The Form Factors of the Nucleon

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XXII International Baldin Seminar on High Energy Physics meeting
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Academician Alexander Mikhaejlovich Baldin

This twenty second seminar is in part to remember
Academician Alexander Mihaejlovich Baldin
for his scientific contribution, and in part to remember his personality and humanity.

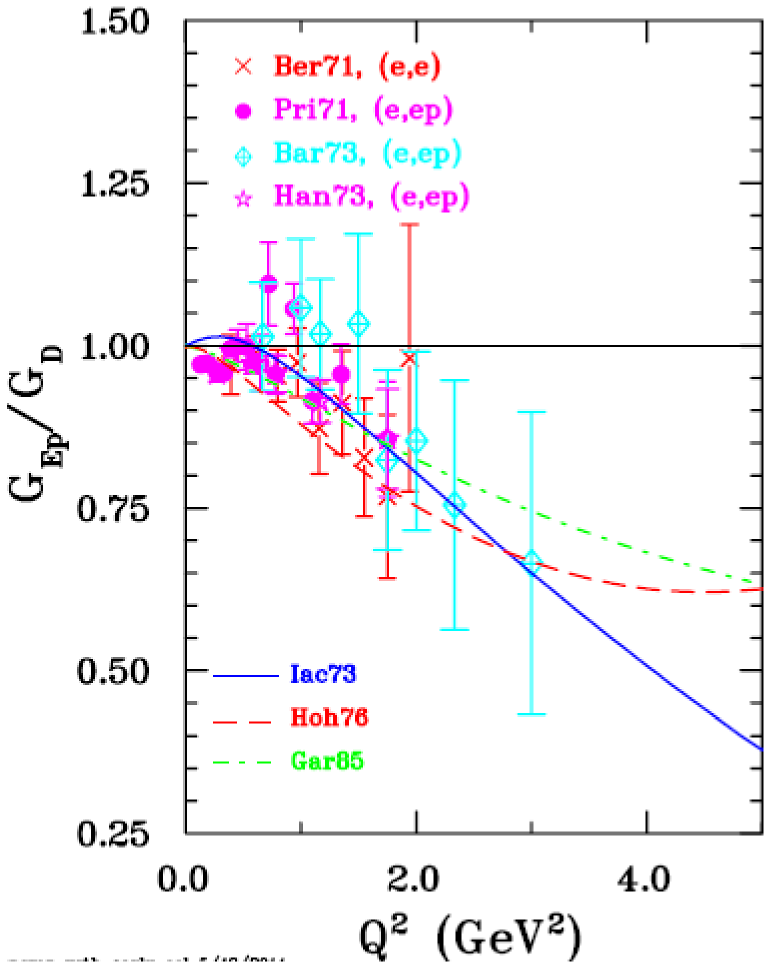
I met Academician Baldin for the first time in 1991, during my first attendance of the Deuteron workshop, and we had a long discussion while he was showing me the laboratory on a walk.

He was an engaging, interesting person with a wide range of interests and knowledge in nuclear physics and many other fields.

Professor Anatoly Efremov

Best wishes for your 80th Birthday Anniversary, and for continued success in your research.

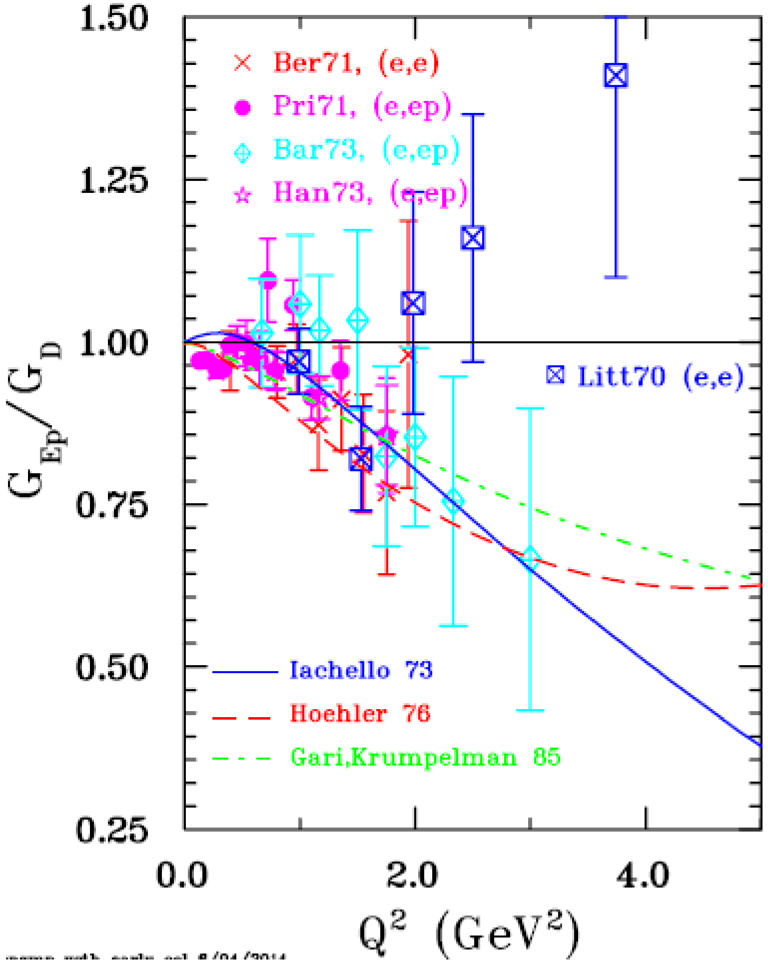
Prologue



Nucleon 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-1950s.

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

Prologue



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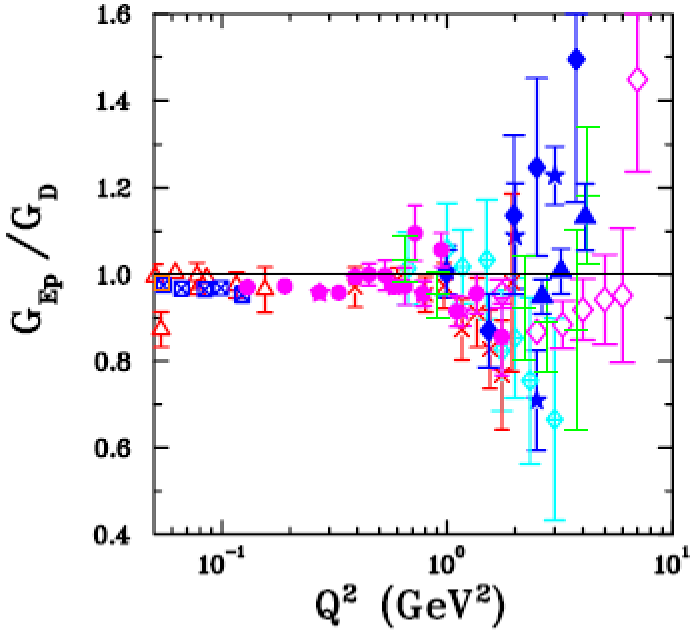
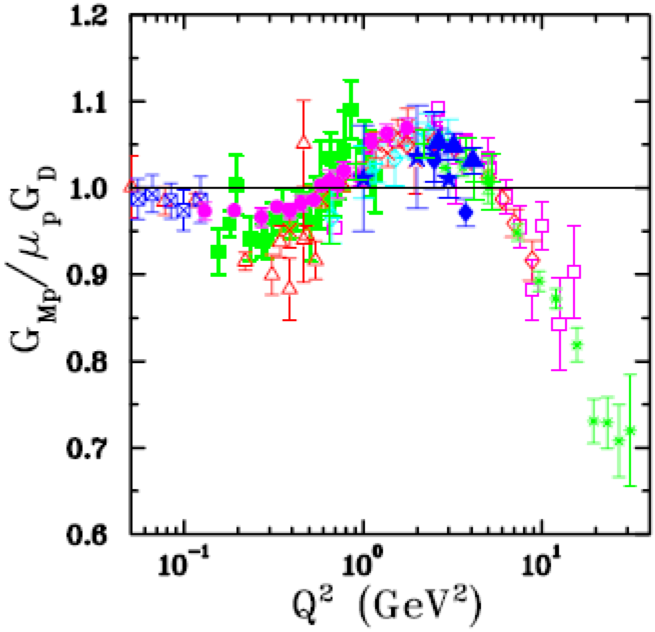
The first experiment to show a strong preference for $G_{Ep}/G_D \sim 1$ was that of Litt et al. published in 1970, included in this figure.

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).

Rosenbluth separation data for G_{Ep} and G_{Mp}

Results for the proton's G_{Ep} and G_{Mp} form factors had reached apparent stability by the 1990's, indicating that G_{Ep}/G_D and $G_{Mp}/\mu_p G_D$ were ≈ Q^2 independent, and ≈ 1; G_D is the dipole form factor,





Double-polarization Experiments

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 1960's.

Spectacular experimental progress in measuring G_E/G_M followed the opening of Jefferson Lab, for both proton and neutron. Understanding of 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 factors, has followed in short order.

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)

Outline of the talk: 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:

- the Rosenbluth separation based on differential cross section of *ep* scattering
- and the double polarization technique, either recoil polarization or final state asymmetry:

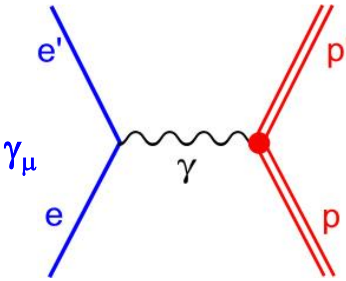
$$\vec{e}N \rightarrow e\vec{N}, \quad \text{or} \quad \vec{e}\vec{N} \rightarrow eN.$$

So here I will:

- Compare old and new results for G_E and G_M, proton and neutron.
- Present a short theory overview.
- Highlight new paradigms.

- Compare G_E/G_M and F_2/F_1 to theoretical predictions, for proton and neutron.
- Highlight some consequences for structure and shape of the nucleon.
- Discuss validity of Born approximation: Radiative corrections? 2 photon exchange?
- Say a few words about the proton radius "dilemna"

One-photon exchange or Born approximation



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

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

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 expressed in terms of the Sachs form factors G_E (electric) and G_M (magnetic)

$G_E = F_1 - \tau F_2$, $G_M = F_1 + F_2$ with $\tau = Q^2/4m_p^2$, is then

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

the kinematic factor or degree of linear polarization of the virtual photon.

Rosenbluth Separation Method

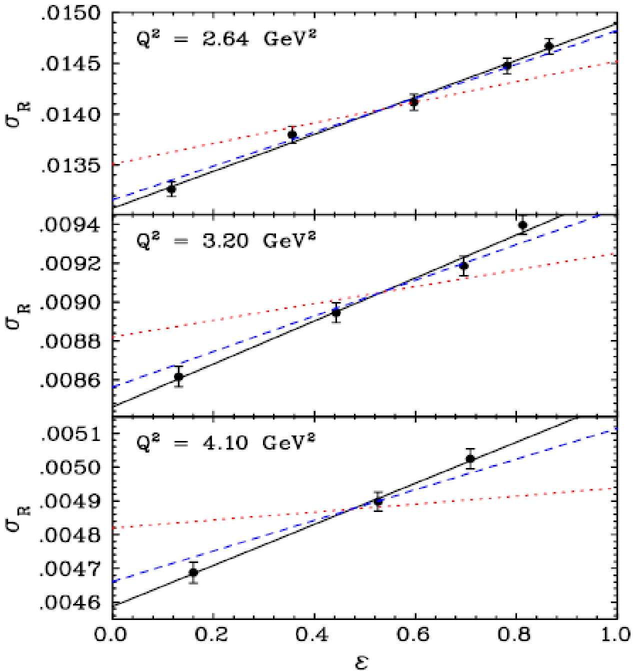
A "reduced cross section" can be defined as:

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

- Measuring angular dependence of cross section at fixed Q^2.

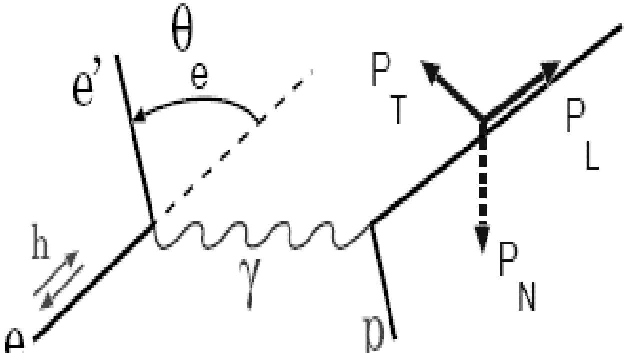
- The ε-dependence of the "reduced cross section" σ_R is linear in Born approximation, with slope G_E^2 and intercept τG_M^2.

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



---- recoil polarization ---- previous Rosenbluth

Polarization Transfer Method in OPEX



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

$$P_t = hP_e \frac{\sqrt{1-\varepsilon^2}}{G_M^2 + \frac{\varepsilon}{\tau} G_E{}^2} G_E G_M$$

$$P_\ell = \sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}} \frac{G_M^2}{{}_t\, G_M^2 + \frac{\varepsilon}{\tau} G_E{}^2}$$

$$P_n = 0$$

h **beam helicity,** ***P***

$$r = \frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}$$

$$\tau{=}Q^2/4MM_p^2{}^2$$

$$\varepsilon = [1 + 2(1+\tau)tan^2\frac{\theta}{2}]^{-1}$$

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

Polarization Transfer

The main advantage of the double polarization method is the much enhanced sensitivity to G_E at large Q^2, because $P_t \sim r = G_{Ep}/G_{Mp}$, rather than G_{Ep}^2 and G_{Mp}^2, as in Rosenbluth.

Another advantage is that measuring the entire azimuthal distribution in a polarimeter with 2π acceptance, provides simultaneous measurement of P_t and P_ℓ, giving a robust determination of $r = G_{Ep}/G_{Mp}$. Residual systematic uncertainty comes then dominantly from uncertainty in spin precession in spectrometer dipoles.

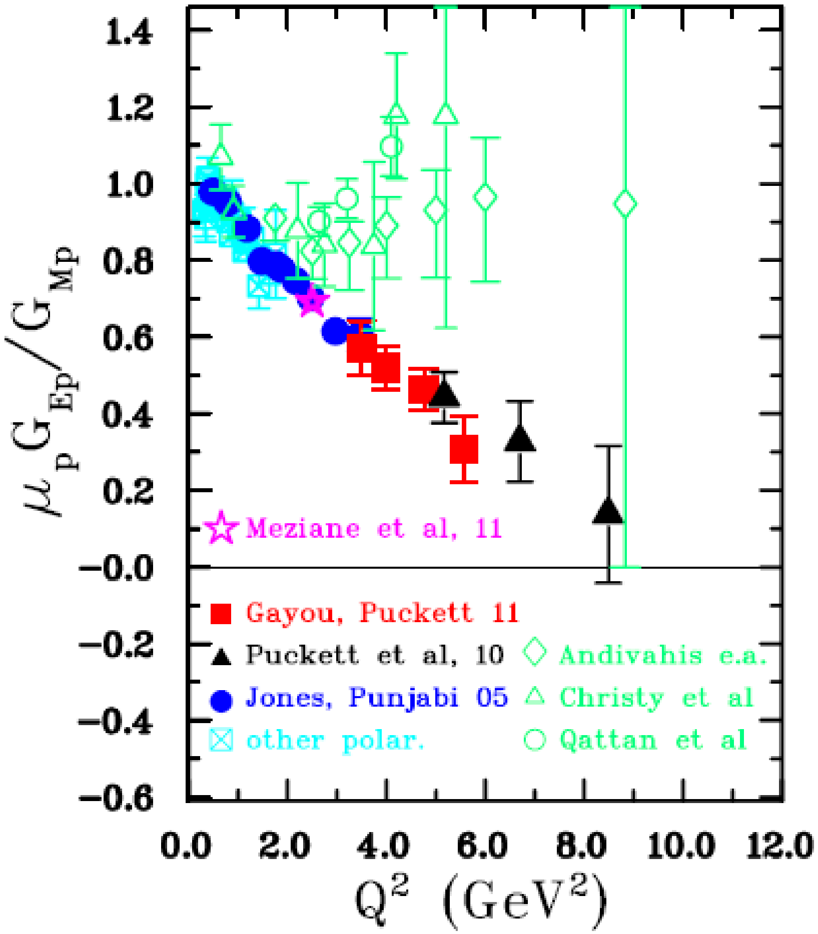
→ → ⟶

Very similar situation for the other double polarization experiment, *e* +*n* *e*+*n* ; when the neutron polarization is perpendicular to both the momentum transfer vector and the
reaction plane, the asymmetry A_{perp} is:

$$A_{perp} = -\frac{2\sqrt{\tau(1+\tau)}}{\frac{\tau}{\varepsilon}+r^2}\tan\frac{\theta_e}{2}\,\frac{G_{Ep}}{G_{Mp}},$$

similar to P_t in recoil polarization.

Recoil Polarization Results for G_{Ep}/G_{Mp} Ratio



The JLab recoil polarization results for the proton stand out, and are internally consistent.

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

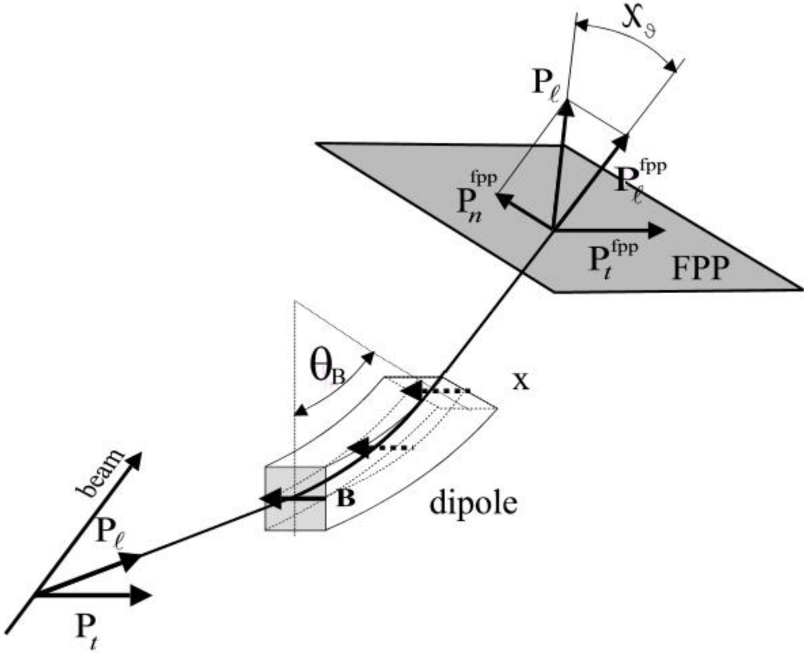
Note decrease of slope past 6 GeV^2.

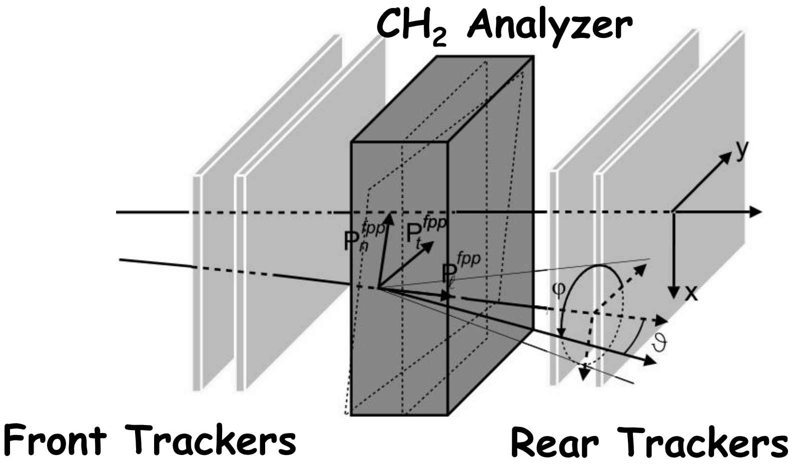
Also shown are selected, recent Rosenbluth data in green, including:
Andivahis et al., Phys. Rev. D 50, 5491 (1994),
Christy et al., Phys. Rev. C 70, 015206 (2004),
Qattan et al.,Phys. Rev. Lett. 94, 142301 (2005).

The discrepancy between Rosenbluth and double polarization results for the proton is well established.
M.K. Jones et al. (2000), O. Gayou et al. (2002), V. Punjabi et al. (2005), A.J.R. Puckett et al. (2010), M. Meziane et al. (2011).

Spin Precession, Focal Plane Polarimeter,

The 2 main ingredients of all recoil polarization experiments are: spin precession in a dipole, and rescattering of the recoil particle in an analyzer





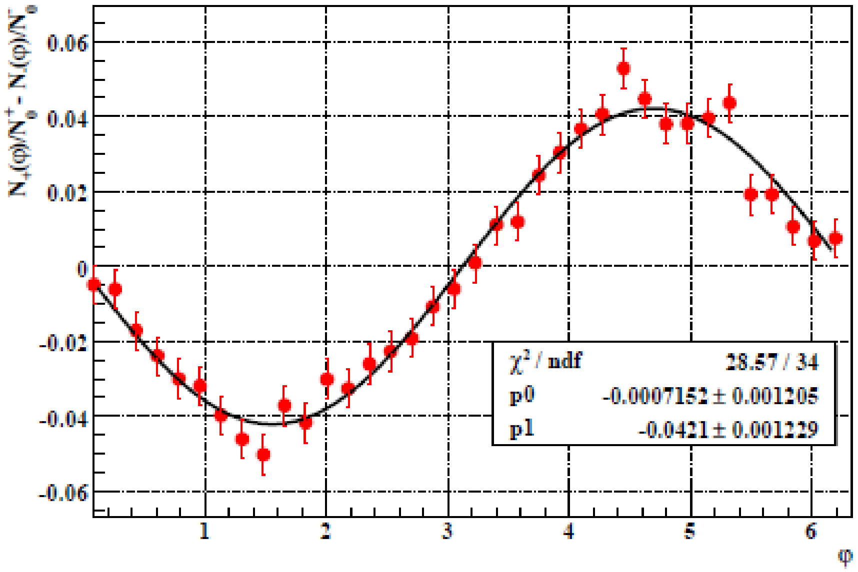
$$f^{\pm}(\vartheta,\varphi)=\frac{\varepsilon(\vartheta,\varphi)}{2\pi}\left[1\pm A_y\left(P_t^{fpp}\cos\varphi-P_n^{fpp}\sin\varphi\right)\right]$$

Precession angle, $\chi_\theta = \gamma\,(\mu_p-1)\,\theta_B$

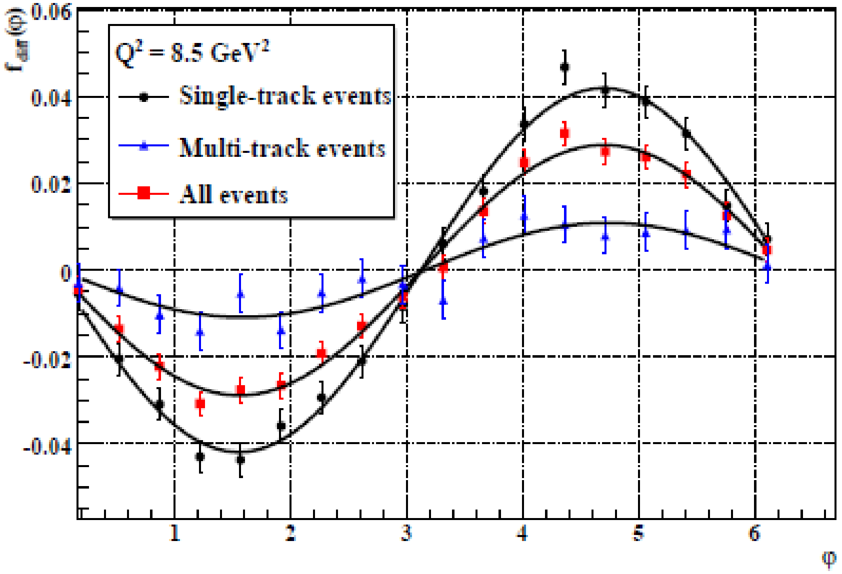
where $\varepsilon(\vartheta,\phi)$ and Ay are efficiency and analyzing power of the polarimeter

$$P_n^{fpp}=P_\ell^{tgt}\sin\chi_\theta \qquad P_n^{fpp}\cong P_n^{tgt}$$

What we know

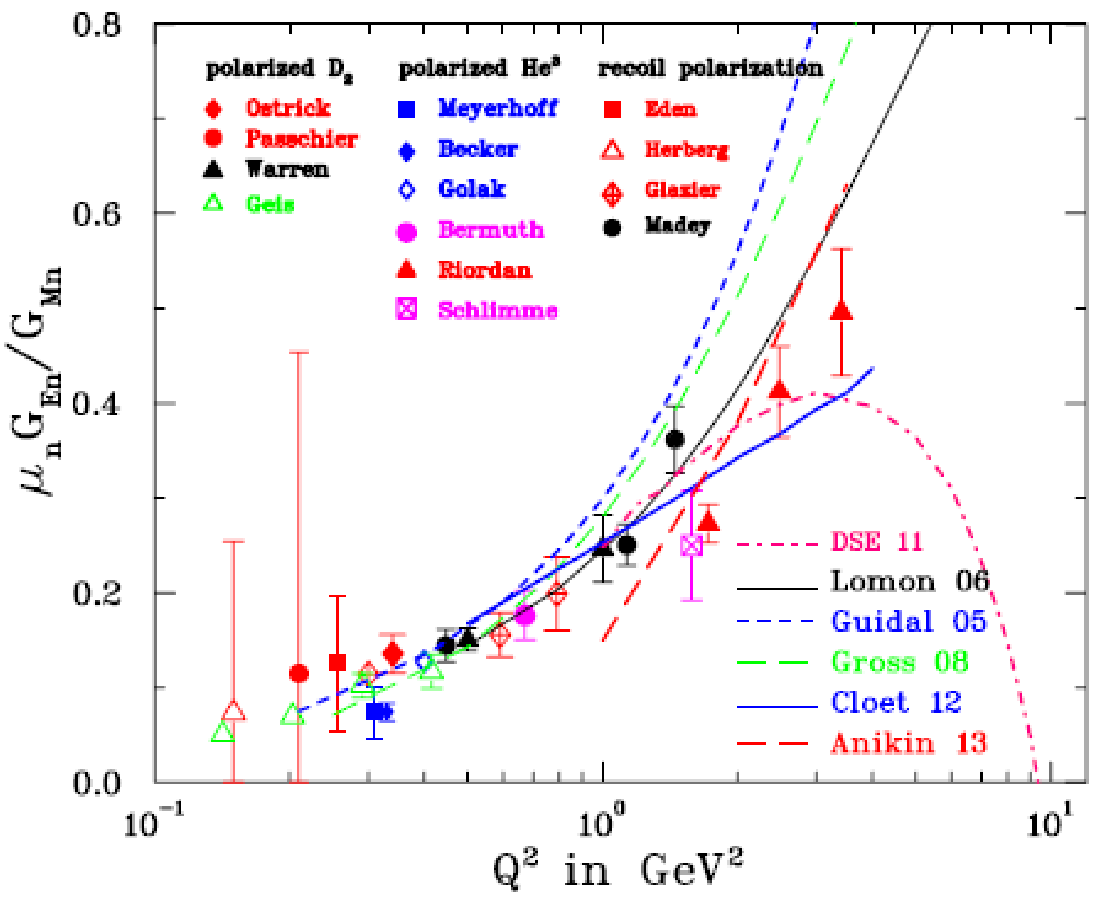


Azimuthal distribution of the asymmetry at the highest proton momentum reached so far, (5.4 GeV/c)



Effect of accepting multitrack events in the polarimeter on the amplitude of the asymmetry at same momentum.

Double Polarization Results for the Neutron



All double polarization results for G_{En}, including JLab Hall A (GEn(1)).

Most recent:

Schlimme B.S.et al., Phys. Rev. Lett. 111 (2013) 132504

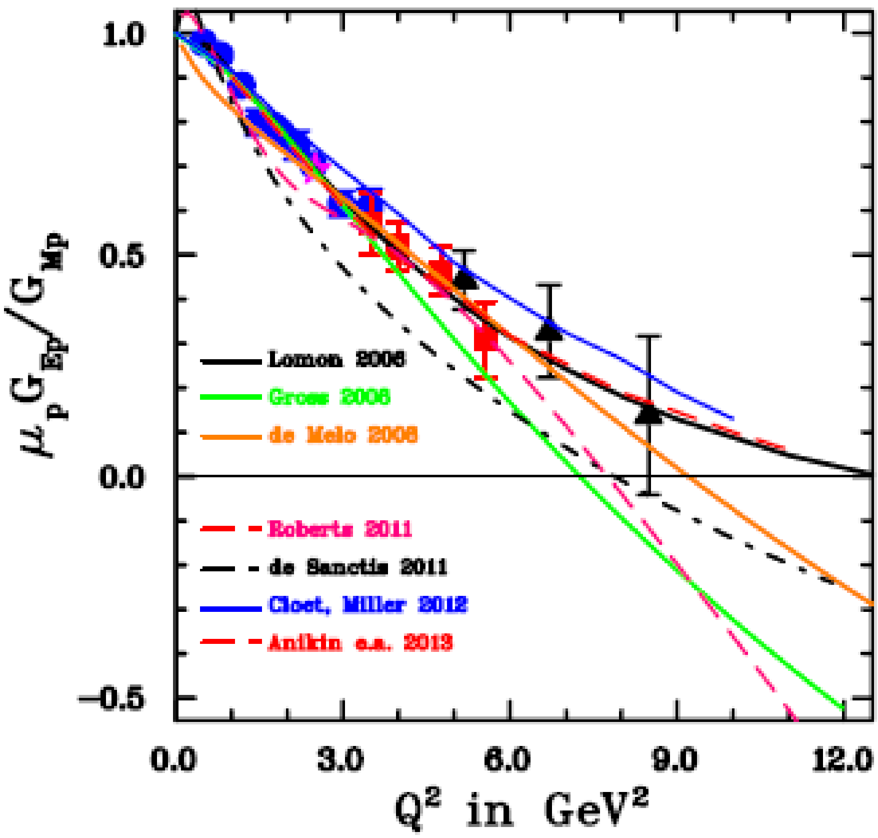
Riordan *et al.*, Phys Rev Lett 105, (2010) 262302

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

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

Note also Cloet et al, Dyson Schwinger equation prediction.

For Proton most theoretical Models agree with double Polarization Data



Just a fast, first overview, details to come next:

VMD-based models (Lomon)

Relativistic constituent quark (rCQM), F. Gross

(Lattice QCD models)

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

Quark-diquark interaction (De Sanctis)

Quark-diquark in meson cloud (Cloet an Miller)

Light-cone sum rules in QCD (Anikin) ...

Other Consequences of Polarization FF Results

1. The previously dominating Vector Dominance (VMD) and Constituent Quark (CQM) models were revisited, made relativistic, then more of less left the front row. (with the exception of Lomon, Miller and a few others).

2. The argument that form factors are Fourier transforms of nucleon density was abandoned, as it makes sense only in the extreme non-relativistic case. The wave front or infinite momentum frame densities are drastically different from the non-relativistic ones (Carlson, Miller).

3. The proton in its ground state is not necessarily spherically symmetric, but can show a typical multipole shape, when referred to the spin direction of one of its quarks (constituents) (Miller).

4. Elastic ep scattering in the 1 to 10 GeV^2 range of 4-momentum transfer is The domain of non-perturbative QCD; consequence of Dynamical Chiral Symmetry Breaking. (Roberts et al)

5. Scaling as a consequence of Perturbative QCD may have visible consequences even in the non-perturbative domain (Galynskii and Kuraev)

6. The di-quark structure of the nucleon has observable consequences (Roberts et al).

Consequences Continued

7. The mass of the dressed quarks originates from the QCD vacuum; it results from accretion of quark-antiquark pairs from decaying gluons spontaneously "emerging" from the vacuum.

8. Assuming isospin symmetry one can obtain flavor separated dressed quark form factors from simple linear relations between the Dirac and Pauli form factors. The dressed up and down quarks have significantly different form factors.

9. A zero crossing of G_{Ep} would provide information on the dressed-quark mass function (Cloet et al.).

10. Di-quark structure embedded in a pion cloud model in excellent agreement with G_{Ep}/G_{Mp} (Cloet and Miller)

11. Nucleon form factors determine the parameters of the valence quark GPDs; these can be used to obtain corresponding valence quark densities (Diehl and Kroll).

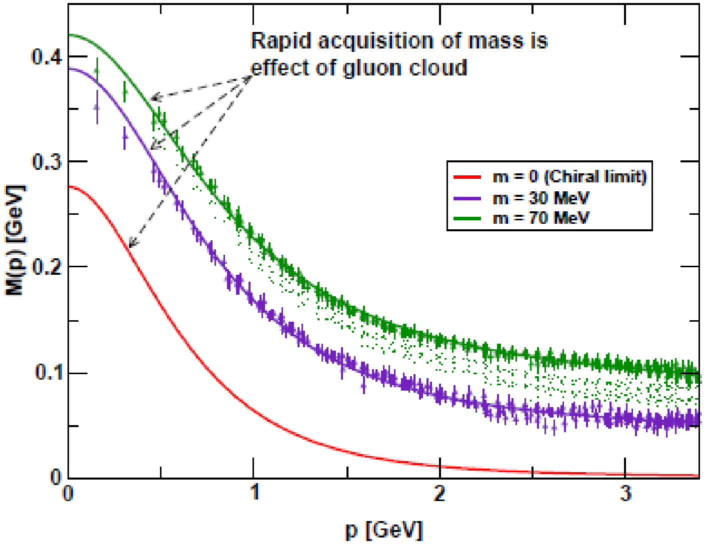
12. The isovector electric form factor (G_{Ep}-G_{En}) has a zero at Q^2 ~ 4.3 GeV^2; can be predicted in lattice calculations, from the connected diagram only?

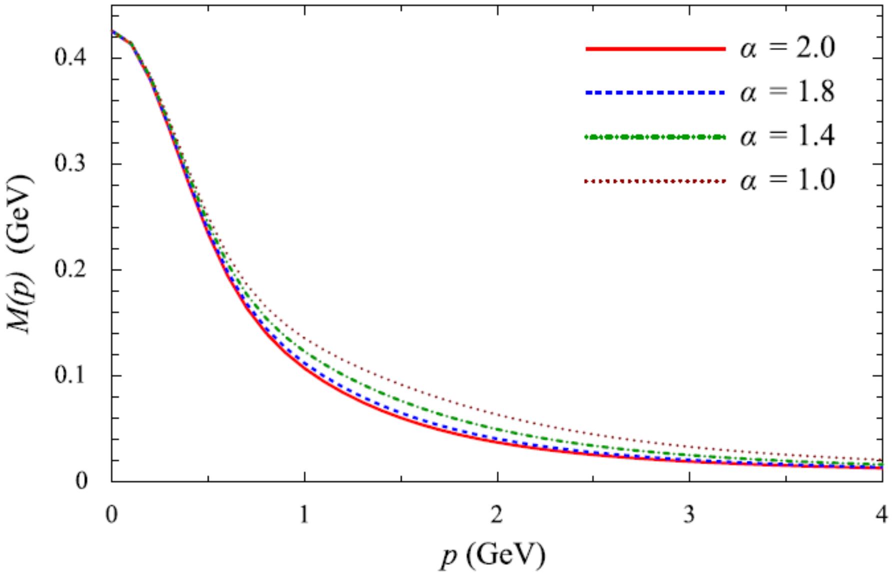
13. Soft Collinear Effective Theory' (SCET), Kivel and Vanderhaeghen (2013) for two-photon exchange.

Dressed quarks in the Nucleon

Dressed quarks a consequence of dynamical chiral symmetry breaking (DCSB) in QCD.
They are described by Dyson-Schwinger Equations (DSEs); I.C. Cloet, C.D. Roberts and A.W. Thomas, PRL 111, 101803 (2013). The quarks-partons of QCD acquire a momentum dependent mass 2 orders of magnitudes larger than the current-quark mass in infra-red region; cloud of gluons surrounding a low-momentum quark.

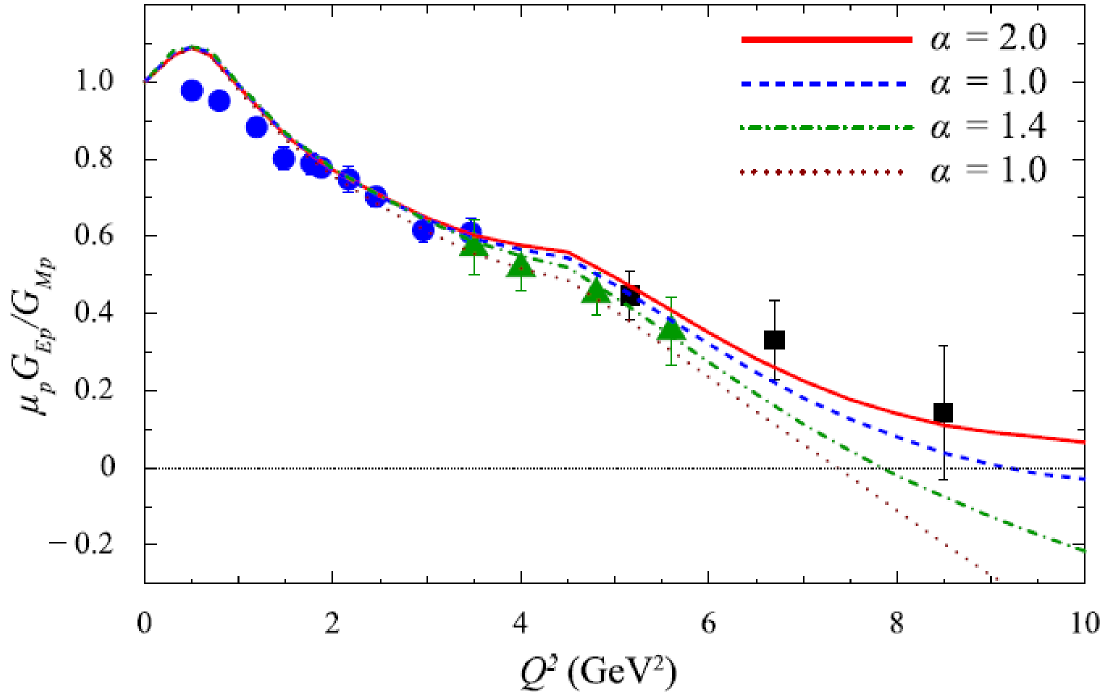
Evolution of the dressed quark mass as its momentum decreases
a (alpha) is a damping factor in the dressed quark propagator.





Position of zero crossing of G_{Ep} versus α

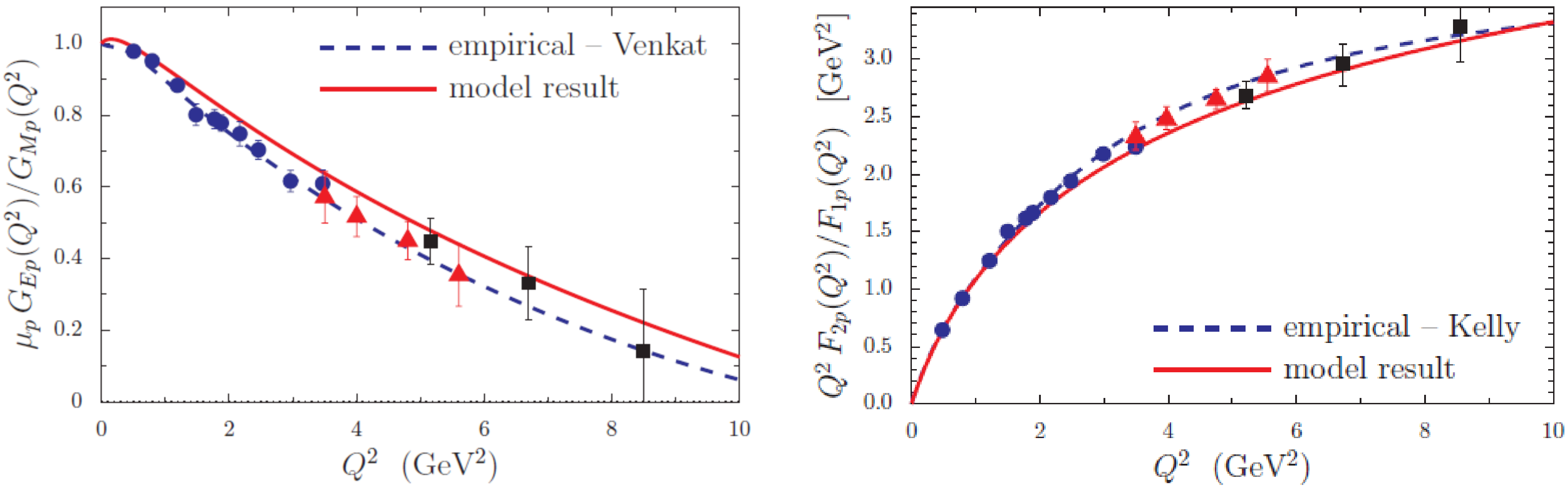
Or how knowledge of the position of the zero-crossing of G_{Ep}/G_{Mp} would inform about the growth rate of the QCD quark mass.



quark-diquark model with a pion cloud

quark-diquark configurations immersed in a pion cloud are treated in a manner consistent with Poincare invariance.

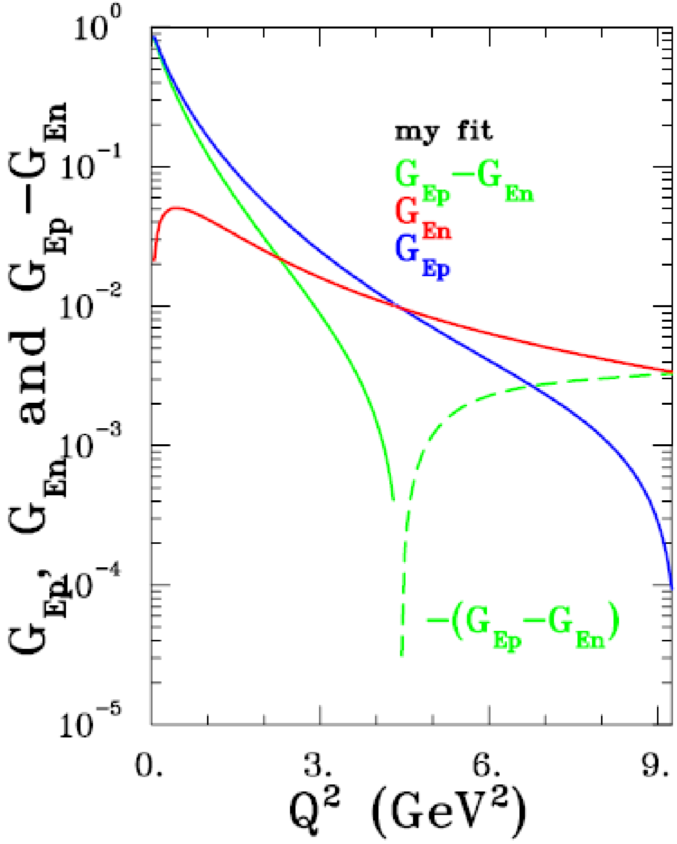
(Cloet and Miller, Phys. Rev. C 86, 015208 (2012))



Isovector combination G_{Ep}-G_{En}

As pointed out by Diehl and Kroll, EPJ C73 (2013) 2397, the isovector combination G_{Ep}-G_{En} has a zero at relatively low Q^2; amenable to lattice calculation of the connected contribution only.

The zero occurs around 4.3 GeV^2, i.e. quite close to the largest Q^2 for which we have actual G_{En} data (rather than extrapolated values).

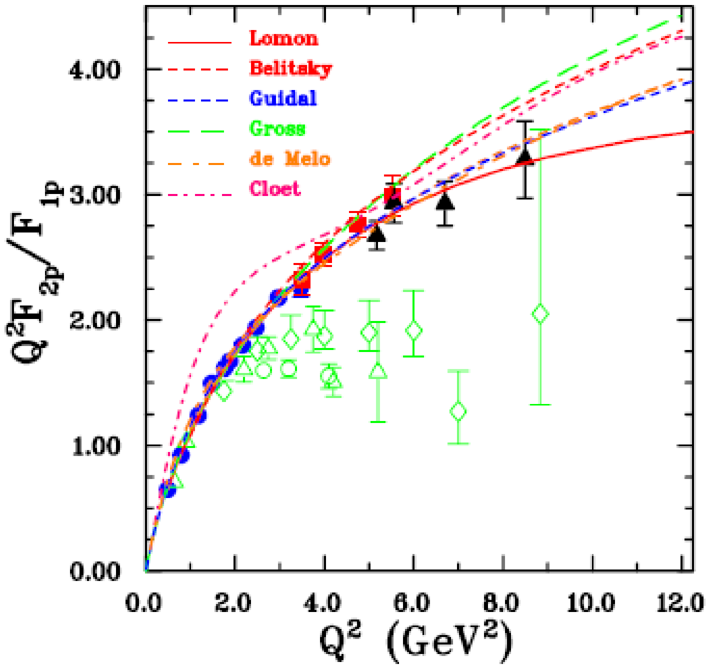


Asymptotic Behavior of F_1 and F_2?

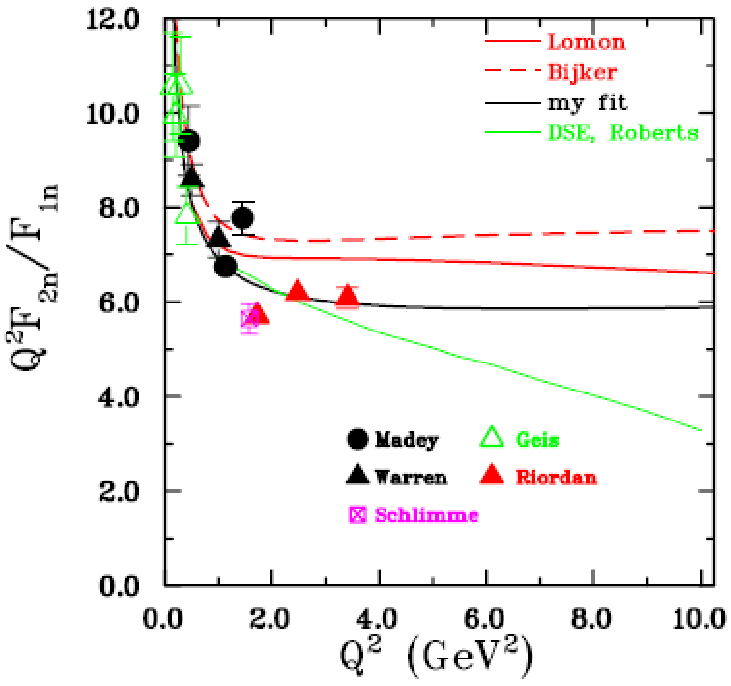
Perturbative QCD (pQCD): $Q^2F_2/F_1 \to 1$ for (very) large Q^2 (Brodsky and Farrar, 1975).

Definitively not occurring yet for the neutron; what is the significance of very different behavior for proton and neutron, beyond the consequence of neutron's electric neutrality, which requires $F_{1n} \to 0$ for $Q^2 \to 0$?

proton



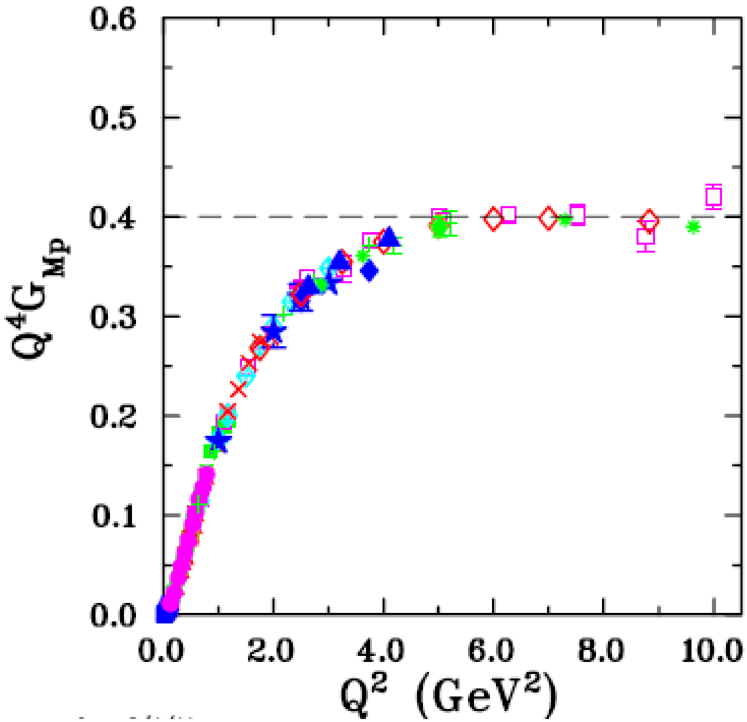
neutron



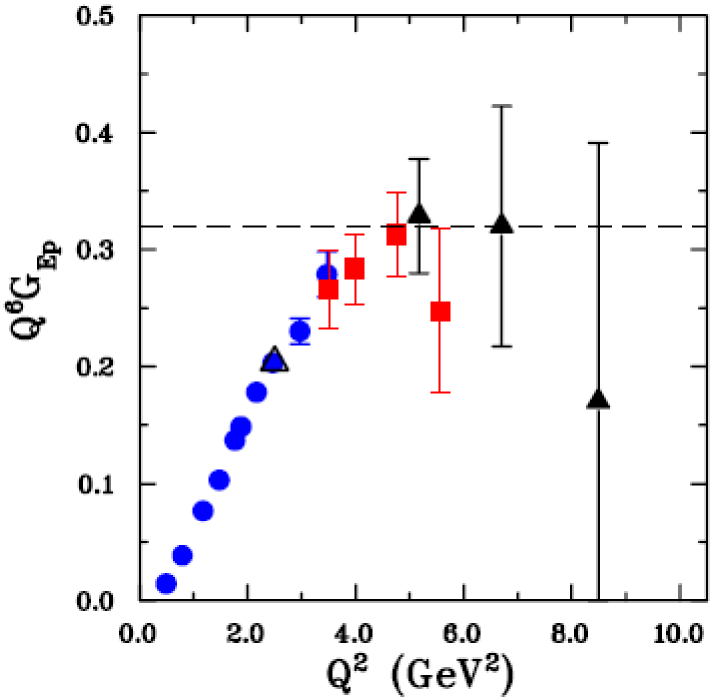
Asymptotic Behavior of G_{Ep} and G_{Mp}?

Leaving out the data up to 30 GeV^2 for comparison with Q^6G_{Ep}.

G_{Ep} from recoil polarization G_{Ep}/G_{Mp}, using the Kelly fit for G_{Mn}.



Q^4G_{Mp}~0.4 GeV^4



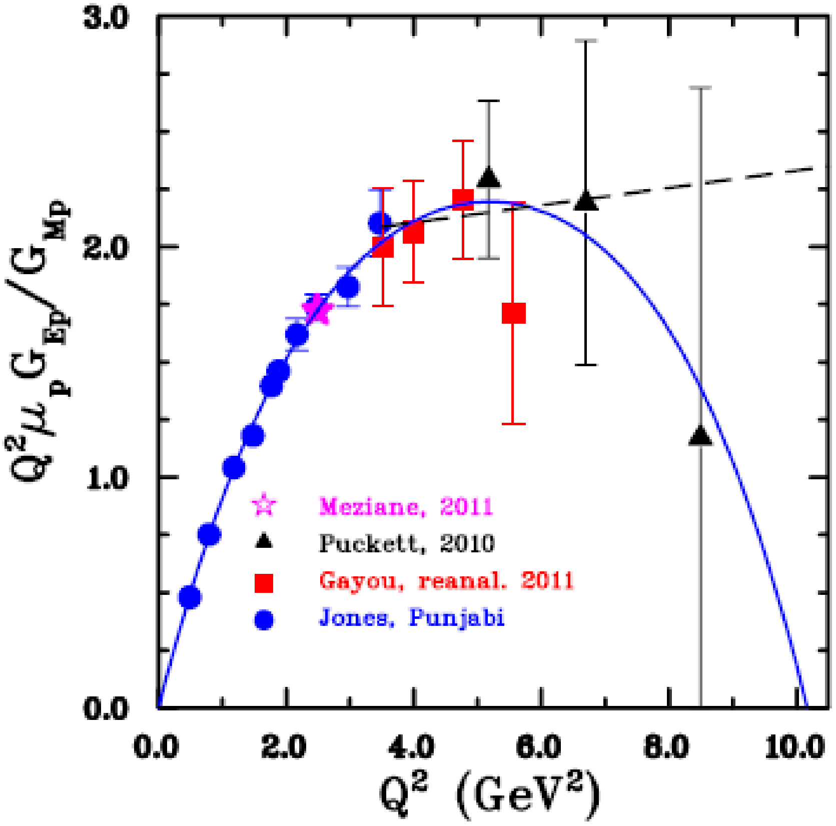
Q^6G_{Ep}~0.32 GeV^6

$Q^2\mu_pG_{Ep}/G_{Mp}$ Scaling?

Apparent scaling of the ratio Q^2G_{Ep}/G_{Mp} for Q^2 larger than ~3.5 GeV^2 recently discussed by Galiynskii and Kuraev (2014):

Interpreted within perturbative QCD assumption, as direct evidence for spin flip of all 3 quarks, in matrix elements of proton spin-flip transition in the diagonal spin basis. In other words:

Data suggest dominance of contribution from no quark spin-flip to nucleon non-spin flip amplitude, and three quark spin-flips to nucleon spin-flip amplitude, starting at relatively low Q^2 (~3.5 GeV^2).



$Q^2\mu_pG_{Ep}/G_{Mp}$~2.0 GeV^2

Quark Flavor separation (1)

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 assuming isospin symmetry:

$$F^d_{1n}=F^u_{1p},\quad F^u_{1n}=F^d_{1p}$$

$$F^d_{2n}=F^u_{2p},\quad F^u_{2n}=F^d_{2p}$$

the Dirac and Pauli form factors of the dressed quarks are then:

$$F^u_{1p}=2F_{1p}+F_{1n}\qquad F^d_{1p}=F_{1p}+2F_{1n}$$

$$F^u_{2p}=2F_{2p}+F_{2n}\qquad F^d_{2p}=F_{2p}+2F_{2n}$$

See for example: Cates, de Jager, Riordan, Wojtsekhowski (2011), Rohrmoser, Choi and Plessas, (2011), Wilson, Cloet, Chang and Roberts,(2012), Cloet and Miller (2012), Qattan and Arrington (2012).

Dirac and Pauli nucleon form factors

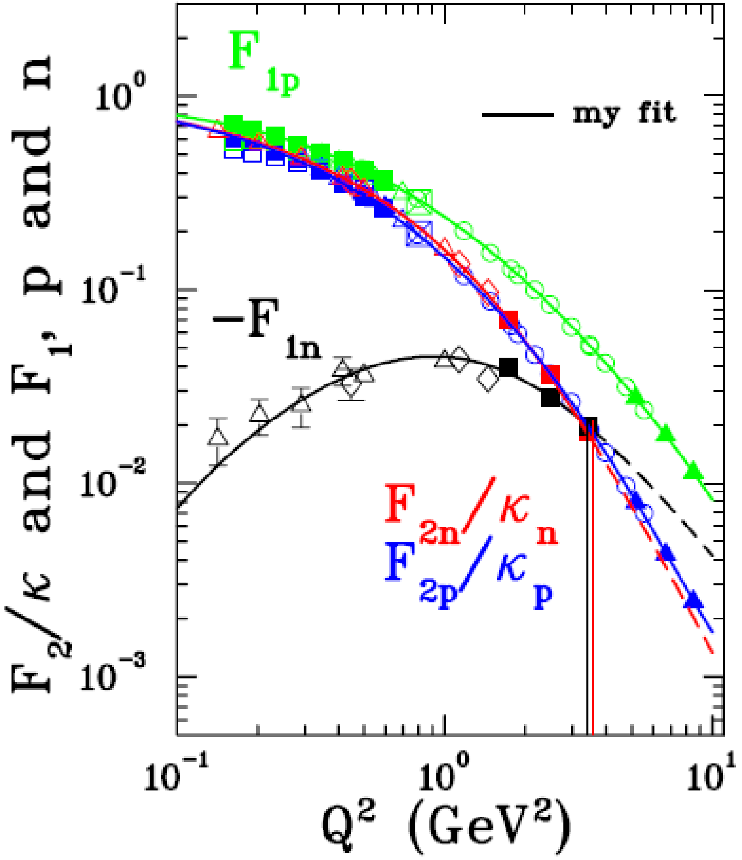
Parametrize the four Sachs form factors, calculate F_1 and F_2, using Kelly form **polynomial/polynomial**
with asymptotic $1/Q^2$ behavior (except for G_{En}).

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

Note that:
1) $F_{2n}/\kappa_n \sim F_{2p}/\kappa_p$,
2) the neutron data are extrapolated.

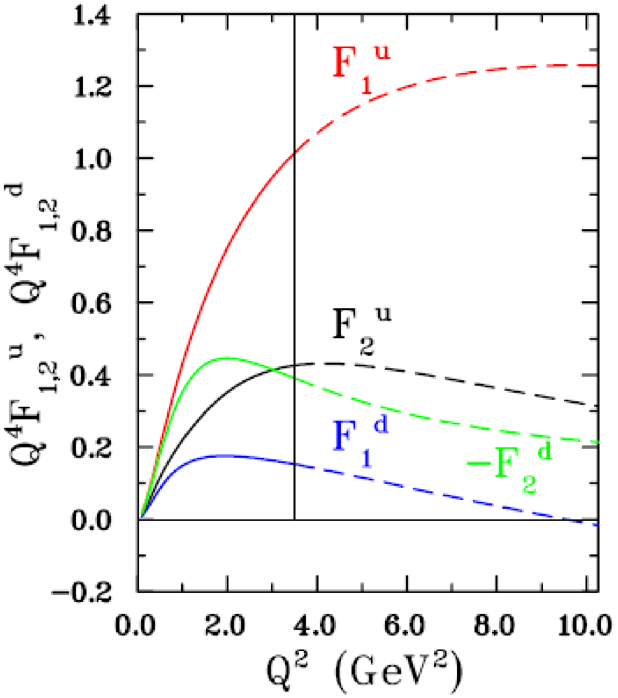
All 4 form factors have a smooth behavior, and the data are internally consistent.

Alternately, will use Roberts et al prediction for $\mu_n G_{En}/G_{Mn}$ shown earlier.

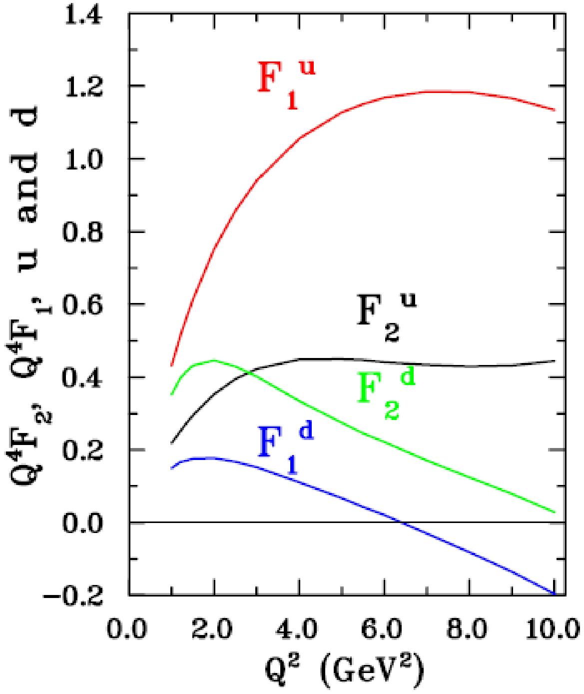


The “flavor separated” form factors

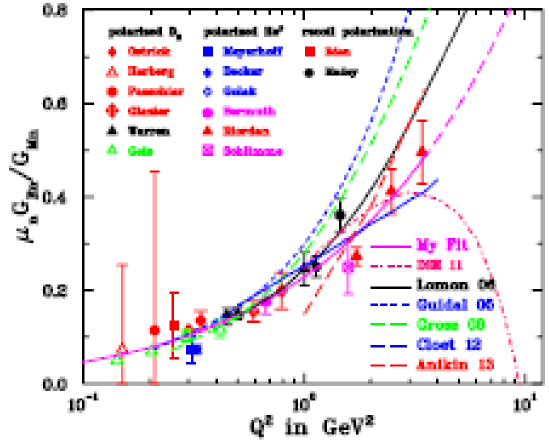
With “My Fit” for $\mu_n G_{En}/G_{Mn}$



With Roberts et al for $\mu_n G_{En}/G_{Mn}$



$\mu_n G_{En}/G_{mn}$ from Roberts et al

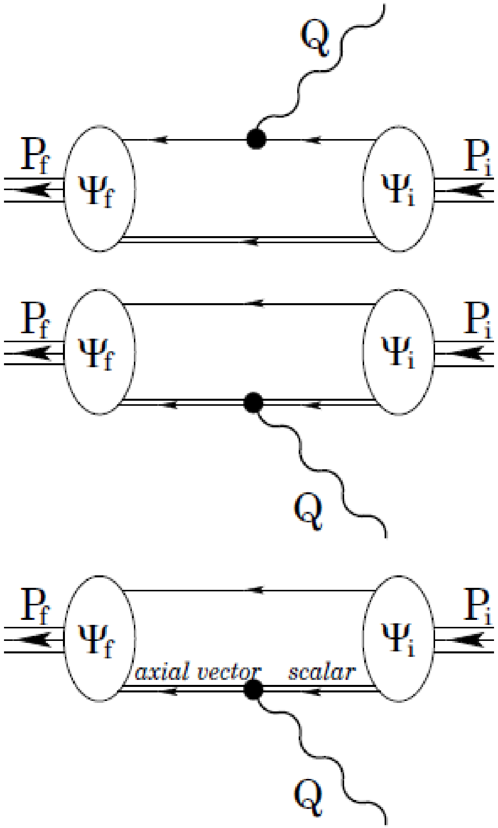


Quark Flavor separation (II)

Interference of axial-vector and scalar di-quark produces a zero of the Dirac form factor of the d quark in the proton: F_{1p}^{d}.

Curves in previous transparency calculated from the fits to the *p* and *n* data, with extrapolation shown in previous earlier. Suggest evidence for significant di-quark component in nucleon.

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



What about two-hard-photon exchange?

The two-hard-photon exchange hypothesis was reactivated by Guichon and Vanderhaeghen (2003) after publication of the Jlab GEp(1+2) results.

ep cross sections require large radiative corrections; the accuracy of these corrections has improved over time. But direct and quantitative proof that the "form factor discrepancy" is specifically (even entirely) due to the neglect of two-(hard) photon exchange in radiative correction is not available yet. Ongoing work!

At Jlab Hall C in GEp(2ϒ) experiment, looked for a two-photon effect from variation of the G_{Ep}/G_{Mp} ratio versus kinematics, i.e. constant Q^2, variable energy and angle of the scattered electron. No effect at the 1% level.

Recently 3 experiments have obtained data on the e+/e- cross section ratio at various (but small) Q^2, at Novosibirsk, Jlab Hall B (preliminary results shown at 2014 Users meeting) and DESY (Olympus). This ratio should differ from 1 because of the two-photon contribution to cross section …
but it requires significant radiative corrections too!

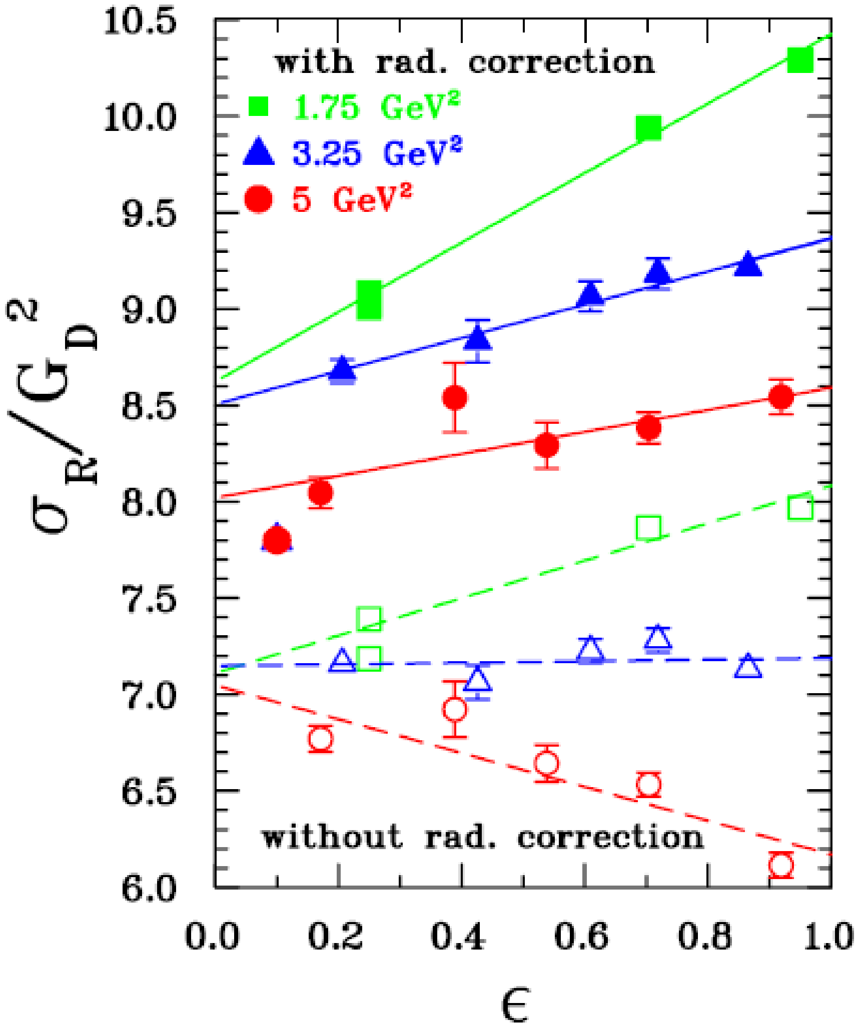
Radiative corrections to Cross Section Data

Andivahis et al, 1992 Rosenbluth

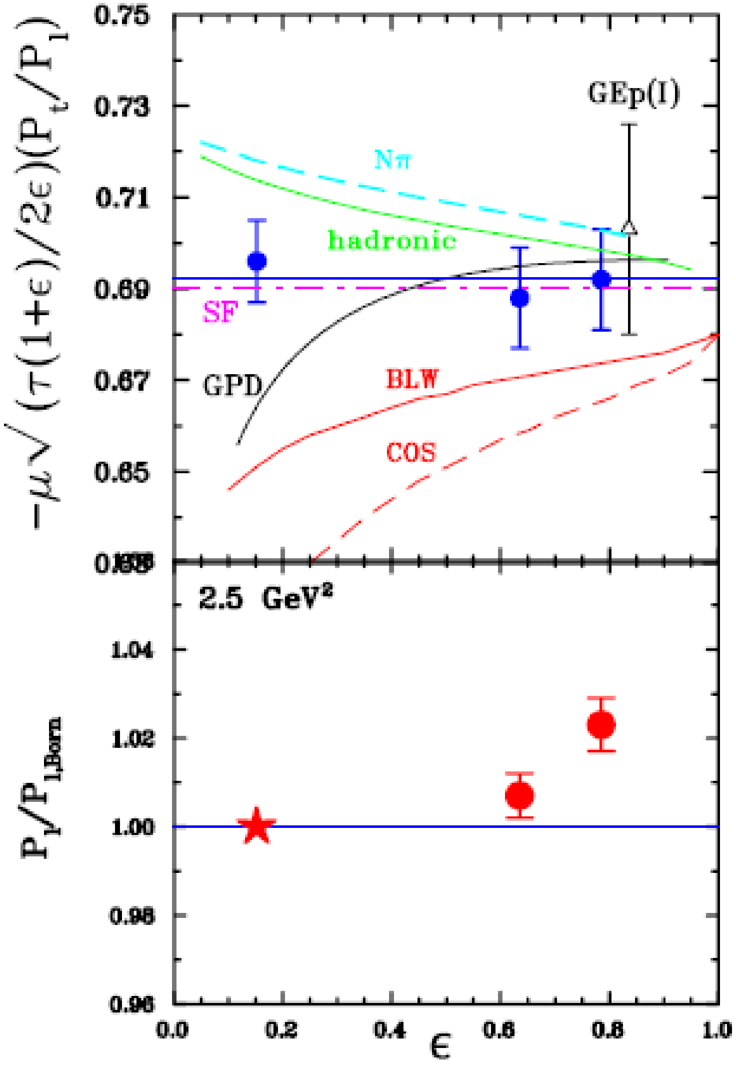
Illustration of drastic effect of correcting cross section data (at the bottom) for radiative effects (at the top).

Note negative slope (i.e. G_{Ep}) for Q^2=5 GeV^2!

The slope change resulting from radiative correction increases significantly with Q^2.



Is the exchange of two hard photons responsible for the cross section/polarization form factor discrepancy?



Meziane et al, 2011 2Υ experiment

Should be subject of another talk.

Theoretical curves:

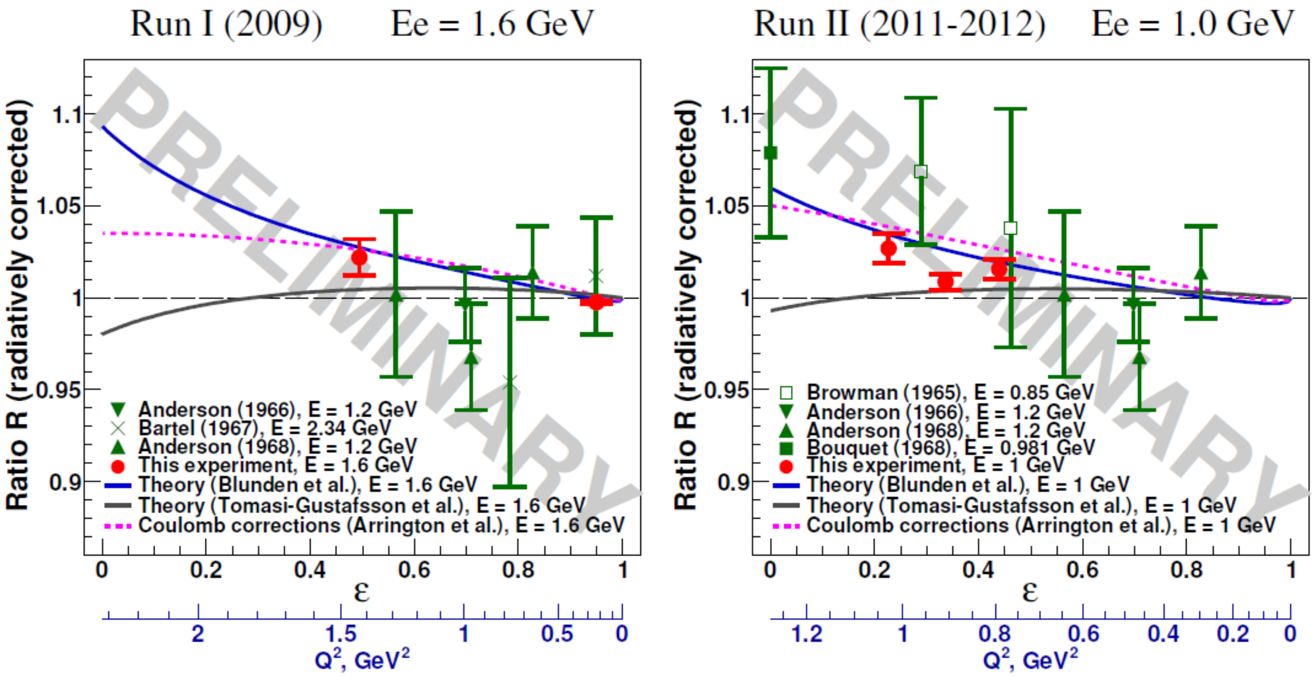
hadronic	Blunden et al
Nπ	Borisyuk and Kobushkin
SF	Bistritskyiy et al
BLW/COZ	Kivel and Vanderhaeghen
GPD	Afanasev et al

Lower panel: P_l/P_l^{Born} .

Taking the ratio of the two polarization components cancels the small effect seen in display of P_ℓ alone, in bottom right panel.

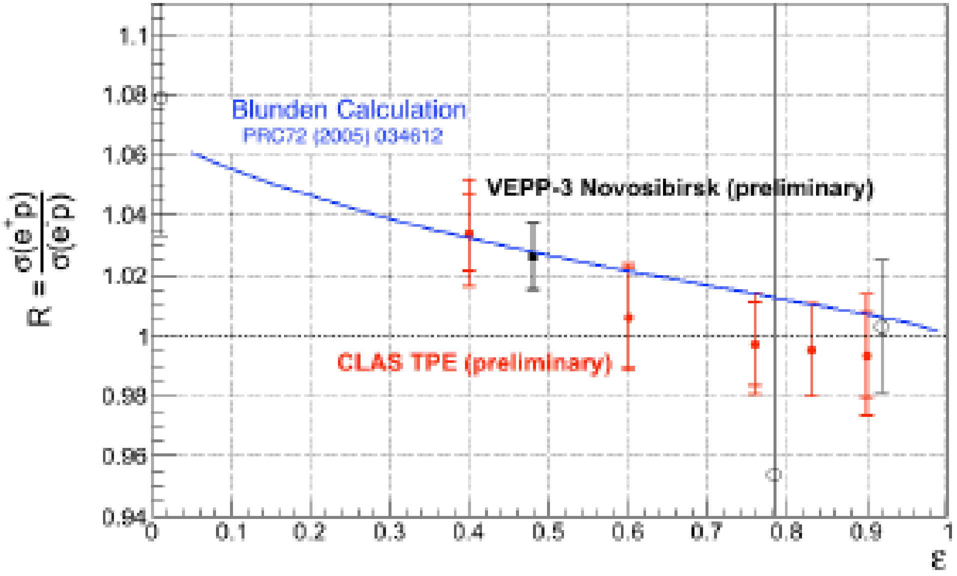
Novosibirsk VEPP-3

Two-photon exchange evidence in elastic electron-proton scattering, experiment at the VEPP-3 storage ring: D.M. Nikolenko, EPJ Web of Conferences 66, 06002 (2014)



Jlab Hall B

Dasuni Adikaram (Old Dominion University in Norfolk Virginia) presented at Jlab User Collaboration meeting, June 4, 2014, for Q^2=1.4 GeV^2.



Olympus experiment at DESY: results available at the end of 2014 (quoting M. Kohl from Hampton University in Hampton Virginia).

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.

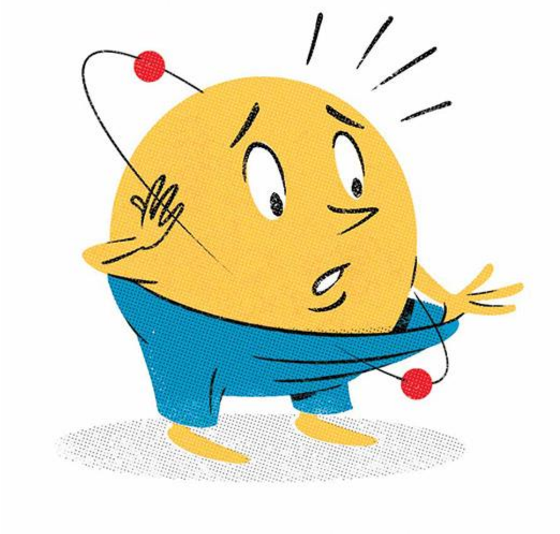
Traditionally, the root mean square radius $<r_p^2>^{1/2}$ has been derived from a long list of elastic electron scattering *ep*, based on the low Q^2 expansion of the form factors G_E and G_M:

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

and from Lamb shift of atomic hydrogen. I. 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 6-7.9 standard deviations, and with an error bar many times smaller than the uncertainty on the *ep* and hydrogen Lamb shift results.

Proton Charge Radius Puzzle



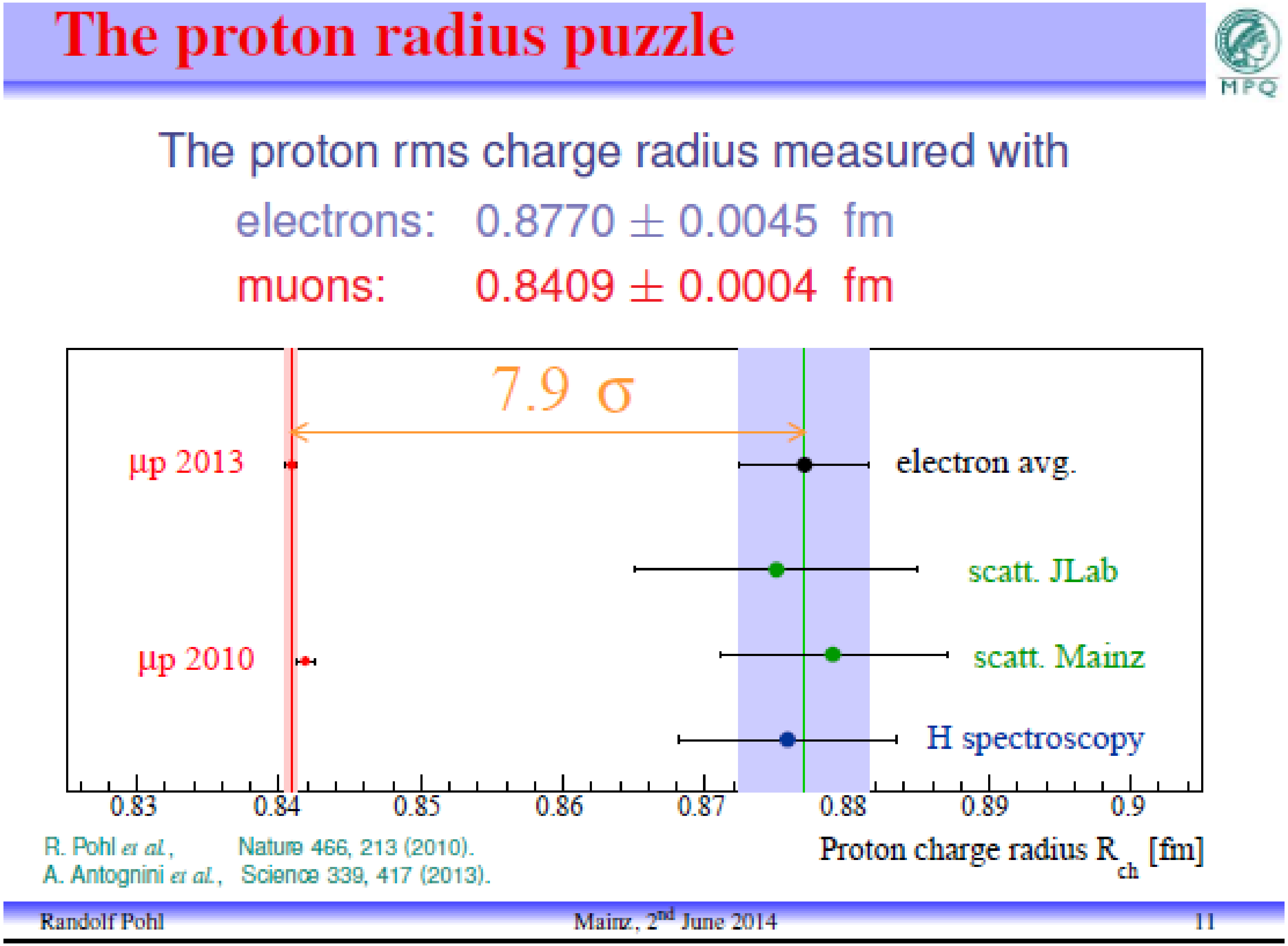
From the New York Times, July 13, 2010.

“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, then to 0.8409±0.0004 femtometer.

In preparation: MUSE experiment at Paul Scherrer Institute, Switzerland: compare μp with ep, $\mu^{\pm}p$ and $e^{\pm}p$ to help correct for two gamma effects, Q^2 from 0.002 to 0.07 GeV^2.

and PRAD in hall B at JLab, ep scattering down to $Q^2=10^{-4}$ GeV^2.



The proton radius puzzle

The proton rms charge radius measured with

electrons: 0.8770 ± 0.0045 fm

muons: 0.8409 ± 0.0004 fm

R. Pohl *et al.*, Nature 466, 213 (2010).
A. Antognini *et al.*, Science 339, 417 (2013).

Randolf Pohl Mainz, 2^{nd} June 2014 11

To conclude

Even though this was a drastically shortened presentation of the field

(and I apologize for important contributions left out),

I hope to have given a sense of the magnitude of the changes

in understanding of the structure of the nucleon which resulted from

the introduction of polarization in form factor measurements

and the many theoretical progresses which have followed

and were made possible by the exceptional characteristics of CEBAF/JLAB polarized electron beams

Thank you for your patience and interest

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

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