Proton, Neutron Electromagnetic Structure

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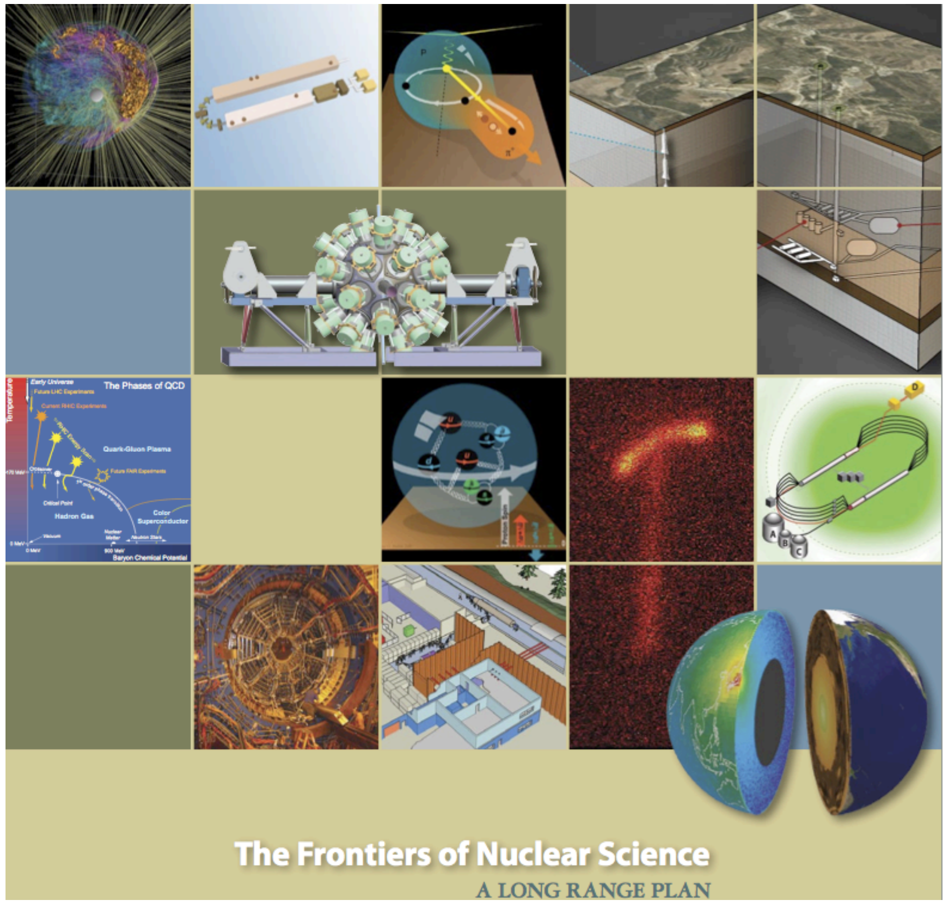
Physics 735

Nucleon substructure has been identified as one of the important frontiers by the Nuclear Science Advisory Committee - *Long Range Plan, Dec 07*

Nuclear/particle physics indistinguishable

Ongoing debate



Charge Distribution of the Neutron

The neutron, as its name implies, is an electrically neutral particle. But the neutron has magnetic properties that are similar to its electrically charged counterpart, the proton, which suggests that its internal charge distribution is quite complex. A sustained effort worldwide over the last decade (including experiments at JLAB and the Bates Laboratory at the Massachusetts Institute of Technology) that utilized new polarized beams and targets has resulted in a much clearer picture of the neutron's charge distribution. The core of the neutron is positively charged. The neutron becomes electrically neutral due to the significant cloud of negative charge produced by virtual mesons that surround the core. These new results provide very strong constraints for theory—particularly lattice QCD calculations—that aim to reproduce the electric and magnetic properties of the neutron.

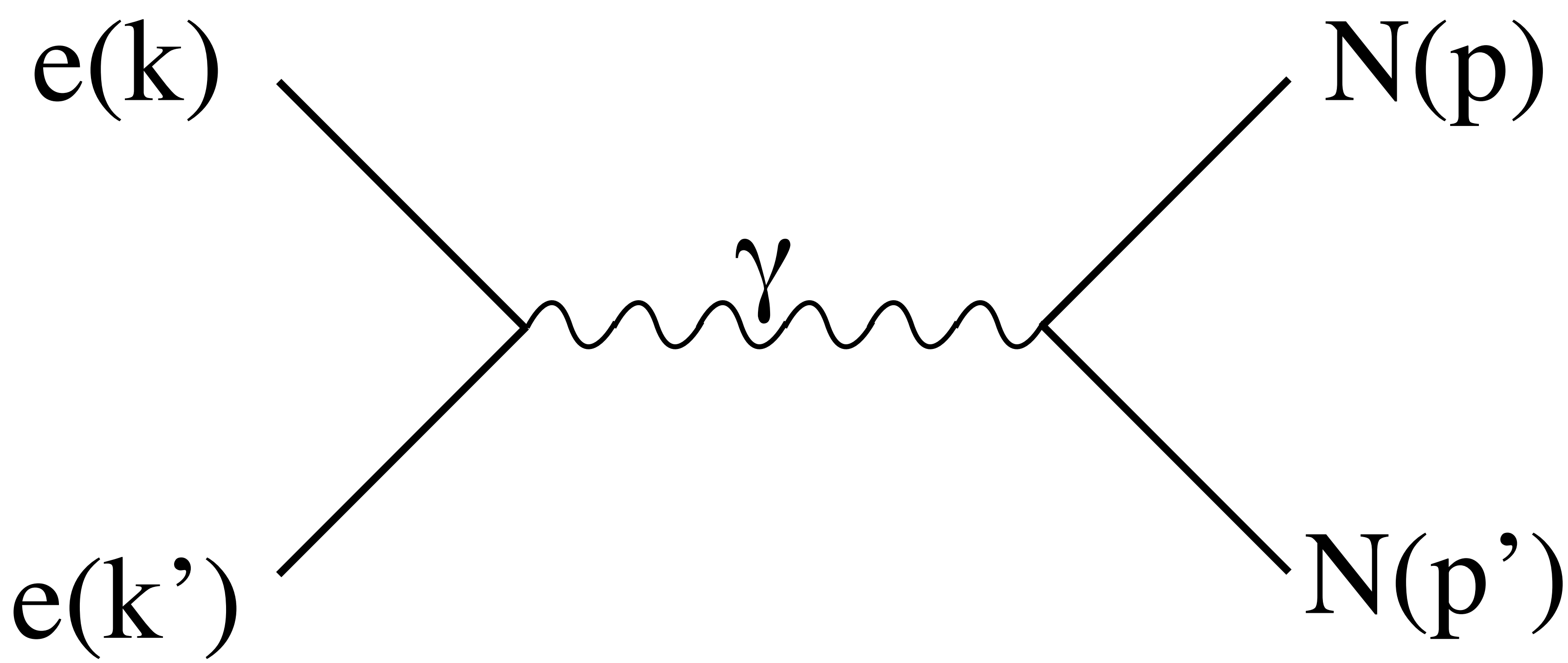
Rutherford - atoms have nuclei

Stern - $\mu_p = (1+\varkappa_p)(e/2M)$

Hofstadter - nuclei are not point-like, rather high density core and sparse surrounding

Mott - light point-like fermion off point-like heavy fermion;

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} = \left(\frac{\alpha}{2k_e^2 \sin^2(\theta/2)}\right)^2 \left(m^2 + k_e^2 \cos^2(\theta/2)\right)$$



Point-like:

$$-i\mathcal{M} = \frac{-ig_{\mu\nu}}{q^2}\left[ie\bar{u}(k_e)\gamma^\nu u(k_e')\right]\left[-ie\bar{N}(p')\gamma^\mu N(p)\right]$$

With structure:

$$-i\mathcal{M} = \frac{-ig_{\mu\nu}}{q^2}\left[ie\bar{u}(k_e)\gamma^\nu u(k_e')\right]\left[-ie\bar{N}(p')\Gamma^\mu(p,p')N(p)\right]$$

$$\Gamma^\mu = \gamma^\mu F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M}F_2(Q^2)$$

Dirac, Pauli Form Factors:

$$F_{1p}(0) = 1 \qquad F_{2p}(0) = \kappa_p$$

$$F_{1n}(0) = 0 \qquad F_{2n}(0) = \kappa_n$$

Sachs Form Factors:

$$G_E = F_1 - \frac{Q^2}{4M^2} F_2 \qquad G_M = F_1 + F_2$$

$$eG_{Ep}(0) = e \qquad G_{Mp}(0) = \mu_p$$

$$eG_{En}(0) = 0 \qquad G_{Mn}(0) = \mu_n$$

$$G_E = F_1 - \frac{Q^2}{4M^2} F_2 \qquad G_M = F_1 + F_2$$

$G_E \rightarrow$ Charge distribution

$G_M \rightarrow$ Current distribution

$$\langle r_E^2 \rangle \simeq -6 \left. \frac{dG_E}{dQ^2} \right|_{Q^2=0}$$

$$\Gamma^\mu = \gamma^\mu F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M}F_2(Q^2)$$

$\cancel{p^\mu}$

$\cancel{1}$

$\cancel{\gamma_5}$

γ^μ

$\cancel{\gamma_5\gamma^\mu}$

$\sigma^{\mu\nu}$

$\cancel{\gamma_5\sigma^{\mu\nu}}$

"At its simplest, the nucleon is nonperturbative three-body bound-state problem..."

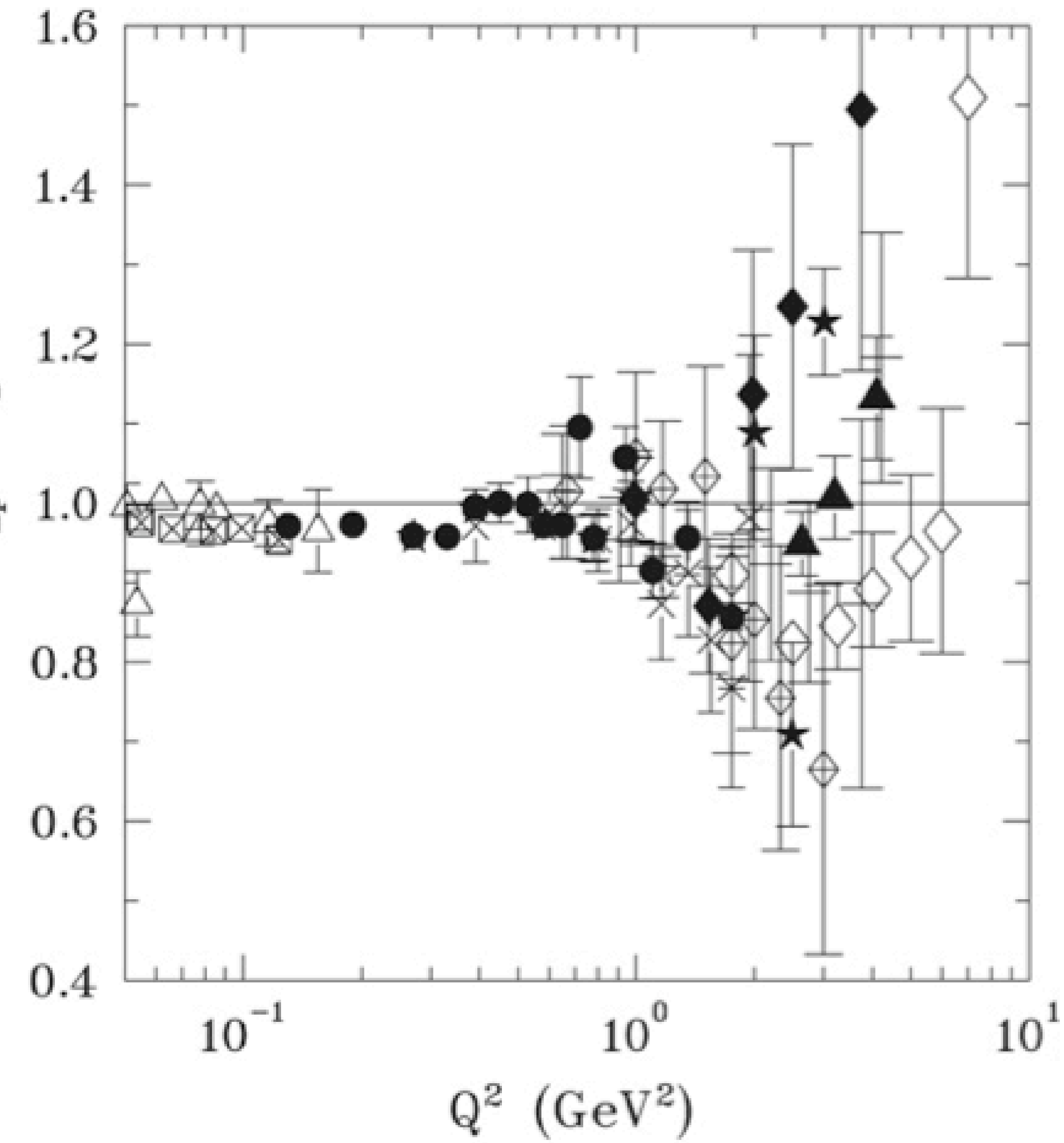
One can argue proportionality, but calculating the FFs from theory is practically impossible. Leave it to us.

$$\frac{d\sigma}{d\Omega} = \frac{1}{1+\tau}\left[G_E^2 + \frac{\tau}{\epsilon}G_M^2\right]\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}}$$

$$\tau \propto Q^2 \qquad \epsilon \propto\sim\ 1/Q^2,\ 1/\theta^2$$

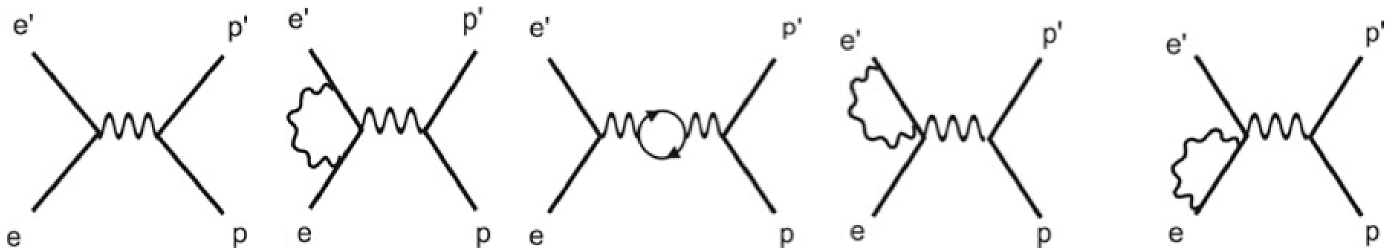
Historically (Rosenbluth separation): use Q^2 and θ to isolate and fit G_E, G_M, $G_M G_E$ or G_M/G_E.

Turns out to be controversial.

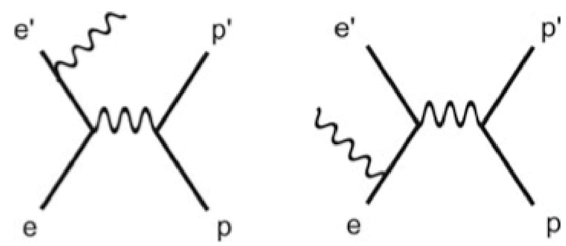


Turns out to be limited: hard to isolate FFs, thus, systematics compound.

Results are inconsistent with each other, and later methods.



(a) Born term. (b) Vertex. (c) Vacuum. (d) Self energy.

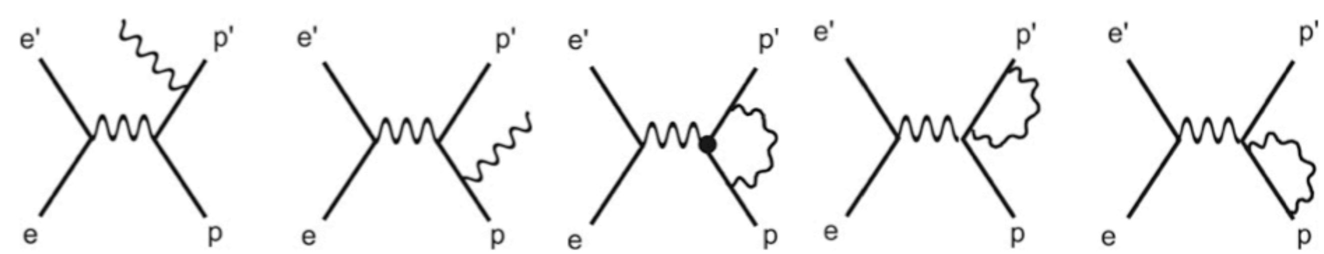


(e) Bremsstrahlung.

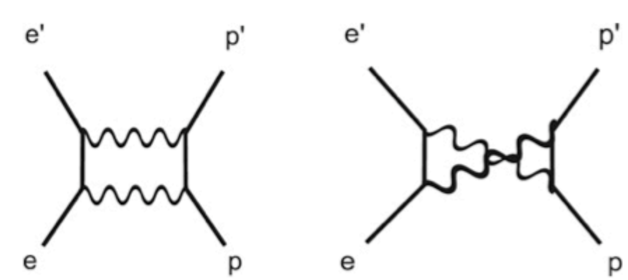
Prevailing scapegoat: the one-photon approximation

2 real FFs --> 3 complex Fs.

Or, switch methods.



(a) Bremsstrahlung. (b) Vertex. (c) Self energy.



(d) Two-photon.

Modern method: polarize beam and/or target

$$\frac{G_E}{G_M} = -\frac{P_x}{P_z}\frac{(E_{\text{beam}} + E_e)}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

Only need one Q^2 value per measurement, no need to know the beam polarization. Reduces systematics

Modern method: polarize beam and/or target

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

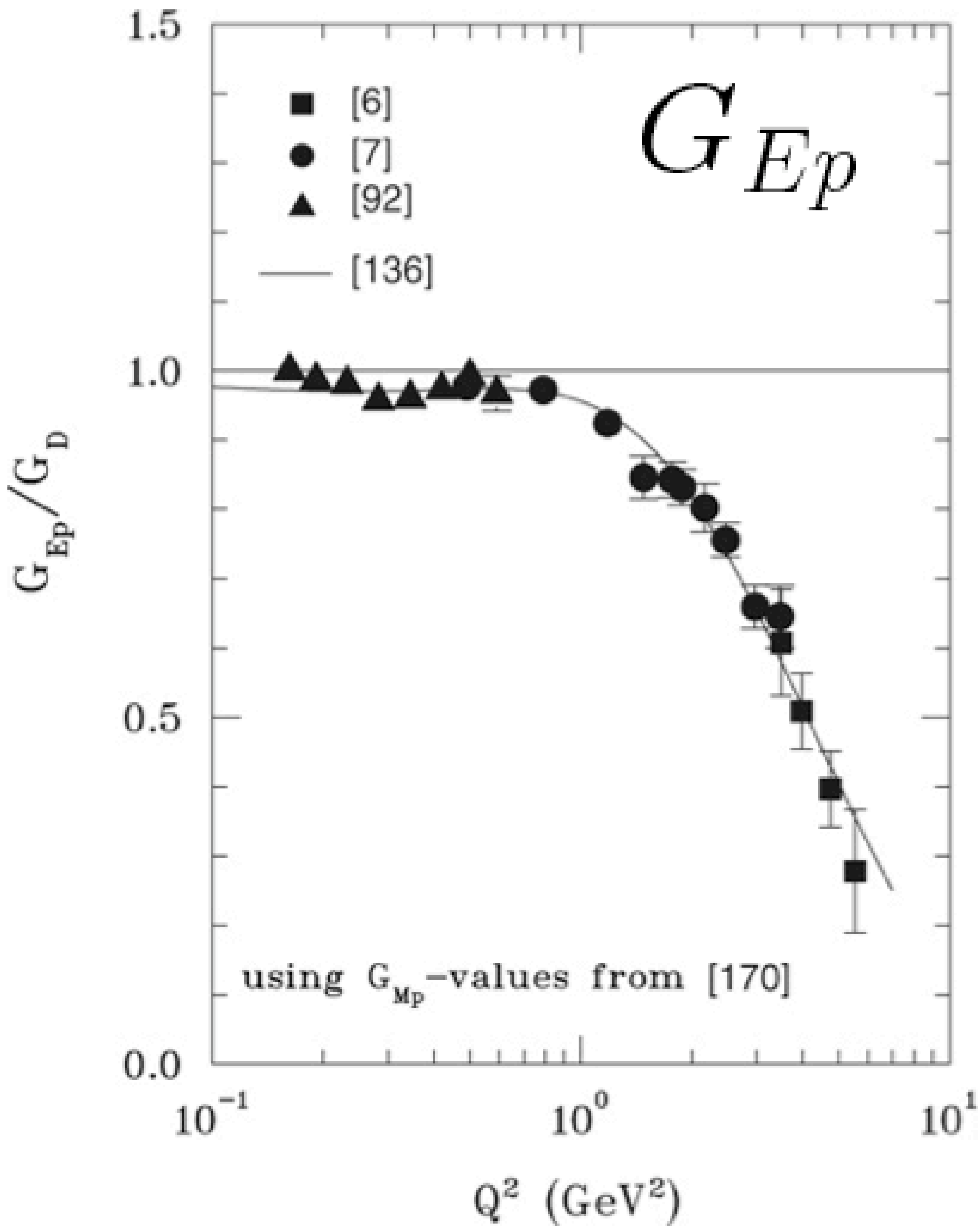
$$= -\frac{2\sqrt{\tau(1+\tau)}\tan(\theta_e/2)}{G_E^2 + \frac{\tau}{\epsilon}G_M^2}\left[\sin\theta^*\cos\phi^* G_E G_M\right.$$

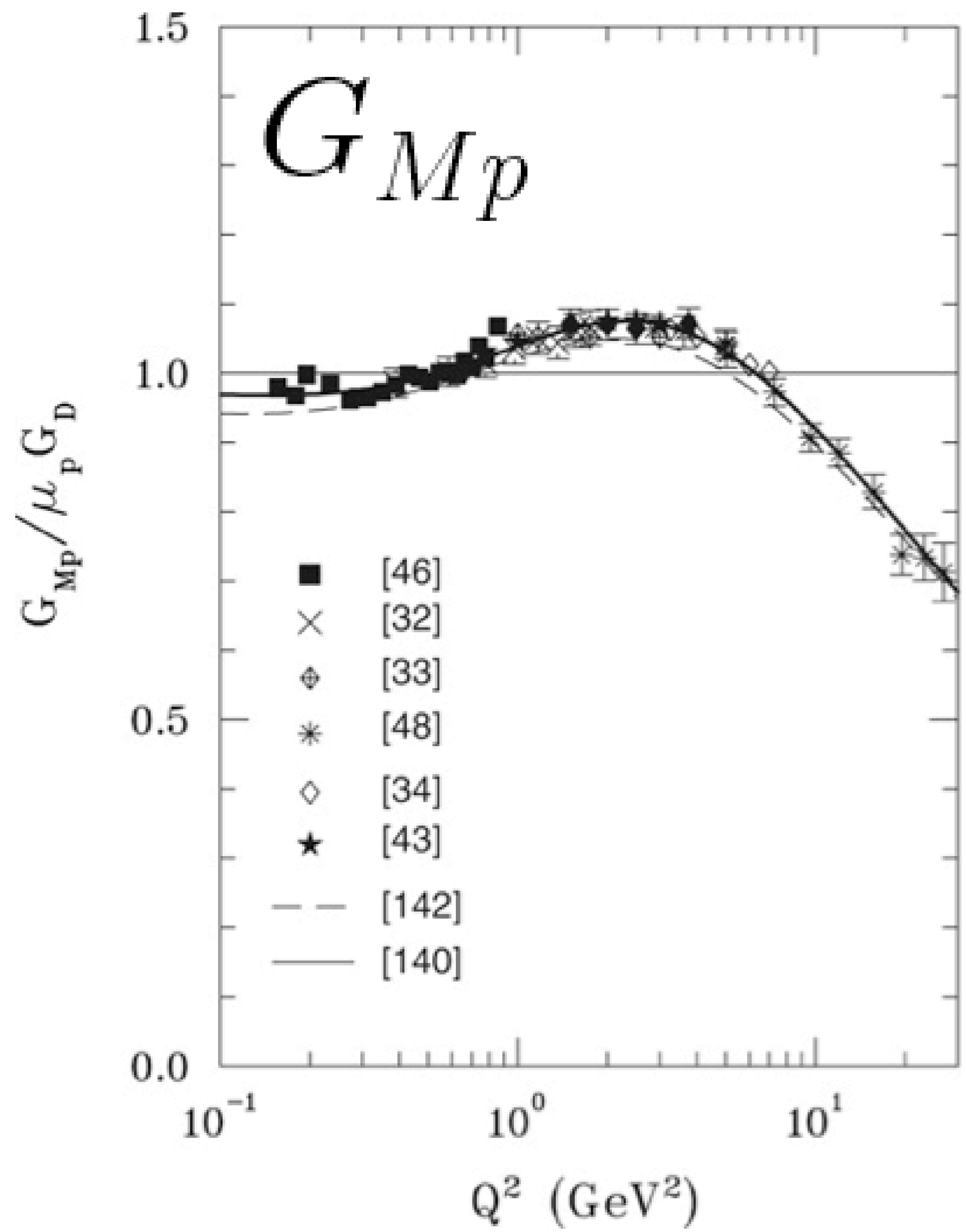
$$\left.+ \sqrt{\tau[1+(1+\tau)\tan^2(\theta_e/2)]}\cos\theta^* G_M^2\right]$$

For the right polarization angles, A ~ G_E/G_M

Rosenbluth Separation vs Polarization Methods

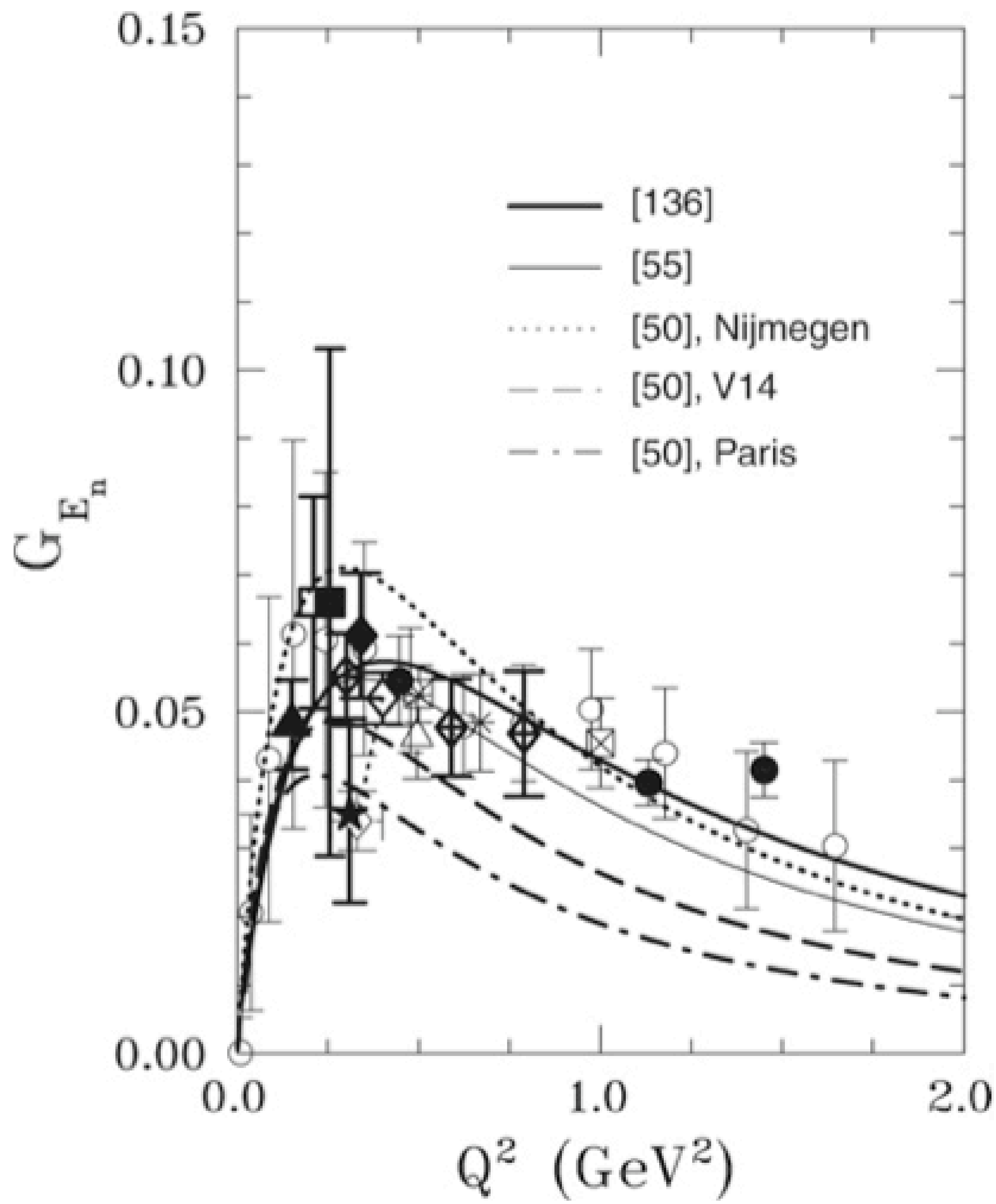
*Both have trouble with neutrons
*Both suffer Breit frame modeling
*But, uncertainty due to two-photon processes impact both cross section and polarization, but the polarization methods rely on ratios.



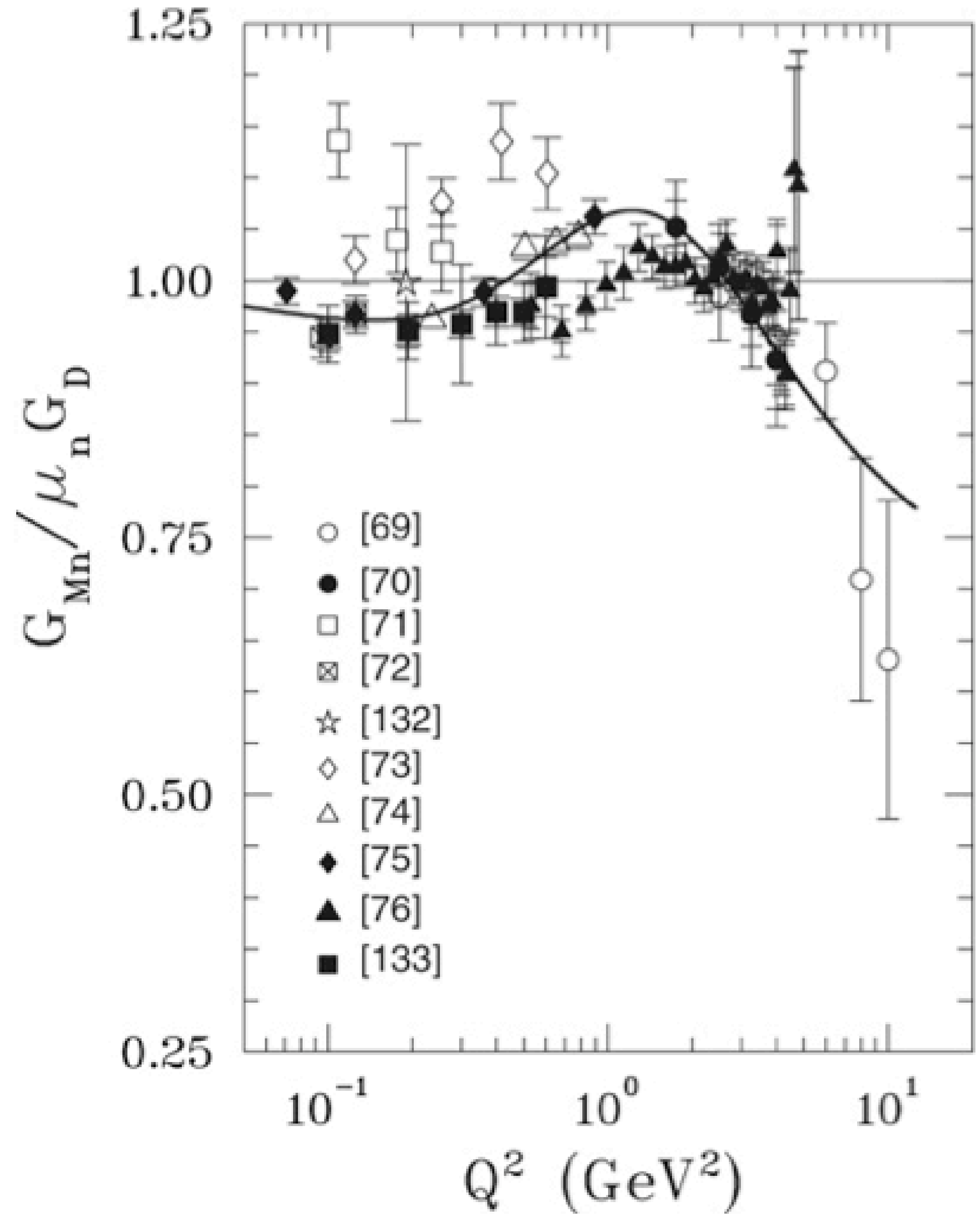


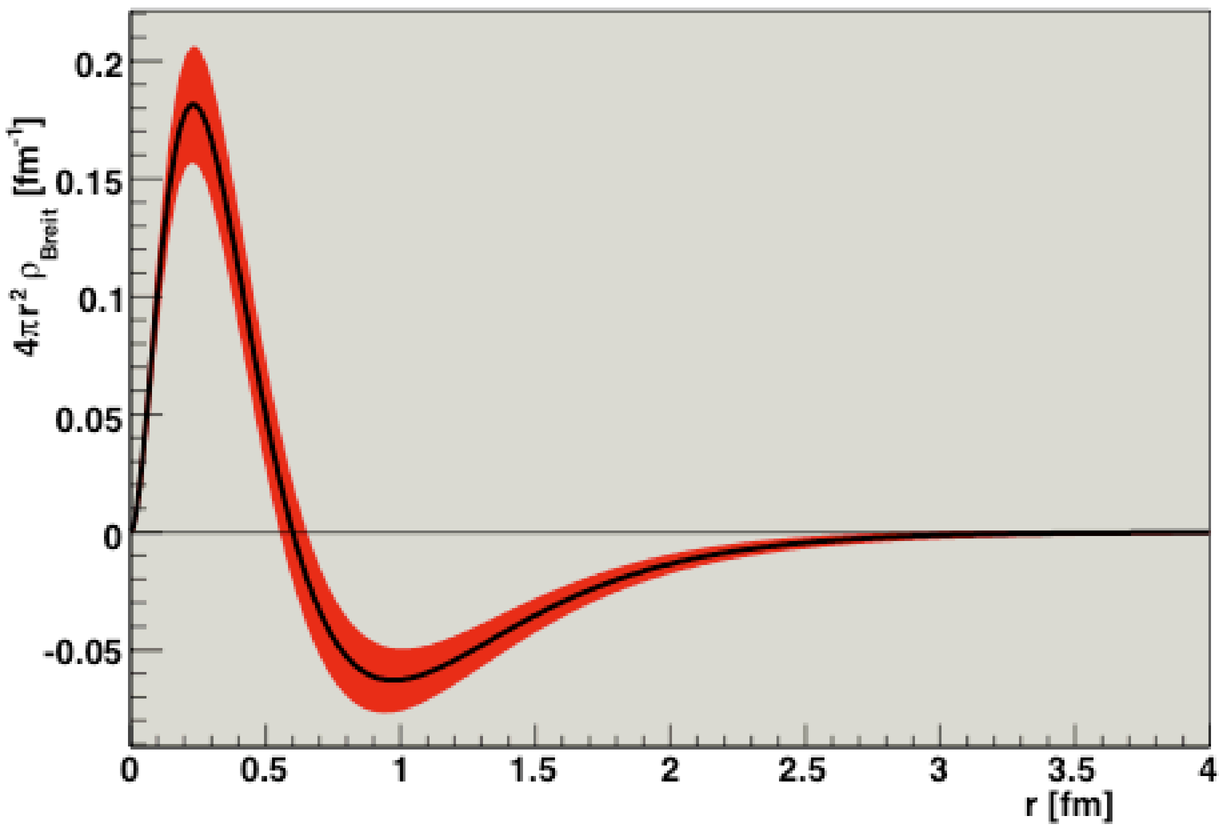
$$G_D = (1 + Q^2/0.71\text{GeV}^2)^{-2}$$

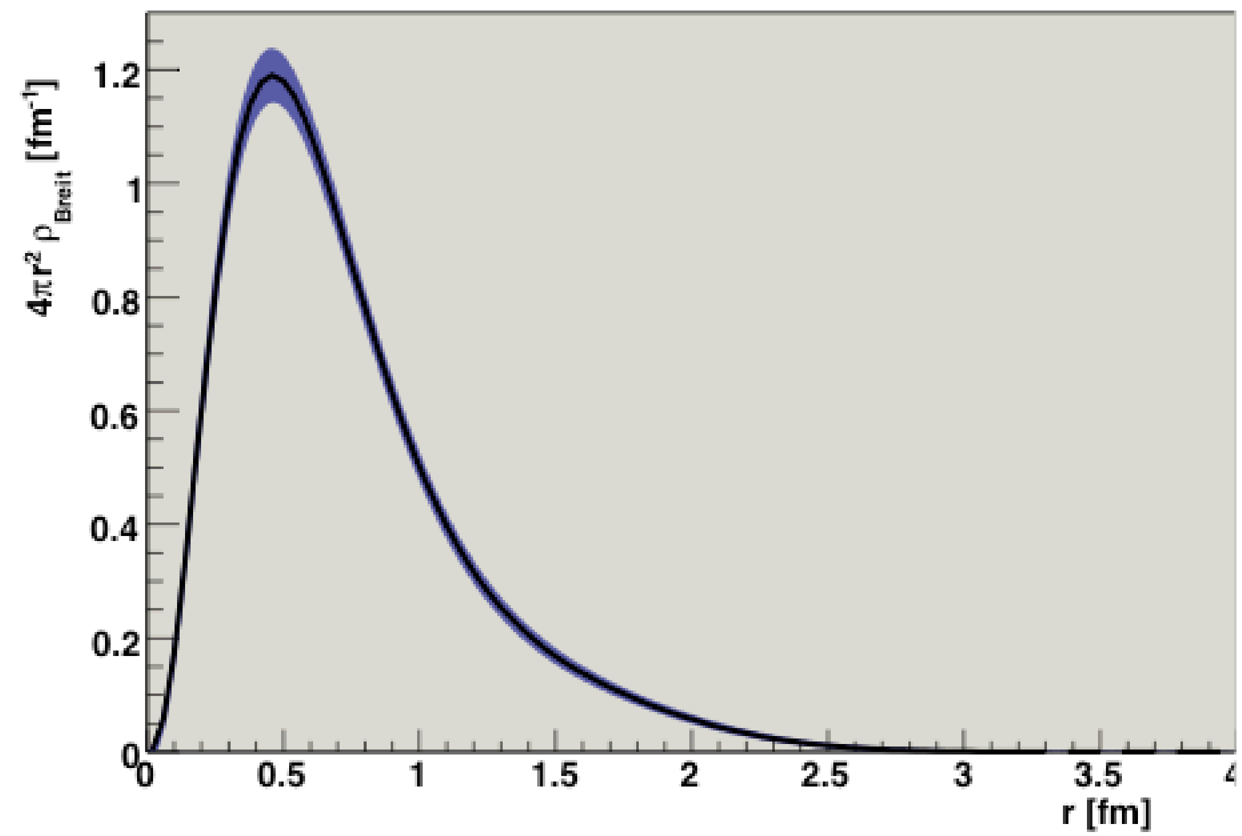
G_{En}


0.15
0.10
0.05
0.00
0.0
1.0
2.0
Q² (GeV²)
G_En
[136]
[55]
[50], Nijmegen
[50], V14
[50], Paris

G_{Mn}


1.25
1.00
0.75
0.50
0.25
10⁻¹
10⁰
10¹
Q² (GeV²)
G_Mn/μ_n G_D
[69]
[70]
[71]
[72]
[132]
[73]
[74]
[75]
[76]
[133]





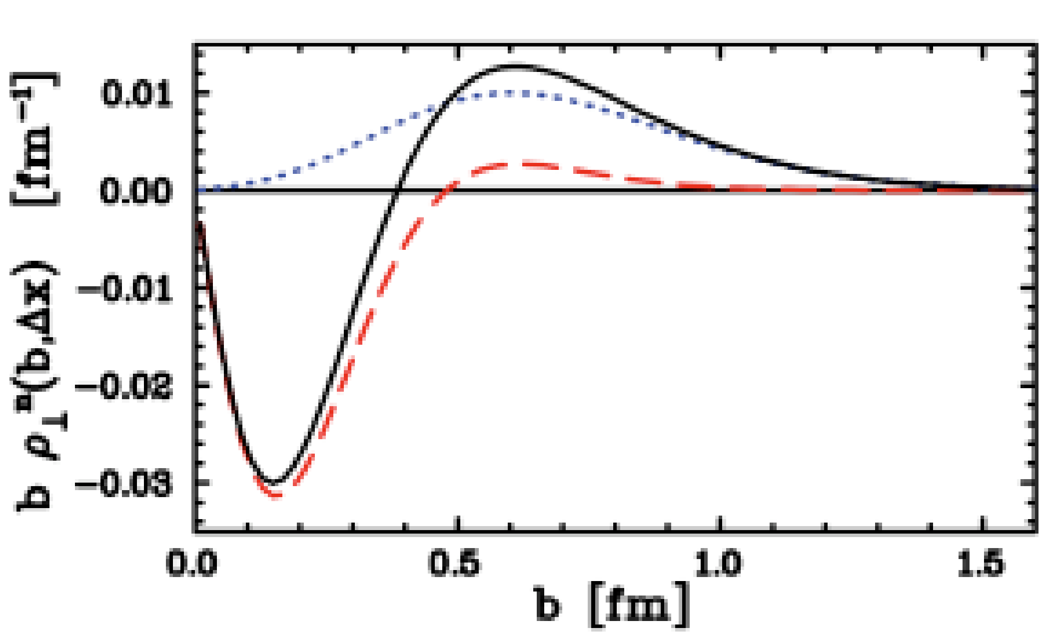


FIG. 3. (Color online) Transverse charge density for the neutron. The dotted line is the contribution from $x < 0.23$, the dashed line is that for $x > 0.23$, and the solid line is the total.

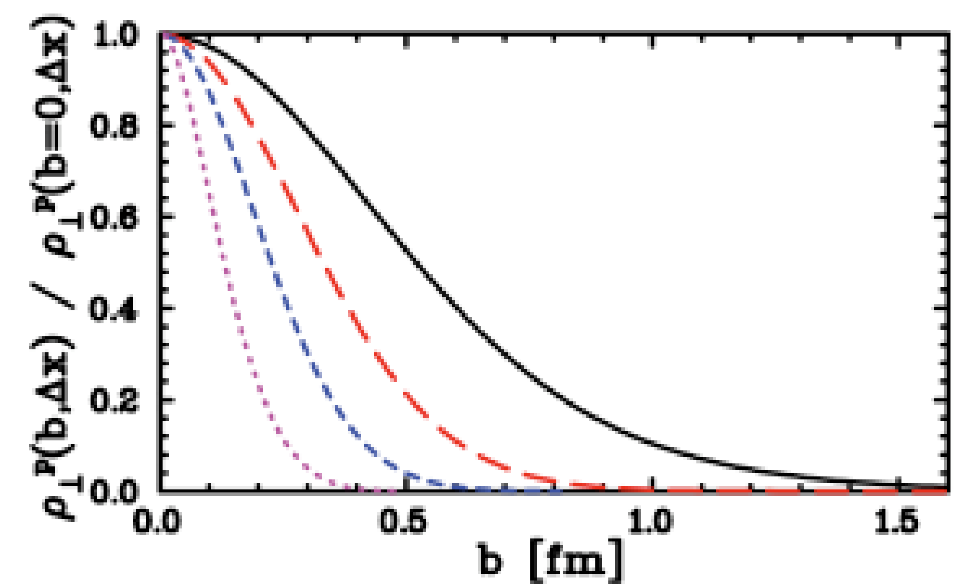


FIG. 1. (Color online) The proton transverse charge density, $\rho_\perp^p(b, \Delta x)$, for quarks in different Δx regions: $x < 0.15$ (solid), $0.15 < x < 0.3$ (long-dash), $0.3 < x < 0.5$ (short-dash), and $x > 0.5$ (dotted). The curves are calculated from the GPD of Ref. [17] and have been normalized to unity at $b = 0$.

References

Predrisat, Punjabi, Vanderhaeghen; 2007

Arrington, Roberts, Zanoti; May 2007

Long Range Nuclear Plan; Dec 2007

Miller, Arrington; Sep 2008

Hiren; Yesterday