Elastic Form Factors of the Nucleon: Experimental Results

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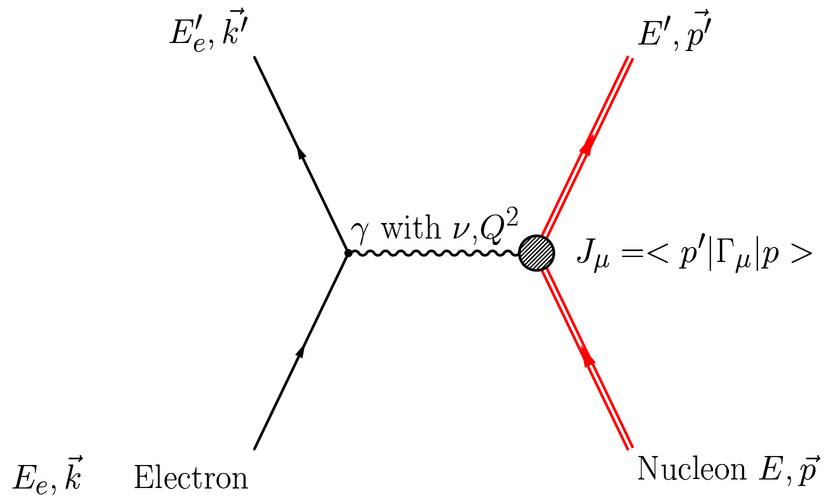
Electron-Nucleon Elastic Scattering



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

F_1 is the helicity conserving and F_2 is helicity non-conserving.

$$G_E(Q^2) = F_1(Q^2) - \kappa_N \tau F_2(Q^2) \qquad \tau = \frac{Q^2}{4M_N}$$

$$G_M(Q^2) = F_1(Q^2) + \kappa_N F_2(Q^2)$$

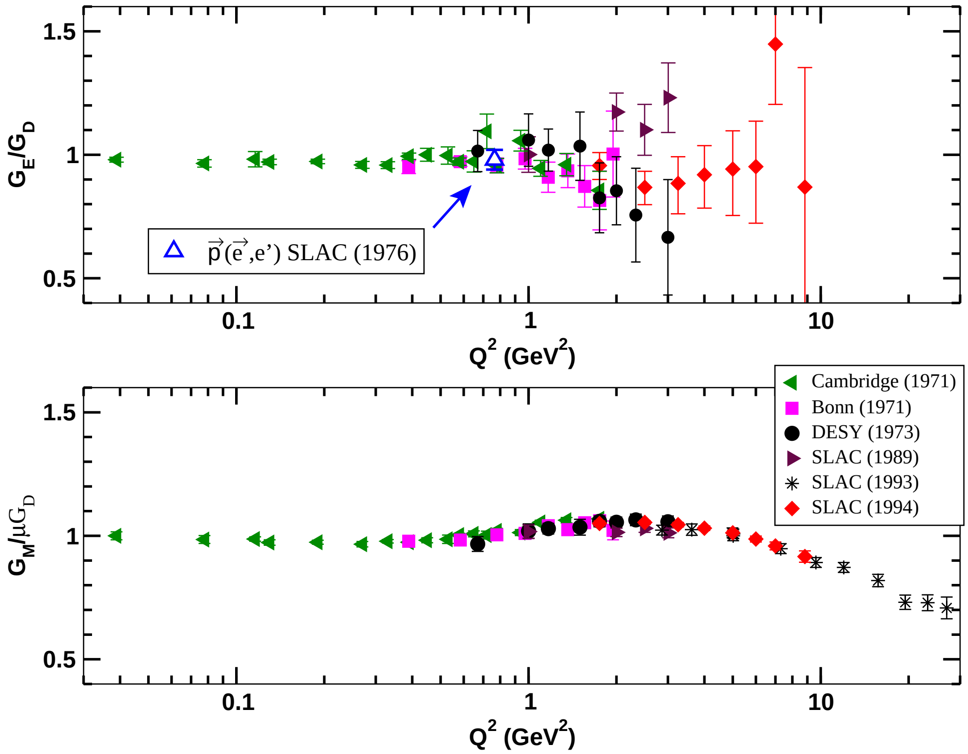
At $Q^2 = 0$

$$G_{Mp} = 2.79, G_{Mn} = -1.91 \text{ and } G_{Ep} = 1, G_{En} = 0$$

Extract G_E and G_M from:

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

Proton G_E and G_M (before ∼1990)



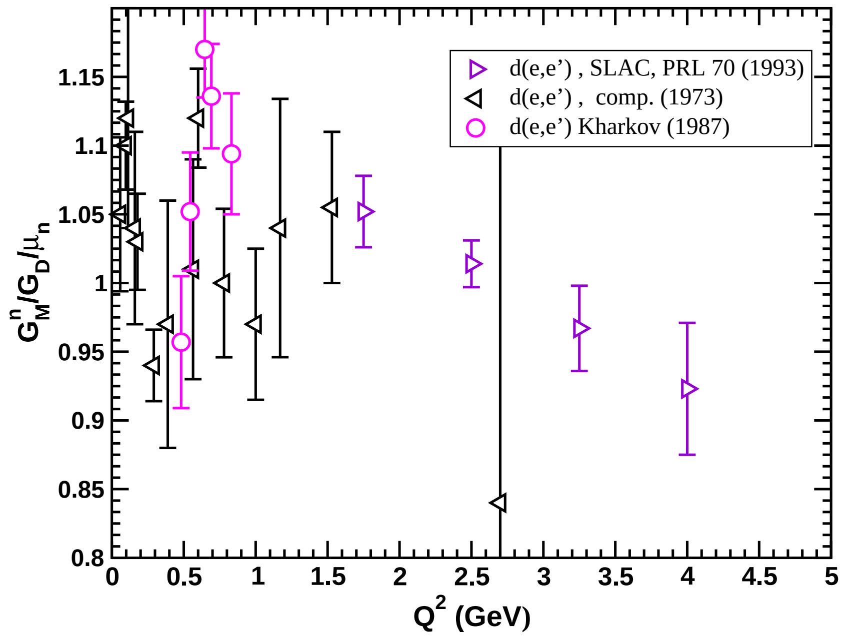
- ep elastic cross section

$$\frac{\sigma_r}{\mu^2 G_D^2} = \frac{d\sigma}{d\Omega}\frac{(1+\tau)\epsilon}{\tau\sigma_{Mott}} = \frac{\epsilon}{\tau}\left(\frac{G_E}{\mu G_D}\right)^2 + \left(\frac{G_M}{\mu G_D}\right)^2$$

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

- $Q^2 > 1$ GeV^2 error on G_E^p grows.
  - G_E^p becomes a smaller fraction of σ
  - At $Q^2 = 5$, G_E^p maximum 8% contribution to σ (assuming $\mu G_E^p/G_M^p = 1$)

Neutron G_M (before ∼1990)



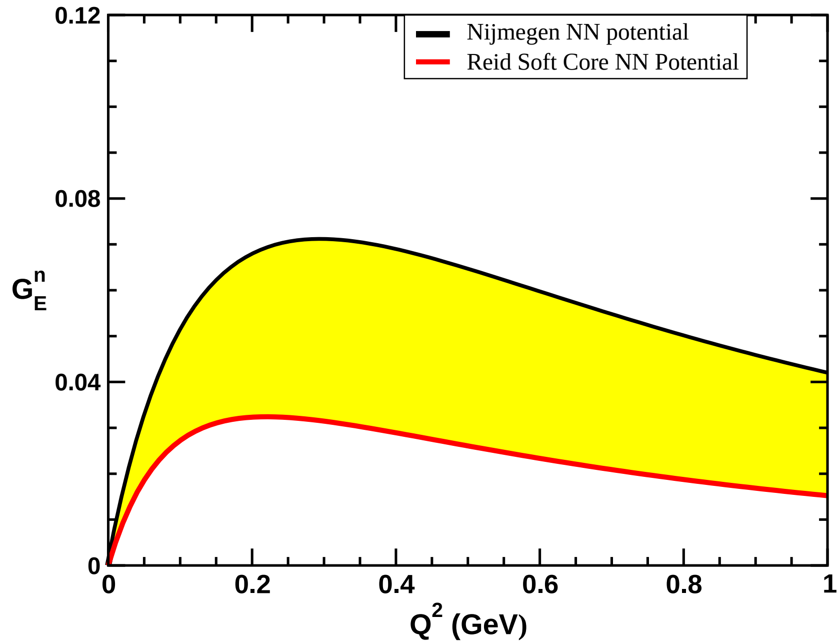
- Define a reduced cross-section:

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

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

- Difficulties:
  - Subtraction of large proton contribution
  - Sensitive to deuteron model. In particular :
    - Final-State Interactions
    - Meson Exchange Currents
    - Relativistic corrections.

Neutron G_E (before ∼1990)

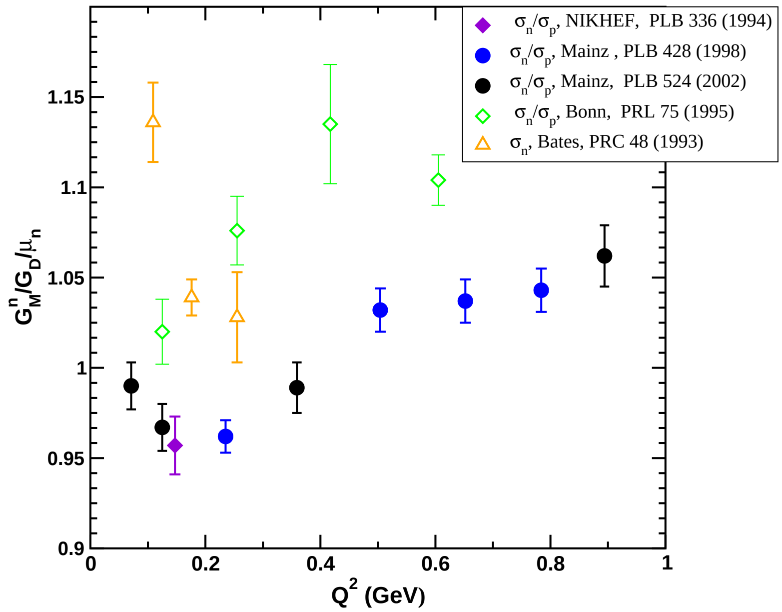


- Elastic ed : $\sigma = \sigma_{Mott}[A(Q^2) + B(Q^2)\tan^2(\frac{\theta}{2})]$ with:
  - $A(Q^2) = F_C^2(Q^2) + \frac{8}{9}\tau^2 F_Q^2(Q^2) + \frac{2}{3}\tau F_M^2(Q^2)$
  - $B(Q^2) = \frac{4}{3}\tau(1+\tau)F_M^2(Q^2)$
  - Extract G_E^n using deuteron model but very sensitive to NN potential.
- Elastic $d(e,e')\vec{d}$ reaction to measure t_{20}, the tensor polarization.
  - $t_{20} \propto F_C$, F_M, and F_Q. ➡ Extract all 3 form factors.
  - F_Q is insensitive to the deuteron model ➡ G_E^n

Developments

- Need make coincidence measurements
  - ➡ continuous beam accelerators like JLab and MAMI
- Need to measure spin observables
  - ➡ High beam polarization (70-80%) at high currents (80 μA)
    - ➡ Recoil polarization measurements possible
  - ➡ Development of polarized ^{3}He, ^{2}H and ^{1}H targets
    - ➡ Beam-Target asymmetry measurement possible
- Need to improve theory of $^3\text{He}(e,e')$,$^3\text{He}(e,e')n$, $^2\text{H}(e,e'n)$ and $^2\text{H}(e,e'p)$
  - ➡ Determine kinematics which reduce sensitivity to nuclear effects
  - ➡ Determine which observables are sensitive to form factors
  - ➡ Use model to extract form factors

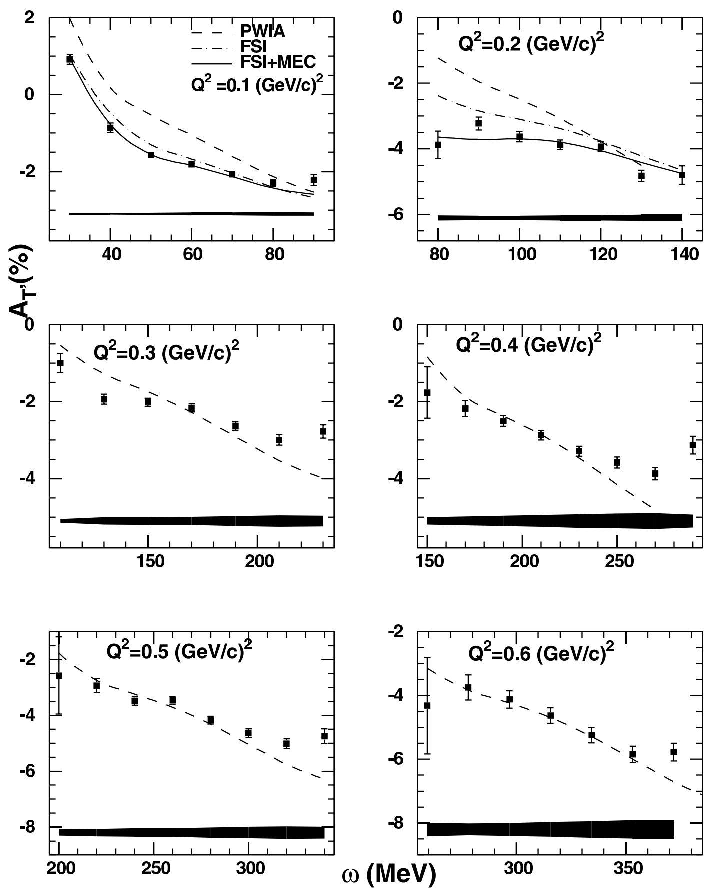
G_M^n from Quasi-free $d(e, e'np)$



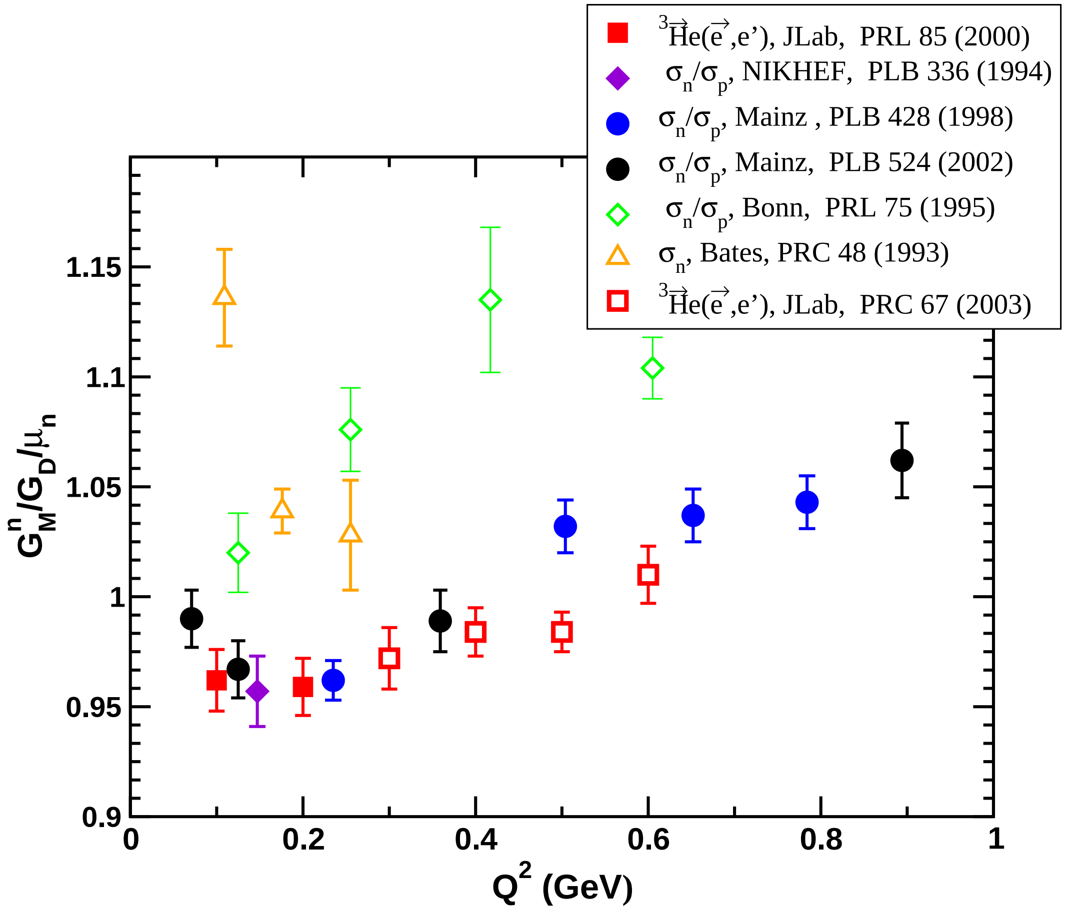
- Measure ratio $R_{meas} = \frac{\sigma(e,e'n)}{\sigma(e,e'p)}$
  - Proton and neutron detected in same detector simultaneously.
  - Need to know absolute neutron detection efficiency.
    - Bonn used $p(\gamma, \pi^+)n \; in - situ$
    - NIKHEF and Mainz used $p(n, p)n$ with tagged neutron beam at PSI.
- Use model to determine δR ➡ the deviation from R_{PWIA} .
  - Sensitivity to deuteron model cancels in ratio. $\delta R \approx$ 10%.
  - $R_{PWIA} = R_{meas} - \delta R$
  - G_M^n is extracted knowing G_E^n, G_M^p and , G_E^p

G_M^n from Quasi-free ${}^3\vec{He}(\vec{e},e')$

- 10μA polarized electron beam with P_B = 75% and spin flipped at 30 hZ.
- Target polarization, P_T = 30% .
  Simultaneously measure elastic ${}^3\vec{He}(\vec{e},e')$ to monitor $P_T \cdot P_B$
- Align the target spin along the q vector and measure $A_T = \frac{\sigma^+ - \sigma^+}{\sigma^+ + \sigma^+}$
- A_T sensitive to G_M^n . Use full three-body non-relativistic Fadeev calculation of A_T and G_M^n modified within the model until agreement with data.



Neutron Magnetic Form Factor



- Agreement between JLab $^3\vec{H}e(\vec{e}, e')$ and Mainz results
- Data has been taken in Hall B at JLab with CLAS, a large acceptance detector.
  - Deuteron and Proton target simultaneously
  - Continuous Q^2 coverage from 0.3 to 5 GeV^2.
  - Error bars 3-10%
  - $p(e, e'n)\pi^+$ to determined neutron effi ciency

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

$^3\vec{\text{He}}(\vec{\text{e}},\text{e}'\text{n})$ at quasi-free kinematic

➡ best approximation to free $\vec{\text{n}}(\vec{\text{e}},\text{e}'\text{n})$.

$$A = P_B P_T V \frac{a \sin\theta \cos\phi G_E^n G_M^n + b \cos\theta (G_M^n)^2}{c(G_E^n)^2 + d(G_M^n)^2}$$

where θ is the angle of the target neutron's spin relative to the momentum transfer.

When θ = 90° :

$$A = A_\perp \propto G_E^n G_M^n$$

To first order when θ = 0°

$A = A_{||}$ depends only on kinematics.

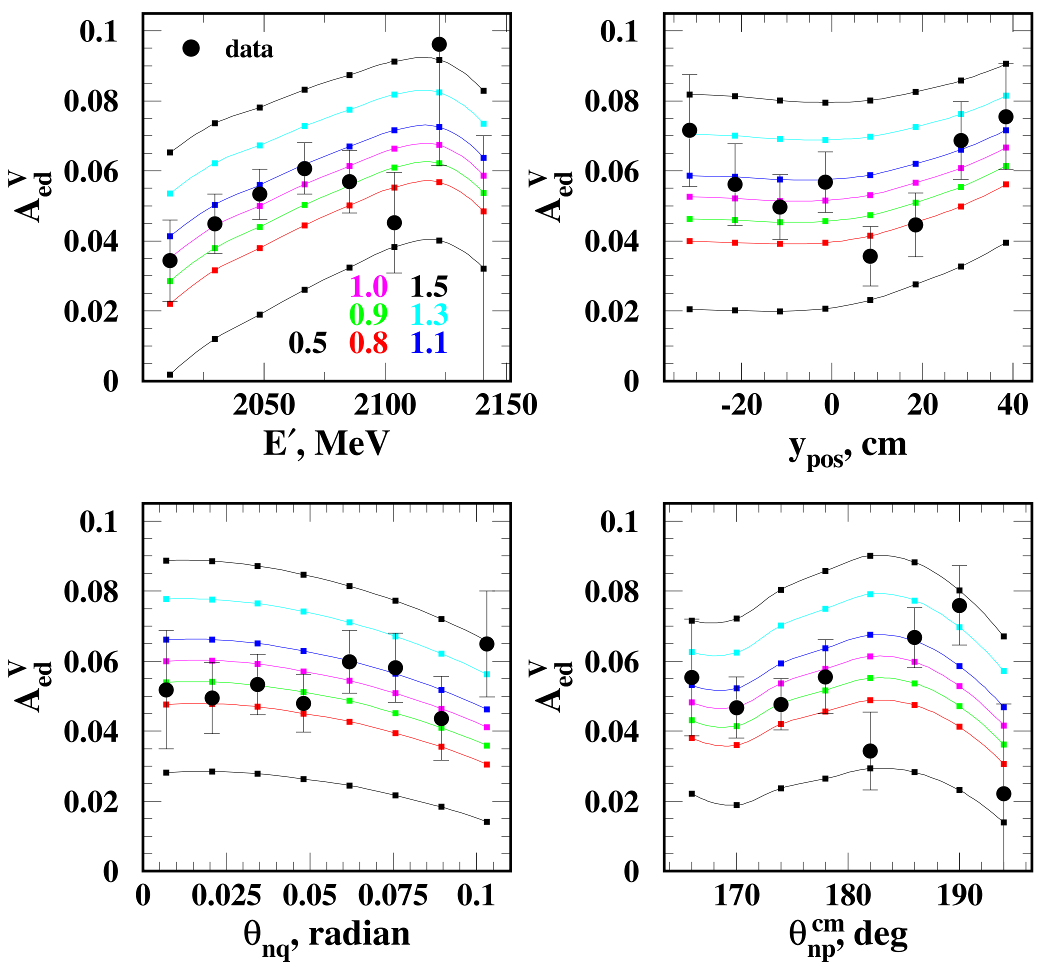
$$G_E^n \approx \frac{b}{a} G_M^n \frac{(P_B P_T V)_{||}}{(P_B P_T V)_\perp} \frac{A_\perp}{A_{||}}$$

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

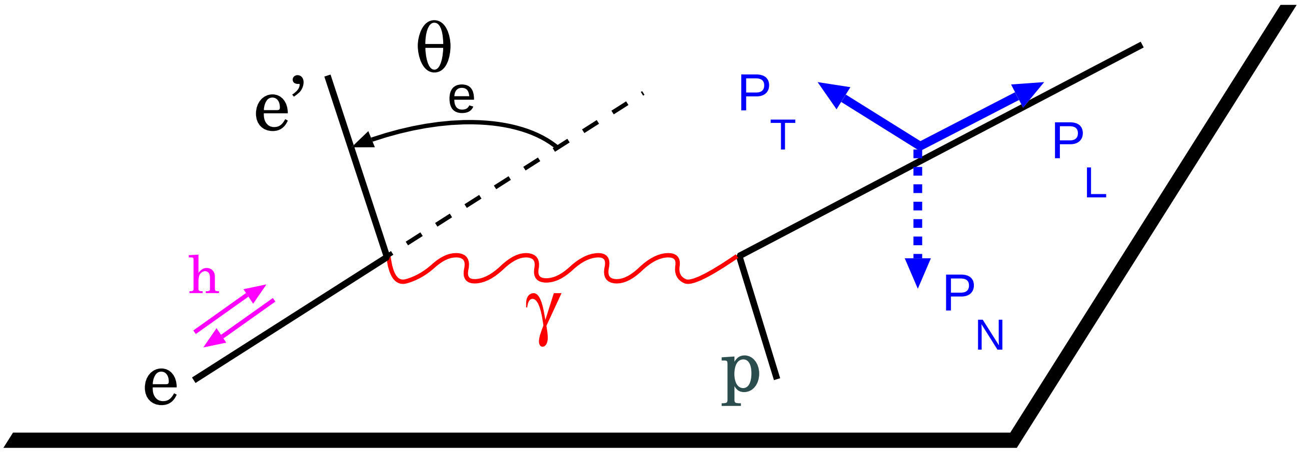
$$A_{ed}^V = \frac{N^+ - N^-}{N^+ + N^-} = P_B P_T V \frac{-2\sqrt{\tau(\tau+1)}\tan(\theta_e/2) G_E^n G_M^n}{G_E^{n^2} + \tau/\epsilon G_M^{n^2}}$$

Extract G_E^n from A_{ed}^V:

- Use full model of Arenhovel to predict A_{ed}^V .
- Modify G_E^n to have agreement with the measured A_{ed}^V



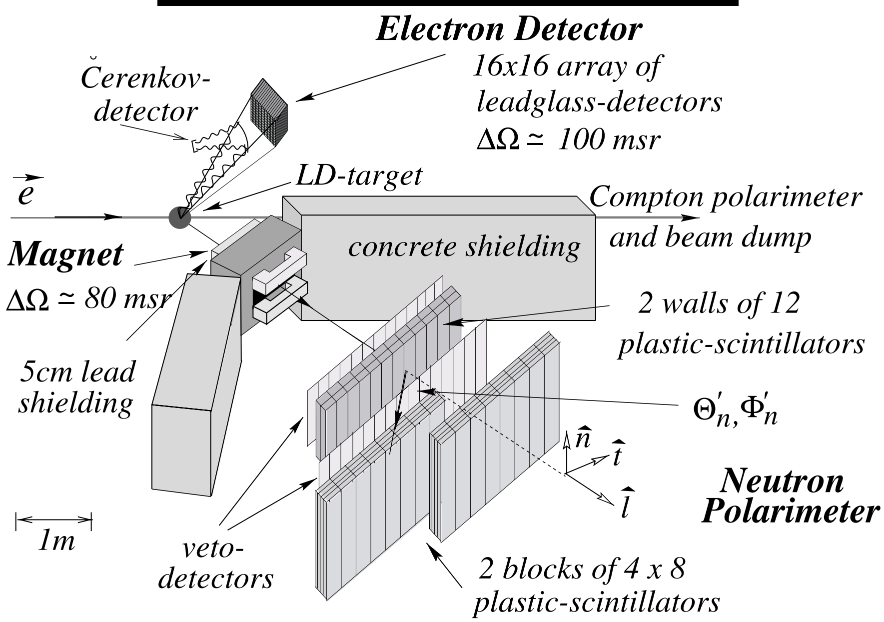
Recoil Polarization in elastic eN



- Helicity independent components are zero.
- Helicity dependent outgoing proton spin components:
  - P_l is along the proton momentum direction
  - P_t is in-plane transverse to momentum direction
  - P_n is out-of-plane transverse to momentum direction $P_n = 0$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_e+E_{e'})}{2M}\tan(\frac{\theta}{2})$$

d($\vec{e}$,e′ $\vec{n}$) at MAMI

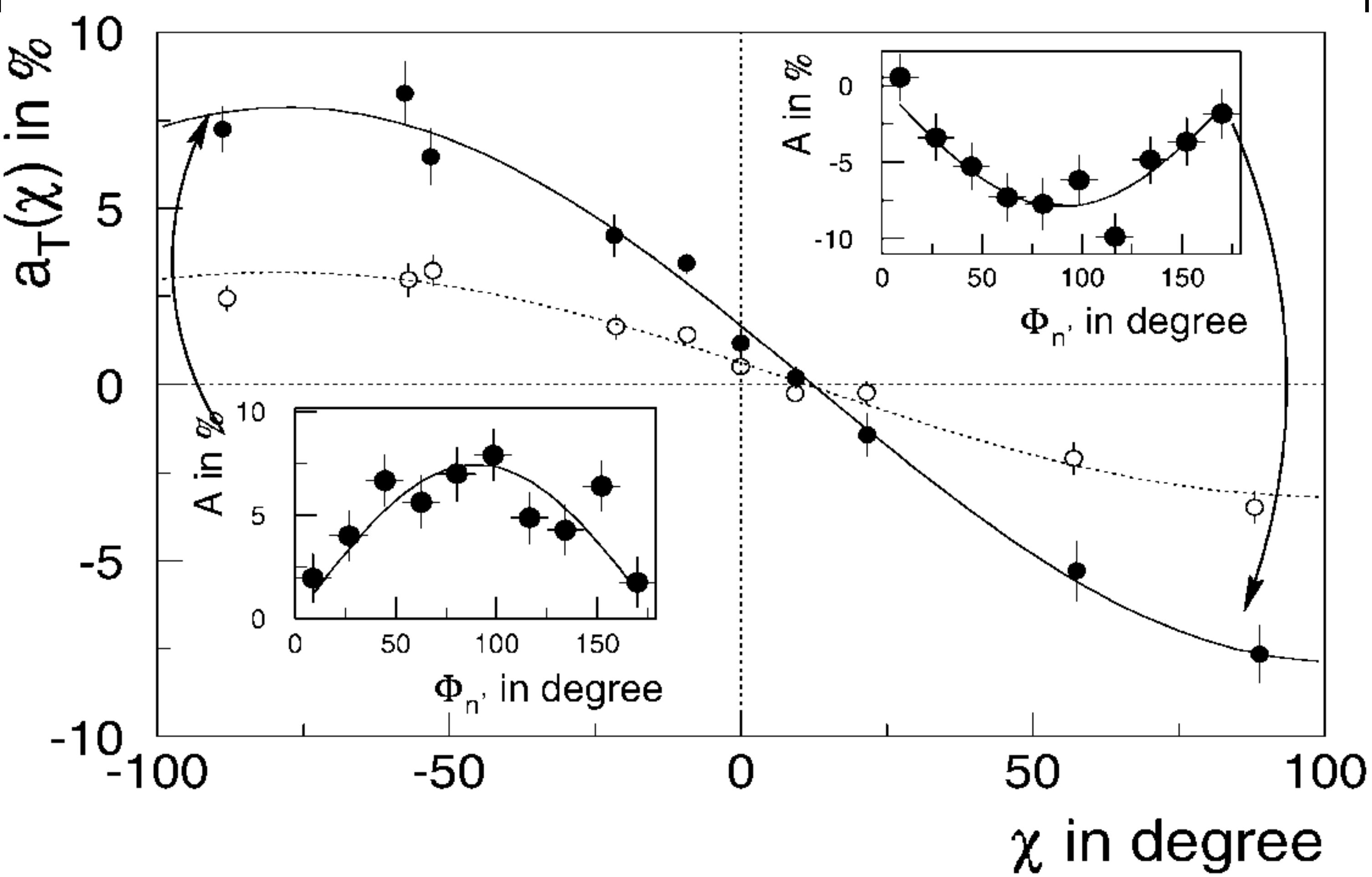


- Outgoing neutrons scatter in CH_2 which is the analyzer for the secondary reaction.
- The analyzer can only measure spin components perpendicular to the incoming particle's momentum. $a_T = A_y P_x$
- To measure P_l need to precess the neutron spin in a magnetic field so transverse polarization at the CH_2 is:

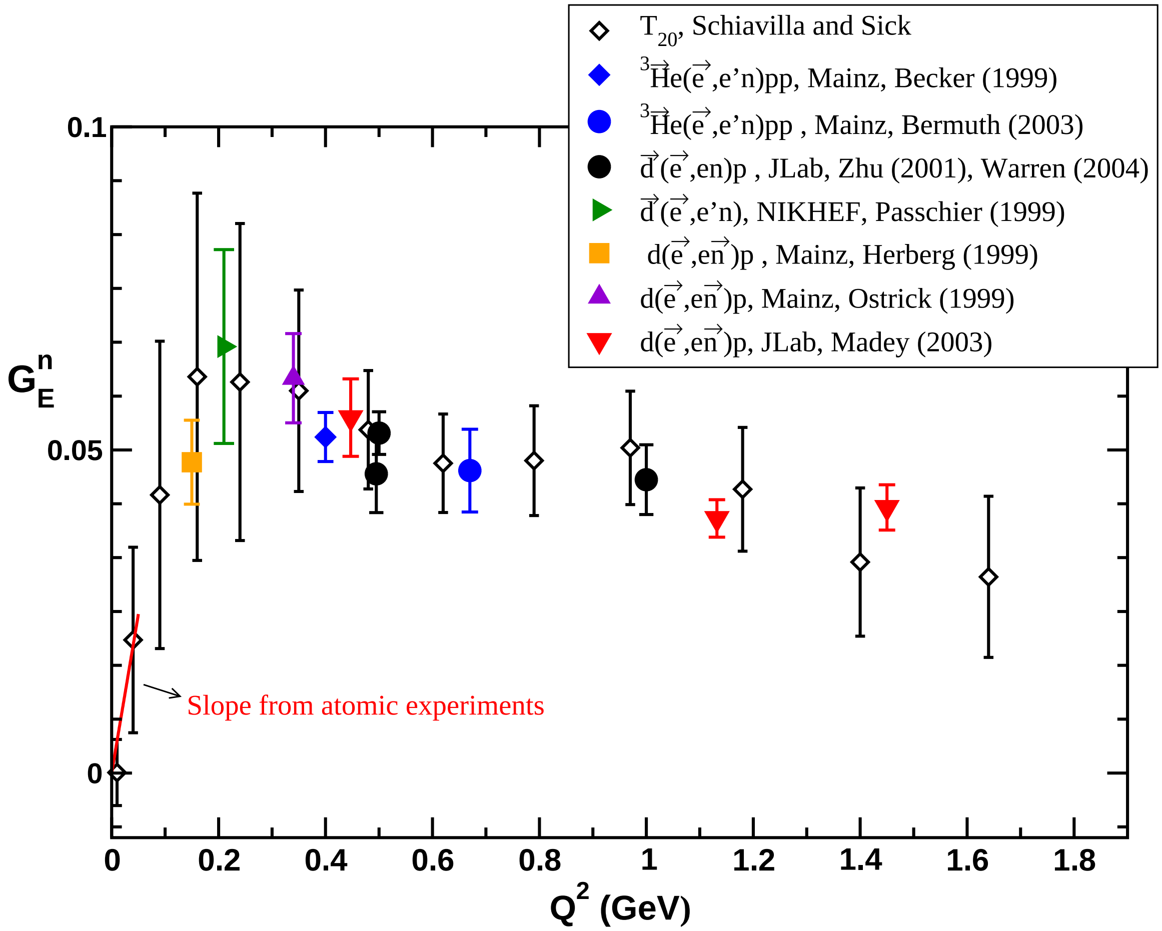
$$P_x = P_l \sin\chi + P_t \cos\chi$$

d($\vec{e}$,e′ $\vec{n}$) at MAMI

$$a_T = P_B A_y (P_l \sin\chi + P_t \cos\chi) = A_o \sin(\chi - \chi_\circ)$$
$$\tan\chi_\circ = \frac{P_B A_y P_t}{P_B A_y P_l}$$

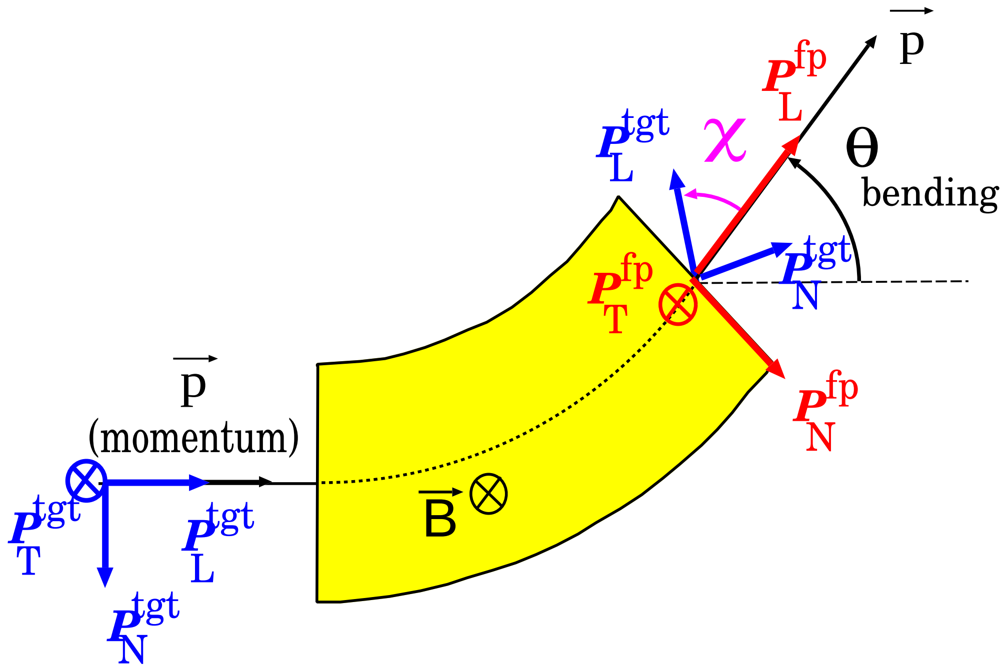


Neutron Electric Form Factor



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

G_E^p/G_M^p by Recoil Polarization



- Both momentum and spin vector precess in the magnet.
- Precession angle, $\chi = \gamma\, \kappa_p\, \theta_{\text{bending}}$

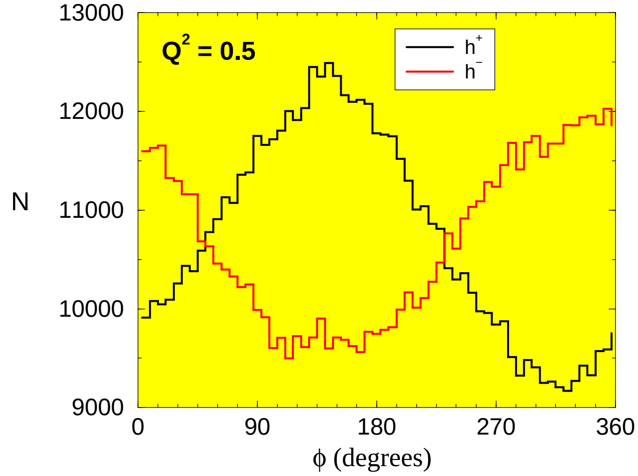
  For simple dipole $$P_T^{fp} = P_T^{tgt}$$

  and in general $P_N^{fp} = -P_L^{tgt} \sin(\chi) + P_N^{tgt} \cos(\chi)$
  but for proton, $P_N^{tgt} = 0$ so

  $$P_N^{fp} = -P_L^{tgt} \sin(\chi)$$

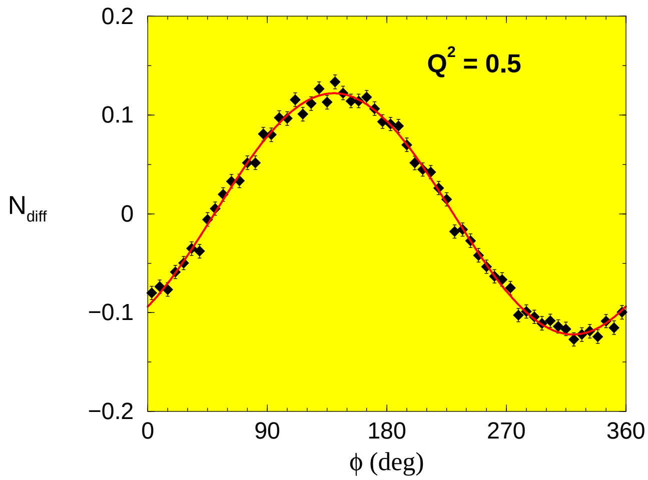
- Unlike neutron recoil polarization measure P_L^{tgt} and P_L^{tgt} separately and simultaneously.

G_E^p/G_M^p by Recoil Polarization

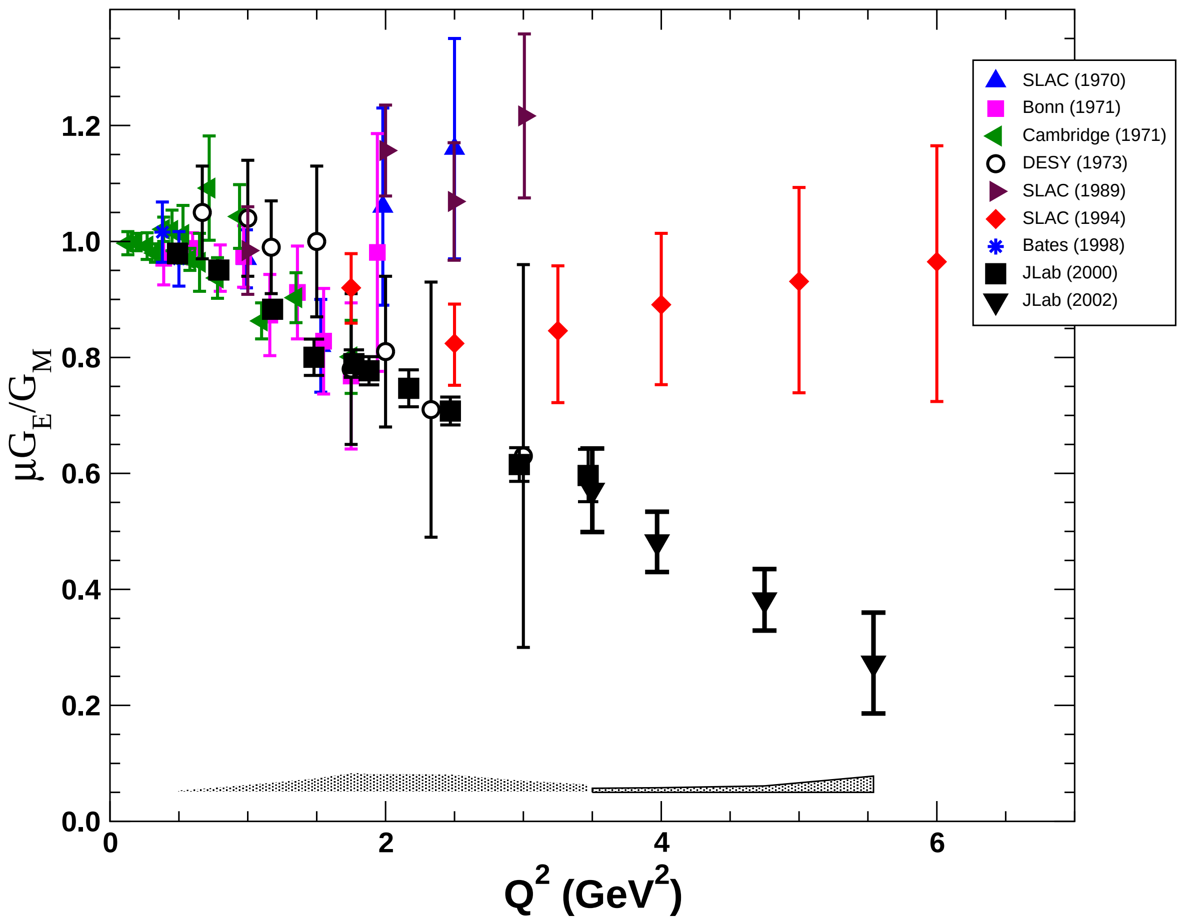


$$N^{\pm}(\theta,\phi) = N_0^{\pm}(\theta)\Big[1 + \left[\pm h A_c(\theta) P_n^{fp} + b_i\right]\cos\phi + \left[\pm h A_c(\theta) P_t^{fp} + a_i\right]\sin\phi\Big]$$

- $P_n^{fp} = -P_l^{tgt}\sin(\chi)$ and $P_t^{fp} = P_t^{tgt}$, $\frac{G_E}{G_M} \propto \frac{P_t^{fp}\sin(\chi)}{P_n^{fp}}$
- a_i and b_i are the instrumental asymmetries which are eliminated by subtracting N^- from N^+.



Proton G_E/G_M

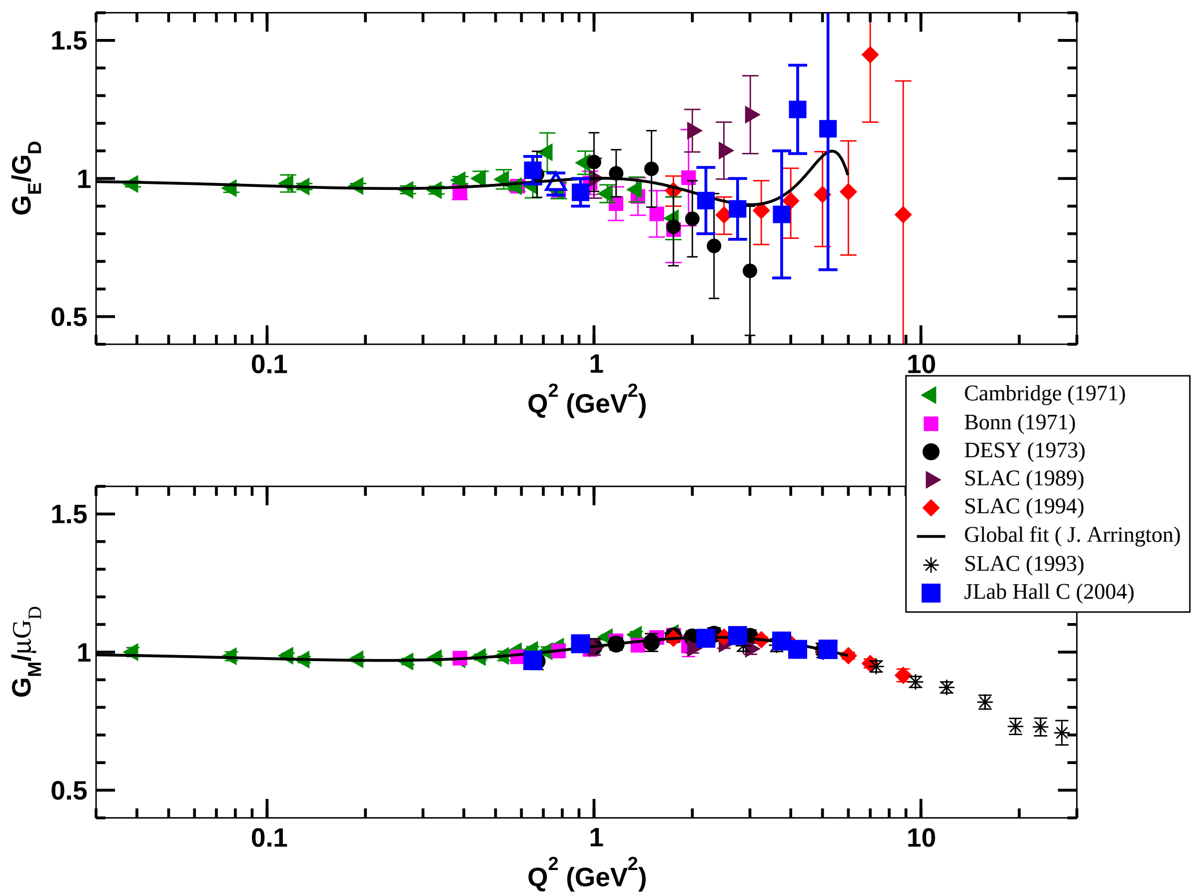


- G_E/G_M from polarization measurement falls linearly with Q^2.
- Disagreement between G_E/G_M extracted from cross section data.

Systematic problems?

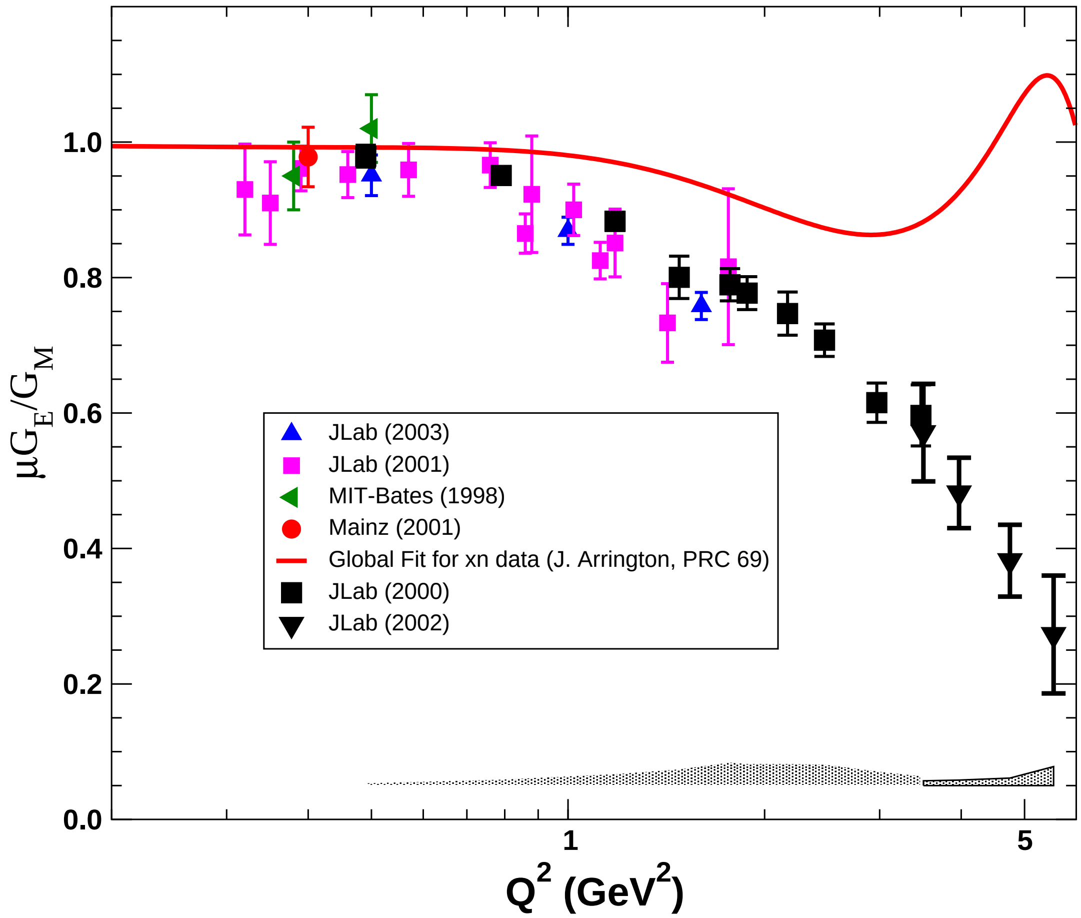
Unaccounted for physics?

Recent Rosenbluth measurements



- Global analysis of previous experiments by J. Arrington indicates no inconsistencies between experiments.
- When trying to combine the cross section data and polarization data, the global fi t has a larger χ^2 indicating that the data are inconsistent with each other.
- New measurements at JLab in Hall C at consistent with previous experiments.

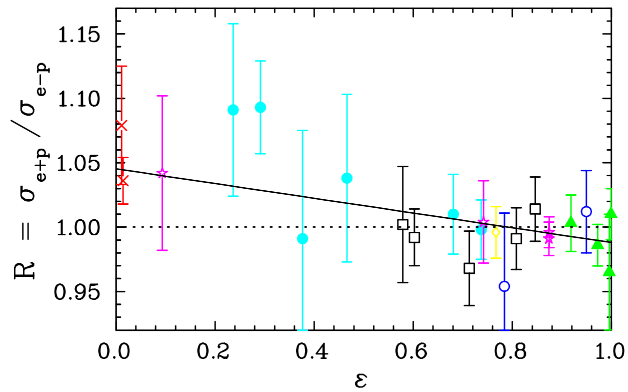
Comparison to Global Fit



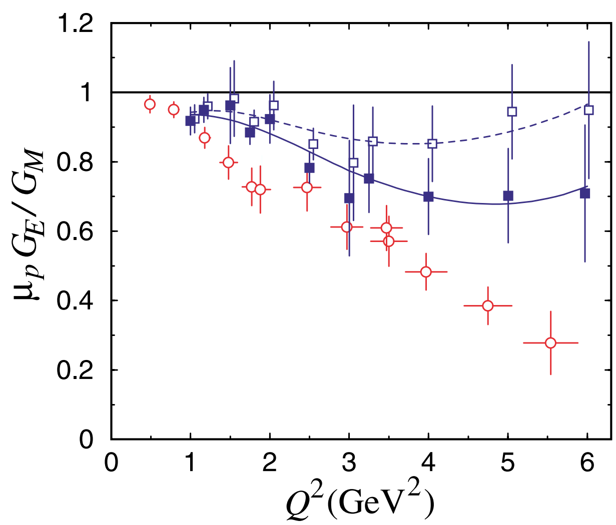
- A dedicated measurement at JLab in Hall A has preliminary results which also agree with previous experiments. Detected the elastically scattered proton instead of electron which has advantages:
  - Proton momentum fixed at each ϵ
  - Cross section is nearly constant with ϵ
  - Reduces size of ϵ-dependent radiative corrections
  - Reduces systematic error on beam energy and scattering angle

Two-photon Contributions

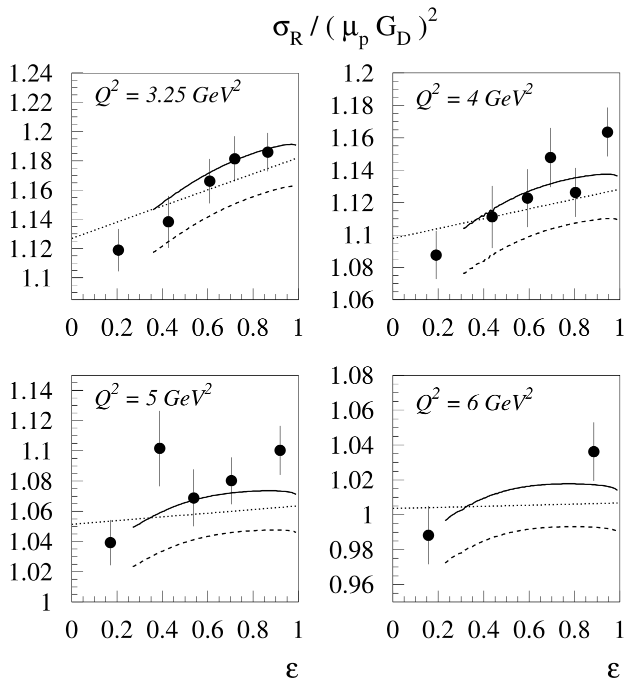
- John Arrington (nucl-ex/0311019)looked at $\frac{\sigma_{e+p}}{\sigma_{e-p}}$ data for Q$^2 < 2$ but covered wide ϵ range. Determines a slope of -(5.7 $\pm$ 1.8)%.



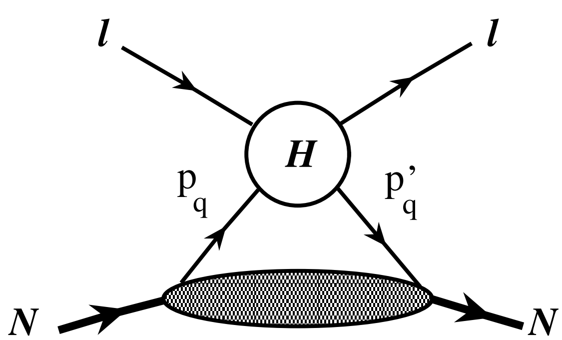
- Calculation by Blunden,Melnitchouk and Tjon (PRL 91,142304 (2004)). Only includes nucleon intermediate states.



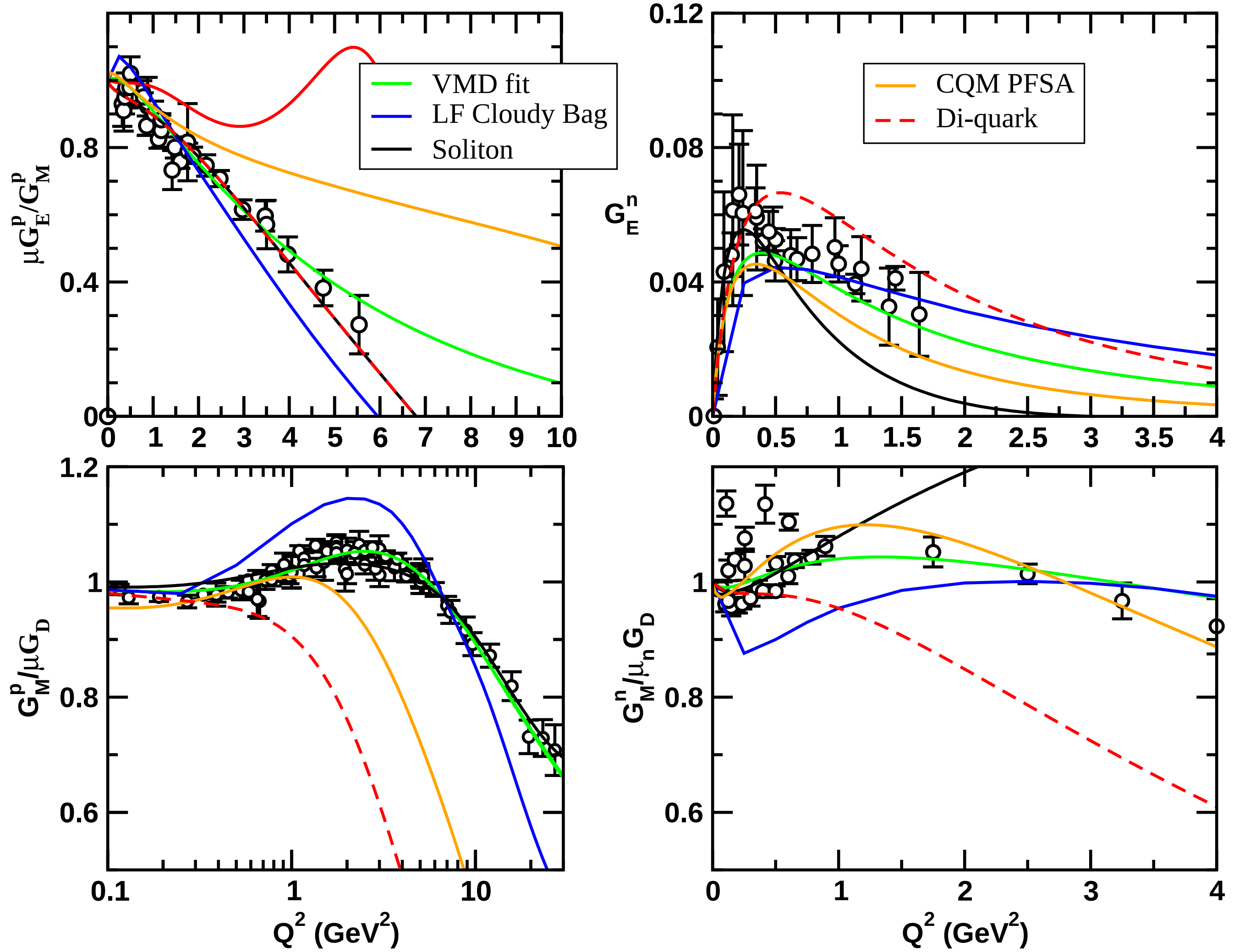
Two-photon Contributions



- Chen, Afanasev, Brodsky, Carlson and Vanderhaegen (hep-ph/0403058) calculates the hard part of the 2γ exchange using the "handbag" diagram.



- Limited ϵ and Q^2 range since $s, -u, Q^2 << M^2$



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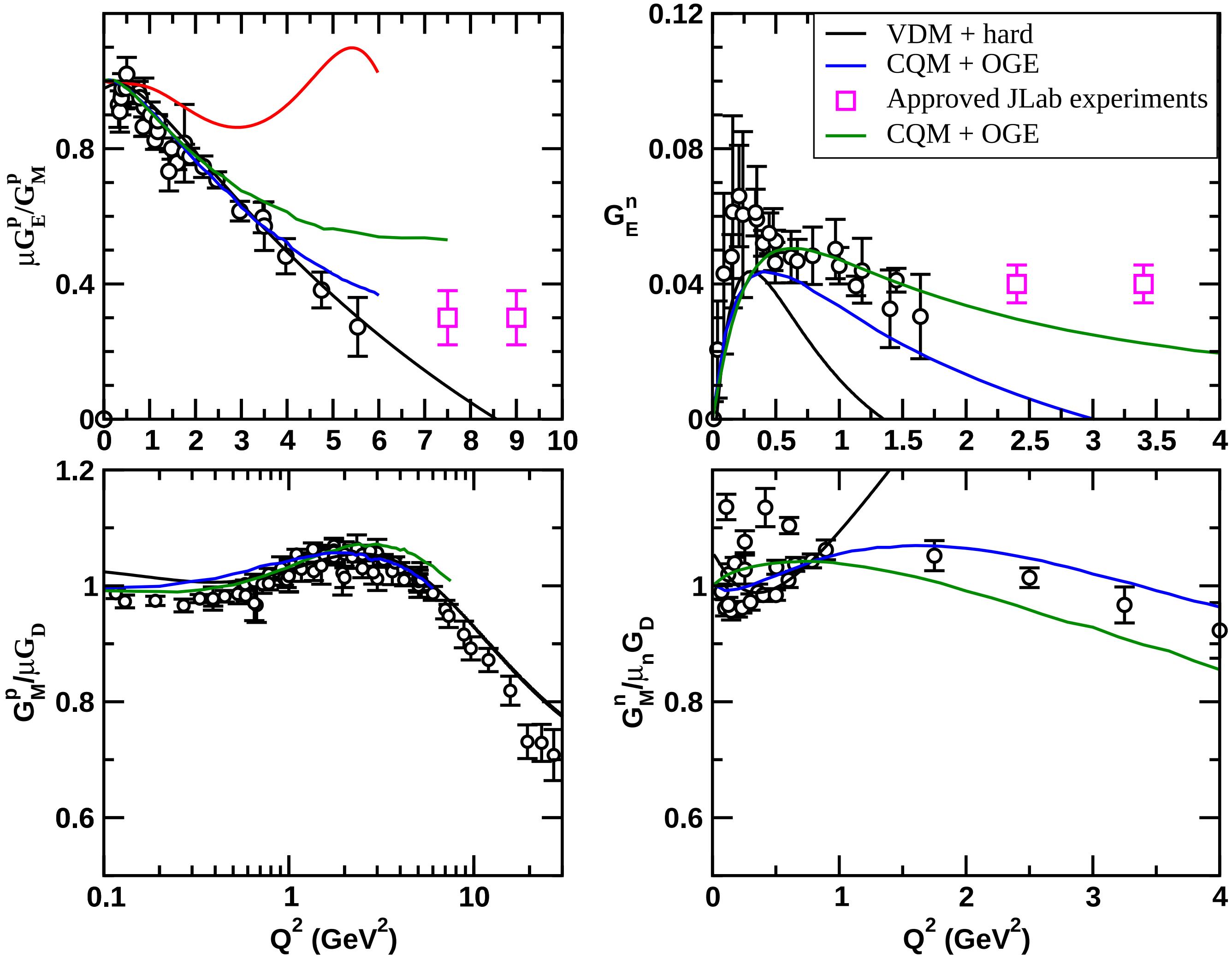

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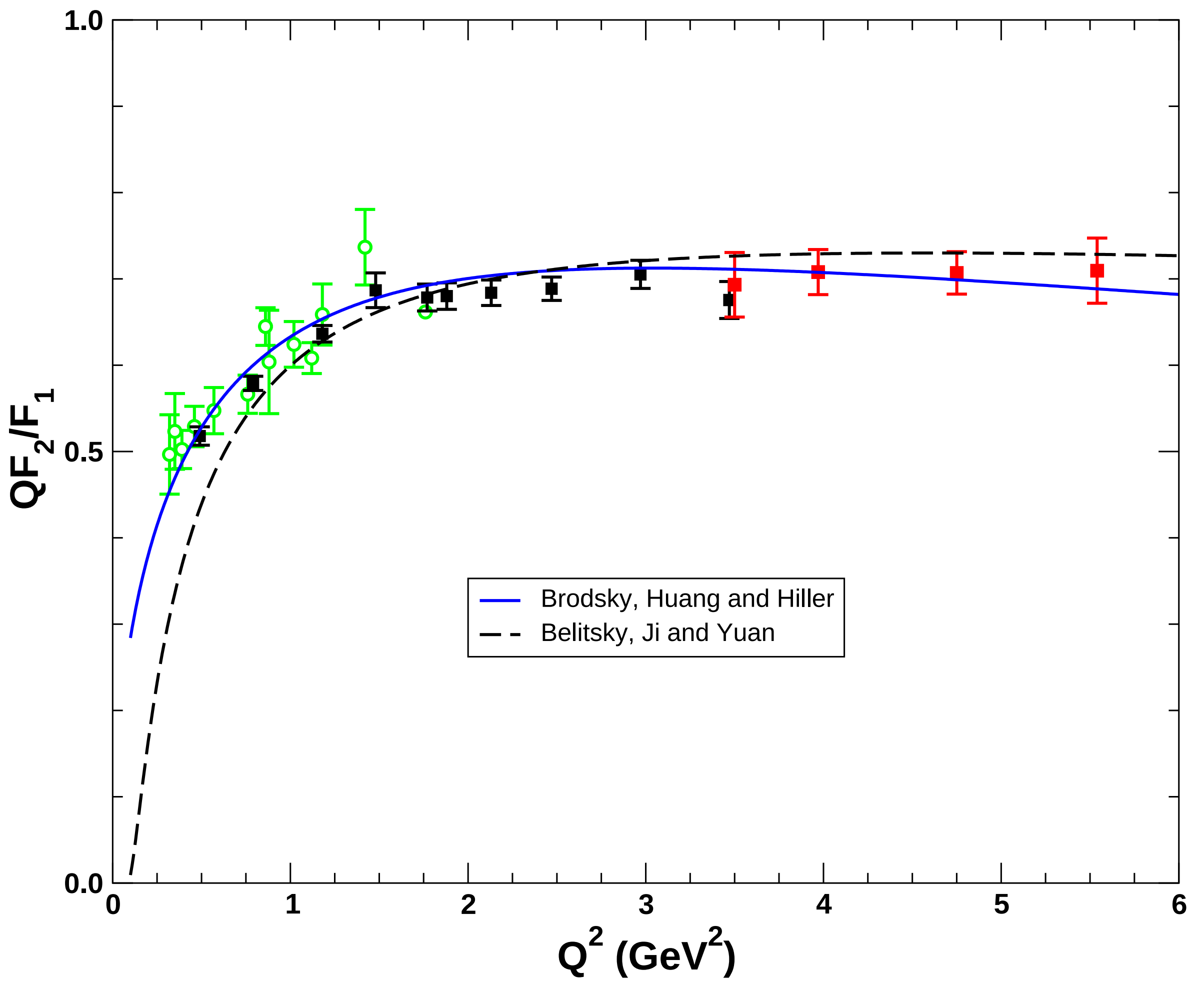
Comparison to pQCD



Comparison to Lattice QCD