The Form Factors of the Nucleons: Present Status

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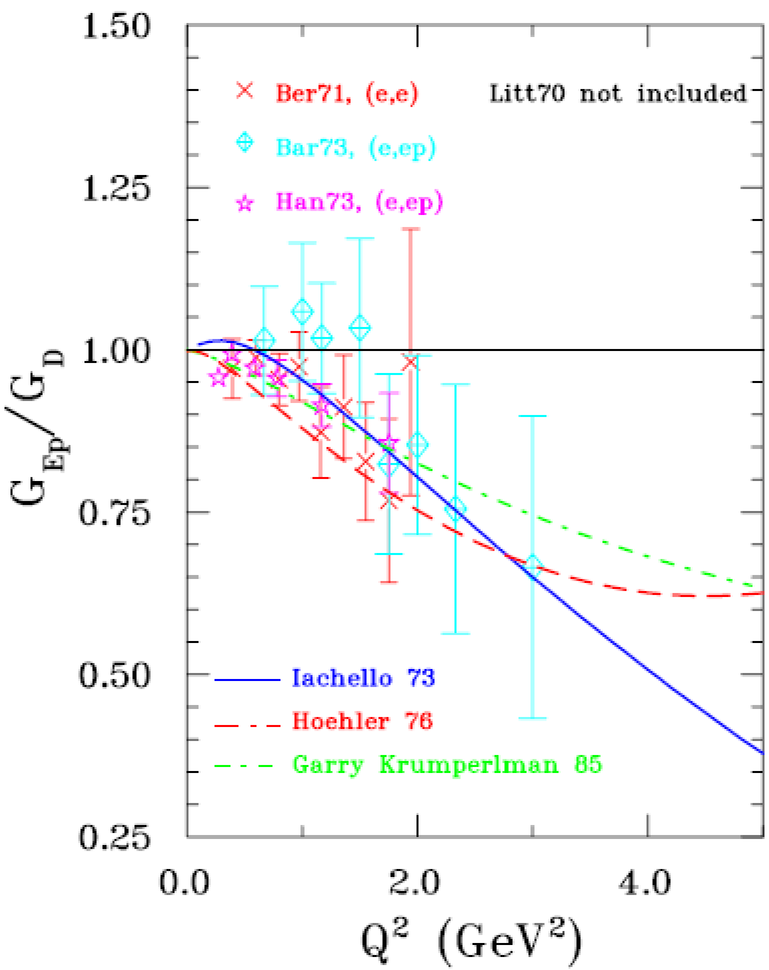
Scattering and Annihilation Electromagnetic Processes
Trento, Italy
February 18th to 22nd 2013

Nucleon Form Factors



Form factors have been obtained from elastic electron scattering cross sections from the very beginning of R. Hofstadter's pioneering work at Stanford in the mid-1900s.

In early 70's the data available suggested that G_{Ep} decreased faster than the dipole form factor $G_D=(1+Q^2/0.71)^{-2}$(see figure).

The first experiment to show a strong preference for $G_{Ep}/G_D \sim 1$ was that of Litt et al. published in 1970, not included in this figure.

Following experiments mostly confirmed the Litt results (Walker et al. 1994, Andivahis et al, 1994)) including two experiments at Jlab (Christy et al 2004, and Qattan et al. 2005).

Results for the proton's G_{Ep} and G_{Mp} form factors had reached apparent stability by 1990's, indicating that "scaling", i.e. the fact that G_{Ep}/G_D, $G_{Mp}/\mu_p G_D$ are approximately independent of Q^2, and ≈1, may be true.

In the late 1990s it became experimentally feasible to obtain the nucleon form factors from double-polarization experiments, also based on the assumption of single photon exchange, or Born approximation, as had been first suggested by Akhiezer and Rekalo in the late sixties.

Spectacular experimental progress in measuring G_E/G_M followed the opening of Jefferson Lab, for both proton and neutron. Our understanding of the shape, and charge and current distributions in the nucleon has increased considerably, and changed drastically.

New information on hadron structure, such as role of quark orbital angular momentum, transverse charge density distribution, dressed quark form factor has followed in short order.

Outline: Nucleon Form Factors

The two methods to obtain G_E and G_M, the space-like electromagnetic form factors of the proton and neutron, are Rosenbluth separation based on cross sections, and asymmetry in double polarization as in

$$\vec{e}N \rightarrow e\vec{N}, \quad \vec{e}\vec{N} \rightarrow eN.$$

Compare old and new results for G_E and G_M, proton and neutron.

Highlight new paradigm.

Short theory overview.

Comparison of G_E/G_M and F_2/F_1 to theoretical model predictions, for proton and neutron.

Some consequences for structure and shape of the nucleon.

Validity of Born approximation: Radiative corrections? Or just physics.

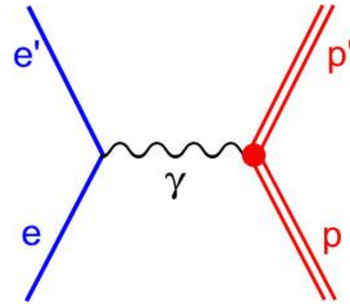
What is the radius of the proton?

C.F. Perdrisat, V. Punjabi, M. Vanderhaeghen, Progress in Particle and Nuclear Physics, 59 (2007), 694, and, on the web:

C.F. Perdrisat, V. Punjabi www.scholarpedia.org/article/Nucleon_Form_factors (2010)

One-photon exchange or Born approximation

$j_\mu = \langle e'|\gamma_\mu|e\rangle$



$J_\mu = \langle p'|\Gamma_\mu|p\rangle$

OPEX

The hadronic current is: $\Gamma^\mu = F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M}$

- F_1 (Dirac): electric charge and Dirac magnetic moment
- F_2 (Pauli): anomalous magnetic moment

The *ep* cross section is then (cumbersome)

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{E_e}{E_{beam}}$$

$$\left\{F_1^2(Q^2) + \tau\left[F_2^2(Q^2) + 2(F_1^2(Q^2) + F_2^2(Q^2))^2 \tan^2\frac{\theta_e}{2}\right]\right\}$$

The Sachs form factors G_E (electric) and G_M (magnetic) are more convenient experimentally.

The two sets of form factors are connected by linear relations

$$G_E = F_1 - \tau F_2, \qquad G_M = F_1 + F_2$$

or in the opposite direction, as we actually measure G_E and G_M:

$$F_1 = (G_E + \tau G_M)/(1 + \tau), \quad F_2 = (G_M - G_E)/(1 + \tau)$$

with $\tau = Q^2/4m_p^2$

Rosenbluth Separation Method

In terms of the Sachs form factor the cross section for detection of an *electron* is:

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

Where ε is longitudinal polarization of the virtual photon, also called the kinematic factor:

$$\epsilon \equiv \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

with $0 < \varepsilon < 1$

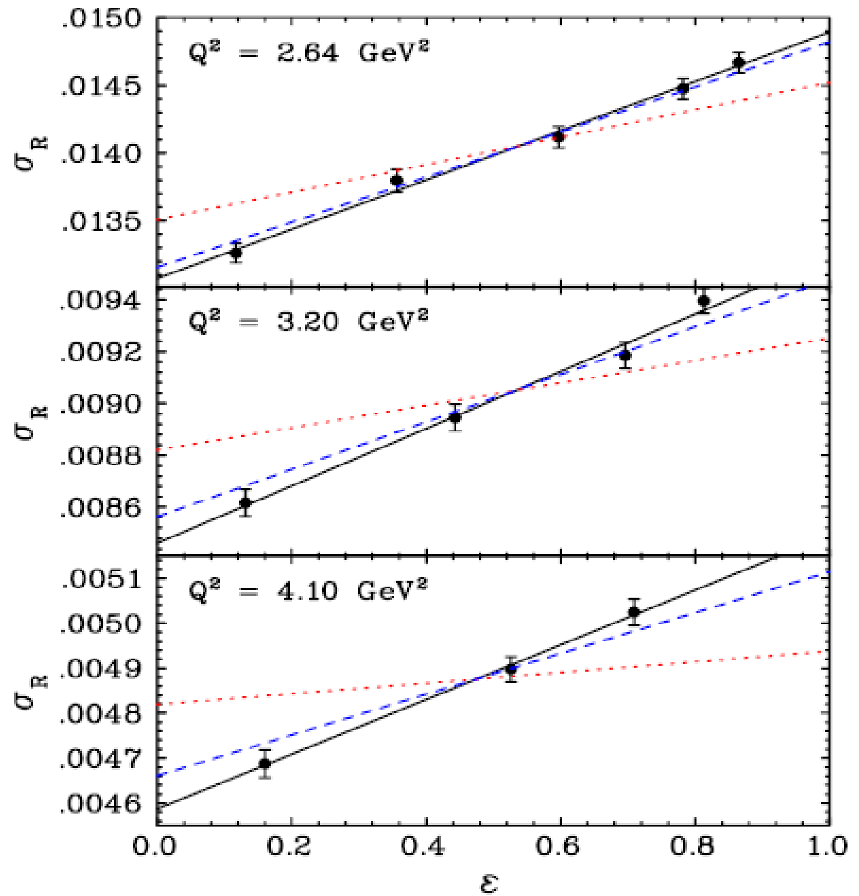
Rosenbluth (continued)

A "reduced cross section" can be defined as:

$$\sigma_R \equiv \epsilon(1+\tau)\frac{\sigma}{\sigma_{Mott}} = \epsilon G_E^2 + \tau G_M^2$$

- Measuring angular dependence of cross section at fixed Q^2.
- The ε-dependence of the "reduced cross section" σ_R is linear in Born approximation, with slope G_E^2 and intercept τG_M^2.

Qattan et al.,PRL 94, 142301 (2005)

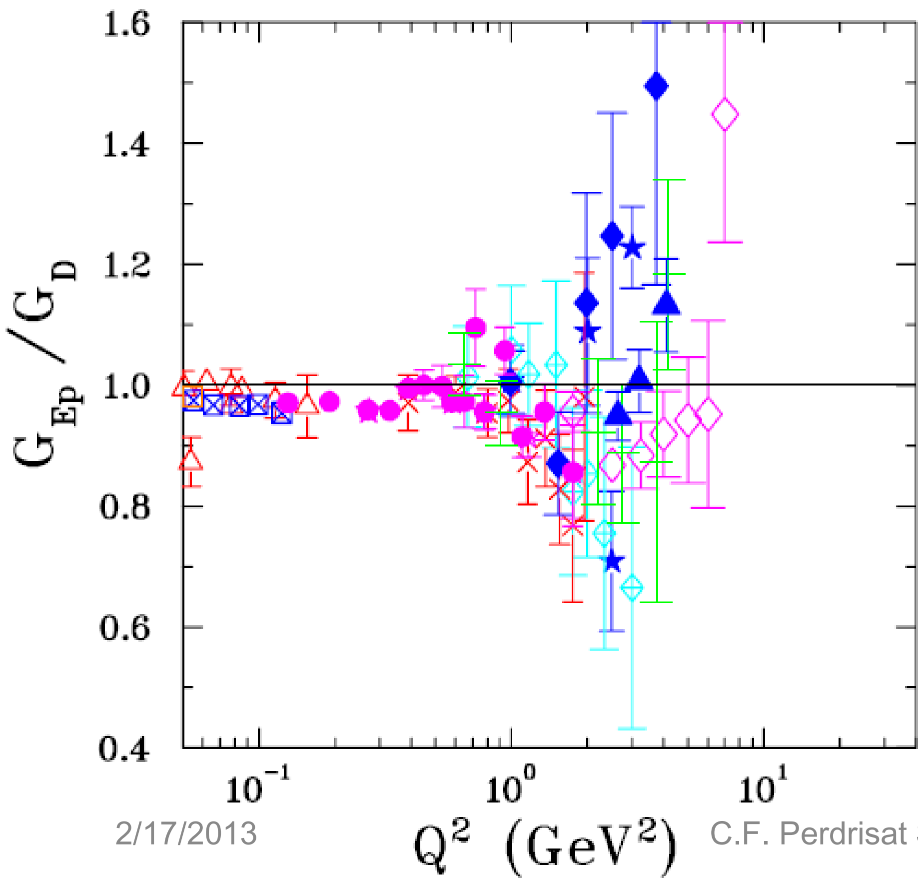


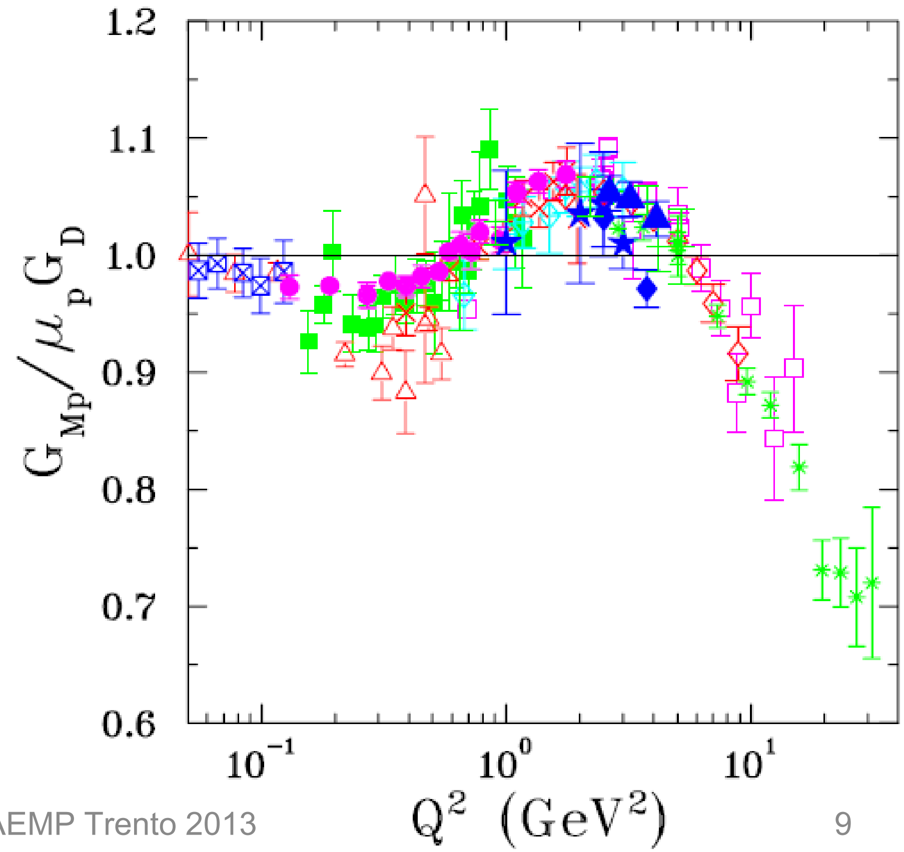
------- from recoil polarization

------- previous Rosenbluth

All Rosenbluth separation data for the proton Form Factors

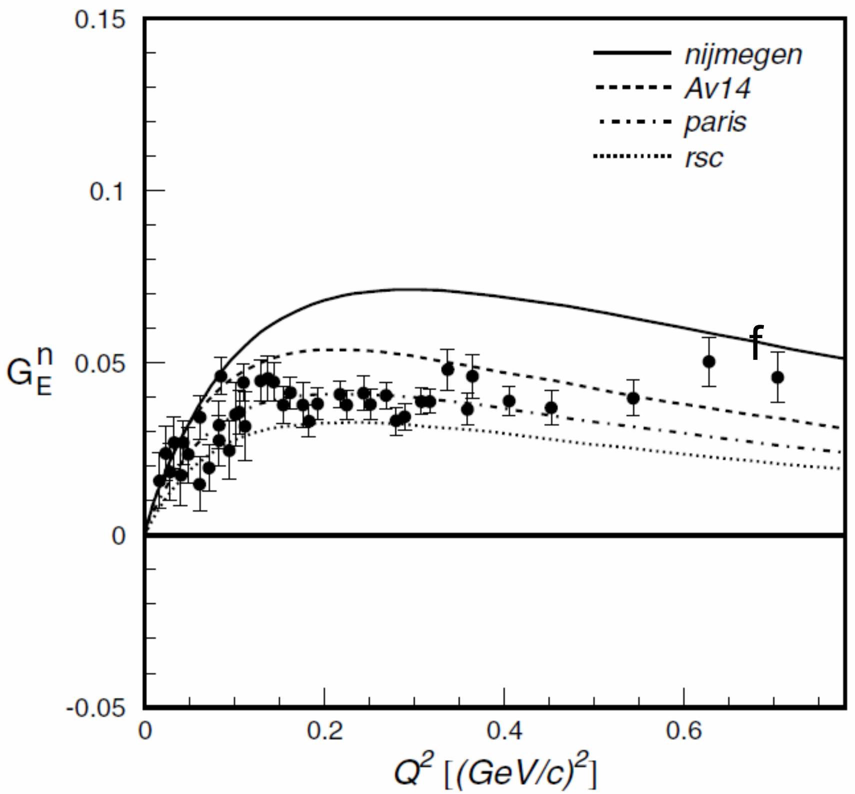
Results from all published Rosenbluth separation data for G_{Ep} and G_{Mp}.
Note that the "scaling" apparent after dividing by the dipole FF, $G_D=(1+Q^2/0.71)^{-2}$, did not survive the emergence of double polarization results in 1999.



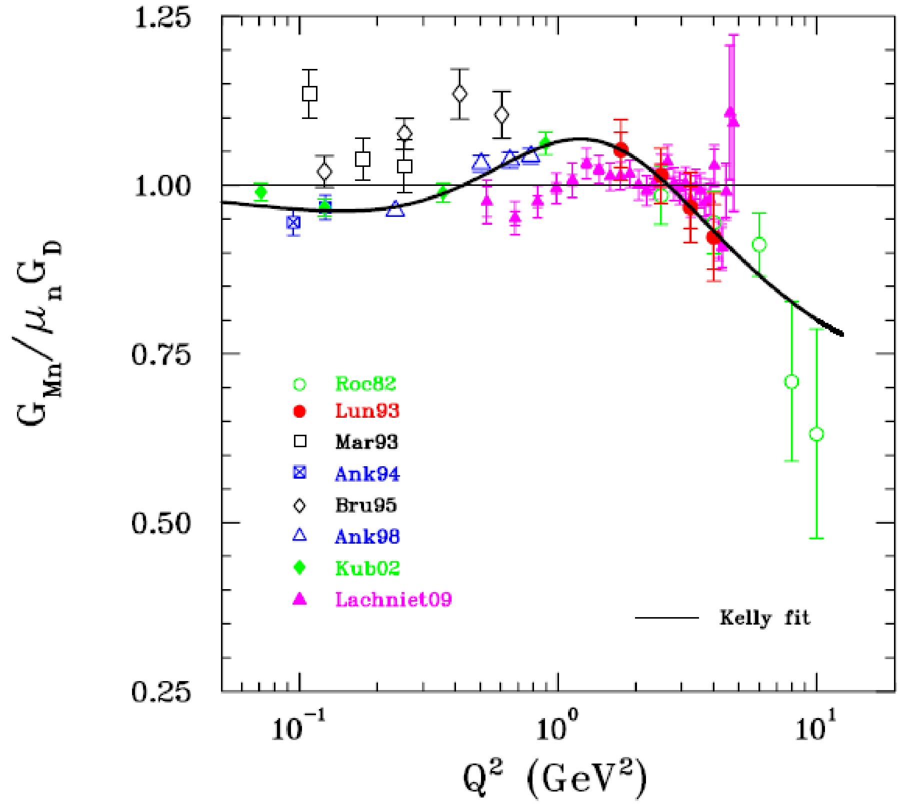


Neutron Form Factors

From elastic and quasi elastic electron-deuteron scattering from cross sections only.

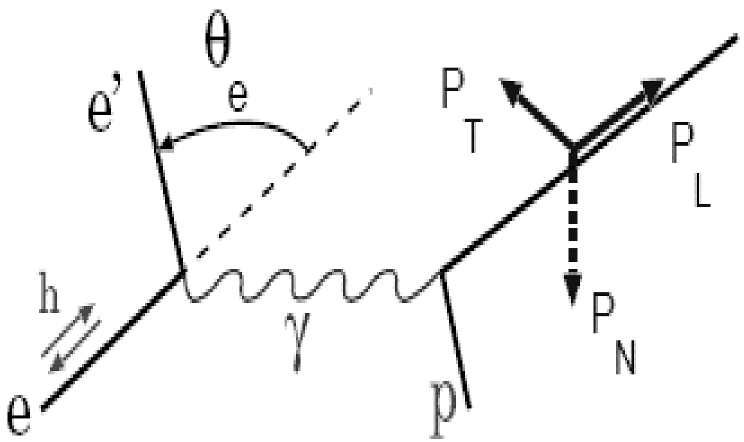


Unpolarized deuterium target,
Platchkov *et al*, N.P. A510 (1990),740.



Lachniet *et al.*, Phys. Rev. Lett. 102 192001 (2009).

Polarization Transfer Method



$$H(\vec{e}, e'\vec{p})$$

$$P_t = -hP_e\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\frac{r}{1+\frac{\epsilon}{\tau}r^2}$$

$$P_\ell = hP_e\frac{\sqrt{1-\epsilon^2}}{1+\frac{\epsilon}{\tau}r^2}$$

$$r = \frac{G_E}{G_M}$$

$$P_n = 0$$

$$R = \mu\frac{G_E}{G_M} = -\mu\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}}$$

h beam helicity, P_e beam polarization

Pioneering theoretical work by: Akhiezer, Rosentweig, Shmushkevich (1958), Akhiezer, Rekalo (1968,1974), Dombey (1969), Arnold, Carlson, Gross (1981), and others.

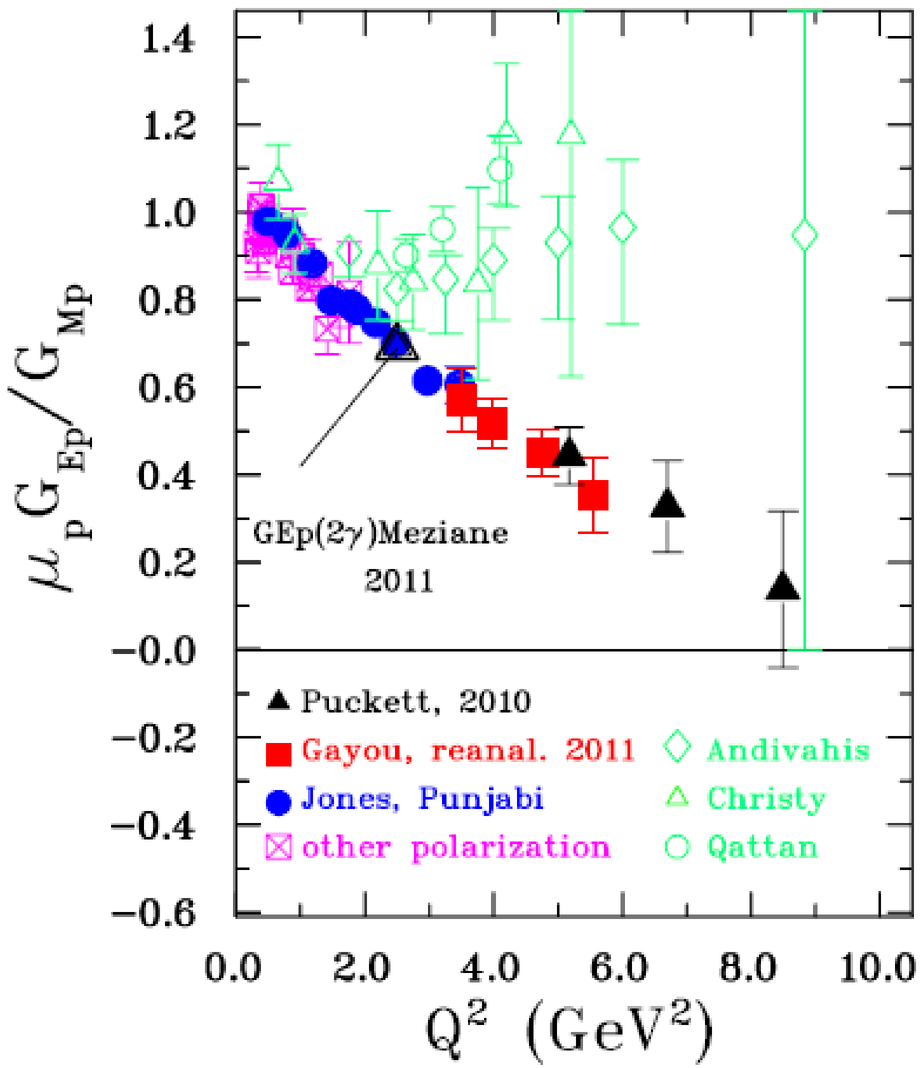
Advantage #1: much enhanced sensitivity to G_E at large Q^2, because $P_t \sim r = G_{Ep}/G_{Mp}$.

Advantage #2: simultaneous measurement of P_t and P_ℓ provides a robust determination of $R=\mu r$. Residual systematic uncertainty comes dominantly from uncertainty in spin precession.

Very similar situation for another double polarization experiment, $\vec{e} + \vec{n} \rightarrow en$; when the neutron angle is perpendicular to the momentum transfer vector $\vec{q}$ (and in the reaction plane), the asymmetry A_{perp} is:

$$A_{perp} = -\frac{2\sqrt{\tau(1+\tau)}}{1+\frac{\varepsilon}{\tau}\frac{G_{En}^2}{G_{Mn}^2}} \frac{G_{En}}{G_{Mn}}$$

Results for the G_{Ep}/G_{Mp} ratios from all double polarization experiments



The recoil polarization results stand out, and are internally consistent.

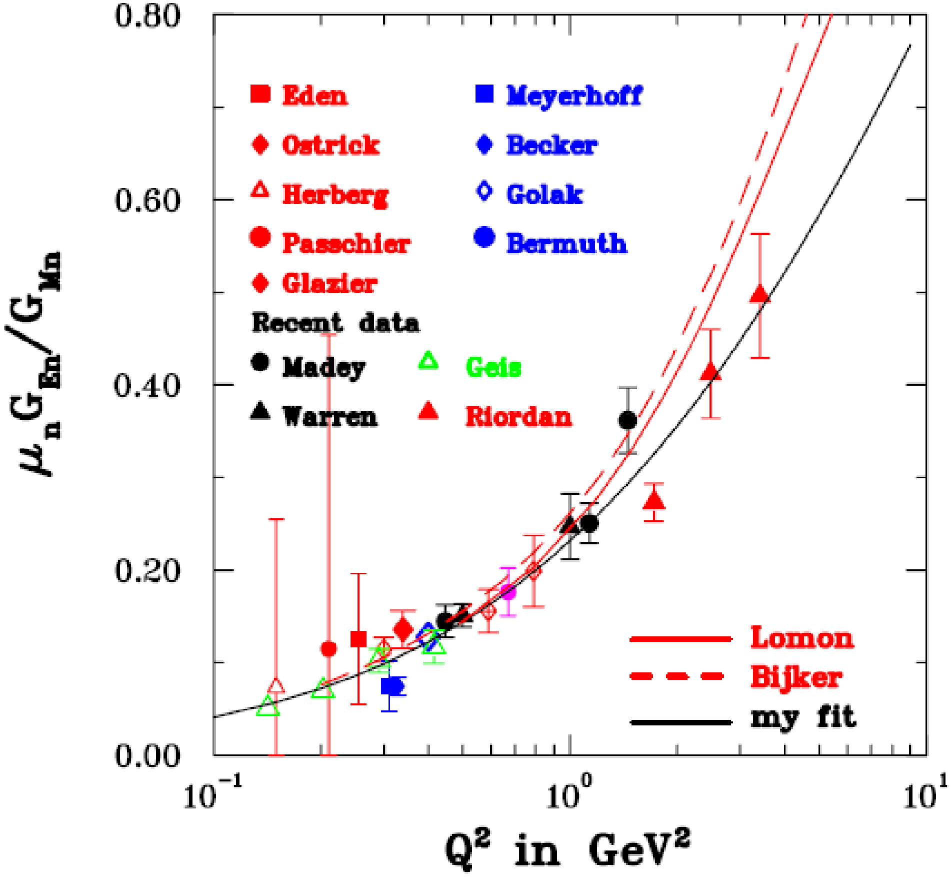
Other polarization results in cyan including recoil polarization and beam-target asymmetry results also shown.

Also shown are recent Rosenbluth data (in green) including:

Andivahis et al., Phys. Rev. D 50, 5491 (1994), Christy et al., Phys. Rev. C 70, 015206 (2004), Qattan I.~A. et al., Phys. Rev. Lett. 94, 142301 (2005).

Thus, the discrepancy between Rosenbluth and double polarization results is well established

Electric Form Factor of the Neutron



My Fit

Bijker

Lomon

All double polarization results for G_{En}, including new JLab Hall A (Gen(I)).

Most recent:

Riordan *et al.*, Phys Rev Lett 105, (2010) 262302

Geis et al., Phys. Rev. Lett. 101, 042501 (2008)

Take notice of energy log scale, chosen to amplify the role of small Q^2 data.

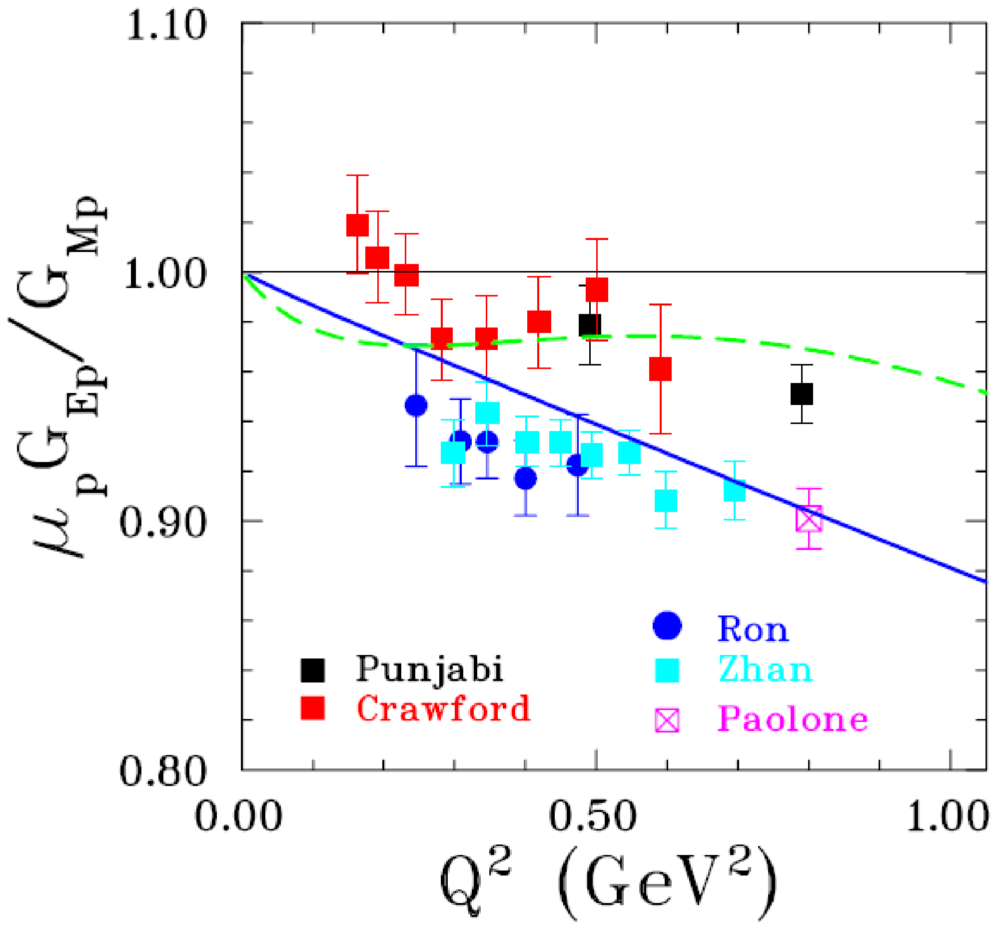
Previous slides illustrate discrepancy between Rosenbluth and double-polarization data for the proton data; for the neutron all data shown are double-polarization. Older cross section data are not compatible with the modern results (they required large nuclear structure corrections).

So a possible incompatibility of the G_{En}/G_{Mn} results from cross sections (Rosenbluth) and from double polarization is not documented for the neutron.

The proton discrepancy has been called the form factor crisis. It is not solved yet. I will address it later in this talk.

Low Q^2 Region

New results from Jlab, MIT-Bates for G_{Ep}/G_{Mp} in low Q^2 region. Notice significant differences between various experiments!



Punjabi et al., et al., Phys. Rev. C 71, 055202 (2005) [Erratum-ibid. C 71, 069902 (2005)].

C.B. Crawford et al. Phys. Rev. Lett. 98,052301 (2007)

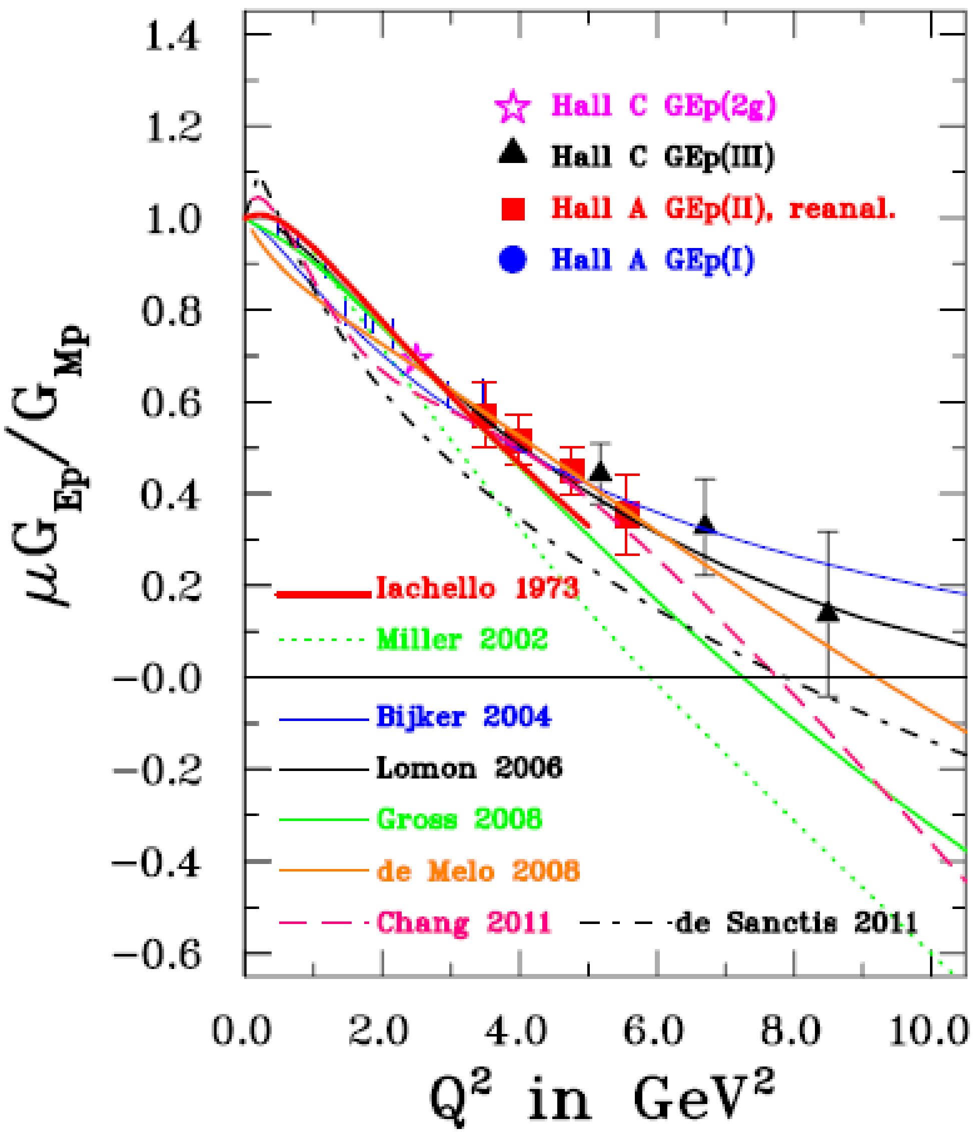
Paolone et al. Phys. Rev. Lett. 105, 072001 (2010)

Ron et al. arXiv:1103.5784 [nucl-ex]

X. Zhan et al. arXiv:1108.4441 [nucl-ex]

Recent Mainz results not included (Bernauer et al. 2010).

Many theoretical models agree with double polarization data



Just an overview:

VMD-based models (Iachello, Lomon, Bijker)

Relativistic constituent quark (rCQM), G.A. Miller, many others

Behavior of G_{Ep}/G_{Mp} at large Q^2 related to u/d ratio at small distances (Miller et al.)

Lattice QCD models

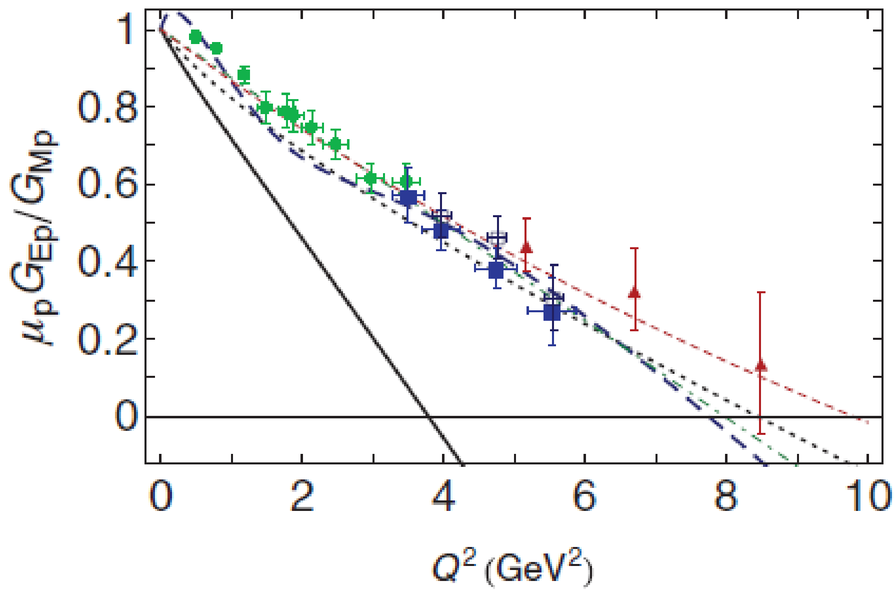
Dyson-Schwinger equations, as continuum approach to QCD (Roberts, Cloet et al.)

The new practice of flavor separation for "dressed" quarks in nucleon to be discussed further.

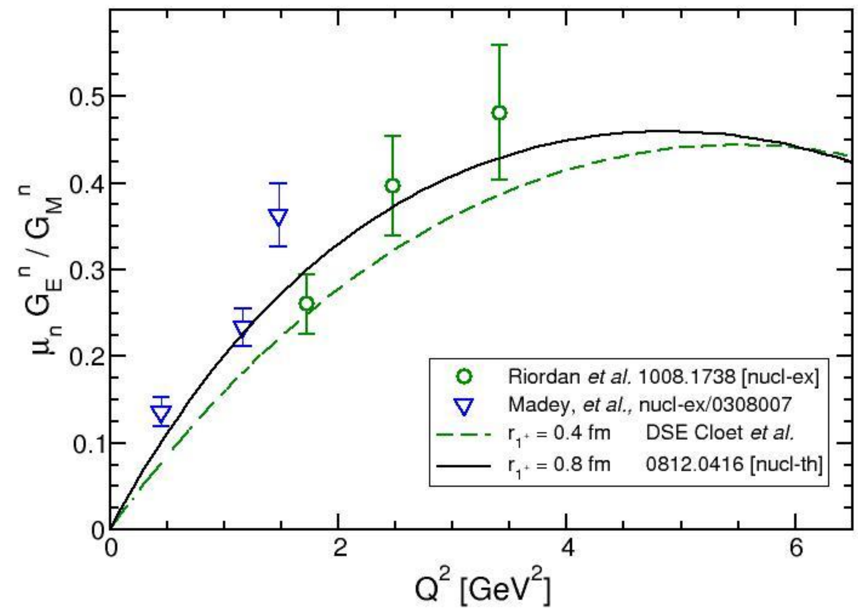
Dyson-Schwinger Equations

Comparison of DSE results with data, extrapolation?

proton



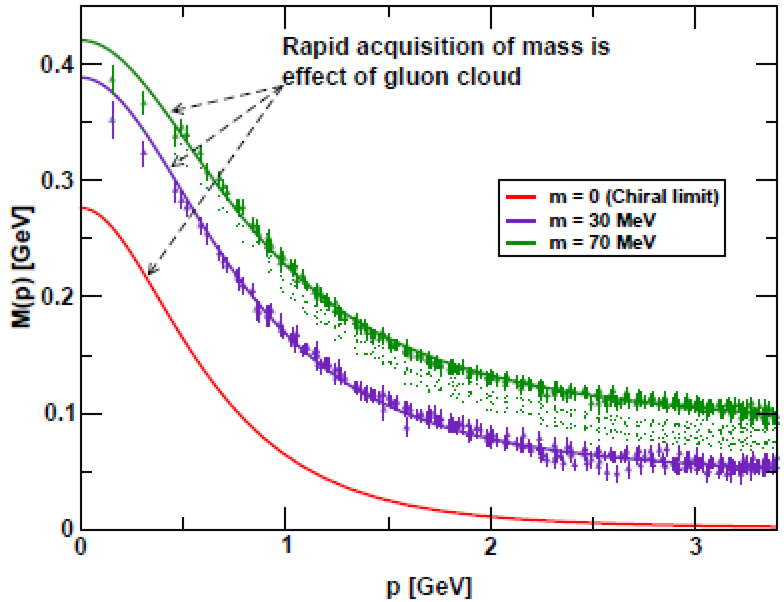
neutron



"Interpreting experiments with GeV electromagnetic probes requires Poincaré covariant treatment of baryons, covariant dressed-quark Faddeev equation, and correlations in Faddeev amplitude; quark orbital angular momentum is essential to that agreement". C.D. Roberts et al

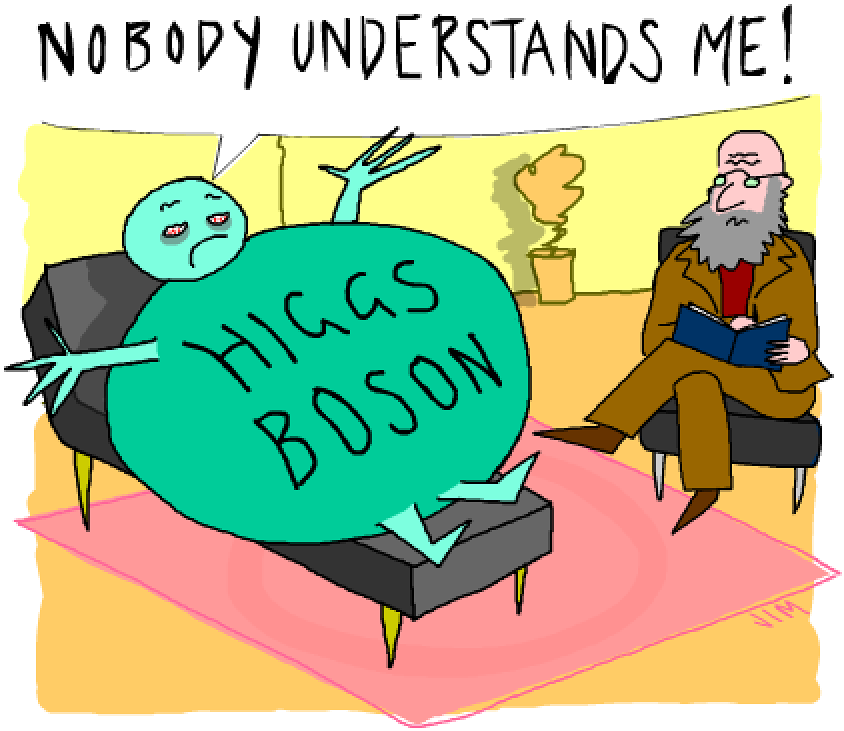
Dressed quarks in the Nucleon

Dressed quarks are a consequence of dynamical chiral symmetry breaking (DCSB) in QCD.
Dressed quarks and antiquarks constituents are described/predicted by Dyson-Schwinger Equations (DSEs). The quarks-partons of QCD acquire a momentum dependent mass that in the infra-red limit is 2 orders of magnitudes larger than the current-quark mass; mostly due to a cloud of gluons surrounding a low-momentum quark.



In this approach the Higgs boson does not contribute to the mass of the visible universe!

Le Monde, July 2012:
the Word of the Month: HIGGS BOSON



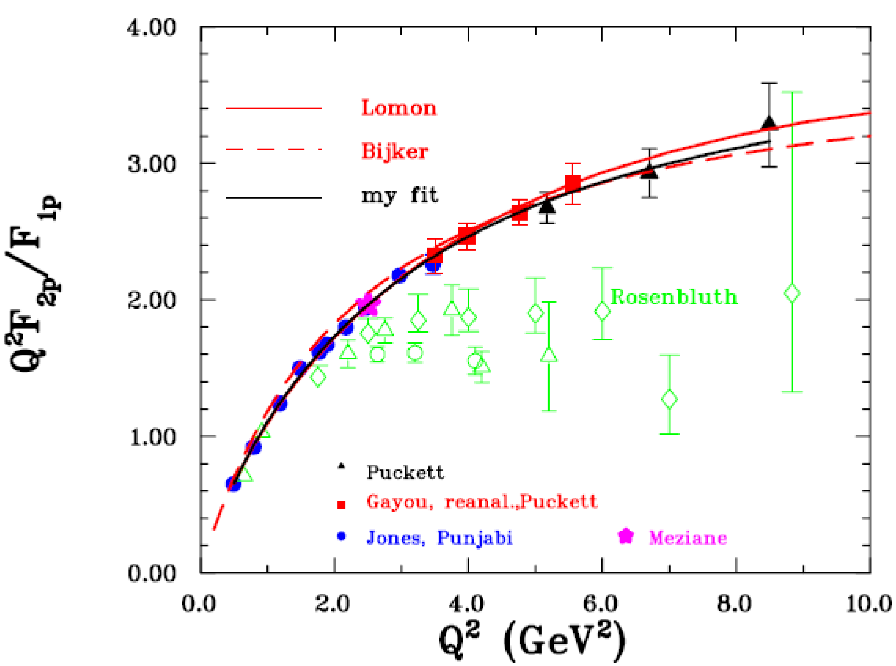
Asymptotic Behavior?

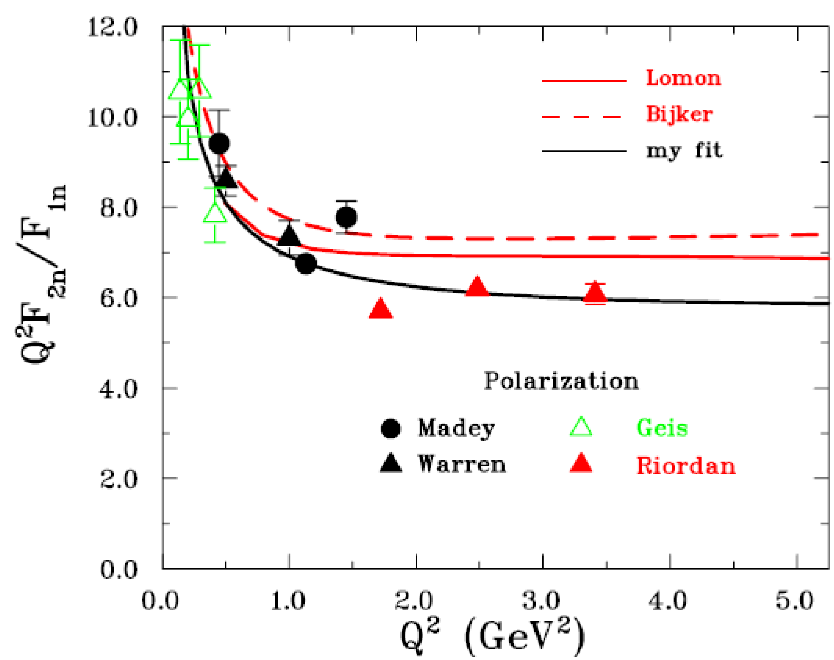
Perturbative QCD (pQCD):

Q^2F_2/F_1->1 for (very) large Q^2 (Brodsky and Farrar, 1975).

Definitively not occurring yet for the proton, perhaps just starting for the neutron; what is the significance of different behavior for proton and neutron, beyond the consequence of neutrality, implying that $F_{1n} \to 0$ for $Q^2 \to 0$?

proton **neutron**

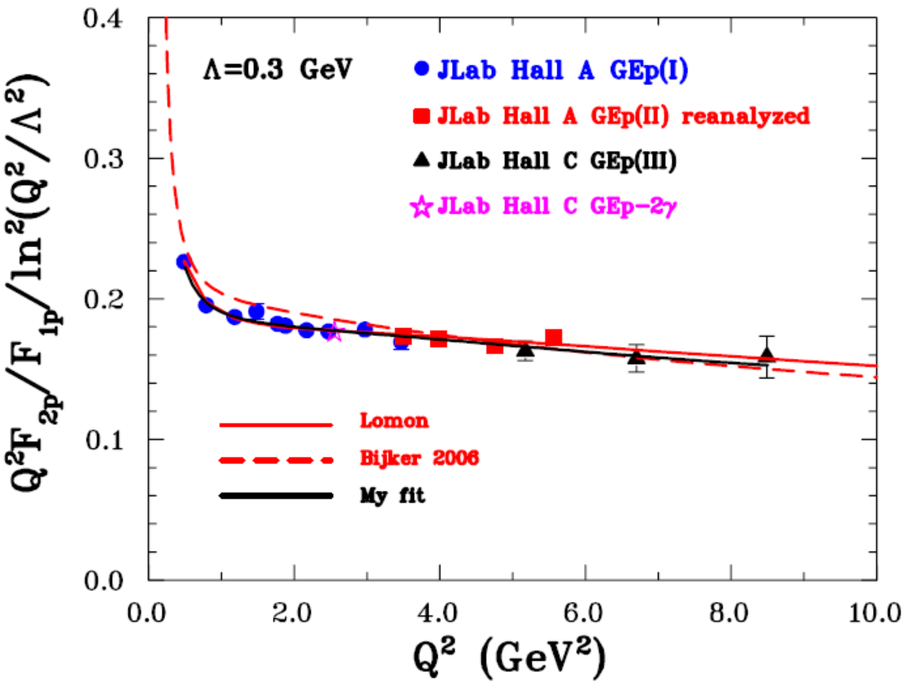




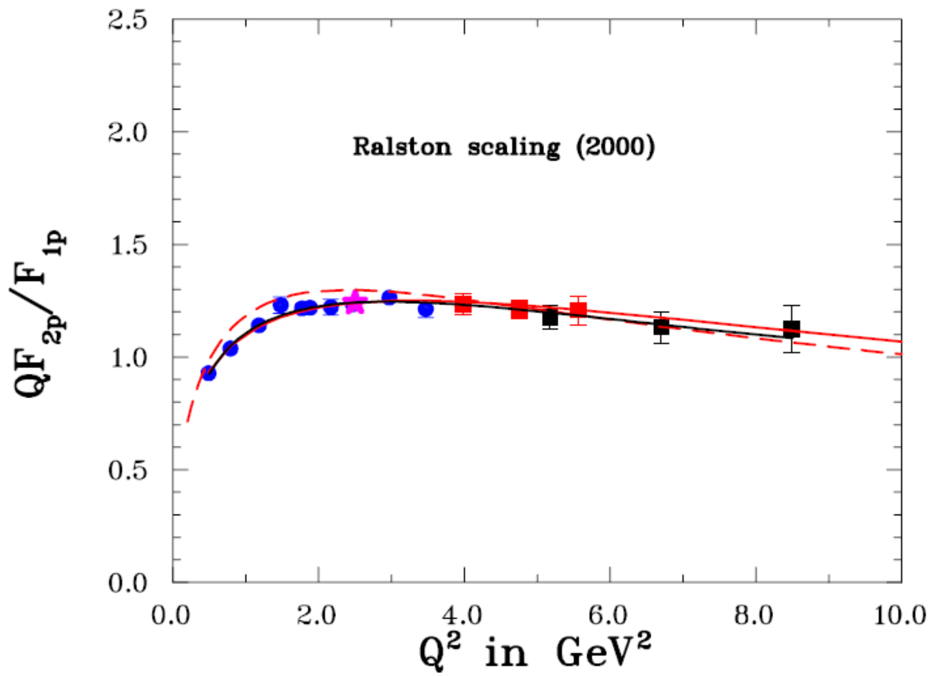
Scaling of F_2/F_1?

The $F_2/F_1 \sim 1/Q^2$ pQCD scaling prediction was modified by Belitsky, Ji and Yan (2003) to include quark angular momentum; better for the proton, with $\Lambda \sim 0.3$ GeV (on the left).
Older modified pQCD prediction of Ralston et al (2000), also included effect of quark angular momentum, on F_2 only; predicted QF_2/F_1 would scale, and it does equally well as Belitsky's scaling (on the right,no free parameter).

Belitsky, Ji and Yuan



Ralston

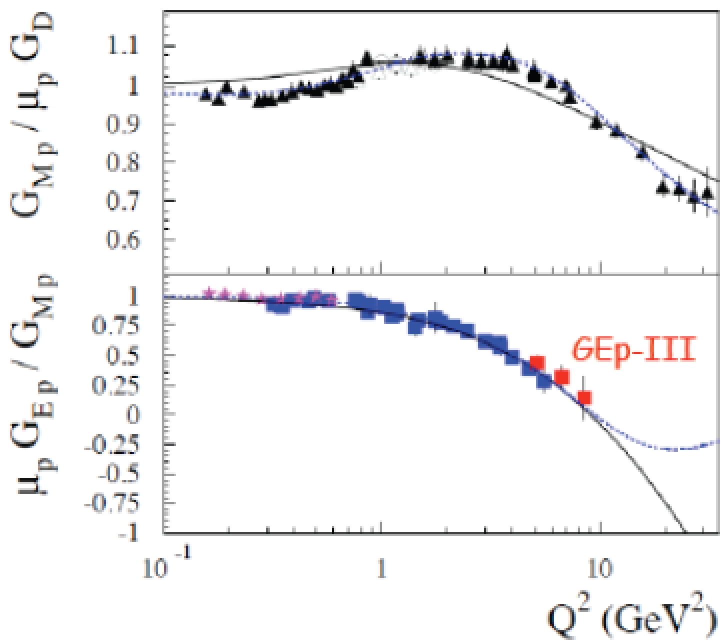


GPDs and Electromagnetic FF

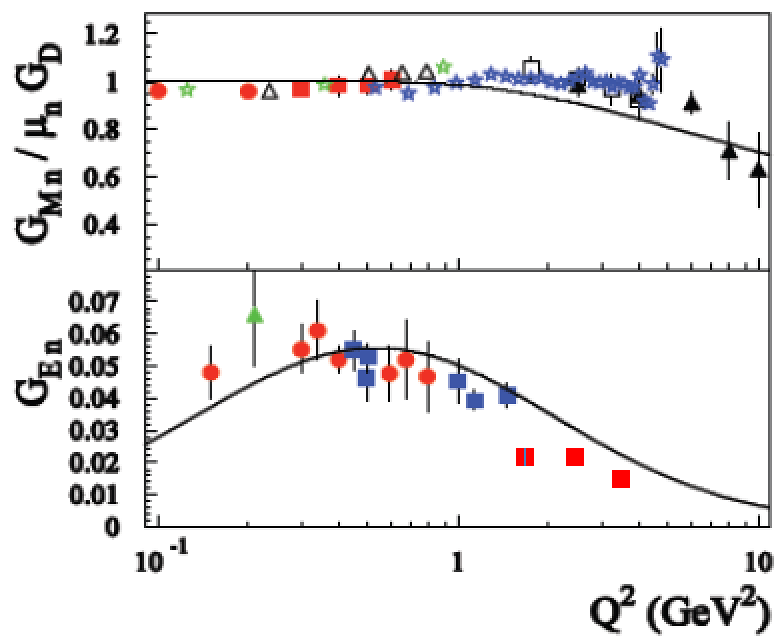
The first moments of GPDs are related to the elastic FF (Ji, 97)

$$\int_{-1}^{+1} dx\, H^q(x,\xi,Q^2) = F_1^q(Q^2)\,, \qquad \int_{-1}^{+1} dx\, E^q(x,\xi,Q^2) = F_2^q(Q^2)\,,$$

PROTON



NEUTRON

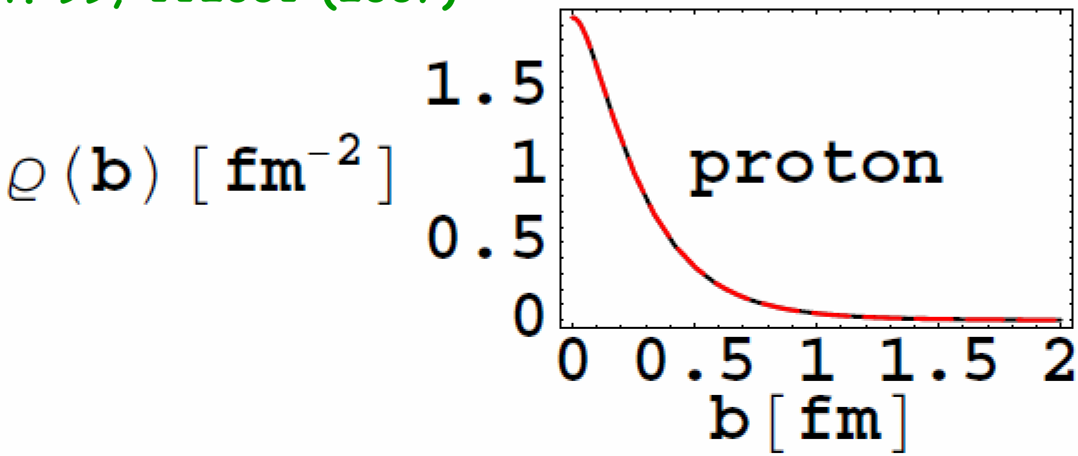


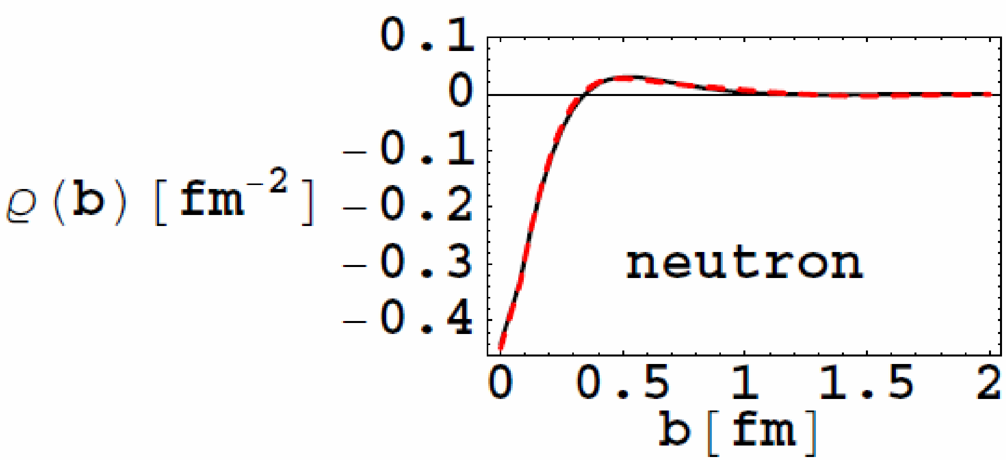
Modified Regge Parametrization for H and E (Guidal et al., (2005)

$$H^q(x,0,Q^2) = q_v(x)x^{\alpha'(1-x)Q^2}, \qquad E^q(x,0,Q^2) = \frac{\kappa^q}{N^q}(1-x)^{\eta^q} q_v(x)x^{\alpha'(1-x)Q^2}$$

Transverse Charge Densities in infinite momentum frame.

Charge density ρ(b) of partons in the transverse plane is a two-dimensional Fourier transform in the infinite momentum frame of the F_1 form factor calculated from the measured FF G.A. Miller, Phys. Rev. Lett. 99, 112001 (2007)



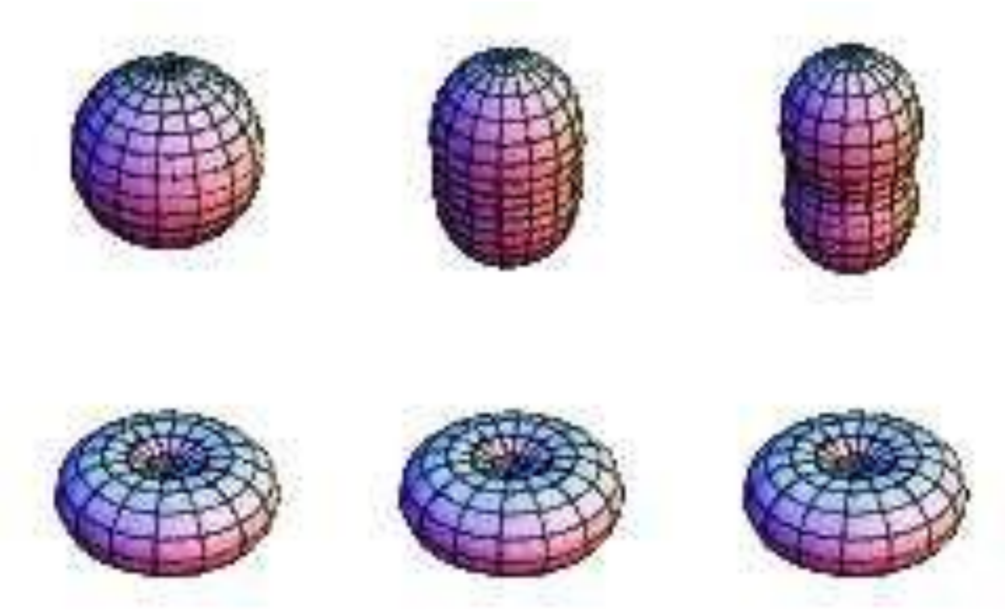


Only in the Breit frame can the FF be associated with charge and current distributions in the nucleon; but the velocity of the Breit frame depends on Q^2. Hence these distributions are not "really" physical observables.

The proton is not spherical?

Not a crisis, but an unexpected consequence of fast decreasing G_E/G_M "a la Gerry Miller".

Shape of the proton: spin dependent quark density; depends upon angle between spin of 1 quark relative to nucleon spin. Direct consequence of apparent scaling of QF_2/F_1.
G.A. Miller, PR C 68:022201(2003)



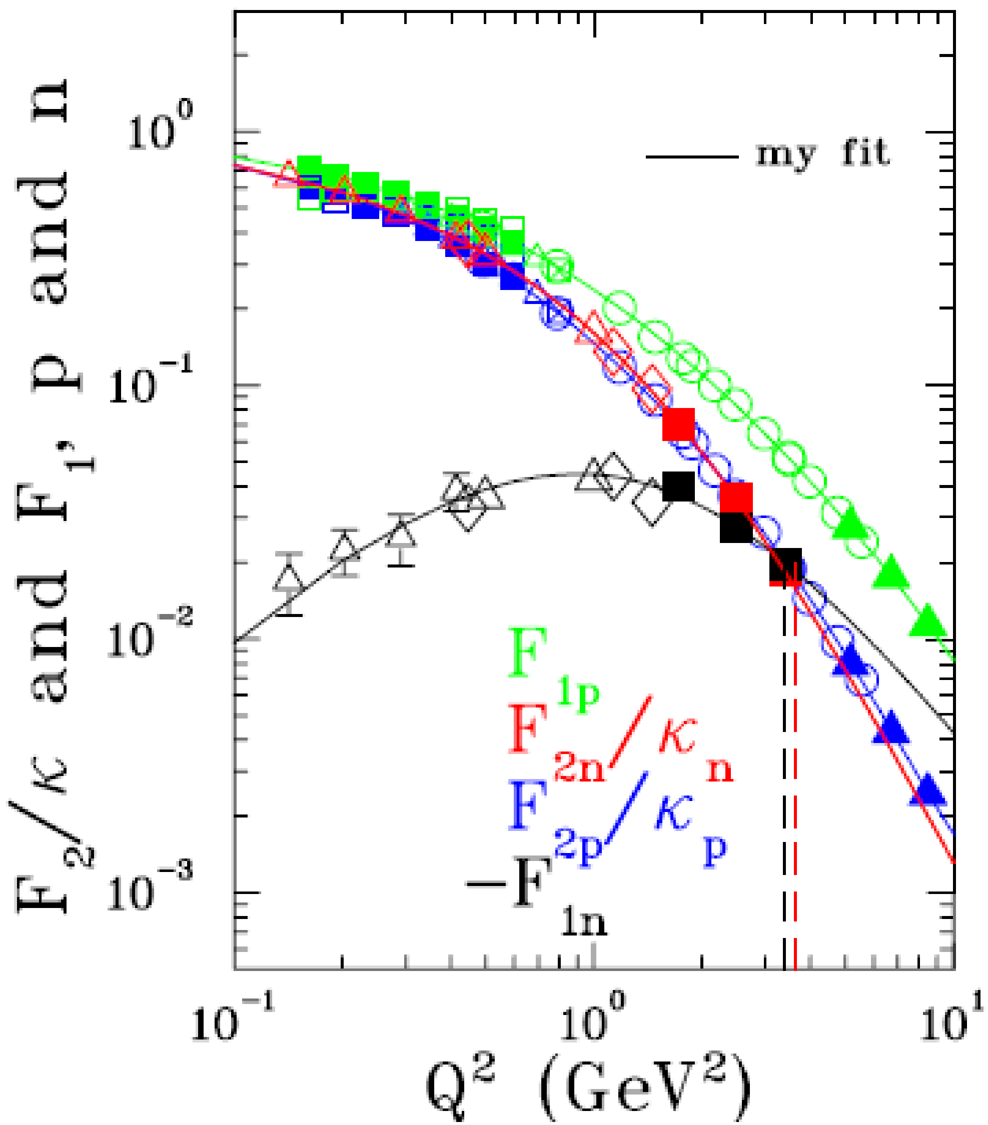
Dirac and Pauli nucleon form factors

Parametrize the four Sachs form factors, and calculate F_1 and F_2. Use Kelly form: polynomial/polynomial with asymptotic $1/Q^2$ ratio behavior.

F_{1n} negative at $Q^2 \sim 0$ because $G_{En} \sim 0$ and G_{Mn} is negative.

$F_{2n}/\kappa_n \sim F_{2p}/\kappa_p$; but the neutron data are extrapolated.

All 4 factors have a smooth behavior, and the data are internally consistent.



Quark Flavor separation

Assume that hadron current: $\langle p|e_u\bar{u}\gamma_\mu u+e_d\bar{d}\gamma_\mu d|p\rangle$, with e_u and e_d the charge of the *up* and *down* quarks

and isospin symmetry:

$$F_{1n}^{d} = F_{1p}^{u}, \quad F_{1n}^{u} = F_{1p}^{d}$$

$$F_{2n}^{d} = F_{2p}^{u}, \quad F_{2n}^{u} = F_{2p}^{d}$$

Then the Pauli and Dirac form factors of the dressed quarks in the proton are (with related relations for the neutron):

$$F_{1p}^{u} = 2F_{1p} + F_{1n} \qquad F_{1p}^{d} = F_{1p} + 2F_{1n}$$

$$F_{2p}^{u} = 2F_{2p} + F_{2n} \qquad F_{2p}^{d} = F_{2p} + 2F_{2n}$$

See for example: Cates, deJager, Riordan, Wojtsekhowski (2011), Rohrmoser, Choi and Plessas, (2011), Wilson, Cloet, Chang and Roberts, (2012), Cloet and Miller (2012)

Note: $F_{1p}^{d} \sim F_{2p}^{u} \sim -F_{2p}^{d}$ at $Q^2 < 3.5$ GeV^2 (current limit for complete data base)

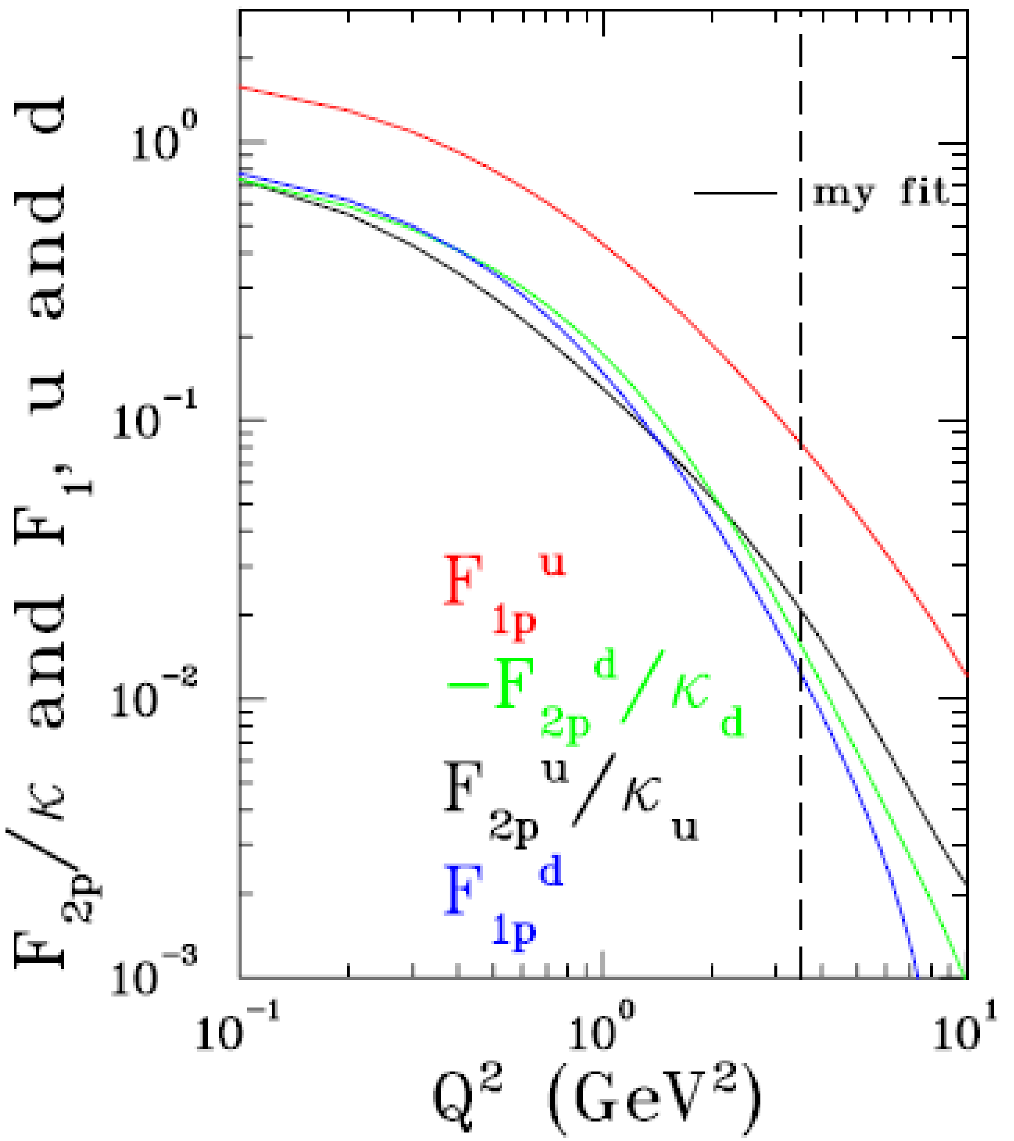
Is this new physics, or just another representation of the FF of the nucleons?

Or, is this more than a another linear transformation between the nucleon F-form factors, similar to the one between the F_1 and F_2 and G_E and G_M?

at Q^2=0

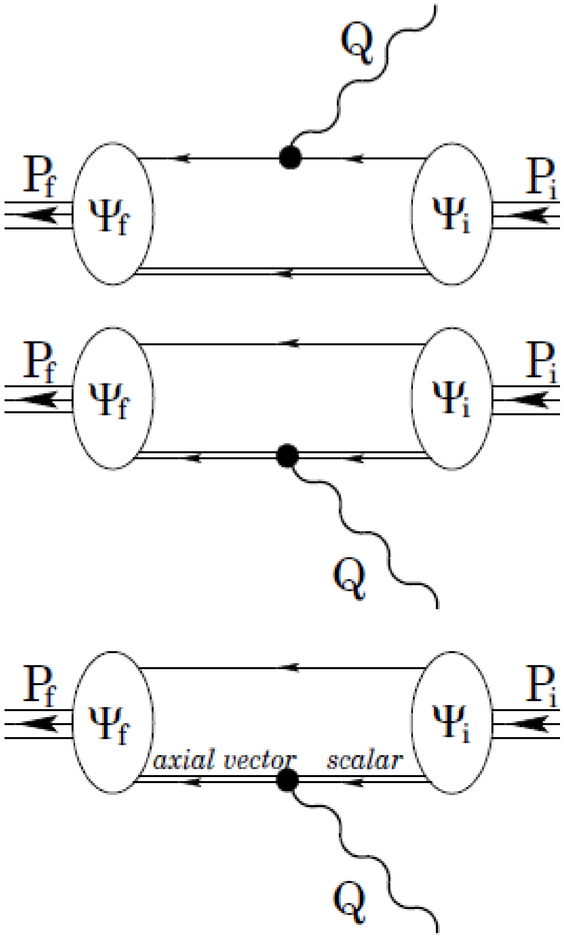
$F_{1p}^{u} = 2$ $\qquad F_{2p}^{u}/\kappa_u = 1$

$F_{1p}^{d} = 1$ $\qquad F_{2p}^{d}/\kappa_d = 1$



Quark Flavor separation (II)

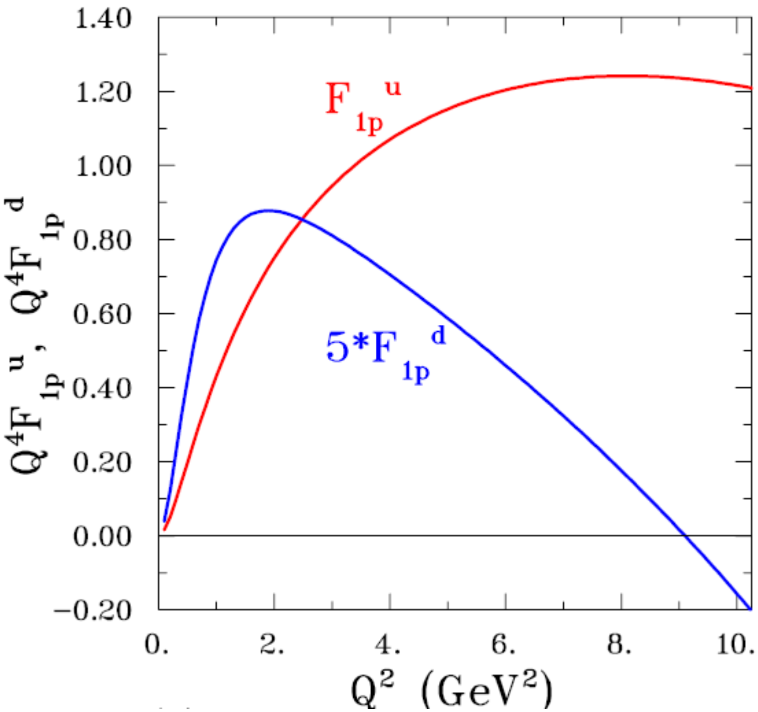
In Roberts et al application of the Dyson Schwinger/Fadeev QCD approach, nucleon contains a diquark, and interference of the axial-vector and scalar di-quark produces the zero a the Dirac form factor of the *d* quark in the proton: F_{1p}^{d}. Curves in next 2 transparencies calculated from the fits to the *p* and *n* data, with extrapolation shown in previous transparency.



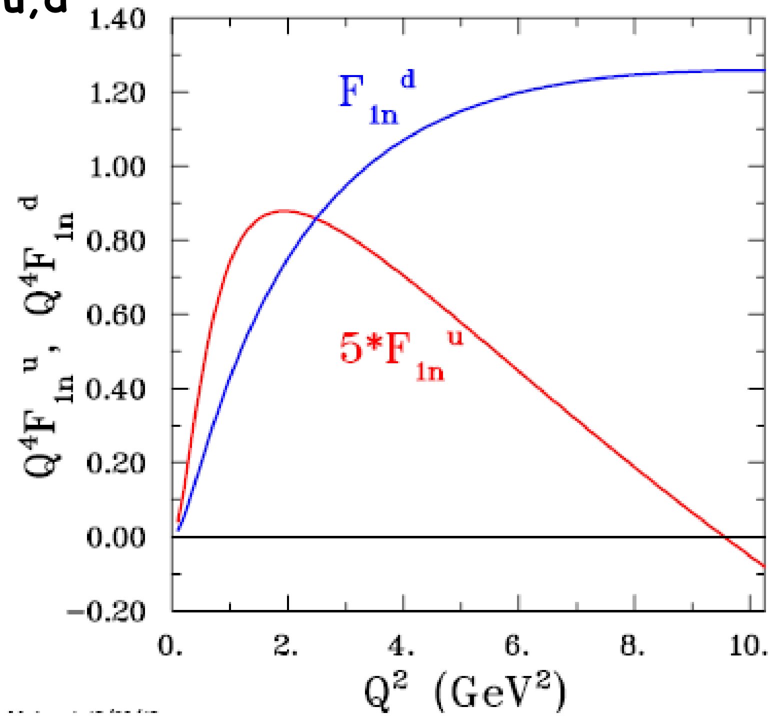
Wilson, Cloët, Chang, Roberts, Phys. Rev. *C* 85, 025205 (2012)

Obtained from fits to the Dirac and Pauli FF data shown earlier, that use Kelly-like polynomial forms (J. Kelly, P.R. C70, 068202 (2004)) and extrapolating beyond the experimentally determined Q^2-region for the neutron.
Both proton and neutron are shown to highlight the initial assumption of isospin symmetry.

$F_1^{u,d}$

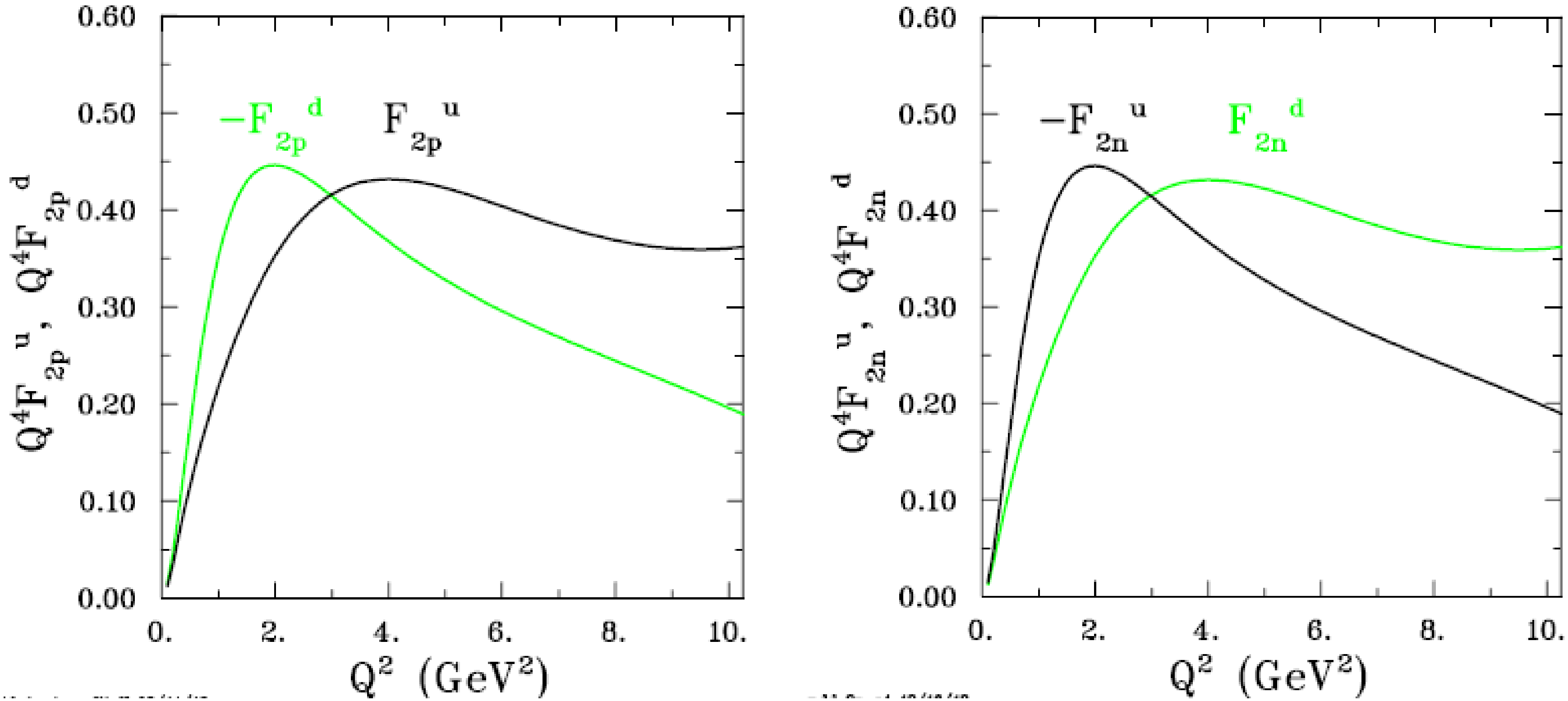


Proton



Neutron

Proton $F_2^{u,d}$ Neutron



$$F_{1n}^{d} = F_{1p}^{u}, \quad F_{1n}^{u} = F_{1p}^{d}$$

$$F_{2n}^{d} = F_{2p}^{u}, \quad F_{2n}^{u} = F_{2p}^{d}$$

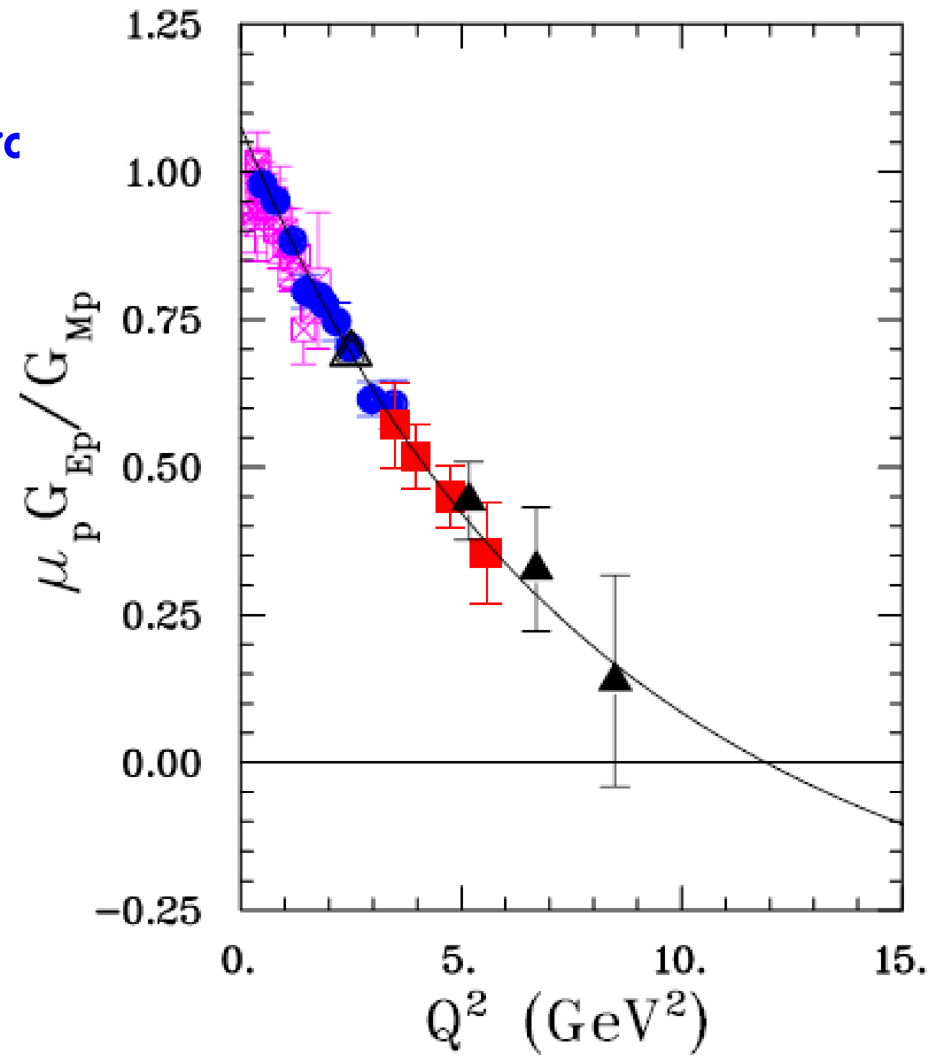
Was required initially, hence is seen!

PROTON

Each one of the Sachs form factc
has been fitted with a Kelly-like
polynomial.

Then G_{ep}/G_{Mp} obtained from
these.

The result is extremely smooth
and independent of a forced
asymptotic $1/Q^2$ dependence.

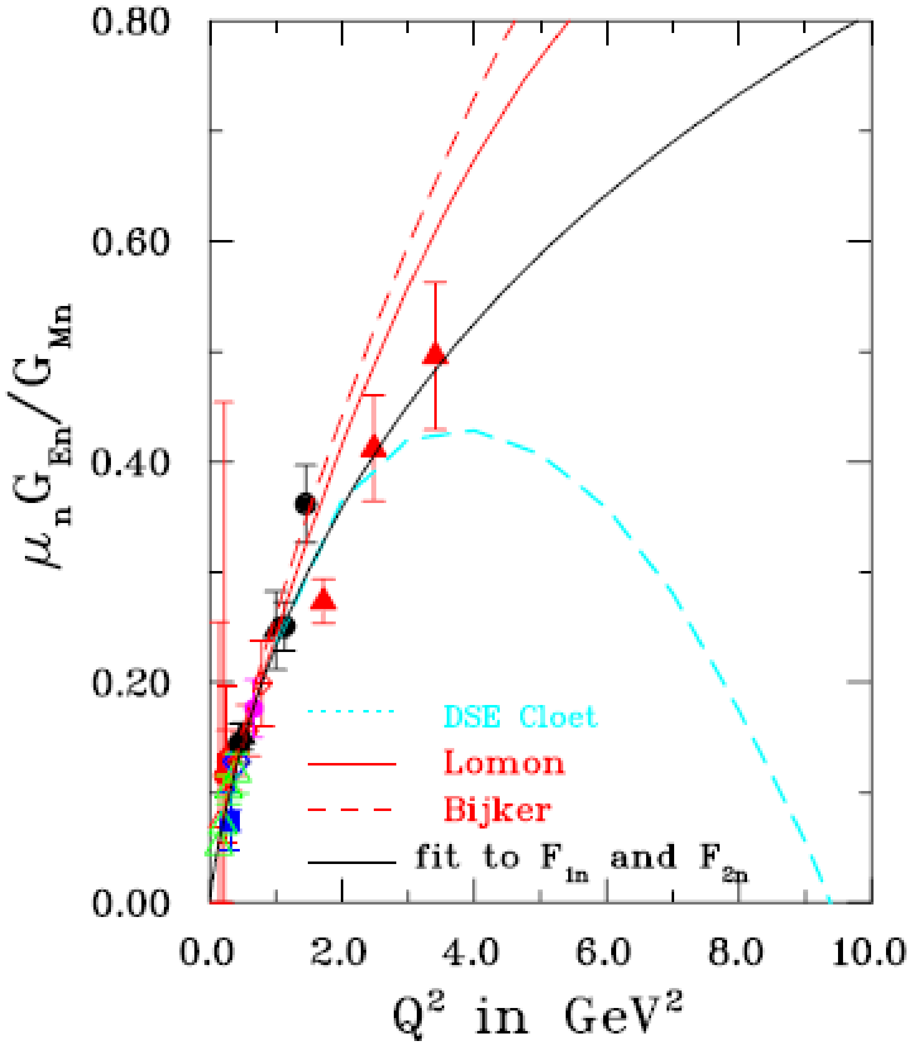


NEUTRON

Each of the neutron Sachs form factors has been fitted with Kelly-like polynomial.

Then G_{En}/G_{Mn} obtained from these.

The result is extremely smooth and independent of a forced $1/Q^2$ dependence.



Indication of two hard photon exchange?

The striking and significant difference between the Rosenbluth data for G_{Ep}/G_{Mp}, and the recoil polarization from P_t/P_ℓ, for Q^2 larger than 2-3 GeV^2, has triggered a re-examination of all older models of the nucleon.

Rosenbluth data give $\mu_p G_{Ep}/G_{Mp}$ values hovering around 1, polarization data give $\mu_p G_{Ep}/G_{Mp} \sim 1-0.14(Q^2-0.04)$, up to approximately 6 GeV^2, followed by slightly slower decrease with Q^2.

A hypothesis favored by a majority of theorists, but not all theorists or experimentalists is that the difference arises due to the hard two-photon exchange, a term neglected in radiative corrections until recently .

Here note that a two-photon contribution tends, in first approximation, to decrease the Rosenbluth values of G_{Ep}/G_{Mp}, but leaves the polarization values unchanged.

More about the Rosenbluth versus double polarization "discrepancy"?

So far we have no direct, experimental evidence, that two-photon exchange is the answer to the "form factor crisis", even though much has been written about it. Rosenbluth and double polarization results are incompatible.

It is well known that radiative corrections (RC) to *ep* cross sections can be as large as ~30 % and that they are ε-dependent. The slope of Rosenbluth plots is changed significantly by the RC correction; and the slope directly determines G_{Ep}^2/τ.

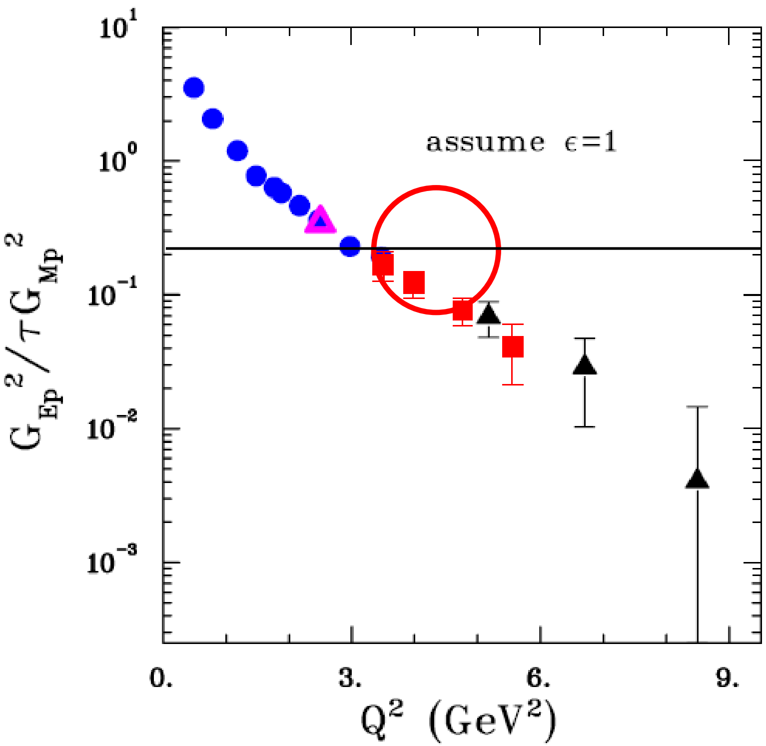
Are the RC corrections applied to cross section data accurate enough? Bystritskiy,Kuraev, and Tomasi-Gustafsson answer no, based on structure function calculation, which leaves little room for measurable two-photon effects.

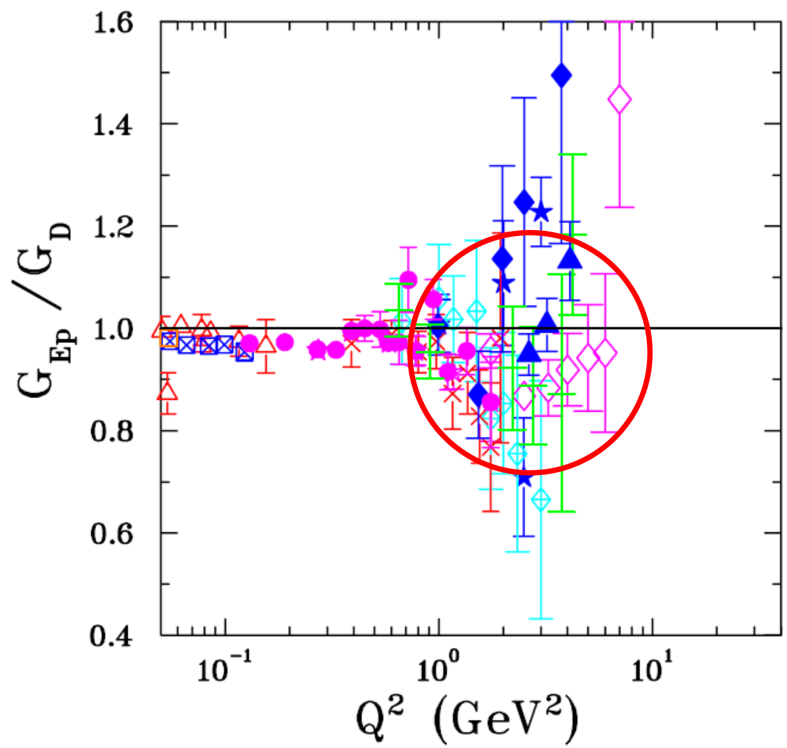
Others see the discrepancy as mostly explainable in terms of two-photon effect. For example Afanasev, Brodsky, Carlson, Chen and Vanderhaeghen; Arrington; Blunden, Melnitchouk and Tjon; Borysyuk and Kobushkin; Guttmann, Kivel, Meziane and Vanderhaeghen; and others.

The relative contribution of G_{Ep} to the cross section becomes of order of the experimental uncertainty (10-20%) by $Q^2 \approx 3.5$ GeV^2. Which is where the LT data for G_{Ep} seem to loose track of G_{Ep}! Coincidence?

$$\frac{d\sigma}{d\Omega} \approx \frac{\tau G_M^2}{\varepsilon(1+\tau)} \left[1 + \frac{\varepsilon}{\tau} \frac{G_E^2}{G_M^2} \right]$$

A similar point was argued by Egle Tomasi several years ago.





Radiative correction to the last data from SLAC, of Andivahis et al.

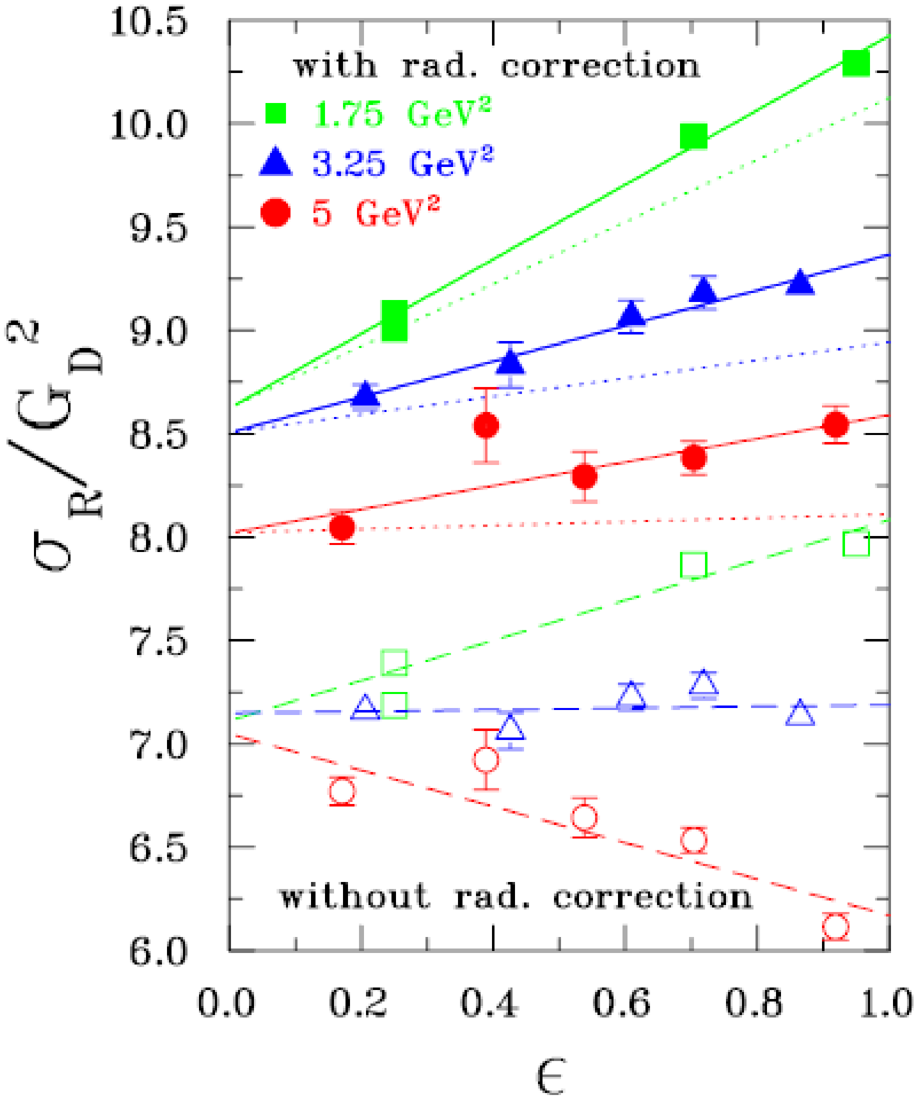
Dashed lines at bottom: raw data, no radiation correction.

Solid line: after full radiative correction (but no two hard photons

Dotted line: the slope from the double polarization experiment GEp(I) Jones et al/Punjabi et al and GEp(II) Gayou et al/Puckett et al.

Note that rad. corrections systematically increases the slope (which here is G_{Ep}^2/τ).

All two-photon corrections are ε-dependent and tend to decrease the slope.



Are we dealing with a simple measurement problem: separating G_E^2 from G_M^2 fails when $G_E \ll \tau G_M$ and increasingly so for larger Q^2?

Or are we dealing with the problem of calculating the standard radiative corrections with enough accuracy?
Or are we really observing the effect of the next order diagram, namely the exchange of two hard photons, as distinct from the infra-red two-photon exchange included in past RC?

The calculation of two photon exchange is difficult because the intermediate state proton is off-the-mass shell, so it is model dependent. Consequently there are many calculations, most of them agreeing within a factor of 2 with each other, and bringing the Rosenbluth data in partial agreement with the double polarization data. Closest to the truth are the double polarization results because they are obtained as ratios: P_t and P_ℓ are function of G_E/G_M, and we measure P_t over P_ℓ, in first order cancelling the radiative correction.

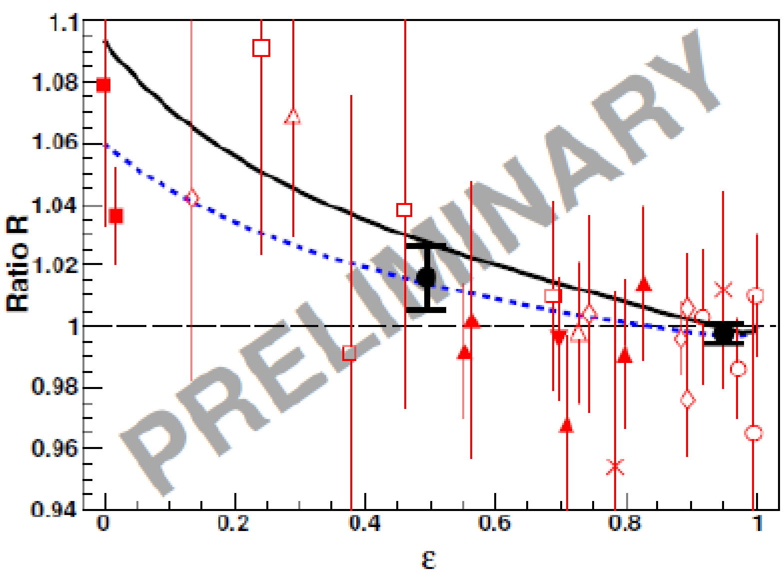
Measuring the ratio of the e^+ to e^- cross sections is the most direct way to verify the calculations, but it suffers from its own problem: radiative corrections (again), which are of the same order of magnitude as the presently available data for $\sigma(e^+p)/\sigma(e^-p)$.

Currently 3 attempts to measure two-gamma contribution from e^+p/e^-p cross section ratio

$$R = \frac{\sigma(e^+p)}{\sigma(e^-p)} \approx 1 + 4\frac{\mathrm{Re}\left(\mathcal{M}^\dagger_{\mathrm{Born}}\mathcal{M}_{2\gamma}\right)}{|\mathcal{M}_{\mathrm{Born}}|^2},$$

1) Novosibirsk VEPP-3 storage ring: preliminary results from run I: Q^2=2.0 GeV^2. Older data shown with Q^2<2 GeV^2

Solid curve, Blunden et al for these data; dashed, same for future data.



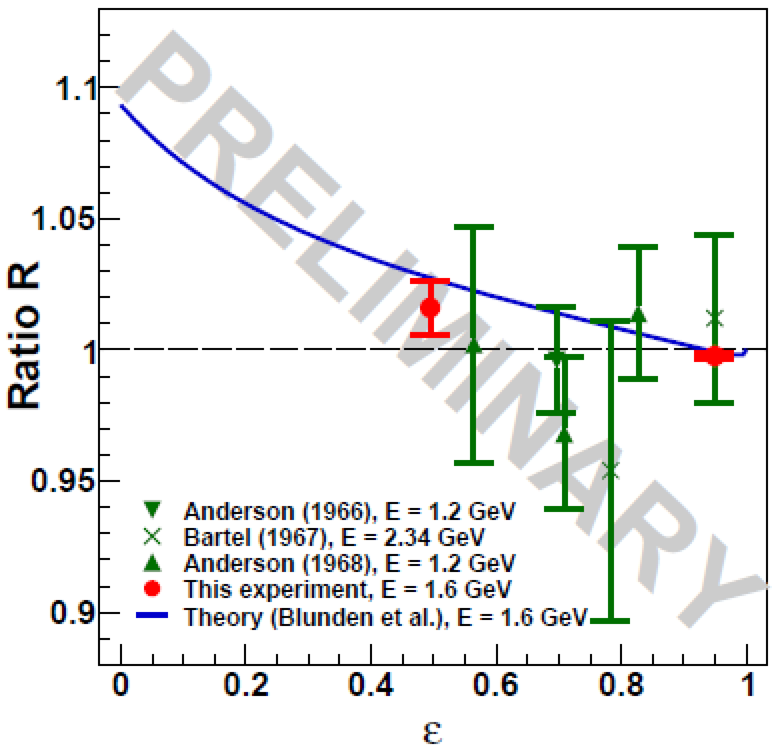
Run I, E=1.6 GeV.

A.V. Gramolin et al, arXiv:1112.5369
A.V. Gramolin et al. Nucl. Phys B Proc. Supp. 225 (2011).

Includes full radiation correction.

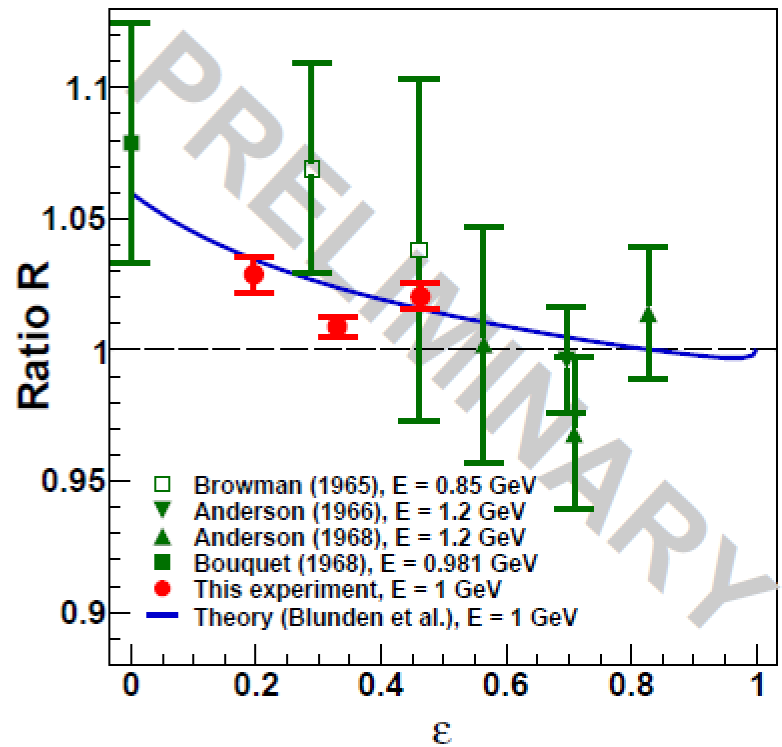
Run I (2009):

$E_{\text{beam}} = 1.6$ GeV



Run II (2011–2012):

$E_{\text{beam}} = 1$ GeV

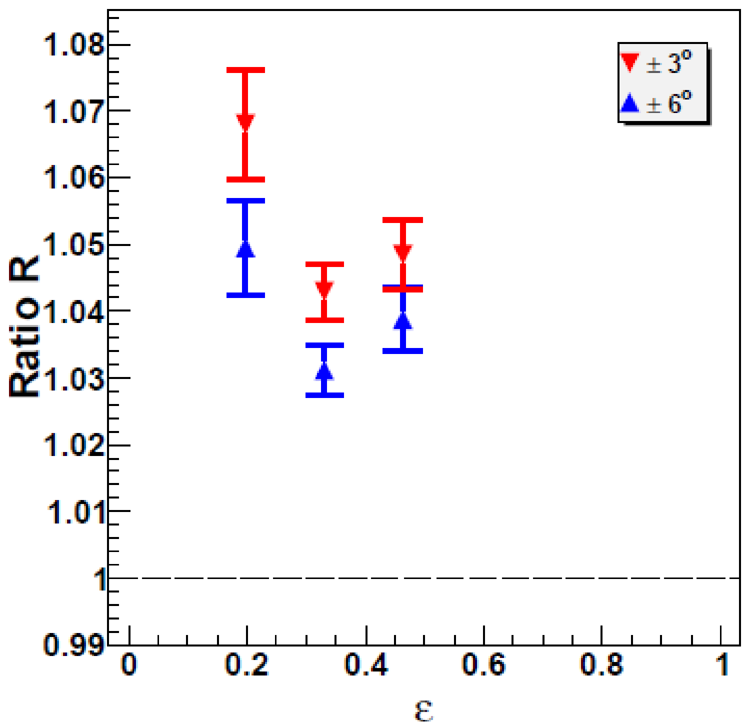


Theory: *P. G. Blunden, et al.*, Phys. Rev. C **72** (2005) 034612

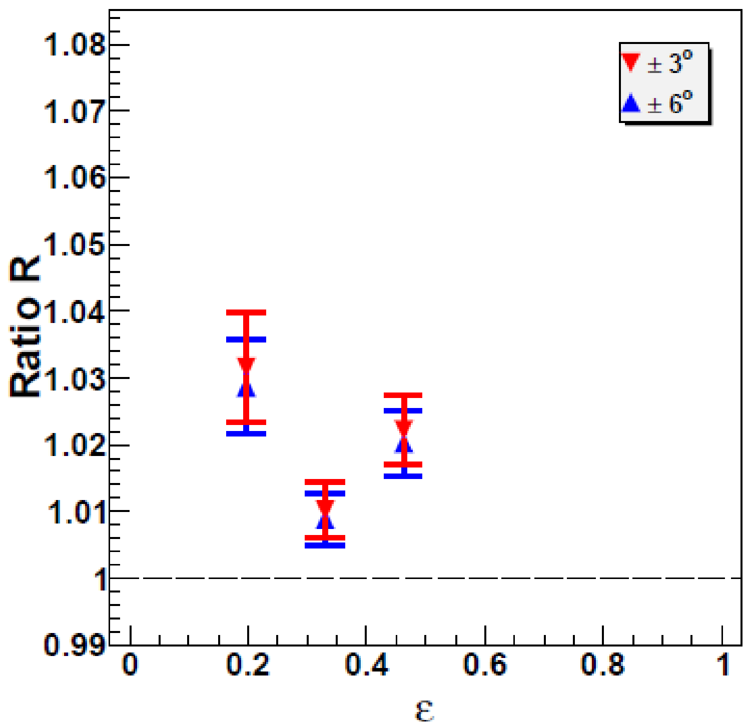
Only statistical errors are shown. Systematic errors for both the runs: $\leqslant 0.3\%$

Preliminary results from run II, Novosibirsk experiment.
Emphasizing the effect and importance of radiative corrections.

Raw data for the ratio R:

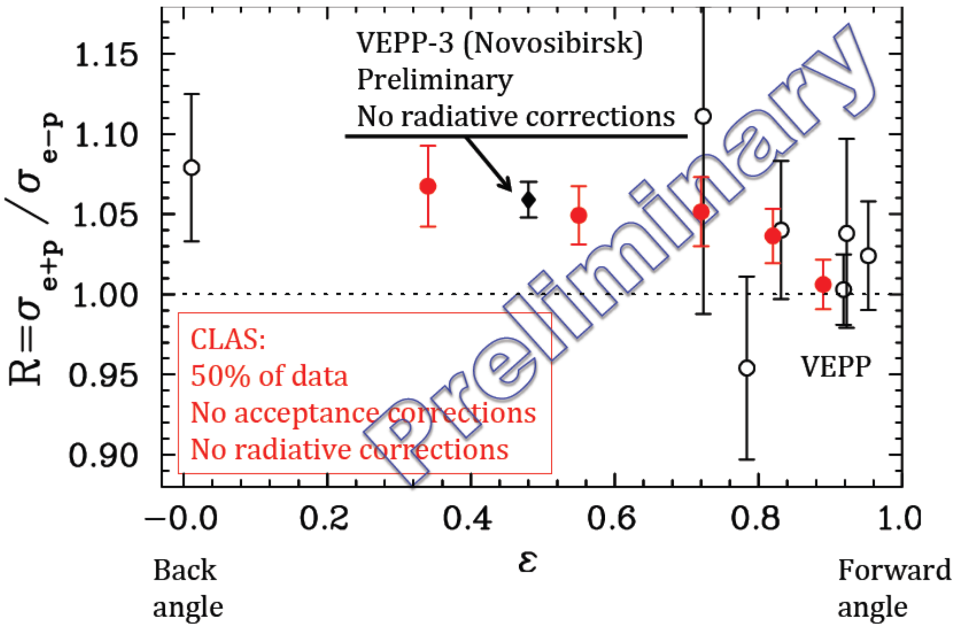


Radiatively corrected ratio R:



Presented at PNPI, St. Petersburg, July 9, 2012, by A.V. Gramolin

2) JLab Hall B, data taken, currently in data analysis phase.



Larry Weinstein, Hall B
VERY PRELIMINARY
presented in Nov. 2012

no radiative corrections.
systematics not known.

$$R = \frac{\sigma(e^+p)}{\sigma(e^-p)} \approx 1 + 4\frac{\mathrm{Re}\left(\mathcal{M}^{\dagger}_{\mathrm{Born}}\mathcal{M}_{2\gamma}\right)}{|\mathcal{M}_{\mathrm{Born}}|^2},$$

3) Olympus at DESY, currently nearing end of data taking mode.

Two-photon exchange is next term to the Born approximation. Affects form factor observables through interference between the single- and two-photon processes. Requires third form factor, and modification of G_{Ep} and G_{Mp} .

$$u(p, \lambda_N)\left(\tilde{G}_M \gamma^\mu - \tilde{F}_2 P^\mu/M + F_3\, \gamma\cdot K\ P^\mu/M^2\right) u(p, \lambda_N)$$

with: $\tilde{G}_M = G_M + \delta\tilde{G}_M$, and $\tilde{G}_E = G_E + \delta\tilde{G}_E$,

Define

$$Y_M \equiv Re\,(\delta\tilde{G}_M/G_M);\ \ Y_E \equiv Re\,(\delta\tilde{G}_E/G_M);\ \ Y_3 \equiv (\nu/M^2)\, Re\,(F_3/G_M)$$

Then, in double-polarization experiments, the measured Pt/Pl ratio Contains 3 additional terms from two-photon exchange

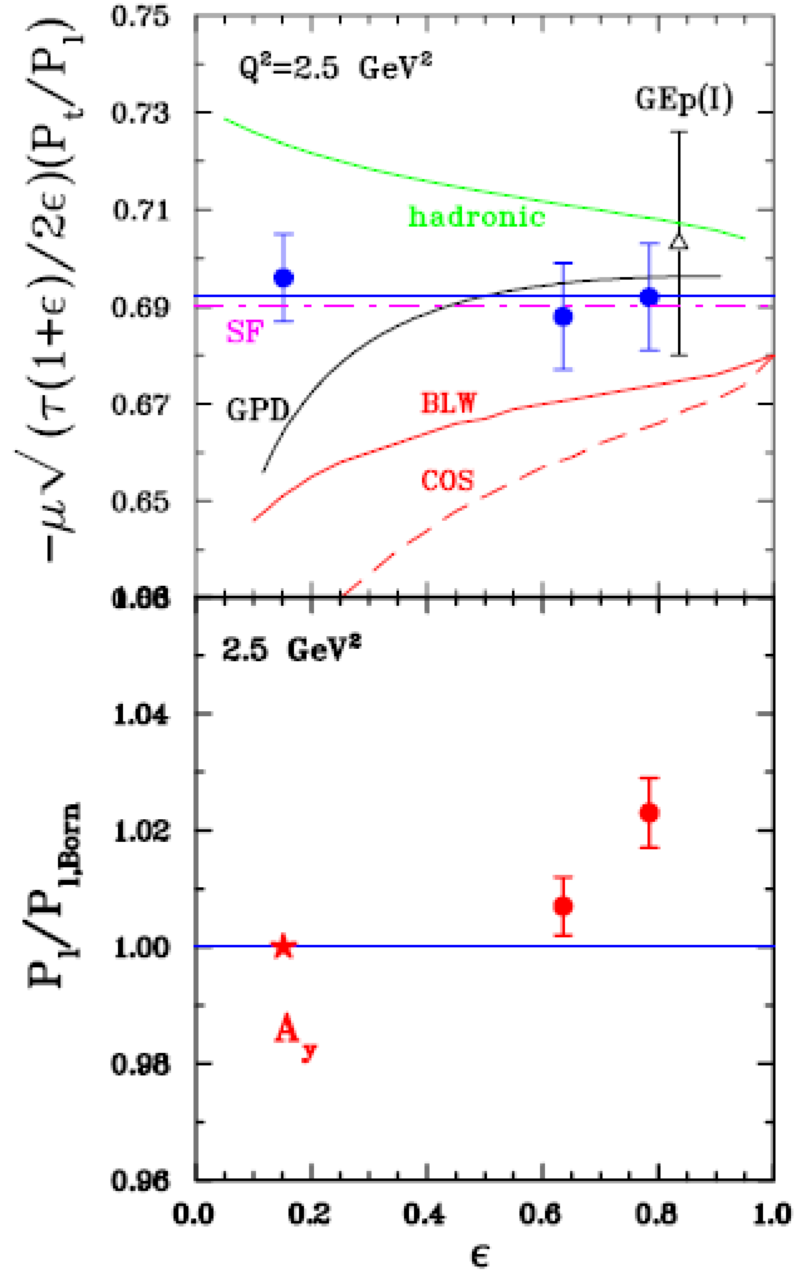
$$P_t/P_l = \sqrt{\frac{2\varepsilon}{\tau(1+\varepsilon)}}\left\{\frac{G_E}{G_M} + Y_E - \left(\frac{G_E}{G_M}\right)Y_M + \left(1-\frac{2\varepsilon}{1+\varepsilon}\right)\left(\frac{G_E}{G_M}\right)Y_3\right\}$$

At Jefferson Lab the 2γ experiment measured P_t/P_ℓ at Q^2=2.5 GeV^2 for 3 values of ε, with unprecedented small error bars.

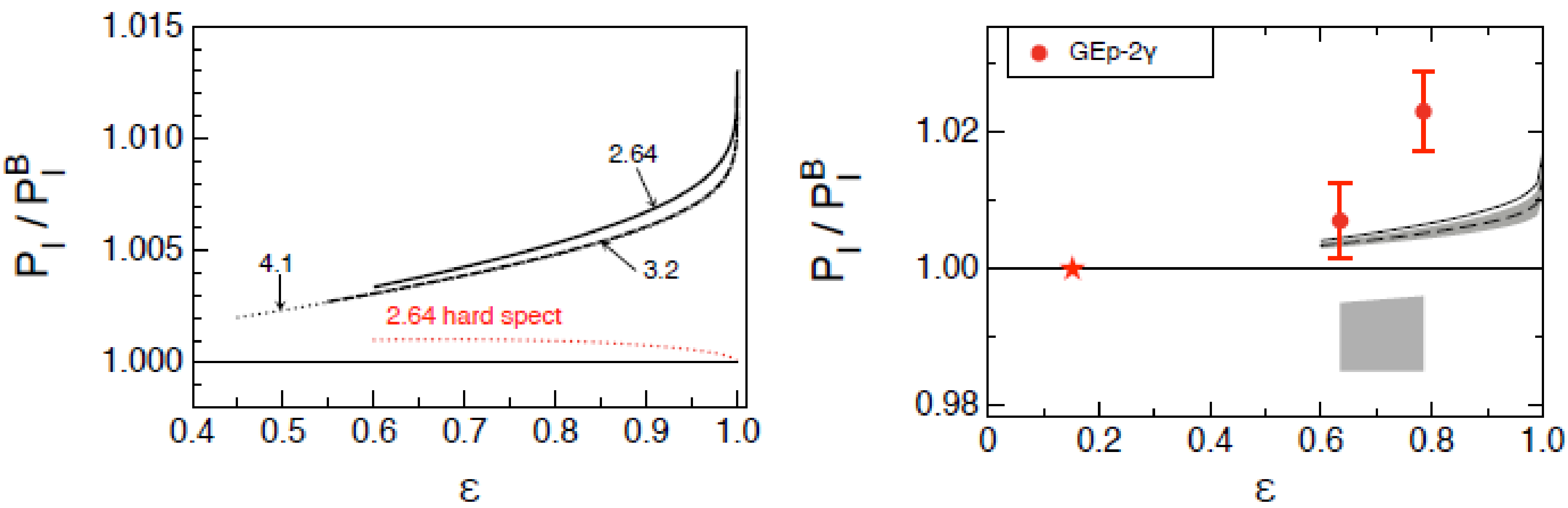
Also, obtained P_ℓ for two values of ε, the third being used to determine the analyzing power.

Data published: M. Meziane et al. PRL 106, 132501 (2011)

COZ BLW nuclear distribution amplitudes: Kivel and Vanderhaeghen
GPD Afanasev et al.
Hadronic Blunden et al.
SF Bystritskiy et al, shifted down!



P_ℓ / $P_{\ell\ \mathrm{Born}}$



Kivel and Vanderhaeghen, arXiv:1212.0683

QCD factorization in soft collinear effective theory together with hard spectator contribution

Yet another "crisis"?

The proton form factor "crisis" had many consequences. But some of the limelight has recently been taken away by another "crisis", or "puzzle", that of the proton radius.

Traditionally, the root mean square radius $<r_p^2>^{1/2}$ has been derived from a long list of elastic electron scattering *ep*, based on the low Q^2 expansion of the form factors G_E and G_M :

$$G_{E,M}(Q^2) = 1 - 1/6<r^2_{E,M}>Q^2 + 1/120<r^4_{EM}>Q^4 - 1/5040<r^6_{E,M}>Q^6 + \ldots$$

and from Lamb shift of atomic hydrogen. Sick PL B576, 62 (2003).
The results of these experiments have agreed closely in the past.

A muonic hydrogen Lamb shift experiment at PSI has recently (Pohl et al, Nature 466 (2010) and Antognini et al, SCIENCE, 339, 417 (2013)) changed this consistency, deviating from the previous average by 5 standard deviation, and with an error bar many times smaller than the uncertainty on the *ep* and hydrogen Lamb shift results.

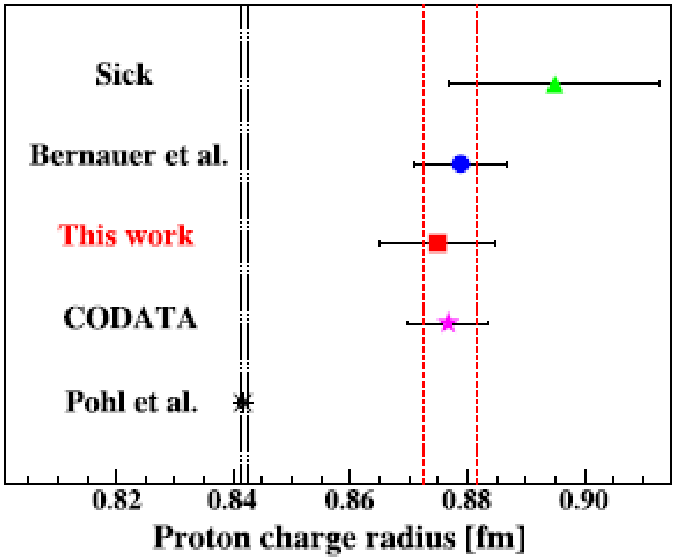
Proton Charge Radius Puzzle

Mainz

JLab

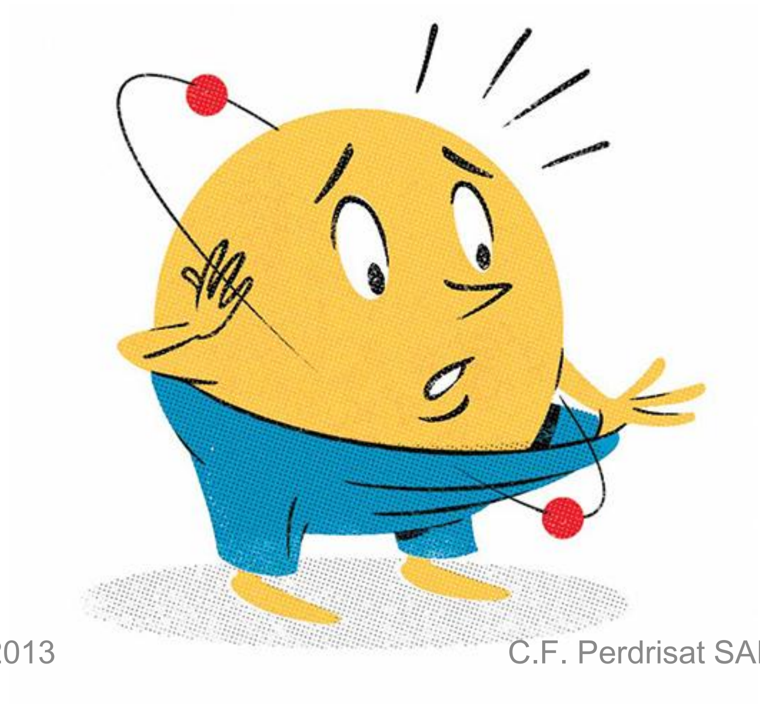
Mostly Hydrogen Lamb shift

Muonic Hydrogen Lamb shift



The figure is from X. Zhan et al., PLB 705, 59 (2011)

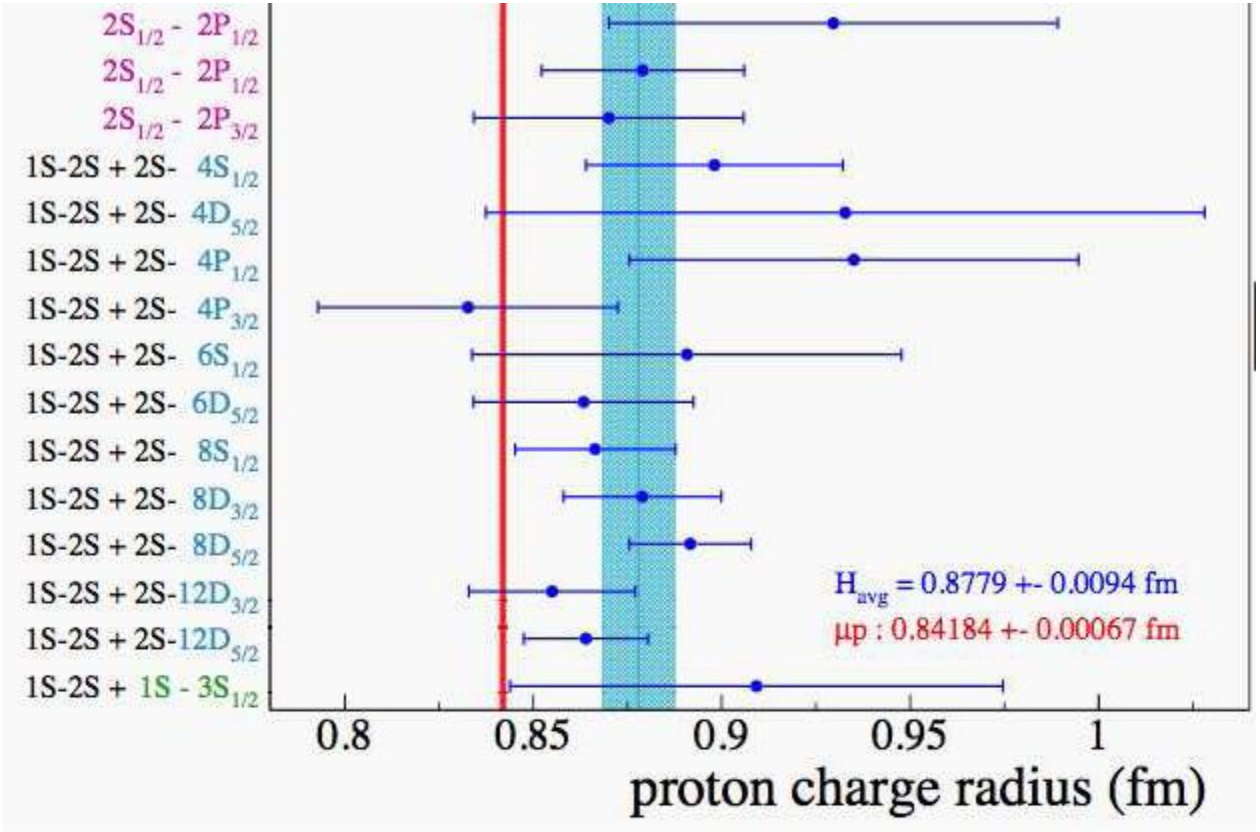
Dotted red lines combined CODATA, Bernauer (Mainz).



From the New York Times, July 13, 2010.

"For a Proton, a Little Off the Top (or Side) Could Be Big Trouble"

It went from 0.8768±0.0069 fm to 0.8418±0.0007 fm.



Proton charge radius for hydrogen Lamb shift. With permission of Aldo Antognini (2012).

Note that in the Science paper (Jan. 25, 2013) Antognini et al, the value of R_E=0.84087(39), with a 7σ variance from the CODATA value.

What comes next for p-radius?

1) At Jlab E08-007, data taking completed, elastic ep, $0.25<Q^2<0.85$ GeV^2

2) at Jlab C12-11-106, approved hall B *ep/ee* (Moeller scattering) $10^{-4}<Q^2<10^{-2}$ GeV^2. jet target.

3) At PSI, just approved, elastic $\mu^{\pm}p$ and $e^{\pm}p$ scattering, between $0.004<Q^2<0.08$ GeV^2 (p_μ of 115, 153 and 210 MeV/c).

and in the same spirit:
4) ed scattering too at Mainz, MAMI-A101, approved.

Various mechanisms could be at the origin of different interaction for *ep* and *μp*. (new gauge symmetry, new vector gauge boson.

Proton "distortion" due to close presence of orbiting muon important in muonic hydrogen.

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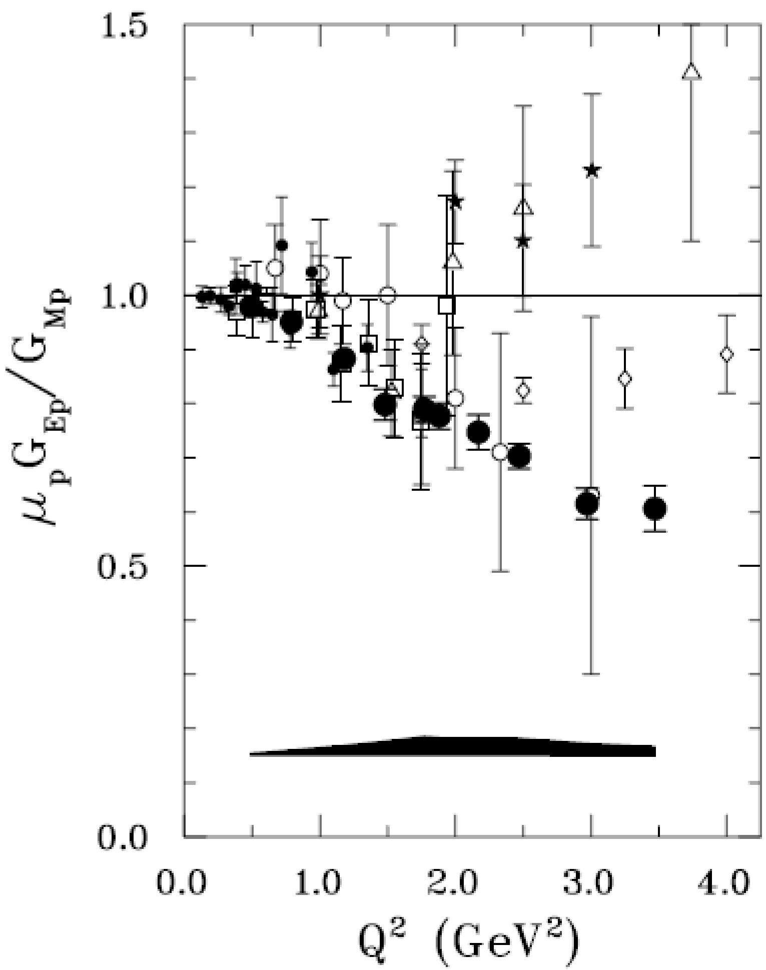
Conclusions



It has been 13+ years since the first recoil polarization measurement above 0.5 GeV^2 of G_{Ep}/G_{Mp} was completed.

Nothing great had been expected, and the results were only suggestive of something new. Initial approval was to 3 GeV^2, granted 3.5 GeV^2 by Larry Cardman during the experiment.

Fig. 18 in Punjabi et al, Phys. Rev. C71, 055202 (2005); (revised from M.K. Jones et al. PRL 84, 1398 (2000)).

Please note size of both statistical and systematic uncertainties.

Conclusions continued

• Much has happened since the results of the first double-polarization *ep* Form Factor experiment at Jlab (GEp(I)); the results of GEp(II) and GEp(III) have challenged half a century of cross section measurements!

•Theorists have suggested that two photon exchange might explain the difference, between Rosenbluth and polarization, demonstrating that polarization experiments *give* ~ the correct results (with per percent level 2-photon correction).

•The neutron is slowly revealing its electric structure, with tantalizing possibilities, which need to be verified; does G_{En} cross zero near 10 GeV^2?

•Now new challenge: why is the proton radius from μ-onic hydrogen Lamb shift smaller than that from hydrogen Lamb shift and elastic ep?

•On the theoretical front, all older models were revised in the last 10 years, and new ones developed; getting closer to QCD.

Future Form Factor measurements at Jlab with 11 GeV beams starting in 2015

Hall	Form Factor	max. Q^2	Expt. number	GE
A	G_{Mp}	17.5	12-07-108	spectrometer
	G_{Mn}	18	12-09-019	SBS Cross section
	G_{En}	10	12-09-016	SBS asym.
	G_{Ep}/G_{Mp}	12(14)	12-07-109	SBS Recoil polarization
B	G_{Mn}	14	12-07-104	Cross section
	$\langle r_p^2 \rangle^{1/2}$	10^{-4}-10^{-2}	12-11-106	
C	G_{En}	7	12-11-009	Recoil polar.

The following collaborators were instrumental for the success of the 3 GEp experiments at Jefferson Lab:

V. Punjabi, Norfolk State U.
E. J. Brash, Christopher Newport U.
G. Quemener, CNRS-IN2P3, Grenoble
A. Puckett, Jefferson Lab
M.K. Jones, Jefferson Lab
L. Pentchev, Jefferson Lab.
O. Gayou, CNRS-IN2P3 Aubiere
M. Meziane, TUNL, Duke U.
Wei Luo, Lanzhou U.

Thank you for your attention