High t Form Factors and OAM

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Connection between elastic form factors and OAM through models

Model wave functions, compute form factors

OAM content of Models

History -Definitions

$$\langle N, \lambda' p' \,|J^\mu|\, N, \lambda p\rangle = \bar{u}_{\lambda'}(p')[F_1(Q^2)\gamma^\mu + F_2(Q^2)\sigma^{\mu\nu}\,\frac{(p'-p)_\nu}{2M_p}]u_\lambda(p)$$

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

$$F_1(Q^2) = \langle N,\uparrow |J^+|N,\uparrow\rangle, \qquad QF_2(Q^2) = -2M_p\langle N,\uparrow |J^+|N,\downarrow\rangle$$

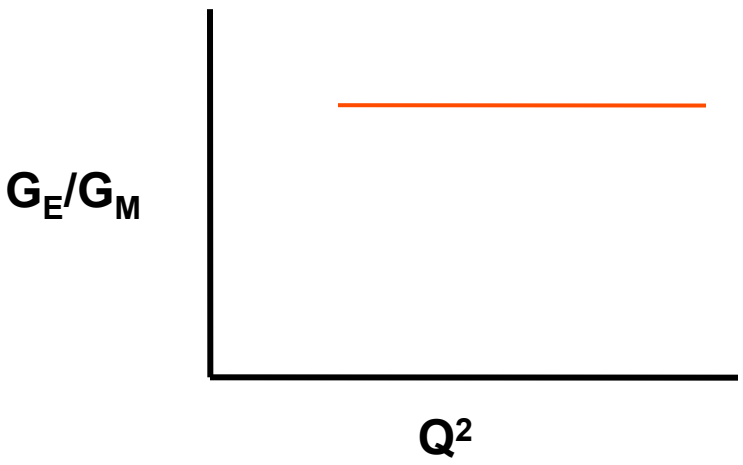
old pQCD:

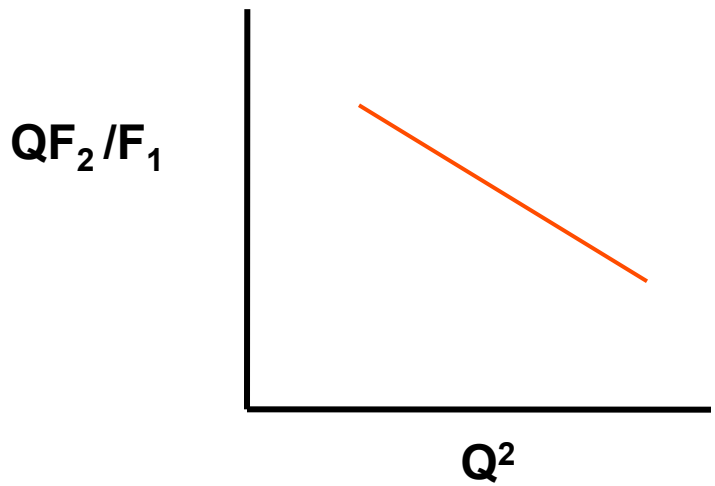
$$\frac{QF_2(Q^2)}{2M_N F_1} \sim \frac{m_{\rm quark}}{Q} \to \frac{G_E}{G_M} = \text{const}$$

Same as non-relativistic

JLab 2000,2002

Expectations- Pre Jlab

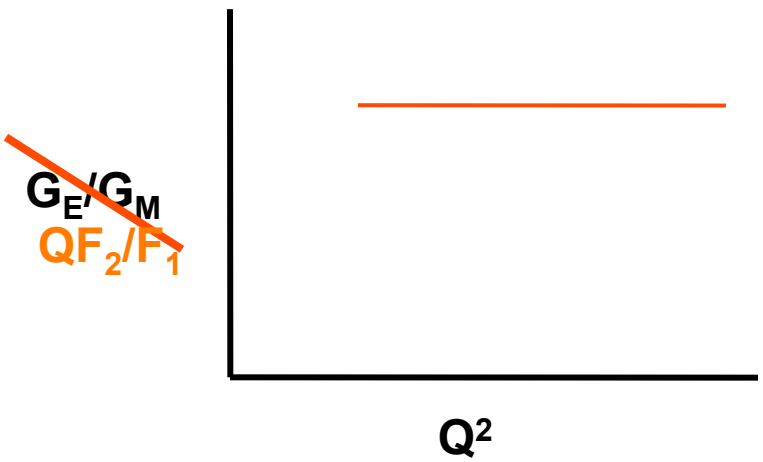


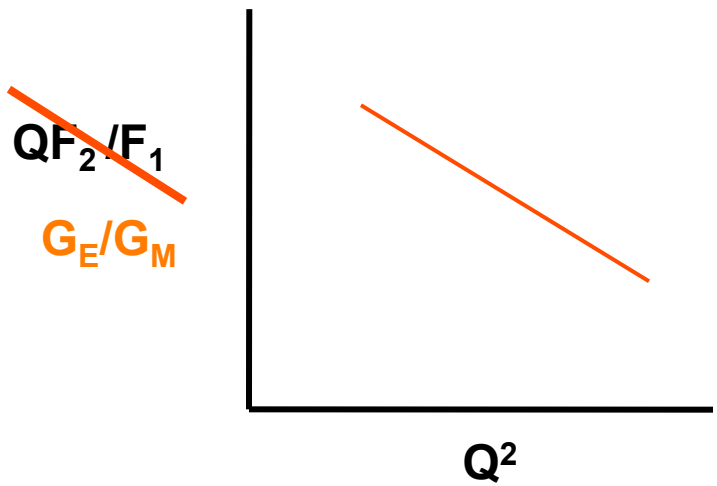


Frank, Jennings, Miller PR C54, 920 (1996)
Relativistic model for color transparency

JLab 2000,2002

Expectations- Pre Jlab





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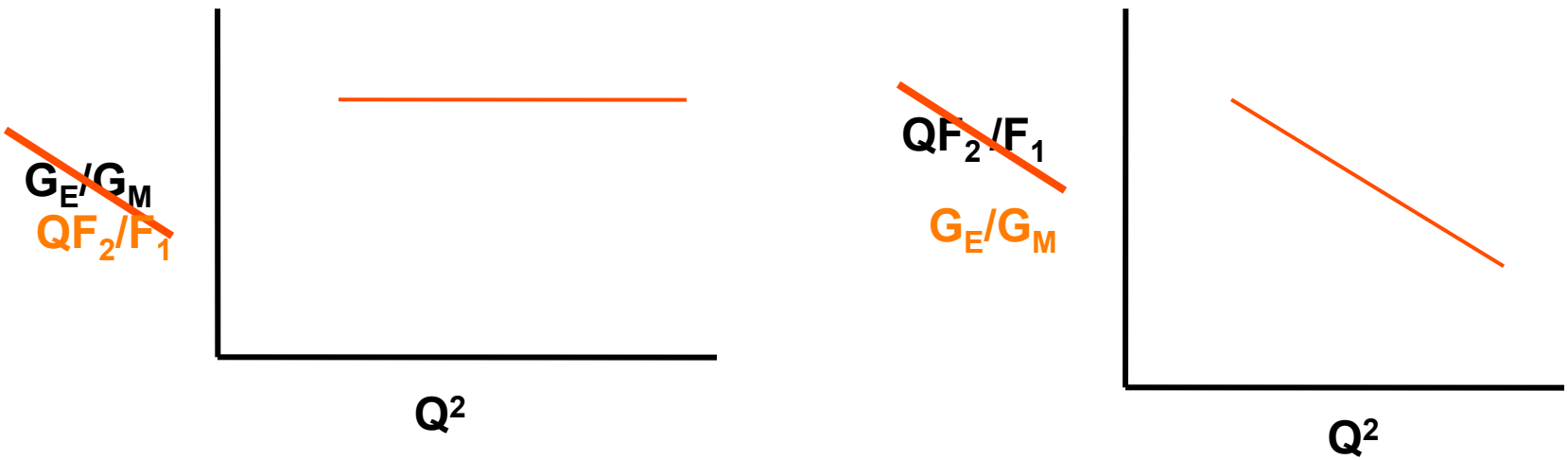
Jlab



Frank, Jennings, Miller PR C54, 920 (1996)
Relativistic model for color transparency

Relativistic Wave function

- 3 quark anti-symmetric
- relative variables, frame independent **Light front variables**
- eigenstate of spin operator- rotational invariant
- reduces to non-relativistic if $m \to \infty$

$\Psi = \Phi(M_0^2) u(p_1) u(p_2) u(p_3 = K) \psi(s_i, t_i)$ Terentev, Coester

spatial dist DIRAC SPINORS spin-ispin color amp

Schlumpf Mom space wf $\Phi(M_0) = N/(M_0^2 + \beta^2)^\gamma$

$\beta = 0.607$GeV $\gamma = 3.5$ $m = 0.267$ GeV

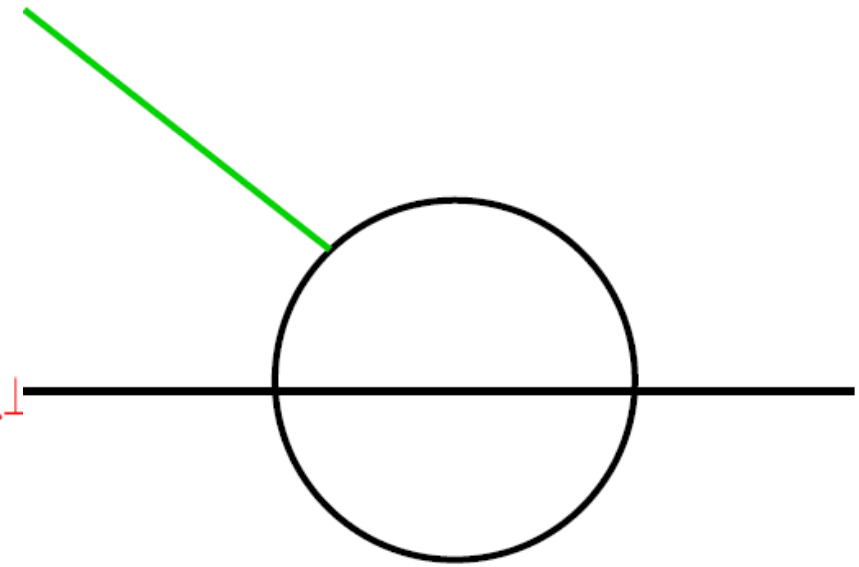
Impulse Approximation

Model proton wave function $\Psi(\mathbf{k}_\perp, \mathbf{K}_\perp, \xi, \eta)$

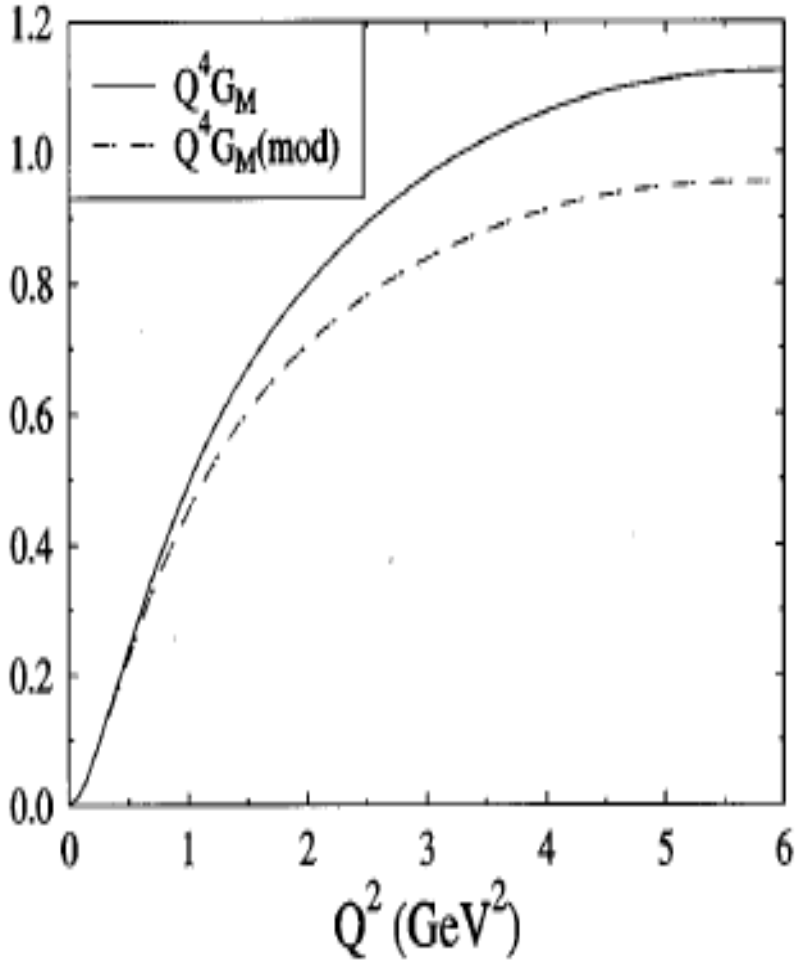
Poincare invariant

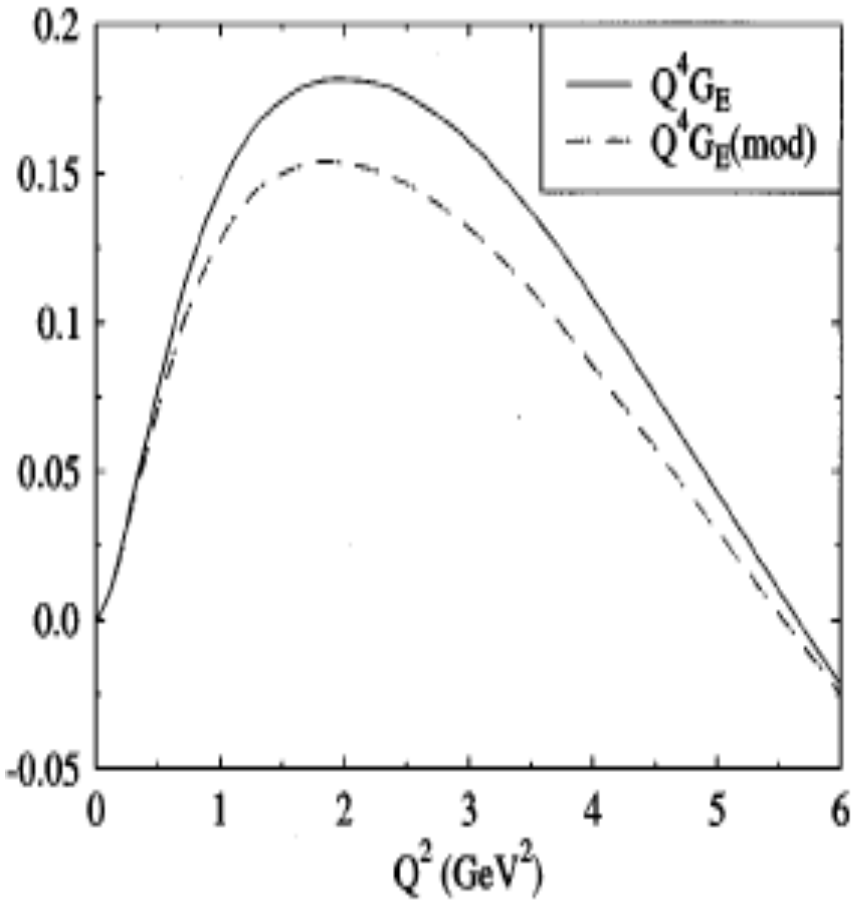
Light front variables for boost: $\mathbf{K} \to \mathbf{K} + \eta \mathbf{q}_\perp$

Dirac spinors

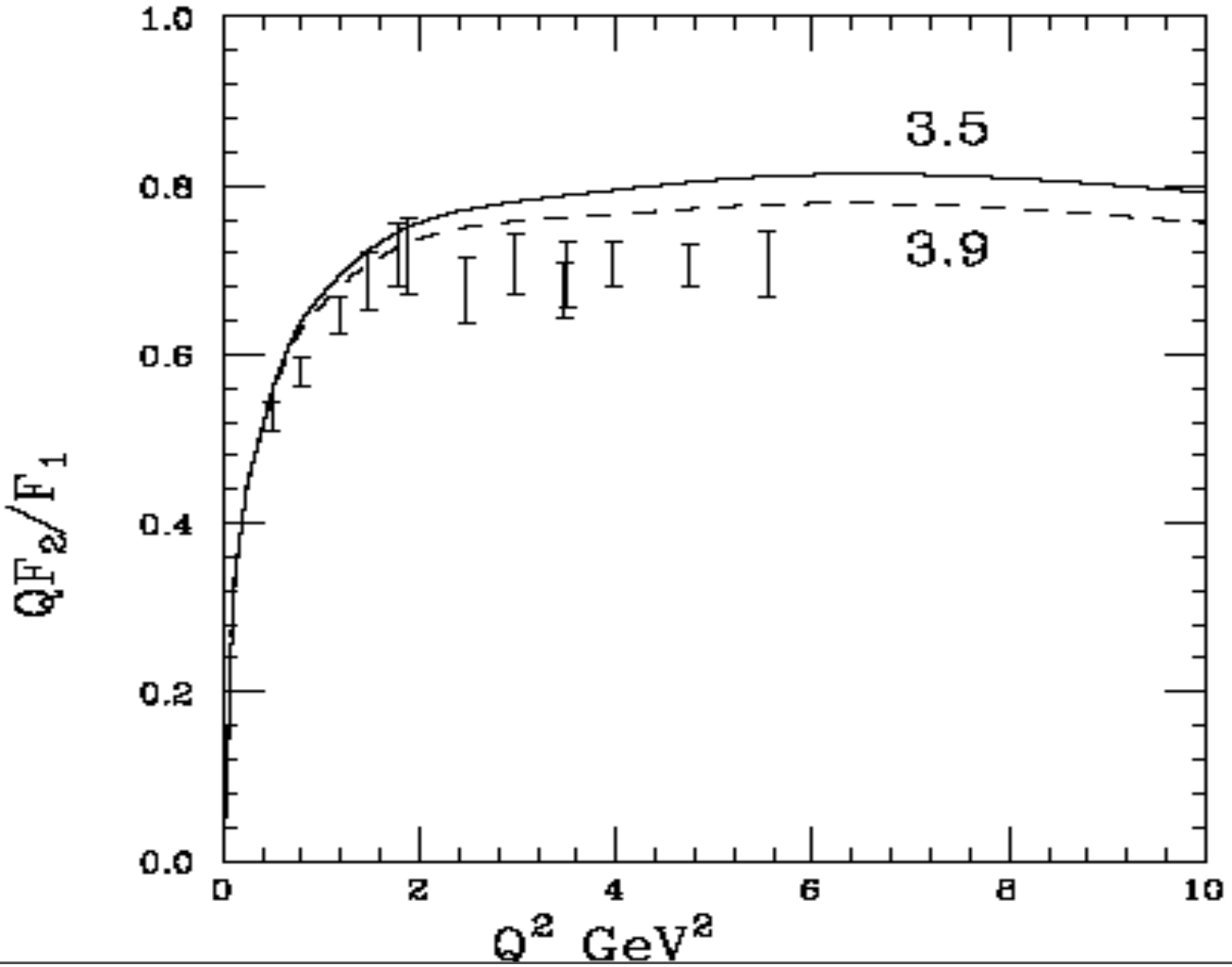


1995 Frank, Jennings, Miller





Ratio of Pauli to Dirac Form Factors 1995



Relativistic Explanation

J^+ acts on third quark, other two have 0 spin

$$u(K,s) = \begin{pmatrix} (E(K)+m)|s\rangle \\ \boldsymbol{\sigma}\cdot\mathbf{K}|s\rangle \end{pmatrix}$$

$\boldsymbol{\sigma}_y|s\rangle$: quark spin $\neq$ proton ang mom

lower components $\equiv L_z \neq 0$

$\bar{u}(K',s')\gamma^+u(K,s) \sim \langle s'|K^+ + i\sigma_y Q|s\rangle$ Large Q

spin non-flip $F_1(Q^2) = \int \cdots Q\Phi\Phi$, flip $QF_2 = \int \cdots Q\Phi\Phi$

$\frac{QF_2}{F_1} \sim Constant$

Miller, Frank **Phys.Rev. C65 (2002) 065205**

Spin content - OAM

$$s_\mu \Delta q = \langle N, s | \bar{q} \gamma_\mu \gamma_5 q | N, s \rangle$$

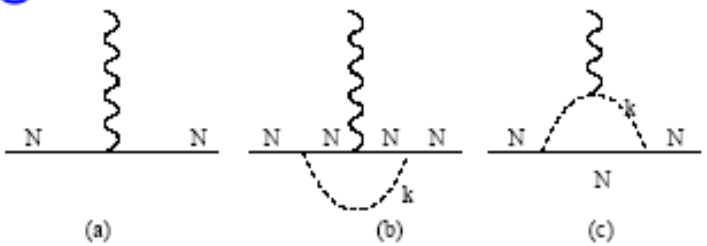
$$\Sigma = \Delta u + \Delta d + \Delta s$$

75 % of proton angular momentum carried by quark spin

Textbook reduction of axial vector coupling constant

Neutron: Need π cloud effect at low Q^2

Cloudy Bag Model 1980



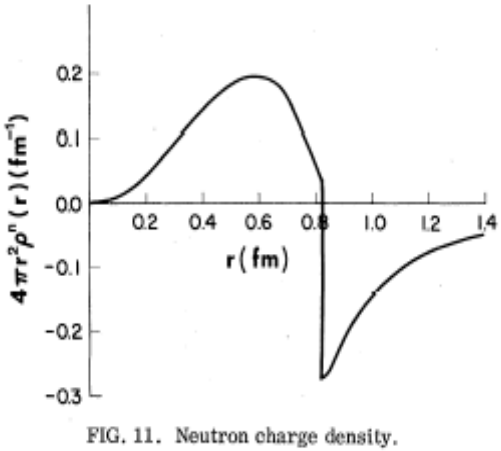


FIG. 11. Neutron charge density.

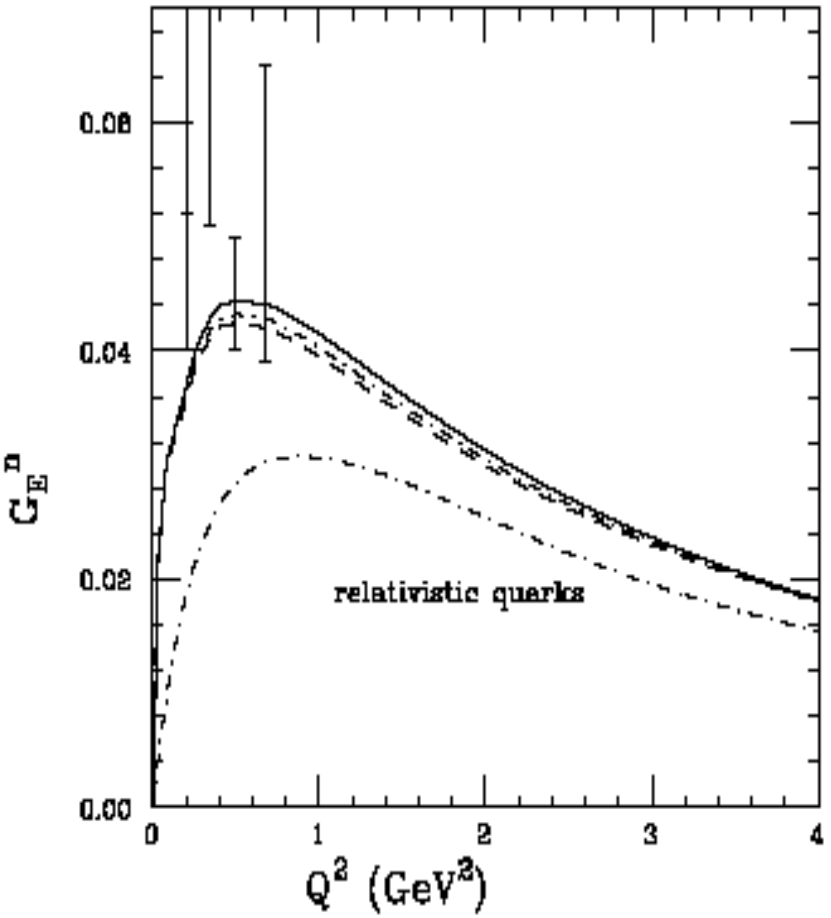
Relativistic treatment needed Feynman graphs, $\int dk^-$

Light front cloudy bag model LFCBM 2002

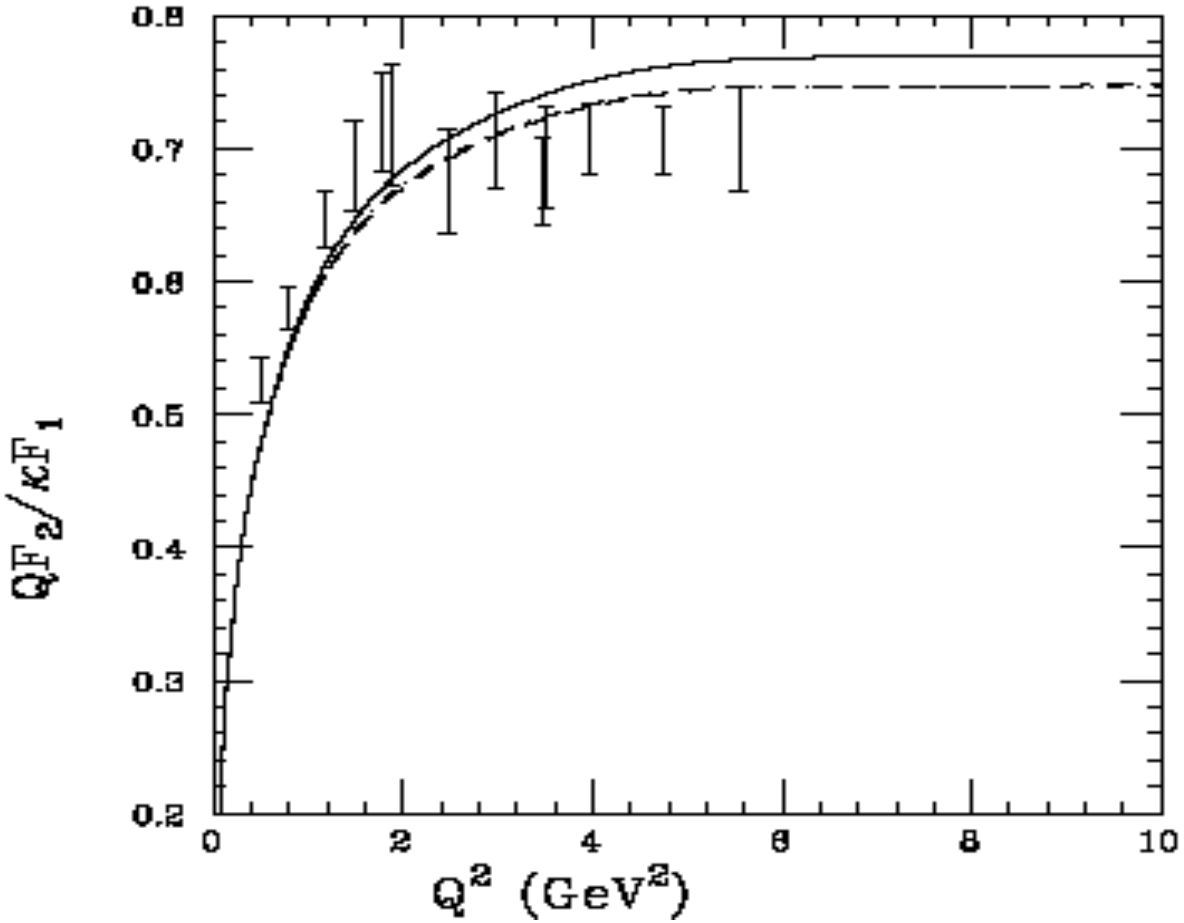
Miller Phys.Rev. C66 (2002) 032201

- γN form factors from model (our model)
- rel. πN form factor $\Lambda_{\pi N}$
- Model parameters: $m, \beta, \gamma, \Lambda_{\pi N}$

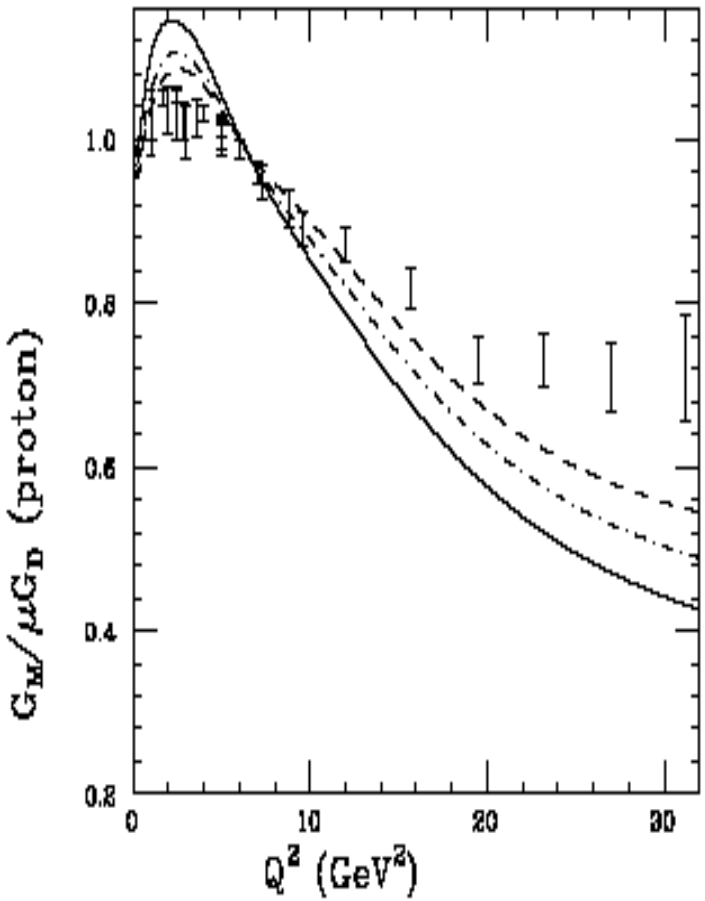
Neutron Electric Form Factor

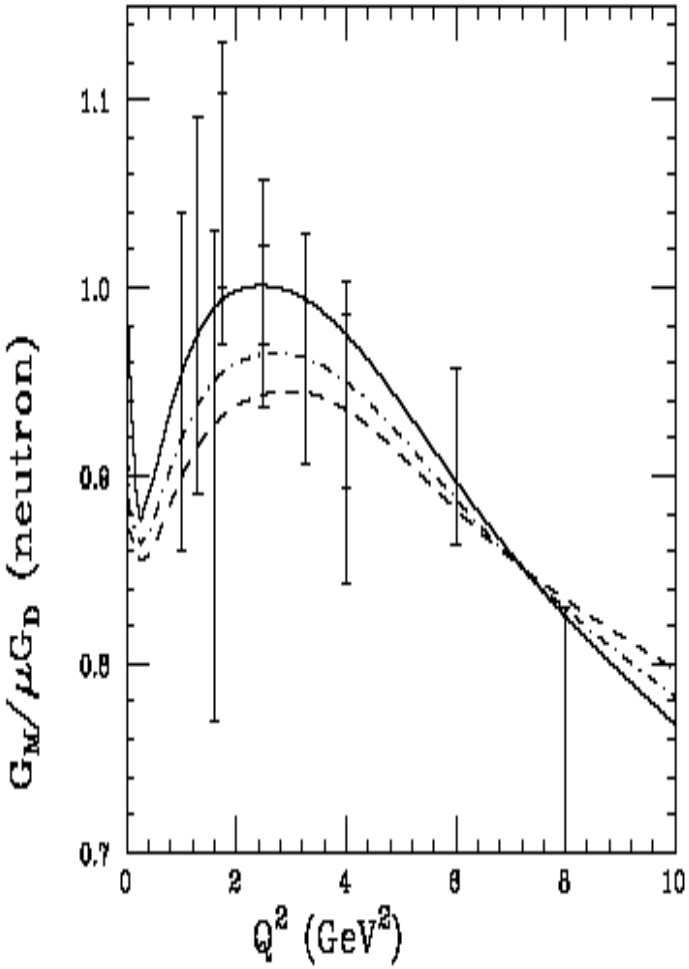


Ratio of Pauli to Dirac Form



Two More Form Factors Needed





OAM content of light front cloudy bag model

$$\Sigma \to (Z - \frac{1}{3}P_{N\pi} + \frac{5}{3}P_{\Delta\pi})\Sigma$$

Schreiber, Thomas PLB215, 141(88)

$$LFCBM: \; P_{N\pi} \approx .25, \; P_{\Delta\pi} = 0$$

$$\Sigma \to \frac{2}{3}\Sigma \sim \frac{2}{3}\frac{3}{4} = \frac{1}{2}$$

Can include Δ Alberg, Miller **arXiv:1201.4184**

2011 Update model

- In LFCBM G_E/G_M falls too fast with Q^2
- New data -slower fall, flavor decomposition not good, get smaller quark spin?
- Many invariant forms of nucleon wave function
- Cloet & Miller quark di-quark model:
- uses other invariant wave functions

(Brodsky, Hiller, Karmanov, Hwag)

Cloet Miller 2011-12

Scalar diquark

$$\Phi^{\lambda_N}_{\lambda_q\,\lambda_D}(k,p) = \bar{u}(k,\lambda_q)\left[\varphi_1^s + \frac{M}{p^+}\,\gamma^+\,\varphi_2^s\right] u_N(p,\lambda_N)$$

$$+\bar{u}(k,\lambda_q)\,\varepsilon^*_\nu(q,\lambda_D)\gamma^\nu\gamma_5\left[\varphi_1^a + \frac{M}{p^+}\,\gamma^+\,\varphi_2^a\right] u_N(p,\lambda_N)$$

Axial vector diquark

$$|p\rangle = \frac{1}{\sqrt{2}}|u\,S_0\rangle + \frac{1}{\sqrt{6}}|u\,T_0\rangle - \frac{1}{\sqrt{3}}|d\,T_1\rangle,$$

Plus pion cloud- 9 parameters

χ^2	M	M_s	M_a	c_s	β_s	γ_s	c_a	β_a	γ_a	Λ	μ_p	μ_n
0.078516	0.191	0.414	0.167	1.509	1.226	5.719	0.008	1.104	8.586	1.035	2.794	-1.849

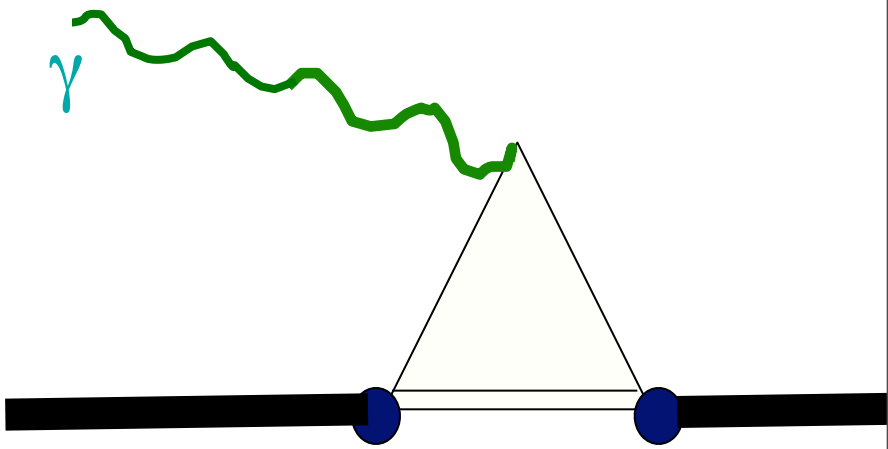
Cloet &Miller ’11

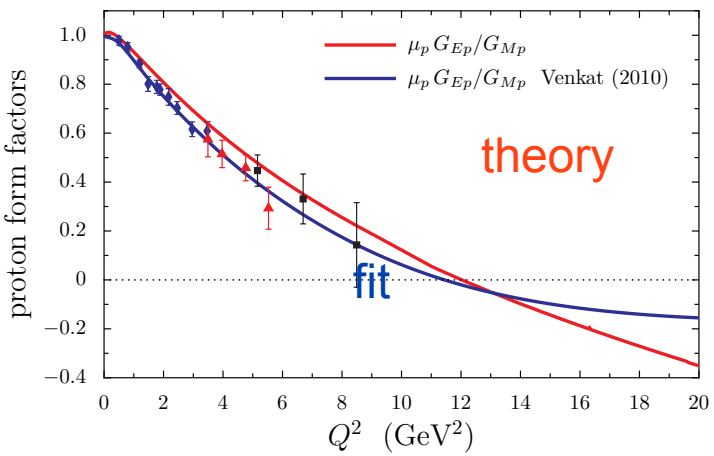
Model proton wave function: quark-diquark

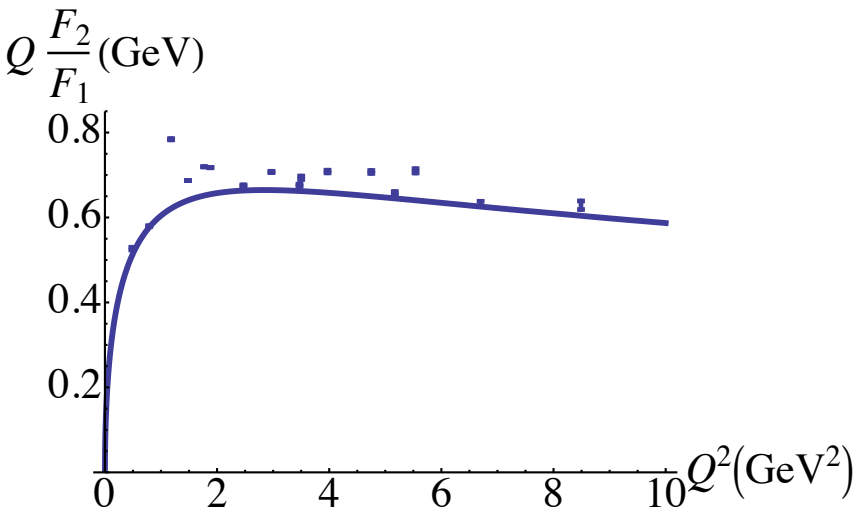
Lorentz and rotationally invariant-different forms!

Light front variables

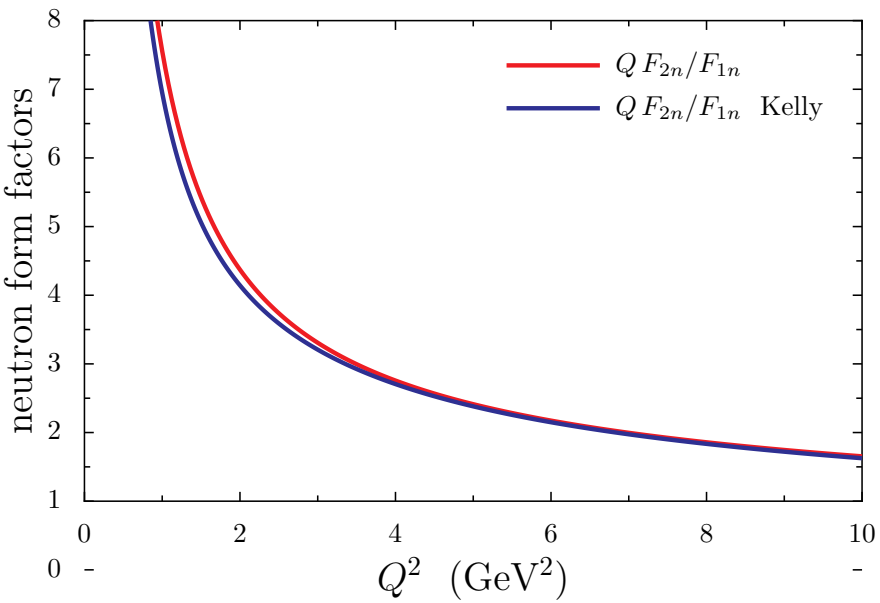
Dirac spinors-orbital angular momentum

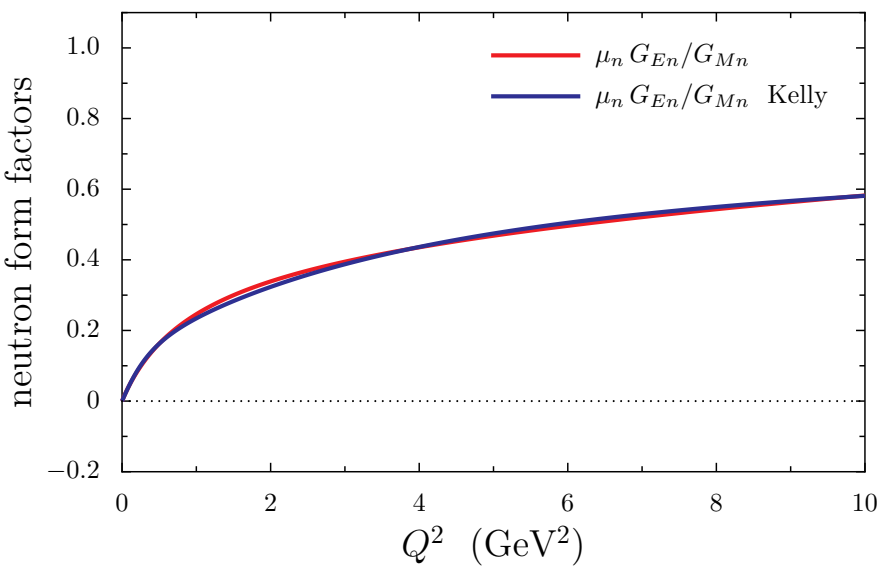




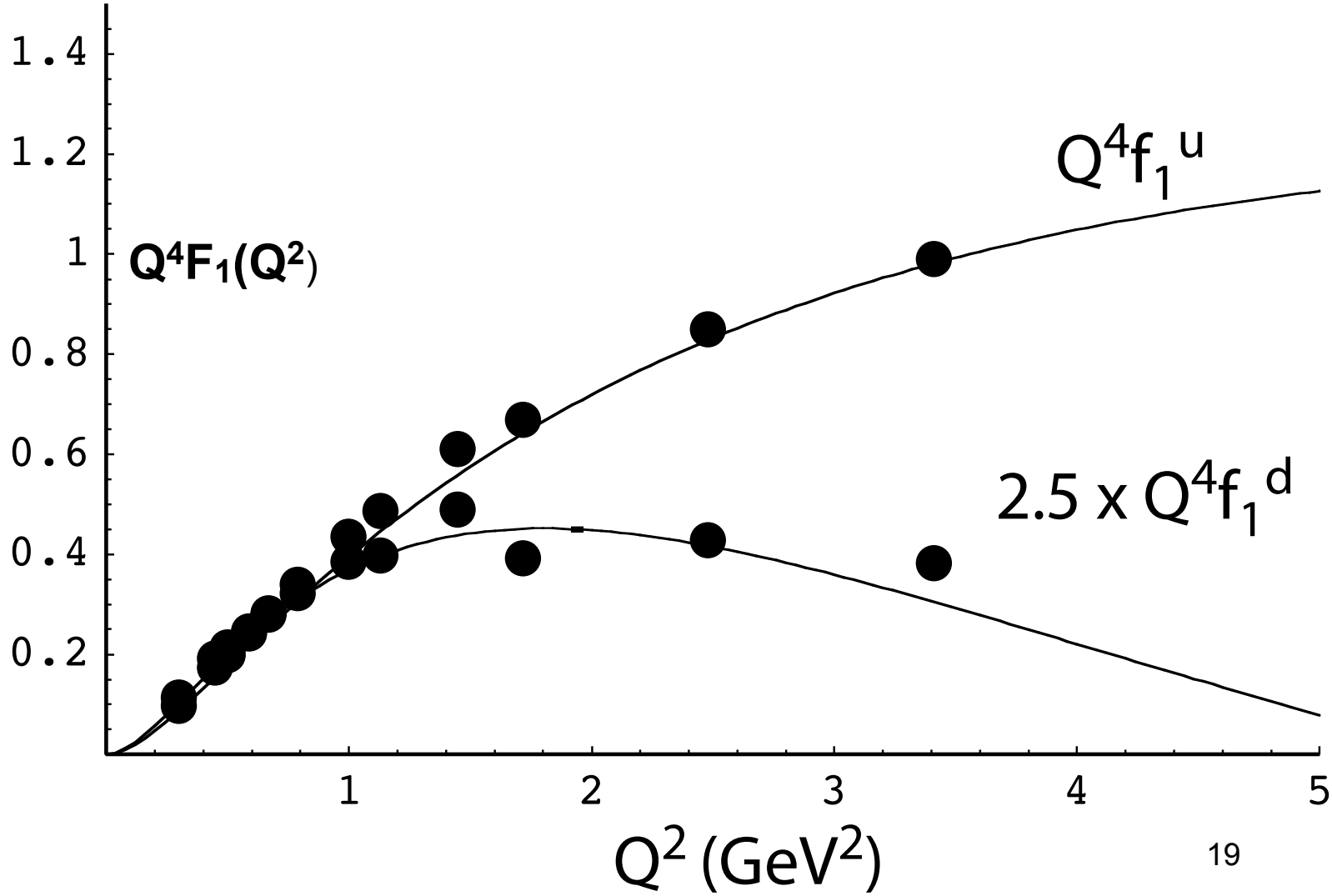


Neutron form factors





Flavor separation: Cates, de Jager, Riordan, Wojtsekhowski PRL 106,252003



Quark-Diquark model -spin content

- Quark spin fraction:
- 1/2 (.782 (scalar) +.167(Axial Vector))=.474
- **With pion cloud 0.7 (0.474)=0.34**

Summary

- Relativistic light front quark model with pion cloud can reproduce nucleon form factors
- Model quark spin is 35 % of total angular momentum
- Relativistic quark model alive and well