The G^0 Experiment

Allison Lung, Jefferson Lab
representing the G^0 collaboration:

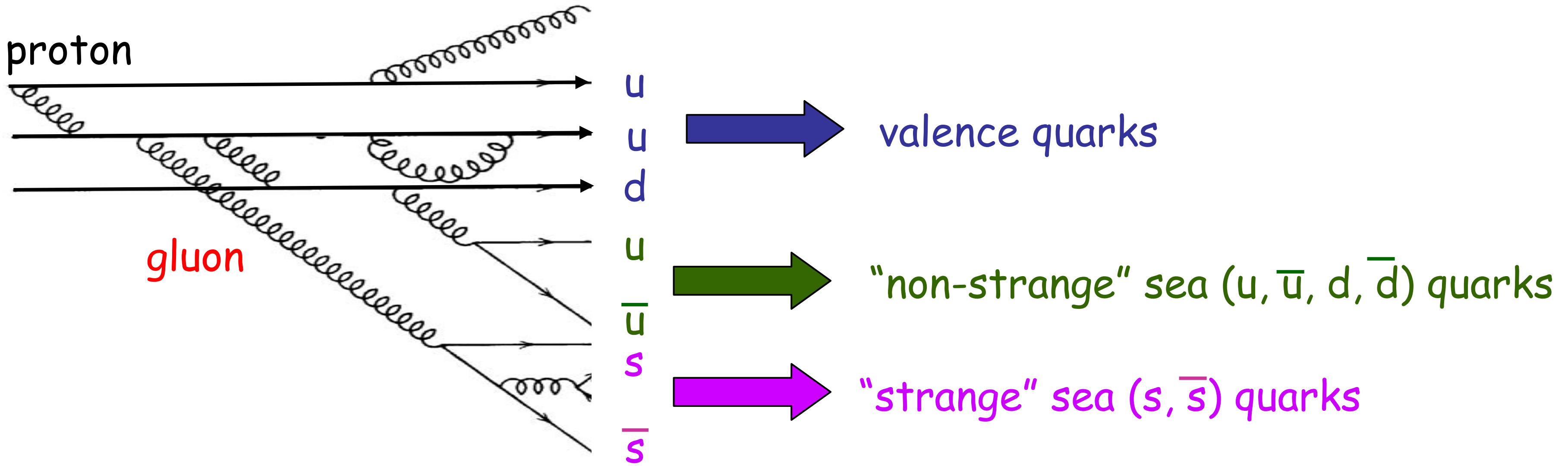
Caltech, Carnegie-Mellon, William & Mary, Hampton, IPN-Orsay, ISN-Grenoble, JLab, Kentucky, LaTech, NMSU, TRIUMF, U Conn, UIUC, U Manitoba, U Maryland, U Mass, UNBC, VPI, Yerevan

~ 100 scientists from 19 institutions

Our sponsors:

What role do strange quarks play in nucleon properties?

Momentum ; Spin ; Mass ; Charge and Current



Main goal of G^0

determine contributions of strange quark sea (s, $\bar{s}$) to electromagnetic properties of the nucleon

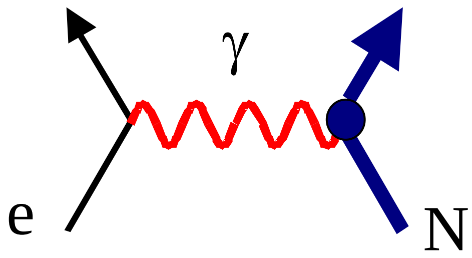
"strange form factors"

Charge and current:

$$< N | \bar{s} \; \gamma^{\mu} \; s | N > \; = \; ?? \; \rightarrow \; G_E^s \;\; G_M^s$$

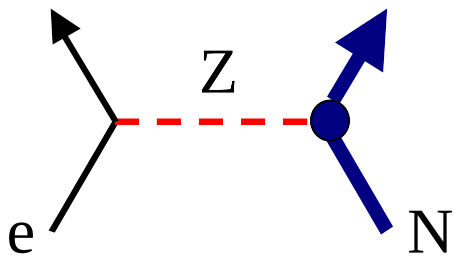
Nucleon form factors measured in elastic e-N scattering

- well defined experimental observables
- provide 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



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

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

ELECTROWEAK CURRENTS

$$J_\mu^{\gamma} = \sum_i Q_i^{\gamma}\, \bar{q}_i \gamma_\mu q_i \qquad J_\mu^{Z} = \sum_i Q_i^{Z}\, \bar{q}_i \gamma_\mu q_i$$

Flavor decomposition of nucleon E/M form factors:

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

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

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

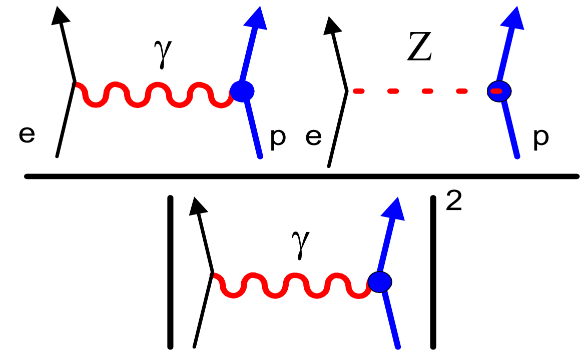
Invoke proton/neutron charge symmetry → 3 equations, 3 unknowns

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

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:

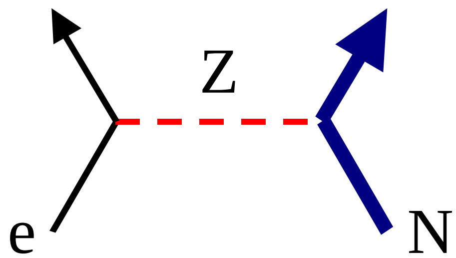
Forward angle $\vec{e}$ + p (elastic)
Backward angle $\vec{e}$ + p (elastic)
Backward angle $\vec{e}$ + d (quasi-elastic)

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

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

Z^0 has axial, as well as vector couplings $\rightarrow$ we measure axial FF too

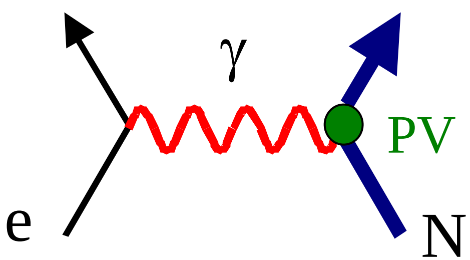
$$G_A^e = G_A^Z + \eta F_A + R^e$$



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

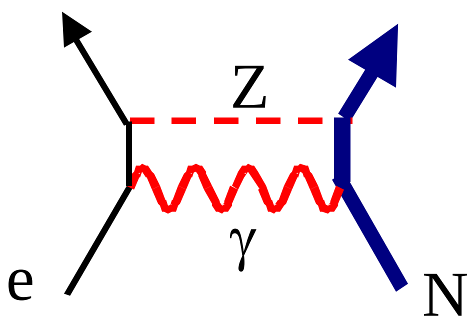
$\rightarrow$ multiplied by $g_e^v = 1 - 4\sin^2\theta_W \sim 0.074$

+



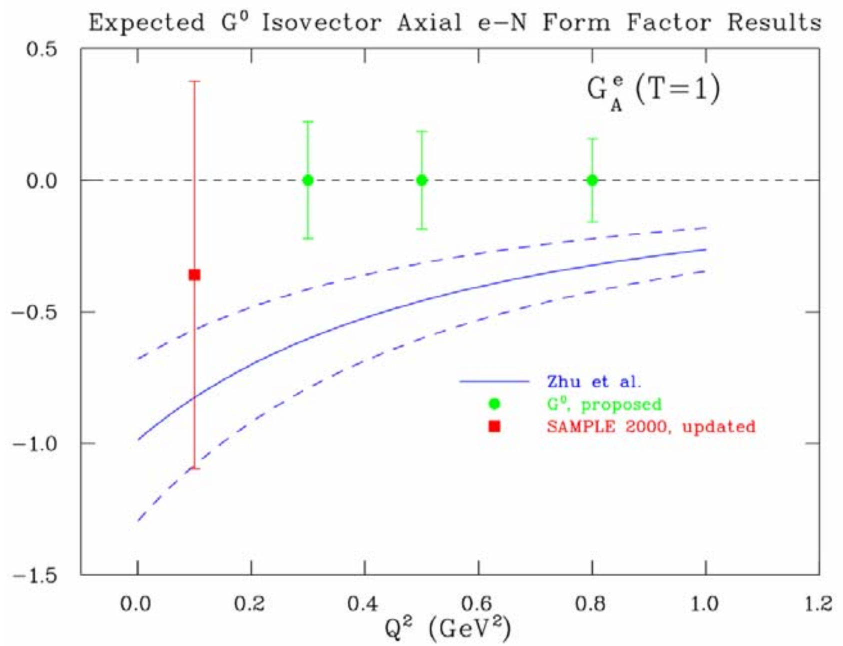
F_A: nucleon's anapole moment – parity-violating electromagnetic moment

+



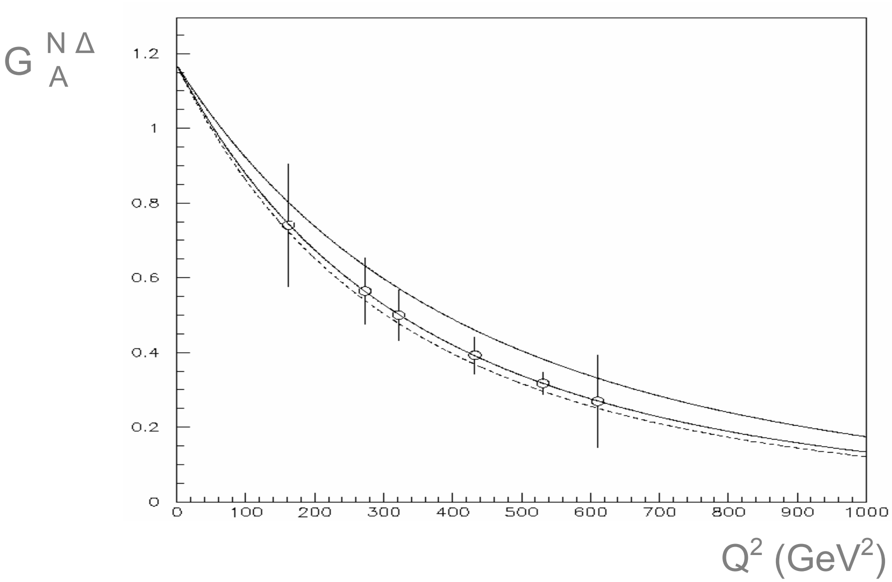
R^e: electroweak radiative corrections to e-N scattering

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→Δ 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

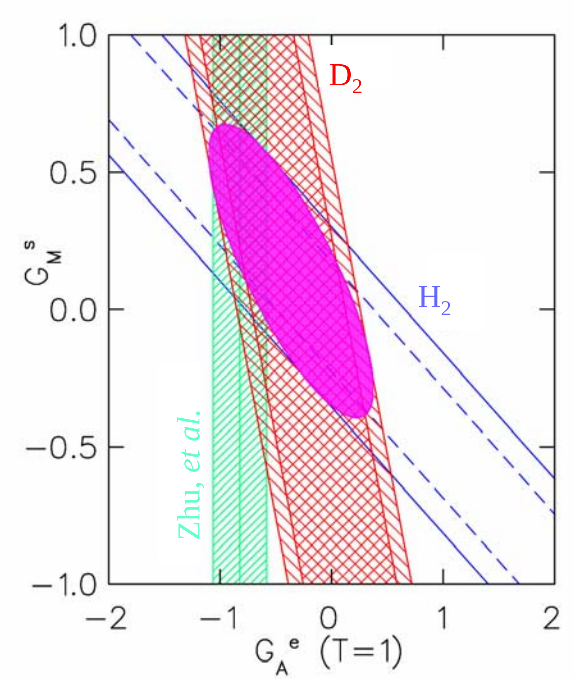
SAMPLE at MIT-Bates:

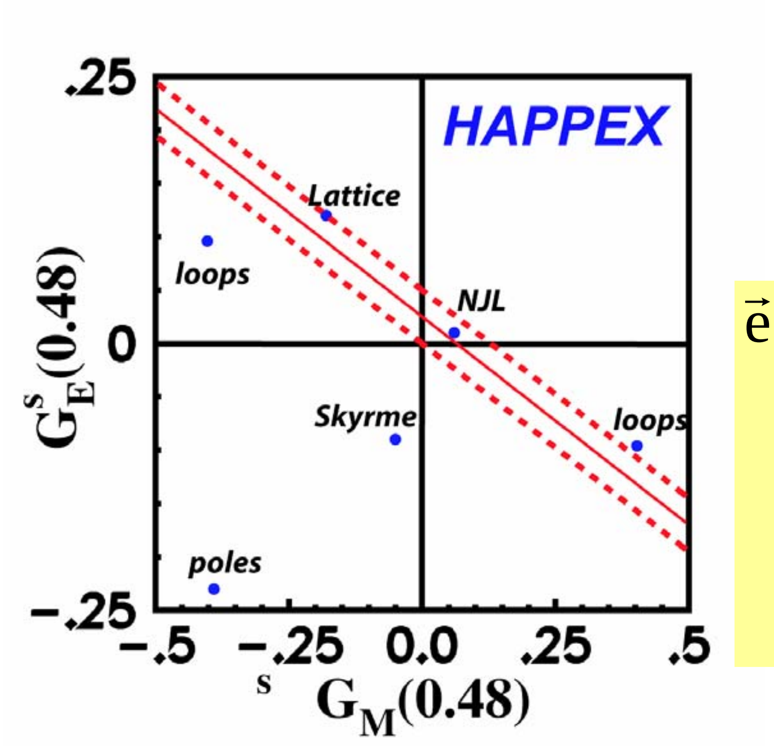
$\vec{e} + p$ elastic: $A_p = -4.92 \pm 0.61 \pm 0.73$ ppm

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

(updated results, publication in progress)

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





HAPPEX at Jefferson Lab:

$\vec{e} + p$ 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 $Q^2 = 0.48\,\text{GeV}^2$

G^0 Experimental Program

- 1^{st} Engineering Run

⇐ **we are here**

- 2^{nd} Engineering Run

- **Forward angle measurement**
- **Expected Results:**

  $(G_E^s + \alpha\, G_M^s)$ for 7 values of Q^2 between 0.1 – 1.0 $(GeV/c)^2$

- **3 Backward angle measurements**
- **Expected Results:**

  Separated G_E^s , G_M^s , and G_A^e for Q^2 of 0.3, 0.5, and 0.8 $(GeV/c)^2$

  $N \rightarrow \Delta$ axial transition form factor

General Experimental Requirements

measure A_{PV} ~ -3 to -40 ppm with precision $\Delta A_{PV} / A_{PV}$ ~ 5%

Statistics (5% ⟹ 10^{13} - 10^{14} events):

- high e- polarization (70-80%)
- high e- current (40 μAmps)
- high luminosity (2.1×10^{38} cm^{-2} s^{-1})
- large acceptance detector (0.5-0.9 sr)
- long target (20 cm)
- high count rate capability detectors/electronics (1 MHz)

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

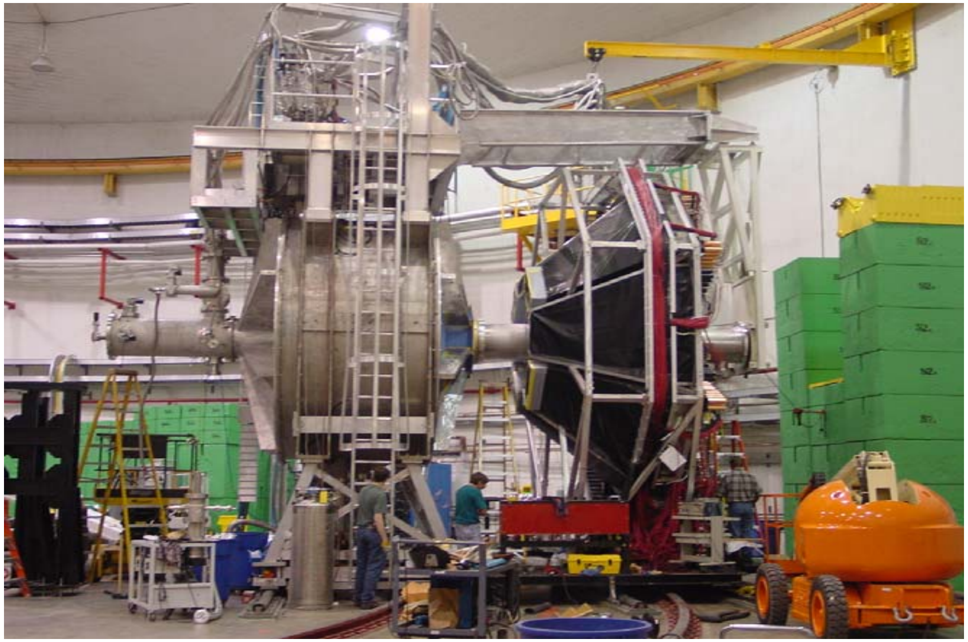
- small helicity-correlated beam properties
- ability to isolate elastic scattering from other processes

statistics ~55%-75% of total error on separated G_E^s and G_M^s

The G^0 Experiment in Jefferson Lab Hall C

All New Hall C Equipment:

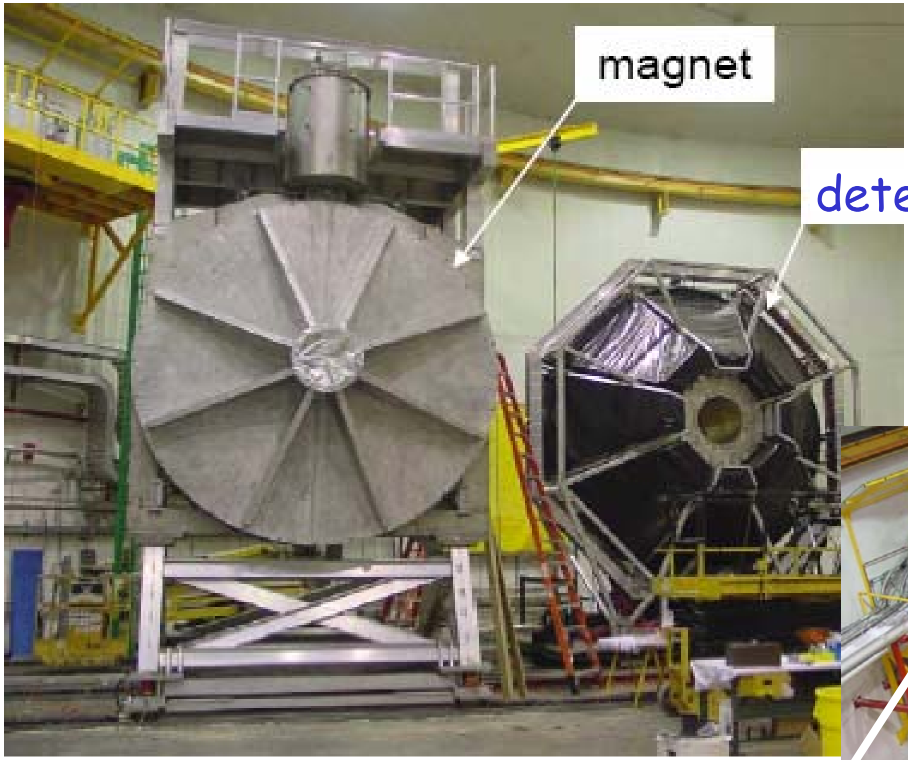
Superconducting toroidal **magnet** – Univ of Illinois
High power H_2 /D_2 **targets** – Caltech, UMd, JLab
Scintillator **detector** array – French/Canadian/NAmerican
Custom **electronics** – Orsay, Grenoble, CMU
Jefferson Lab polarized **source** - JLab



Design and Construction (1993–2001)
Installation (Fall 2001–Fall 2002)

G0 installed in Hall C at JLab

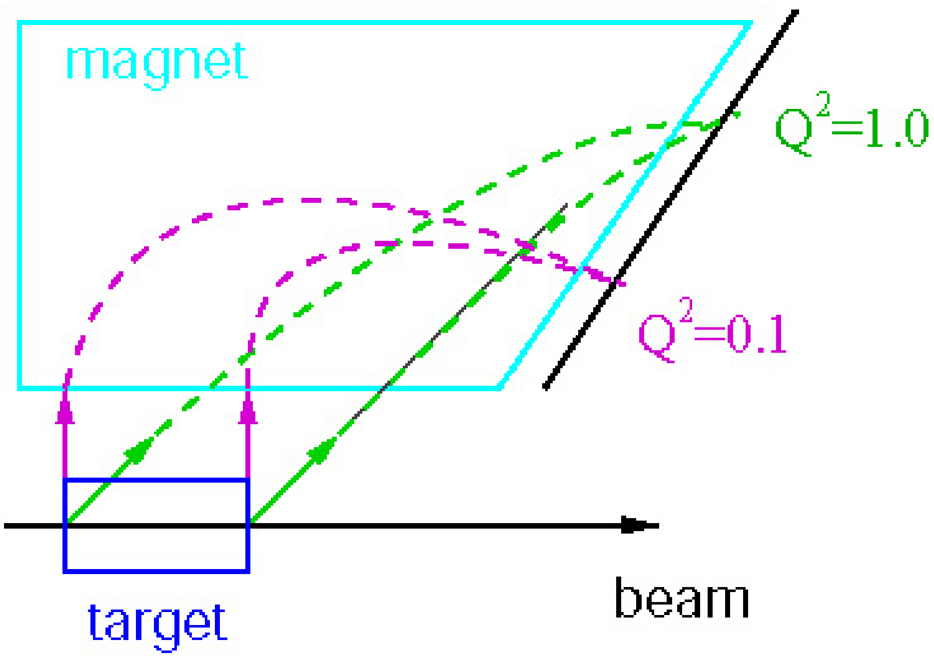
April '02

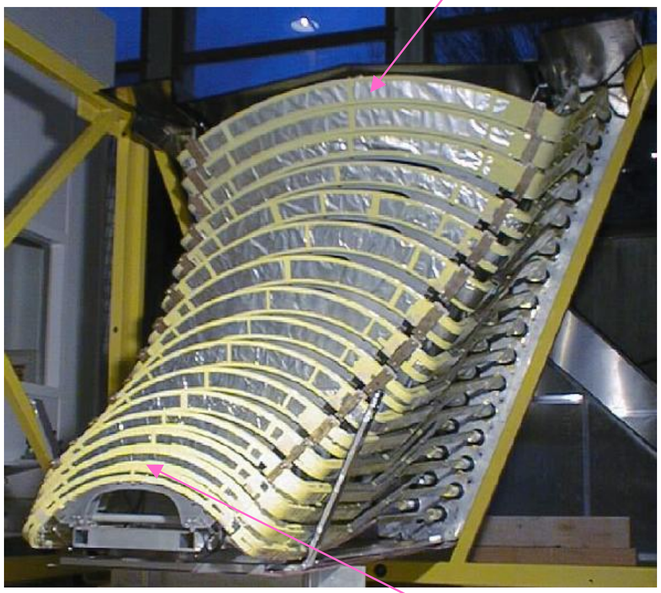


August '02

G^0 Forward Angle Measurement

- 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)





French octant

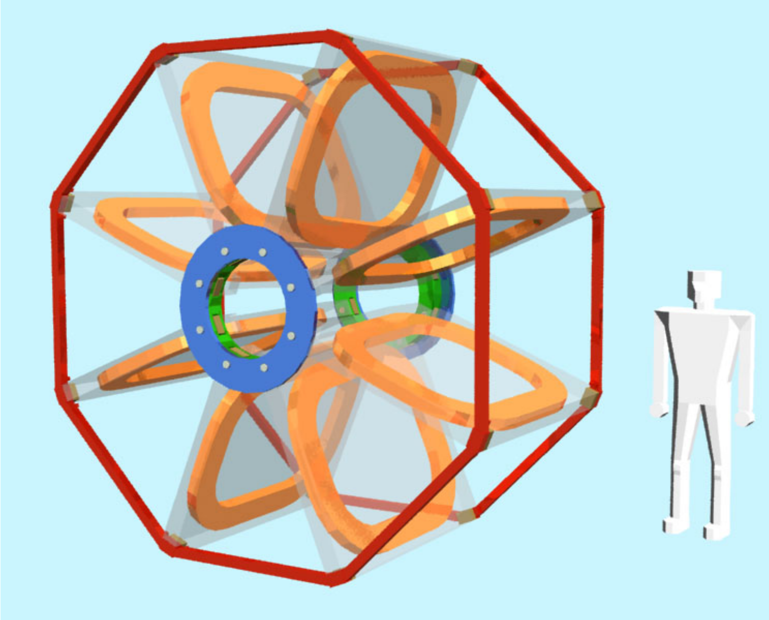
G^0 Superconducting Magnet System

Superconducting toroidal magnet:
8 coils ; common cryostat

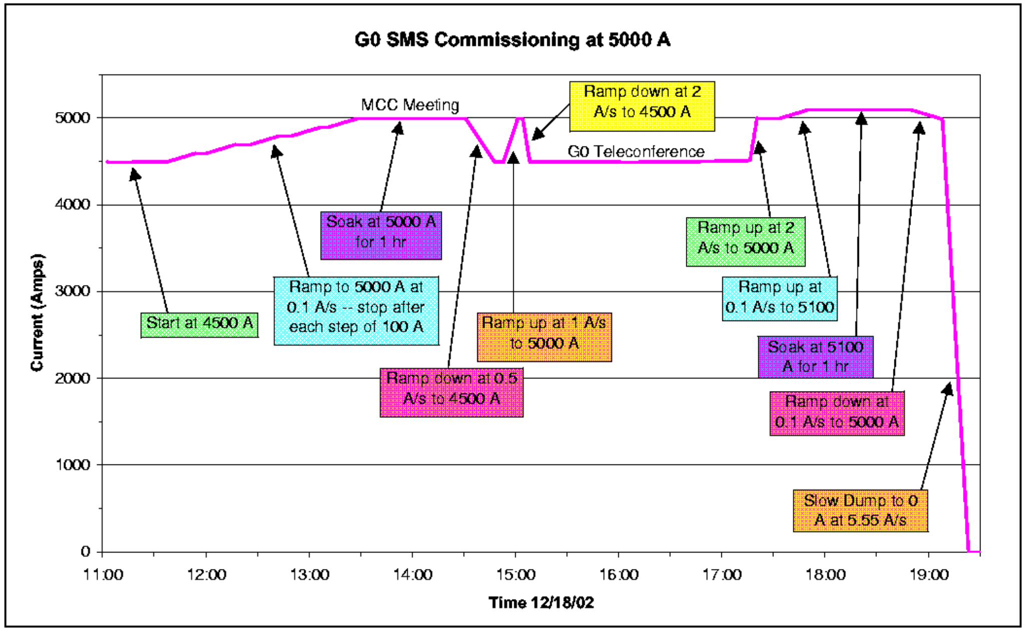
$$\int B \cdot dl = 1.6 \text{ Tm}$$

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

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

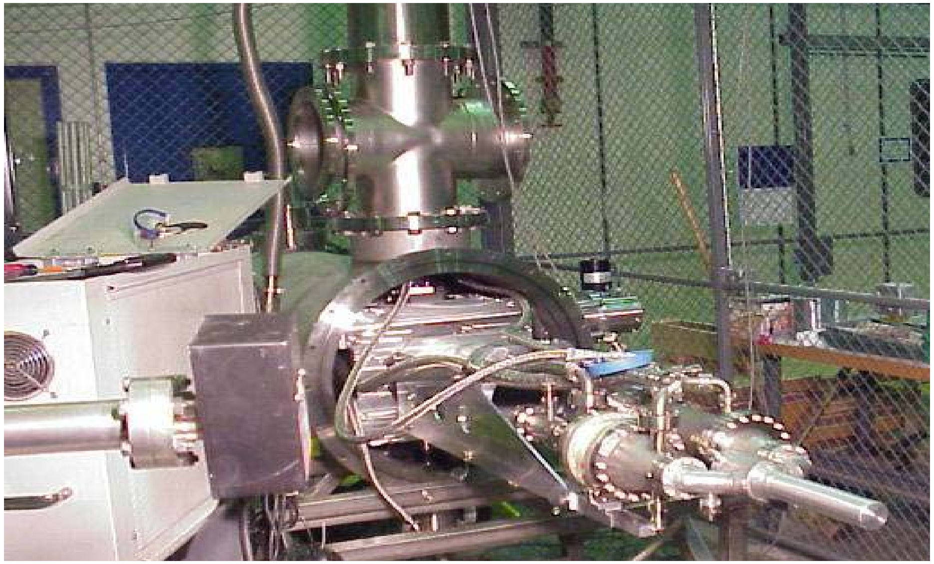


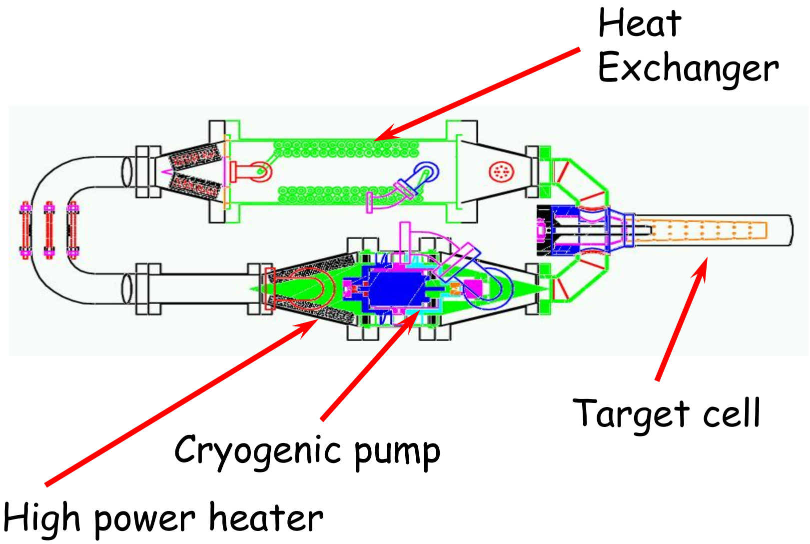
- Initial manufacturing defects repaired in early 2002
- Ran at 4500 A initially (Aug. - Dec. 2002)
- Ran at full design current (5000 A) during Jan 2003 run

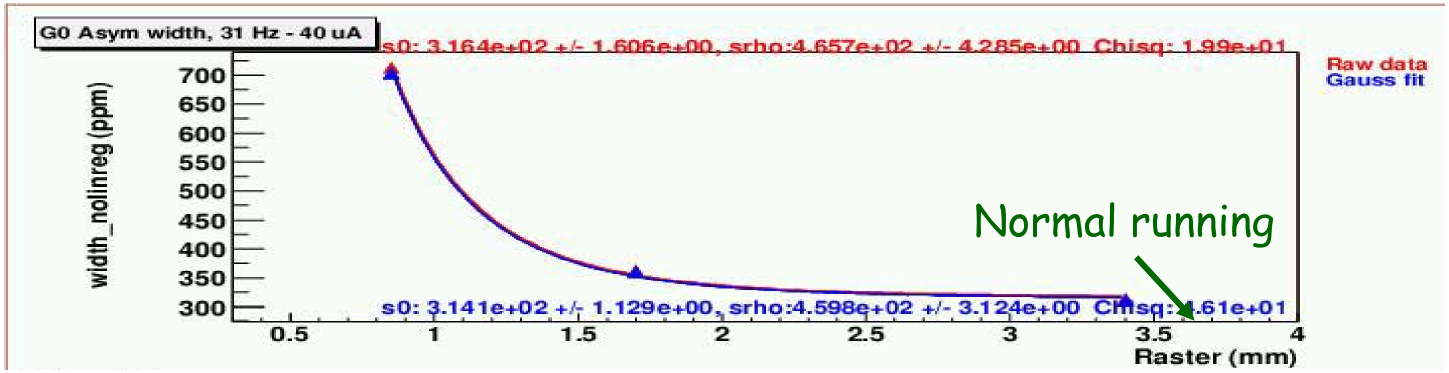


G^0 Target

- 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





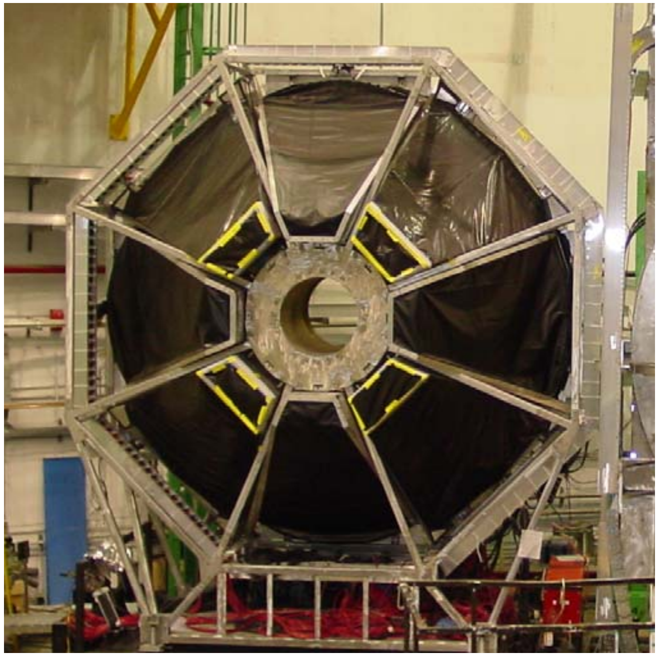


G^0 Focal Plane Detectors (FPD)

- 8 octants ; 256 signals total
- 16 pairs of arc-shaped scintillators each
- back and front coincidences to eliminate neutrals
- 4 PMTs (one at each end of each scintillator)
- long light guides (PMT in low B field)

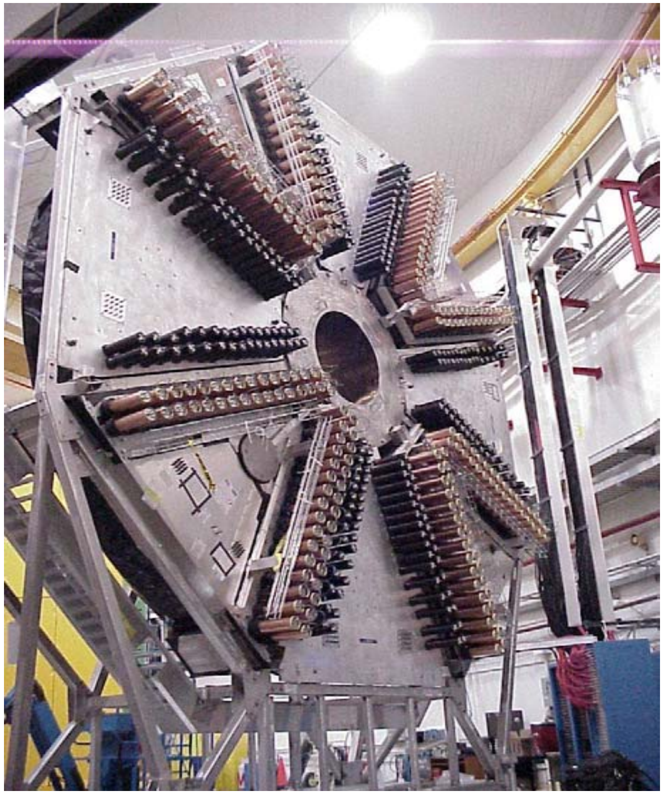
North American octant

Detector
"Ferris Wheel"



front

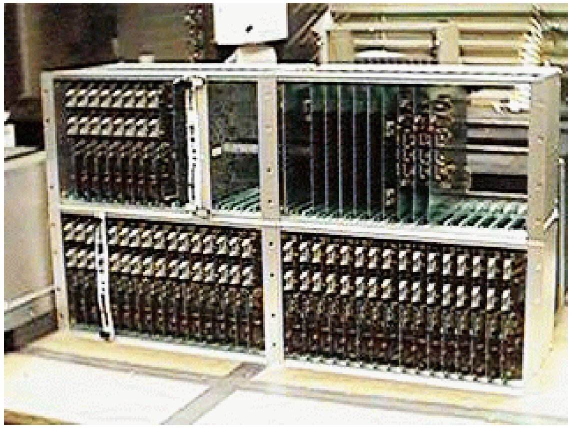
Detector
"Ferris Wheel"



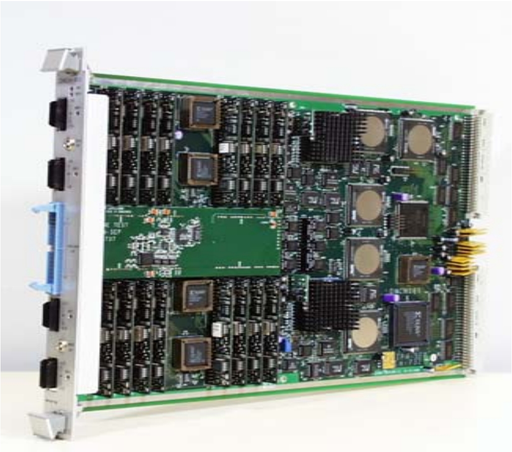
back

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

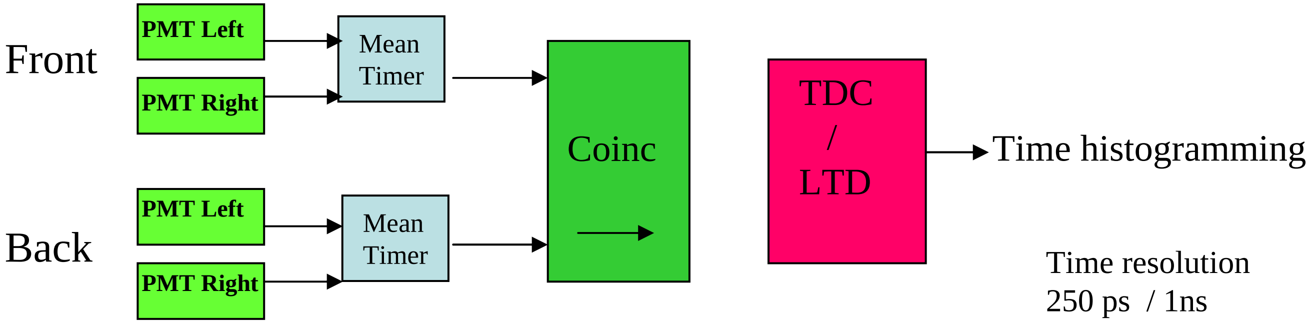


NA LTD crate (1/2)



French DMCH16 Module 1/8

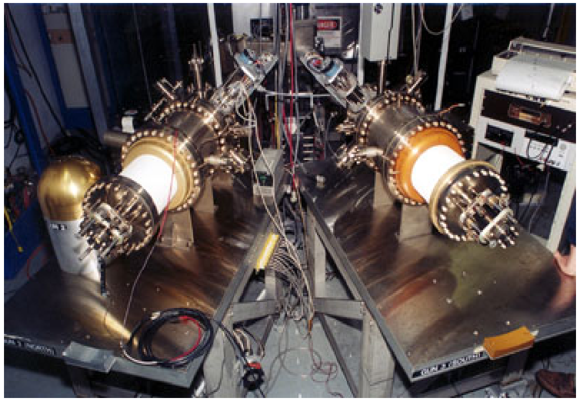
Time of Flight measurement



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 quality closest to operating specs during Jan 2003 delivery
  - Beam current 40 μA
  - Beam fluctuations at (30 Hz/4) ~ $\Delta X, \Delta Y < 20\ \mu m$ $\Delta I/I < 2000$ ppm
- Ongoing Beam Work
  - multiple Hall delivery
  - beam position feedback
  - reliable control of helicity-correlated properties

CEBAF polarized injector



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)

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

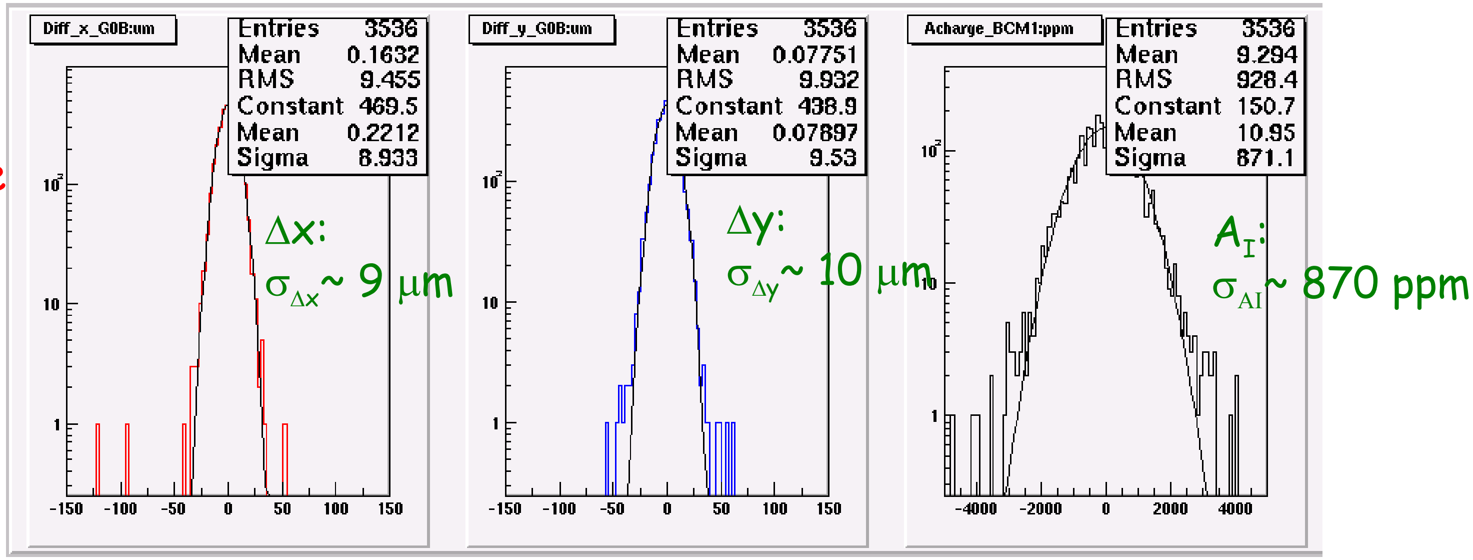
asymmetry (detector yield or intensity):

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

differences (beam position differences)

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

Typical difference and charge asymmetry histograms



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:

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

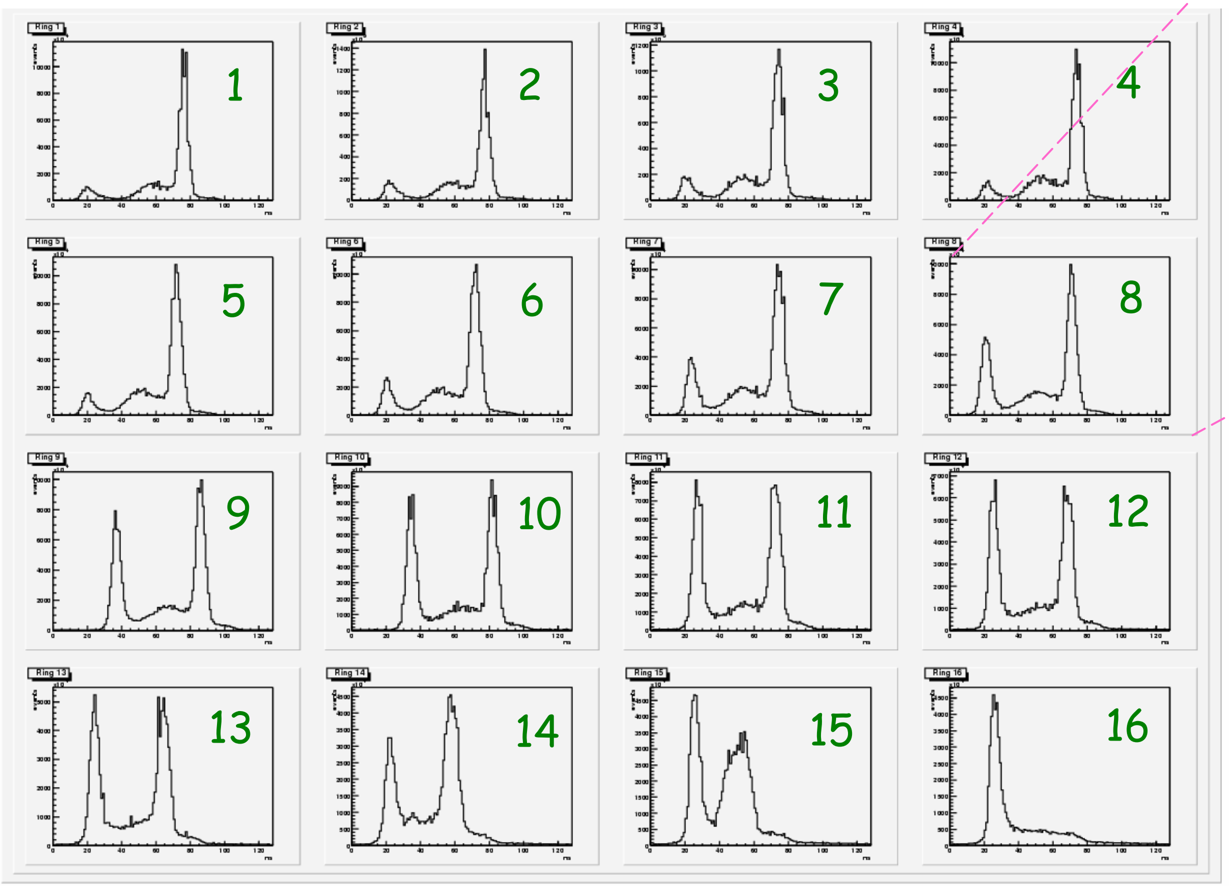
- $\langle Q^2 \rangle$ determination
- electromagnetic form factors

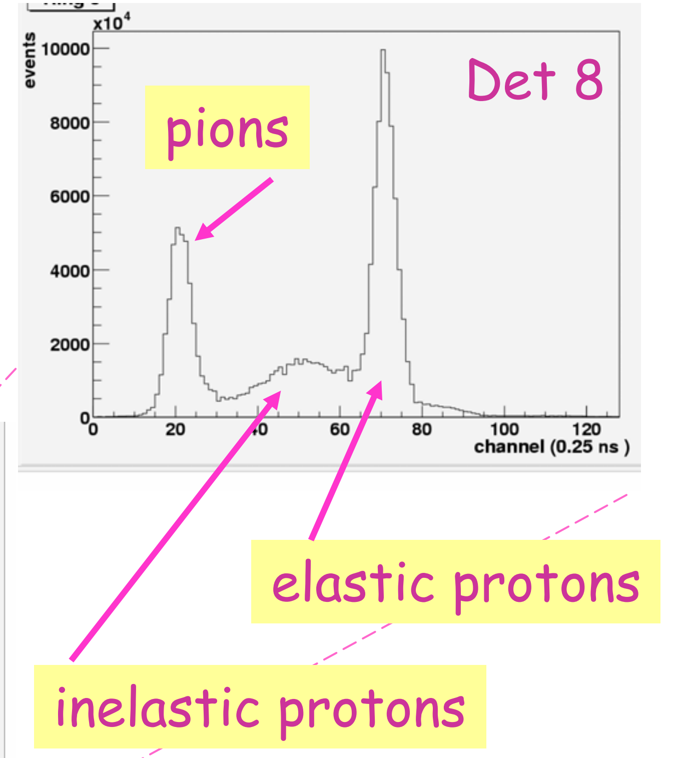
Time of Flight Spectra from G^0 Engineering Run

16 detectors of a single octant

-t.o.f recorded every 33 msec

-good spectra for all octants, all detectors





Behavior of raw asymmetry results under slow half wave plate reversal

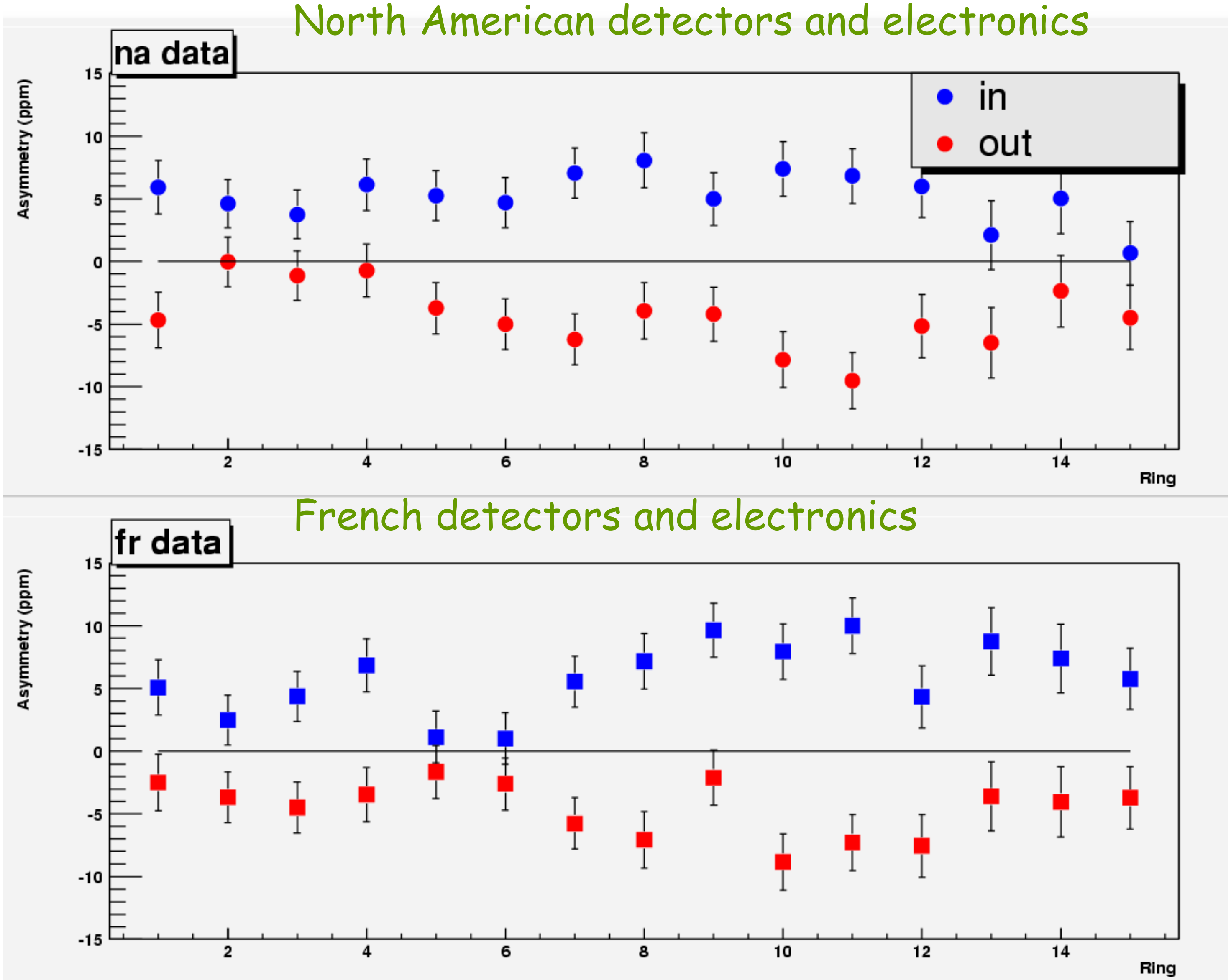
Based on 51 hours of data at 40 μA

Jan 2003 Engineering Run

No unexpected false asymmetries seen

North American detectors and electronics

French detectors and electronics

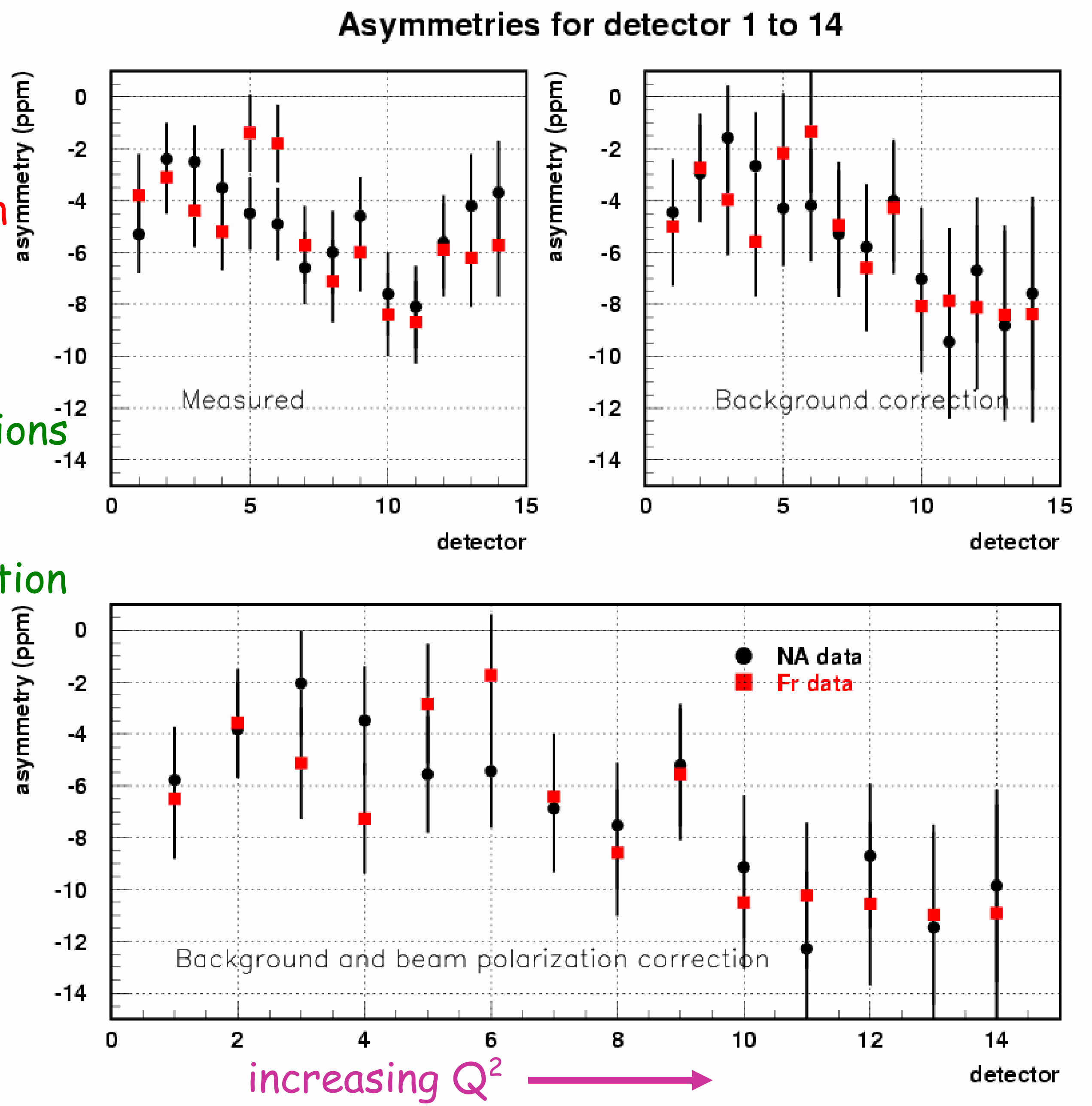


Asymmetry results from Jan. 2003 Engineering Run

- 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



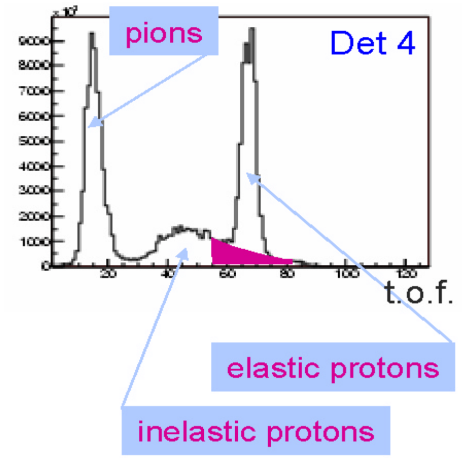
1st Engineering Run - *successfully completed*

Current Work

- **False Asymmetries**
  - Helicity correlated beam charge effects (goal <1ppm over 700 hours)
  - Helicity correlated beam position effects (goal <20 nm over 700 hours)

- **Deadtime**
  - typical deadtime ~10% with rates of ~1-2 MHz/detector
  - causes false asymmetries when combined w/nonzero charge asymmetry
  - uncorrected effect ~15% ; after correction ~1% ; A_{false} ~0.01ppm

- **Background Determination**
  - requires both yield and asymmetry of background
  - yield ~10-25% depending on detector
  - $|A_{back}| \sim |A_{elastic}|$ near elastic peak (preliminary)



G^0 Backward Angle Measurement

- detect scattered electrons at $\theta_e \sim 110°$
- need three runs each for LH_2 and LD_2

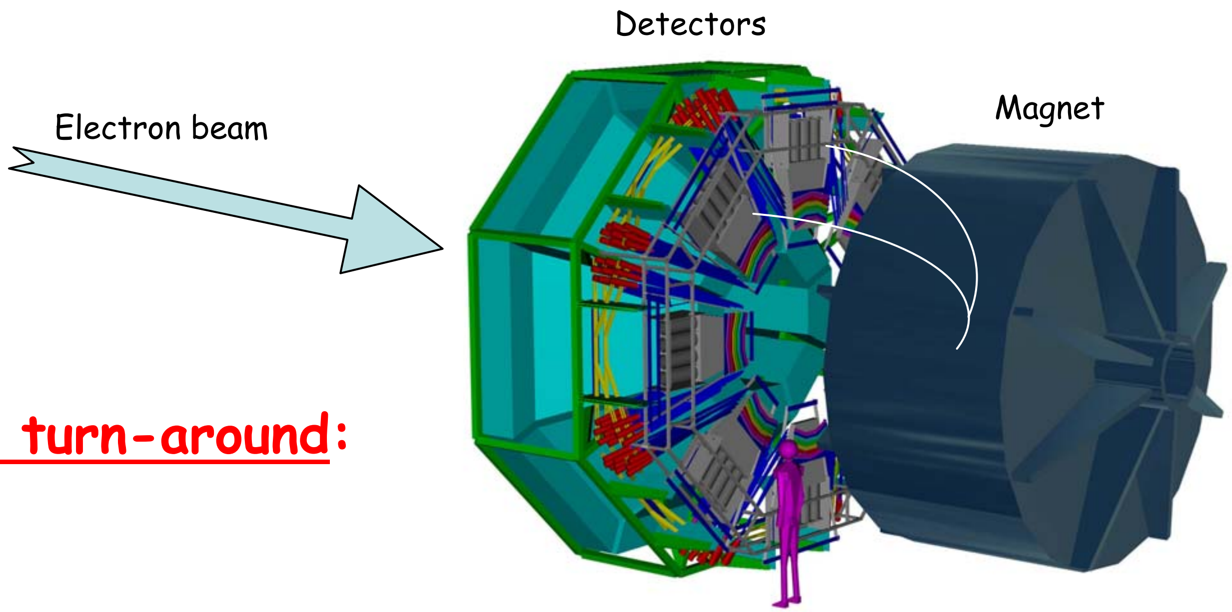
at E = 424, 576, 799 MeV

for Q^2 = 0.3, 0.5, 0.8 $(GeV/c)^2$

(total of 6 runs x 700 hours each)

Requires additional hardware:

- Cryostat Exit Detectors (CED) to separate elastic and inelastic electrons used in coincidence with FPDs
- Cerenkov detector for pion rejection (primarily for LD_2 target)
- additional electronics
- LD_2 target

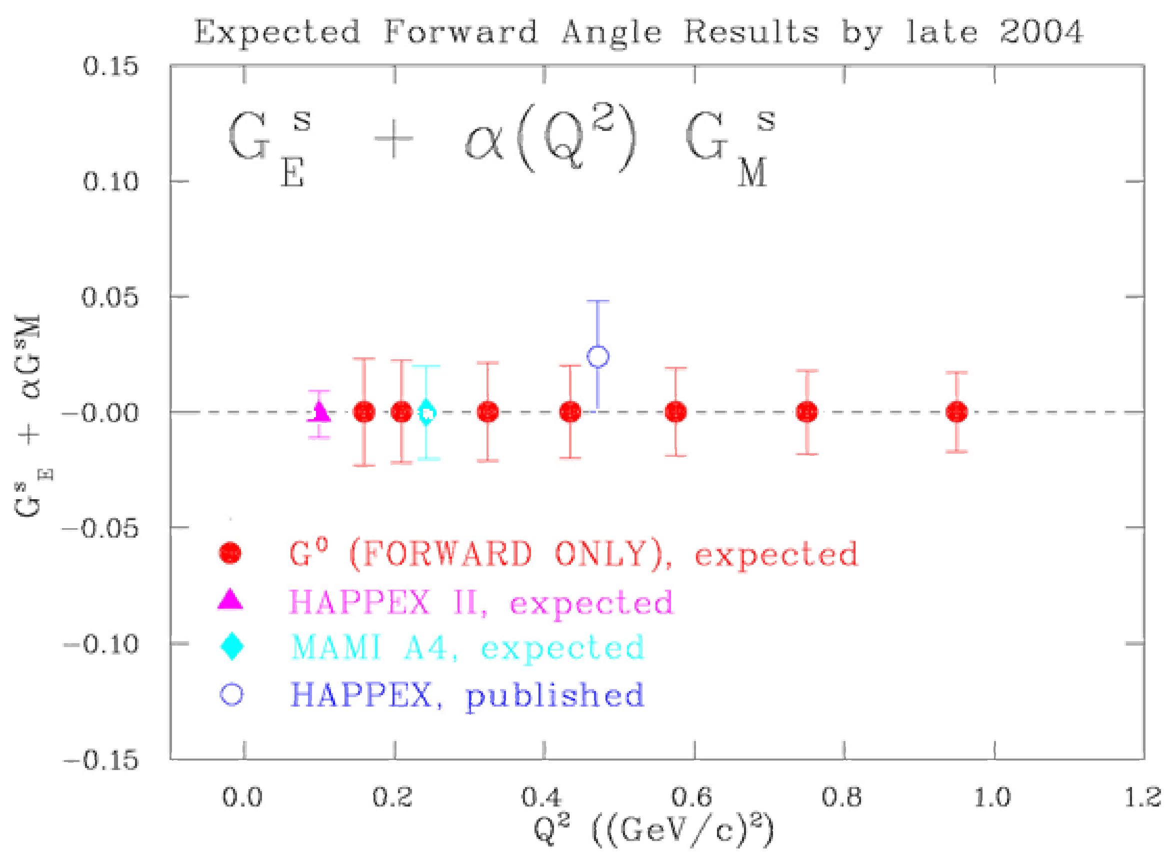


Requires physical turn-around:

Near Future

- 2^{nd} G^0 engineering run in Oct-Dec 2003
- Forward angle production run in Feb 2004

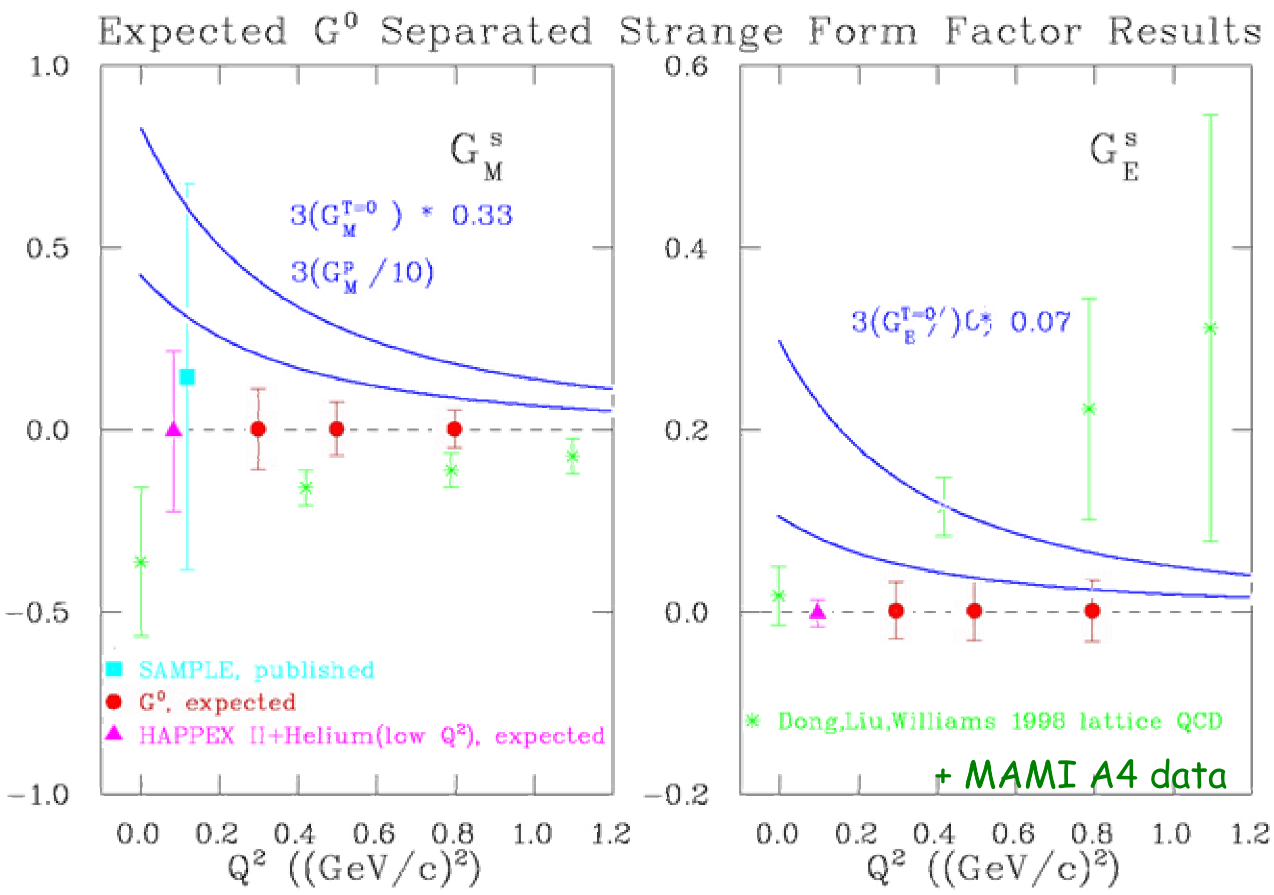
Hopefully by late 2004 we can compare world's forward angle data....



Future

Back angle running starting early in 2005

.....and a few years later,
we can present a wide Q^2 range of separated form factors



SUMMARY

- G^0 has a broad experimental program that will result in the first separated values of G_E^s, G_M^s, and G_A^e over a wide range of Q^2

- 1st G^0 Engineering Run successfully completed
  - all hardware operational
  - obtained ~2 days of test asymmetry data
  - clearly see weak interaction
  - no unexpected false asymmetries seen

- On track to resume running in October 2003

- Look forward to first physics results late 2004