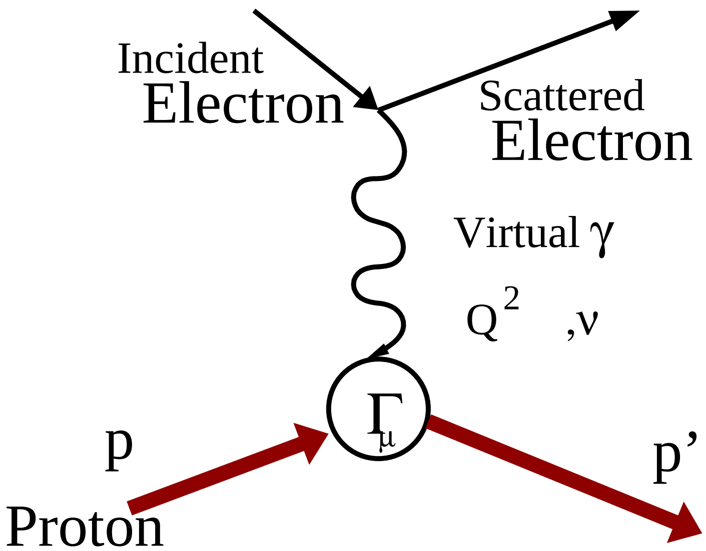
Recent and future measurements of the proton electric form factor

Mark K. Jones, Jefferson Lab

Workshop on Nucleon Form Factors

Elastic Electron-Nucleon Scattering



Nucleon vertex:

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

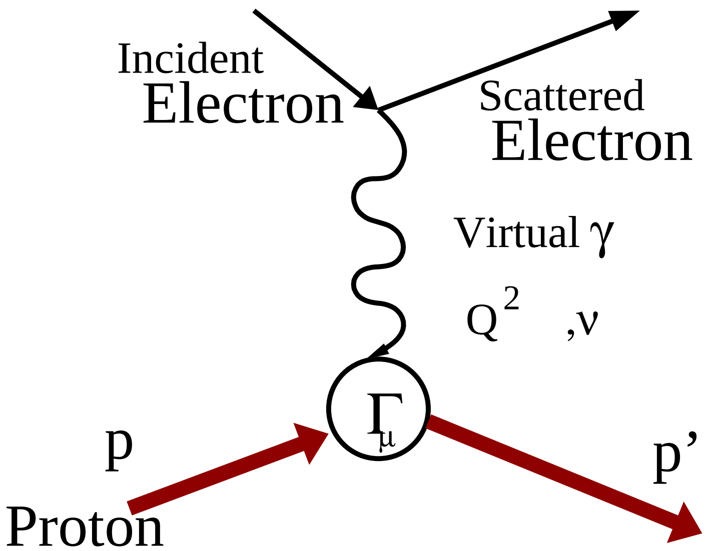
$$G_E(Q^2) = F_1(Q^2) - \kappa_N \tau F_2(Q^2)$$

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

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

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

Elastic Electron-Nucleon Scattering



Nucleon vertex:

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

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

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

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

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

Extract G_E^2 and G_M^2 from:

- ➡ Cross-section measurements $\quad N(e,e')$

Extract G_E/G_M from:

- ➡ Beam-target Asymmetries $\quad \vec{N}(\vec{e},e')N$
- ➡ Recoil polarization $\quad N(\vec{e},e')\vec{N}$

Rosenbluth separation technique

ep elastic cross-section:

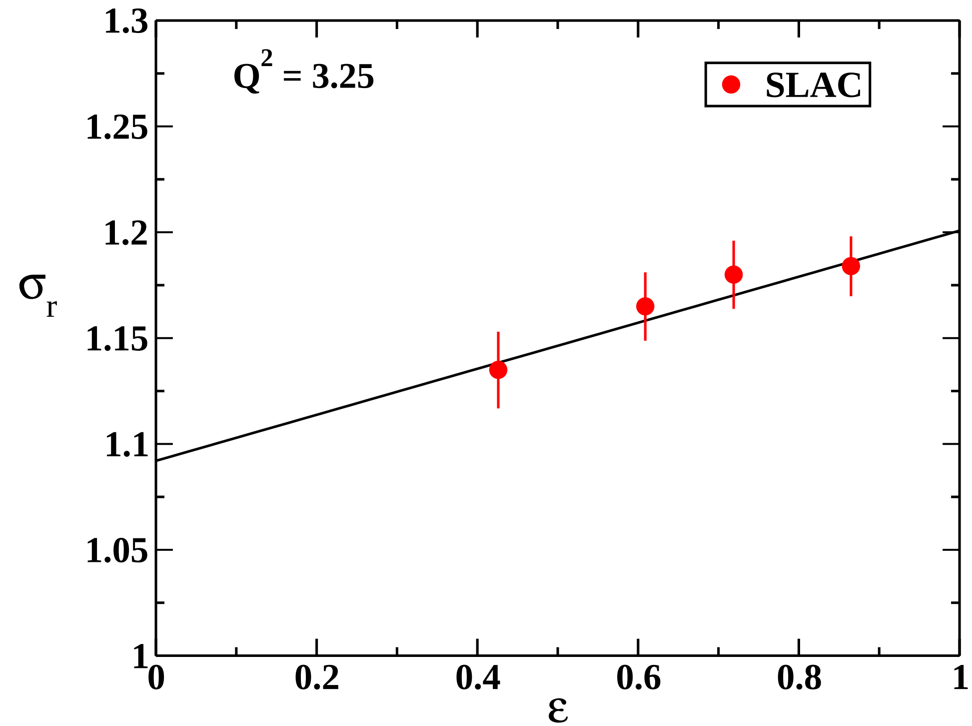
$$\sigma_r \propto \frac{\epsilon}{\tau}\left(\frac{G_E}{G_D}\right)^2 + \left(\frac{G_M}{G_D}\right)^2$$

$G_D = (1 + Q^2/.71)^{-2}$ $\qquad \tau = Q^2/4M^2$

At fixed Q^2: Vary ϵ

G_E is slope

G_M is intercept



Rosenbluth separation technique

ep elastic cross-section:

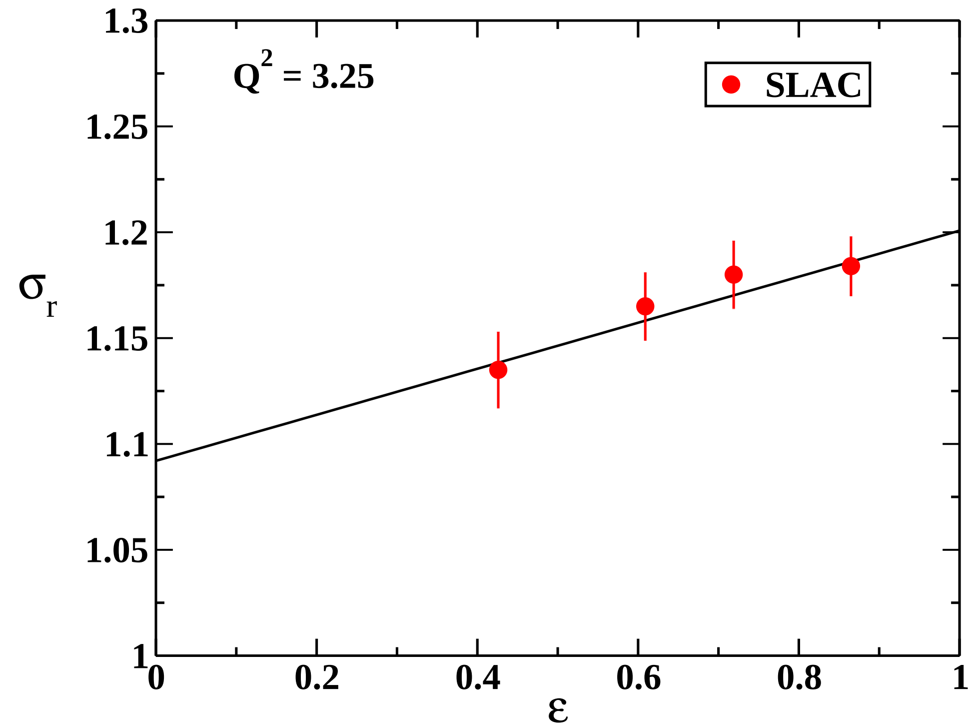
$$\sigma_r \propto \frac{\epsilon}{\tau}\left(\frac{G_E}{G_D}\right)^2 + \left(\frac{G_M}{G_D}\right)^2$$

$G_D = (1 + Q^2/.71)^{-2} \qquad \tau = Q^2/4M^2$

At fixed Q^2: Vary ϵ

G_E is slope

G_M is intercept

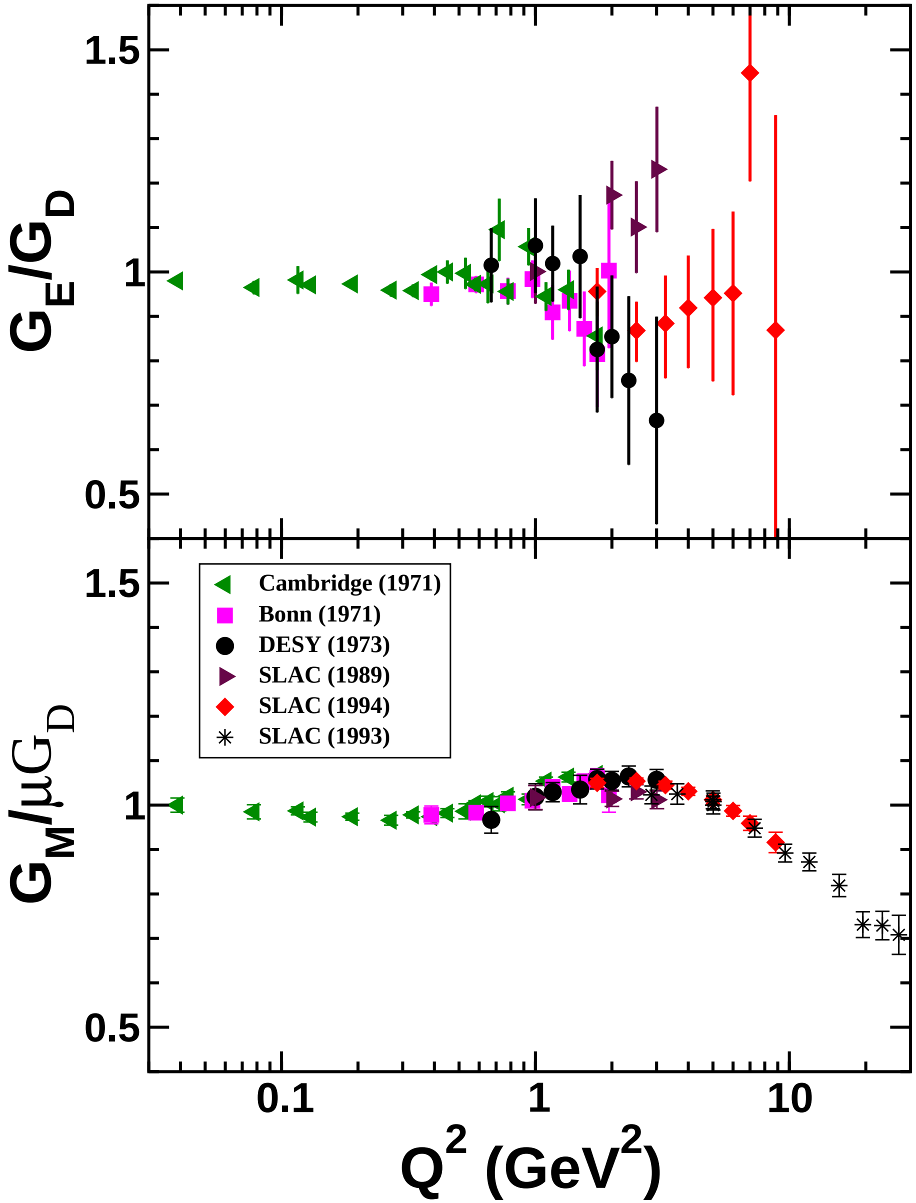


For $Q^2 > 1$ measuring G_E becomes more difficult

- G_E becomes a smaller fraction of σ
- At Q^2 = 5, G_E maximum 8% contribution to σ

  (assuming $\mu G_E/G_M$ = 1)

Proton Form Factors : G_M and G_E



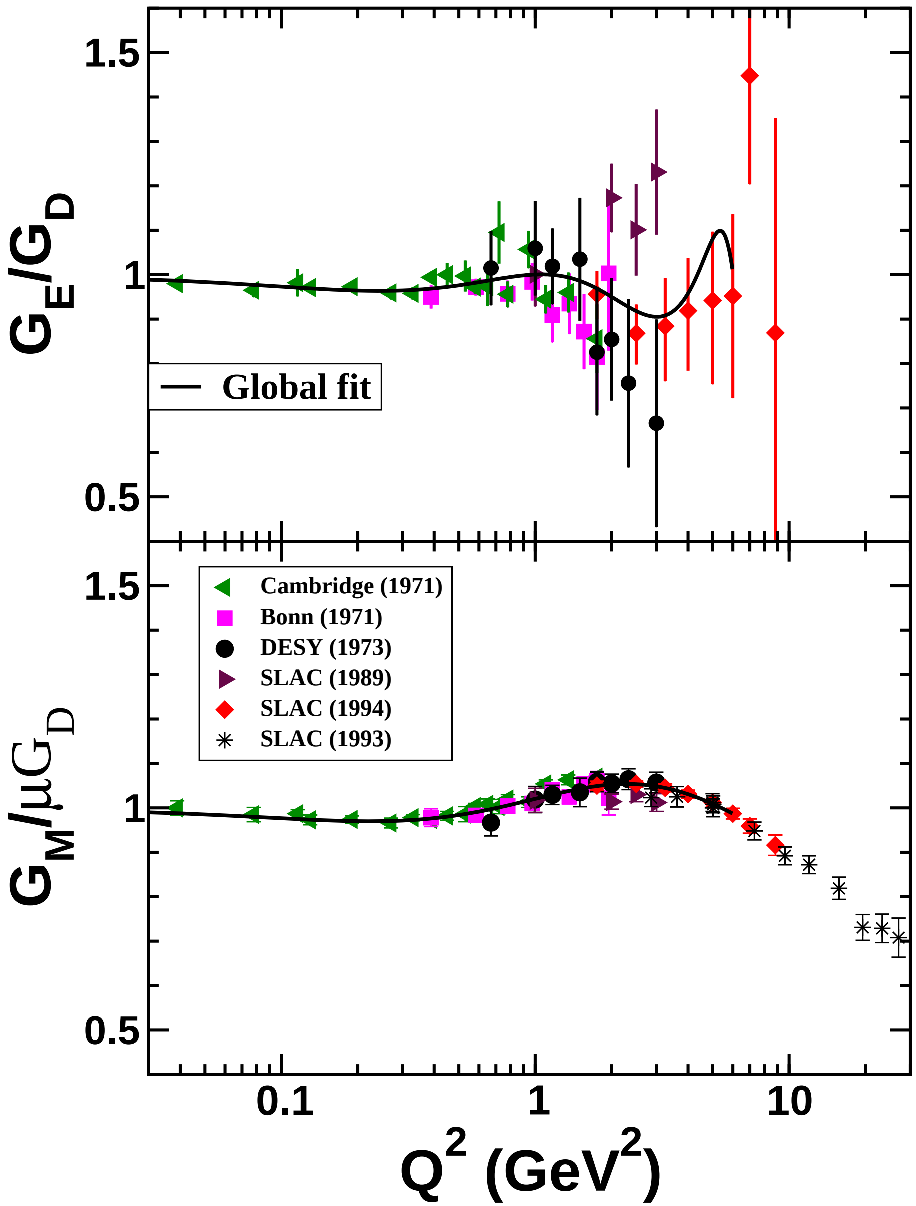
At all Q^2

➡ G_M well measured

At $Q^2 > 1$

➡ Error on G_E large

Proton Form Factors : G_M and G_E



At all Q^2

➡ G_M well measured

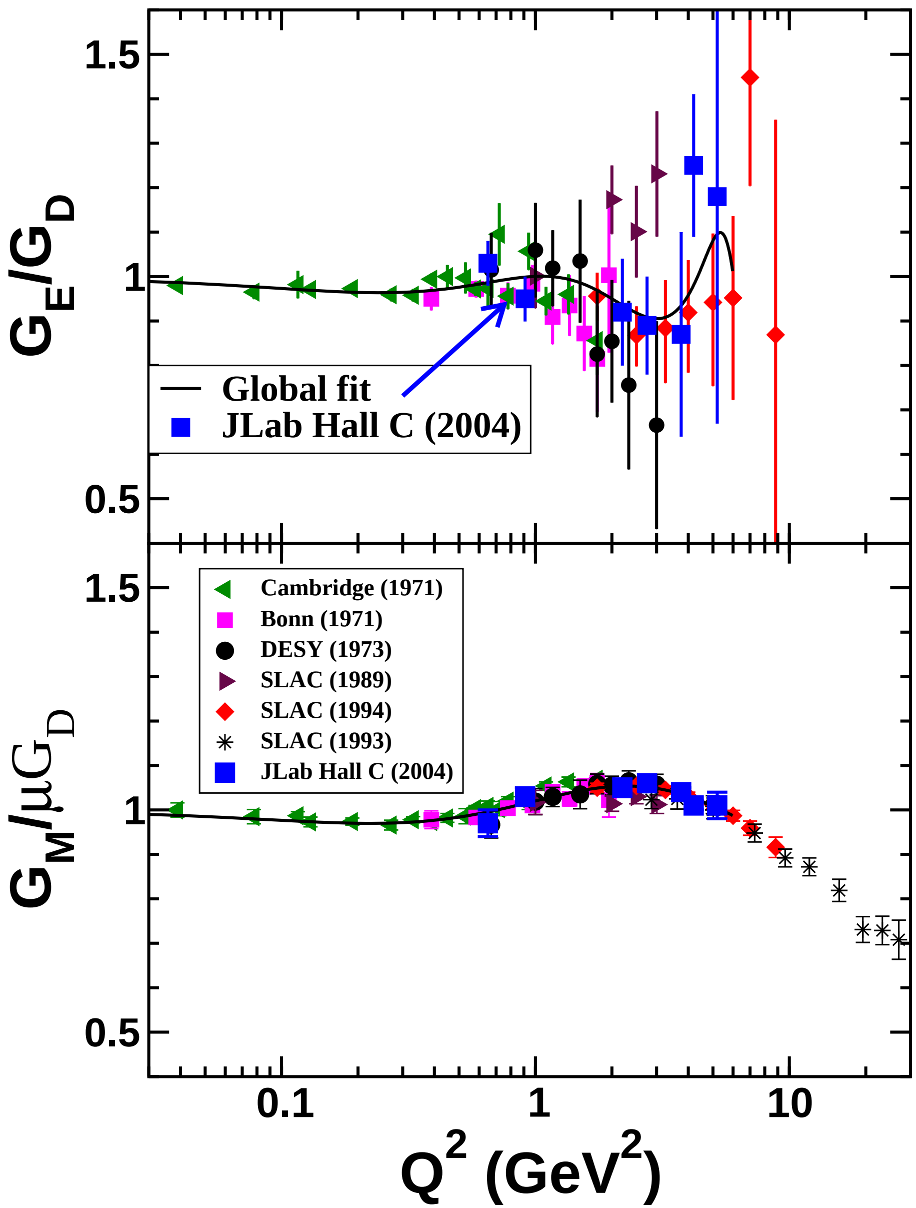
At $Q^2 > 1$

➡ Error on G_E large

➡ Recent global fit to world cross section data

J. Arrington PRC 69, 02201R (2004)

Proton Form Factors : G_M and G_E



At all Q^2

→ G_M well measured

At $Q^2 > 1$

→ Error on G_E large

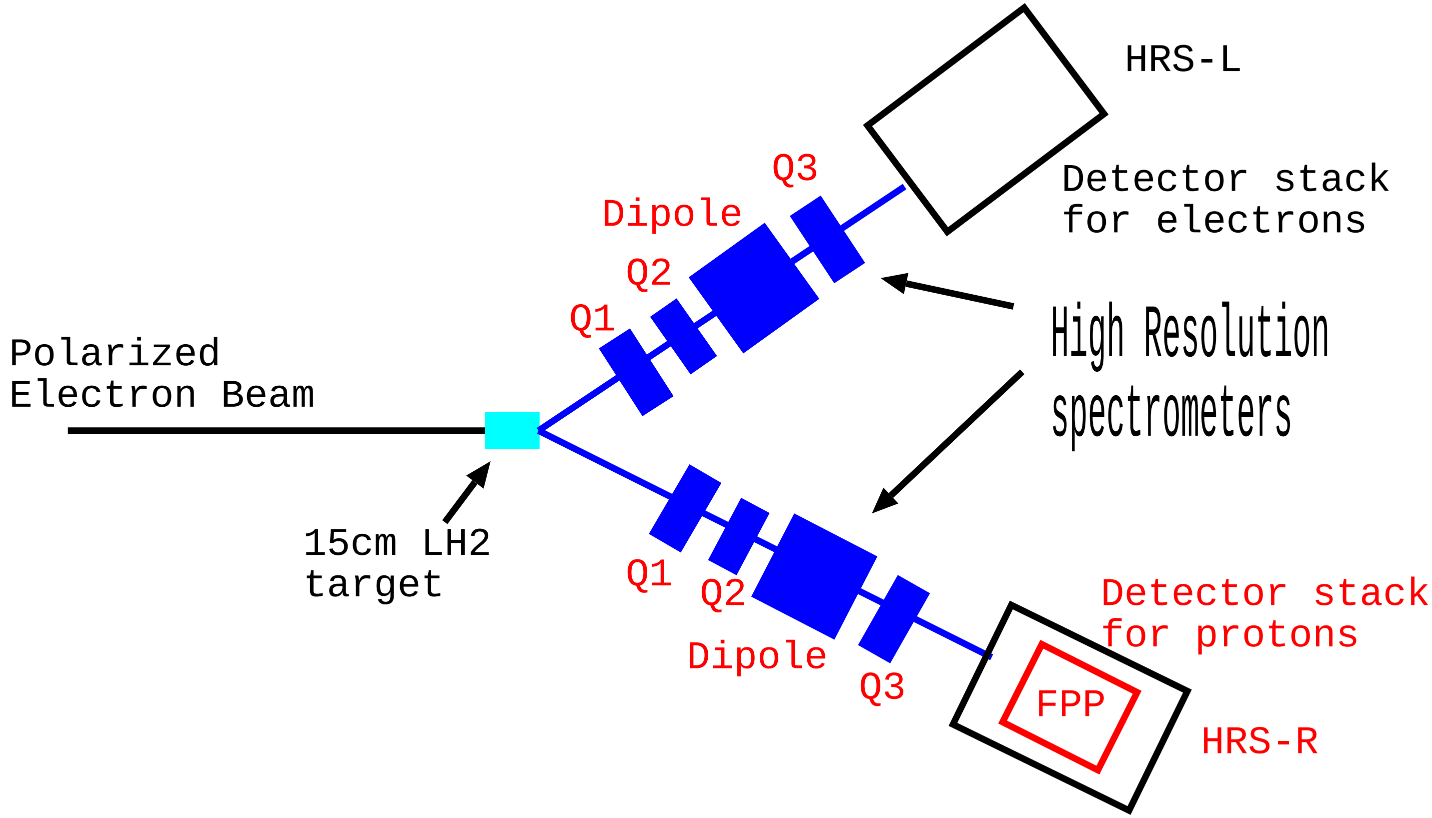
→ Recent global fit to world cross section data

J. Arrington PRC 69, 02201R (2004)

→ Recent Hall C data

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

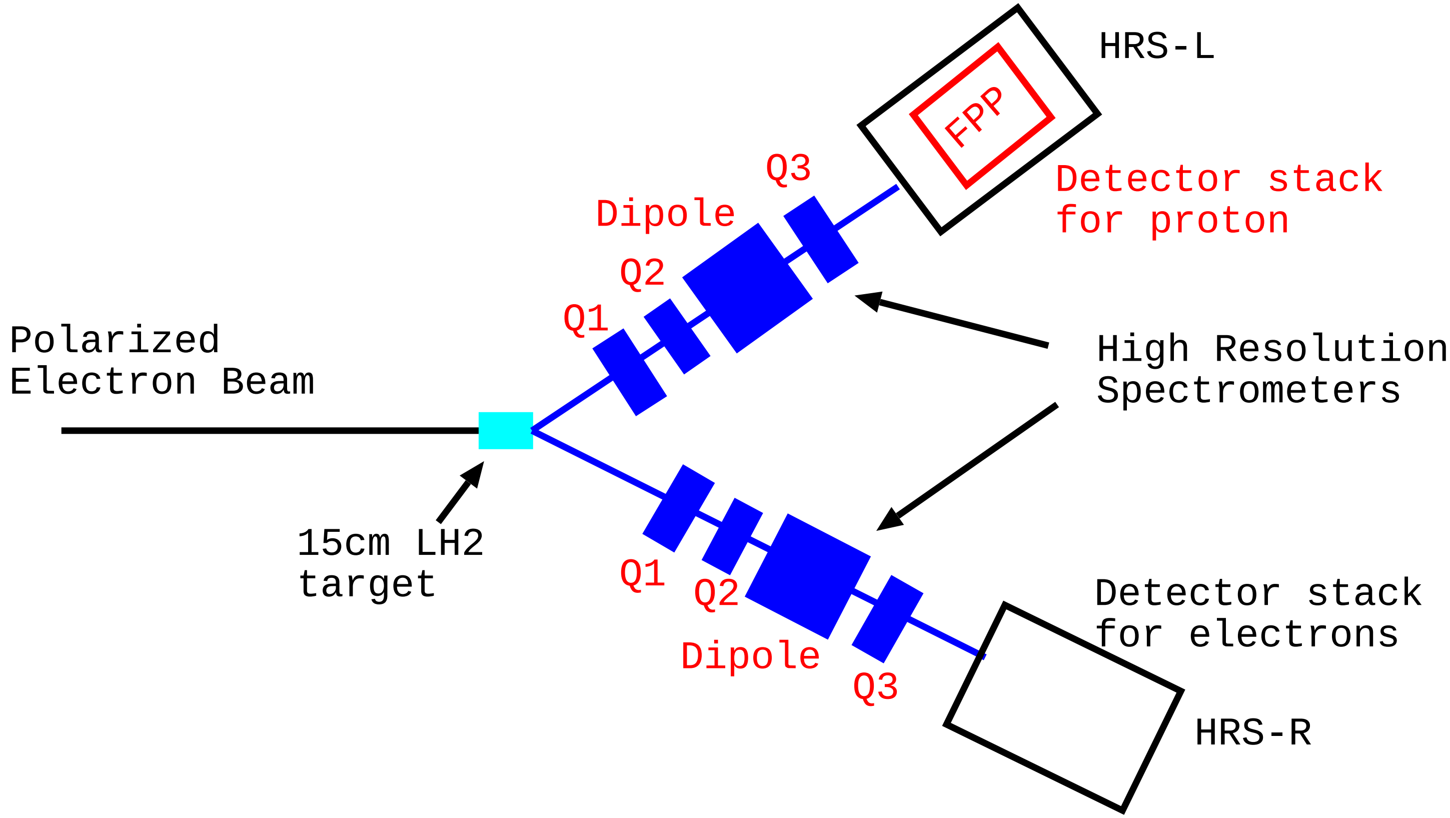
JLab Recoil Polarization Experiments



1st JLab experiment Electrons detected HRS-L
Protons detected HRS-R

Covered Q^2 from 0.5 to 3.5 GeV^2.

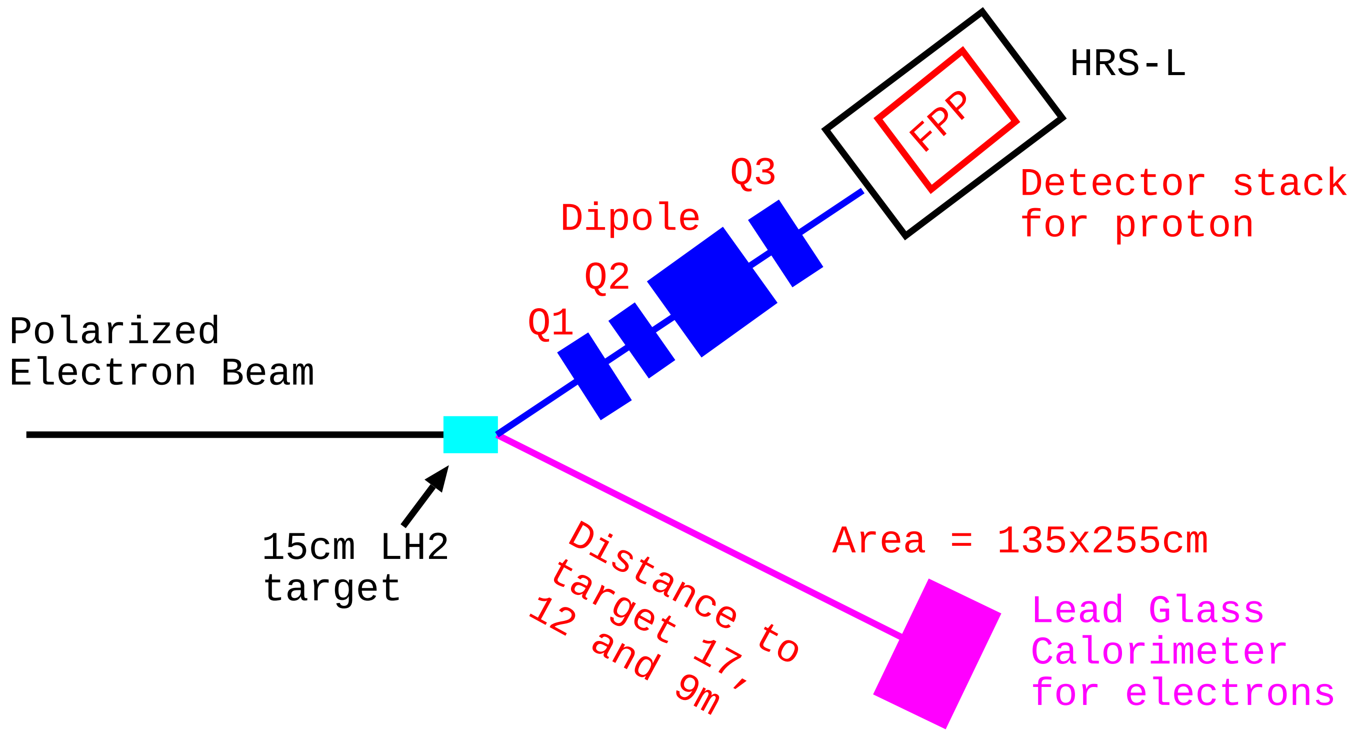
JLab Recoil Polarization Experiments



2nd JLab experiment   Protons detected HRS-L

Covered Q^2 from 3.5 to 5.6 GeV^2.

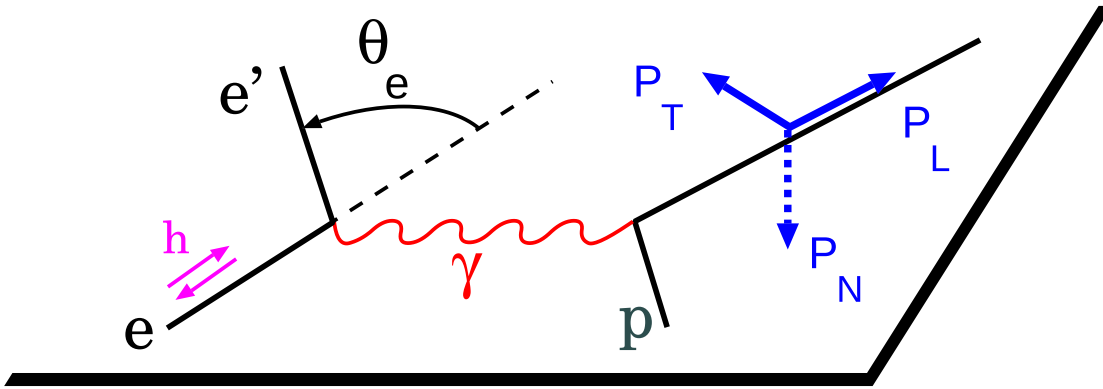
JLab Recoil Polarization Experiments



2nd JLab experiment — Protons detected HRS-L
Electrons detected calorimeter

Covered Q^2 from 3.5 to 5.6 GeV^2.

Spin Transfer Reaction $^1\mathbf{H}(\vec{e}, e'\vec{p})$



Helicity dependent : P_N, P_T, P_L

$P_N = 0$ for elastic

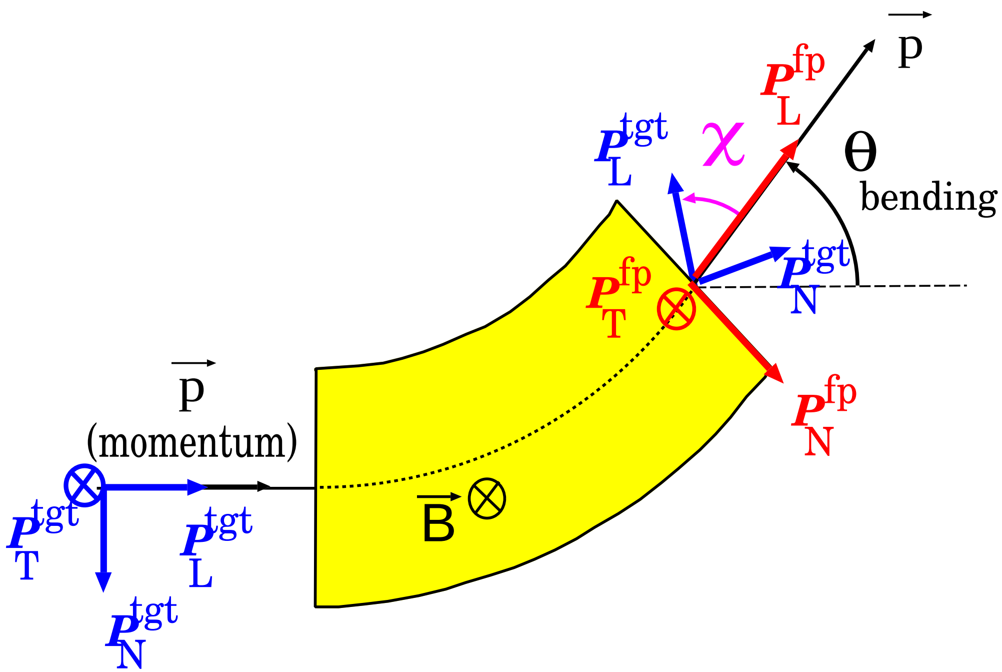
In 1γ approx.

Helicity independent $P_N = 0$

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

- Experiments detect the electron and proton in coincidence
- Proton spin measured by second scattering in polarimeter
- Experiments done at MIT-Bates, Mainz and JLab

Spin precession



Precession angle

$$\chi = \gamma \kappa_p \theta_b$$

For Hall A HRS $\theta_b = 45°$

For $Q^2 = 2.2$, $\chi = 180°$

FPP measures P_N^{fp}, P_T^{fp}

Simple dipole magnet

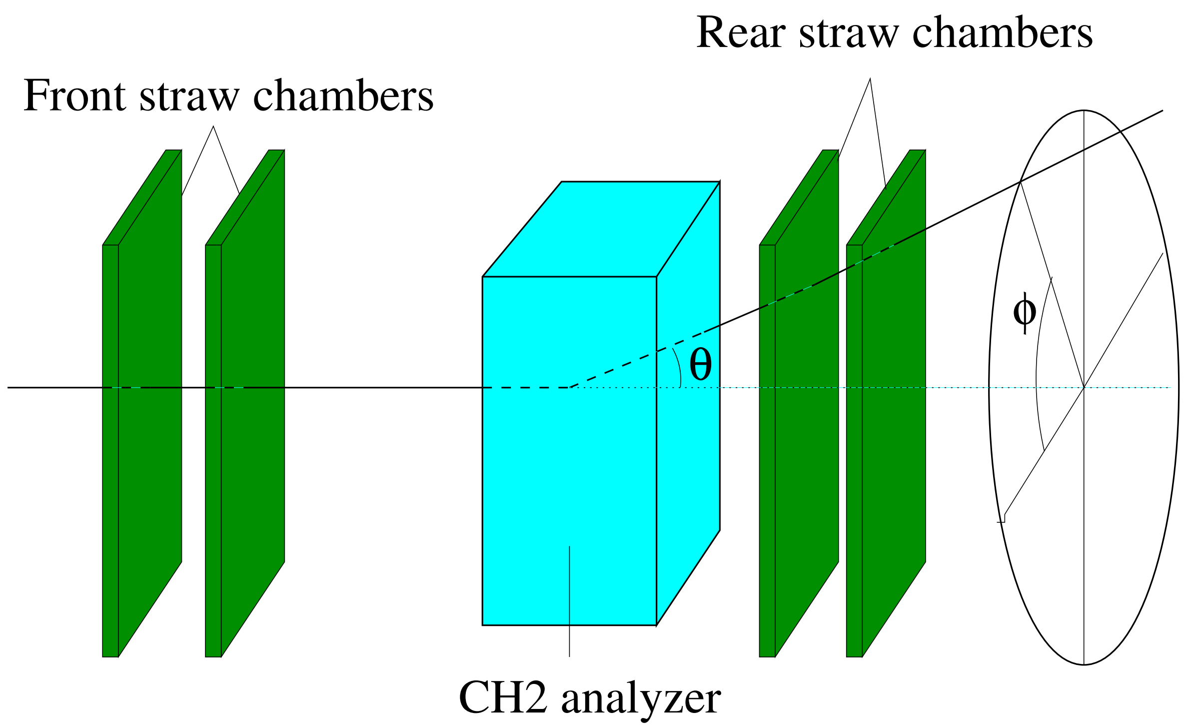
$$P_T^{fp} = P_T^{tgt}$$
$$P_N^{fp} = P_L^{tgt} \sin\chi$$

In general

$$P_T^{fp} = S_{tt} P_T^{tgt} + S_{tl} P_L^{tgt}$$
$$P_N^{fp} = S_{nt} P_T^{tgt} + S_{nl} P_L^{tgt}$$

$S_{tt}, S_{tl}, S_{nt}, S_{nl}$
calculated from model of spectrometer

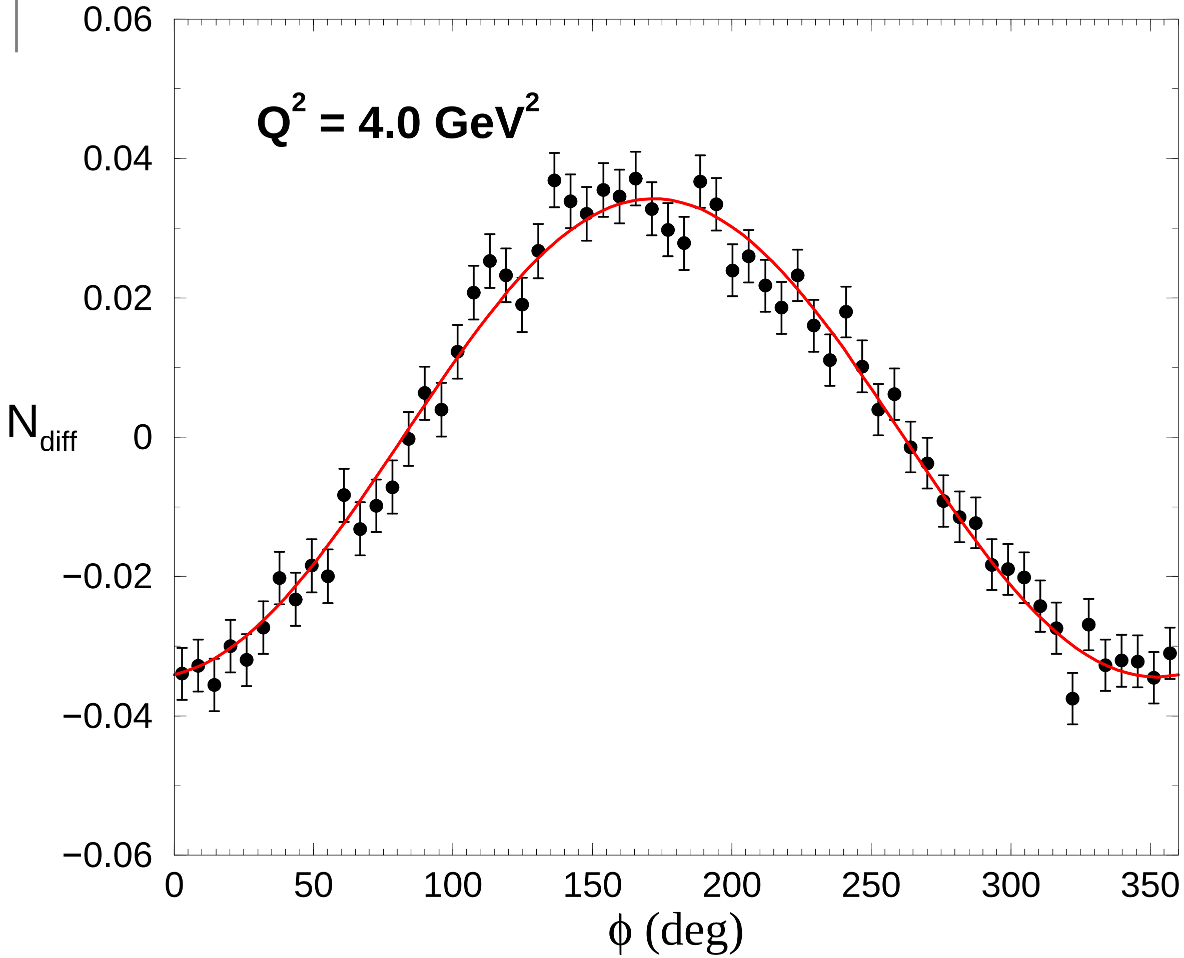
Focal Plane Polarimeter



Measure $N^{\pm}(\theta, \phi)$, ϕ distribution of protons scattered in an analyzer (A_c) for each beam helicity (h)

$$N_D = \frac{1}{2}\Big[\frac{N^+(\theta,\phi)}{N_o^+(\theta)} - \frac{N^-(\theta,\phi)}{N_o^-(\theta)}\Big] = hA_c\Big[P_N^{fp}\cos\phi + P_T^{fp}\sin\phi\Big]$$

FPP ϕ Distributions



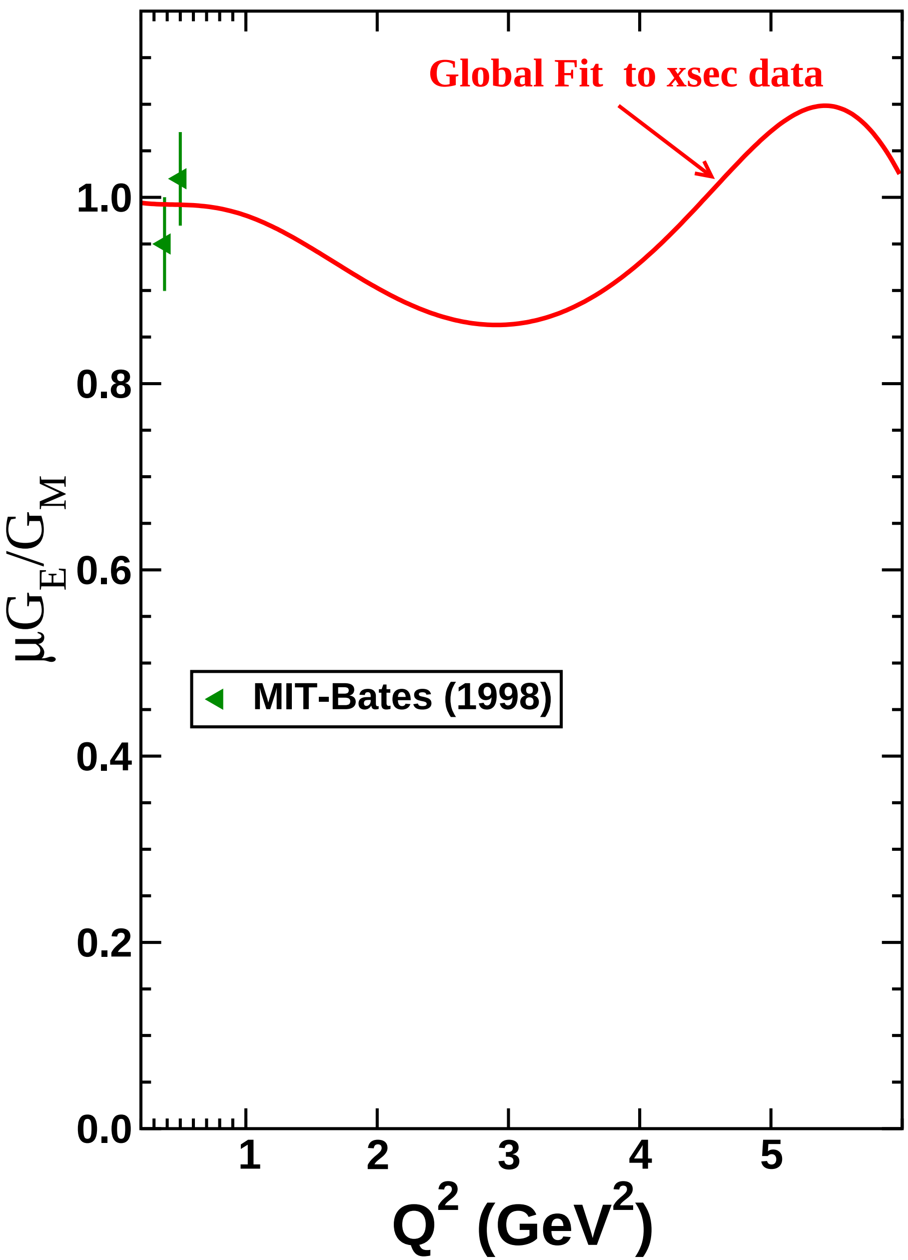
Simple dipole magnet

$$\frac{P_T^{tgt}}{P_L^{tgt}} = \frac{P_T^{fp}}{P_N^{fp}} \sin\chi$$

hA_c cancels !

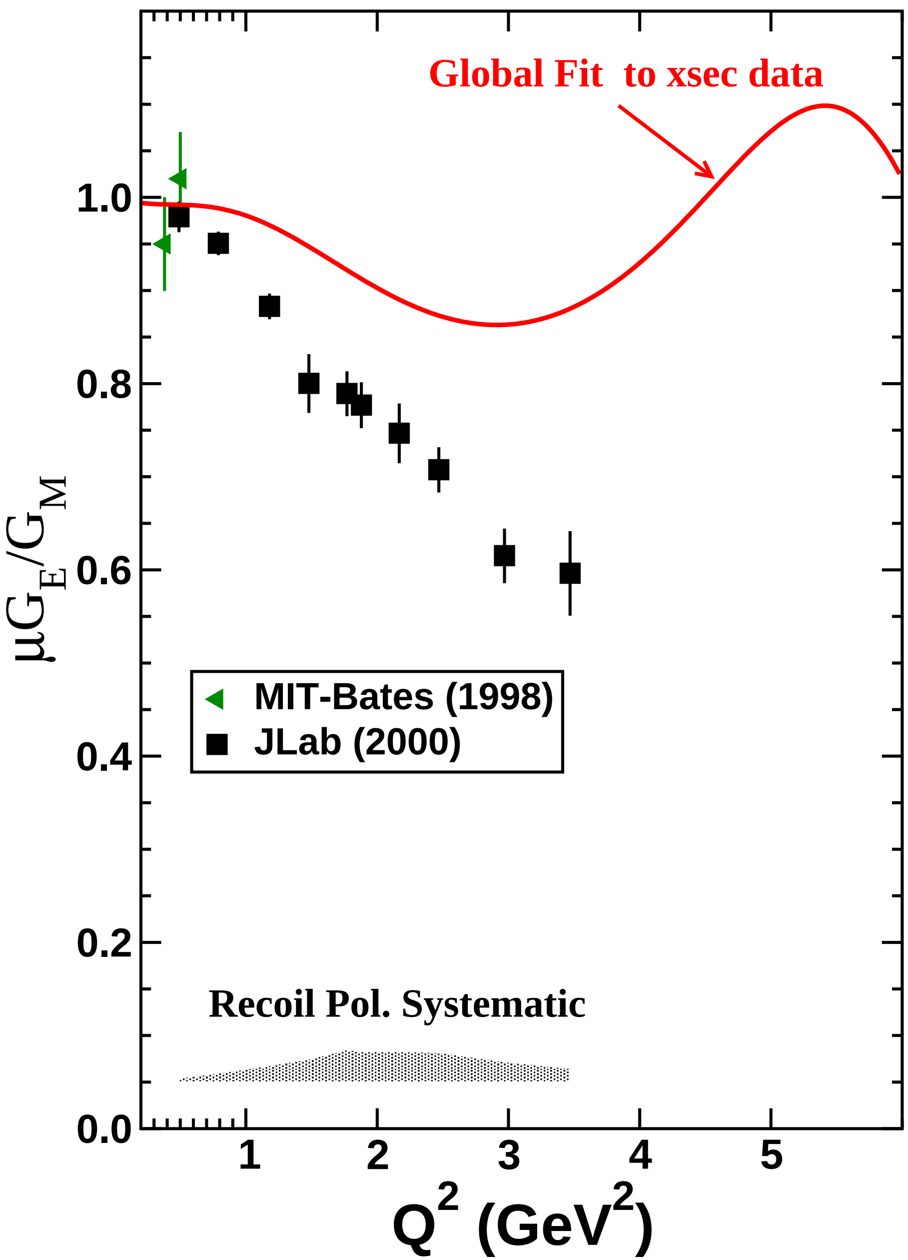
$$N_D = hA_c\left[P_N^{fp}\cos\phi + P_T^{fp}\sin\phi\right]$$

G_E/G_M from recoil polarization



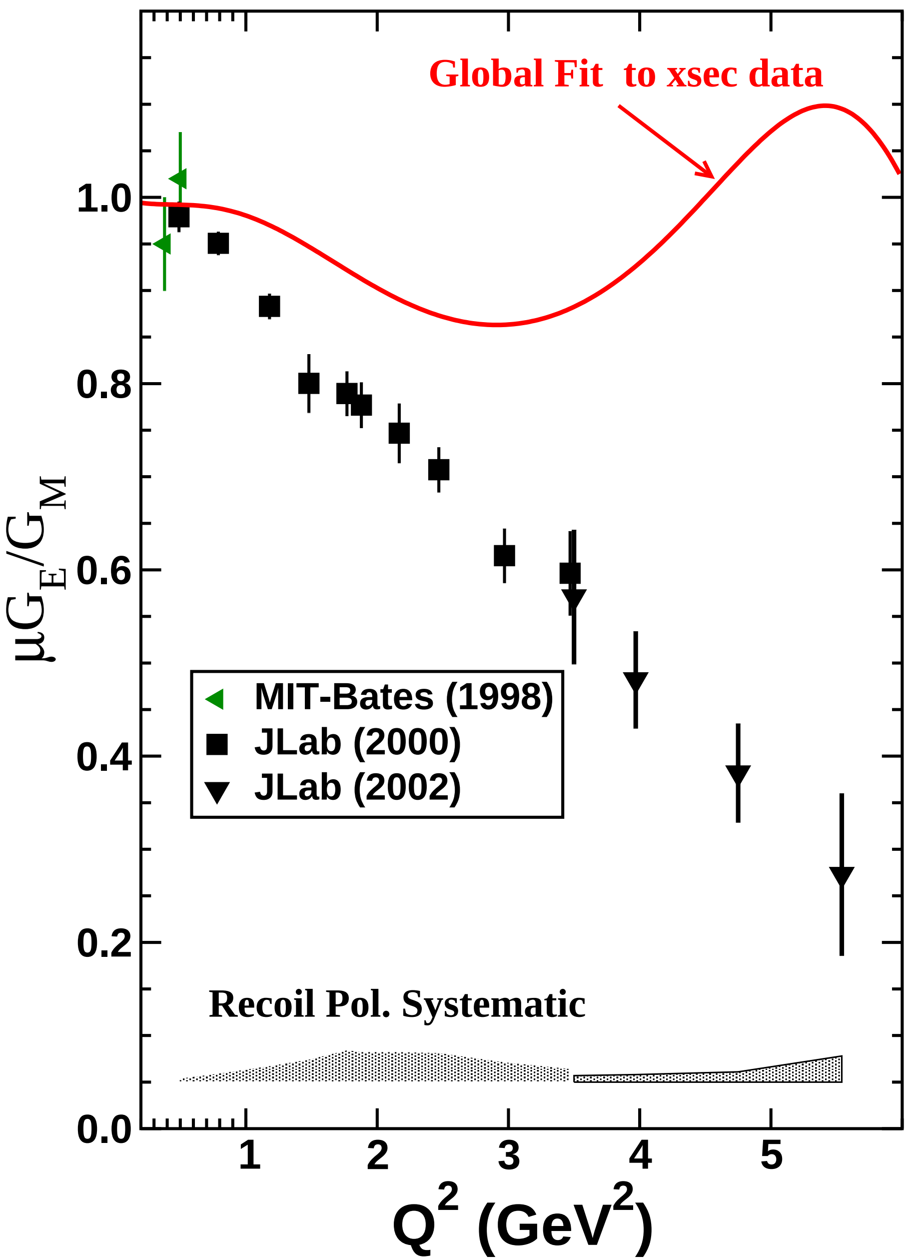
- MIT-Bates experiment

G_E/G_M from recoil polarization



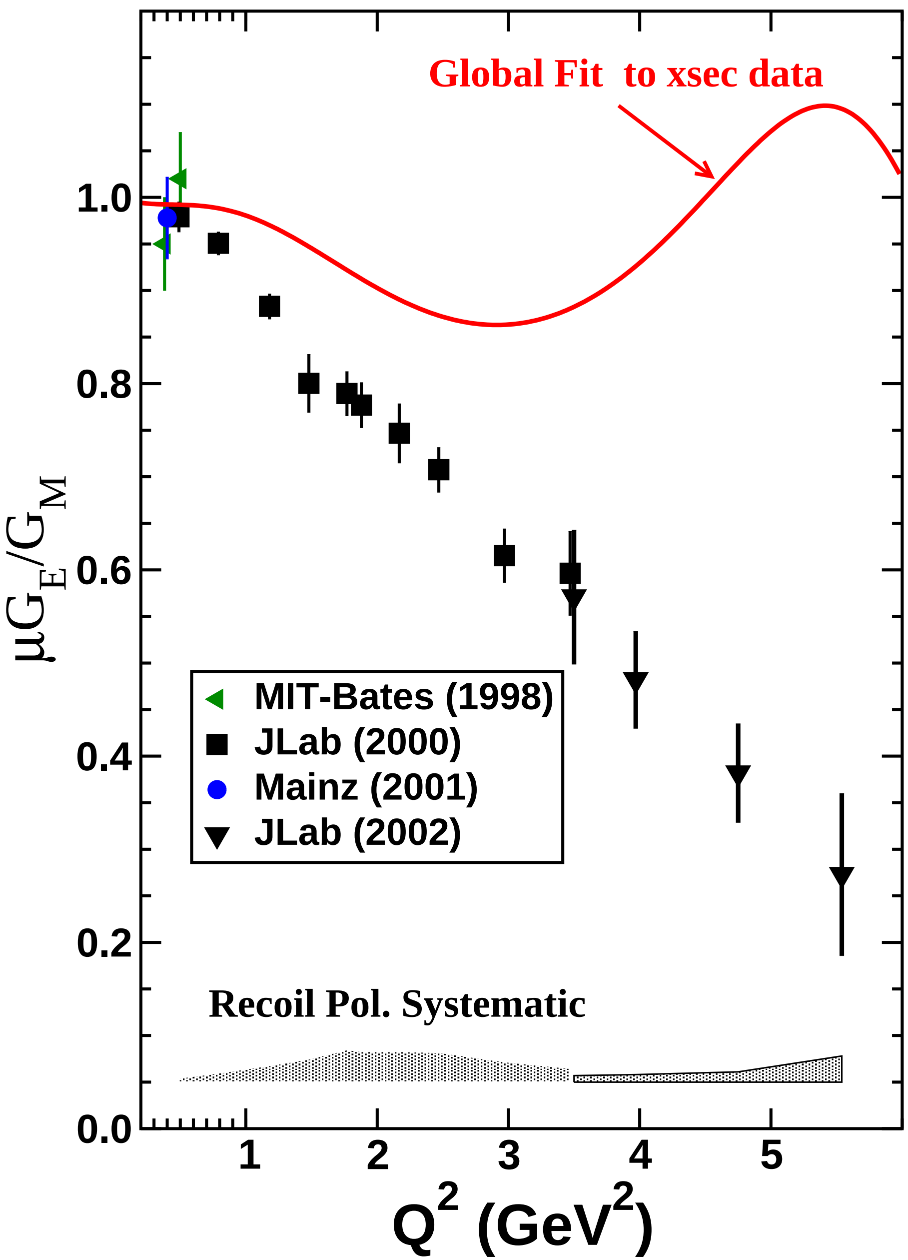
- MIT-Bates experiment
- 1st JLab experiment
  Used two HRS

G_E/G_M from recoil polarization



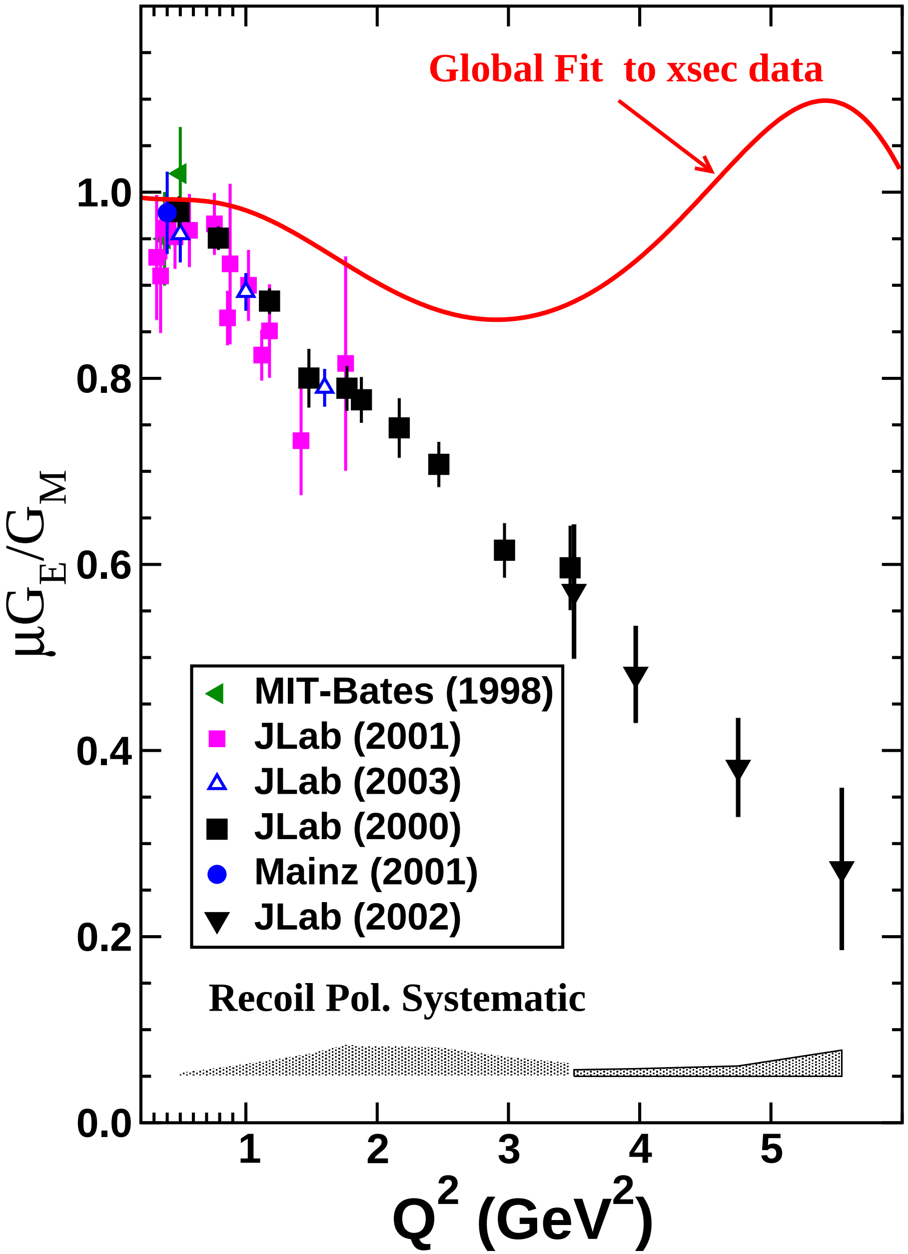
- MIT-Bates experiment
- 1st JLab experiment
  Used two HRS
- 2nd JLab experiment
  Used HRS+Calo

G_E/G_M from recoil polarization



- MIT-Bates experiment
- 1st JLab experiment
  Used two HRS
- 2nd JLab experiment
  Used HRS+Calo
- Mainz experiment

G_E/G_M from recoil polarization



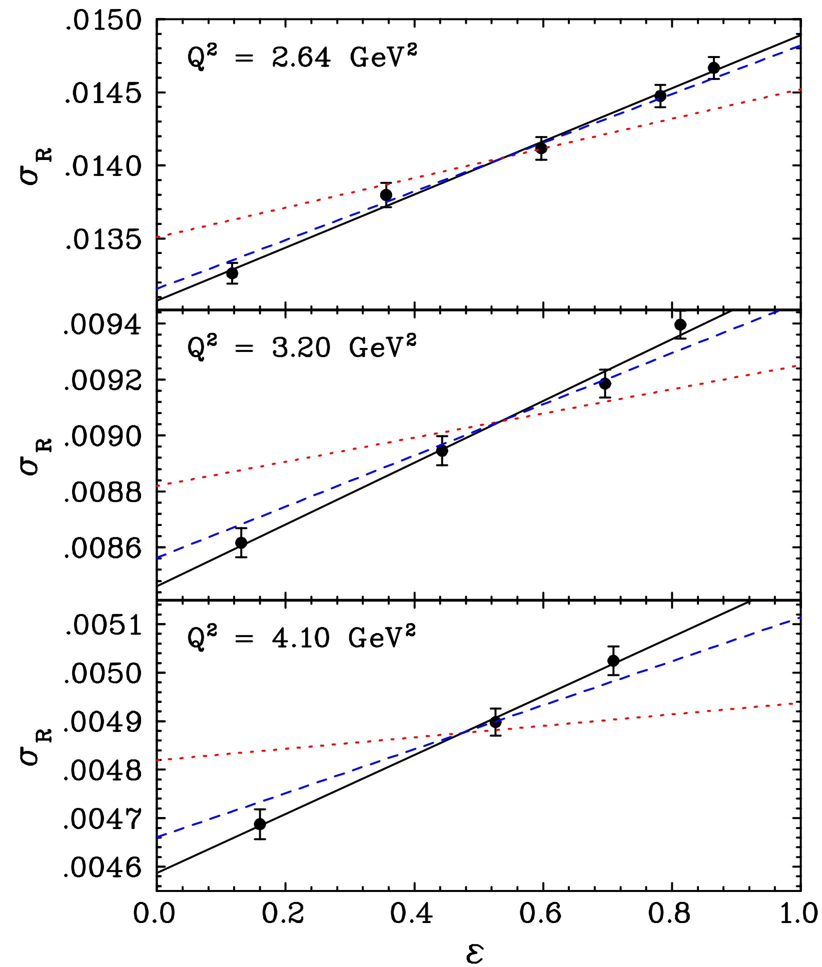
- MIT-Bates experiment
- 1st JLab experiment
  Used two HRS
- 2nd JLab experiment
  Used HRS+Calo
- Mainz experiment
- Secondary part of other JLab experiments.

JLab Hall A Rosenbluth experiment

- At JLab in Hall A did Rosenbluth separation
  ➡ Single arm proton detection
- Advantages:
  - Proton momentum fixed at each ϵ
  - Rate 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)

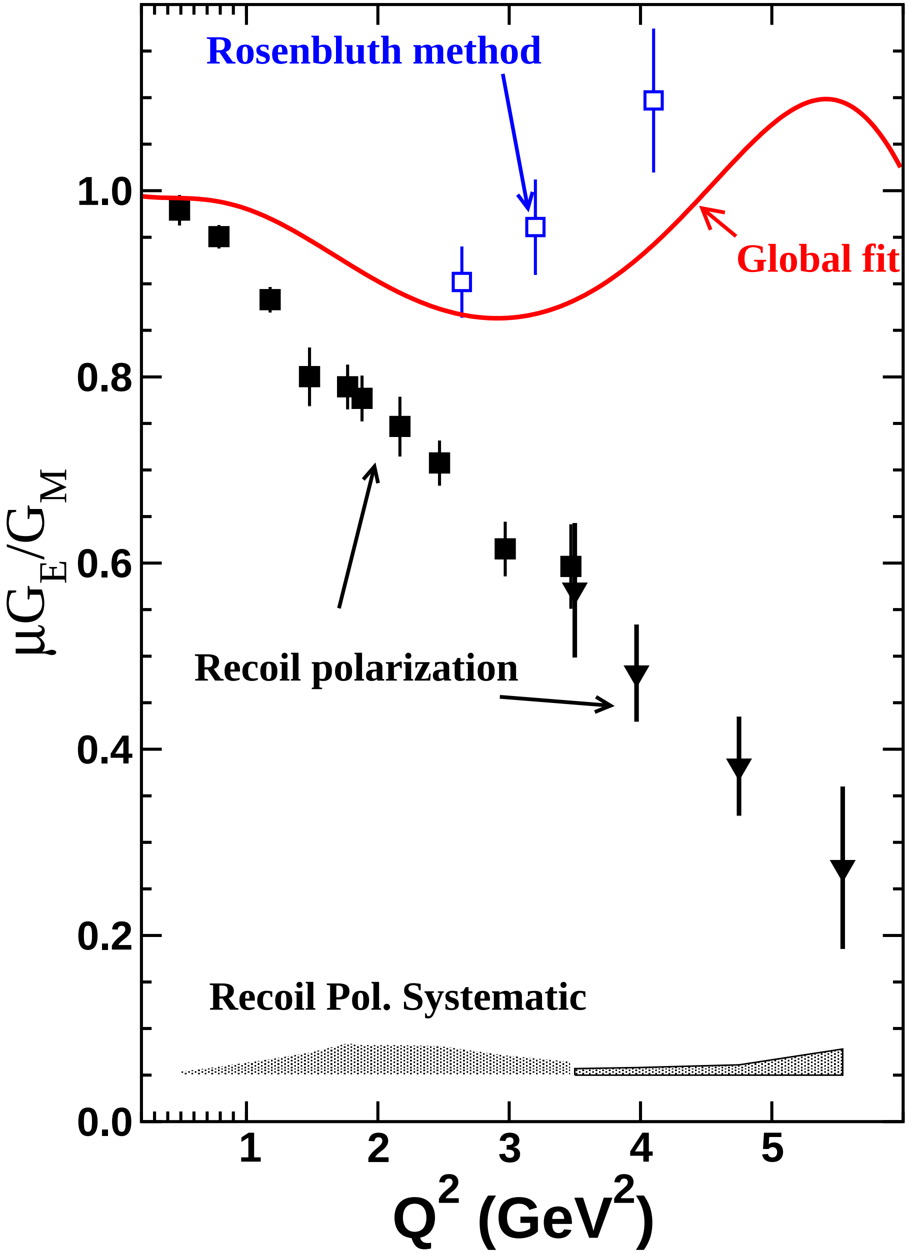
JLab Hall A Rosenbluth plots

- Plot σ_r versus ϵ
  - Solid black line is fit to data
  - Dashed blue line is from a fit to previous cross section data.
  - Dotted red line is using G_E/G_M from recoil polarization
- Systematic error on slope is 0.55%



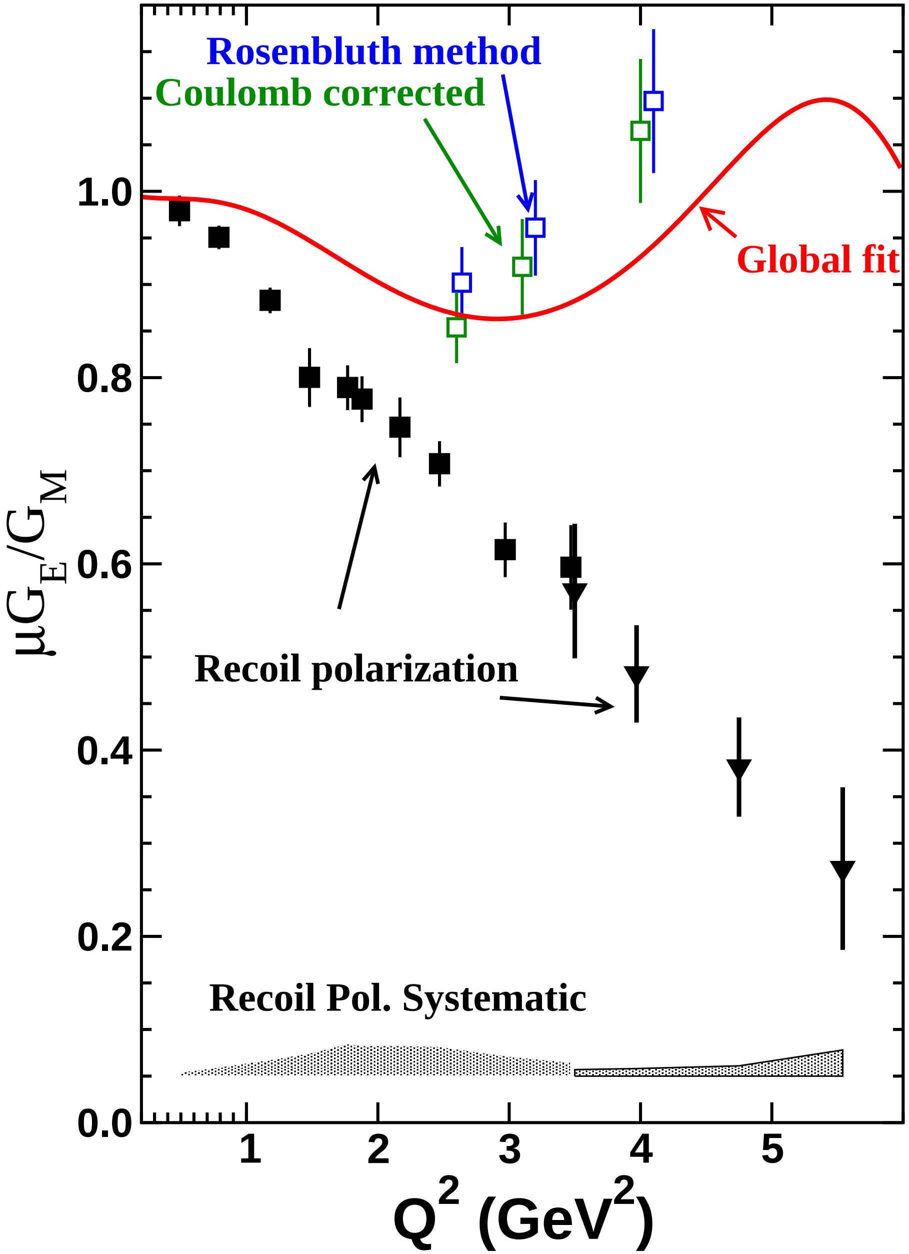
Slope $\propto G_E$ Intercept $\propto G_M$

Comparison of G_E/G_M



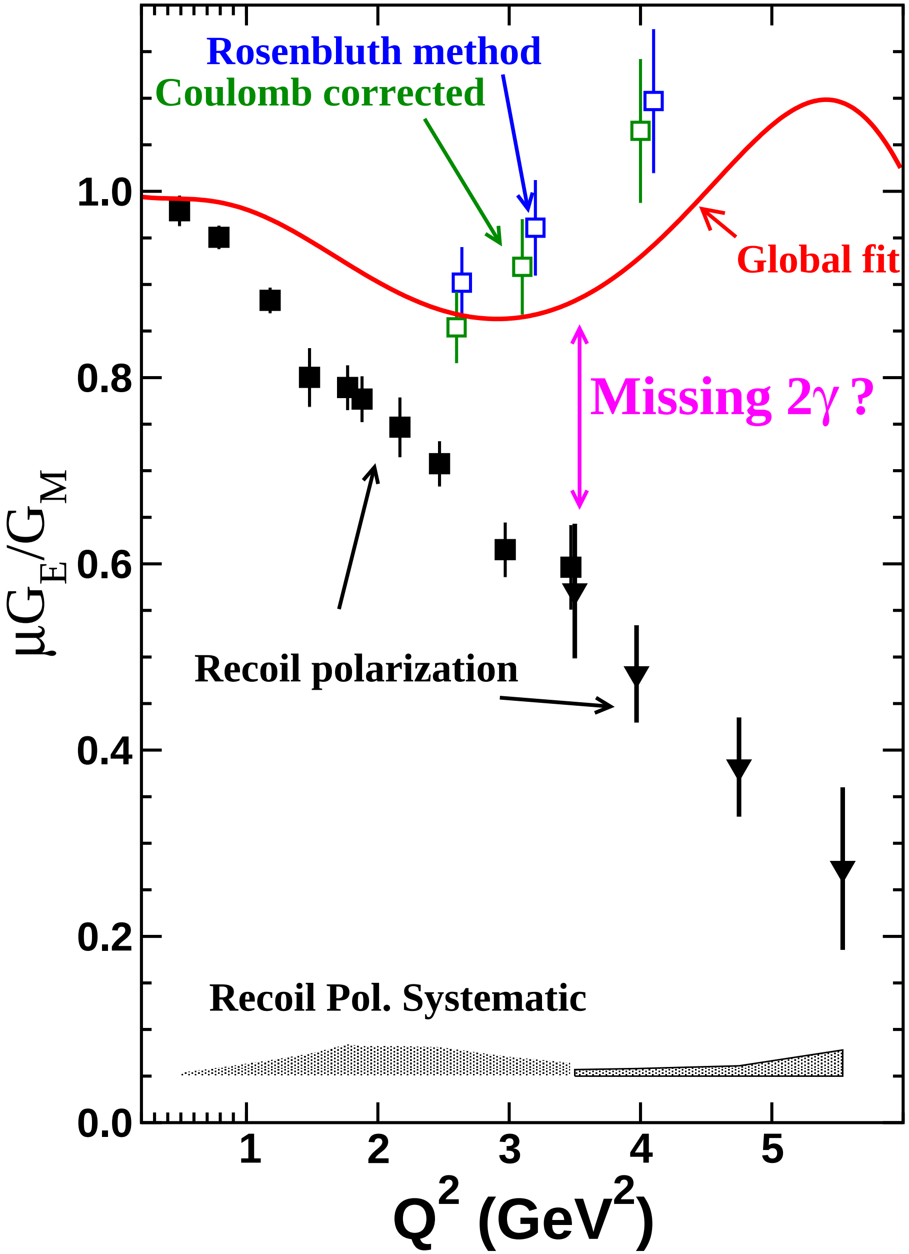
- Hall A Rosenbluth G_E/G_M agrees with previous cross section measurements
- Discrepancy between G_E/G_M from recoil polarization and from cross section measurement persistent

Comparison of G_E/G_M



- Coulomb correction (soft multi-γ) is small correction to xsec data

Comparison of G_E/G_M



- Coulomb correction (soft multi-γ) is small correction to xsec data
- Missing physics from 2γ exchange?

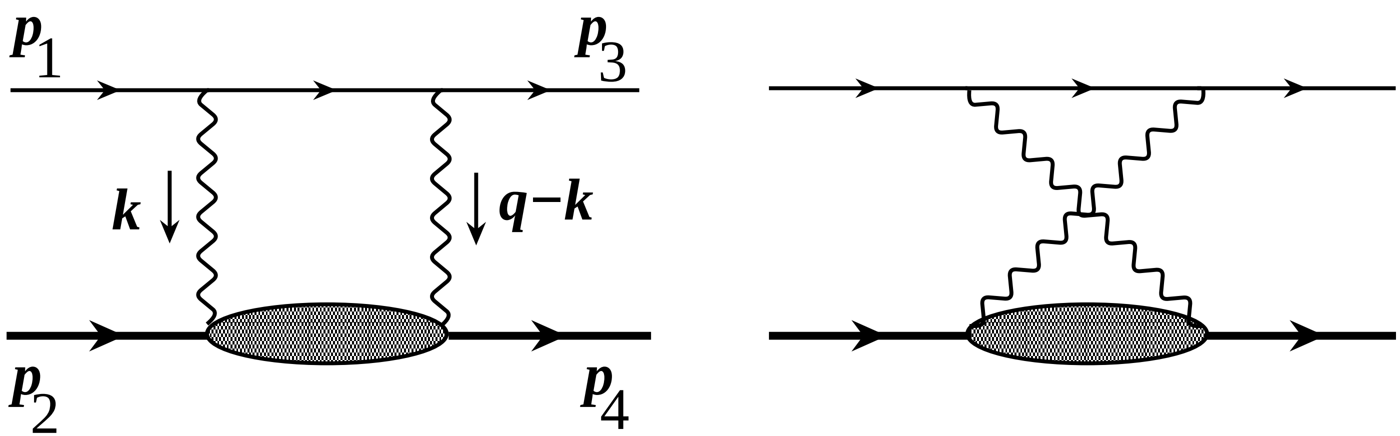
$$\sigma_r \propto \frac{\epsilon}{\tau} G_E^2 + G_M^2 + \epsilon \sigma_{2\gamma}(\epsilon, Q^2)$$

Explain discrepancy with

$$\sigma_{2\gamma}(\epsilon, Q^2) \sim 6\%$$

with small ϵ, Q^2 dependence

2γ exchange contribution



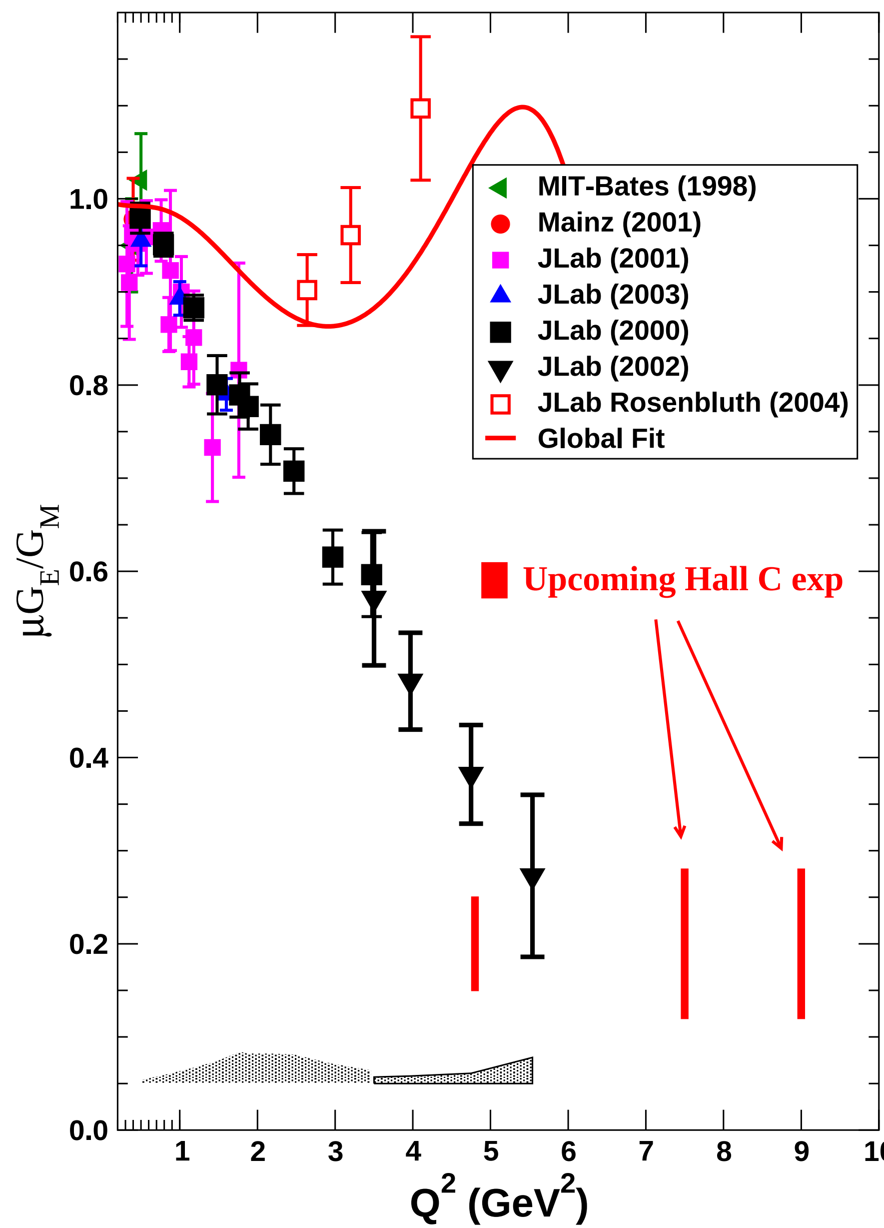
- Nucleon elastic intermediate state *P.G. Blunden, W. Melnitchouk, J.A. Tjon*
- GPD calculation *A. V. Afanasev, S. J. Brodsky, C. E. Carlson, Y. Chen, M. Vanderhaeghen*
- Various proposals to measure 2γ exchange contribution
  - ϵ dependence of $\sigma_{e^+p}/\sigma_{e^-p}$
  - Precision ϵ dependence of σ_{e^-}
  - ϵ dependence of P_T/P_L.
- Talks in the afternoon 2γ session

Future G_E/G_M at JLab in Hall C

- At JLab to reach higher Q^2 need to detect protons in the Hall C HMS
- As in Hall A, to maximize rate need to use large calorimeter to detect electron
- At Dubna measured $A = 0.05$ for CH_2 at proton momentum 5.3 GeV/c and test various thickness of CH_2
- From these tests decided on using a double polarimeter in Hall C.

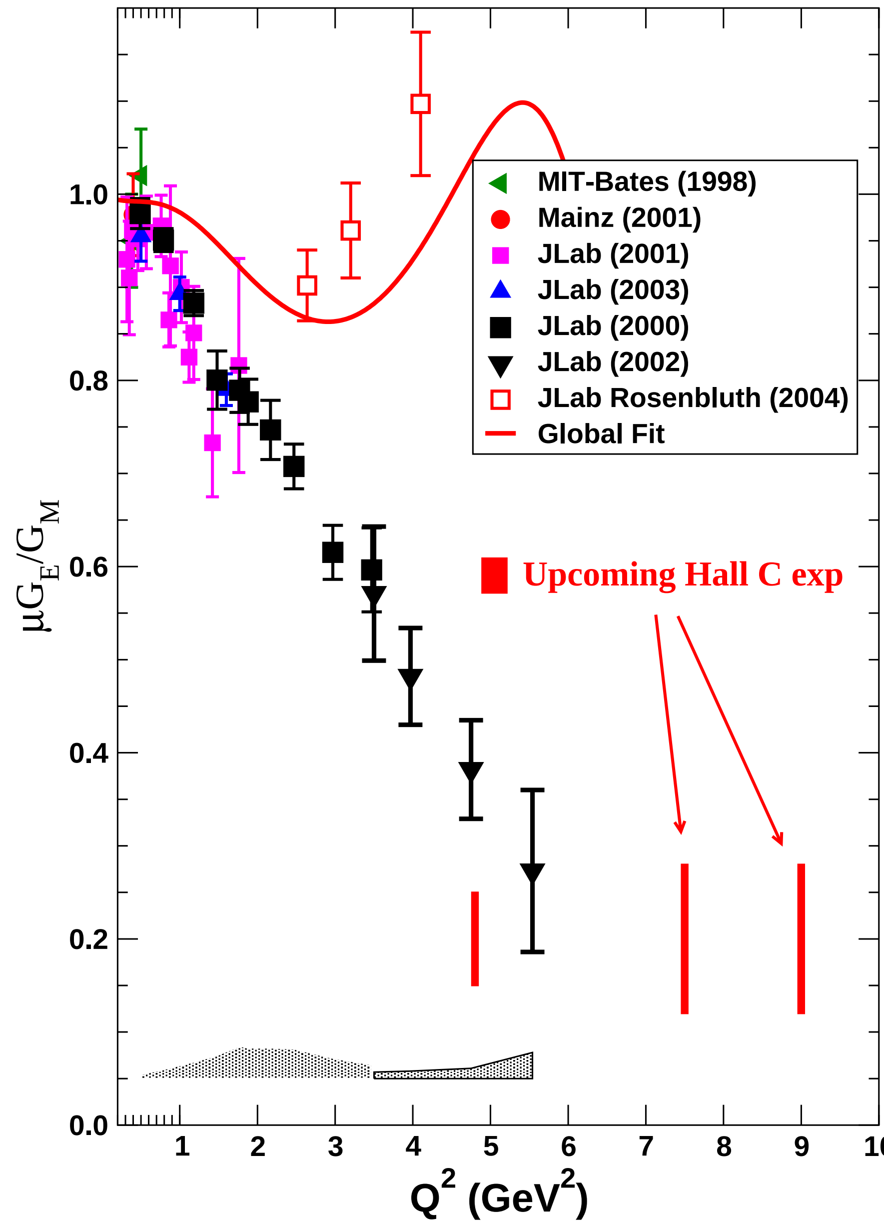
Future G_E/G_M at JLab in Hall C

- FPP has been built at Dubna and will be installed in the HMS
- A large calorimeter has been assembled with help of IHEP and Yerevan.
- Scheduled to run in 2007.



Future G_E/G_M at JLab in Hall C

- FPP has been built at Dubna and will be installed in the HMS
- A large calorimeter has been assembled with help of IHEP and Yerevan.
- Scheduled to run in 2007.
- With the 12 GeV upgrade at JLab can reach $Q^2 = 14$

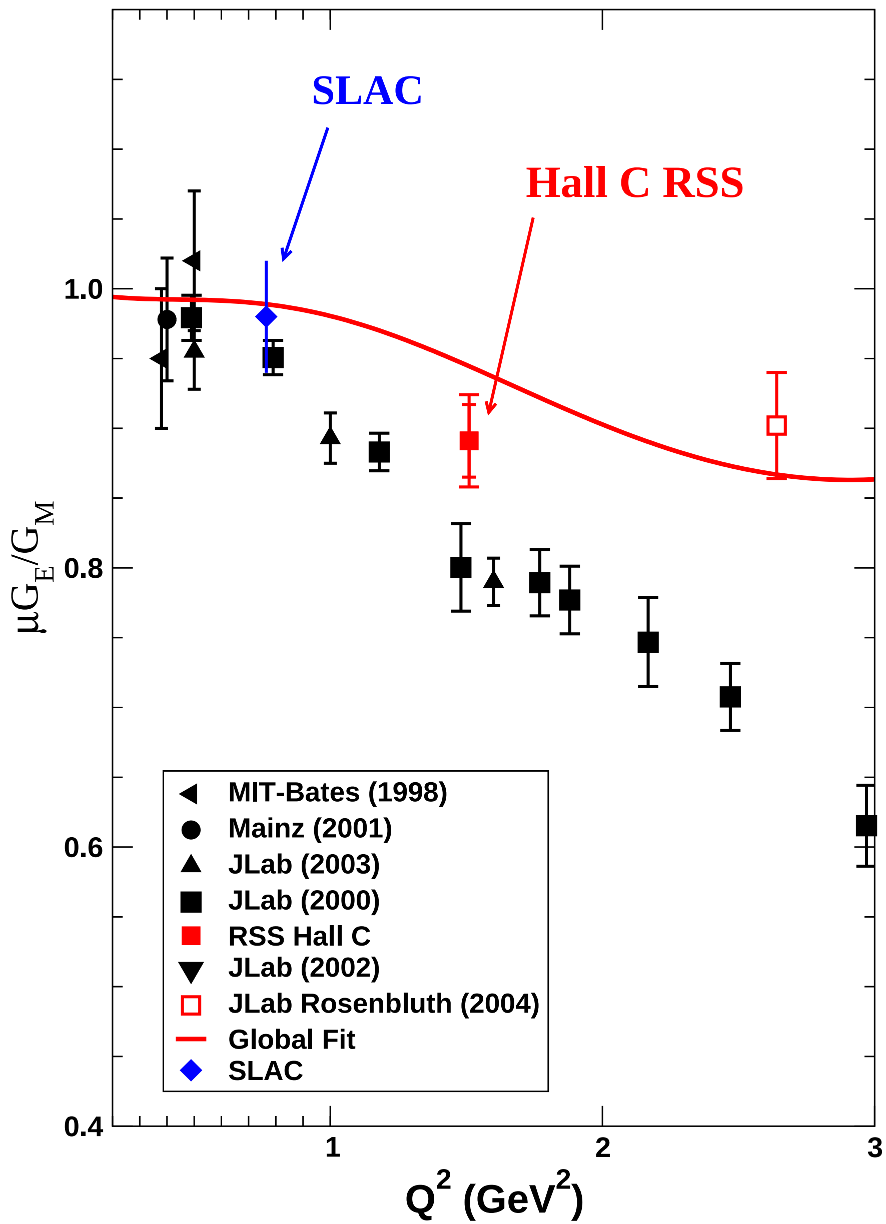


Summary

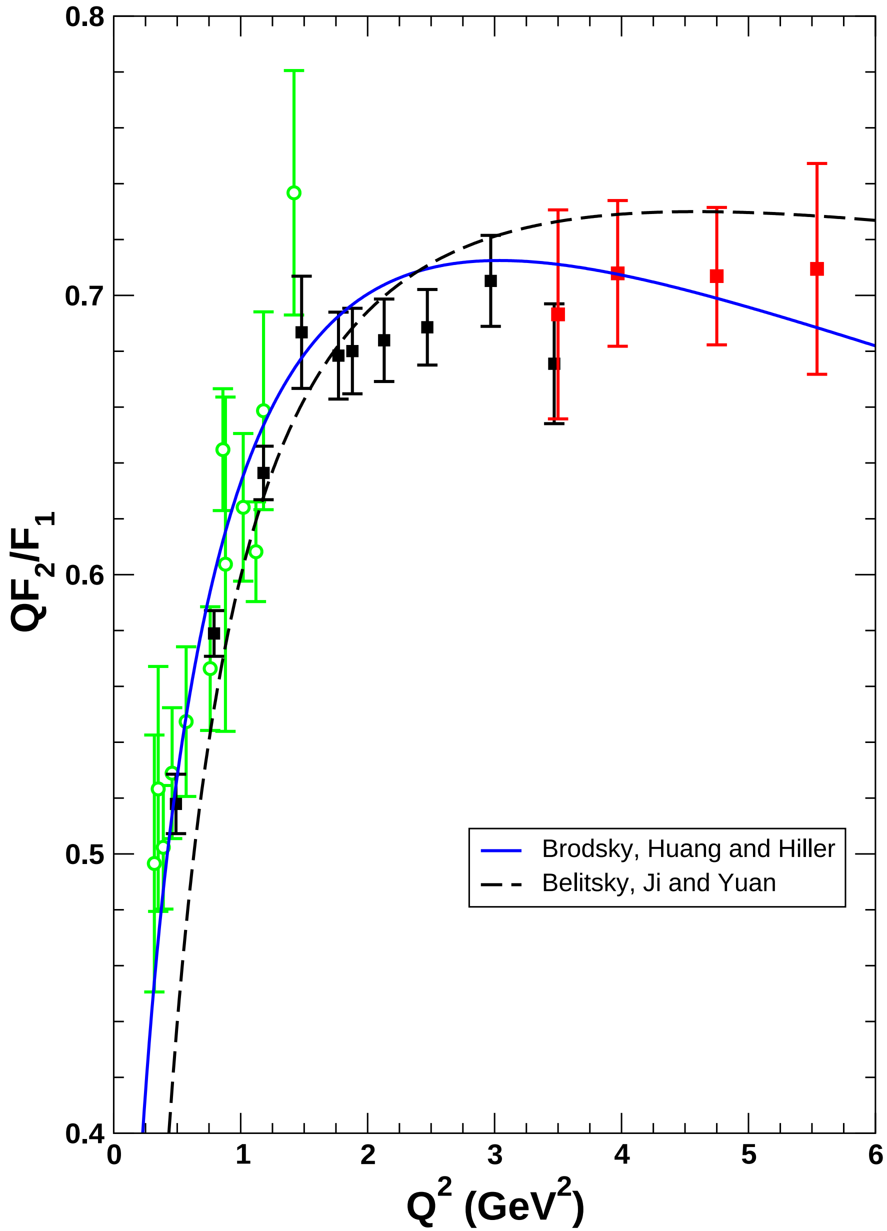
- Proton G_E/G_M has been measured to Q^2 = 5.6
  ➡ In Hall C at JLab 2007
  Measure G_E/G_M at Q^2 = 7.5 and 9 GeV^2
- Precision data on G_E/G_M from recoil polarization and cross section measurements disagree
  ➡ Need to include 2γ contributions when extracting G_E/G_M from cross section measurements.
  ➡ Need other experiments to study 2γ
- Combined with precision data on the neutron has stimulated study of nucleon structure
  - Relativistic effects
  - Angular momentum
  - Constituent quark models

Backup slides

Polarized target experiments



F_2/F_1 and pQCD



- F$_1 \sim 1/Q^4$, F$_2$ is helicity-flip amplitude and expected to have extra $1/Q^2$ dependence.
- Brodsky, Hiller and Hwang propose a pQCD-motivated fi t with form: $\frac{F_2(Q^2)}{F_1(Q^2)} \sim \frac{\kappa_p}{1+(Q^2/c)\ln^b(1+Q^2/a)}$ with a, b, c fi t to the data. The extra logarithmic factor is motivated by expected higher twist.
- Belitsky,Ji and Yuan is a pQCD calc which has quark angular momentum and gluon polarization as the dominant mechanism for helicity-flip.

$$\frac{F_2(Q^2)}{F_1(Q^2)} \sim \frac{\ln(Q^2/\Lambda^2)}{Q^2}$$

Λ is the soft scale related to the nucleon's size.

Systematic error

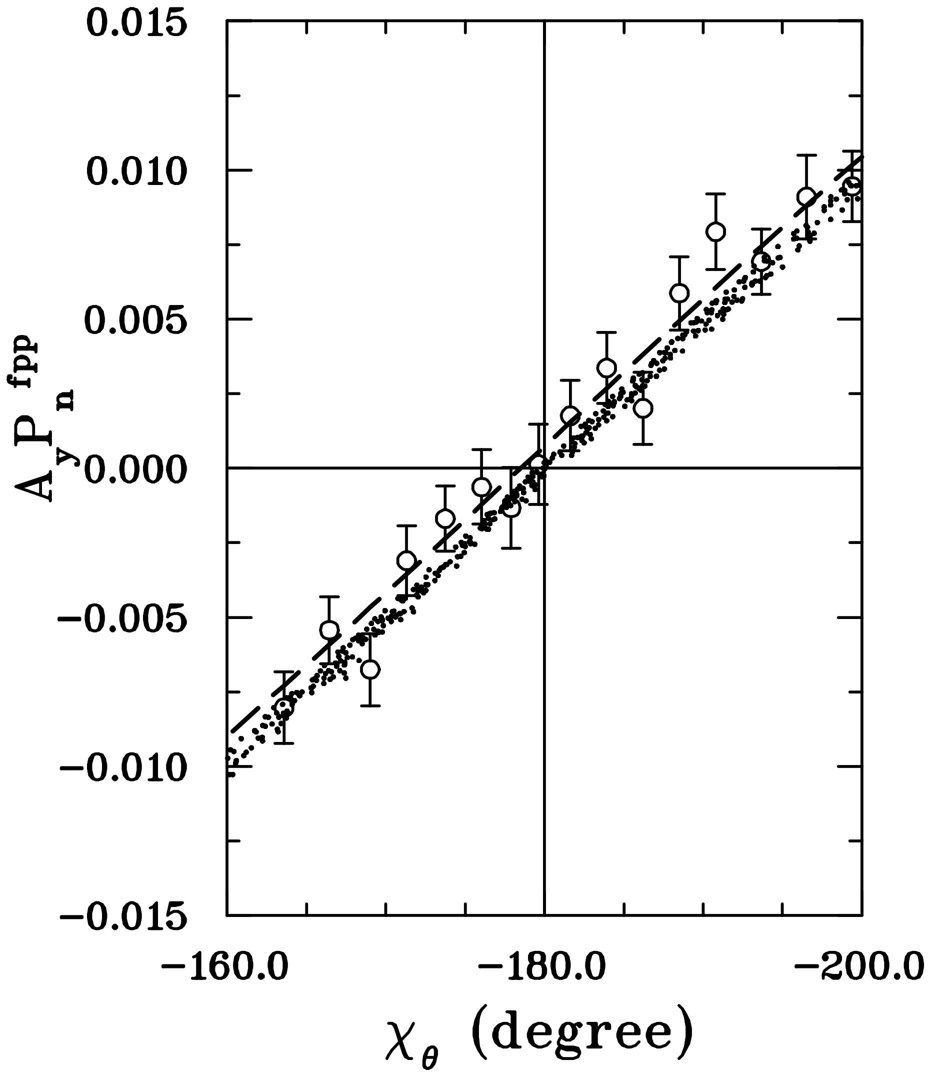
TABLE VII: Dominant contributions to the systematic uncertainty of $\mu_p G_{Ep}/G_{Mp}$, which results from the variations in the quantities listed in the table. The total systematic uncertainties Δ_{sys} given in Table VI are obtained from the values below in quadrature.

Q^2 GeV^2	$\theta - \theta^{fp}$ 7 mrad	$\phi - \phi^{fp}$ 0.3 mrad	$\phi^d, \Delta\phi^d$ from Table VIII	ϕ^{fpp} 2 mrad	Δ_{sys}
0.49	-0.004	0.001	0.001	-0.004	0.006
0.79	-0.009	0.001	0.003	-0.004	0.010
1.18	-0.017	0.002	0.004	-0.003	0.018
1.48	-0.025	0.002	0.004	-0.005	0.026
1.77	-0.034	0.002	0.006	-0.002	0.035
1.88	-0.032	0.002	0.006	-0.005	0.033
2.13	-0.032	0.003	0.009	-0.006	0.034
2.47	0.030	0.003	0.010	-0.009	0.033
2.97	0.018	0.004	0.009	0.003	0.021
3.47	0.009	0.005	0.010	-0.001	0.014

- $\theta - \theta^{fp}$ is bend angle in dispersive plane
- $\phi - \phi^{fp}$ is bend angle in nondispersive plane
- ϕ^d is mean angle in dipole
- $\Delta\phi^d$ is half of the bending angle in nondispersive plane
- ϕ^{fpp} is the azimuthal angle of the scattering proton in the analyzer

Used geometrical model of HRS to estimate error in magnetic model

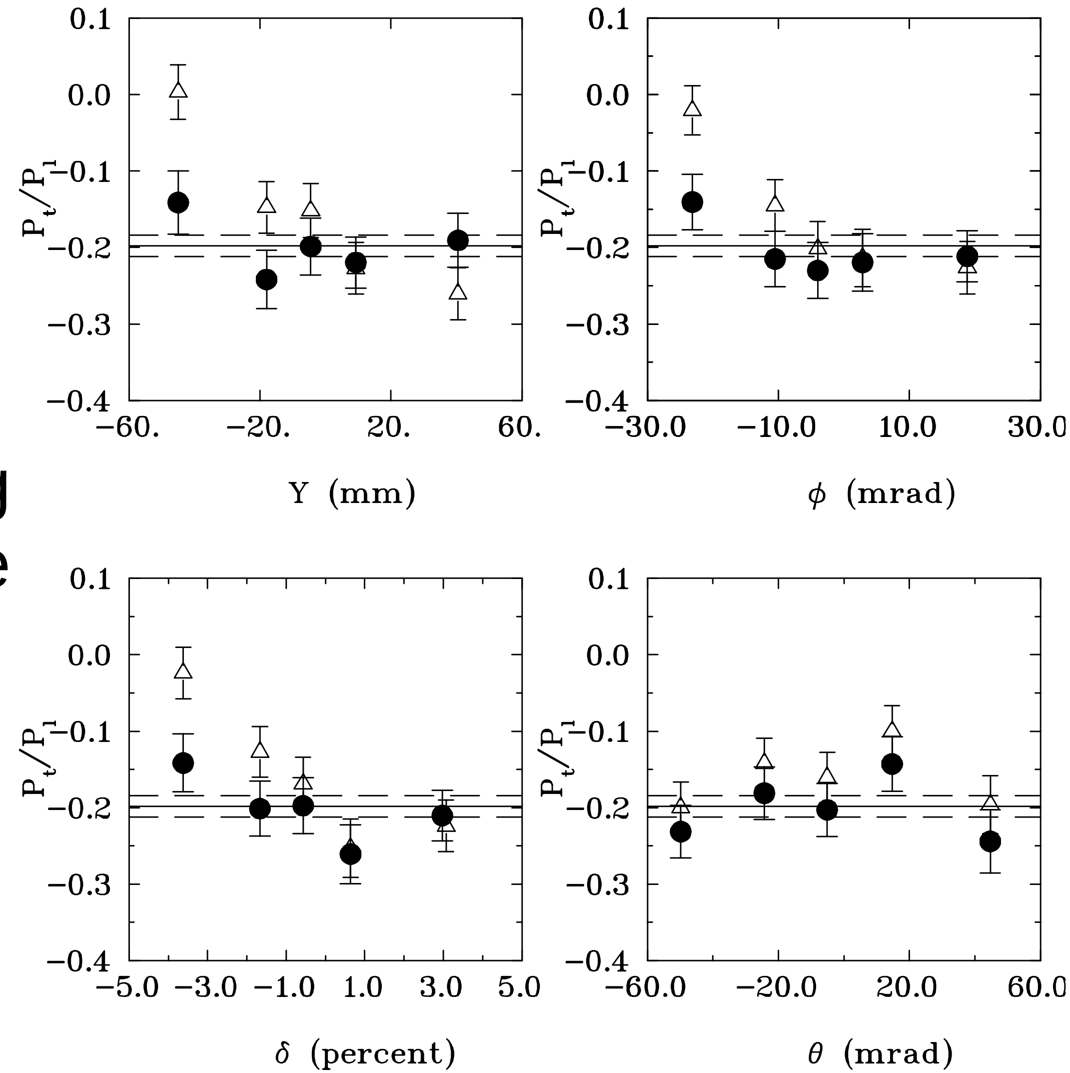
Focal plane P_N at $Q^2 = 2.2$



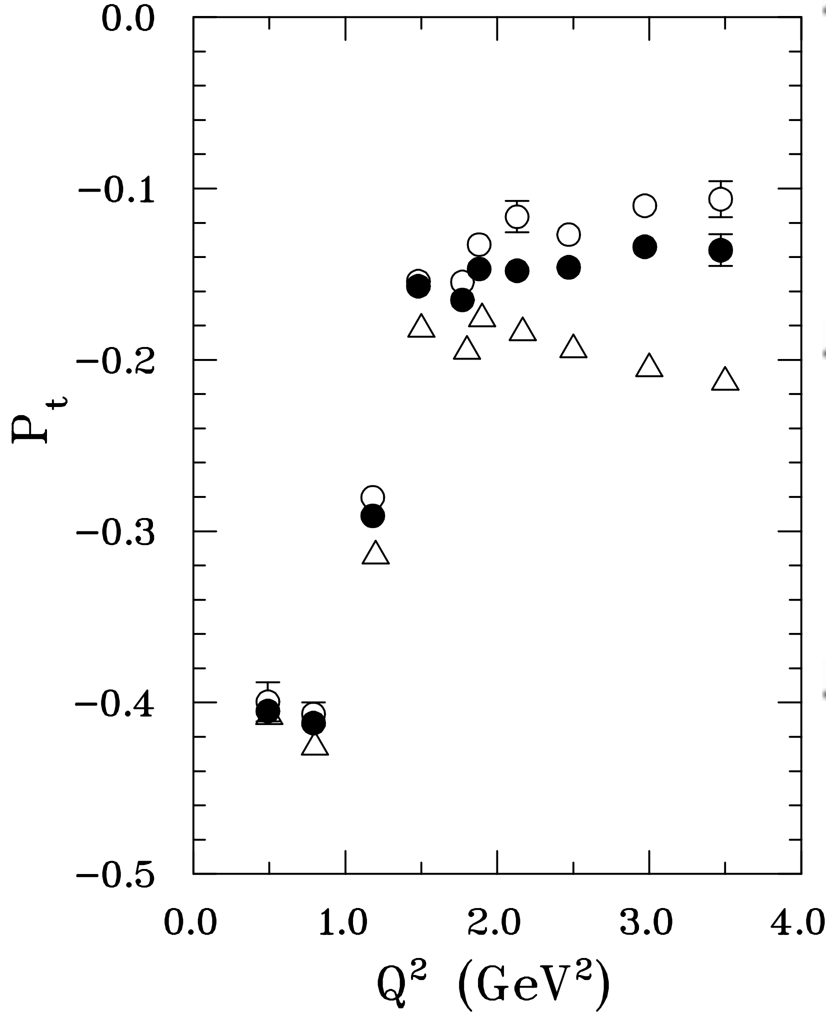
For Q^2 = 2.2 expect P_N^{fp} to be zero at $\chi = 180^\circ$

P_T/P_L versus target quantities

- Solid circle:
  Final P_T/P_L from full COSY model of HRS
- Open circle:
  P_T/P_L assuming the HRS is a simple dipole



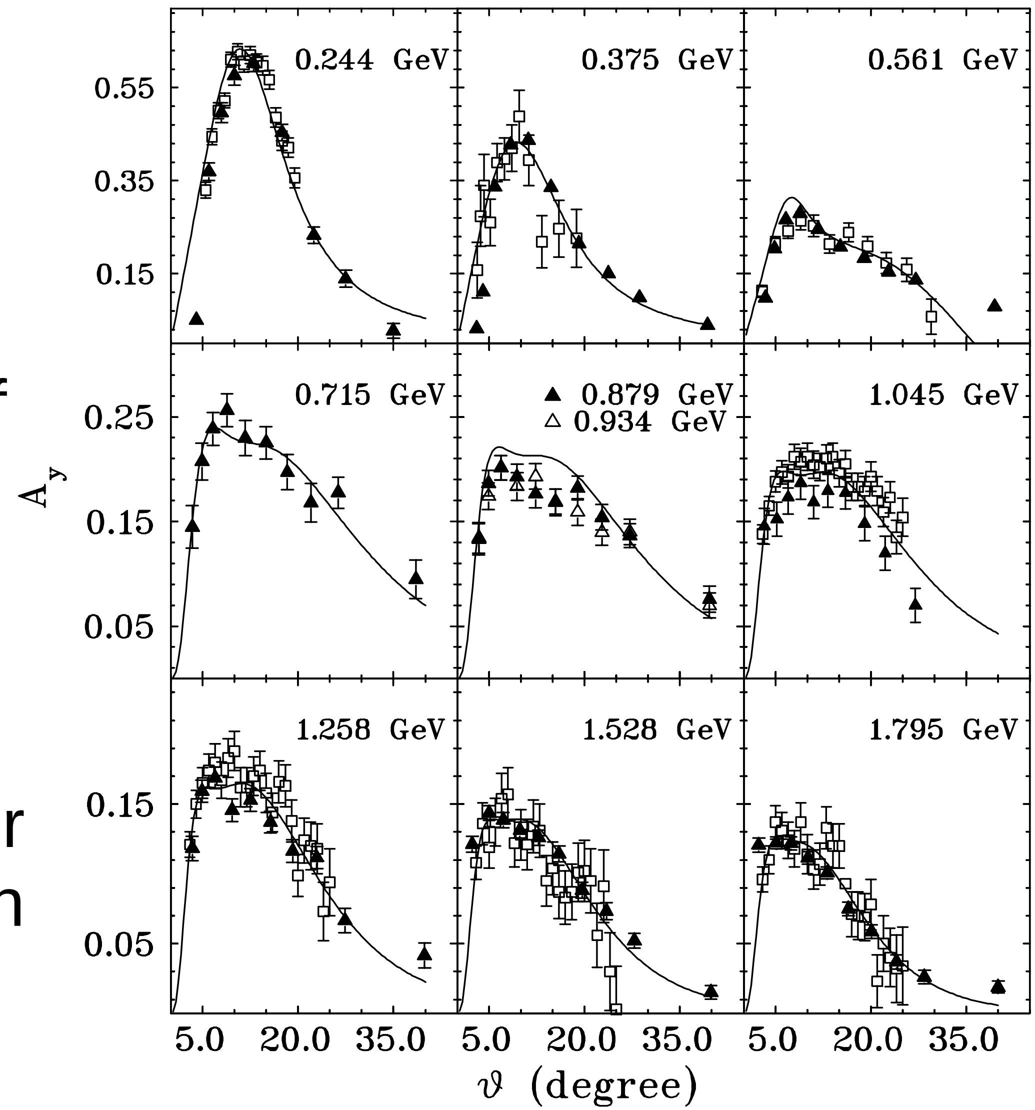
Transverse polarization



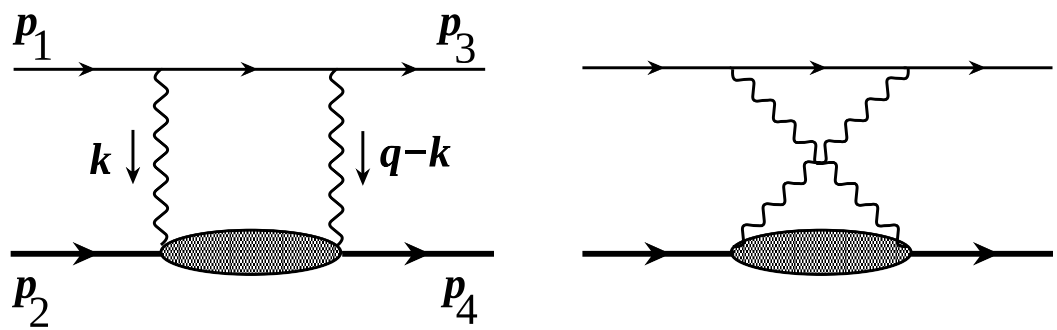
- Open triangles: P_T calculated assuming $\mu G_E/G_M = 1$.
- Open circles: P_T extracted from data assuming that magnet is a simple dipole.
- Solid circles: Final result from P_T extracted from data

Analyzing power

- Solid Triangles: Data from Hall A experiment
- Solid Lines: Parametrizations of analyzing power data from hadron experiments.
- Open squares: Analyzing power data from hadron experiments.



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

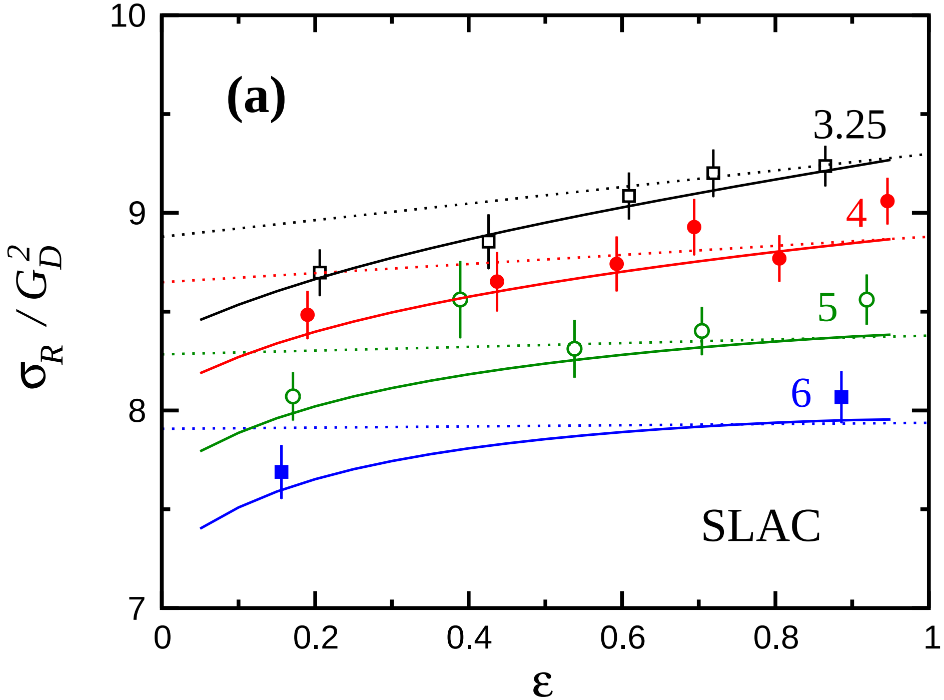
$$\sigma_R \sim \frac{\tilde{G}_M^2}{\tau}\{\tau + \epsilon \frac{\tilde{G}_E^2}{\tilde{G}_M^2} + 2\epsilon(\tau + \frac{\tilde{G}_E}{\tilde{G}_M})\mathcal{R}(\frac{\nu \tilde{F}_3}{M^2 \tilde{G}_M})\}$$

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

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

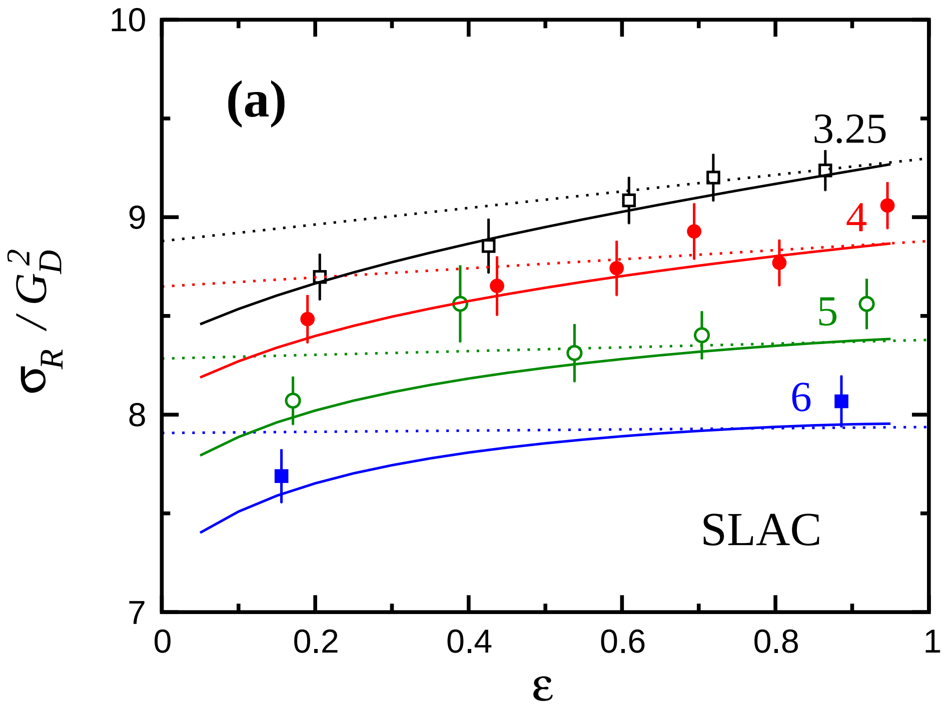
Nucleon elastic
intermediate state



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

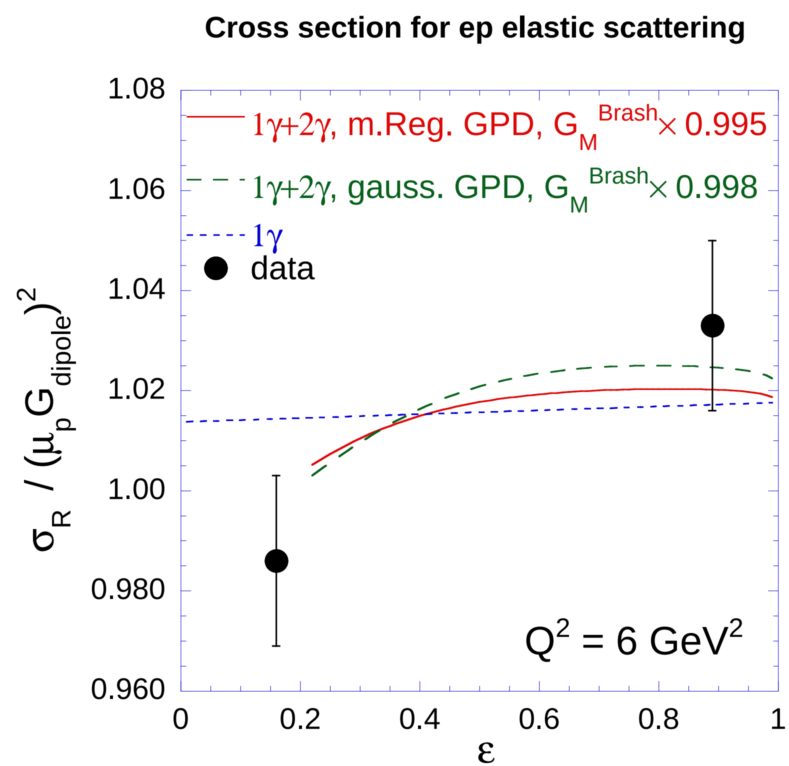
Calculation 2γ exchange contribution

Nucleon elastic intermediate state



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

GPD calculation



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