Overview of nucleon form factor measurements

Mark Jones
Jefferson Lab
HUGS 2009

Overview of nucleon form factor measurements

Review articles

C. F. Perdrisat, V. Punjabi, M. Vanderhaeghen **Prog.Part.Nucl.Phys.59:694,2007**

J. Arrington, C. D. Roberts, J. M. Zanotti, **J.Phys.G34:S23-S52,2007**

Hyde-Wright C. E. and K. de Jager, Ann. Rev. Nucl. Part. Sci. **54**, 217 (2004).

Gao H. Y., Int. J. Mod. Phys. E **12**, 1 (2003) [Erratum-ibid. E **12**, 567 (2003)].

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In the beginning …

- 1918, Rutherford discovers the proton
- 1932, Chadwick discovers the neutron and measures the mass as 938 +/- 1.8 MeV
- 1933, Frisch and Stern measure the proton's magnetic moment = 2.6 +/- 0.3 $\mu_B = 1 + \kappa_p$
- 1940, Alvarez and Bloch measure the neutron's magnetic moment = 1.93 +/- 0.02 $\mu_B = \kappa_n$

Frisch, R.O., Stern, O.: Z. Phys. 85, 4 (1933)

L. Alvarez and F. Bloch, Phys. Rev., 57, 111 (1940).

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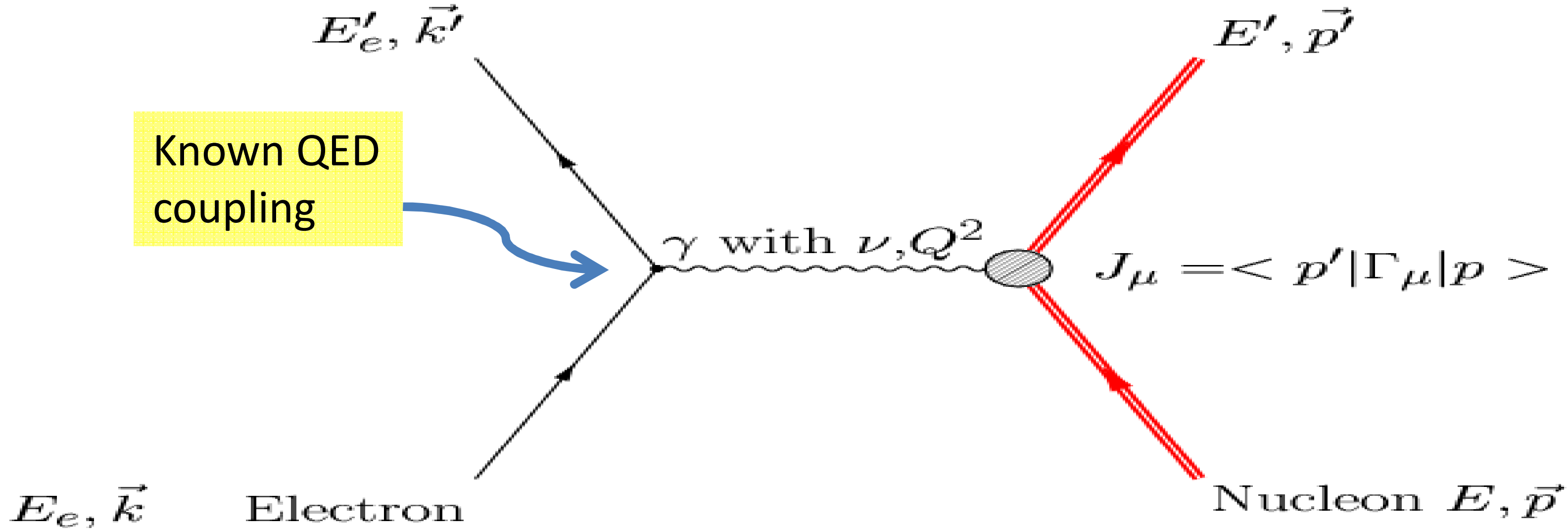
Proton and neutron have anomalous magnetic moments $\longrightarrow$ a finite size.

Frisch, R.O., Stern, O.: Z. Phys. 85, 4 (1933)

L. Alvarez and F. Bloch, Phys. Rev., 57, 111 (1940).

Electron as probe of nucleon elastic form factors



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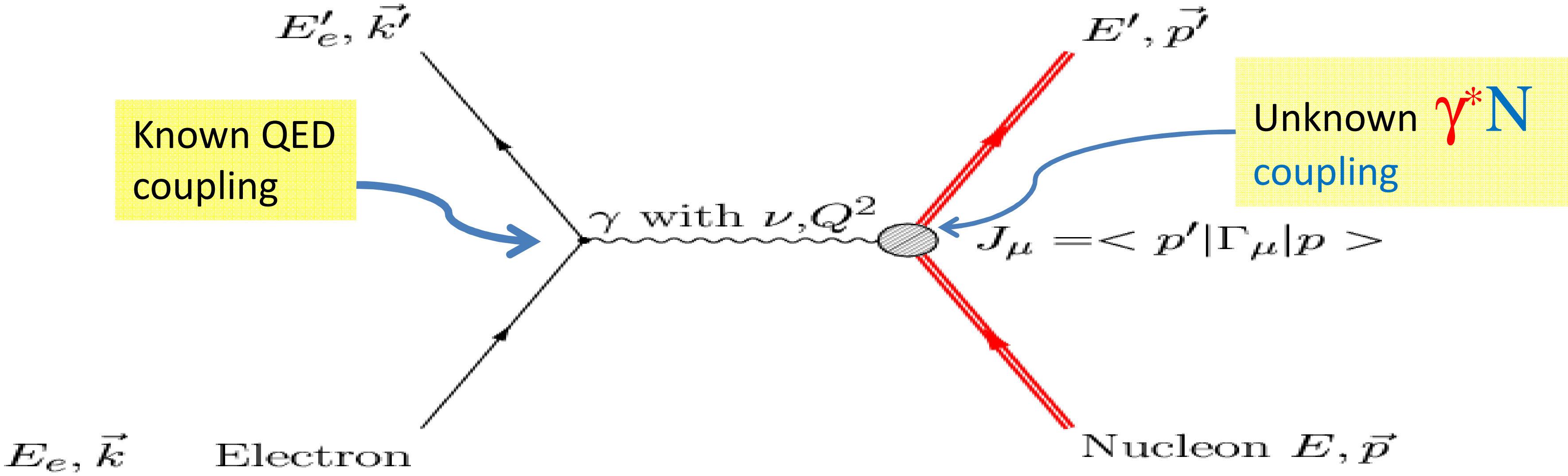

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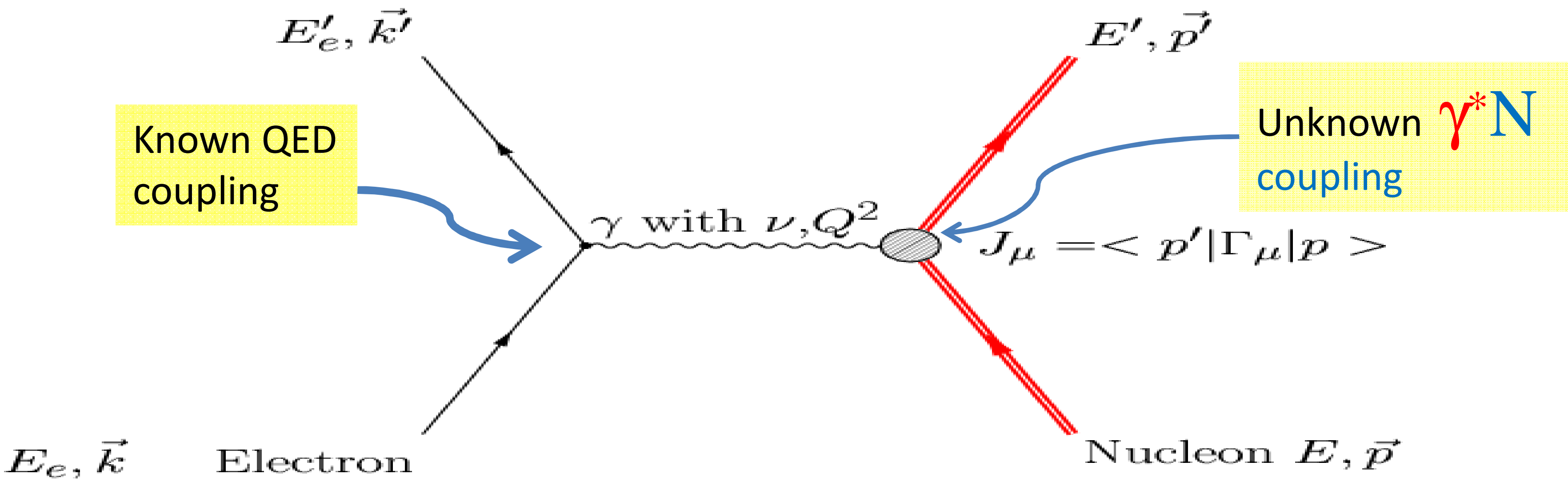
Electron as probe of nucleon elastic form factors



Nucleon vertex:

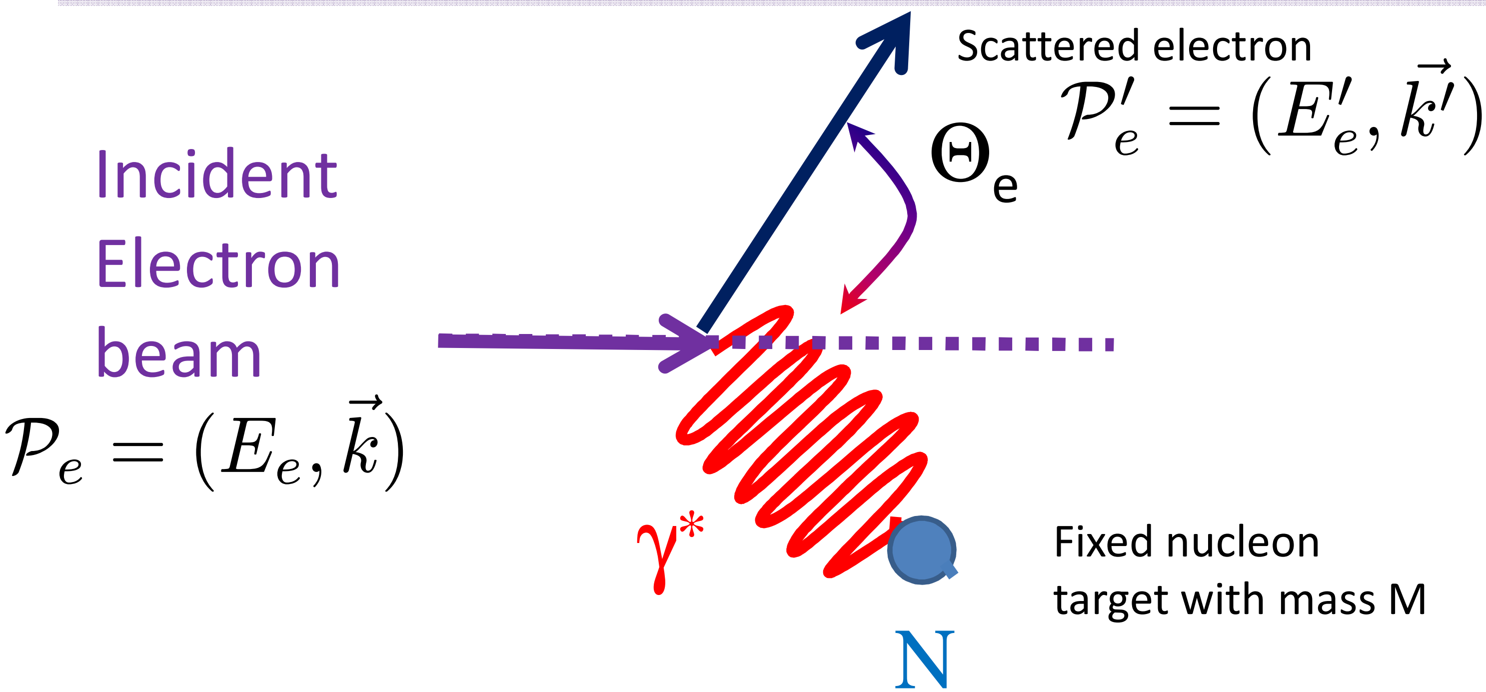
$$\Gamma_\mu(p', p) = \underbrace{F_1(Q^2)}_{Dirac}\gamma_\mu + \frac{i\kappa_p}{2M_p}\underbrace{F_2(Q^2)}_{Pauli}\sigma_{\mu\nu}q^\nu$$

Elastic form factors

F_1 is the helicity conserving (non spin-flip)

F_2 is helicity non-conserving (spin-flip)

Electron-Nucleon Scattering kinematics



Virtual photon kinematics

$$Q^2 = -(\mathcal{P}_e - \mathcal{P}'_e)^2 = 4E_e E'_e \sin^2(\theta_e/2) \quad (m_e = 0)$$

$$\nu = E_e - E'_e$$

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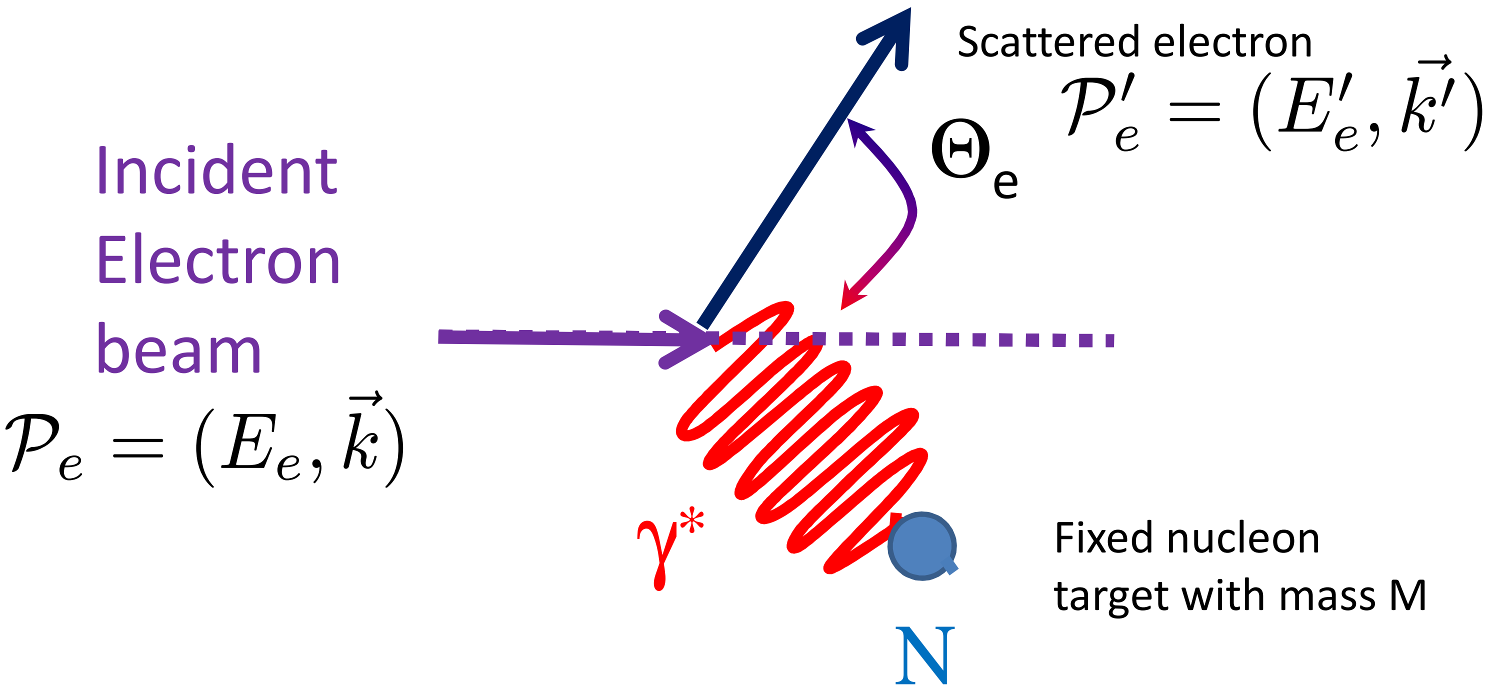

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γ^*N center of mass energy $\quad W = \sqrt{M^2 + 2M\nu - Q^2}$

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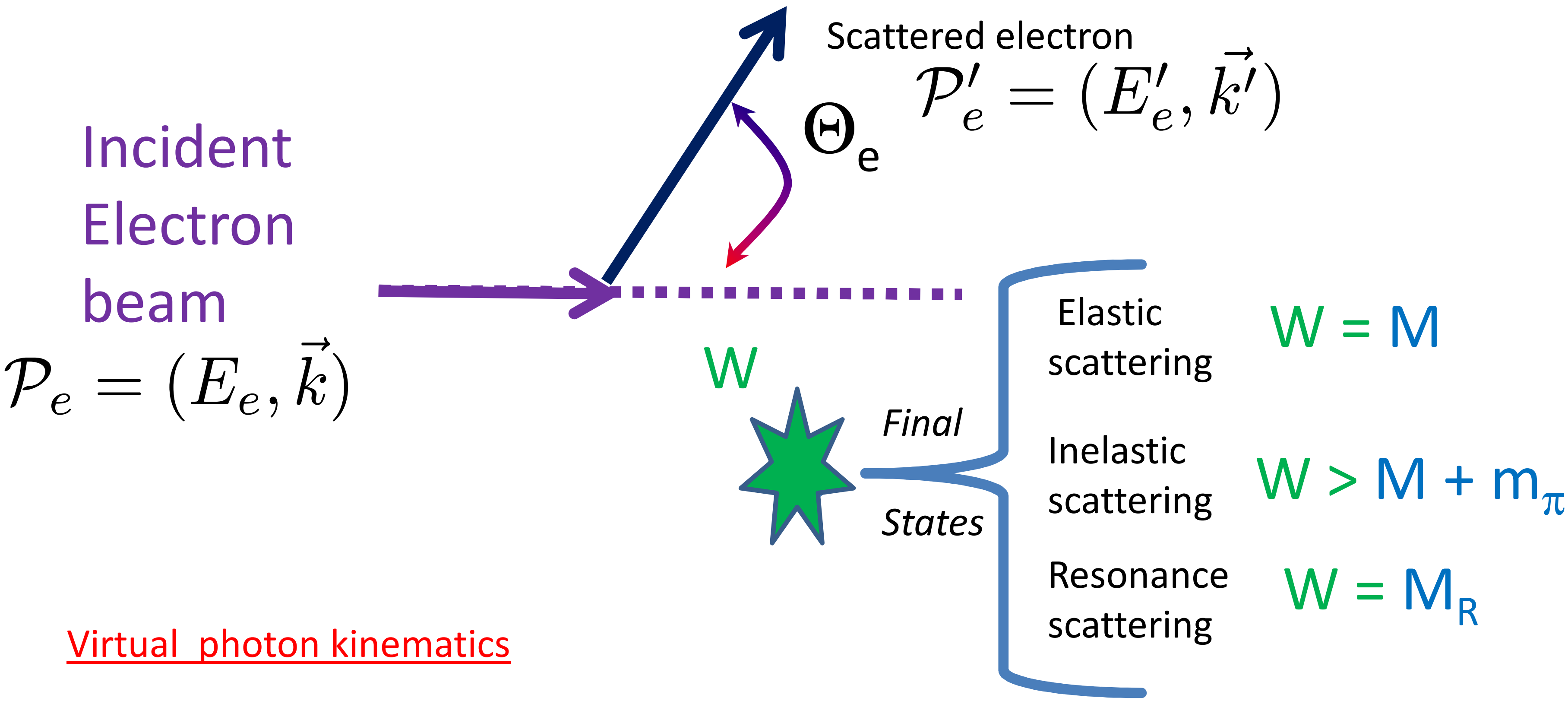

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<u>γ^*N center of mass energy</u> $\qquad W = \sqrt{M^2 + 2M\nu - Q^2}$

Electron-Nucleon cross section

Single photon exchange (Born) approximation

$$\boxed{\begin{aligned}\frac{d\sigma}{d\Omega} = \quad & (\frac{d\sigma}{d\Omega})_{\text{Mott}} \frac{E'_e}{E_e}\{F_1^2(Q^2) \\ + \quad & \tau\left[\kappa^2 F_2^2(Q^2) + 2(F_1(Q^2) + \kappa F_2(Q^2))^2 \tan^2\frac{\theta_e}{2}\right]\}\end{aligned}}$$

$$\boxed{\tau = Q^2/4M^2}$$

Low Q^2 $\Rightarrow$ $$\boxed{\frac{d\sigma}{d\Omega} = (\frac{d\sigma}{d\Omega})_{\text{Mott}} \frac{E'_e}{E_e} F_1^2(Q^2)}$$

Early Form factor measurements

Proton is an extended charge potential $\rho(\vec{r})$

$$\sigma = \sigma_{\mathrm{Mott}} \left| \int \rho(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3\vec{r} \right|^2$$

$$\sigma = \sigma_{\mathrm{Mott}} |F(\vec{q})|^2$$

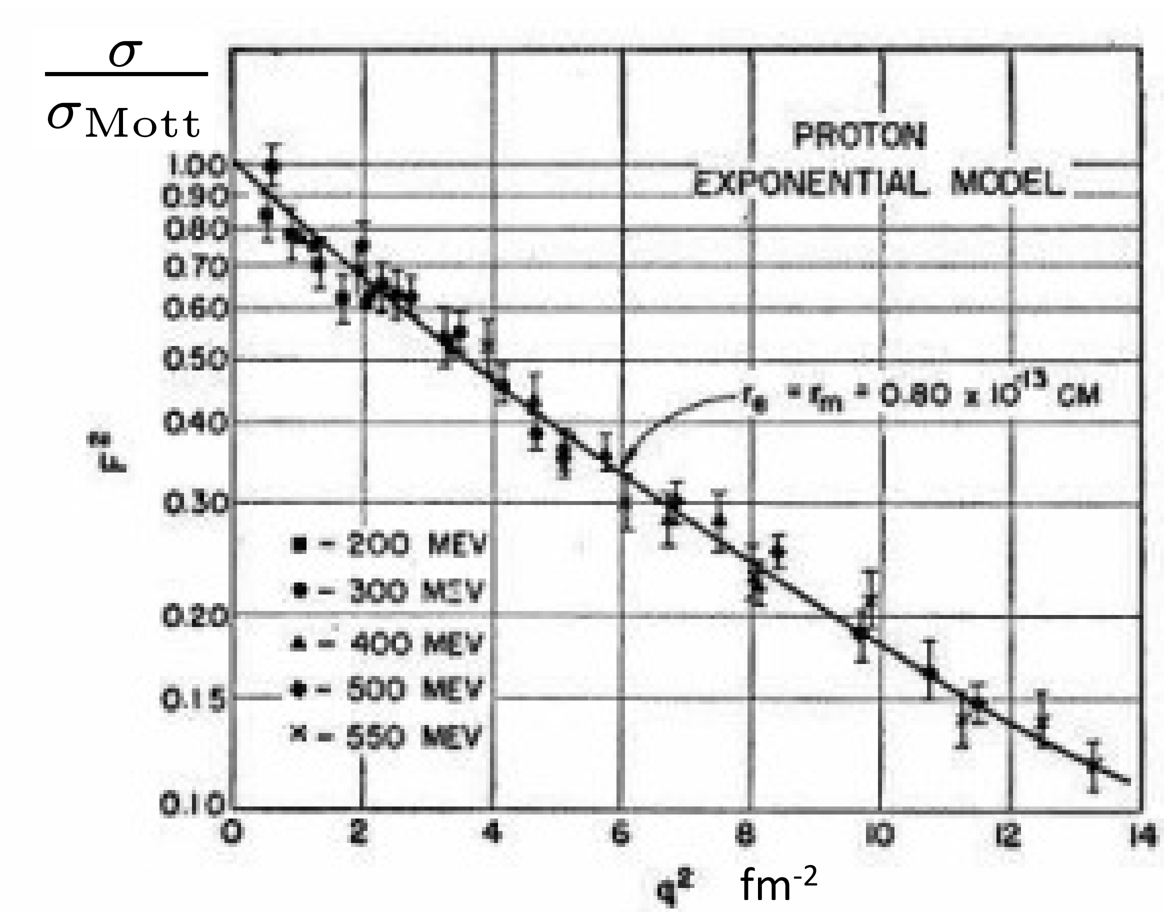
Proton has a radius of 0.80 x 10^{-13} cm

$$\rho(\vec{r}) = \sqrt{3a} e^{a^2 \vec{r}}$$

$$F(\vec{q}) = \left(1 + \frac{q^2}{a^2}\right)^{-2}$$

"Dipole" shape

$\frac{\sigma}{\sigma_{\mathrm{Mott}}}$



fm^{-2}

$Q^2 = 0.5$ GeV^2

Hofstadter R., Rev. Mod. Phys. **28**, 214 (1956).

Sach's Electric and Magnetic Elastic Form Factors

In center of mass of the eN system (Breit frame),

no energy transfer ν_{CM} = 0 so $|\mathbf{q}|^2 = |\vec{q}|^2$

$\rho(\vec{r})$ = charge distribution

$\mu(\vec{r})$ = magnetization distribution

$$G_E = \int \rho(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3\vec{r} \qquad G_M = \int \mu(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3\vec{r}$$

$$\frac{< r^2 >}{6} = -\frac{dG_E(Q^2)}{dQ^2}|_{Q^2=0} \qquad \frac{< r^2 >}{6} = -\frac{1}{\mu_N}\frac{dG_M(Q^2)}{dQ^2}|_{Q^2=0} \, ,$$

$$\text{At } Q^2 = 0$$

$$G_{Mp} = 2.79 \; G_{Mn} = -1.91$$

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

Electron-Nucleon cross section

Single photon exchange (Born) approximation

$$\boxed{\tau = Q^2/4M^2}$$

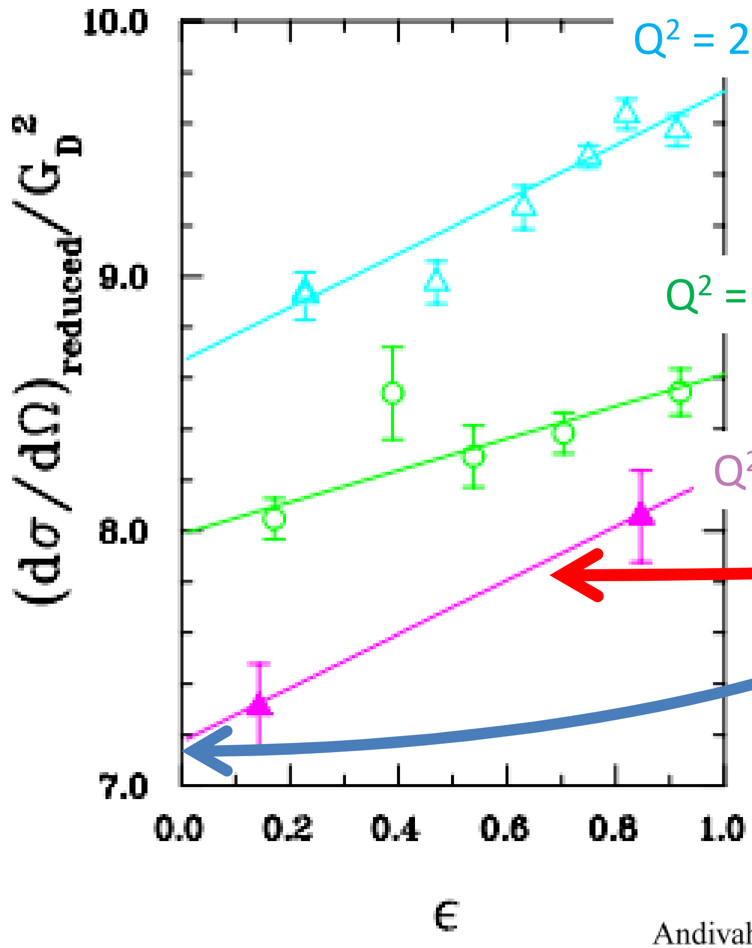
$$\boxed{\begin{aligned}\frac{d\sigma}{d\Omega} = & \quad (\frac{d\sigma}{d\Omega})_{\mathrm{Mott}} \frac{E'_e}{E_e} \{ F_1^2(Q^2) \\ + & \quad \tau \left[\kappa^2 F_2^2(Q^2) + 2(F_1(Q^2) + \kappa F_2(Q^2))^2 \tan^2 \frac{\theta_e}{2} \right] \}\end{aligned}}$$

$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \kappa_N \tau F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + \kappa_N F_2(Q^2) \end{aligned}$$

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

Elastic cross section in G_E and G_M

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



$$\left(\frac{d\sigma}{d\Omega}\right)_{reduced} = \frac{\epsilon(1+\tau)}{\tau}\left(\frac{d\sigma}{d\Omega}\right)_{exp} / \left(\frac{d\sigma}{d\Omega}\right)_{Mott}$$

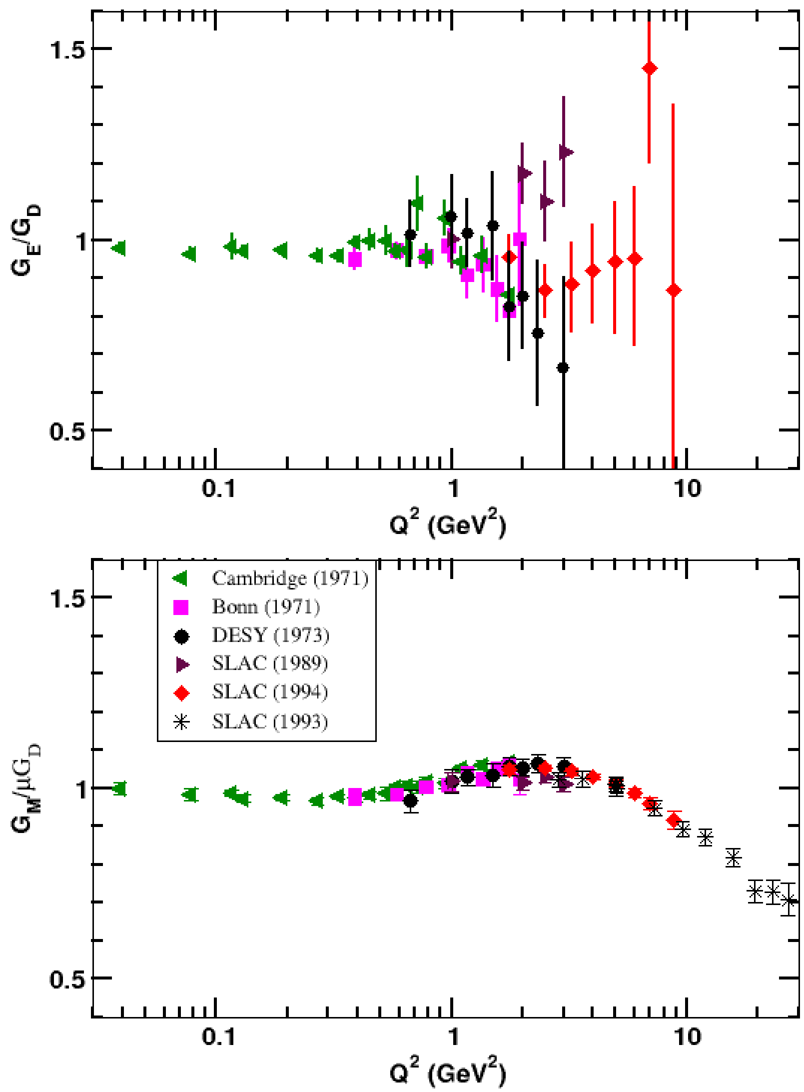
$$= G_M^2 + \frac{\epsilon}{\tau}G_E^2$$

Slope

Intercept

Andivahis L. *et al.*, Phys. Rev. D **50**, 5491 (1994)

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



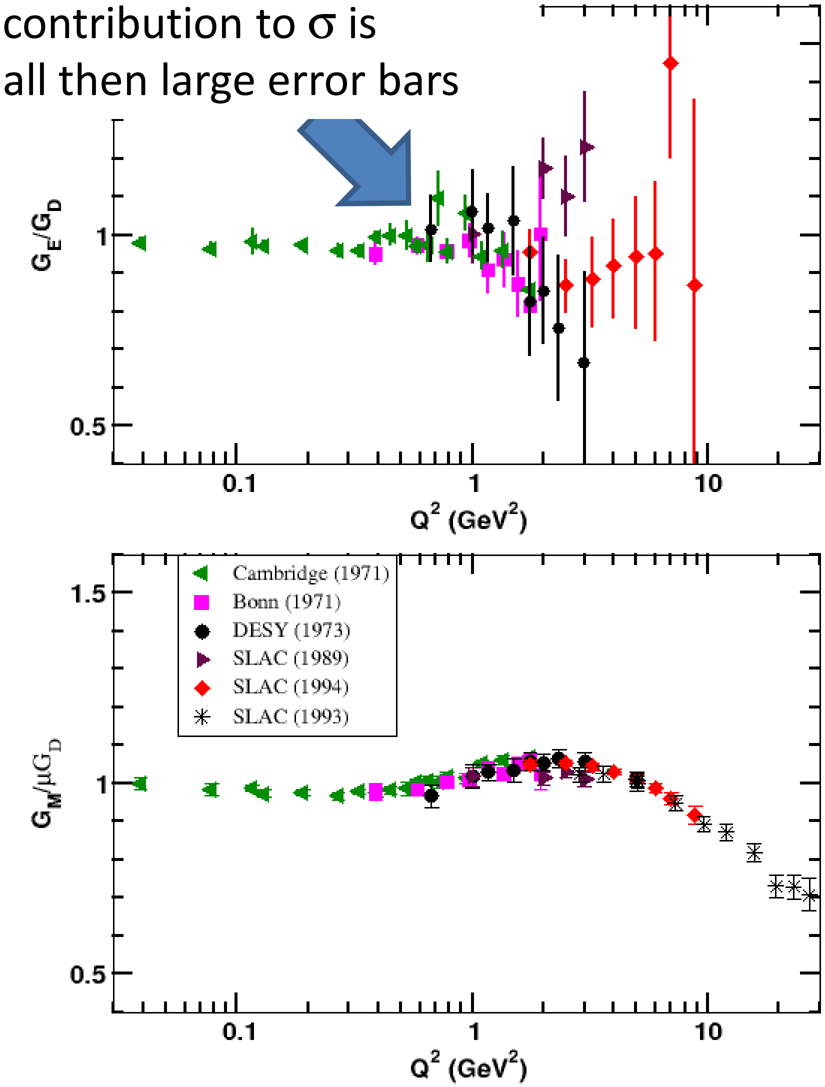
Experiments from the 1960s to 1990s gave a cumulative data set

$$G_E/G_D \approx G_M/(\mu_p G_D) \approx 1$$

$$G_D = (1 + \frac{Q^2}{0.71})^{-2}$$

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

G_E contribution to σ is small then large error bars



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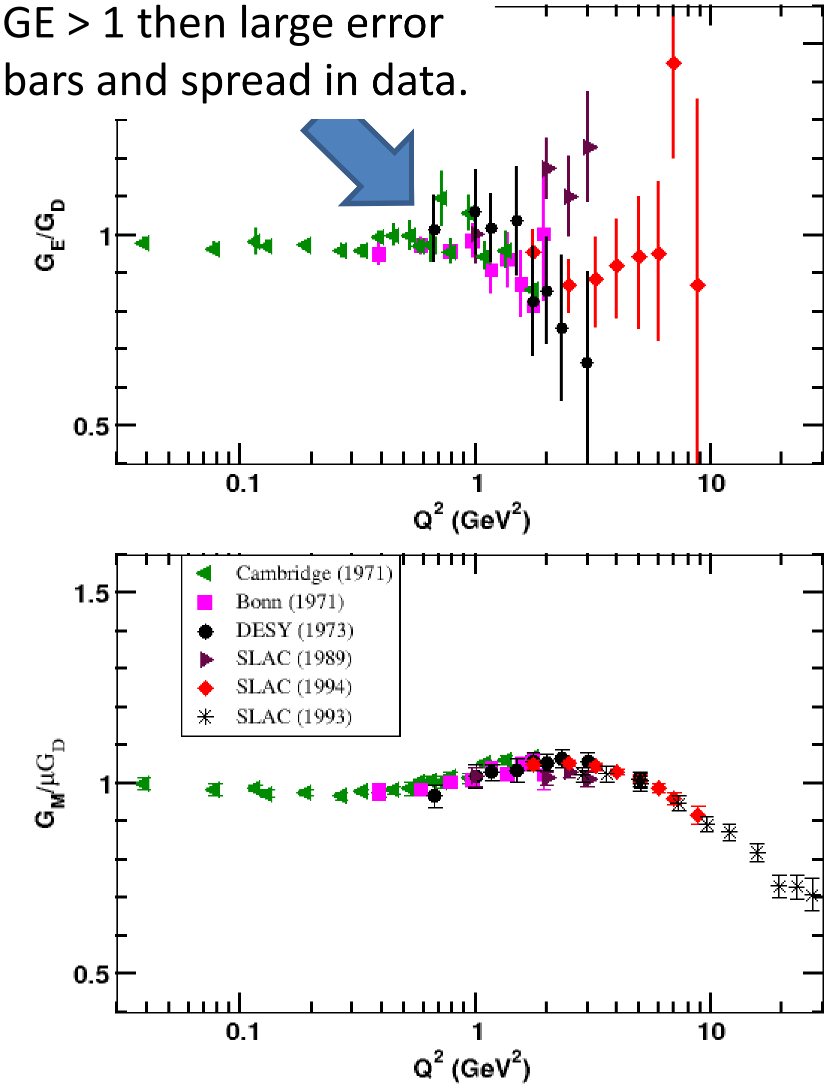
Proton Form Factors: G_{Mp} and G_{Ep}

GE > 1 then large error bars and spread in data.



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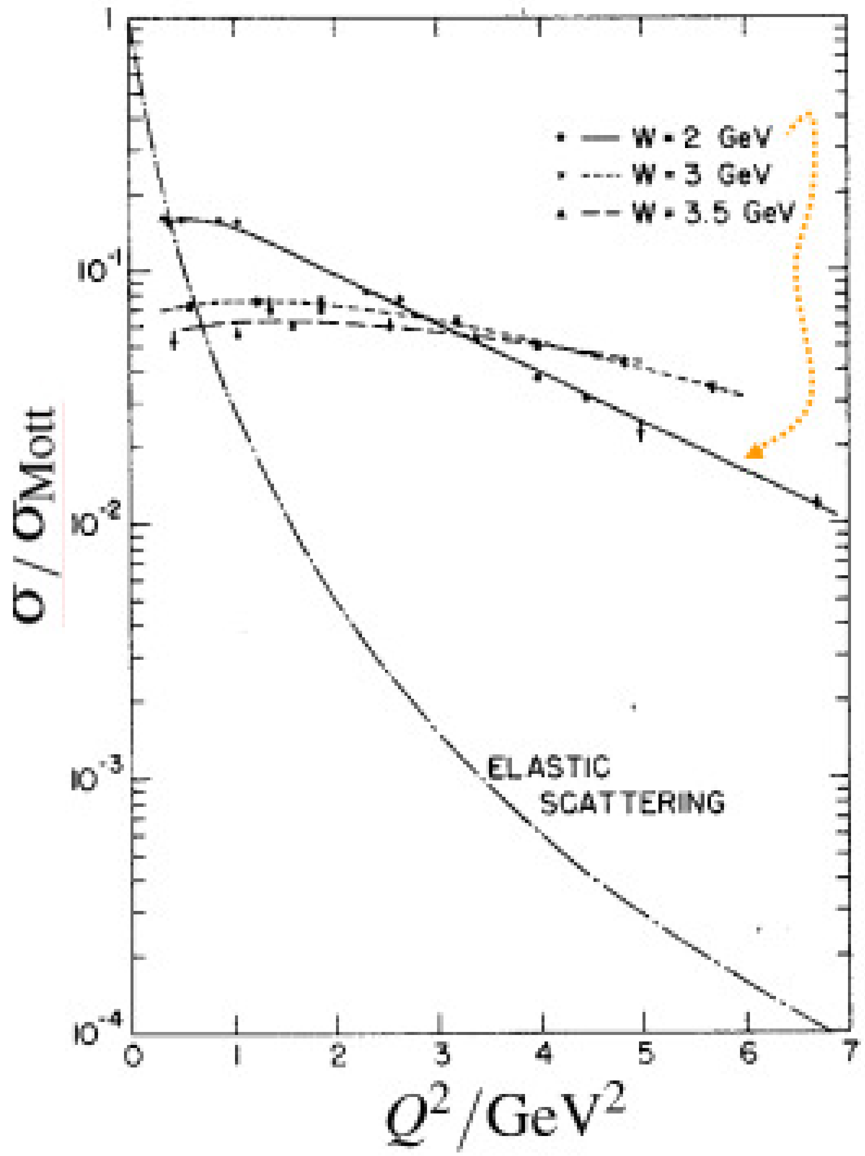
G_M measured to $Q^2 = 30$

G_E measured well only to $Q^2 = 1$

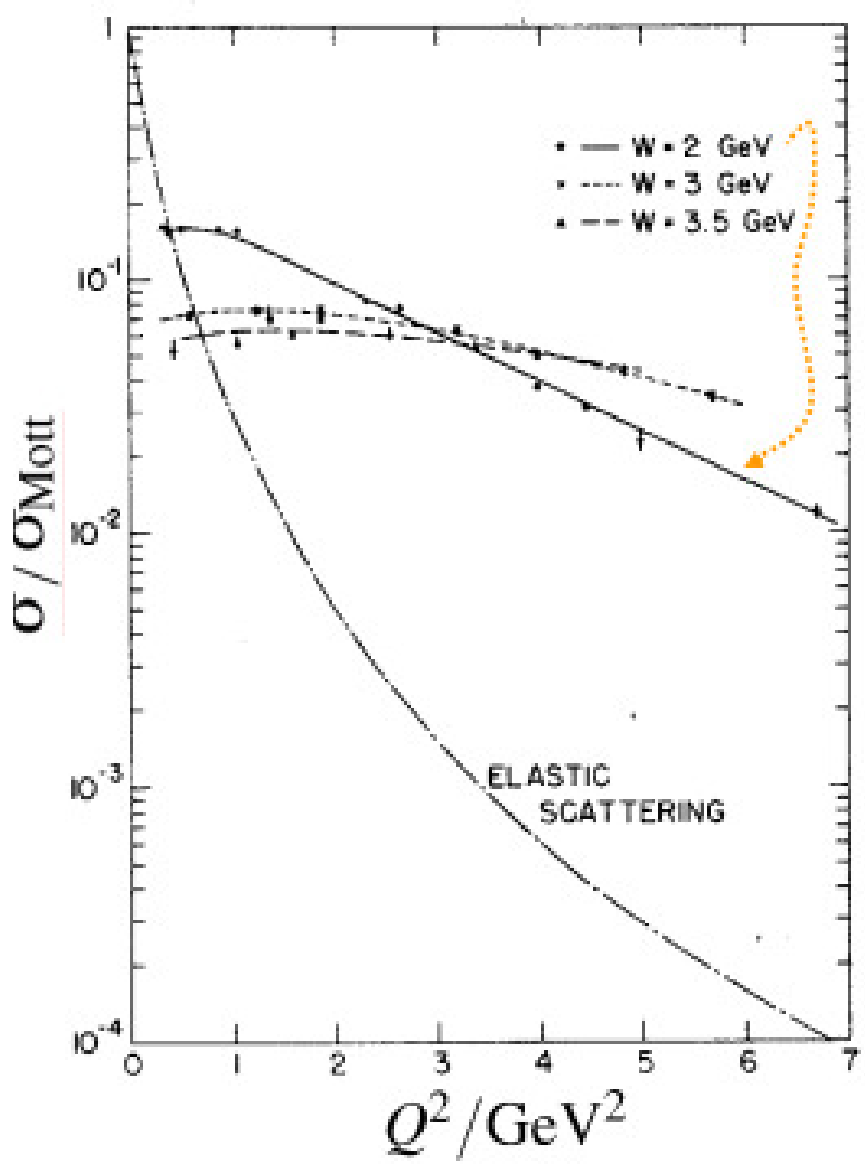
Q^2 dependence of elastic and inelastic cross sections



As Q^2 increases

$\sigma_{elastic}/\sigma_{Mott}$ drops dramatically

Q^2 dependence of elastic and inelastic cross sections



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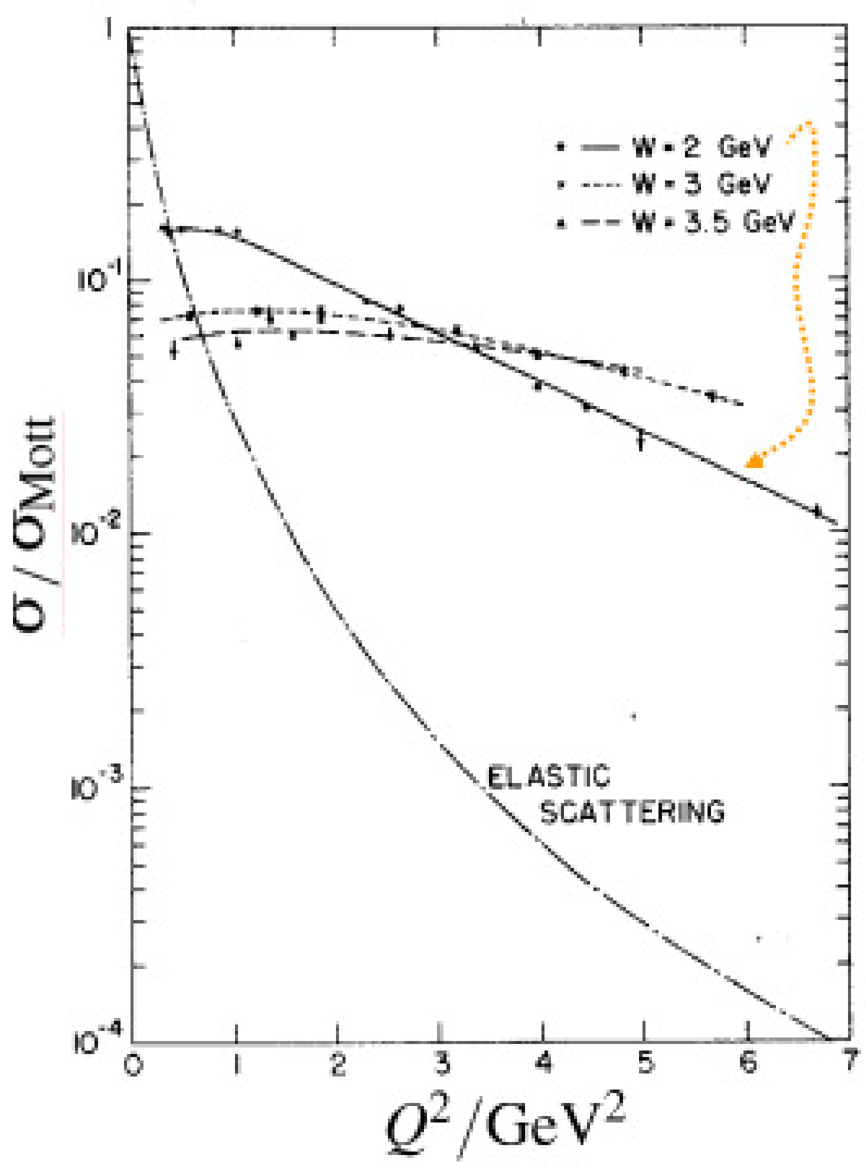

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$\sigma_{inel} / \sigma_{Mott}$ almost constant

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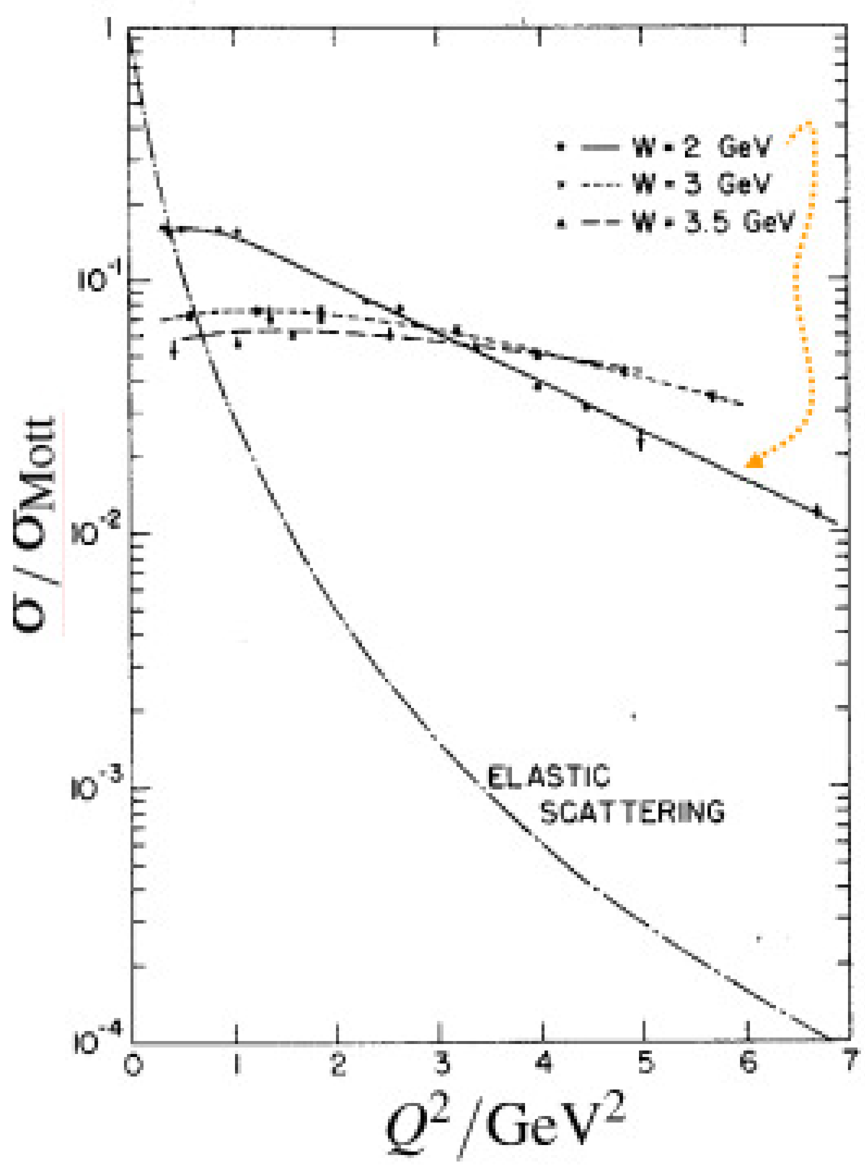

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Point object inside the proton

Asymptotic freedom to confinement

• "point-like" objects in the nucleon are eventually identified as quarks
•Theory of Quantum Chromodynamics (QCD) with gluons mediating the strong force.
•At high energies , the quarks are asymptotically free and perturbative QCD approaches can be used.

Asymptotic freedom to confinement

- "point-like" objects in the nucleon are eventually identified as quarks
- Theory of Quantum Chromodynamics (QCD) with gluons mediating the strong force.
- At high energies , the quarks are asymptotically free and perturbative QCD approaches can be used.

No free quarks $\Longleftrightarrow$ **Confinement**

- The QCD strong coupling increases as the quarks separate from each other

- Quantatitive QCD description of nucleon's properties remains a puzzle

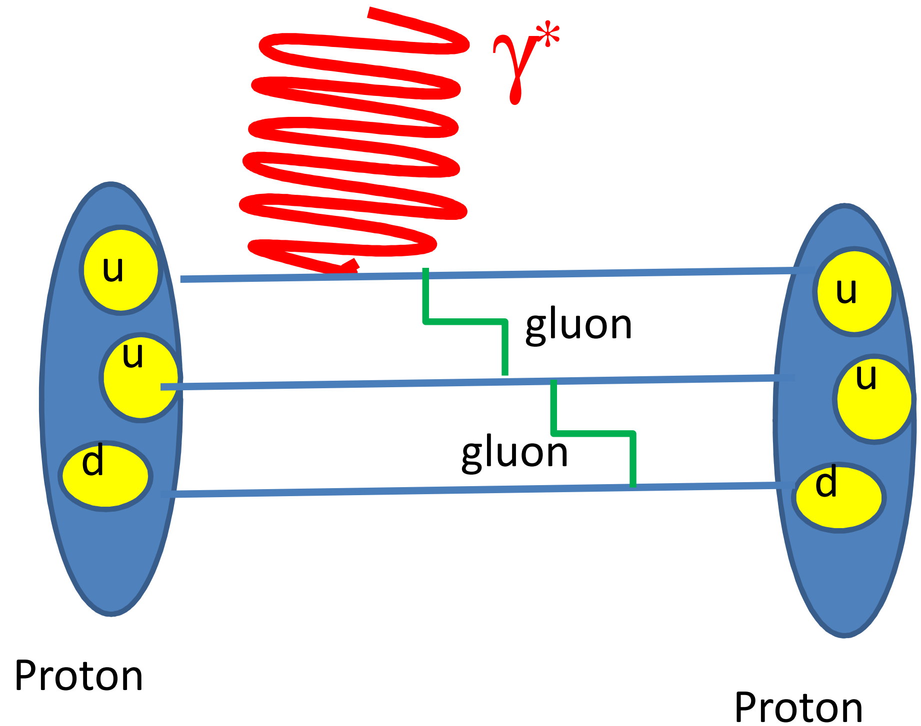
- Study of nucleon elastic form factors is a window see how the QCD strong coupling changes

Elastic FF in perturbative QCD

Infinite momentum frame

- Nucleon looks like three massless quarks
- Energy shared by two hard gluon exchanges
- Gluon coupling is $1/Q^2$

$$F_1(Q^2) \propto 1/Q^4$$



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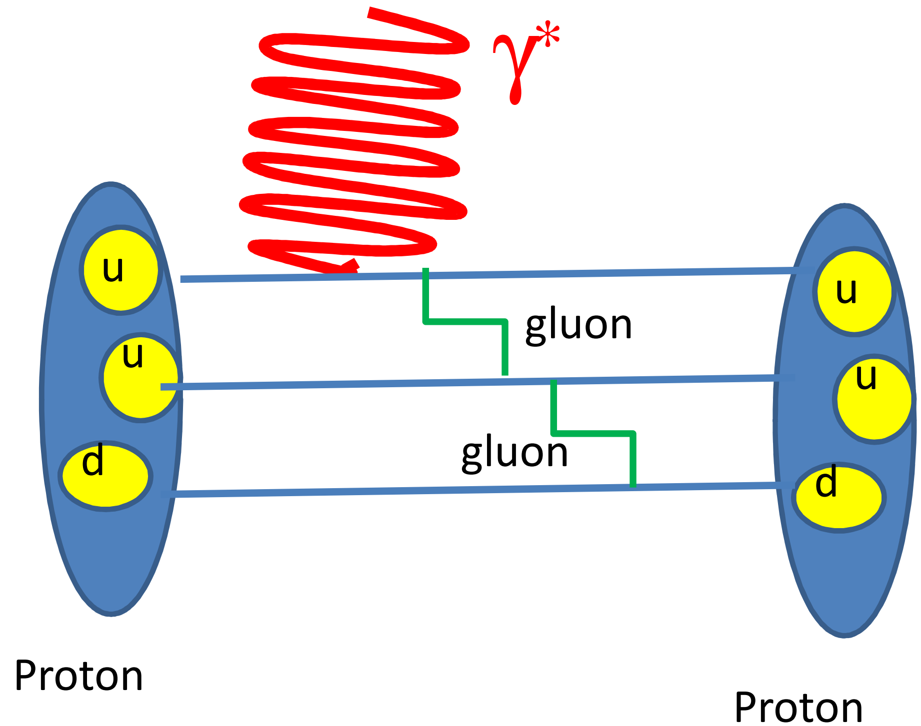
- Energy shared by two hard gluon exchanges
- Gluon coupling is $1/Q^2$

$$F_1(Q^2) \propto 1/Q^4$$

- F_2 requires an helicity flip the spin of the quark. Assuming the L = 0

$$F_2(Q^2) \propto 1/Q^6$$

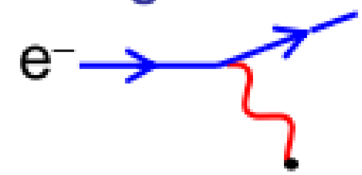


Brodsky S. J. and G.R. Farrar, Phys. Rev. D **11**, 1309 (1975).

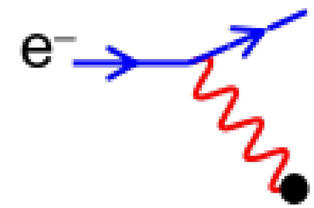
Electron as probe of nucleon structure

★ **In $e^-p \rightarrow e^-p$ scattering the nature of the interaction of the virtual photon with the proton depends strongly on wavelength**

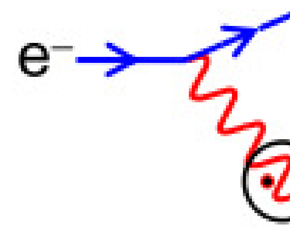
- **At very low electron energies $\lambda \gg r_p$: the scattering is equivalent to that from a "point-like" spin-less object**



- **At low electron energies $\lambda \sim r_p$: the scattering is equivalent to that from a extended charged object**



- **At high electron energies $\lambda < r_p$: the wavelength is sufficiently short to resolve sub-structure. Scattering from constituent quarks**



- **At very high electron energies $\lambda \ll r_p$: the proton appears to be a sea of quarks and gluons.**