Nucleon Form Factors @JLab

Mark K. Jones, Jefferson Lab

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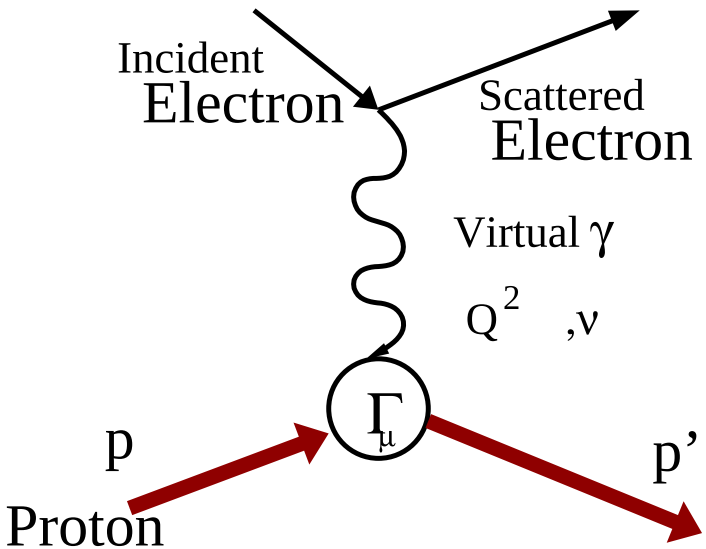

Nucleon vertex:

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

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

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

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

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

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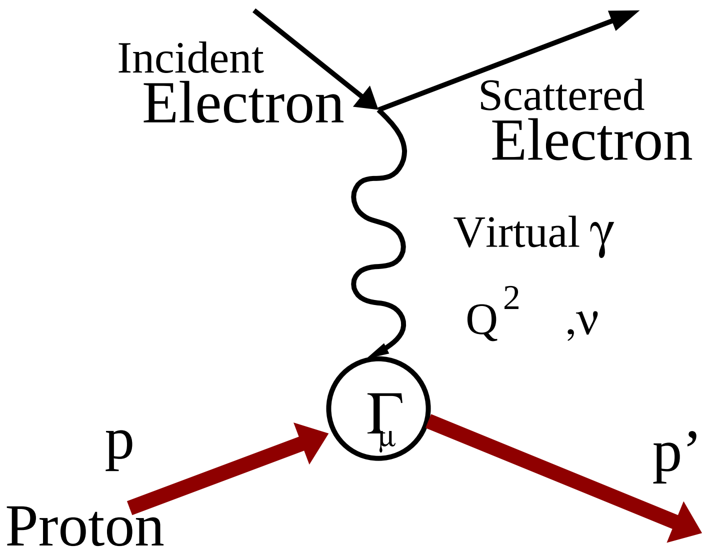

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At $Q^2 = 0$ $\quad G_{Mp} = 2.79 \; G_{Mn} = -1.91$

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

Extract G_E and G_M from:

- Cross-section measurements $N(e,e')$
- Beam-target Asymmetries $\vec{N}(\vec{e},e')N$
- Recoil polarization $N(\vec{e},e')\vec{N}$

Neutron Magnetic Form Factor : G$_{Mn}$

Extract G$_{Mn}$ from inclusive d(e,e′) quasielastic scattering cross section data.

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

In PWIA :

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

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

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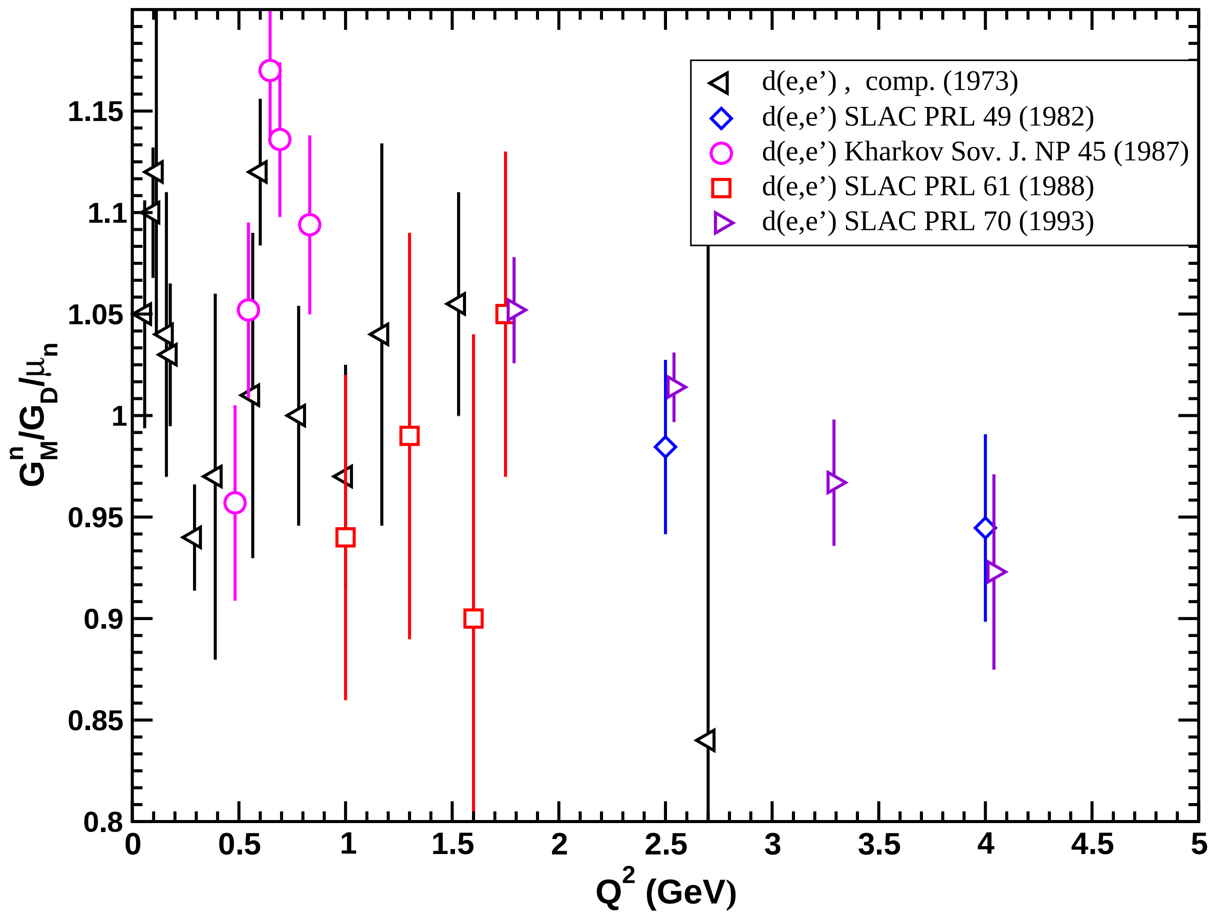

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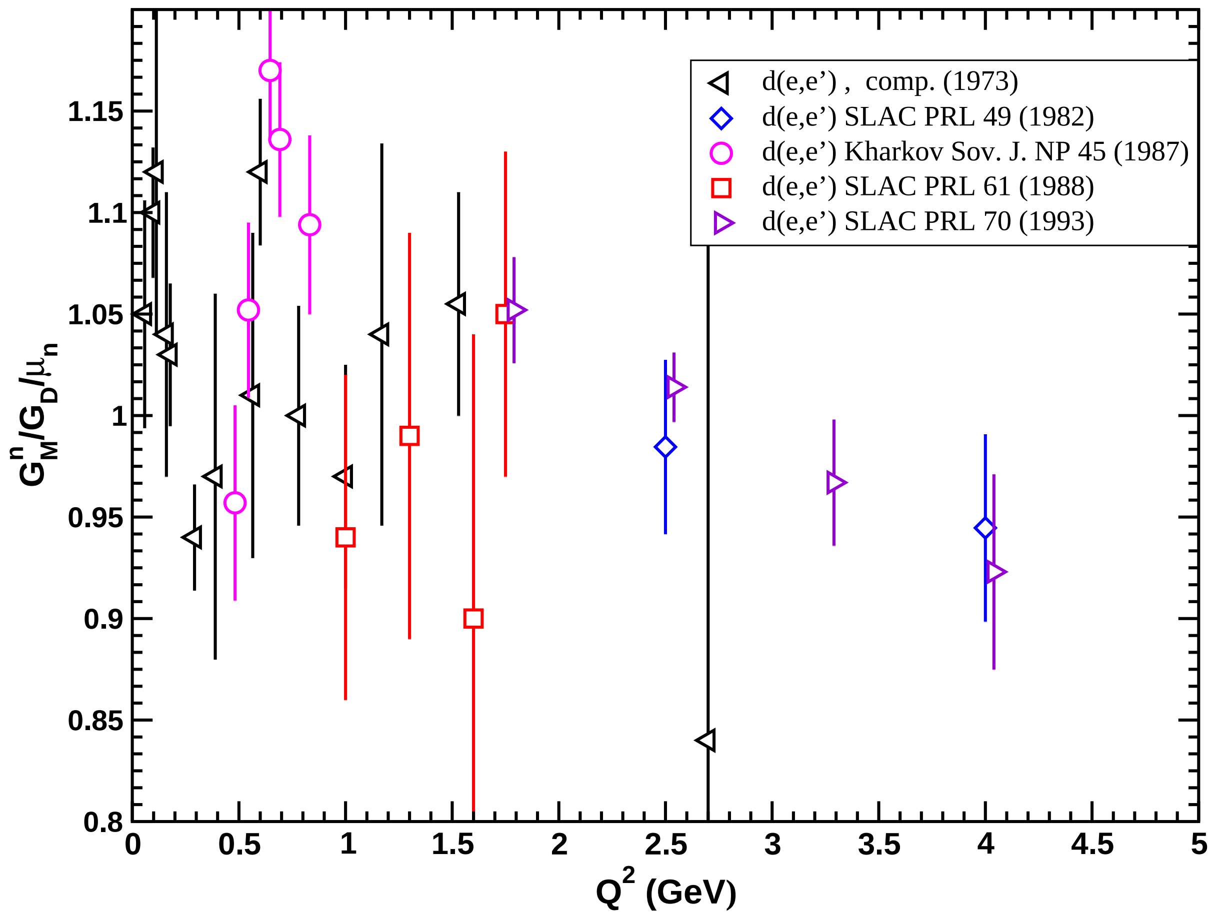
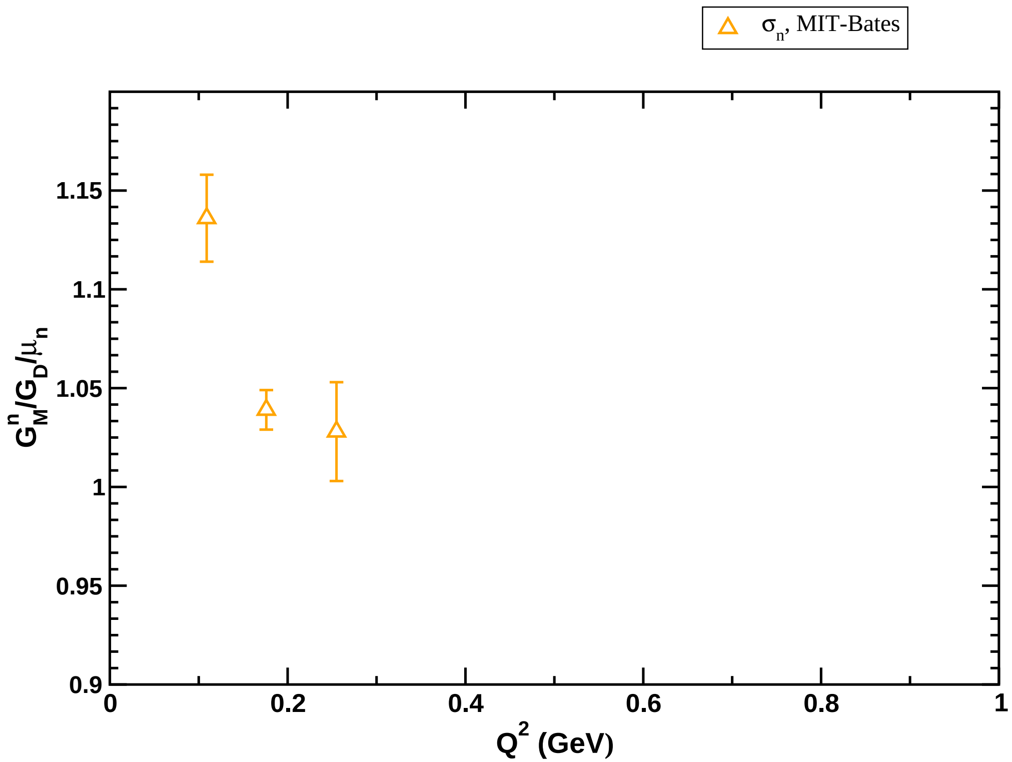


Difficulties:

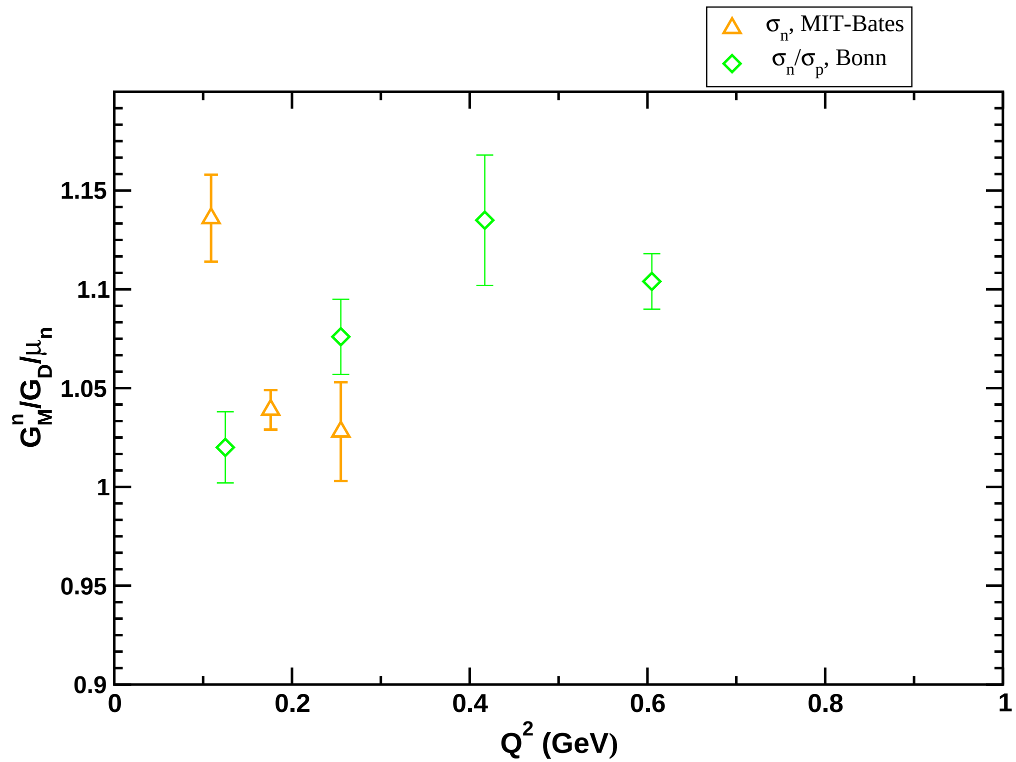
- Subtraction of large proton contribution
- Sensitive to deuteron model.

Neutron Magnetic Form Factor : G_{Mn}



- Measure $\sigma(e, e'n)$ quasi-elastic. ➡ Reduce proton contribution.
- But still sensitive to deuteron model.
- Need to know absolute neutron detection effi ciency.

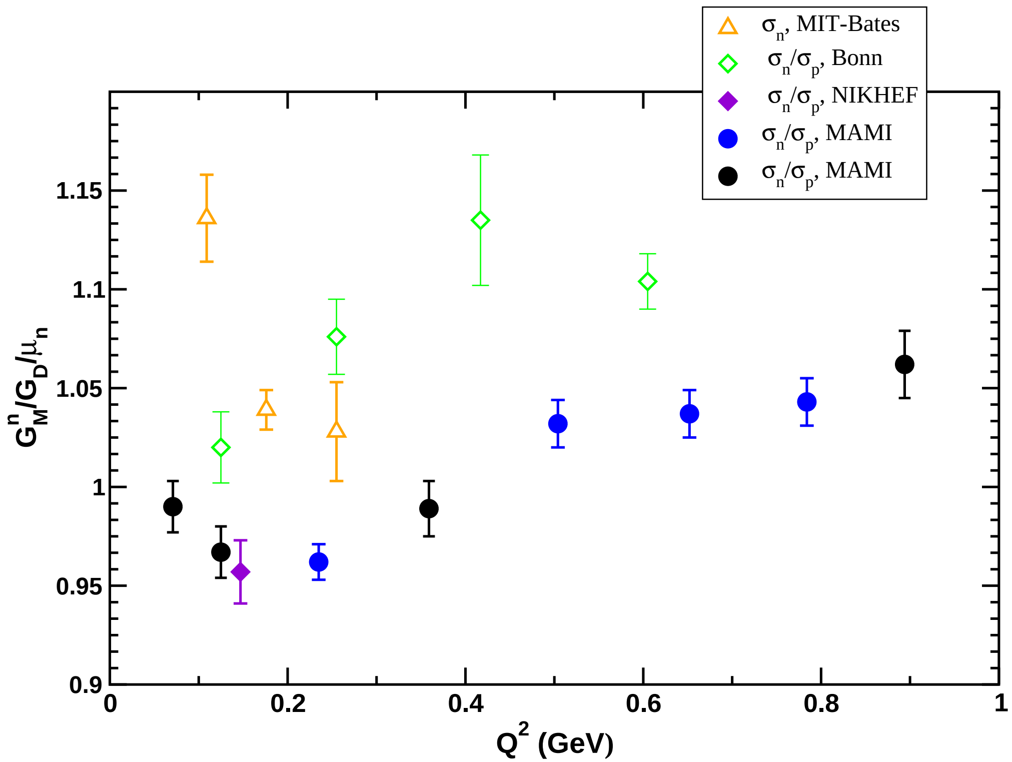
Neutron Magnetic Form Factor : G_{Mn}



- Measure $\frac{\sigma(e,e'n)}{\sigma(e,e'p)}$ ➡ Sensitivity to ^{2}H model cancels in ratio.
- Proton and neutron detected in same detector simultaneously.
- Need to know absolute neutron detection effi ciency.

➡ Bonn used $p(\gamma,\pi^+)n\ in-situ$

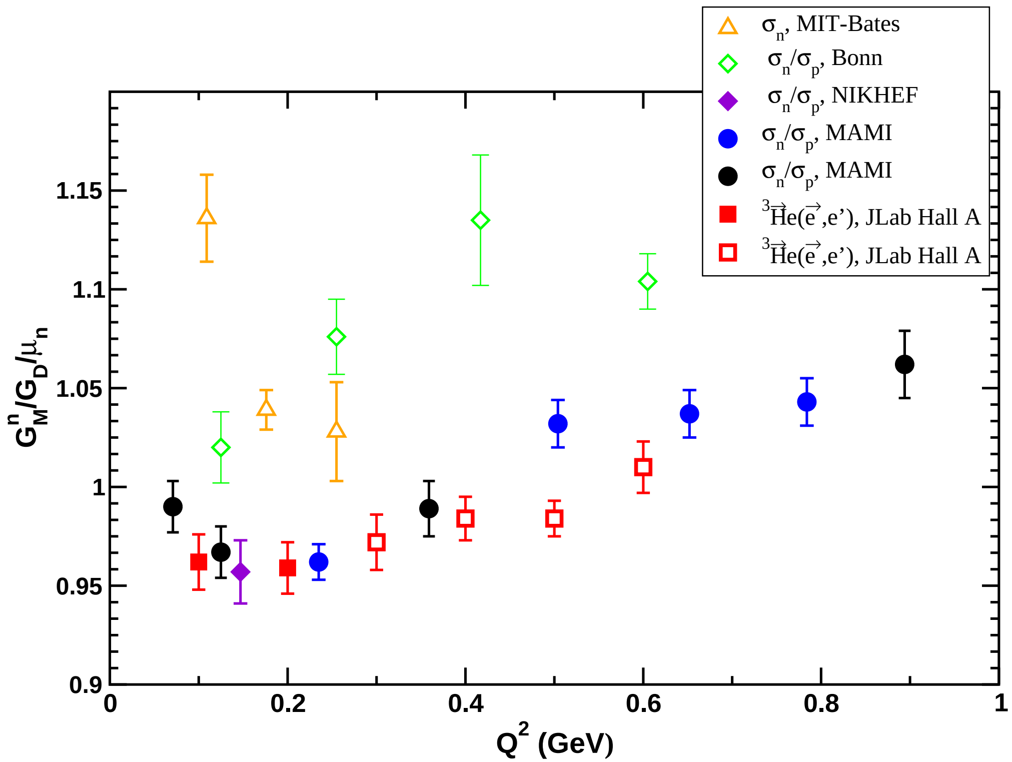
Neutron Magnetic Form Factor : G_{Mn}



- Measure $\frac{\sigma(e,e'n)}{\sigma(e,e'p)}$ ➡ Sensitivity to ^{2}H model cancels in ratio.
- Proton and neutron detected in same detector simultaneously.
- Need to know absolute neutron detection effi ciency.

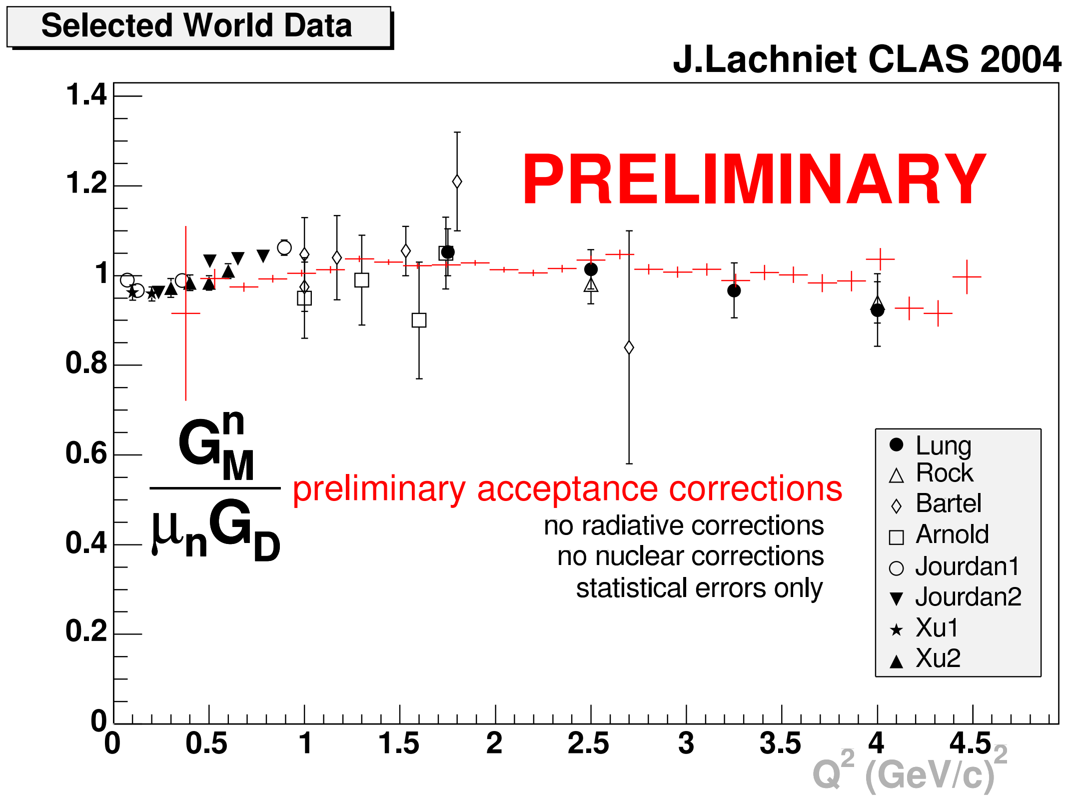
➡ NIKHEF and Mainz $p(n,p)n$ with tagged neutron beam at PSI.

Neutron Magnetic Form Factor : G_{Mn}



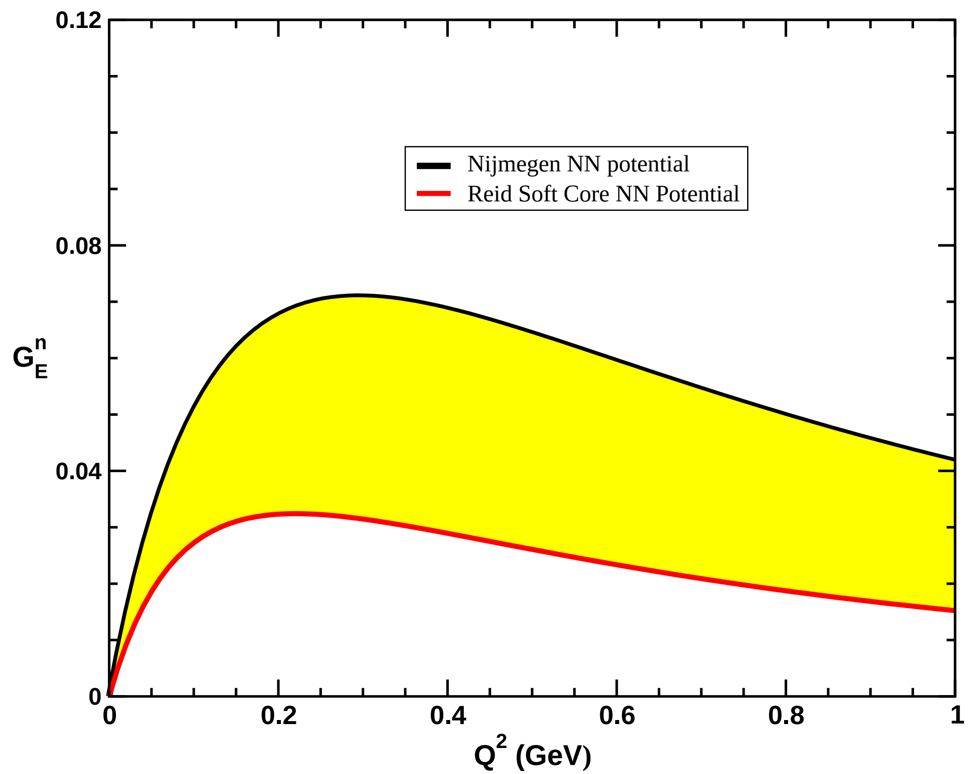
- Extract G_{Mn} from $^3\vec{\text{He}}(\vec{\text{e}},\text{e}')$ transverse asymmetry, A_T
- At Q^2 = 0.1 and 0.2, use full three-body non-relativistic Fadeev calculation of A_T.
- $Q^2 > 0.2$, use PWIA calculation of A_T.

G_{Mn} measurement in Hall B



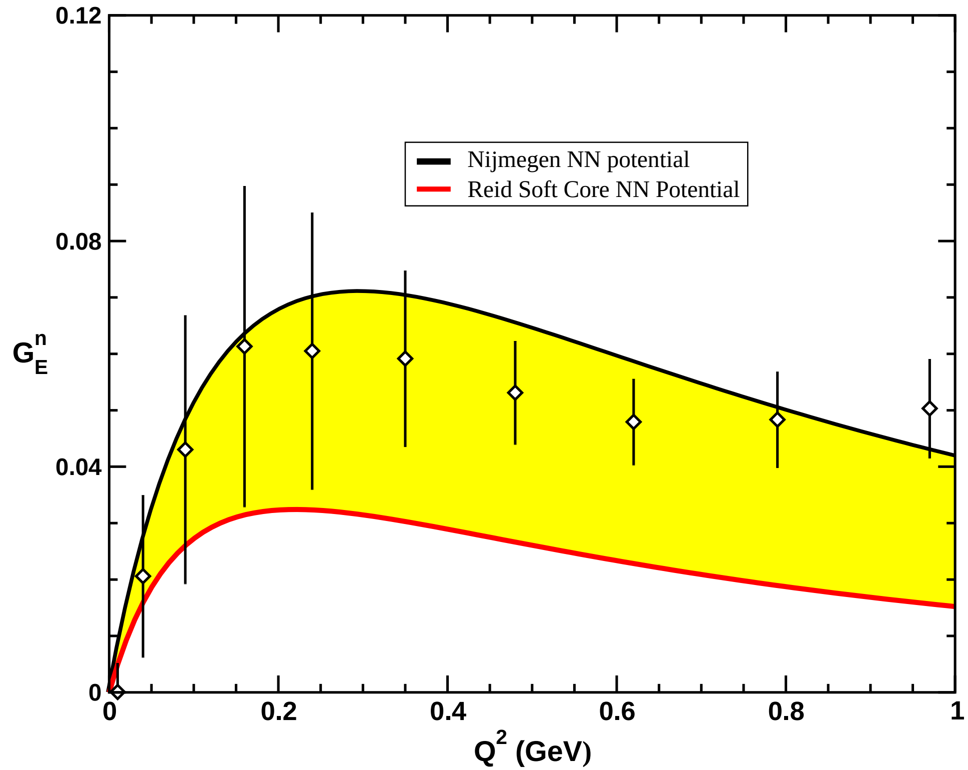
- Extract G_{Mn} ➡ $\frac{\sigma[d(e,e'n)_{QE}]}{\sigma[d(e,e'p)_{QE}]}$
- Red points new Hall B data (*Brooks and Lachinet nucl-ex/0504028*)
- Determine neutron efficiency by simultaneous measurement of ^{1}H(e,e$'\pi^+$)n. LH_2 and LD_2 both in beam (5cm apart)

Neutron Electric Form Factor , G_{En}



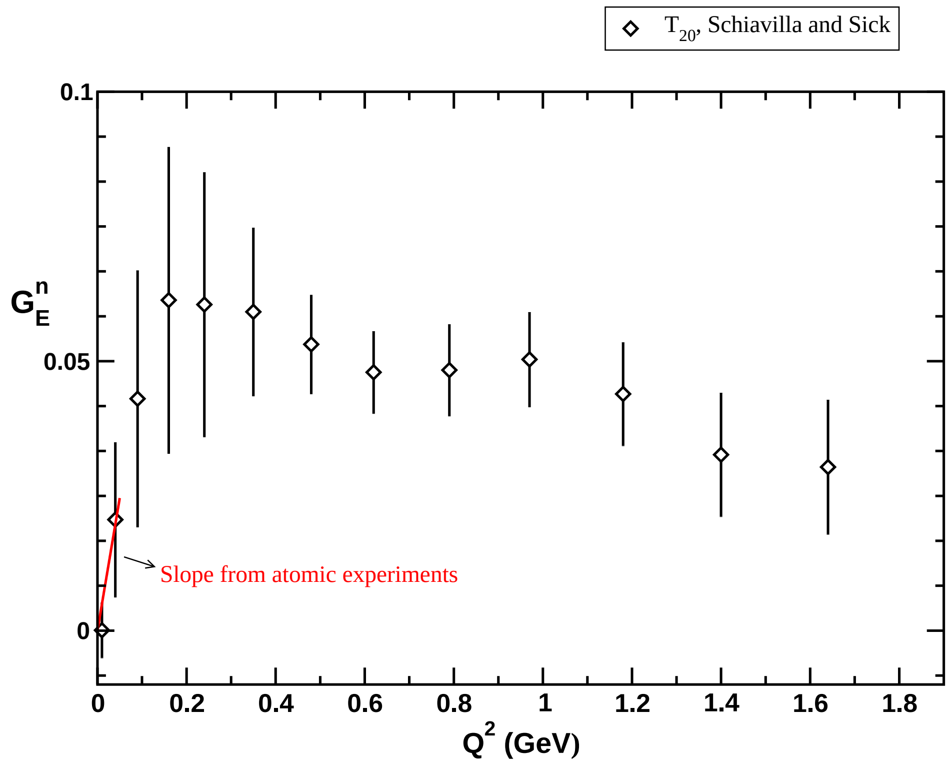
- G_E from elastic ed cross sections *(Galster (1971), Platchkov (1990))*
- $\sigma \propto A(Q^2) + B(Q^2)\tan^2(\frac{\theta}{2})$
- Extract G_E^n from $A(Q^2)$ using deuteron model
- But very sensitive to NN potential.

Neutron Electric Form Factor , G_{En}



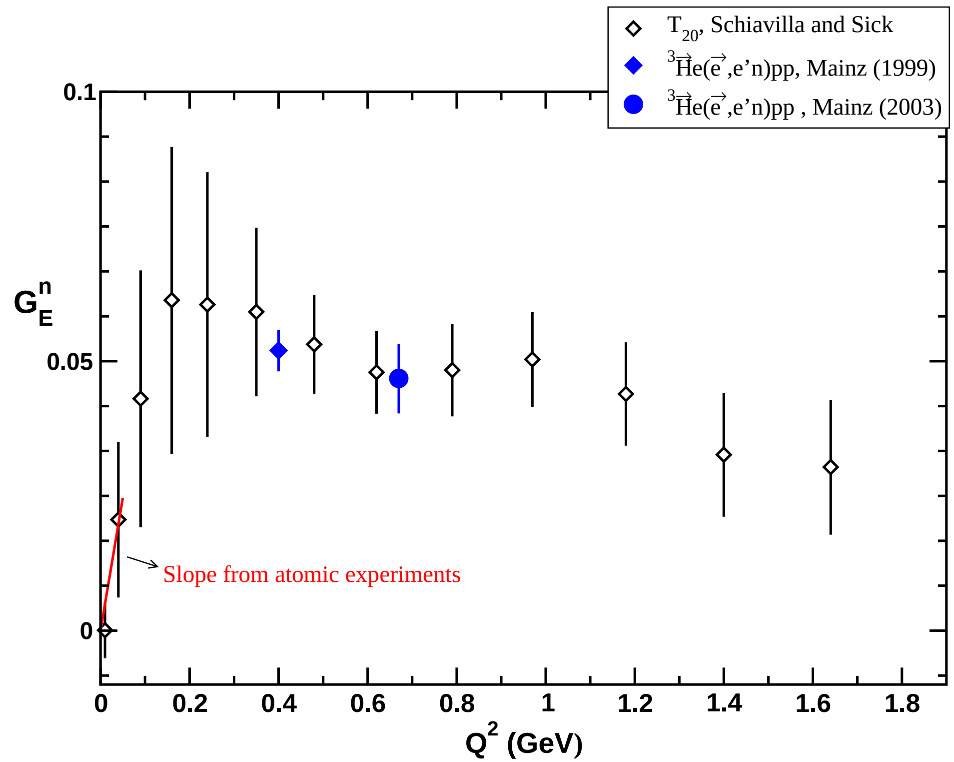
- T_{20} from elastic d(e,e′ $\vec{d}$) (JLab Hall C).
- Combine $T_{20}(Q^2)$ with world data to determine F_{C2}.
- Extract G_E with less theory uncertainty
- (Schiavilla and Sick, PRC 64, 041002 (2001))

Neutron Electric Form Factor , G_{En}



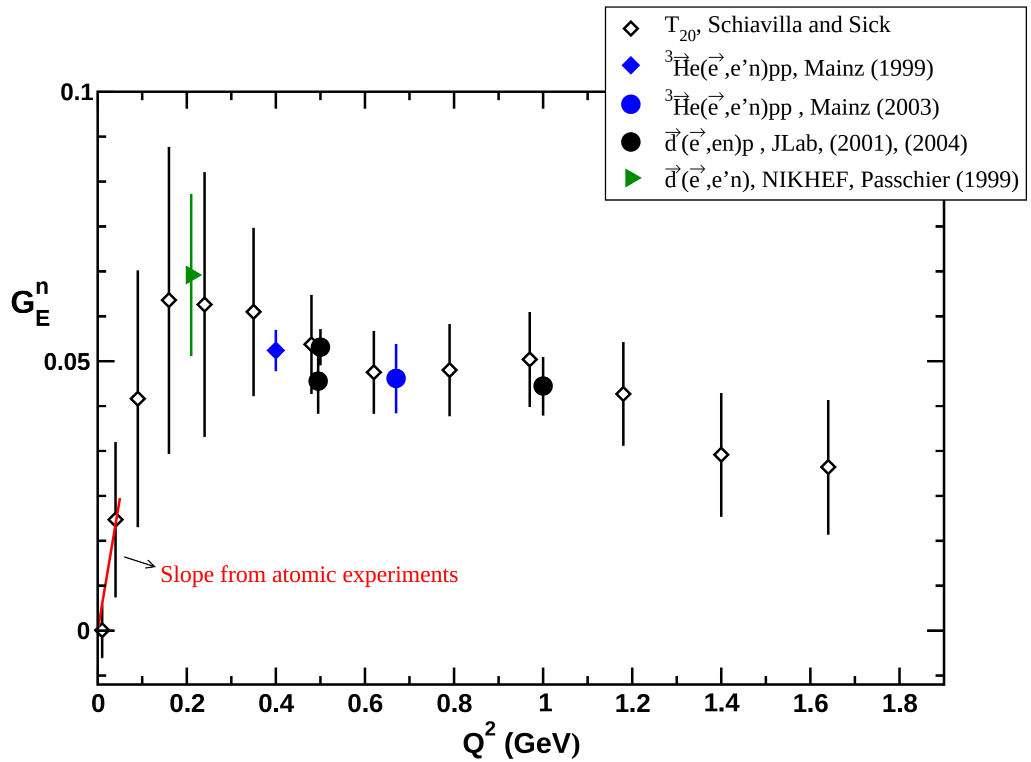
- Determine neutron charge radius from low energy neutron-electron scattering using ^{208}Pb and ^{209}Bi
- S. Kopecky *et al.*, PRC 56, 2229 (1997).

Neutron Electric Form Factor , G_{En}



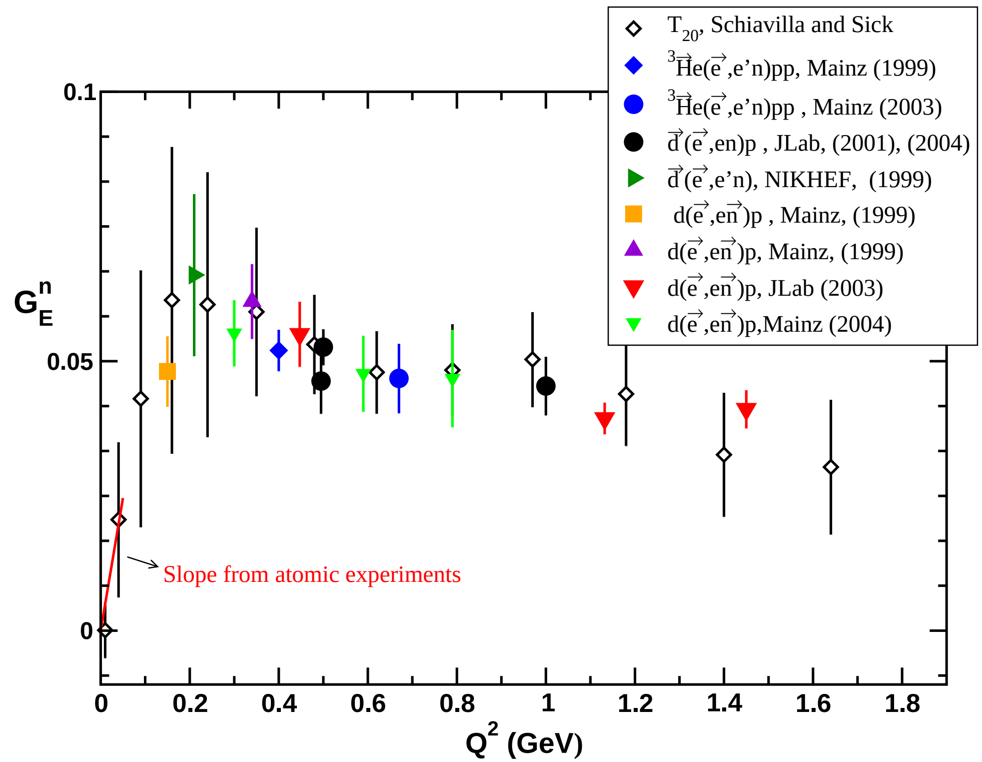
- G_E from Quasi-free $^3\vec{He}(\vec{e},e'n)$
- Set $\theta^* = 90°$, $A_\perp \propto P_B P_T G_E/G_M$
- Set $\theta^* = 0°$, $A_\parallel \propto P_B P_T$ ➡ In PWIA, $G_E/G_M \propto A_\perp/A_\parallel$

Neutron Electric Form Factor , G_{En}



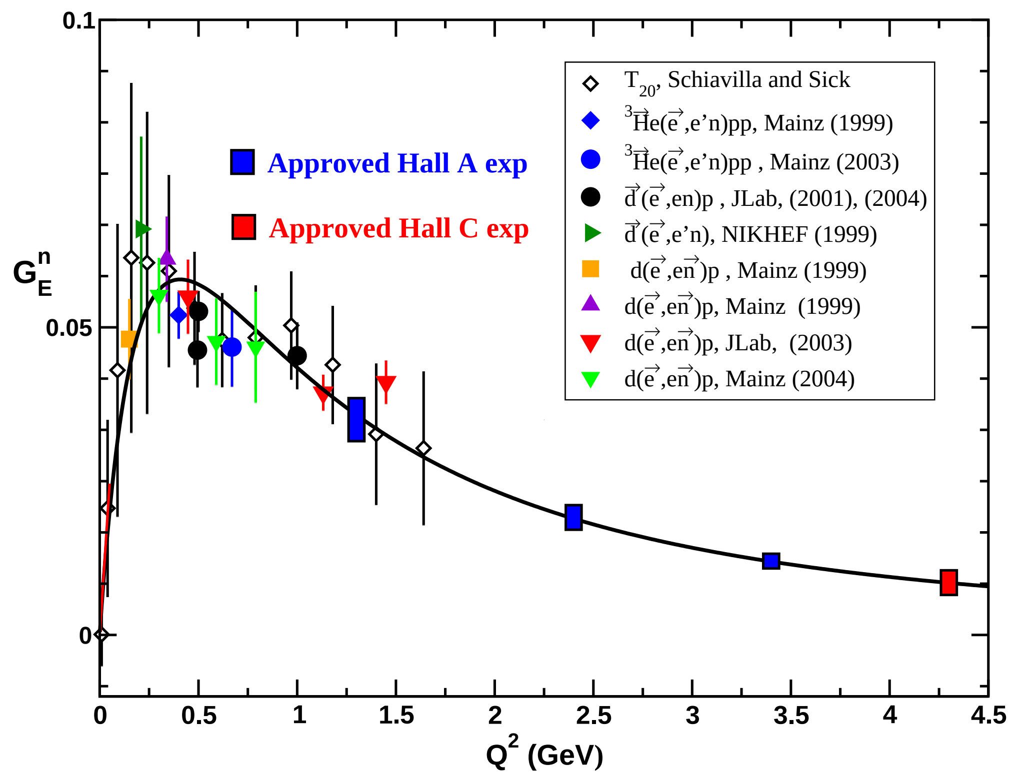
- G_E from beam-target asymmetry with $\vec{d}(\vec{e},e'n)$
- Set $\theta^* = 90^\circ$ ➡ In PWIA $A^V_{ed} = P_B P_T V \frac{a G_E G_M}{G_E^2 + \tau/\epsilon G_M^2}$
- NIKHEF used electron storage ring with internal $\vec{d}$ gas target.
- JLab used UVa solid $^{15}ND_3$ target.

Neutron Electric Form Factor , G_{En}



- G_E from recoil polarization d($\vec{e}$,e′ $\vec{n}$)
- $\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E_e+E_{e'})}{2M}\tan(\frac{\theta}{2})$
- At Mainz, Q^2 = 0.15 to 0.80
- At JLab, Q^2 = 0.45, 1.13, 1.45 ➡ Highest Q^2 yet!

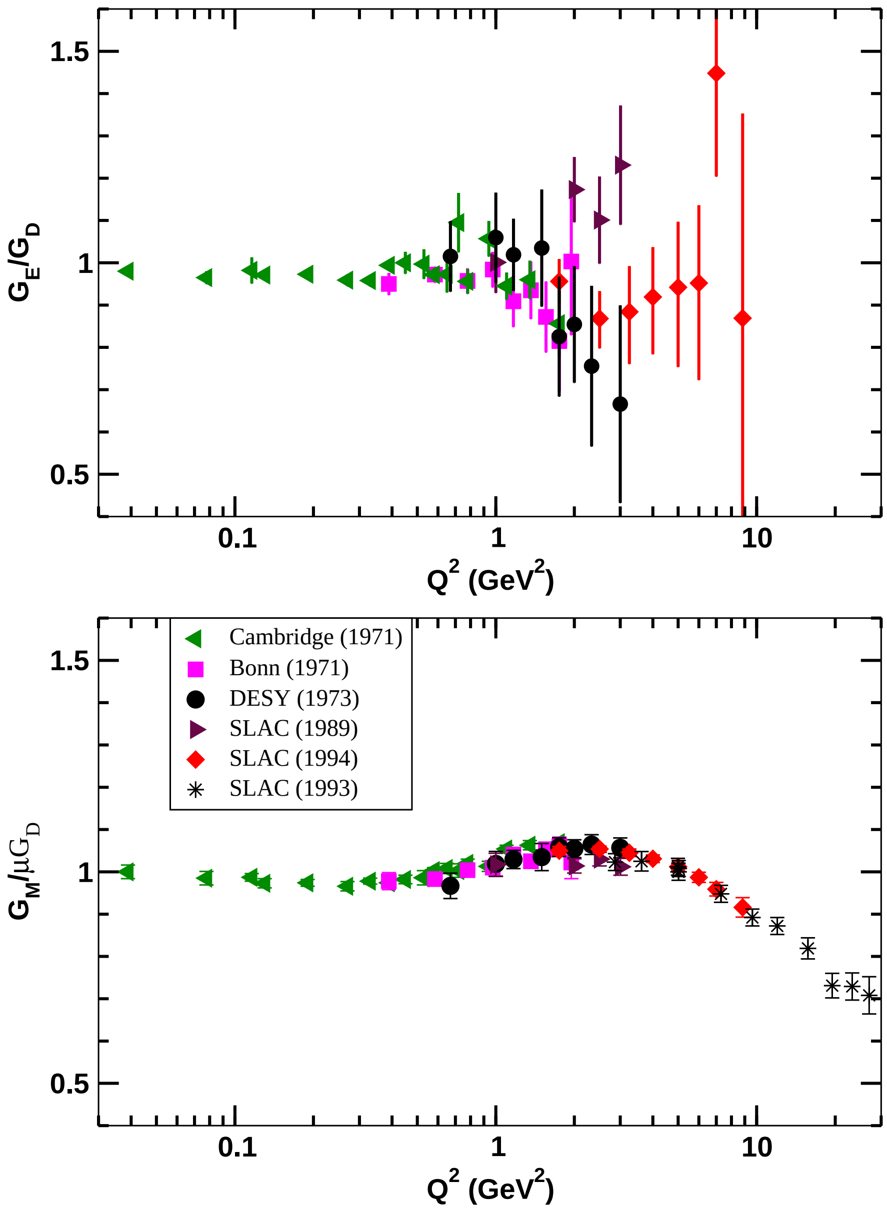
Neutron Electric Form Factor , G_{En}



Approved experiments at JLab to measure G_E:

- Q^2 = 3.5 in Hall A by $^3\vec{He}$(e⃗,e′n) Run in Spring 2006 !
- Q^2 = 4.3 in Hall C by d(e⃗,e′ $\vec{n}$)

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

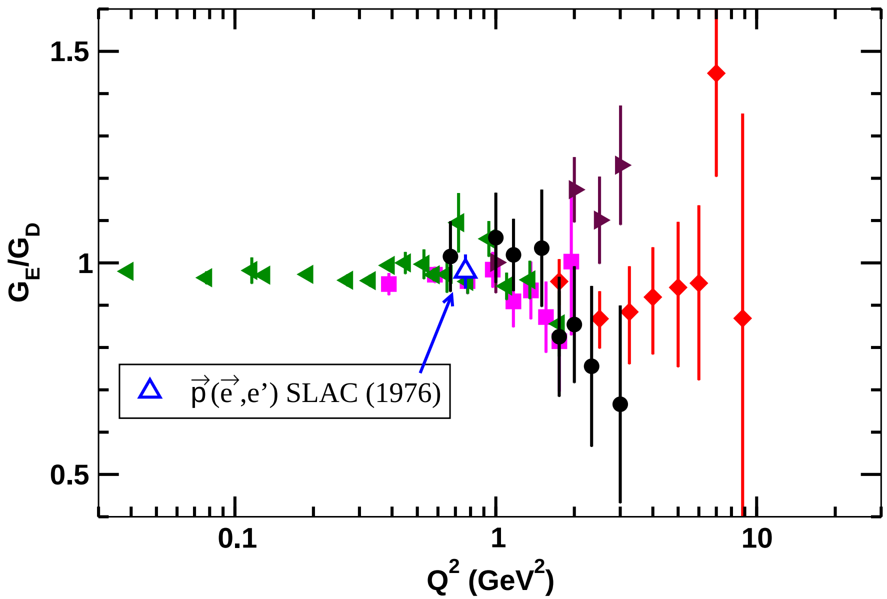


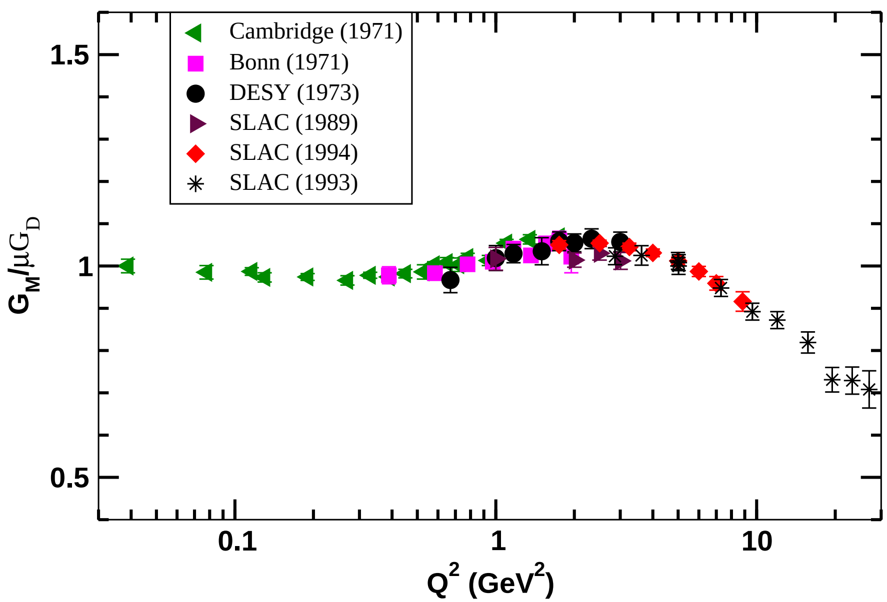
- ep elastic cross-section:

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

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

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





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- $\vec{e}\vec{p}$ elastic asymmetry:

$$A \propto G_E/G_M$$

Relative sign of G_E/G_M

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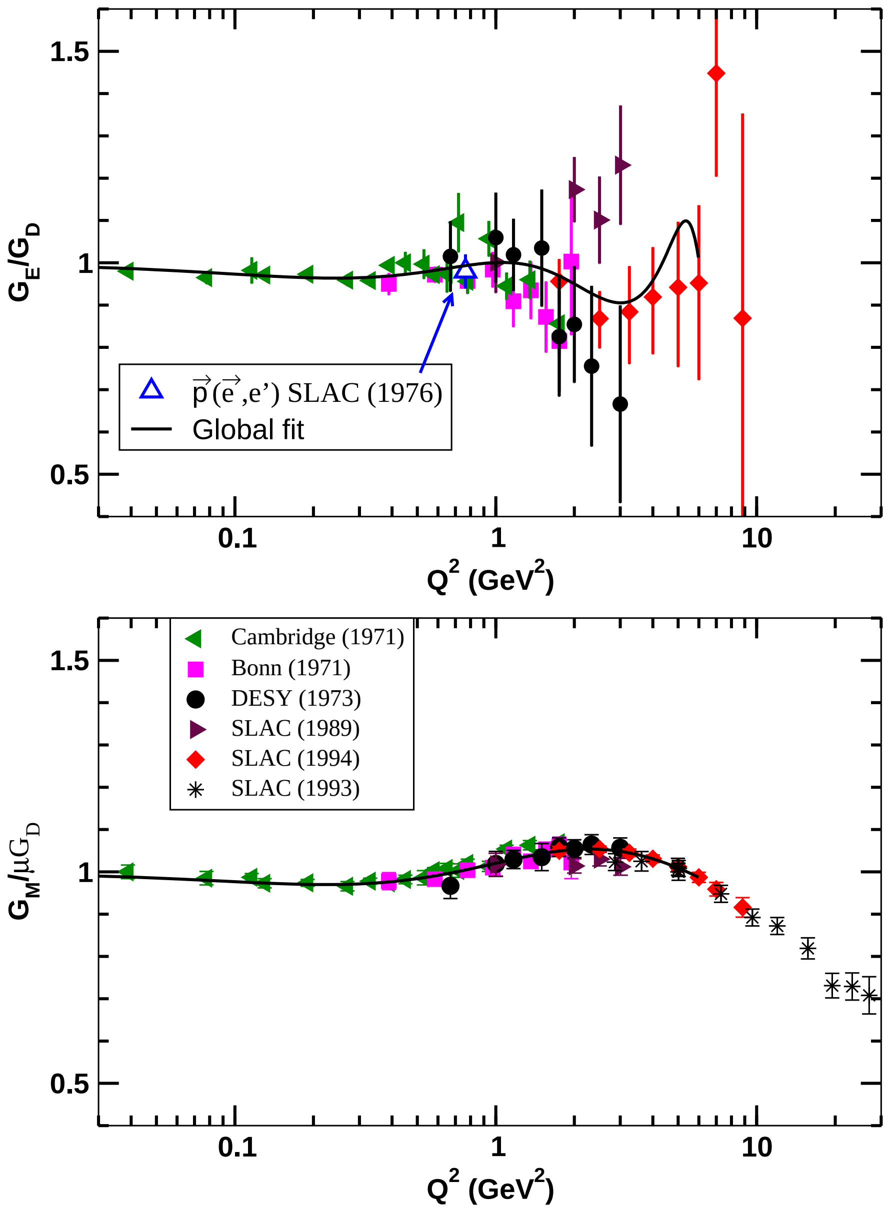

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Recent global fit

PRC 69, 02201R (2004)

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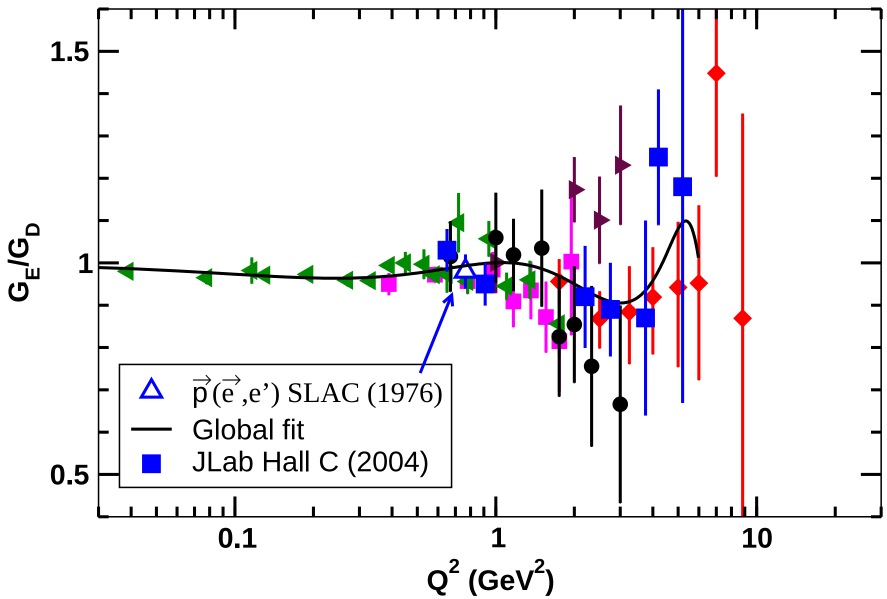

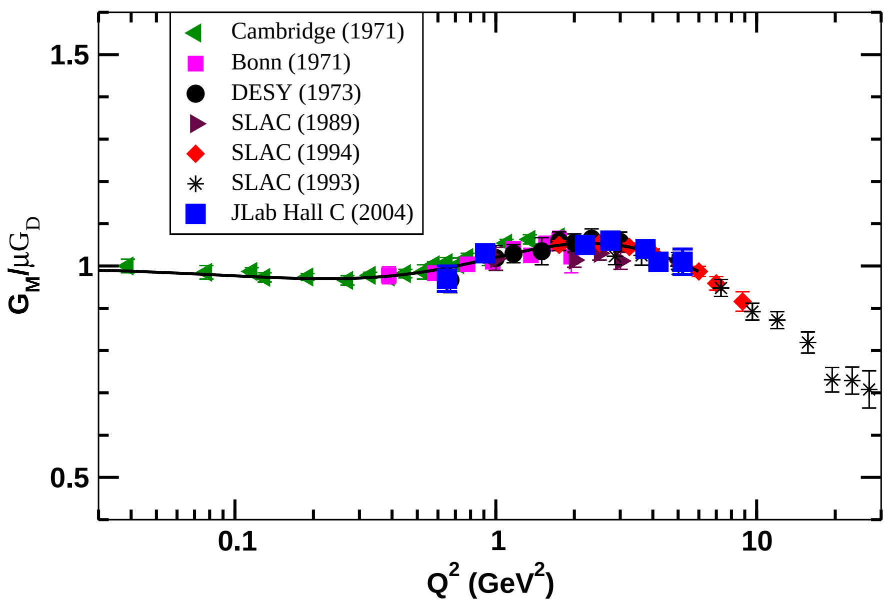

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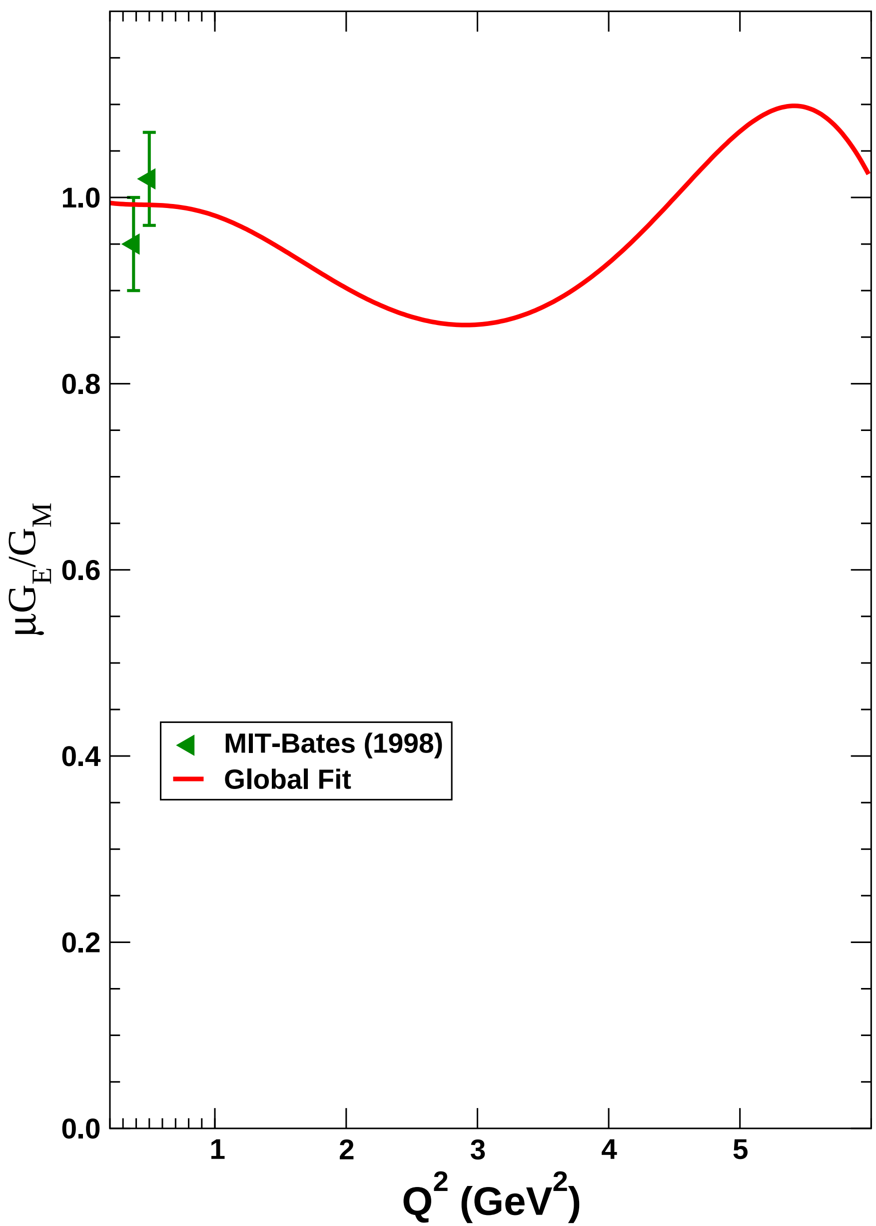
Recent global fit

PRC 69, 02201R (2004)

Recent data in Hall C

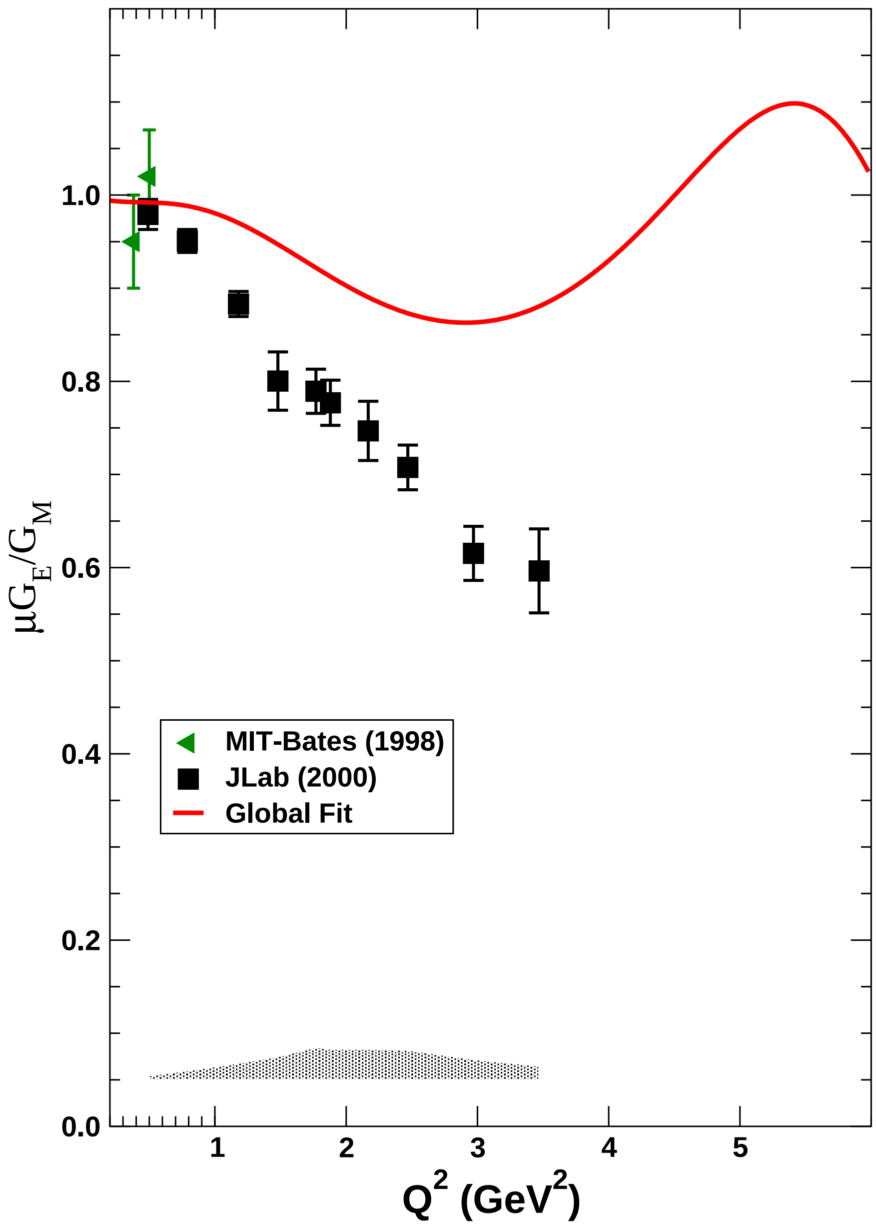
M. E. Christy, PRC 70, 015206 (2004)

Recent G_{Ep}/G_{Mp} measurements



- Measure recoil polarization in $p(\vec{e}, e'\vec{p})$
- $\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E_e+E_{e'})}{2M}\tan(\frac{\theta}{2})$
- First measurement at MIT-Bates

Recent G_{Ep}/G_{Mp} measurements



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- $\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E_e+E_{e'})}{2M}\tan(\frac{\theta}{2})$
- In Hall A $0.5 < Q^2 < 3.5$

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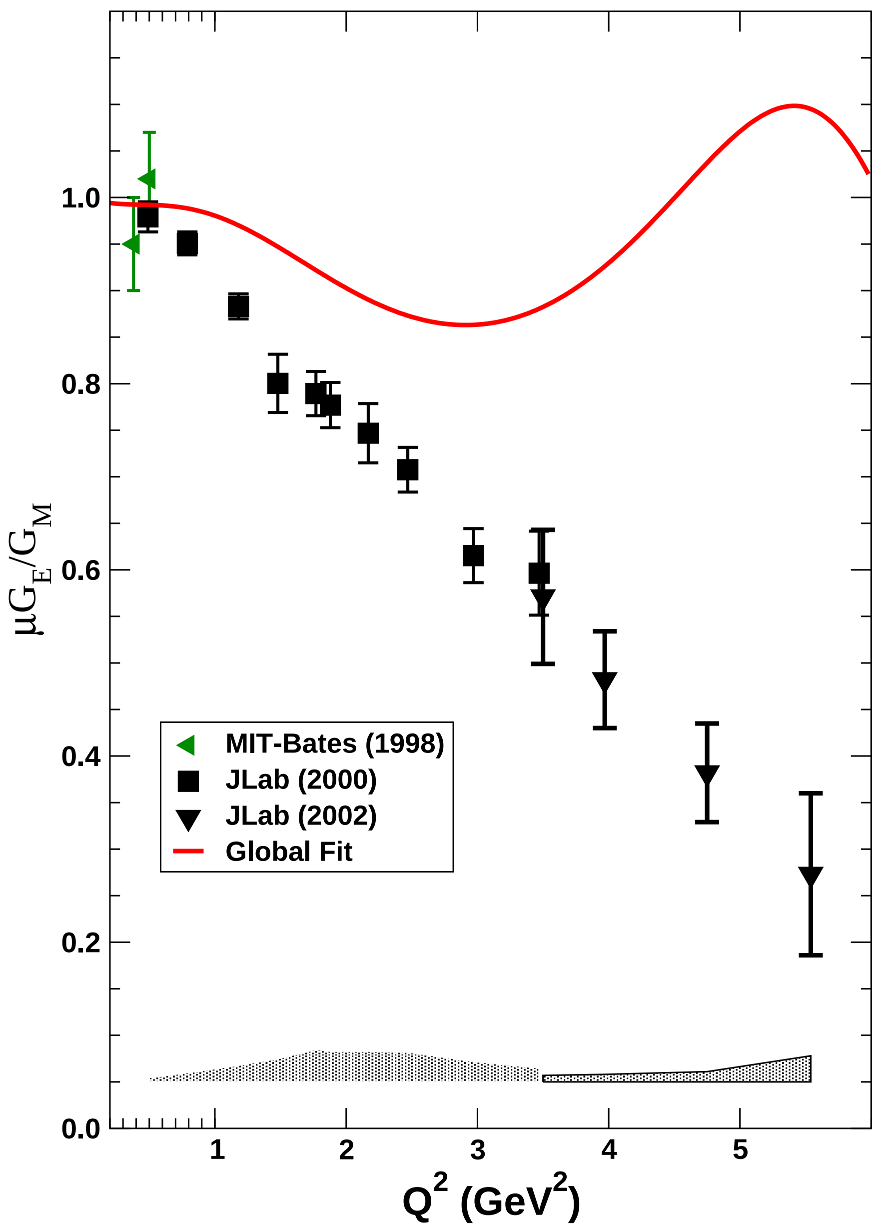

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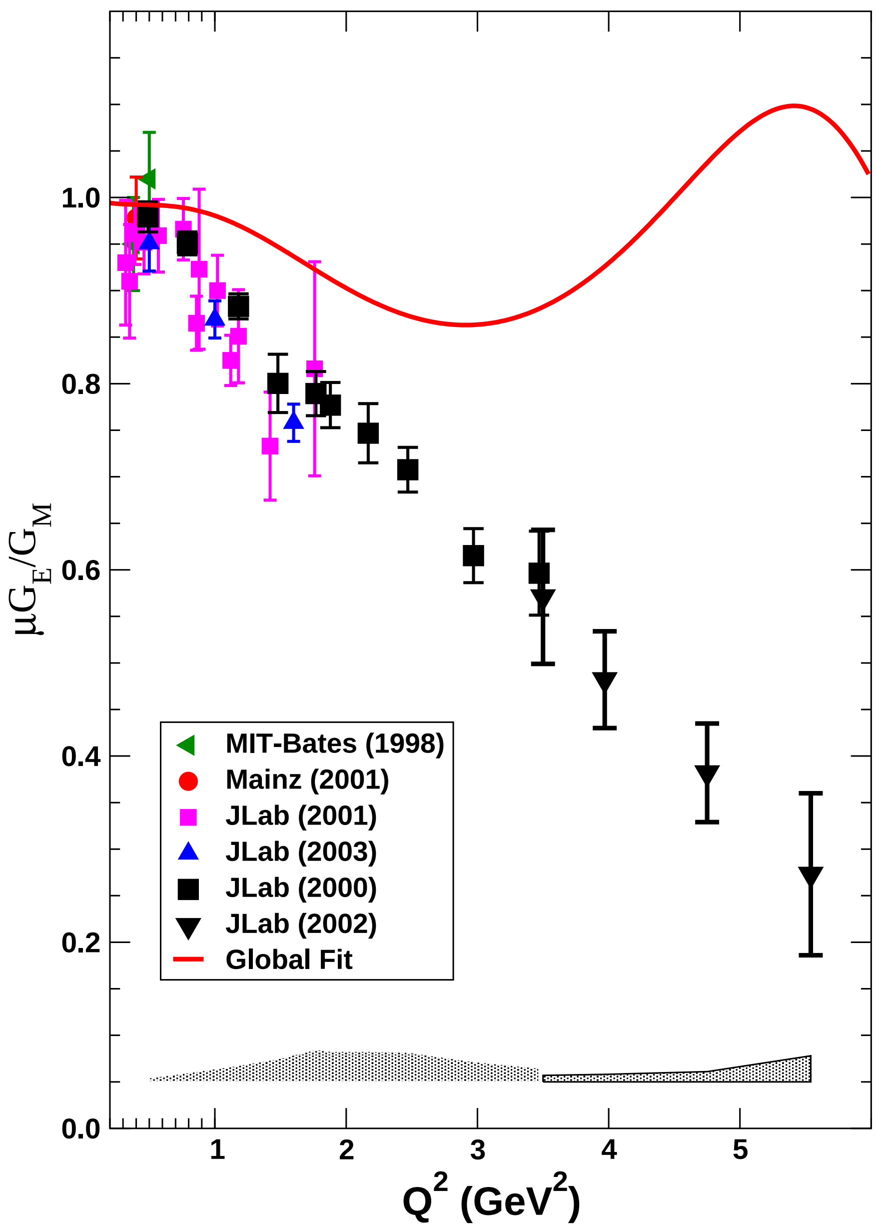
- $\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E_e+E_{e'})}{2M}\tan(\frac{\theta}{2})$
- In Hall A, $3.5 < Q^2 < 5.6$
- Did measurements to improve systematics
- Reanalyzed the low Q^2 data
  - Added Q^2 = 2.2 point
  - Reduced systematics
  - V. Punjabi *et al.*, PRC 71, 055202 (2005)

Recent G_{Ep}/G_{Mp} measurements



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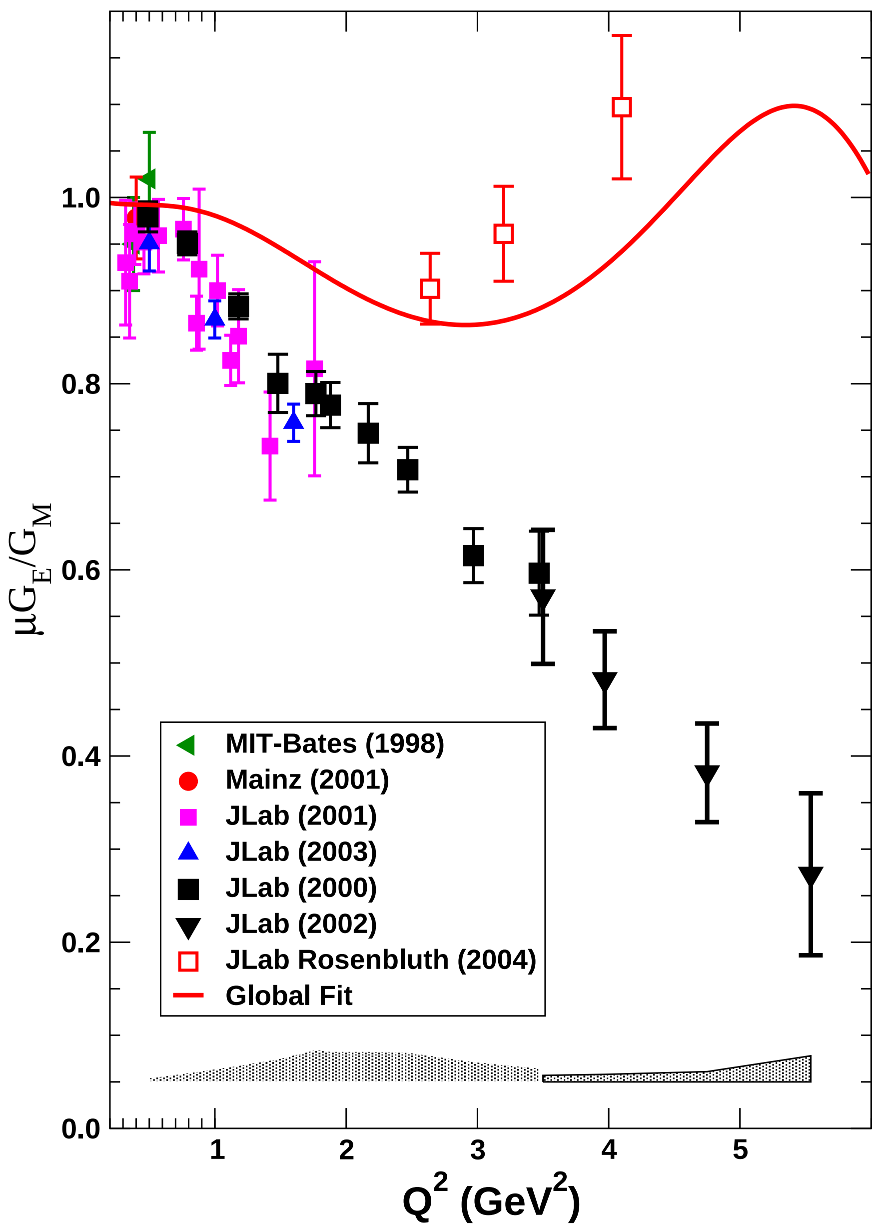
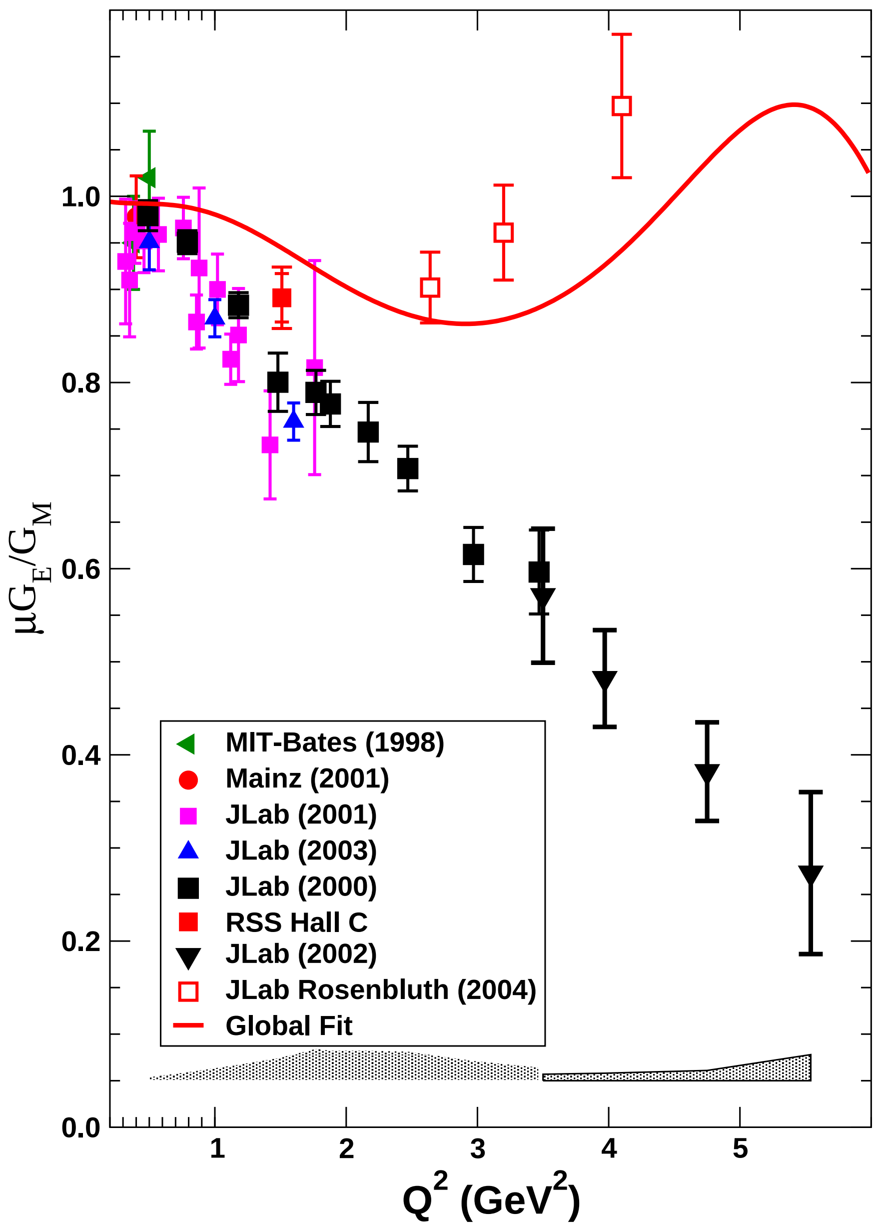


- At JLab in Hall A did Rosenbluth separation with proton detected
- Advantages:
  - Proton momentum fixed at each ϵ
  - Cross section is nearly constant with ϵ
  - Reduces size of ϵ-dependent radiative corrections
  - Reduces systematic error from beam energy and scattering angle
  - I. Qattan *et al.* PRL 94, 142301 (2005)

Recent G_{Ep}/G_{Mp} measurements



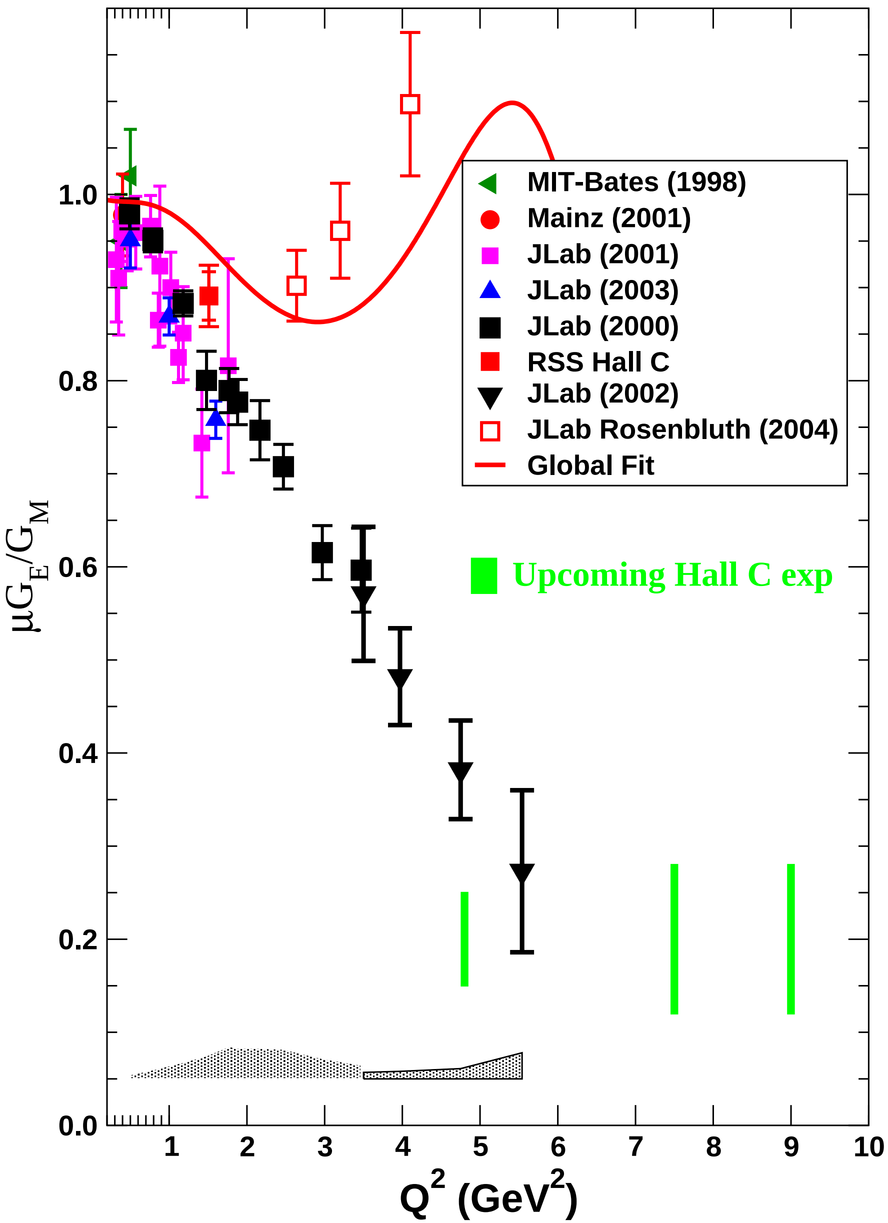
- Hall C RSS experiment

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

$\theta^\star, \phi^\star$ = polar and azimuthal angles between $\vec{q}$ and target spin

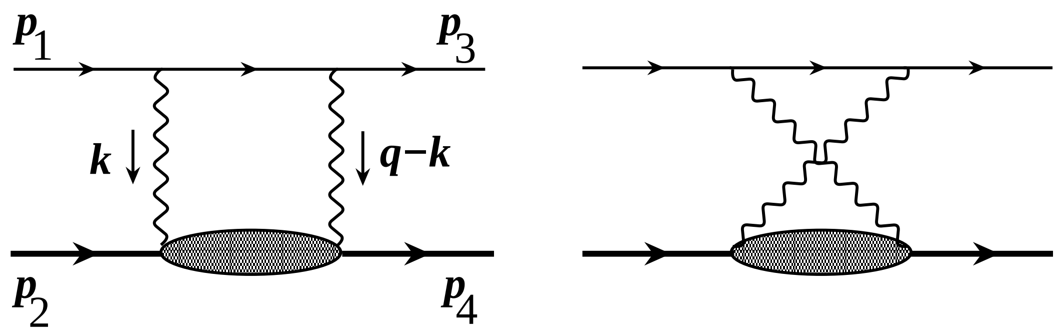
K_1, K_2 = kinematic factors

Future G_{Ep}/G_{Mp} measurements



- $p(\vec{e}, e')\vec{p}$ in Hall C.
- Measure $\frac{G_E}{G_M}$ to Q^2 = 9
- FPP Status
  - Four Chambers have arrived and assembled in their frame.
  - Chambers tested with source and now being tested with cosmics.
- Calorimeter status
  - Calorimeter is assembled and tested with cosmics
  - Found problem with optical grease. Need to reattach PMT.

Estimate of 2γ exchange contribution



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

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

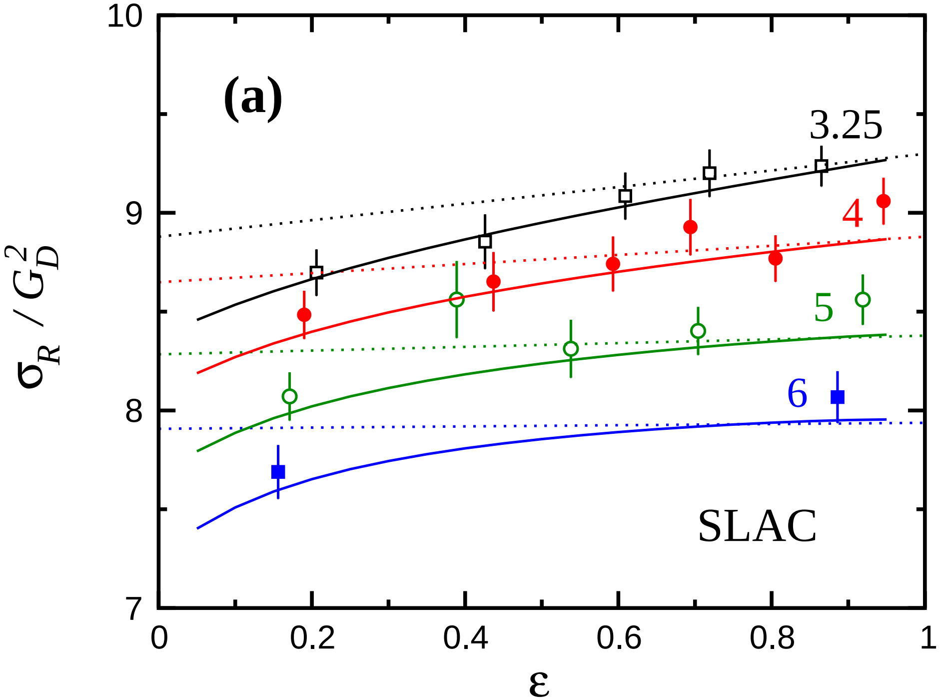
$$\sigma_R \sim \frac{\tilde{G}_M^2}{\tau}\{\tau + \epsilon\frac{\tilde{G}_E^2}{\tilde{G}_M^2} + 2\epsilon(\tau + \frac{\tilde{G}_E}{\tilde{G}_M})\mathcal{R}(\frac{\nu\tilde{F}_3}{M^2\tilde{G}_M})\}$$

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

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)

Calculation 2γ exchange contribution

Nucleon elastic
intermediate state



P.G. Blunden, W. Melnitchouk, J.A. Tjon, nucl-th/0506039

Calculation 2γ exchange contribution

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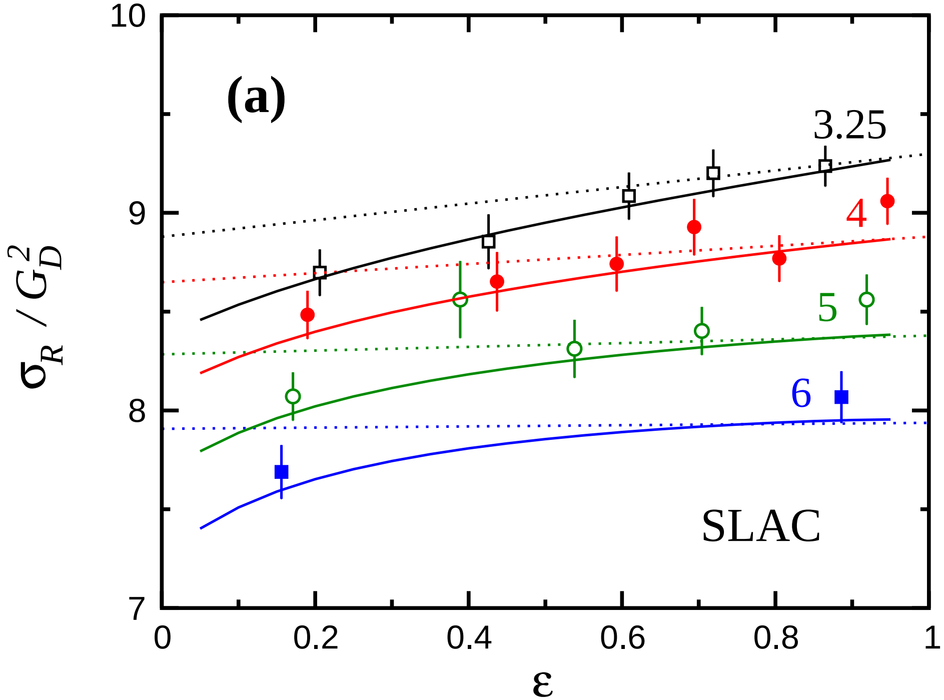
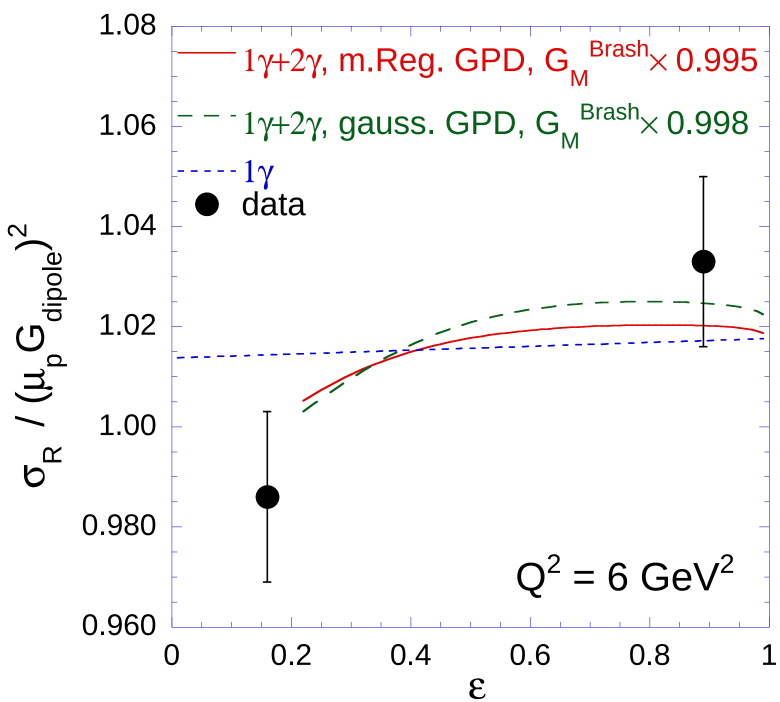


P.G. Blunden, W. Melnitchouk, J.A. Tjon, nucl-th/0506039

GPD calculation

Cross section for ep elastic scattering



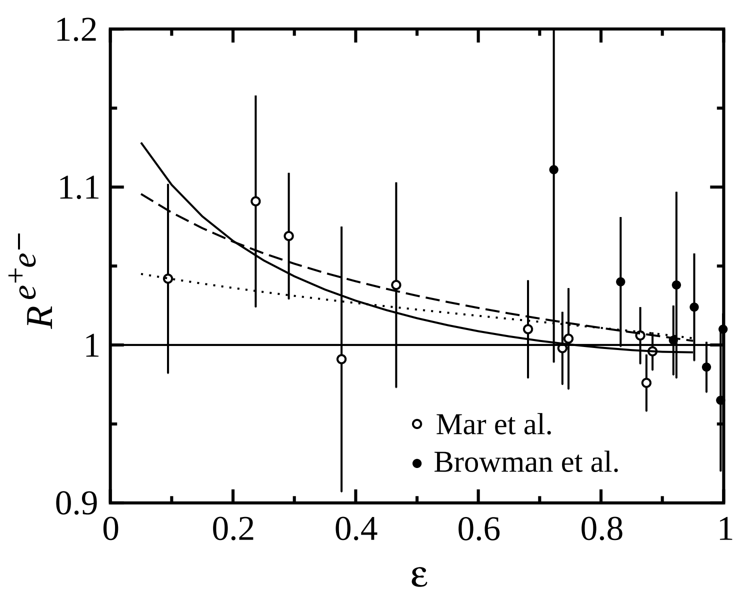
A. V. Afanasev, S. J. Brodsky, C. E. Carlson, Y. Chen, M. Vanderhaeghen, Phys.Rev. D72 (2005) 013008

Measurement of 2γ contribution

- Precision measurement of ϵ-dependence of ep elastic cross section in Hall C. (*J. Arrington, E05-017*)

Measurement of 2γ contribution

- Precision measurement of ϵ-dependence of ep elastic cross section in Hall C. (*J. Arrington, E05-017*)
- Measure ϵ-dependence of ratio of e^-p/e^+p elastic cross section in Hall B



(*A. Afanasev, J. Arrington, W. Brooks, K. Joo, L. Weinstein, E-04-116*)

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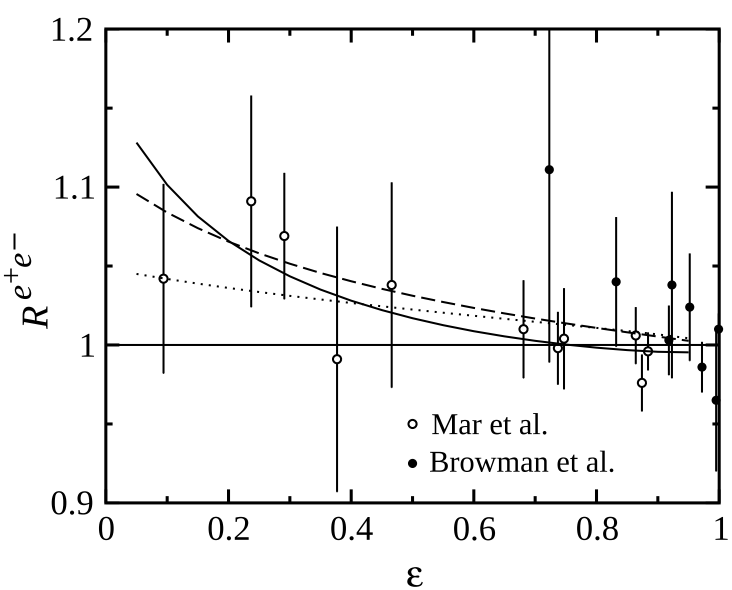
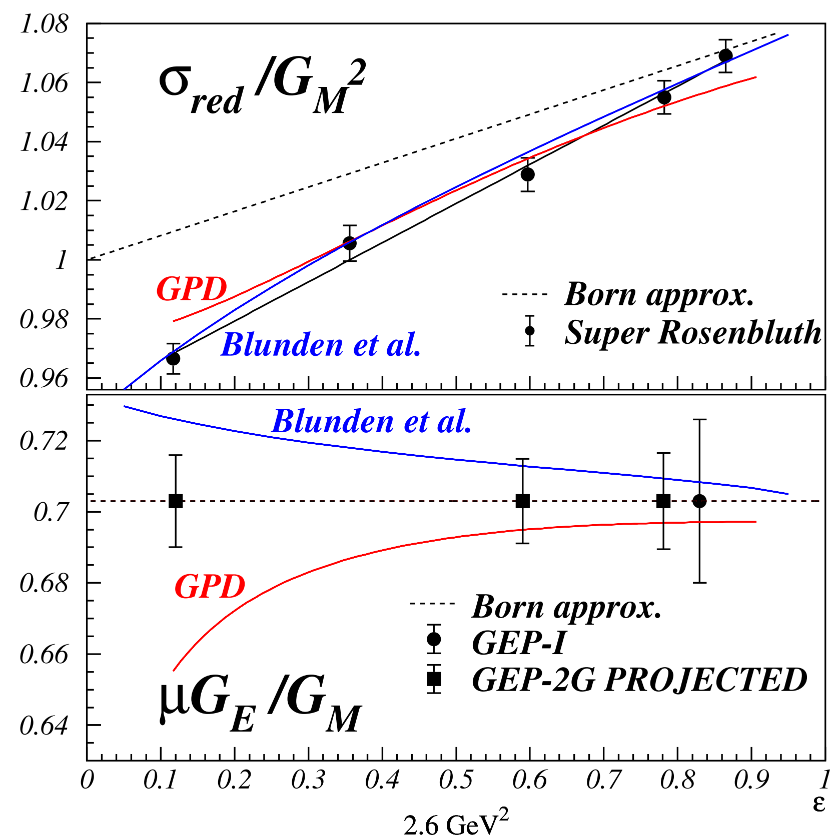


(*A. Afanasev, J. Arrington, W. Brooks, K. Joo, L. Weinstein, E-04-116*)

Measure ϵ-dependence of $\frac{G_E p}{G_M p}$ measured by recoil polarization method in Hall C .

(*R. Gilman, L. Pentchev, C. Perdrisat, R. Suleiman E04-019*)



Summary of form factors