THE NUCLEON ELECTROMAGNETIC FORM FACTORS AT LOW Q^2

The JLab Experimental Program

Guy Ron
The Weizmann Institute of Science

Chiral09
Bern

Outline

- Review of Nucleon Form Factors
- The Physics Case - Or: Why Low Q^2?
- Measurement Techniques 101
- Review of JLab Results:
    - Neutron Experiments
    - Proton Experiments
- Future measurement(s)

Review of Nucleon Form Factors

- Cross section for eN elastic scattering (1γ approximation):

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}\bigg|_{\mathrm{Mott}} \times \left[G_E/^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right]$$

- Form factors parametrize our ignorance of complex internal structure.

- Normalized to give static properties:

$$\begin{array}{ll} G_E^p(0) = 1 & G_E^n(0) = 0 \\ G_M^p(0) = \mu_p & G_E^n(0) = \mu_n \end{array}$$

- FFs are (but not really) Fourier transforms of charge and magnetization densities, such that:

$$G^p_{E(M)}(Q^2) = \int \rho_{Ch(M)}(\vec{r}) e^{-\vec{q}\cdot\vec{r}} d^3r \sim \int \rho d^3r - \frac{\vec{q}^2}{6} \int \rho \vec{r}^2 d^3r = Ch(M) - \frac{\vec{q}^2}{6} < r^2 >_{Ch(M)}$$

- Also written as the Dirac & Pauli form factors:

$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \tau F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + F_2(Q^2) \end{aligned}$$

What we know

- Experimentally found to approximately follow (to about 10%) the dipole form:

$$\mathbf{F_D(Q^2) = \left(1 + Q^2/0.71\right)^{-2}}$$

- Dipole form in Q space → exponential in r space.
- We know the limiting values at Q^2=0.
- But... We know that there are deviations from dipole (very pronounced at high Q^2).

Why We Care

- FF are a basic property of the nucleon, related to the complex internal structure.
- Completely describe the EM structure of the nucleon ground state.
- Comparing G_E and G_M → difference between spatial distributions of charge and magnetization.
- Input to other calculations (more later).
- Different theories constrained by different Q^2 regions.
- An important place to look for quark/gluon → hadron/meson p picture transition.
- EM structure expected to change in the nuclear medium.

Rosenbluth Separation

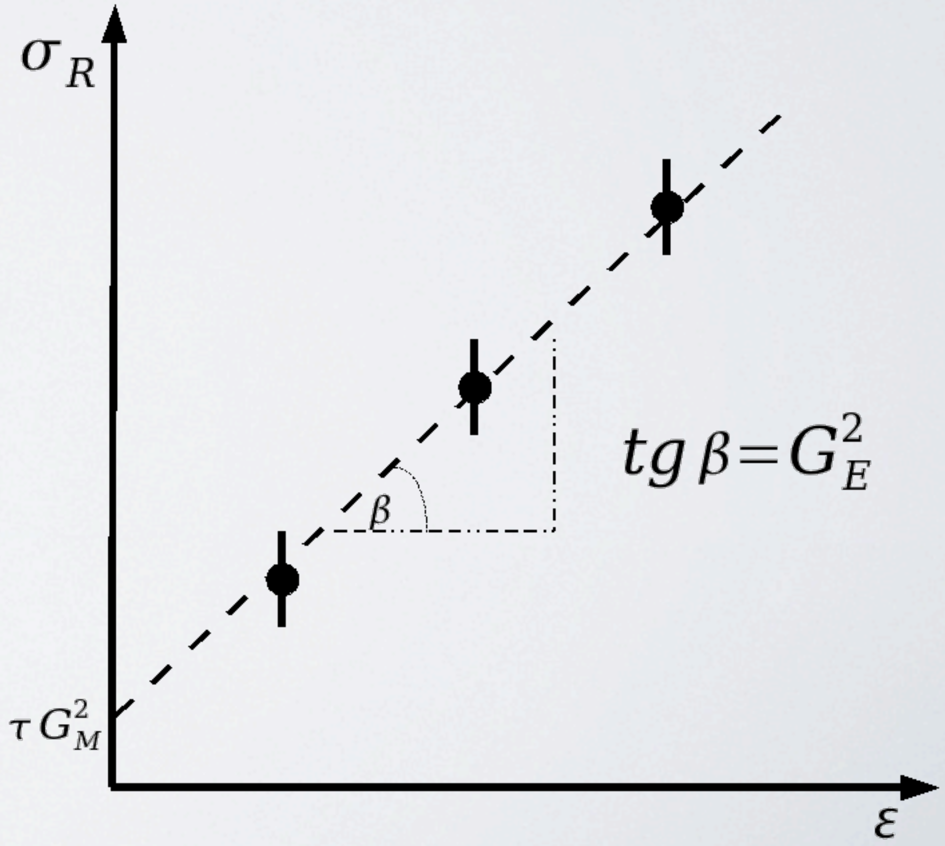
$$\sigma_R = (d\sigma/d\Omega)/(d\sigma/d\Omega)_{\text{Mott}} = \tau G_M^2 + \varepsilon G_E^2$$

- Measure the reduced cross section at several values of ε (angle/beam energy combination) while keeping Q2 fixed.

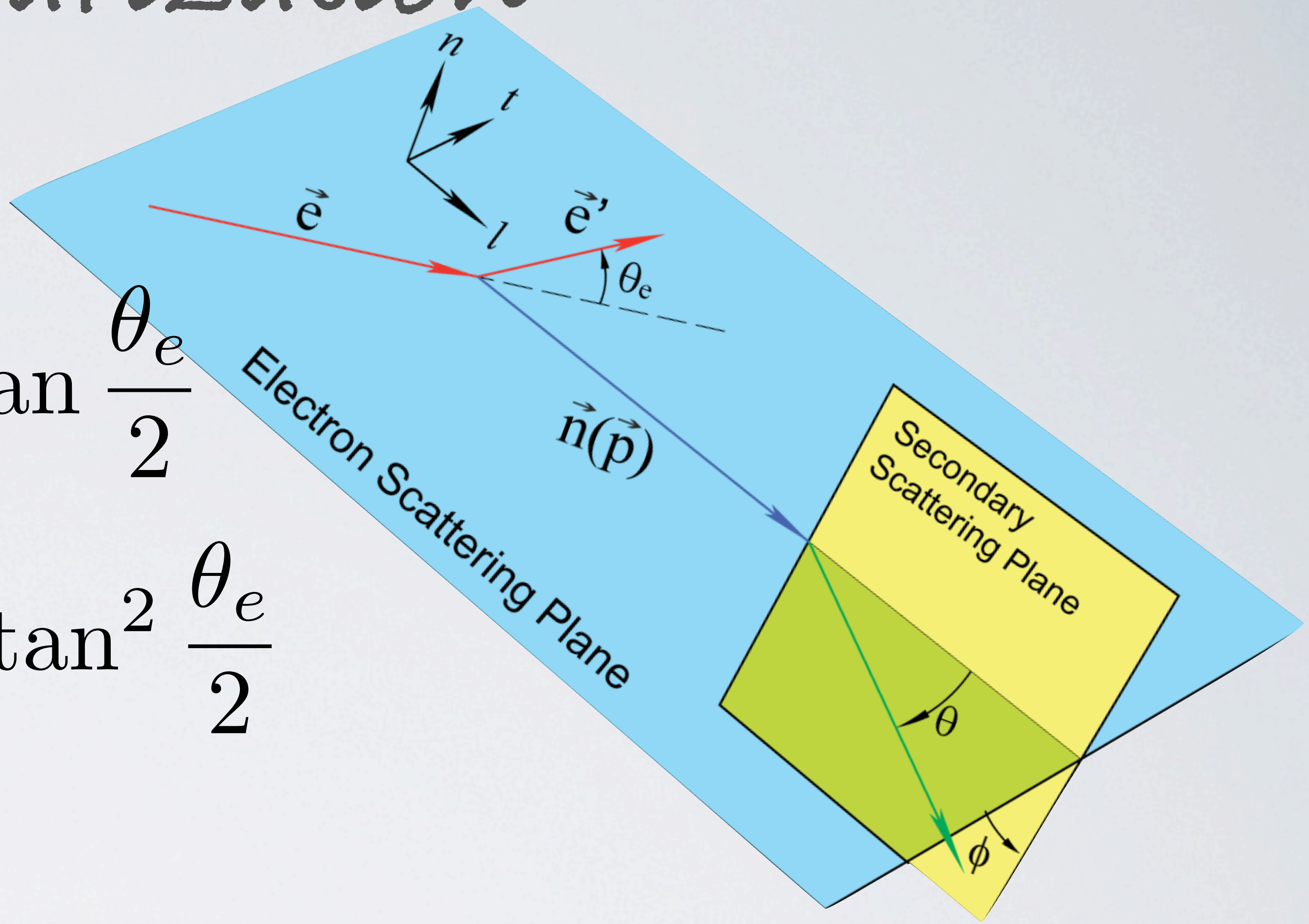
- Linear fit to get intercept and slope.

- But... G_M suppressed for low Q^2 (and G_E for high).

- Also normalization issues/acceptance issues/etc. make it hard to get high precision.



Recoil Polarization



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

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

$$P_n = 0 \; (1\gamma)$$

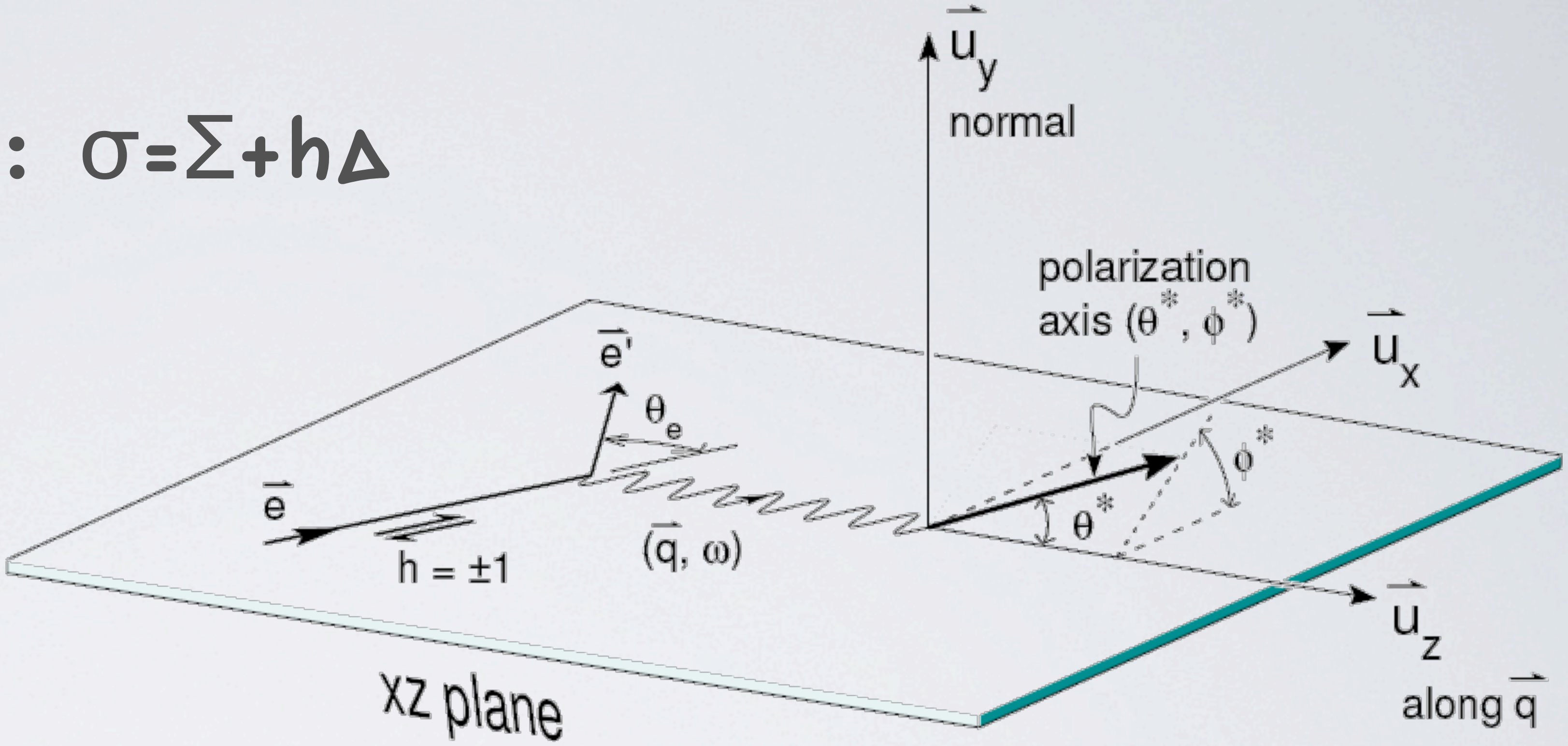
$$\mathcal{R} \equiv \mu_p \frac{G_E}{G_M} = -\mu_p \frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\frac{\theta_e}{2}$$

- A single measurement gives ratio of form factors.
- Interference of "small" and "large" terms allow measurement at practically all values of Q^2.

Beam-Target Asymmetry

Polarized Cross Section: $\sigma=\Sigma+h\Delta$

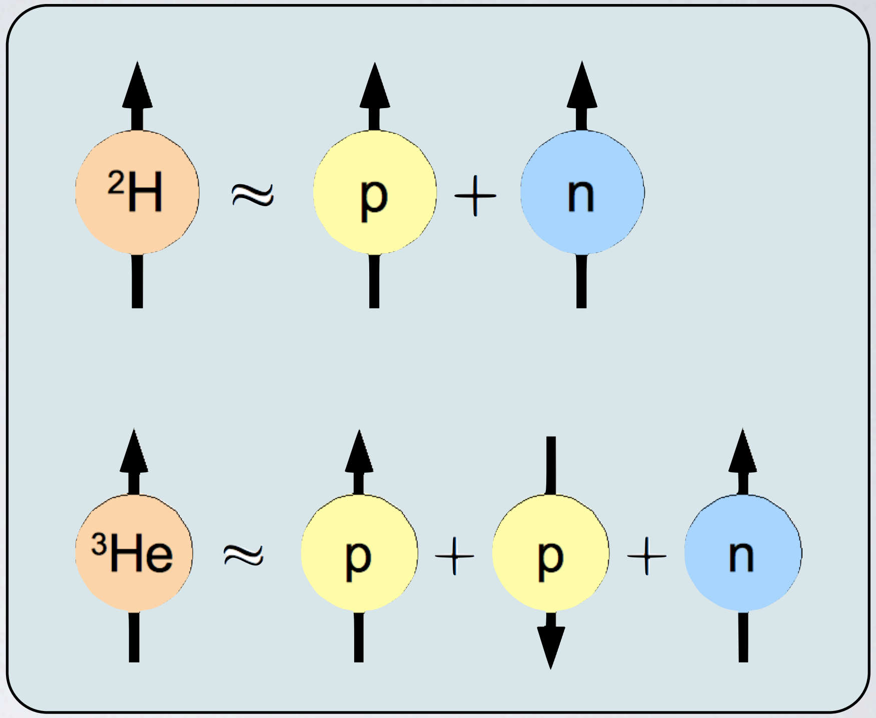
$$\mathcal{A}=\frac{\sigma_+-\sigma_-}{\sigma_++\sigma_-}$$



$$\mathcal{A}=fP_bP_t\frac{\overbrace{a\,cos\theta^*G_M^2}^{A_T}+\overbrace{b\,sin\theta^*\;cos\phi^*G_EG_M}^{A_{LT}}}{cG_M^2+dG_E^2}$$

Measure asymmetry at two different target settings, say $\theta^*=0$, 90.
Ratio of asymmetries gives ratio of form factors.
Functionally identical to recoil polarimetry measurements.

The curious case of the neutron



- No free neutron targets.
- Must use light nuclei to measure neutron form factors.
- Ratio method (LJab Hall B):

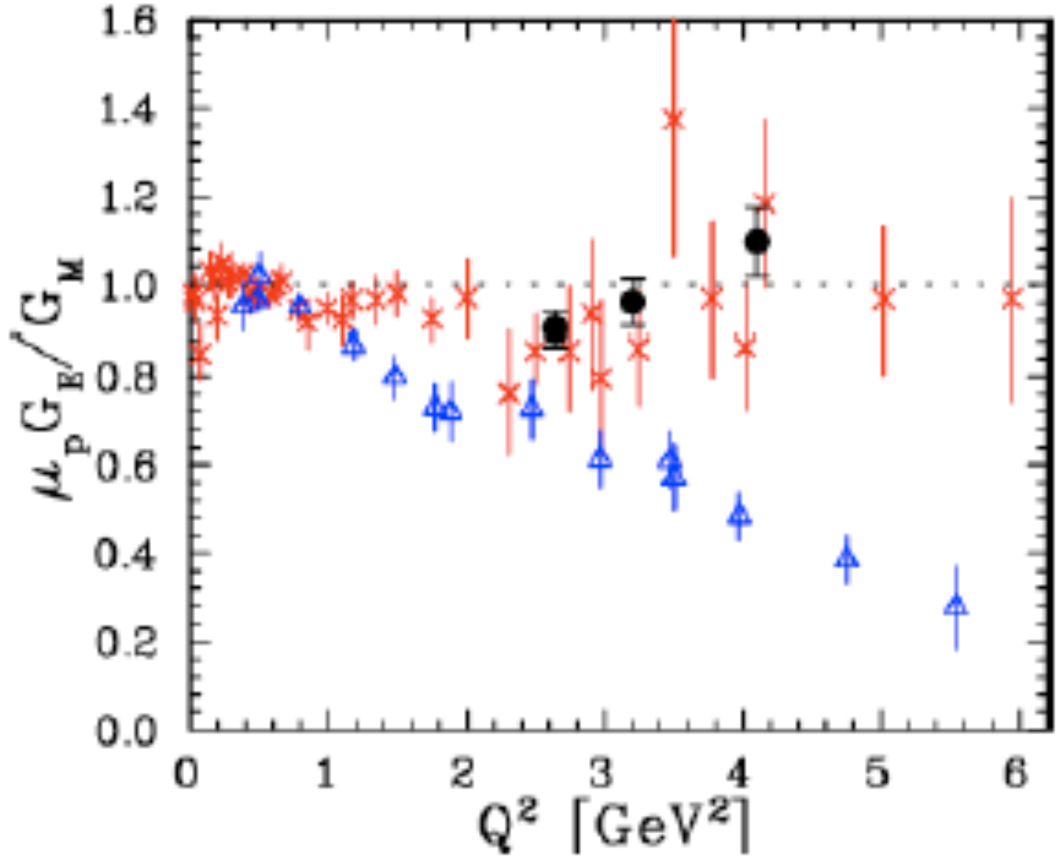
$$R \equiv \frac{d\sigma}{d\Omega}\left[{}^2H(e,e'n)_{QE}\right] / \frac{d\sigma}{d\Omega}\left[{}^2H(e,e'p)_{QE}\right]$$

$$R = a\left(E, Q^2, \theta_{pq}^{max}, W^2_{max}\right) \frac{\sigma_{\mathrm{Mott}}\left(\frac{(G_E^n)^2+\tau(G_M^n)^2}{1+\tau} + 2\tau\tan^2\frac{\theta_e}{2}(G_M^n)^2\right)}{\frac{d\sigma}{d\Omega}\left[{}^1H(e,e')p\right]}$$

- Polarization:
  - Recoil polarization from ^{2}H (Bates, Mainz, JLab Hall C).
  - Beam target asymmetry on polarized ND$_3$ (NIKHEF, JLab Hall C).
  - Beam target asymmetry on polarized ^{3}He (Bates, NIKHEF, Mainz, JLab Hall A).

The high Q^2 discrepancy

- At high Q^2 Rosenbluth and polarization measurements for the proton are in violent disagreement.



I. Qattan *et al.*, Phys. Rev. Lett. **94**, 142301 (2005).

- Almost certainly explained by multi-γ effects.
- *But what about low Q^2?*

Why Low Q^2?

- Deviations from dipole form evident.
- Probe static properties ($Q^2 \to 0$) and peripheral structure.
- Small Q^2 does not allow for pQCD, many competing EFTs.
- Potentially impacts many high precision measurements (nucleon GPDs, parity violation, Zemach radius,...).

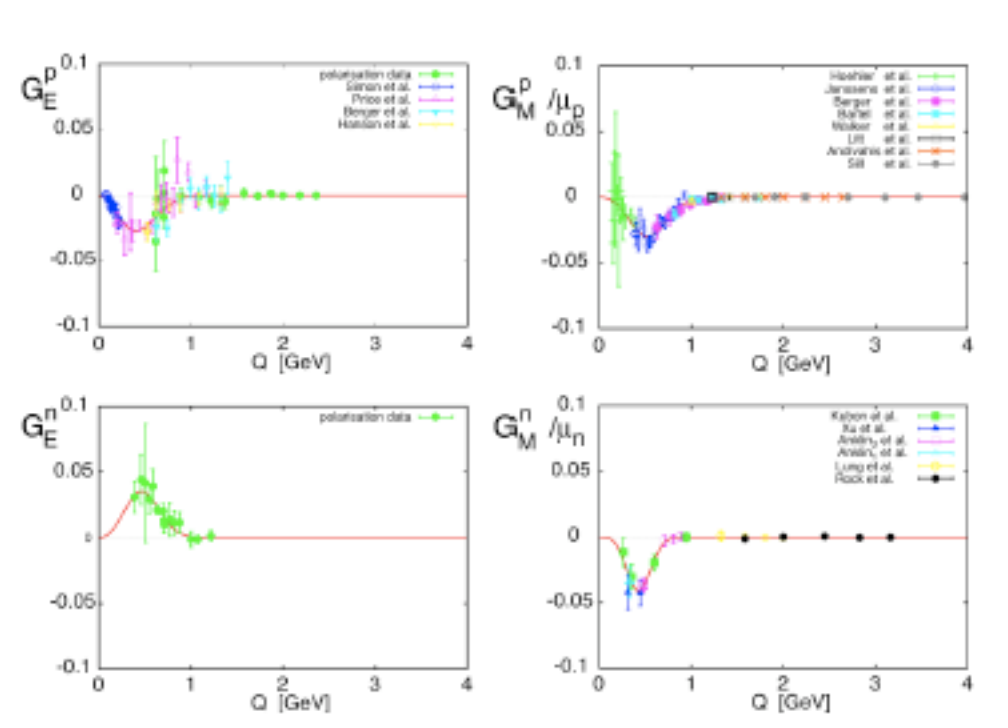
Some Models

VMD	$F(Q^2) = \Sigma \frac{C_{\gamma V_i}}{Q^2 + M_{V_i}^2} F_{V_i N}(Q^2)$ Breaks down at high Q^2
Lattice QCD	(not really a model....)
RCQM	Point Form Light Front
di-Quark	
CBM/LFCBM	
pQCD	Helicity Conservation Counting rules $\frac{Q^2 F_2}{F_1} \to \text{Constant}$

Low Q^2 Notable Results

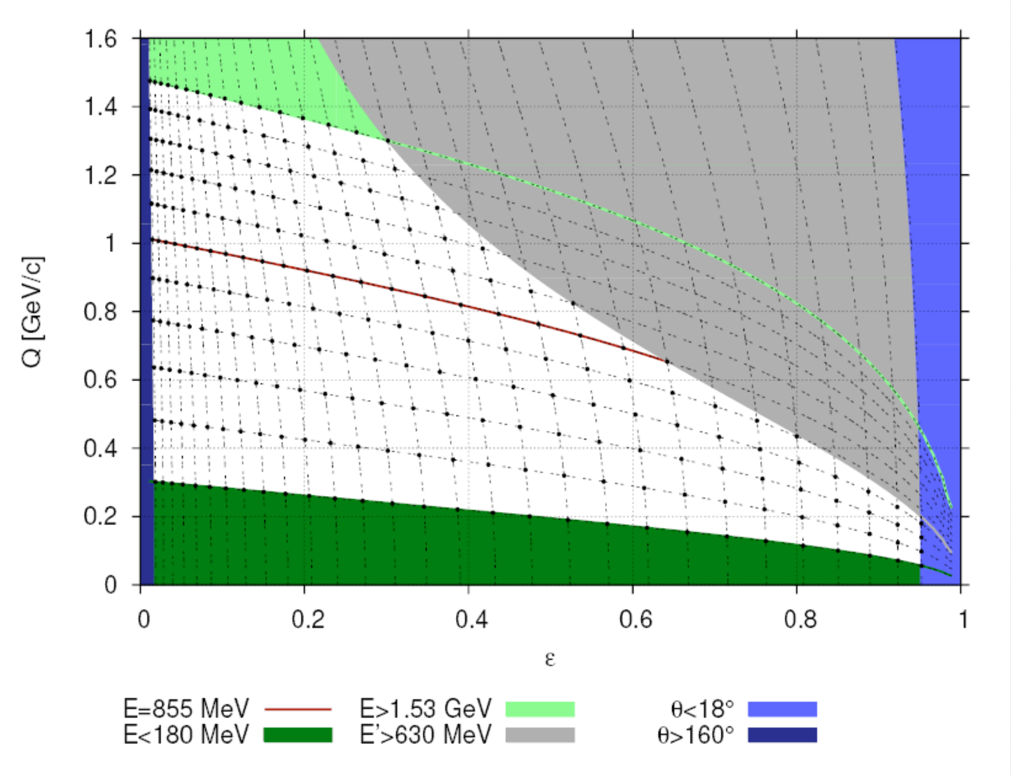
Friedrich & Walcher analysis

Eur. Phys. J. A17, 607 (2003)



- Bump/dip (+2 dipoles) structure in all 4 form factors.
- Possibly interpreted as effects of a virtual meson cloud.

Mainz A1 FF Experiment



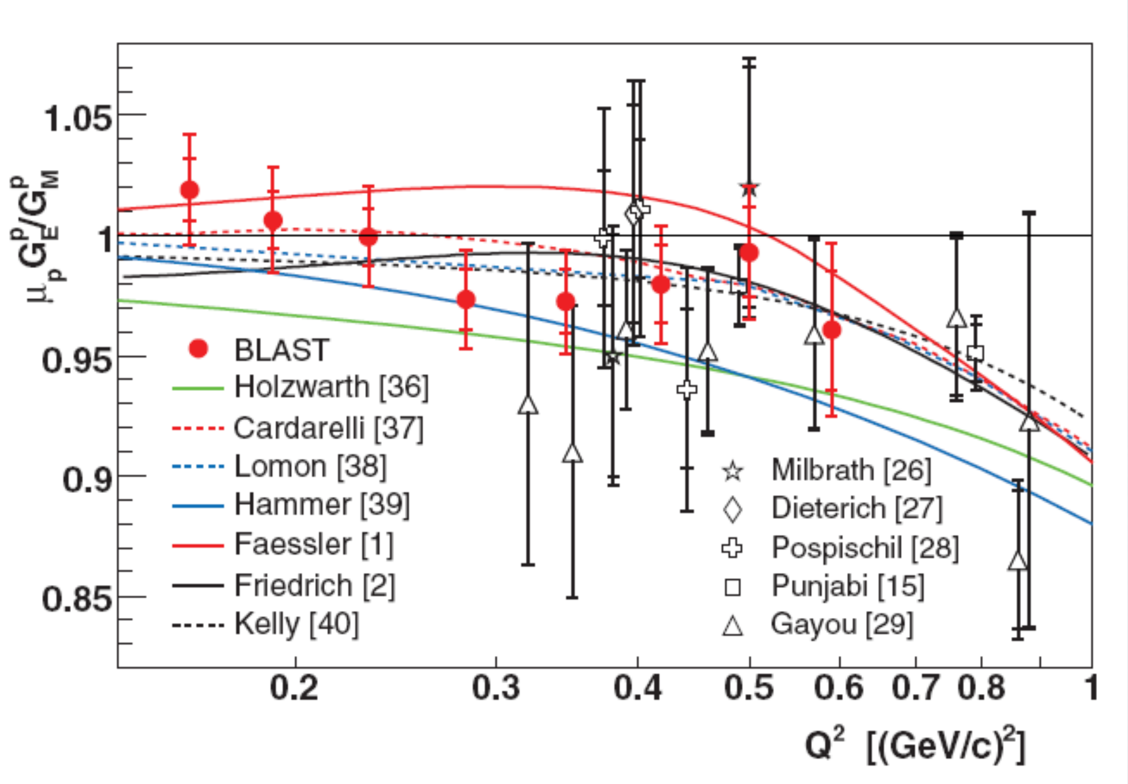
- High precision cross section survey down to $Q^2 \sim 0.01 \mathrm{GeV}^2$.
- Preliminary results for XS vs. scattering angle already shown.
- F&W analysis not supported.

Low Q^2 Notable Results

BLAST @ MIT Bates - proton

C.B. Crawford et al., Phys. Rev. Lett. 98, 052301 (2007)

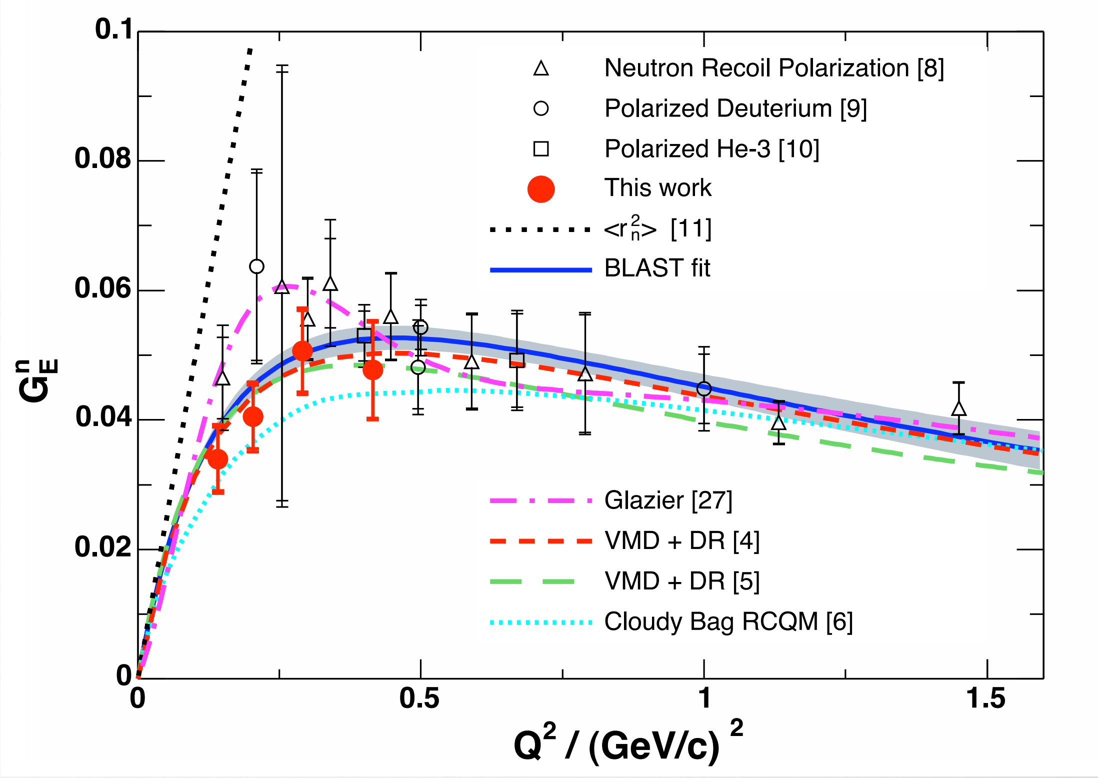
- Beam target asymmetry measurement using polarized H internal gas target.
- (Barely) consistent with unity and the F&W analysis.



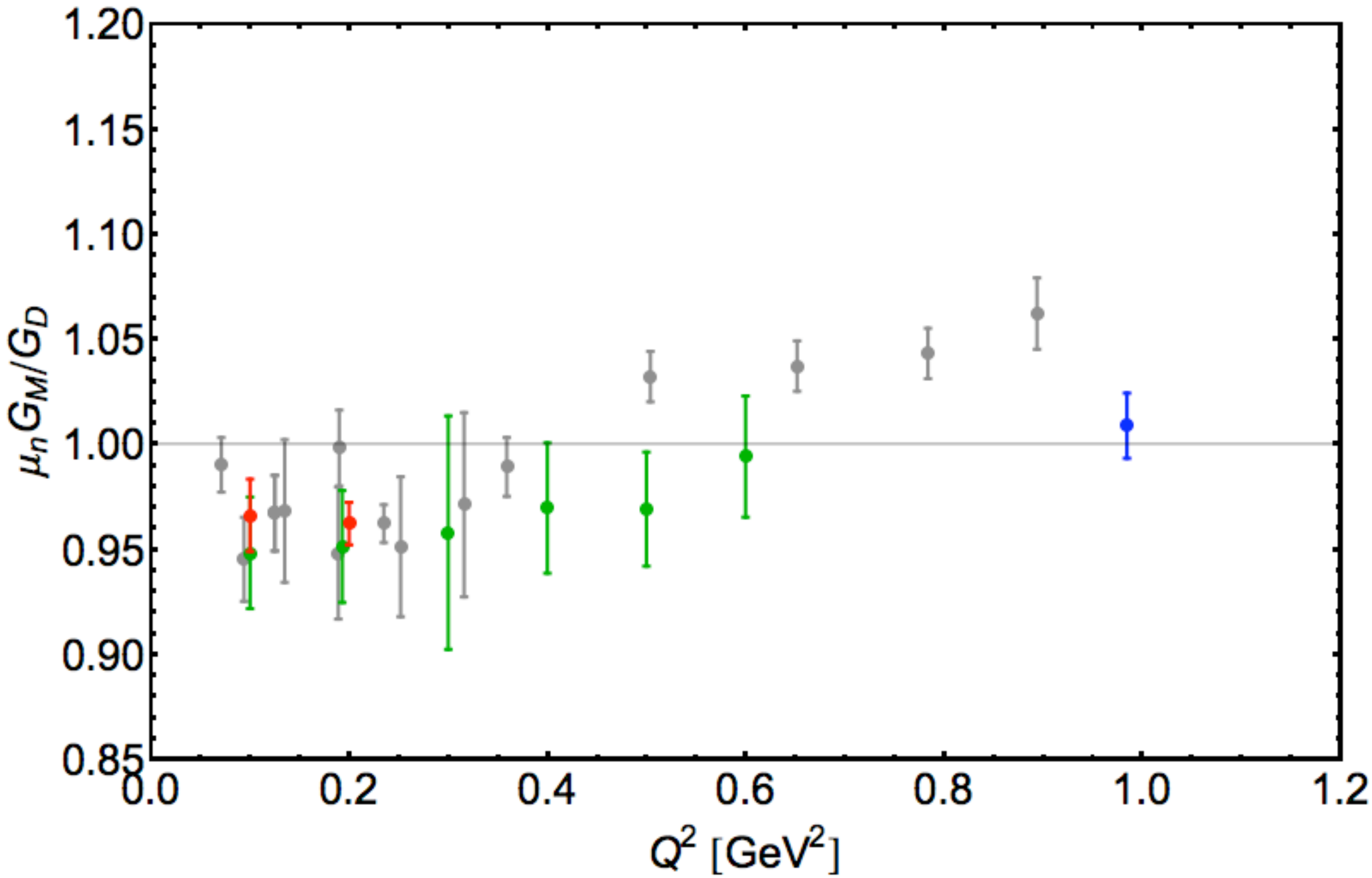
BLAST @ MIT Bates - neutron

E. Geis et al., Phys. Rev. Lett. 101, 042501 (2008)

- Beam target asymmetry measurement using vector polarized ^{2}H internal gas target.
- Inconsistent with Bump/Dip structure.



The JLab low Q^2 program
Neutron FFs - G_M



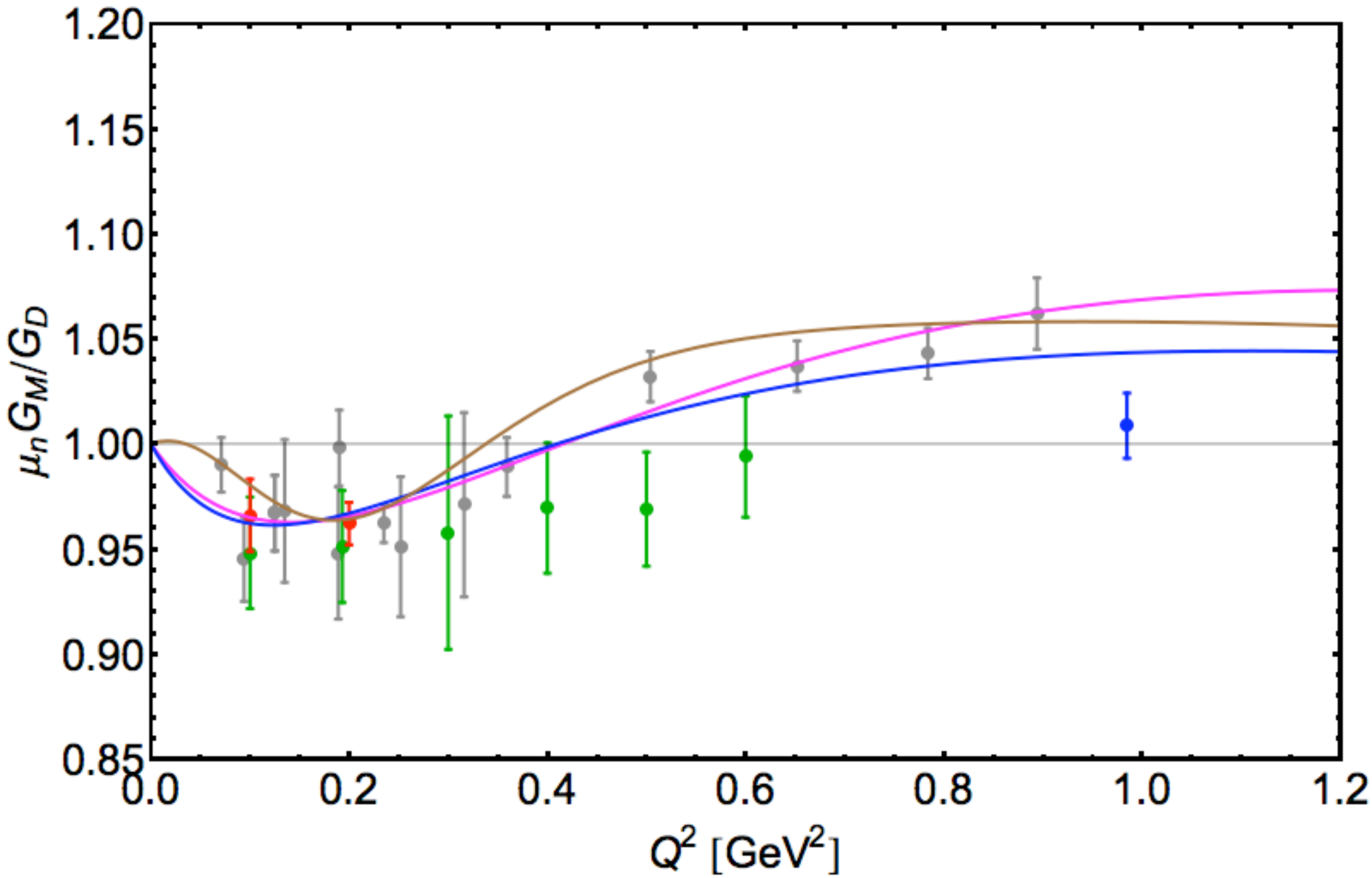
B. Anderson et al., Phys. Rev. C 75, 034003 (2007)

J. Golack et al., Phys. Rev. C 63, 034006 (2001)

J. Lachniet et al., Phys. Rev. Lett. 102, 192001 (2009)

The JLab low Q^2 program

Neutron FFs - G_M

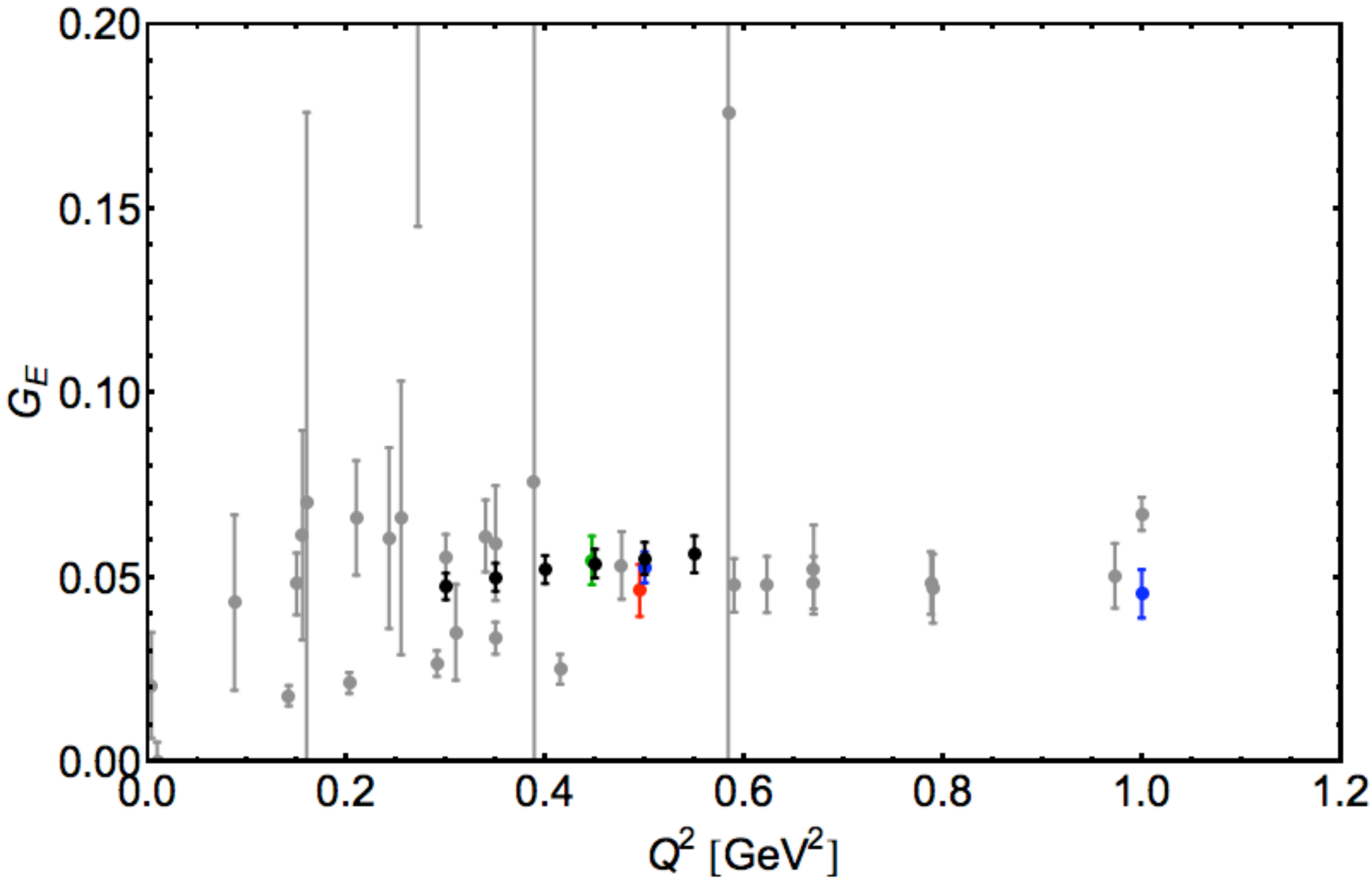


B. Anderson et al., Phys. Rev. C 75, 034003 (2007)
J. Golack et al., Phys. Rev. C 63, 034006 (2001)
J. Lachniet et al., Phys. Rev. Lett. 102, 192001 (2009)

J. Kelly, Phys. Rev. C 70, 068202 (2004)
W. M. Alberico, Phys. Rev. C 79. 065204 (2009)
J. Friedrich & Th. Walcher, EPJA 17, 607 (2003)

The JLab low Q^2 program

Neutron FFs - G_E



B. Plaster et al., Phys. Rev. C 73, 025205 (????)

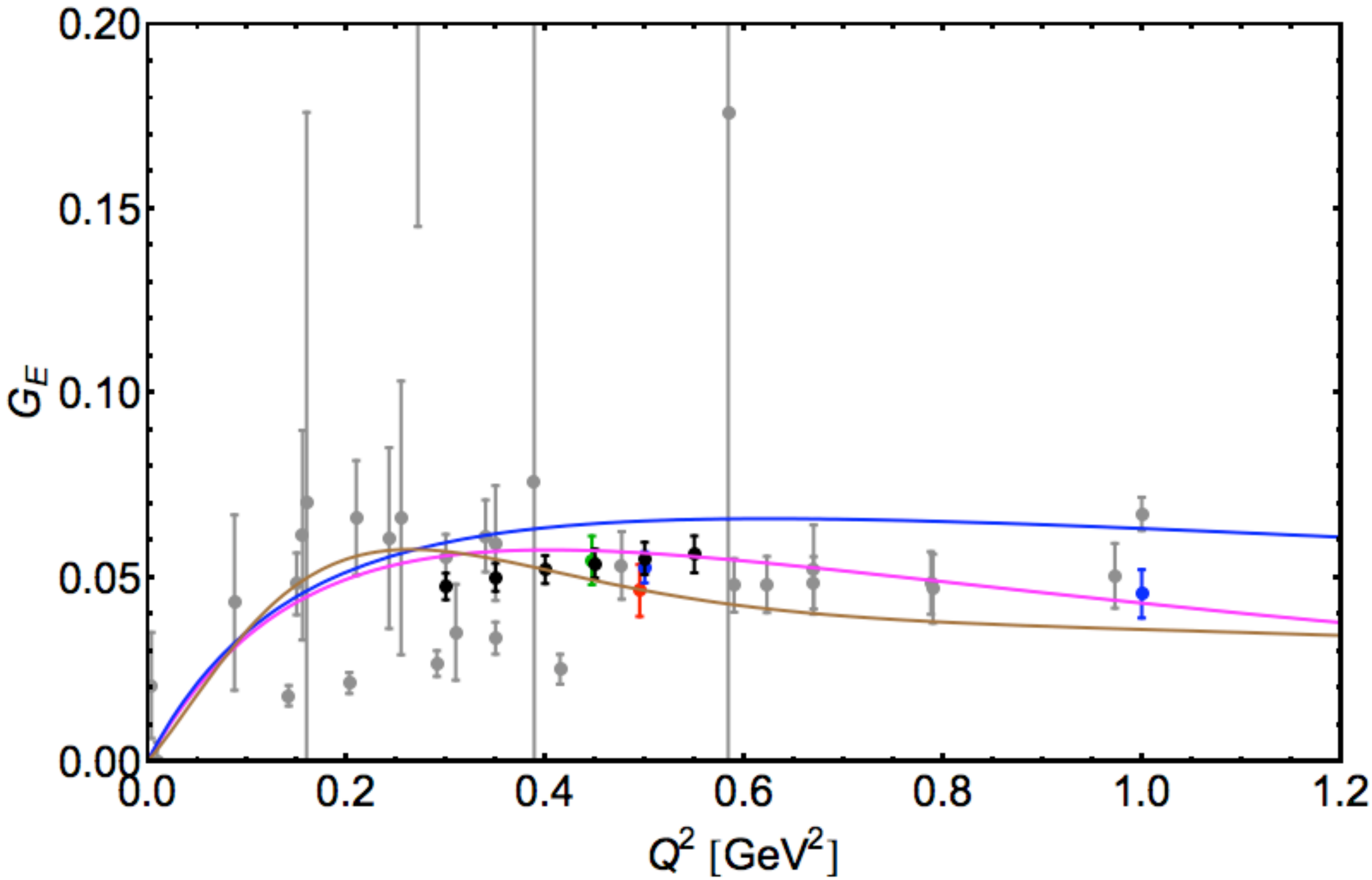
H. Zhu et al., Phys. Rev. Lett. 87, 081801 (2001)

G. Warren et al., Phys. Rev. Lett. 92, 042301 (2004)

J. Golack et al., Phys. Rev. C 63, 034004 (2001)

The JLab low Q^2 program

Neutron FFs - G_E



B. Plaster et al., Phys. Rev. C 73, 025205 (????)

H. Zhu et al., Phys. Rev. Lett. 87, 081801 (2001)

G. Warren et al., Phys. Rev. Lett. 92, 042301 (2004)

J. Golack et al., Phys. Rev. C 63, 034004 (2001)

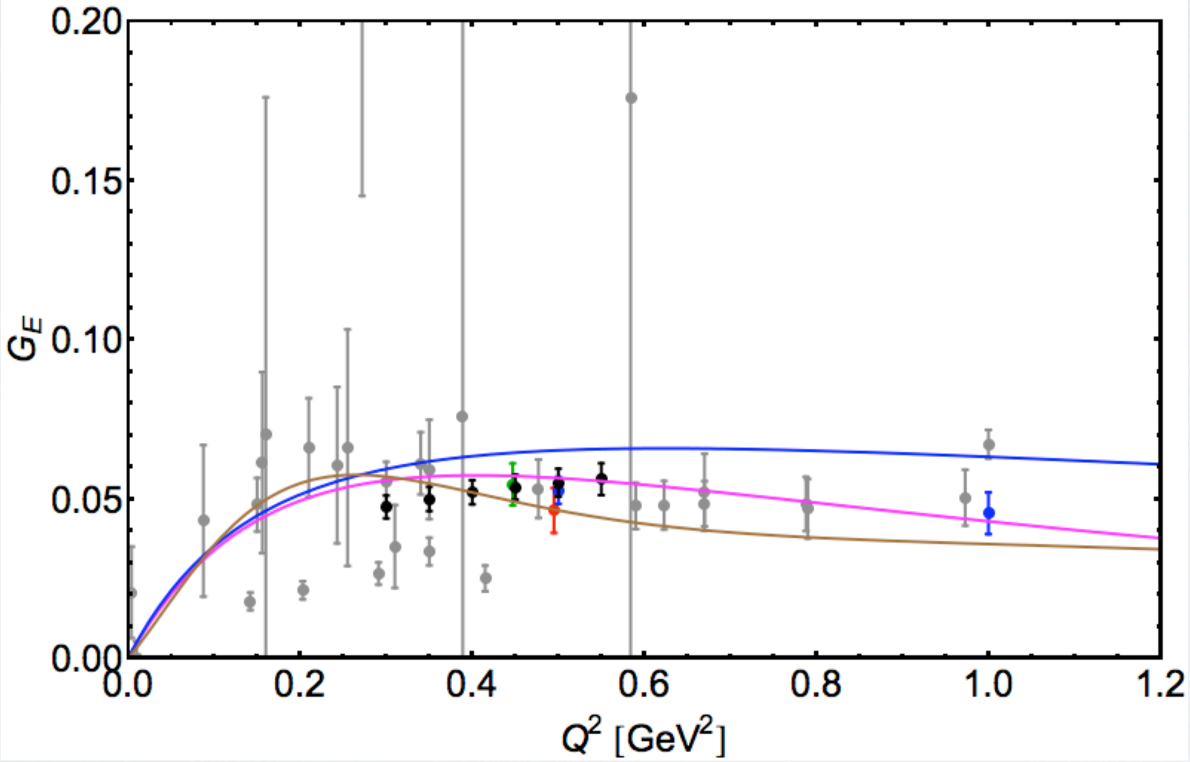
J. Kelly, Phys. Rev. C 70, 068202 (2004)

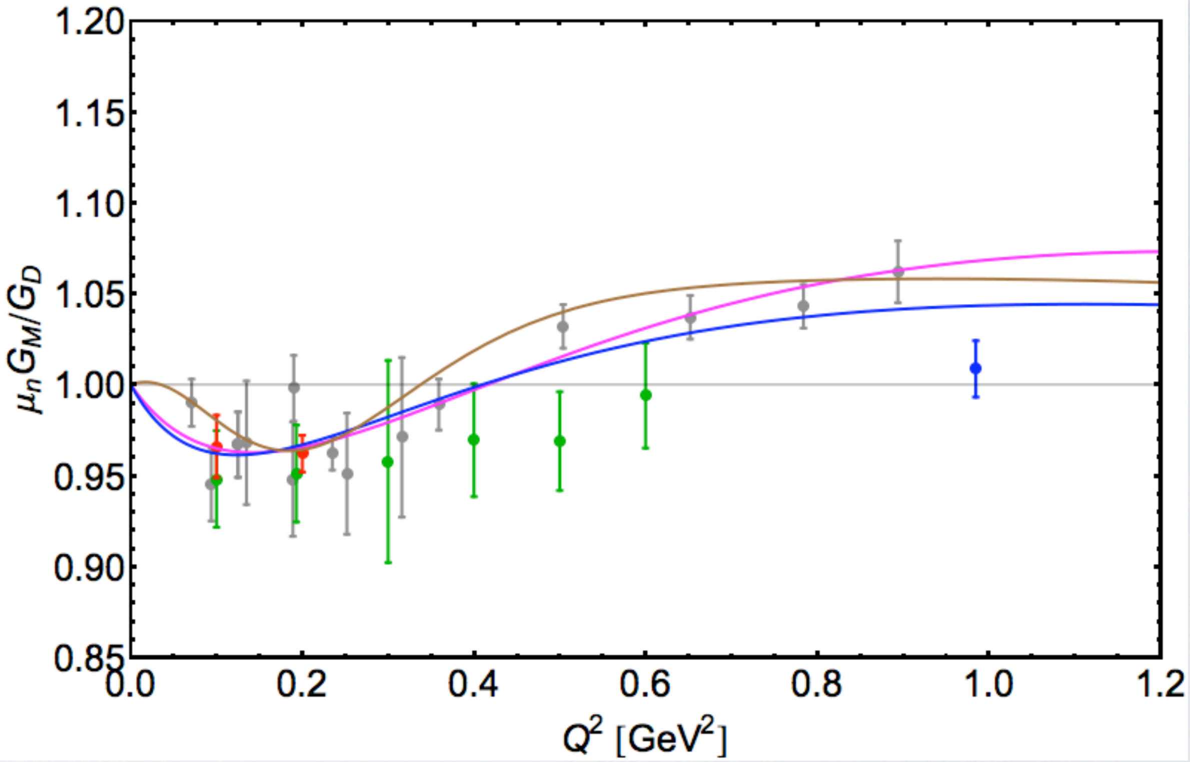
W. M. Alberico, Phys. Rev. C 79. 065204 (2009)

J. Friedrich & Th. Walcher, EPJA 17, 607 (2003)

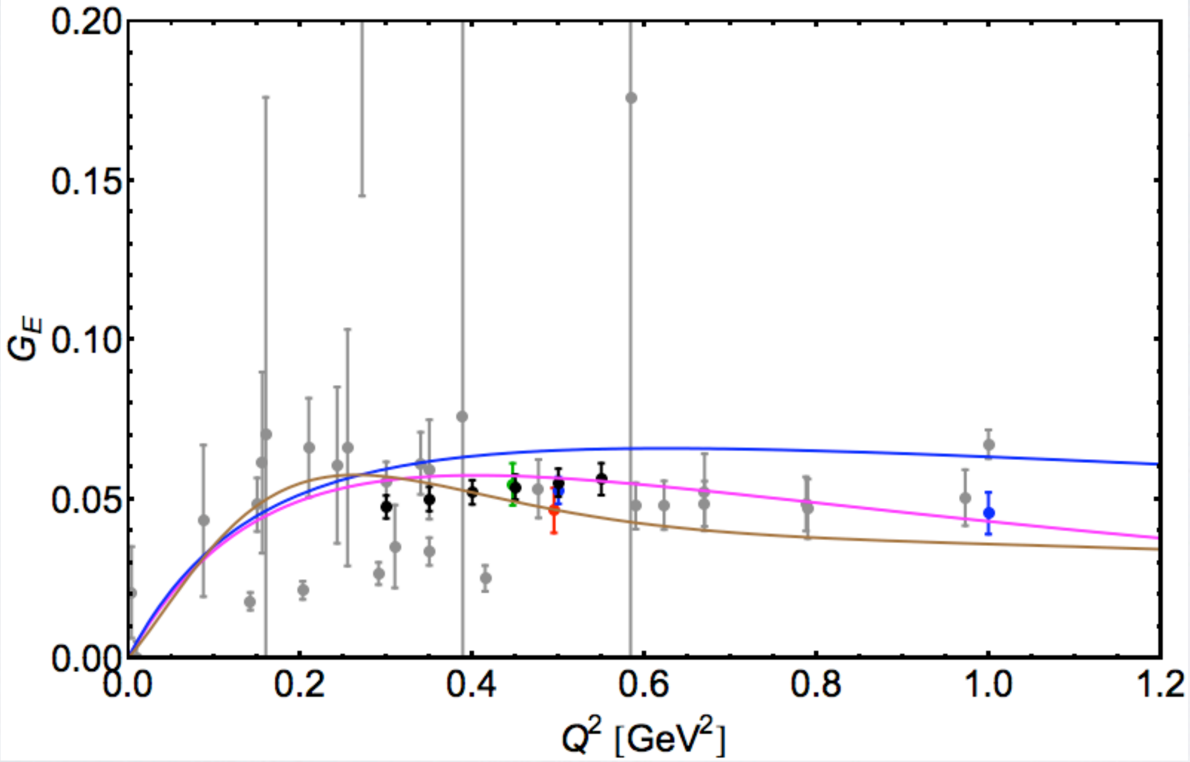
The JLab low Q^2 program

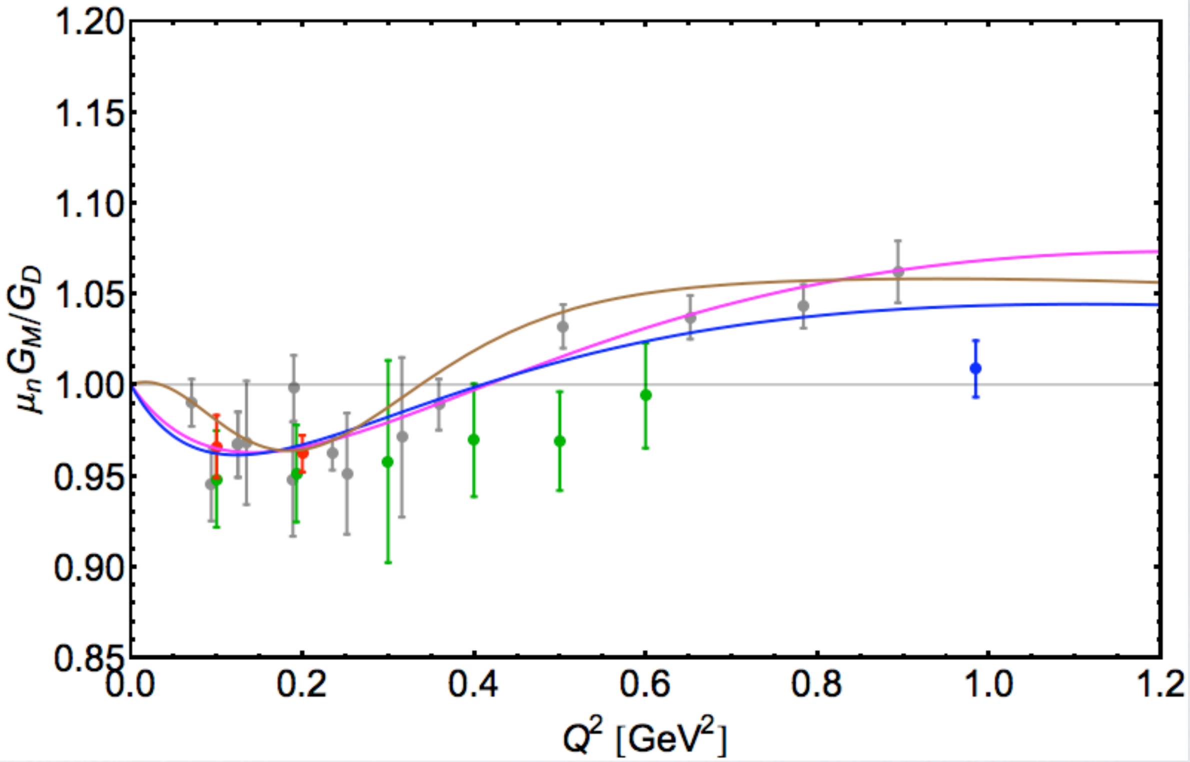
Neutron FFs - What we've learned





The JLab low Q^2 program
Neutron FFs - What we've learned





More data needed at low Q^2
(but currently no plans).
F&W parameterization seems not to fit data.

The JLab low Q^2 program
Proton FFs

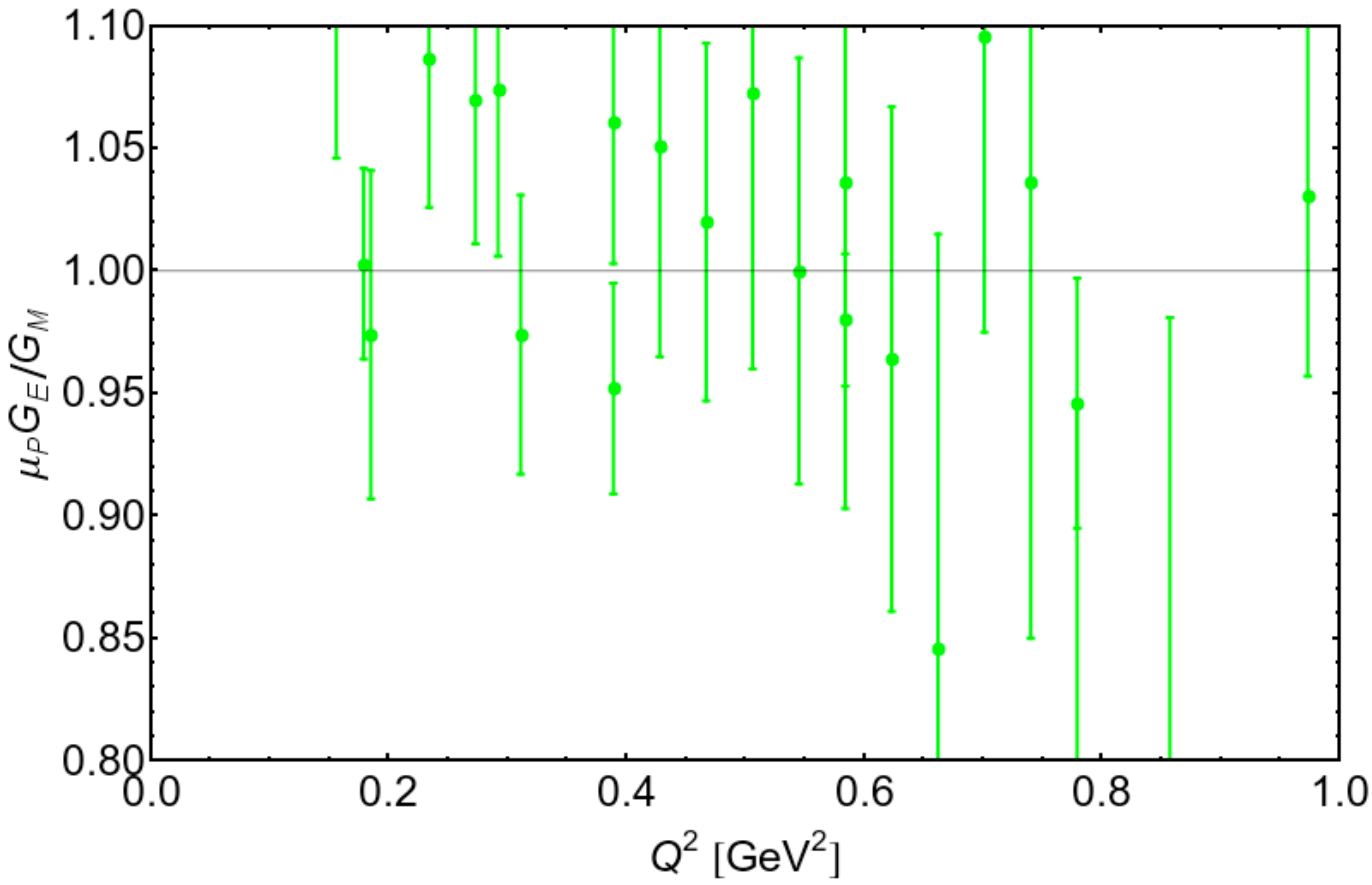
- LEDEX -
  - Parasitic to G0.
  - Recoil polarization measurement of the FF ratio.
  - Calibration run form γD measurement.
  - 8 Q^2 data points (0.25 - 0.5 GeV^2) with ~ 1.5% uncertainty on best data points.
  - Led to the proposal of:

The JLab low Q^2 program
Proton FFs

- LEDEX -
  - Parasitic to G0.
  - Recoil polarization measurement of the FF ratio.
  - Calibration run form γD measurement.
  - 8 Q^2 data points (0.25 - 0.5 GeV^2) with ~ 1.5% uncertainty on best data points.
  - Led to the proposal of:
- E08-007 -
  - A dedicated 2 part experiment to map the proton FF ratio at low Q^2.
  - First part used recoil polarization to achieve:
    - ~ 1% uncertainty (*best ever achieved*) at Q^2~ 0.3 - 0.7 GeV^2.
  - Second part will use beam target asymmetry (more later).

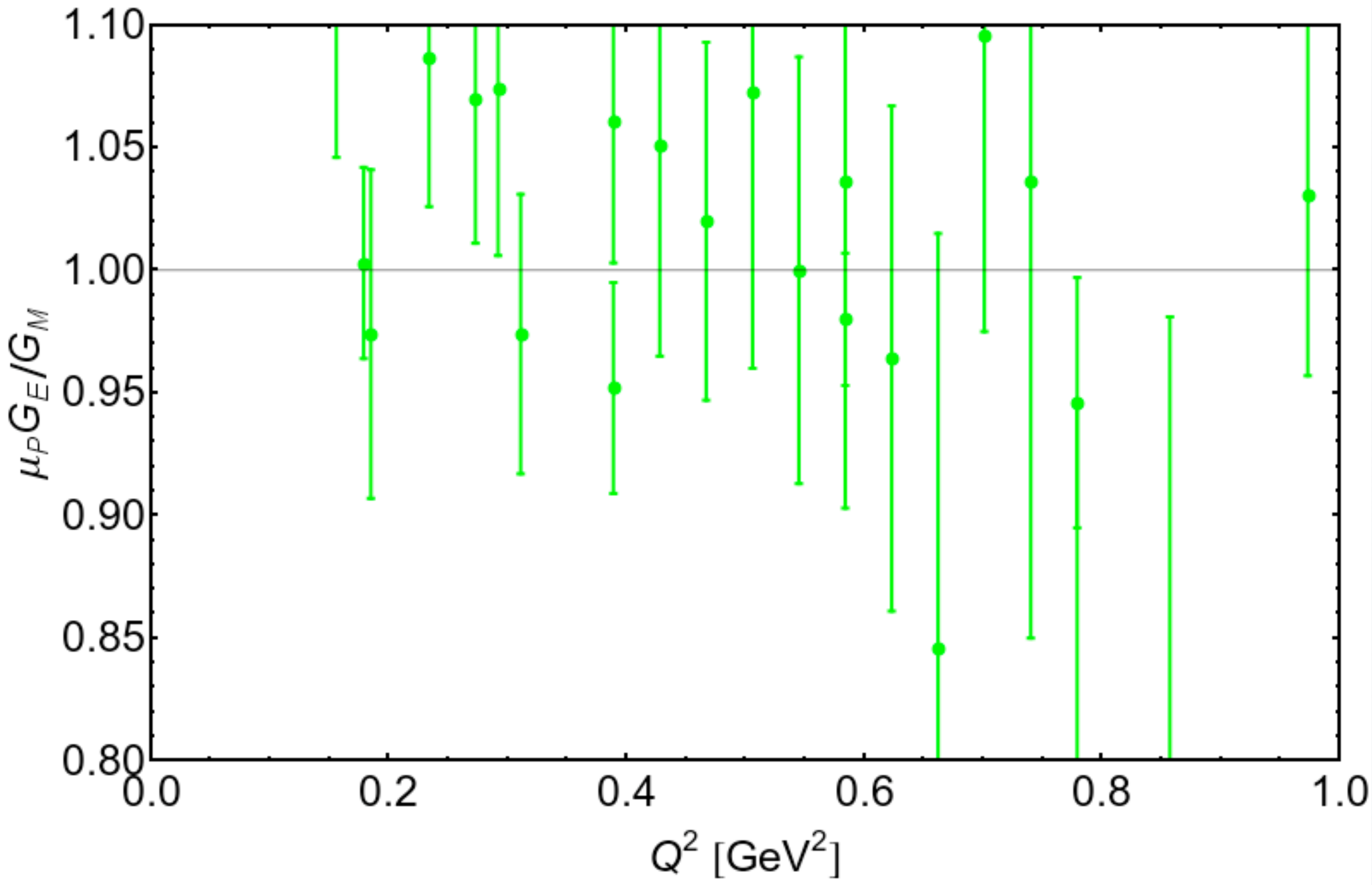
A Sense of Scale

Rosenbluth



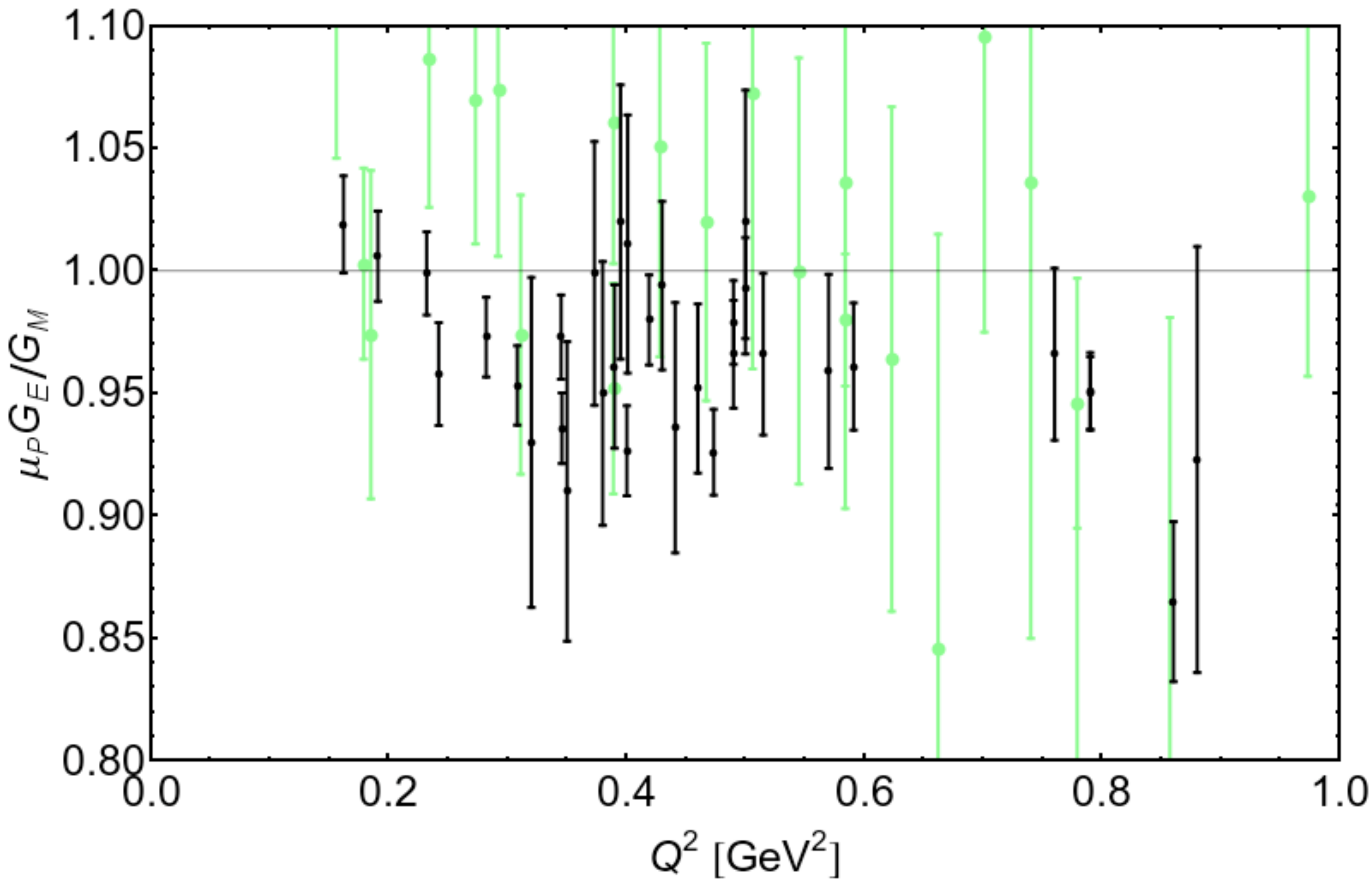
A Sense of Scale

Rosenbluth



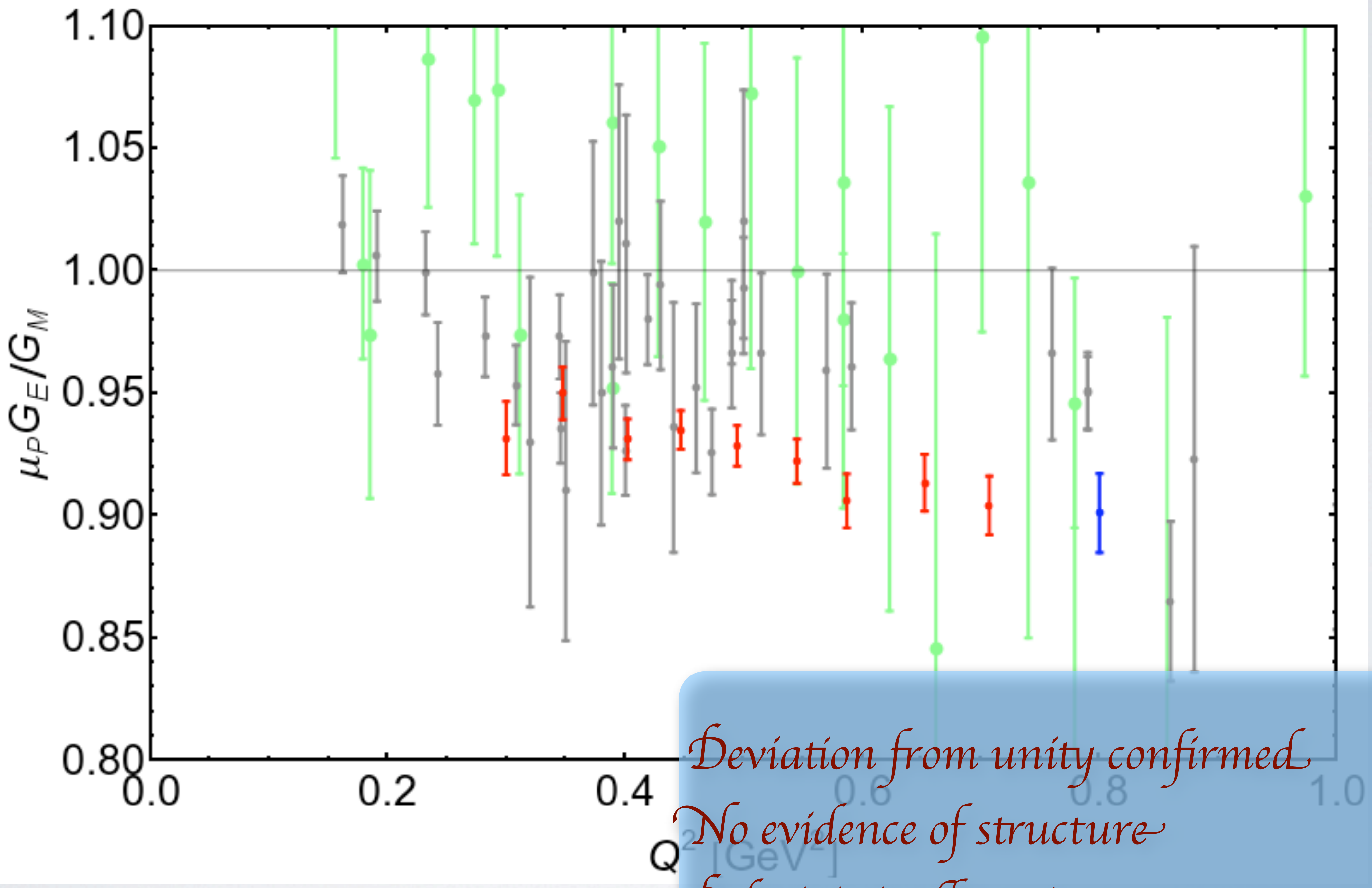
A Sense of Scale

World Polarization Data



A Sense of Scale

E08007 - Part I



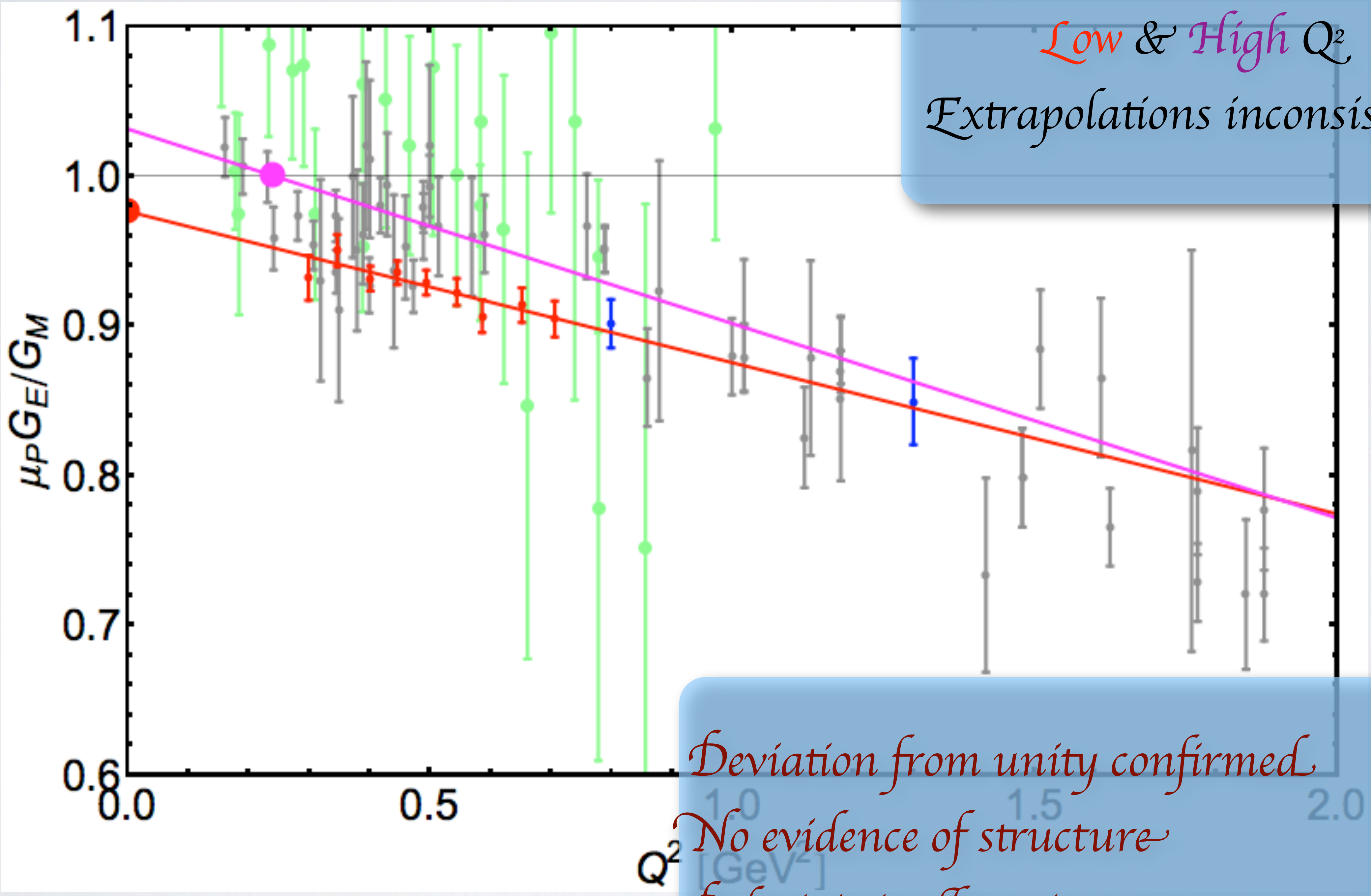
Deviation from unity confirmed

No evidence of structure

Relativistic effects important even at low Q^2

A Sense of Scale

E08007 - Part I



Low & High Q^2

Extrapolations inconsistent.

Deviation from unity confirmed

No evidence of structure

Relativistic effects important even at low Q^2

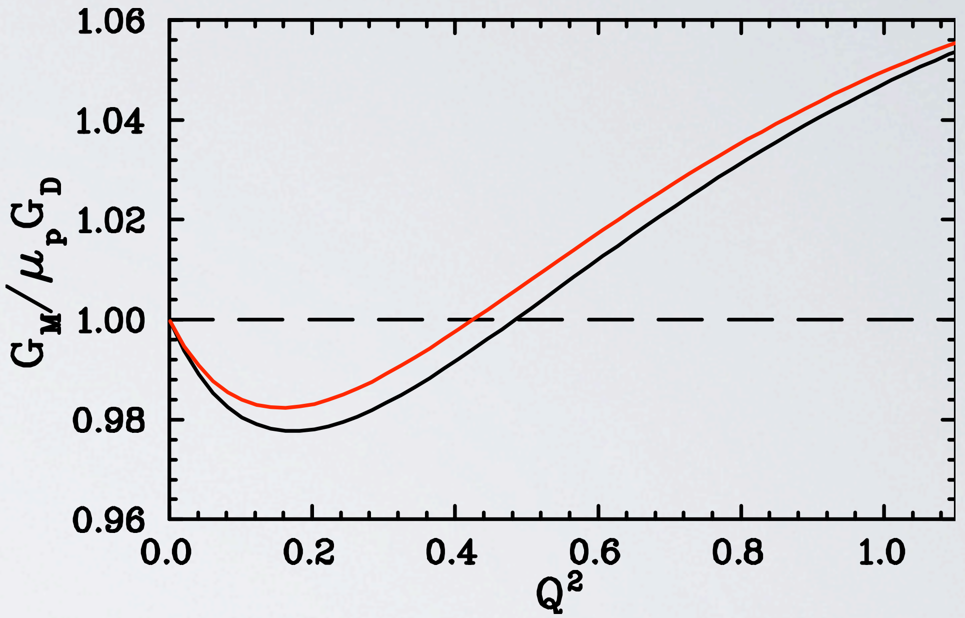
What we've learned

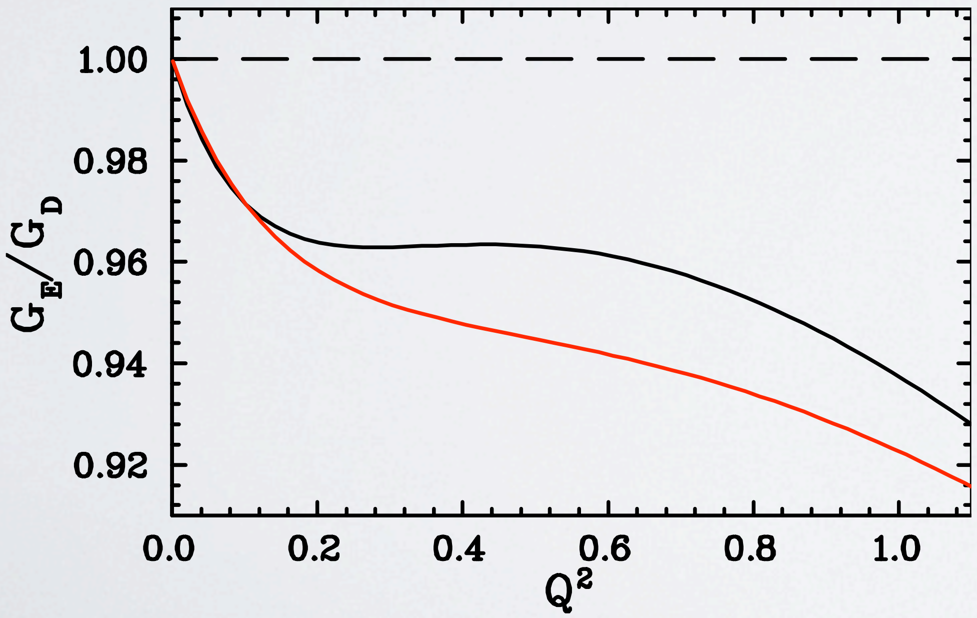
Recent Fits

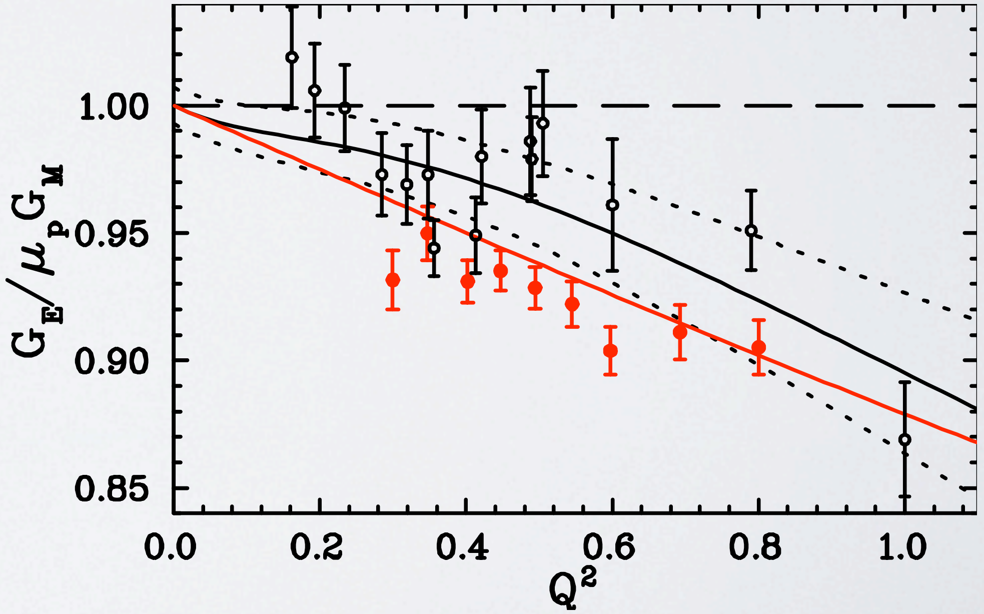
- Plots compare (2007) AMT fit to fit using newest data.

- New fits reduce G_E by ~ 2%.

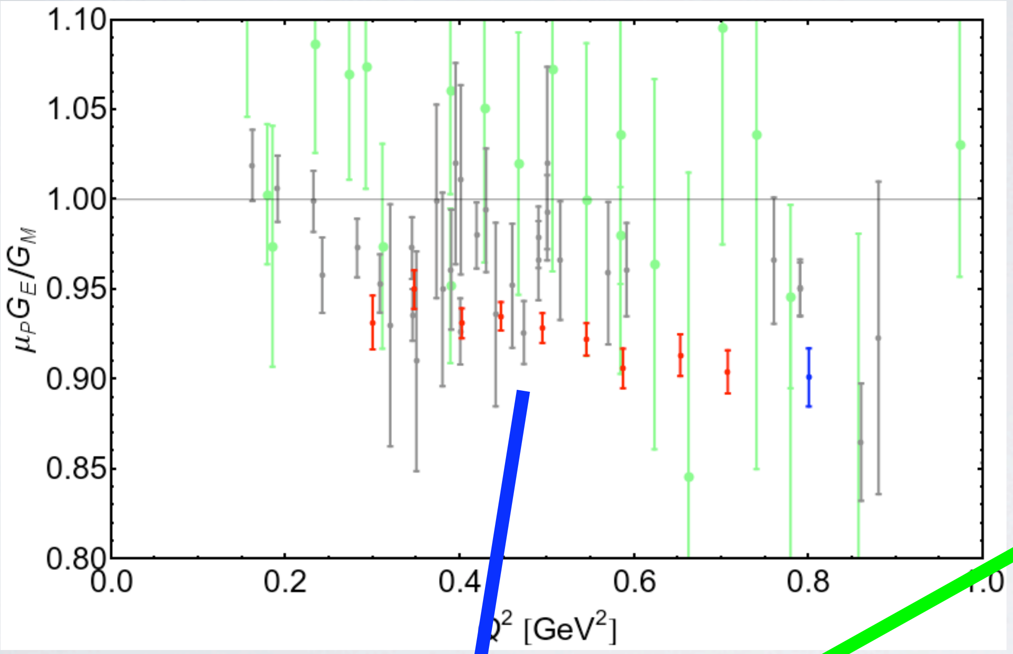
- Slope as $Q^2 \rightarrow 0$ changed (impacts radii).







Extracting the individual FFs



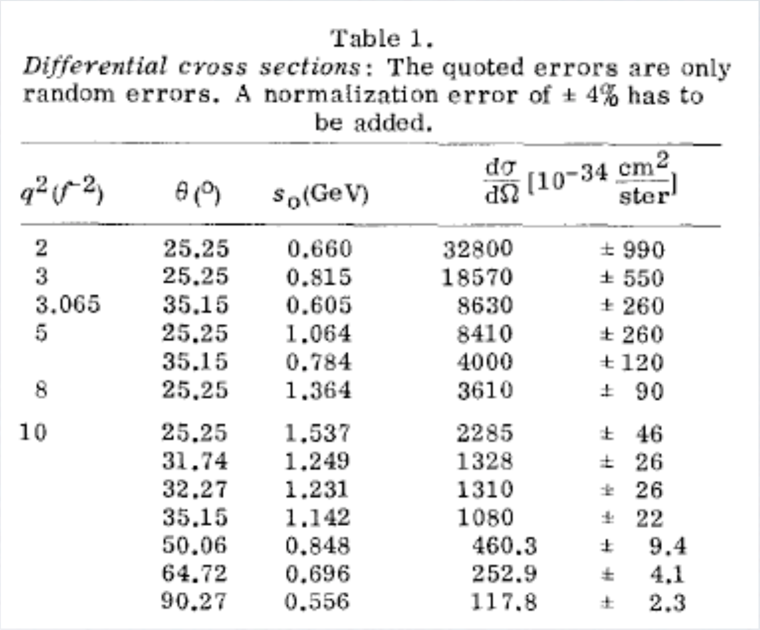
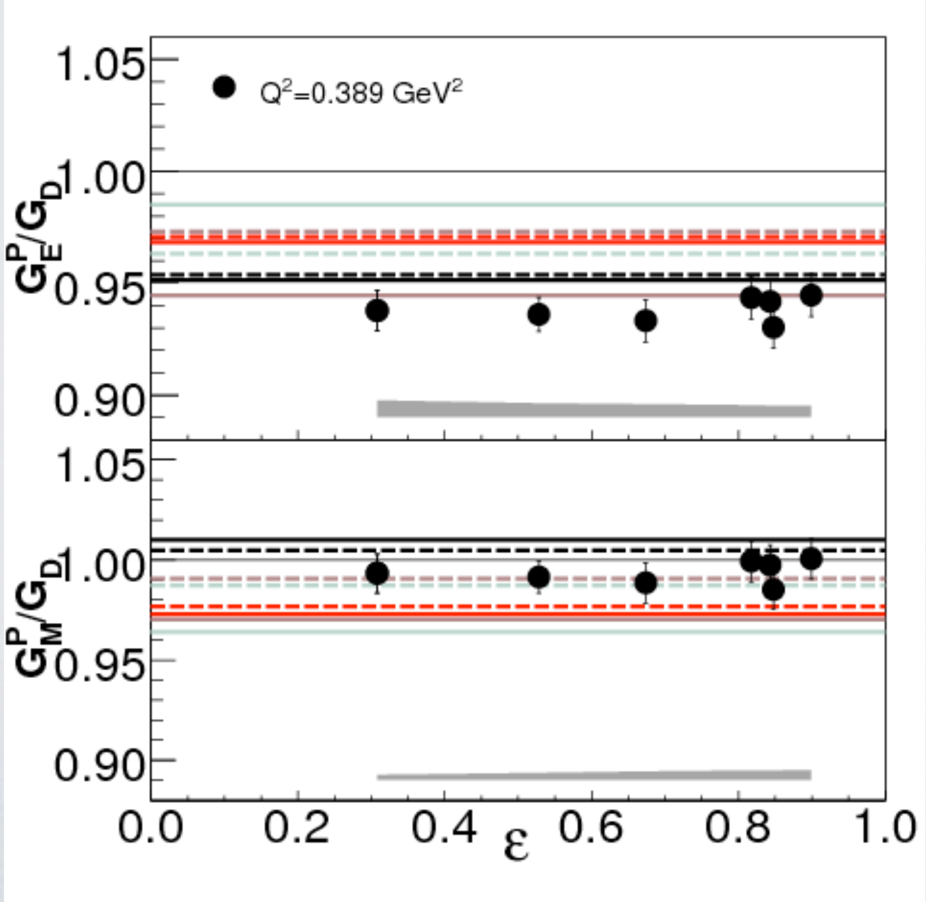


Table 1.
Differential cross sections: The quoted errors are only random errors. A normalization error of ± 4% has to be added.

$q^2 (f^{-2})$	θ (°)	s_0(GeV)	$\frac{d\sigma}{d\Omega}$ [10^{-34} $\frac{cm^2}{ster}$]	
2	25.25	0.660	32800	± 990
3	25.25	0.815	18570	± 550
3.065	35.15	0.605	8630	± 260
5	25.25	1.064	8410	± 260
	35.15	0.784	4000	± 120
8	25.25	1.364	3610	± 90
10	25.25	1.537	2285	± 46
	31.74	1.249	1328	± 26
	32.27	1.231	1310	± 26
	35.15	1.142	1080	± 22
	50.06	0.848	460.3	± 9.4
	64.72	0.696	252.9	± 4.1
	90.27	0.556	117.8	± 2.3



High precision cross section and FFR combined → High precision individual form factors.

Deviation from unity (at least for Q^2 ~ 0.39 GeV^2) caused by G_E.

Will eventually combine with high precision Mainz XS database.

G. Ron et al., Phys. Rev. Lett. 99, 202002 (2007)

What we've learned

Charge Densities

- Sachs FFs cannot be related to charge/magnetization densities:

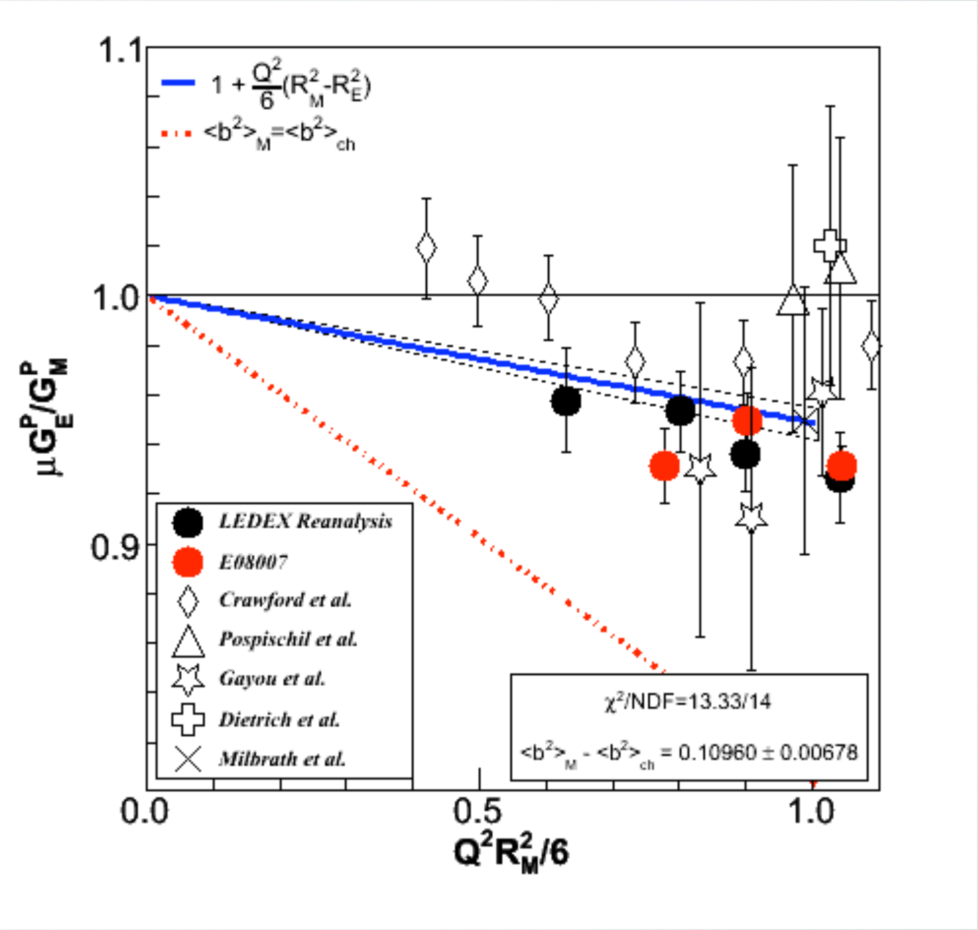
$$\rho_{Ch}(\vec{b}) = \mathcal{F}^{-1}\left[F_1(Q^2)\right]$$
$$\rho_M(\vec{b}) = \mathcal{F}^{-1}\left[F_2(Q^2)\right]$$

- Relativistic effects (Lorentz contraction).
- Initial/Final states not identical (cannot be interpreted as density).
- Can be shown that F_1 & F_2 are 2D transforms of charge and magnetization densities.
- Low Q^2 expansion gives:

$$\langle b^2\rangle_M - \langle b^2\rangle_{Ch} = \frac{\mu}{\kappa}\frac{2}{3}(R_M^{*2} - R_E^{*2}) + \frac{\mu}{M^2}$$

- And fit to data gives:

$$\left\langle b^2\right\rangle_M - \left\langle b^2\right\rangle_{ch} = 0.0909 \pm 0.0039\ \mathrm{fm}^2$$



G. Miller, Phys. Rev. Lett. 99, 112001 (2007)

G. Miller, E. Piasetzky & G. Ron, Phys. Rev. Lett. 101, 082002 (2008)

What we've learned

Charge Densities

- Sachs FFs cannot be related to charge/ magnetization densities:

- Relativistic effects (Lorentz contraction).

- Initial/Final states not identical (cannot be interpreted as density).

- Can be shown that F_1 & F_2 are 2D transforms of charge and magnetization densities.

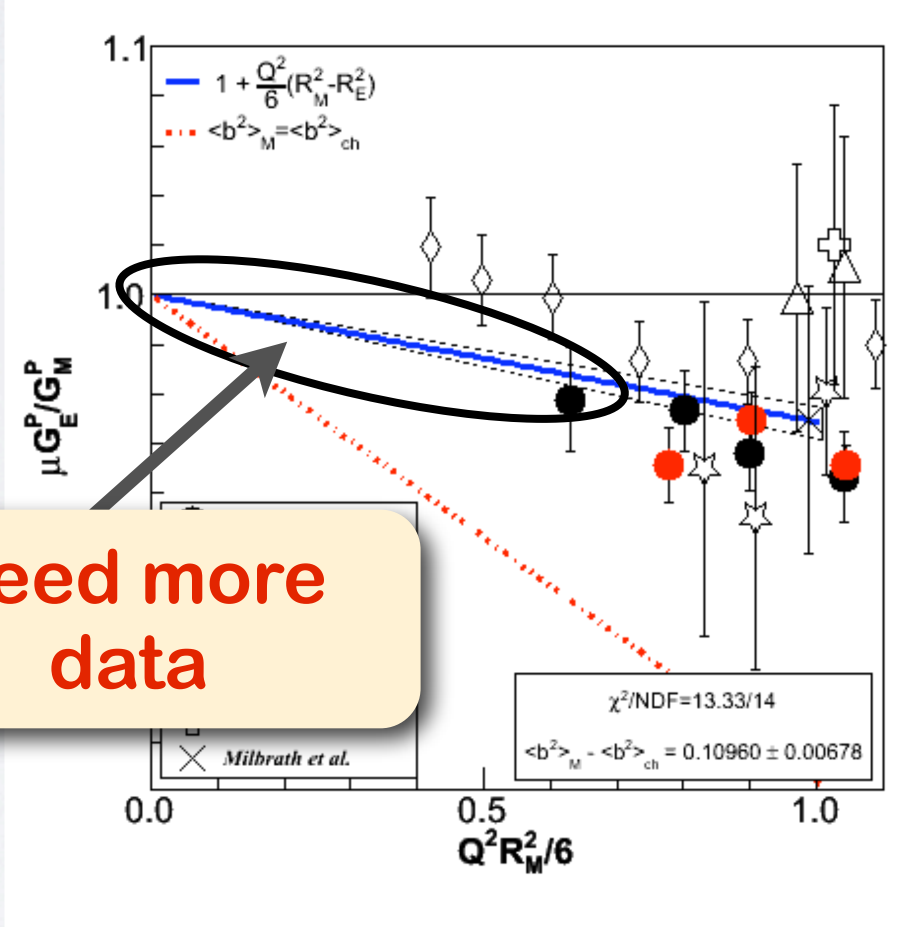
- Low Q^2 expansion gives:

$$\langle b^2 \rangle_M - \langle b^2 \rangle_{Ch} = \frac{\mu}{\kappa}\frac{2}{3}(R_M^{*2} - R_E^{*2}) + \frac{\mu}{M^2}$$

- And fit to data gives:

$$\left\langle b^2 \right\rangle_M - \left\langle b^2 \right\rangle_{ch} = 0.0909 \pm 0.0039 \text{ fm}^2$$

$$\rho_{Ch}(\vec{b}) = \mathcal{F}^{-1}\left[F_1(Q^2)\right]$$
$$\rho_M(\vec{b}) = \mathcal{F}^{-1}\left[F_2(Q^2)\right]$$



Need more data

G. Miller, Phys. Rev. Lett. 99, 112001 (2007)

G. Miller, E. Piasetzky & G. Ron, Phys. Rev. Lett. 101, 082002 (2008)

The Zemach Radius

- Hyperfine splitting of the hydrogen ground state:

$$E_{hfs}(e^- p) = \left(1 + \Delta_{QED} + \Delta_R^P + \Delta_{h\nu p}^P + \Delta_{\mu\nu p}^P + \Delta_{weak}^P + \Delta_S\right) E_F^P$$

$$\Delta_S = \Delta_Z + \Delta_{pol}, \ \Delta_Z = -2\alpha m_e r_Z \left(1 + \delta_Z^{rad}\right)$$

- Zemach radius (effect of proton internal structure on energy level shift):

$$r_Z = -\frac{4}{\pi} \int_0^\infty \frac{dQ}{Q^2} \left[G_E(Q^2) \frac{G_M(Q^2)}{1 + \kappa_P} - 1 \right]$$

- Sensitivity to details in the FFs is completely contained in the $Q^2 < 1$ GeV^2 region.

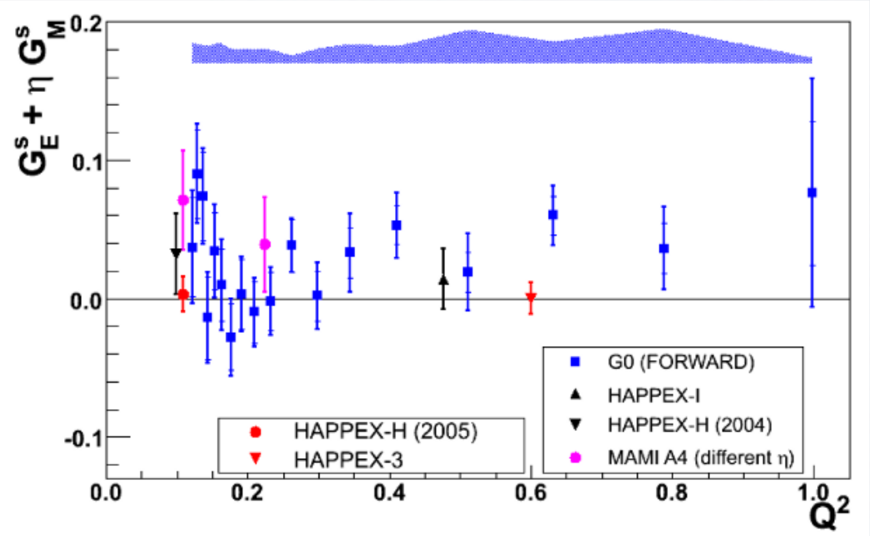
- Leading theoretical uncertainty in one of the most precisely measured experimental quantities (test of QED).

FF	r_p [fm]	r_Z [fm]	ΔZ [ppm]
AMT	0.885	1.080	−41.43
AS	0.879	1.091	−41.85
Kelly	0.878	1.069	−40.99
F&W	0.808	1.049	−40.22
Dipole	0.851	1.025	−39.29
New	0.868	1.075	−41.22

PV Experiments

- Parity violation experiments aim to measure the strange quark content of the nucleon by detecting interference between elastic EM scattering and neutral weak ep scattering.
- Determination of strange quark form factors relies on knowledge of EMFF.
- Shifts of ~ 0.5σ "easy".

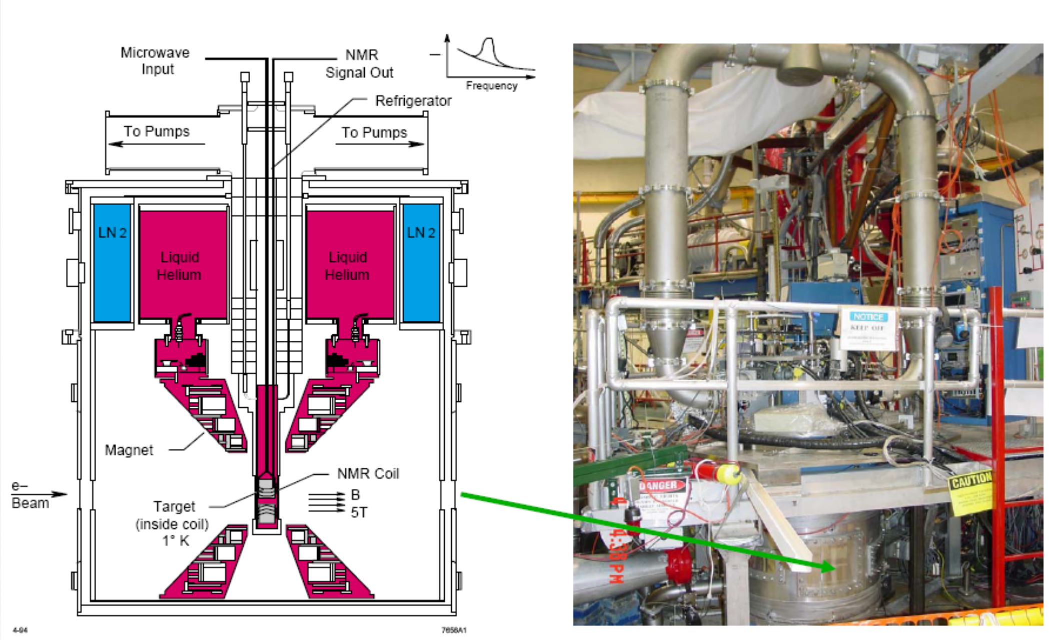
Q^2	$\Delta A/\sigma$	$\Delta A/A$	
0.38	0.42	1.6%	GO FWD
0.56	0.50	1.6%	GO FWD
1.0	0.30	0.8%	GO FWD
0.50	0.50	1.7%	HappexII
0.231	0.12	0.2%	GO BCK
0.65	0.14	0.3%	GO BCK

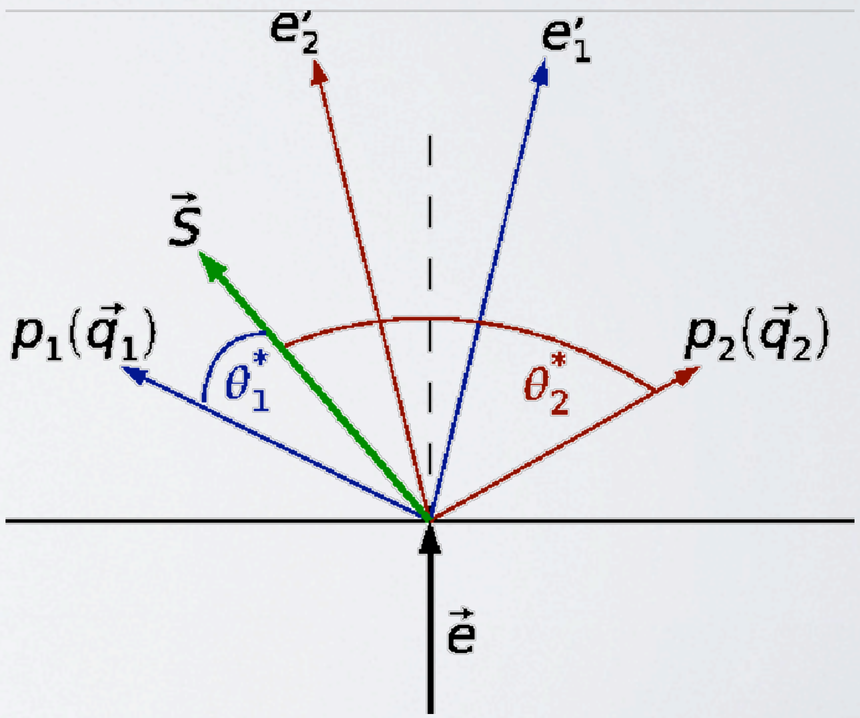


$$A^{PV} = \left[-\frac{G_F M_p^2 Q^2}{\pi\alpha\sqrt{2}}\right]\left[\left(1 - 4\sin^2\theta_W\right) - \frac{\varepsilon G_E^{p\gamma}\left(G_E^{n\gamma} + G_E^s\right) + \tau G_E^{p\gamma}\left(G_M^{n\gamma} + G_M^s\right)}{\varepsilon\left(G_E^{p\gamma}\right)^2 + \tau\left(G_M^{p\gamma}\right)^2}\right] - A_A$$

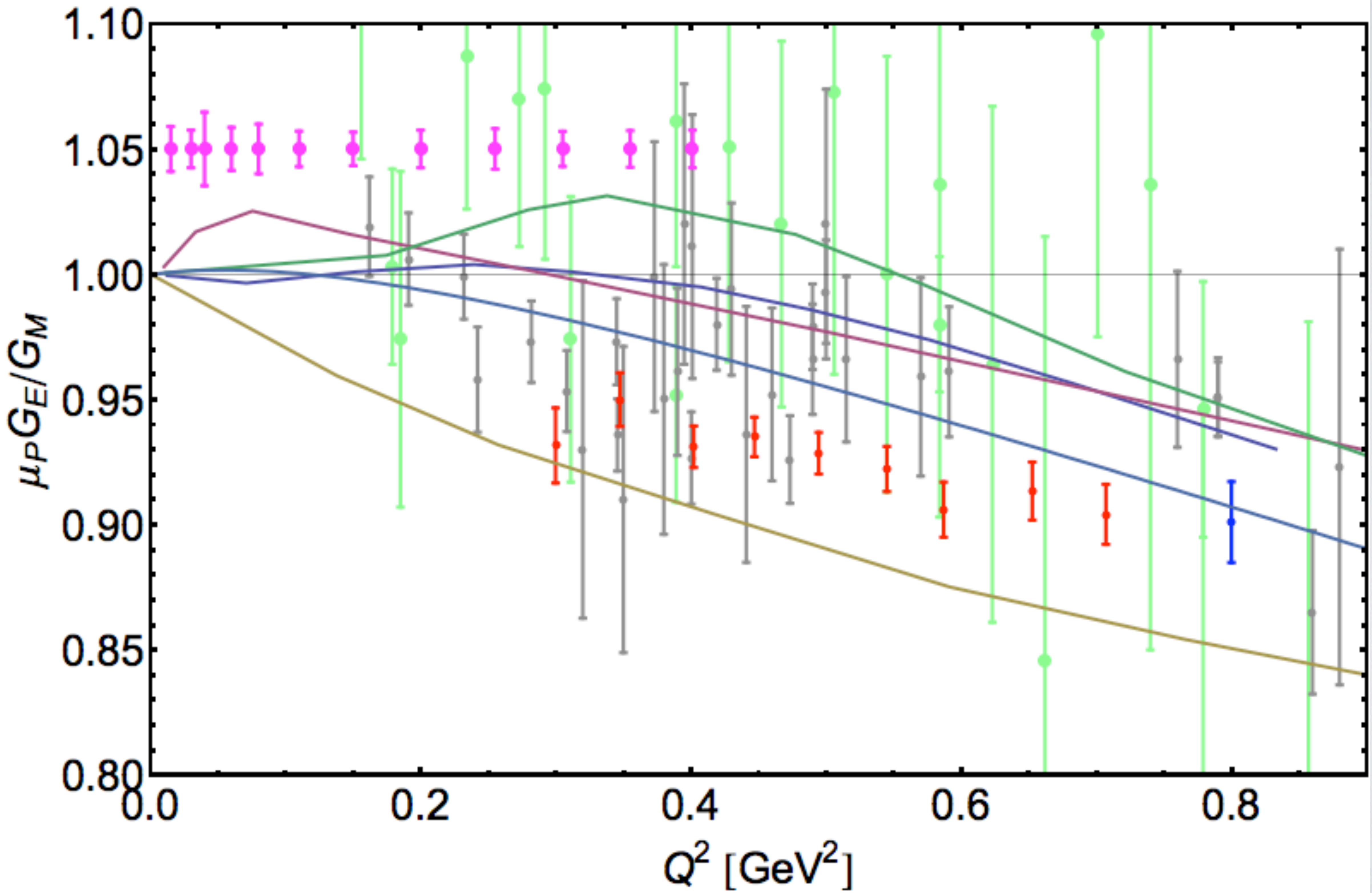
E08007 - Part II

- High precision (< 1%) survey of the FF ratio at Q^2=0.01 - 0.4 GeV^2.
- Beam-target asymmetry measurement by electron scattering from polarized NH_3 target.
- Electrons detected in two matched spectrometers.
- Ratio of asymmetries cancels systematic errors → only one target setting to get FF ratio.
- Designed to overlap E08007-I and Bates BLAST.
- Scheduled for 2012 (*but depends on budget...*)





E08007 - Part II
Projected uncertainties



Summary

- Form factors are physical, model-independent, observable of the nucleon.
- Many discoveries over the years have changed our understanding of one of the basic constituents of matter.
- While high energy (and Q^2) are, of course, important, there is great significance to performing low Q^2 measurements (only real way to discriminate between EFTs).
- Very high precision measurements are now possible and required for high precision experiments.
- It seems that there is no evidence (at least in the FF ratio) for narrow structures.
- One more high precision, low Q^2 experiment before the 12 GeV upgrade. Limited number of candidate facilities for more low Q^2 experiments.