Overview of nucleon form factor measurements

Focus on neutron
form factor measurements

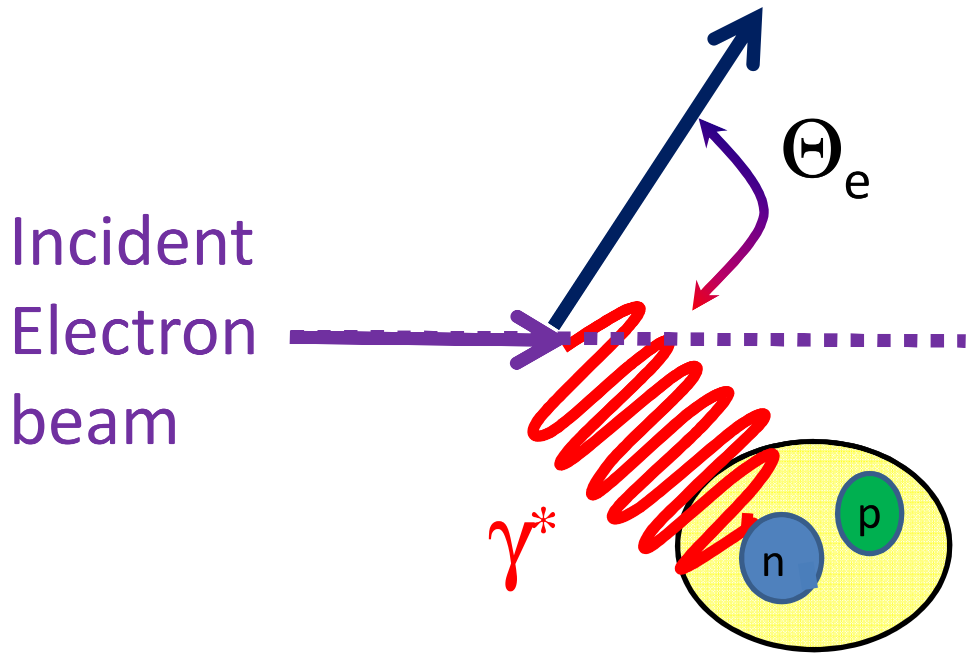
Mark Jones

Jefferson Lab

HUGS 2009

Where to get a free neutron target?

Use the deuteron as neutron target



Measure $ed \to eX$ cross section

Detect only electron at E'_e and θ_e

when $W = M$ or $Q^2 = 2M\nu$, Quasi-elastic kinematics

d(e,e') inclusive cross section

$$\sigma_r = \epsilon(1 + \frac{\nu^2}{Q^2})\frac{\sigma}{\sigma_{Mott}} = R_T + \epsilon R_L$$

$$\epsilon = \left[1 + 2(1 + \frac{\nu^2}{Q^2})\tan^2\frac{\theta}{2}\right]^{-1}$$

R_T and R_L are the transverse and longitudinal response functions

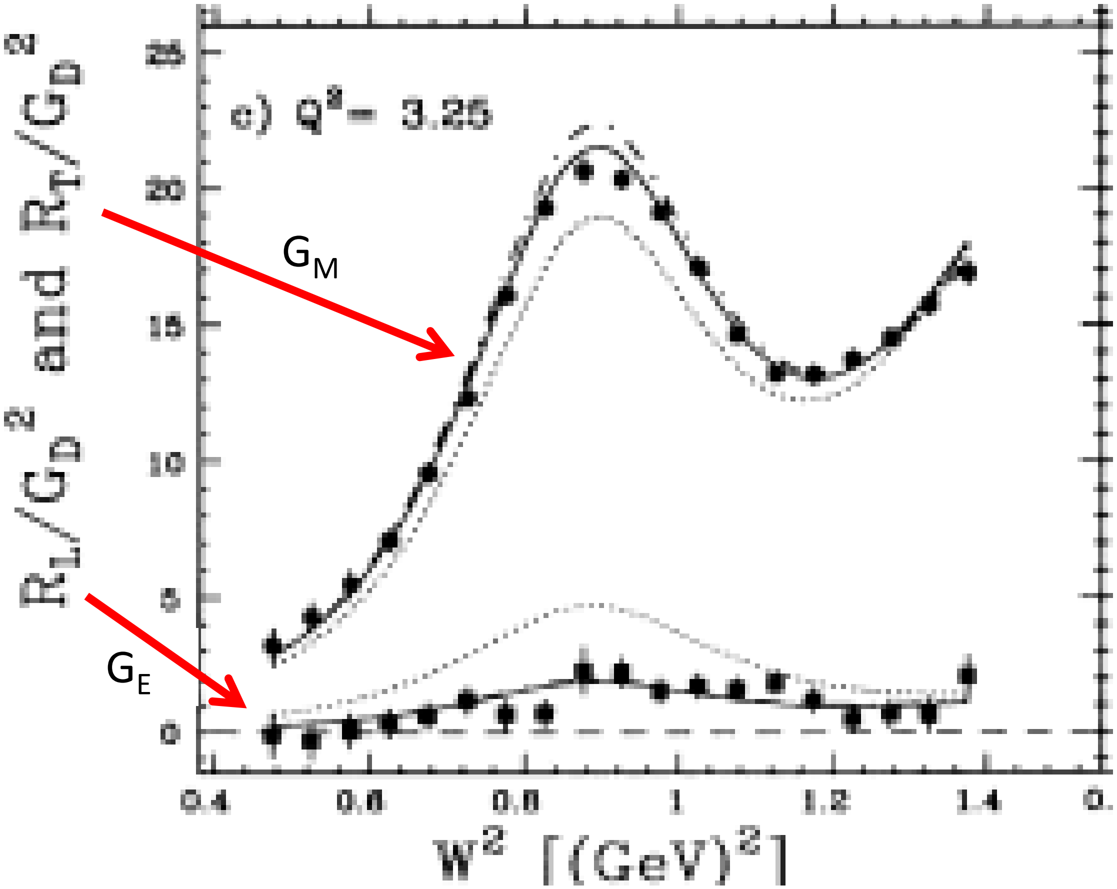
Assume Plane Wave Impulse Approximation

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

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

Extracting G_{Mn}

- Measure cross sections at several energies
- Separate R_T and R_L as function of W^2



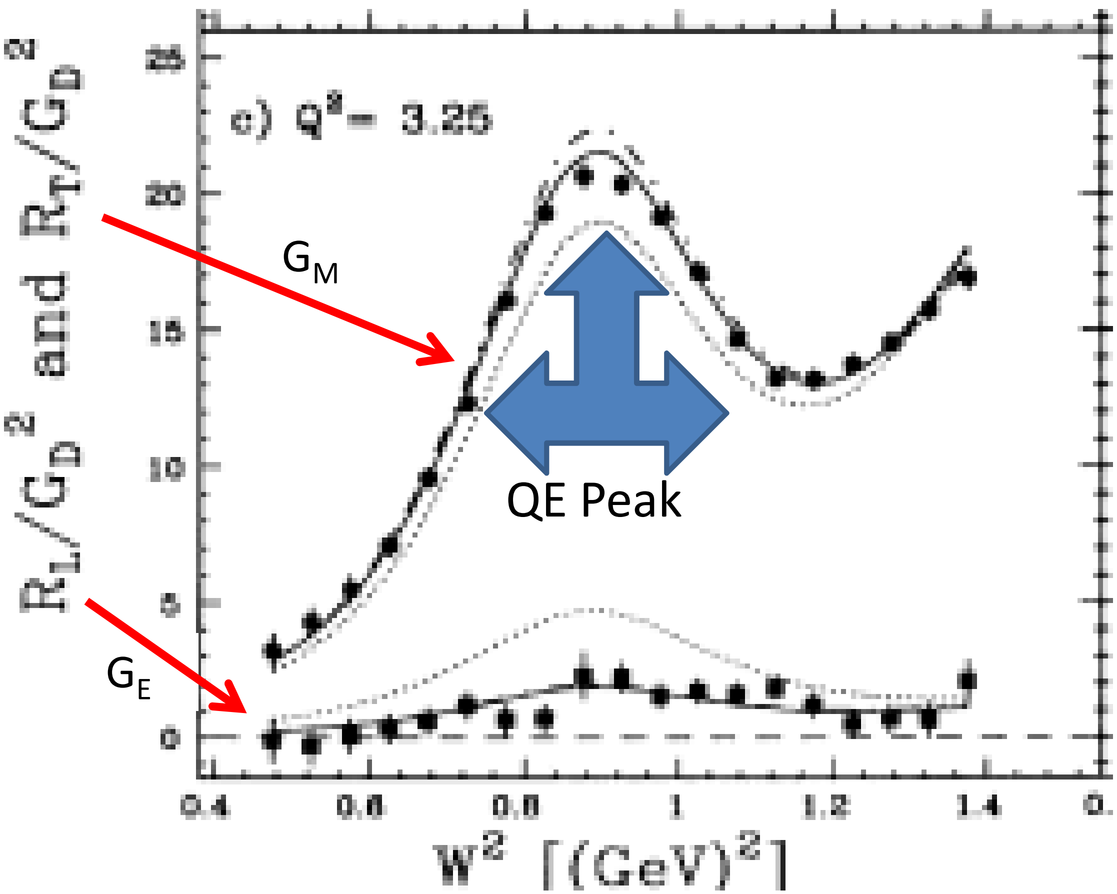
$$\sigma_r = R_T + \epsilon R_L$$

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

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

A. Lung *et al.*, Phys. Rev. Lett. **70**, 718 (1993).

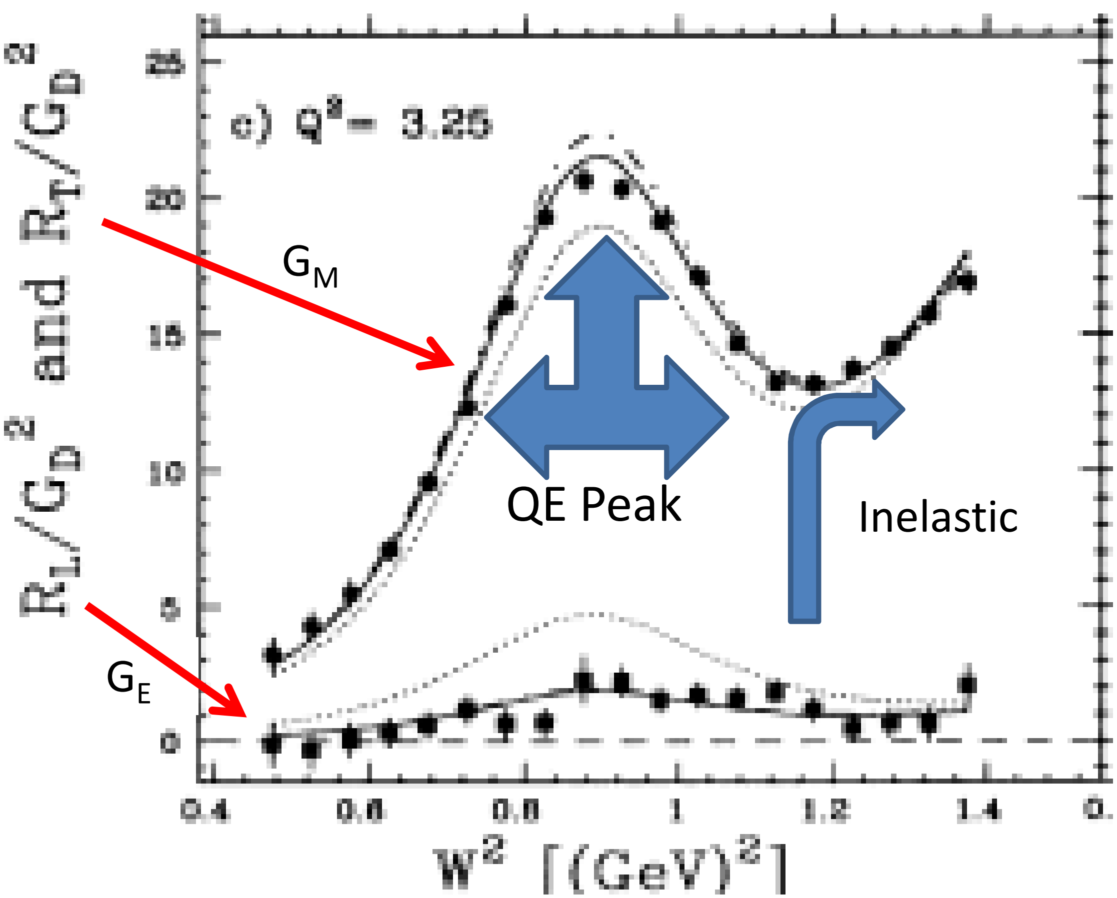
Extracting G_{Mn}



A. Lung *et al.*, Phys. Rev. Lett. **70**, 718 (1993).

- Quasi-Elastic peak at $W_2 = M_N^2 = 0.88$ GeV^2
- Fermi motion gives width to the QE peak

Extracting G_{Mn}

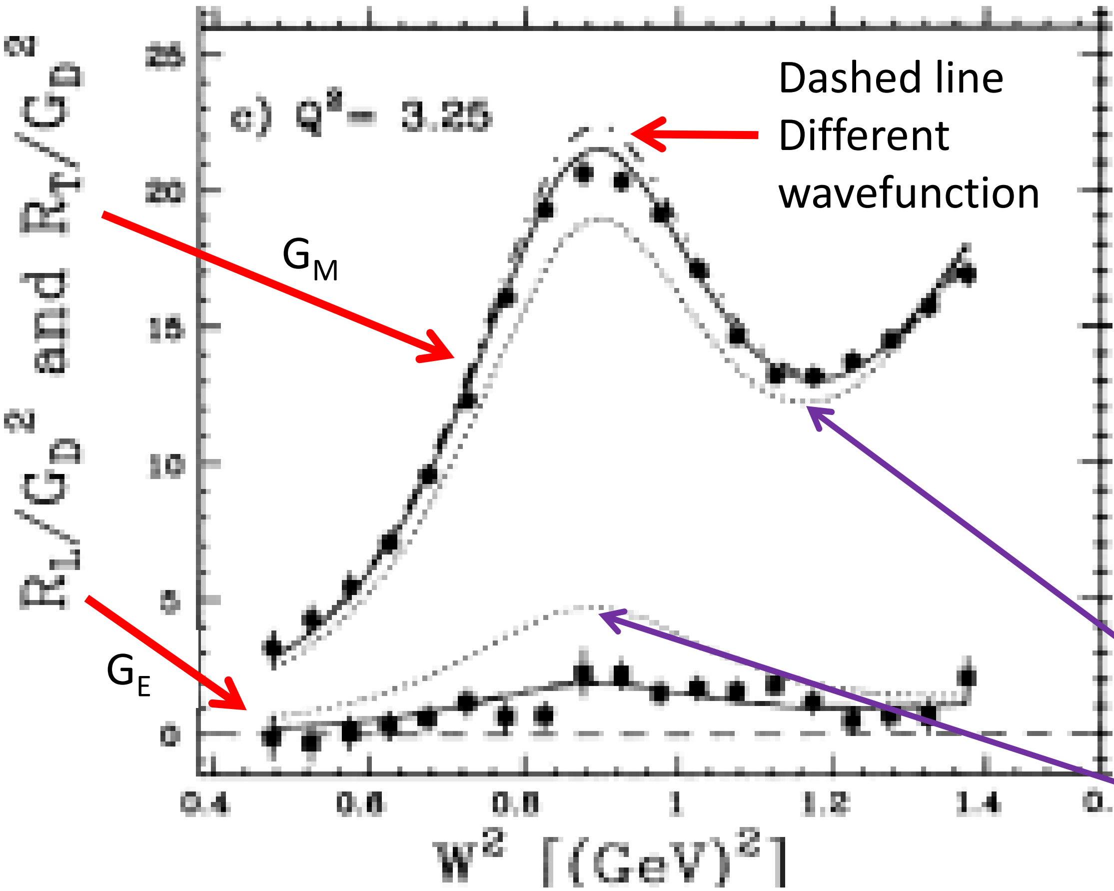


A. Lung *et al.*, Phys. Rev. Lett. **70**, 718 (1993).

- Quasi-Elastic peak at $W_2 = M_N^2 = 0.88$ GeV^2
- Fermi motion gives width to the QE peak
- Inelastic reaction for $W^2 > (M + M_\pi)^2$

Extracting G_{Mn}

- Calculate R_T and R_L in a model: Sensitive to deuteron wavefunction.
- Need a model of the inelastic cross section.



Solid line is fit

$$\mu G_{Mn}/G_D = 0.967 \pm 0.03$$

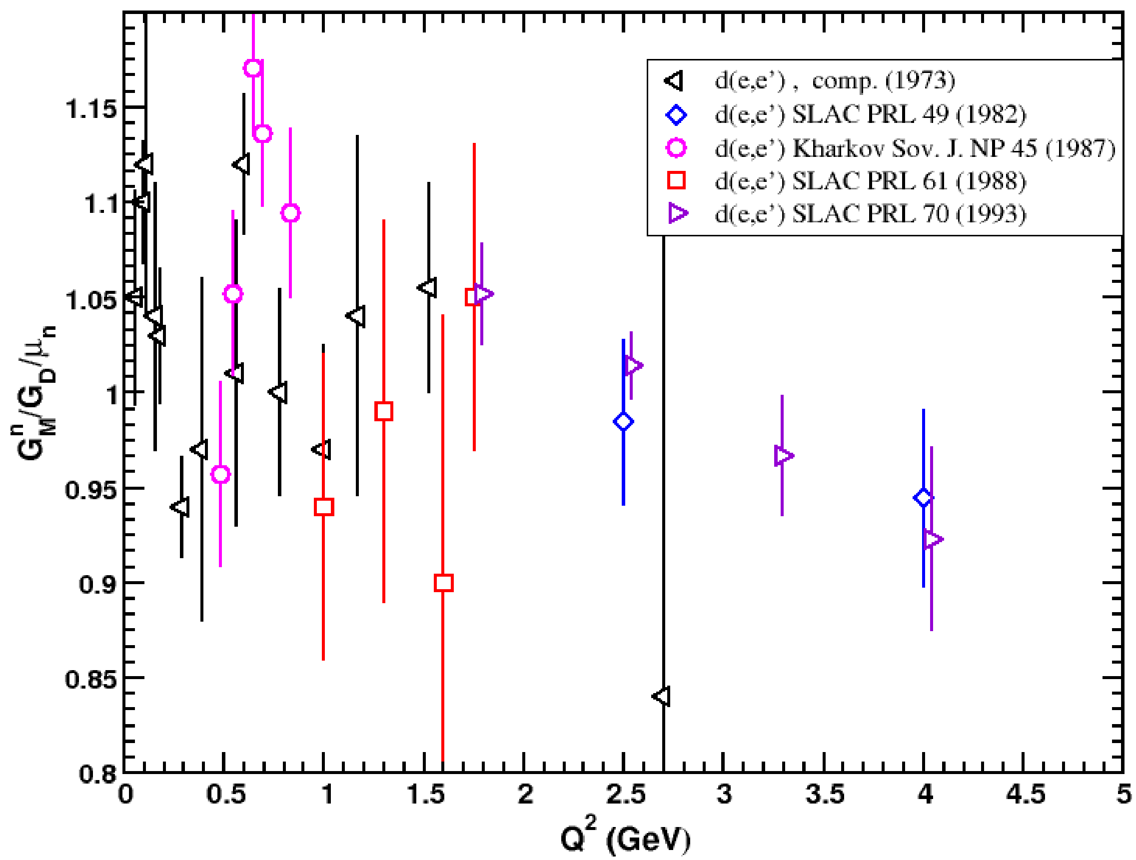
$$G_{En}^2/G_D^2 = 0.164 \pm 0.154$$

Dotted line shows sensitivity to Neutron form factor

Reduce G_{Mn} by 80%

Set $G_{En}^2/G_D^2 = 1.5$

G_{Mn} from d(e,e') experiments



Difficulties:

- Subtraction of large proton contribution
- Sensitive to deuteron model

$$\boxed{G_{Mn}/(\mu_p G_D) \approx G_{Mp}/(\mu_p G_D) \approx G_{Ep}/G_D}$$

Neutron Electric Form factor from elastic ed cross sections

Elastic ed cross section $$\frac{d\sigma}{d\Omega} = \sigma_M \left[A(Q^2) + B(Q^2) \tan^2 \frac{\theta}{2} \right]$$

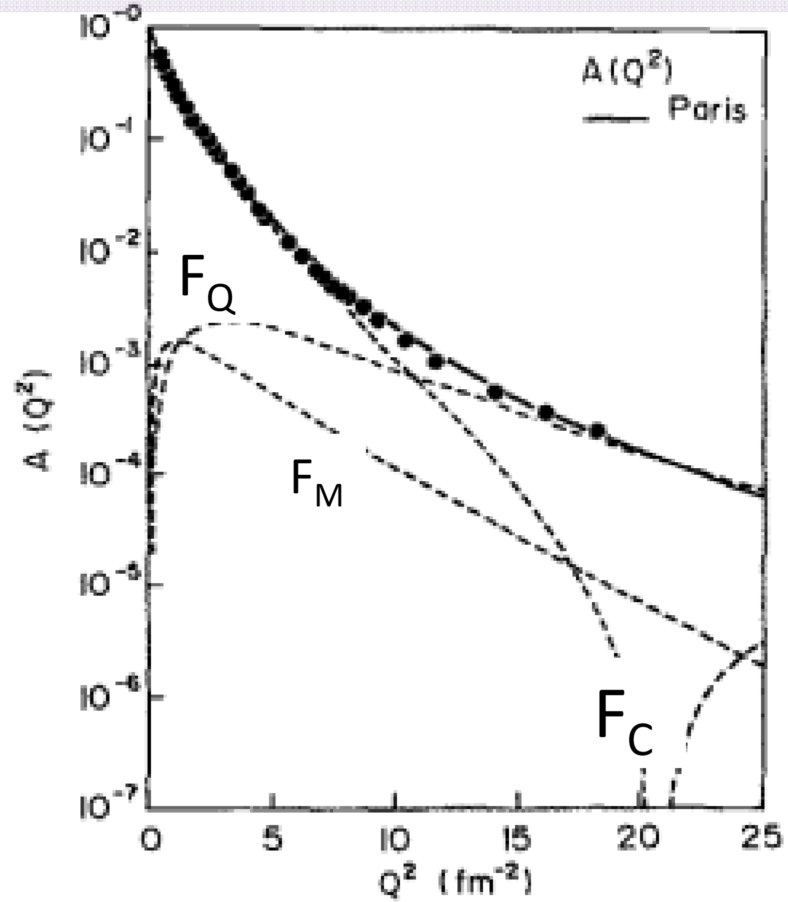
Deuteron is spin 1 nucleus described by three form factors:

Charge monopole F_C , quadrupole F_Q and magnetic dipole F_M

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

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

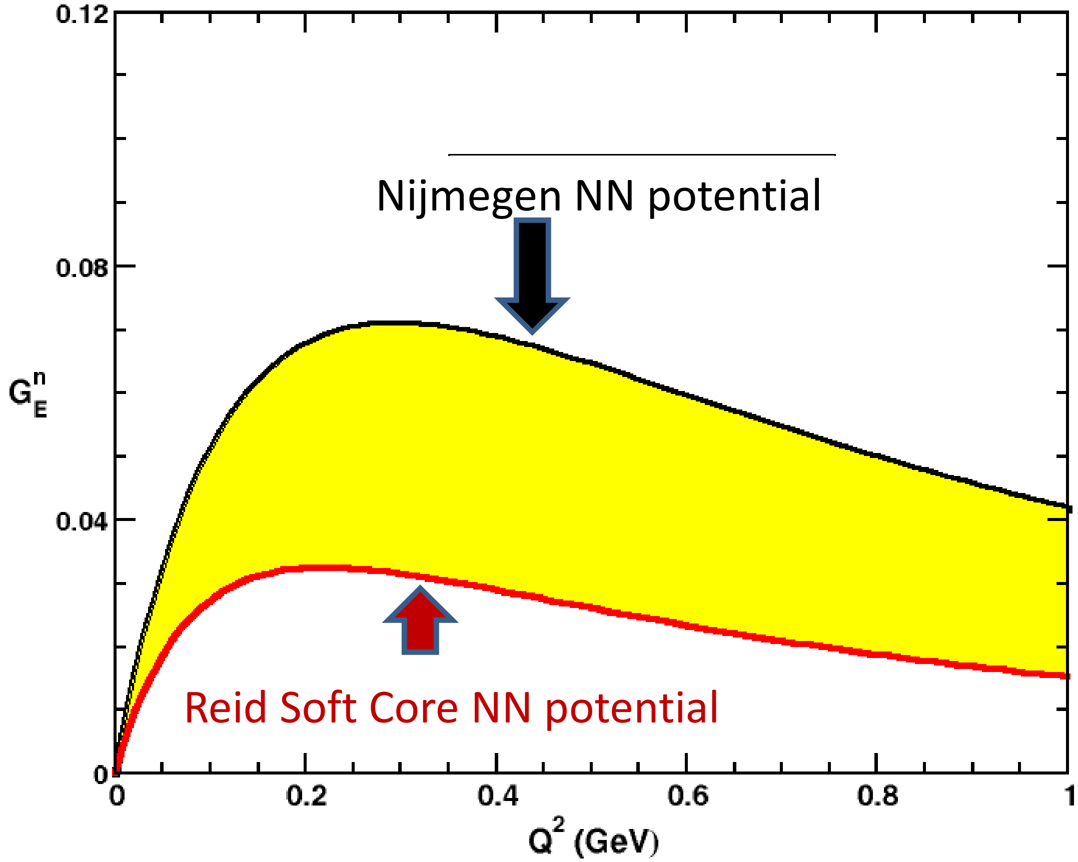
Neutron Electric Form factor from elastic ed cross sections



S. Platchkov *et al.*, Nucl. Phys. **A510**, 740 (1990).

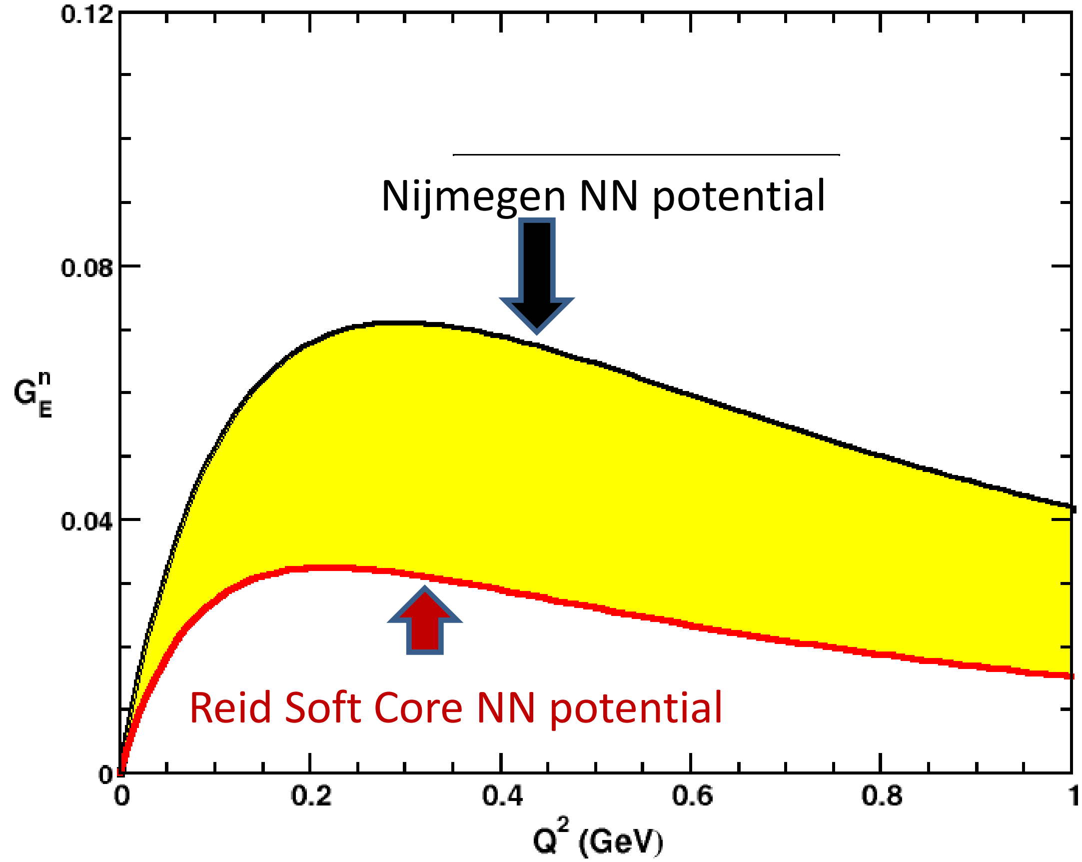
- ❑Need model of deuteron wave function
- ❑Input to model are the proton and neutron form factors.

Neutron Electric Form Factor: G_{En}



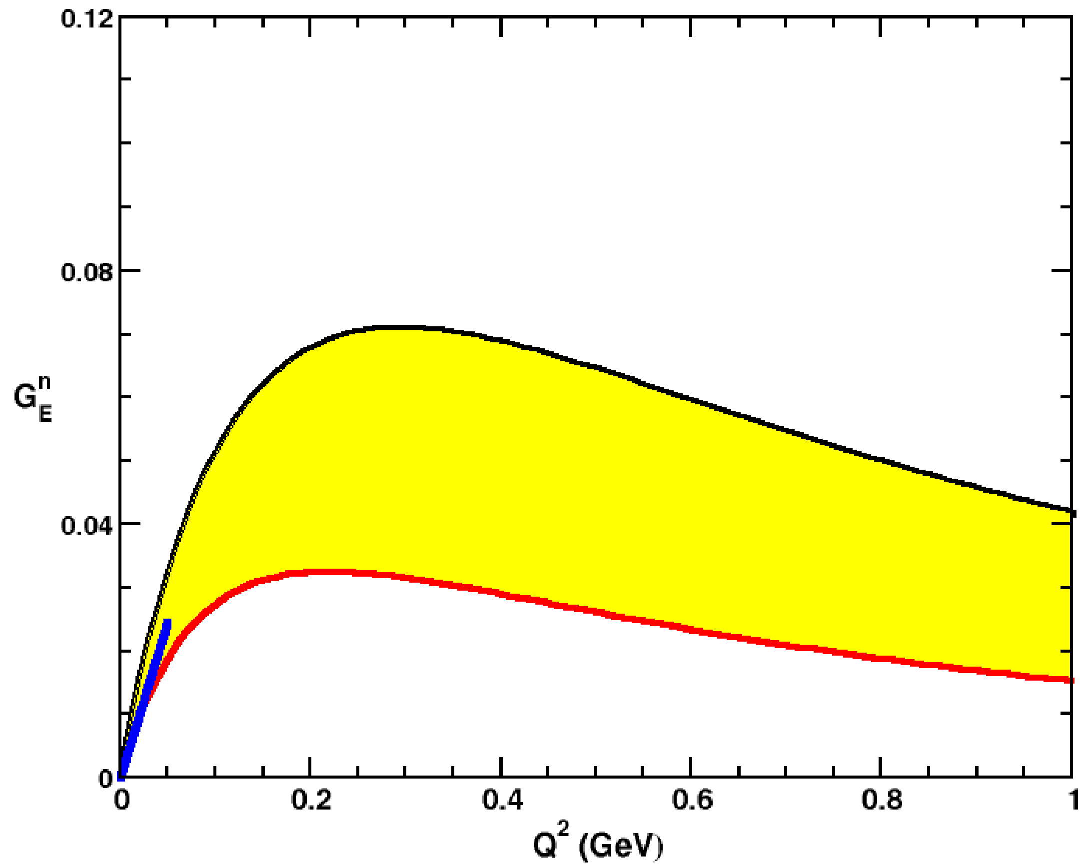
Extract G_{En} using deuteron model
but very sensitive to NN potential.

Neutron Electric Form Factor: G_{En}



How do we know the sign of neutron G_E?

Neutron Electric Form Factor: G_{En}



How do we know the sign of neutron G_E?

Measurement of neutron radius from scattering of thermal neutrons from heavy nuclei.

How to improve form factor measurements?

- High current continuous-wave electron beams
  - Double arm detection
  - Reduces random background so coincidence quasi-free deuteron experiments are possible
- Polarized electron beams
  - Recoil polarization from ^{1}H and ^{2}H
- Highly polarized, dense ^{3}He, ^{2}H and ^{1}H targets
  - Beam-Target Asymmetry
  - Polarized ^{3}He, ^{2}H as polarized neutron target.

How to improve form factor measurements?

Theory of electron quasi-free scattering on ^{3}He and ^{2}H

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

Neutron G_M using d(e,e'n) reaction

- Detect neutron in coincidence with electron
- Detect neutron at energy and angle expected for a "free" neutron.

Sensitive to detection efficiency

- In same experimental setup measure d(e,e'p)
- Theory predicts that

$$R = \sigma(e,e'n)/\sigma(e,e'p)$$

is less sensitive to deuteron wavefunction model and final state interactions compared predictions of $\sigma(e,e'n)$

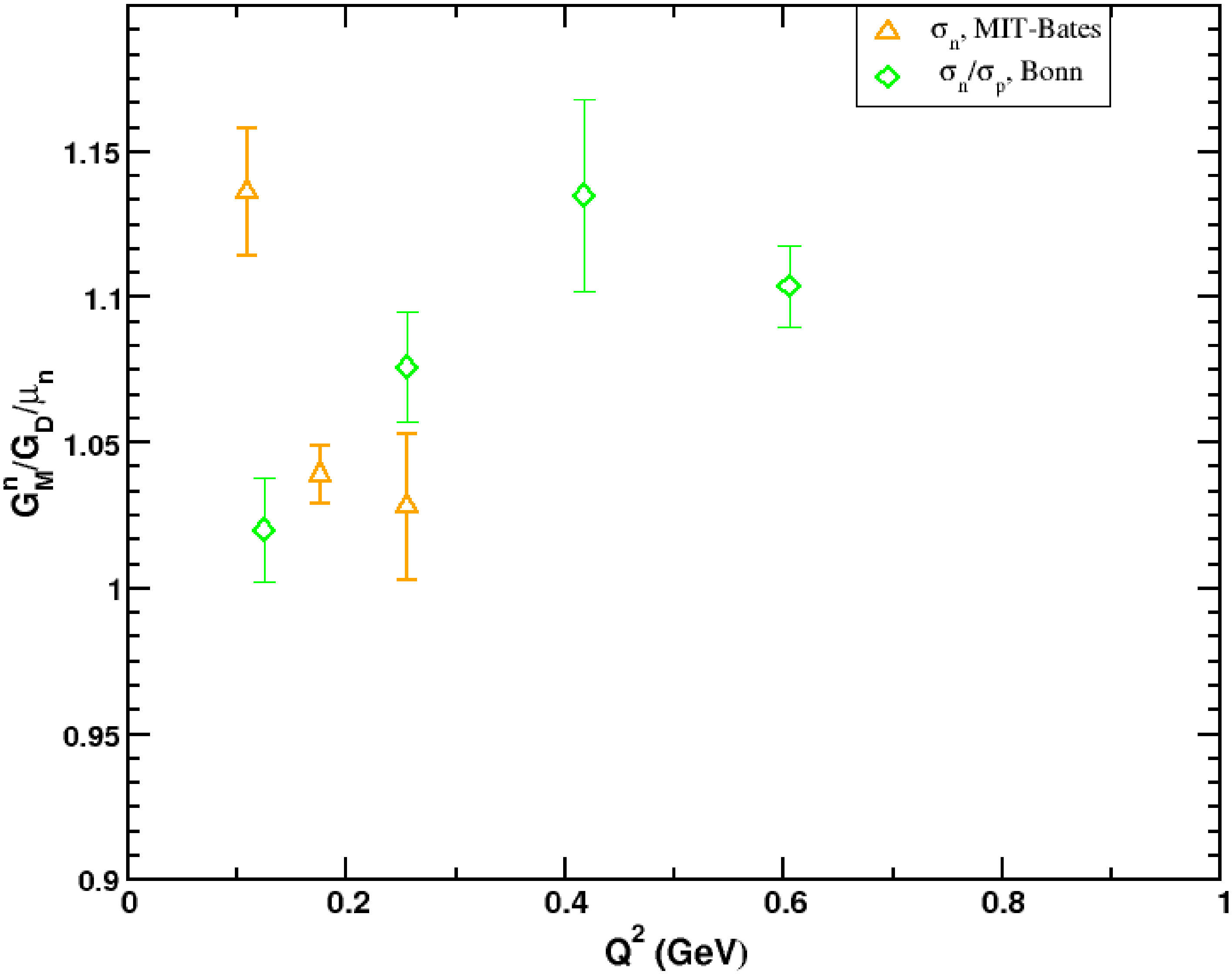
- $R_{PWIA} = \sigma_{en}/\sigma_{ep} = R(1\text{-}D)$

D is calculated from theory

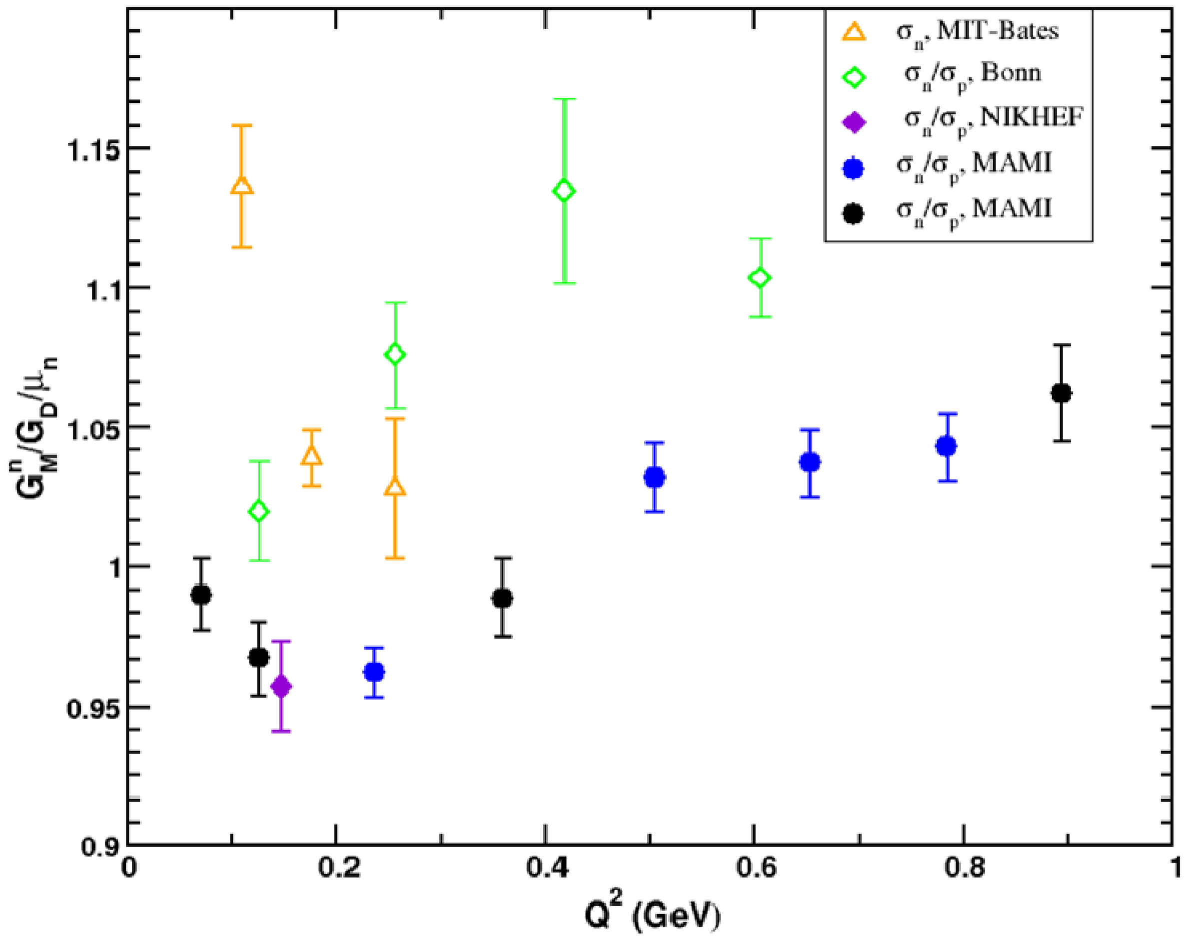
Neutron G_M using d(e,e'n) reaction

- Experiments done at:
  - ❑ ELSA, use $p(\gamma, \pi^+)n$ to calibrate neutron detection efficiency during the experiment. Q^2 = 0.1 to 0.6
  - ❑ NIKHEF and MAMI, calibrate neutron detection efficiency using $p(n,p)n$ at PSI. Transport detector from Switzerland to experiment at NIKHEF (Amsterdam) and later to Germany. Q^2 = 0.07 to 0.9
  - ❑ CLAS at JLAB, calibrate neutron efficiency using $p(e,e'\pi^+)n$ during the experiment. Q^2 = 1.0 to 5.0

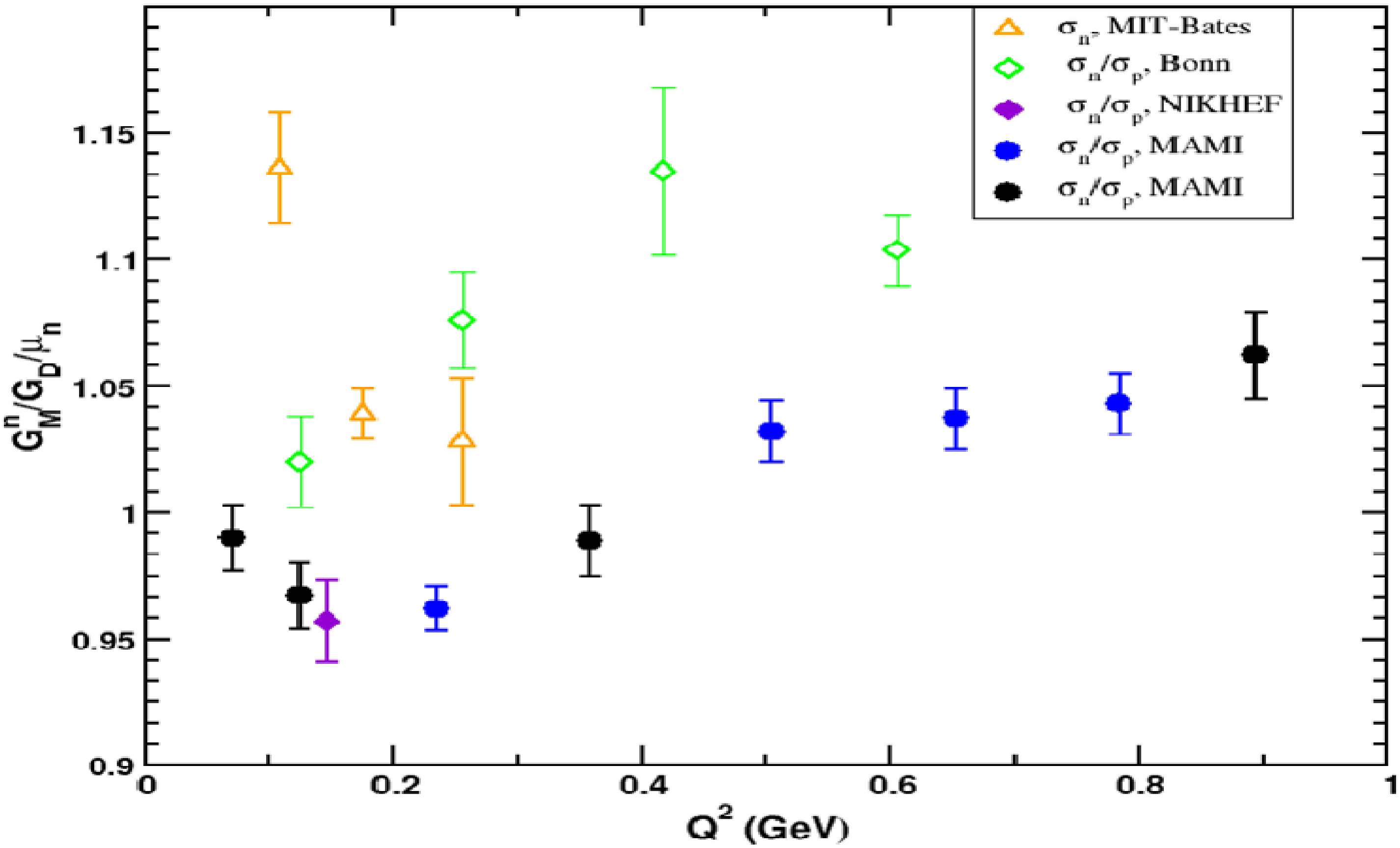
G_{Mn} from ratio $\frac{\sigma(e,e'n)}{\sigma(e,e'p)}$



G_{Mn} from ratio $\boxed{\dfrac{\sigma(e,e'n)}{\sigma(e,e'p)}}$



G_{Mn} from ratio $\frac{\sigma(e,e'n)}{\sigma(e,e'p)}$

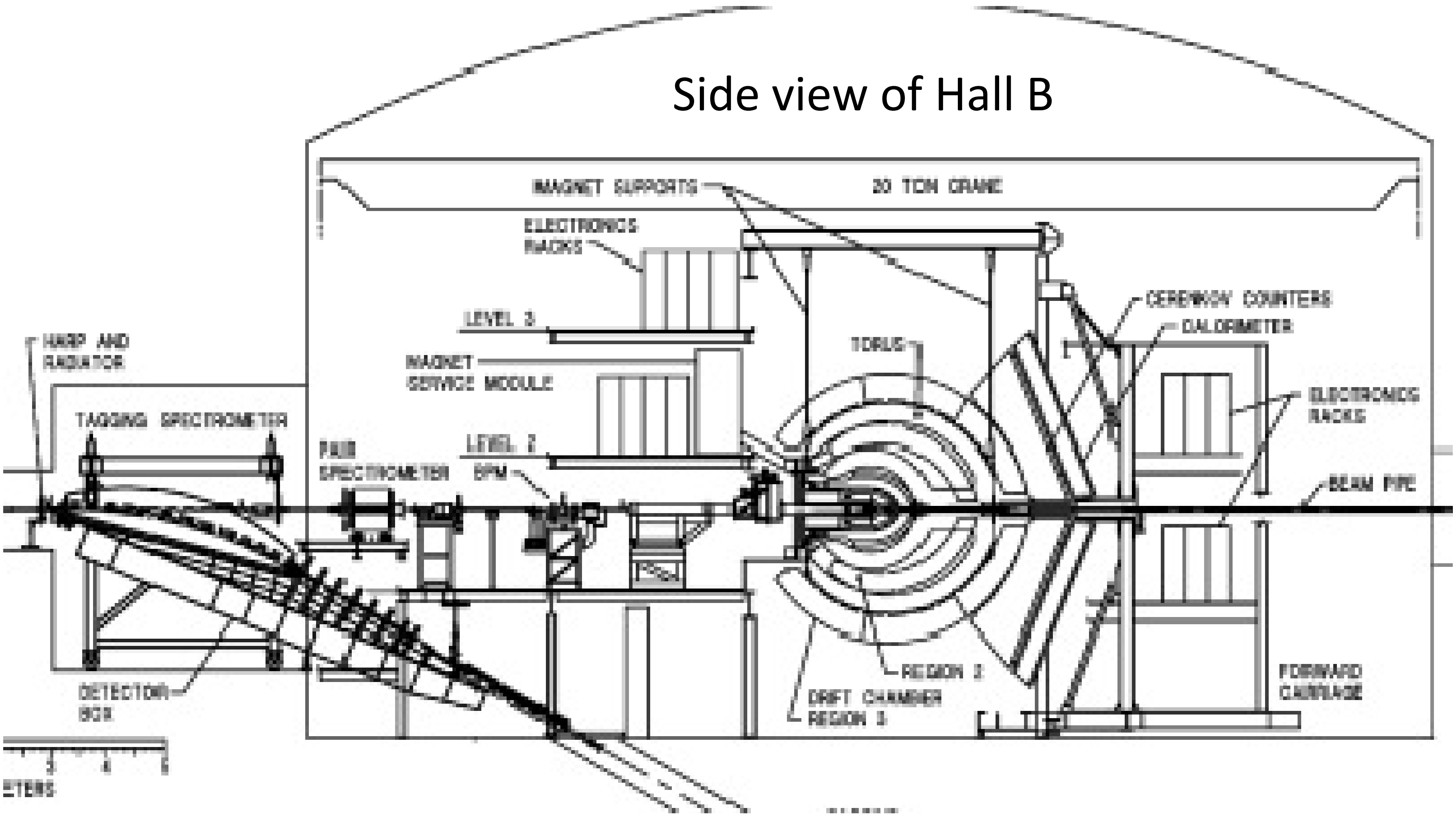


$R_{PWIA} = \sigma_{en}/\sigma_{ep} = R(1\text{-}D)$

Q2	0.07	0.125	0.36	0.90
D	-24%	-10	-4%	-1%

Jlab Experimental Hall B

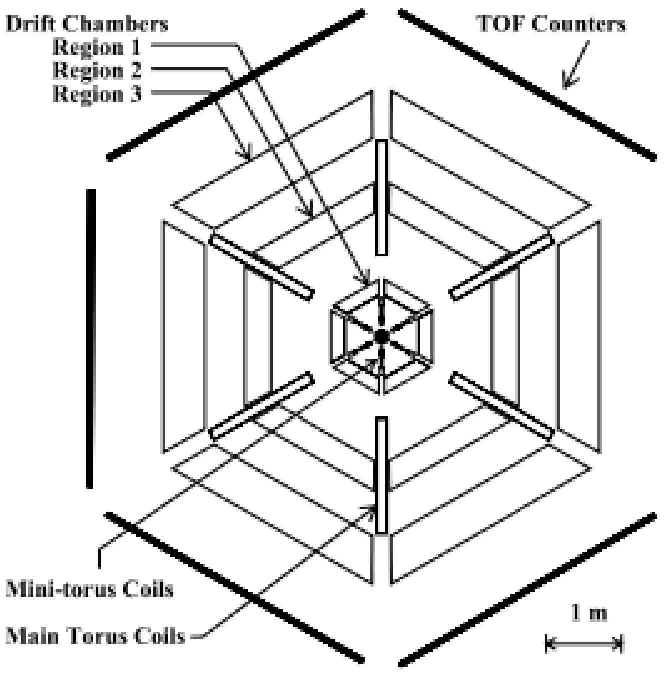
Side view of Hall B

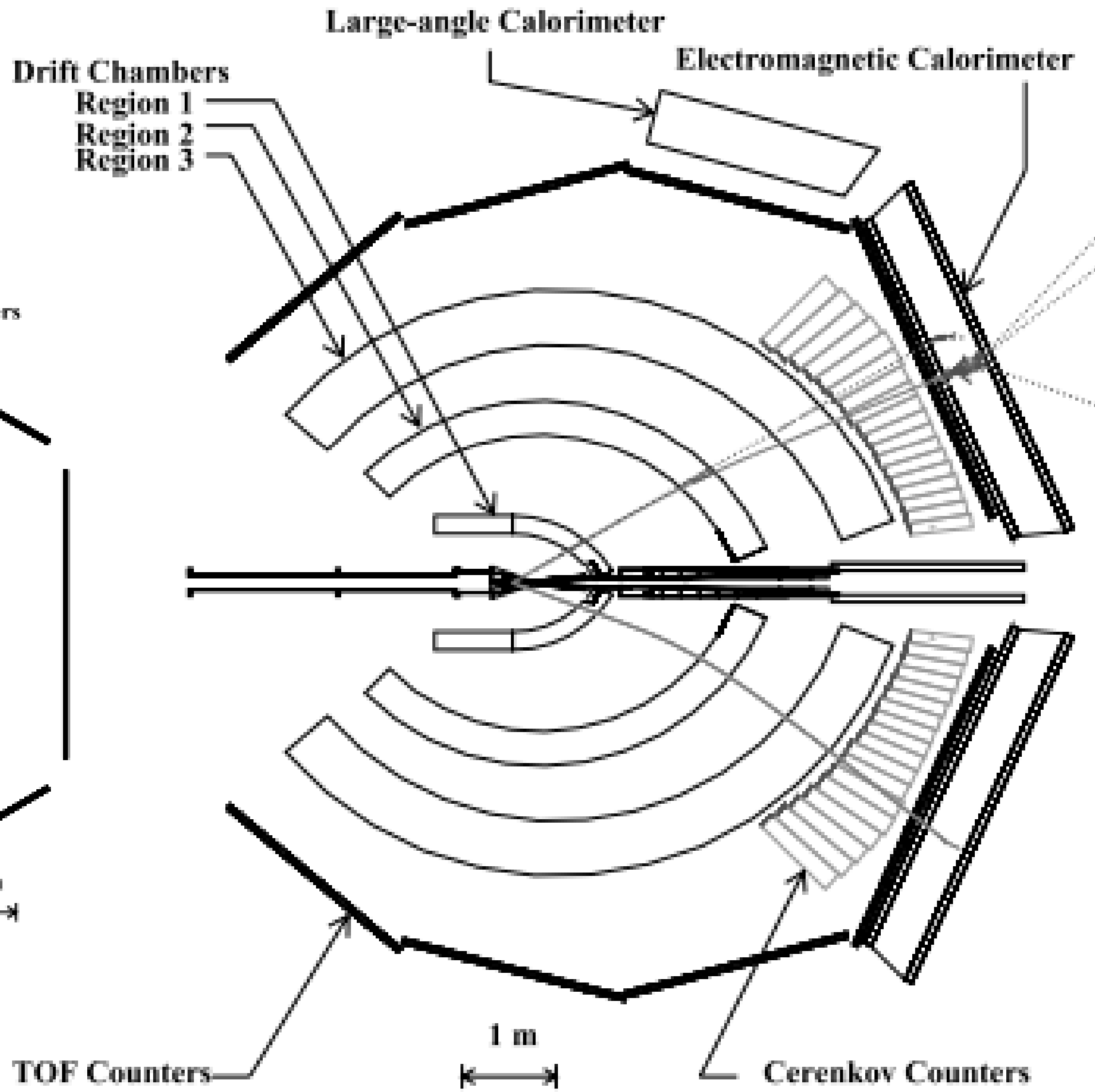


B. A. Mecking *et al.* (CLAS), Nucl. Instrum. Meth. A **503**, 513 (2003).

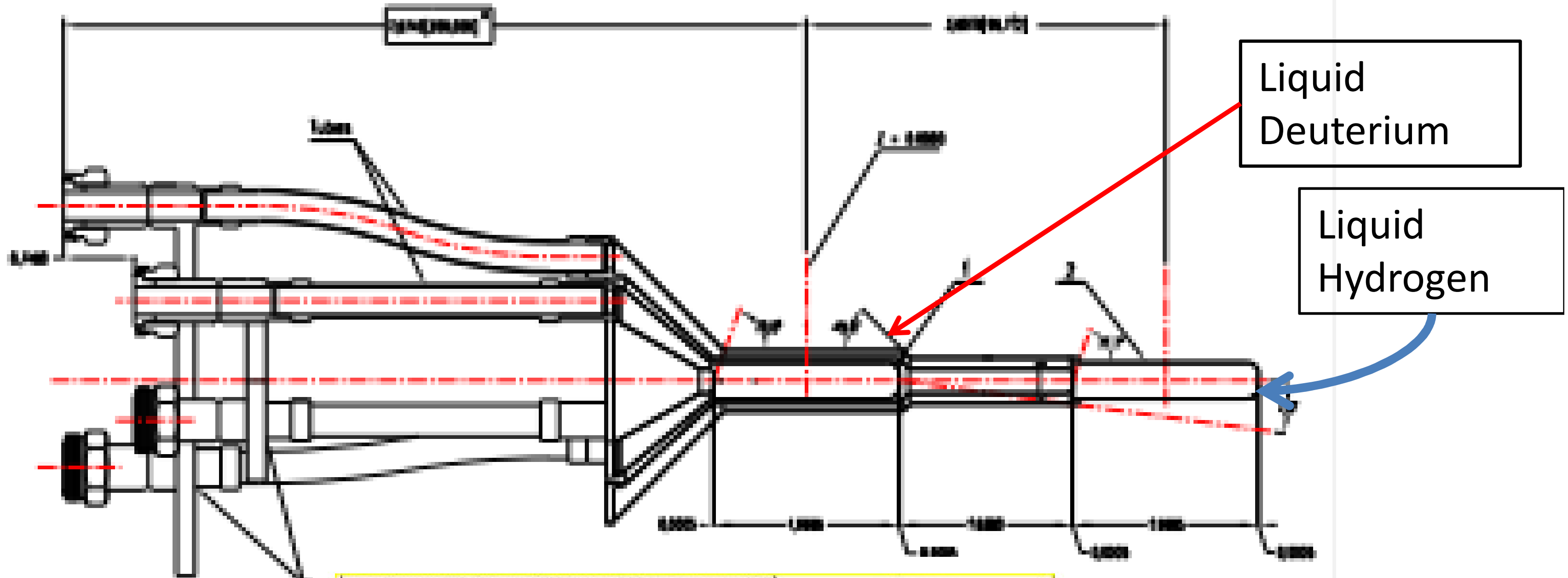
Hall B CLAS detector

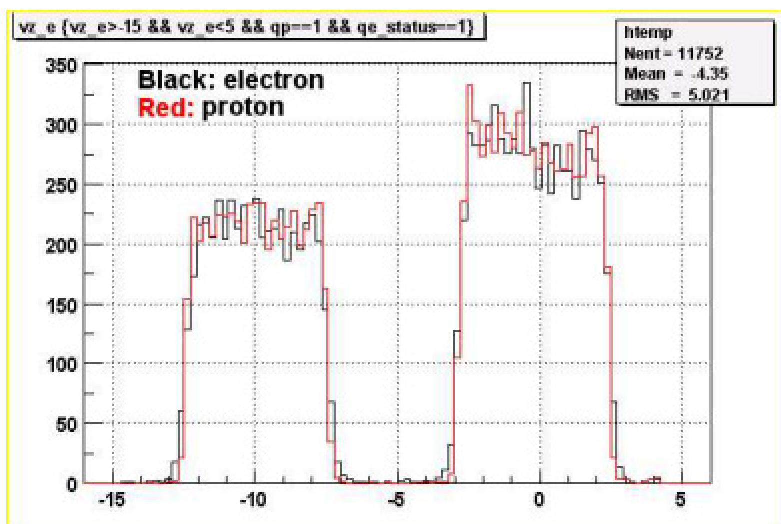
Six section
superconducting
toriodal magnet



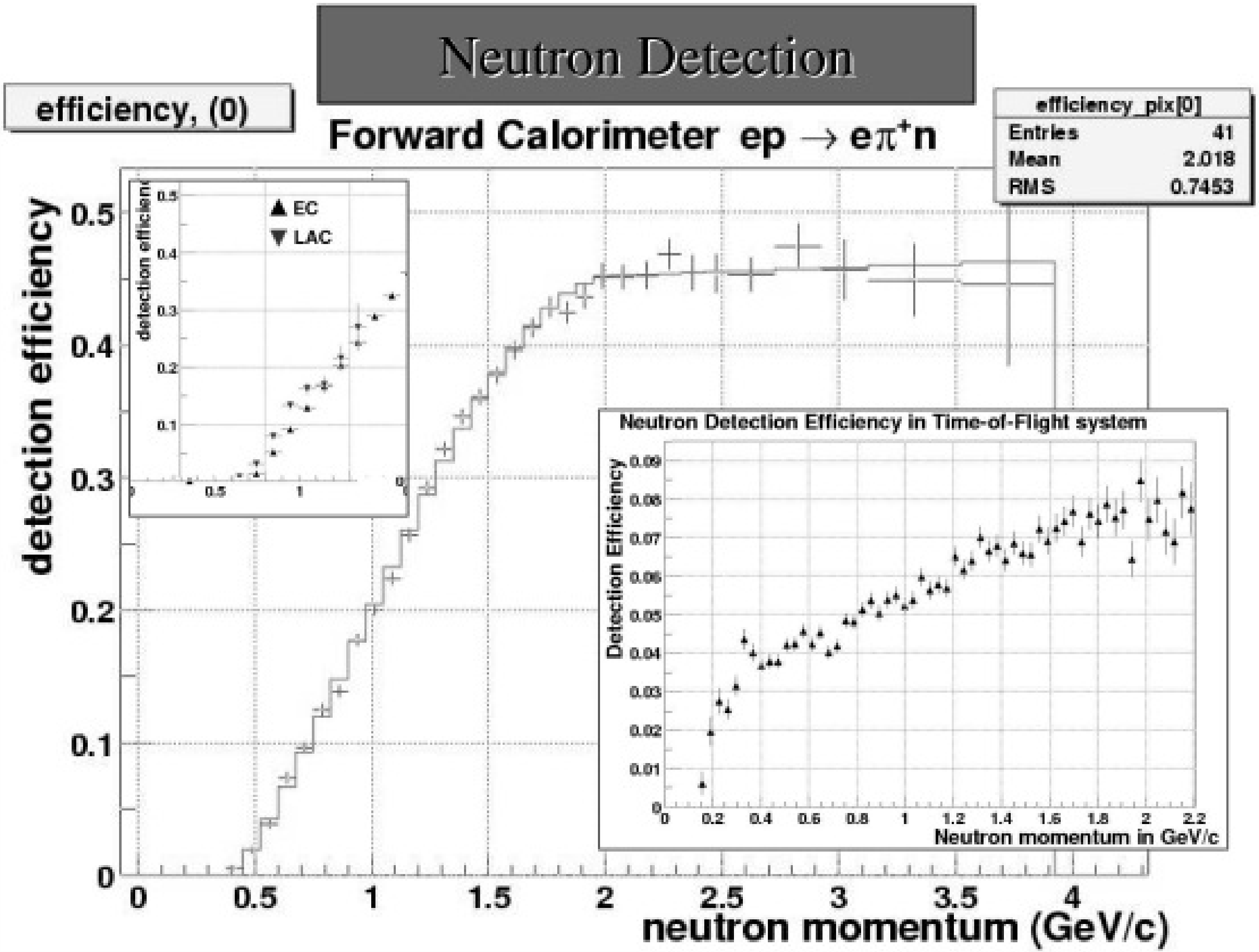


Special dual cell target

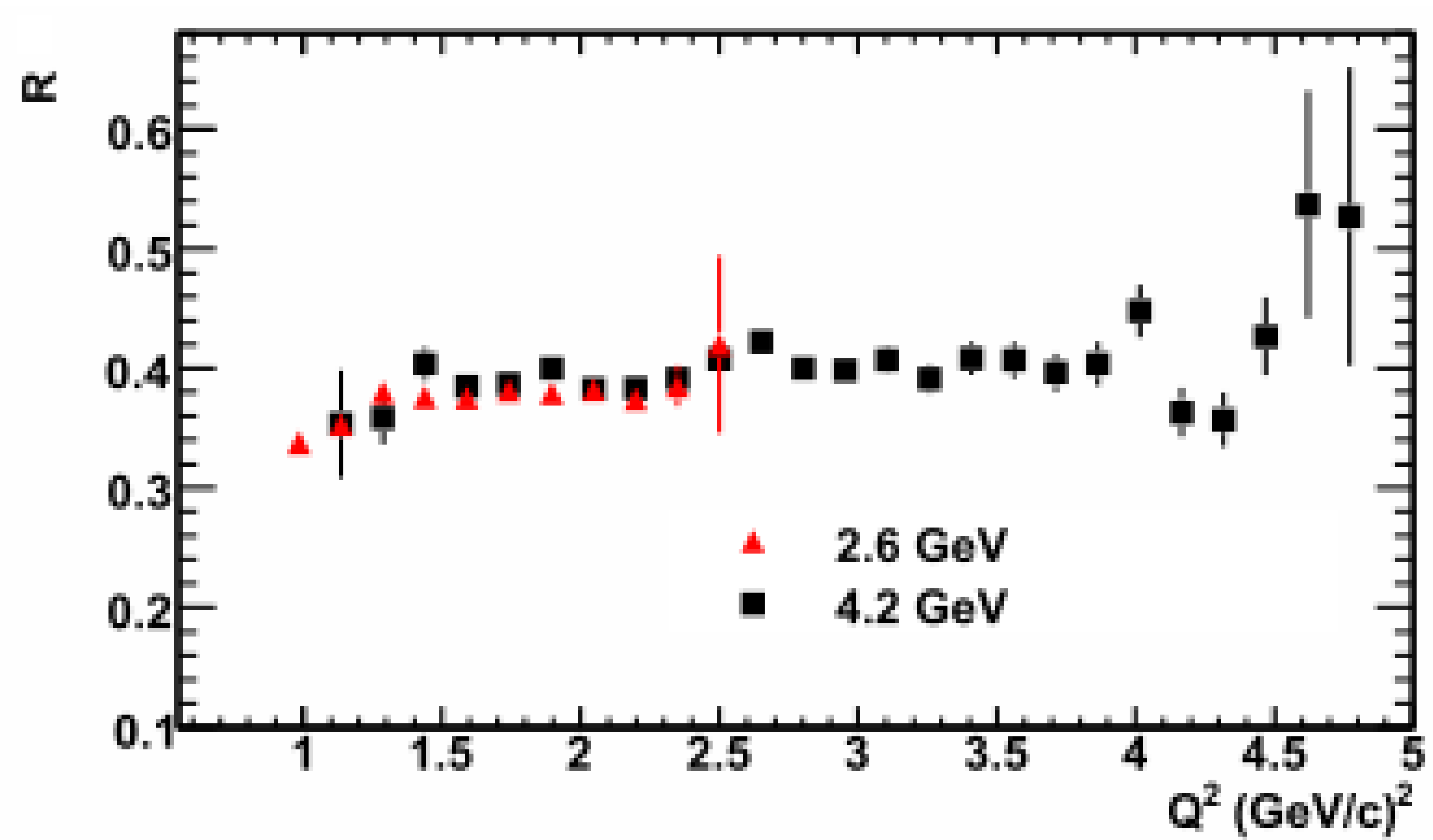




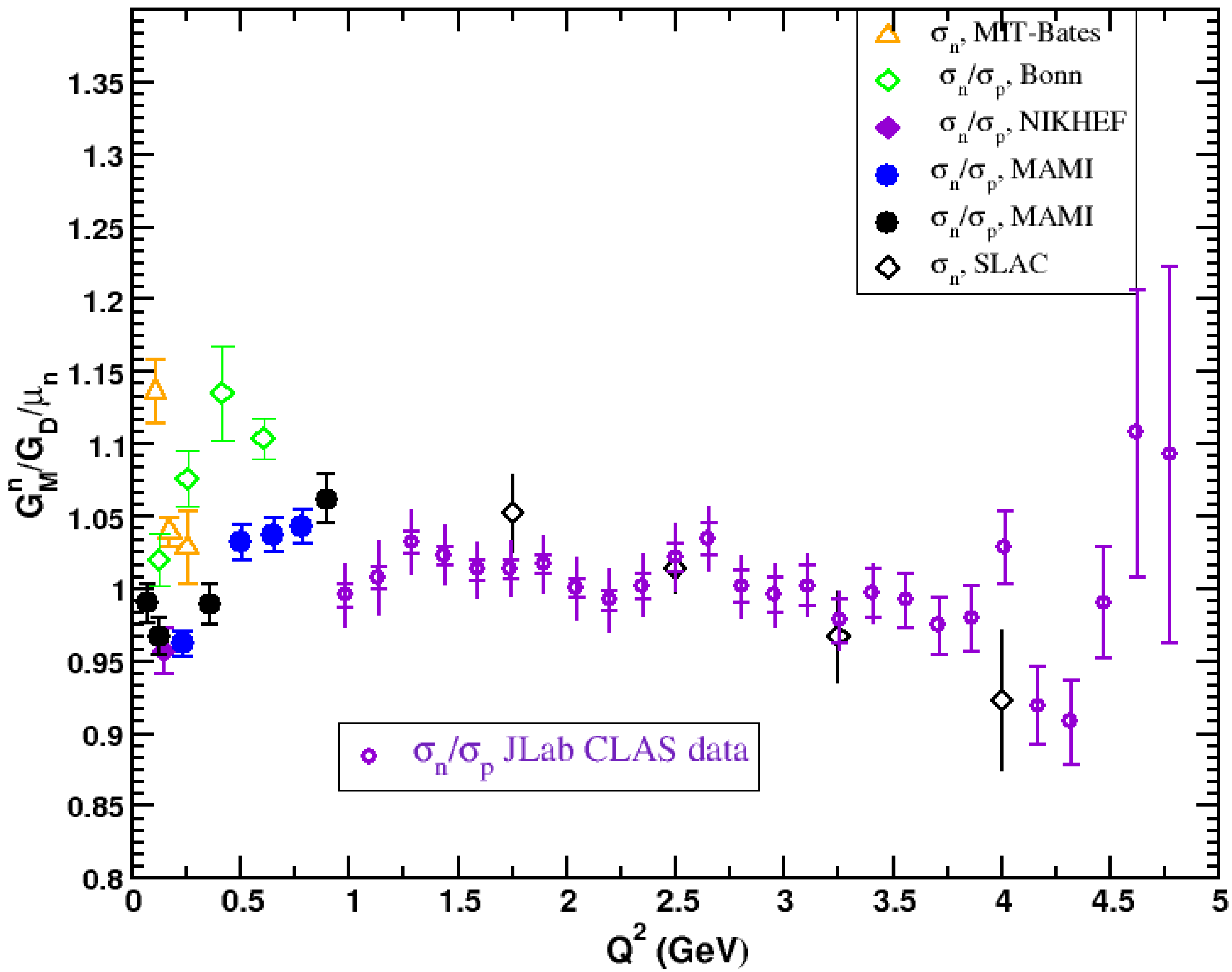
Neutron detection in Hall B



Comparing results at different energies



G_{Mn} with Jlab Hall B results



Summary

- ❑ Focused on cross section measurements to extract proton and neutron form factors.
  - ➢ Proton G_M measured to Q^2 = 30 GeV^2
  - ➢ Neutron G_M measured to Q^2 = 4.5 GeV^2
  - ➢ Discrepancy in neutron G_M near Q^2 = 1.0 GeV^2

- ❑ Need new experimental observable to make better measurements of neutron electric form factor and proton electric form factor above Q^2 = 1 GeV^2
  - ➢ Spin observables sensitive to $G_E x G_M$ and G_M
  - ➢ Get the relative sign of G_E and G_M

Summary

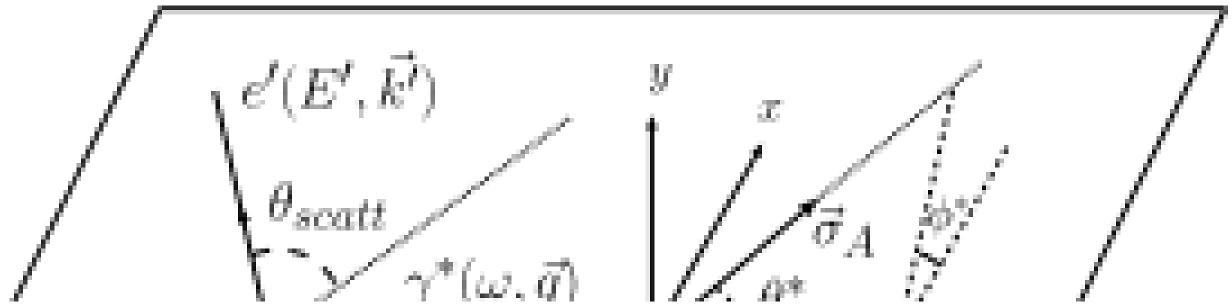
- Focused on cross section measurements to extract proton and neutron form factors.
  - Proton G_M measured to Q^2 = 30 GeV^2
  - Neutron G_M measured to Q^2 = 4.5 GeV^2
  - Discrepancy in neutron G_M near Q^2 = 1.0 GeV^2

- Need new experimental observable to make better measurements of neutron electric form factor and proton electric form factor above Q^2 = 1 GeV^2
  - Spin observables sensitive to G_ExG_M and G_M
  - Get the relative sign of G_E and G_M
- Next talk about spin observable experiments

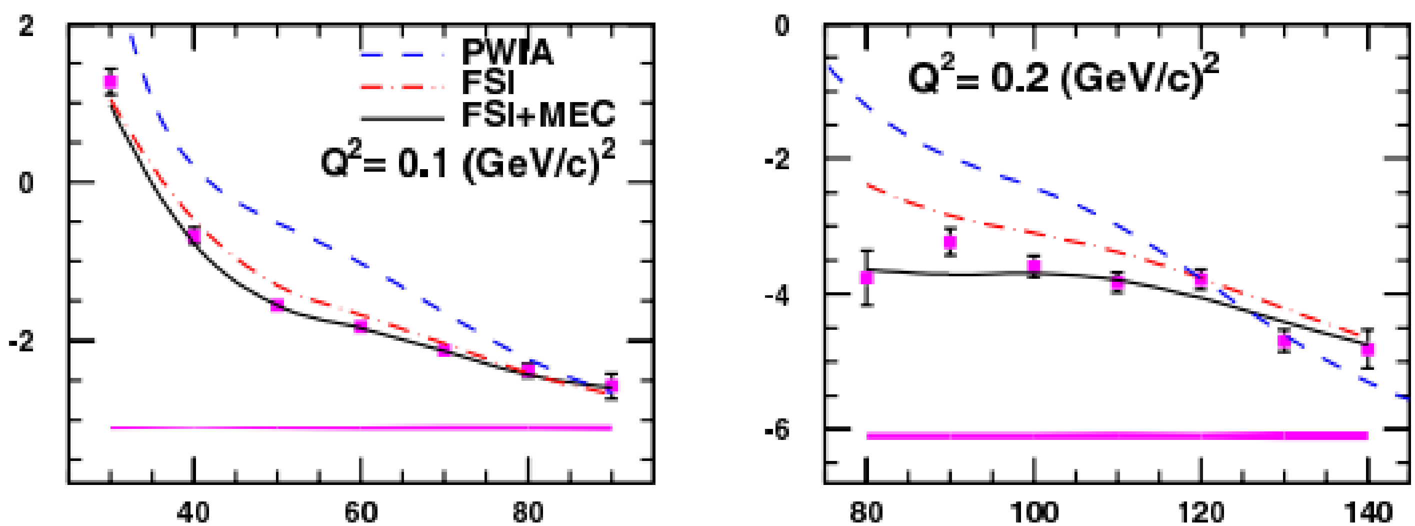
$$\text{Measure asymmetries in } \vec{e}\vec{N} \to eN$$

$$\text{Measure recoil polarization in } \vec{e}N \to e\vec{N}$$

Backup



$e'(E', \vec{k}')$
θ_{scatt}
$\gamma^*(\omega, \vec{q})$
y
x
$\vec{\sigma}_A$



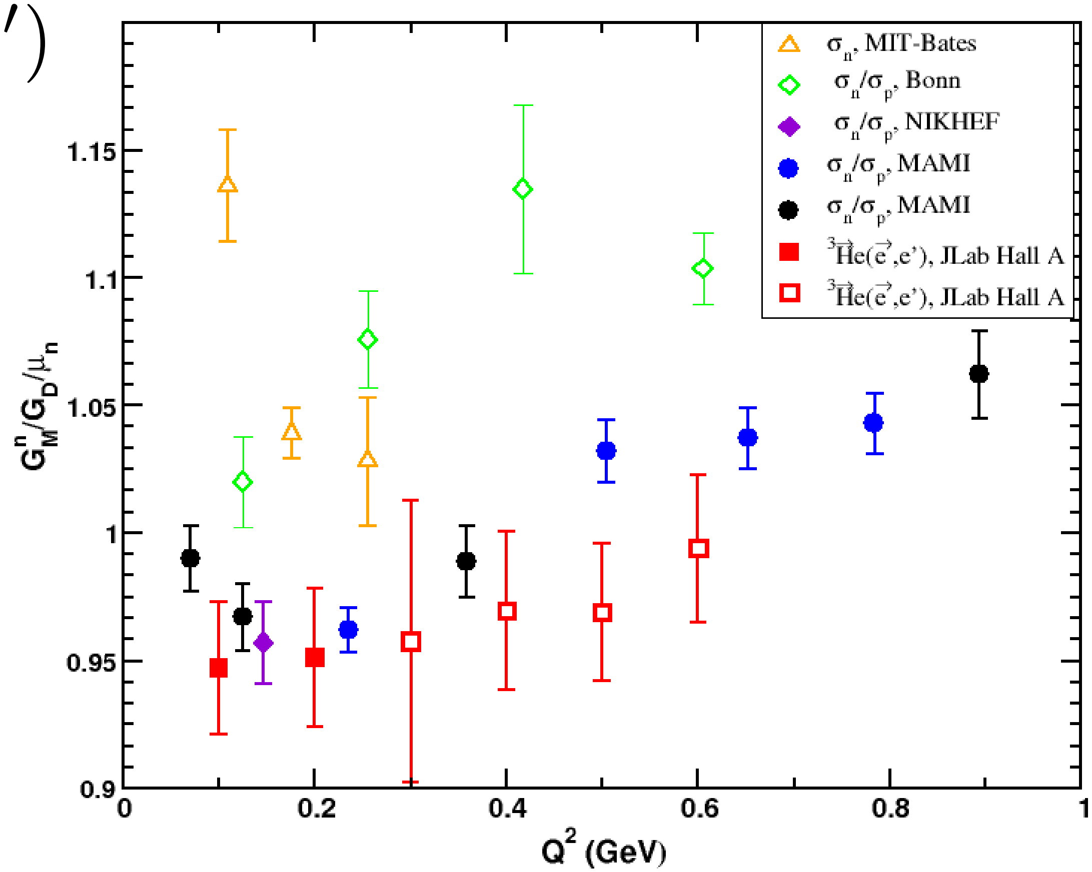
PWIA
FSI
FSI+MEC
Q^2= 0.1 (GeV/c)^2
Q^2= 0.2 (GeV/c)^2
2
0
-2
40
60
80
0
-2
-4
-6
80
100
120
140

Neutron Magnetic Form Factor: G_{Mn}

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

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

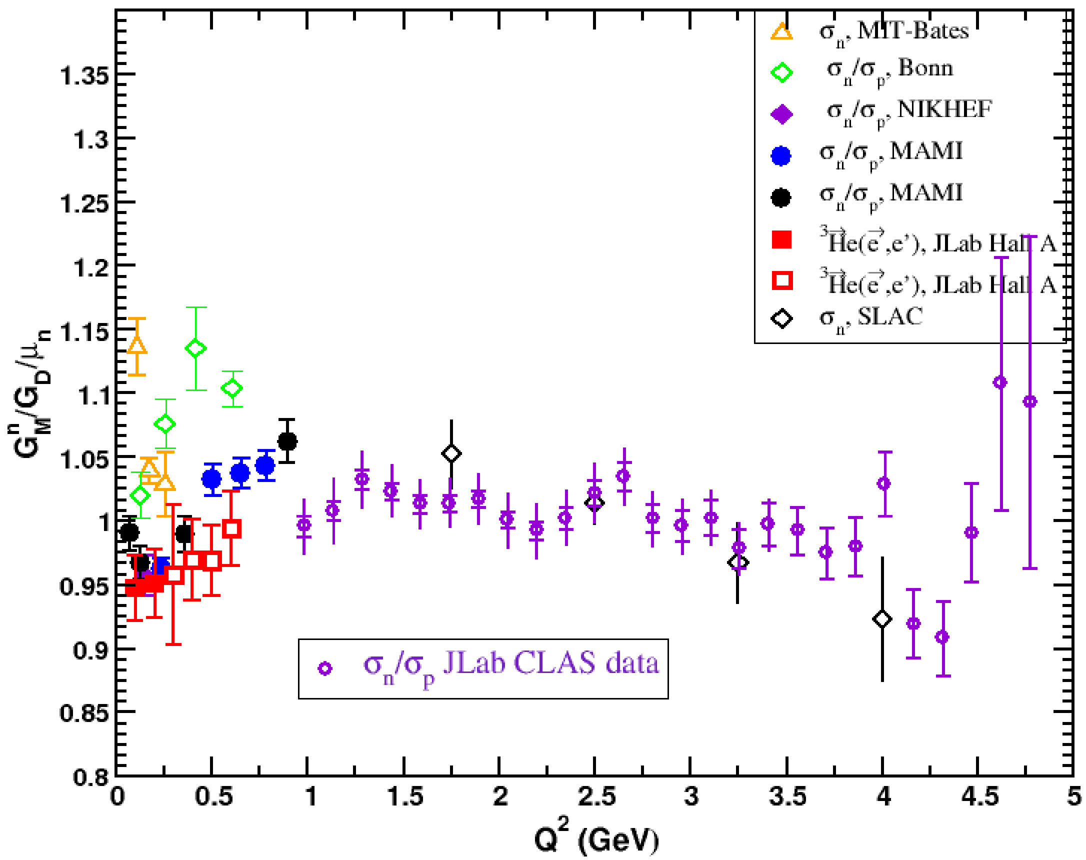
- Q^2 > 0.2 use PWIA calculation of A_T



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 : Phys. Rev. Lett. 102,192001 (2009)

Neutron Magnetic Form Factor: G_{Mn}

- New preliminary results using the BLAST detector at MIT-Bates
- Electron ring and internal gas target
- Use inclusive $^2\vec{\mathrm{H}}(\vec{\mathrm{e}},\mathrm{e}')$ which is sensitive to G_{Mn}/G_{Mp}