Parity Violating Elastic $\vec{e}$-p Scattering Asymmetries from the G^0 Experiment

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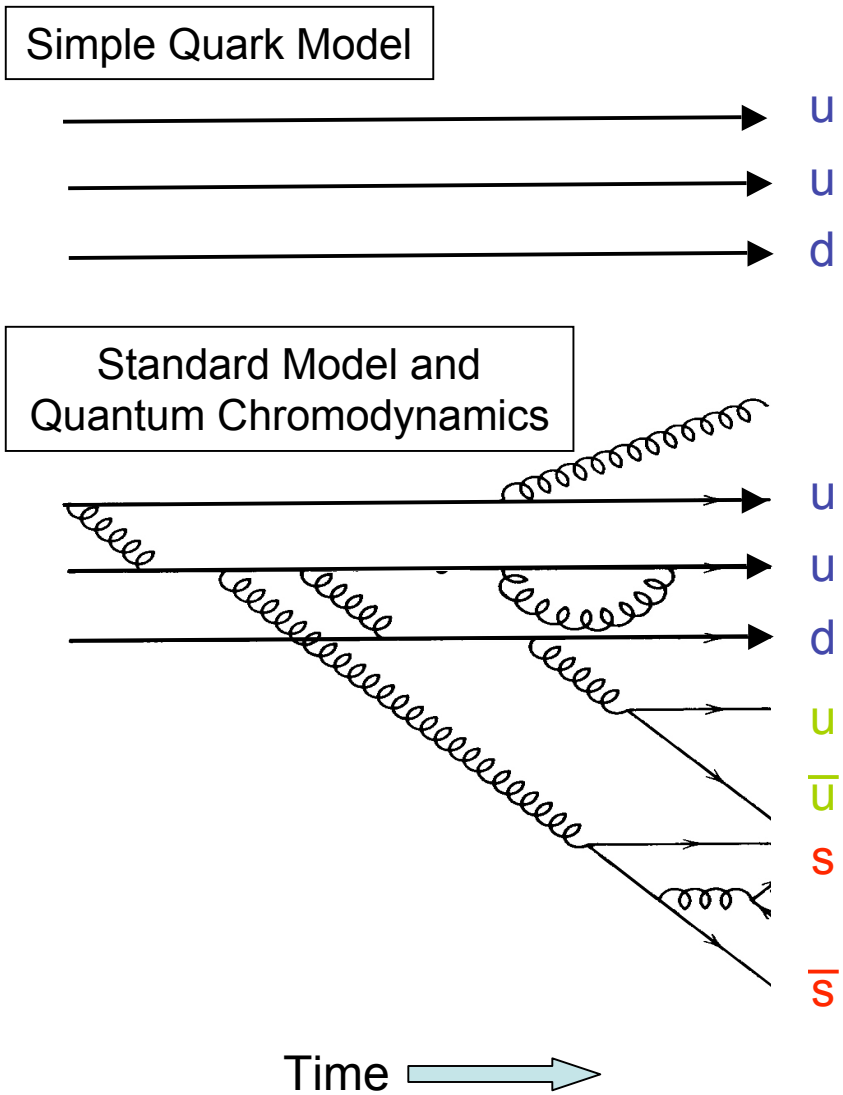
For the G^0 collaboration:

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

Précis

- Goal: Measure strange quark contributions to electric and magnetic nucleon form factors.
- Experiment:
  - Parity violating electron scattering from protons and deuterons.
  - Dedicated experimental apparatus in Hall C at Jefferson Lab.
  - Data required at forward and backward scattering angles ➔ multiple data runs over several years.
- Status:
  - Completed forward angle data taking in May (5.5 months ago).
  - Significant experimental problem solved towards end of run: “leakage” current with different time structure from Halls A and B.
  - Good progress on data analysis. Current work focuses on correcting for background in the elastic yields and asymmetries.
  - Will present preliminary, “blinded” asymmetries.

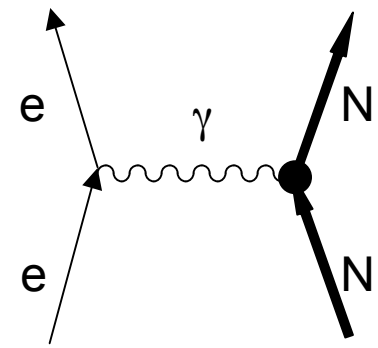
Strange Quarks in the Proton



- Contributions to static properties
  - Spin: -10% (polarized DIS)
  - Mass: 30% (πN scattering)
  - Momentum: 4% (DIS)
  - Charge Radius: ?
  - Magnetic Moment: ?
- Appear only in quark sea
- Goal of G^0:

  Determine contribution of strange quarks to EM form factors of protons and neutrons (nucleons)

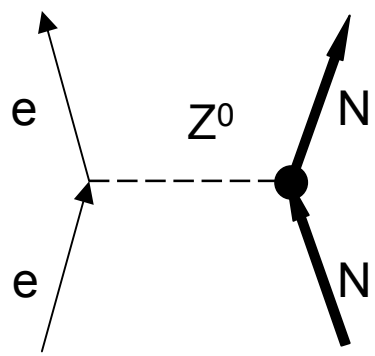
Nucleon Structure



$$G_E^p = \frac{2}{3}G_E^{p,u} - \frac{1}{3}G_E^{p,d} - \frac{1}{3}G_E^{p,s}$$

$$G_M^p = \frac{2}{3}G_M^{p,u} - \frac{1}{3}G_M^{p,d} - \frac{1}{3}G_M^{p,s}$$

Strange quark form factors



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

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

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

Assume charge symmetry

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

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

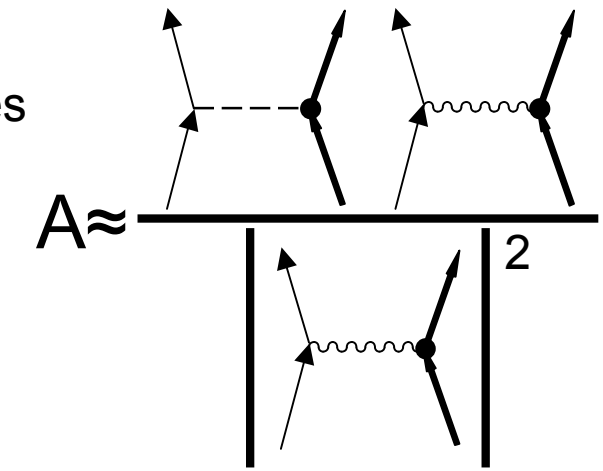
Two unknowns, two equations.
But how do we measure the G^Z . . .

Parity Violating Electron Scattering

Scatter longitudinally polarized electrons from unpolarized nucleons . . .

Forward Angles Backward Angles

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



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

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

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

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

Kinematic Factors

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

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

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

Extracting Strange Quark Form Factor Contributions

$$G_{E,M}^{Z} = (1 - 4\sin^2\theta_W)(1 + R_V^p)G_{E,M}^{p} - (1 + R_V^n)G_{E,M}^{n} - G_{E,M}^{s}$$

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

Rewrite PV asymmetry in terms of unknown quantities:

$$A = \xi G_E^s + \chi G_M^s + \phi G_A^e + \eta$$

Three unknowns therefore need three equations:

$$\begin{pmatrix} A_f \\ A_b \\ A_d \end{pmatrix} = \begin{pmatrix} \xi_f & \chi_f & \phi_f \\ \xi_b & \chi_b & \phi_b \\ \xi_d & \chi_d & \phi_d \end{pmatrix} \begin{pmatrix} G_E^s \\ G_M^s \\ G_A^e \end{pmatrix} + \begin{pmatrix} \eta_f \\ \eta_b \\ \eta_d \end{pmatrix}$$

Three scattering measurements required per Q^2:

A_f: Forward angle elastic $\vec{e}$+p

A_b: Backward angle elastic $\vec{e}$+p

A_d: Backward angle quasielastic $\vec{e}$+d

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

G^0 will perform these measurements at 3 Q^2 settings: 0.3, 0.5, & 0.8 $(\mathrm{GeV/c})^2$

Previous Results

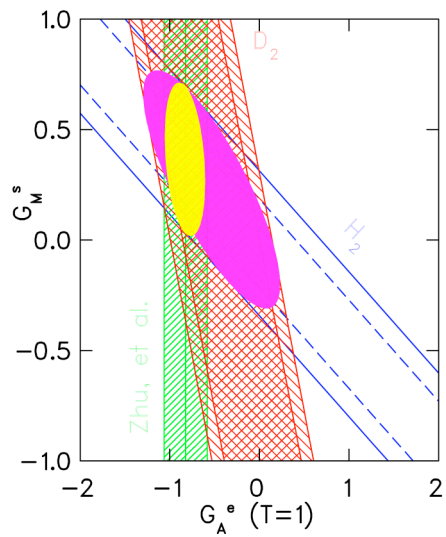
Backward Angles

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

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



Forward Angles

HAPPEX in Hall A at Jefferson Lab

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

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

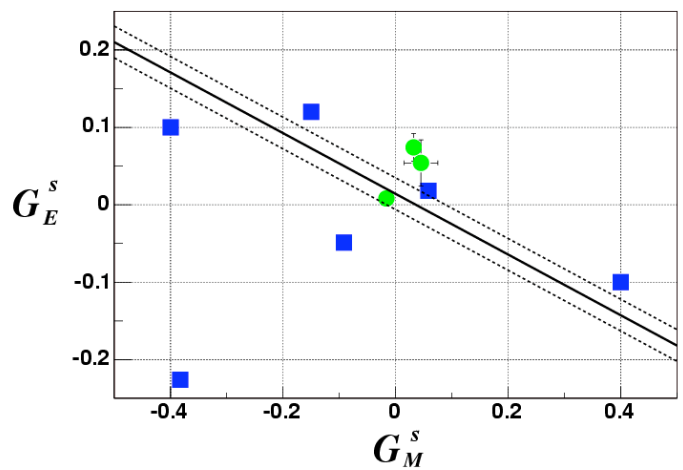
at $Q^2 = 0.477\ \mathrm{GeV}^2$

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 $Q^2 = 0.230\ \mathrm{GeV}^2$



General Requirements of PVES Experiments

$$A_{PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \approx 10^{-6}$$

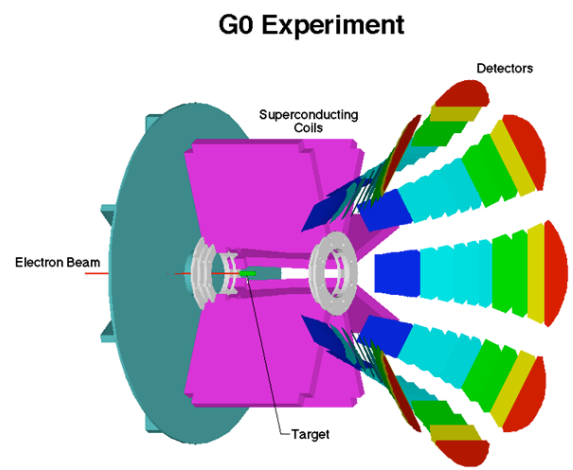
$$\frac{\sigma_A}{A} = \frac{1}{A}\frac{1}{\sqrt{2N}} = 5\%$$

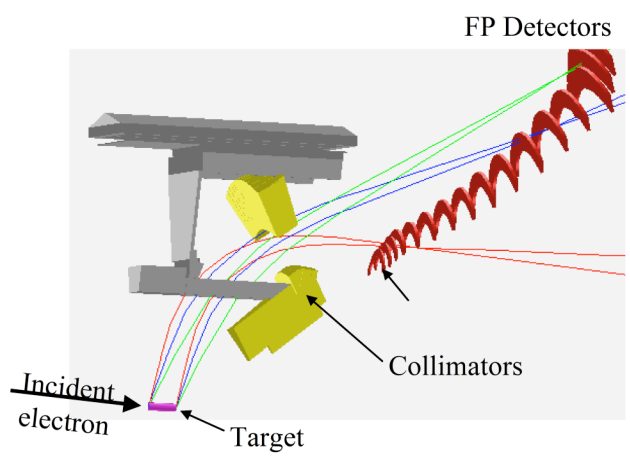
$$N \approx 10^{13} - 10^{14} \text{ !!!}$$

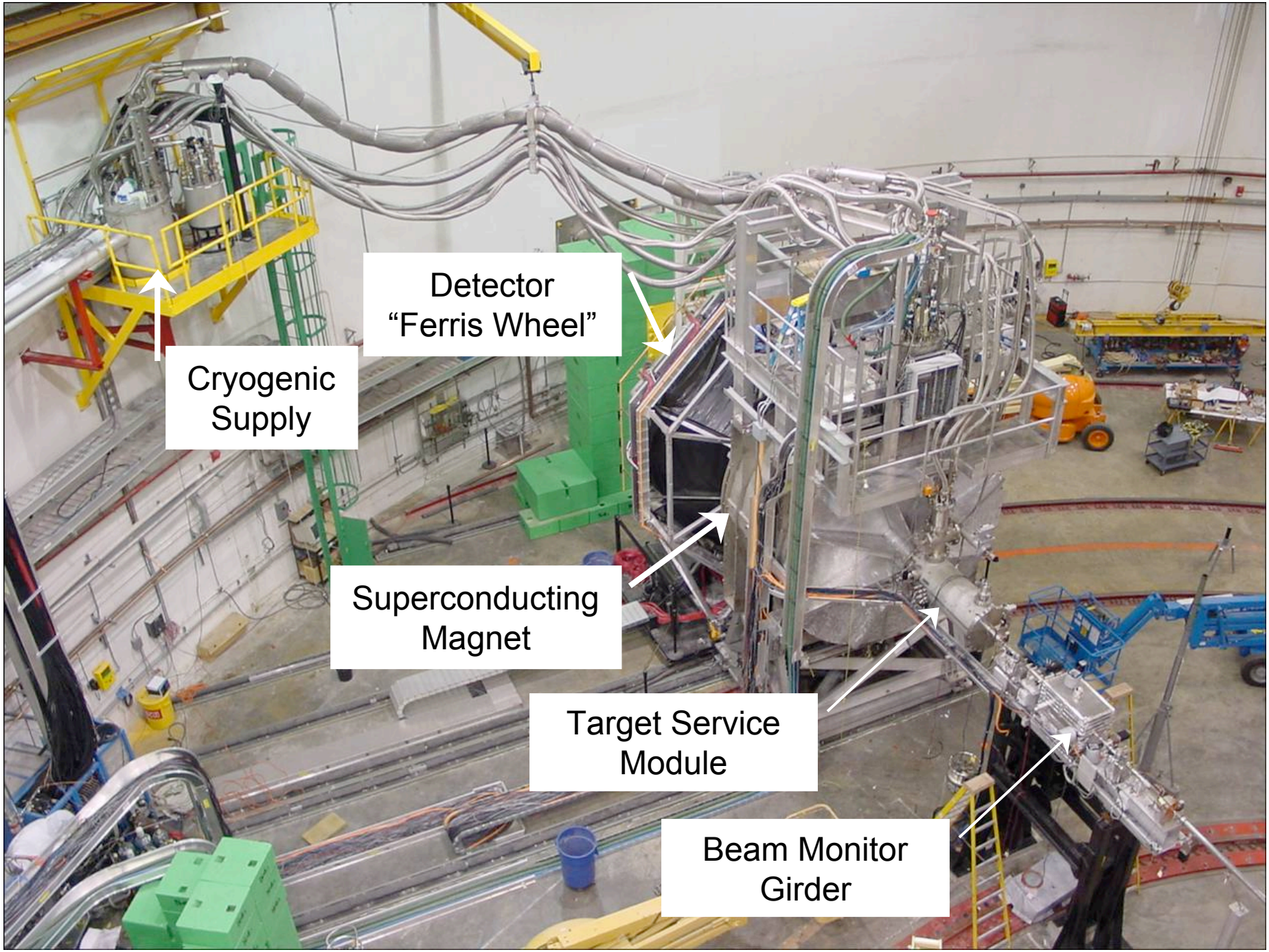
- Statistics
  - Large numbers of polarized electrons
  - Large numbers of target protons
  - Large acceptance detector
  - Ability to handle high count rates
- Systematics
  - Small helicity-correlated beam properties (charge, position, energy)
  - Ability to separate elastic from inelastic events
  - High degree of detector symmetry

G^0 Forward Angle Mode

- Installed in Hall C at Jefferson Lab
- Detect recoil protons
- One energy setting for all Q^2
  - Q^2 = 0.1-1.0 (GeV/c)^2
  - E = 3.0 GeV
  - Liquid hydrogen target
- Details
  - Beam bunches separated by 32 ns
  - Spectrometer sorts protons by Q^2 in focal plane detectors
  - Time-of-flight separates protons from pions
- Status
  - Run completed in May 2004 (began in November 2003)
  - 744 hours of parity quality beam (103 Coulombs)






Detector
“Ferris Wheel”
Cryogenic
Supply
Superconducting
Magnet
Target Service
Module
Beam Monitor
Girder

Data Analysis Workflow

- ✓ Measure raw TOF spectra (Y_m) for each helicity state (+/-)
- ✓ Correct for deadtime

$$Y_c = \frac{Y_m}{1-f_d} \qquad f_d \approx 10-20\%$$

- ✓ Correct for helicity correlated beam effects

$$Y_{cc} = \sum_i \frac{\partial Y}{\partial P_i}\Delta P_i \qquad P_i = \left(x, y, \theta_x, \theta_y, E, Q\right)$$

- ✓ Form the raw asymmetry

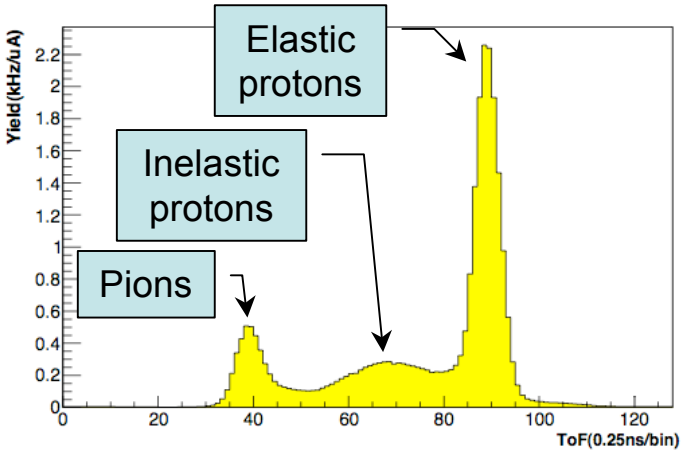
$$A_m = \frac{Y_{cc}^+ - Y_{cc}^-}{Y_{cc}^+ + Y_{cc}^-}$$

- Correct for the background contribution

$$A_m = f_e A_e + f_b A_b \qquad f_b = 1 - f_e$$

- Correct for beam polarization and EM radiative effects

$$A_{PV} = \frac{R_C}{P_B} A_e = f\left(G_M^s, G_E^s, G_A^e\right)$$



Helicity Correlated Beam Properties

False asymmetries due to non-zero ΔP_i can arise from detector sensitivities to beam parameters. . .

$$A_{false} = \sum_i \frac{1}{2\langle Y \rangle}\left(\frac{\partial Y}{\partial P_i}\right)\Delta P_i$$

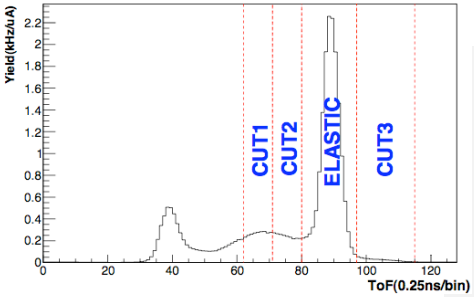
- Requirements on helicity correlated beam properties ΔP_i
  - Small ΔP_i ➔ small A corrections ($\Delta A < 10^{-7}$)
  - Measure ΔP_i accurately ➔ small error on correction ($\sigma_{\Delta A} < 5\times10^{-9}$)
- Use beam feedback systems to modulate laser intensity and position at the cathode in a helicity correlated manner.

Parameter	Achieved	"Specs"
A_Q	-0.28 ± 0.28 ppm	1 ppm
ΔX	6 ± 4 nm	20 nm
ΔY	8 ± 4 nm	20 nm
$\Delta\theta_X$	2 ± 0.3 nrad	2 nrad
$\Delta\theta_Y$	3 ± 0.5 nrad	2 nrad
ΔE	58 ± 4 eV	75 eV

Parameter	False asymmetry
Charge	10^{-8}
Position	10^{-9}
Angle	10^{-8} to 10^{-9}
Energy	10^{-9}

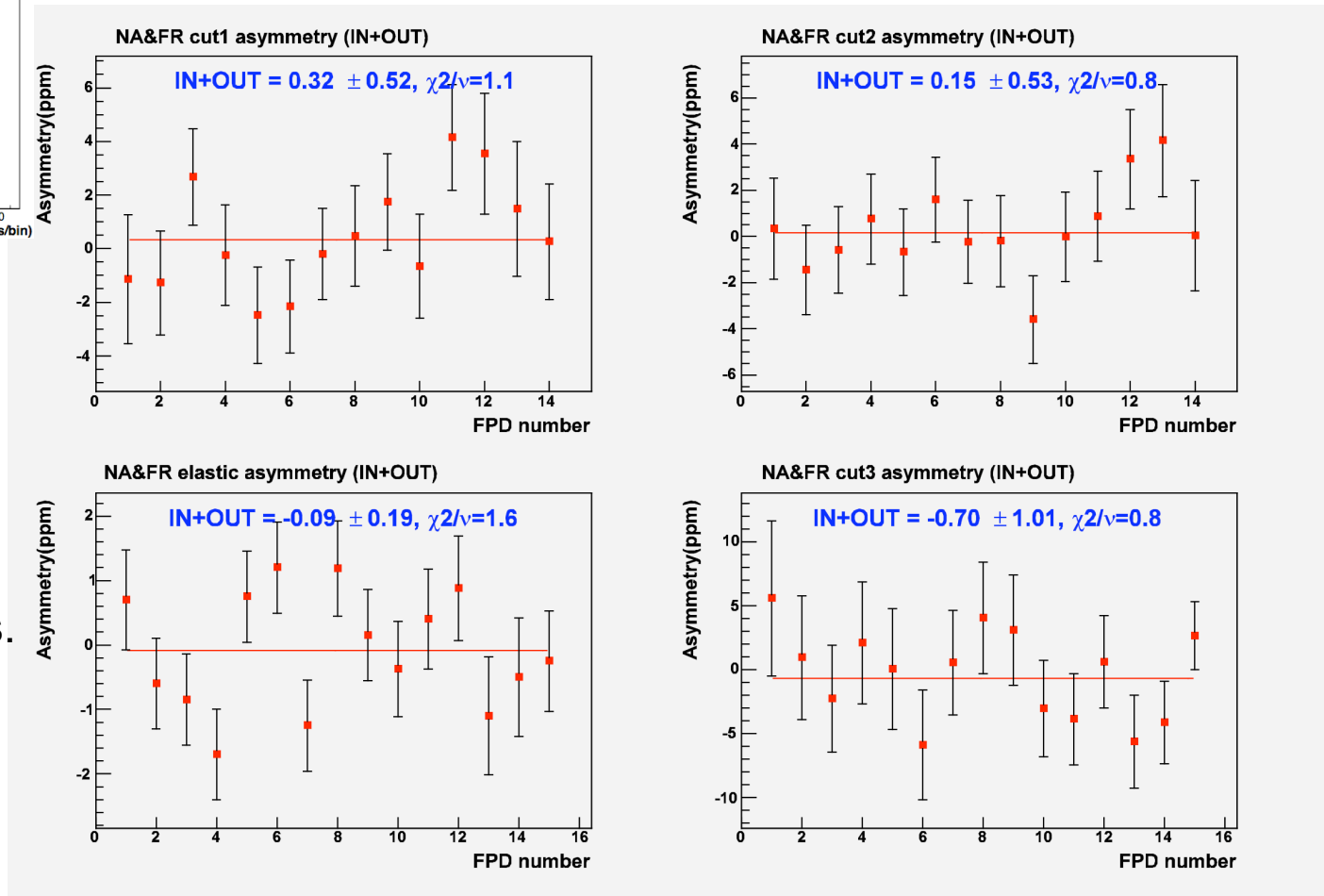
Total false asymmetry from beam parameters of order 10^{-8}!

Asymmetries and Data Quality



Asymmetries reverse nicely under half wave plate reversal.

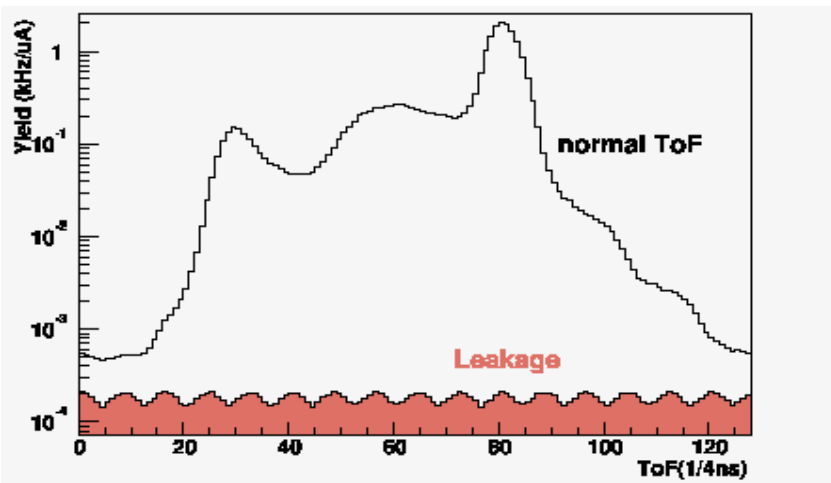
No indication of false asymmetries.



Leakage from Other Halls

- Small amount of current (I_L) from Halls A & B leaks into Hall C beam (I_C)
- Leakage current has large, uncorrected asymmetry (A_{IL})
- Leakage has a different time structure from the main beam
  - 32 MHz for Hall C (beam pulse every 32 ns)
  - 499 MHz for Halls A & B (beam pulse every 2 ns)
- Time-of-flight and current dependent false asymmetry induced!
- Asymmetries corrected by
  - measuring false asymmetry in signal-free region of TOF,
  - performing studies with other halls's lasers off, and
  - cross-checking against low current runs.

$$I_L = 50\,\text{nA}$$
$$I_C = 40\,\mu\text{A}$$
$$A_{IL} = 350\,\text{ppm}$$



In elastic region:

$$A_{false} \approx \frac{I_L}{I_C} A_{IL} \approx 0.4\ \text{ppm}$$

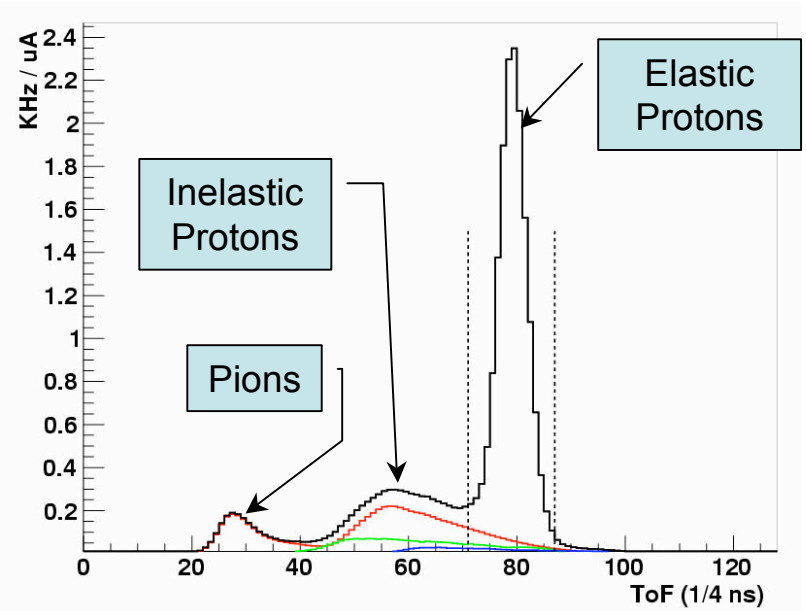
Correction of order 0.4 ppm.
Systematic error of 0.1 ppm.

Background Corrections (Yield)

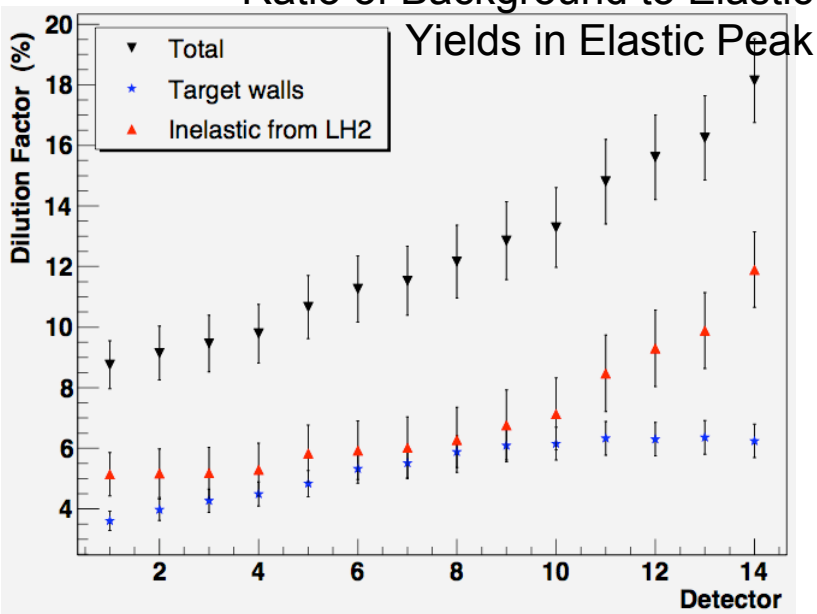
Estimate of background yield under the elastic peak is performed using

- data with full and empty (gaseous H_2) targets, different pressures
- data with dummy entrance and exit windows (Al)
- data with tungsten radiator and dummy windows (electro/photo production)

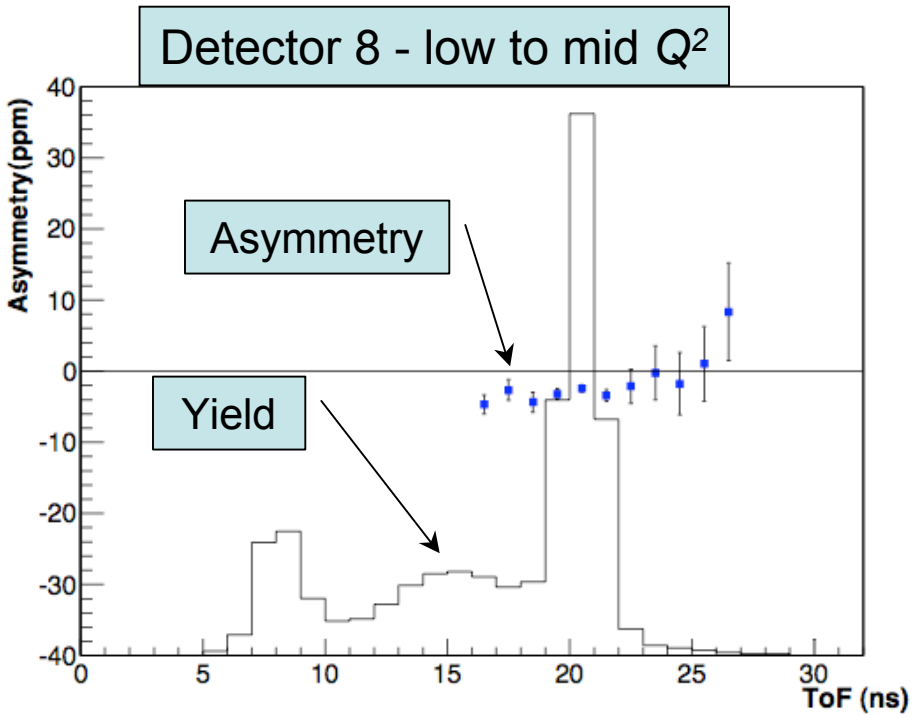
→ Unfold backgrounds from target windows and inelastic LH_2 processes

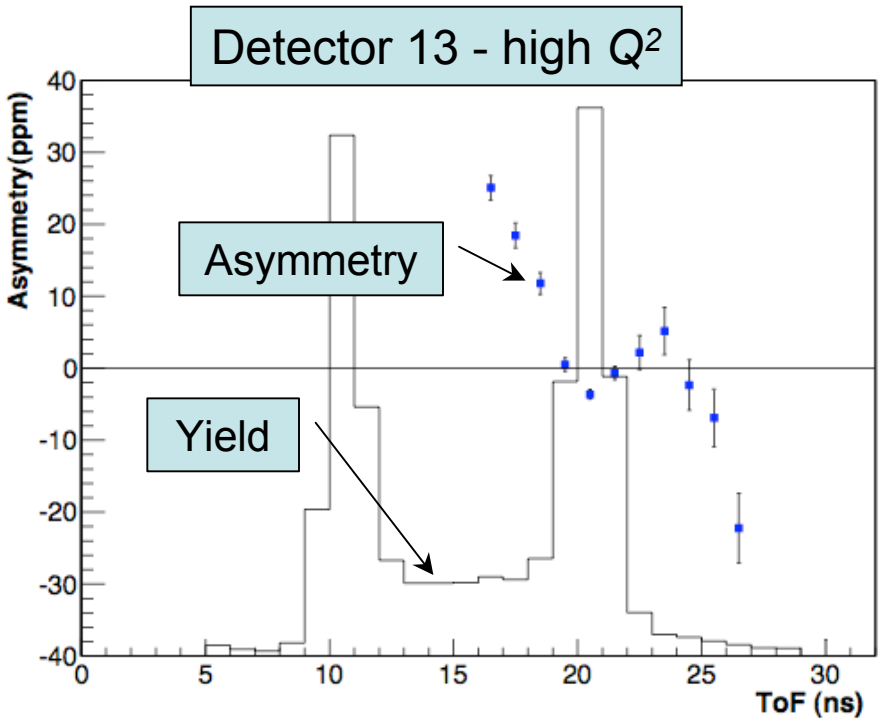


Ratio of Background to Elastic Yields in Elastic Peak



Background Corrections (Asymmetry)

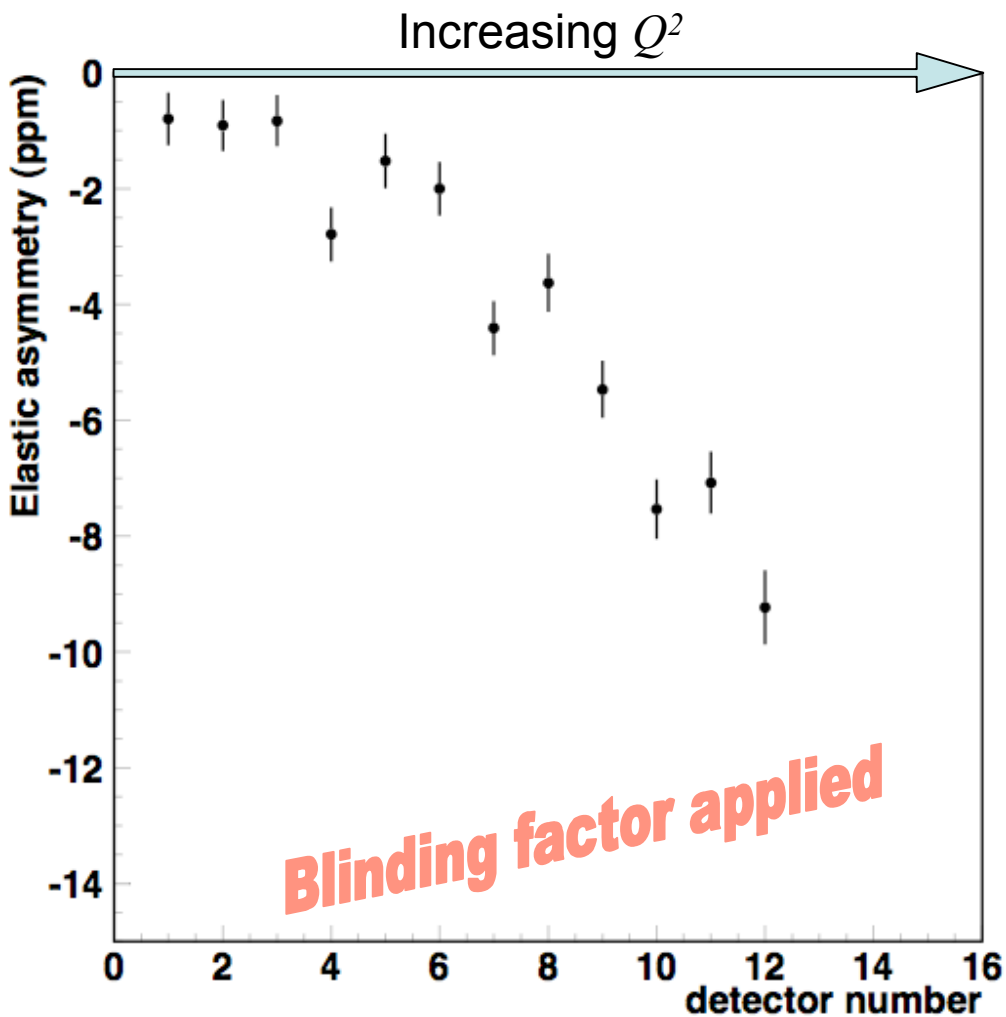




- Yields and asymmetries vary smoothly across elastic peak ➔ linear interpolation
- Small increase in systematic error on elastic asymmetry

- Large variation in asymmetry across elastic peak
- Positive asymmetry under study
- Correction likely to dominate systematic error on elastic asymmetry

Preliminary Results

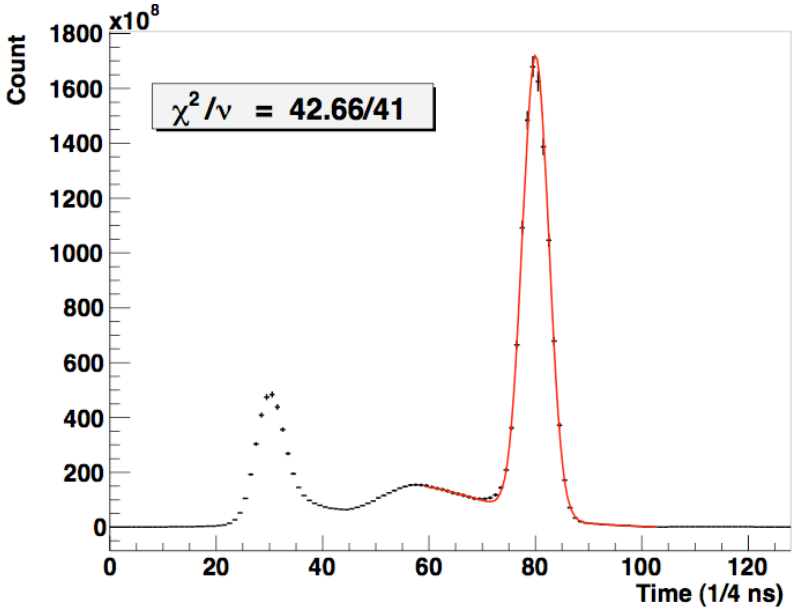


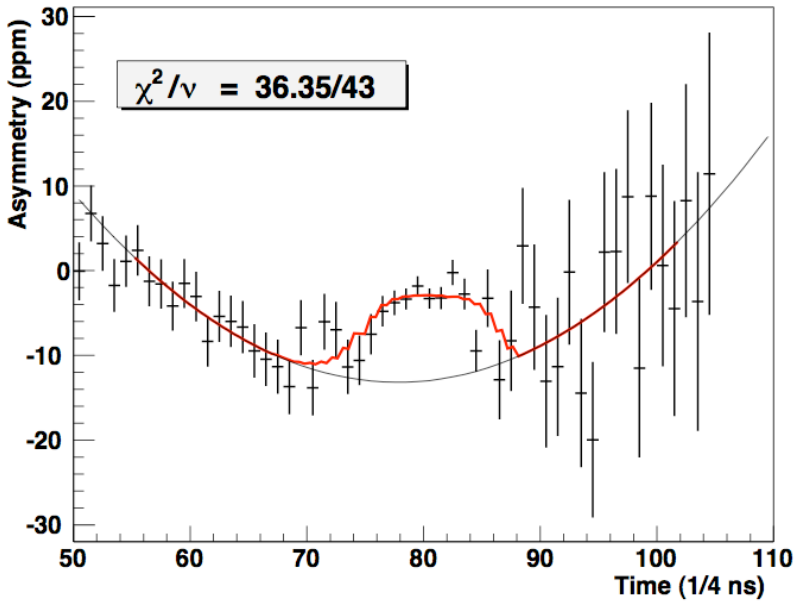
- 25% blinding factor applied
- Full statistics
- Preliminary background correction
- Detectors 13-15 not shown

Preliminary Systematic Errors

Systematic Effect	Error
Deadtime Correction	2%
Beam Parameter Correction	0.01 ppm
Leakage Correction	0.10 ppm
Beam Polarization	2%
Q^2 Determination	1%
Background Correction	Under Study
Radiative Corrections	Still to do
EM Form Factors	Still to do

Improved Background Correction





- Extract bin-by-bin dilution factor f_e by fitting time-of-flight spectra (gaussian signal + 4th order polynomial background)
- Use results to perform asymmetry fit

$$f_e(t) = \frac{N_S(t)}{N_S(t) + N_B(t)}$$

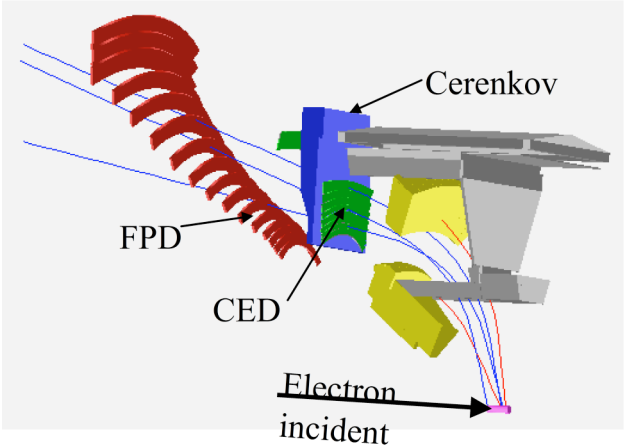
$$A_m(t) = f_e(t) A_e + \left(1 - f_e(t)\right) A_b(t)$$

Constant

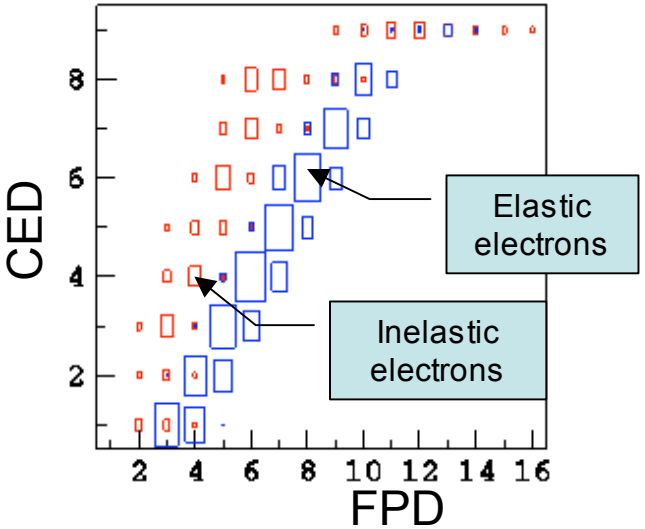
Quadratic

G^0 Backward Angle Mode

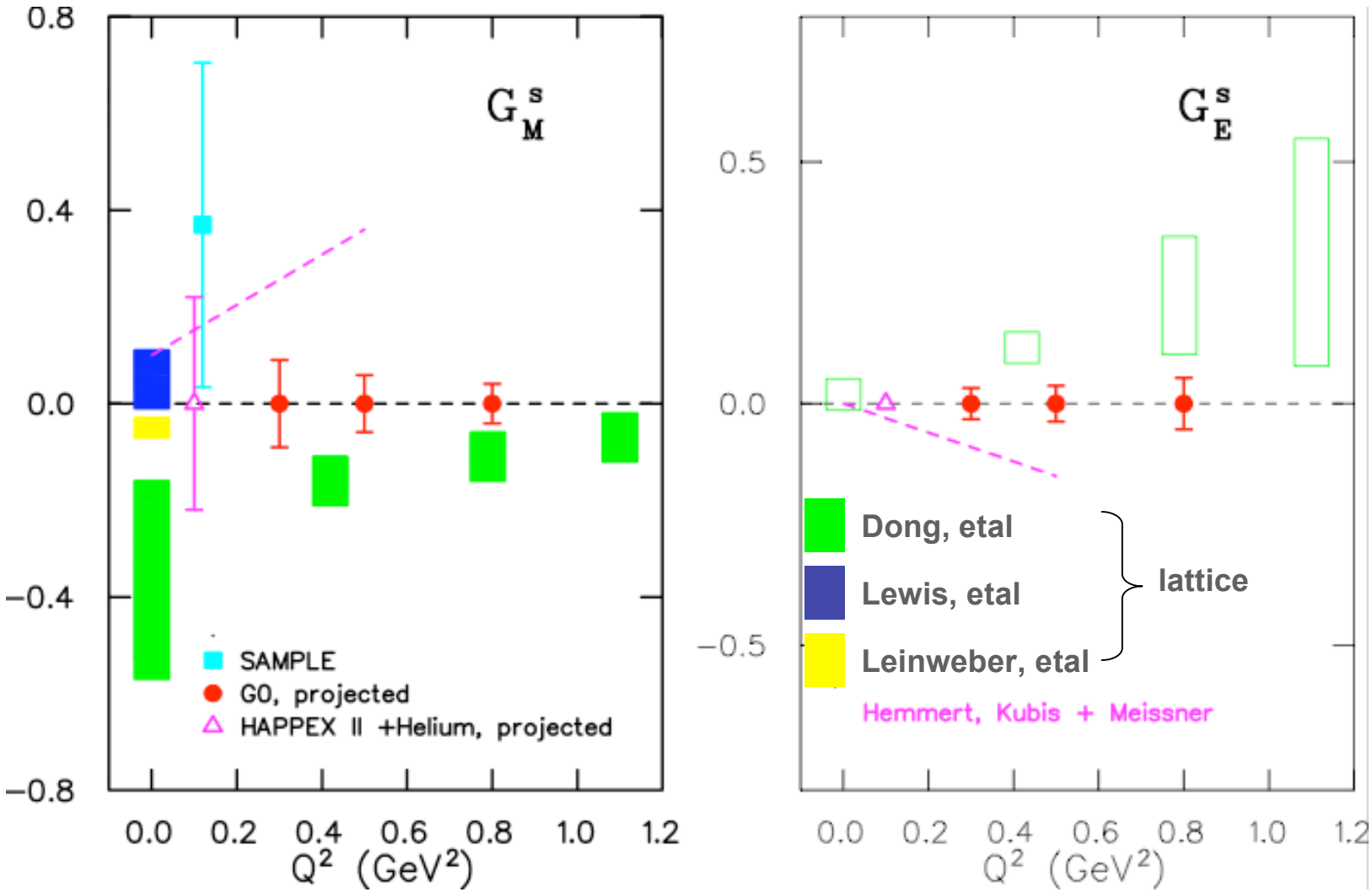
- Detect scattered electrons at 110 °
- One energy/magnet setting per Q^2
  - Q^2 = 0.3, 0.5, 0.8 $(GeV/c)^2$
  - E = 424,576, 779 MeV
  - Liquid hydrogen and deuterium targets
  - 700 hours of beam per run
- Additional Detectors
  - Cryostat Exit Detectors (CEDs): separate elastic and inelastic electrons by trajectory
  - Cerenkov Detectors: pion detection
- Timeline
  - Turnaround of magnet and existing detectors complete
  - Installation of remaining detectors and commissioning run late 2005
  - First data run in early 2006



CED-FPD Coincidences at Q^2 = 0.3 $(GeV/c)^2$



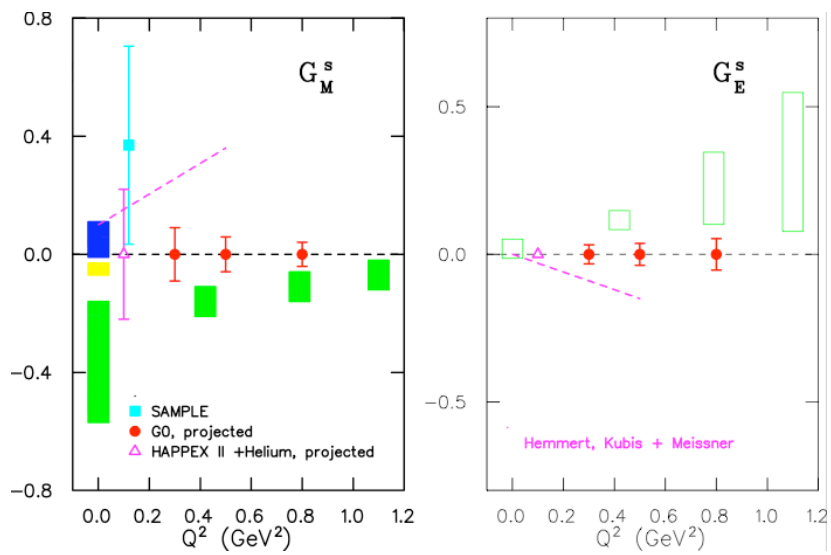
Expected Results: Separated Strange Form Factors



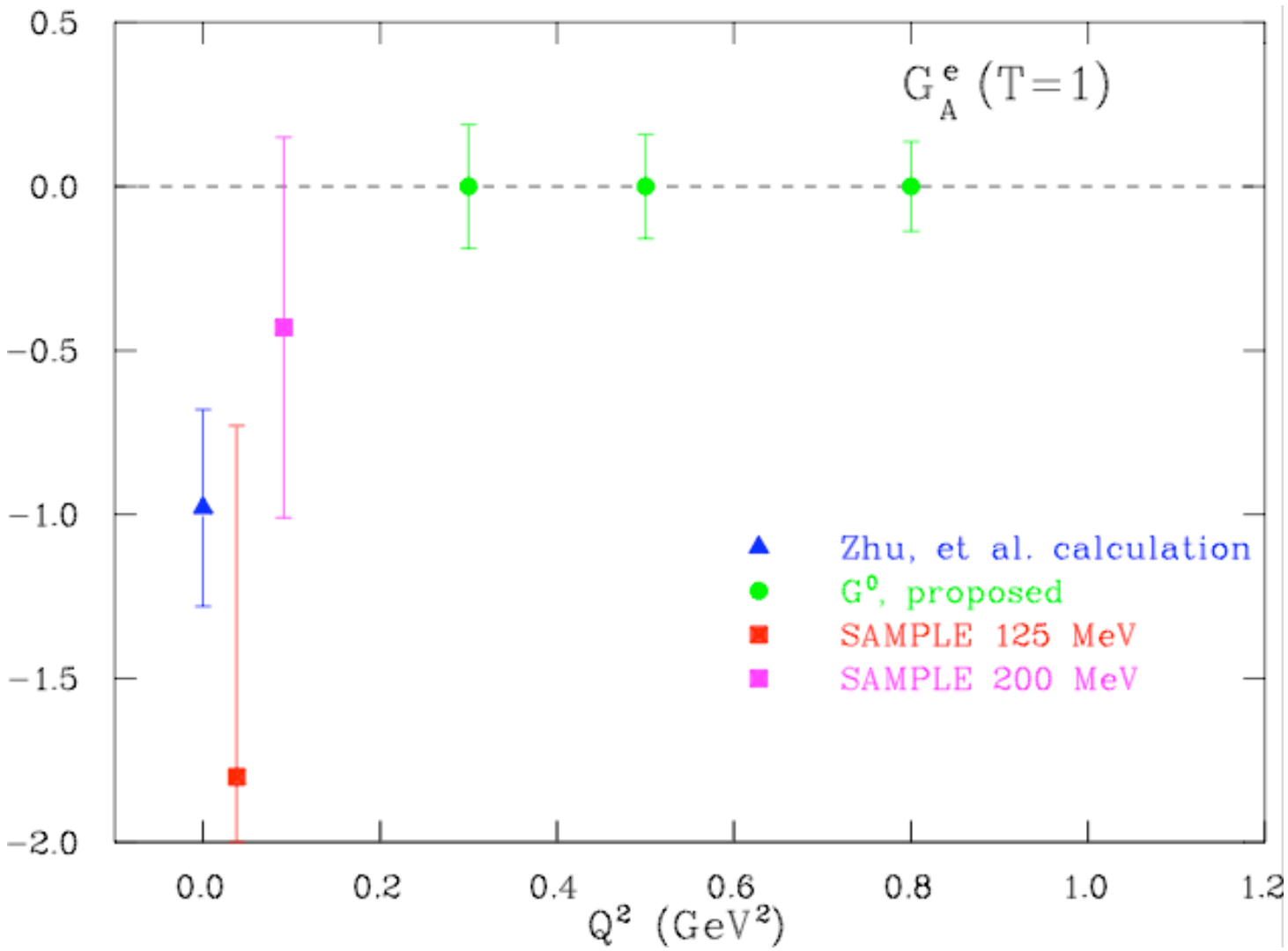
Summary

- G^0 forward angle running completed in May 2004.
- Analysis of data is underway:
  - Leakage current correction is small and well determined.
  - Background correction is focus of current work.
- Turnaround and upgrade of G^0 apparatus for remaining measurements has begun.
- Goal: Extract electric and magnetic strange form factors at three Q^2.

By 2008 (?)



Additional Physics from Backward-Angle Runs

- Axial Form Factor $G_A^e(Q^2)$
  - related to anapole moment of the nucleon.
- Two photon exchange
  - related to electromagnetic radiative corrections for EM form factor determination (also measured at forward angles).
- Parity-violation in the $N \rightarrow \Delta$ transition
  - Electro-excitation: Axial Form Factor
  - Photo-excitation: Mixing with Negative-Parity Resonances, electroweak radiative corrections.

Expected Results: Isovector Axial e-N Form Factor