Jefferson Lab's Contribution to the Characterization of the Proton Form Factors

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Group on Hadronic Physics
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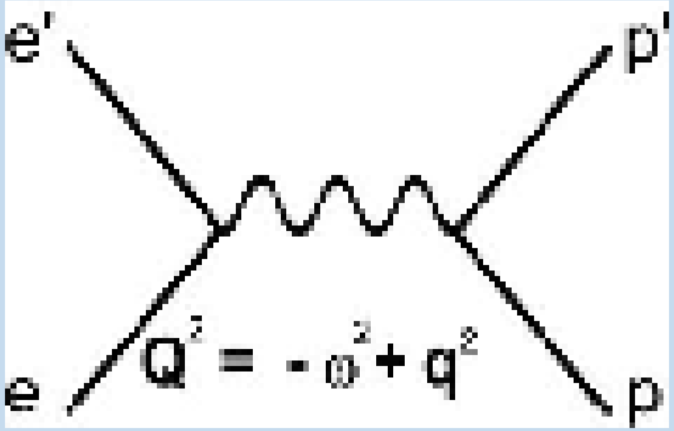
First, what are form factors

For a spin-½ nucleon, and assuming that *ep* elastic scattering proceeds by the exchange of a single virtual photon:



the finite size of the proton requires 2 form factors to describe the hadron current:

one related to the electric charge and Dirac magnetic moment:

F_1 (named Dirac form factor),

the other for the anomalous part of the proton magnetic moment, $\kappa_p = \mu_p - 1$, F_2 (named Pauli form factor).

R. Hofstadter (1961 Nobel) introduced a *form factor* for the *ep ->e'p'* cross section:

$$(d\sigma/d\Omega)= (d\sigma/d\Omega)_{Mott} \left| \int_{volume} \rho(r) \exp(i q . r) dr \right|^2 = \sigma_{Mott} |F(q)|^2$$

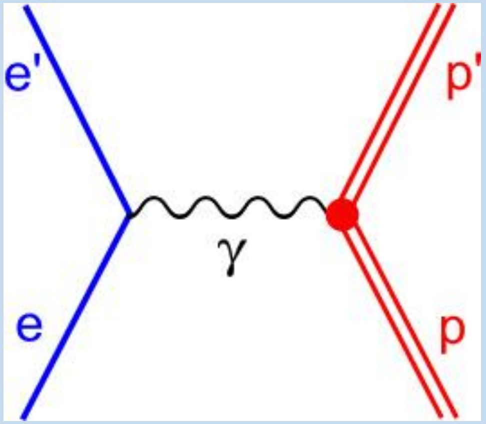
$$F(q)=\frac{4\pi}{q}\int_0^\infty \rho(r)\, \sin(qr)\, r dr$$

F(q) Fourier transform of charge distribution; $(d\sigma/d\Omega)_{Mott}$ for massless e^- and point-like target, all spin ½.

In lowest order, one virtual photon exchange, or OPEX, amplitude is product of leptonic and hadronic currents:

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

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



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

Both F_1 (Dirac) and F_2 (Pauli) depending on *q*, momentum transfer, only.

Cross Section:the Rosenbluth method

$$\sigma_R = \varepsilon(1+\tau)\frac{\sigma}{\sigma_{Mott}} = \varepsilon G_{Ep}^2 + \tau G_{Mp}^2$$

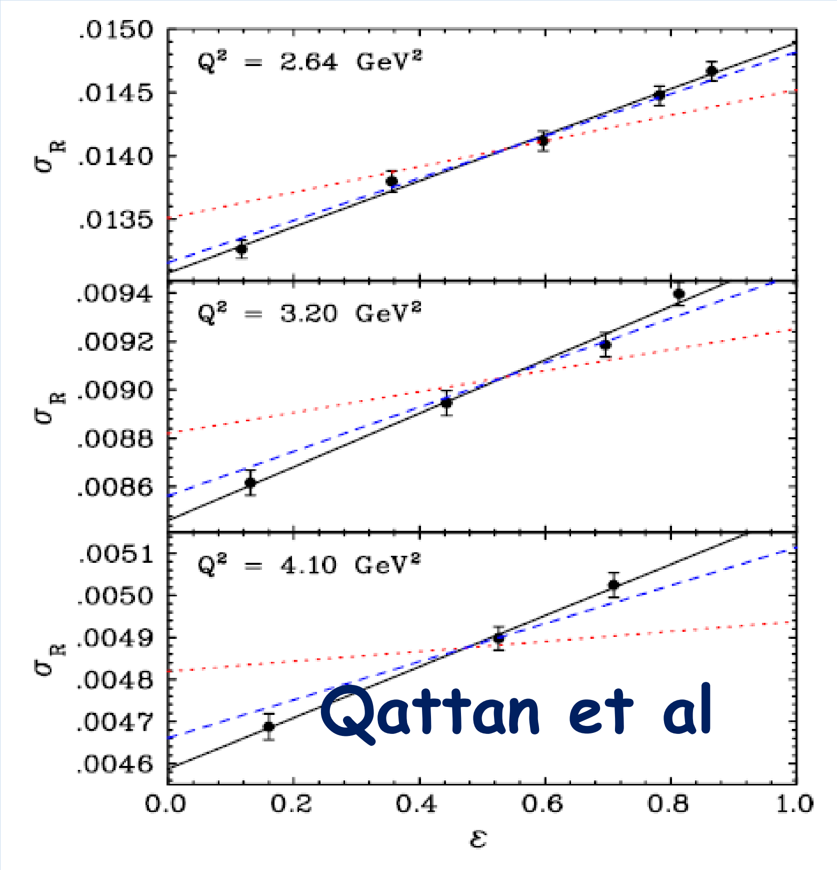
Better to write the Cross sections in terms of the Sachs form factors:

electric $G_{Ep} = F_1 - \tau F_2$ and

magnetic $G_{Mp} = F_1 + F_2$

with $\tau = Q^2/4m_p^2$; then:

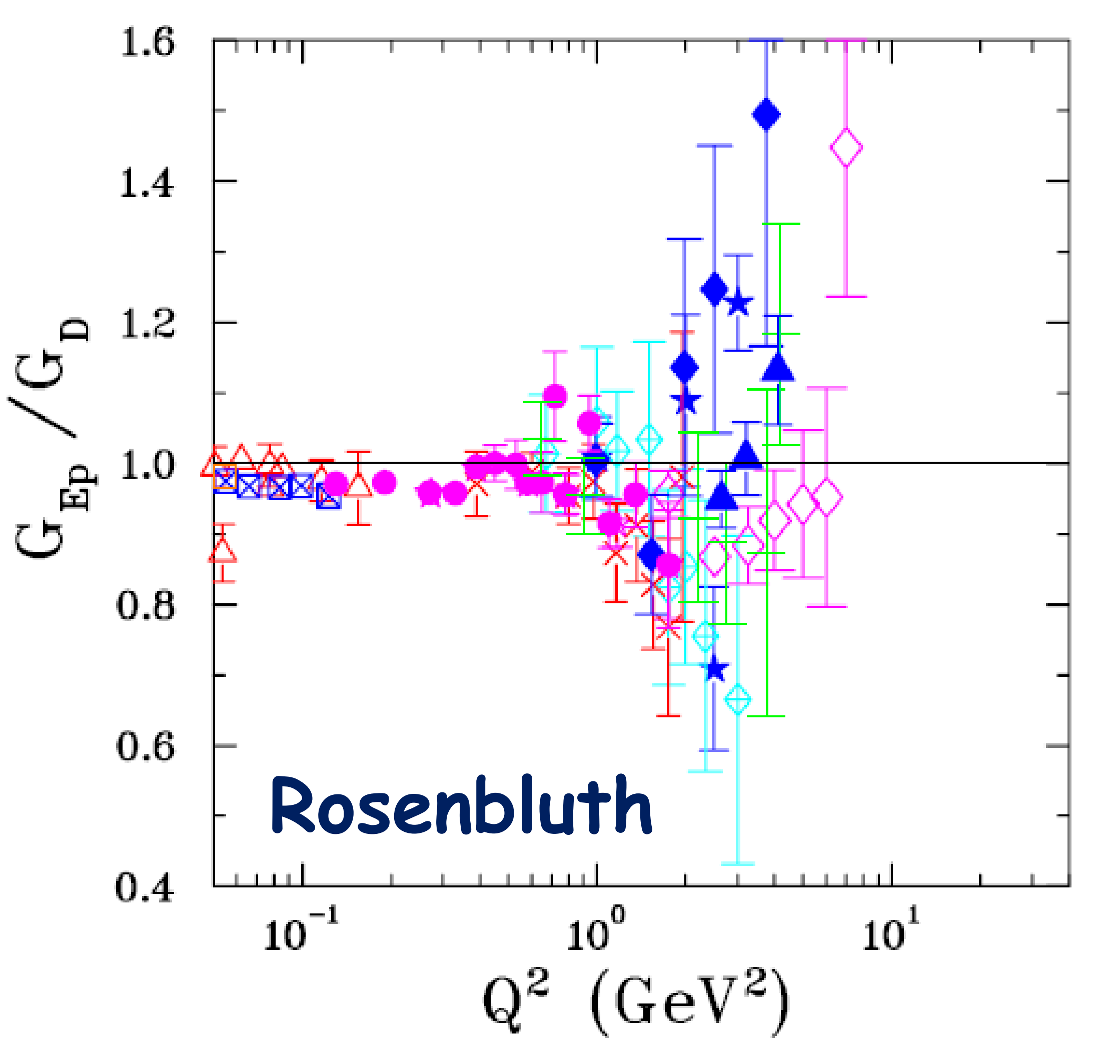
$$d\sigma/d\Omega = (d\sigma/d\Omega)_{Mott}\,\{G_{Mp}^2 + (\varepsilon/\tau)G_{Ep}^2\}\tau/\varepsilon(1+\tau)$$

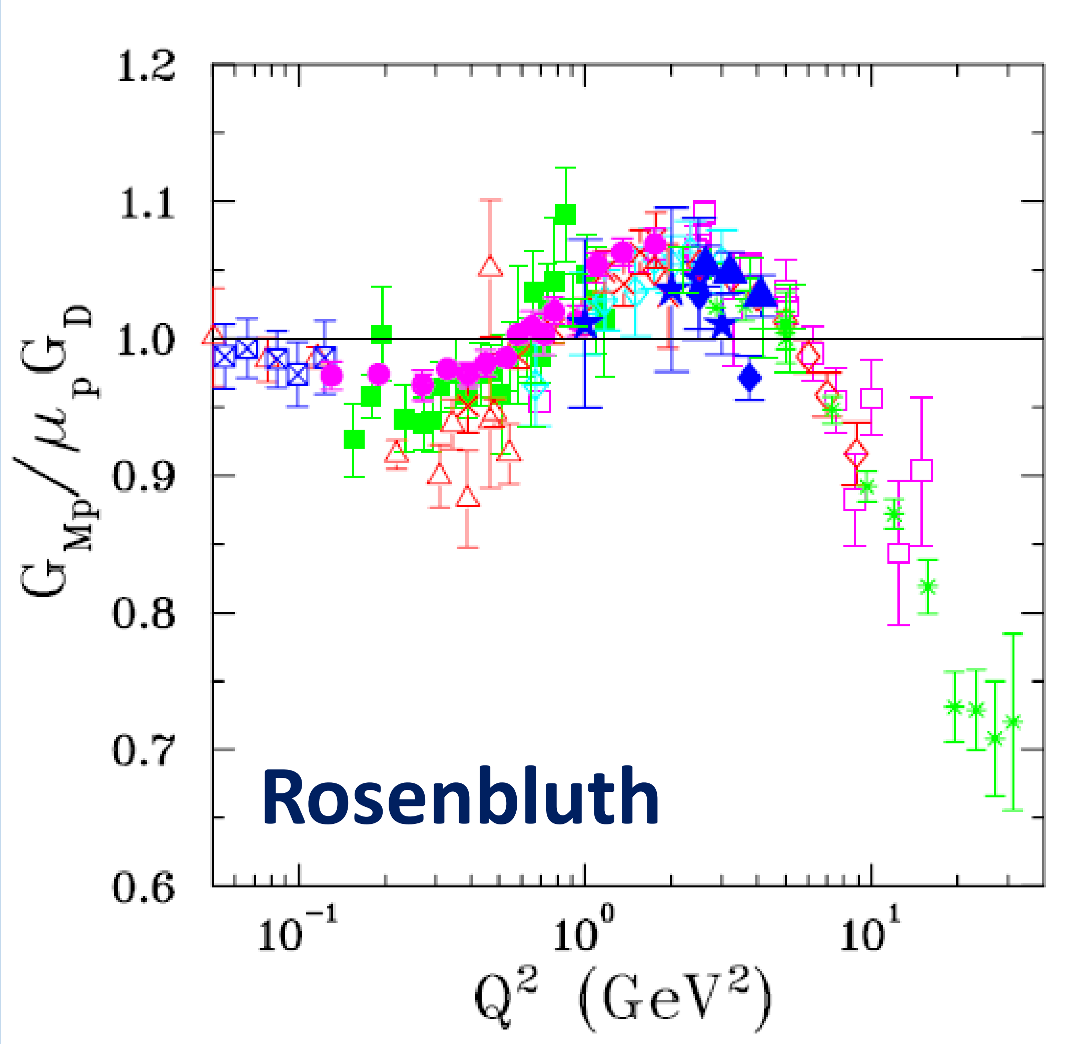


with $\varepsilon = [1+2(1+\tau)\tan^2(\theta_e/2)]^{-1}$

and $(d\sigma/d\Omega)_{Mott} = \dfrac{\alpha^2}{4E_e^2}\,\dfrac{\cos^2\frac{\theta}{2}}{\sin^4\frac{\theta}{2}}$

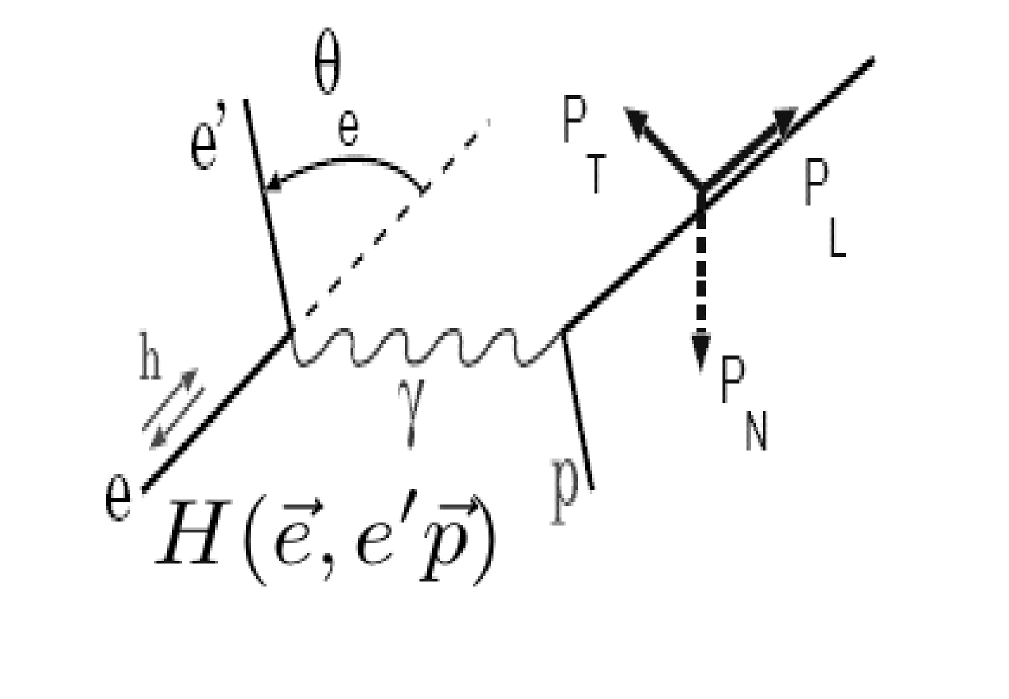
By the 1990's G_{Ep} and G_{Mp} showed stability, both G_{Ep}/G_D and $G_{Mp}/\mu_p G_D$ ≈ Q^2 -independent, with $G_D=(1+Q^2/0.71)^{-2}$ the dipole FF.





Recoil Polarization Observables in OPEX

The theoretical work had been done: Akhiezer e a. (1958), Scofield (1959), Akhiezer e a.(1968,1974), Dombey (1969), Arnold, Carlson and Gross (1981)….



$$P_t = -hP_e 2\sqrt{\tau(1+\tau)}\,\frac{G_{Ep}G_{Mp}}{G_{Ep}^2 + \frac{\tau}{\varepsilon}G_{Mp}^2}\tan\frac{\vartheta e}{2}$$

$$P_l = hP_e \frac{E_e + E_{e'}}{M}\sqrt{\tau(1+\tau)}\,\frac{G_{Mp}^2}{G_{Ep}^2 + \frac{\tau}{\varepsilon}G_{Mp}^2}\tan^2\frac{\theta_e}{2}$$

$$P_n = 0$$

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_l}\,\frac{E_e + E_{e'}}{2M}\tan\frac{\theta_e}{2}$$

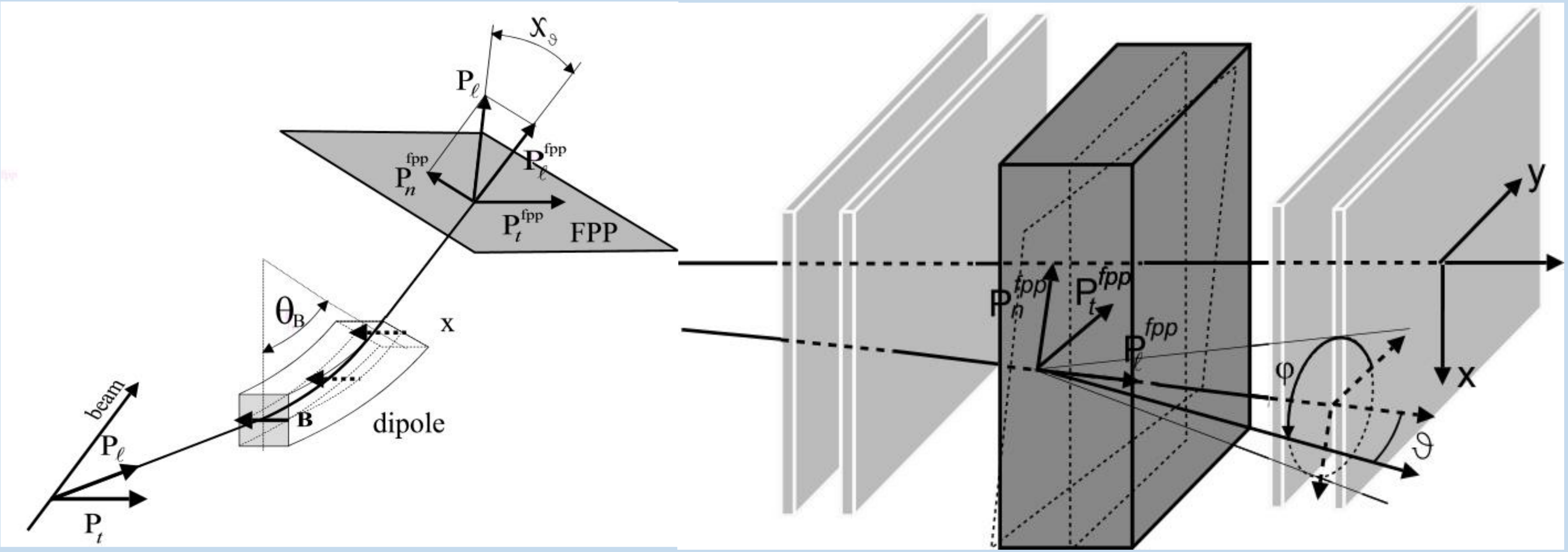
h = + or -1 is beam helicity, P_e beam polarization

most importantly, G_E and G_M are measured, not G_E^2 and G_M^2

In a first proposal (Perdrisat and Punjabi, 1989), we aimed at getting P_t and P_ℓ, then calculate P_t/P_ℓ and use the good G_{Mp} data base to get G_{Ep}. In a second submission (1993) we proposed to obtain G_{Ep}/G_{Mp} directly from measured P_t/P_ℓ, for smaller uncertainties, statistical and systematic. Best way!

Measuring the polarization ratio cancels the radiative corrections, requires no knowledge of the analyzing power of the reaction, and cancels many other fluctuating effects like beam polarization, target density, detector efficiencies… Little did we expect to get G_{Ep} at Q^2 of 8.5 GeV^2, so we now know that it contributes less than one 2 parts in 1000 to the cross section at that Q^2!

Spin Precession, Focal Plane Polarimeter



ϑ and φ polar- and azimuthal angles after re-scattering in analyzer. If ε(ϑ, φ) efficiency, and $A_y(\vartheta)$ analyzing power, then proton detection probability for both beam helicities, $f^{\pm}$:

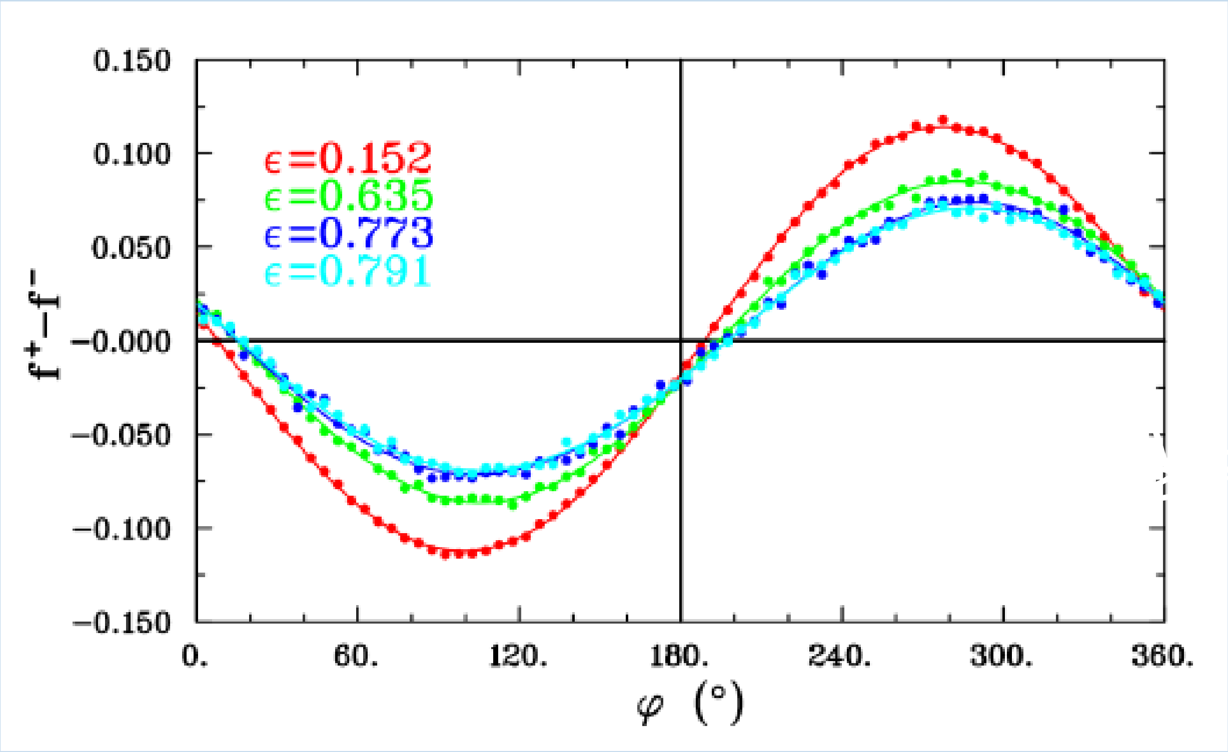
$$f^{\pm}(\vartheta,\varphi) = \frac{\epsilon(\vartheta,\varphi)}{2\pi}\{1 \pm A_y(\vartheta)(P_t^{fpp}\cos\varphi - P_n^{fpp}\sin\varphi)\}$$

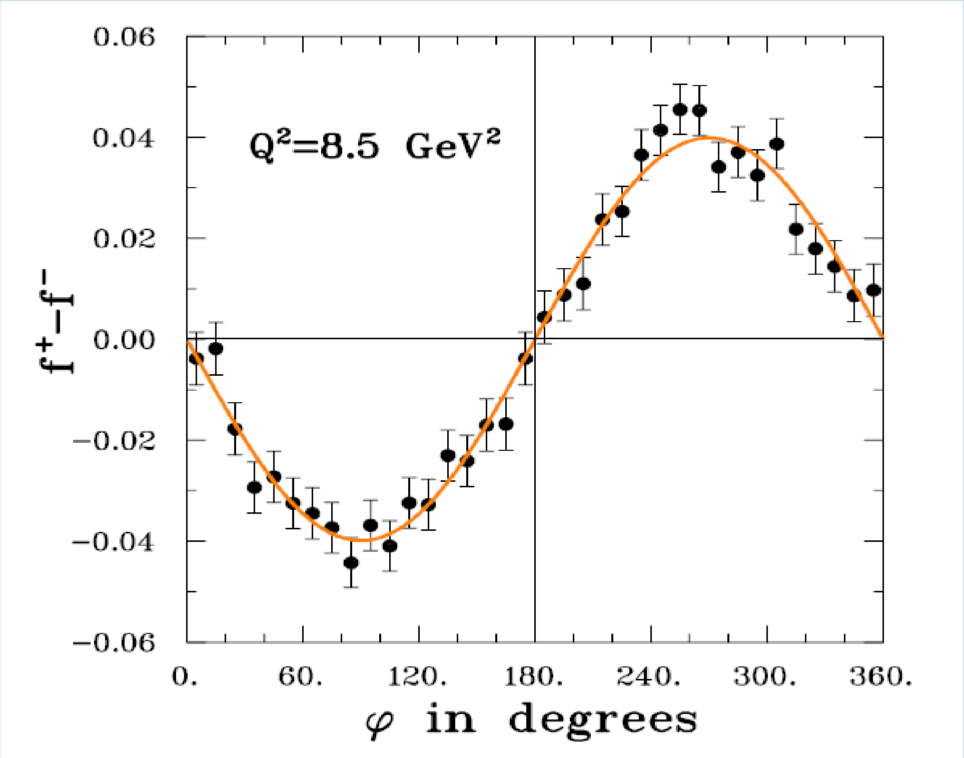
Obtain azimuthal asymmetry difference by flipping beam helicity

$$f^{+} - f^{-} = \frac{1}{\Delta\varphi}\left[\frac{N^{+}(\varphi)}{N^{+}_{in}(\varphi)} - \frac{N^{-}(\varphi)}{N^{-}_{in}(\varphi)}\right] = A_y(\vartheta)\left[P_t^{fpp}\, cos\varphi - P_n^{fpp}\, sin\varphi\right]$$

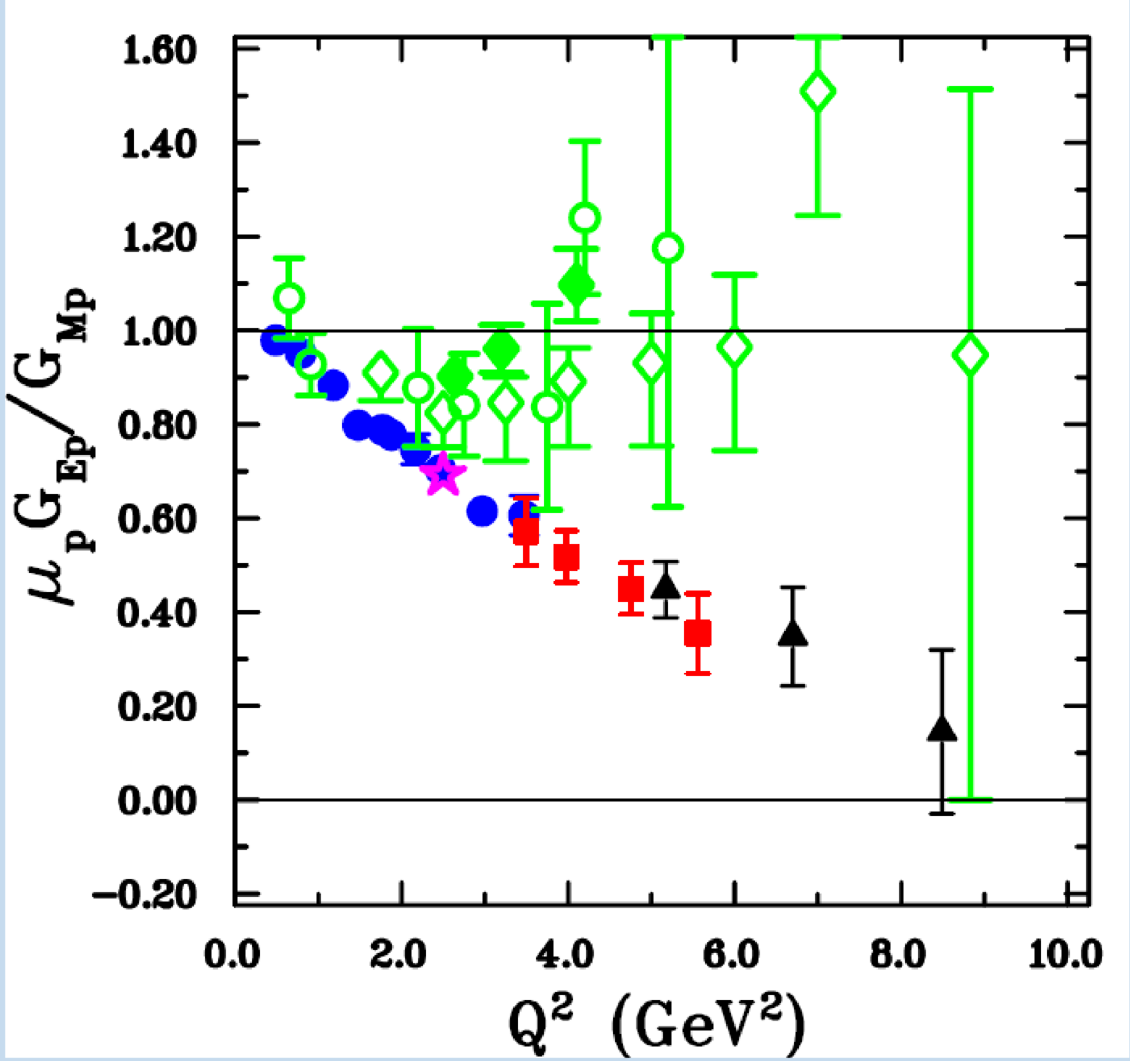
Left, Q^2=2.5 GeV^2, M. Meziane et al, P.R.L. 106, 132501 (2011)

Right, Q^2=8.6 GeV^2, A. Puckett et al, P.R.L.104, 242301 (2010)





Following GEp(1), GEp(2), GEp(3) and GEp(2ϒ), form factor ratios from Jlab differ drastically from most recent Rosenbluth data:



Andivahis, Christy and Qattan

Rosenbluth cross sections corrected for radiative effects

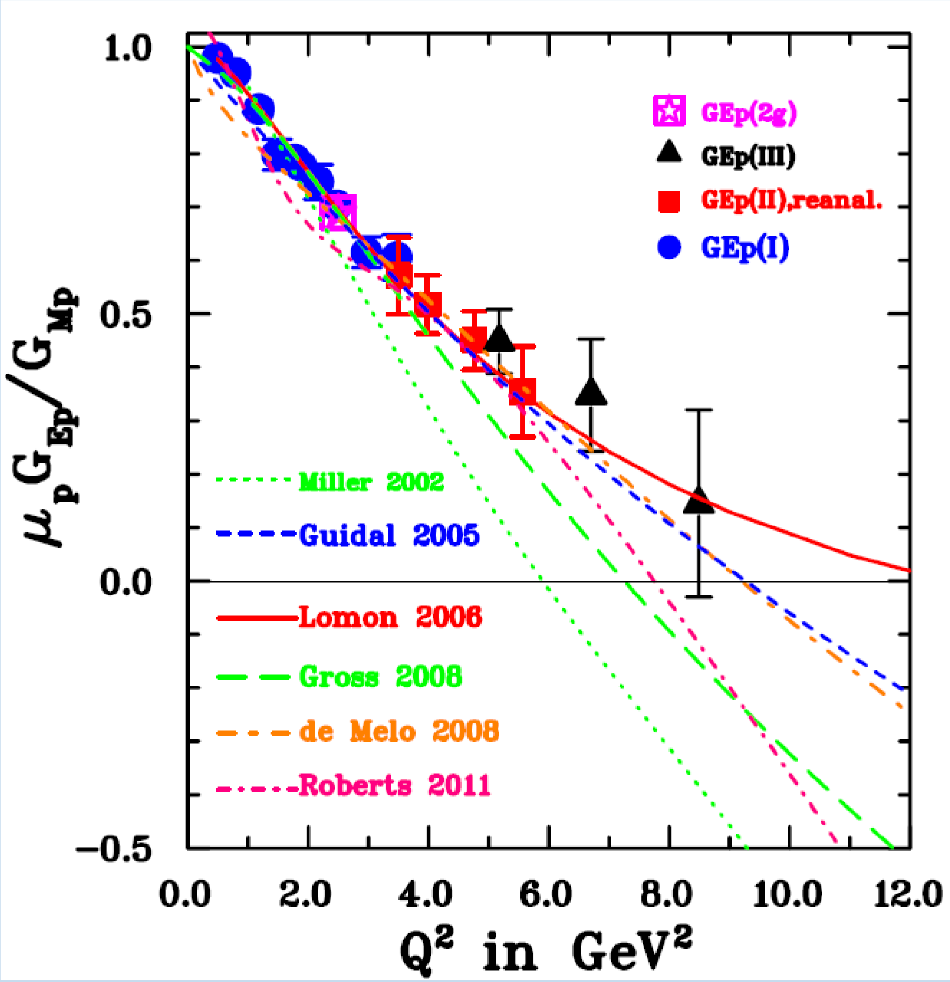
Double polarization results:

Blue, red, black and magenta: GEp(1 to 3 and 2ϒ).

No significant radiative corrections for polarization ratio required at the ~% level.

A.V. Afanasev et al, P.L. 514 (2001)269

Overall Picture



Vector Meson Dominance (VMD) models describe all four nucleon *FF's* well (Lomon, Iachello, Bijker…)

Relativistic Constituent Quark Models show importance of relativistic dynamics; can separate dynamical from nucleon structure effects (Chung & Coester, Miller, Gross, de Melo ….).

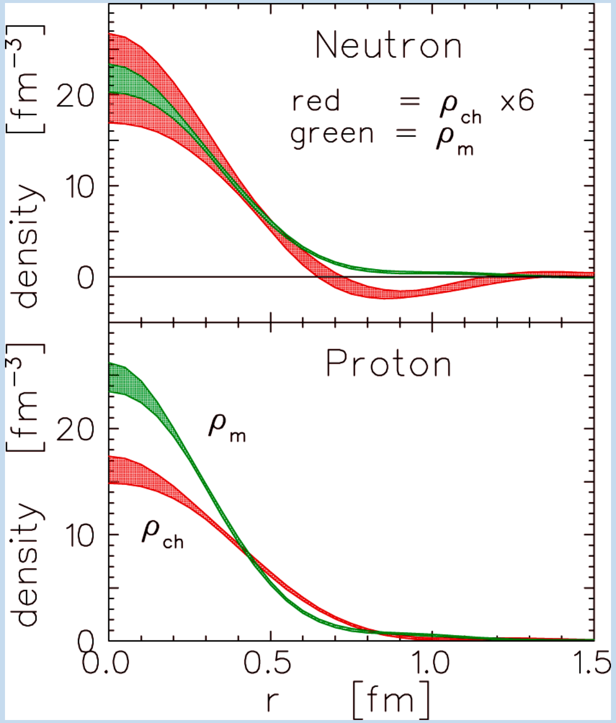
Dyson-Schwinger equations, continuum approach to QCD (Roberts et al.)

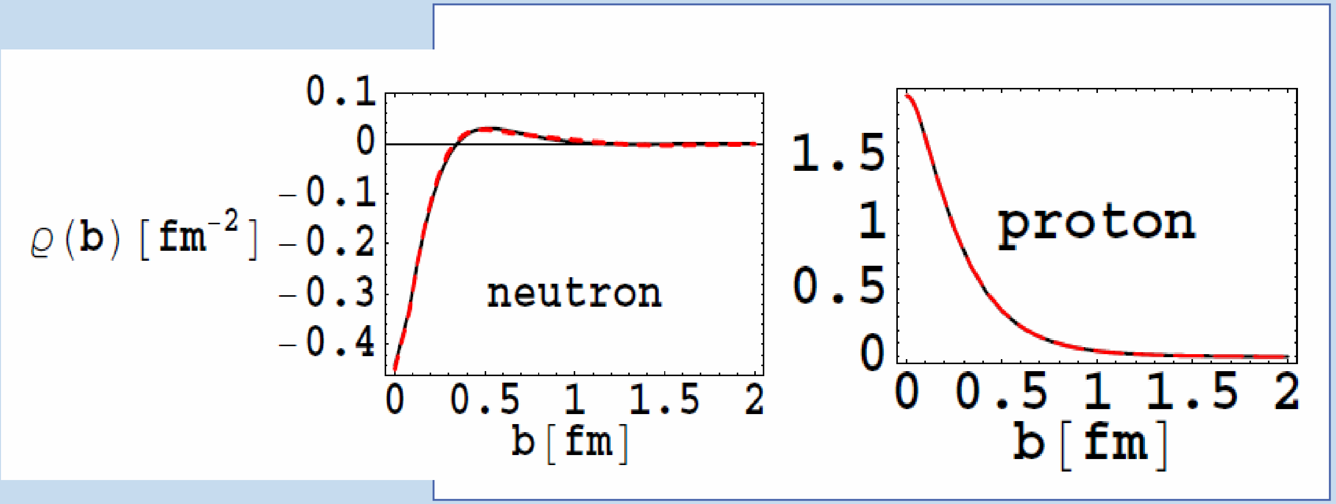
Generalized Parton Distribution (GPD) related to Form Factors (see Guidal…)

J.J. Kelly, Phys. Rev. C66, 065203 (2002)

G.A. Miller, PRL 99,112001 (2007), PR C80 015201 (2009)

Simultaneous fits of all 4 form factors in Fourier transf. including relativistic effects due to use of Breit frame.





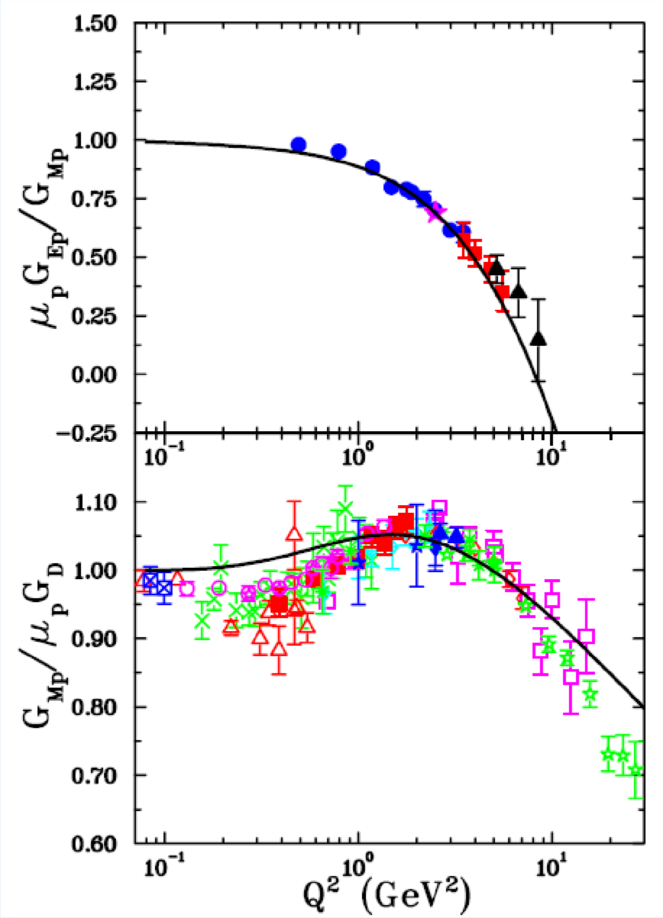
In infinite momentum frame transverse charge density

ρ(b) is a relativistic invariant, 2-dim. Fourier transform of F_1:

$$\rho(b) \equiv \sum_q e_q \int dx\, q(x, \mathbf{b}) = \int \frac{d^2q}{(2\pi)^2} F_1(Q^2 = \mathbf{q}^2) e^{i\mathbf{q}\cdot\mathbf{b}}.$$

GPDs and FF

First moments of Generalized Parton Distributions (GPD) from deeply virtual Compton scattering are related to Form Factors (Radyushkin, 96, Ji, 97) at valence quark level.



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

x-ξ initial, x+ξ final momentum fraction of valence quark struck.

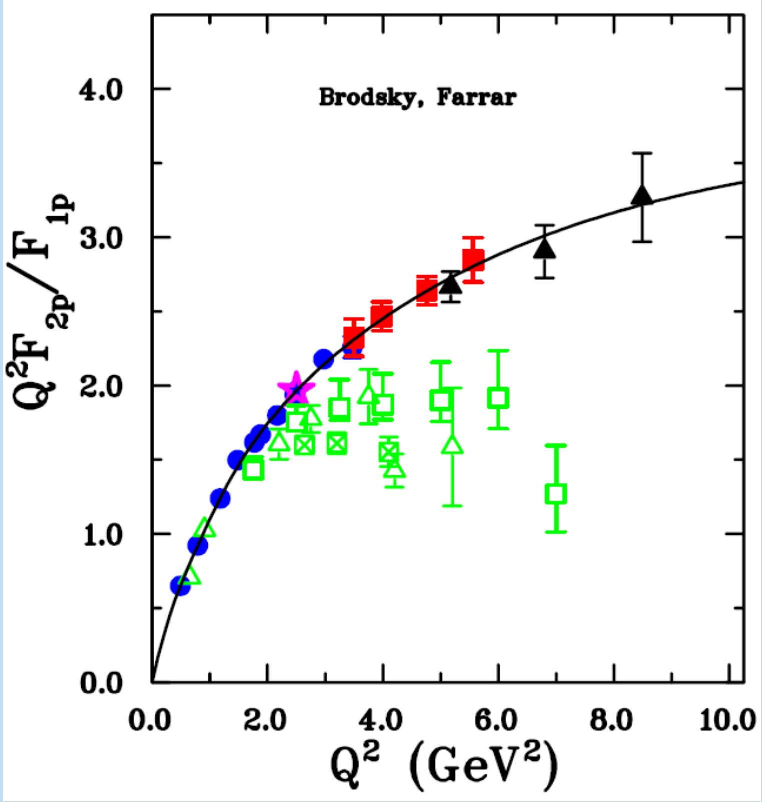
H^q and E^q: quark correlation functions; emission, re-absorption of quark in non-perturbative realm.

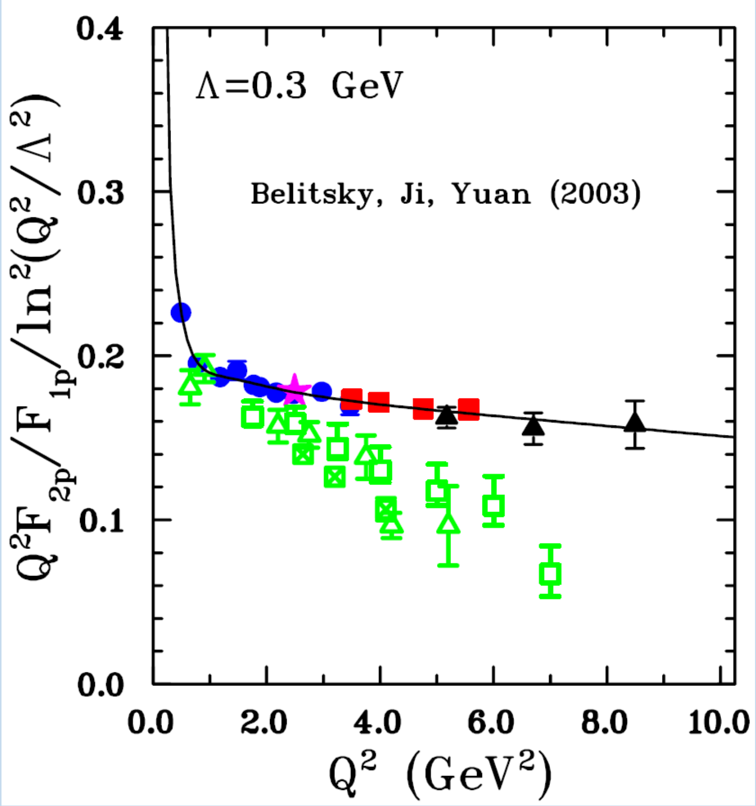
Curves shown from Regge parametrization for H and E (from Guidal e. a., PR D72 (2005), 054013)

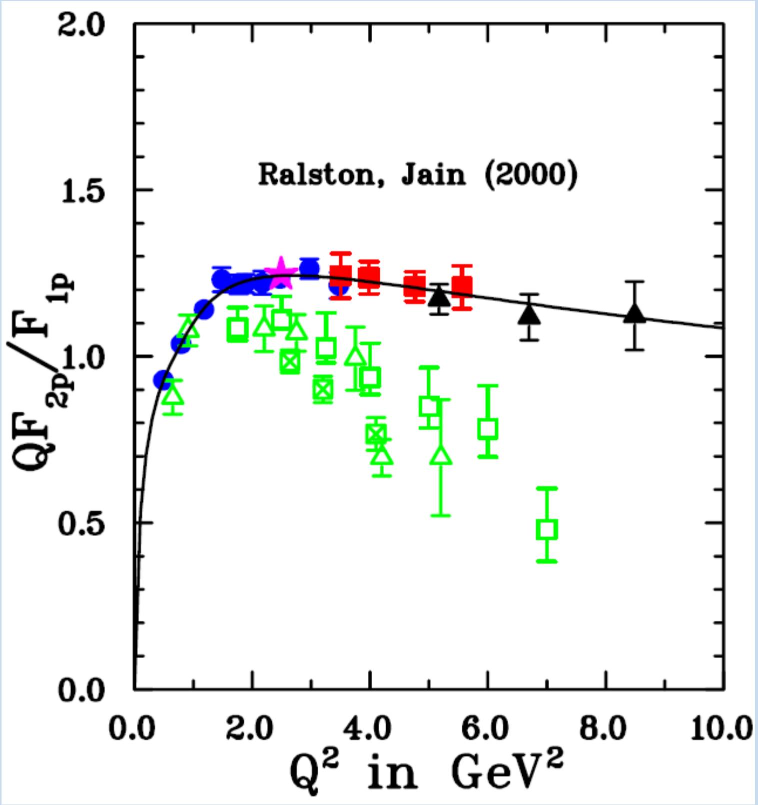
Perturbative QCD for F_2/F_1, (Brodsky and Farrar, 1973))

Virtual photon absorbed on 1 of the 3 leading quarks; momentum of that quark must be shared equally among the 3 quarks by exchange of 2 gluons, each with virtuality α $1/Q^2$:

$Q^2F_2/F_1 \approx$ constant. Data do not agree with expectation



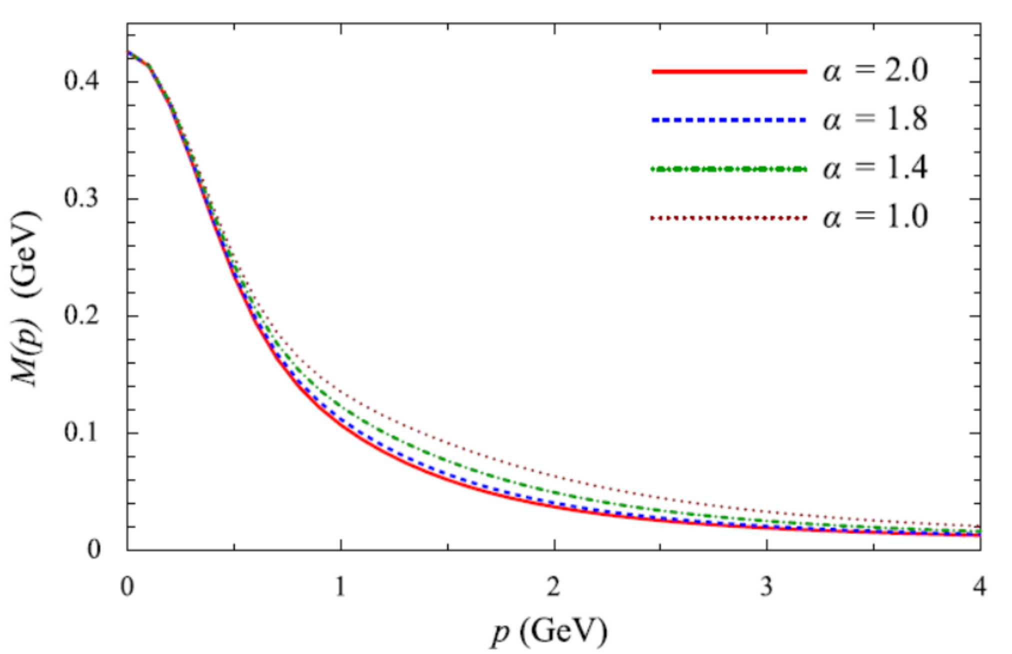


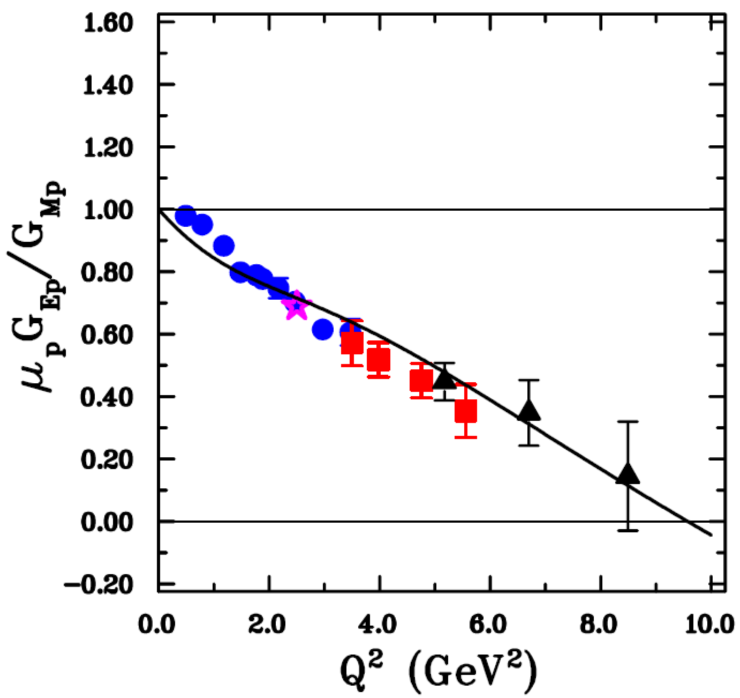


Dyson-Schwinger

Elastic *ep* scattering in 1-10 GeV^2 Q^2 range is in domain of non-perturbative QCD. Dressed quarks from Dynamical Chiral Symmetry Breaking: (C. Roberts e.a. PRL 111, 101803 (2013)). Described by Dyson-Schwinger equations.

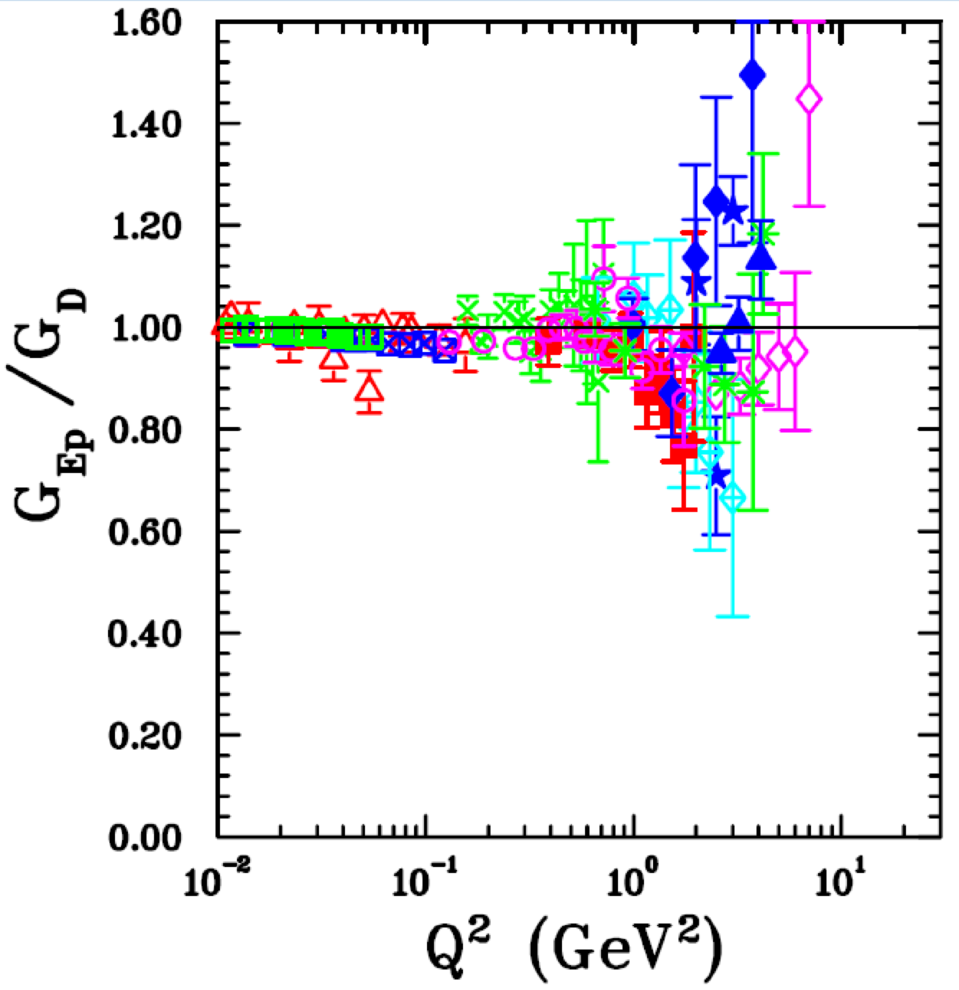
The quark-partons of QCD acquire in infra-red region a momentum-dependent mass 2 orders of magnitude larger than current-quark mass; from cloud of gluons surrounding a low-momentum quark.



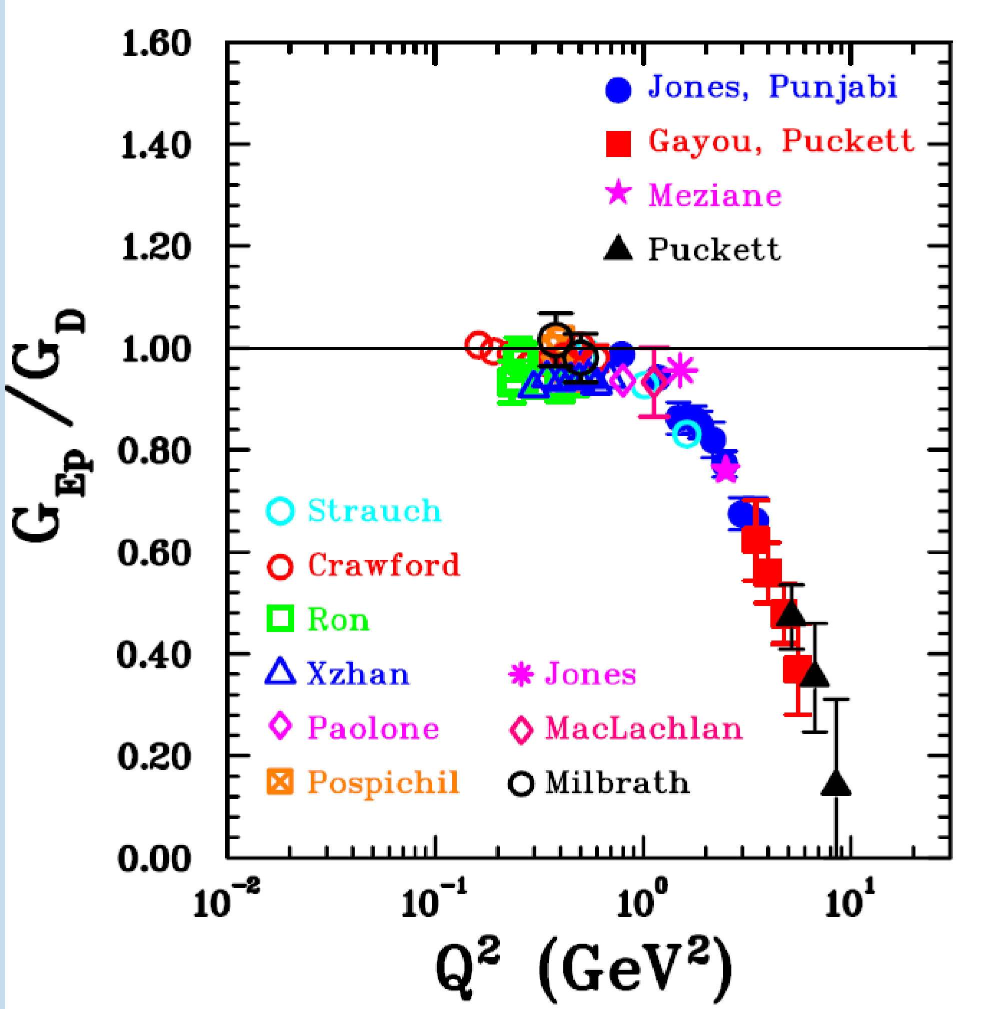


Can both data be physically true?

Cross sections only (Rosenbluth)

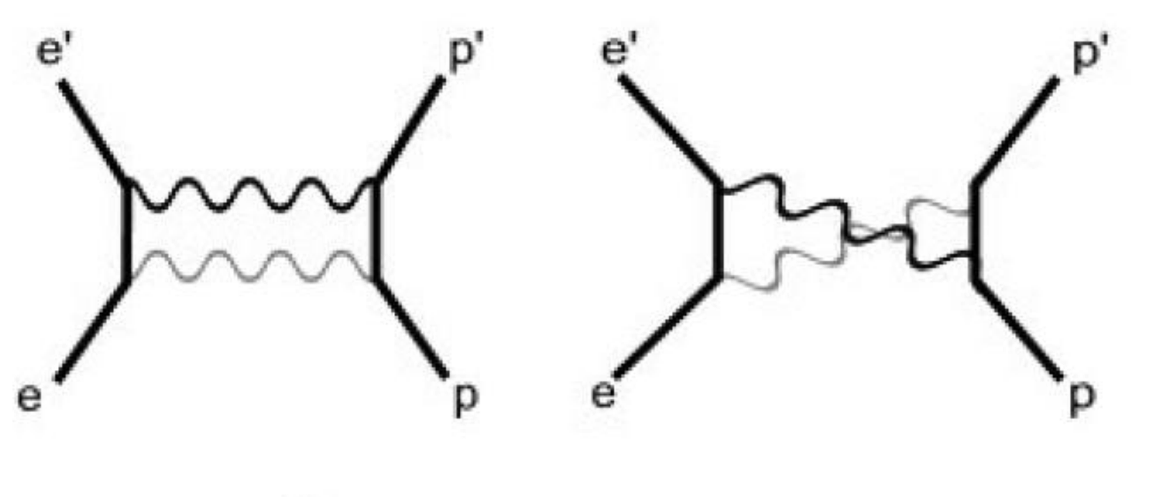


Double polarization only



Is there explanation for "dramatic" difference between results of the 2 types of experiments: Rosenbluth and Polarization? is this difference real?

Results of both obtained within OPEX approximation. But, in 2003 Guichon and Vanderhaeghen proposed two-photon exchange as origin.



e) two-photon

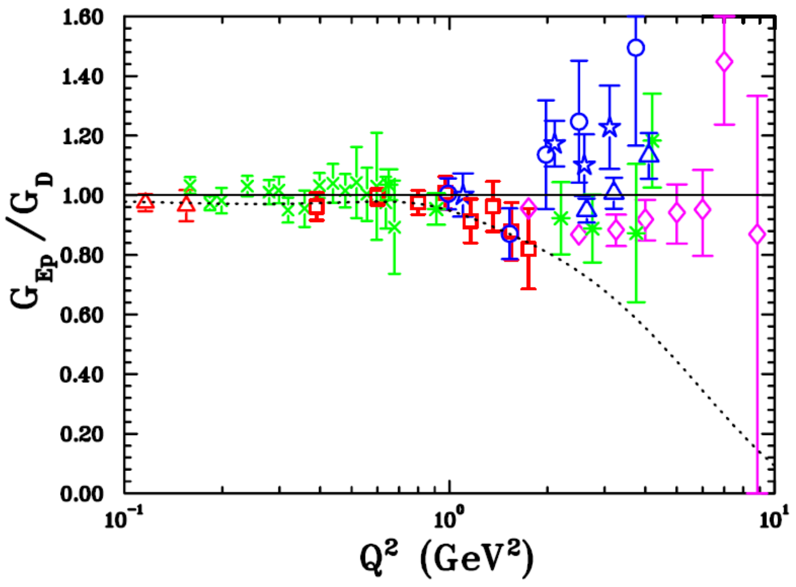
Must be evaluated, or measured.
Difficult to calculate: virtual nucleon can be any excited baryon.

Many model calculations since: Afanasev ea., Arrington, Kondratyuk ea., Bystritskiy ea., Vanderhaeghen ea., Blunden, Carlson and Vanderhaeghen)….

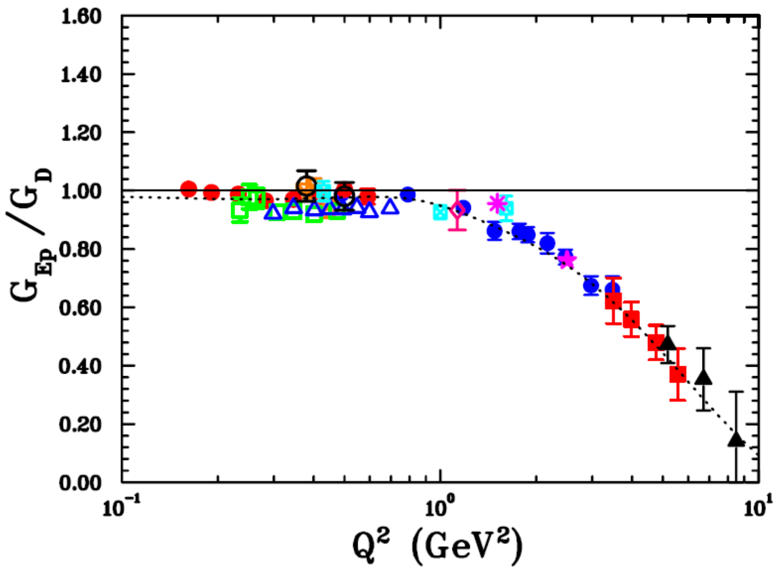
Direct way to measure TPE from the cross section ratio for electrons and positrons on the proton. (VEEP-3, Jlab HallB , Olympus).

Hall B $e^{+-}p$ results (Rinal et al, PR C95 (2017)): Rosenbluth and polarization compatible up to Q^2=1.77 GeV^2; extend these results to 8.5 GeV^2 ! Main culprit 1994 Andivahis data? reanalyzed by Tomasi-Gustafsson, and Arrington and others: better agreement with polarization results possible, but not proven!

Cross section



Double polarization



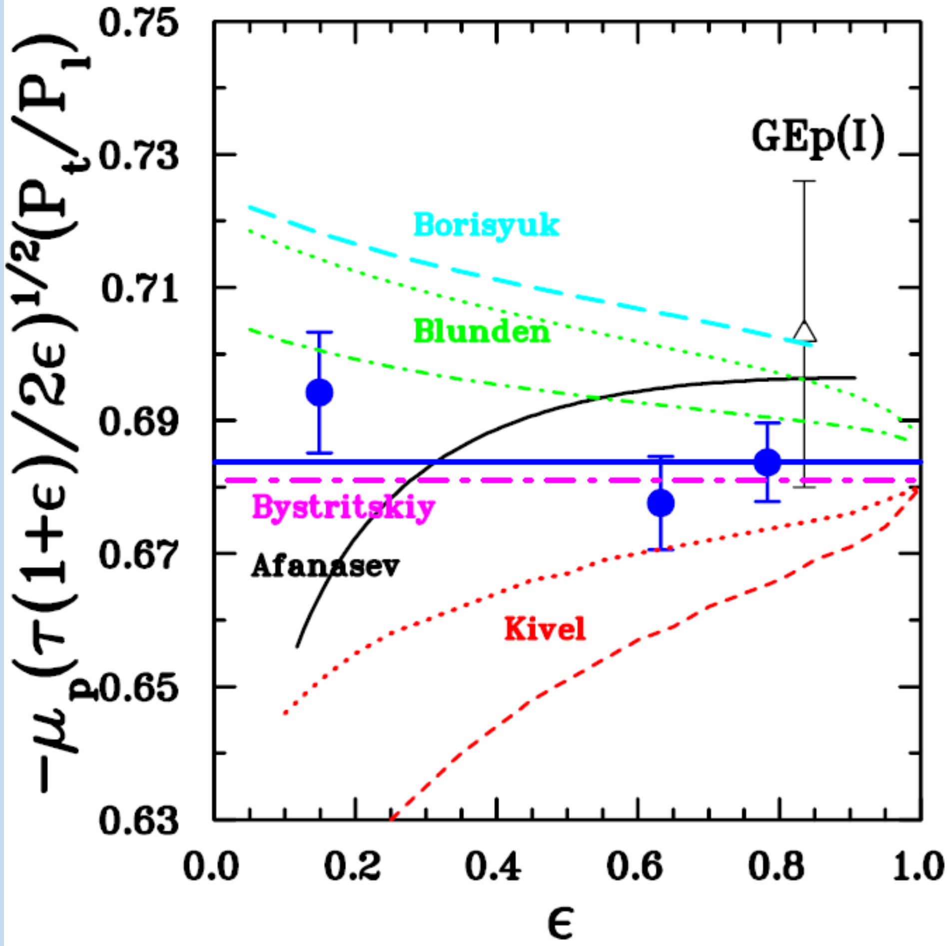
At Jefferson Lab $G_{Ep}(2\gamma)$ experiment measured P_t/P_ℓ and obtained $\mu G_E/G_M$ at Q^2=2.5 GeV^2 for 3 values of ε, with small error bars.

Average $\mu G_{Ep}/G_{Mp}$=0.688+/-0.004 (~ 0.6%)

Lack of an ε-dependence confirms form factor ratio results unaffected by TPEX contribution at this Q^2.

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

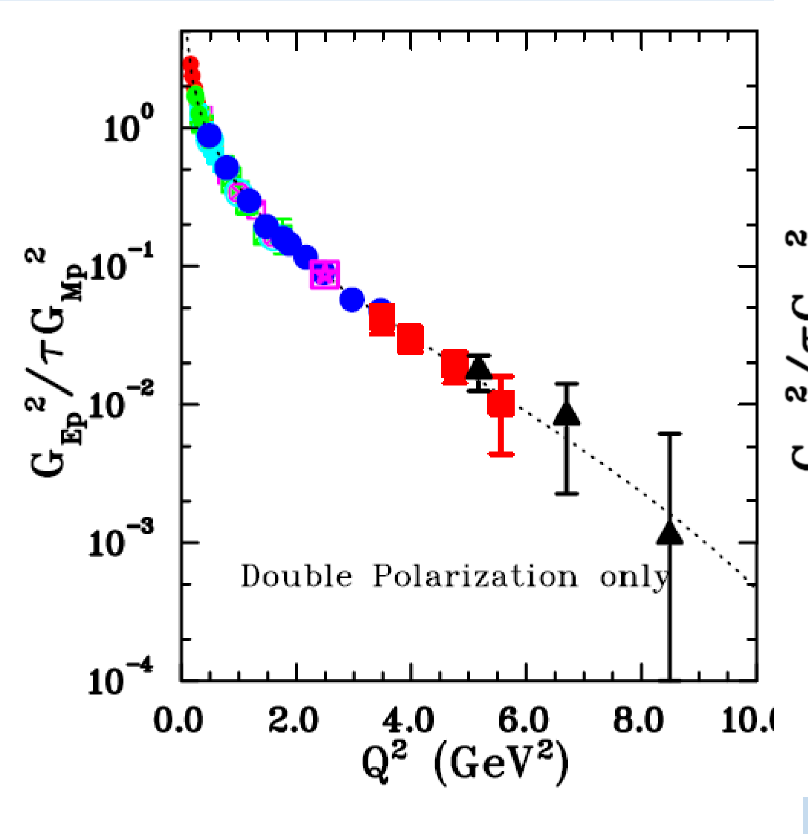
Y-axis is in fact $\mu G_{Ep}/G_{Mp}$ in the absence of a 2-photon effect.



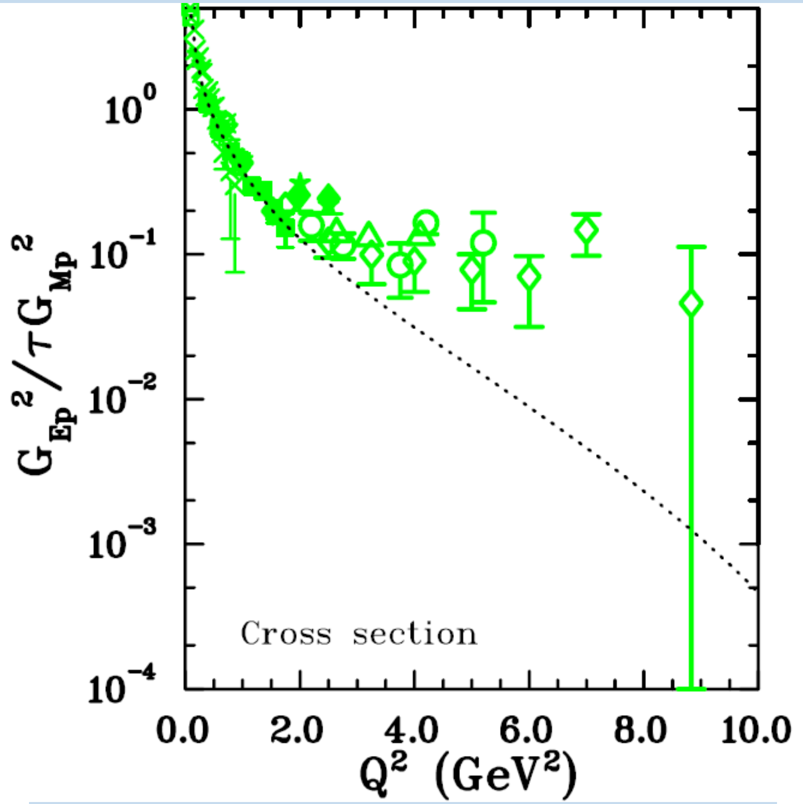
Is there a physical reason for the "difference", or are we seeing the limit of sensitivity to G_{Ep} of cross section data?

$$\sigma/\sigma_{Mott} = \frac{\tau}{\varepsilon(1+\tau)} G_M^2\left(1 + \frac{\varepsilon}{\tau}\frac{G_E^2}{G_M^2}\right)$$ Then plot $\frac{\varepsilon}{\tau}\frac{G_E^2}{G_M^2}$ versus Q^2.

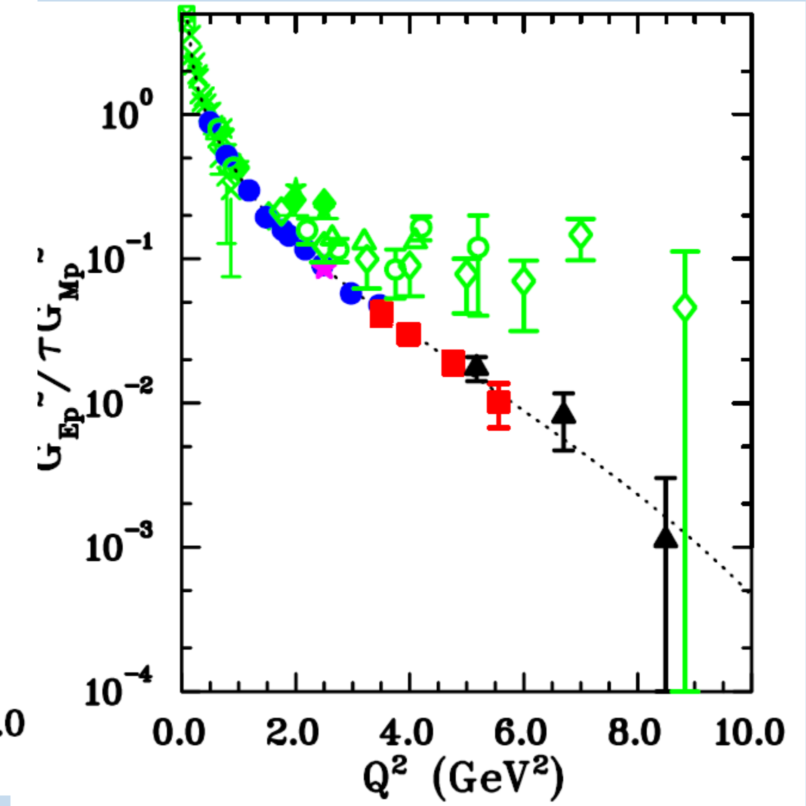
Polar. transfer



Rosenbluth



together



Quark Flavor separation

If assume **charge symmetry** for hadron current at the dressed quark level: $\langle p|e_u\bar{u}\gamma_\mu u+e_d\bar{d}\gamma_\mu d|p\rangle$, with e_u and e_d the charge of the *up* and *down* quarks, then: the **dressed quark** Dirac and Pauli *form factors* obey:

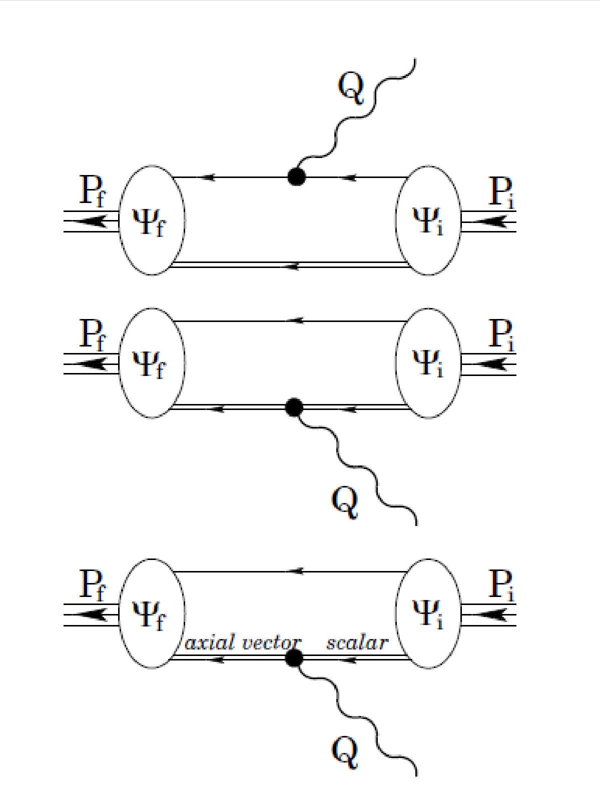
$$f^u_{1(2)p} = f^d_{1(2)n} \qquad f^d_{1(2)p} = f^u_{1(2)n}$$

and the Dirac and Pauli **dressed quark** *ff's* can be obtained from the **nucleon** Dirac and Pauli proton *FF's*, $F_{1(2)p}$ and $F_{1(2)n}$

$$f^u_{1(2)p} = 2F_{1(2)p} + F_{1(2)n} \quad \textit{and} \quad f^d_{1(2)p} = F_{1(2)p} + 2F_{1(2)n}$$

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), and others.

Quark Flavor separation and di-quark

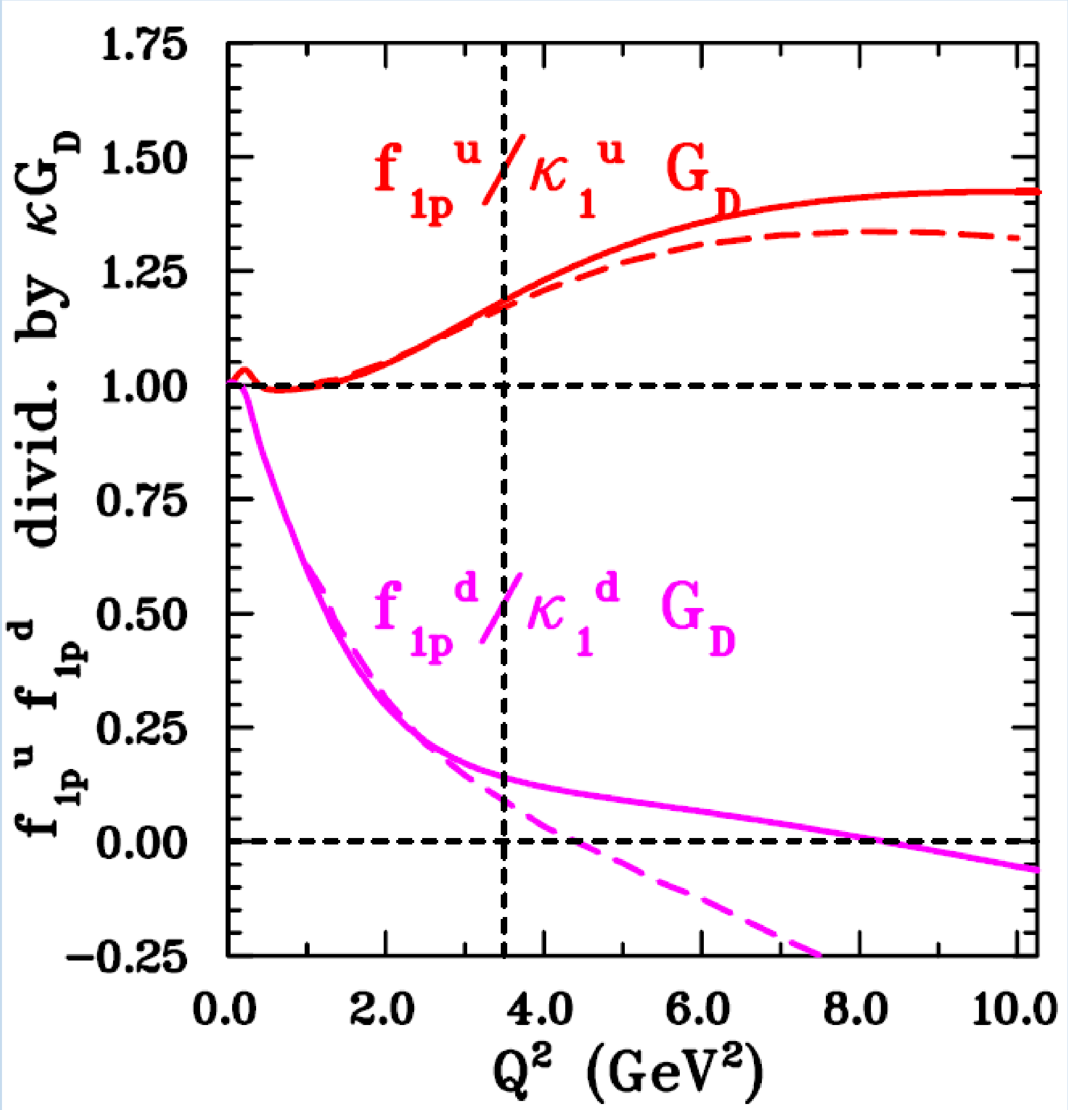


Wilson, Cloët, Chang, Roberts, Phys. Rev. C 85, 025205 (2012).

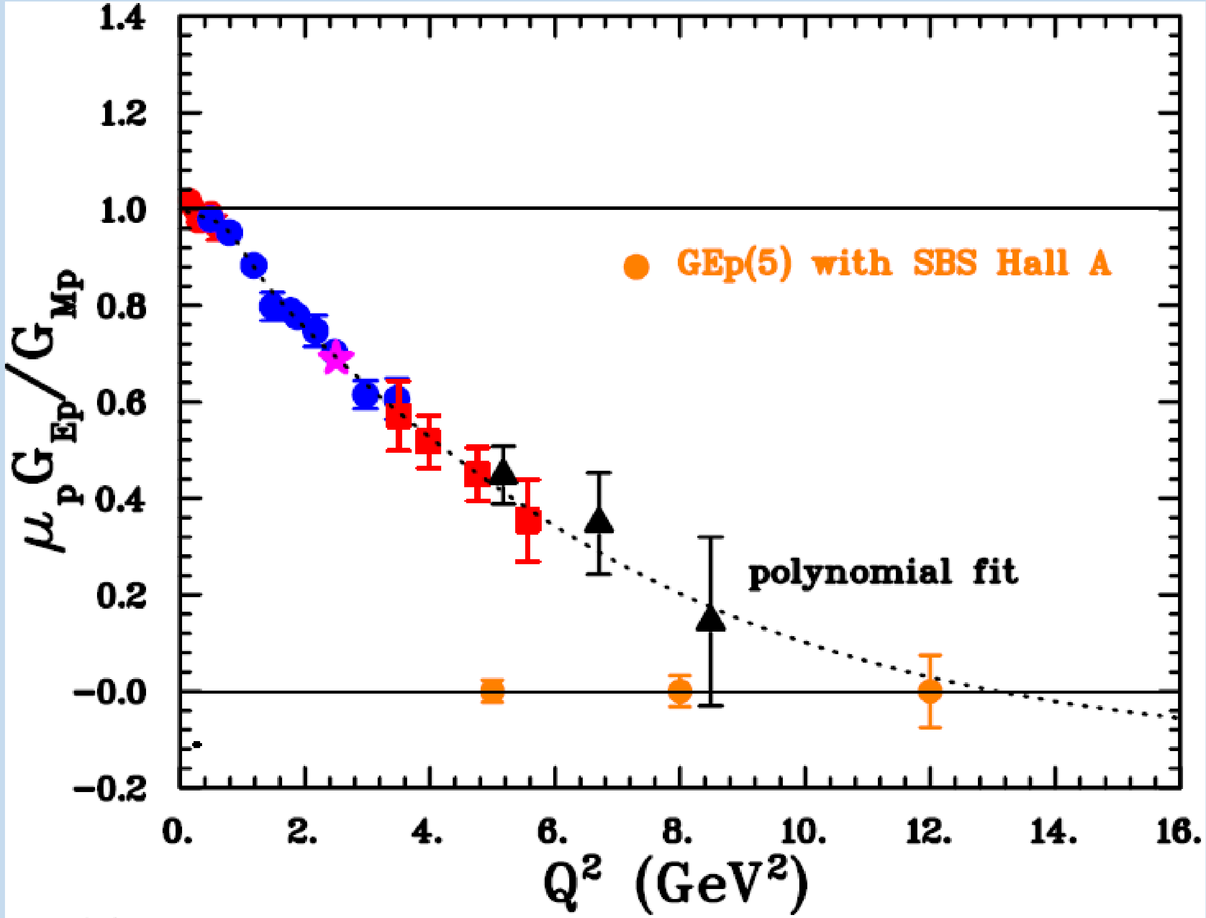
Solid lines for polynomial fits to nucleon FF

Interference of axial-vector and scalar di-quark generates zero in f_{1p}^d

Dashed lines for Dynamical Chiral Sym. Breaking



Next experiment, GEp(5), with upgraded Jlab accelerator,SuperBigbiteSpectrometer in Hall A, and significant others improvements



CONCLUSION

Even though this was a drastically shortened presentation of the field of elastic electron/nucleon scattering, as it evolved towards increasing Q^2 after our start of double polarization experiments at Jefferson Lab,

I hope to have given you a sense of the magnitude of the changes in understanding of the proton structure resulting from the use of the polarization ratio method to obtain the proton form factors.

For further information go to http://www.scholarpedia.org/article/NucleonFormFactors
first posted in Aug. 2010 by C.F. Perdrisat and V. Punjabi, visited ~45,000 times by 1/28/2019.

Also C.F. Perdrisat and V. Punjabi and M. Vanderhaeghen, PPNP 59, 694-769 (2004)

and V. Punjabi, C.F. Perdrisat, M.K. Jones, E.J. Brash and C.E. Carlson, EPJ A (2015) 51: 1-79.

Also A.J.R. Puckett et al. PR C96 (2017) 055203.

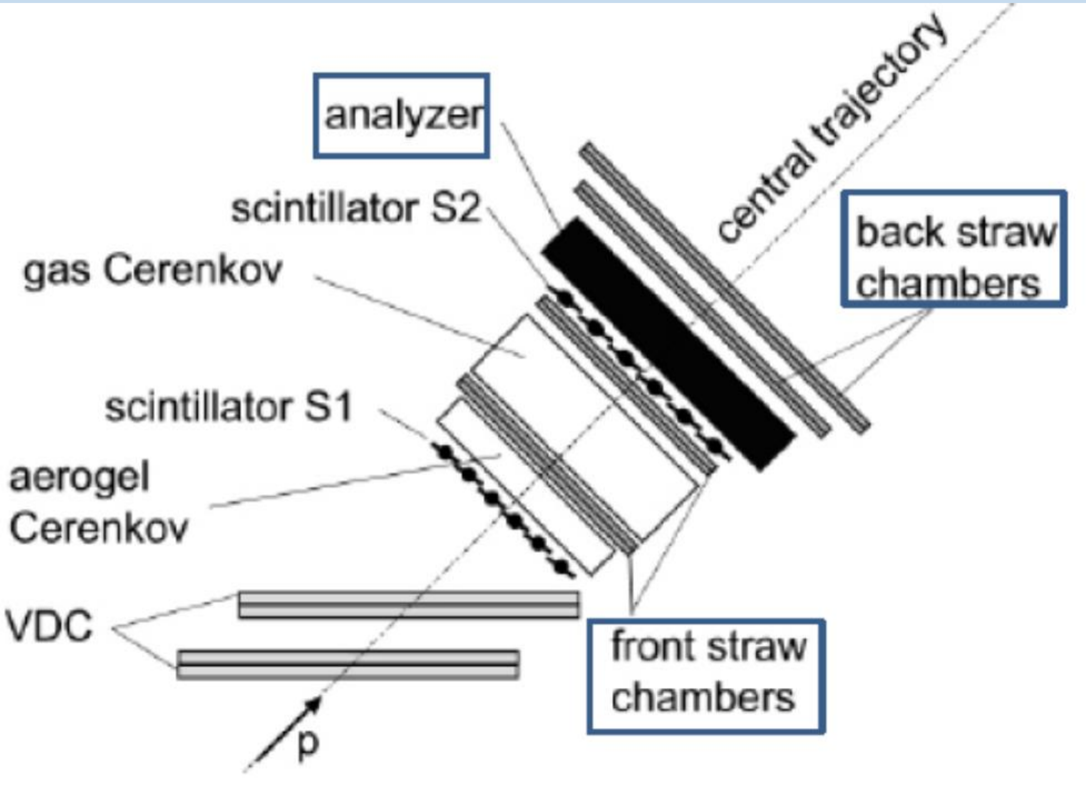
The END

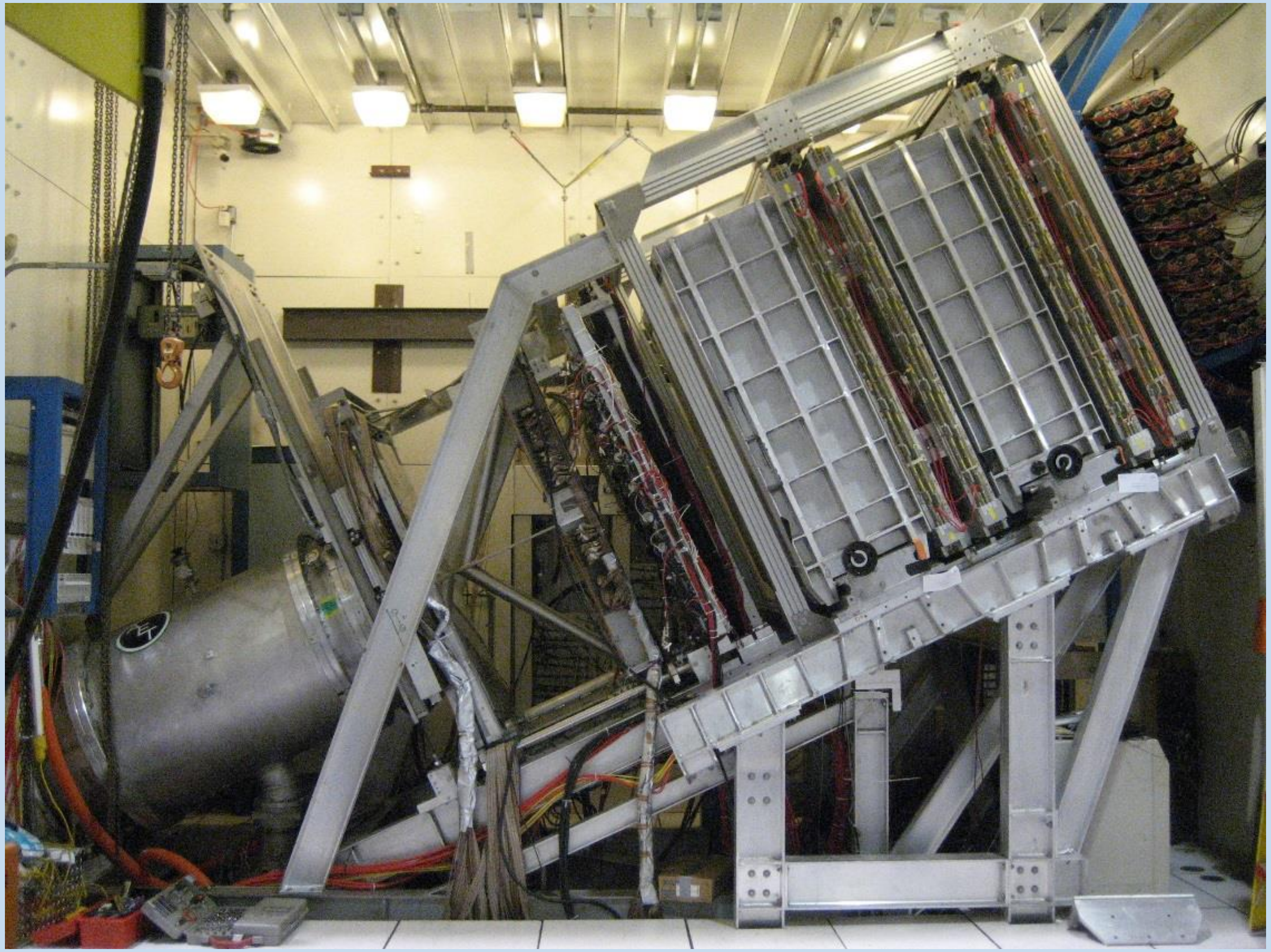
The Jefferson Lab physics results I have shown here were obtained by a large collaboration, lasting from the late nineteen-eighties to this day. I mention particularly Prof. Vina Punjabi, who presented the first proposals, and got them first conditionally (1989), and then fully approved in 1993.

Mark Jones, Ed Brash, L. Pentchev and F. Wesselmann.
were crucially involved in this work.
I also mention the graduate students of these experiments:
G. Quemener, O. Gayou, A. Puckett, M. Meziane and W. Luo.

Grants from NSF and DOE and the support of Jefferson Lab and William and Mary, are thankfully acknowledged.

The polarimeter in HRS in Hall A: $G_{Ep}(1)$ and $G_{Ep}(2)$





The double polarimeter in HMS in Hall C: $G_{Ep}(3)$ and $G_{Ep}(2\gamma)$

Some consequences of Polarization results

1. Vector Dominance (VMD) and Constituent Quark models (CQM) revisited, made relativistic (E. Lomon, G. Miller)

2. Concept that F_1 is Fourier transf. of charge densities lost: F_1 Fourier transf. of 2-dimens. transverse density in IMF (G. Miller)

3. Proton in ground state not necessarily spherically symmetric, may show a typical multipole shape (G. Miller)

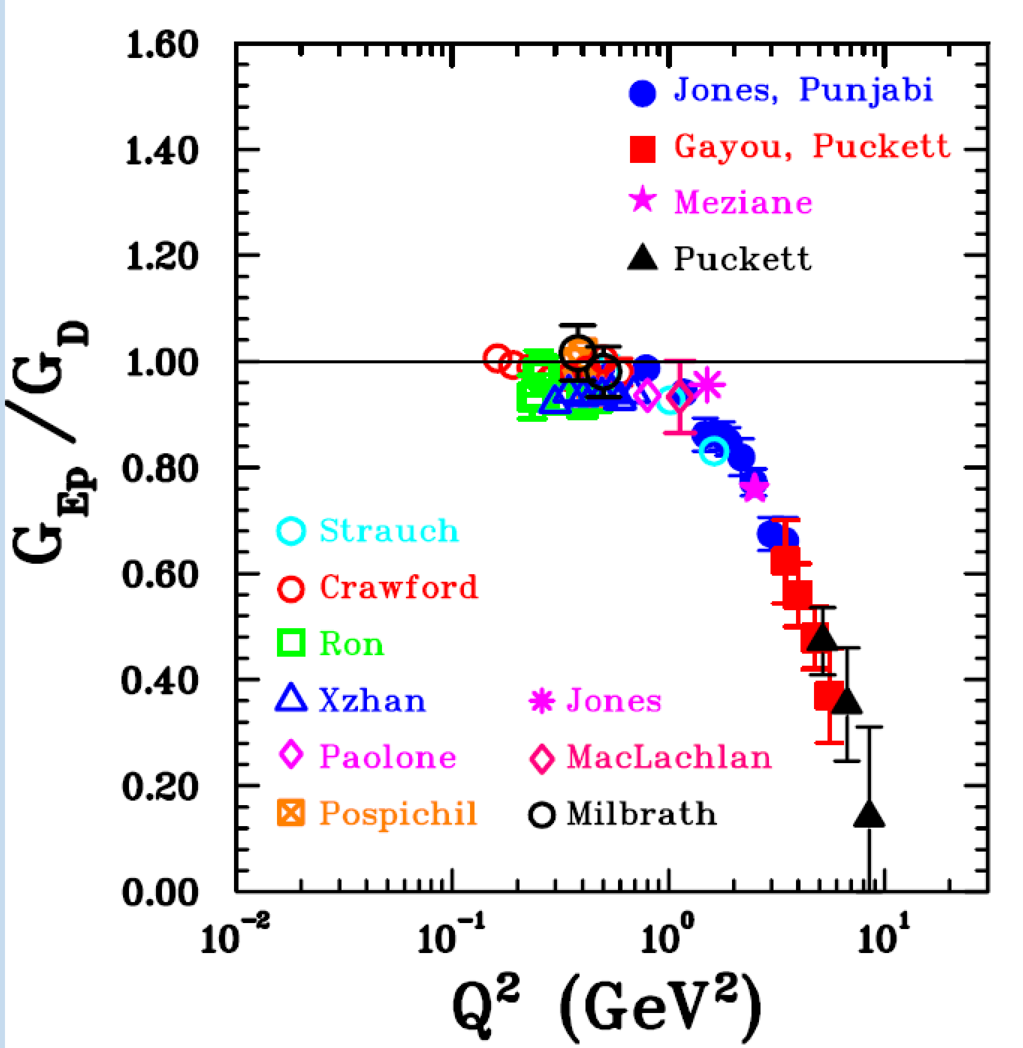
4. Elastic *ep* scat. in 1-10 GeV^2 in non-perturbative QCD realm; Dynam. Chiral Symm. Breaking has visible effects. (C. Roberts)

5. Di-quark structure of the nucleon has observable consequences (I. Cloet and C. Roberts e.a)

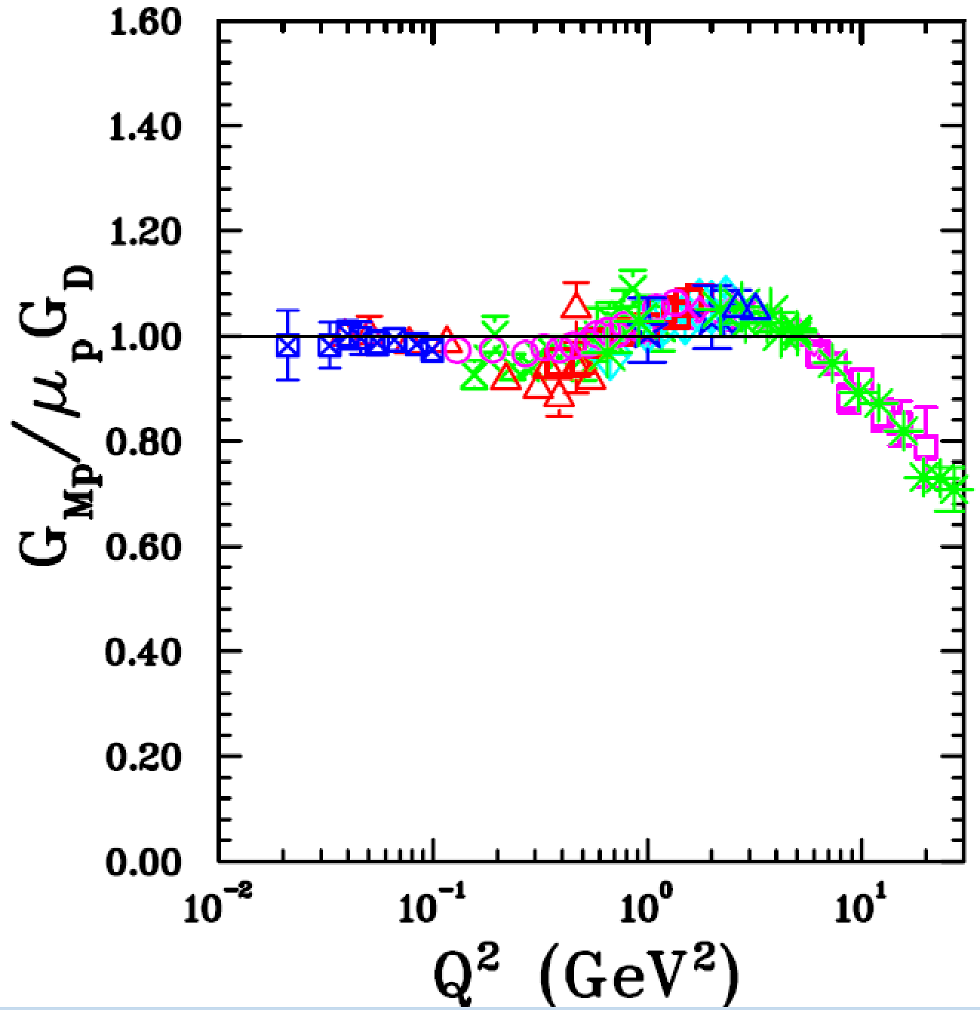
6. Obtain flavor separated dressed quark form factors: different for *u* and *d* quarks.

"Best" knowledge of G_{Ep} and G_{Mp}

Recoil polarization



Rosenbluth



“Patience et longueur de temps font plus que force ni que rage”

dans la fable du Lion et du Rat,

de Jean de la Fontaine, 1621-1695

Patience and length of time achieve more than force or rage

Sachs FF: $F_{1p,n}$ and $F_{2p,n}$ from Kelly-like polynomial fits to G_{Ep}, G_{Mp} and G_{En}, G_{Mn}, as in Punjabi et al EPJA (2015) 51: 79

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