Nucleon form factors in the space-like region

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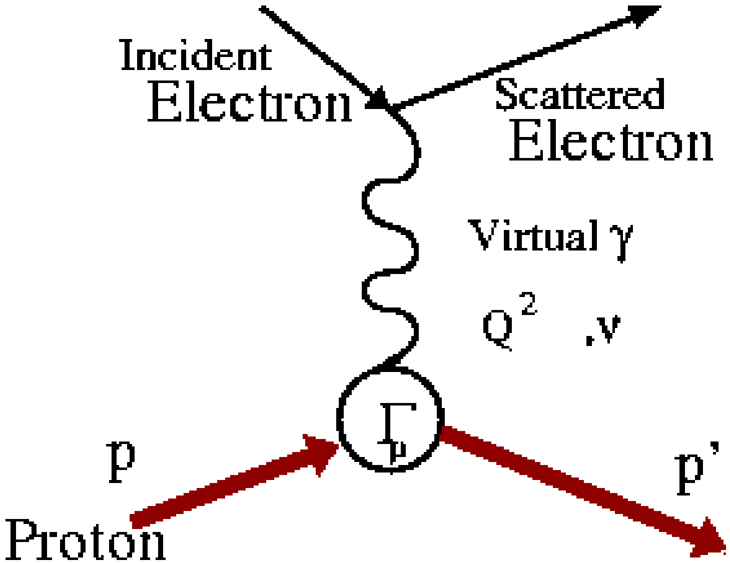
Jefferson Lab
PHIPSI08

Electron as probe of nucleon FF



Nucleon vertex:

$$\Gamma_\mu(p',p) = \underbrace{F_1(Q^2)}_{Dirac}\gamma_\mu + \frac{i\kappa_p}{2M_p}\underbrace{F_2(Q^2)}_{Pauli}\sigma_{\mu\nu}q^\nu$$

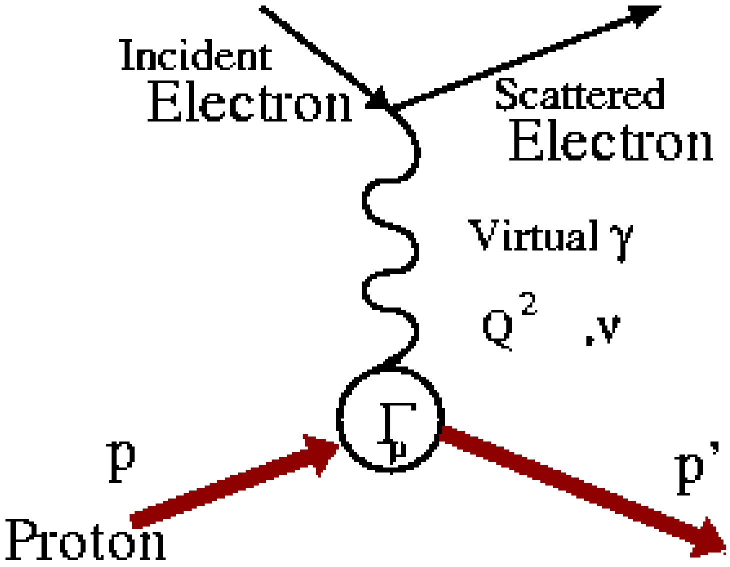
$$G_E(Q^2) = F_1(Q^2) - \kappa_N\tau\, F_2(Q^2)$$

$$G_M(Q^2) = F_1(Q^2) + \kappa_N\, F_2(Q^2) \;, \tau = \frac{Q^2}{4M_N^2}$$

At $Q^2 = 0 \quad G_{Mp} = 2.79\ G_{Mn} = -1.91$

$$G_{Ep} = 1\ G_{En} = 0$$

Electron as probe of nucleon FF



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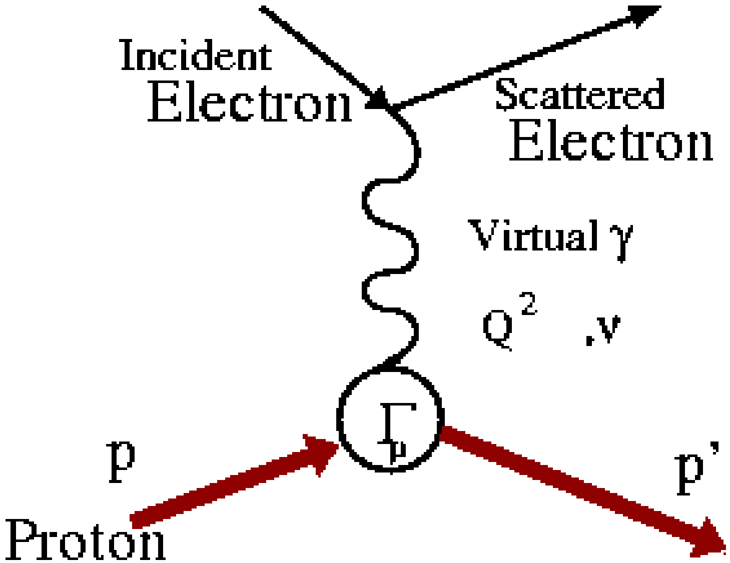
- Form factors are a window into the nucleon's constituents

Electron as probe of nucleon FF



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- Form factors are a window into the nucleon's constituents

$Q^2 = 0$
Probe entire nucleon

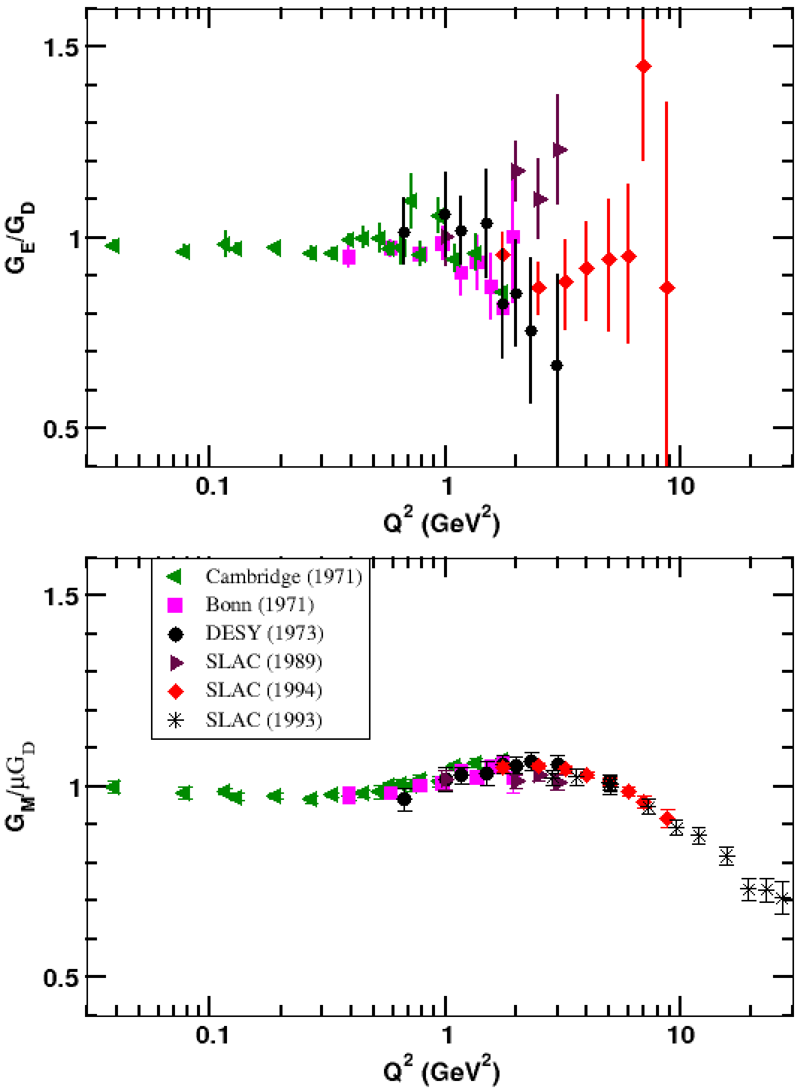
→

Probe nucleon
meson baryon DOF
Constituent quark

→

Probe quark gluon DOF
Current quarks
pQCD

Proton Form Factors: G_{Mp} and G_{Ep}



$$\sigma \propto \frac{\epsilon}{\tau}\left(\frac{G_E}{G_D}\right)^2 + \left(\frac{G_M}{G_D}\right)^2$$

$$G_D = (1 + Q^2/.71)^{-2}$$

Measure cross section at several ε and separate G_E and G_M

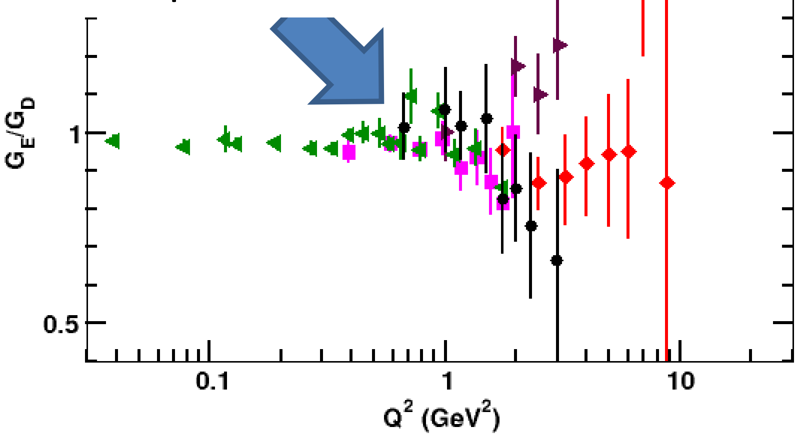
At large Q^2, G_E contribution is smaller so difficult to extract

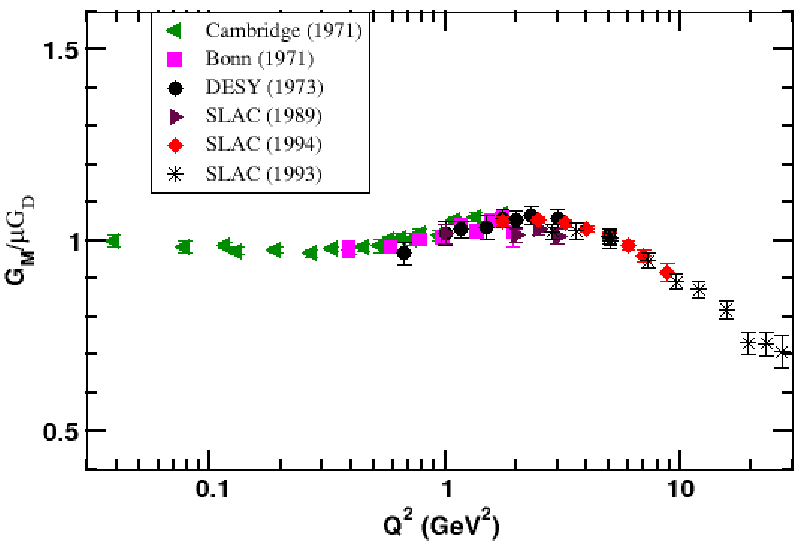
G_M measured to $Q^2 = 30$

G_E measured well only to $Q^2 = 1$

Proton Form Factors: G_{Mp} and G_{Ep}

GE > 1 then large error bars and spread in data.





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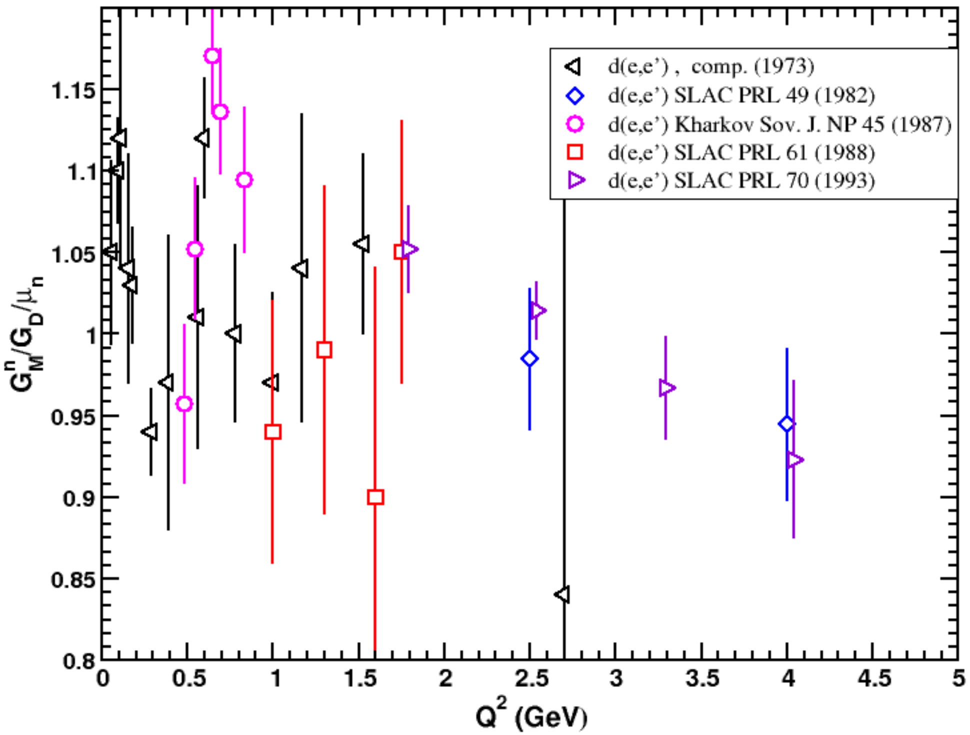
Neutron Magnetic Form Factor: G_{Mn}



Extract G_{Mn} from inclusive d(e,e') quasielastic scattering cross section data

$$\sigma \propto R_T + \epsilon R_L$$

$$R_L \propto (G_E^n)^2 + (G_E^p)^2$$

$$R_T \propto (G_M^n)^2 + (G_M^p)^2$$

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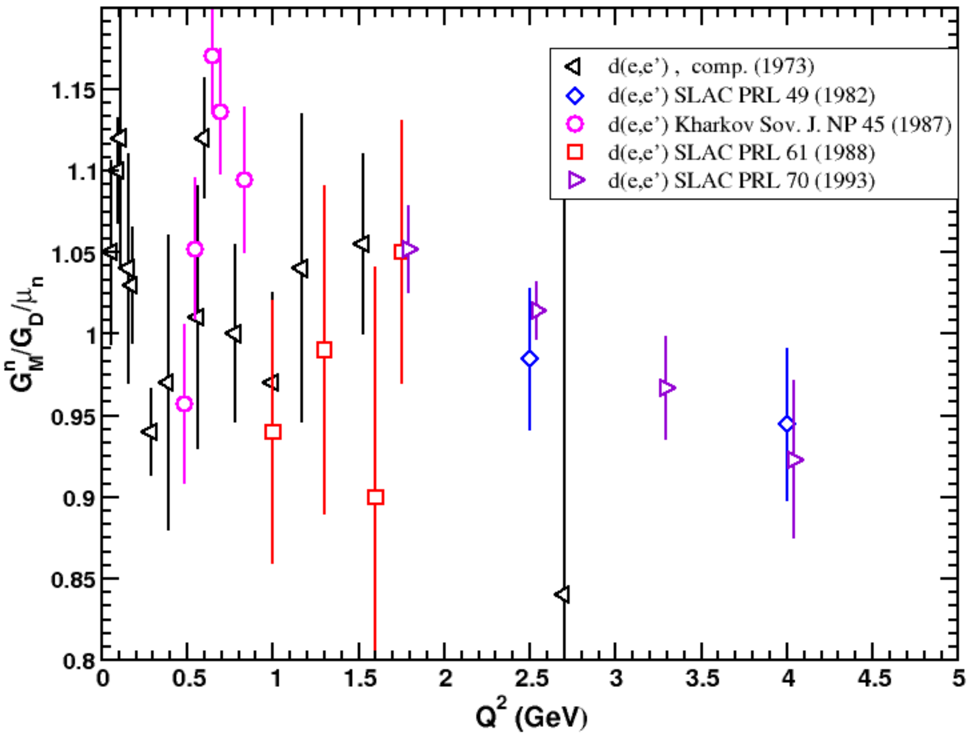

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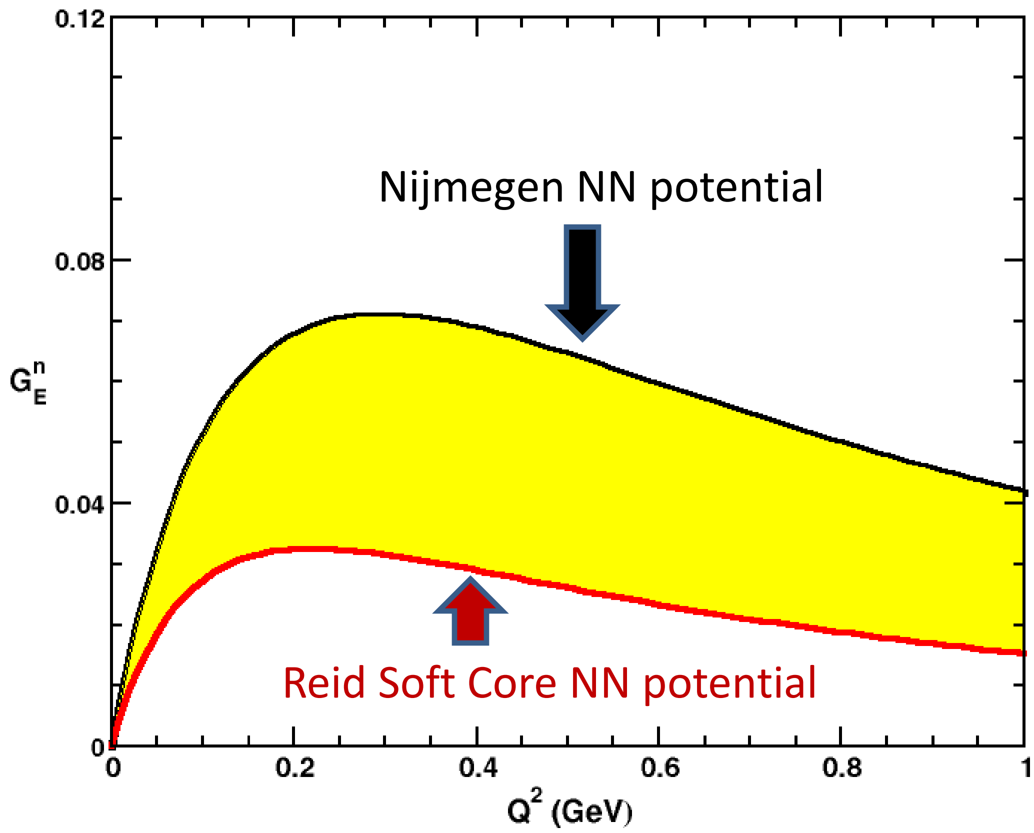
Difficulties:

- Subtraction of large proton contribution
- Sensitive to deuteron model

Neutron Electric Form Factor: G_{En}



Measure elastic electron-deuteron cross section

$$\sigma \propto A(Q^2) + B(Q^2)\tan^2(\tfrac{\theta}{2})$$

$$A(Q^2) = F_C^2(Q^2) + \tfrac{8}{9}\tau^2 F_Q^2(Q^2) + \tfrac{2}{3}\tau F_M^2(Q^2)$$

$$B(Q^2) = \tfrac{4}{3}\tau(1+\tau)F_M^2(Q^2)$$

Extract G_{En} using deuteron model
but very sensitive to NN potential.

Extend Q^2 range of proton G_E

Measure spin observables: Sensitive to G_E/G_M

Need high intensity, high duty factor and high polarization electron beams

Continuous beam accelerators like JLab and MAMI

Recoil polarization measurements $$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E_e + E_{e'})}{2M}\tan(\frac{\theta}{2})$$

Combine with fixed and internal polarized ^1H targets

Beam-target asymmetry measurement

$$A = \frac{K_1 \cos\theta^\star + K_2 G_E/G_M \sin\theta^\star \cos\phi^\star}{G_E^2/G_M^2 + \tau/\epsilon}$$

Extend Q^2 range of Neutron FF

Measure spin observables and coincidence deuteron quasi-free cross-sections

Recoil polarization measurements $$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E_e+E_{e'})}{2M}\tan(\frac{\theta}{2})$$

Fixed and internal polarized ^3He and ^2H targets

Beam-target asymmetry measurement

$$A = \frac{K_1 \cos\theta^\star + K_2 G_E/G_M \sin\theta^\star \cos\phi^\star}{G_E^2/G_M^2 + \tau/\epsilon}$$

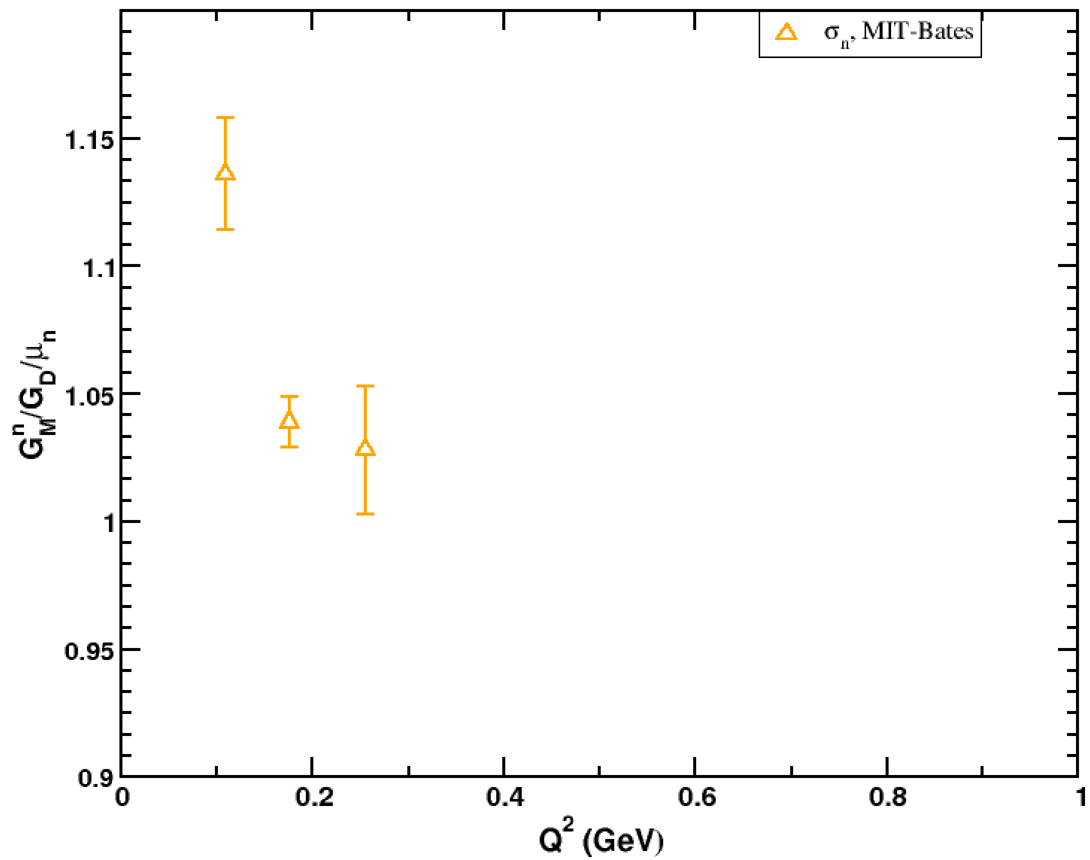
Need improved theory of electron quasi-free scattering on ^3He and ^2H

- Determine kinematics which reduce sensitivity to nuclear effects
- Determine which observables are sensitive to form factors
- Use model to extract form factors

Neutron Magnetic Form Factor: G_{Mn}

$$\mathrm{d}(e, e'n)$$

- Detect neutron in coincidence
- But still sensitive to the deuteron model
- Need to know absolute neutron cross section efficiency



Neutron Magnetic Form Factor: G_{Mn}

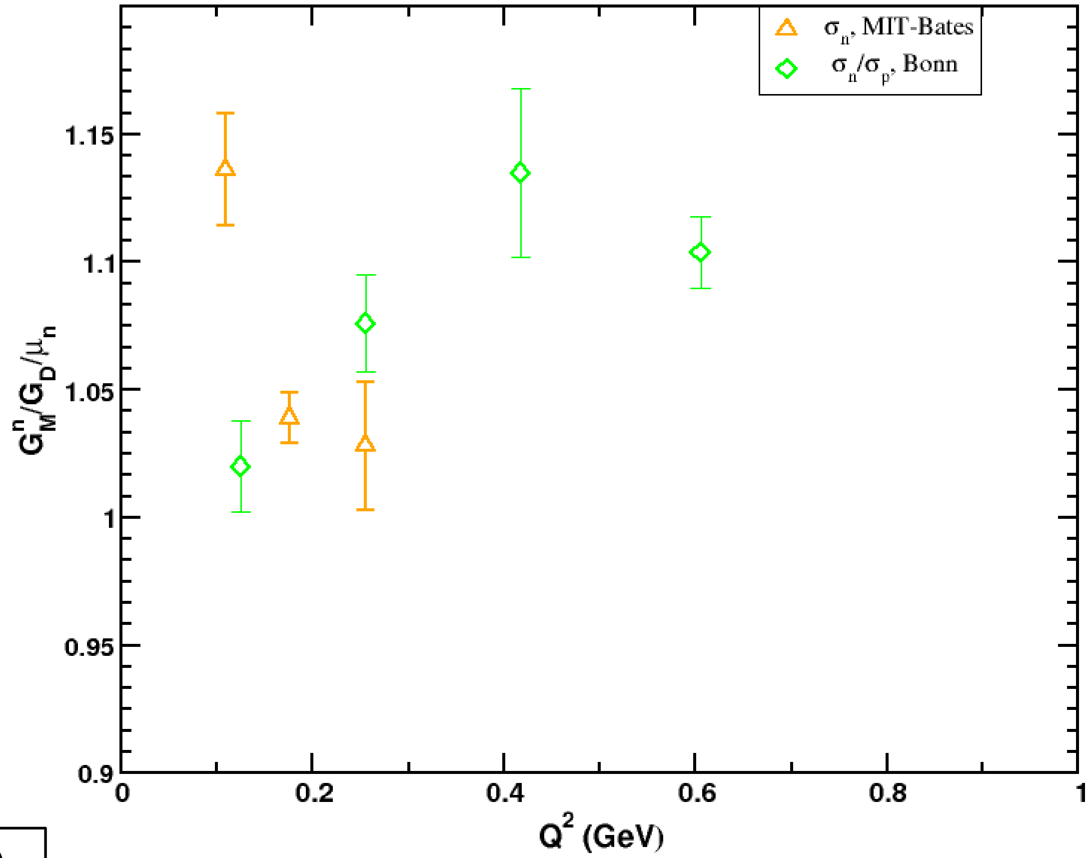
$$\frac{\sigma(e,e'n)}{\sigma(e,e'p)}$$

- Measure ratio of quasi-elastic n/p from deuterium

- Sensitivity to deuteron model cancels in the ratio

- Proton and neutron detected in same detector simultaneously

- Need to know absolute neutron detection efficiency



Bonn used $p(\gamma,\pi^+)n$

Neutron Magnetic Form Factor: G_{Mn}

- Measure $\frac{\sigma(e,e'n)}{\sigma(e,e'p)}$

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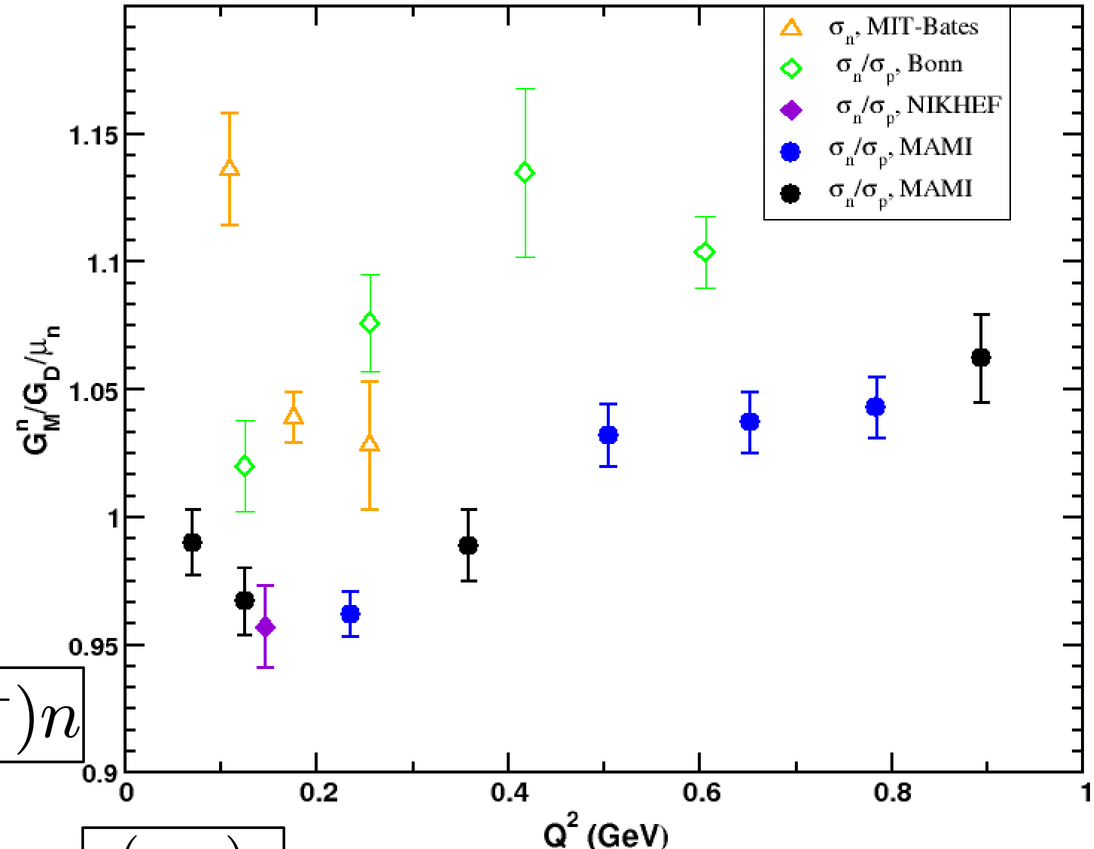


→ Bonn used $p(\gamma,\pi^+)n$

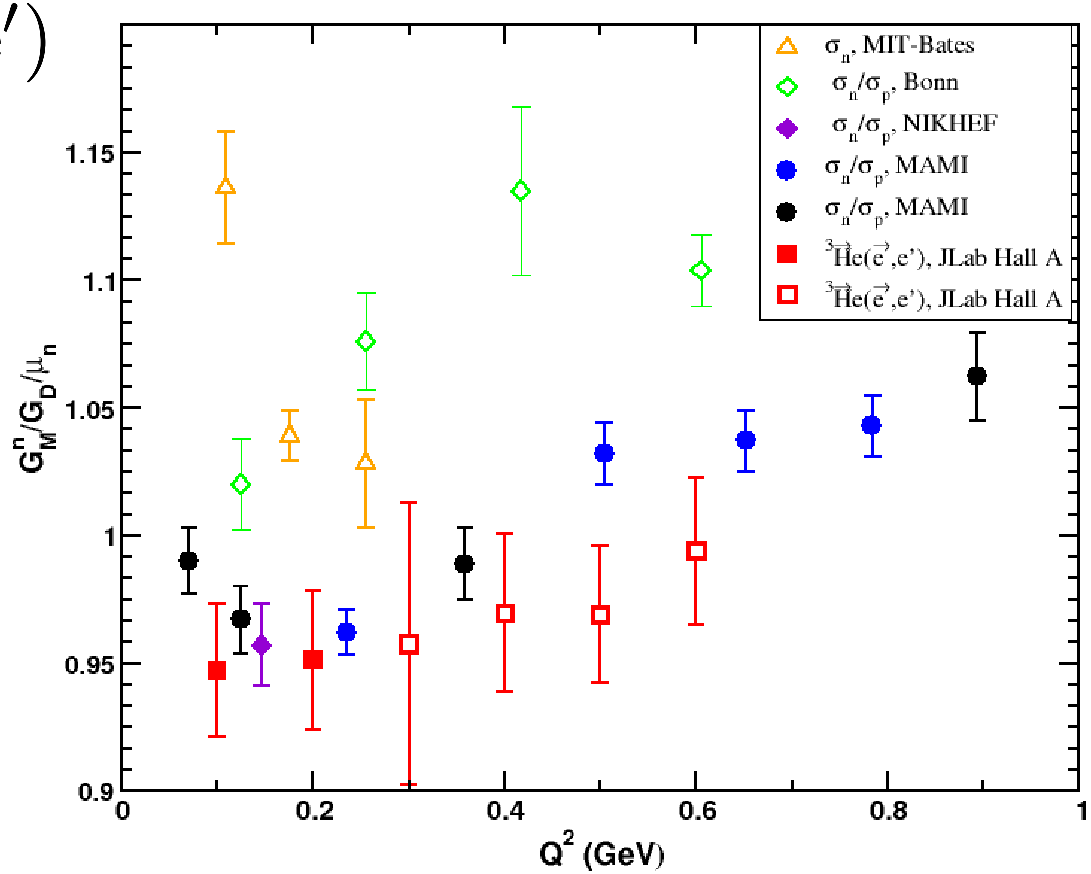
→ NIKHEF and Mainz used $p(n,p)n$ with tagged neutron beam at PSI

Neutron Magnetic Form Factor: G_{Mn}

- Extract from $^3\vec{\mathrm{He}}(\vec{e}, e')$ Transverse asymmetry, A_T

•At Q^2 = 0.1 and 0.2 , use full 3-body non-relativistic Fadeev calculation of A_T

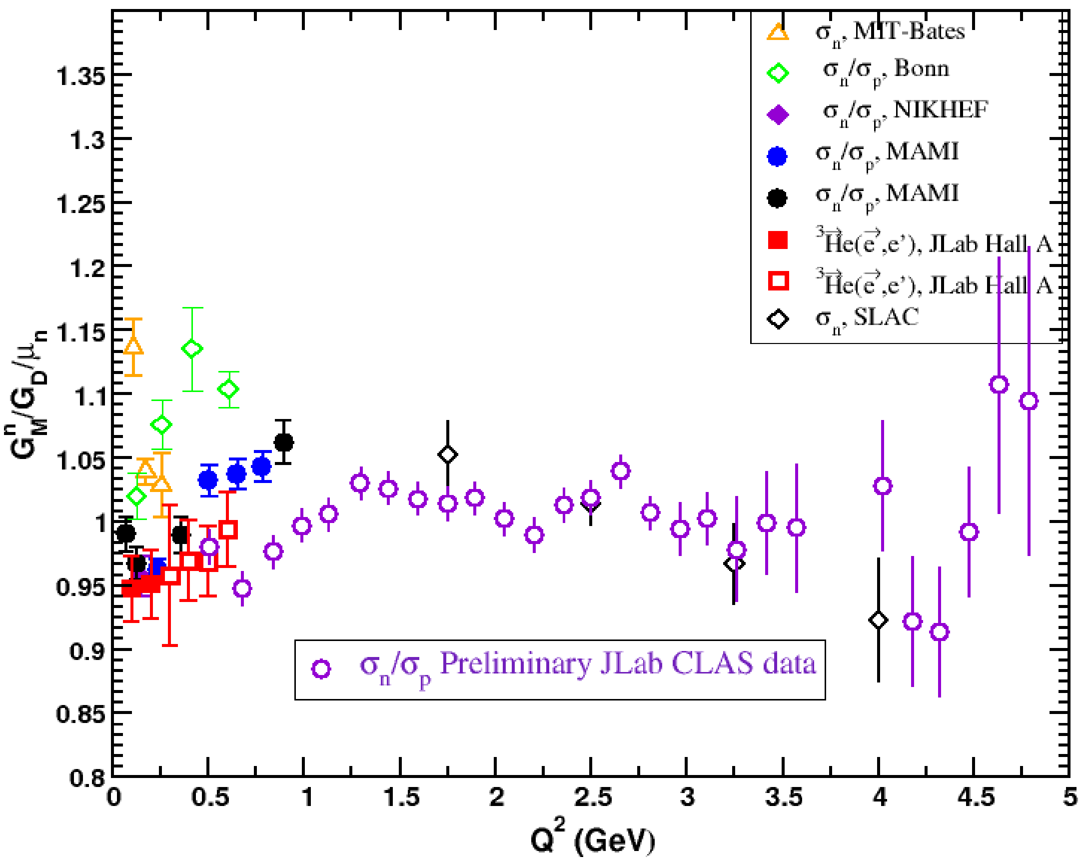
•Q^2 > 0.2 use PWIA calculation of A_T



Neutron Magnetic Form Factor: G_{Mn}

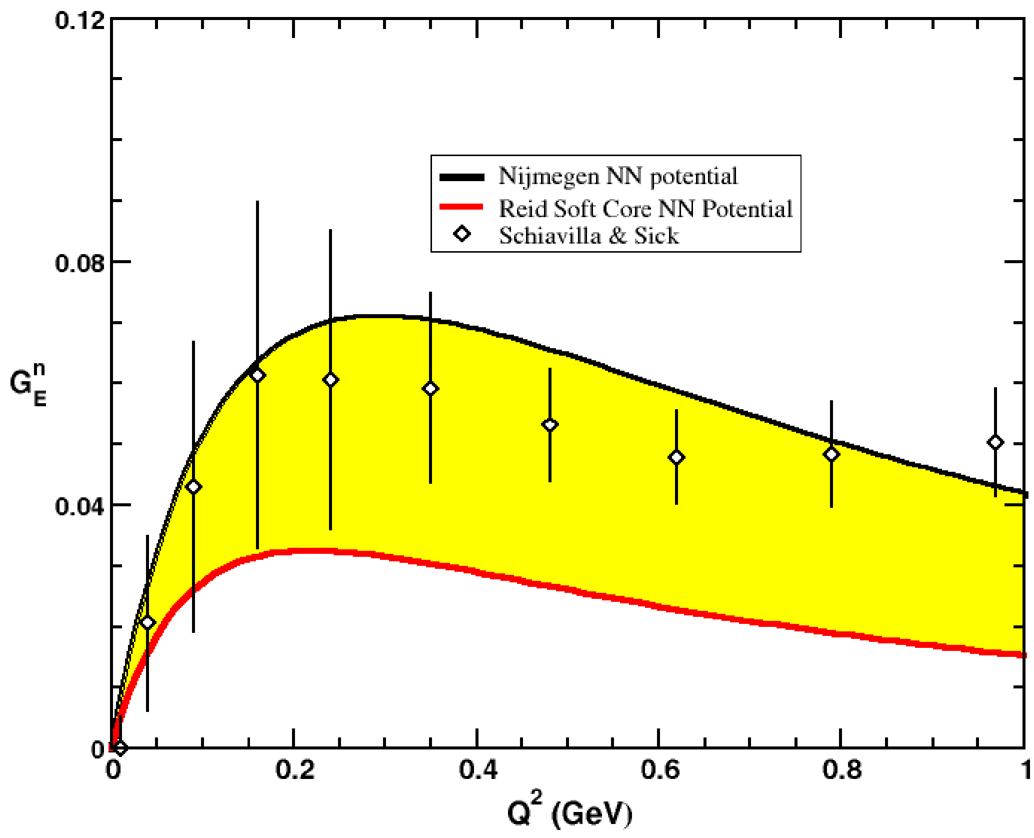
- Measured $\frac{\sigma(e,e'n)}{\sigma(e,e'p)}$ with CLAS in Hall B at Jlab

- Simultaneously have ^1H and ^2H targets



CLAS data from W. Brooks and J. Lachniet, NPA 755 (2005)

Neutron Electric Form Factor: G_{En}



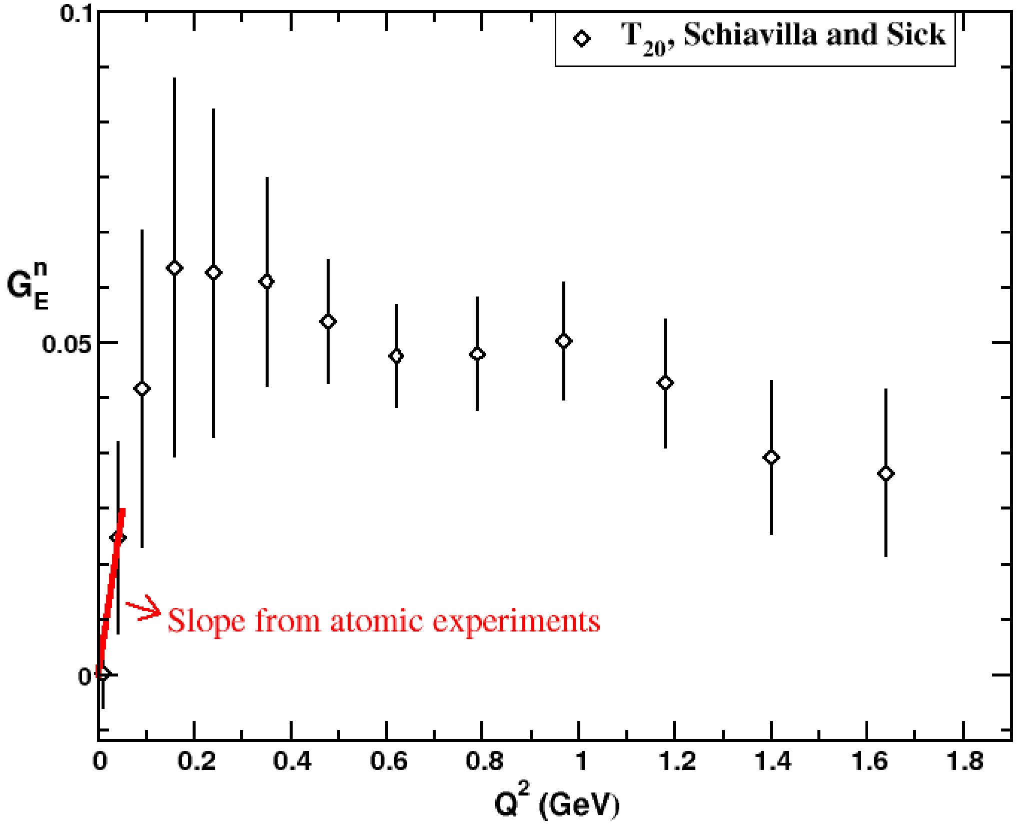
Schiavilla and Sick,PRC64:041002,2001.

In Hall C at Jlab measured T_{20} from <u>elastic</u> $d(\mathrm{e},\mathrm{e}'\,\vec{d})$

Combine $T_{20}(Q^2)$ with $A(Q^2)$ and $B(Q^2)$ to determine all 3 deuteron form factor

Extract G_E with less theory uncertainty

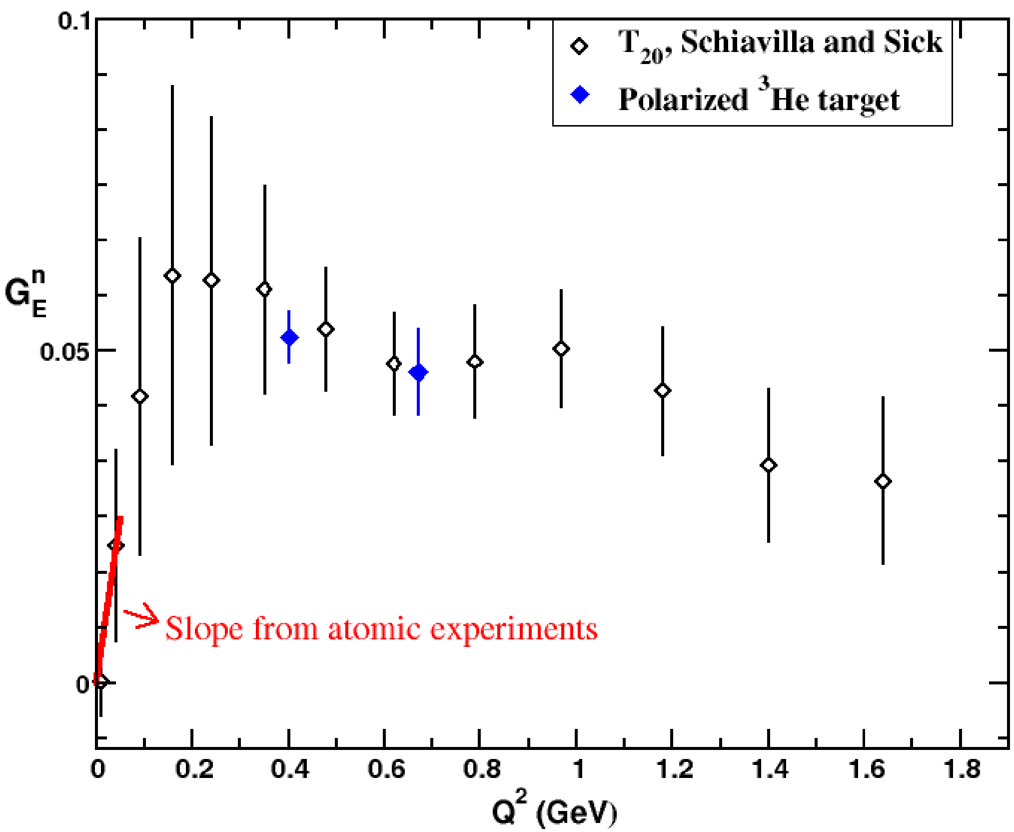
Neutron Electric Form Factor: G_{En}



- Determine neutron charge radius from low energy neutron-electron scattering using ^{208}Pb and ^{209}Bi

- S. Kopecky et al., PRC 56, 2229 (1997).

Neutron Electric Form Factor: G_{En}



Theory important for reliably extracting G_E/G_M from nuclear effects

At MAMI using polarized 3He

G_{En} from quasi-free $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})$

In PWIA

$$\theta^* = 90^\circ$$

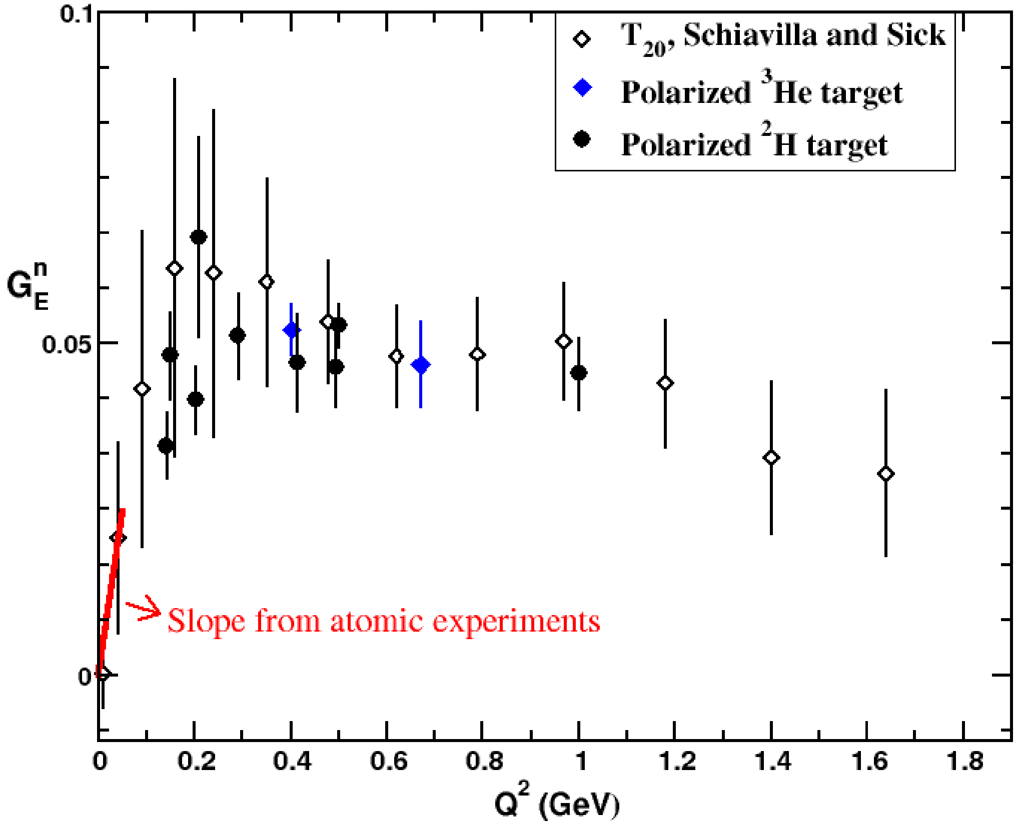
$$A_\perp \propto P_B P_T G_E/G_M$$

$$\theta^* = 0^\circ$$

$$A_\parallel \propto P_B P_T$$

$$G_E/G_M \propto A_\perp/A_\parallel$$

Neutron Electric Form Factor: G_{En}



$$\vec{\mathrm{d}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})$$

G_{En} from beam-target asymmetry

In PWIA

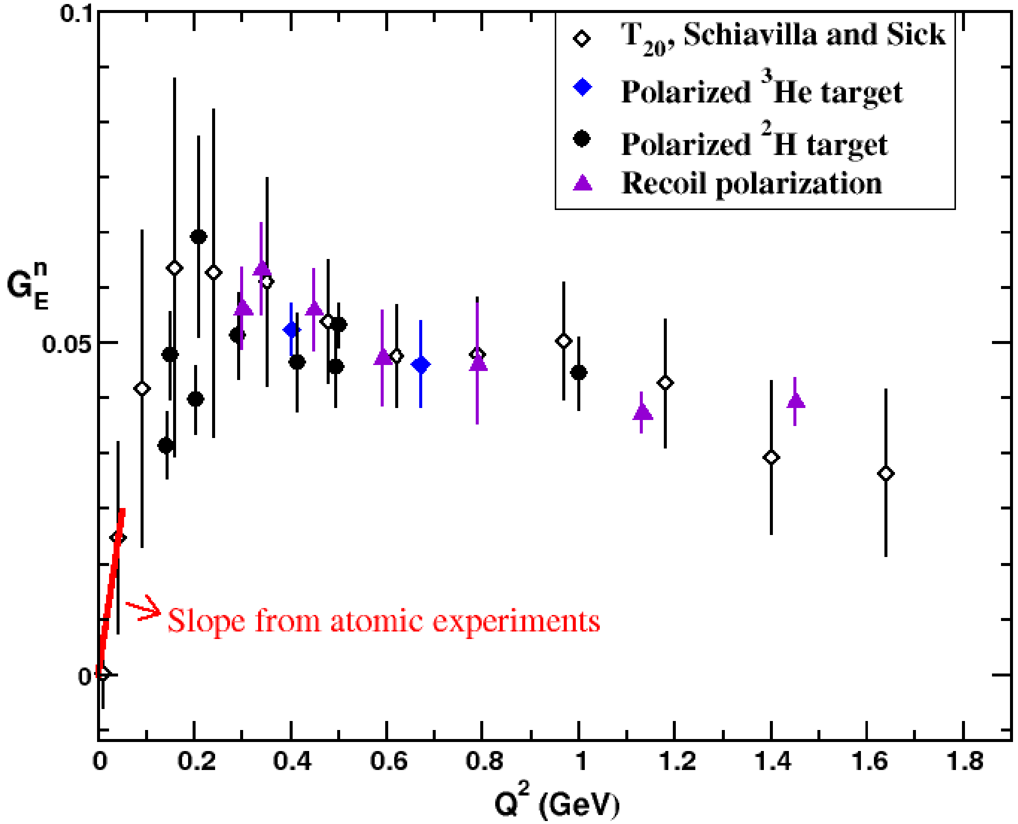
$$A_{ed}^V = P_B P_T V \frac{aG_E G_M}{G_E^2 + \tau/\epsilon G_M^2}$$

NIKHEF used electron storage ring with internal gas target.

JLab used solid $^{15}ND_3$ target
Measured to $Q^2 = 1$

Recent data from MIT-Bates used internal gas target and large acceptance BLAST detector

Neutron Electric Form Factor: G_{En}



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

Recoil Polarization

In PWIA

$$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E_e + E_{e'})}{2M}\tan\left(\frac{\theta}{2}\right)$$

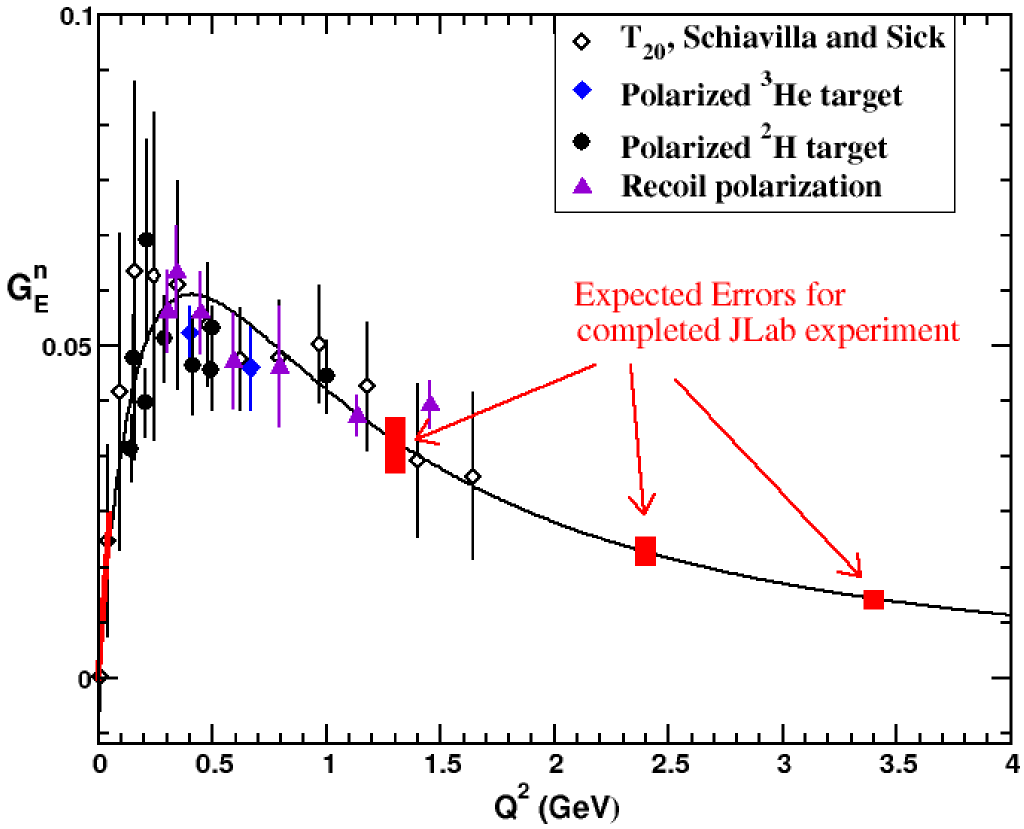
At Mainz,

Q^2 = 0.15 to 0.8

At JLab,

Q^2= 0.45, 1.13, 1.45

Neutron Electric Form Factor: G_{En}



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

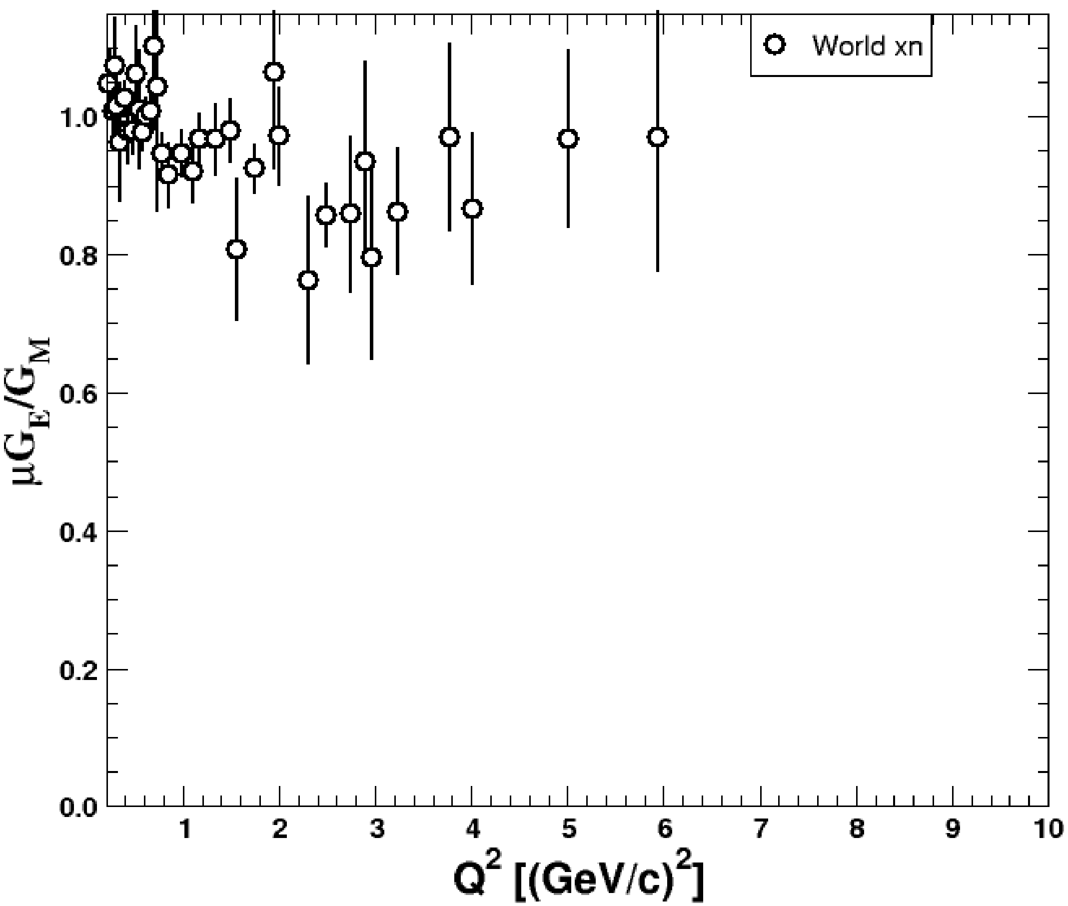
Recently completed JLab experiment

Large solid angle electron spectrometer combined with a large solid angle neutron detector

45% polarization in ^{3}He

JLab Hall A Spokespeople: G. Cates, K. McCormick, B. Reitz and B. Wojtsekhowski

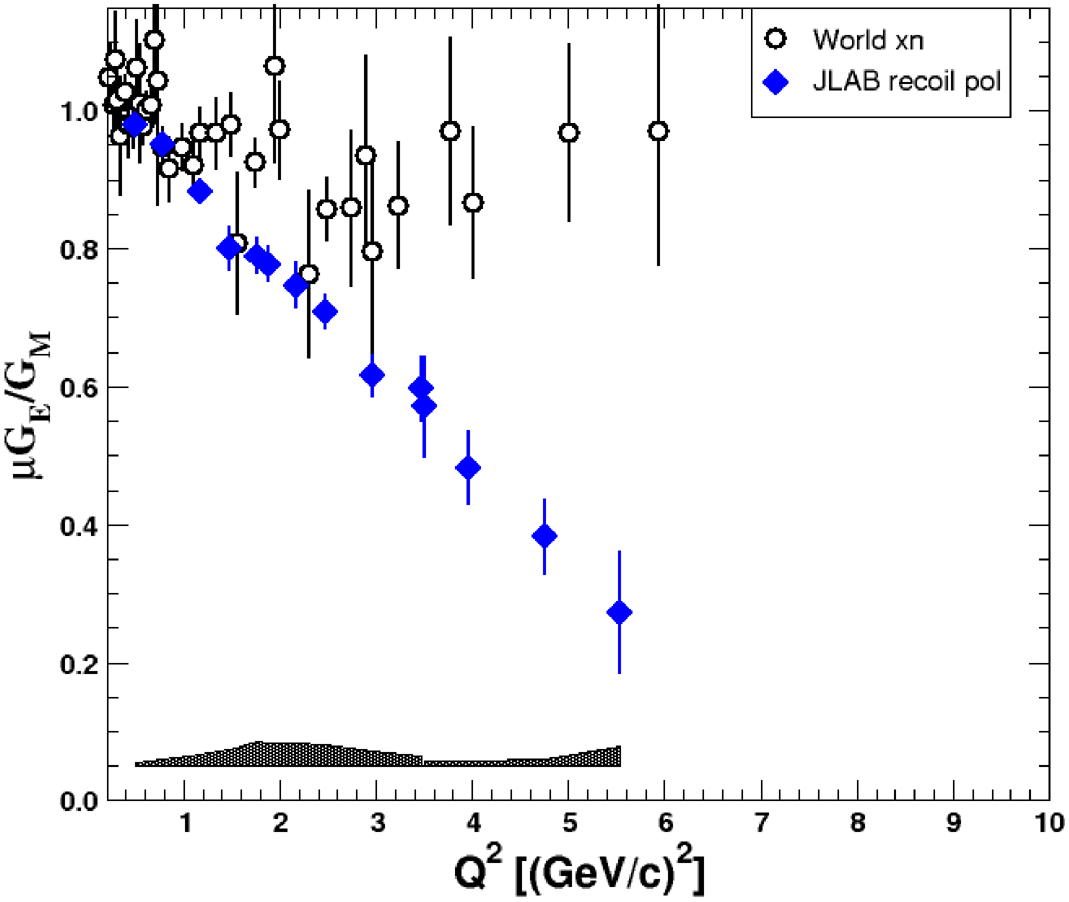
Measuring G_{Ep} / G_{Mp} at $Q^2 > 1$ GeV^2



J. Arrington PRC 68:034325, 2003

Recent compilation of world data which was careful in combining data from different experiments and correlating normalization systematics

Measuring G_{Ep} / G_{Mp} at $Q^2 > 1$ GeV^2



Measure recoil polarization

$$p(\vec{e}, e'\vec{p})$$

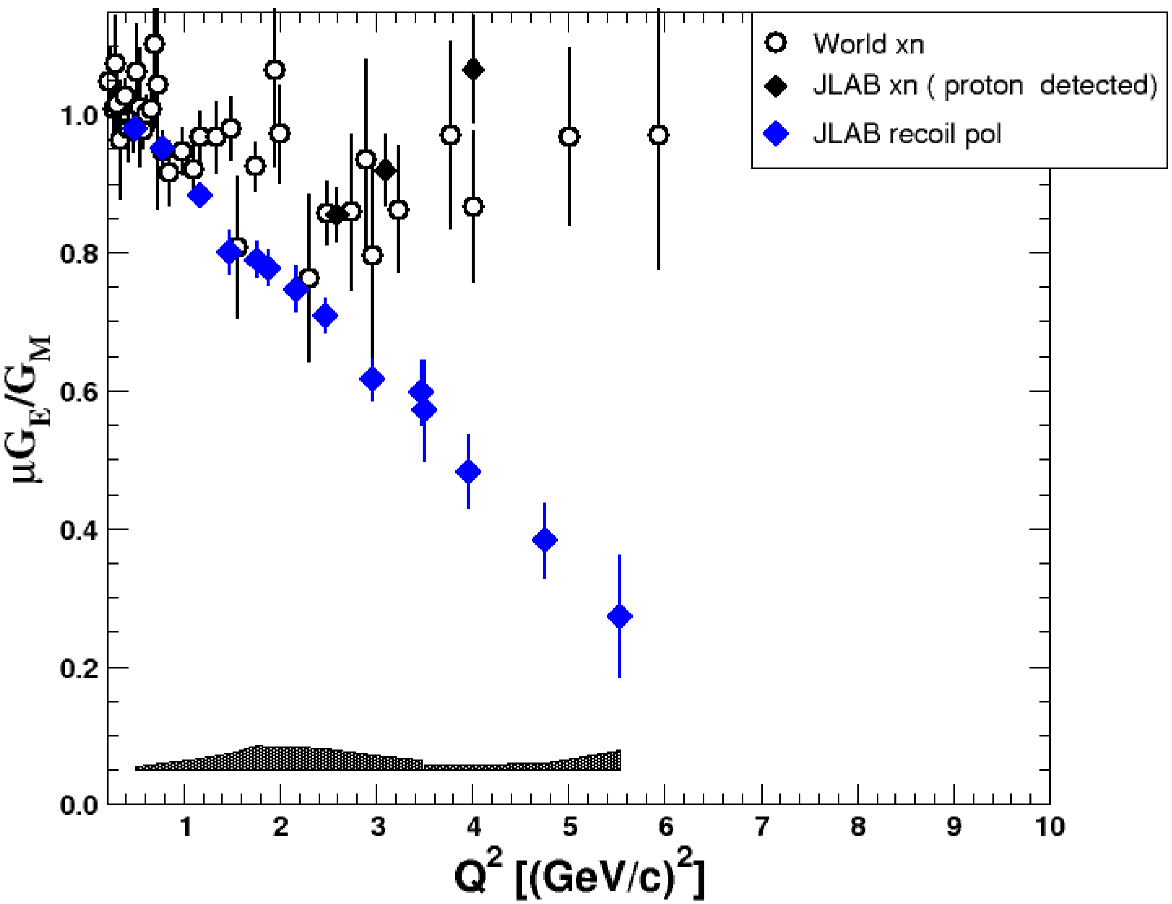
$$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E_e + E_{e'})}{2M}\tan\left(\frac{\theta}{2}\right)$$

Measurements done in Hall A at JLab

First set $0.5 < Q^2 < 3.5$
Measured using two spectrometers

First set $3.5 < Q^2 < 5.6$
Measured using large calorimeter to detect electrons and spectrometer for protons

Measuring G_{Ep}/G_{Mp} at $Q^2 > 1$ GeV^2



I. Qattan et al. PRL 94, 142301 (2005)

At JLab in Hall A measured elastic ep detected scattered proton *instead of electron*

Advantages:

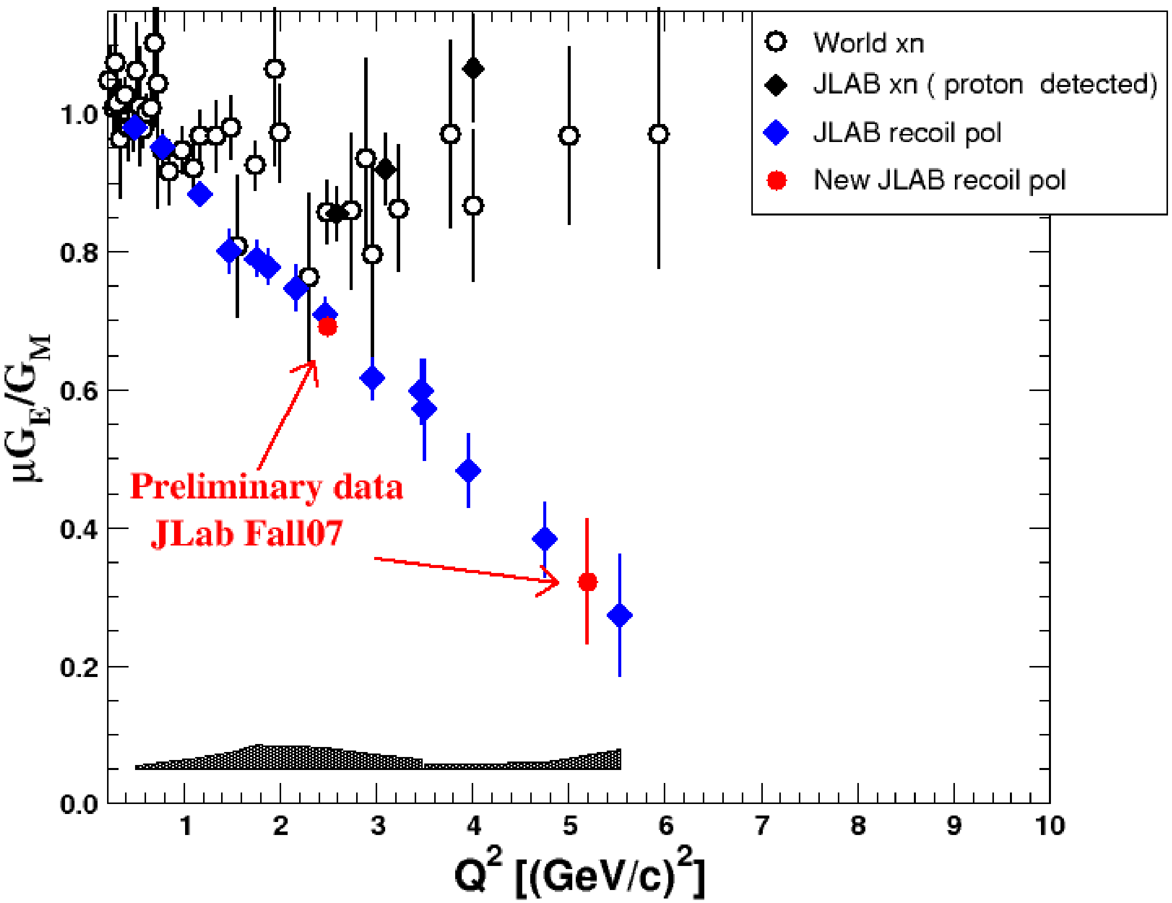
•Proton momentum fixed at each ε

•Cross section is nearly constant with ε

•Reduces size of ε-dependent radiative corrections

•Reduces systematic error from beam energy and scattering angle

Measuring G_{Ep} / G_{Mp} at $Q^2 > 1$ GeV^2

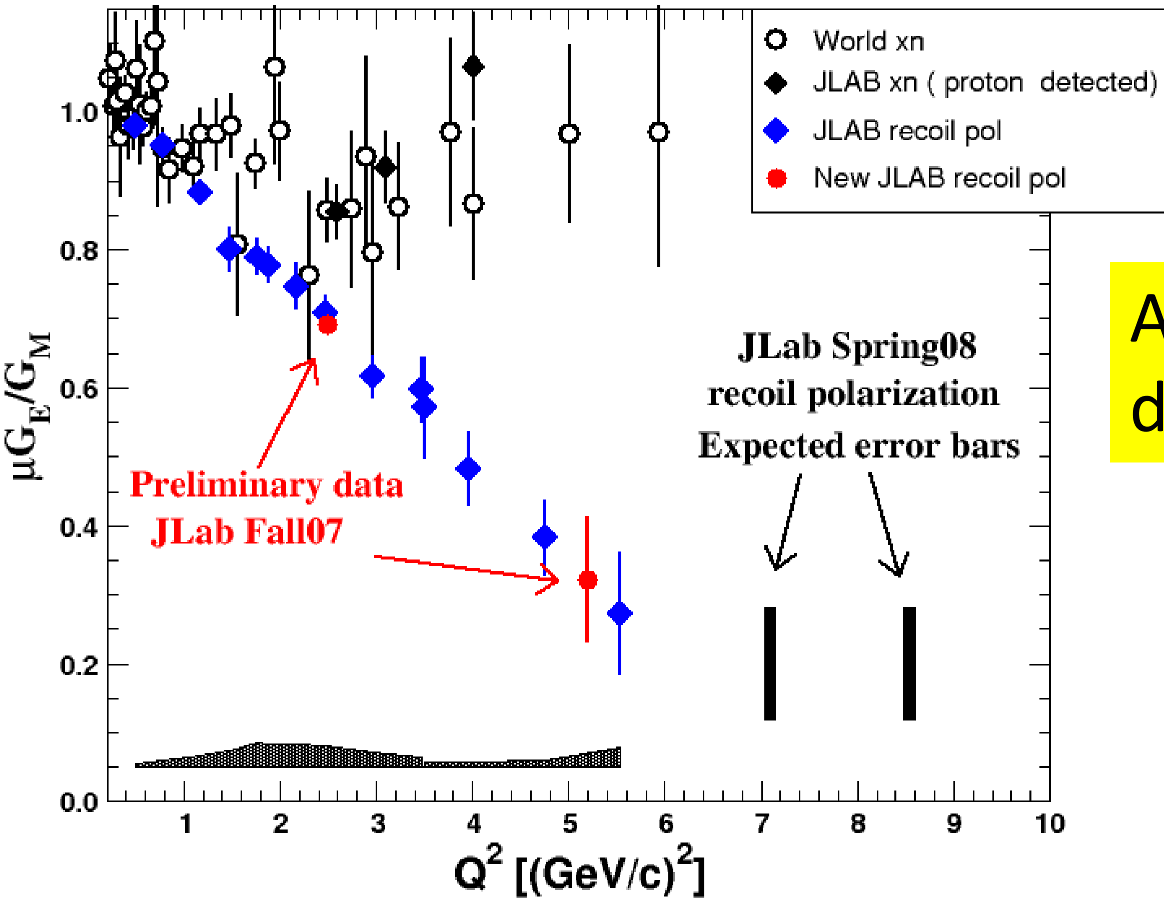


In middle of new experiment at Jlab in Hall C

Use a large calorimeter to detect electron combined with Hall C HMS spectrometer with new focal plane polarimeter

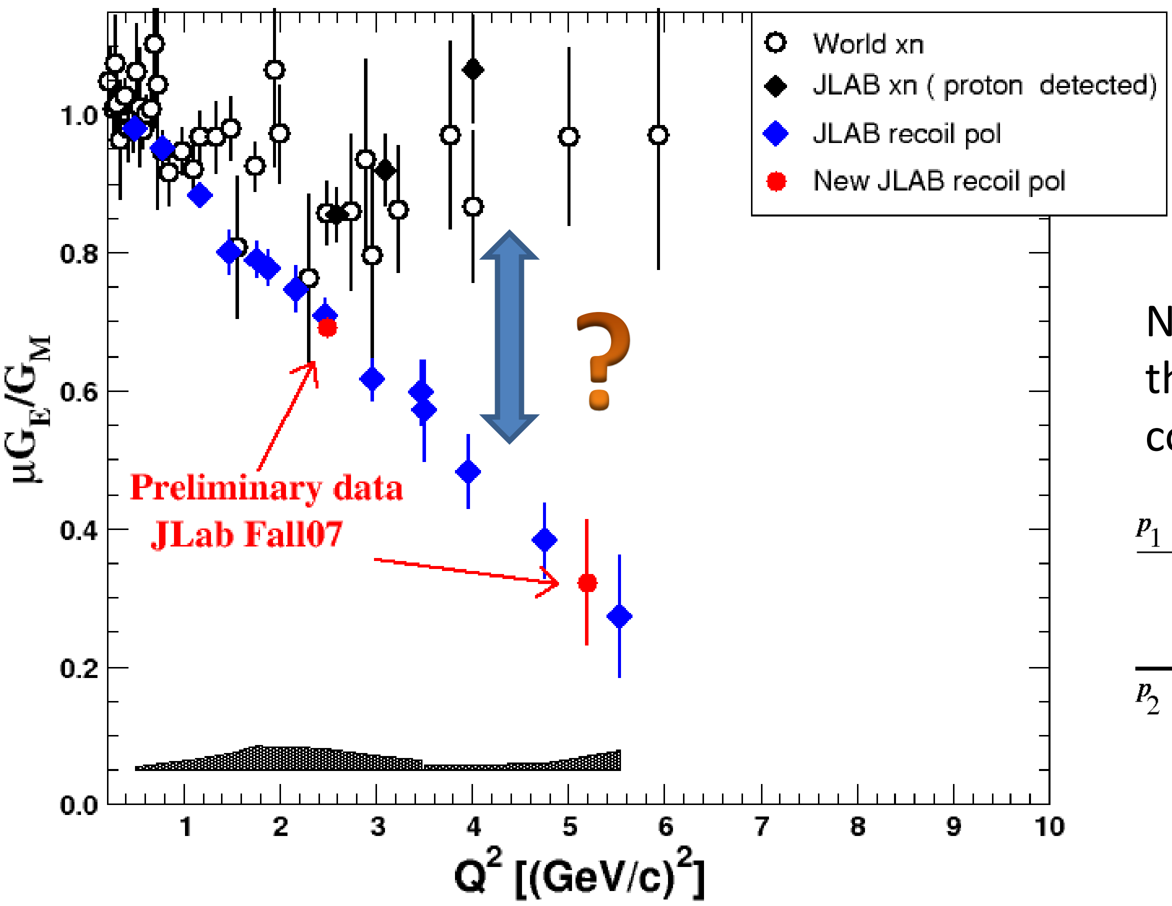
Data taken the fall confirm earlier Hall A measurements

Measuring G_{Ep}/G_{Mp} at $Q^2 > 1\ GeV^2$



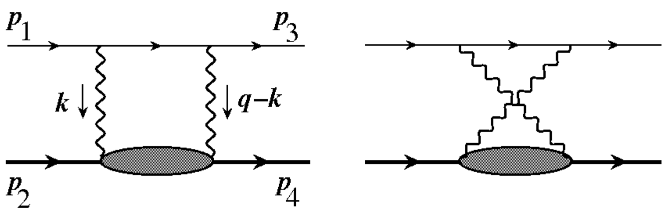
April 4th started taking data for high $Q^2 = 8.5$

Why the discrepancy in G_E/G_M?



Multiple experiments with different methods rule out experimental problem

Neglected 2γ contributions to the ep elastic cross section could explain the difference



Theory of 2γ in *ep* elastic reaction

$$\Gamma_\mu(p',p) = \tilde{G}_M\gamma_\mu + -\tilde{F}_2\frac{P^u}{M} + \tilde{F}_3\frac{\gamma\cdot K P^u}{M^2}$$

$$\tilde{G}_M = G_M + \delta\tilde{G}_M\ ,\ \tilde{F}_2 = F_2 + \delta\tilde{F}_2,\ \tilde{F}_3 \text{ purely from } 2\gamma$$

$$\sigma_R \sim \frac{\tilde{G}_M^2}{\tau}\{\tau + \epsilon\frac{\tilde{G}_E^2}{\tilde{G}_M^2} + 2\epsilon(\tau + \frac{\tilde{G}_E}{\tilde{G}_M})\mathcal{R}(\frac{\nu\tilde{F}_3}{M^2\tilde{G}_M})\}$$

$$\frac{P_T}{P_L} \sim -\sqrt{\frac{2\epsilon}{\tau(1+\epsilon}}\{\frac{\tilde{G}_E}{\tilde{G}_M} + (1 - \frac{2\epsilon}{1+\epsilon}\frac{\tilde{G}_E}{\tilde{G}_M})\mathcal{R}(\frac{\nu\tilde{F}_3}{M^2\tilde{G}_M})\}$$

To explain discrepancy need $\mathcal{R}(\frac{\nu\tilde{F}_3}{M^2\tilde{G}_M}) \sim 3\%$ with small Q^2 and ϵ dependence. P.A.M. Guichon and M. Vanderhaegen, PRL (2003)

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Calculations by E. Tomasi-Gustafsson and G. I. Gakh predict large non-linearities in e-dependence of cross section which are not seen in the data.

Calculations of 2γ effects

- Effects predicted to change cross sections but small effect on polarization observables:
  - » Hadronic Model of Blunden, Melnitchouk and Tjon
  - » GPD model of Chen, Afanasev, Brodsky, Carlson and Vanderhaeghen

•But no significant 2γ effect predicted in calculation of Y. Bystritskiy, E. Kureav and E. Tomasi-Gustafsson

•Recent calculation of Jain, Joglekar and Mitra predict large effects to the polarization observables.

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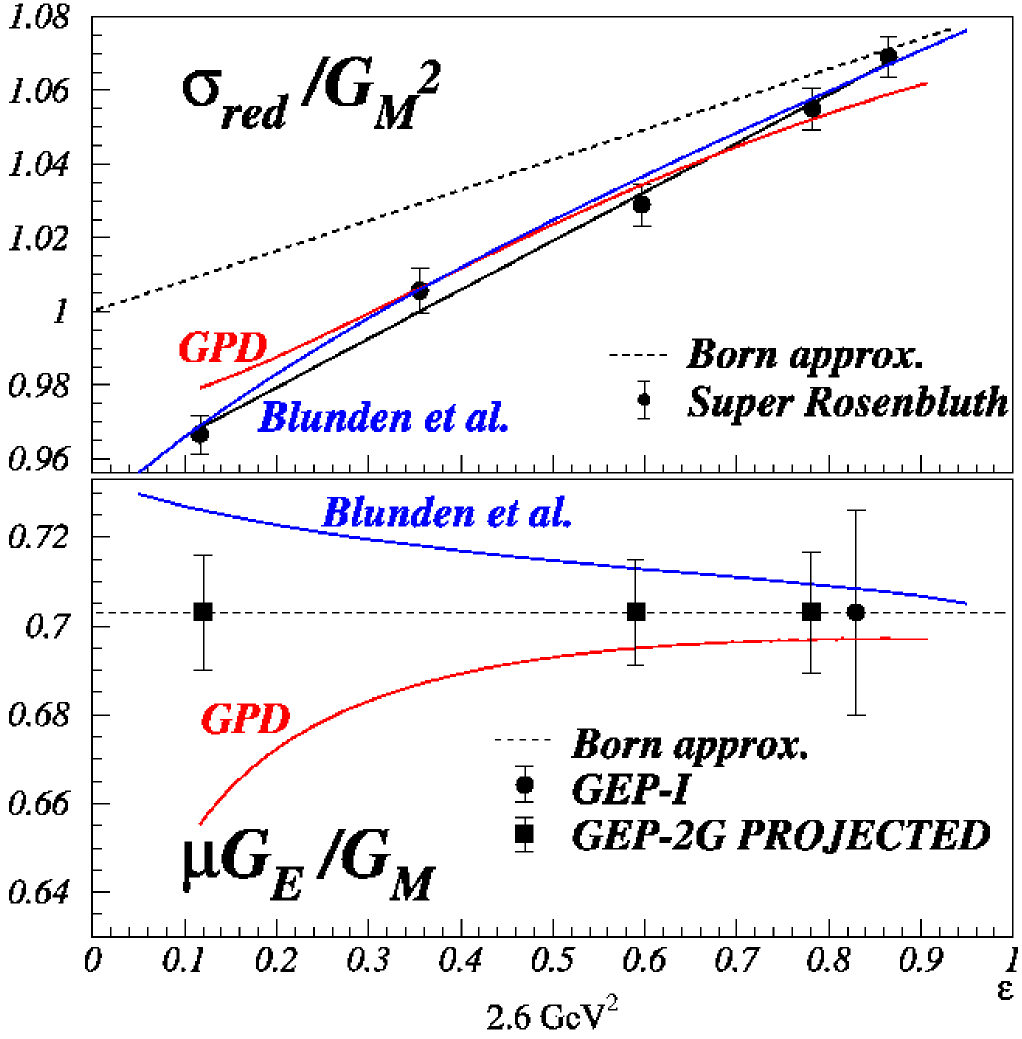
Need new experimental data

Experimental searches for 2γ effects



Measure G_E/G_M as function of ε

Look for deviations from a constant

Experimental searches for 2γ effects

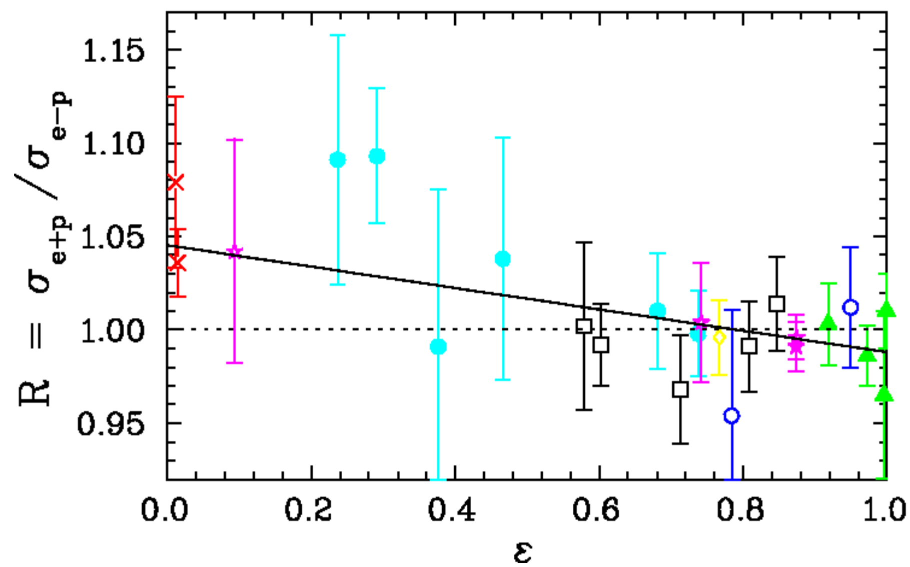
Experiment at Jlab in Hall C measured ep elastic cross sections
$0.4 < Q^2 < 5.0$ and $0.05 < \varepsilon < 0.95$

completed Spring 2007

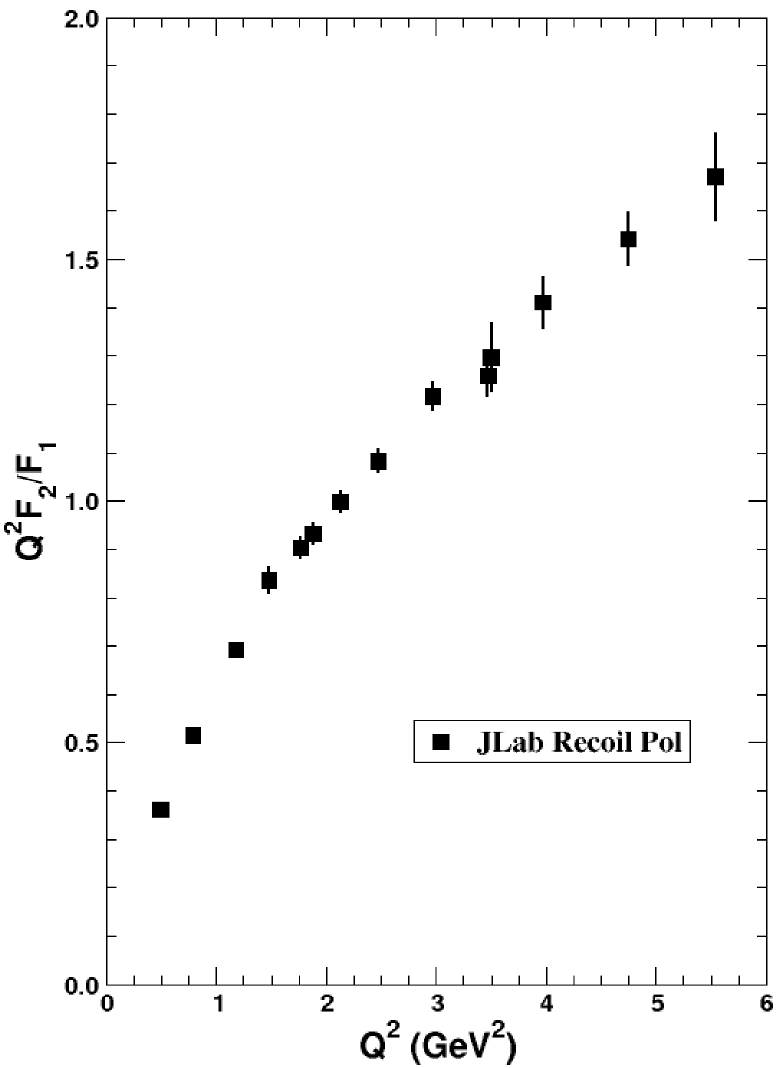
Measure cross section ratio of e^+p/e^-p as function of ε

- ❑ Approved JLab Hall B experiment to measure e^+p/e^-p

- ❑ Proposal at VEPP-3 to measure e^+p cross sections



pQCD and proton G_E/G_M



Convert G_E/G_M directly to F_2/F_1

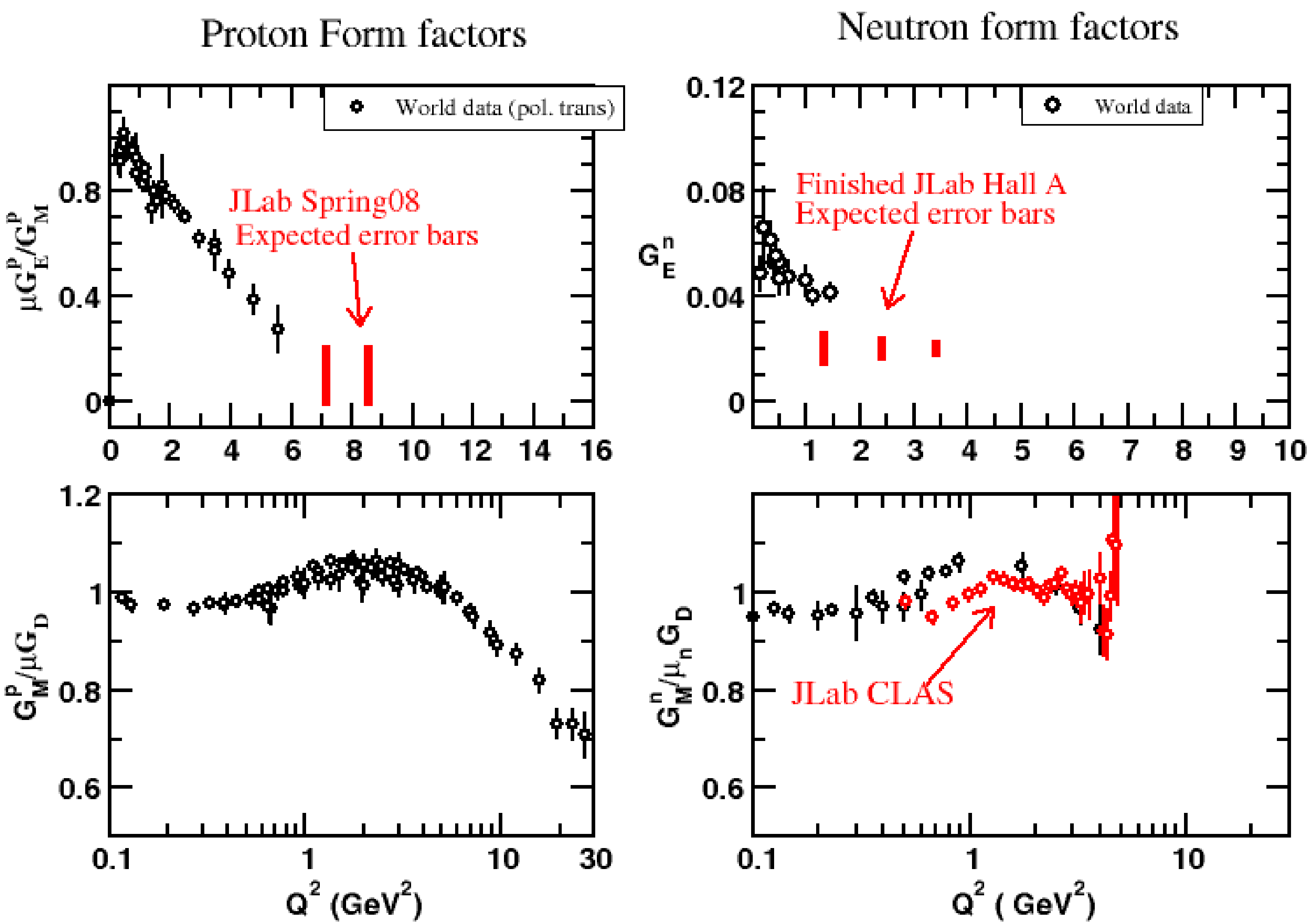
F_2 is helicity non-conserving amplitude

In pQCD, F_2 is power-law suppressed

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

- The Q^2 scale were pQCD applies is not predicted
- Data indicates that is above Q^2 = 6

Summary of present data set



Relevant features of new data set

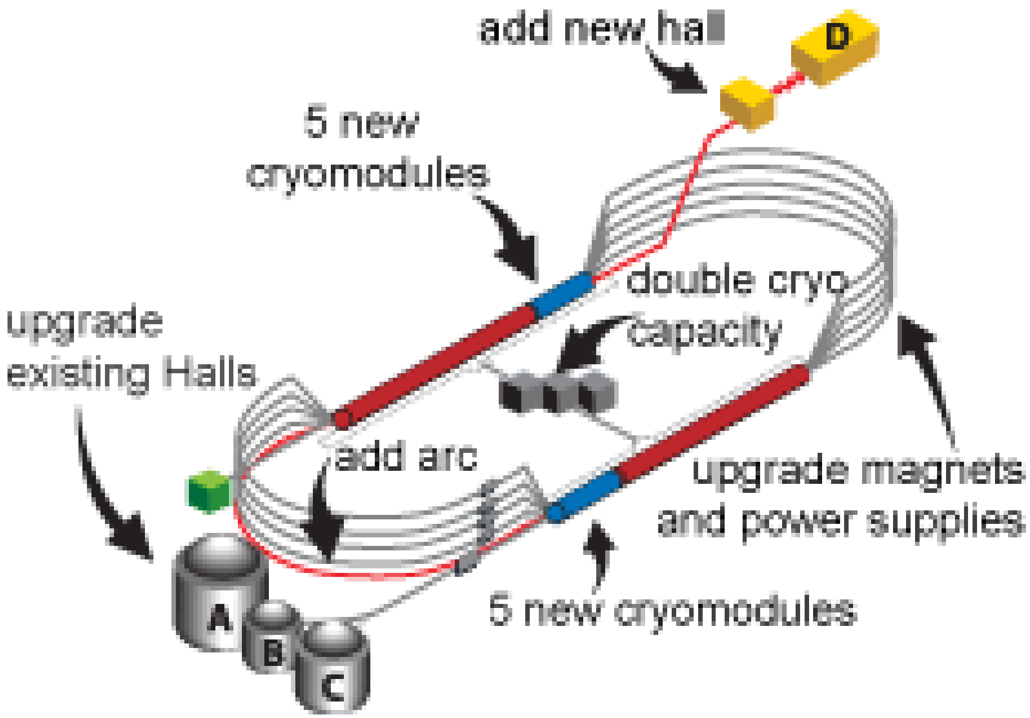
- Measured all form factors to Q2 = 3.5

  ❑Allows comparison of models from where pion clouds or constituent quarks are important to Q^2 region where sensitive to quark core.
  ❑Can determine isoscalar and isovector form factors for comparison to LQCD, since it presently can't handle disconnect diagrams.

- Linear fall-off in proton G_E/G_M to Q2 = 5.6

  ❑ Helicity non-conservation .
  Quark counting rules do not apply in this Q^2 region
  ❑Demonstrates the importance of relativity in understanding nucleon structure
  Indicates angular momentum in nucleon

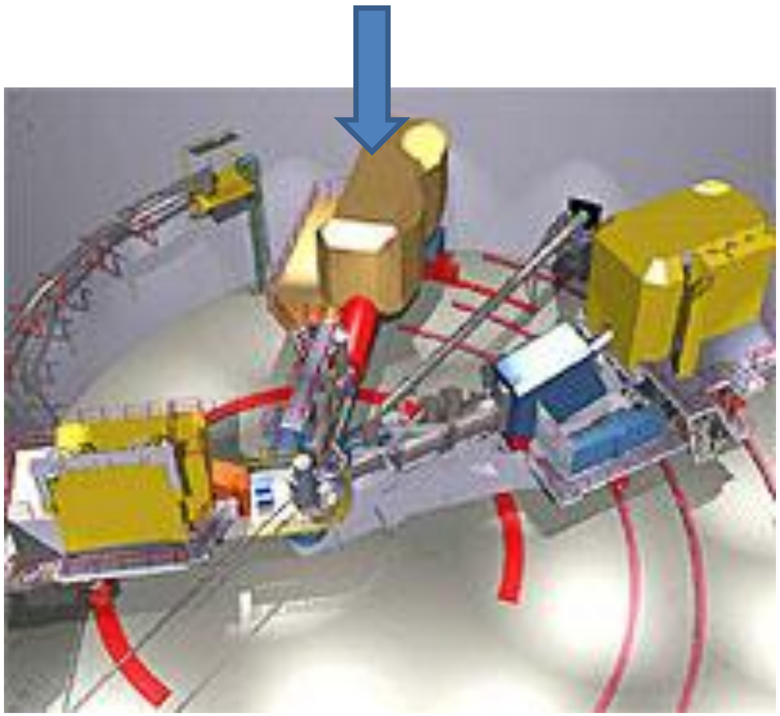
Upgrade of Jlab to 12 GeV



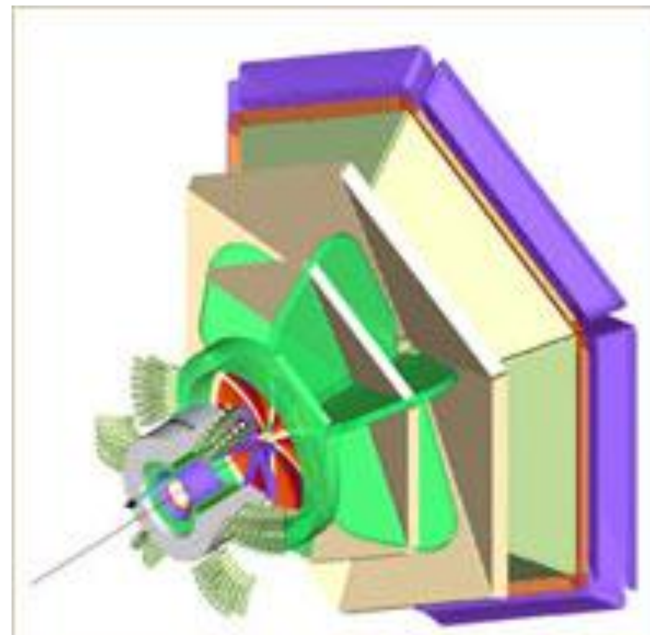
Upgrade expected to be completed by 2013

Upgrade of Jlab to 12 GeV

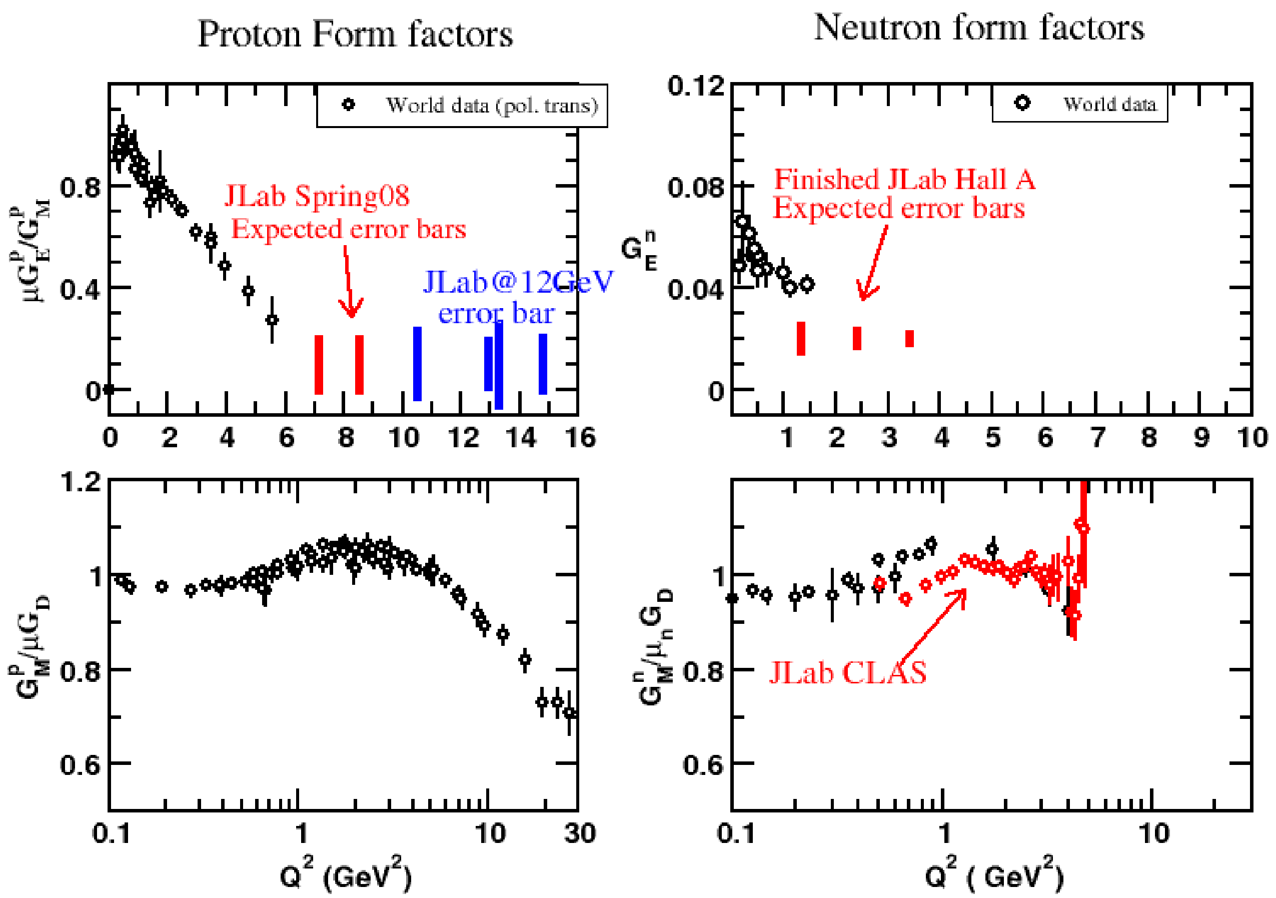
New 11 GeV spectrometer in Hall C



Upgrade large acceptance spectrometer in Hall B



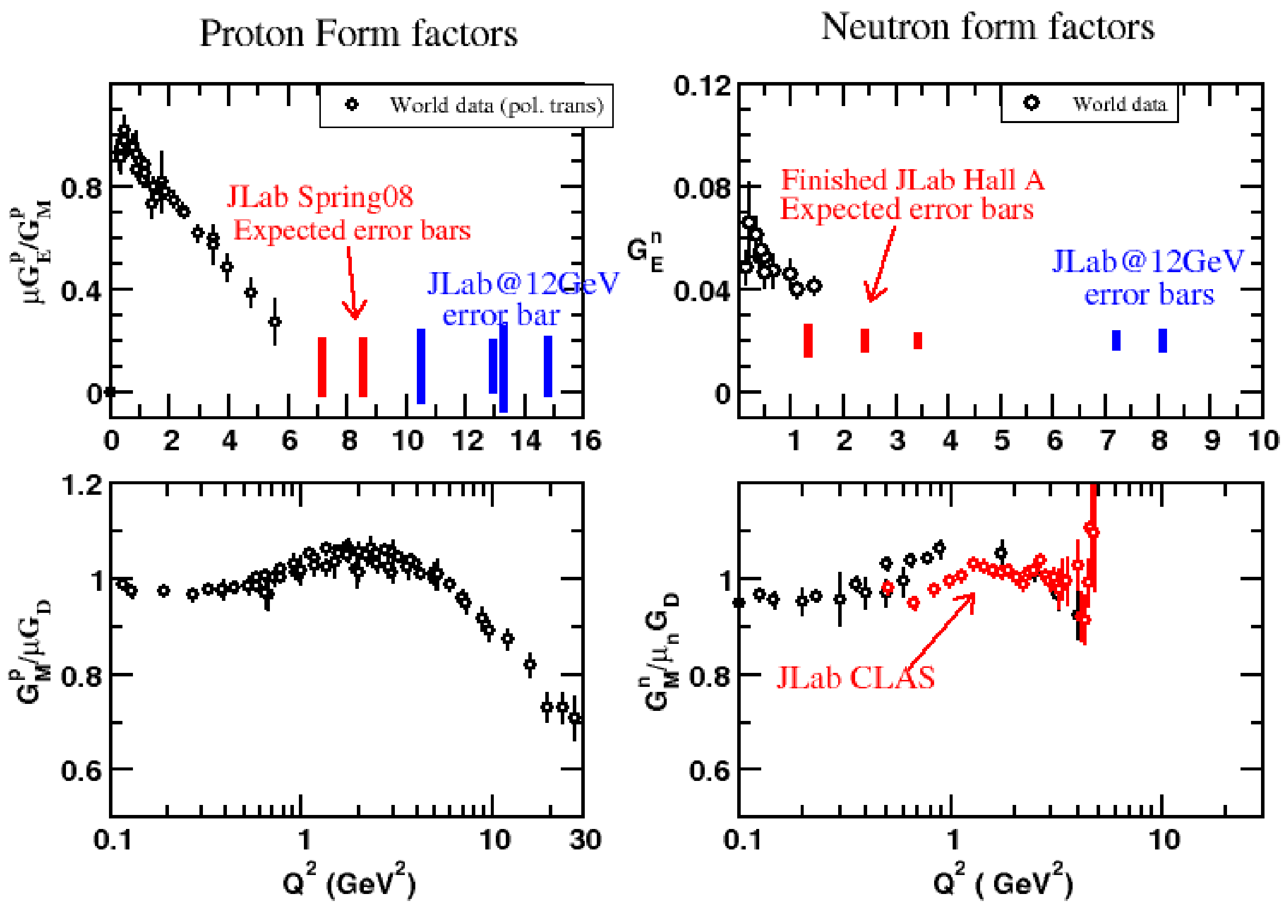
Nucleon FF with Jlab@12GeV



Can continue proton Ge/Gm to $Q^2 = 13$ by moving FPP into Hall C SHMS

Possible to go to $Q^2 = 14.8$ specially built polarimeter and electron detector in Hall A

Nucleon FF with Jlab@12GeV



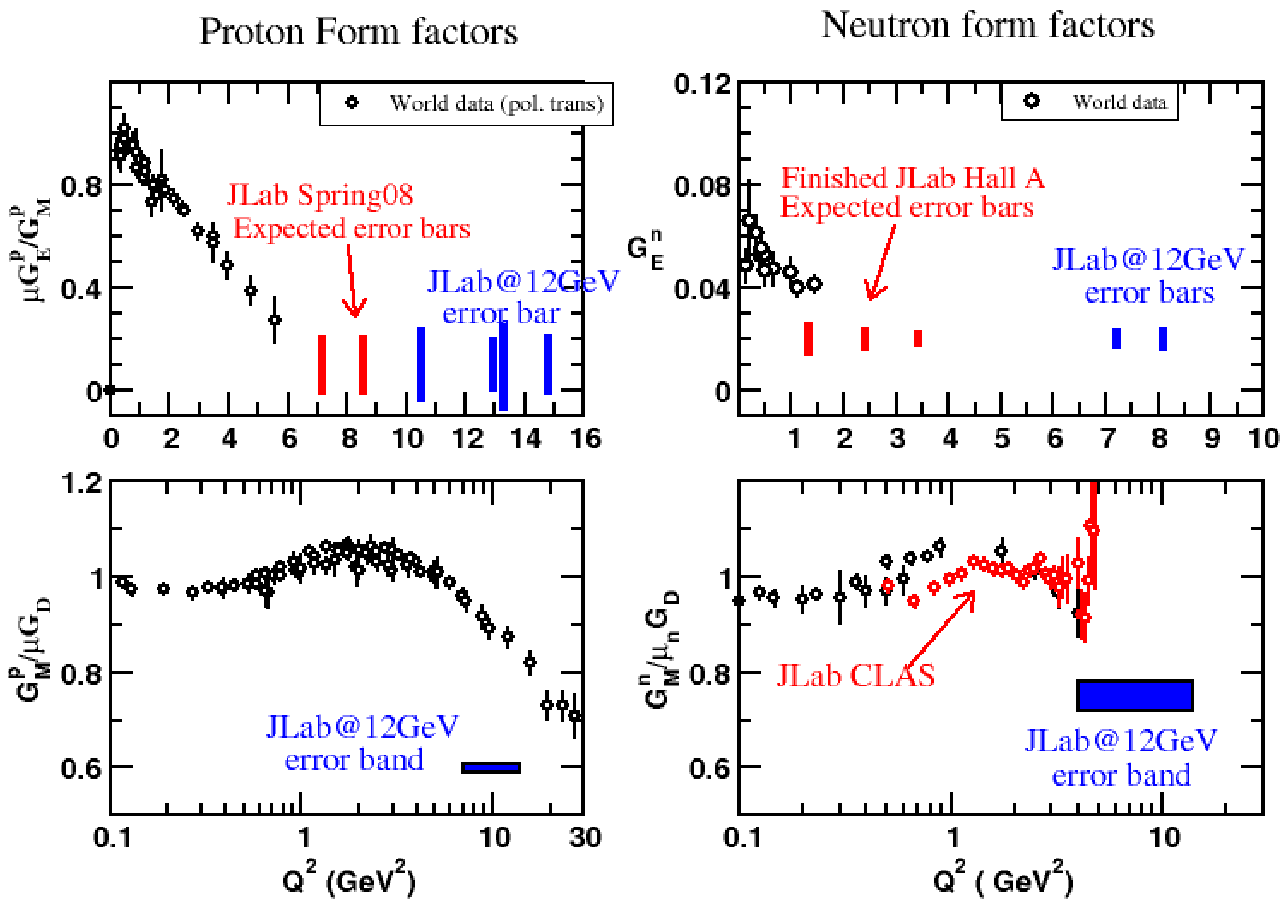
Extend neutron electric form factor by either

$$^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})$$

or

$$\mathrm{d}(\vec{\mathrm{e}},\mathrm{e}'\,\vec{n})$$

Nucleon FF with Jlab@12GeV



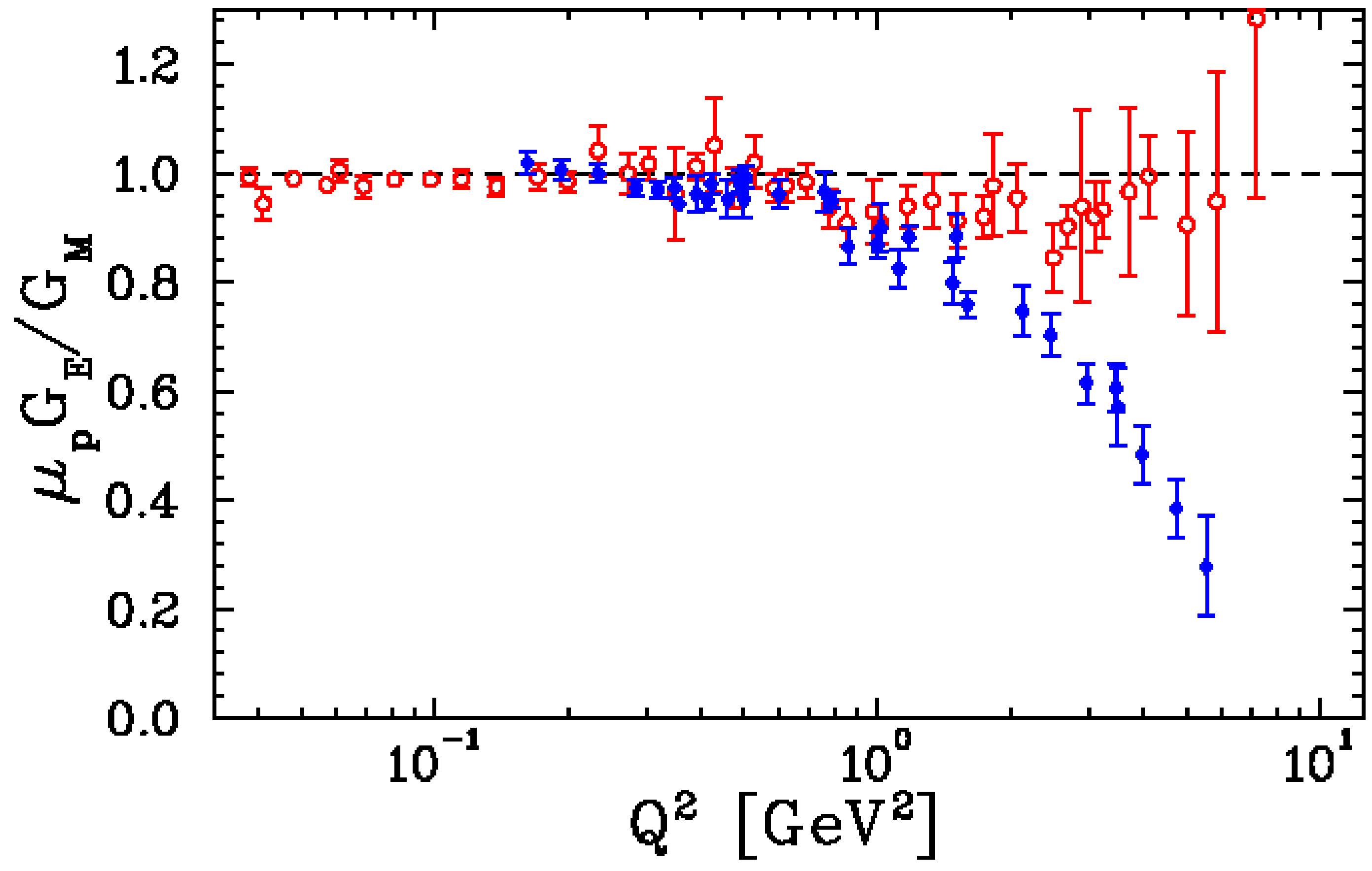
Extension of previous techniques will measurement of neutron G_M to $Q^2 = 14$ GeV^2 with new CLAS12

Proposed measurement of proton G_M between $7 < Q^2 < 14$ GeV^2

Backup slides

Calculations of 2γ effects

New paper using the "hadronic" model by J. Arrington, W. Melnitchouk, J. A. Tjon nucl-ex/0702002



Calculations of 2γ effects

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