# The $G^0$ Experiment: Parity Violation in e-N Scattering

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For the $G^0$ Collaboration:

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Hall C Users Meeting January 2006

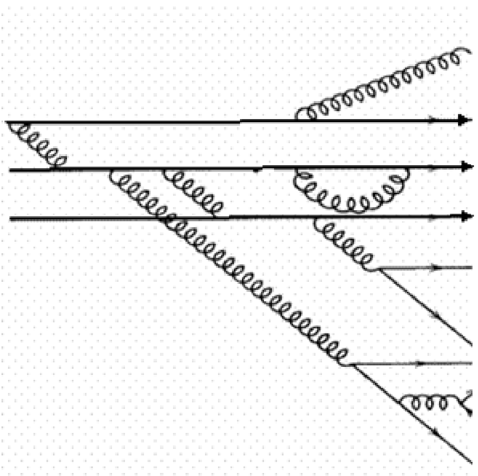
# Outline

- Experiment Theory
- Experiment Overview
- Expected Results

# Experiment Theory

- Strange Quarks in the Nucleon
- Electron and Proton Interactions
- Nucleon Structure
- Parity Violating Electron Scattering
- Axial Vector Form Factor
- Previous Results

# Strange Quarks in the Nucleon



u
u
d

valence quarks

u
$\bar{u}$

"non-strange" sea (u, $\bar{u}$, d, $\bar{d}$) quarks

s
$\bar{s}$

"strange" sea (s, $\bar{s}$) quarks

Strange quark contribution to nucleon properties:

- Momentum: 4%
- Spin: 10%
- Mass 30%
- Charge distribution?
- Current distribution?

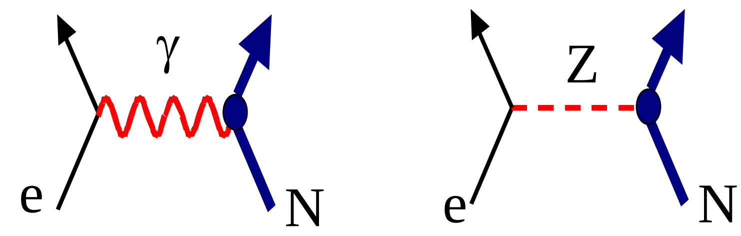
(Momentum, Spin, Mass: controversial)

Goal of $G^0$: to determine contributions of strange quark sea to electromagnetic properties of the nucleon

$$G_E^s, G_M^s$$

# Electron and Proton Interactions

- Electromagnetic Force
  - Charge dependent
  - Parity conserving
- Weak Force
  - Carrier particles: $W^+$, $W^-$ and Z bosons
  - $Z^0$ interaction charge independent, parity violating




$$G_E^{0,P} = \left[2 - 4\sin^2\theta_W\right] G_E^{P,\gamma} - 4 G_E^{P,Z}$$

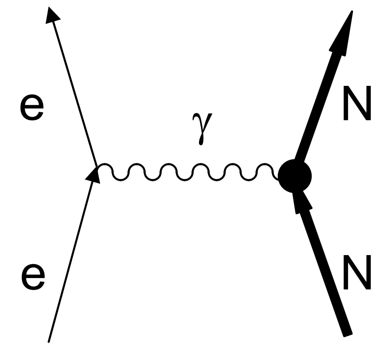
$$G_E^{0,P} = \left(\frac{1}{3}\right)\left(G_E^{u,p} + G_E^{d.p} + G_E^{s,p}\right)$$

Amplitude of electron-proton interaction $M = M^\gamma + M^Z$

Probability $|M|^2 = |M_\gamma|^2 + 2\,\mathrm{Re}\left[(M_\gamma)^*(M_z)\right] + |M_z|^2$

Asymmetry $A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{|M_\gamma + M_z|_R^2 - |M_\gamma + M_z|_L^2}{|M_\gamma + M_z|_R^2 + |M_\gamma + M_z|_L^2} = 2\frac{M_\gamma^* M_z}{|M_\gamma|^2}$

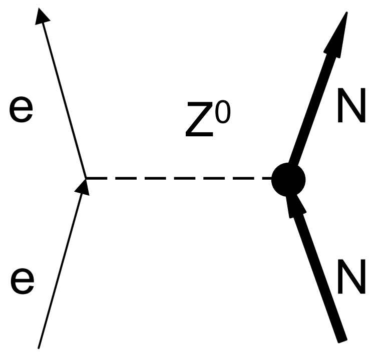
# Nucleon Structure




$$G_{E/M}^{\gamma,p} = \frac{2}{3}G_{E/M}^{p,u} - \frac{1}{3}G_{E/M}^{p,d} - \frac{1}{3}G_{E/M}^{p,s}$$

$$G_{E/M}^{\gamma,n} = \frac{2}{3}G_{E/M}^{n,u} - \frac{1}{3}G_{E/M}^{n,d} - \frac{1}{3}G_{E/M}^{n,s}$$

Strange quark form factors




$$G_{E/M}^{Z,p} = \left(1-\frac{8}{3}\sin^2\theta_W\right)G_{E/M}^{p,u} + \left(-1+\frac{4}{3}\sin^2\theta_W\right)G_{E/M}^{p,d} + \left(-1+\frac{4}{3}\sin^2\theta_W\right)G_{E/M}^{p,s}$$

$$G_{E/M}^{Z,n} = \left(1-\frac{8}{3}\sin^2\theta_W\right)G_{E/M}^{n,u} + \left(-1+\frac{4}{3}\sin^2\theta_W\right)G_{E/M}^{n,d} + \left(-1+\frac{4}{3}\sin^2\theta_W\right)G_{E/M}^{n,s}$$

$$G_{E/M}^{u,n} = G_{E/M}^{d,p}$$

$$G_{E/M}^{d,n} = G_{E/M}^{u,p}$$

$$G_{E/M}^{s,n} = G_{E/M}^{s,p} = G_{E/M}^{s}$$

Assume charge symmetry (good to 1%)

$$G_E^{Z,p} = (1-4\sin^2\theta_W)G_E^{\gamma,p} - G_E^{\gamma,n} - G_E^{s}$$

$$G_M^{Z,p} = (1-4\sin^2\theta_W)G_M^{\gamma,p} - G_M^{\gamma,n} - G_M^{s}$$

Two unknowns, two equations.
But how do we measure the $G^Z$ . . .

# Parity Violating Electron Scattering

Scatter longitudinally polarized electrons from unpolarized nucleons . . .

Forward Angles     Backward Angles

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = 2\frac{M_\gamma^* M_z}{\left|M_\gamma\right|^2} = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{A_E + A_M + A_A}{2\sigma_u}$$

$$A_E = \varepsilon(\theta) G_E^Z(Q^2) G_E^\gamma(Q^2)$$

$$A_M = \tau(Q^2) G_M^Z(Q^2) G_M^\gamma(Q^2)$$

$$A_A = -(1 - 4\sin^2\theta_W)\varepsilon' G_A^e(Q^2) G_M^\gamma(Q^2)$$

$$2\sigma_u = \varepsilon\left(G_E^\gamma\right)^2 + \tau\left(G_M^\gamma\right)^2$$

nucleon's axial vector form factor as seen by an electron

### Kinematic Factors

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

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

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

At a given $Q^2$ decomposition of $G^s_E$, $G^s_M$, $G^e_A$
Requires 3 measurements:
Forward angle e + p (elastic)
Backward angle e + p (elastic)
Backward angle e + d (quasi-elastic)

$G^0$ will perform all three measurements at two different $Q^2$ values

# Axial Vector Form Factor

Charged weak coupling constant

$$M_Z = \frac{G_F}{\sqrt{2}} J^{Z\mu} J_\mu^Z$$

Associated current for proton

Amplitude for e-p scattering via weak neutral interaction

Electron-nucleon axial vector form factor

$$J_\mu^Z = \bar{u}\left[\gamma_\mu F_1^Z + i\frac{\sigma_{\mu\nu}q^\nu}{2M_p}F_2^Z + \gamma_\mu\gamma_5 G_A^e\right]u$$

Weak neutral form factors

Nucleon anapole form factor

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

Weak axial form factor

Radiative corrections

$$G_A(Q^2) = \frac{G_A(Q^2=0)^2}{1+\frac{Q^2}{M_A^2}}$$

(charged current neutrino scattering)

Integrated difference of strange quark

$$G_A^Z = G_A\tau_3 + \Delta s$$

(neutron beta decay)

# Previous Results

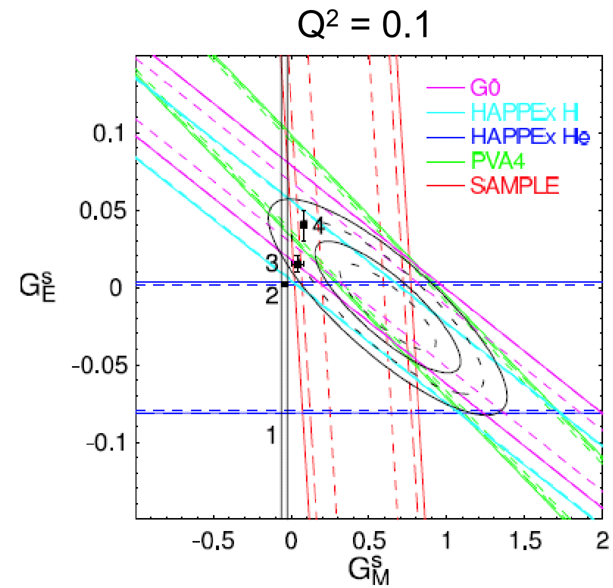
Backward Angles

## SAMPLE at MIT-Bates Linear Accelerator

$\vec{e}$ + p elastic: $A_p = -5.61 \pm 0.67 \pm 0.88$ ppm

$\vec{e}$ + d quasielastic: $A_d = -7.77 \pm 0.73 \pm 0.62$ ppm

$$G_M^s(Q^2 = 0.1\,\text{GeV}^2) = 0.37 \pm 0.20 \pm 0.26 \pm 0.07$$




Forward Angles

## HAPPEX in Hall A at Jefferson Lab

$\vec{e}$ + p elastic: $A_p = -14.92 \pm 0.98 \pm 0.56$ ppm

$$G_E^s + 0.392 G_M^s = 0.014 \pm 0.020 \pm 0.010$$

at $Q^2$ = 0.477 $\text{GeV}^2$

$\vec{e}$ + p elastic: $A_p = -1.14 \pm 0.24 \pm 0.06$ ppm

$$G_E^s + 0.080 G_M^s = 0.030 \pm 0.025 \pm 0.006 \pm 0.012$$

at $Q^2$ = 0.099 $\text{GeV}^2$

$\vec{e}$ + $^4$He: $A_p = 6.72 \pm 0.84 \pm 0.21$ ppm

$$G_E^s = -0.038 \pm 0.042 \pm 0.010$$

at $Q^2$ = 0.091 $\text{GeV}^2$

## A4 at the Mainz Microtron

$\vec{e}$ + p elastic: $A_p = -5.44 \pm 0.54 \pm 0.26$ ppm

$$G_E^s + 0.225 G_M^s = 0.039 \pm 0.034$$

at $Q^2$ = 0.230 $\text{GeV}^2$

$\vec{e}$ + p elastic: $A_p = -1.36 \pm 0.29 \pm 0.13$ ppm

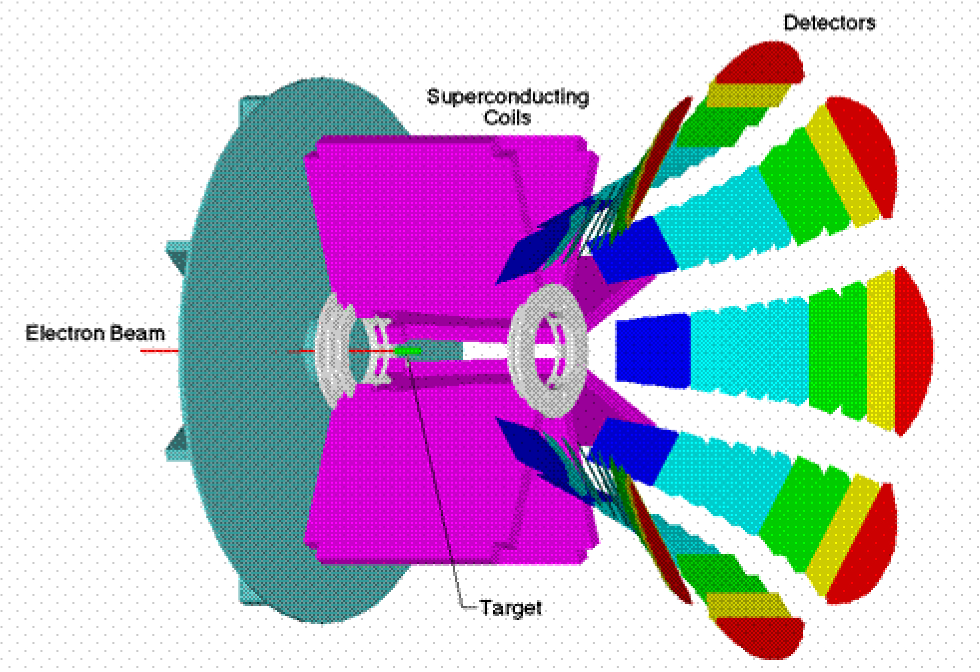
$$G_E^s + 0.106 G_M^s = 0.071 \pm 0.036$$

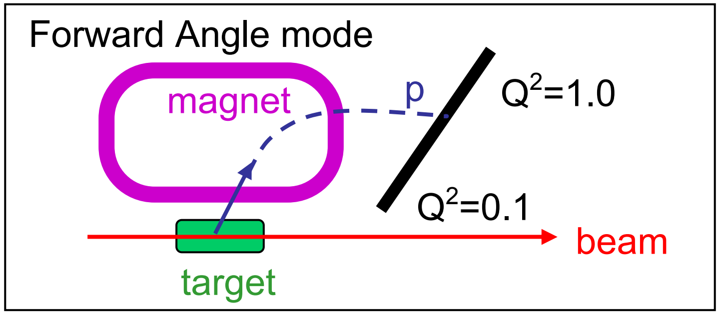
at $Q^2$ = 0.108 $\text{GeV}^2$

# Experiment Overview

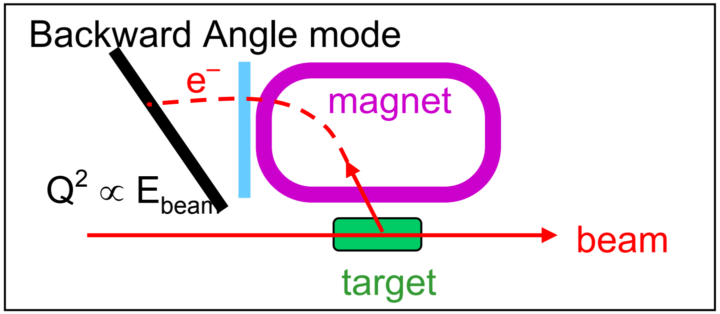
- Experiment Schematic
- Forward Angle Mode
  - Strangeness Form Factors
- Backward Angle Mode
  - Backward Angle Configuration
  - Cryostat Exit Detectors
  - $\pi^-$ Backgrounds
  - $\pi^-$ Rates
  - Parity Quality Beam Specifications
  - Pockels Cell Alignment
- Backward Angle Tentative Schedule

# Experiment Schematic



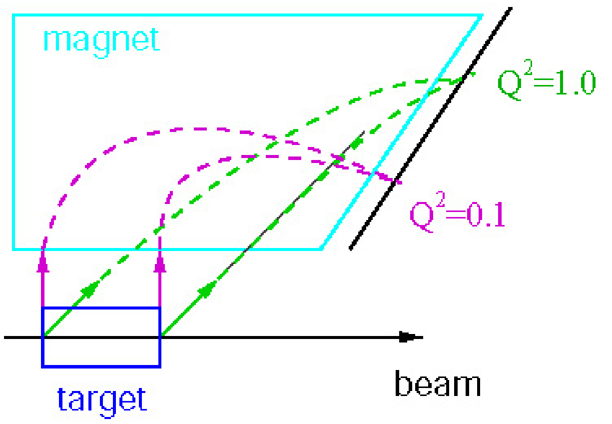

All measurements at 1 beam energy

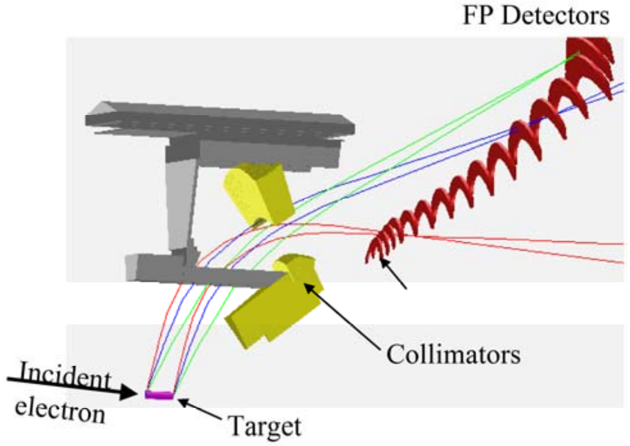



Measurements at 2 separate beam energies

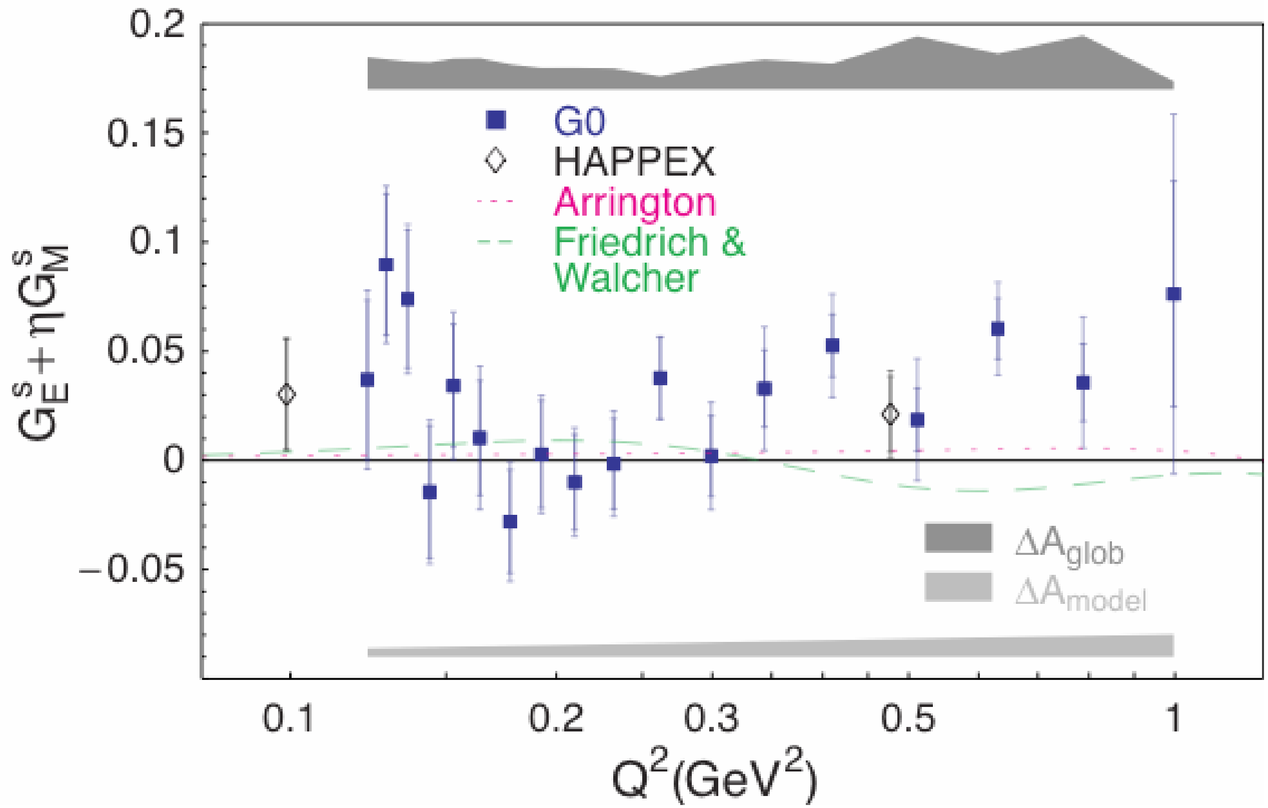
# Forward Angle Mode

- 40 μA polarized electron beam
- Electron beam energy 3.0 GeV
- Beam bunches separated by 32 ns (31.25 MHz )
- Detect recoil protons
- Strained GaAs
- Target: liquid hydrogen
- One energy setting for all $Q^2$ (0.1-1.0 $GeV^2$)
- $A_{NVS}$: -1.96 ppm to -48.61 ppm
- Spectrometer sorts protons by $Q^2$ in focal plane detectors
- Time-of-flight separates p (~20 ns) from $\pi^+$ (~8 ns)
- Status:
  - Run completed in May 2004 (began in November 2003)
  - 744 hours of parity quality beam (103 Coulombs)



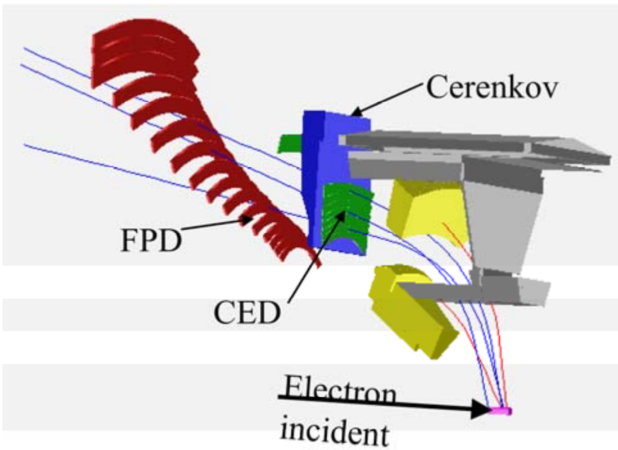



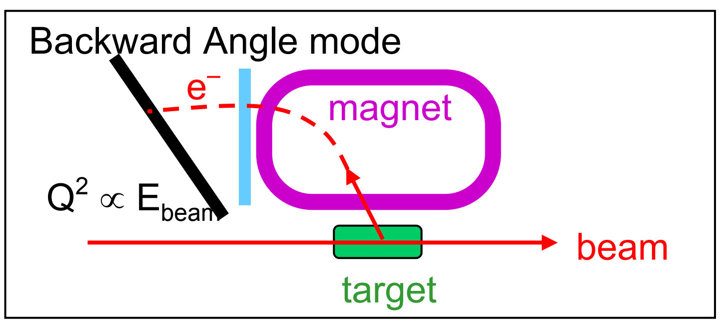
# Strangeness Form Factors




- $\eta \approx (0.81\text{-}0.93) \times (Q^2/GeV^2)$ with the Kelly form factors
- $G_E^s = G_M^s \equiv 0$ hypothesis excluded at 89% CL
- Error bars: inside = stat., outside = stat. & pt-pt syst.

# Backward Angle Mode

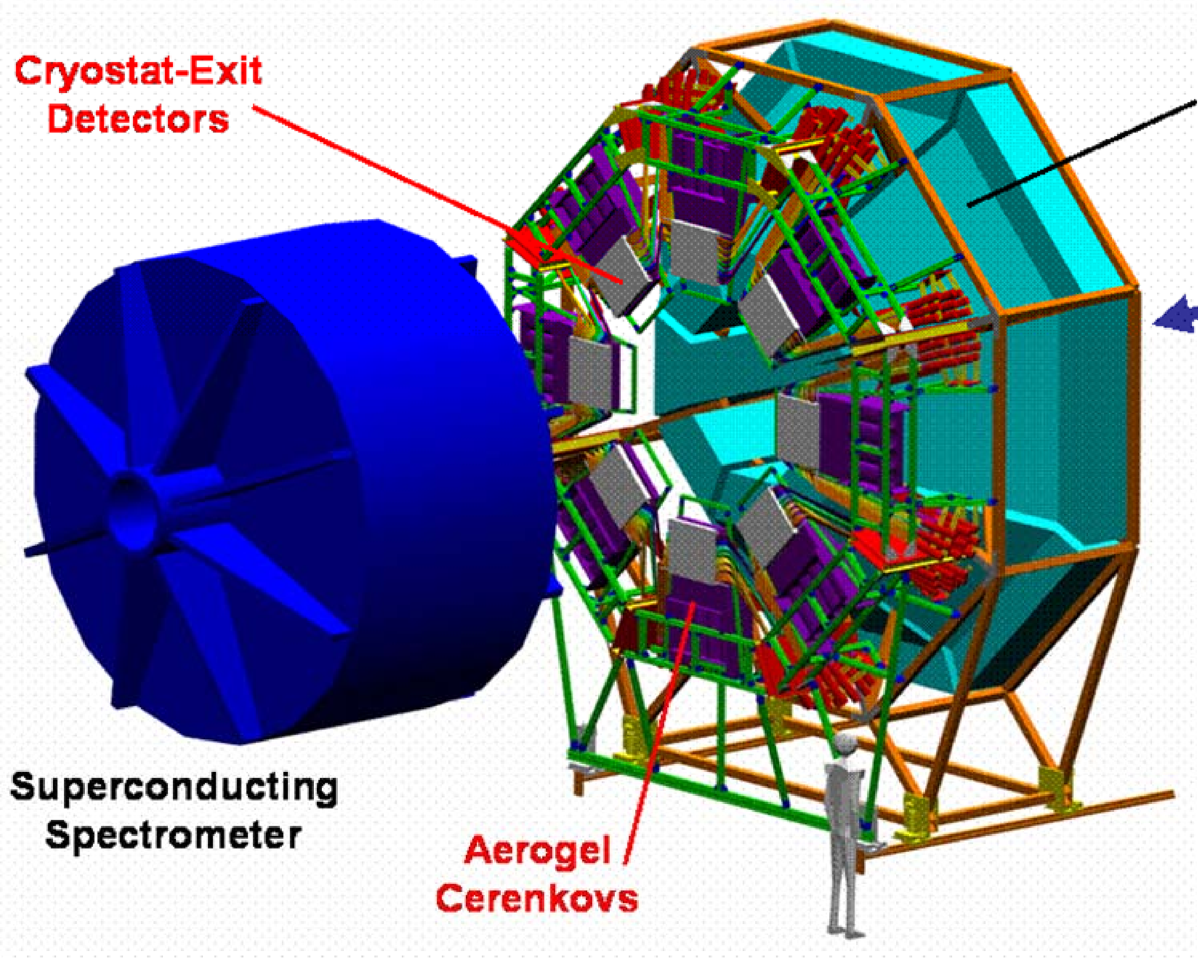



Measurements at 3 separate beam energies

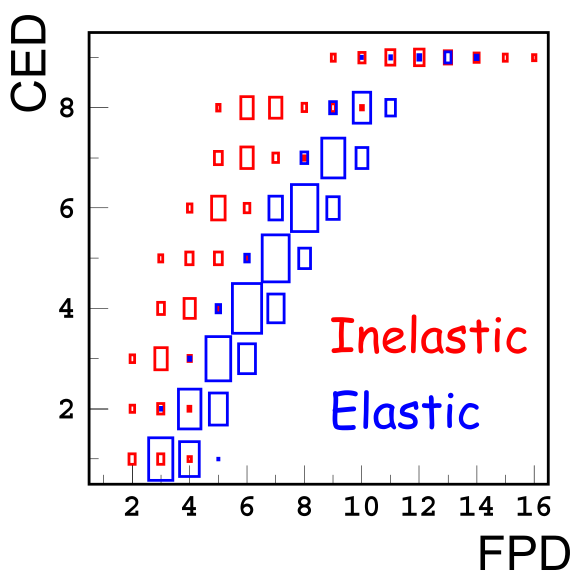
- 80 μA polarized electron beam
- Standard CEBAF time structure (499 MHz)
- Detect scattered electrons
- Target: liquid hydrogen and deuterium
- Superlattice GaAs
- One energy/magnet setting per $Q^2$
  - E = 360, 687 MeV
- 700 hours of beam per run
- $A_{NVS}$: -15 ppm to -50 ppm
- Additional Detectors:
  - Cryostat Exit Detectors (CEDs) - separate elastic and inelastic electrons by trajectory
  - Cerenkov Detectors - pion detection
- First data run in early 2006

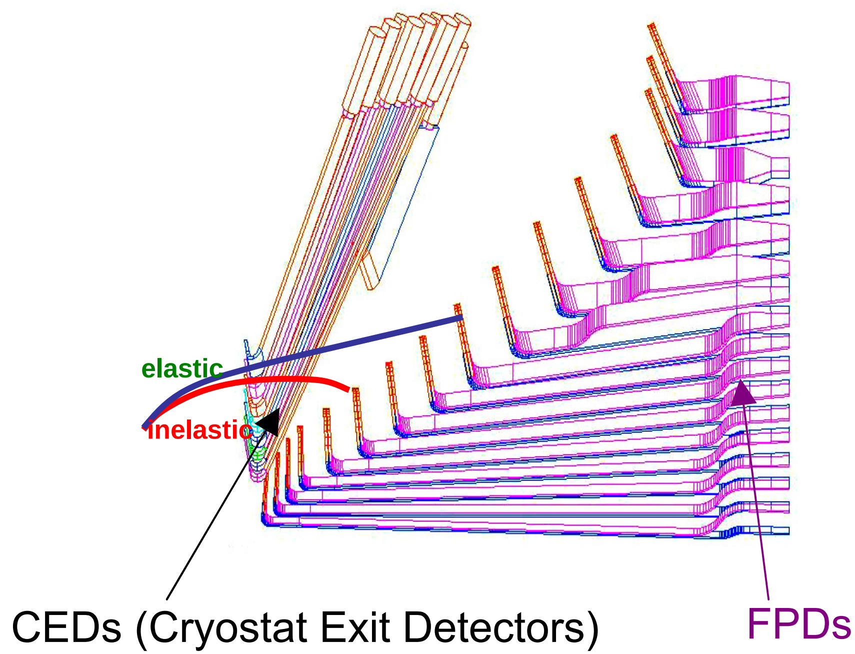
# Backward Angle Configuration



# Cryostat Exit Detectors

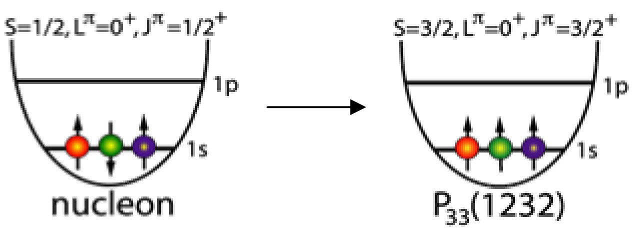
- Measure back scattered electrons
- 9 detectors per octant
- CED-FPD coincidence to separate elastics/inelastics electrons



# $\pi^-$ Backgrounds

- Negatively charged pions will produce a large background to the rates
- Photo-production near delta resonance
  - Hydrogen target
    - $\gamma + p \rightarrow \pi^+ + n$
    - $\gamma + p \rightarrow \pi^0 + p$
    - $\gamma + p \rightarrow \pi^- + \Delta^{++} \rightarrow \pi^- + (p + \pi^+)$ X
  - Deuterium target
    - $\gamma + d \rightarrow \pi^0 + n + p$
    - $\gamma + d \rightarrow \pi^- + p + p$
    - $\gamma + d \rightarrow \pi^+ + n + n$

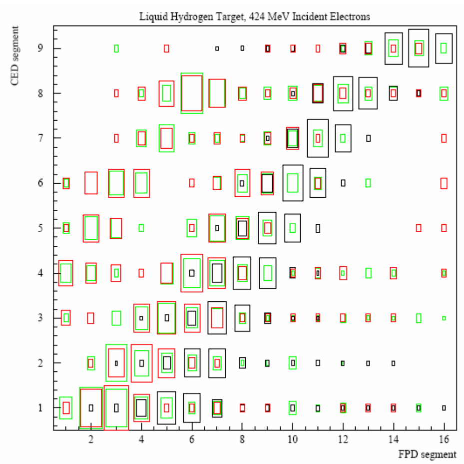



- Cross Sections
  - Measured using Short Order Spectrometer (SOS) in Hall C
  - GRAAL simulations
  - MAID-based calculations

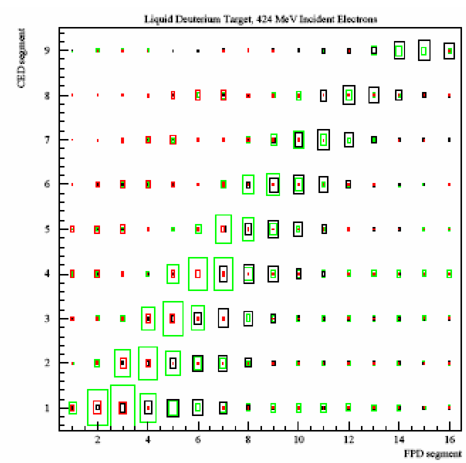
Black: elastic e⁻ rates
Red: inelastic e⁻ rates
Green: π⁻ Rates

# π⁻ Rates

hydrogen




deuterium




- Rates are proportional to the size of the box
- Hydrogen: By selecting certain CED/FPD combinations, we can separate:
  - Elastic and inelastic electrons
- Deuterium:
  - Negative pion rates considerably larger
  - Large pion contamination prevents measurement of asymmetry so we need additional particle identification (aerogel Cherenkov detector)

# Parity Quality Beam Specs

desired central value

how far central value can shift

std dev between diffs of 2 successive integration periods

upper limit on random noise

max value of hc diff or asym

| Property | Nominal | Max deviation | Helicity "noise" 1/30$^{th}$ | Other "noise" e.g. 60 Hz | Run averaged helicity correlation | Forward Specified | Forward Achieved |
|---|---|---|---|---|---|---|---|
| Energy | 687, 360 MeV | ±0.1% | 0.003% (105um) | 0.01% (350 um) | <$5\times10^{-8}$ (180 nm) | <75 eV | 29 ± 4 eV |
| Energy Spread | <0.1% | <0.1% | | | | | |
| CW Intensity | 80 $\mu$A (100 uA) | ± 5% | 0.2% | 1.0% | <2 ppm | <1 ppm | -0.14 ± 0.32 ppm |
| Position at Target | "0" | ± 0.2 mm | 20 $\mu$m | 0.2 mm | <40 nm | <20 nm | 4 ± 4 nm |
| Angle at Target | "0" | ± 0.05 mrad | 2 $\mu$rad | 0.02 mrad | <4 nrad | <2 nrad | 1.5 ± 1 nrad |
| Divergence at Target | 100 $\mu$rad | ± 50% | | | | | |
| Unrastered RMS Size at Target | 200 $\mu$m | ± 25% | 20 $\mu$m | 0.2 mm | 4 $\mu$m | ? | ? |
| Polarization | >70% | | | | | | |
| Halo at Target | <$10^{-6}$ outside 3 mm radius | | | | <0.2% of nominal | ? | ? |

# Laser Systematics

- Types and sources of laser systematics
- What is a Pockels Cell?
- Why do we care about laser systematics?
- Controlling laser systematics

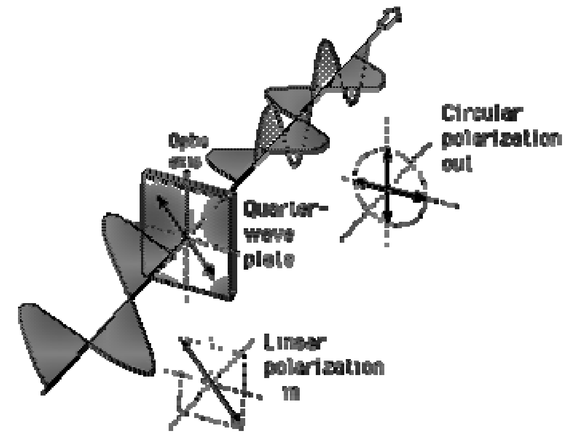
# Types and Sources of Laser Systematics

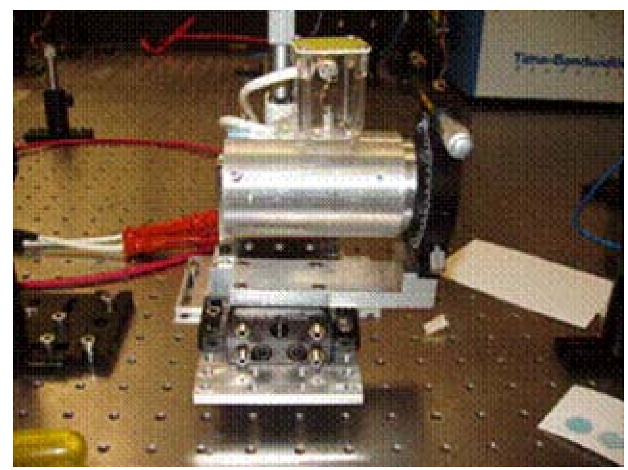
- Helicity Correlated Charge Asymmetry
  - In making circularly polarized light, there are small admixtures of linear polarization which cause a small degree of ellipticity
- Helicity Correlated Position Differences
  - Phase gradient across the laser spot
  - Gradient in analyzing power of cathode
  - Pockels Cell Steering effects

What is this?

# What is a Pockels Cell?

- Acts as a quarter-wave plate and changes linearly polarized light to circular.
- Retardation flips sign pseudorandomly on a pulse by pulse basis, generating circularly polarized light of either helicity.



# Why Do We Care About Laser Systematics?

- Helicity correlations in laser light → helicity correlation correlations in electron beam
- Critical to achieving accurate measurements

# Controlling Laser Systematics

- Helicity Correlated Charge Asymmetry
  - Phase adjustments: apply voltage to PC to zero asymmetry
  - IA Cell: charge asymmetry varies with voltage
  - Rotatable half waveplate: charge asymmetry varies with angle
- Helicity Correlated Position Differences
  - Minimize steering: center laser beam on PC
  - Minimize phase gradient: center laser beam on PC to zero phase gradient

# Tentative Schedule

- First Run Period (687 MeV, 1 pass, high Q2 measurement)
- G0 accelerator commissioning 3/15 & 3/16
- G0 physics commissioning 3/17-4/2
- G0 physics production run 4/3-4/29

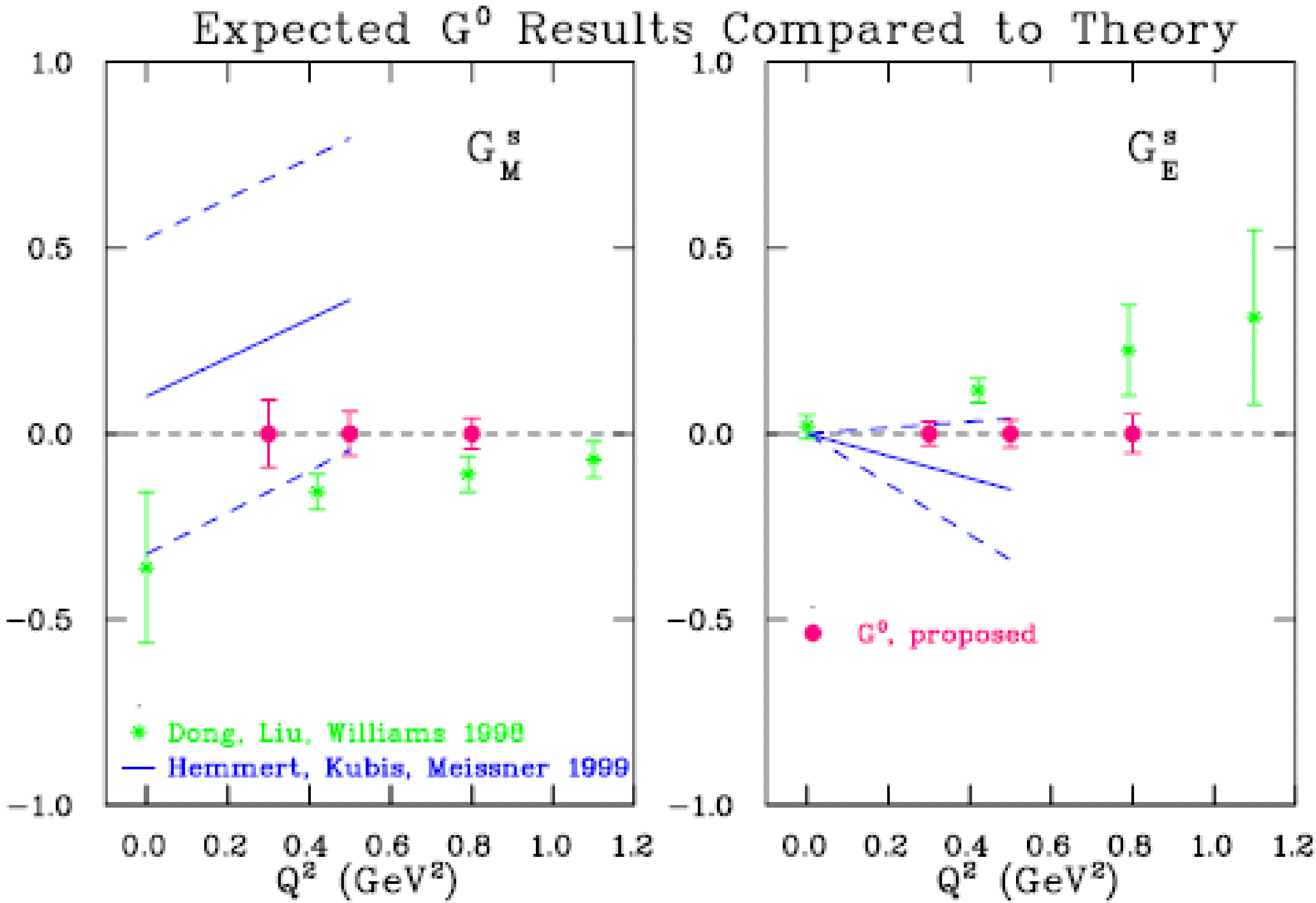
- Second Run Period (360 MeV, 1 pass, low Q2 measurement)
- G0 accelerator commissioning 7/21 & 7/22
- G0 physics production run 7/23-9/1

- Third Run Period (687 MeV, 1 pass, high Q2 measurement)
- 9/22-12/22

# Expected Results

- Electric and Magnetic Strange Form Factor
- Isovector Axial e-N Form Factor

# Expected Electric and Magnetic Strange Form Factor Results



# Expected Isovector Axial e-N Form Factor Results