Electromagnetic form factors for the proton, neutron, and pion

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*With significant contributions from
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Experimental Overview/Status

- Brief summary of status in mid-90s
- **New tools, techniques in the last 5-10 years**
- **New results in the next 3-4 years**
- Extensions with JLab@12 GeV

Issues that I think you care about

- Impact of FFs on constraining models
- Comparisons of proton, neutron
- Two-photon exchange corrections

**Synergy Between Experiment and Lattice QCD in Exploring Hadron Structure,
Institute for Nuclear Theory, University of Washington, April 24, 2006**

Unpolarized Elastic Scattering

$$\sigma_R\,(e\text{-}N) = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\sigma_{Mott}} = \tau G_M^2(Q^2) + \varepsilon G_E^2(Q^2)$$

$\tau = Q^2/4M^2$

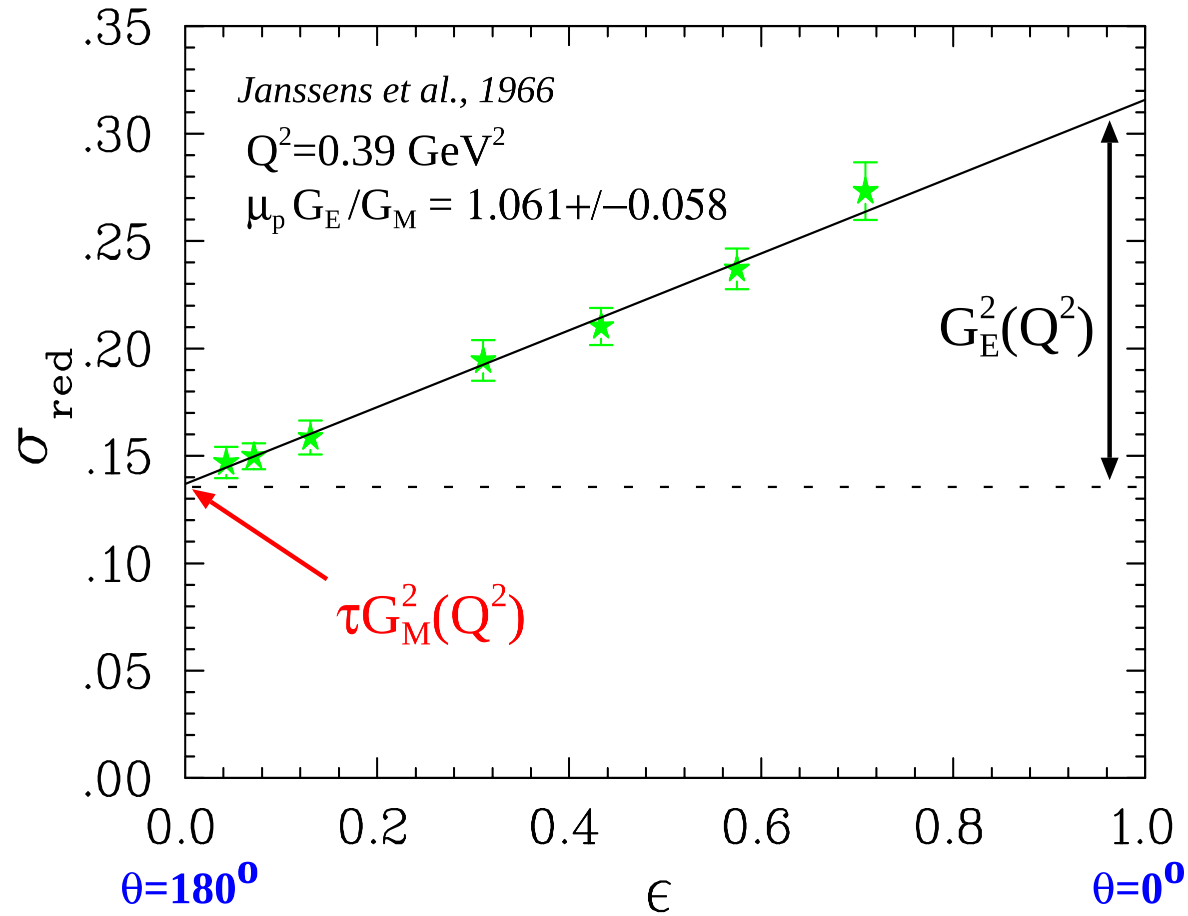
$\varepsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}$

Difficult to extract G_M if Q^2 is very small ($\tau << 1$)

Difficult to extract G_E when Q^2 is large ($\tau >> 1$) or when $G_E^2 << G_M^2$

e.g. for neutron

G_E very sensitive to angle- (ε-)dependent corrections



First nucleon form factor measurement-1955

Hofstadter and McAllister, Phys. Rev. ***98****, 217*

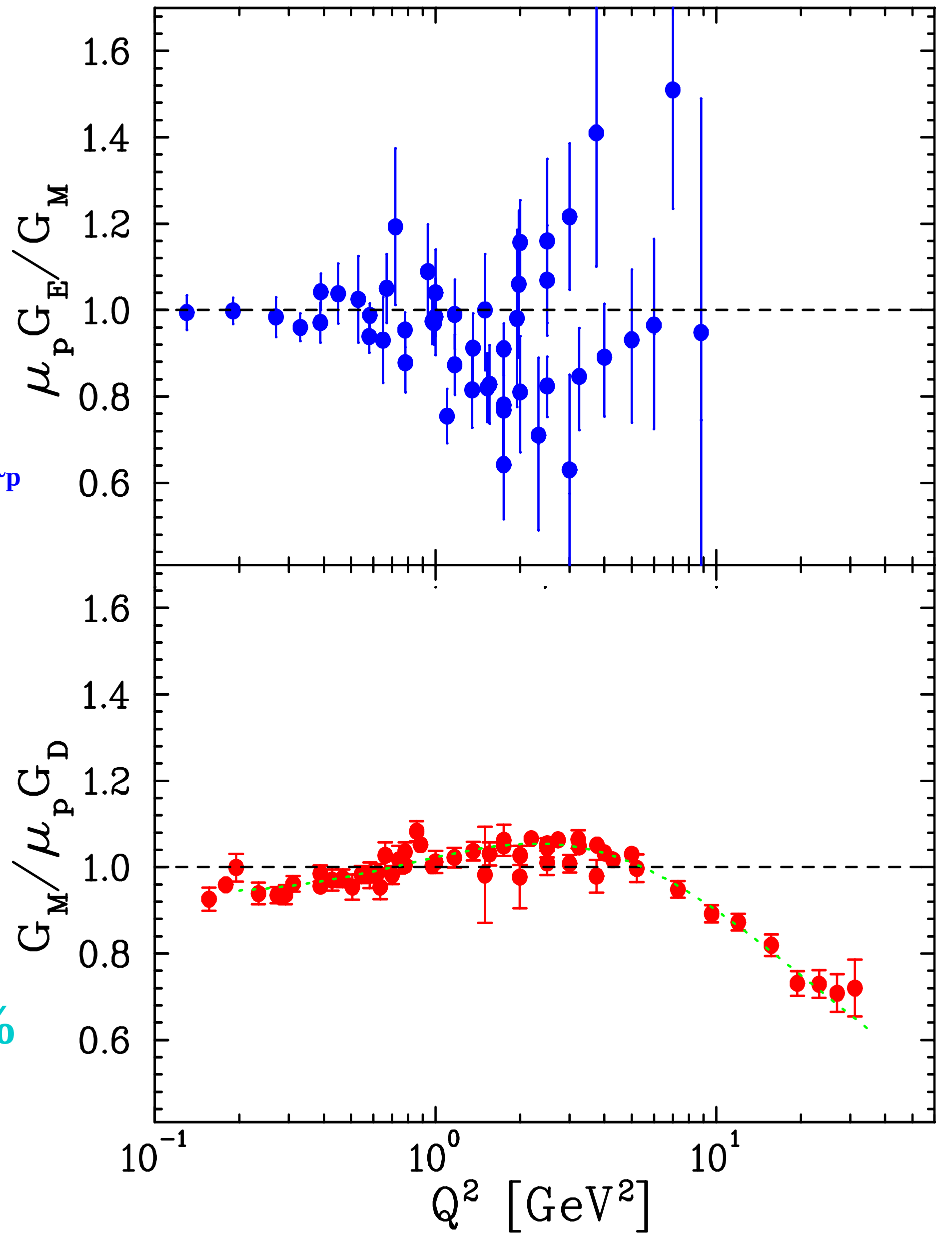
First Rosenbluth separations-1961

Bumiller, Croissiaux, Dally, and Hofstadter, Phys. Rev. ***124****, 144*

Olson, Schopper, and Wilson, PRL ***6****, 286*

Rosenbluth extractions of G_E^p and G_M^p

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



G_E^p extracted to ~10 GeV^2

Show approximate scaling: $G_E(Q^2) \sim G_M(Q^2)/\mu_p$

Identical charge, magnetization distributions

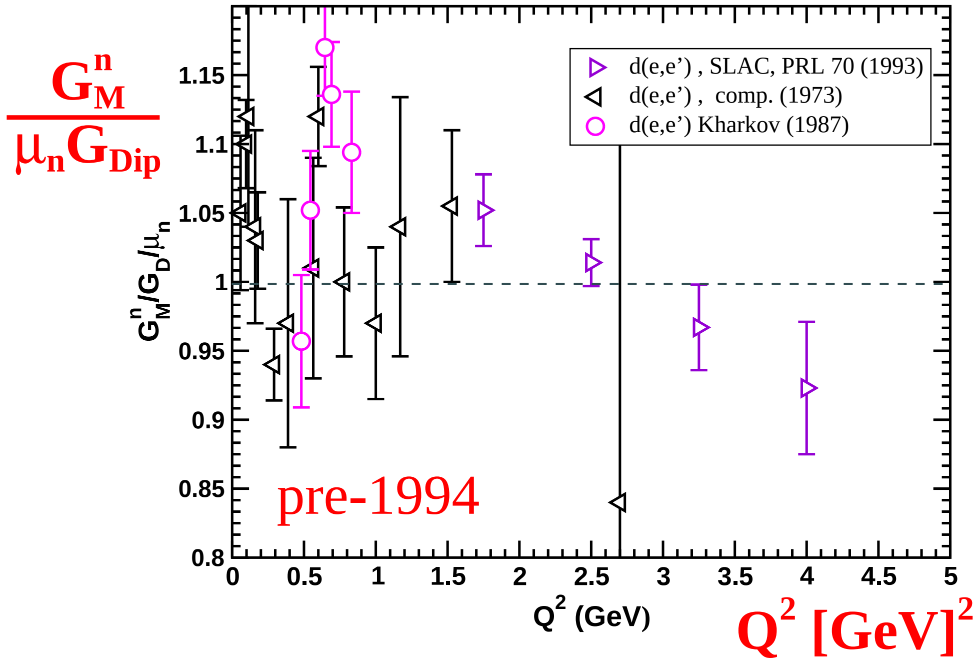
Need higher precision at large Q^2

Precise check of scaling: $G_E(Q^2) = G_M(Q^2)/\mu_p$?

G_E^p difficult to extract at high Q^2

For $Q^2 > 10$ GeV^2, G_E^p contributes <5%

Quasielastic D(e,e') Scattering



- Define a reduced cross-section:

  $\sigma_R = \epsilon(1+\tau)\frac{\sigma(E,E',\theta)}{\sigma_{Mott}} = R_T + \epsilon R_L$

- In PWIA : $R_T \propto (G_M^n)^2 + (G_M^p)^2$ and $R_L \propto (G_E^n)^2 + (G_E^p)^2$

Limitations for neutron magnetic form factor: G_M^n

- Large correction from proton scattering

Proton G_M at large Q^2, G_E at small Q^2

- Sensitive to nuclear corrections:

FSI, MEC, Relativistic corrections

Almost no sensitivity to G_E^n

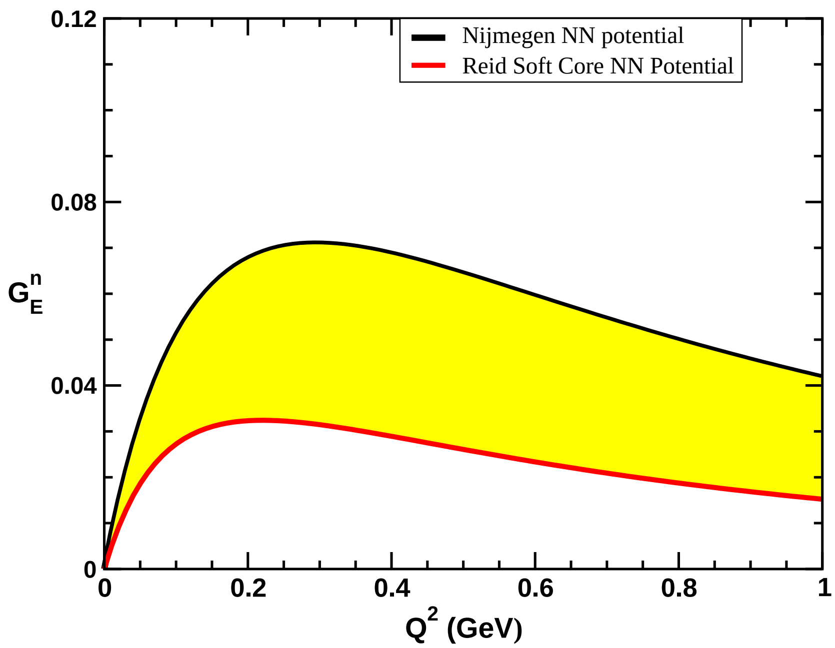
- G_E^n << G_E^p, G_M^n, and G_M^p ; all terms enter as $G_{E,M}^2$

- All measurements consistent with zero

- Better sensitivity, but large model-dependence, from measurements of deuteron elastic form factors

Elastic electron-deuteron Scattering

Small size of G_E^n --> larger proton subtraction
larger nuclear correction



- *neutron(beam)-electron scattering: slope at Q^2=0*
- Elastic ed : $\sigma = \sigma_{Mott}[A(Q^2) + B(Q^2)\tan^2(\frac{\theta}{2})]$ with:
  - $A(Q^2) = F_C^2(Q^2) + \frac{8}{9}\tau^2 F_Q^2(Q^2) + \frac{2}{3}\tau F_M^2(Q^2)$
  - $B(Q^2) = \frac{4}{3}\tau(1+\tau)F_M^2(Q^2)$
  - Extract G_E^n using deuteron model but very sensitive to NN potential.

    --> Precise deuteron data yields poor measurement of G_E^n

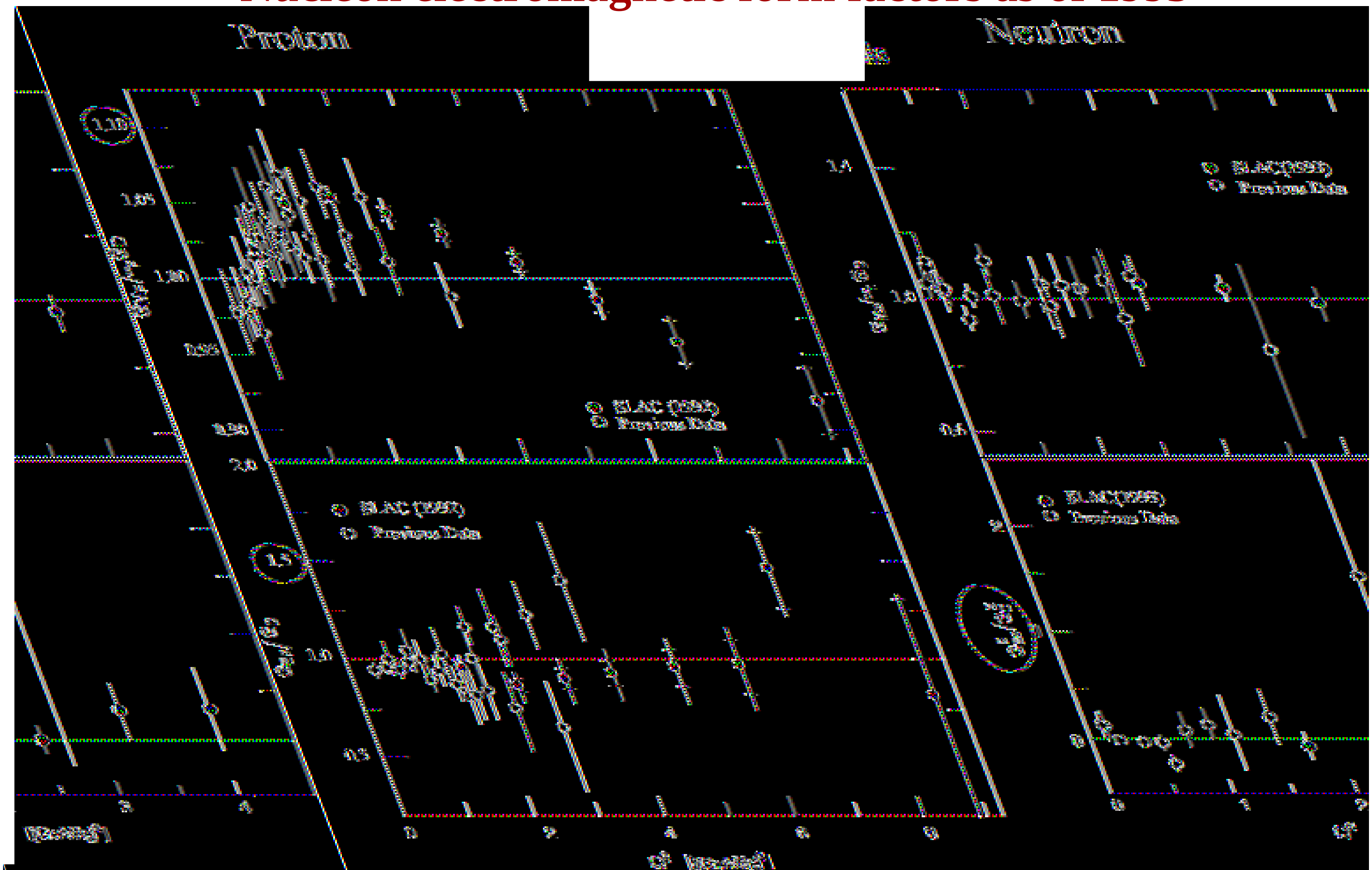
- Extraction from d(e,e') quasielastic

  Data exist up to Q^2=4 GeV^2

  Sensitive to nuclear effects, proton contributions

  Measurements consistent with G_E= 0

Nucleon electromagnetic form factors as of 1993



G_M^p well known up to 30 GeV^2, roughly follows dipole form

G_M^n, G_E^p also close to dipole, but with larger uncertainties and lower Q^2 range

Same deviations from dipole as G_M^p ?

G_E^n poorly measured, only upper limits above 1 GeV^2

1990s: New techniques, better tools

Rosenbluth: insensitive to G_E for large Q^2 or small G_E

No free neutron target

Improved techniques were already known:

* Coincidence d(e,e'n) and ratio [d(e,e'n)/d(e,e'p)]
* Recoil polarization measurements
* Polarized target asymmetries

Required better beams, targets, detectors

The 90s brought improvements in the tools:

* Electron beams with 100% duty factor
* High current, high polarization beams
* Polarized targets: ^{1}H, ^{2}H, ^{3}He
* Large acceptance detectors

as well as input from theory:

* Improved models of nuclear effects
* Better understanding of which observables are more sensitive to form factors, less sensitive to nuclear structure

G_E/G_M from Polarization Transfer: $^1H(\vec{e},e'\vec{p})$

Use polarized electron beam, unpolarized proton target, measure the polarization transferred to the struck proton

$P_L = M_p^{-1}(E+E')\sqrt{\tau(1+\tau)}\,G_M^2\tan^2(\theta_e/2)$ — Polarization along $\boldsymbol{q}$

$P_T = 2\sqrt{\tau(1+\tau)}\,G_E G_M\tan(\theta_e/2)$ — Polarization perpendicular to $\boldsymbol{q}$ (in the scattering plane)

$P_N = 0$ — Polarization normal to scattering plane

N. Dombey, Rev. Mod. Phys. 41, 236 (1969)

$$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E+E')\tan(\theta_e/2)}{2M_p}$$

Necessary technique for neutron, where L-T nearly impossible

Significantly more precise extraction of G_E for the proton

*L-T separation, G_E^2 extracted from *small* difference of two cross sections
--> large error magnification in extraction of G_E

*G_E/G_M goes like *ratio* of two components
--> insensitive to absolute polarization, analyzing power

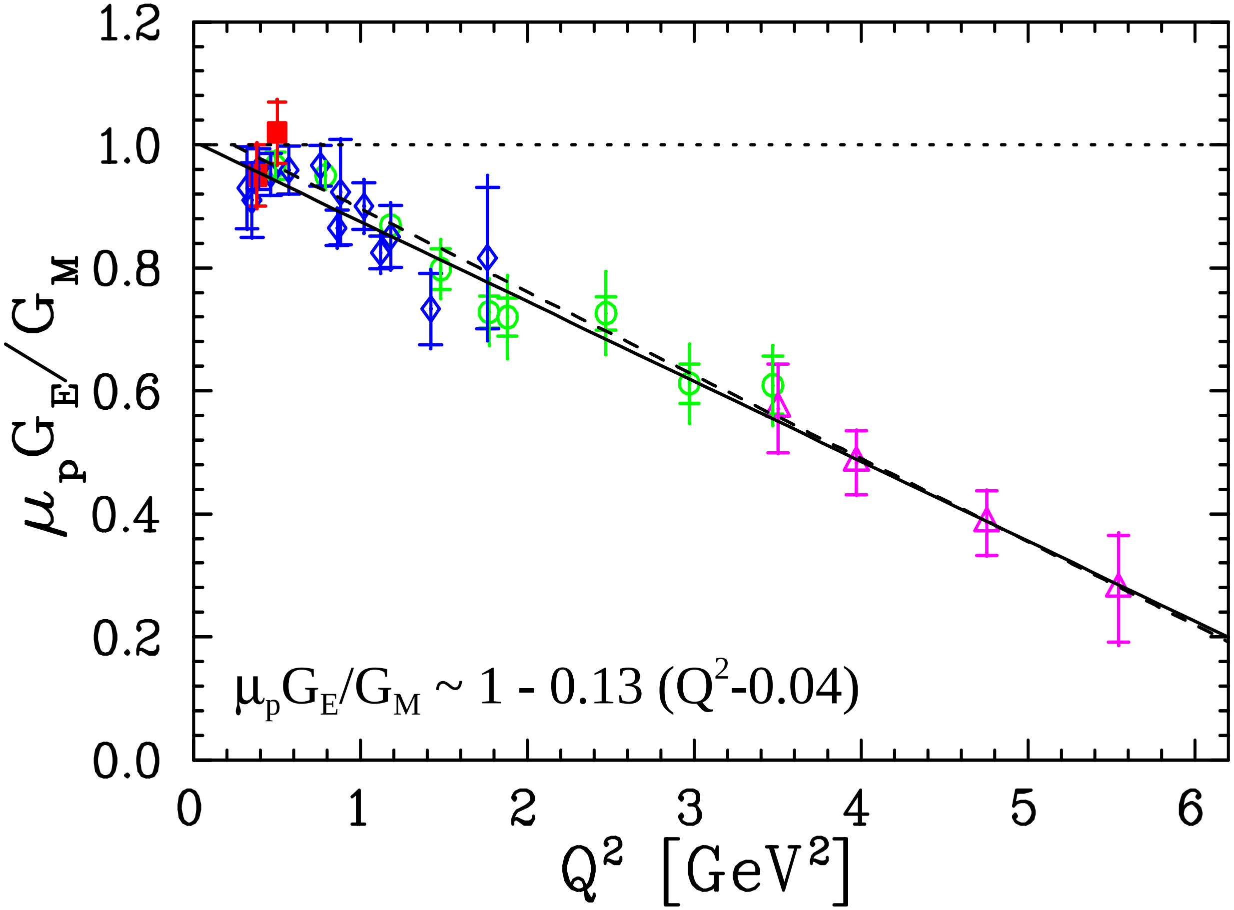
*Comparison of different electron polarizations
--> cancellation of false asymmetries

G_E/G_M from Polarization Transfer

MIT-Bates:
B. D. Milbrath, *et. al.*,
PRL **82** (1999) 2221(E)

Jefferson Lab:
M. K. Jones, *et. al.*,
PRL **84** (2000) 1398
O. Gayou, *et. al.*,
PRC **64** (2001) 038202
O. Gayou, *et. al.*,
PRL **88** (2002) 092301

Mainz:
Th. Pospischil, *et. al.*,
EPJA **12**, (2001) 125



Surprising result: $\mu_p G_E \neq G_M$ **at large** Q^2

-Renewed interest in nucleon form factors, nucleon structure

-New examination of long-standing pQCD predictions

-Highlighted the role of relativity, angular momentum

-Generated interest outside of the field

Articles in Science News, Physics Today, New York Times, USA Today, etc...

Improvements for G_M^n

Problem: no free neutron target

- **Need to use light nuclei as targets**
- **Need to apply nuclear corrections**
- **Inclusive data need to subtract proton contributions**

New developments:

Ratio measurements: d(e,e'n)/d(e,e'p)

Large cancellation of nuclear effects in the ratio

Need high luminosity, large/efficient neutron detectors

Polarized target measurements: $^3\vec{He}(\vec{e},e')$

Smaller nuclear corrections

Need high polarization beams, targets

Experiments ($Q^2 < 1$ GeV^2):

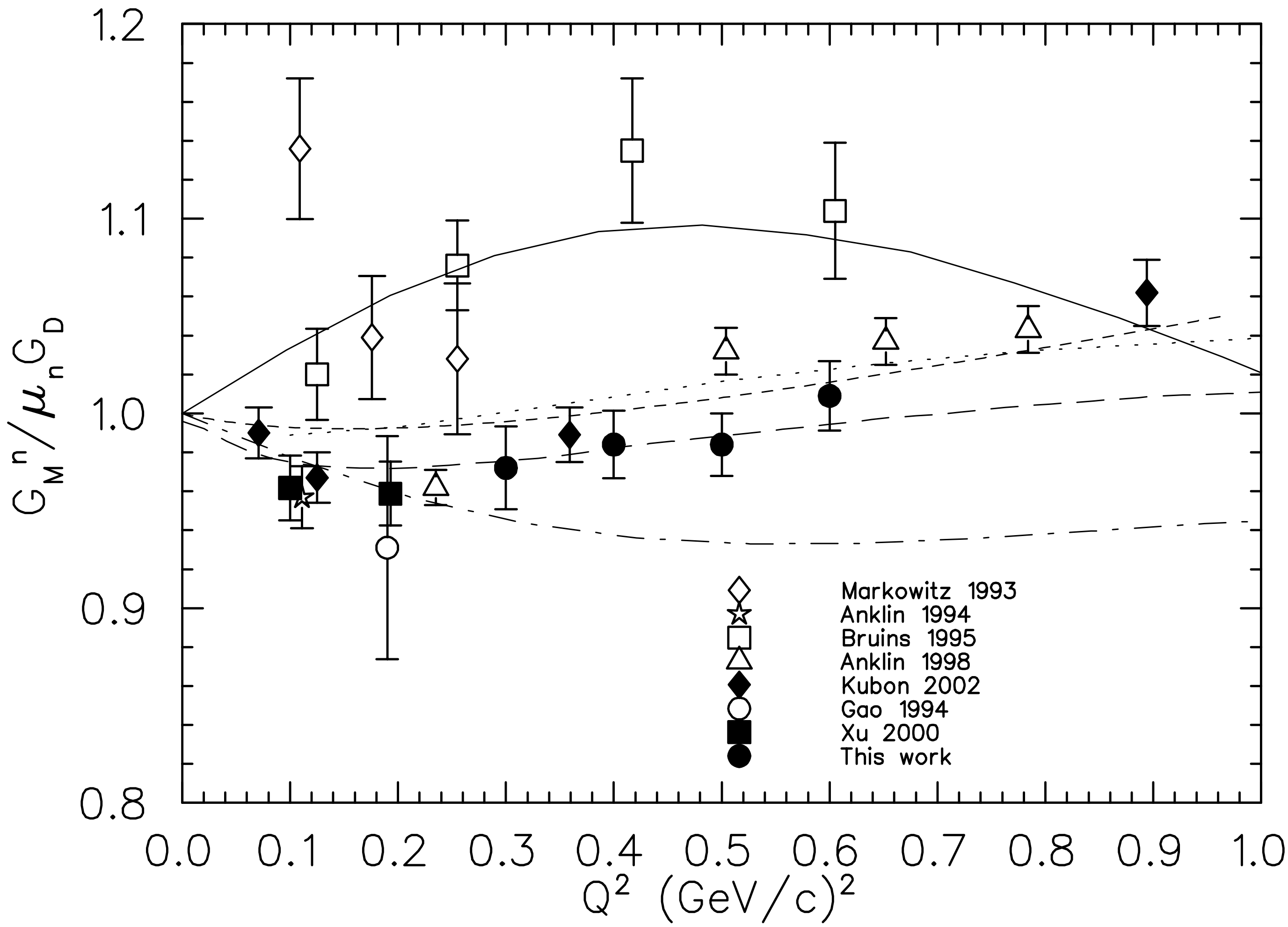
Bonn: Bruins, et al. (1995)
Mainz: Anklin, et al. (1998)
DESY: Kubon, et al. (2001)

Bates: Gao, et al. (1994)
JLab: Xu, et al. (2000, 2003)

Experiments ($Q^2 > 1$ GeV^2):

JLab: Brooks, et al. (preliminary)

New measurements of G_M^n



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Mainz: Anklin, et al. (1998)
DESY: Kubon, et al. (2001)

d(e,e'n) / d(e,e'p)

JLab: Xu, et al. (2000, 2003)
Bates: Gao, et al. (1994)

Polarized ^{3}He

High precision data (<2%) from 0.1 - 1.0 GeV^2

Previous data 4-8% uncertainties at these Q^2 values

Slightly below dipole at $Q^2 \cong 0.2$, slightly above for $Q^2 \cong 1.0$

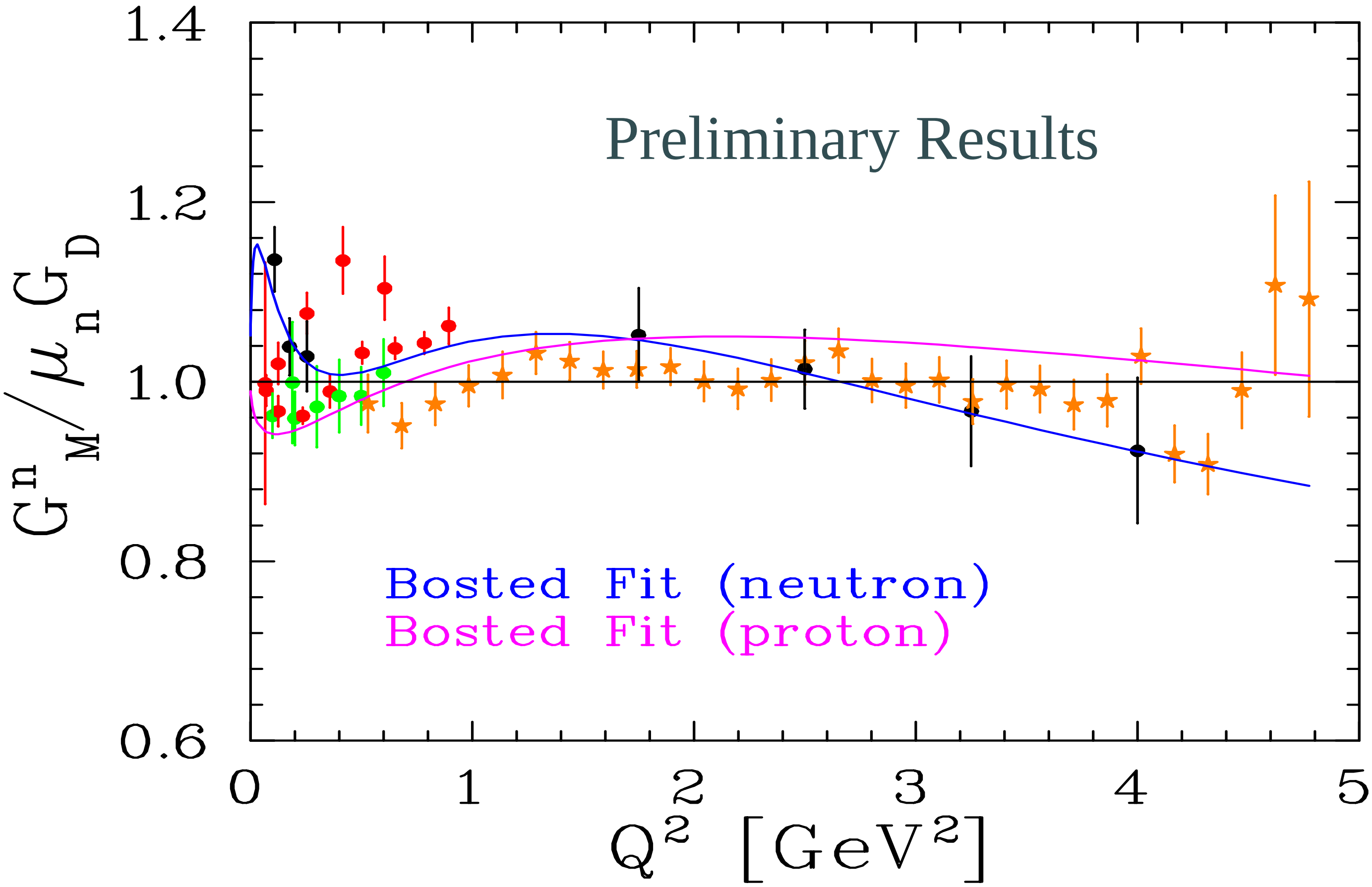
Consistent with G_M^p, very limited Q^2 range

High-Q^2 measurements of G_M^n

Recent data: G_M^n and G_M^p consistent up to Q^2 ~ 1 GeV^2

JLab Hall B data will extend measurements to ~5 GeV^2

1) $\frac{D(e,e'n)}{D(e,e'p)}$ Large acceptance spectrometer (CLAS)



2) BONUS: "Barely off-shell Neutron Structure" experiment

Elastic scattering from an "effective" free neutron target up to $Q^2 \cong 5$ GeV^2 (JLab Hall B - 2005)

$D(e,e'p_s)$ or $D(e,e'p_sn)$ where "p_s" is a tagged, low energy, backward going proton

Improvements for G_E^n

Problems:

No free neutron target

G_E^n gives a small contribution to the e-n cross section

G_E^n --> 0 as Q^2 --> 0

G_E^n suppressed with respect to G_M^n as Q^2 becomes large

G_E^n gives a small contribution to the e-d cross section

Difficult to extract from $A(Q^2)$, $B(Q^2)$

New developments:

Deuteron elastic scattering:

Data on t_{20} allow cleaner extraction of G_E^n

JLab E94-018: measured t_{20} up to 2.0 GeV^2

Polarized target measurements: $^3\vec{He}\,(\vec{e},e'n)$, $\vec{d}\,(\vec{e},e'n)$

Need to use light nuclei

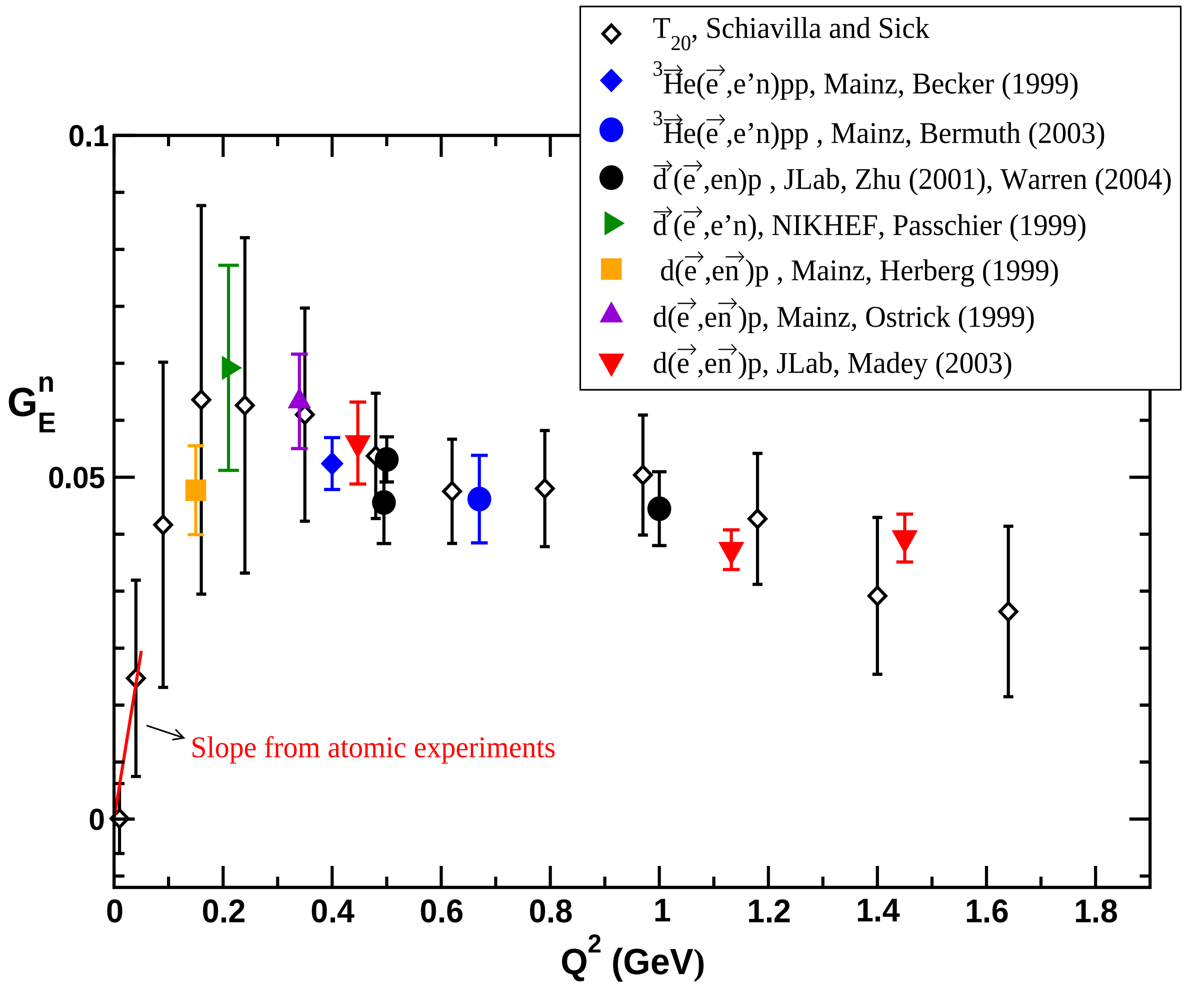
Nuclear corrections smaller than for cross section

Polarization transfer: $d\,(\vec{e},e'\vec{n})$

Similar to polarized target measurements

Need high luminosity, recoil polarimeter

Neutron Electric Form Factor



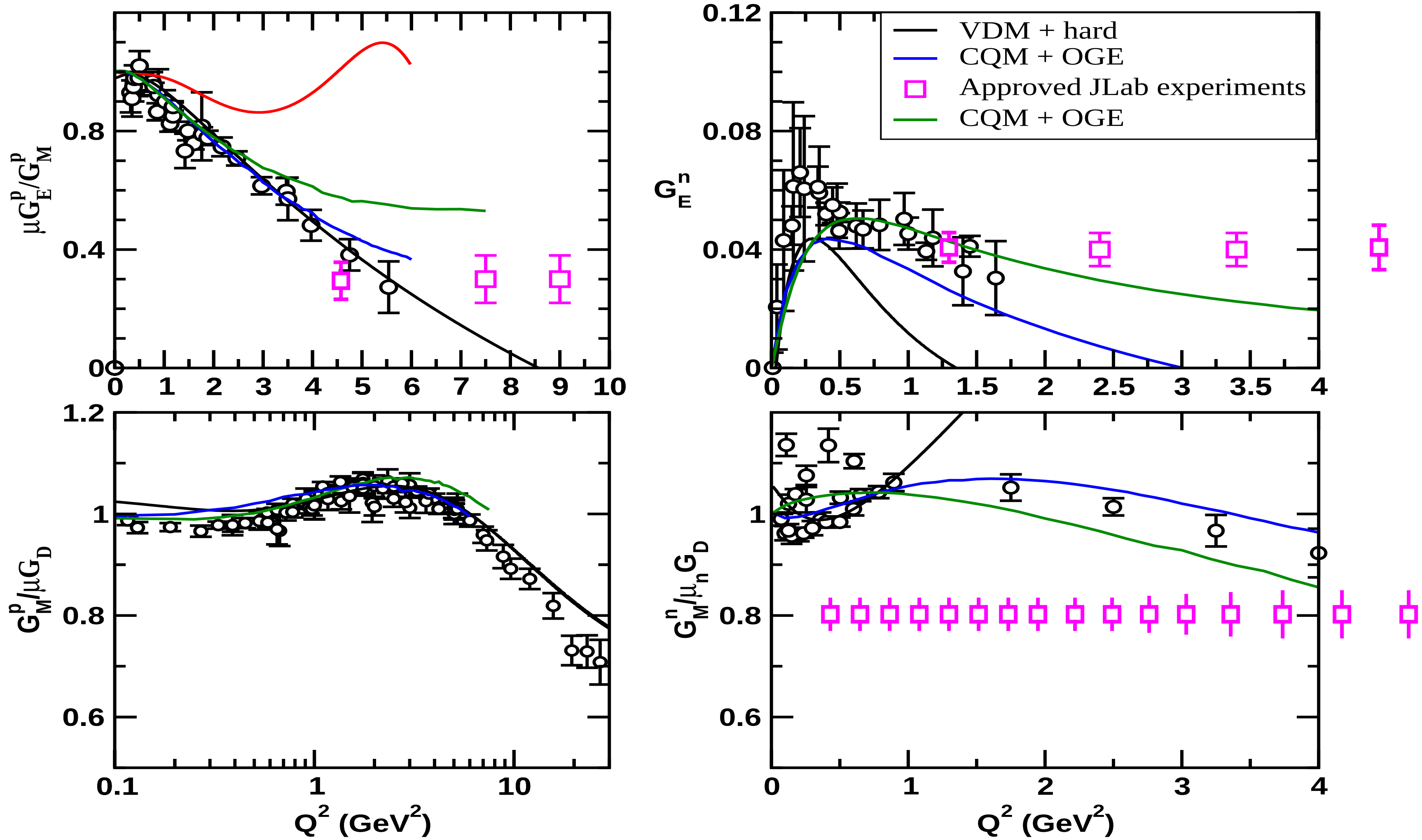
- ~~Planned~~ Running experiment at JLab in Hall A to use $^3\vec{\mathrm{He}}(\vec{e},e'n)$ quasi-free reaction to measure G_E^n to Q^2 = 3.4 GeV^2.
- Hall C Proposal to extend polarization transfer to ~4.5 GeV^2

High precision data up to 1.5 GeV^2

Above the Galster parameterization at high Q^2

Current/Near Future Summary of Nucleon FFs

The new data help constrain models of the form factors, especially when combined with new G_E^n and upcoming G_E^n and G_M^n measurements



VMD+ hard part , F. Iachello, A.D. Jackson, A. Lande, Phys. Let. 43B (1973)

CQM + OGE, F. Cardarelli, E. Pace, G. Salme, S. Simula, Nucl. Physc. A666 (2000)

CQM + OGE, F. Cardarelli and S. Simula, Phys. Rev. C 62, 065201 (2000)

Issues with Comparison to Theory

New data: Mainly 2000-2008

Most of the world's high-Q^2 and high-precision data for G_E^p, G_E^n, and G_M^n

For study of non-singlet (proton-neutron) form factors, want similar Q^2 range, similar uncertainties for p, n

- ***Absolute*** uncertainties for G_E^p and G_E^n are similar up to 1.5 GeV^2
- Current G_E^n run will extend coverage to 3.4 GeV^2, again with similar precision
- G_M^p and G_M^n will also have very similar uncertainties, up to 4-5 GeV^2

Consistent extractions of form factors extremely important

- Consistent extration of G_E and G_M
- Careful treatment of two-photon exchange corrections
- Inclusion of correlations between: G_E and G_M, proton and neutron

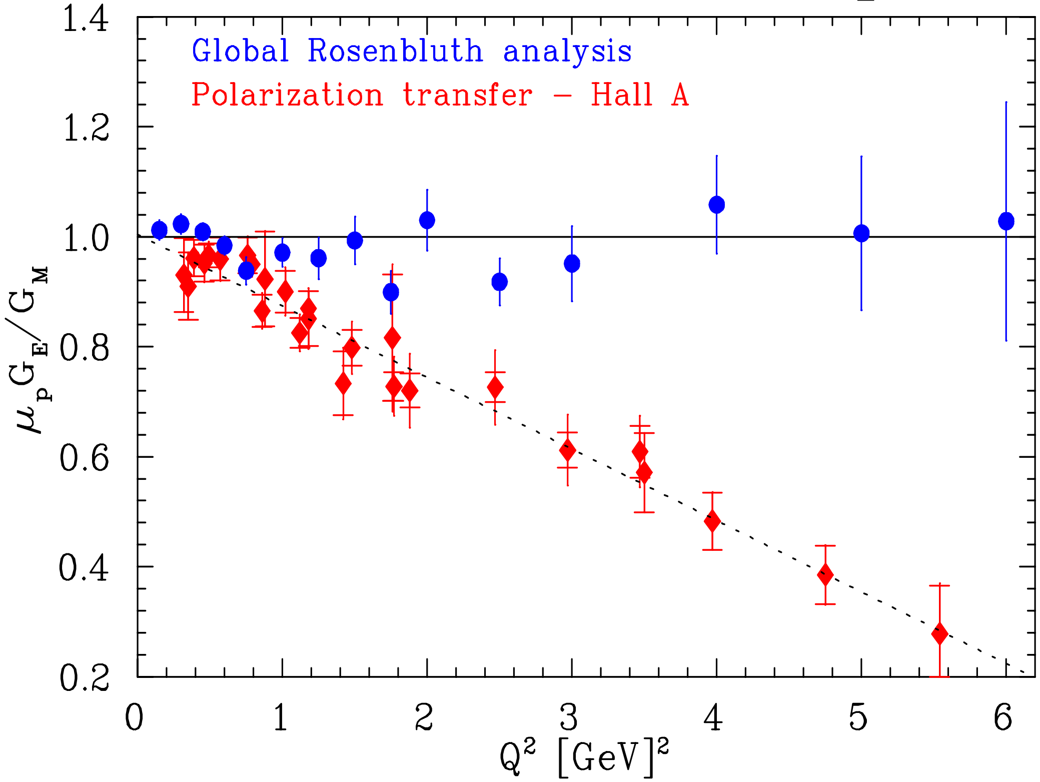
TPE contributions:

Effect on G_E^p (100+%) much larger than for G_M^p (3-5%)

Impact on G_M^p can be more important in global fitting

Even if negligible for neutron or parity-violating scattering, TPE corrections to proton form factors can propogate into neutron extraction

One last experiment...



Recoil polarization results for G_E^p have much smaller uncertainties than previous Rosenbluth results

However, they disagree by a factor of three at large Q^2 values!

Experimental issues?

"Missing" physics in Rosenbluth or polarization transfer?

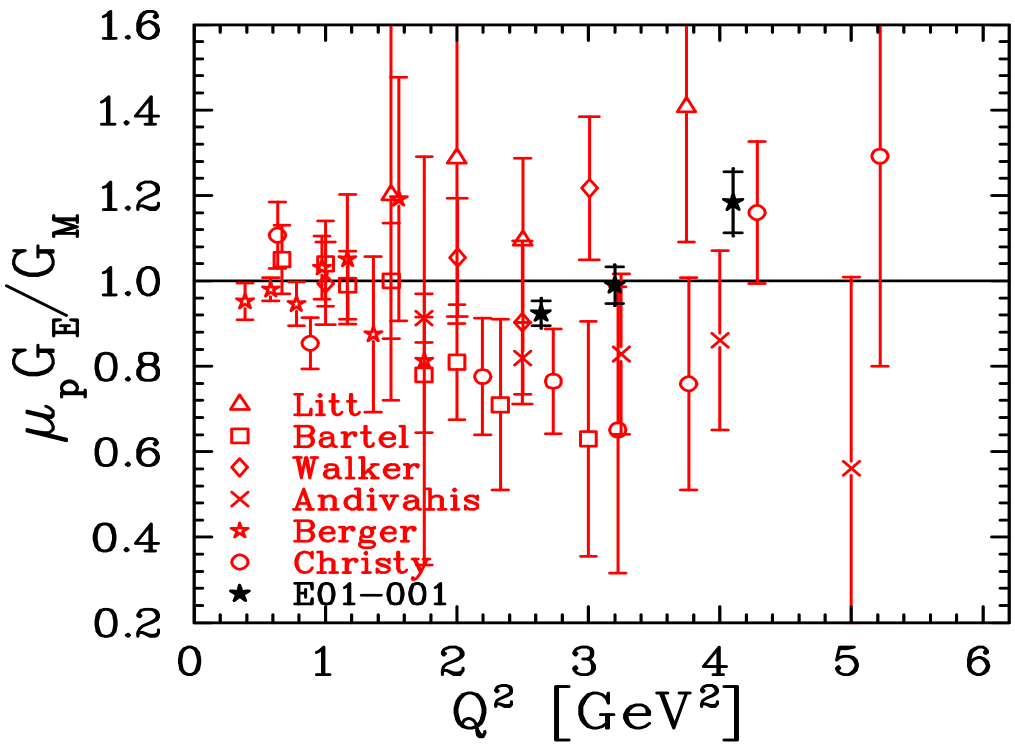
JLab E01-001: "Super-Rosenbluth" extraction of G_E^p/G_M^p

- High precision Rosenbluth extraction, ***greatly reduced systematic uncertainties***
- Reduced ε-dependent corrections (and thus potential systematic errors)

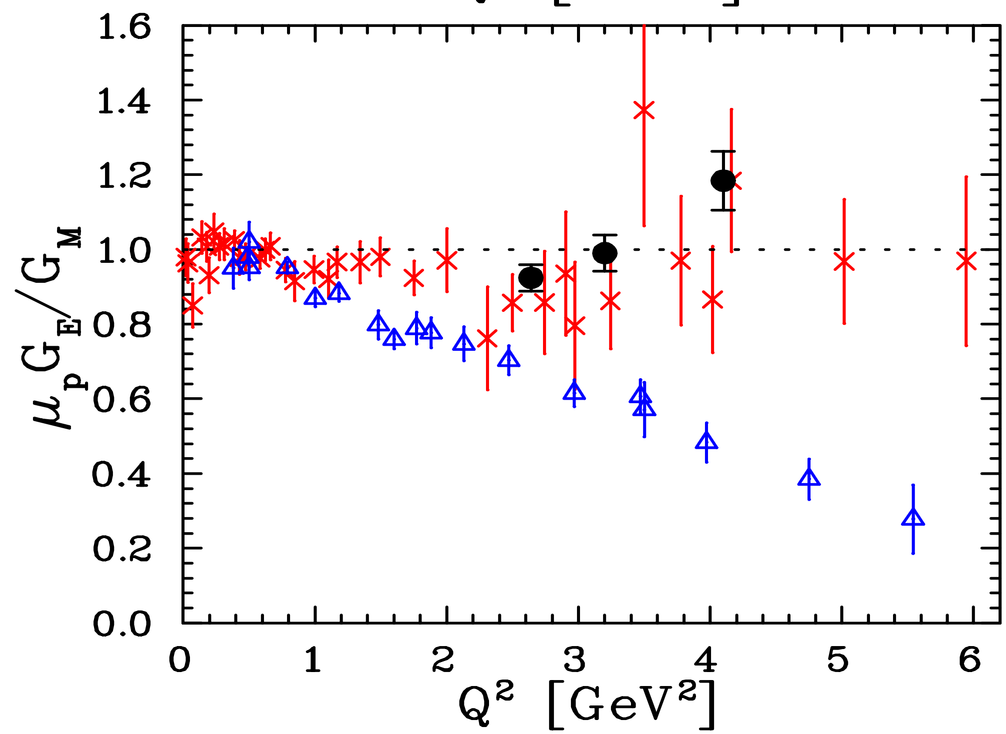
★ **Detect struck protons instead of scattered electrons**

★ **Low Q^2 (non-)separation: luminosity monitor**

"Super-Rosenbluth" (JLab E01-001) Results



Much smaller uncertainties than any previous Rosenbluth data



Uncertainties better than combined analysis of world's data

Confirms inconsistency between Rosenbluth and Polarization transfer experiments

Rules out explanation of discrepancy in terms of experimental error

Precise test on some radiative corrections (Bremsstrahlung of the scattered electron)

Two-photon exchange corrections

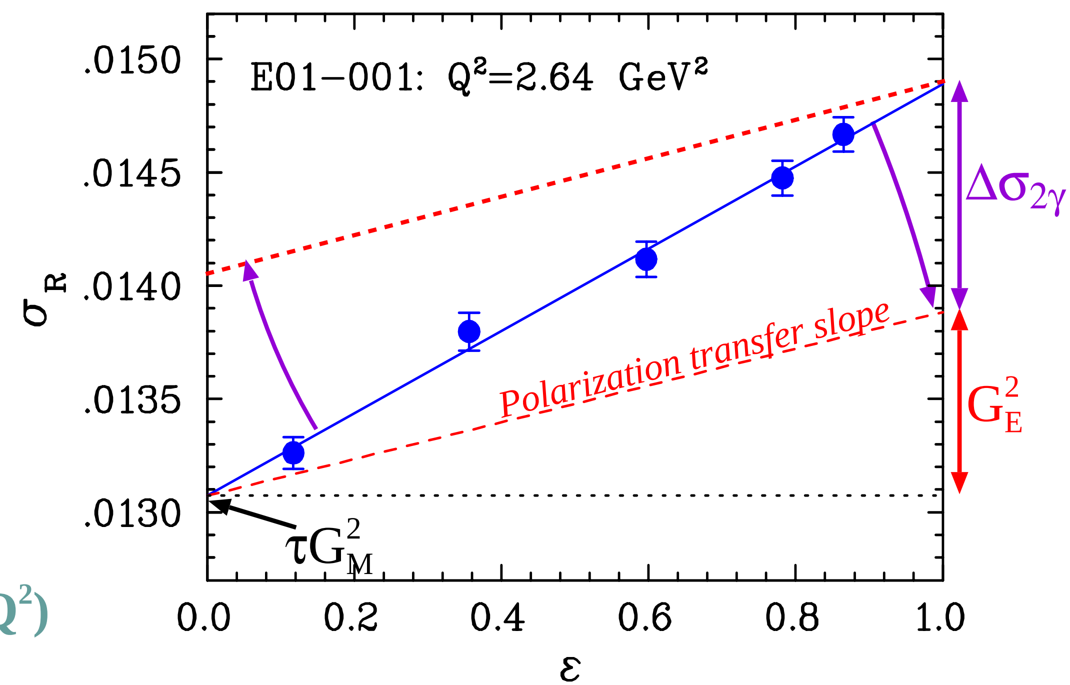
Two-photon exchange effects
can explain the discrepancy in G_E

Guichon and Vanderhaeghen, PRL 91, 142303 (2003)

Requires ~6% ε-dependence,
weakly dependent on Q^2,
roughly linear in ε

JA, PRC 69, 022201 (2004)

$$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\sigma_{Mott}} = \tau\, G_M^2(Q^2) + \varepsilon\, G_E^2(Q^2)$$



If this were the whole story, we would be done: L-T would give G_M, PT gives G_E

However, still need to be careful when choosing form factors as input in data analysis

There are still issues to be answered

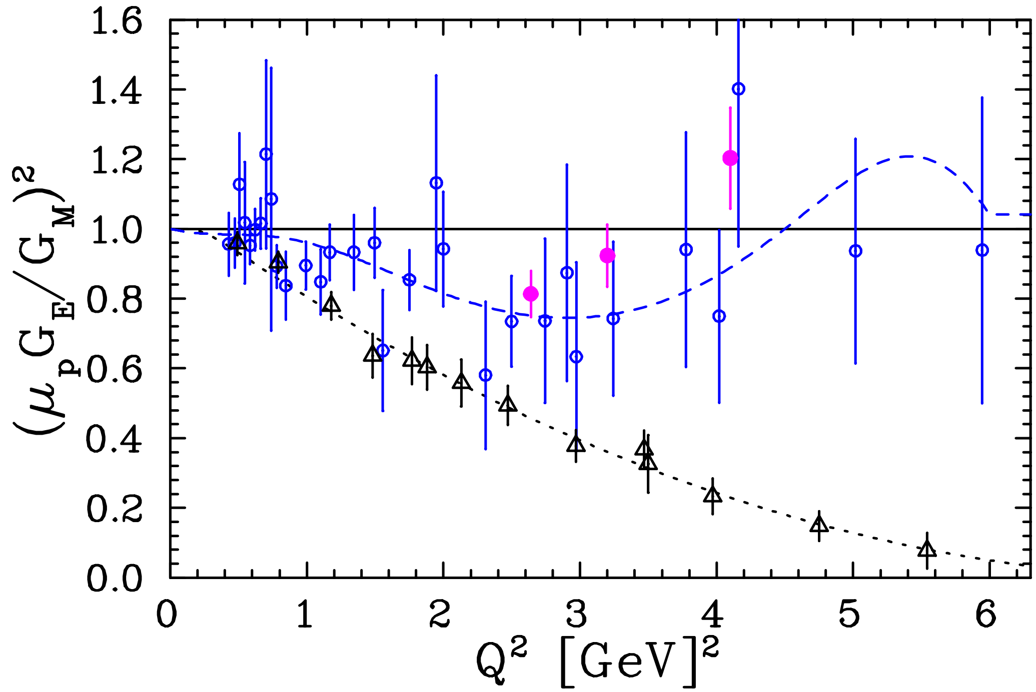
What about the constraints (~1%) from positron-electron comparisons?

TPE effects on ***polarization transfer***?

TPE effects on $\boldsymbol{G_M}$?

TPE effects on ***other measurements***?

Two-photon exchange corrections to G_E, G_M



Good news:

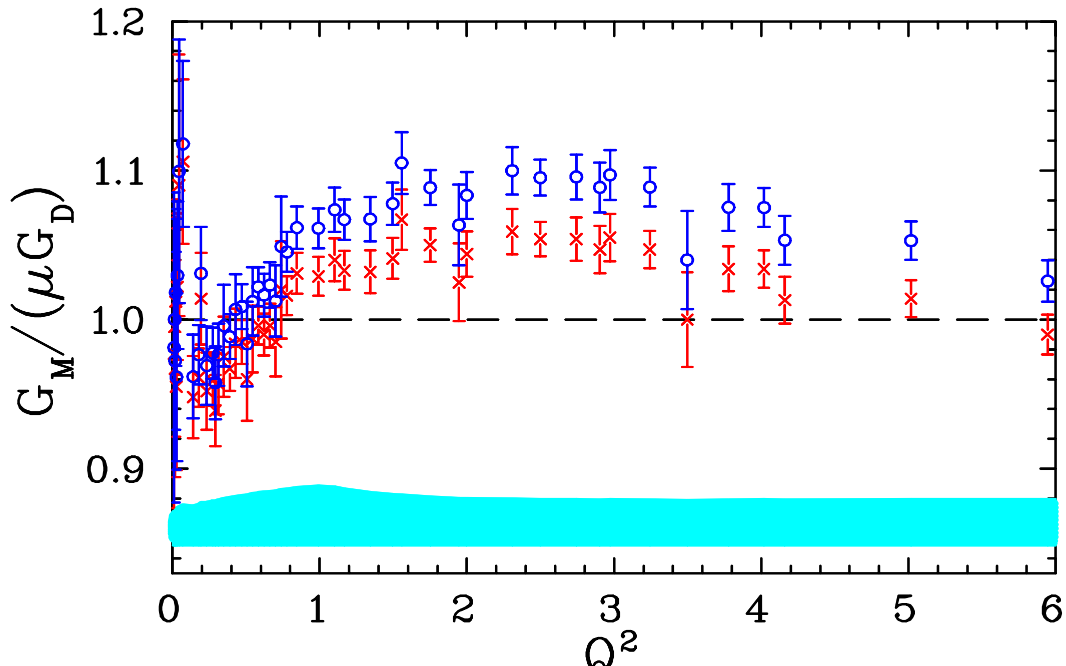
Discrepancy can be explained with small two-photon amplitudes (2-4%)

These amplitudes also explain the (very limited) low ε e+/e- data

Bad news:

Large corrections

- Up to 200% for G_E (Rosenbluth)
- Could be 30% for G_E (polarization)
- 3-5% for G_M



Large uncertainties, even neglecting uncertainty in ε dependence

$\delta G_M^{TPE} \cong 1.0\text{-}1.5\%$
$\delta G_E^{TPE} \cong 5\%$ (low Q^2) 15% (high Q^2)

As large or larger than the experimental uncertainties

While correction much larger on G_E,
uncorrected G_M may have greater impact *on fits than uncorrected G_E!*

Progress on the theory front...

P.A.M. Guichon and M. Vanderhaeghen, PRL 91, 142302 (2003)

-Generalized formalism for elastic scattering beyond Born approximation

P. Blunden, W. Melnitchouk, and J. Tjon, PRL 91 142304 (2003)

-Improved calculation of box diagrams, unexcited proton intermediate state, not valid at large Q^2

-More recently: neutron and 3He, check model-dependence, Δ intermediate state, look at very low-Q^2,...

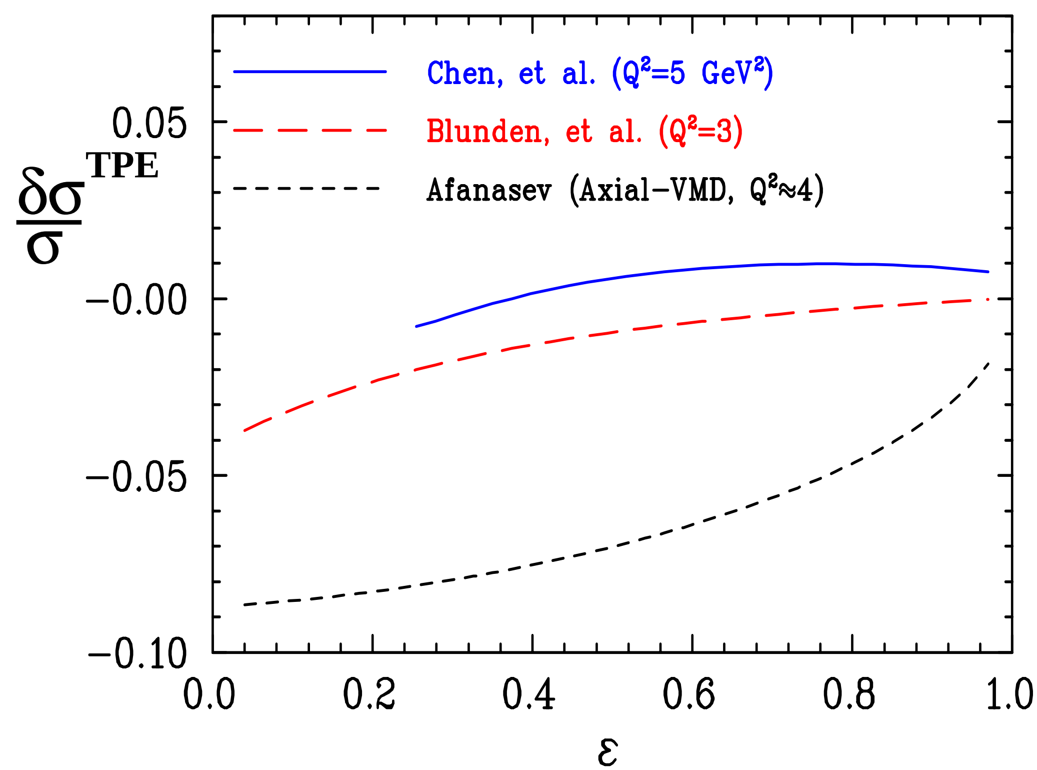
-Small model dependence from FFs, resolves the discrepancy and consistent with all data, up to ~2 GeV^2

Chen, Afanasev, Brodsky, Carlson, Vanderhaeghen: PRL 93 122301 (2004)

-GPD based model, γ-q coupling, not valid at low Q^2 or ε values

-More recently: Check model dependence, formalism for parity violating scattering

-Larger model dependence (GPD), resolves half-or-more of the discrepancy at large Q^2



My summary:

1) Calculations differ in magnitude and ε-dependence, but rapidly improving

2) **<u>All</u> show small effects at large ε**

<u>All</u> show decrease at low ε

<u>All</u> show weak Q^2-dependence

➡ **Consistent with e+/e- ratios and observed form factor discrepancy**

3) Largest effect on G_E at large Q^2, but greatest impact overall is on high precision, low-Q^2 measurements. Calculations of Blunden, Melnitchouk, and Tjon, combined with formalism of Vanderhaeghen and Afanasev/Carlson, may allow adequate treatement of TPE for most experiments.

Progress on the experimental front...

Real part of TPE amplitudes:

Positron-electron comparisons *(VEPP, JLab)*

-Clean extraction of two-photon terms

-Map out Q^2 and ε dependence of $\Delta\sigma^{TPE}$

Can test TPE explanation

Map out TPE for $Q^2 < 1\text{-}2$ GeV^2

Precise e-p elastic cross sections *(JLab)*

-ε-dependence of cross section

Polarization transfer: P_l / P_t *(JLab)*

-ε-dependence of polarization ratio

→ **Map out TPE for $Q^2 > 1\text{-}2$ GeV^2**

Imaginary part of TPE amplitudes:

Born-forbidden observables (e.g. normal polarization transfer P_N)

-No *direct* impact on form factors, but provide additional ***independent constraints*** on TPE calculations

Already have data from SAMPLE, A4, G0. More to come...

Approved experiment to measure A_y (target single spin asymmetry) from ^{3}He

Issues with Comparison to Theory

TPE contributions:

Even if negligible for neutron or parity-violating scattering, TPE corrections to proton form factors can propogate into neutron extraction

Need consistent treatment of data, TPE to get ***corrected*** G_E^p, G_M^p

Can't use these form factors as model for $\sigma_{e\text{-}p}$ without same TPE correction

Inconsistent treatment (e.g. G_M^p from Rosenbluth, G_E^p from polarization) will yield errors that are propogated (and magnified) in other form factors

Example: improper treatment of TPE for proton

--> error in e-p cross section [as large or larger than initial TPE correction]

--> equal and opposite error in e-n cross section from ^{2}H(e,e')

--> error magnified in G_M^n, due to smaller e-n cross section

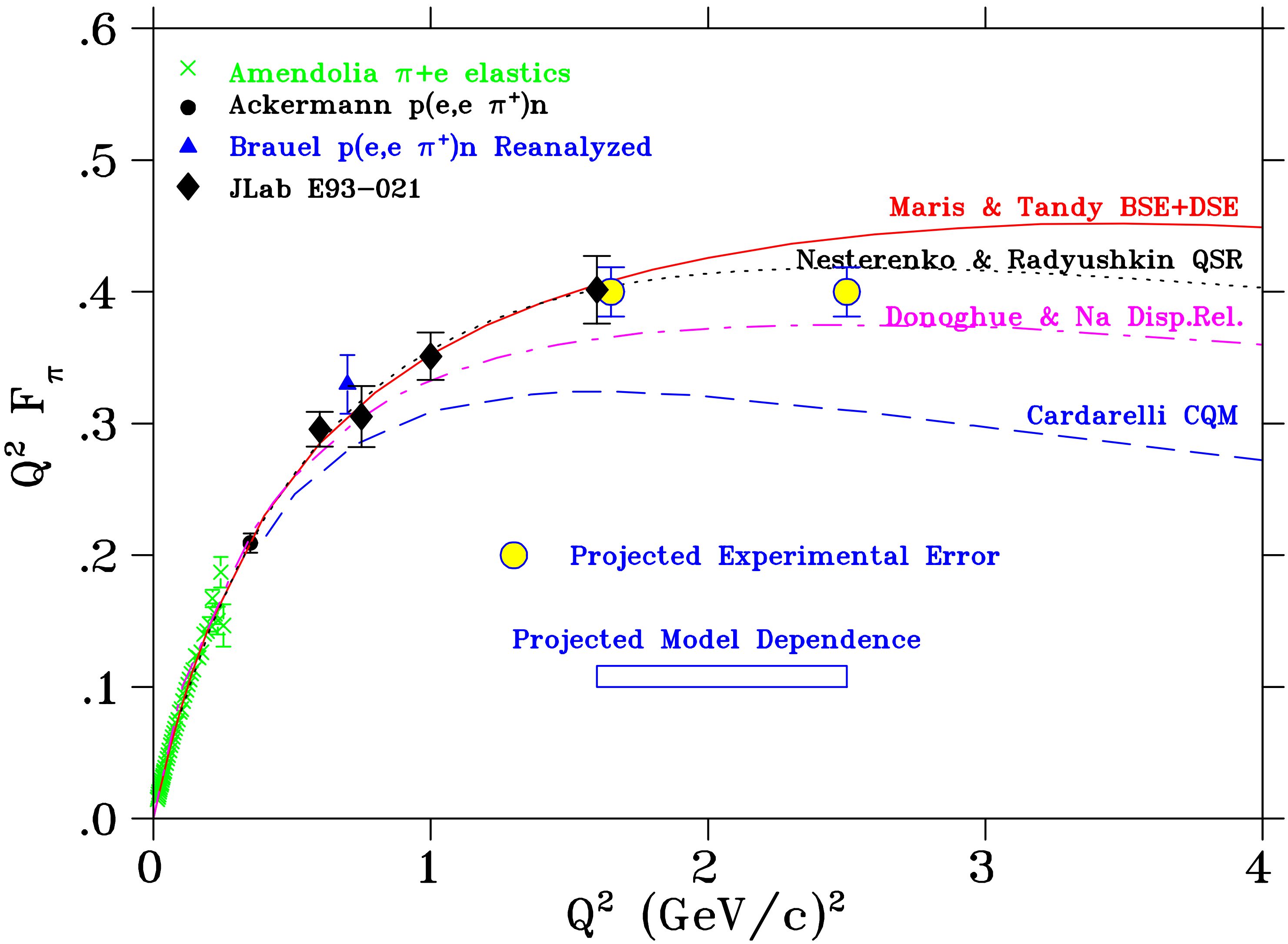
--> error propogated to G_E^n, when measure ratio of G_E/G_M

--> can be further magnified in difference between proton and neutron

--> errors in precision measurements of A(e,e'N), parity-violating scattering, neutrino scattering, etc....

Details strongly dependent on experimental technique and analysis procedures and assumptions of the form factor measurement

The Pion Form Factor: F_π



π-e elastic data at low Q^2 (pion beam on atomic electrons)

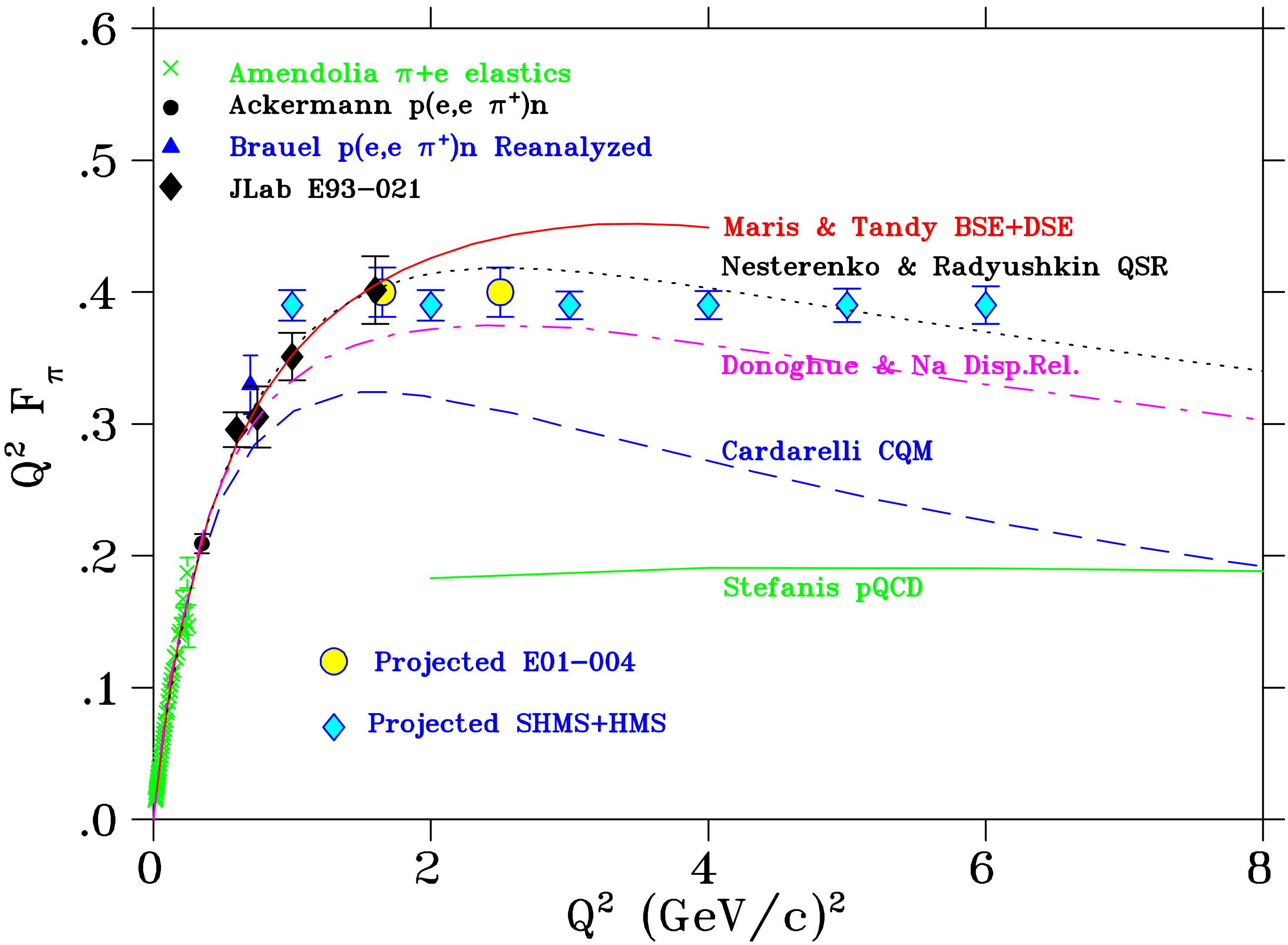
Higher Q^2 data from pion electroproduction: $p(e,e'\pi^+)n$

E01-004 data ("projected" point) taken in 2003

Preliminary results released later this week at APS

Note: updated results for E93-021 expected soon

The Pion Form Factor: F_π



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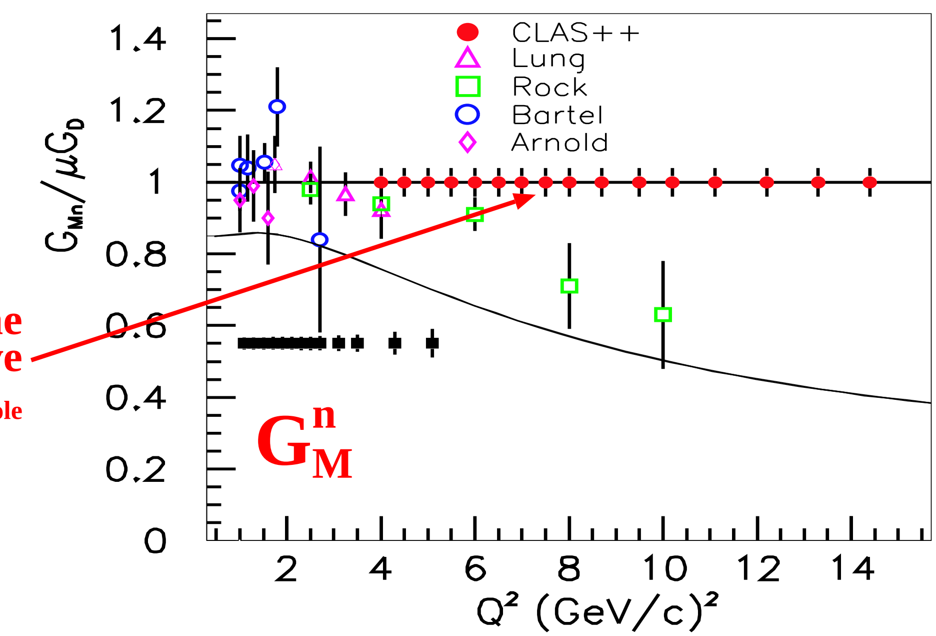
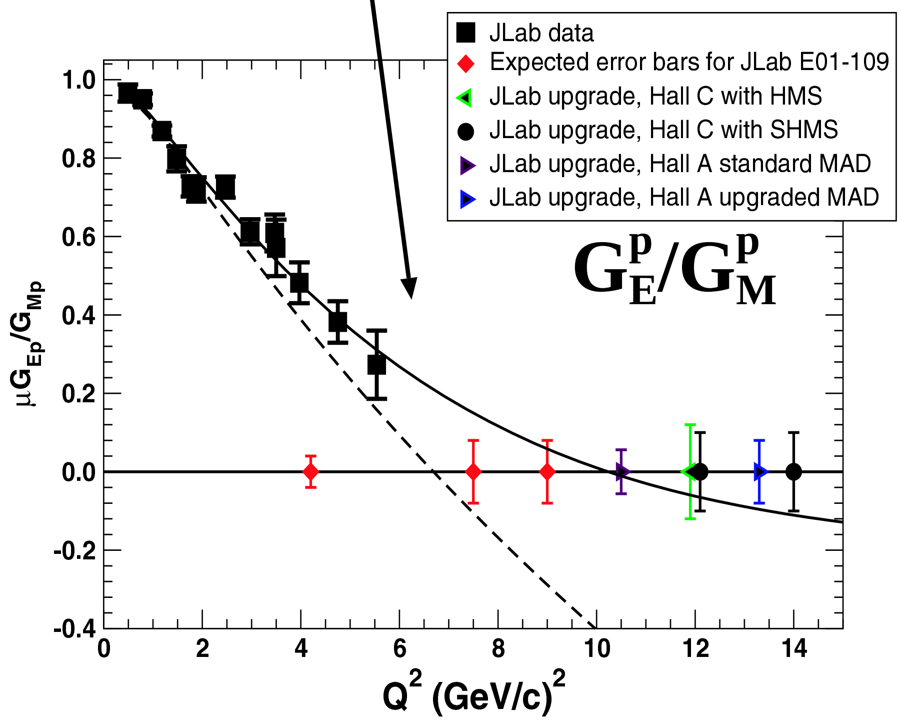
JLab@12 GeV: Higher beam energy combined with SHMS spectrometer (small angle, high momentum) will improve precision and more than double the Q^2 range

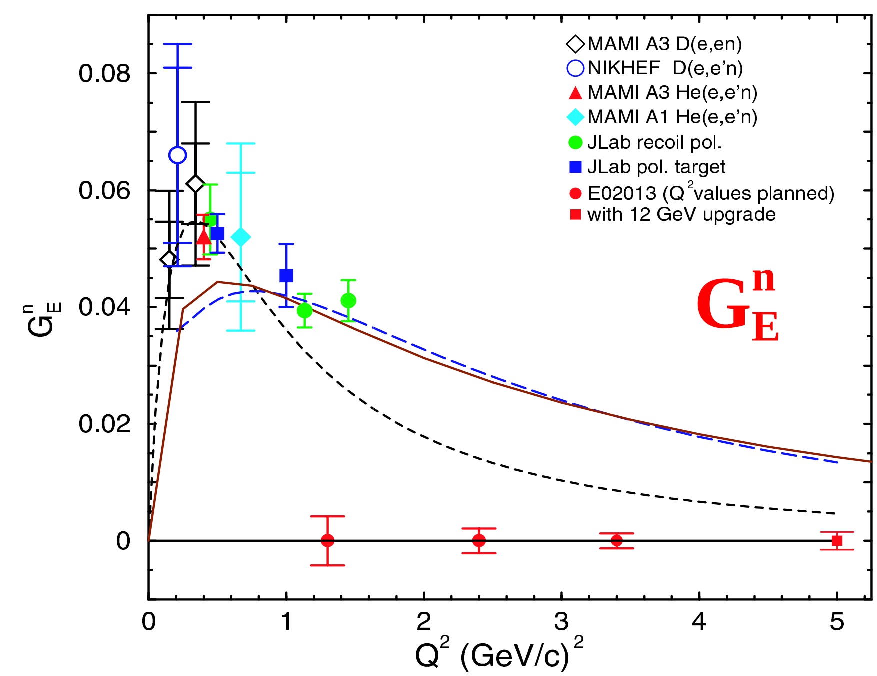
Even greater reach with the JLab 12 GeV upgrade

Determine if G_M for the proton and neutron have identical deviations from G_{Dipole}



Determine if G_E/G_M for the proton becomes negative





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