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# The JLab polarization transfer measurements of proton elastic form factor

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**Abstract.** The ratio of the electric and magnetic proton form factors, $G_{Ep}/G_{Mp}$, has been obtained in two Hall A experiments, from measurements of the longitudinal and transverse polarizations of the recoil proton, $P_\ell$ and $P_t$, in the elastic scattering of polarized electrons, $\vec{e}p \rightarrow e\vec{p}$. Together these experiments cover the $Q^2$ range of 0.5 to 5.6 GeV$^2$. A new experiment is currently being prepared, to extend the $Q^2$ range to 9 GeV$^2$ in Hall C.

**Keywords.** Proton; electromagnetic; structure.

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## 1. Introduction

Although the structure of the proton has been taken for well-known until recently, the experimental results to be reported here show that it held secrets which are only now being revealed. By comparison, the neutron has received greater attention; perhaps because it is a greater challenge experimentally: there are no free neutron targets, the free neutron has a 15 min life time, and in addition it carries no net electric charge.

The proton is the first elementary particle for which evidence of non-elementariness was discovered. It does not have the magnetic moment, $\mu_p$, of a spin-$\frac{1}{2}$ Dirac particle. The anomaly of its magnetic moment, first measured 70 years ago by Stern [1], is not a small effect as it is for the electron, but a very large one. The proton magnetic moment is much larger than that of a Dirac particle of the same mass and charge: $\mu_p = 2.79e\hbar/2m_p$.

The first measurement of the proton's size was reported 46 years ago by McAllister and Hofstadter [2]; they found it to be 0.8 fm, quite close to the modern value.

In 1955, Hofstadter [3] measured the proton form factor, $F^2$, which he defined as: $F^2 = (\mathrm{d}\sigma/\mathrm{d}\Omega)_{\mathrm{exp}}/(\mathrm{d}\sigma/\mathrm{d}\Omega)_{\mathrm{ns}}$, where 'exp' refers to the experimental $e,e'$ elastic cross-section, and 'ns' to the no-structure Mott cross-section for a spin-$\frac{1}{2}$ particle:

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{ns}} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{Mott}} \left[1 + \frac{Q^2}{4m_p^2} 2\tan^2\left(\frac{\theta_e}{2}\right)\right], \tag{1}$$

with the Mott cross-section given by

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm Mott} = \frac{\alpha^2}{4E^2\sin^4(\theta_e/2)}\frac{E'}{E}\cos^2\left(\frac{\theta_e}{2}\right), \tag{2}$$

where $E$ and $E'$ are the incident and scattered electron laboratory frame energies, $m_p$ the proton mass, and $\theta_e$ the laboratory electron scattering angle. $Q^2$ is the negative of the invariant four-momentum transfer squared where

$$Q^2 = -q_\mu^2 = -(\omega^2 - q^2), \tag{3}$$

with $\omega = E - E'$ and $\vec{q} = \vec{k} - \vec{k}'$, where $\vec{k}$ and $\vec{k}'$ are the incident and scattered electron momenta.

The most important result of Hofstadter's investigation was the verification of the scaling of $F^2$ with $Q^2$, and its independence from either beam energy or scattering angle. This is most beautifully illustrated in figure 27 of the review in ref. [3], which shows $F^2$ vs. $Q^2$ over the range 0.5 to 14 fm$^{-2}$ (corresponding to 0.02 to 0.55 GeV$^2$) obtained with beam energies between 200 and 550 MeV: all data points scale on a single curve. Two conclusions were drawn from this experimental results. First the scaling with $Q^2$ indicates that the process can be described in terms of form factors which take into account the spread of the charge distribution and of the magnetic moment distribution; both form factors are Lorentz scalars depending upon $Q^2$ only. Second, charge and magnetization distributions are approximately of exponential shape, with $r_{\rm charge} \sim r_{\rm magn} = 0.8$ fm.

The nucleon elastic form factors describe the internal structure of the nucleon; in the non-relativistic limit, for small four-momentum transfer squared, they are Fourier transforms of the charge and magnetization distributions in the nucleon. In the Breit frame the hadron electromagnetic 4-vector current $J_\mu$ has time- and space-components proportional

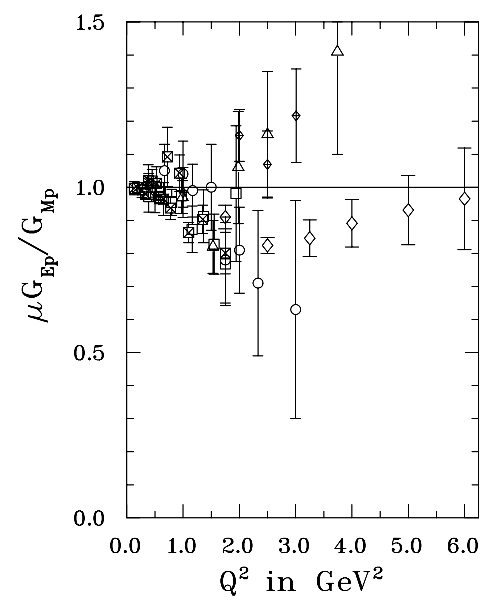


**Figure 1.** World data for $\mu_p G_{Ep}/G_{Mp}$ vs. $Q^2$.

to the Sachs form factors $G_{Ep}$ and $G_{Mp}$, respectively. Hence, in this frame, it is generally true that the electric and magnetic form factors $G_{Ep}$ and $G_{Mp}$ are the Fourier transform of the charge and magnetization distributions, respectively. The difficulties associated with the calculations of the charge and magnetization distributions in the laboratory have been discussed recently by Kelly [4].

The unpolarized elastic $ep$ cross-section can be written in terms of the Sachs form factors $G_{Ep}$ and $G_{Mp}$:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\alpha^2 E_e' \cos^2(\theta_e/2)}{4E_e^3 \sin^4(\theta_e/2)} \left[G_{Ep}^2 + \frac{\tau}{\varepsilon} G_{Mp}^2\right] \left(\frac{1}{1+\tau}\right), \tag{4}$$

where $\tau = Q^2/4M_p^2$. Both $G_{Ep}^2$ and $G_{Mp}^2$ can be extracted from cross-section measurements made at fixed $Q^2$, and over a range of values of the kinematic factor $\varepsilon$, with the Rosenbluth separation method; different values of $\varepsilon$ are obtained by changing beam energy and scattering angle at fixed $Q^2$. In general, radiation corrections are an important part of the procedure to extract $G_{Ep}^2$ and $G_{Mp}^2$ from cross-section data.

Up to $Q^2 \sim 8$ GeV$^2$, $G_{Ep}^2$ and $G_{Mp}^2$ have been determined by the Rosenbluth method and $\mu_p G_{Ep}/G_{Mp}$ was found to be $\approx$1. The ratio $\mu_p G_{Ep}/G_{Mp}$ obtained from world cross-section data (refs [5–11]) is shown in figure 1; the error bars are seen to grow with $Q^2$. Above $Q^2 \approx 1$ GeV$^2$, systematic differences between different experiments are evident. At larger $Q^2$, the cross-section becomes dominated by the $G_{Mp}$ contribution; $G_{Mp}$ has been determined without separation from cross-section data with the assumption $\mu_p G_{Ep}/G_{Mp} \sim 1$, to $Q^2 = 31$ GeV$^2$ [12].

The JLab results have been obtained by measuring the recoil proton polarization in $\vec{e}p \to e\vec{p}$ [13,14] instead of the cross-section. In one-photon exchange, the scattering of longitudinally polarized electrons on unpolarized hydrogen results in a transfer of polarization to the recoil proton with two components, $P_t$ perpendicular to, and $P_\ell$ parallel to the proton momentum in the scattering plane [15]:

$$I_0 P_t = -2\sqrt{\tau(1+\tau)} G_{Ep} G_{Mp} \tan\frac{\theta_e}{2}, \tag{5}$$

$$I_0 P_\ell = \frac{1}{m_p} \left(E + E'\right) \sqrt{\tau(1+\tau)} G_{Mp}^2 \tan^2\frac{\theta_e}{2}, \tag{6}$$

where $I_0 \propto G_{E_p}^2 + (\tau/\varepsilon) G_{Mp}^2$. Measuring these two components simultaneously and taking their ratio gives the ratio of the form factors:

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell} \frac{(E+E')}{2m_p} \tan\left(\frac{\theta_e}{2}\right). \tag{7}$$

The form factor ratio $G_{Ep}/G_{Mp}$ at a given $Q^2$ can be obtained without change of beam energy or detector angle, eliminating important sources of systematic uncertainties; radiative corrections have been shown to be very small for polarization observables [16]. The principal remaining source of systematic uncertainty comes from the need to account accurately for the precession of the spin in the spectrometer detecting the recoil proton. Optical studies of the HRS have resulted in greatly improved systematic uncertainties, compared to the original experiment of ref. [13].

## 2. Experiments

In 1998, $G_{Ep}/G_{Mp}$ was measured at JLab for $Q^2$ from 0.5 to 3.5 GeV$^2$ [13]. Protons and electrons were detected in coincidence in the two high-resolution spectrometers (HRS) of Hall A. The polarization of the recoiling proton was obtained from the asymmetry of the azimuthal distribution after rescattering the proton in a focal plane polarimeter (FPP) with graphite analyser.

In 2000, new measurements were made at $Q^2 = 4.0$, 4.8 and 5.6 GeV$^2$ with overlap points at $Q^2 = 3.0$ and 3.5 GeV$^2$ [14]. To extend the measurement to these higher $Q^2$, two changes were made. First, to increase the figure-of-merit of the FPP, a $CH_2$ analyzer was used; the thickness was increased from 50 cm of graphite to 100 cm of $CH_2$ (60 cm for $Q^2 = 3.5$ GeV$^2$). Second, the electrons were detected in a lead–glass calorimeter with 9 columns and 17 rows of $15 \times 15 \times 35$ cm$^3$ blocks placed so as to achieve complete solid angle matching with the HRS detecting the proton. At the largest $Q^2$ the required solid angle of the calorimeter was six times that of the HRS.

The combined results from both experiments are plotted in figure 2a as the ratio $\mu_p G_{Ep}/G_{Mp}$, compared to the world cross-section data [5–10] and polarization data [11,17]. If the $\mu_p G_{Ep}/G_{Mp}$ ratio continues the observed linear decrease with the same slope, it will cross zero at $Q^2 \approx 7.5$ GeV$^2$.

## 3. Results and discussion

At high $Q^2$ values, the nucleon is treated as a system of three valence quarks; perturbative QCD predicts the $Q^2$ dependence of the form factors. At $Q^2$ between 1 and 10 GeV$^2$, relativistic constituent quark models currently give the best understanding of the nucleon form factors, with the strongest dynamical input; vector meson dominance (VMD) also describes the form factors well in this $Q^2$-region, but differences between different models are evident.

In figure 2b–d, the time evolution of both data and theory is displayed. Figure 2b shows the situation in the early seventies, when only four experiments had been done, and all calculations were in the vector meson dominance (VMD) model [18–20]. Remarkable is the VMD prediction of Iachello *et al* [18] with a zero crossing near 8.5 GeV$^2$. In figure 2c the data of two SLAC experiments [9,10] have been added, and several contemporary calculations including VMD [21,22], the constituent quark model (CQM) [23,24], QCD counting rules [25] and the soliton model [26] are shown. Finally in figure 2d the JLab data appear again, now with the results of calculations made after their first publication in [13]; they include VMD [27], relativistic CQM [28,29], the point form approach in the CQM [30], the soliton model revisited [31] and a new pQCD fit [32]. In 2002, Lomon [27] updated the original VMD calculation of Gari and Kruempelman [21] and obtained good agreement with the JLab data for reasonable parameters for the vector–meson masses and coupling constants.

In figure 3a the JLab data are shown as $Q^2F_2/F_1$, the ratio of the Pauli and Dirac form factors $F_2$ and $F_1$; these are connected to the Sachs form factor as follows:

$$F_2 = \frac{G_{Mp} - G_{Ep}}{\kappa_p(1+\tau)}, \quad F_1 = \frac{\tau G_{Mp} + G_{Ep}}{1+\tau}, \tag{8}$$

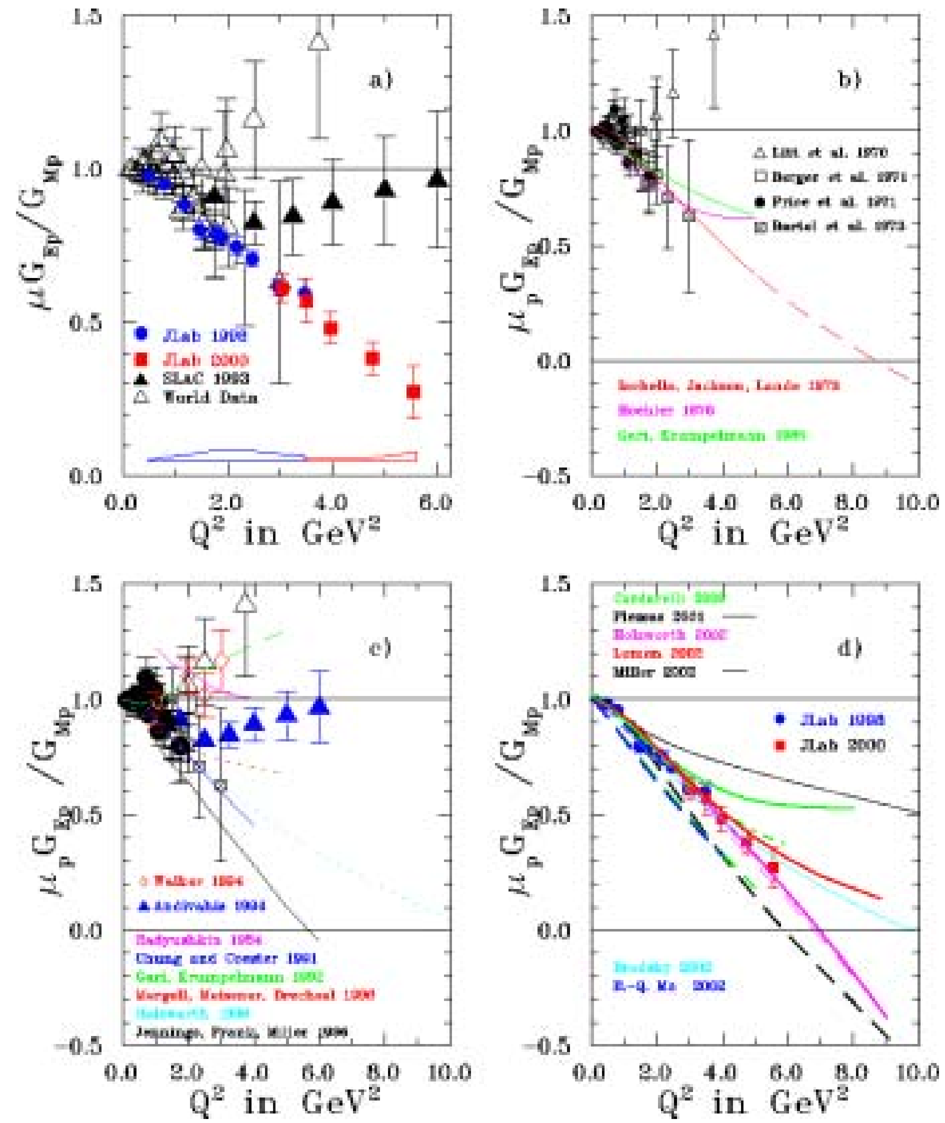

**Figure 2.** (**a**) The JLab data showed together with the world data. Panels (**b**), (**c**) and (**d**) show the history of experimental results and theoretical calculations. In (b) the experiments of the early seventies are shown together with three early vector meson dominance (VMD) predictions; in (c) the two SLAC results are added, and predictions from VMD, CQM, soliton and QCD counting rules are shown; in (d) the JLab data are shown again, and this time compared only with calculations made in the last few years.

where $\kappa_p$ is the anomalous part of the proton magnetic moment, in units of nuclear magneton $\mu_N$. The prediction of pQCD [33] is that at large $Q^2$ quenching of the spin flip form factor $F_2$ occurs, or equivalently helicity conservation should hold true; higher order con-

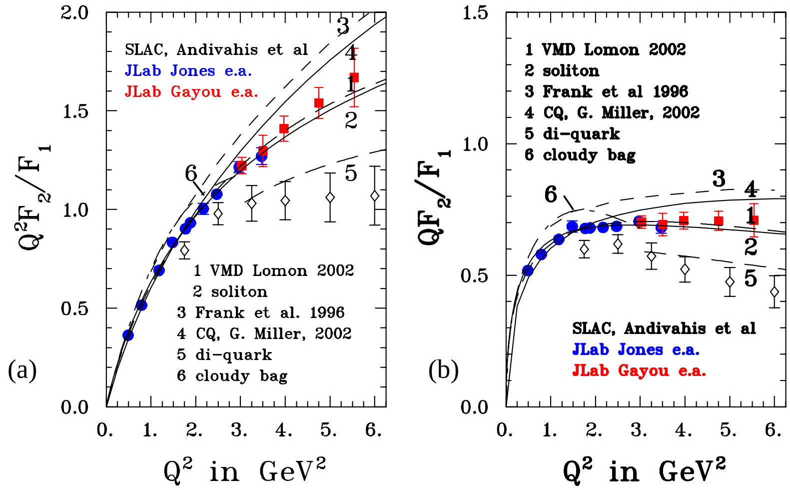


**Figure 3.** The $F_2/F_1$ ratio obtained from the JLab data, multiplied by (**a**) $Q^2$ and (**b**) $Q$, respectively.

tributions should make $Q^2F_2/F_1$ asymptotically constant. Unlike the SLAC [10] data, the JLab data clearly contradict this prediction over the $Q^2$ region covered. Shown in figure 3b is $Q$ times $F_2/F_1$, which appears to reach a constant value at $Q^2 \sim 2$ GeV$^2$. This $\frac{1}{Q}$-behavior has been interpreted by Ralston *et al* [34] as an indication of the contribution of the non-zero orbital angular momentum part of the proton quark wave function; in this picture the proton may be non-spherical. In a different approach Miller and Frank [28] have shown that imposing Poincaré invariance leads to violation of the helicity conservation rule, and reproduces the $QF_2/F_1$ behavior.

More demanding for models are predictions for all four form factors of the nucleon, $G_{Ep}$, $G_{Mp}$, $G_{En}$ and $G_{Mn}$, respectively. The VMD fits are done in terms of the isoscalar and isovector form factors and thus naturally include all four form factors. In figure 4 predictions from the $r$CQM with $SU(6)$ symmetry breaking [29], the soliton model [26], the point form model [30], and the VMD model of [27] are shown; all models predict at least two form factors. The soliton model does well only for the proton. The recent VMD analysis of Lomon [27] reproduces $G_{Ep}$, $G_{Mp}$ and $G_{Mn}$ well, and predicts $G_{En}$ values larger than the Galster fit [39], but in agreement with the preliminary data of [40].

Isospin invariance at the quark level requires that $F_2/F_1$ become the same for proton and neutron starting at some large, but undefined, $Q^2$ value. In figure 5 we show the prediction for $QF_2/F_1$ and $Q^2F_2/F_1$ for proton and neutron from [27]; $F_2/F_1$ may become equal for the proton and the neutron for $Q^2 > 10$ GeV$^2$. The evolution of $QF_2/F_1$ at small $Q^2$ is dominated by the charge neutrality of the neutron, which results in $F_{1n} = 0$ at $Q^2 = 0$.

A future experiment in JLab Hall A [41], to measure $G_{En}$ up to 3.4 GeV$^2$, will significantly improve our knowledge of the neutron form factors. A third phase of the $G_{Ep}/G_{Mp}$ measurements with the recoil polarization technique to 9 GeV$^2$, is planned for Hall C during 2005 [42]. Also, a new Rosenbluth separation experiment was done in Hall A during 2002, up to $Q^2 = 4.1$ GeV$^2$ [43]; the experiment used a technique which strongly reduces systematic uncertainties compared to the standard Rosenbluth separation; the results are expected in mid-2003.

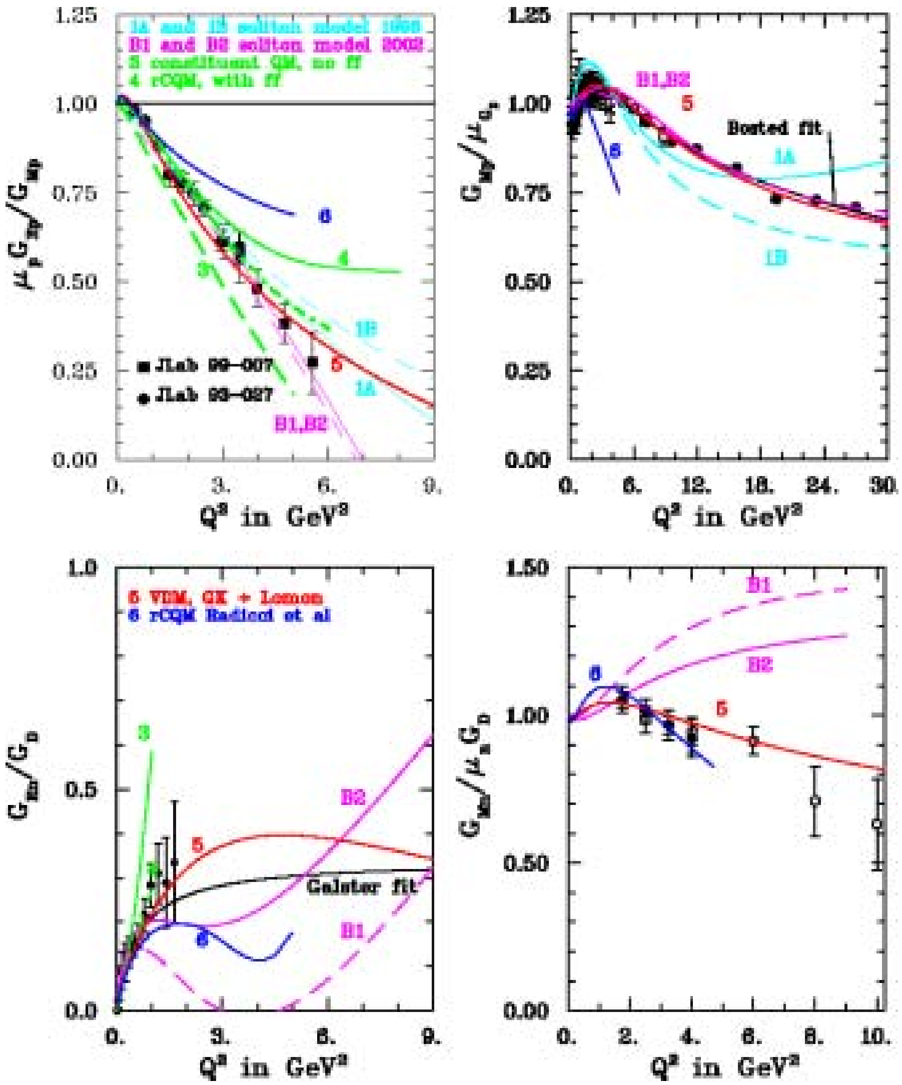


**Figure 4.** Theoretical predictions for $G_E$ and $G_M$ of the proton and neutron, along with selected data. For $G_{En}$ only the results of a recent analysis of elastic ed data from ref. [35] are shown; for $G_{Mn}$ only the larger $Q^2$ data of refs [36] and [37] are shown. Curves labeled Bosted fit and Galster fit are from refs [38] and [39], respectively.

## 4. Conclusion

The precise new JLab $G_{Ep}/G_{Mp}$ data show that this ratio drops off approximately linearly with increasing $Q^2$ up to 5.6 GeV$^2$, contrary to what had been assumed based on earlier cross-section measurements. As a consequence, the ratio $F_2/F_1$ does not follow the $1/Q^2$ behavior predicted by pQCD. Thus, the JLab data may indicate the continuing dominance

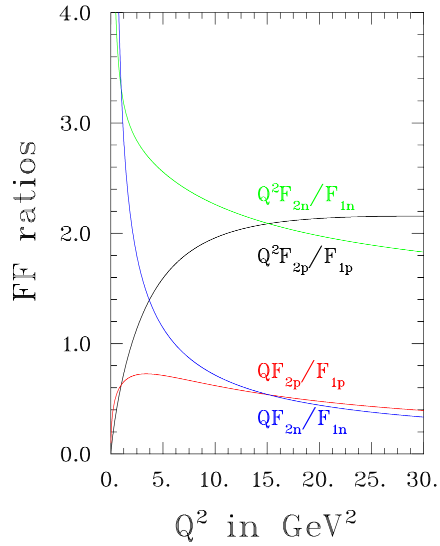


**Figure 5.** The ratios $QF_2/F_1$ and $Q^2F_2/F_1$ for proton and neutron, from Lomon's [27] recent VMD fits. Both ratios tend toward the same value for proton and neutron above 15 GeV$^2$, which is also the $Q^2$ value at which this ratio might become constant; for the neutron $QF_{2n}/F_{1n}$ does not show the same low $Q^2$ maximum as seen for the proton, because $F_{1n} \to 0$ as $Q^2 \to 0$, and hence both $QF_{2n}/F_{1n}$ and $Q^2F_{2n}/F_{1n} \to \infty$.

of soft physics in the $Q^2$-range explored so far. This behavior must be compared with the scaling of $Q^4G_{Mp}$ seen in [12], starting already at $Q^2 \sim 5$ GeV$^2$, which has been interpreted by many as a signature of the onset of pQCD.

The previous discussion emphasizes the need for more and better data at higher $Q^2$, to challenge theoretical models in this difficult range of momentum transfer.

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