Nucleon Form Factors Experiments and Data

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Outline

* Introduction: History, Proposals, Formalism
* Form Factor Data: Proton and Neutron, pre-1998
* Models
* Experiments at Jefferson Lab
* Conclusion, Prospects and Credits

Form Factors at CEBAF

✳ Long history – NEAL was proposed in 1980 by SURA

First in the list of Illustrative Proposals

✔ *Nucleon Electric Form Factors* by R. Arnold and F. Gross

Why measure the FF?

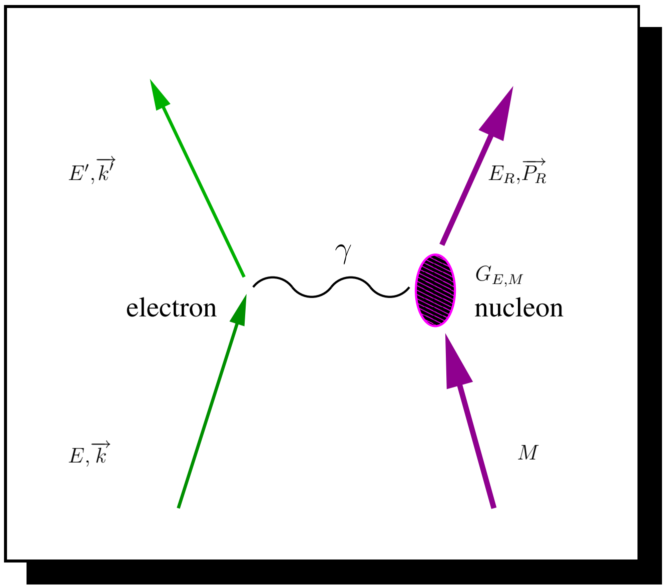
✳ Since 1989 22 proposals for the elastic form factors. 9 were approved. 7 have taken data 2 – G_E^n , 2 – G_M^n , 3 – G_E^p

Proposal	Technique	Reaction	Form Factor	Year	Data
93-026	Asymmetry	$\vec{D}(\vec{e}, e' n)p$	G_E^n	1998/2001	Pub./Prelim.
93-027	Recoil	$^1\mathrm{H}(\vec{e}, e' \vec{p})$	G_E^p / G_M^p	1998	Pub.
93-038	Recoil	$^2\mathrm{H}(\vec{e}, e' \vec{n})p$	G_E^n / G_M^n	2000,2001	Prelim.
94-017	Ratio	$\frac{d(e,e' n)p}{d(e,e' p)n}$	G_M^n	2000	Analysis
95-001	Asymmetry	$^3\overrightarrow{\mathrm{He}}(\vec{e}, e')X$	G_M^n	1999	Pub.
99-007	Recoil	$^1\mathrm{H}(\vec{e}, e' \vec{p})$	G_E^p / G_M^p	2000	Pub.
01-001	Rosenbluth	$^1H(e, p)$	G_E^p	2002	Analysis
01-109	Recoil	$^1\mathrm{H}(\vec{e}, e' \vec{p})$	G_E^p / G_M^p	2005	–
02-013	Asymmetry	$^3\overrightarrow{\mathrm{He}}(\vec{e}, e' n)$	G_E^n	2004	–

Two others, T_{20} (E94-018) and E94-110, have also contributed.

Formalism

$$\frac{d\sigma}{d\Omega} = \sigma_{\mathrm{Mott}} \frac{E'}{E_0} \left\{ (F_1)^2 + \tau \left[2\left(F_1 + F_2\right)^2 \tan^2\left(\theta_e\right) + \left(F_2\right)^2 \right] \right\}$$



$$\boxed{\begin{array}{ll} F_1^p = 1 & F_1^n = 0 \\ F_2^p = 1.79 & F_2^n = -1.91 \end{array}}$$

In Breit frame F_1 and F_2 related to charge and spatial curent densities:

$$\rho = J_0 = 2eM[F_1 - \tau F_2]$$

$$J_i = e\bar{u}\gamma_i u[F_1 + F_2]_{i=1,2,3}$$

$$\boxed{G_E\left(Q^2\right) = F_1(Q^2) - \tau F_2\left(Q^2\right) \qquad G_M\left(Q^2\right) = F_1\left(Q^2\right) + F_2\left(Q^2\right)}$$

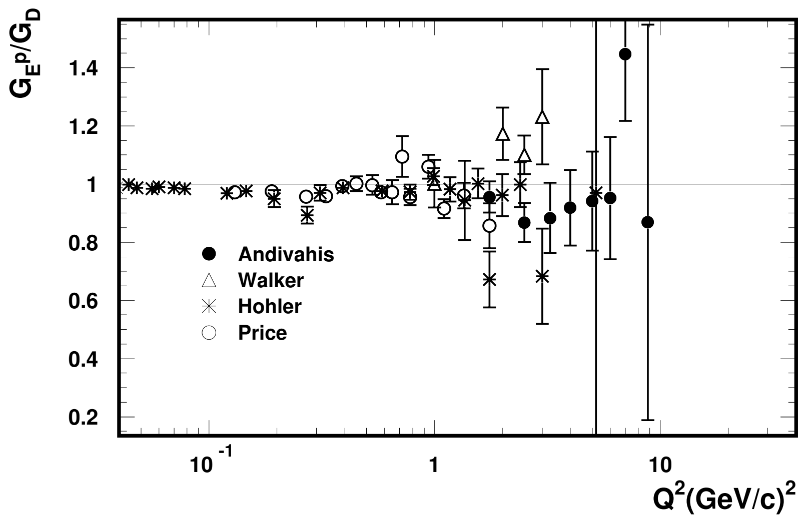
✴ For a point like probe G_E and G_M are the FT of the charge and magnetizations distributions in the nucleon, with the following normalizations

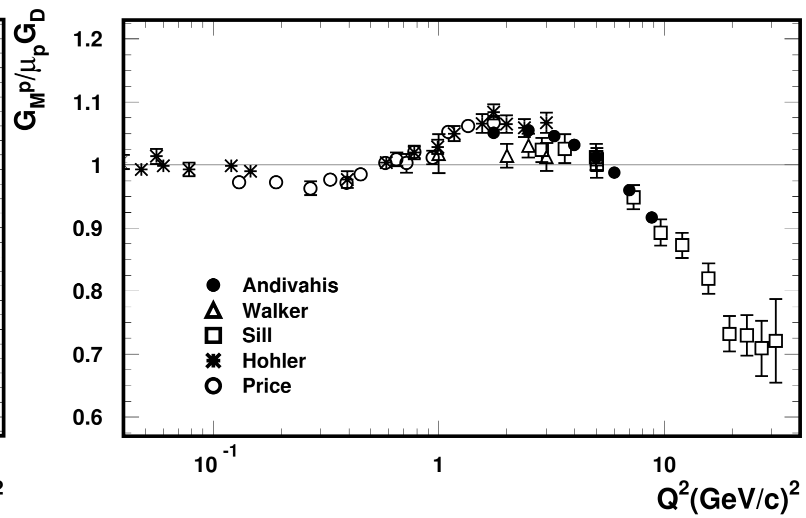
$$\boxed{Q^2 = 0 \text{ limit:} \quad G_E^p = 1 \; G_E^n = 0 \;\; G_M^p = 2.79 \; G_M^n = -1.91}$$

Proton Form Factor Data (pre-1998)

Rosenbluth separation

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{Mott}}{(1+\tau)}\frac{E'}{E_0}\left[G_E^2 + \underbrace{\tau(1+(1+\tau)2\tan^2(\theta/2))G_M^2}\right]$$



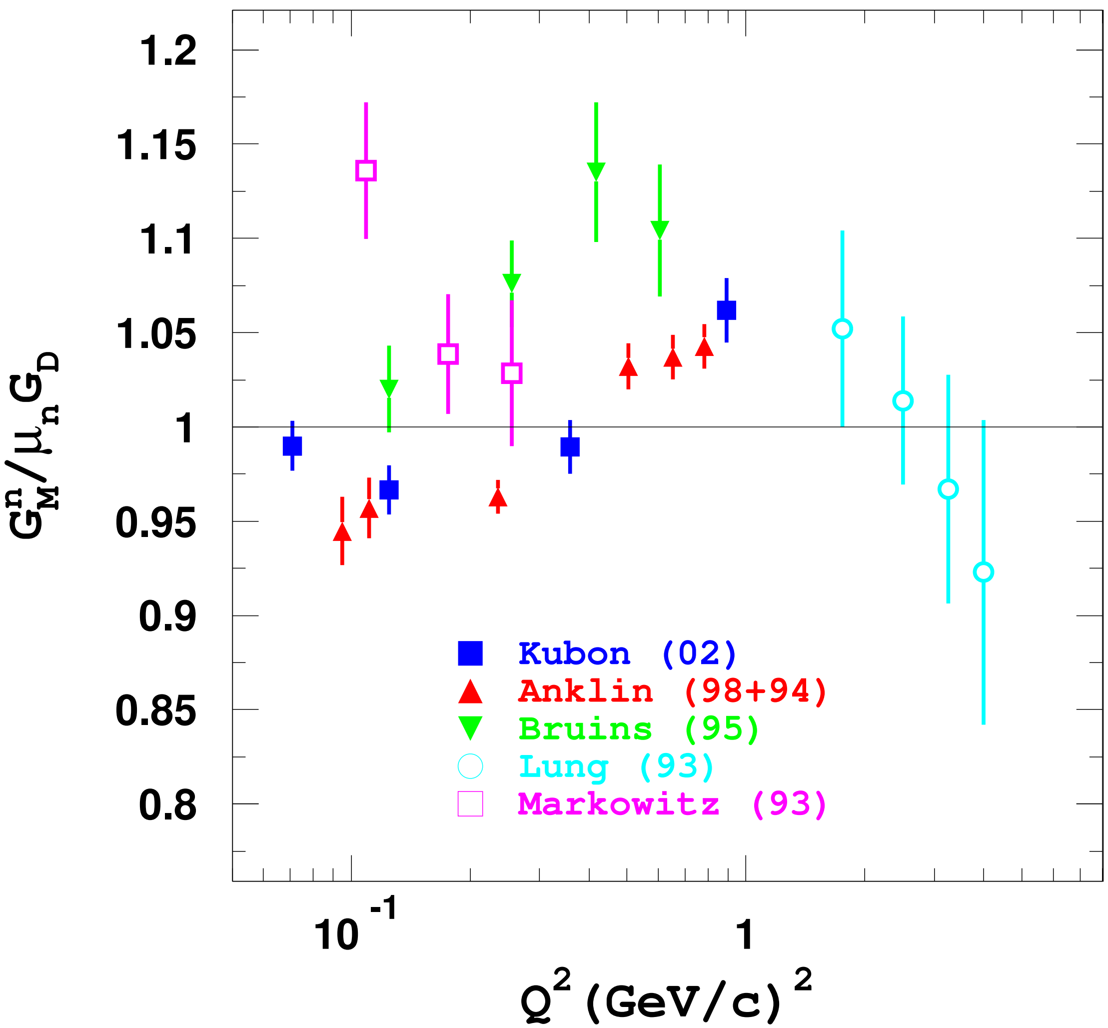


- ✳ G_M^p well measured via Rosenbluth, but not G_E^p
- ✳ Dipole Parametrization: Good description of early $G_{E,M}^p$ data

$$G_E^p = \frac{G_M^p}{\mu_p} = G_D = \left(1 + \frac{Q^2}{0.71}\right)^{-2}$$

$G_D = \left(1 + \frac{Q^2}{k^2}\right)^{-2}$ implies an exponential charge distribution: $\rho\,(r) \propto e^{-kr}$

G_M^n unpolarized



Kubon	ratio
Anklin	ratio
Bruins	ratio
Lung	$D(e,e')X$
Markowitz	$D(e,e'n)p$

$$\text{ratio} \equiv \frac{D(e,e'n)p}{D(e,e'p)n}$$

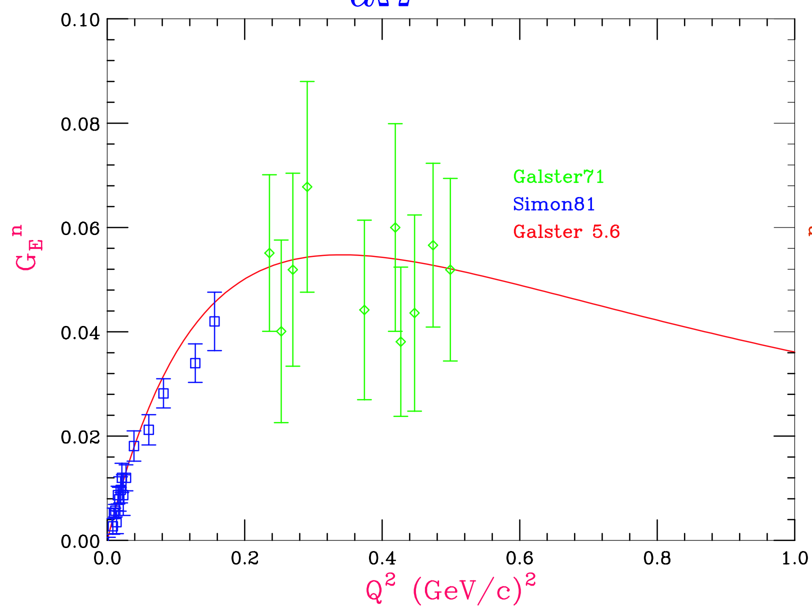
Neutron Form Factors Before Polarization

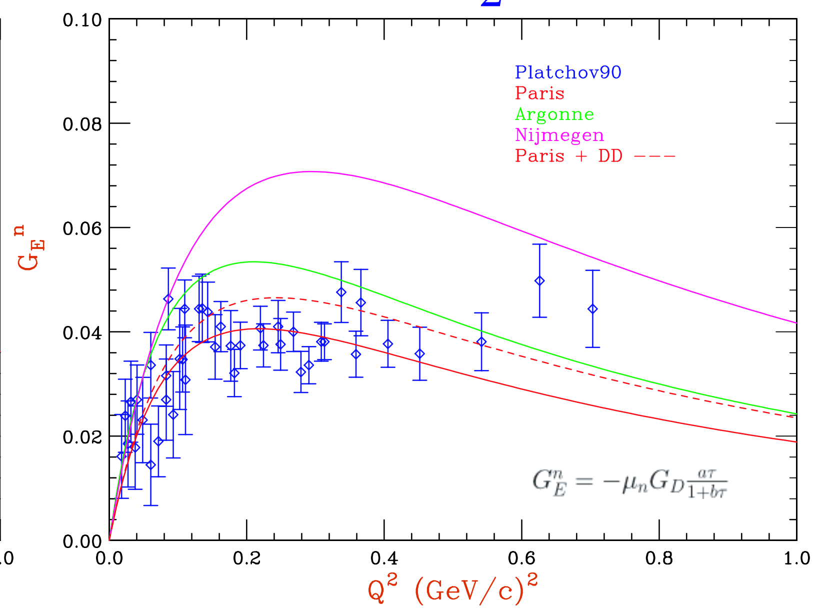
No free neutron – extract from $e - D$ elastic scattering:

$$\frac{d\sigma}{d\Omega} = \sigma_{NS}\left[A\left(Q^2\right) + B\left(Q^2\right)\tan^2\left(\frac{\theta_e}{2}\right)\right]$$

small θ_e approximation

$$\frac{d\sigma}{d\Omega} = \cdots (G_E^p + G_E^n)^2\left[u(r)^2 + w(r)^2\right] j_0(\frac{qr}{2})dr\cdots$$





Galster Parametrization: $G_E^n = -\frac{\tau\mu_n}{1+5.6\tau}G_D$

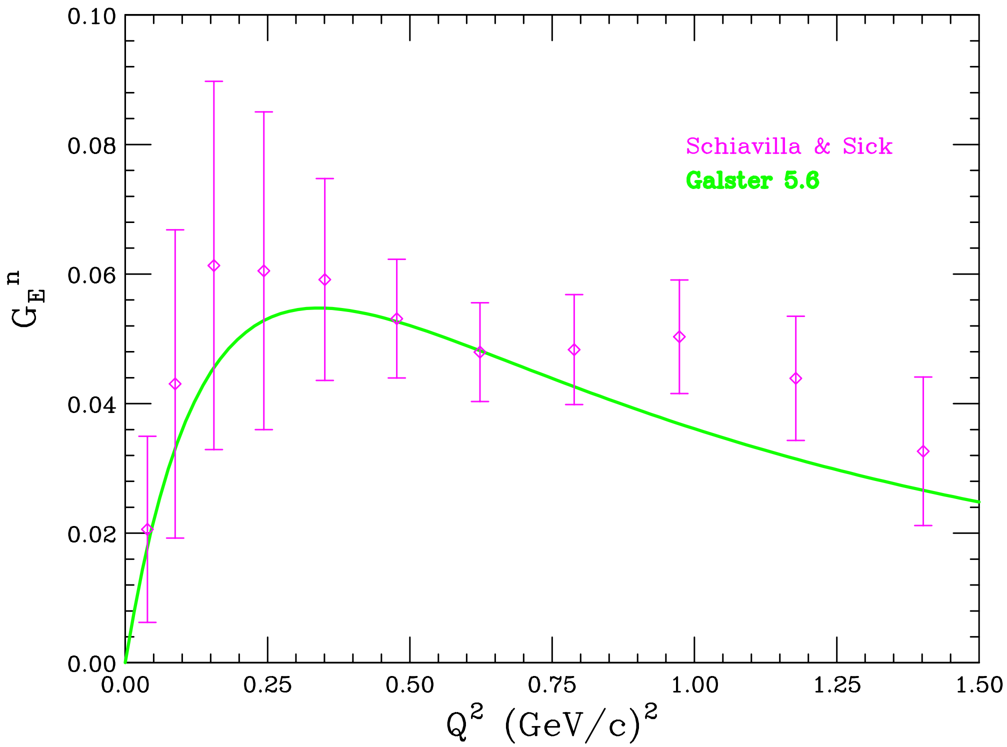
G_E^n from Elastic Scattering – $\mathrm{D}(e, e'\vec{\mathrm{d}})$

Components of the tensor polarization give useful combinations of the form factors,

$$t_{20} = \frac{1}{\sqrt{2}S} \left\{ \frac{8}{3}\tau_d G_C G_Q + \frac{8}{9}\tau_d^2 G_Q^2 + \frac{1}{3}\tau_d \left[1 + 2(1+\tau_d)\tan^2(\theta/2)\right] G_M^2 \right\}$$

allowing $G_Q(Q^2)$ to be extracted. Exploiting the fact that $G_Q(Q^2) = (G_E^p + G_E^n)C_Q(q)$ suffers less from theoretical uncertainties than $A(Q^2)$, G_E^n can be extracted to larger momentum transfers.

E94-018!!



Models of Nucleon Form Factors

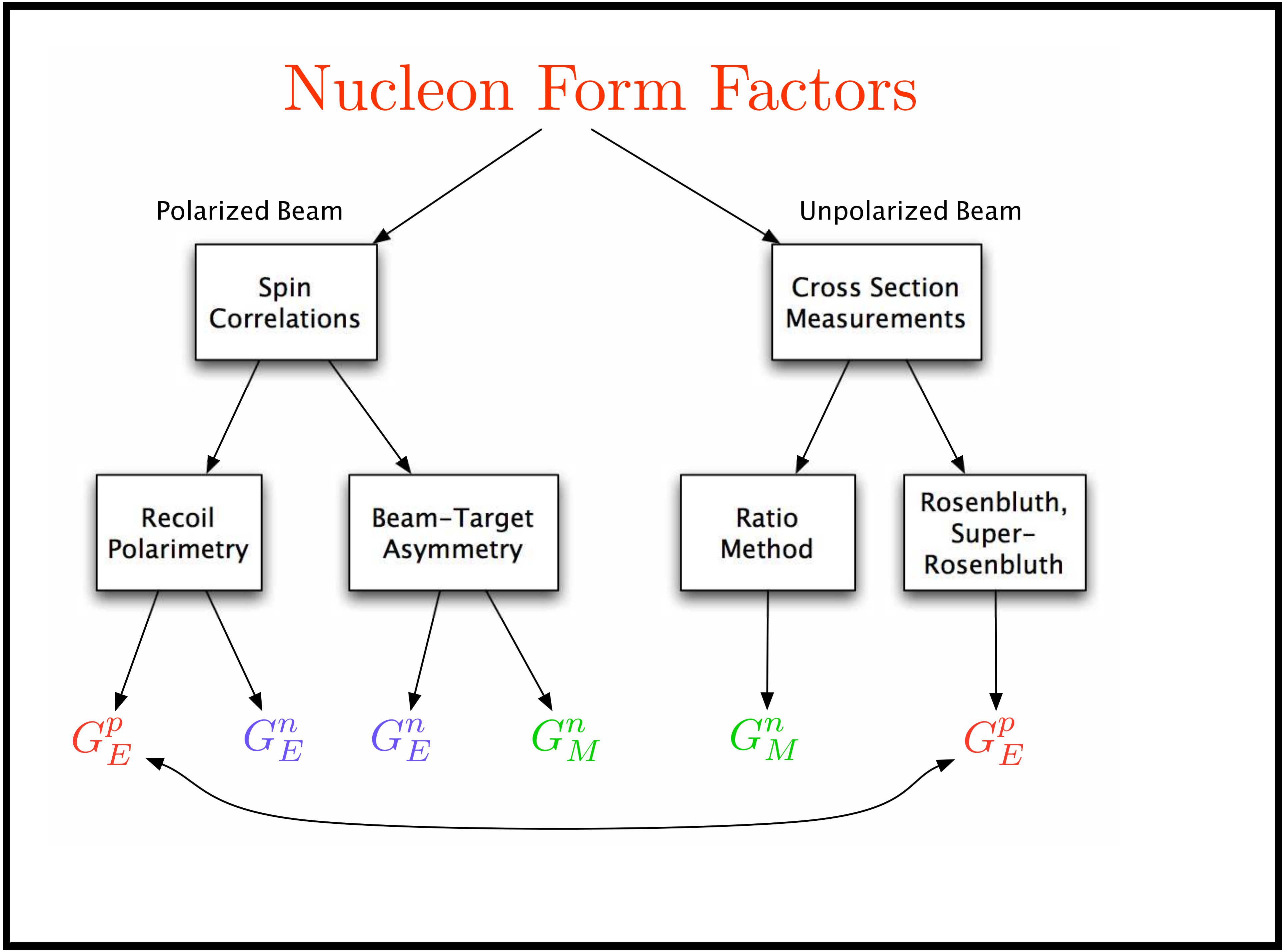
VMD	$F(Q^2) = \sum_i \frac{C_{\gamma V_i}}{Q^2+M_{V_i}^2} F_{V_i N}(Q^2)$
	breaks down at large Q^2
pQCD	$F_2 \propto F_1 \left(\frac{M}{Q^2}\right)$ helicity conservation
	Counting rules: $F_1 \propto \frac{\alpha_s(Q^2)}{Q^4}$
	$Q^2 F_2/F_1 \rightarrow$ constant
	JLAB proton data: $QF_2/F_1 \rightarrow$ constant
Hybrid VMD-pQCD	GK, Lomon
Lattice	Dong .. (1998)
RCQM	point form (Wagenbrunn..)
	light front (Cardarelli ..)
di-quark	Kroll ...
CBM	Lu, Thomas, Williams (1998)
LFCBM	Miller
Helicity non-conservation	pQCD (Ralston..) LF (Miller..)

Spin Correlations in elastic scattering

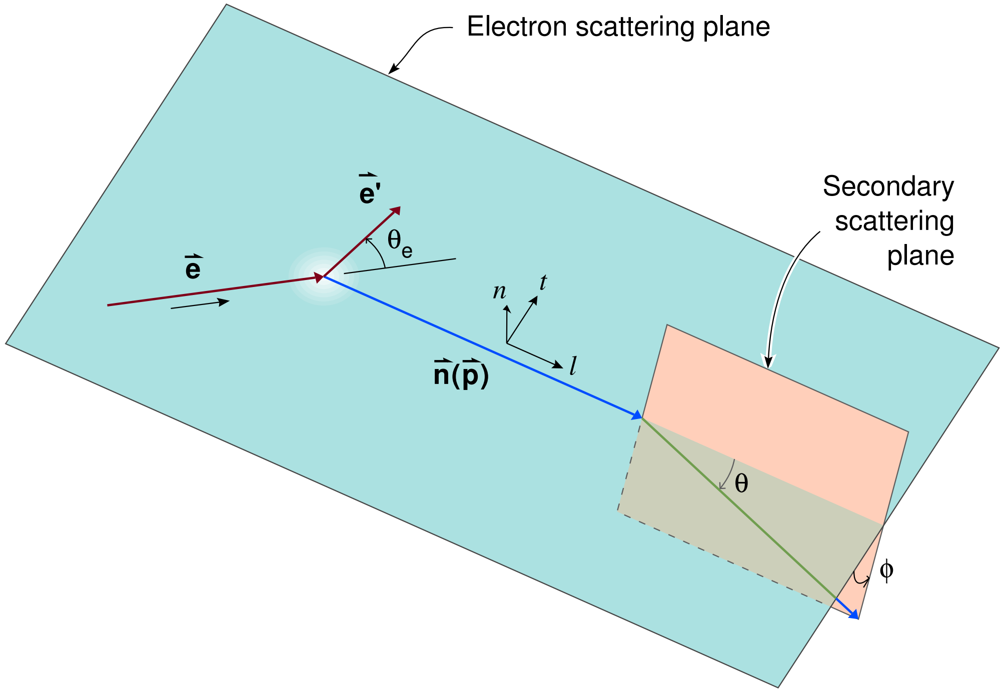
- ✳ Dombey, Rev. Mod. Phys. **41** 236 (1968): $\vec{p}(\vec{e}, e')$
- ✳ Akheizer and Rekalo, Sov. Phys. Doklady **13** 572 (1968): $p(\vec{e}, e', \vec{p})$
- ✳ Arnold, Carlson and Gross, Phys. Rev. C **23** 363 (1981): ${}^2\mathrm{H}(\vec{e}, e'\vec{n})p$

Early work at Bates, Mainz

- ✳ ${}^2\mathrm{H}(\vec{e}, e'\vec{n})p$, Eden *et al.* (1994)
- ✳ ${}^1\mathrm{H}(\vec{e}, e'\vec{p})$, Milbrath *et al.* (1998)
- ✳ ${}^3\overrightarrow{\mathrm{He}}(e, e')$, Woodward, Jones, Thompson, Gao (1990 - 1994)
- ✳ ${}^3\overrightarrow{\mathrm{He}}(e, e'n)$, Meyerhoff, (1994)


Nucleon Form Factors
Polarized Beam
Unpolarized Beam
Spin Correlations
Cross Section Measurements
Recoil Polarimetry
Beam–Target Asymmetry
Ratio Method
Rosenbluth, Super–Rosenbluth
G_E^p
G_E^n
G_E^n
G_M^n
G_M^n
G_E^p

Recoil Polarization



$$I_0 P_t = -2\sqrt{\tau(1+\tau)}\,G_E G_M \tan(\theta_e/2)$$

$$I_0 P_l = \frac{1}{M_N}(E_e + E_{e'})\sqrt{\tau(1+\tau)}\,G_M^2 \tan^2(\theta_e/2)$$

$$\boxed{\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_e+E_{e'})}{2M_N}\tan\left(\frac{\theta_e}{2}\right)}$$

Direct measurement of form factor ratio by measuring the ratio of the transfered polarization P_t and P_l

Recoil Polarization – Principle and Practice

- ✳ Interested in transfered polarization, P_l and P_t, at the target
- ✳ Polarimeters are sensitive to the perpendicular components only, P_n^{pol} and P_t^{pol}

  Measuring the ratio P_t/P_l requires the precession of P_l by angle χ before the polarimeter.

- ✳ If polarization precesses χ (e.g. in a dipole): $P_n^{\mathrm{pol}} = \sin\chi \cdot hP_l$ and $P_t^{\mathrm{pol}} = hP_t$

  $P_t^{\mathrm{pol}} = P_t$ in scattering plane and proportional to $G_E G_M$

  P_n^{pol} is related to G_M^2

- ✳ G_E^p/G_M^p via ${}^1\mathrm{H}(\vec{e}, e'\vec{p})$ in Hall A - HRS and FPP
- ✳ G_E^n/G_M^n via ${}^2\mathrm{H}(\vec{e}, e'\vec{n})p$ in Hall C - Charybdis and N-Pol

G_E^p in Hall A

E93-027 (data taken in 1998)

Jones *et al.*, PRL 84, 1398 (2000)

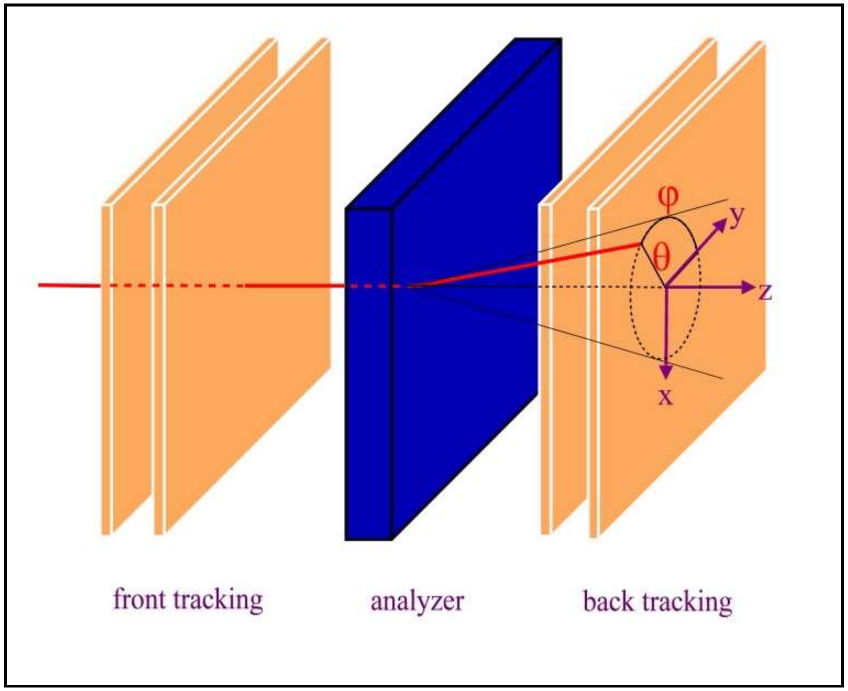
- G_E^p/G_M^p out to $Q^2 = 3.5\ \mathrm{GeV/c}^2$
- Electron in one HRS and proton in FPP in other HRS

E99-007 (data taken in 2000)

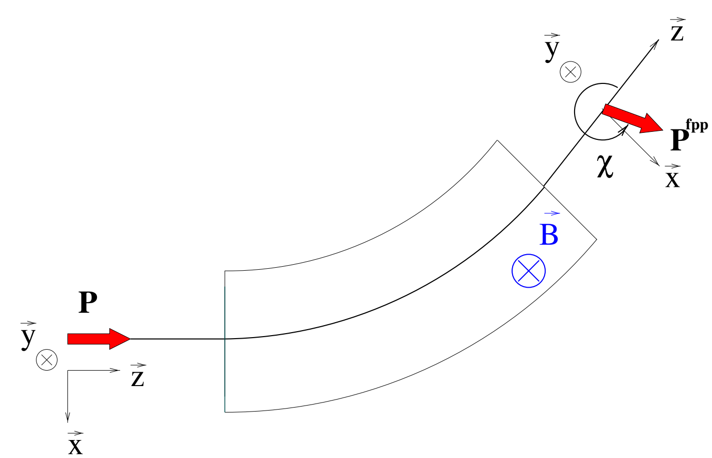
Gayou *et al.* PRL 88, 092301 (2002)

- G_E^p/G_M^p out to $Q^2 = 5.6\ \mathrm{GeV/c}^2$
- electron in one HRS and proton in FPP in other HRS
- above $Q^2 = 3.5$ proton in FPP in one HRS and electron in calorimeter.

G_E^p in Hall A



- ✴ left–right asymmetry $\Rightarrow P_n^{\text{fpp}}$ polarization in vertical direction
- ✴ up–down asymmetry $\Rightarrow P_t^{\text{fpp}}$ polarization in the horizontal direction

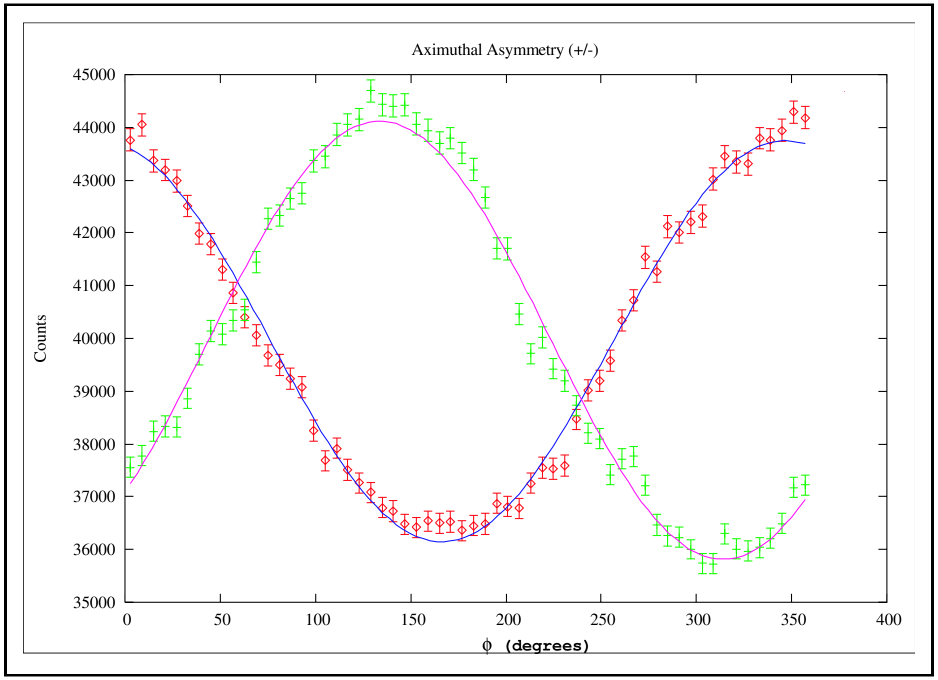


$$P_n^{\text{fpp}} = \sin\chi \cdot hP_l$$
$$P_t^{\text{fpp}} = hP_t$$
$$\chi = \gamma\theta_B(\mu_p - 1)$$

G_E^p in Hall A

Azimuthal Distribution

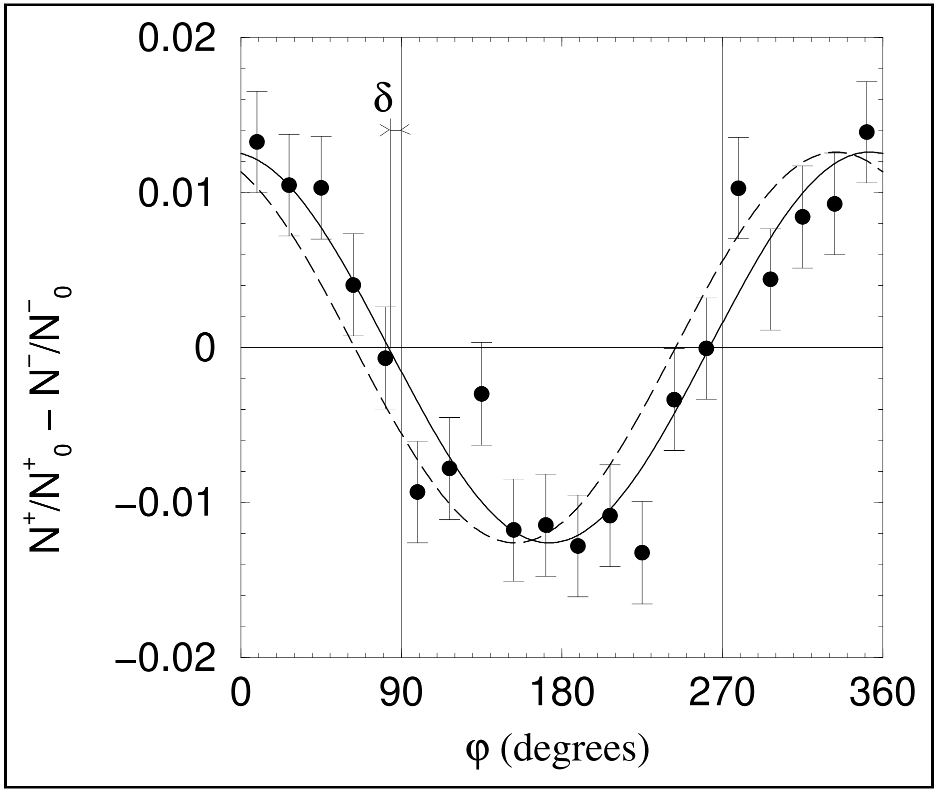
$$N(\vartheta,\varphi) = N_0(\vartheta)\epsilon(\vartheta)\left\{1 + \left[hA_y(\vartheta)P_t^{\text{fpp}} + a_{\text{instr}}\right]\sin\varphi - \left[hA_y(\vartheta)P_n^{\text{fpp}} + b_{\text{instr}}\right]\cos\varphi\right\}$$



- ✳ Difference between 2 helicity states
  - instrumental asymmetries cancel, P_B and A_y cancel.
  - gain access to the polarization components

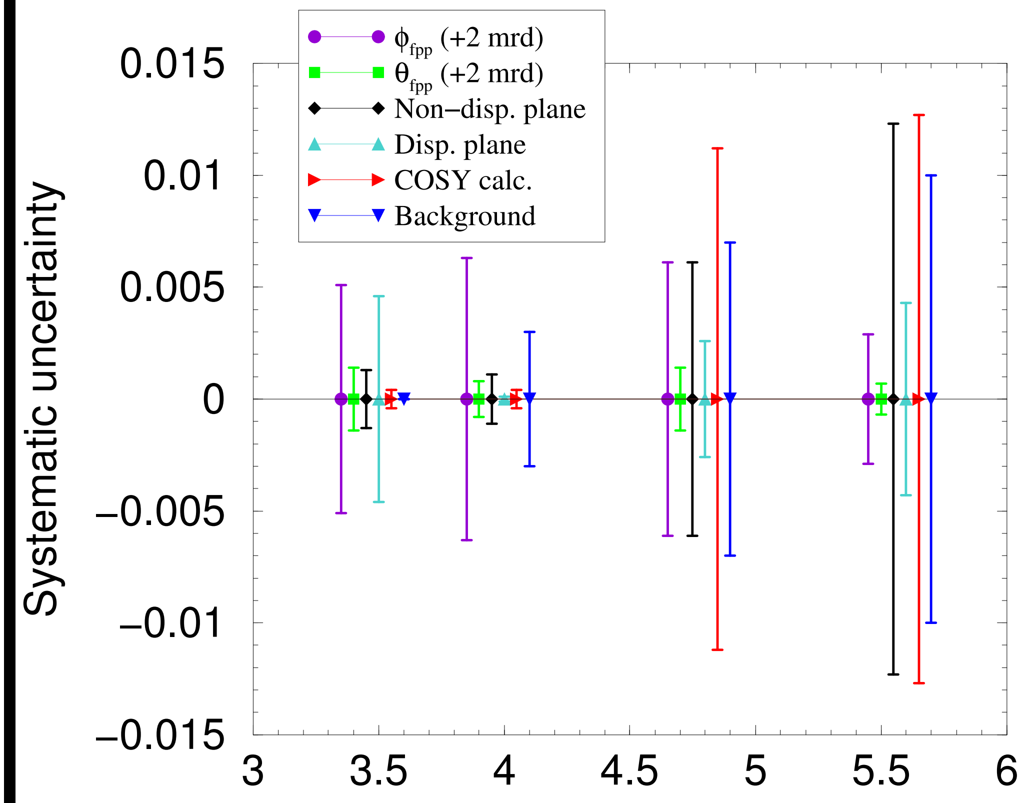
G_E^p in Hall A

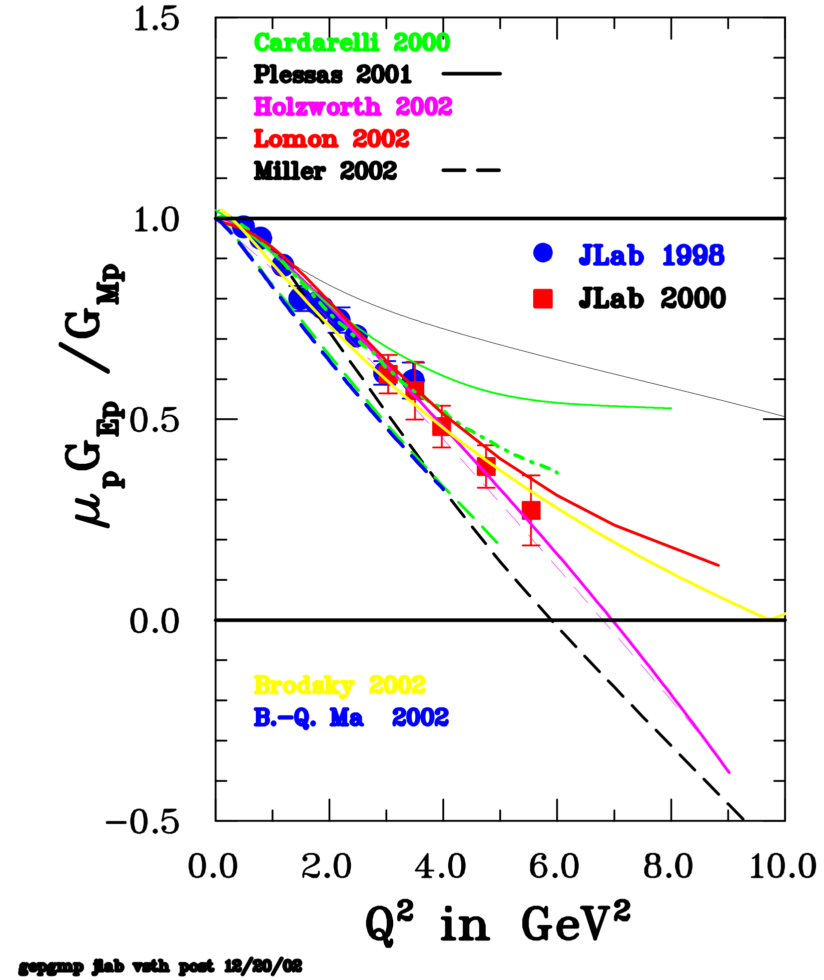
Difference between 2 helicity states ($Q^2 = 5.6$)



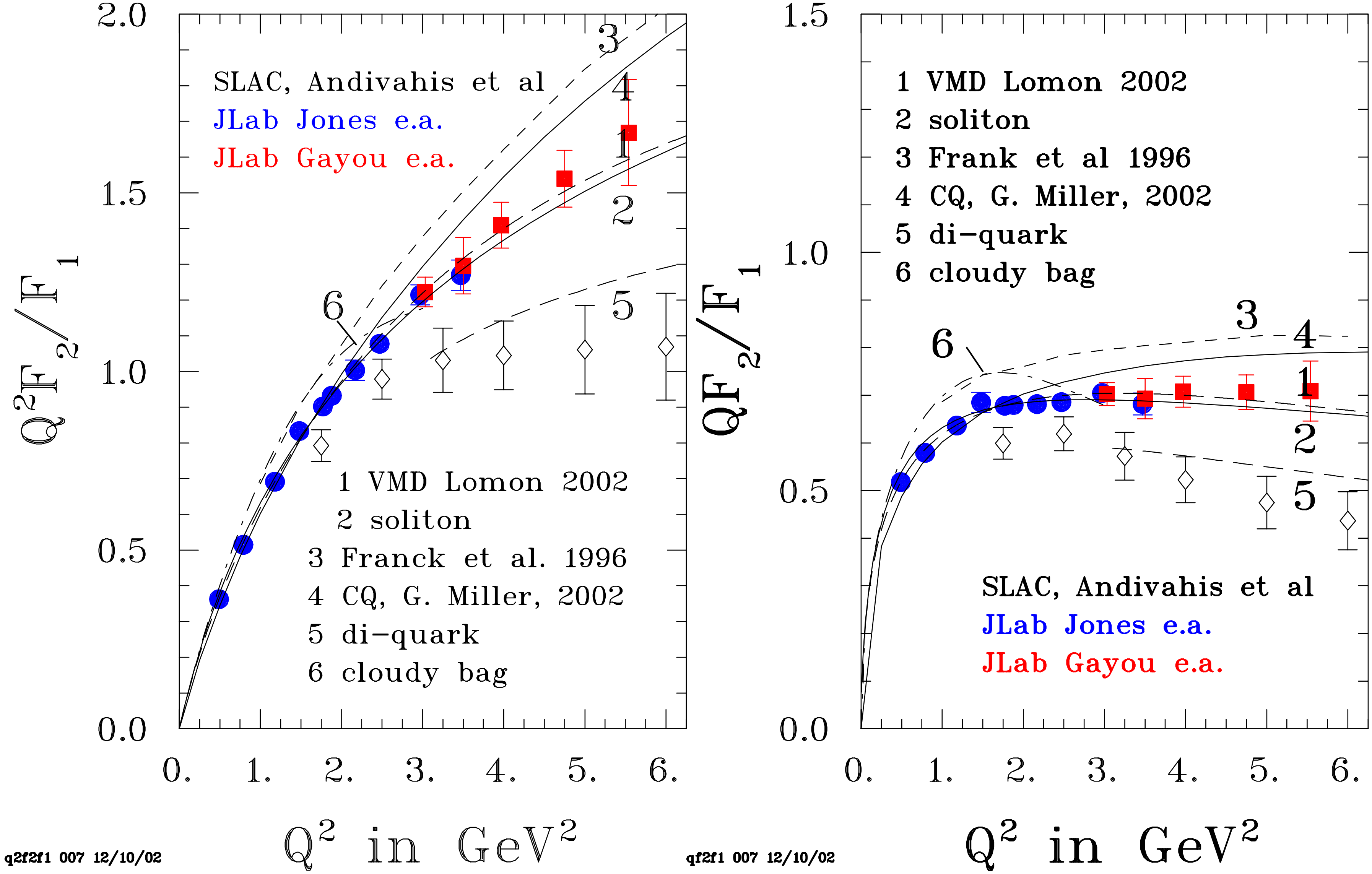
- ✴ Fit $N^+ - N^-$ with $F(\varphi) = C\cos(\varphi + \delta) \rightarrow \tan\delta = P_t^{\mathrm{fpp}}/P_n^{\mathrm{fpp}} \simeq 7^\circ$
- ✴ $P_n^{\mathrm{fpp}} = \sin\chi \cdot hP_l, \qquad P_t^{\mathrm{fpp}} = hP_t$
- ✴ $\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_e + E_{e'})}{2M_N}\tan(\frac{\theta_e}{2})$

G_E^p in Hall A – Results





G_E^p in Hall A – Results

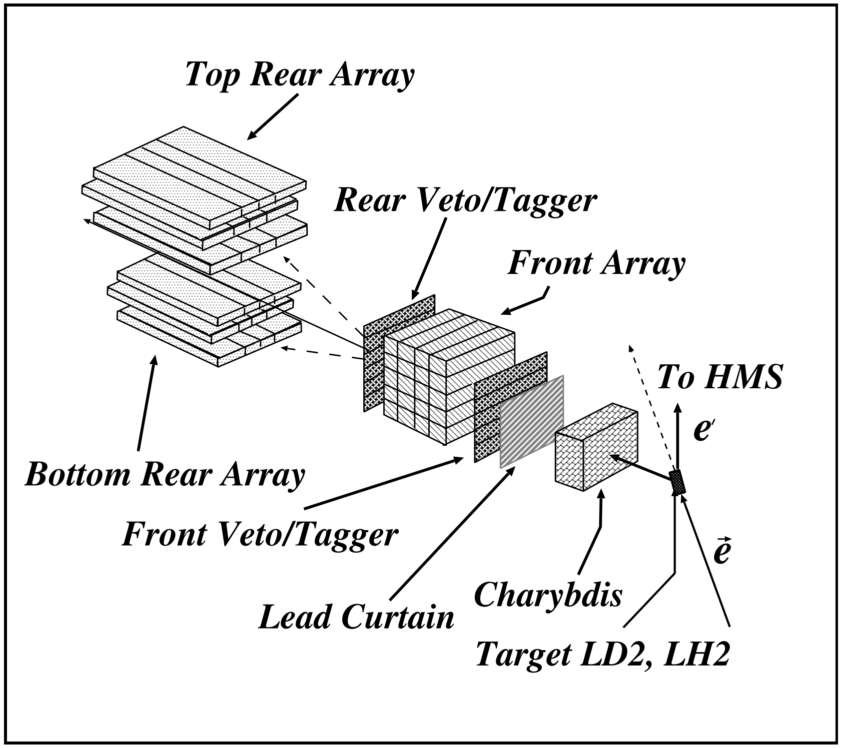


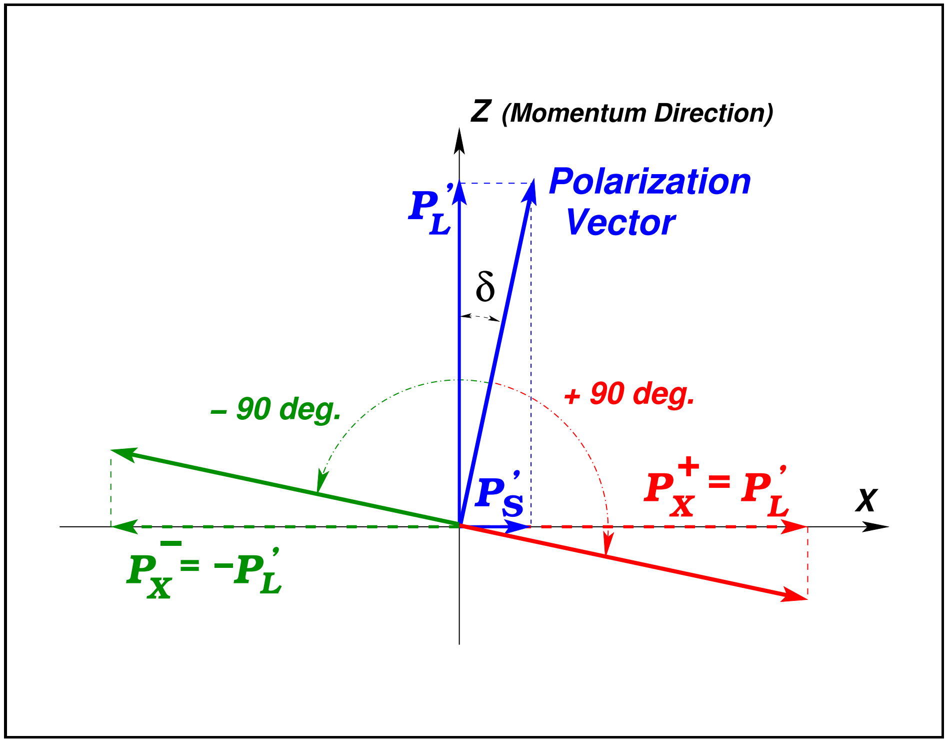
G_E^n in Hall C, E93-038

Recoil polarization, $^2\mathrm{H}(\vec{e}, e'\vec{n})p$

- ✳ In quasifree kinematics, $P_{s'}$ is sensitive to G_E^n and insensitive to nuclear physics
- ✳ Up–down asymmetry $\xi \Rightarrow$ transverse (sideways) polarization $P_{s'} = \xi_{s'}/P_e A_{\mathrm{pol}}$. Requires knowledge of P_e and A_{pol}
- ✳ Rotate the polarization vector in the scattering plane (with Charybdis) and measure the longitudinal polarization, $P_{l'} = \xi_{l'}/P_e A_{\mathrm{pol}}$
- ✳ Take ratio, $\frac{P_{s'}}{P_{l'}}$. P_e and A_{pol} cancel
- ✳ Three momentum transfers, $Q^2 = 0.45, 1.13$, and $1.45(\mathrm{GeV/c})^2$.
- ✳ Data taking $2000/2001$.

G_E^n in Hall C via $^2\mathrm{H}(\vec{e}, e'\vec{n})p$

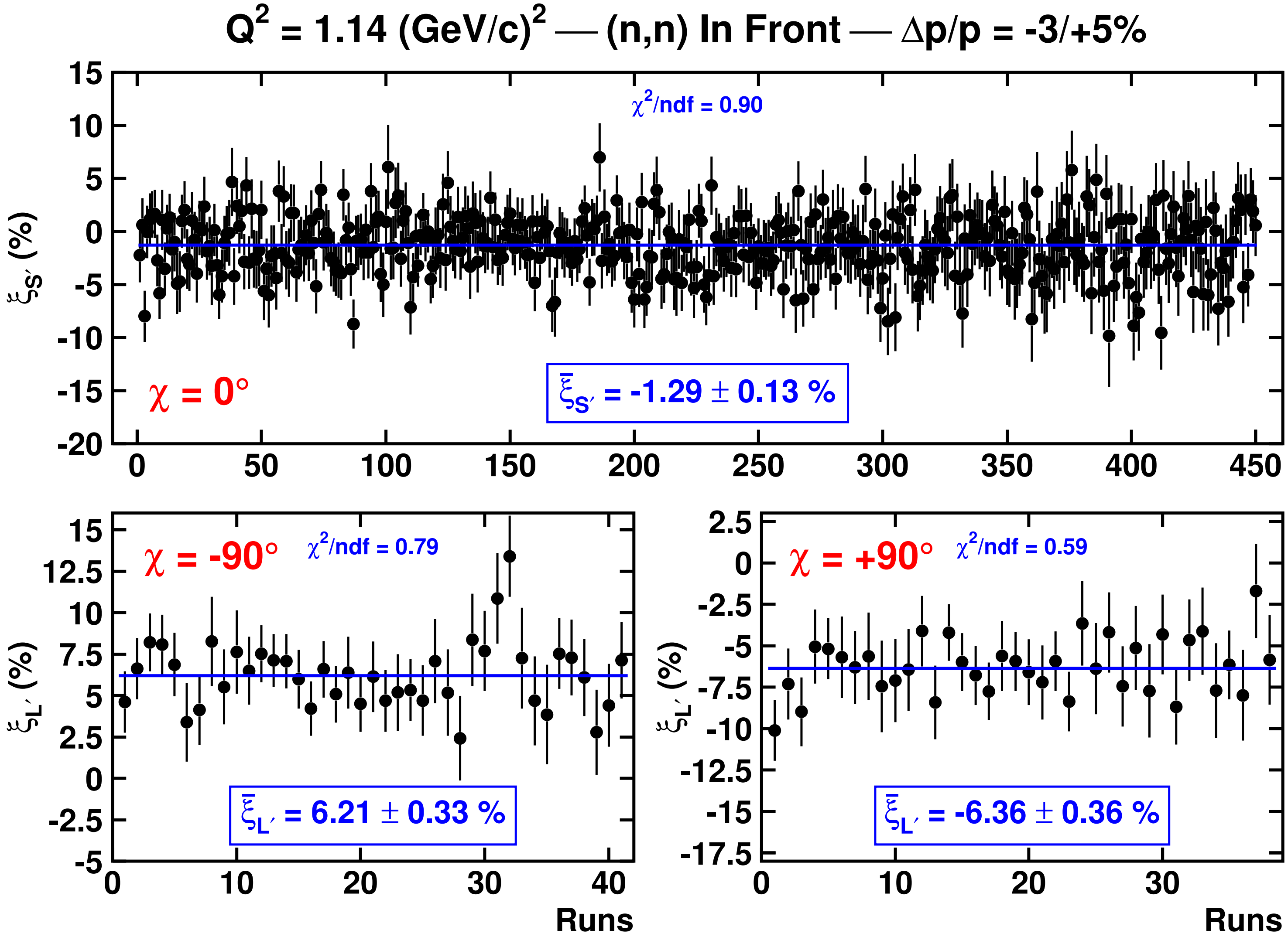




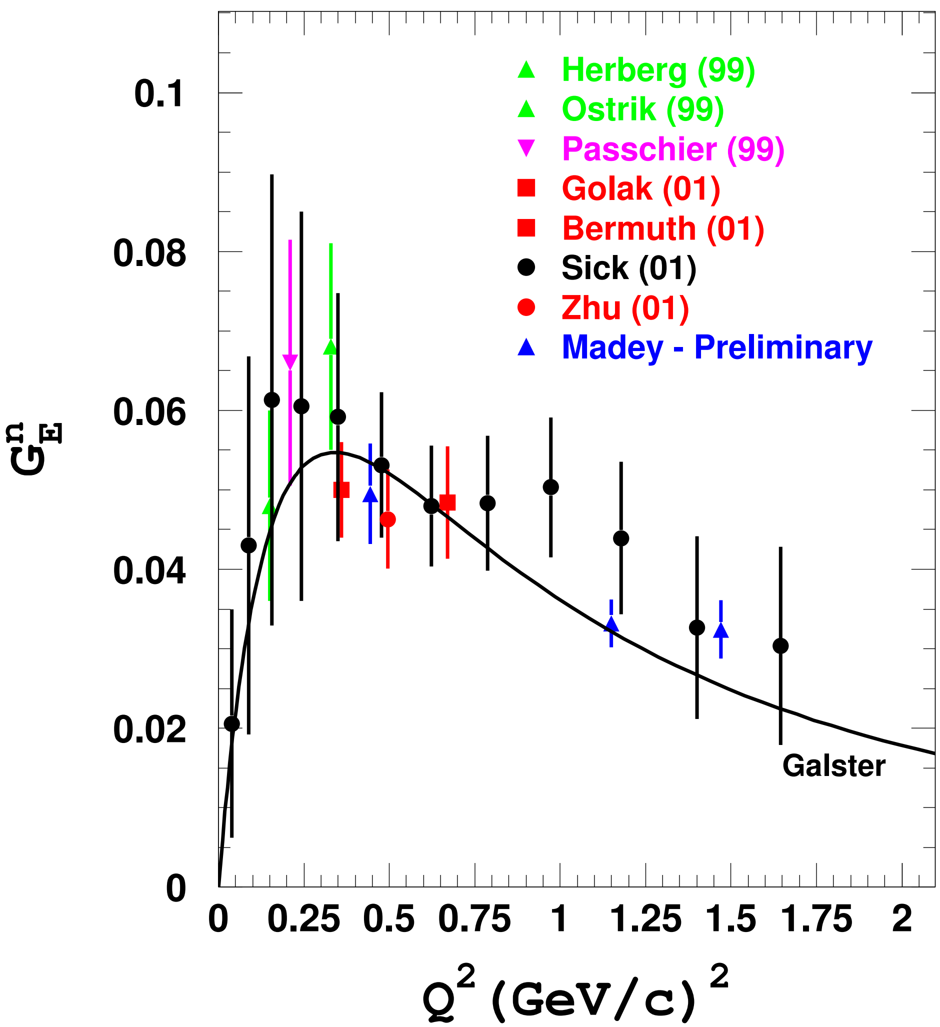
Taking the ratio eliminates the dependence on the analyzing power and the beam polarization → greatly reduced systematics

$$\frac{G_E^n}{G_M^n} = K \tan\delta \qquad \text{where} \qquad \tan\delta = \frac{P_{s'}}{P_{l'}} = \frac{\xi_{s'}}{\xi_{l'}}$$

G_E^n in Hall C via $^2\mathrm{H}(\vec{e}, e'\vec{n})p$



G_E^n in Hall C via $^2\mathrm{H}(\vec{e}, e'\vec{n})p$



Extraction of the neutron form factors

No free neutron targets – scattering from a nucleus, D, ^{3}He

Neutron is not free - can not avoid engaging the details of the nuclear physics.

Minimize sensitivity to the how the reaction is treated and maximize the sensitivity to the neutron form factors by working in quasifree kinematics.

- Indirect measurements: The experimental asymmetries ($\xi_{s'}$, A_V^{ed}, $A_{\exp}^{qe}$) are compared to theoretical calculations.
- Theoretical calculations are generated for scaled values of the form factor.
- Form factor is extracted by comparison of the experimental asymmetry to acceptance averaged theory.

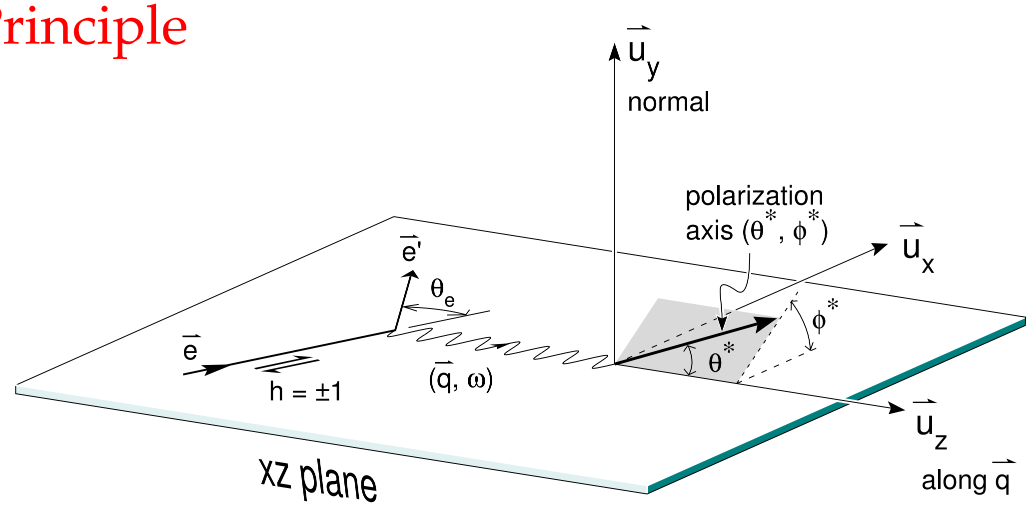
Beam–Target Asymmetry - Principle

Polarized Cross Section:

$\sigma = \Sigma + h\Delta$

Beam Helicity $h \pm 1$

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta}{\Sigma}$$



$$A = \frac{\overbrace{a\cos\Theta^\star (G_M)^2}^{A_T} + \overbrace{b\sin\Theta^\star \cos\Phi^\star G_E G_M}^{A_{TL}}}{c\,(G_M)^2 + d\,(G_E)^2}; \quad \varepsilon = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} = P_B \cdot P_T \cdot f \cdot A$$

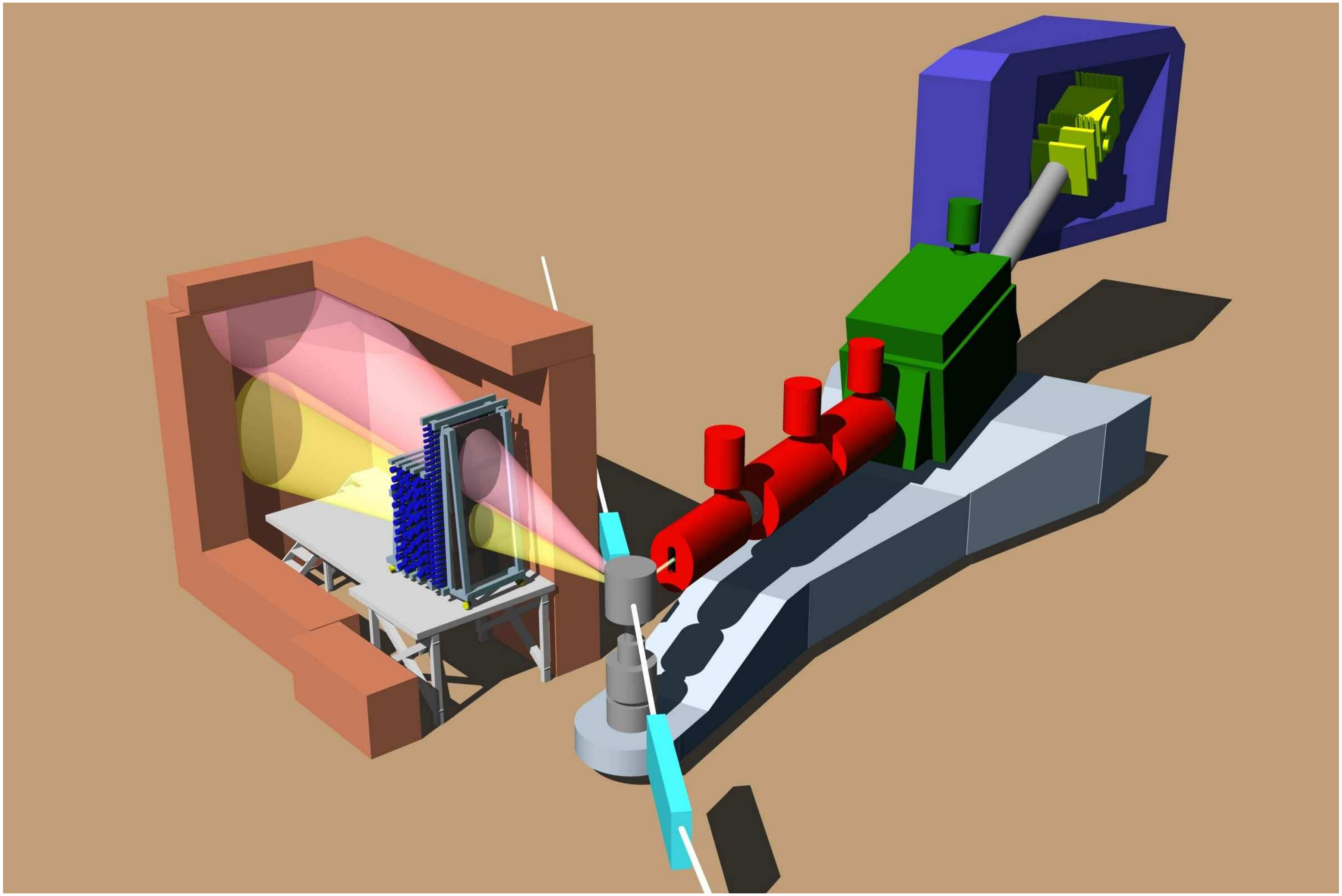
$\Theta^\star = 90^\circ \quad \Phi^\star = 0^\circ$

$$\Longrightarrow A = \frac{b G_E G_M}{c\,(G_M)^2 + d\,(G_E)^2}$$

$\Theta^\star = 0^\circ \quad \Phi^\star = 0^\circ$

$$\Longrightarrow A = \frac{a G_M^2}{c\,(G_M)^2 + d\,(G_E)^2}$$

G_E^n in Hall C



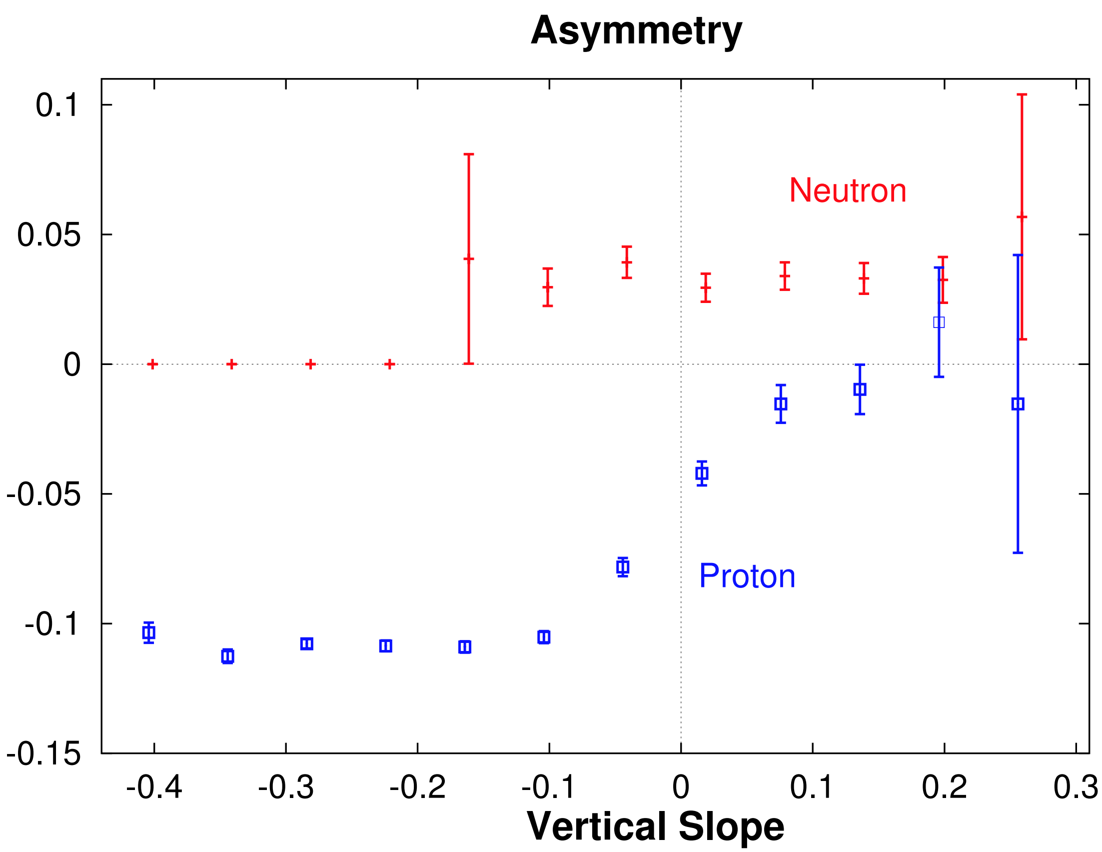
- $\ast$ Polarized Target
- $\ast$ Chicane to compensate for beam deflection of ≈ 4 degrees
- $\ast$ Scattering Plane Tilted
- $\ast$ Protons deflected ≈ 17 deg at $Q^2 = 0.5$
- $\ast$ Raster to distribute beam over 3 cm^2 face of target
- $\ast$ Electrons detected in HMS (right)
- $\ast$ Neutrons and Protons detected in scintillator array (left)
- $\ast$ Beam Polarization measured in coincidence Möller polarimeter

Experimental Technique for $\overrightarrow{\mathrm{D}}(\overrightarrow{e}, e'n)p$

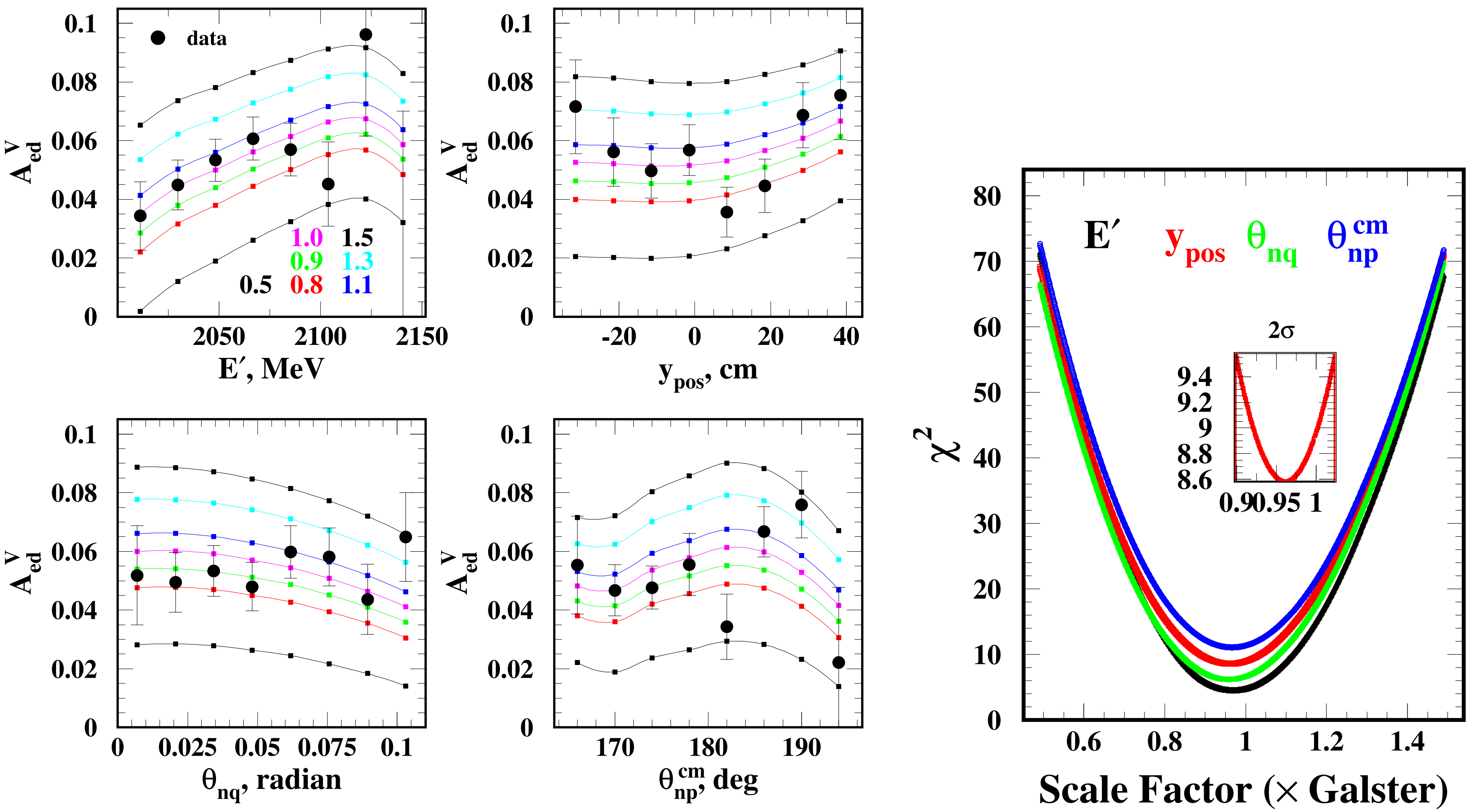
For different orientations of h and P: $N^{hP} \propto \sigma(h, P)$

Beam-target Asymmetry:

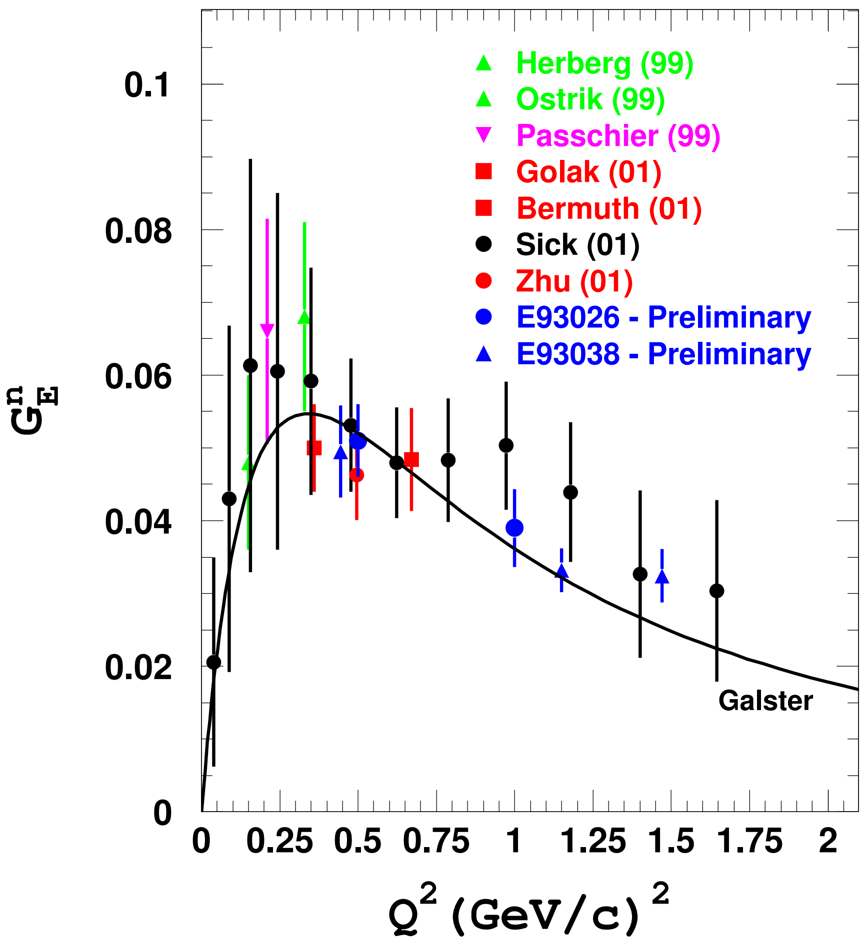
$$\epsilon = \frac{N^{\uparrow\uparrow} - N^{\downarrow\uparrow} + N^{\downarrow\downarrow} - N^{\uparrow\downarrow}}{N^{\uparrow\uparrow} + N^{\downarrow\uparrow} + N^{\downarrow\downarrow} + N^{\uparrow\uparrow}} = hPfA_{ed}^{V}$$

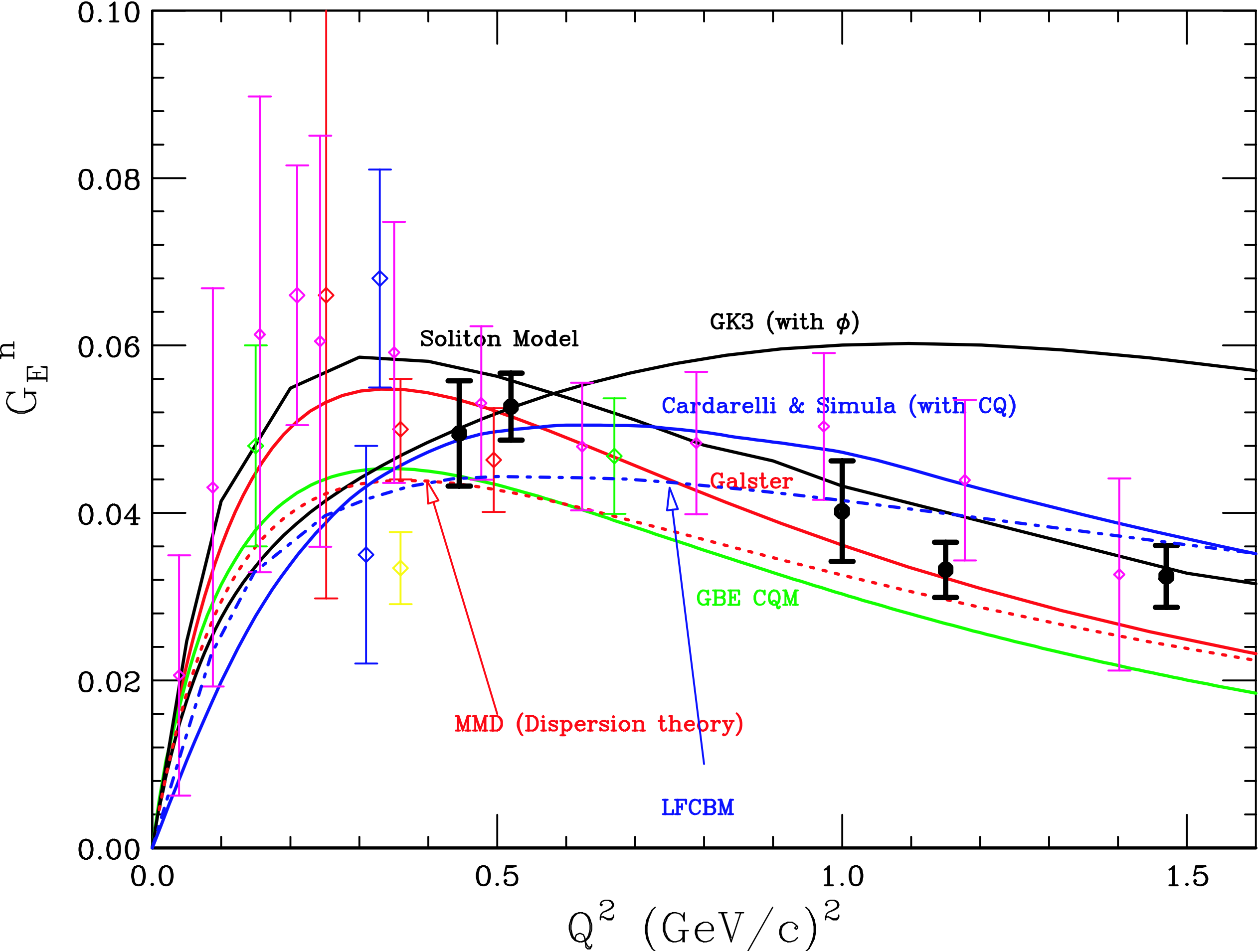


Extracting G_E^n



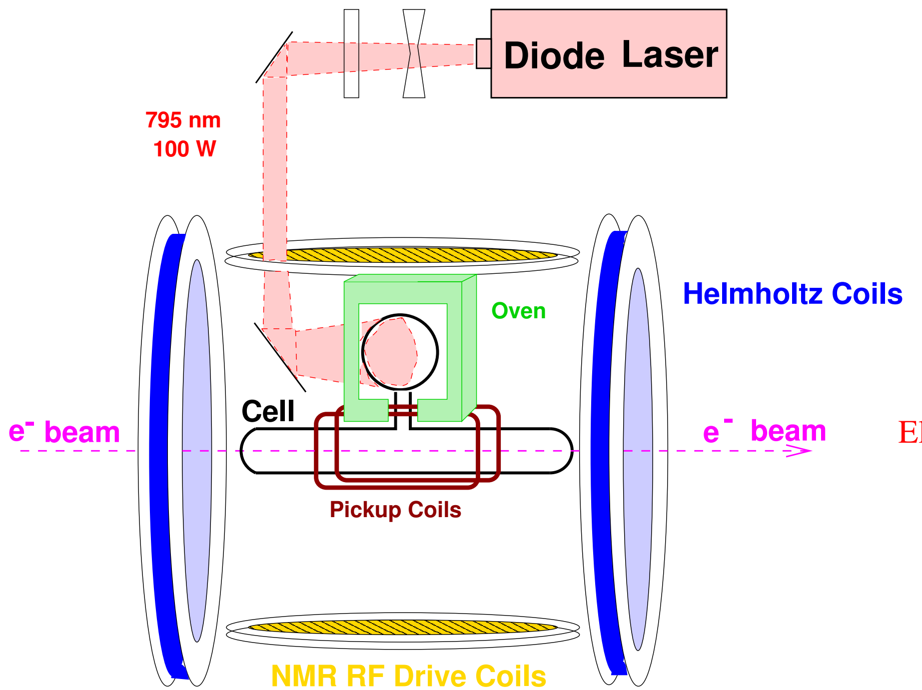
Preliminary results

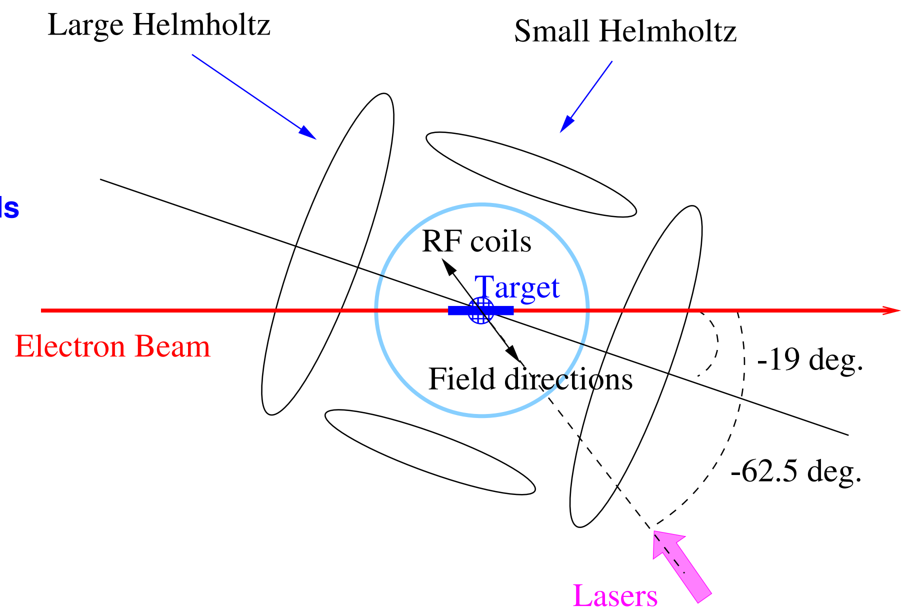




GK3 (with φ)
Soliton Model
Cardarelli & Simula (with CQ)
Galster
GBE CQM
MMD (Dispersion theory)
LFCBM
G_E^n
Q^2 (GeV/c)^2
0.00
0.02
0.04
0.06
0.08
0.10
0.0
0.5
1.0
1.5

G_M^n via $\overrightarrow{^3\mathrm{He}}(\vec{e}, e')X$, E95-001

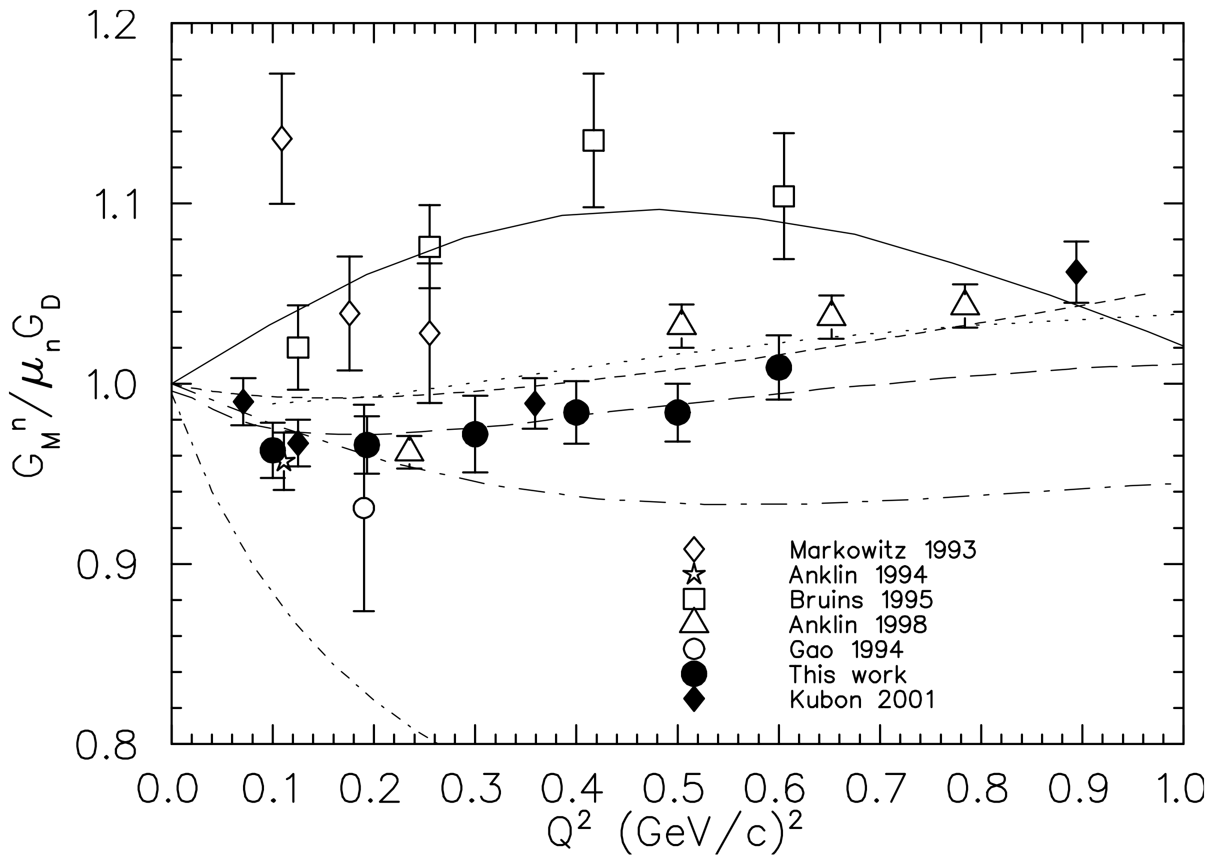




$$A_{\mathrm{raw}}^{\mathrm{qe}} = \frac{Y^{\mathrm{qe}}\uparrow - Y^{\mathrm{qe}}\downarrow}{Y^{\mathrm{qe}}\uparrow + Y^{\mathrm{qe}}\downarrow} = A_{\mathrm{exp}}^{\mathrm{qe}} \times P_b P_t$$

- ✳ Elastic scattering as monitor of $P_b P_t$. Very effective $\rightarrow$ 1.7% contribution to error!
- ✳ P_t^+, P_t^-, h^+, h^- to minimize false asymmetries

G_M^n via $\overrightarrow{^3\mathrm{He}}(e, e')X$



E95001, Wu *et al.*. PRC 67 012201(R) (2003)

- dots: Lomon
- short-dash: Holzwarth
- solid: Lu
- long dash: Mergell

G_M^n measurement in CLAS

Measure ratio of quasielastic $e-n$ scattering to quasielastic $e-p$ scattering off deuterium

$$R_D = \frac{\frac{d\sigma}{d\Omega}^{D(e,e'n)p}_{QE}}{\frac{d\sigma}{d\Omega}^{D(e,e'p)n}_{QE}} \approx \frac{f(G_M^n, G_E^n)}{f(G_M^p, G_E^p)}$$

Using the known values of G_E^p , G_M^p , G_E^n , extract G_M^n .

Has advantages over traditional techniques, $D(e,e')$, $D(e,e'\bar{p})n$, $D(e,e'n)p$

- ✳ No Rosenbluth separation or subtraction of dominant proton
- ✳ Ratio insenstive to deuteron model
- ✳ MEC and FSI are small in quasielastic region - don't get amplified by subtractions

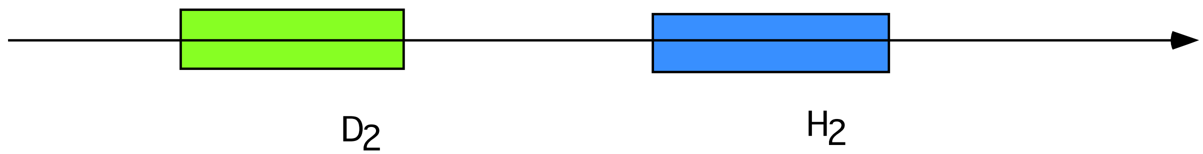
Large acceptance to veto events with extra charged particles

Experimental Advantages/Demands

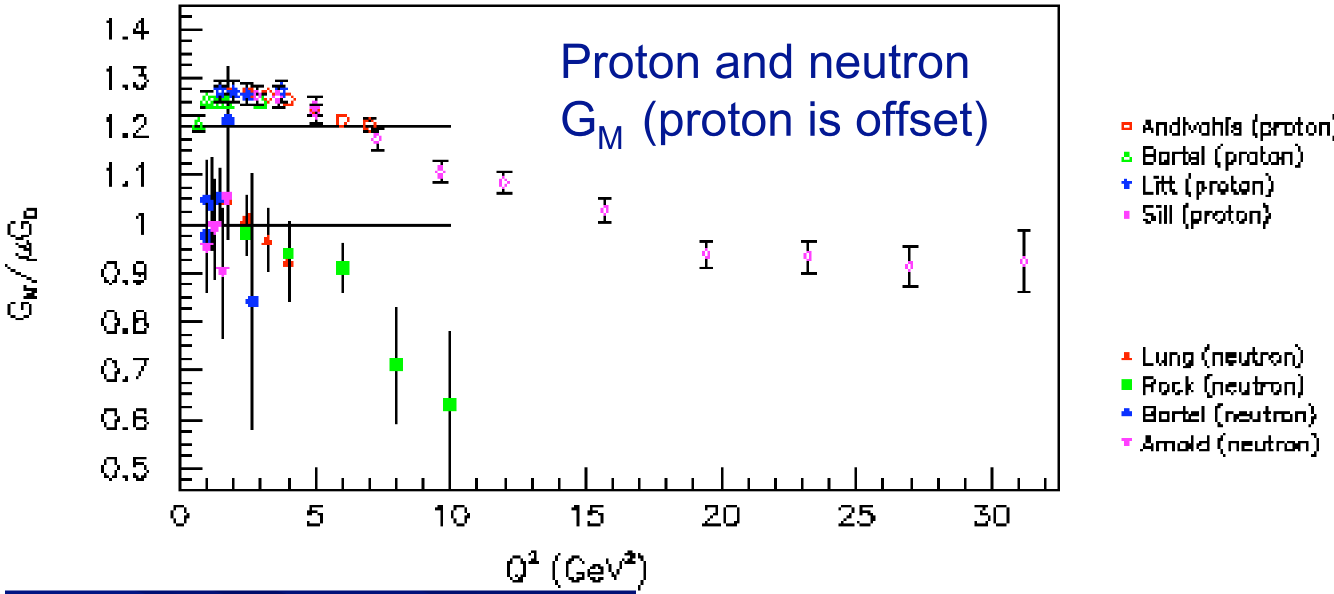
- ✳ Insensitive to
  - Luminosity
  - Electron radiative processes
  - Reconstruction and trigger efficiency
- ✳ Requires
  - Precise determination of absolute neutron detection efficiency
  - Equivalent solid angles for neutron and proton

Neutron Detection Efficiency

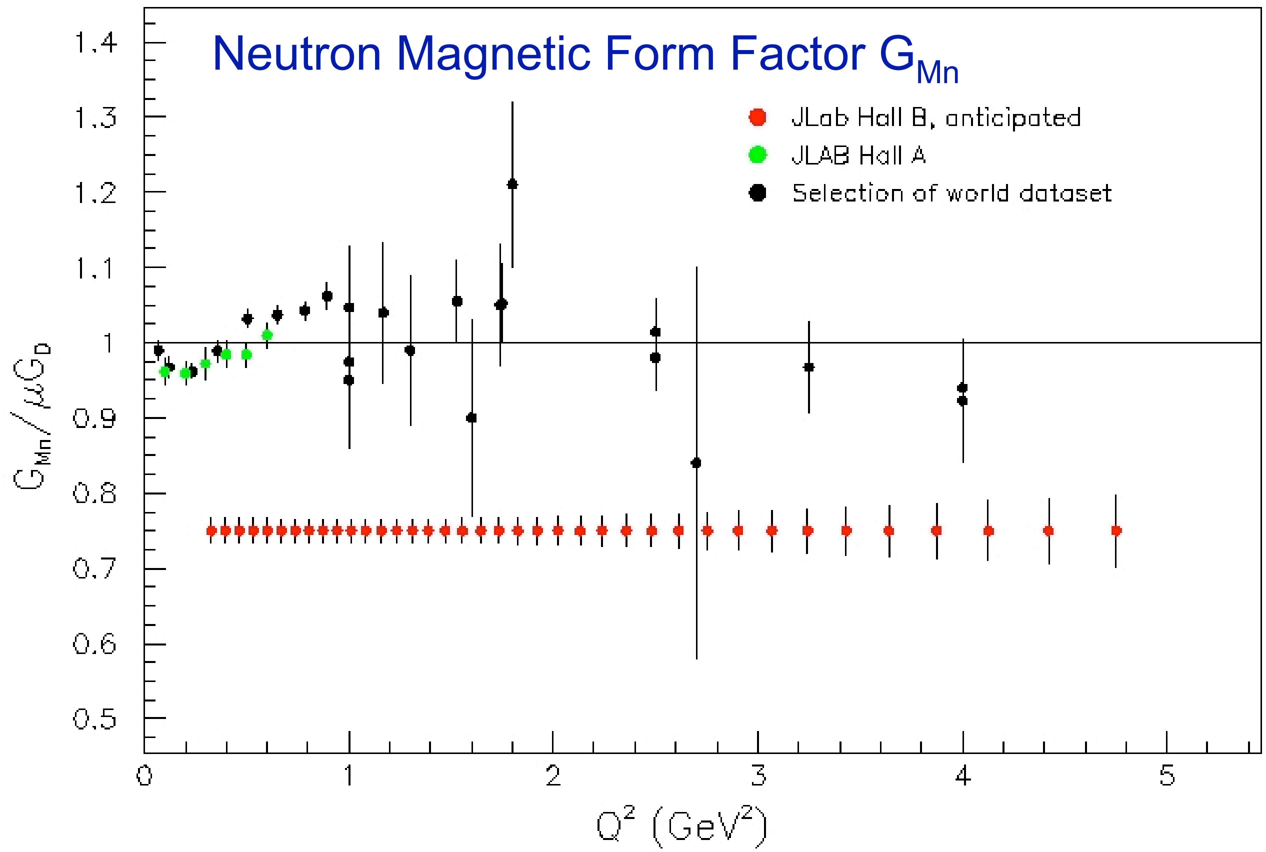
✷ Data taken with hydrogen and deuterium target simultaneously



- ✷ tag neutrons with H_2 target via $H(e, e'n\pi^+)$
  - In-situ efficiency, timing, angular resolution determination
  - Insensitive to PMT gain variations
  - Small acceptance correction



Existing Data

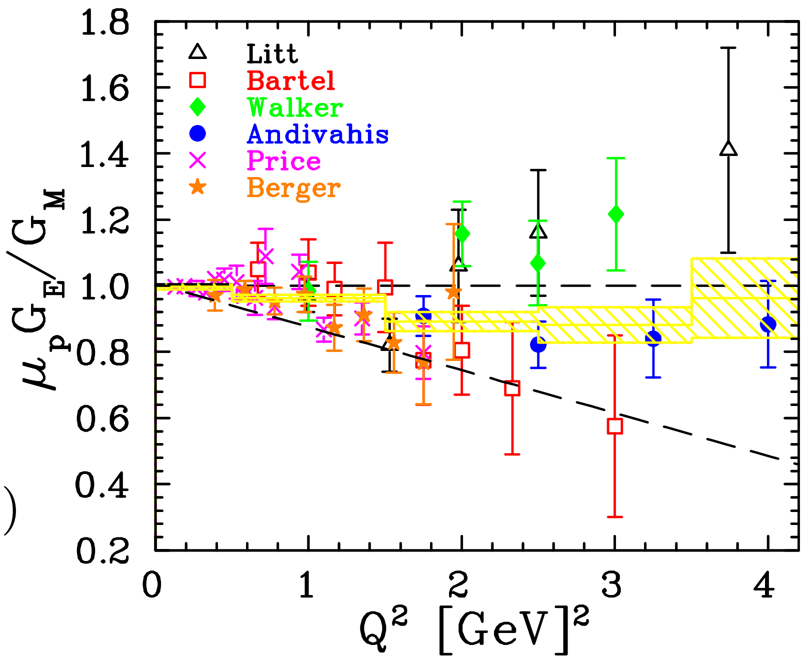


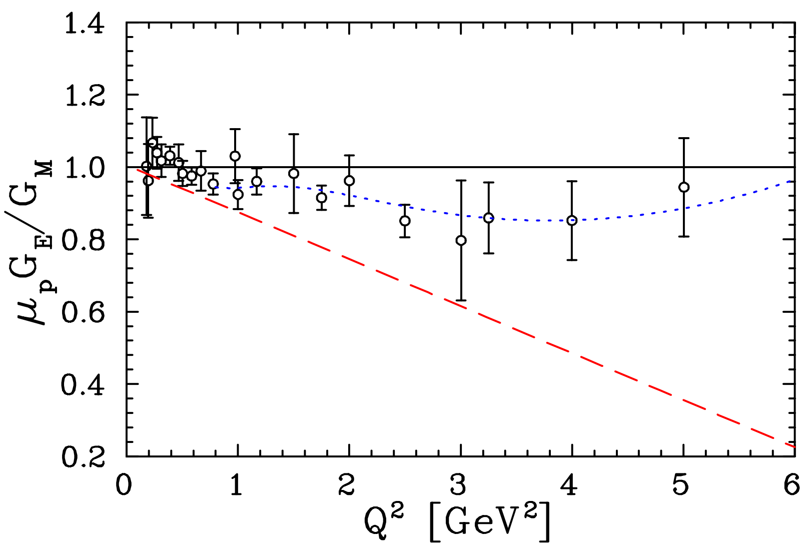
G_E^p , Status of Rosenbluth Separations

$$\sigma_R \equiv \frac{d\sigma}{d\Omega}\frac{\epsilon(1+\tau)}{\sigma_{Mott}} = \tau G_m^2(Q^2)+\epsilon G_E^2(Q^2)$$

Fundamental problem: σ insensitive to G_E^p at large Q^2. With $\mu G_E^p = G_M^p$, G_E^p contributes 8.3% to total cross section at $Q^2 = 5$.

$$\delta G_E \propto \delta(\sigma_R(\epsilon_1)-\sigma_R(\epsilon_2))(\Delta\epsilon)^{-1}(\tau G_M^2/G_E^2)$$



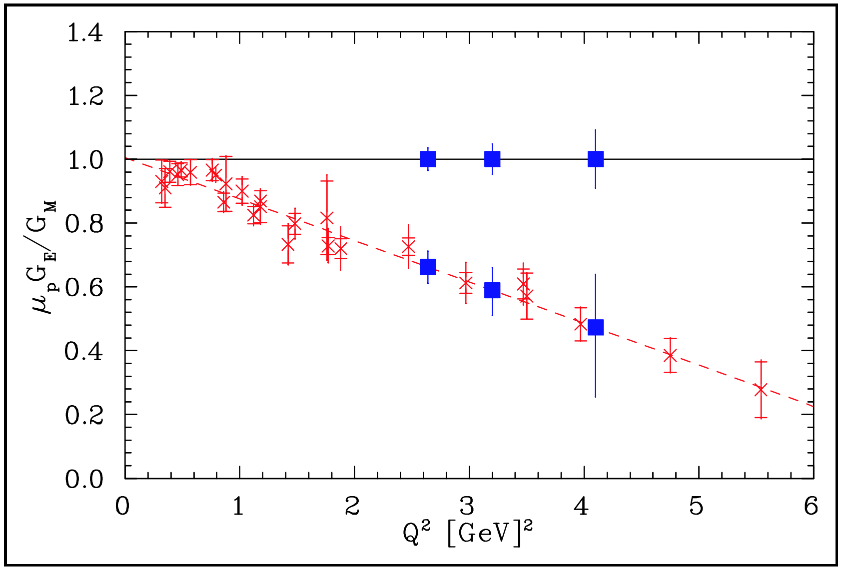


J. Arrington: nucl-ex/0305009 (2003)

- E94-110 consistent with global fit
- Rules out experimental systematics
- ϵ dependence must be large
- Unconsidered ϵ dependent radiative correction

Super–Rosenbluth, E01-001 (Hall A), $p(e,p')$

$Q^2 = 3.2$	Electron	Proton
ϵ	0.13–0.87	0.13–0.87
θ	22.2–106.0	12.5–36.3
p [GeV/c]	0.56–3.86	2.47
$\frac{d\sigma}{d\Omega}[10^{-10}\mathrm{fm}^{-2}]$	6–340	120–170
$\frac{\delta\sigma}{\delta E}[\%/\%]$	11.5–14.2	5.0–5.3
$\frac{\delta\sigma}{\delta\theta}[\%/deg]$	3.6–37.0	5.6–19.0
Rad. Corr.	1.37–1.51	1.24–1.28



Reduces size of dominant corrections

No momentum dependent systematics

Rate nearly constant for protons

Sensitivity to angle momentum reduce

Luminosity monitor (second arm)

Background small

A Promise Fulfilled

✔ A high current, high duty factor electron machine would allow the study of the nucleon form factors out to large momentum transfers, with high precision.

- Outstanding data on G_E^p out to high momentum transfer – spawning a tremendous interest in the subject and the reexamination of our long held conception of the proton.
- For the first time, G_E^n data of very high quality out to 1.5 (GeV/c)^2, allowing rigorous tests of theory.
- A high quality data set on G_M^n at moderate Q^2 from Hall A and a forthcoming data set from Hall B out to large Q^2, which together further constrain any model which attempts to describe the nucleon form factors.
- A resolution of the G_E^p data from recoil polarization and Rosenbluth techniques will have applications in similar experiments from nuclei and deepen our understanding of physics and experiment.

Prospects

Future measurements at Jefferson Lab

- $\ast$ E02-013: ${}^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)$ out to $Q^2 = 3.4$ (GeV/c)^2
  - Extension to 5 (GeV/c)^2 in Hall A with 12 GeV upgrade.
- $\ast$ E01-109 in Hall C will measure form factor ratio out to 9 (GeV/c)^2 with 6 GeV beam.
  - Possible to extend measurement out to 12.4 (GeV/c)^2 with 12 GeV upgrade.
- $\ast$ G_M^n out to 14 (GeV/c)^2 with an upgraded CLAS and 12 GeV upgrade.
- $\ast$ G_M^p to 8 (GeV/c)^2 (as part of new proposal to measure $B(Q^2)$ at 180 degrees in Hall A).

Credits

- ✳ The early proponents of this facility.
- ✳ The spokespersons and collaborations who committed themselves to the physics.
- ✳ Laboratory management and Hall leaders who provided the necessary resources.
- ✳ Jefferson Lab staff, especially the accelerator division that built the facility, the target group and the hall engineering staffs that managed and executed the big installations.
- ✳ Nathan Isgur, who encouraged, promoted and supported this experimental program.