Hadron Form Factors

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- Introduction
- Pion Form Factor
- G_E^p/G_M^p ratio
- G_E^n
- G_M^n
- Strangeness Form Factors
- Outlook

How are the Nucleons Made from Quarks and Gluons?

Why are nucleons interacting via V_{NN} such a good approximation to nature?
How do we understand QCD in the confinement regime?

A) The distribution of u, d, and s quarks in the hadrons

(spatial structure of charge and magnetization in the nucleons is an essential ingredient for conventional nuclear physics; the flavor decomposition of these form factors will provide new insights and a stringent testing ground for QCD-based theories of the nucleon)

B) The excited state structure of the hadrons

C) The spin structure of the hadrons

D) Other hadron properties
(polarizability, quark correlations, ….)

Nucleon and Pion Form Factors

- Fundamental ingredients in "Classical" nuclear theory
- A testing ground for theories constructing nucleons from quarks and gluons.
  - spatial distribution of charge, magnetization
- Experimental insights into nucleon structure from the flavor decomposition of the nucleon form factors

PRECISION

$$\left.\begin{matrix} G_E^p & G_E^n & G_E^{p,Z} \\ G_M^p & G_M^n & G_M^{p,Z} \end{matrix}\right\} \Rightarrow \begin{matrix} G_E^u & G_E^d & G_E^s \\ G_M^u & G_M^d & G_M^s \end{matrix}$$

- Additional insights from the measurement of the form factors of nucleons embedded in the nuclear medium
  - implications for binding, equation of state, EMC…
  - precursor to QGP

Historical Overview

Stern (1932) measured the proton magnetic moment $\mu_p = 2.79\ \mu_{Dirac}$ indicating that the proton was not a point-like particle

Proton

Hofstadter (1950's) provided the first measurement of the proton's radius through elastic electron scattering

Subsequent data (≤ 1993) were based on:

- Rosenbluth separation for proton, severely limiting the accuracy for G_E^p at $Q^2 > 1$ GeV^2

As yet, no "ab initio" calculations available, waiting for Lattice QCD

Main interpretation based on Vector-Meson Dominance

- In simplest form resulting in dipole form factor:

$$\boxed{G_D = \left\{ \frac{\Lambda^2}{\Lambda^2 + Q^2} \right\}^2 \quad \textbf{with} \quad \Lambda = 0.84\,GeV}$$

Adylov et al. (1970's) provided the first measurement of the pion's radius through pion-atomic electron scattering.

Pion

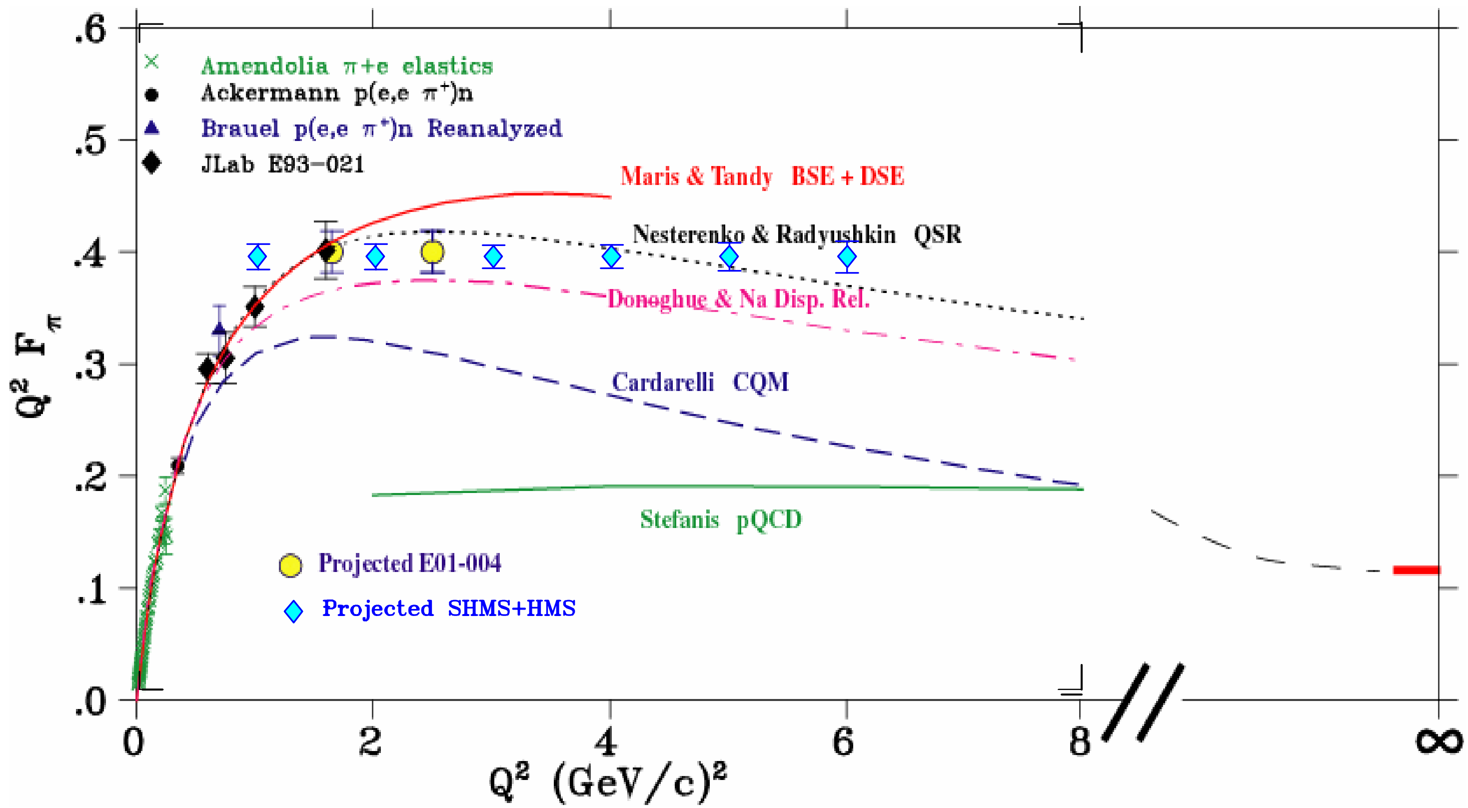
Subsequent measurements at Fermilab and CERN (1980's)

"Ab initio" calculations of the pion far simpler

- In asymptotic region, $F_\pi \to 8\pi\alpha_s f_\pi^2 Q^{-2}$

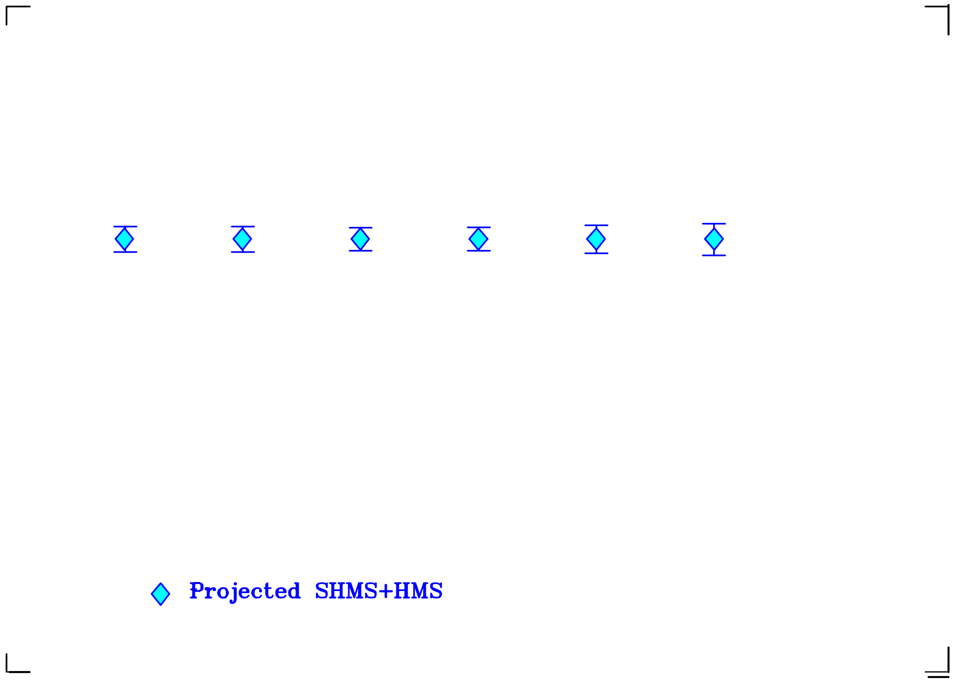
Charged Pion Electromagnetic Form Factor

Potential to approach region where perturbative QCD applies

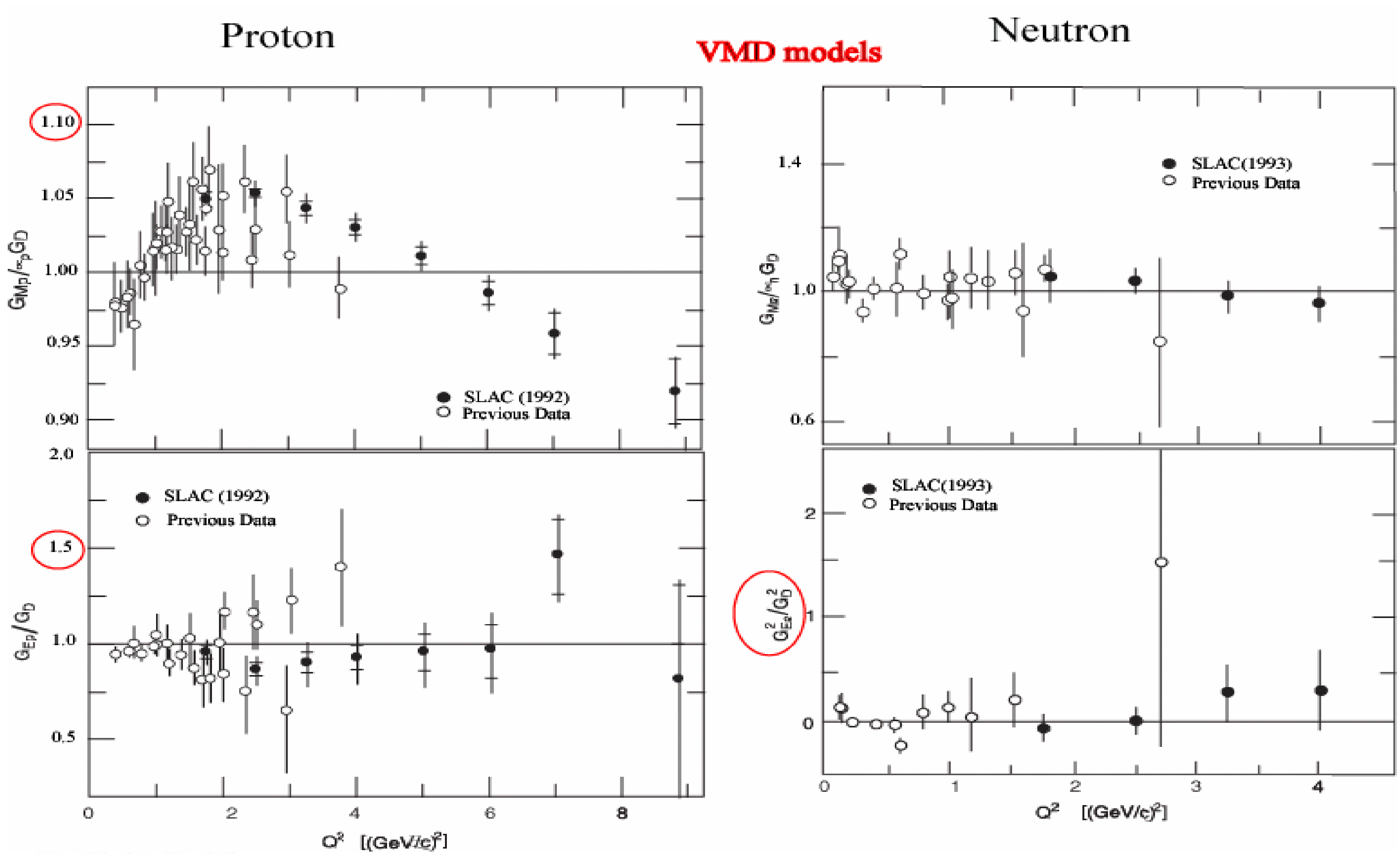


Hall C E93-021 results

Projected E01-004 and 12 GeV results

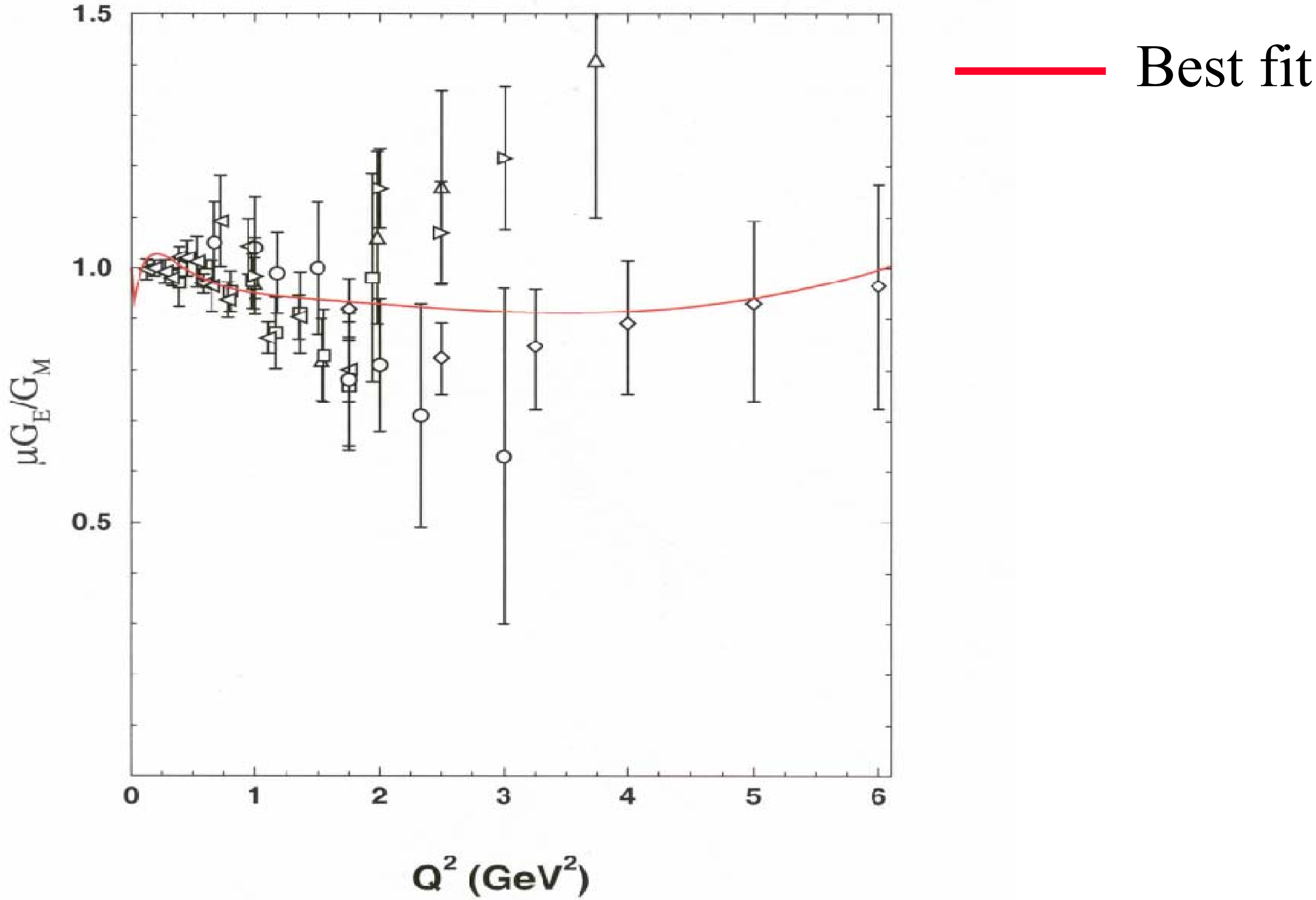

Projected SHMS+HMS

World Data in 1993



Measurement of G_E^p/G_M^p to Q^2 = 5.6 GeV^2 (E99-007)

Earlier nucleon form factor data used Rosenbluth separation
Leading to large systematic errors in G_E^p since $G_E^p < G_M^p$ for $Q^2 > 1$ (GeV/c)^2



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Polarization observables resolve this shortcoming
f.i. by measuring recoil polarization:

$$^1\mathrm{H}(\vec{\mathrm{e}},\mathrm{e}'\vec{\mathrm{p}})$$

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

Key is high beam current
high polarization
focal plane polarimeter

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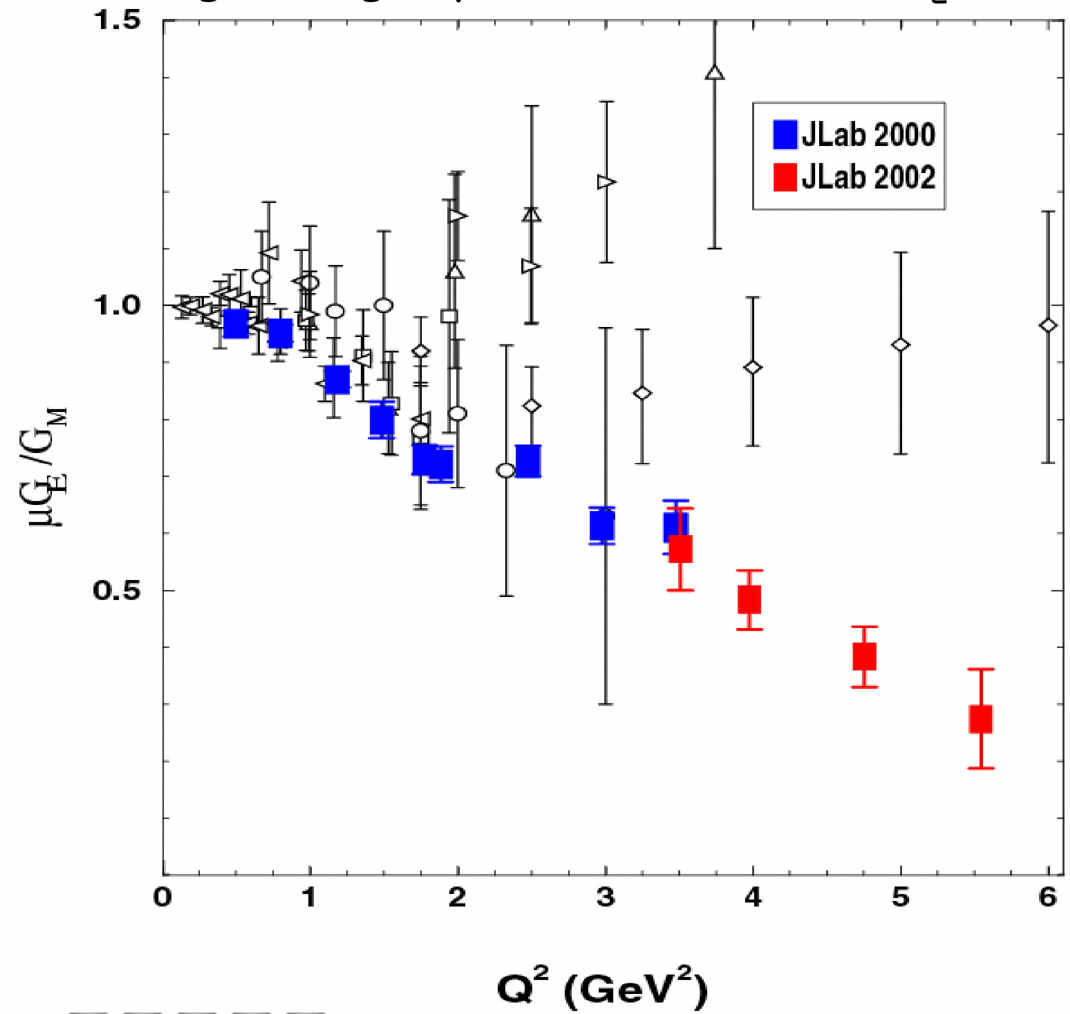


E93-027 observed linear decrease of G_E^p/G_M^p
E99-007 extended the data set to 5.6 $(GeV/c)^2$ using a Pb-glass calorimeter

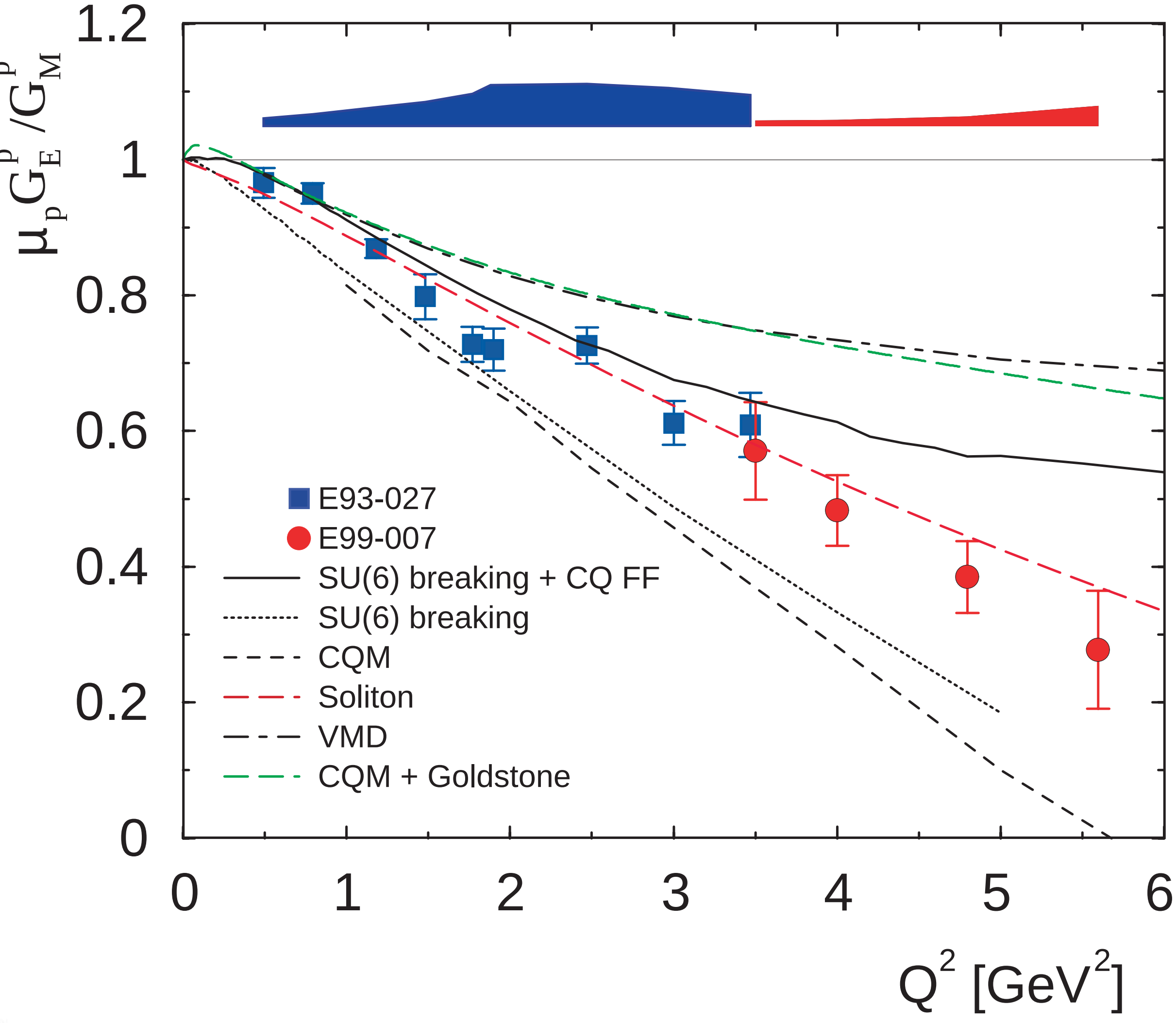
Linear trend is observed to continue

The data do not approach basic pQCD scaling
$F_2/F_1 \propto 1/Q^2$ (Bjørken)

Ralston et al. include quark orbital angular momentum L_q
⊠ $F_2/F_1 \propto 1/Q$

Measurement of G_E^p/G_M^p to Q^2=5.6 GeV^2

Hall A E93-027 and E99-007 results



Radial Charge Distribution

In Breit frame

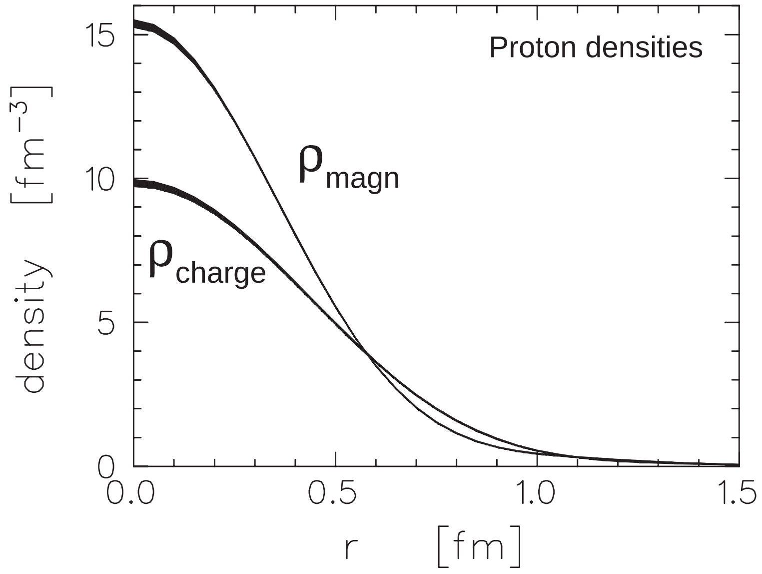
$$G_E^p(k^2) = \int \rho(r) j_0(kr) r^2 dr \textbf{ with } k^2 = \frac{Q^2}{1+\tau}$$

k first-order correction for Breit-frame transformation

- Fourier-Bessel analysis

$$\rho(r) = \sum_{n=1}^{n=n_{\max}} a_n j_0(k_n r)\Theta(R-r) \textbf{ with } k_n = n\pi / R$$

Jim Kelly



Extensions

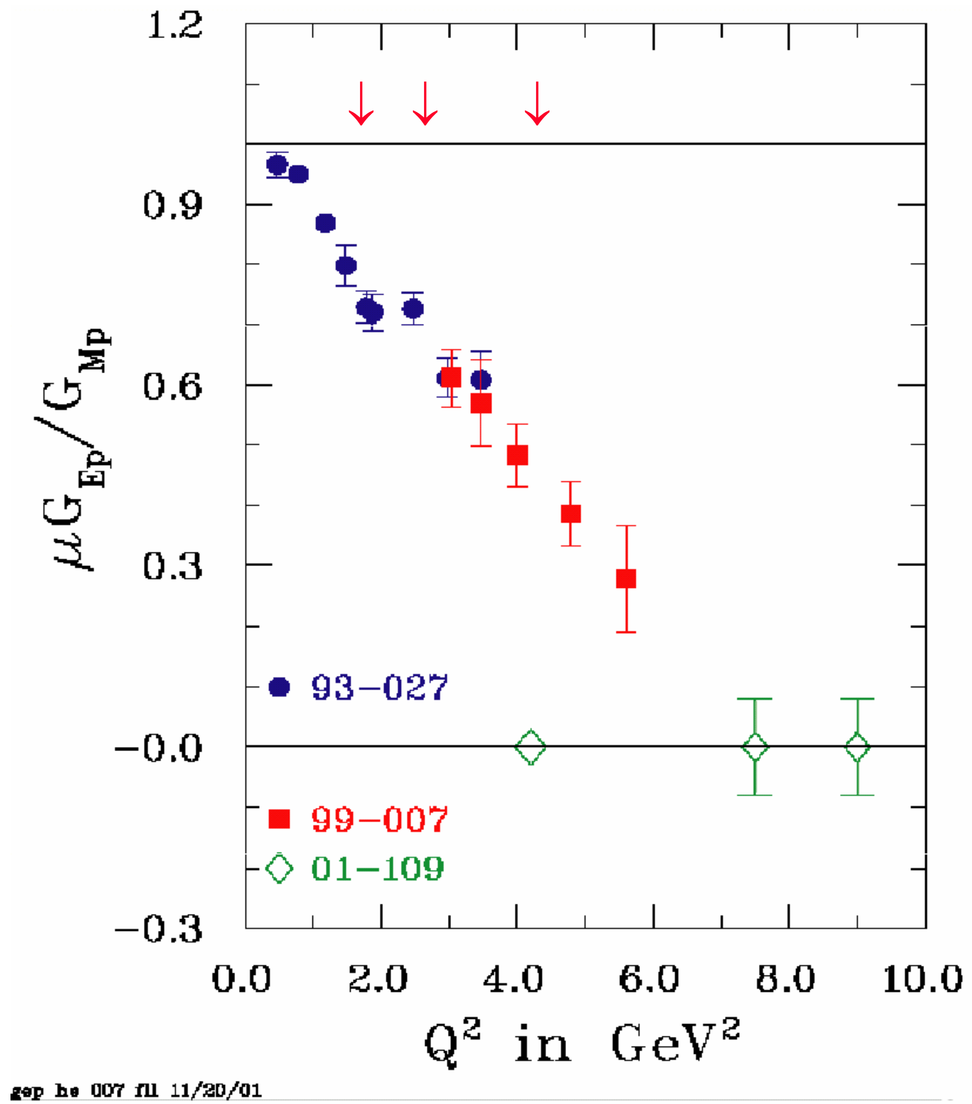
J. Arrington and R. Segel
E01-001 (Hall A)
Super Rosenbluth separation

$$R_1 = \frac{\sigma(E_A, Q_1^2)}{\sigma(E_B, Q_1^2)} = K_1 \frac{\rho_1^2 + \varepsilon_{A1}^{-1} K Q_1^2}{\rho_1^2 + \varepsilon_{B1}^{-1} K Q_1^2}$$

with $\rho_1 = \dfrac{G_E^P}{G_M^P}$

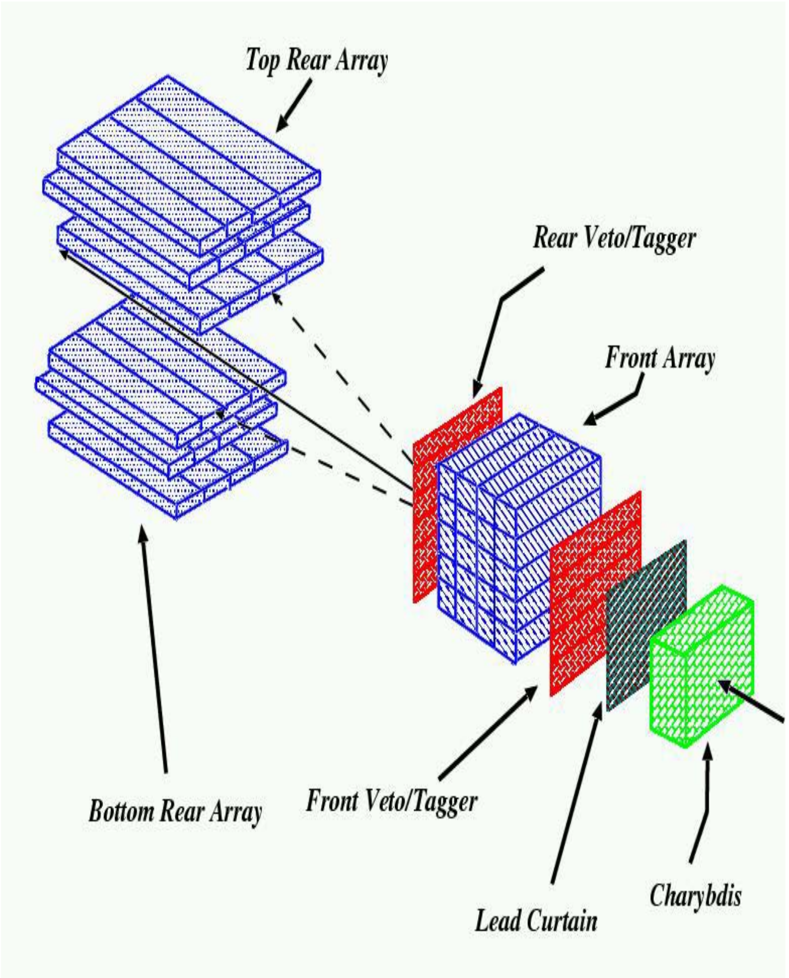
at Q_1^2=1.9, 2.8 and 4.2 GeV^2
and Q_2^2=0.5 GeV^2

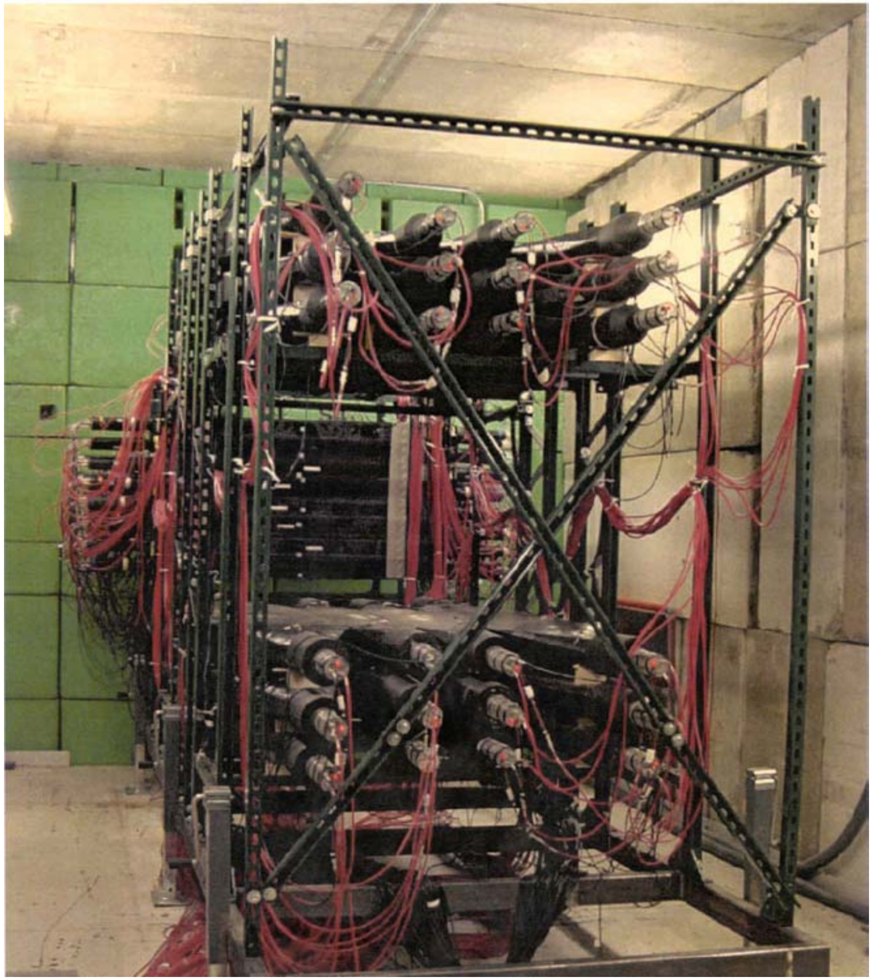
C.F. Perdrisat *et al.*
E01-109 (Hall C)
Use HMS (with new Focal Plane Polarimeter)
and larger Pb-glass calorimeter



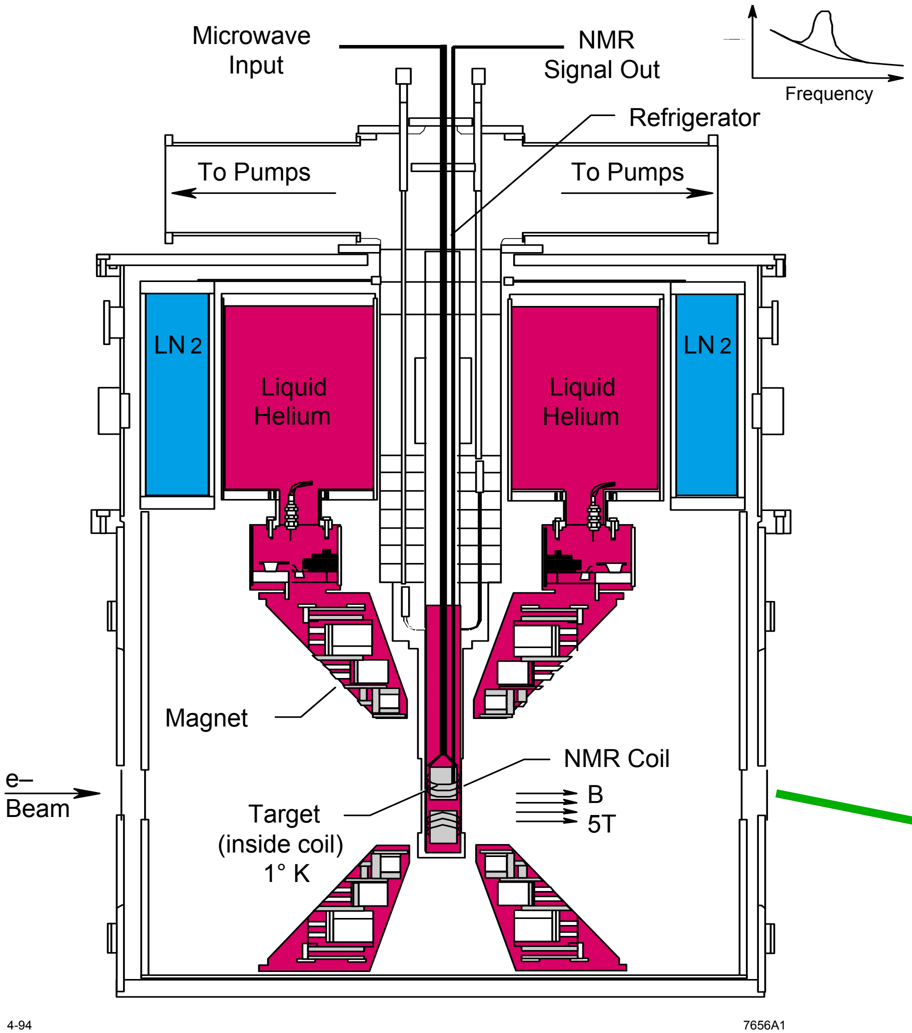
G^n_E Experiment with Neutron Polarimeter

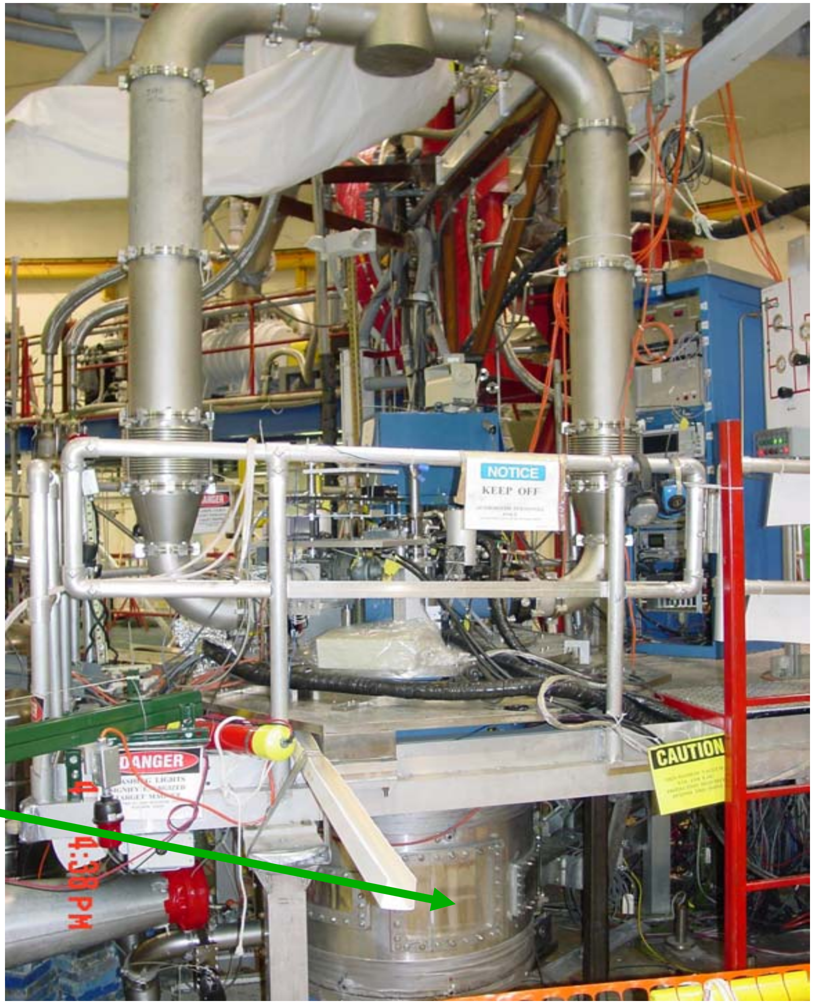
$$^2\mathrm{H}(\vec{e},e'\vec{n})$$





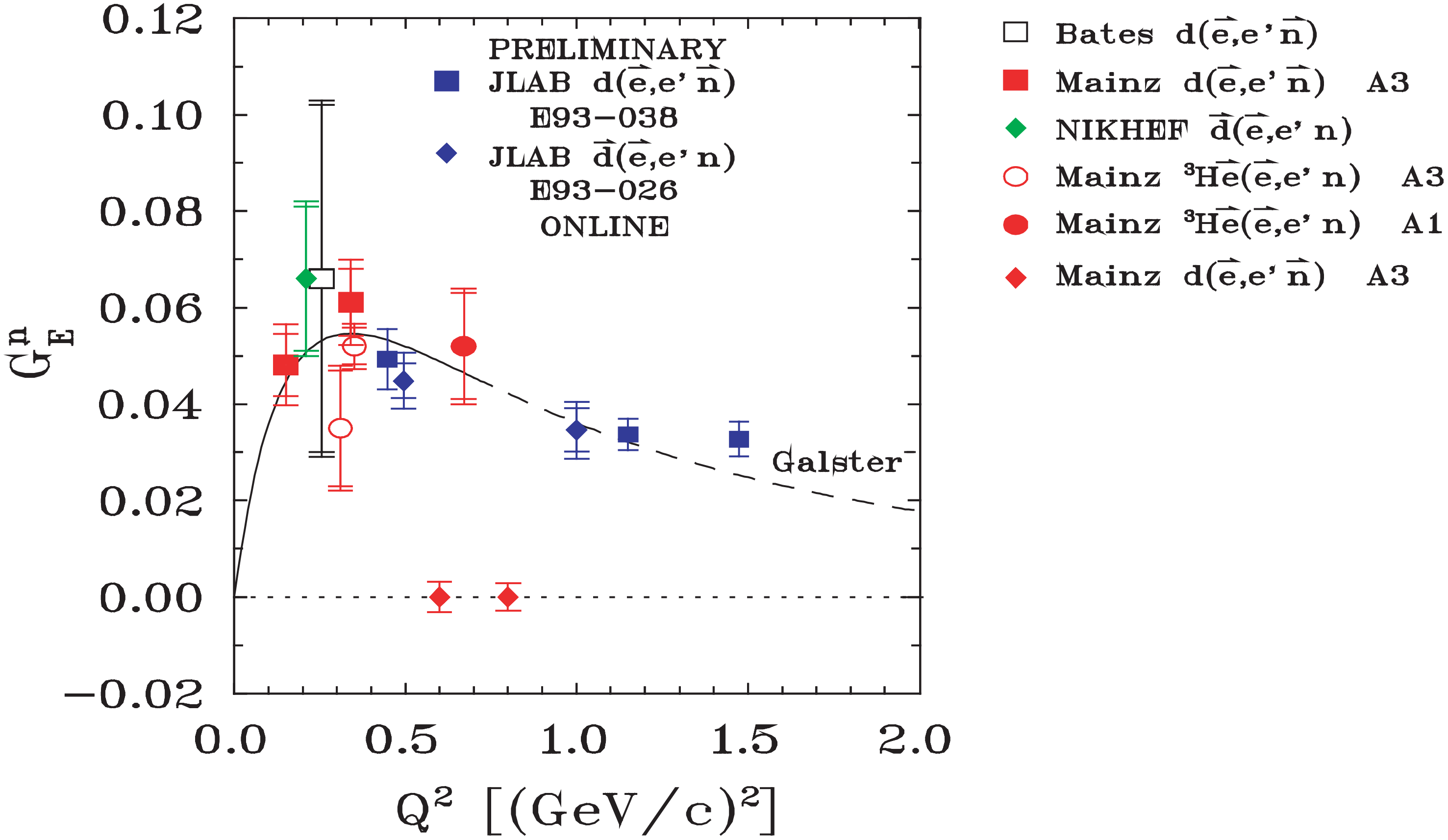
G^n_E Experiment with DNP ND_3 Target $^2\vec{H}(\vec{e},e'n)$





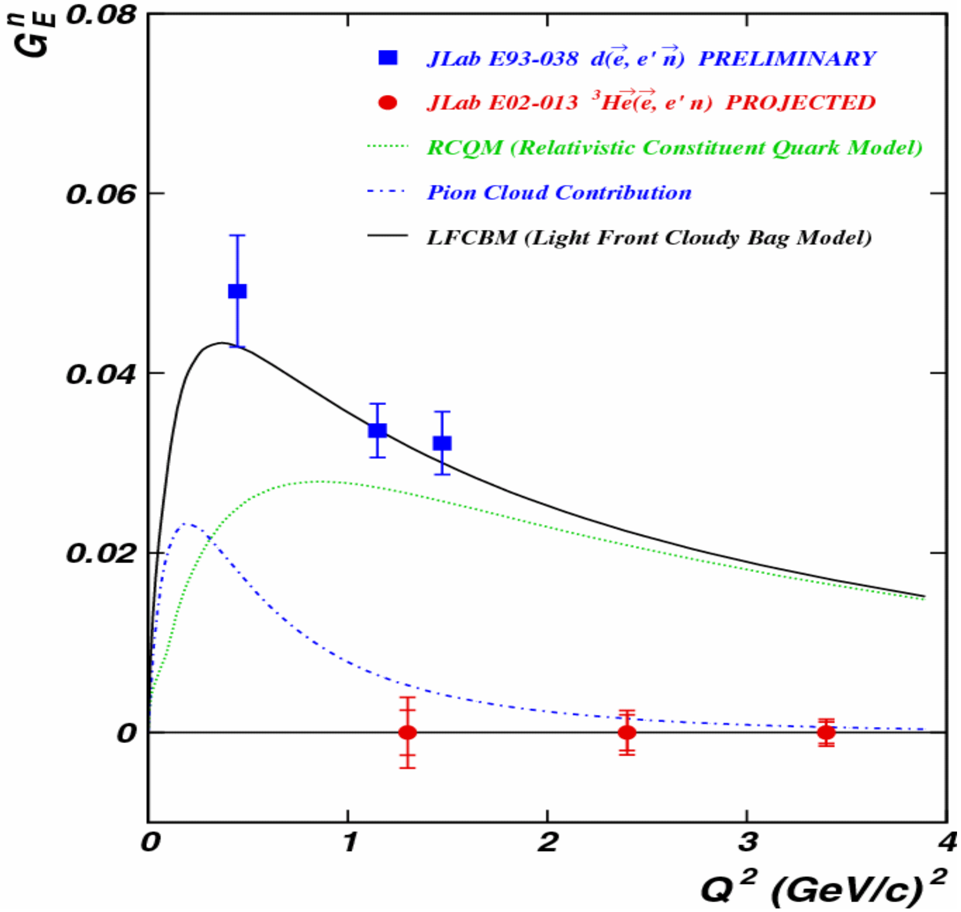
Neutron Electric Form Factor G_E^n

•G_E^n(Madey,Kowalski) – high current polarized beam, unpolarized LD_2 target, neutron polarimeter & neutron precession magnet.
•G_E^n(Day) – low intensity polarized beam ND_3 polarized target and neutron detector.



Neutron Electric Form Factor G_E^n

Hall C Experiment E93-038 (Madey, Kowalski)



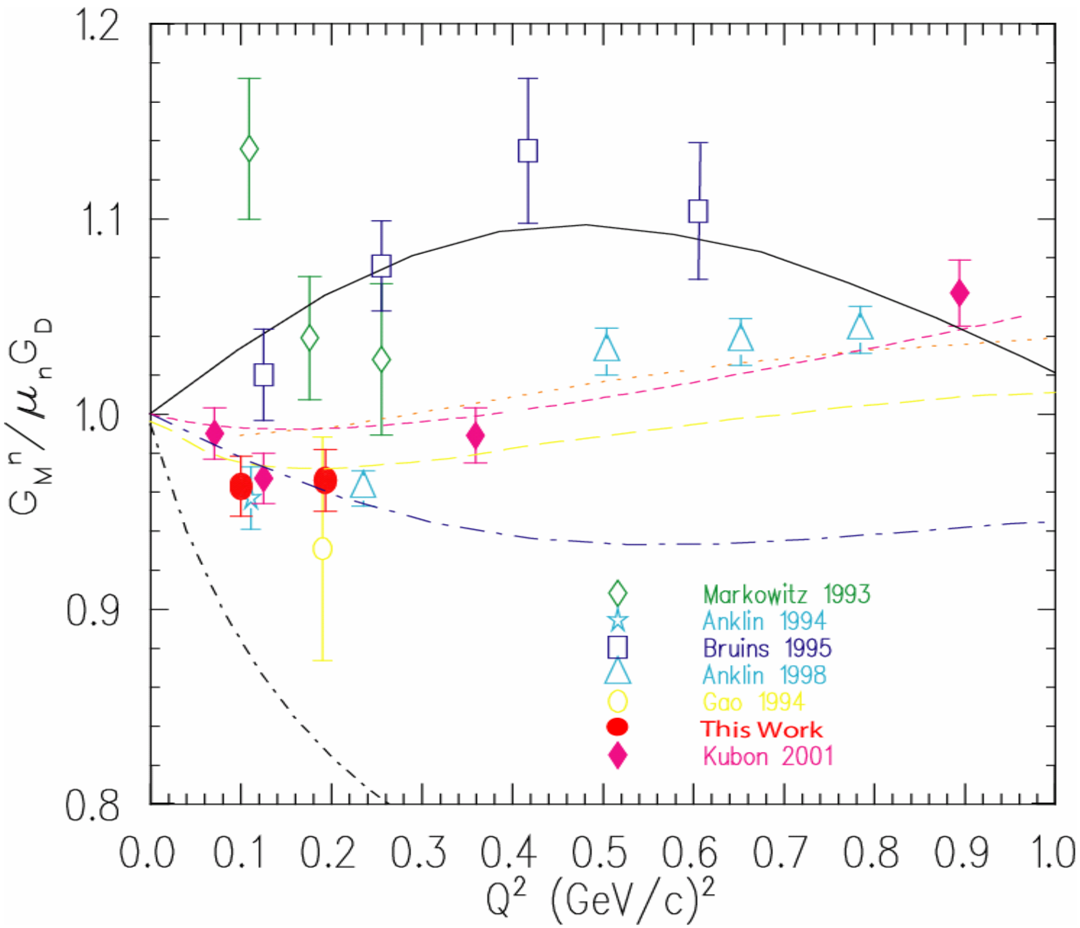
Pion cloud
not sufficient

Relativistic effects
important ingredient

- G_E^n (Hall A) – polarized beam, polarized ^{3}He target, and neutron detector

Measurement of G^n_M at low Q^2 from $^3\vec{H}e(\vec{e},e')$

Hall A E95-001



Q^2=0.1,0.2 (GeV/c)^2 extracted from full calculation (W.Xu et al. PRL 85, 2900 (2000))

Q^2=0.3-0.6 extracted from PWIA, more reliable extraction requires improved theory (in progress)

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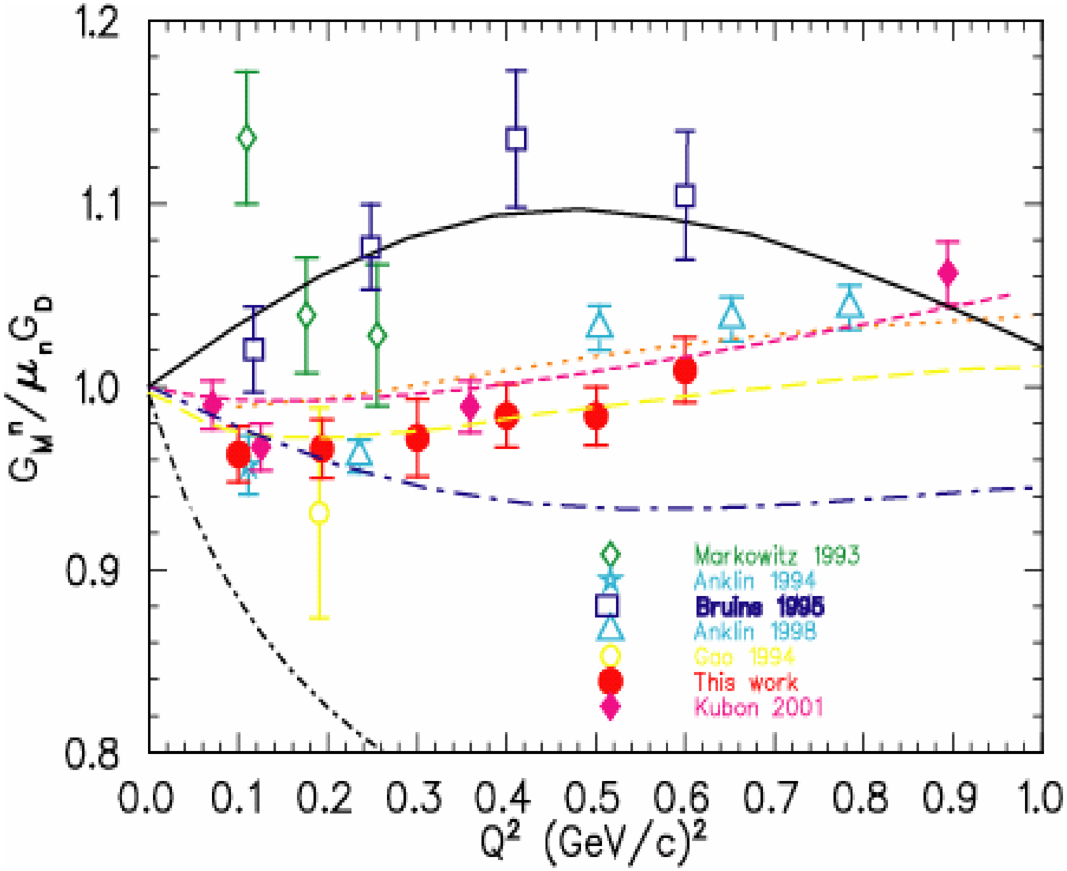
Hall A E95-001



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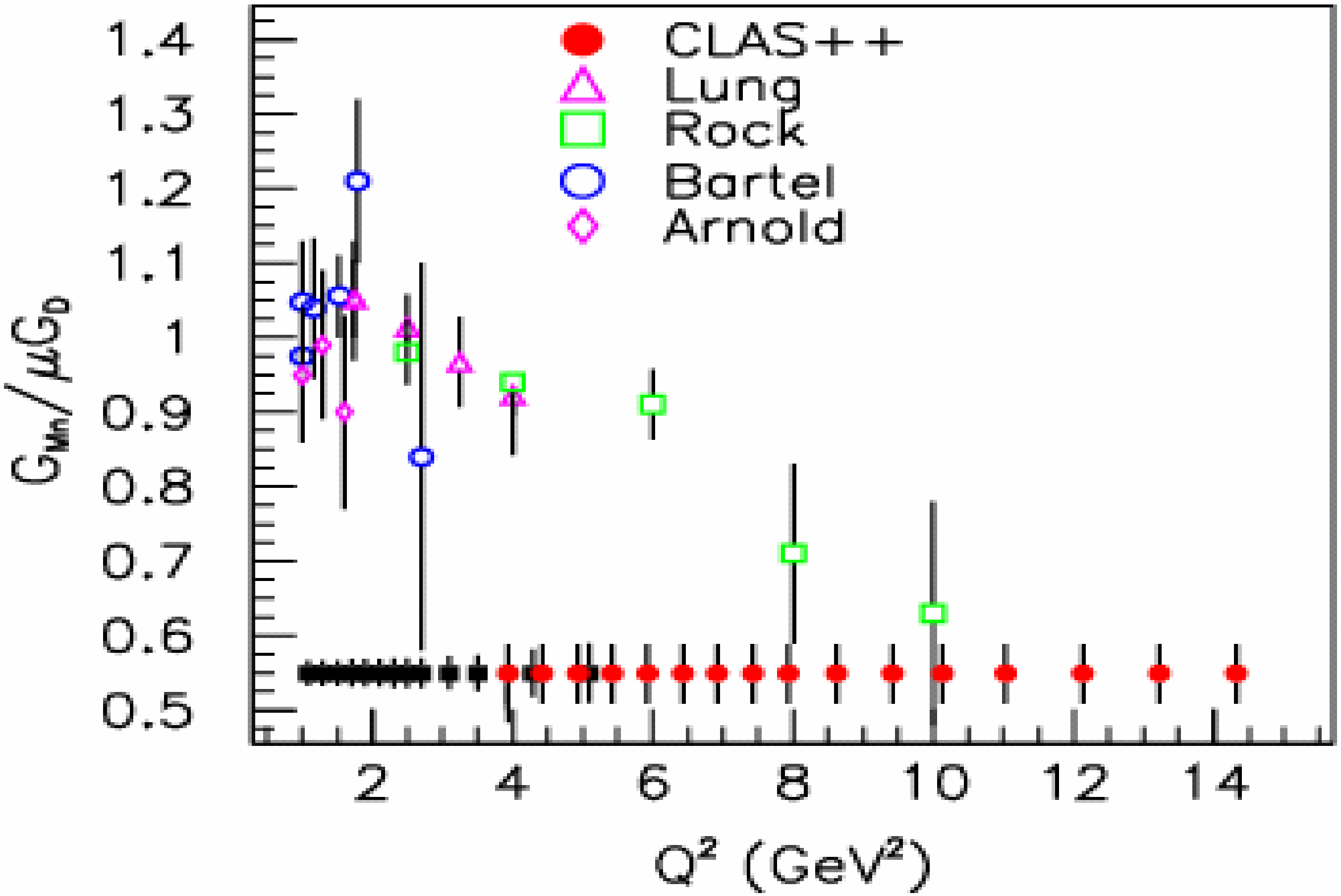
Measurement of G^n_M from CLAS

$$^2\mathrm{H}(e,e'n)/^2\mathrm{H}(e,e'p) \Rightarrow \mathrm{G}^n_M$$

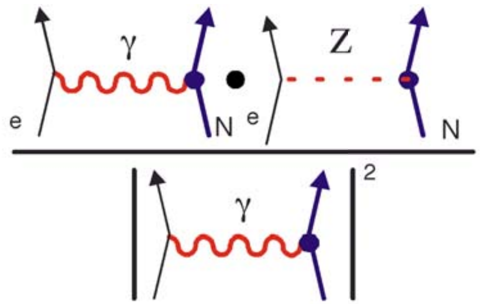


• 6 GeV Projections • 12 GeV Projections

Strange Quark Currents in the Nucleon G_E^s, G_M^s

Polarized Electron
Unpolarized Target

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



For a Nucleon:

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{\varepsilon G_E^{\gamma} G_E^{Z} + \tau G_M^{\gamma} G_M^{Z} - (1-4\sin^2\theta_W)\varepsilon' G_M^{\gamma} G_A^{e}}{\varepsilon (G_E^{\gamma})^2 + \tau (G_M^{\gamma})^2}$$

forward angles
HAPPEX, Mainz, G^0: sensitive to

G_E^s and G_M^s

backward angles
SAMPLE, G^0: sensitive to

G_M^s and G_A^e

weak charge
of the proton

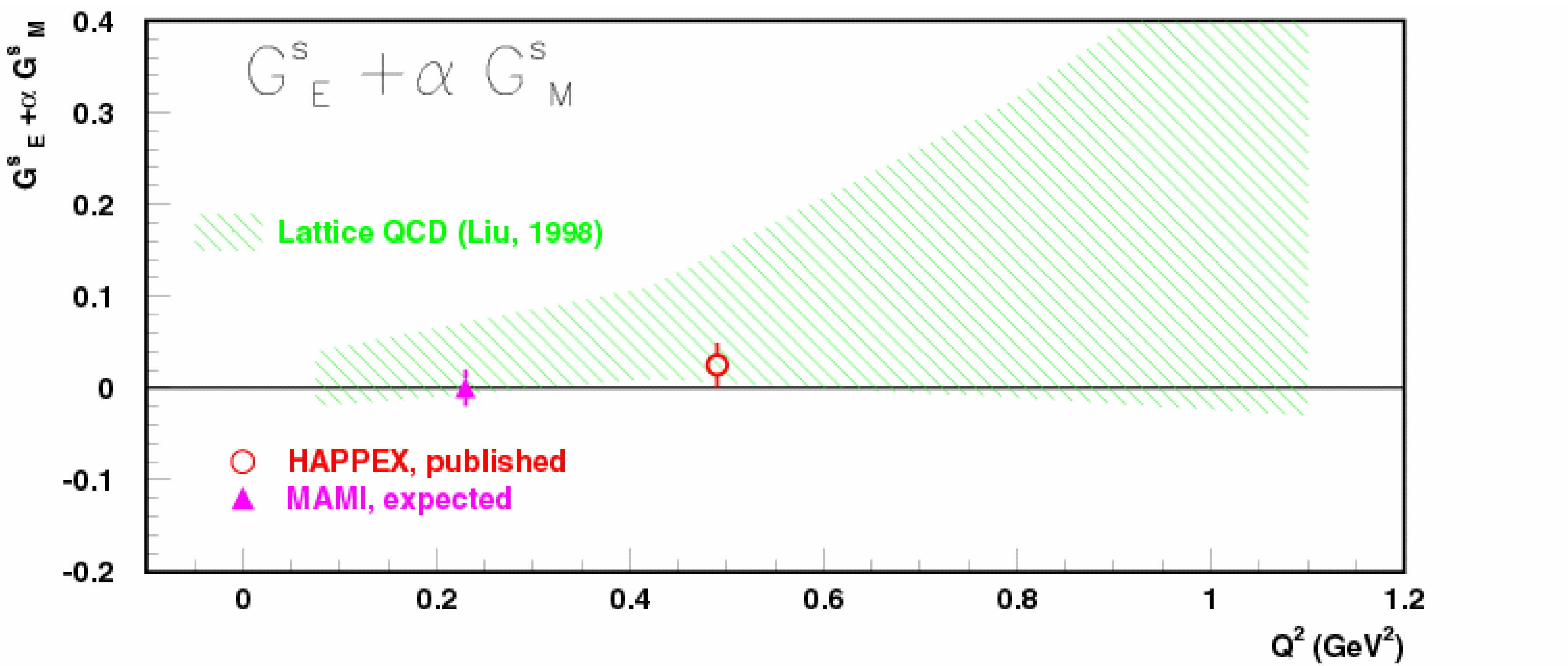
Q^p_{weak}

$\varepsilon = 1 / [1 + 2(1 + \tau) \tan^2 \theta/2]$ $\quad$ $\varepsilon' = [\tau (1 + \tau)(1 - \varepsilon^2)]^{-1/2}$

$\tau = Q^2/4m^2$ $\quad$ Q^2 is the four momentum transfer

θ is the laboratory electron scattering angle

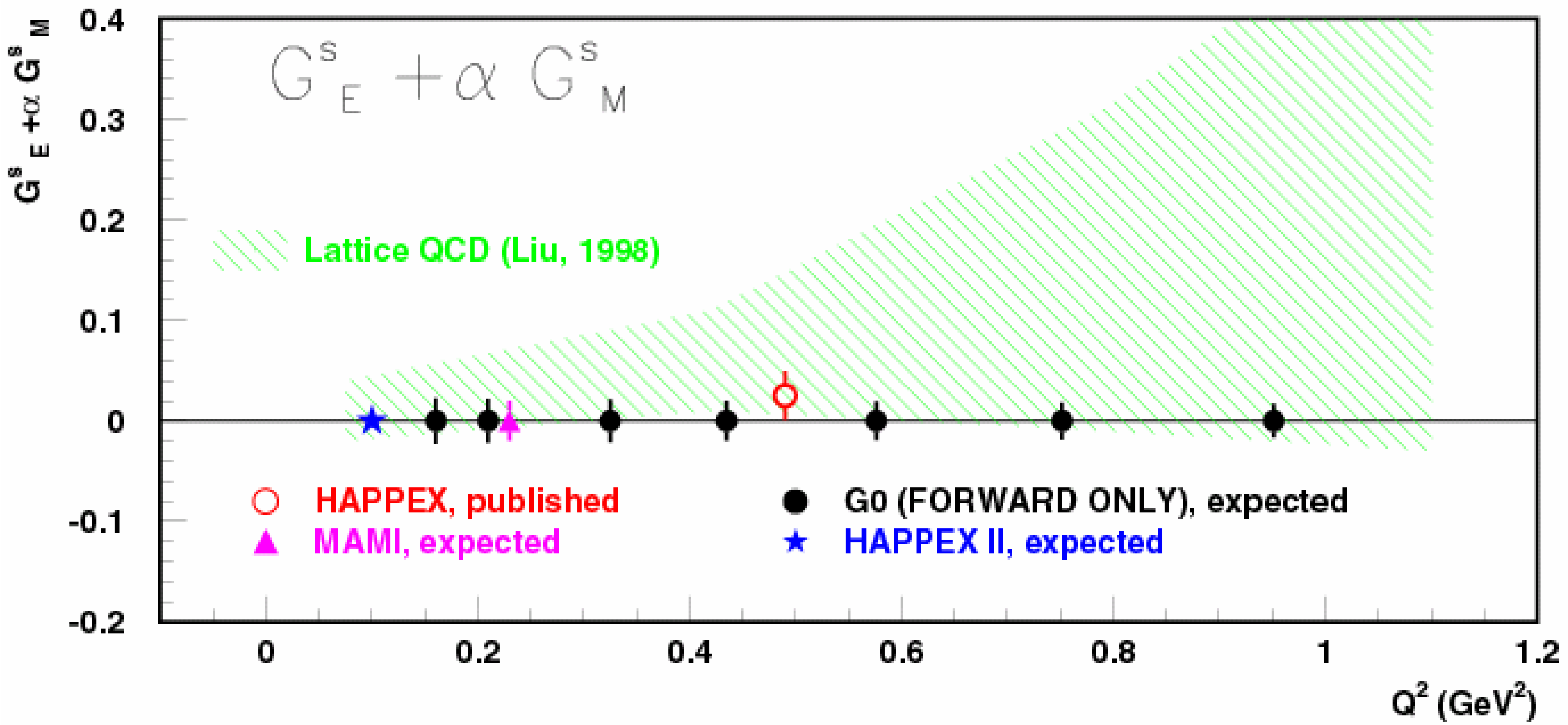
Strange Form Factors G_E^s and G_M^s



What we have on the books now

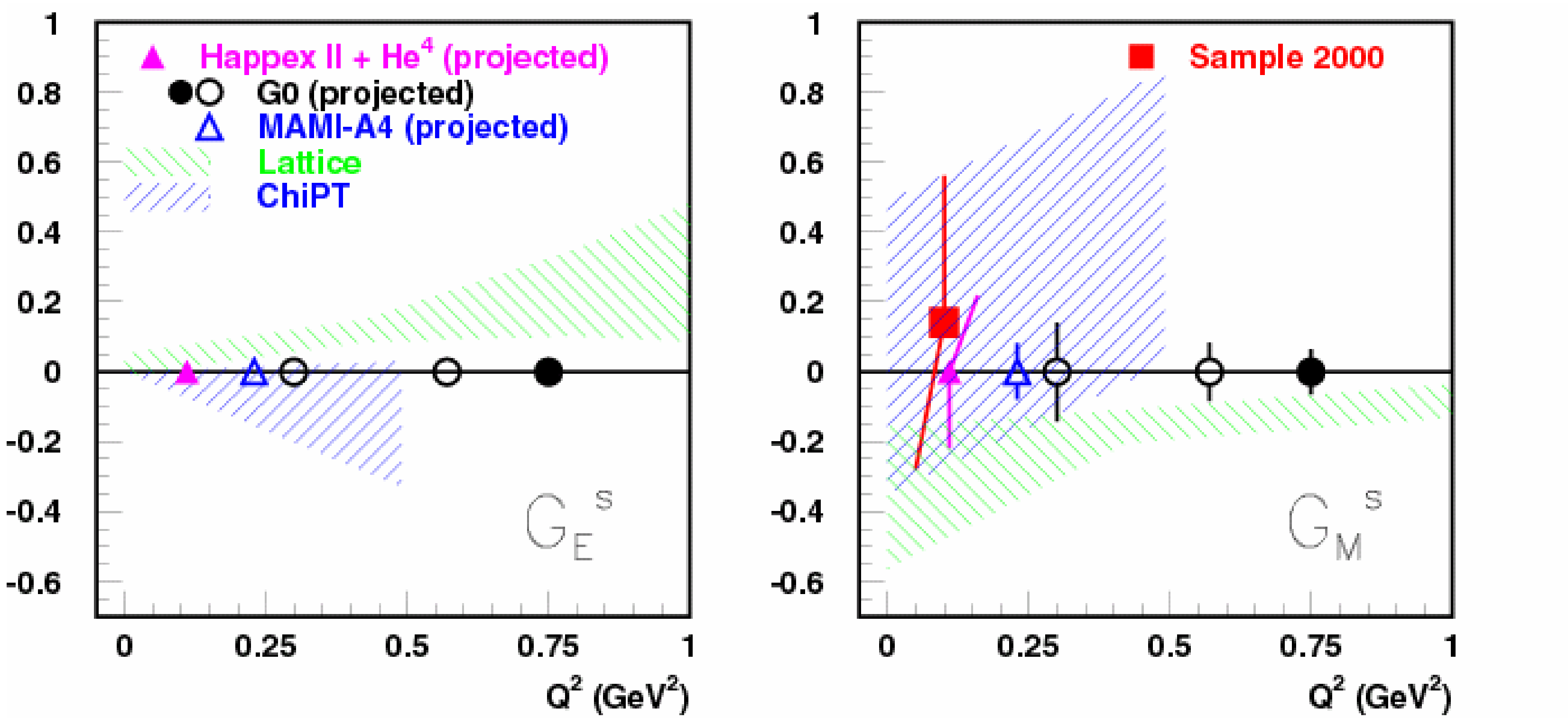
Strange Form Factors G_E^s and G_M^s

Expected Forward Angle Results by late 2003



Strange Form Factors G_E^s and G_M^s

Rosenbluth separation of G_E^s and G_M^s



Projected data indicated by open symbols are not approved yet

High Precision Nucleon Form Factors at JLab

Q^2 range

	Present	Planned (12 GeV)	Comments
G_E^p	5.6	9.0 (14.0)	Precision Measurements Does G_E^p/G_M^p keep dropping linearly?
G_M^p		(20.0)	$Q^2 > 14$ makes assumptions about G_E^p
G_E^n	1.5	3.4 (5.5)	Precision Measurements $^3\vec{\mathrm{He}}(\vec{e}, e'n)$ for $Q^2 > 1.5$
G_M^n	5.0	(14.0)	Precision Measurements
$G_E^s + \alpha G_M^s$	0.5	1.0	α small (non-0), now only at Q^2=0.5
G_M^s		0.8	Presently only approved at Q^2=0.1 and 0.8

Summary

- F^{π} First measurement away from $Q^2 \approx 0$
  no Q^{-2} behavior yet
- G_E^p Precise data set up to $Q^2 = 5.6\ (GeV/c)^2$
  charge differs from current distribution
  $Q^2 = 9\ (GeV/c)^2$ planned
- G_E^n 2 successful experiments, precise data anticipated
  higher Q^2 possible and approved
- G_M^n $Q^2 < 1$ data from $^3He(e,e')$
  high Q^2 data from $^2H(e,e'n)/^2H(e,e'p)$ anticipated
- G_E^s, G_M^s Happex-2, Happex-He, G0 coming up
  \+ Sample, Happex, Mainz
  $\Rightarrow$ Stringent constraints on strangeness contributions
  $\Rightarrow$ Enables Q-Weak Standard Model test