

Developments in the measurement of G_E^n , the neutron electric form factor

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LOWq03

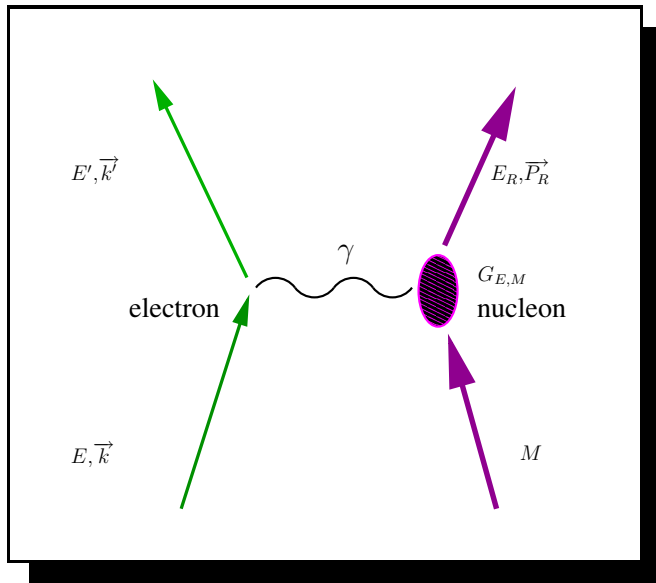
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Outline

- * Introduction: Formalism, Interpretation, Motivation
- * Models
- * Experimental Techniques
 - Traditional (unpolarized beams)
 - Modern (polarized beams, targets, polarimeters)
- * Experiments using polarized electrons at Jefferson Lab
 - Recoil polarization
 - Beam-target asymmetry
- * Outlook

Formalism

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



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

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

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

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

$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2) \quad G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

* 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

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

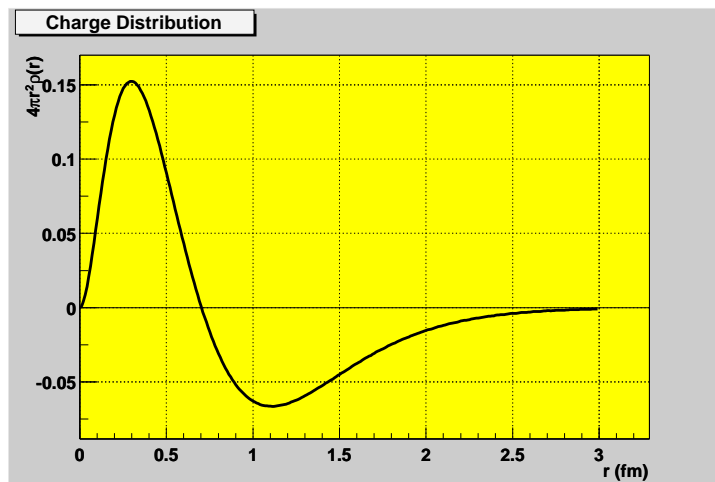
G_E^n Interpretation

In the NR limit (Breit Frame), G_E is FT of the charge distribution $\rho(r)$:

$$G_E^n(\mathbf{q}^2) = \frac{1}{(2\pi)^3} \int d^3r \rho(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}} = 0 - \frac{\mathbf{q}^2}{6} \langle r_{ne}^2 \rangle + \dots$$

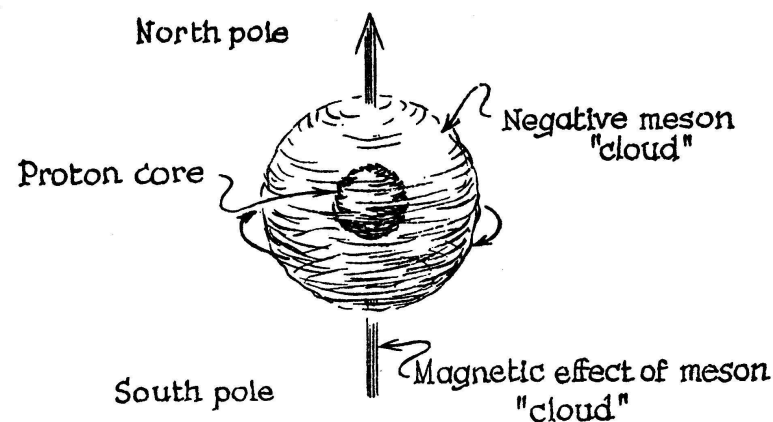
Experimental: Mean square charge radius $\langle r_{ne}^2 \rangle$ is negative.

Theory has intuitive explanation:



pion-nucleon theory:

valence quark model:



$n = p + \pi^-$ cloud

$n = ddu$ & spin-spin force $\Rightarrow d \rightarrow$ periphery

Charge radius, Foldy term

$$\begin{aligned}\langle r_{ne}^2 \rangle &= -6 \frac{dG_E^n(0)}{dQ^2} = -6 \frac{dF_1^n(0)}{dQ^2} + \frac{3}{2M^2} F_2^n(0) \\ &= \langle r_{in}^2 \rangle + \langle r_{\text{Foldy}}^2 \rangle\end{aligned}$$

Foldy term, $\frac{3\mu_n}{2m_n} = (-0.126)\text{fm}^2$, has nothing to do with the rest frame charge distribution.

$\langle r_{ne}^2 \rangle$ is measured through neutron-electron scattering

$$\langle r_{ne}^2 \rangle = \frac{3m_e a_0}{m_n} b_{ne} = -0.113 \pm 0.003 \pm 0.004 \text{ fm}^2.$$

$\langle r_{in}^2 \rangle = -0.113 + 0.126 \approx 0$ suggesting that the spatial charge extension seen in F_1 is about 0 or very small. **Recent Work:**

N. Isgur, Phys. Rev. Lett. 83, 272 (1999)

M. Bawin & A.A. Coon, Phys. Rev. C. 60, 025207 (1999)

G_E^n arises from the neutron's rest frame charge distribution.

A. Glozman & D. Riska, Phys. Lett. B 459 (1999) 49.

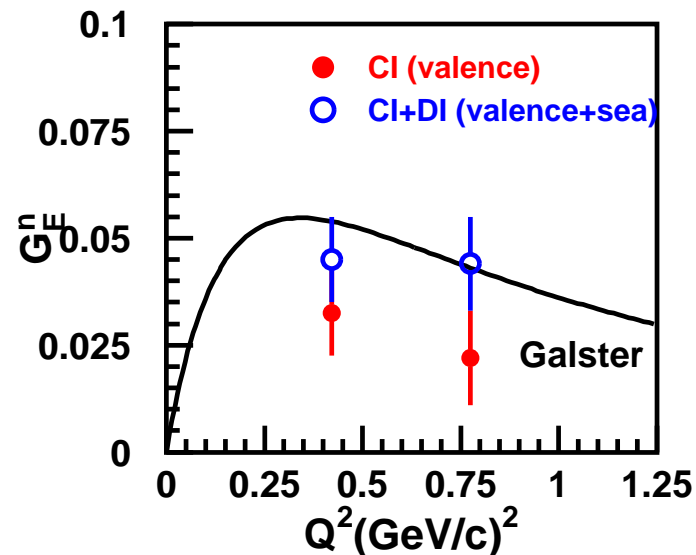
Pionic loop fluctuations make minute contribution to $\langle r_{in}^2 \rangle$.

Why measure G_E^n ?

- * FF are fundamental quantities
- * Test of QCD description of the nucleon

Symmetric quark model, with all valence quarks with same wf: $G_E^n \equiv 0$

$G_E^n \neq 0 \rightarrow$ details of the wavefunctions



- * Sensitive to sea quark contributions
- * Soliton model: $\rho(r)$ at large r due to sea quarks

Dong, Liu, Williams, PRD 58 074504

Necessary for study of nuclear structure.

- * Few body structure functions

Proton Form Factor Data

Rosenbluth separation

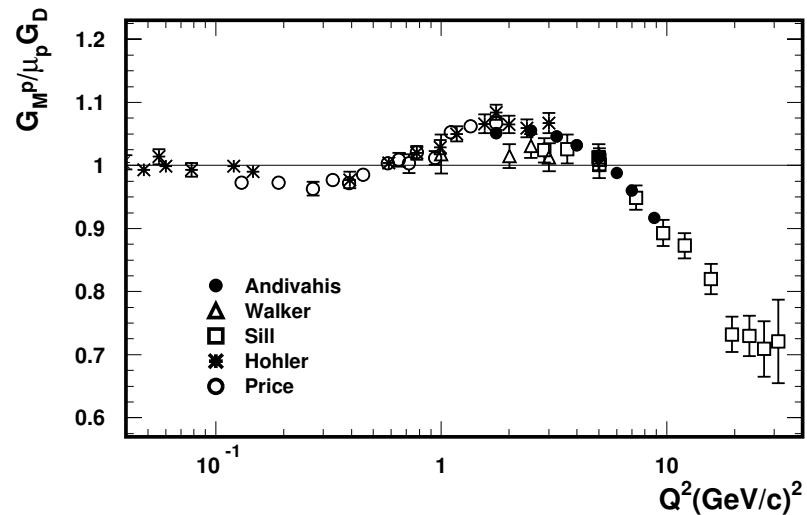
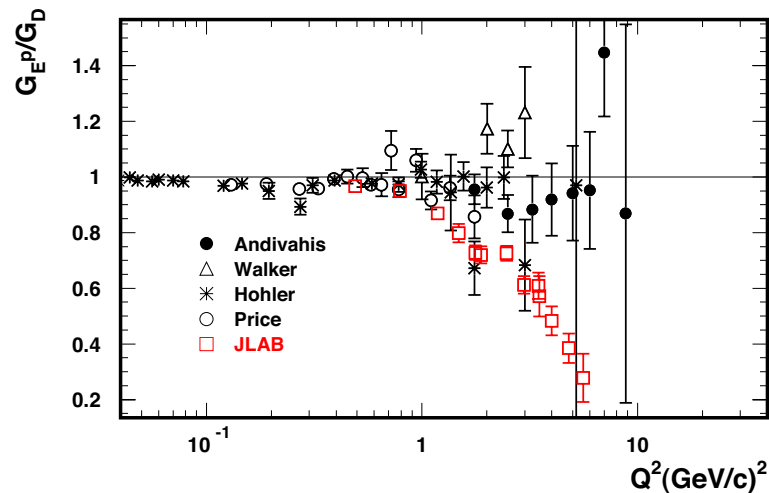
$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{Mott}}{(1 + \tau)} \frac{E'}{E_0} \left[G_E^2 + \underbrace{\tau(1 + (1 + \tau)2 \tan^2(\theta/2))}_{\text{Recoil Polarization}} G_M^2 \right]$$

* G_M^p well measured via Rosenbluth, but not G_E^p hence **Recoil Polarization**

* 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: $\rho(r) \propto e^{-kr}$



Neutron Form Factors without Polarization

No neutron target, G_M^n dominates G_E^n

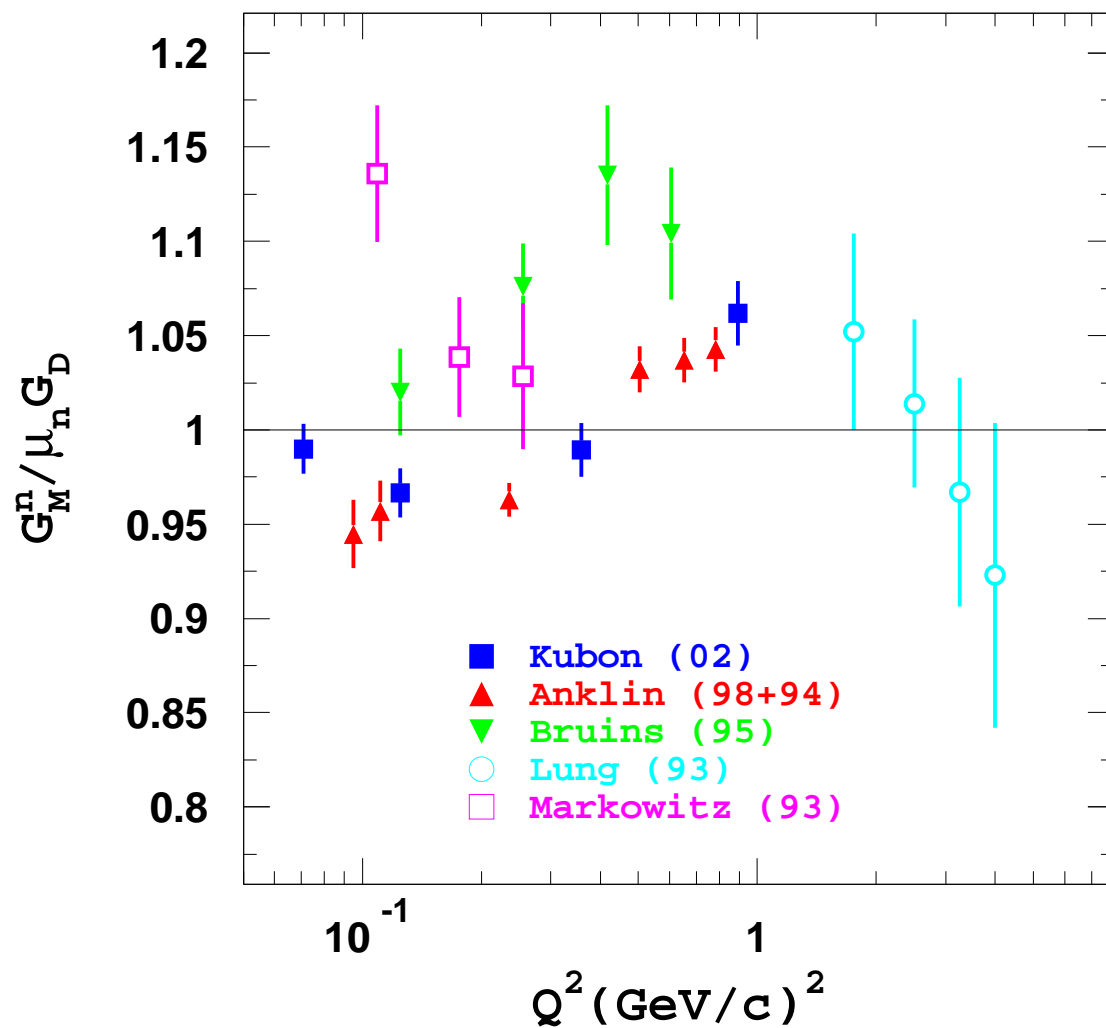
Traditional techniques used to measure G_M^n and G_E^n have been:

- * Elastic scattering ${}^2\text{H}(e, e'){}^2\text{H}$
- * Inclusive quasielastic scattering: ${}^2\text{H}(e, e')X$
- * Neutron in coincidence with electron: ${}^2\text{H}(e, e'n)p$
- * Neutron in **anti**-coincidence with electron: ${}^2\text{H}(e, e'\bar{p})p$
- * Ratio techniques $\frac{d(e, e'n)p}{d(e, e'p)n}$ minimizes roles of g.s. wavefunction and FSI.

Measurements of the Neutron Form Factors

Target	Type	$Q^2(\text{GeV}/c)^2$	Deduced quantities	Reference
^2H	elastic	0.004-0.032	G_{En}	F.A. Bumiller <i>et al.</i> , PRL 25, 1774 (1970)
^2H	elastic	0.012-0.085	G_{En}	Drickey & Hand, PRL 9, 1774 (1962)
^2H	elastic	0.002-0.16	G_{En}	G.G. Simon, <i>et al.</i> , NP A364, 285 (1981)
^2H	ratio	0.11	G_{Mn}	H.A. Anklin <i>et al.</i> , PL B336, 313 (1994)
^2H	quasielastic	0.11-0.16	G_{En}, G_{Mn}	B. Grossette <i>et al.</i> , PR 141, 1435 (1966)
^2H	elastic	0.116-0.195	G_{En}, G_{Mn}	P. Benaksas <i>et al.</i> , PRL 13, 1774 (1964)
^2H	coincidence	0.109-0.255	G_{Mn}	P. Markowitz <i>et al.</i> PR C48, R5 (1993)
^2H	quasielastic	0.06-0.3	G_{En}, G_{Mn}	E.B. Hughes <i>et al.</i> PR 146, 973 (1966)
^2H	elastic	0.116-0.195	G_{Mn}	J.I. Friedman <i>et al.</i> PR 120, 992 (1960)
^2H	elastic	0.2-0.56	G_{En}	S. Galster <i>et al.</i> NP B32, 221 (1971)
^2H	ratio	0.22-0.58	G_{En}, G_{Mn}	P. Stein <i>et al.</i> PR 16, 592 (1966)
^2H	ratio	0.125-0.605	G_{Mn}	E.E. Bruins <i>et al.</i> PRL 75, 21 (1995)
^2H	ratio	0.2-0.9	G_{Mn}	H.A. Anklin <i>et al.</i> , PL B428, 248 (1998)
		0.2-0.9	G_{Mn}	G. Kubon <i>et al.</i> , PL B524, 26 (2002)
^2H	elastic	0.04-0.72	G_{En}	S. Platchov <i>et al.</i> NP A510, 740 (1990)
^2H	ratio	0.39-0.78	G_{En}, G_{Mn}	W. Bartel <i>et al.</i> PL 30B, 285 (1969)
^2H	quasielastic	0.48-0.83	G_{Mn}	A.S. Esaulov <i>et al.</i> Sov. J. NP 45, 258 (1987)
^2H	quasielastic	0.04-1.2	G_{En}, G_{Mn}	E.B. Hughes <i>et al.</i> PR 139, B458 (1965)
^2H	quasielastic	0.04-0.2	G_{Mn}	D. Braess <i>et al.</i> Zeit Phys. 198, 527 (1967) <small>reanalysis of Hughes</small>
^2H	quasielastic	0.39-1.5	G_{En}, G_{Mn}	W. Bartel <i>et al.</i> NP B58, 429 (1973)
^2H	ratio	1.0-1.53	G_{En}, G_{Mn}	W. Bartel <i>et al.</i> PL 39B, 407(1972)
^2H	anticoincidence	0.28-1.8	G_{En}, G_{Mn}	K.M. Hanson <i>et al.</i> PR D8, 753 (1973)
^2H	quasielastic	0.75-2.57	G_{Mn}	R.G. Arnold <i>et al.</i> PRL 61, 806 (1988)
^2H	quasielastic	1.75-4.0	G_{En}, G_{Mn}	A. Lung <i>et al.</i> PRL 70, 718 (1993)
^2H	anticoincidence	0.27-4.47	G_{En}, G_{Mn}	R.J. Budnitz <i>et al.</i> PR 173, 1357 (1968)
^2H	quasielastic	2.5-10.0	G_{Mn}	S. Rock <i>et al.</i> PRL 49, 1139 (1982)

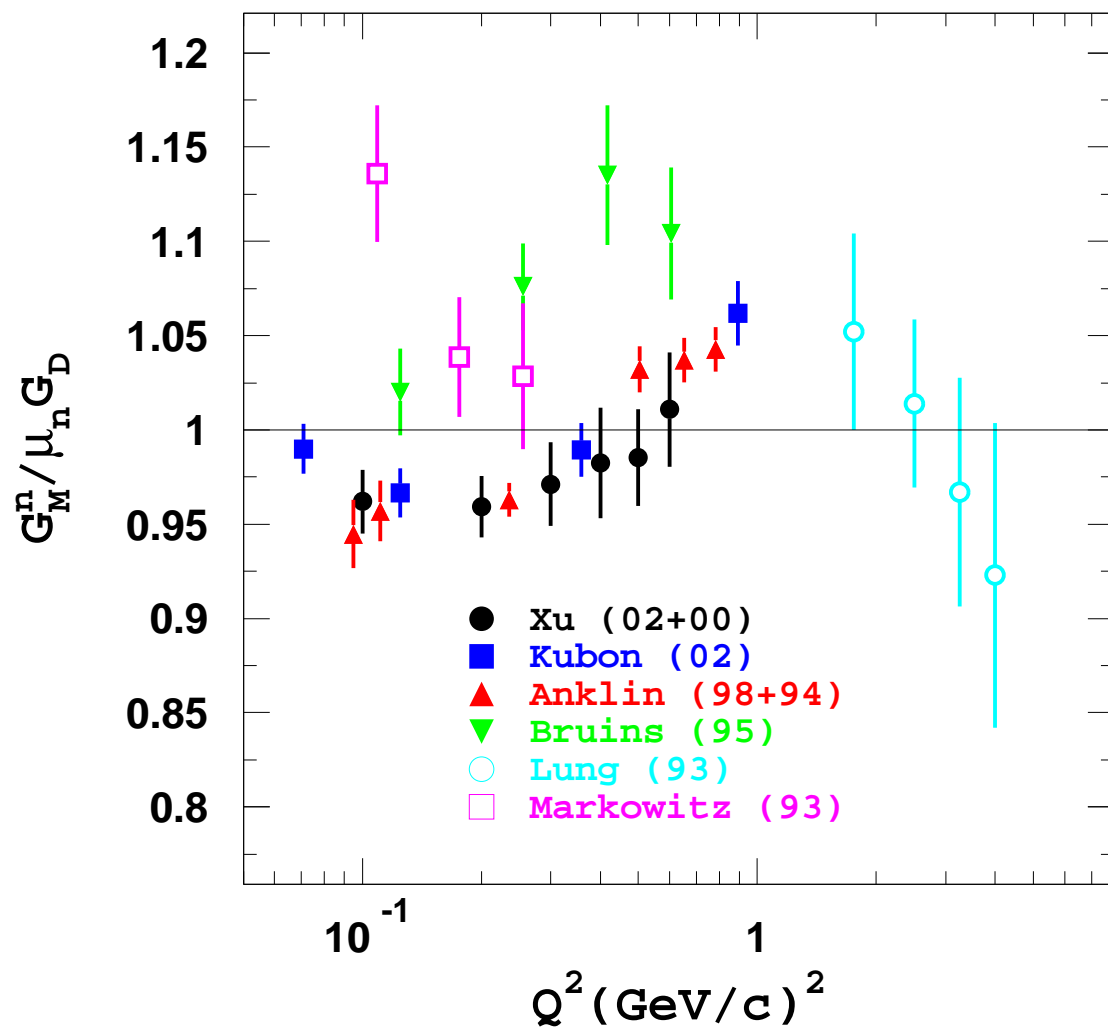
G_M^n unpolarized



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

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

G_M^n unpolarized and polarized



Kubon	ratio
Anklin	ratio
Bruins	ratio
Lung	$D(e, e')X$
Markowitz	$D(e, e'n)p$
Xu	$\overrightarrow{^3\text{He}}(\vec{e}, e')X$

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

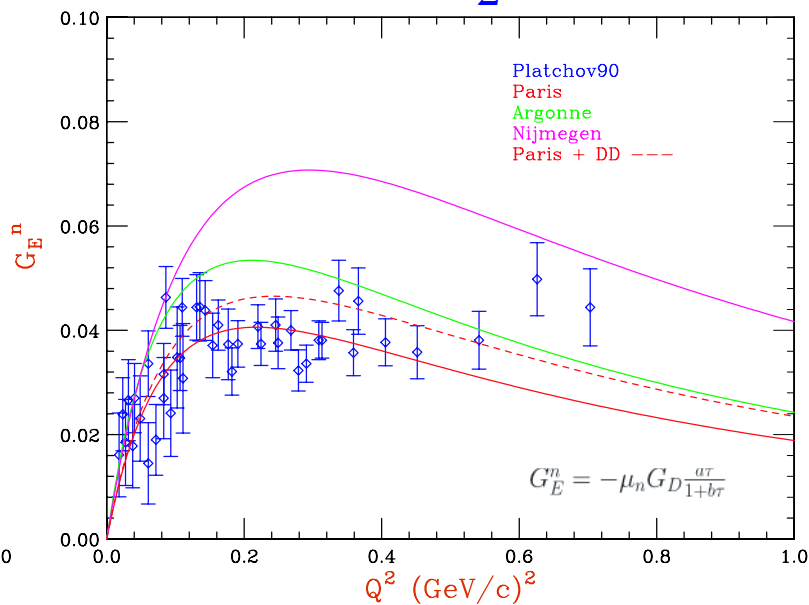
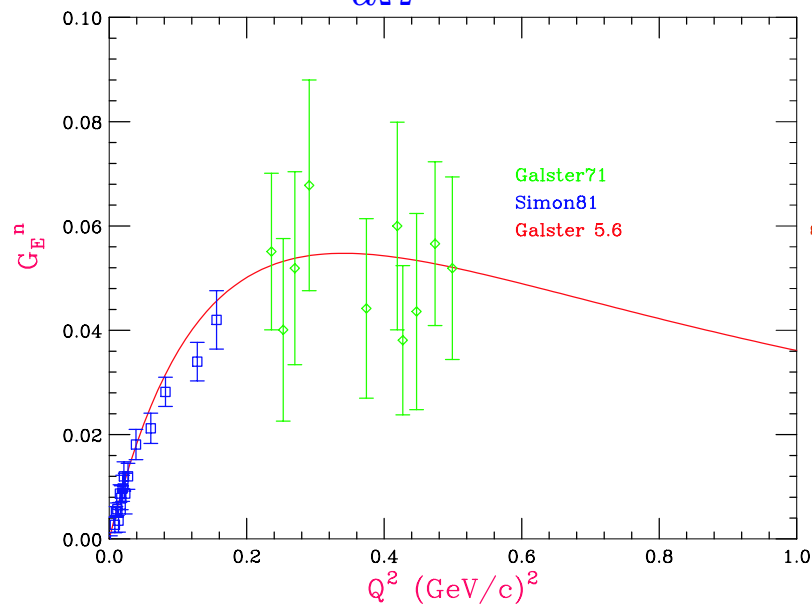
G_E^n Before Polarization

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

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

small θ_e approximation

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



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

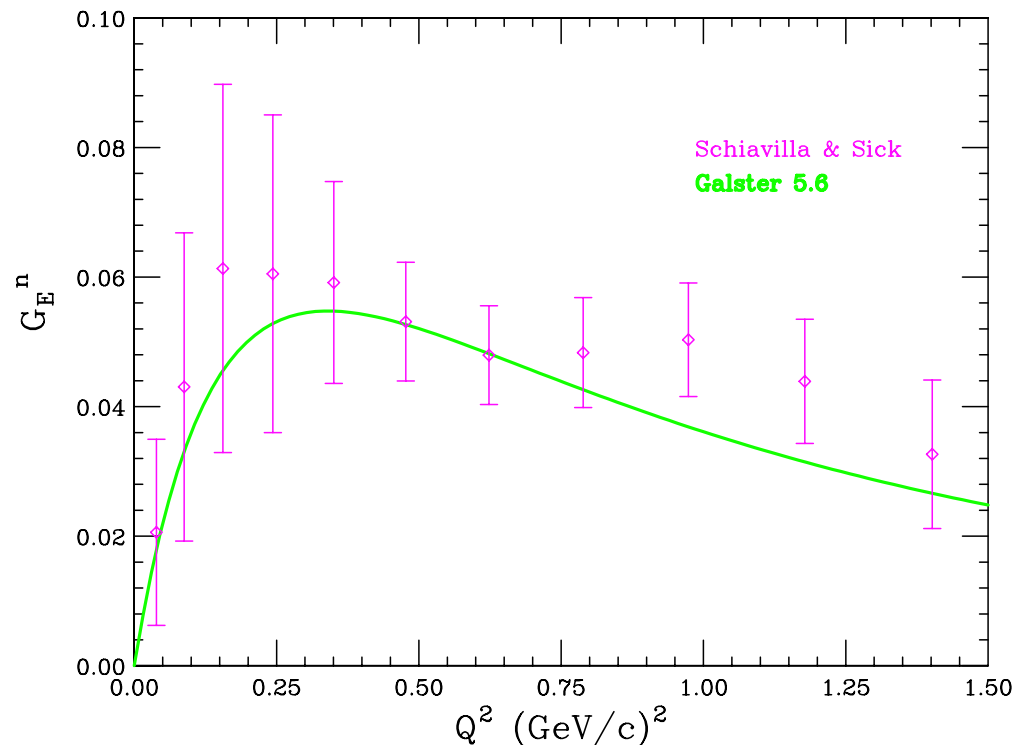
G_E^n from Elastic Scattering – D($e, e'\vec{d}$)

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

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

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!!



G_E^n at large Q^2 through ${}^2\text{H}(e, e')X$

PWIA model σ is incoherent sum of p and n cross section folded with deuteron structure.

$$\begin{aligned}\sigma &= (\sigma_p + \sigma_n) I(u, w) \\ &= \varepsilon R_L + R_T\end{aligned}$$

* Extraction of G_E^n :

Rosenbluth Separation $\Rightarrow R_L$

Subtraction of proton contribution

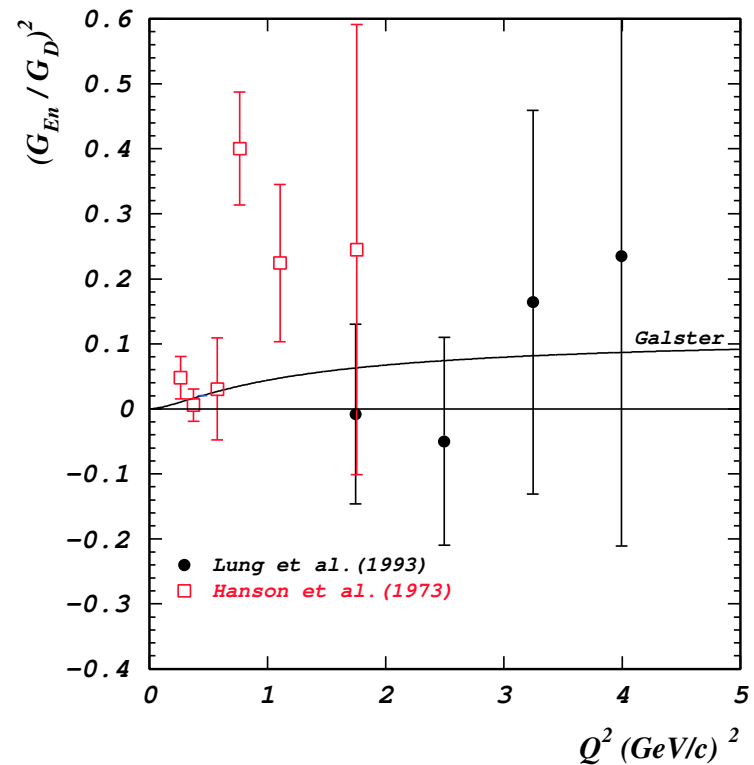
* Problems:

Unfavorable error propagation

Sensitivity to deuteron structure

SLAC: A. Lung et al, PRL. 70, 718 (1993)

\rightarrow No indication of non-zero G_E^n



If G_E^n is small at large Q^2 then F_1^n must cancel τF_2^n , begging the question, how does F_1^n evolve from 0 at $Q^2 = 0$ to cancel τF_2^n at large Q^2 ?

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

$$F_2 \propto F_1 \left(\frac{M}{Q^2} \right) \text{ helicity conservation}$$

$$\text{Counting rules: } F_1 \propto \frac{\alpha_s^2(Q^2)}{Q^4}$$

$$Q^2 F_2 / F_1 \rightarrow \text{constant}$$

$$\text{JLAB proton data: } Q F_2 / F_1 \rightarrow \text{constant}$$

Hybrid VMD-pQCD

GK, Lomon

Lattice

Dong .. (1998)

RCQM

point form (Wagenbrunn..)

light front (Cardarelli ..)

di-quark

Kroll ...

CBM

Lu, Thomas, Williams (1998)

LFCBM

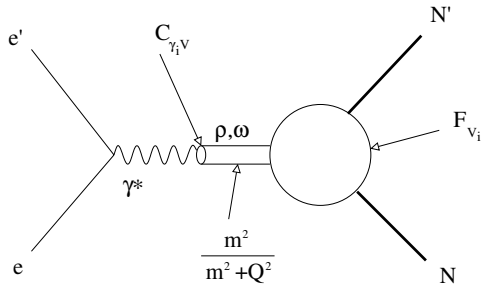
Miller

Helicity non-conservation

pQCD (Ralston..) LF (Miller..)

Theoretical Models

Vector Meson Dominance



Interaction in terms of coupling strengths of virtual photon and vector mesons and vector mesons and nucleon. Success at low and moderate Q^2 offset by failure to accommodate pQCD.

pQCD

High Q^2 helicity conservation requires that $Q^2 F_1 / F_2 \rightarrow \text{constant}$ as F_2 helicity flip arises from second order corrections and are suppressed by an additional factor of $1/Q^2$. Furthermore for $Q^2 \gg \Lambda_{QCD}$ counting rules find $F_1 \propto \alpha_s (Q^2)^2 / Q^4$. Thus $F_1 \propto \frac{1}{Q^4}$ and $F_2 \propto \frac{1}{Q^6} \Rightarrow Q^2 \frac{F_2}{F_1} \rightarrow \text{constant}$.

Lattice calculations of form factors

Fundamental but limited in stat. accuracy

Dong *et al* PRD58, 074504 (1998)

QCD based Models

Try to capture aspects of QCD

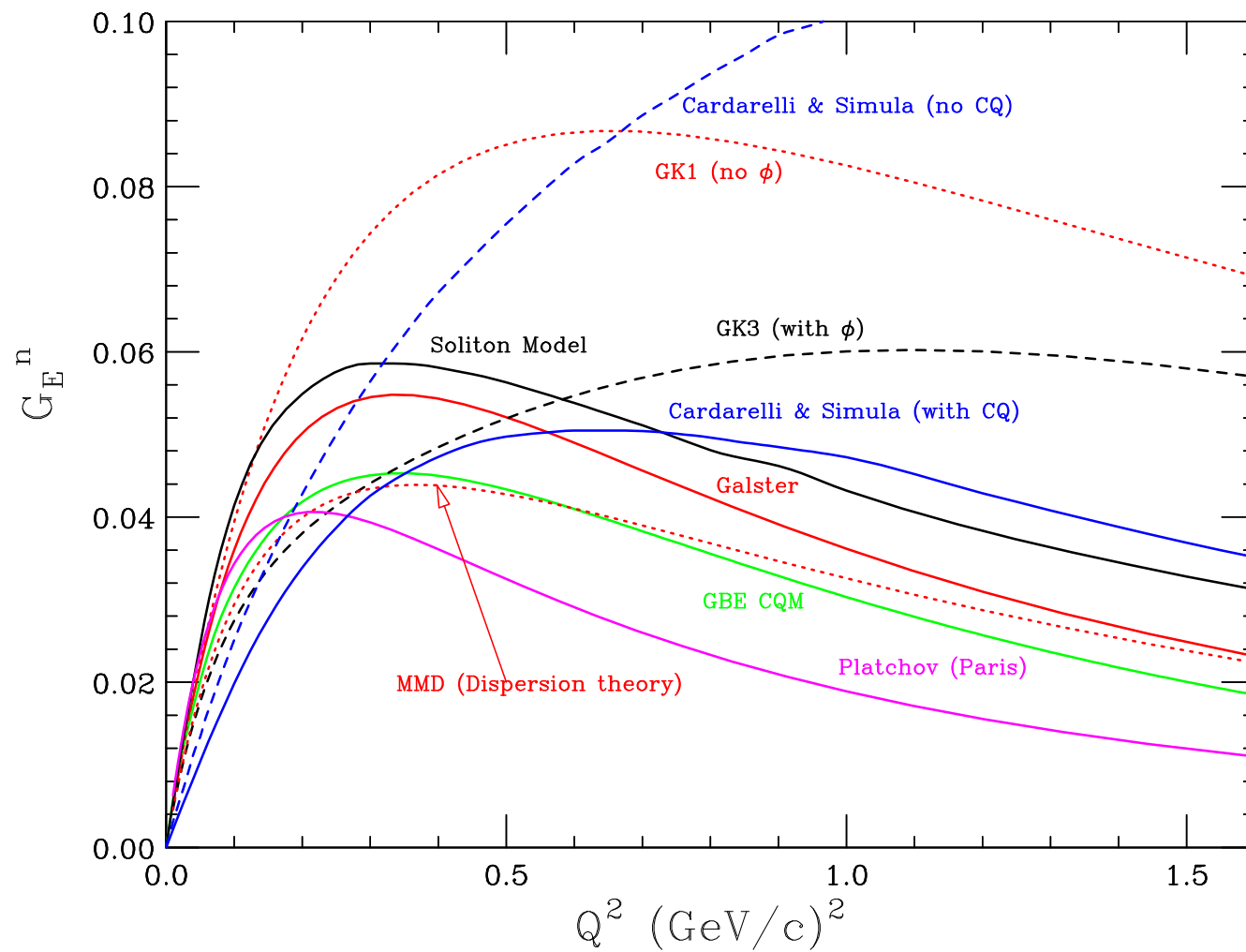
RCQM, Di-quark model, CBM

Hybrid Models

Failure to follow the high Q^2 behavior suggested by pQCD led GK to incorporate pQCD at high Q^2 with the low VMD behavior. Inclusion of ϕ by GK had significant effect on G_E^n . Lomon has updated with new fits to selected data.

Helicity non-conservation shows up in the light front dynamics analysis of Miller which predicted $Q \frac{F_2}{F_1} \rightarrow \text{constant}$ and the violation of helicity conservation. Ralston's pQCD model also predicts that $Q \frac{F_2}{F_1} \rightarrow \text{constant}$. Both models include quark orbital angular momentum.

Theoretical Models



Spin Correlations in elastic scattering

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

Essential statement

Exploit spin degrees of freedom

- * $\mathcal{O} \propto G_E \times G_M$ instead of $\mathcal{O} \propto G_E^2 + G_M^2$

Early work at Bates, Mainz

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

Neutron Form Factors

Polarized Beam

Unpolarized Beam

Spin
Correlations

Cross Section
Measurements

Recoil
Polarimetry

Beam-Target
Asymmetry

Ratio
Method

Quasielastic
eD

Elastic eD

$$D(\vec{e}, e' \vec{n})_p$$

$$\vec{D}(\vec{e}, e' n)_p$$

$${}^3\text{He}(\vec{e}, e')_X$$

$$\frac{D(e, e' n)_p}{D(e, e' p)_n}$$

$$D(e, e')_X$$

$$D(e, e')$$

$$D(e, e' \vec{d})$$

$$G_E^n$$

$$G_E^n$$

$$G_M^n$$

$$G_M^n$$

$$G_E^n$$

$$G_M^n$$

$$G_E^n$$

$$G_M^n$$

$$G_E^n$$

$${}^3\text{He}(\vec{e}, e' n)_{pp}$$

$$G_M^n$$

$$G_M^n$$

$$G_M^n$$

$$G_M^n$$

$$G_E^n$$

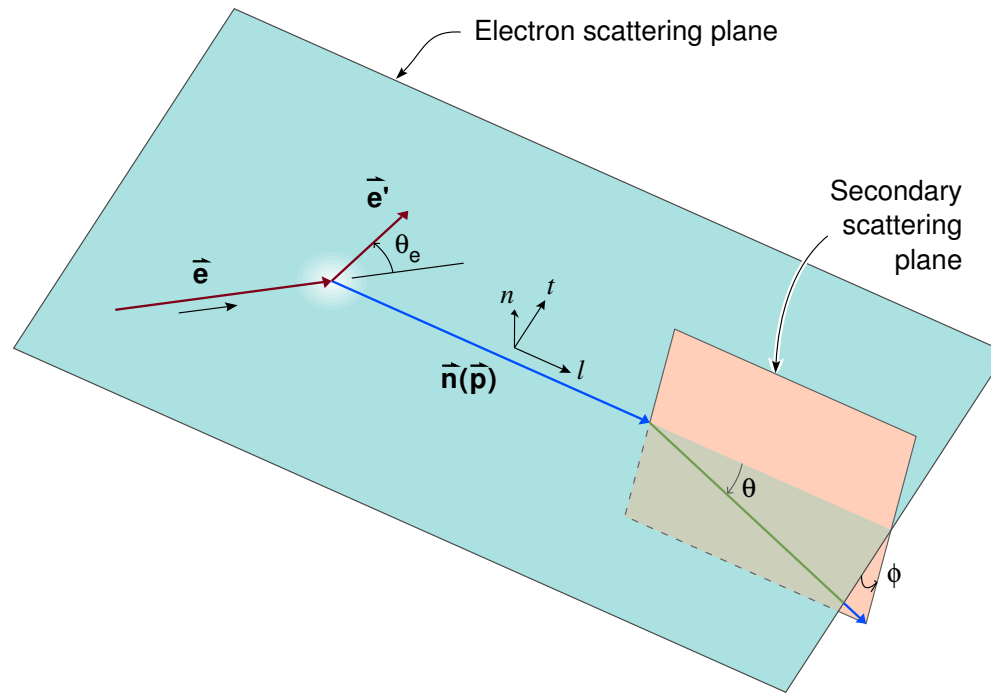
G_E^n from spin observables

No free neutron targets – scattering from ^2H or ^3He – 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. **Detect neutron**.

- * **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. **Monte Carlo**
- * **Polarized targets**
 - The deuteron and ^3He only **approximate** a polarized neutron
 - Scattering from other unpolarized materials, f dilution factor

Recoil Polarization



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

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

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

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

Recoil Polarization – Principle and Practice

- * Interested in transferred 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 with \vec{B} normal to scattering plane):

$$P_t^{\text{pol}} = \sin \chi \cdot P_l + \cos \chi \cdot P_t$$

For $\chi = 90^\circ$, $P_t^{\text{pol}} = P_l$ and is related to G_M^2

For $\chi = 0^\circ$, $P_t^{\text{pol}} = P_t$ and is related to $G_E G_M$

- * G_E^n/G_M^n via ${}^2\text{H}(\vec{e}, e'\vec{n})p$ in JLAB's Hall C - Charybdis and N-Pol

Quality of polarimeter data optimized by taking advantage of **proper flips** (helicity reversals).

$$L_1 = N_o[1 + pA_y(\theta + \alpha)]$$

$$R_2 = N_o[1 - pA_y(\theta + \beta)]$$

$$R_1 = N_o[1 - pA_y(\theta + \alpha)]$$

$$L_2 = N_o[1 + pA_y(\theta + \beta)]$$

Using the geometric means, $L \equiv \sqrt{L_1 L_2}$ and $R \equiv \sqrt{R_1 R_2}$, the false (instrumental) asymmetries, α and β , cancel.

$$\xi = pA_y = \frac{L - R}{L + R}$$

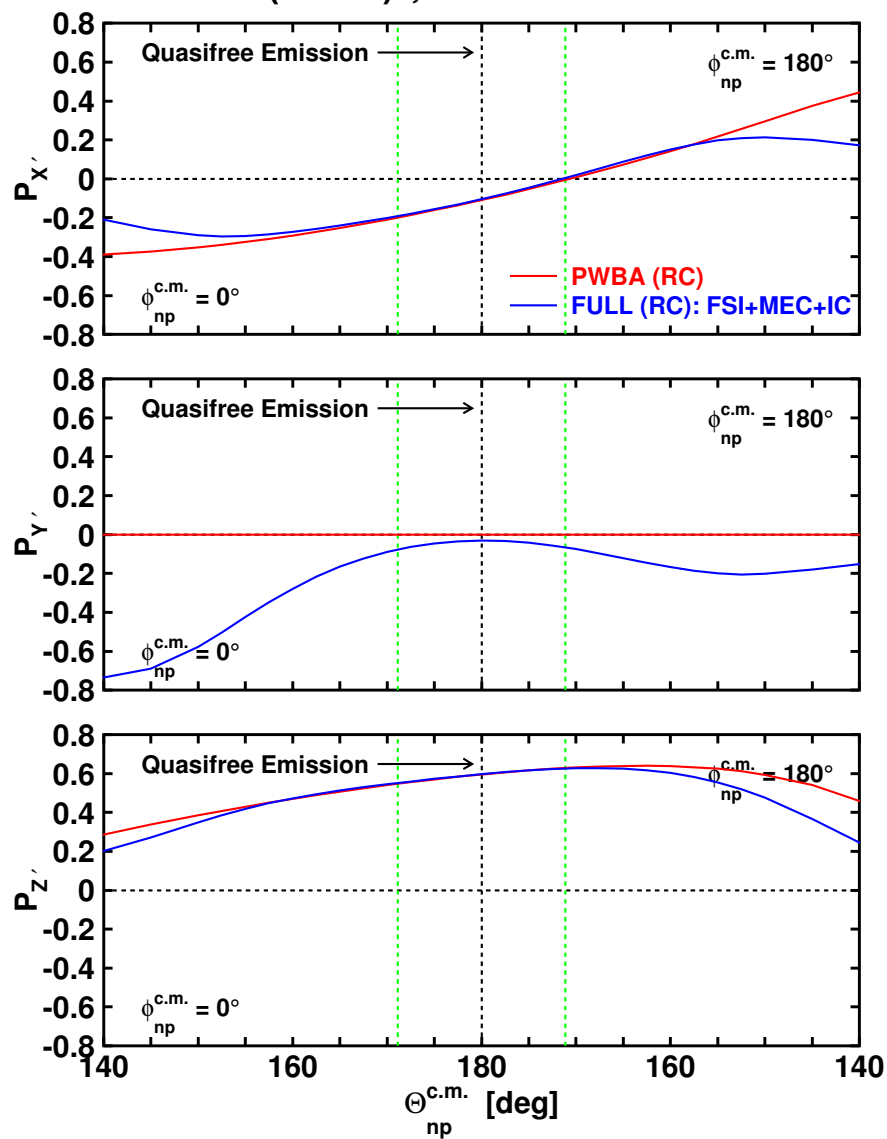
G_E^n in Hall C, E93-038

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

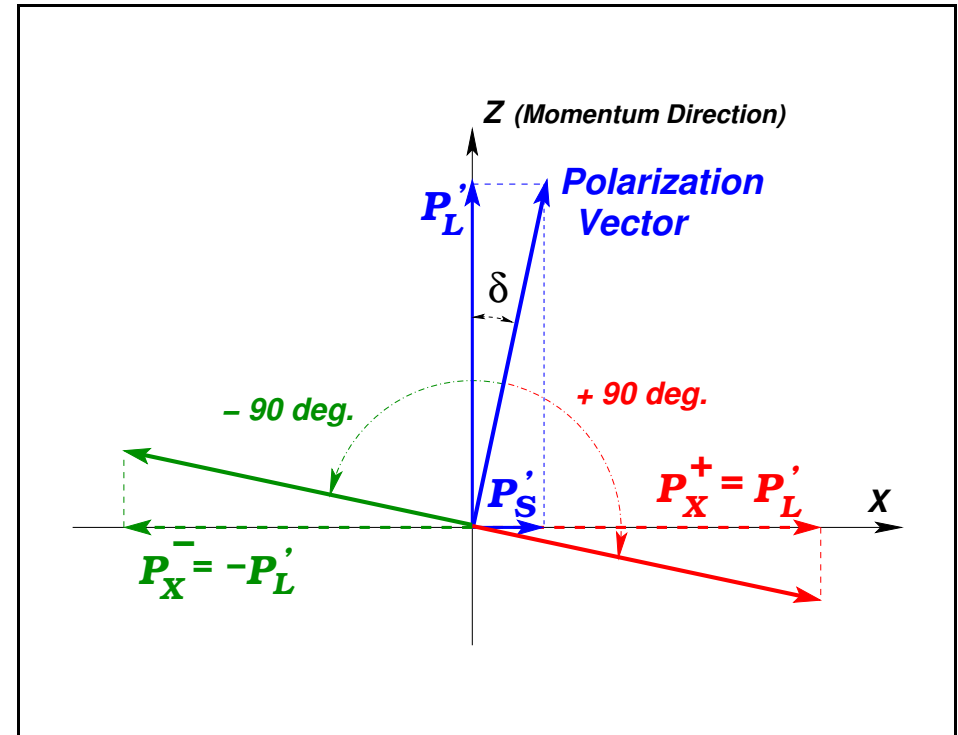
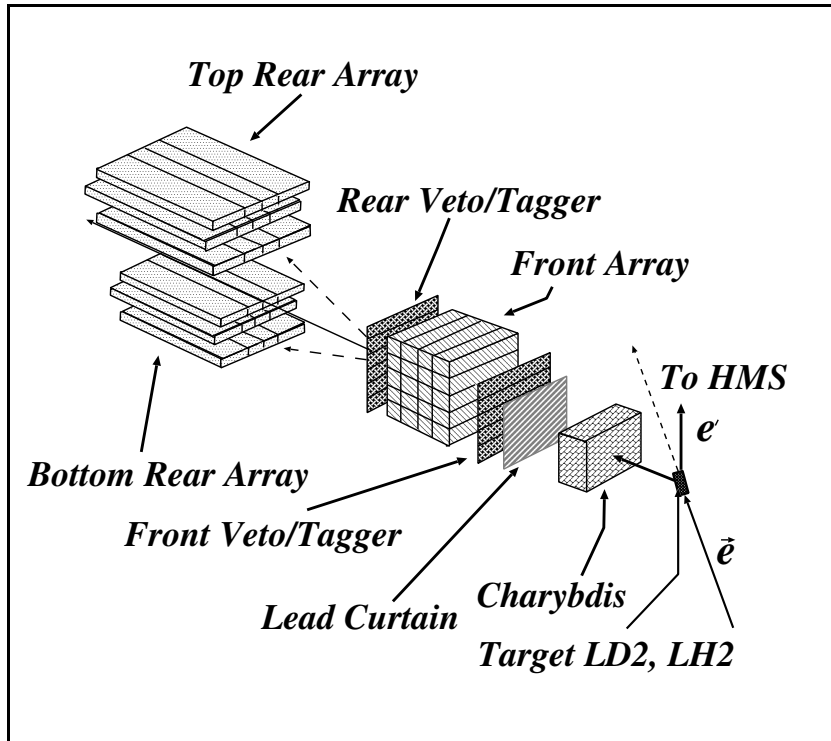
- * In quasifree kinematics, $P_{s'}$ is sensitive to G_E^n and insensitive to nuclear physics
- * Up-down asymmetry $\xi \Rightarrow$ transverse (sideways) polarization
 $P_{s'} = \xi_{s'} / P_e A_{\text{pol}}$. Requires knowledge of P_e and A_{pol}
- * Rotate the polarization vector in the scattering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

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

$E_e = 0.884 \text{ GeV}$; $E_{e'} = 0.643 \text{ GeV}$; $\Theta_{e'} = 52.65^\circ$;
 $Q^2 = 0.45 \text{ (GeV/c)}^2$; Galster Parameterization

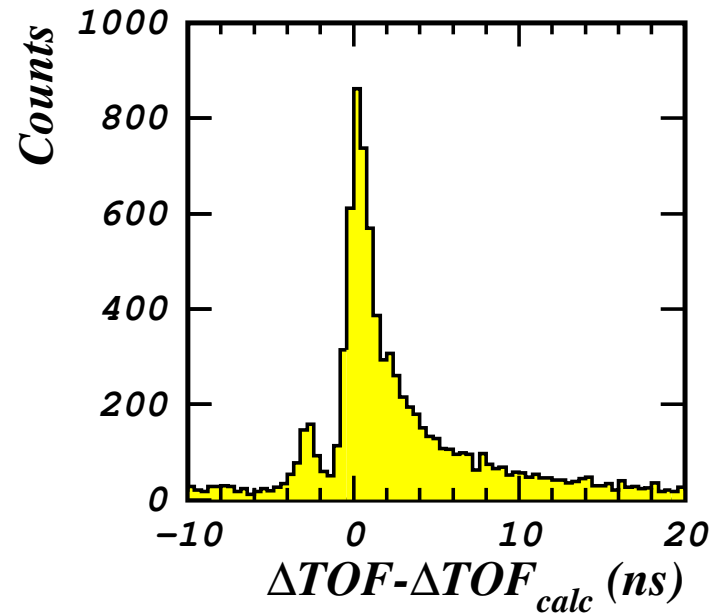
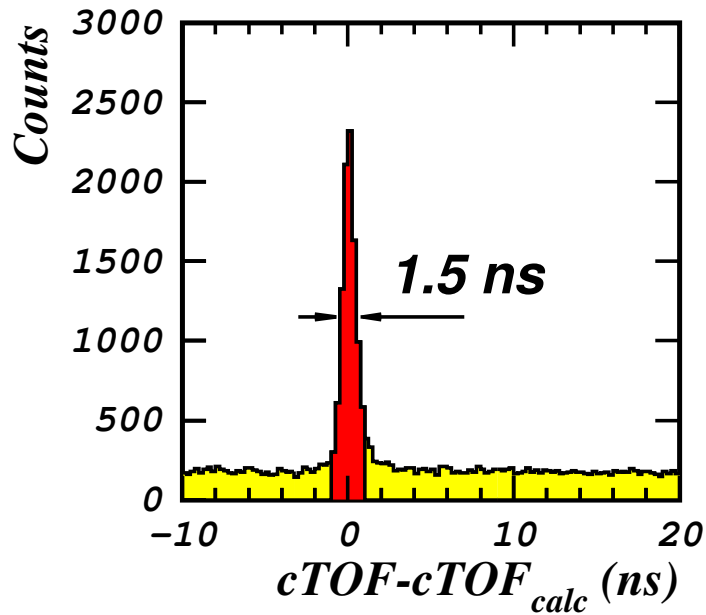


G_E^n in Hall C via ${}^2\text{H}(\vec{e}, e'\vec{n})p$



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

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



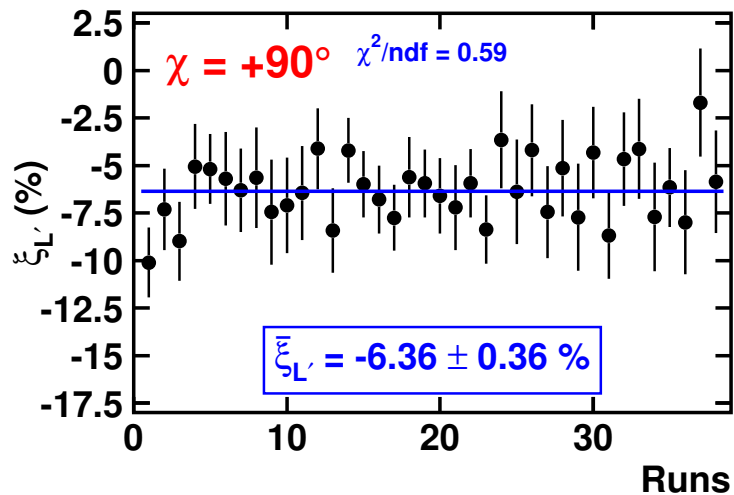
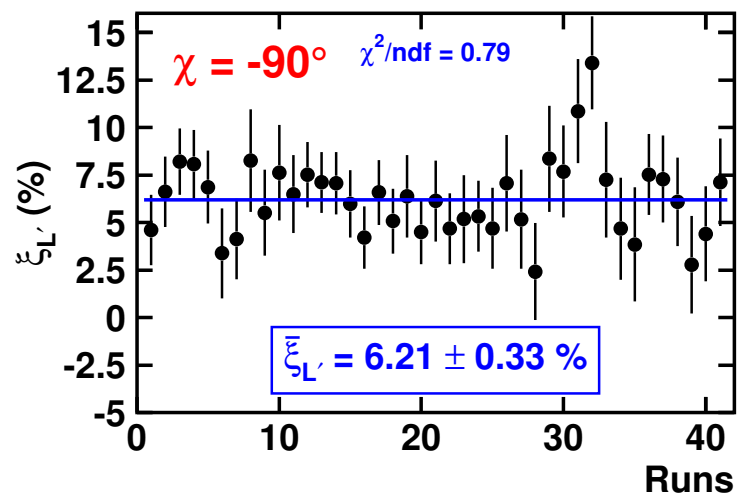
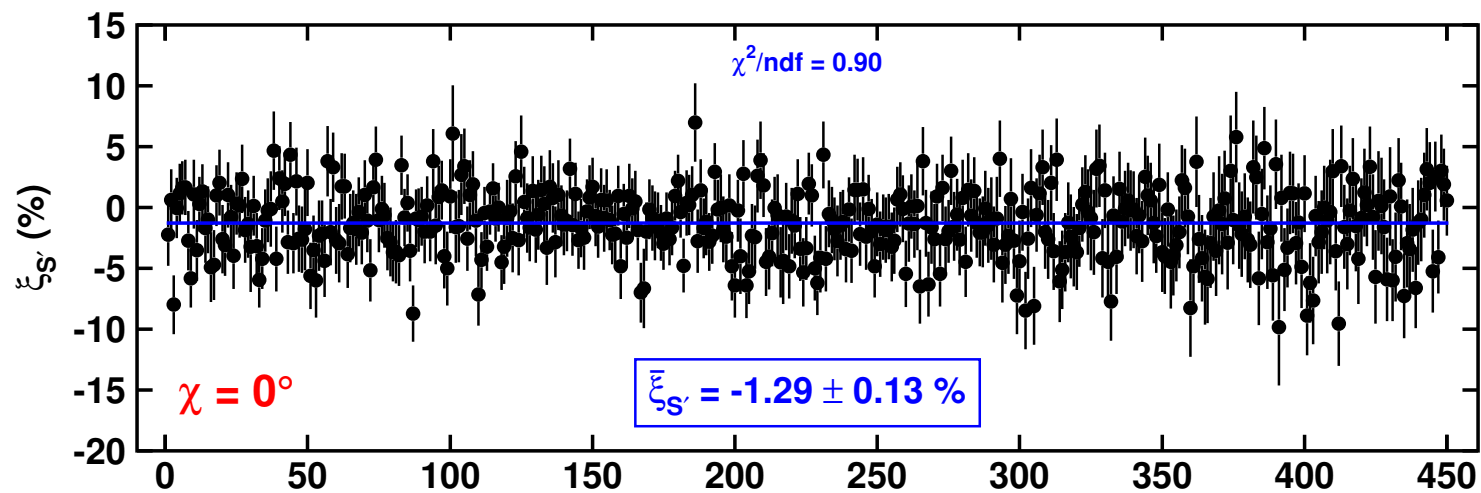
Left: Coincidence TOF for neutrons. Difference between measured TOF and calculated TOF assuming quasi-elastic neutron. **Right:** ΔTOF for neutron in front array and neutron in rear array.

ΔTOF is kept as the four combinations of $(-,+)$ helicity, and (Upper,Lower) detector and cross ratios formed. False asymmetries cancel.

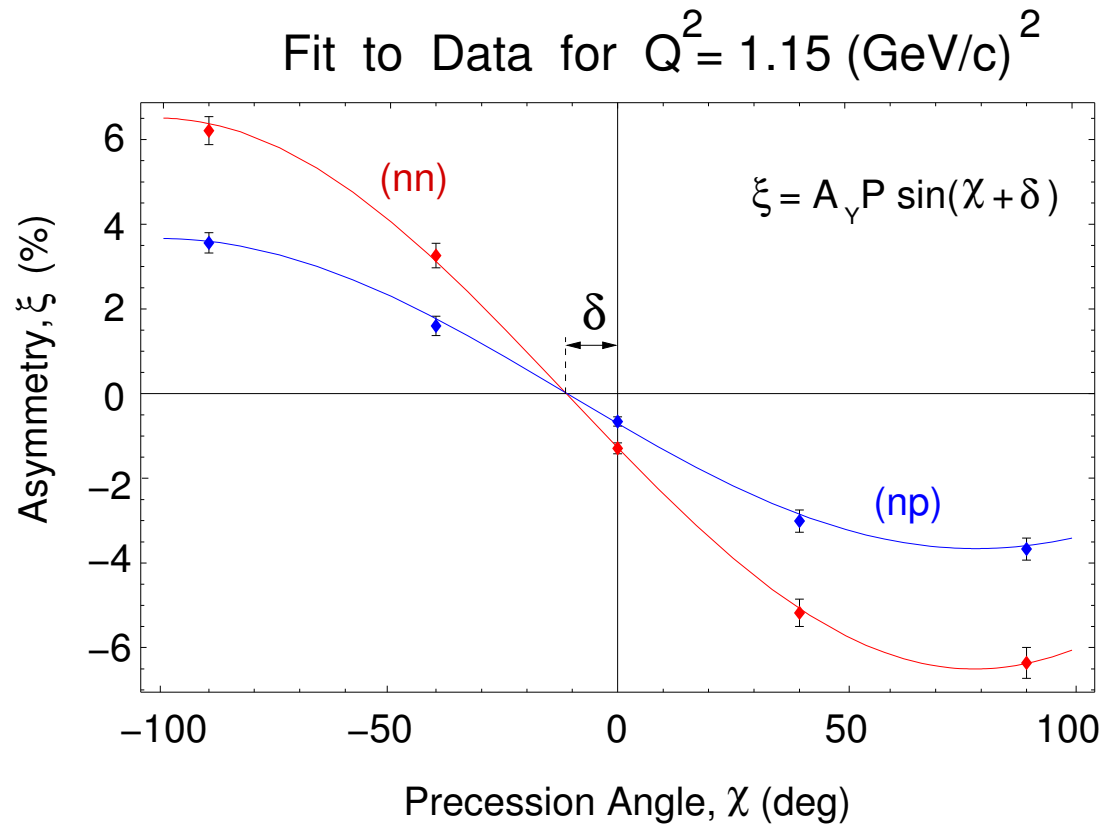
$$r = \left(\frac{N_U^+ N_D^-}{N_U^- N_D^+} \right)^{1/2} \quad \xi = (r - 1)/(r + 1)$$

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

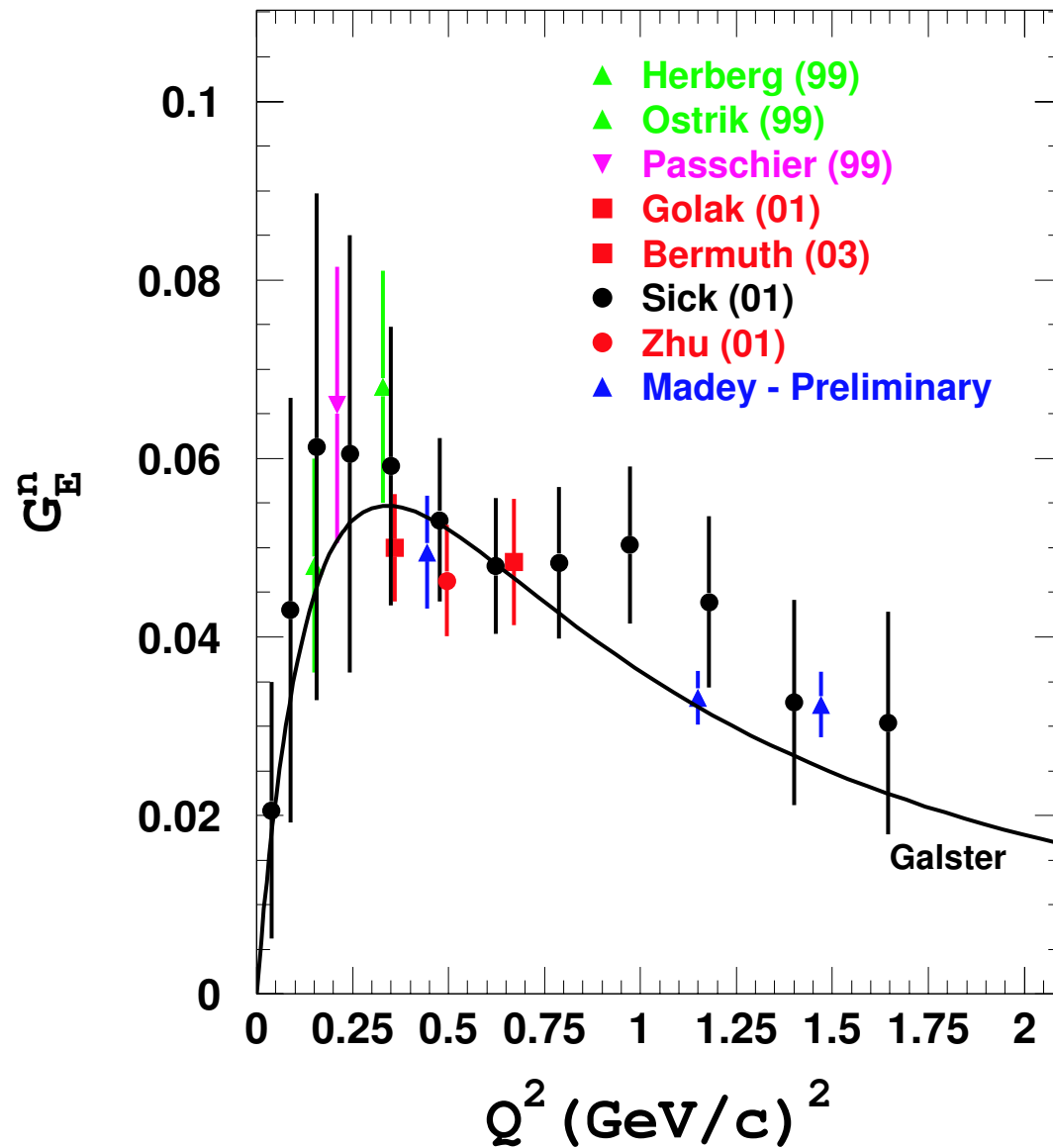
$Q^2 = 1.14 \text{ (GeV/c)}^2$ — (n,n) In Front — $\Delta p/p = -3/+5\%$



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



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



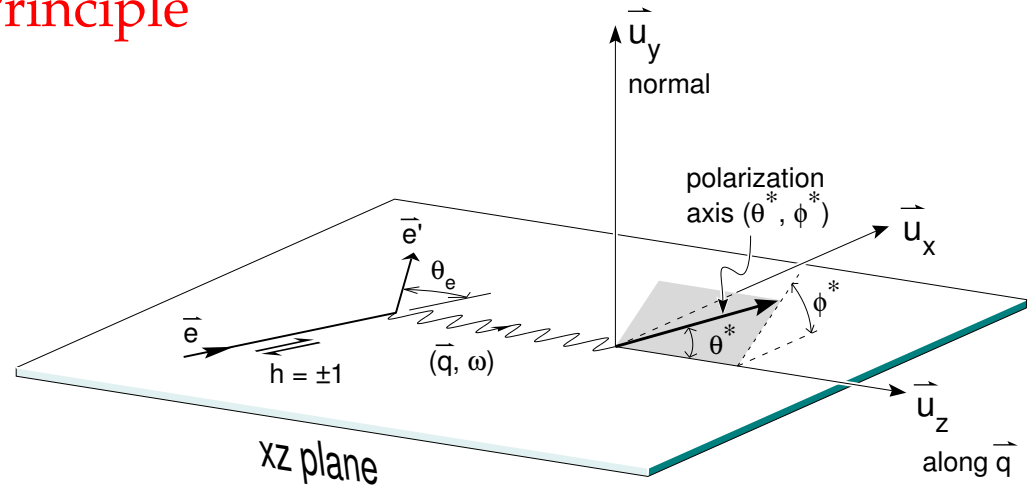
Beam-Target Asymmetry - Principle

Polarized Cross Section:

$$\sigma = \Sigma + h\Delta$$

Beam Helicity $h = \pm 1$

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



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

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

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

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

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

Beam-Target Asymmetry in E93-026

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

$$\sigma(h, P) \approx \sigma_0 (1 + hPA_{ed}^V)$$

h : Beam Helicity

P : Vector Target Polarization

T : Tensor Target Polarization $T = 2 - \sqrt{4 - 3P^2}$

A_d^T is suppressed by $T \approx 3\%$

Theoretical Calculations of electrodisintegration of the deuteron by H. Arenhövel and co-workers

E93-026 $\vec{D}(\vec{e}, e'n)p$

$$\sigma(h, P) = \sigma_0 (1 + hPA_{ed}^V)$$

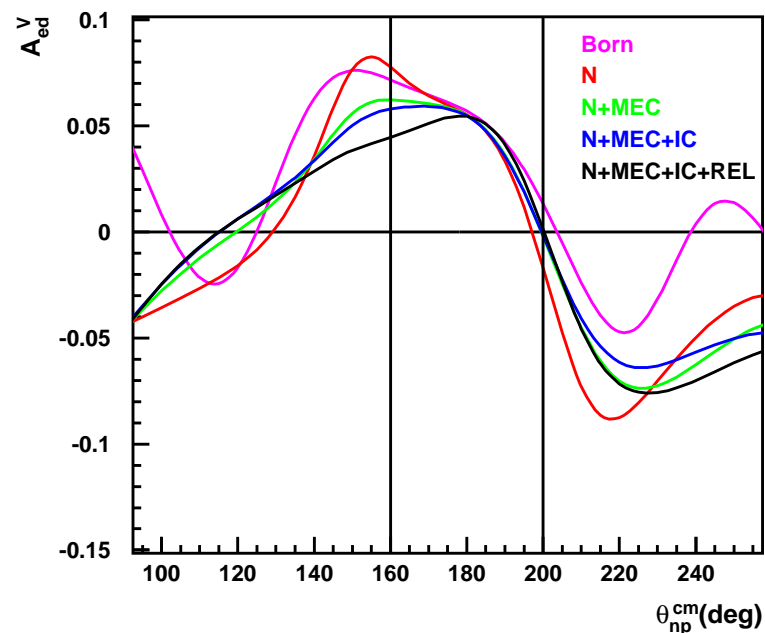
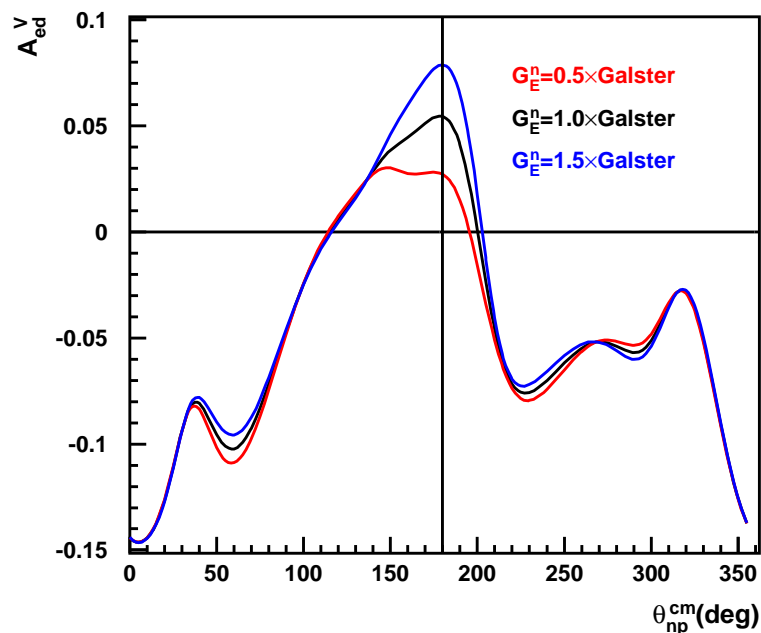
A_{ed}^V is sensitive to G_E^n

has low sensitivity to potential models

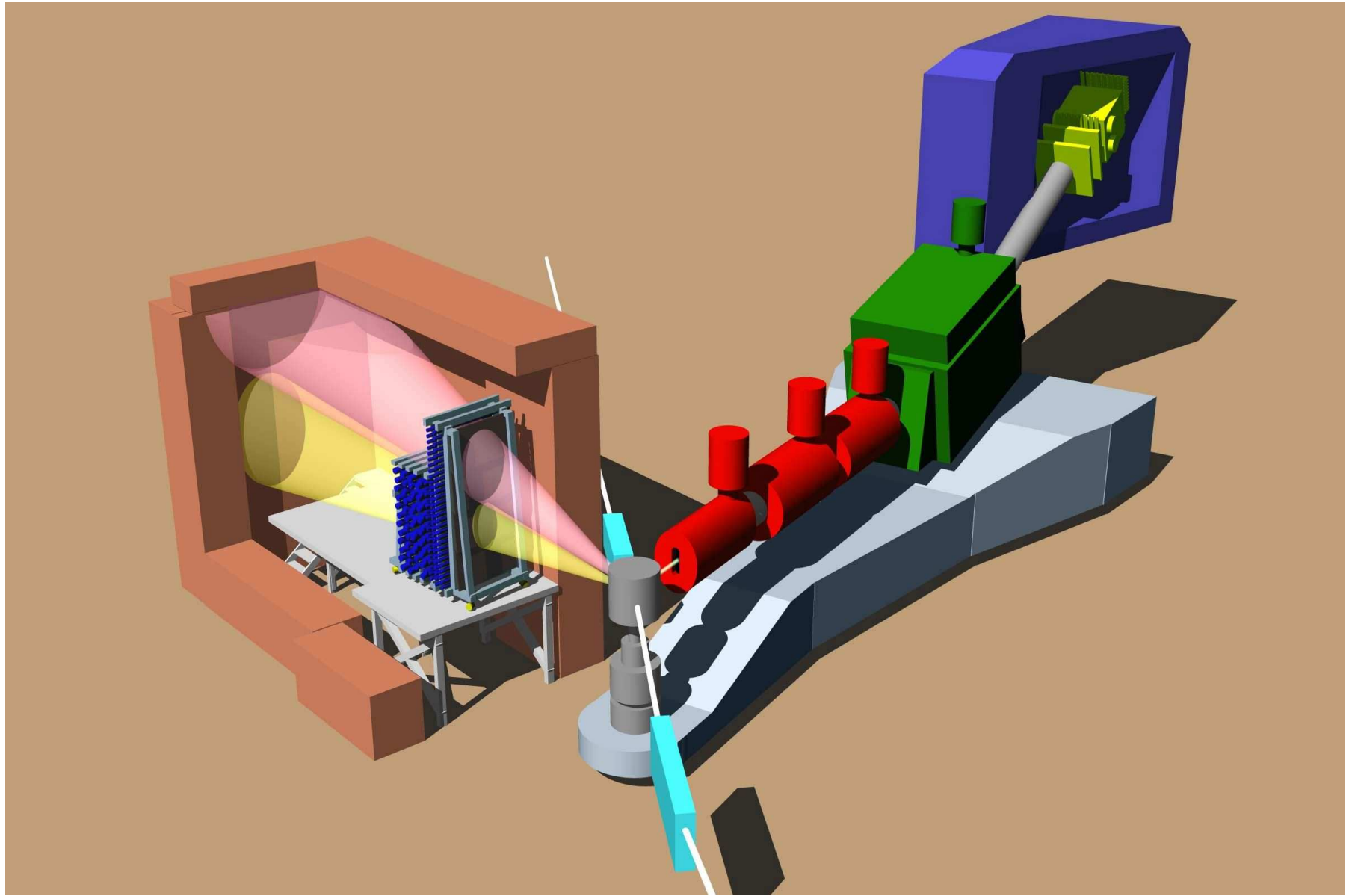
has low sensitivity to subnuclear degrees of freedom (MEC, IC)

in quasielastic kinematics

Sensitivity to G_E^n – Insensitivity to Reaction



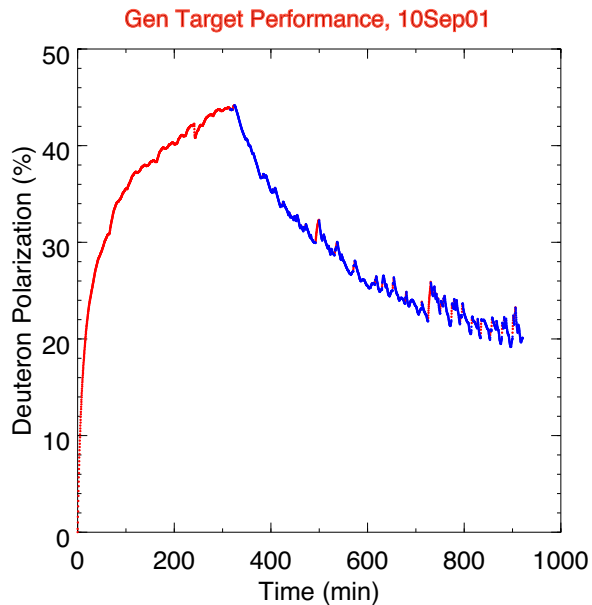
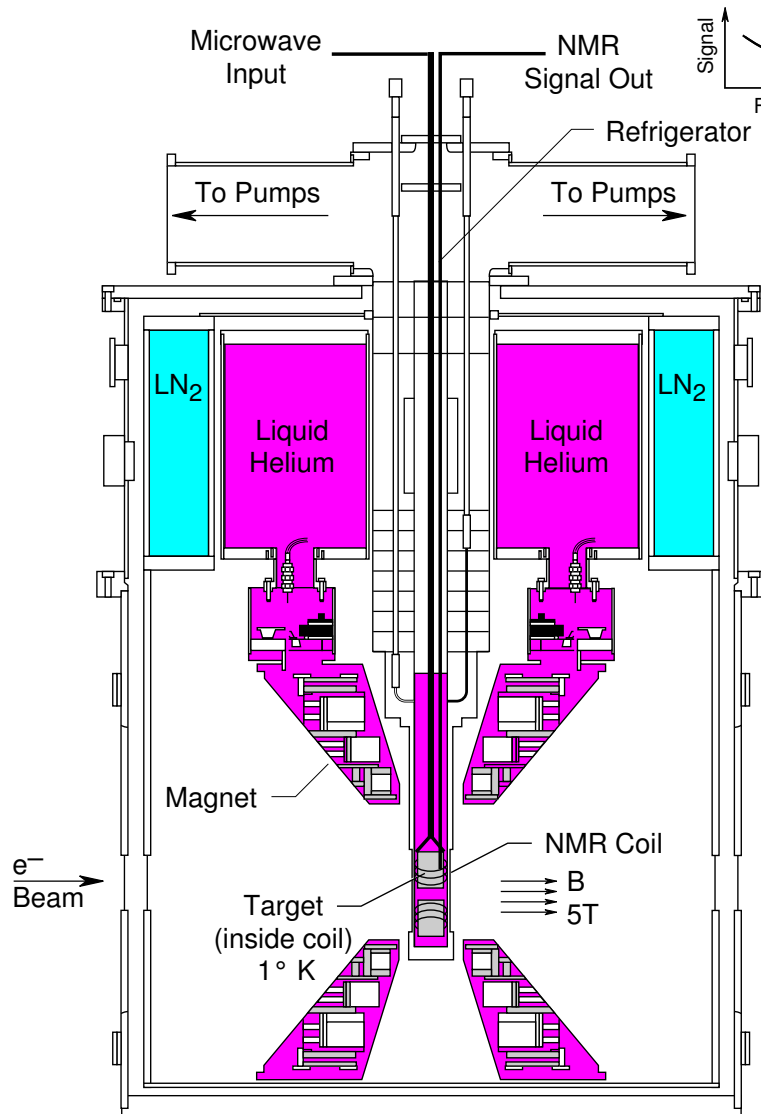
G_E^n in Hall C



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

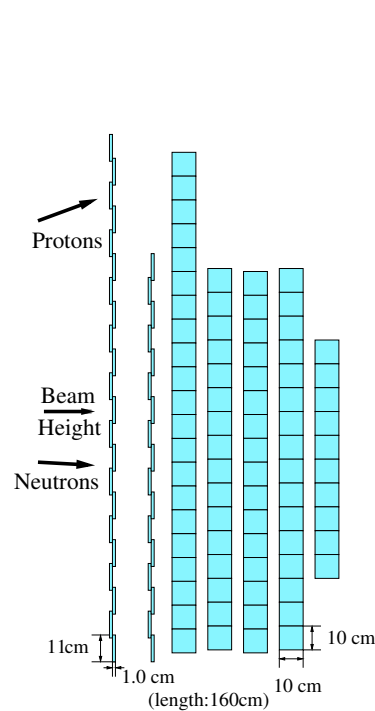
Solid Polarized Targets

- * frozen(doped) $^{15}\text{ND}_3$
- * ^4He evaporation refrigerator
- * 5T polarizing field
- * remotely movable insert
- * dynamic nuclear polarization

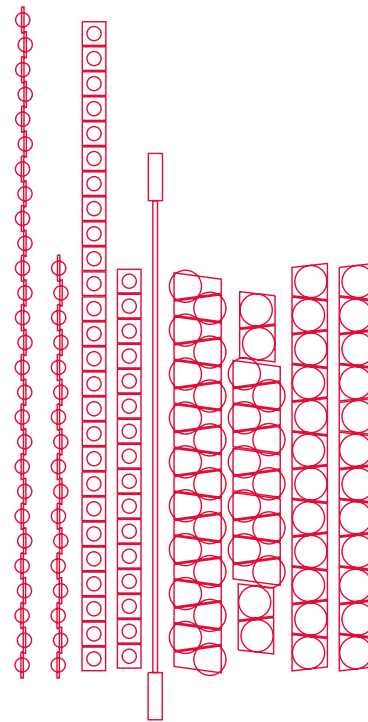


Neutron Detector

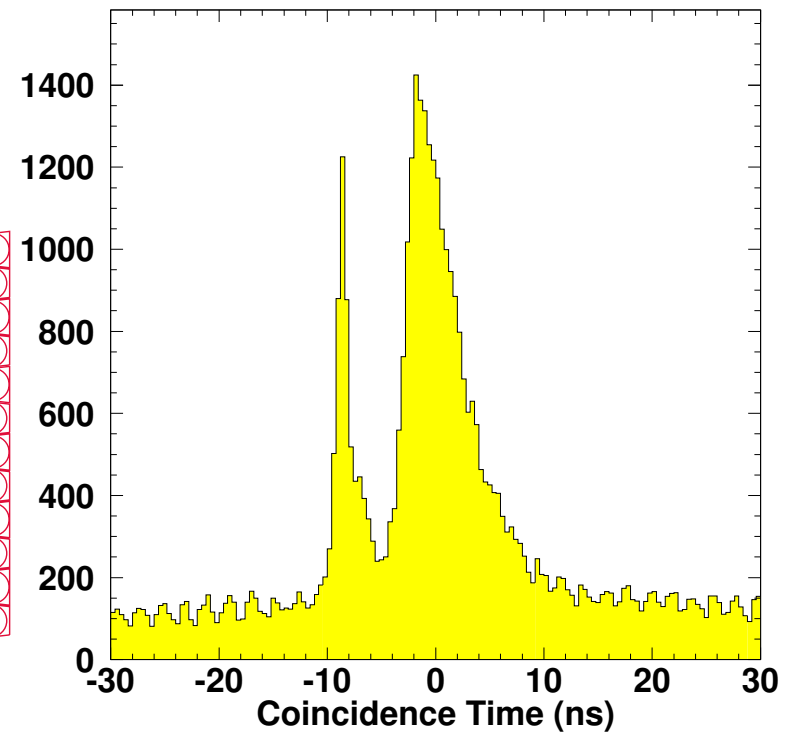
- * Highly segmented scintillator
- * Rates: 50 - 200 kHz per detector
- * Pb shielding in front to reduce background
- * 2 thin planes for particle ID (VETO)
- * 6 thick conversion planes
- * 142 elements total, >280 channels
- * Extended front section for symmetric proton coverage
- * PMTs on both ends of scintillator
- * Spatial resolution $\simeq 10$ cm
- * Time resolution $\simeq 400$ ps
- * Provides 3 space coordinates, time and energy



1998



2001

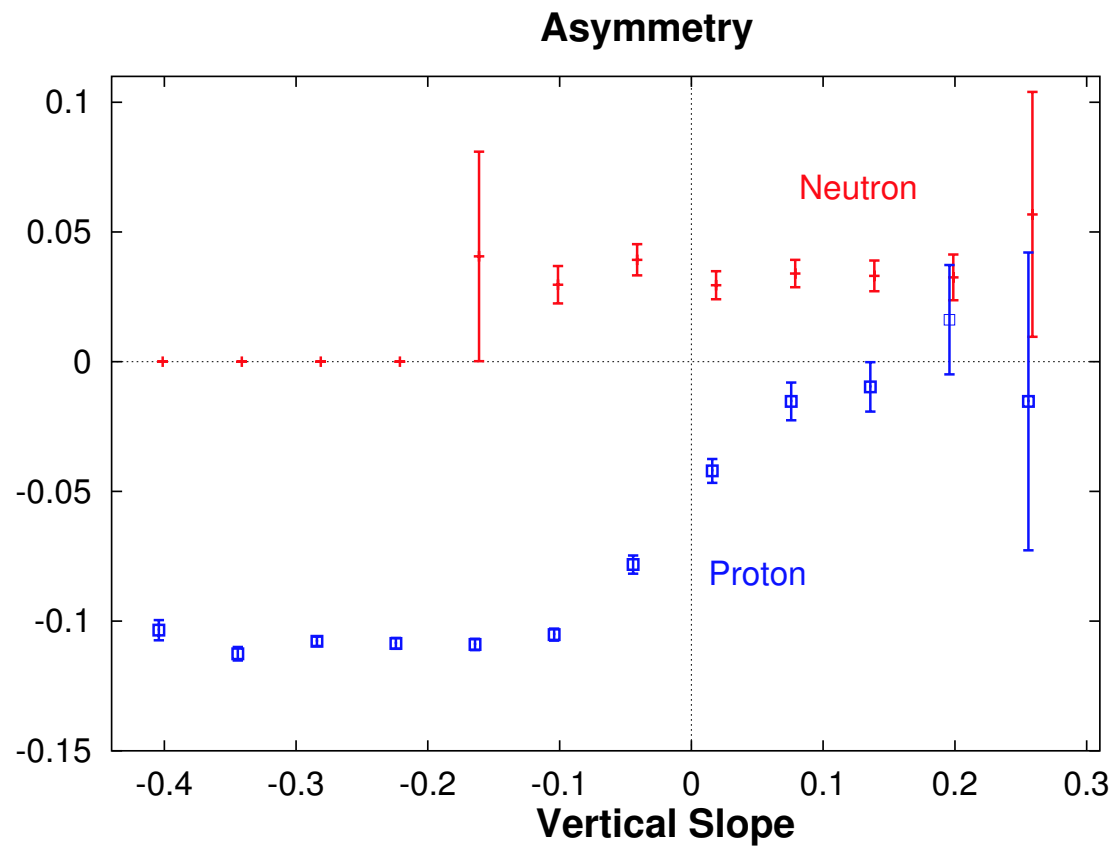


Experimental Technique for $\vec{D}(\vec{e}, e'n)p$

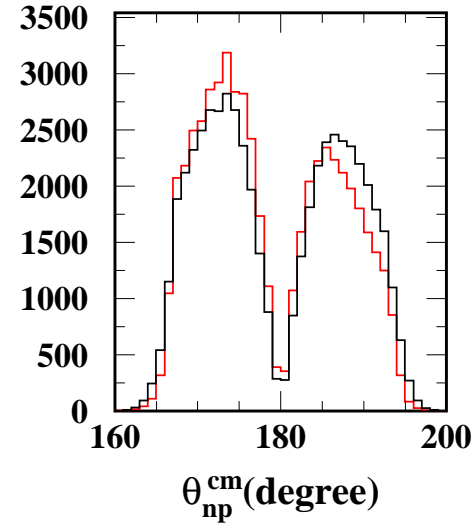
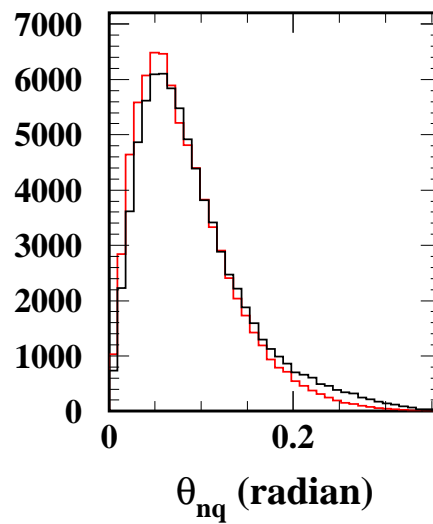
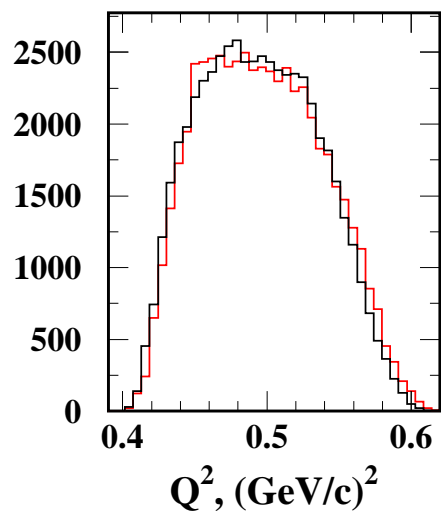
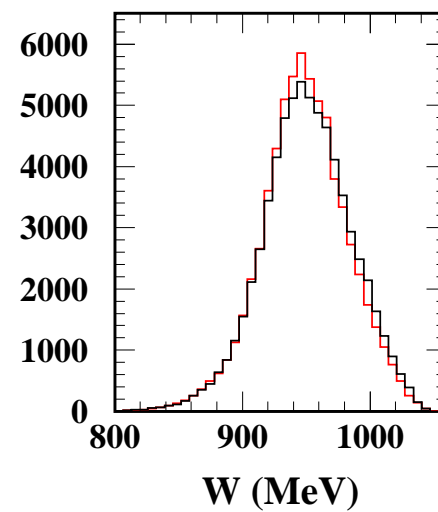
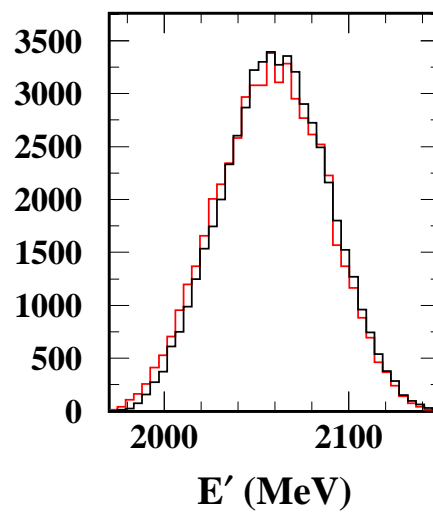
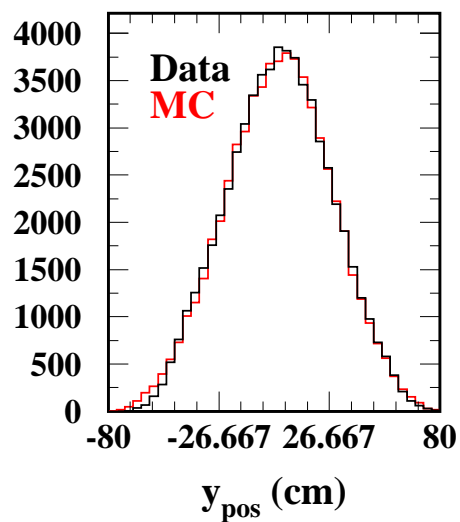
For different orientations of h and P : $N^{hP} \propto \sigma(h, P)$

Beam-target Asymmetry:

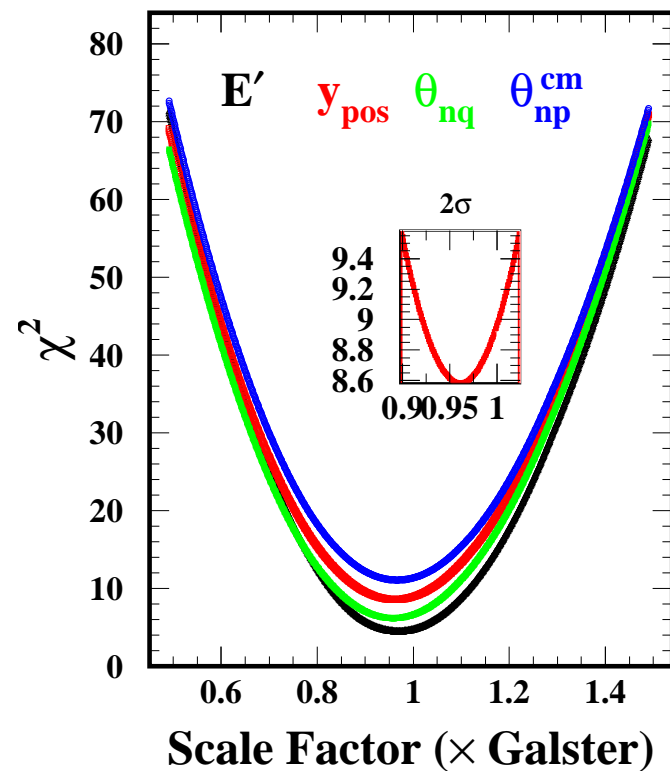
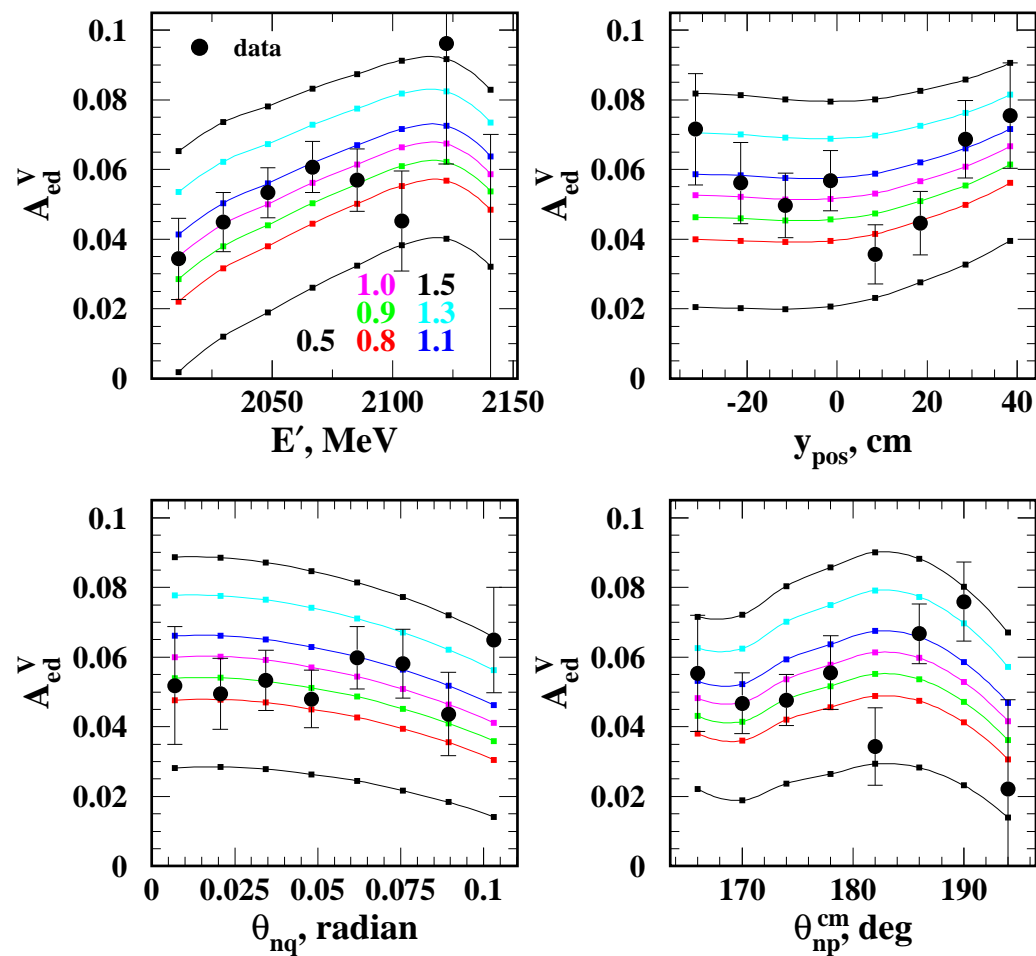
$$\epsilon = \frac{N^{\uparrow\uparrow} - N^{\downarrow\uparrow} + N^{\downarrow\downarrow} - N^{\uparrow\downarrow}}{N^{\uparrow\uparrow} + N^{\downarrow\uparrow} + N^{\downarrow\downarrow} + N^{\uparrow\downarrow}} = hP f A_{ed}^V$$



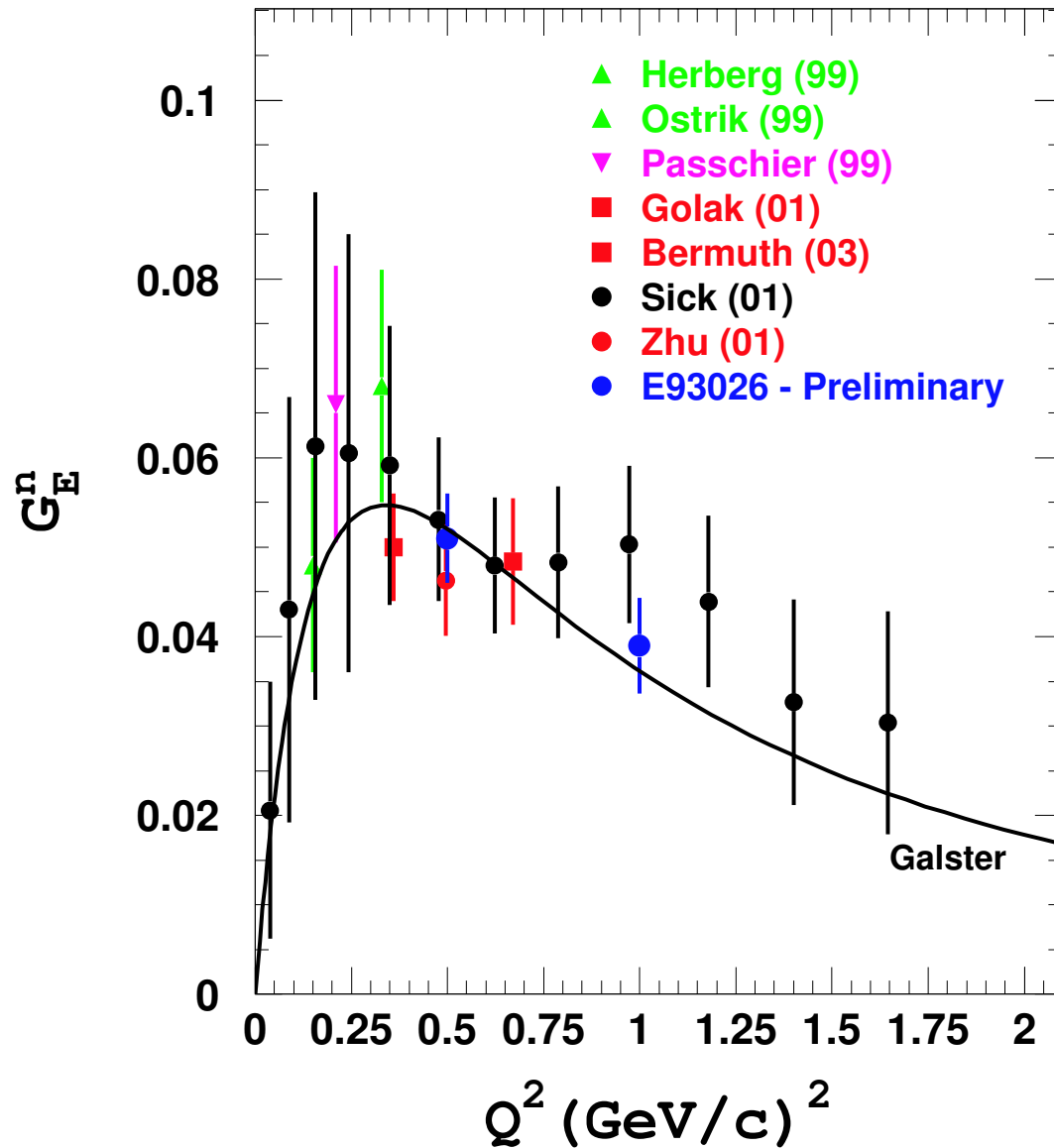
Data and MC Comparison



Extracting G_E^n



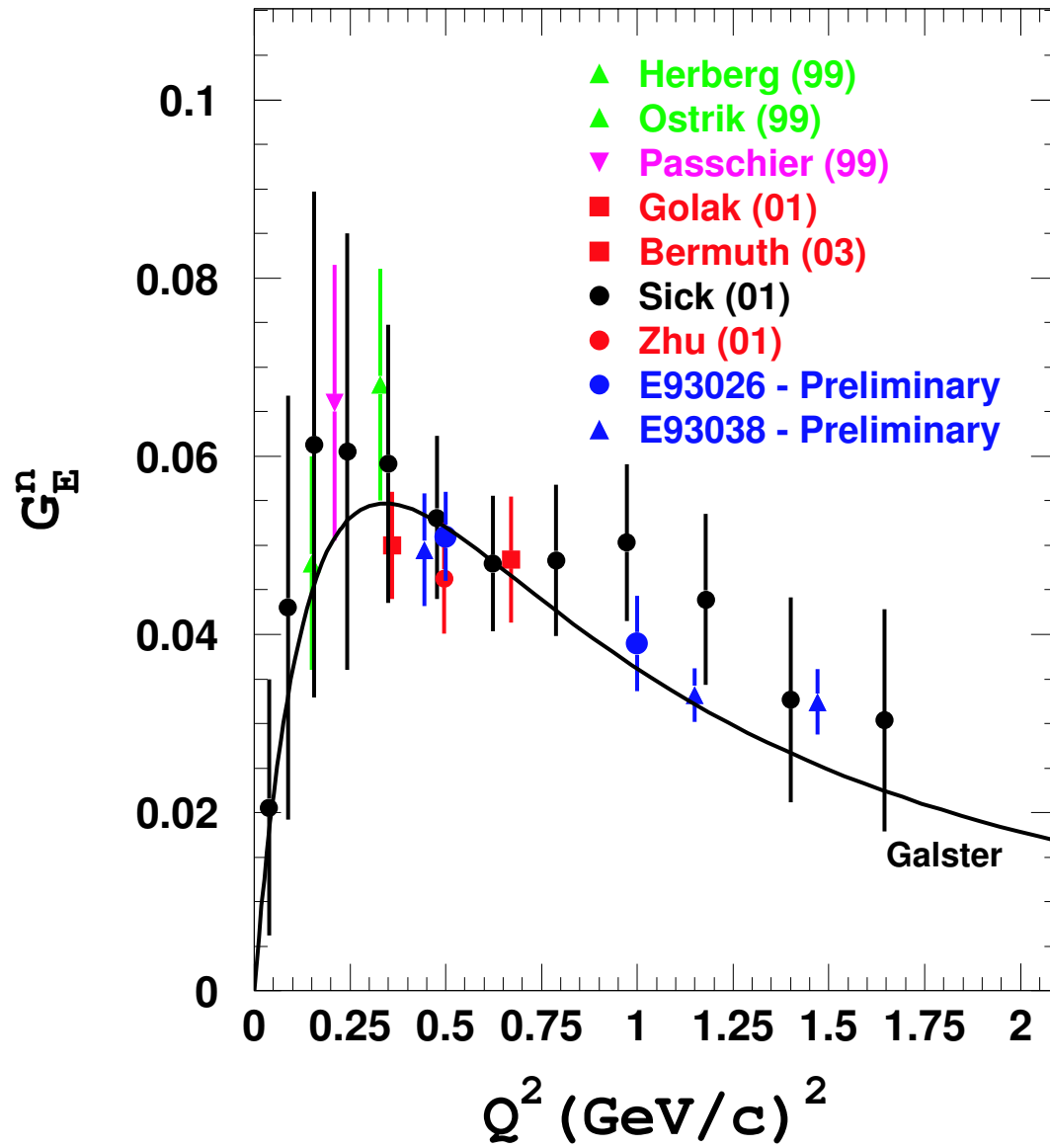
Preliminary results



Systematic
Errors (*included*):

P_{target}	3-5%
f	3%
cuts	2%
kinematics	2%
G_M^n	1.7%
P_{beam}	1-3%
other	1%
total	6-8%

Preliminary results



Laboratory	Collaboration	Q^2 (GeV/c) ²	Reaction	Reported
MIT-Bates	E85-05	0.255	${}^2\text{H}(\tilde{e}, e'n)$	1994
		<0.8	${}^2\tilde{\text{H}}(\tilde{e}, e'n)$	Planned
		<0.8	${}^3\tilde{\text{He}}(\tilde{e}, e'n)$	Planned
Mainz-MAMI	A3	0.31	${}^3\tilde{\text{He}}(\tilde{e}, e'n)$	1994
	A3	0.15, 0.34	${}^2\text{H}(\tilde{e}, e'n)$	1999
	A3	0.385	${}^3\tilde{\text{He}}(\tilde{e}, e'n)$	1999
	A1	0.67	${}^3\tilde{\text{He}}(\tilde{e}, e'n)$	1999/2003
	A1	0.3, 0.6, 0.8	${}^2\text{H}(\tilde{e}, e'n)$	Analysis
NIKHEF		0.21	${}^2\tilde{\text{H}}(\tilde{e}, e'n)$	1999
Jefferson Lab	E93026	0.5, 1.0	${}^2\tilde{\text{H}}(\tilde{e}, e'n)$	2001 / Analysis
	E93038	0.45, 1.15, 1.47	${}^2\text{H}(\tilde{e}, e'n)$	Analysis
	E02013	1.3, 2.4, 3.4	${}^3\tilde{\text{He}}(\tilde{e}, e'n)$	Approved

Conclusions

- * G_E^n remains the poorest known of the four nucleon form factors.
- * G_E^n is a fundamental quantity of continued interest.
- * Significant progress has been made at several laboratories by exploiting spin correlations
- * G_E^n can be described by the Galster parametrization (**surprisingly**) and data under analysis is of sufficient quality to test QCD inspired models.
- * Future progress likely with new experiments and better theory.