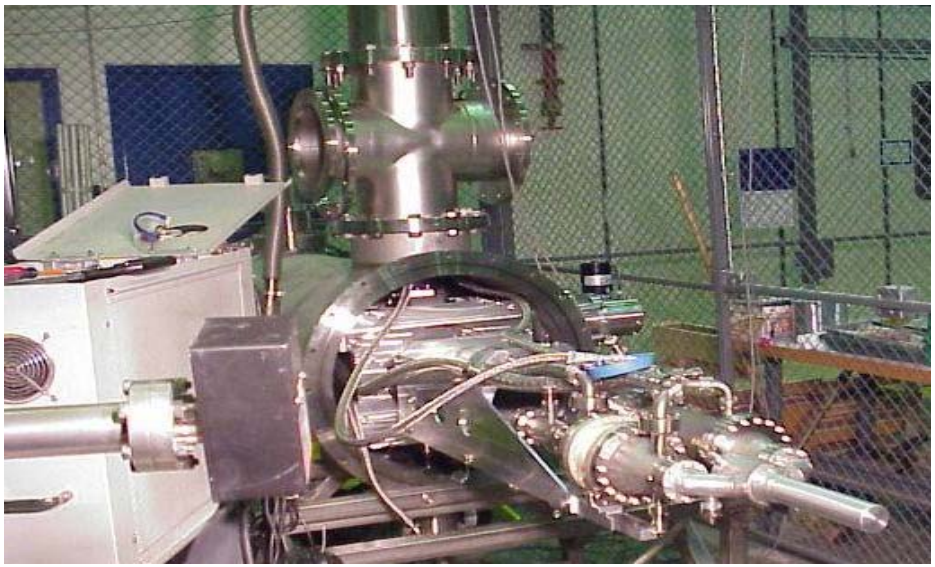


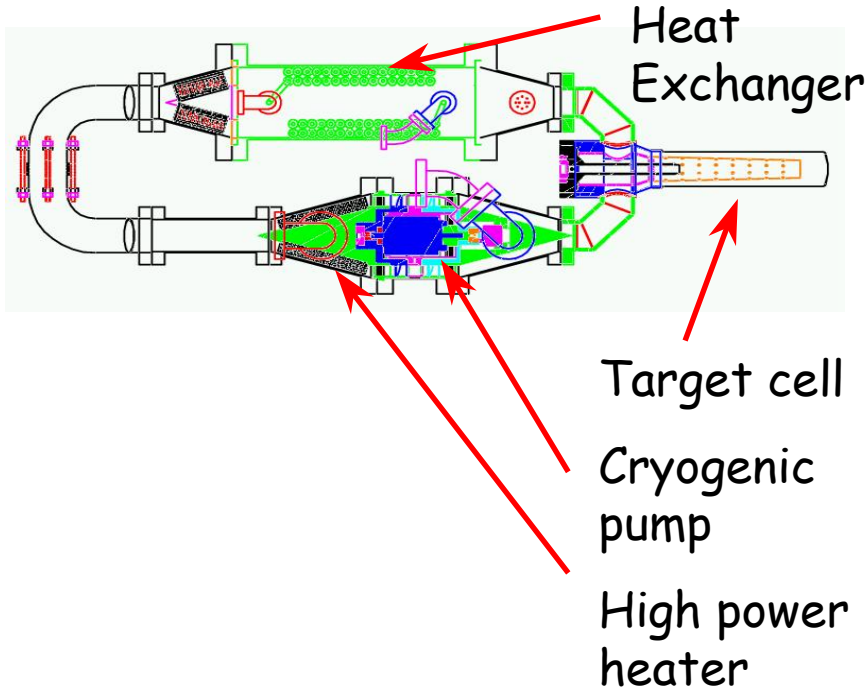
- Initial manufacturing defects repaired in early 2002
- Ran at 4500 A initially (Aug. - Dec. 2002)
- Ran at full design current (5000 A) on Dec. 18, 2002 and during Jan. 2003 running

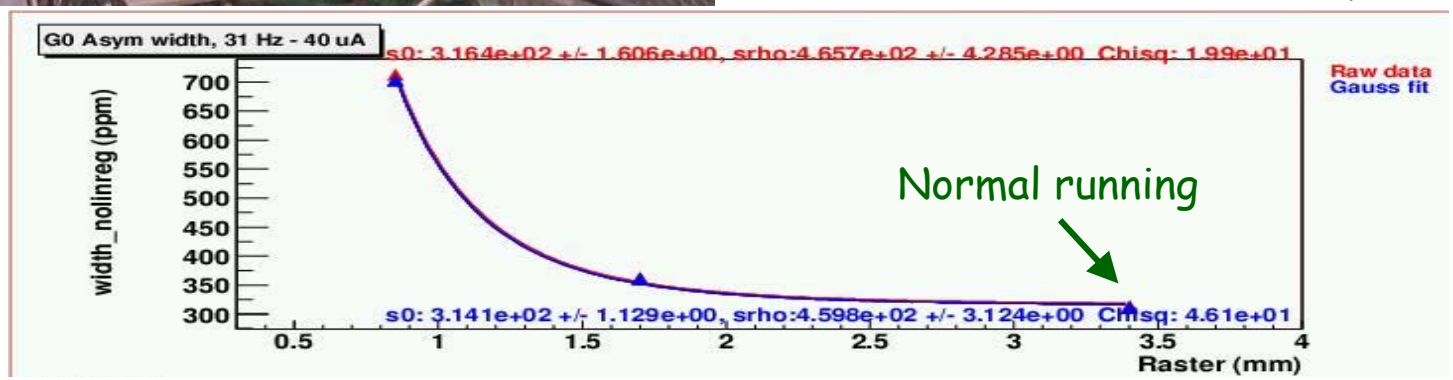


G^0 target

- 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



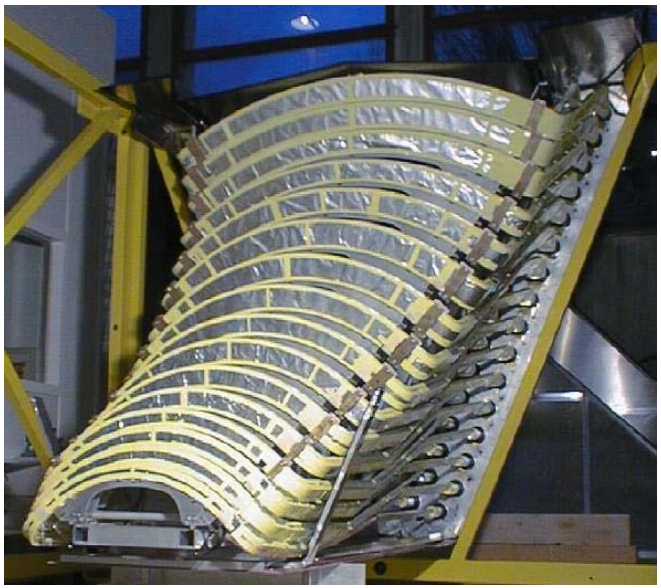




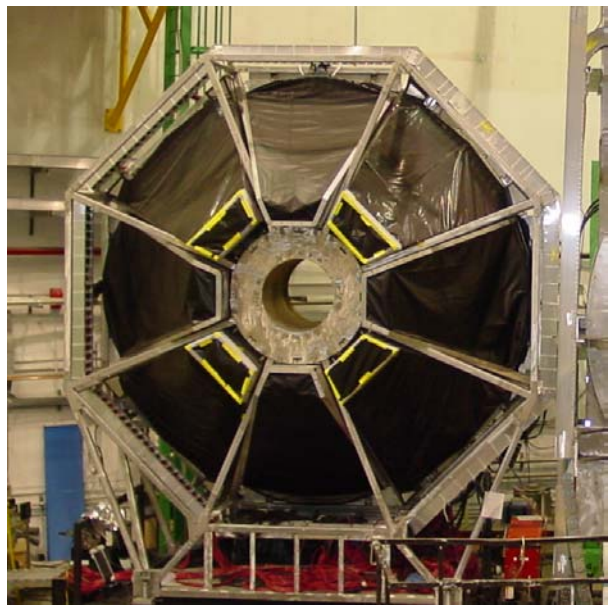
G^0 Focal Plane Detectors (FPD)

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

French octant



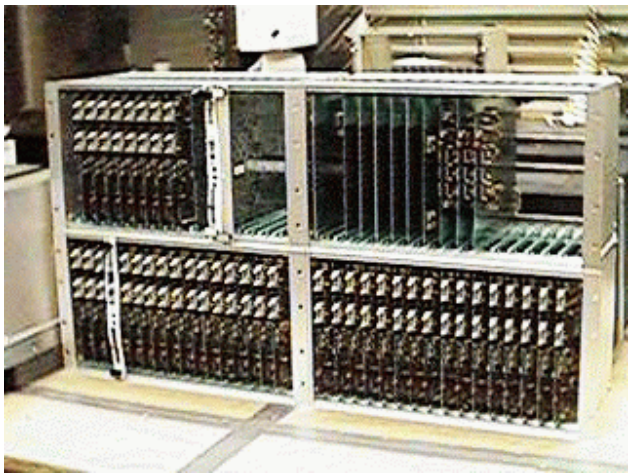
North American octant



Detector
"ferris wheel"

G^0 Forward Angle Electronics

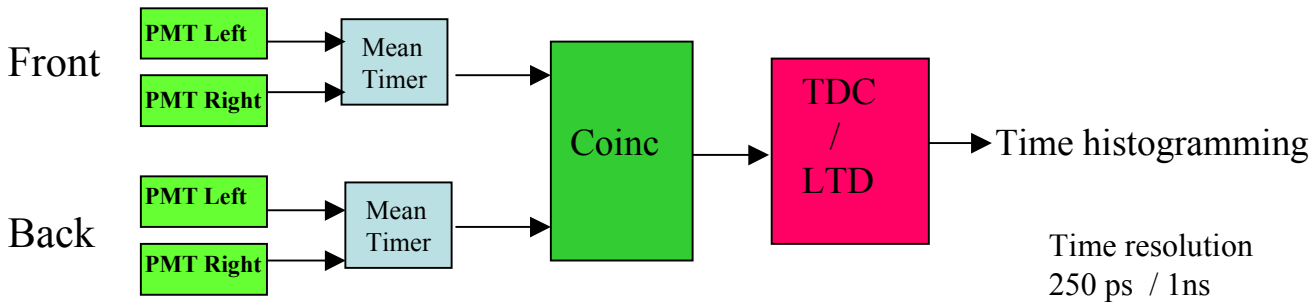
- Custom electronics designed to provide high-rate histogramming
- NA: mean timer → latching time digitizer → scalers (1 ns)
- French: mean timer → flash TDCs (0.25 ns)
- Time histograms read out by DAQ system every 33 msec



NA LTD crate (1/2)

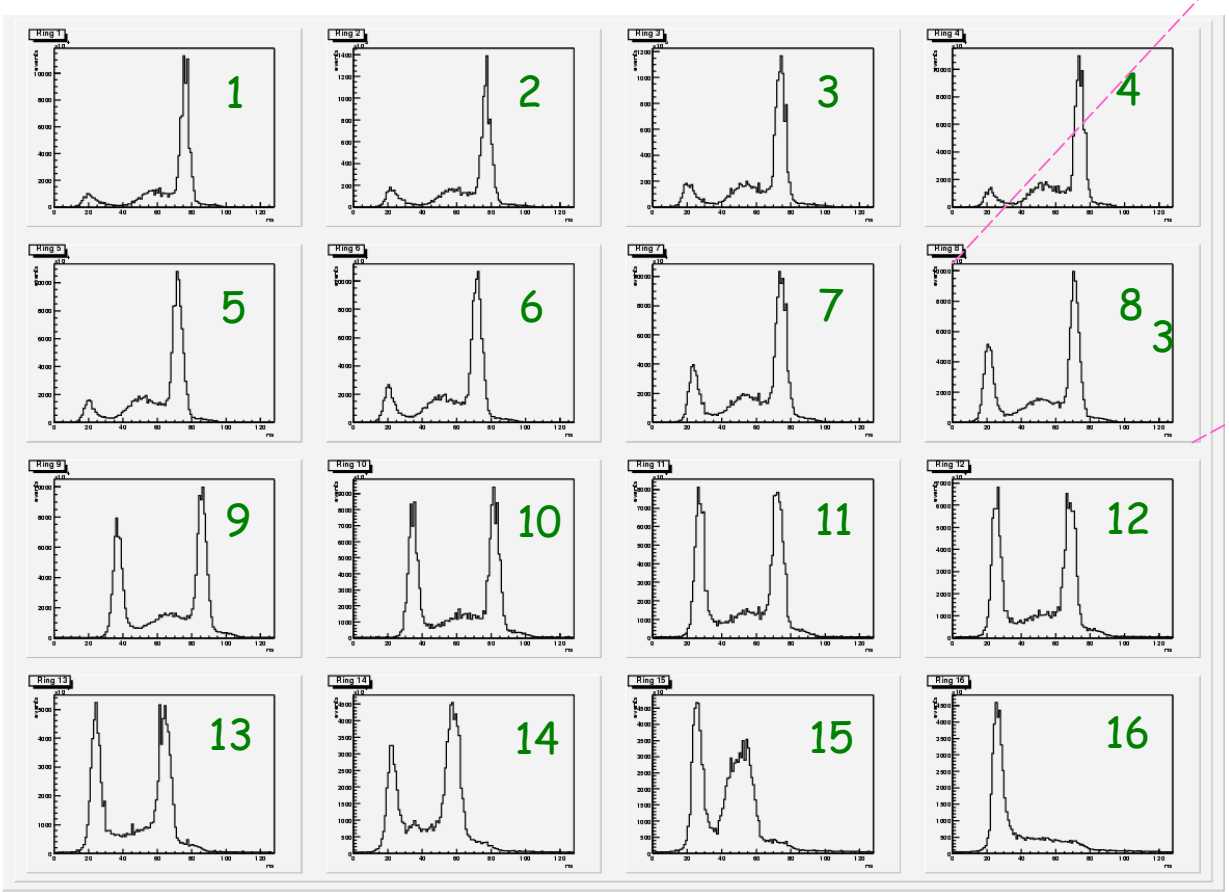
French DMCH16 Module 1/8

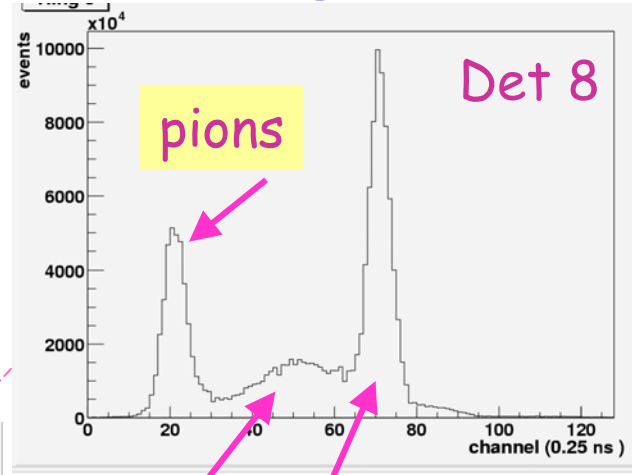
Time of Flight measurement



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



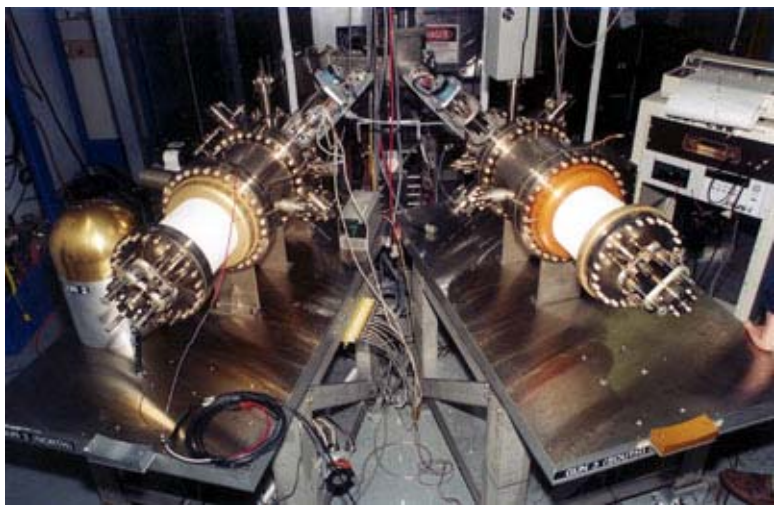


G^0 Beam

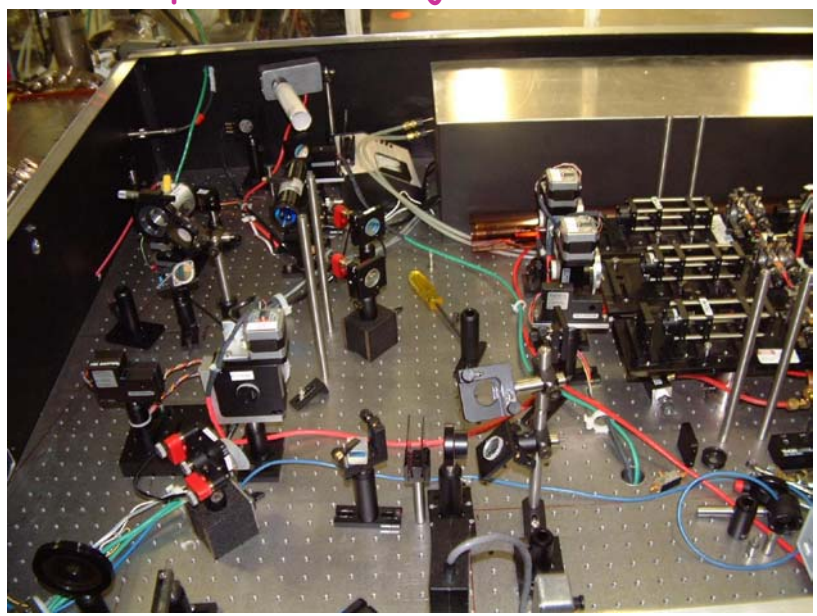
- G^0 beam requires unusual time structure: 31 MHz (32 nsec between pulses) (1/16 of usual CEBAF time structure of 499 MHz (2 nsec between pulses)
- Required new Ti:Sapphire laser in polarized electron gun
- Higher charge per bunch → space charge effects complicated beam transport in injector (challenging beam optics problem)

- Beam with most desired properties delivered for Jan. 2003
  - Beam current 40 μA
  - Beam fluctuations at (30 Hz/4) ~ $\Delta X, \Delta Y < 20\ \mu m$ $\Delta I/I < 2000$ ppm

CEBAF polarized injector



CEBAF polarized injector laser table



Systematics: From raw asymmetry to physics results

Form raw measured asymmetry from the detector yields: $A_{meas} = \frac{Y_{1+} + Y_{2+} - Y_{1-} - Y_{2-}}{Y_{1+} + Y_{2+} + Y_{1-} + Y_{2-}}$

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:

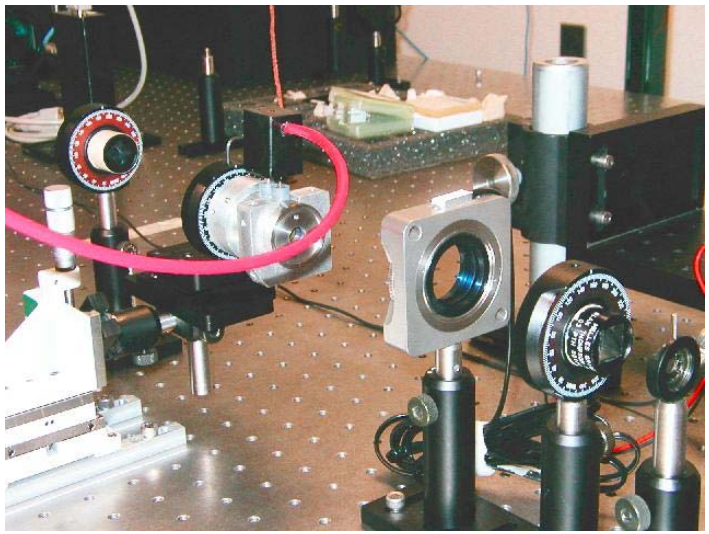
$$A_{phys} \propto Q^2\ f(G_E^\gamma, G_M^\gamma, G_E^s, G_M^s)$$

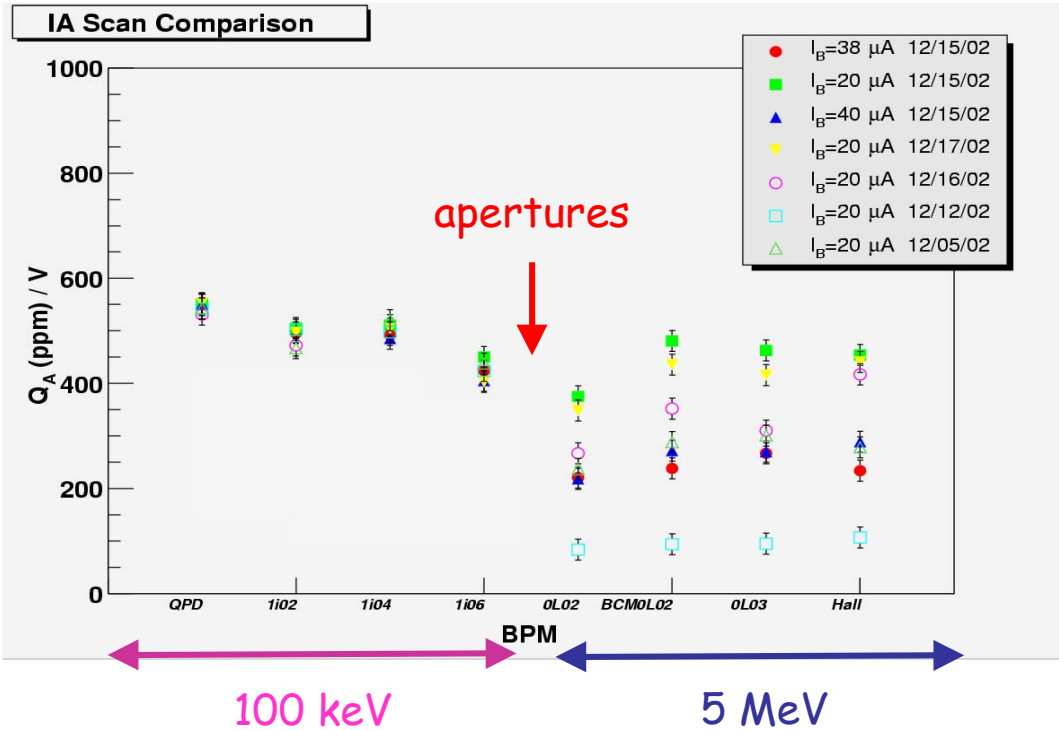
- $\langle Q^2 \rangle$ determination
- electromagnetic form factors

Helicity - Correlated Beam Properties - Feedback

Minimization of helicity-correlated beam properties:
Done with optical devices on polarized injector laser table in feedback mode
Intensity: rotating half-waveplate, IA feedback Position: PZT mirror

Example: intensity feedback, IA cell → electro-optic intensity modulator
→ difficulties due to induced position differences and aperture scraping



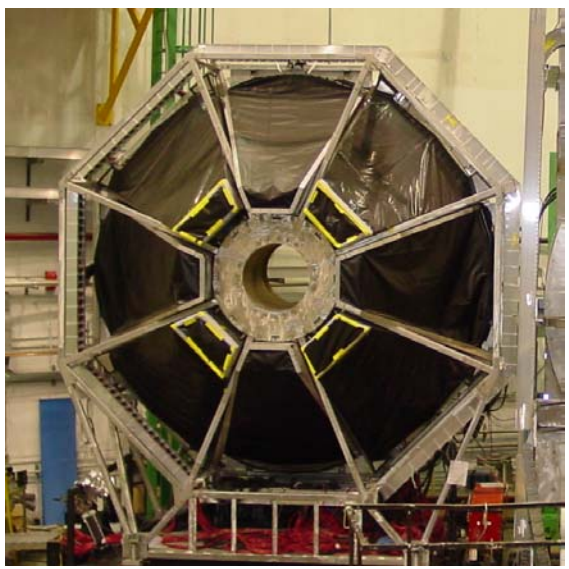


Goals: averaged over 700 hour run: intensity < 1 ppm
beam position differences < 20 nm

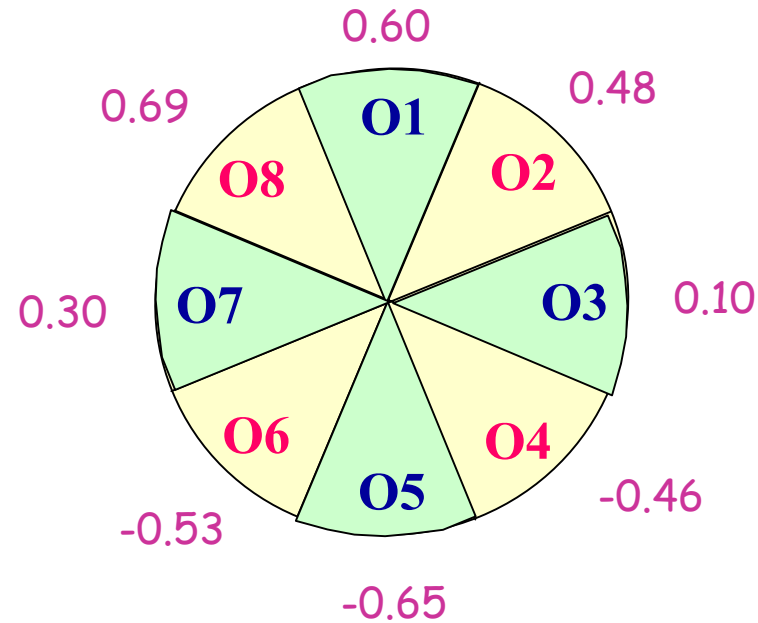
Helicity - Correlated Beam Properties - Sensitivity

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)



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

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

Dead time correction

Typical rates ~ 1 - 2 MHz/detector
→ typical dead fraction ~ 10%

Causes false asymmetries when combined with non-zero beam charge asymmetry

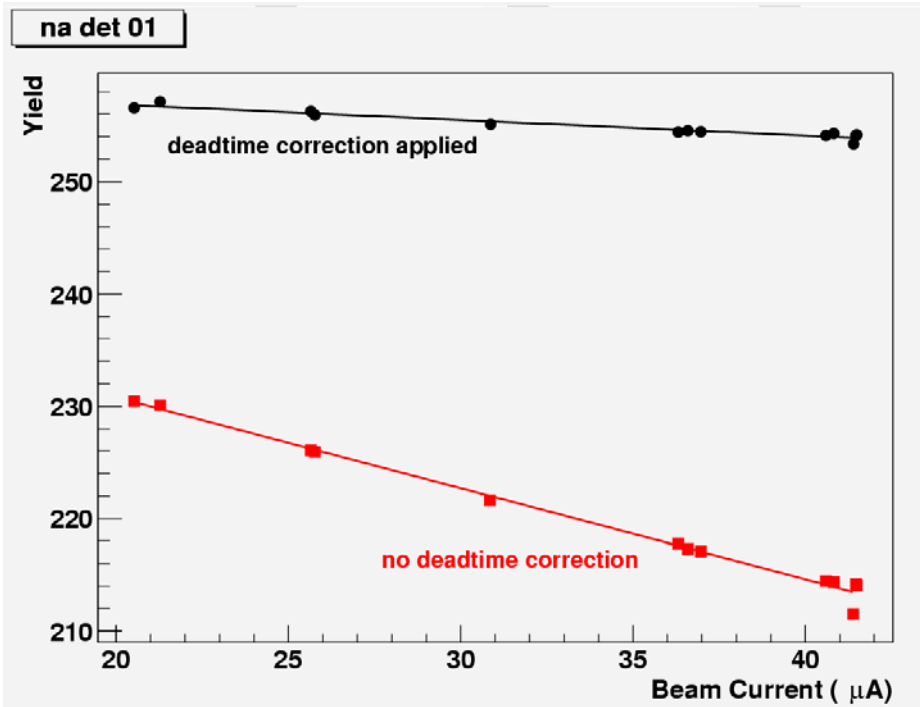
$$A_{false} = f_{dead} A_{charge}$$

- Uncorrected effect ~ 15%
- After correction ~ 1%

Remaining deadtime effect is taken care of in the linear regression procedure that removes effects of helicity-correlated beam properties

A_{false} ~ (0.01) x (1 ppm) ~ 0.01 ppm

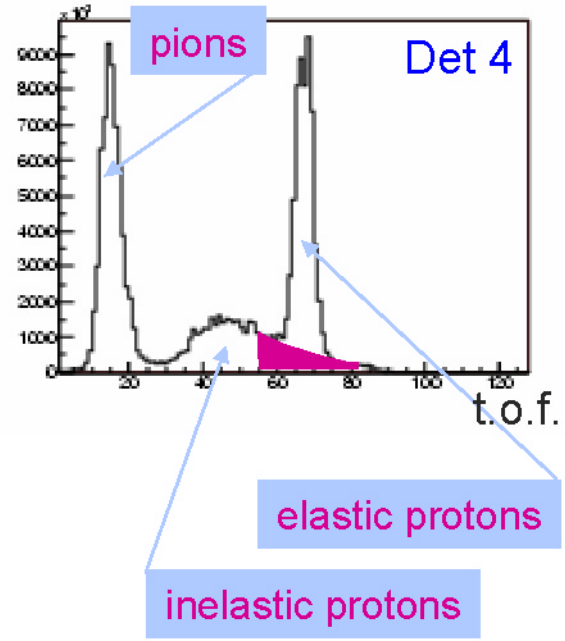
for desired A_{charge} ~ 1 ppm



Background dilution factor

Need both yield and asymmetry of background to correct the elastic asymmetry

- Yield ~ 10 - 25% depending on detector
- $|A_{back}| \sim |A_{elastic}|$ near elastic peak (preliminary)



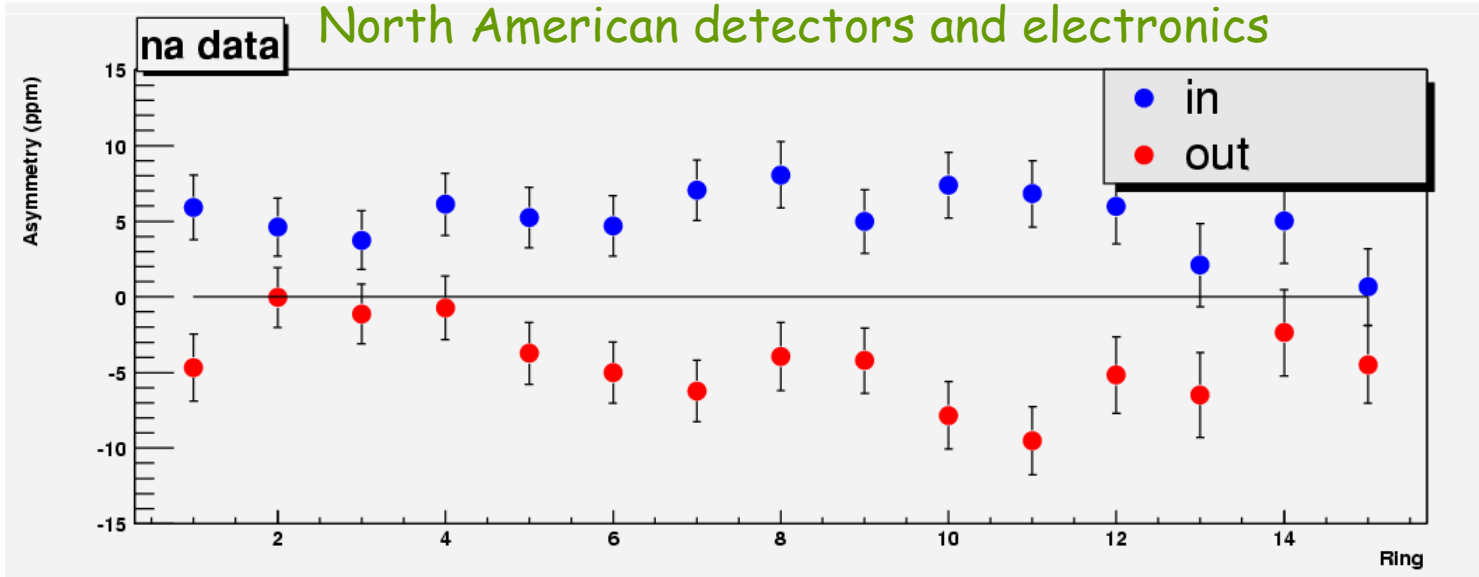
Simulation: important contribution to background comes from the downstream aluminum window

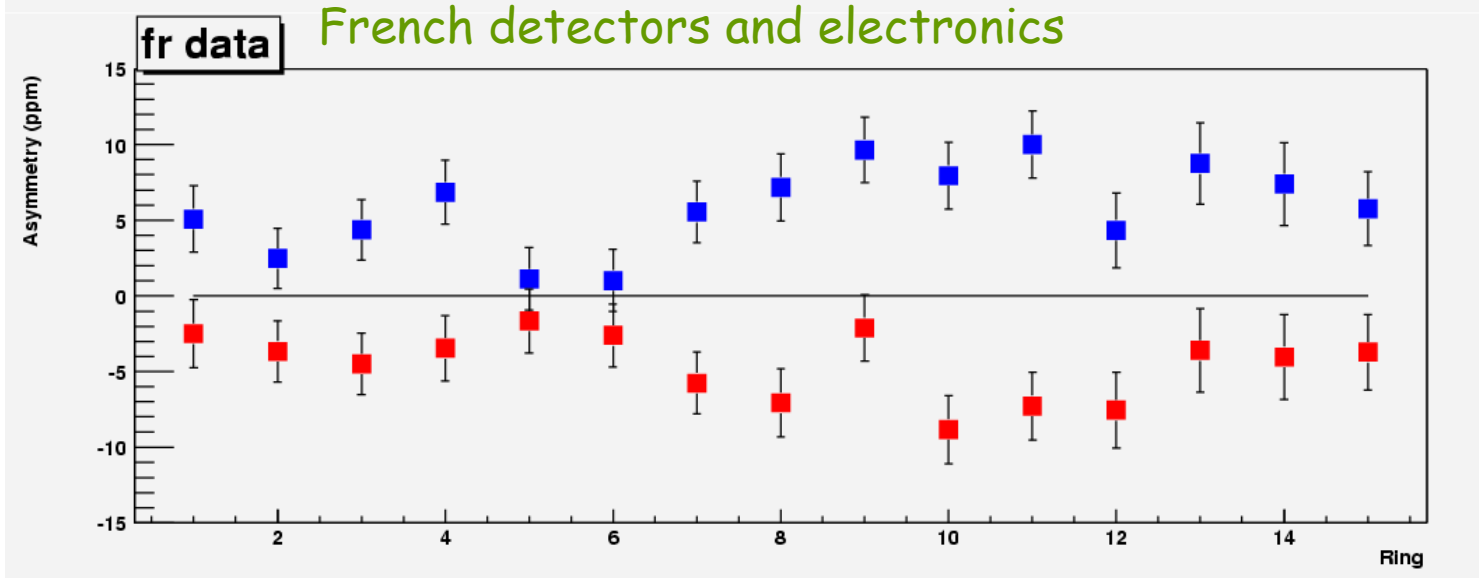
Plans for next run:

- reduce downstream window thickness in region of the beam
- Add insertable dummy window (thicker) for diagnostic runs

Behavior of raw asymmetry results under slow half wave plate reversal, Jan. 2003

Based on 51 hours of data at 40 μA



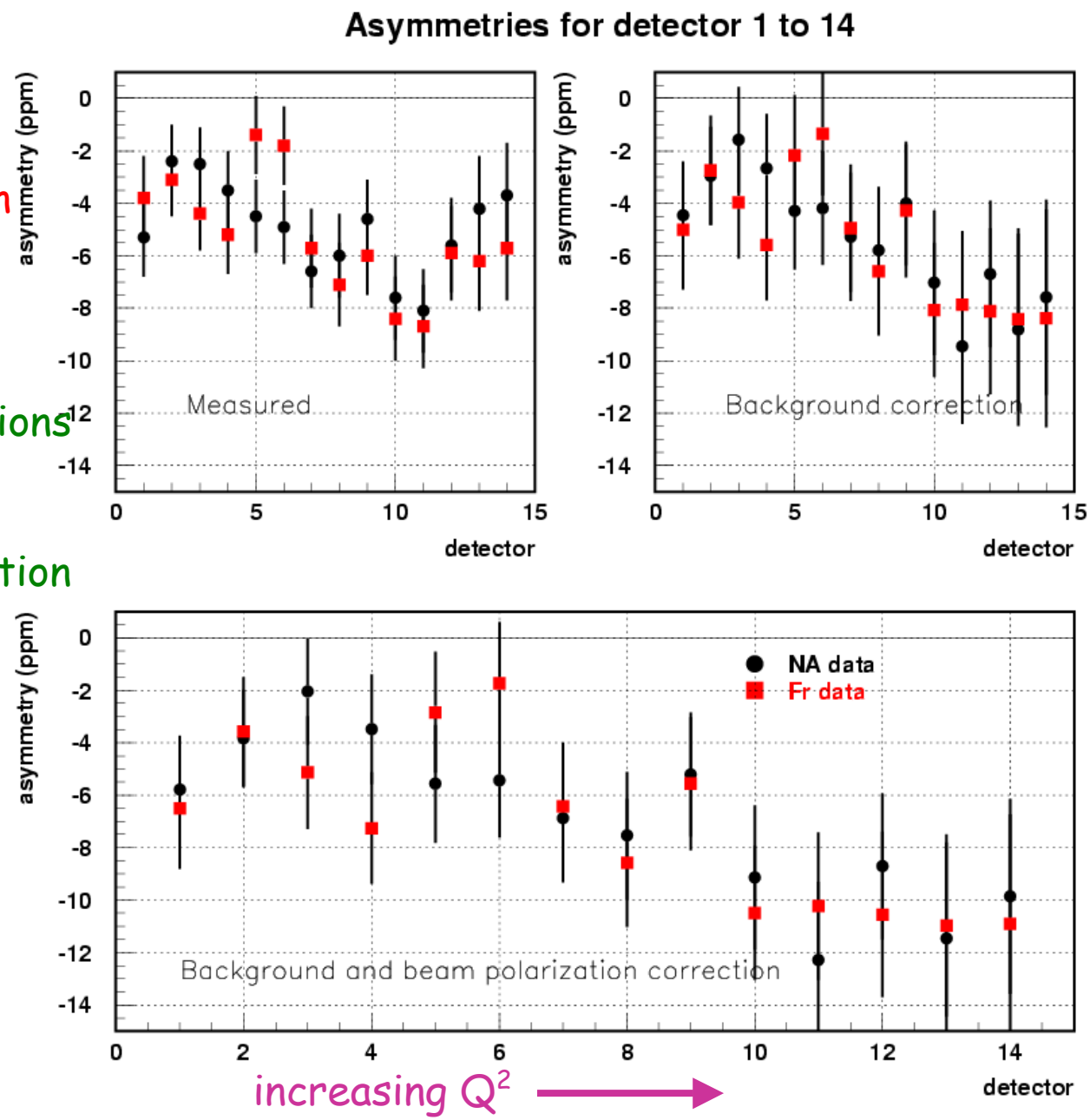


Asymmetry results from Jan. 2003 running

- Based on 51 hours of data at 40 μA (note: full production run will be 700 hours)

- Includes

- false asymmetry corrections
- deadtime corrections
- background corrections
- beam polarization correction



G^0 Backward Angle Measurement

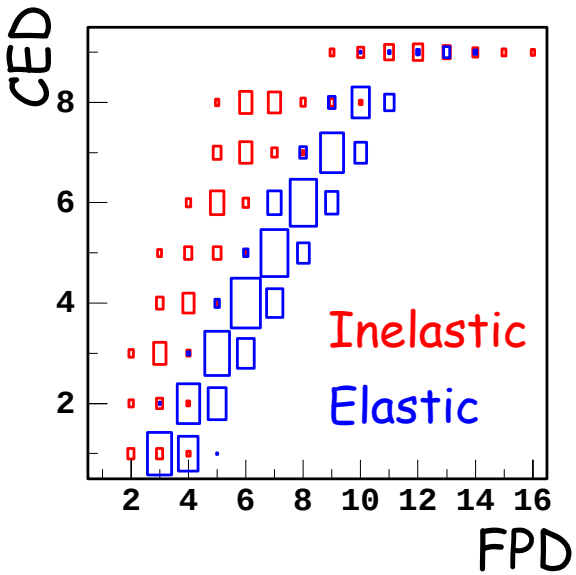
- Detect scattered electrons at $\theta_e \sim 110°$
- At back angles Q^2 only has small variation in G^0 acceptance

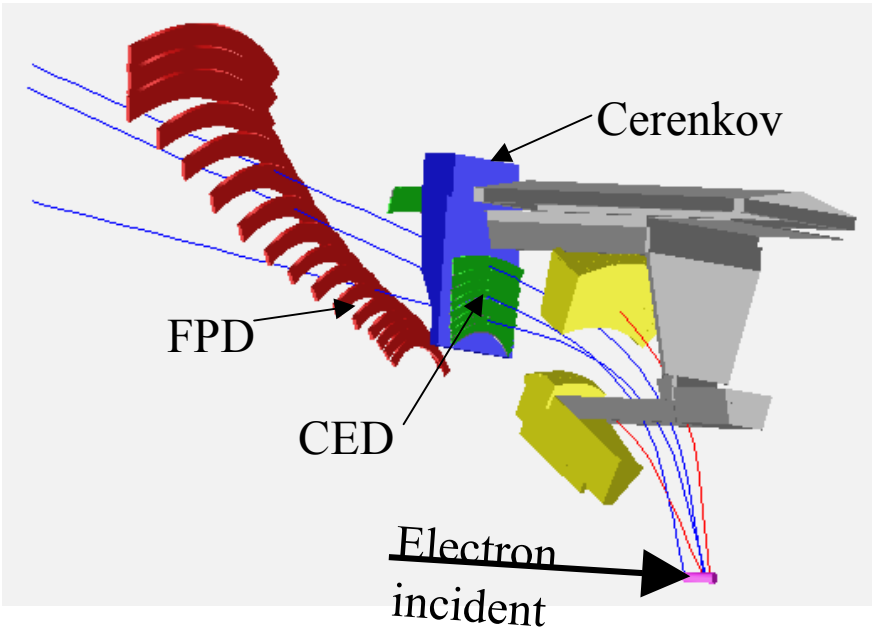
  → Need separate runs at E = 424, 576, 799 MeV
  for Q^2 = 0.3, 0.5, 0.8 $(GeV/c)^2$
  for both LH_2 and LD_2 targets
  (total of 6 runs x 700 hours)

Requires additional detectors:

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

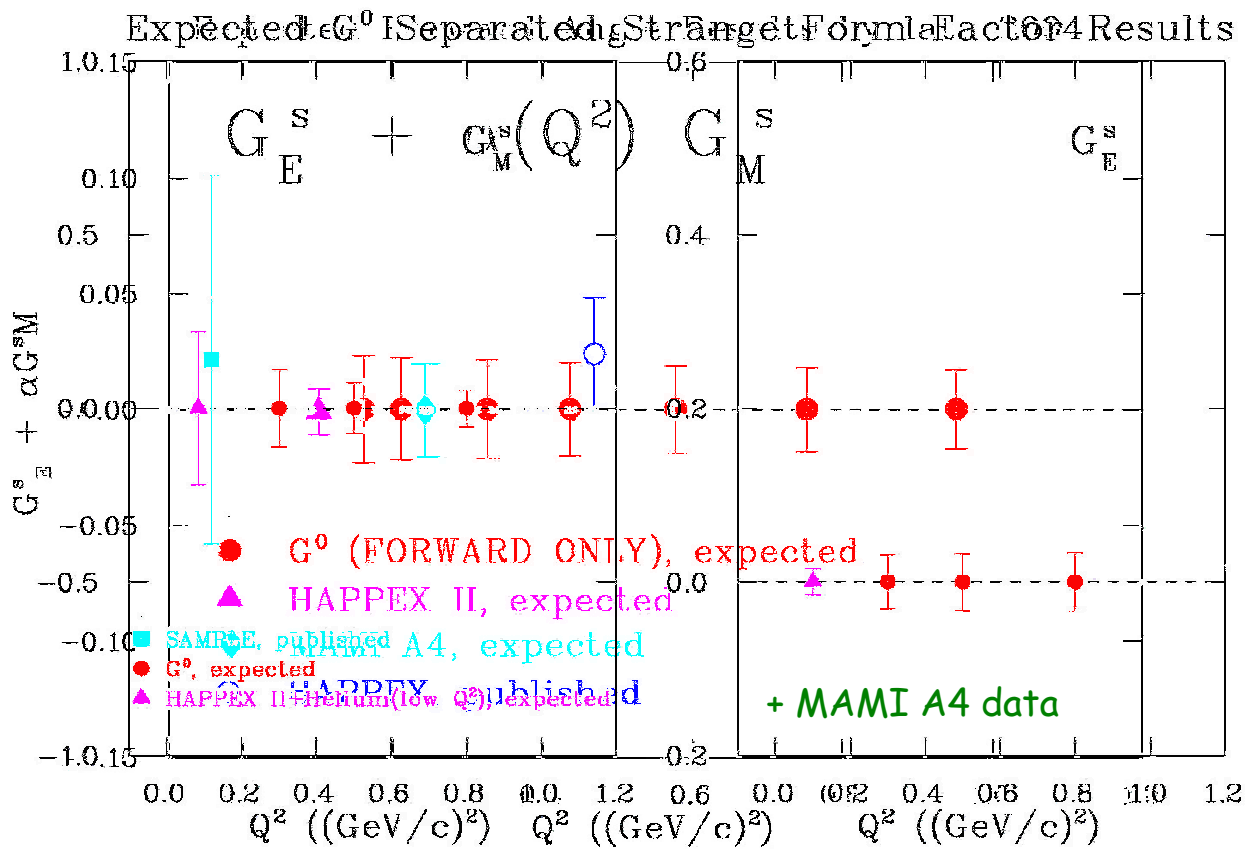
CED/FPD coincidences at $Q^2 = 0.3\ GeV^2$





Outlook

- G apparatus successfully commissioned
- 2nd G^0 commissioning run in Fall 2003
- Forward angle production run in Winter 2004
- Back angle running in 2004 - 2006

Hopefully by late 2004 we can compare world's forward angle factors:

And by late 2006 we can present a wide range of separated form factors: