An Unexpected View of the Structure of the Proton from JLab

The 2017 Jefferson Science Associate (JSA) Outstanding Nuclear Physicist Award Talk

Charles F. Perdrisat
College of William and Mary emeritus
June 21, 2017

The Jefferson Lab physics results I will show here were obtained by a large collaboration, lasting from the late 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; and has never stopped being involved and an inspiring guide in this long lasting effort.

Mark Jones, Ed Brash and Lubomir Pentchev were crucially involved in this work from the very beginning. The graduate students of these experiments, were G. Quemener, O. Gayou, A. Puckett and M. Meziane and W. Luo.

The support of JSA, Jefferson Lab and William and Mary, and grants from NSF and DOE, are thankfully acknowledged.

Needless to say that without the work of Charles Sinclair, these experiments would not have happened.

INTRODUCTION

The physics to be discussed here is centered about the elastic form factors of the proton.

What are "nucleon elastic form factors" in *$ep \rightarrow e'p'$?*
How do they inform on the structure of the proton?
How are they measured?
Traditionally : cross section: Results
New method: polarization transfer or asymmetry: Results
What have we learned?

The title of our proposal for the first G_{Ep} experiment at CEBAF , in 1993 was

"Electric form-factor of proton by **recoil polarization**"

Hofstadter (1961 Nobel) introduced the notion of form factor for electron scattering in terms of the diff. cross section:

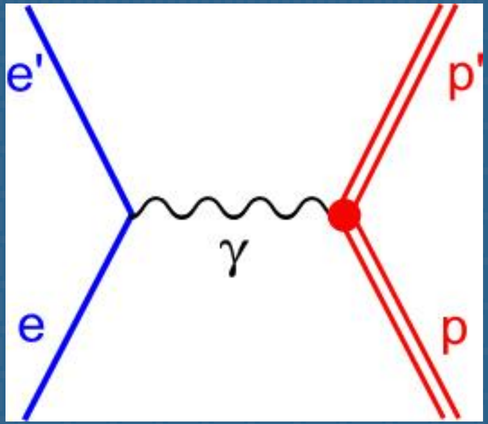
$$\sigma=\sigma_{Mott}\left|\int_{volume}\rho(r)\exp(iq.r)dr\right|^2=\sigma_{Mott}\,|F(q)|^2,$$

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

F(q), the form factor, is Fourier transform of charge distribution.

In lowest order, elastic *ep* scattering proceeds by exchange of one virtual photon, or OPEX.

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



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

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

F_1 (Dirac): electric charge and Dirac magnetic moment,

F_2 (Pauli): anomalous magnetic moment $\kappa_p=\mu_p-1$; induces a spin flip.

Cross Section

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

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

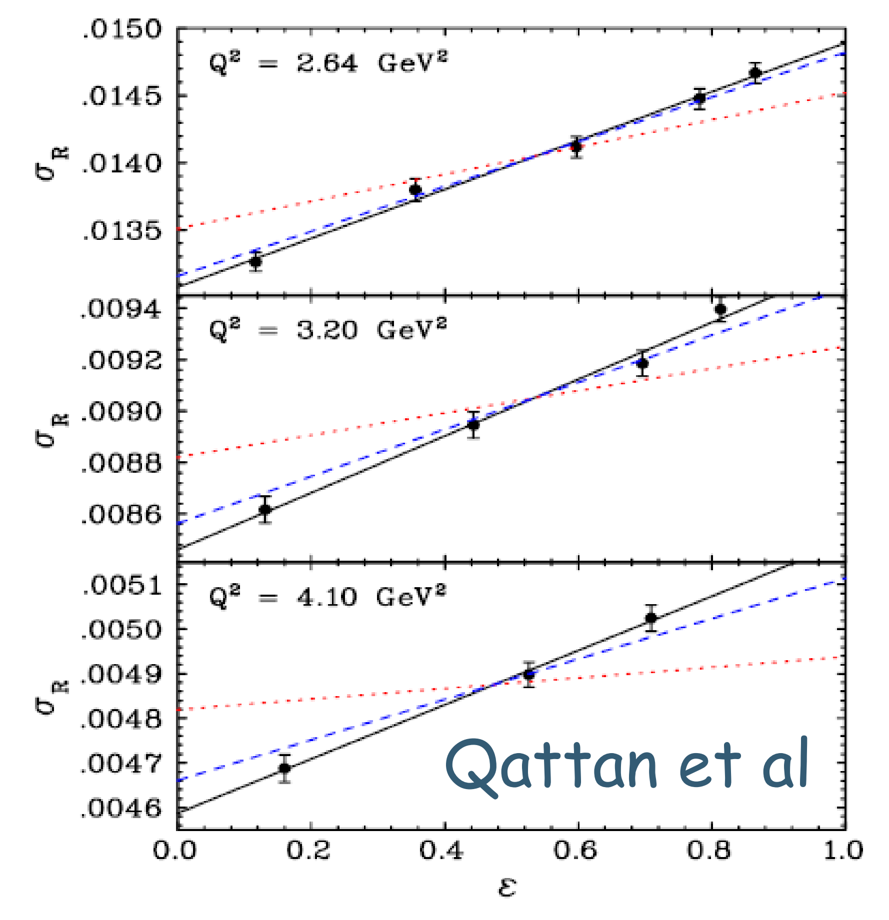
with $\varepsilon = [1 + 2(1+\tau)\tan^2(\theta_e/2)]^{-1}$

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

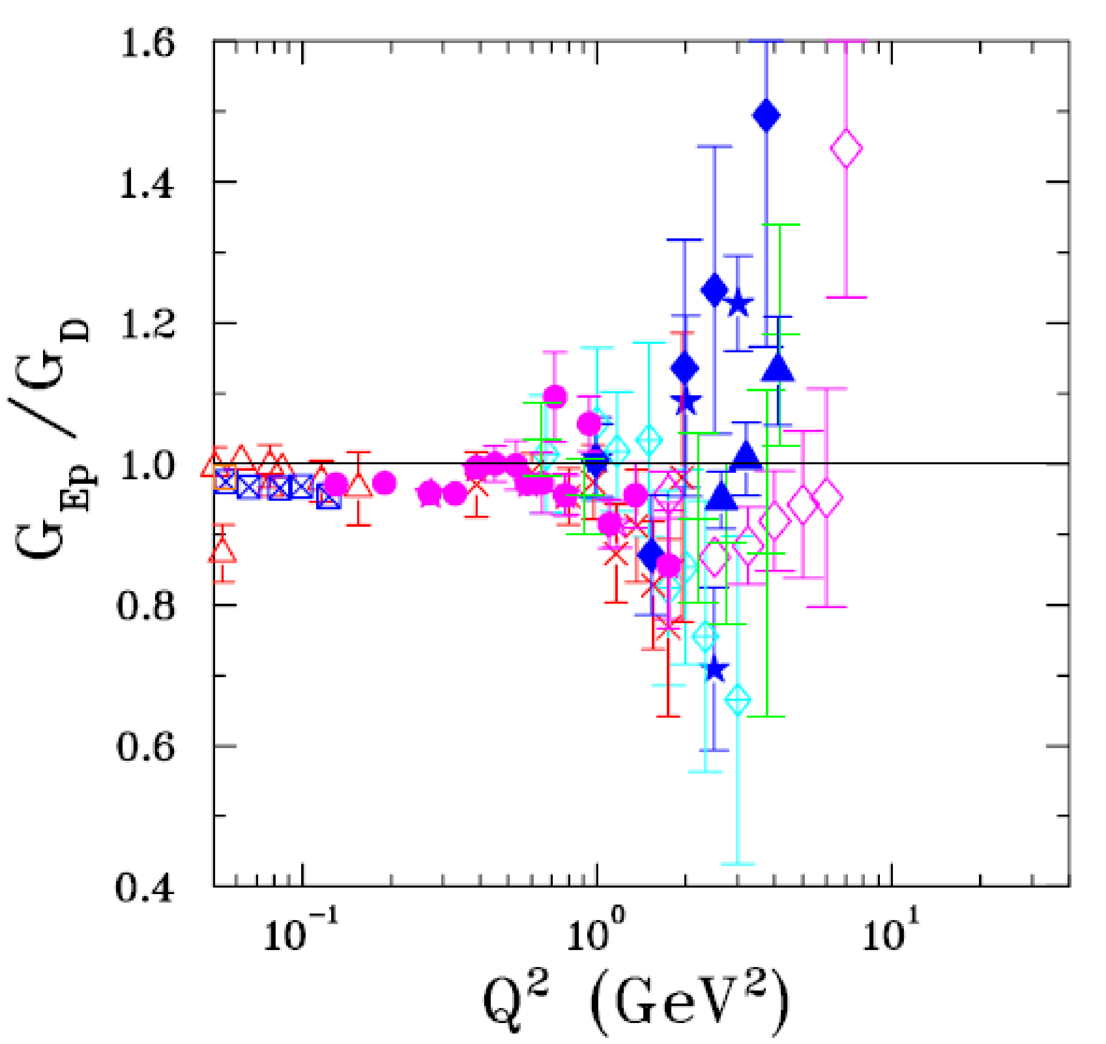
$(d\sigma/d\Omega)_{Mott}$ for massless e^- and point-like target of spin ½.

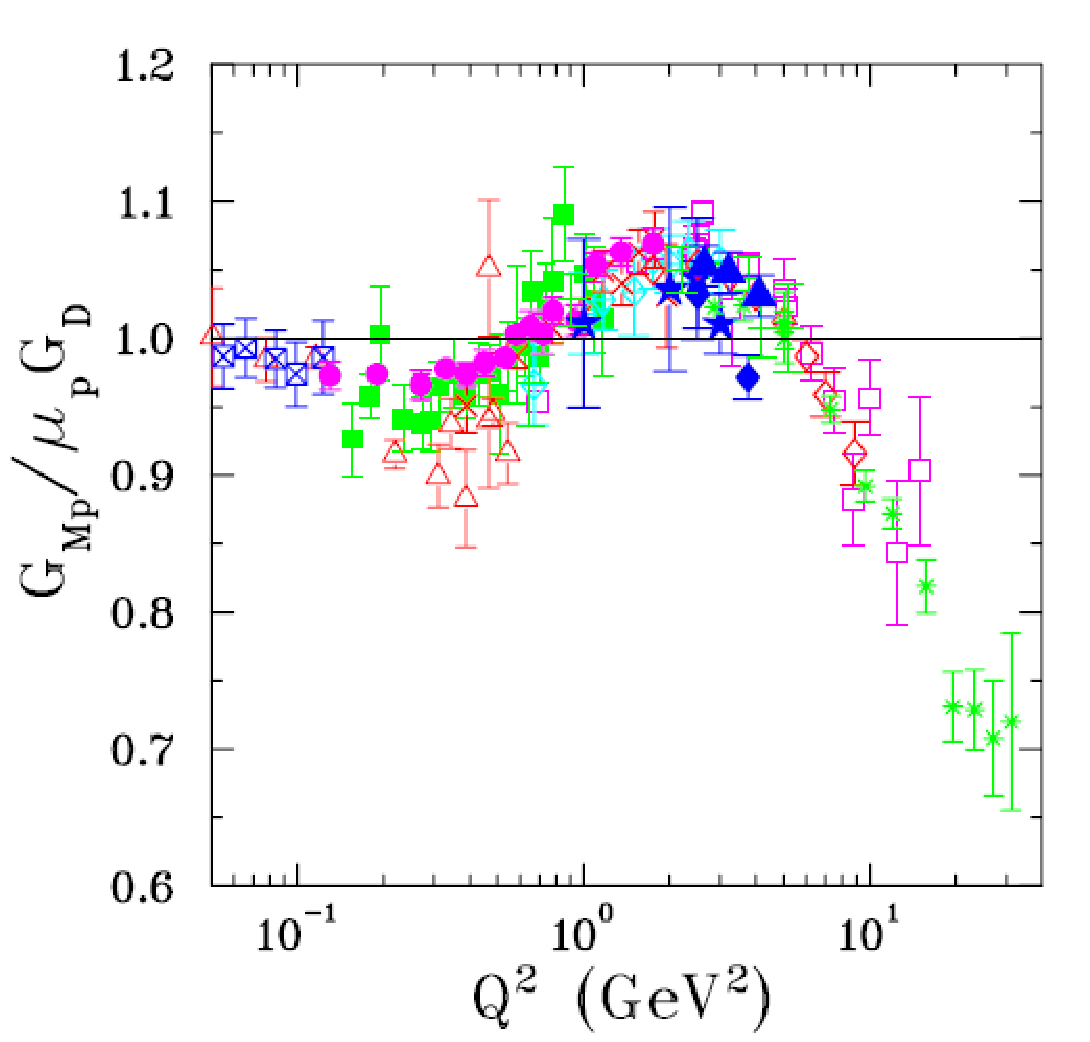
Rosenbluth separation

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



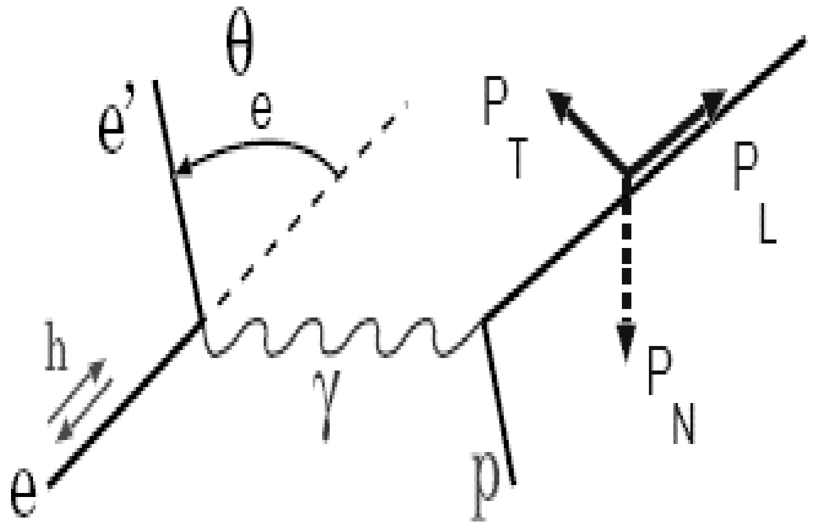
By the 1990's G_{Ep} and G_{Mp} showed stability, both G_{Ep}/G_D and $G_{Mp}/\mu_p G_D$ ≈ Q^2-independent, with $G_D=(1+Q^2/0.71)^{-2}$ the dipole form factor.





Recoil Polarization Observables in OPEX

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



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

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

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

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

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

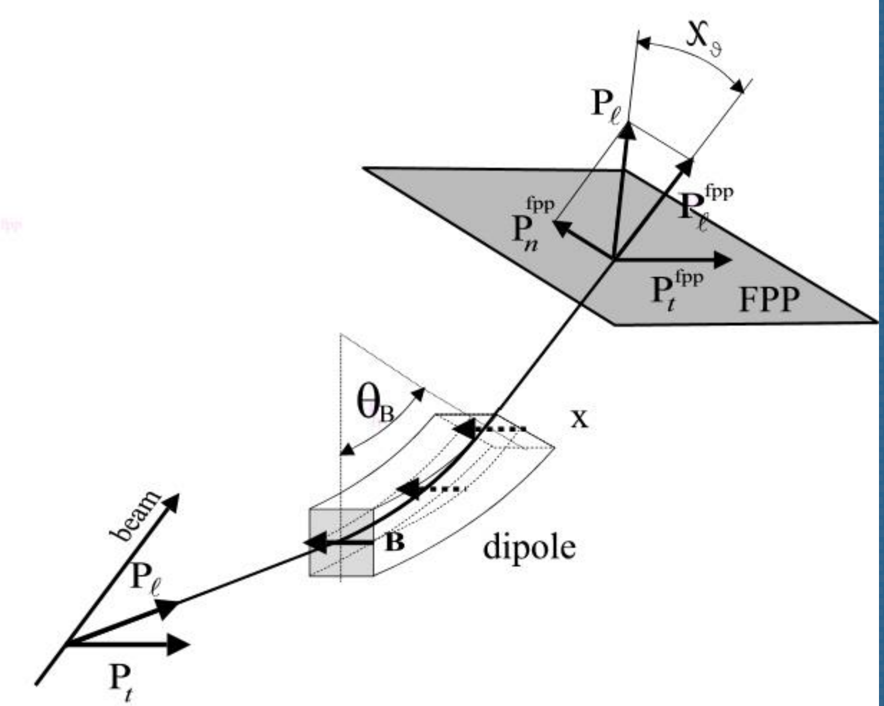
most importantly, it is G_E and G_M which are measured, not G_E^2 and G_M^2.

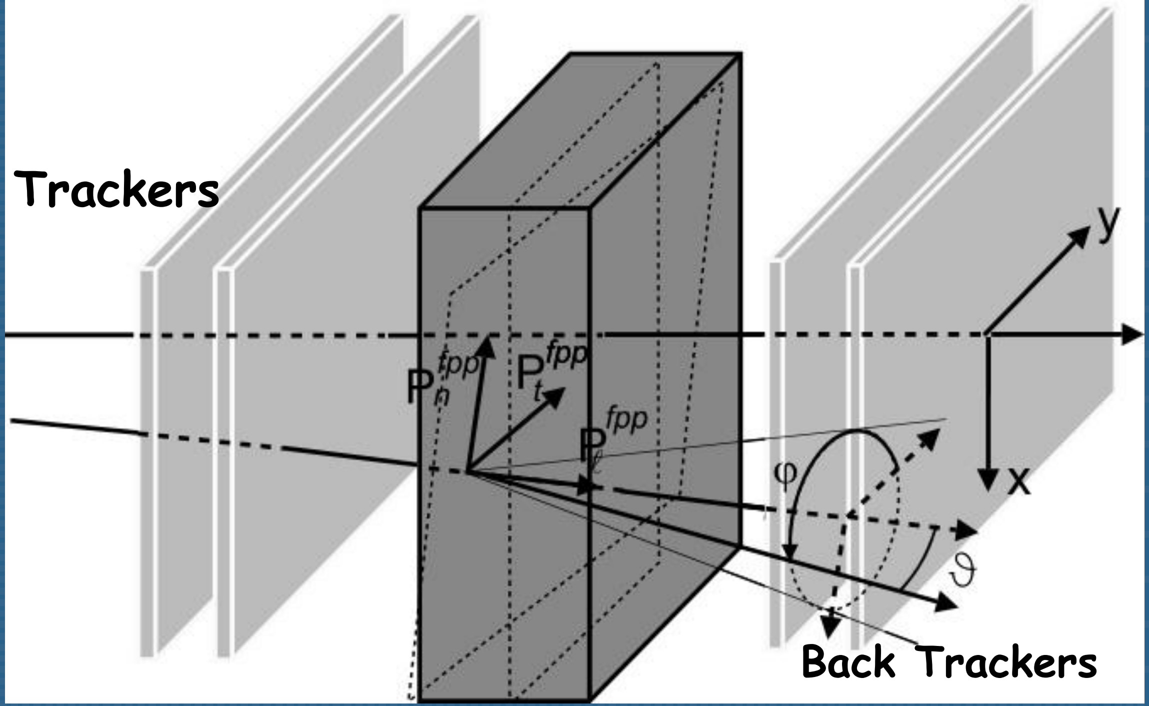
In a first proposal (Perdrisat and Punjabi, 1989), we aimed at getting P_t and P_ℓ, then P_t/P_ℓ and use the good G_{Mp} data base to get G_{Ep}. In a second submission (1993) we proposed to obtain G_{Ep}/G_{Mp} directly from P_t/P_ℓ, resulting in significantly smaller uncertainties, both statistical and systematic. It proved to be the best way to proceed.

Measuring the polarization ratio cancels the radiative corrections, requires no knowledge of the analyzing power of the reaction, and cancel many other fluctuating effects like beam polarization, target density, detector efficiencies, and more.

Little did we expect to get G_{Ep} at Q^2 of 8.5 GeV^2, in spite of the fact that it contributes only one part in 1000 to the cross section.

Spin Precession & Focal Plane Polarimeter





CH_2 Analyzer

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

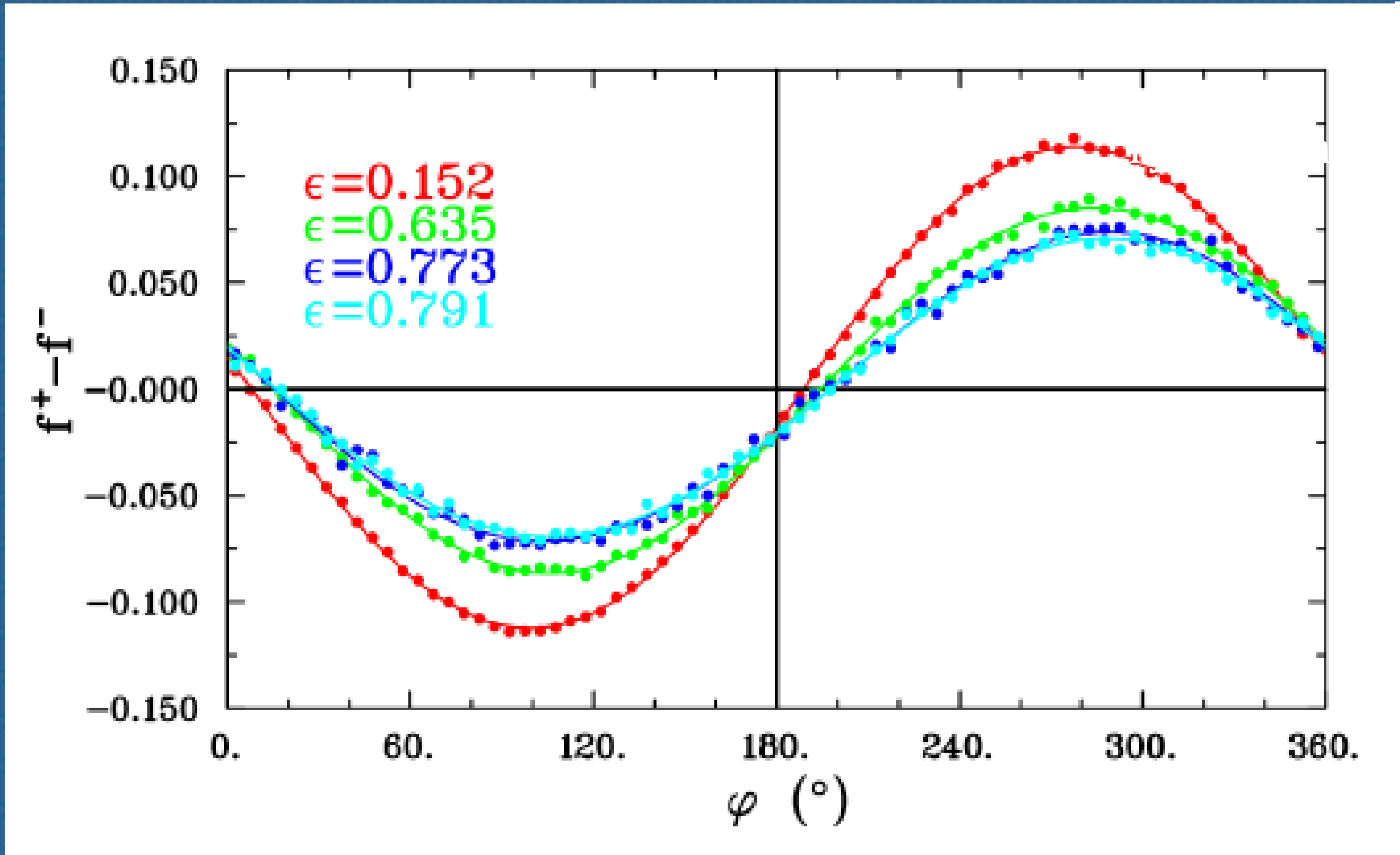
$$f^{\pm}(\vartheta,\varphi) = \frac{\epsilon(\vartheta,\varphi)}{2\pi}\{1 \pm A_y(\vartheta)(P_t^{fpp}\cos\varphi - P_n^{fpp}\sin\varphi)\}$$

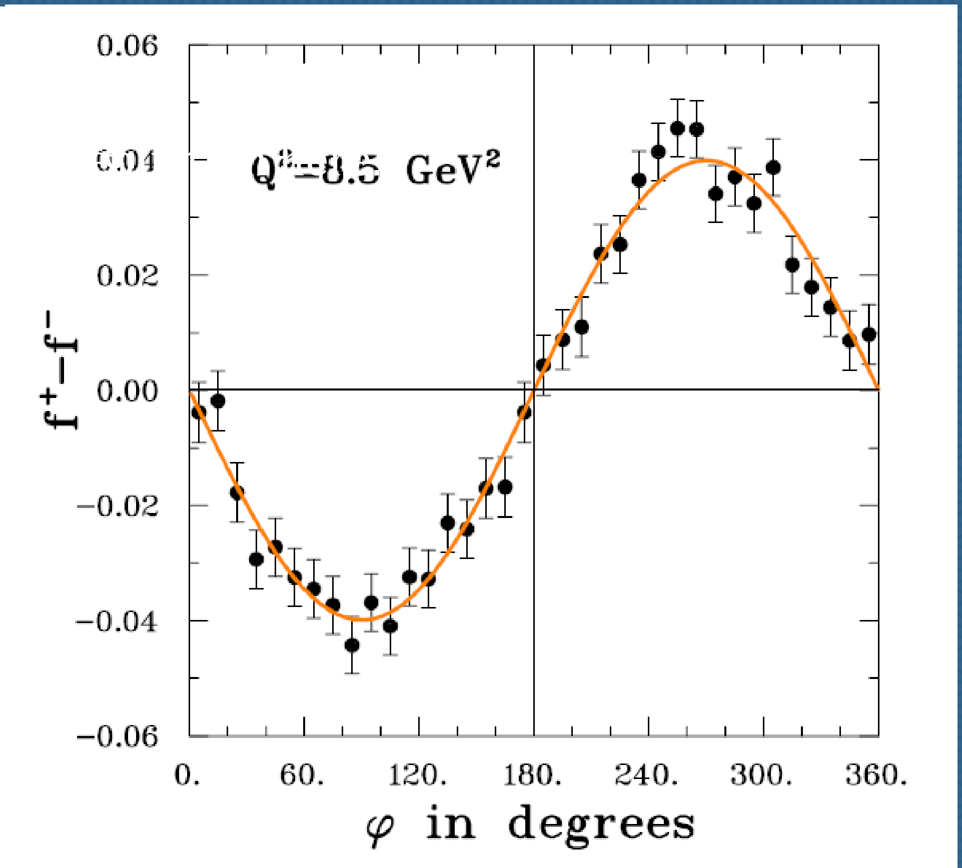
Measure azimuthal asymmetry difference by flipping beam helicity

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

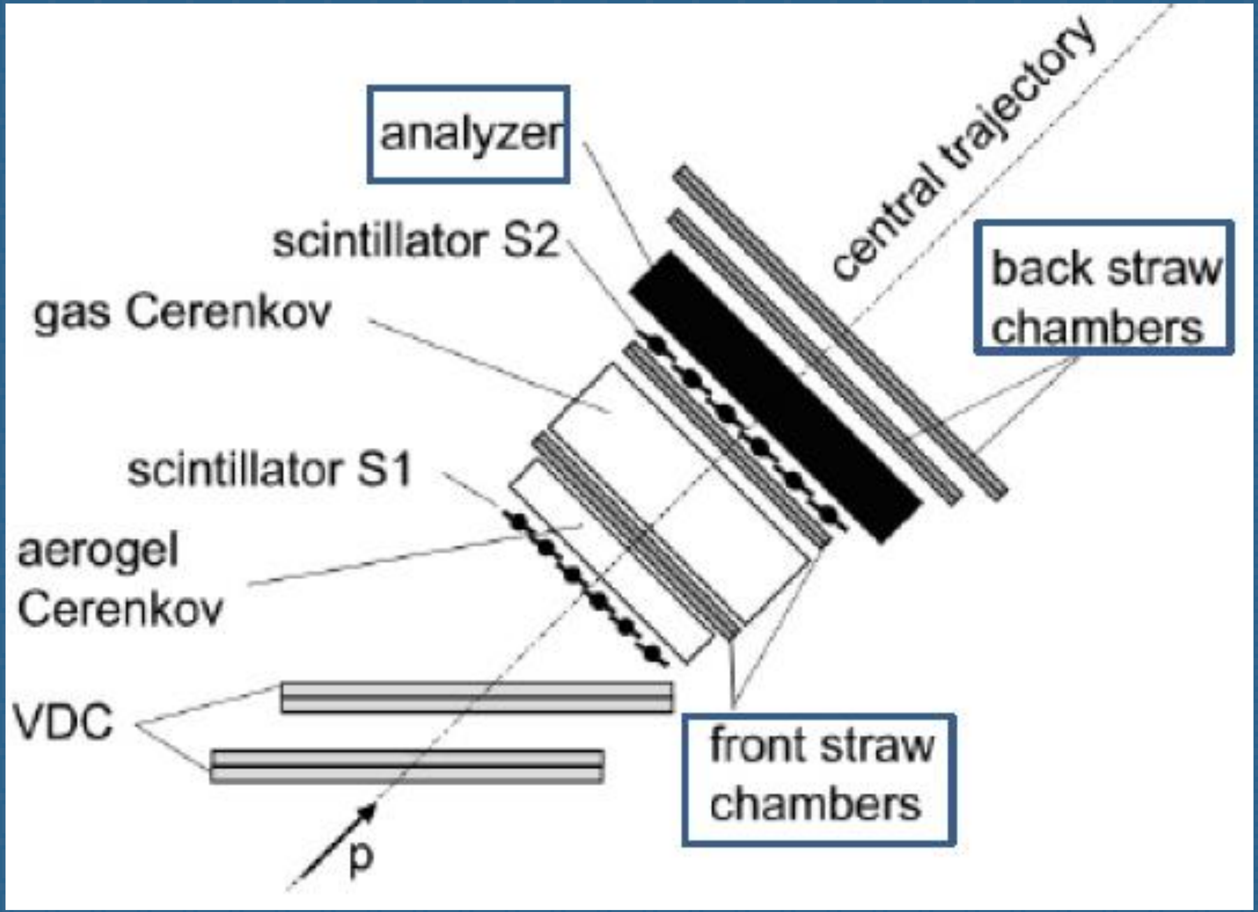
Left, Q^2=2.5 GeV^2, M. Meziane et al, P.R.L. 106, 132501 (2011)

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

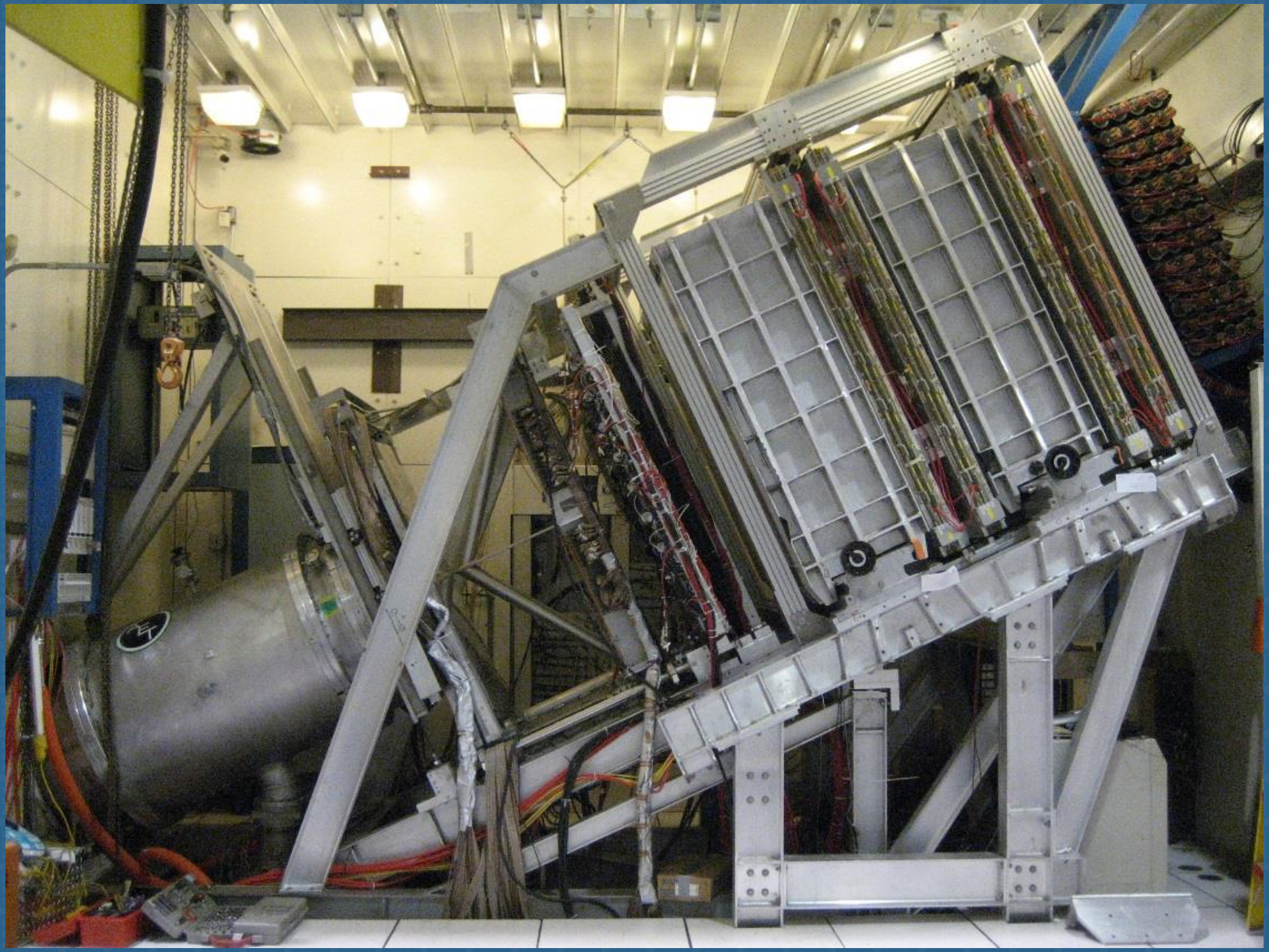


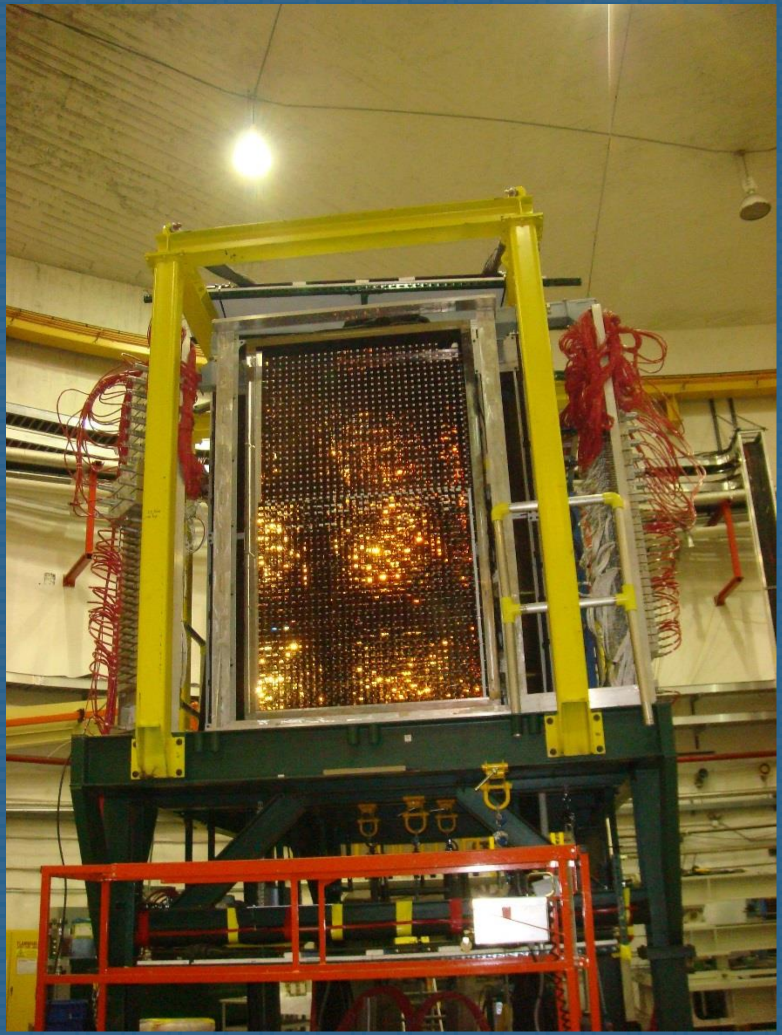


First polarimeter in Hall A HRS used drift tubes for tracking the recoil proton.
Front drift tube chambers built by WM undergrads, grad-students, postdocs:
1056 drift tubes in each chamber! Back chambers built at Rutgers.
Scattered electron detected in coincidence, in second Hall A HRS: GEp(1).

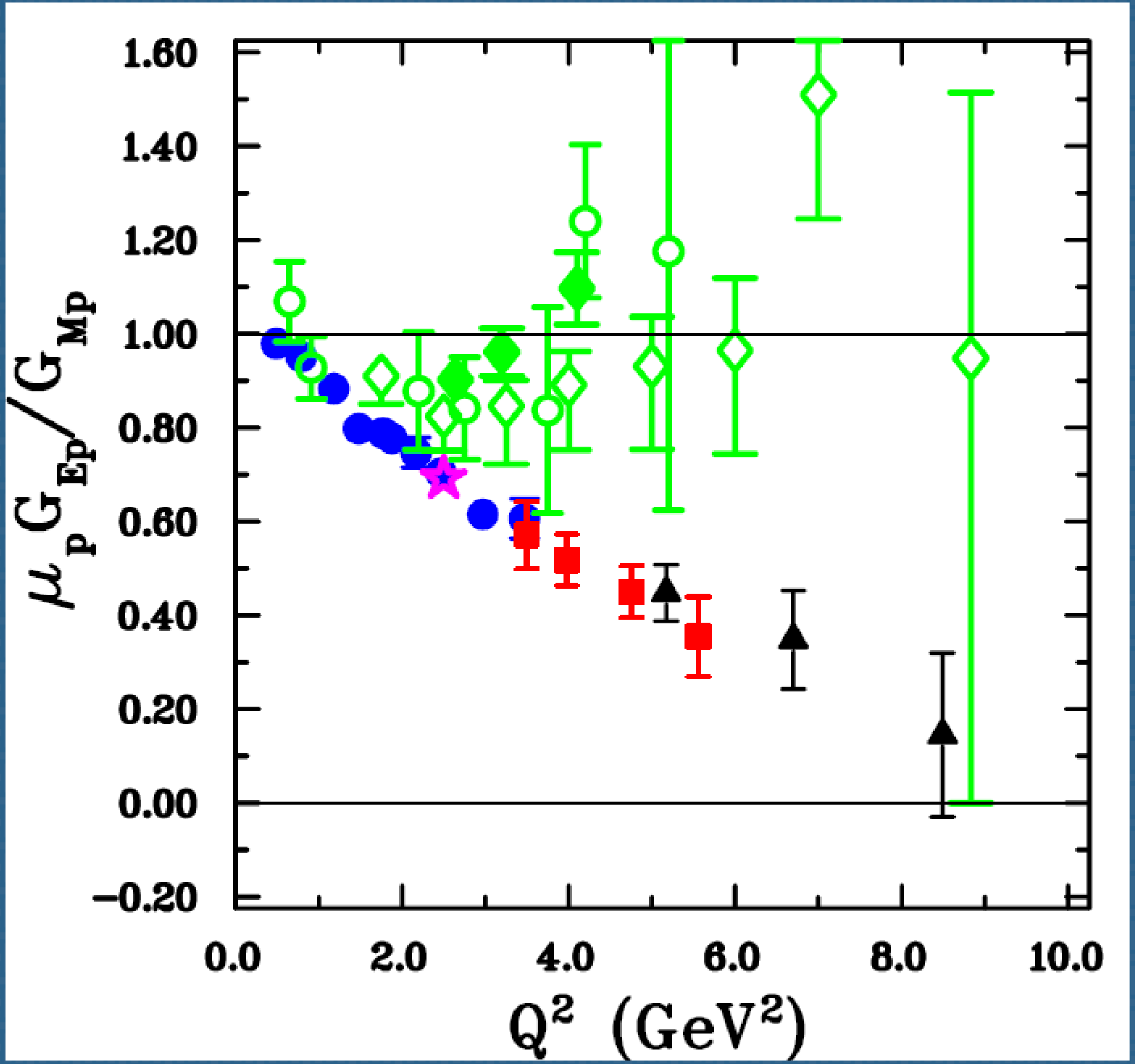


For third experiment, (GEp3), double polarimeter with drift chambers made in Dubna (Y. Zanevsky), installed in focal plane area of the hall C HMS.
Also electromagnetic calorimeter built with 1744 lead glass bars from Protvino (A.Vasiliev) and Yerevan.





Following GEp(1), GEp(2), GEp(3) and GEp(2γ) in 1998-2008, form factor ratios from Jlab differ drastically from Rosenbluth (green): Andivahis, Christy, Qattan.

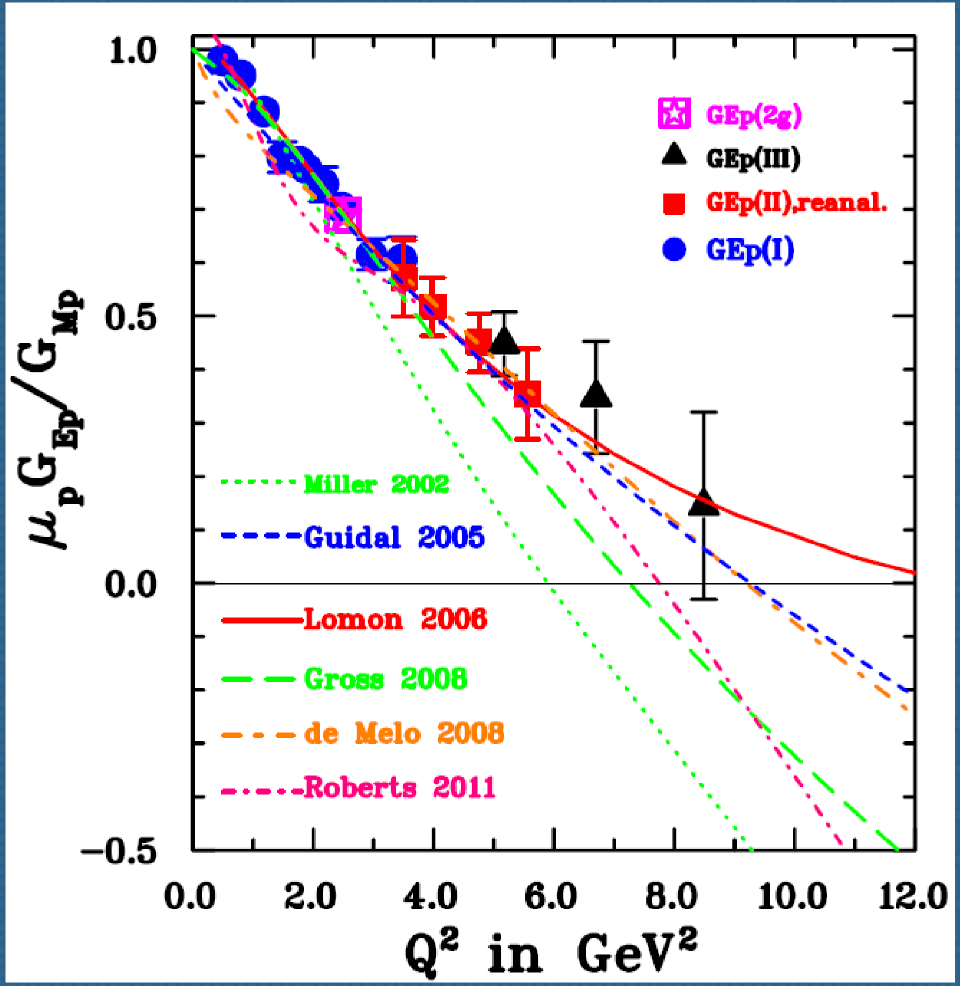


Blue, red, black and magenta: GEp(1 to 3 and 2ϒ).

Rosenbluth cross sections are corrected for radiative effects; up to ~30% at larger Q^2.

No significant radiative corrections for polarization ratio required at the ~% level. (A.V. Afanasev et al, P.L. 514 (2001) 269).

Overall Picture



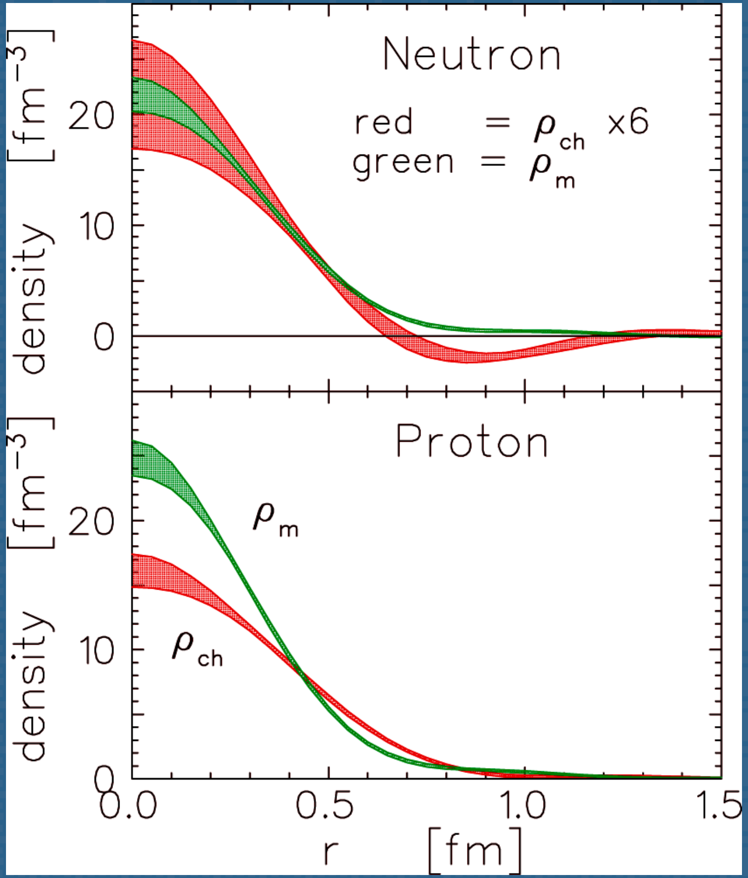
VMD-based models describe all four nucleon *FF'*s well (Lomon, Iachello, Bijker)

rCQM show importance of relativistic dynamics, allow to separate dynamical from nucleon structure effects (Chung & Coester, J. Miller, F. Gross, de Melo and many others).

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

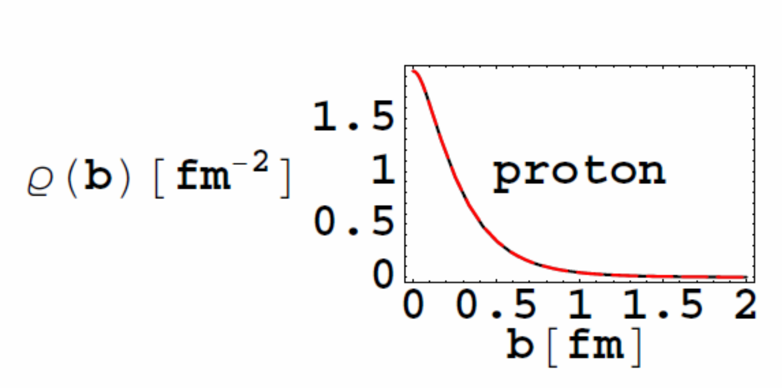
Generalized Parton Distribution related to form factors

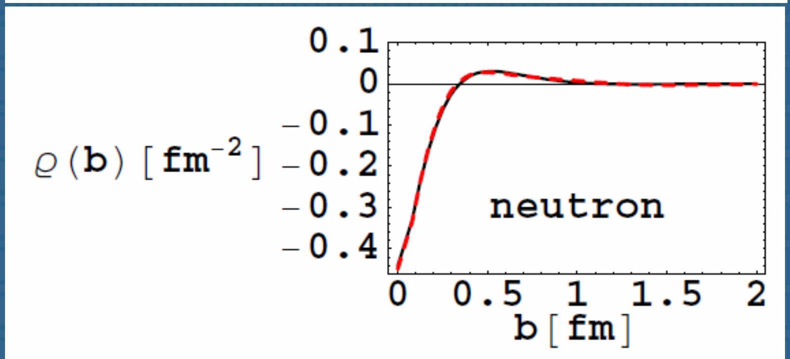
Impact of the results



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

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



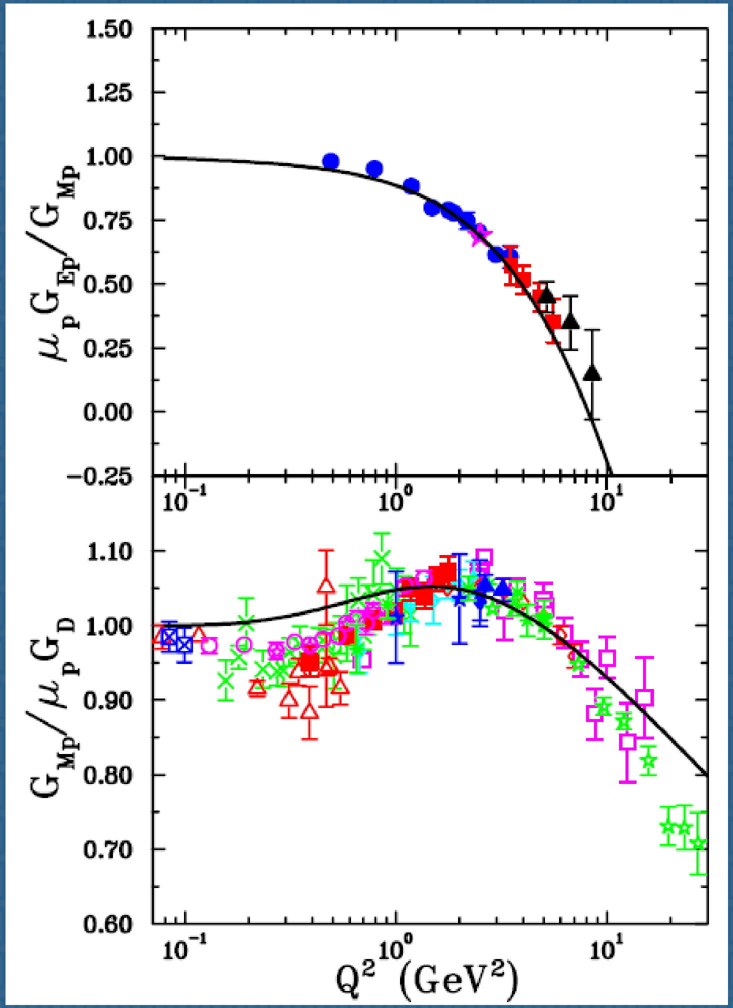


Kelly performed simultaneous fits to all 4 form factors in Fourier transform including relativistic effects required by the use of the Breit frame of reference.

In the infinite momentum frame, transverse charge density ρ(b) is a relativistic invariant, and 2-dimensional 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



The first moments of Generalized Parton Distributions from deeply virtual Compton scatt. related to the 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.

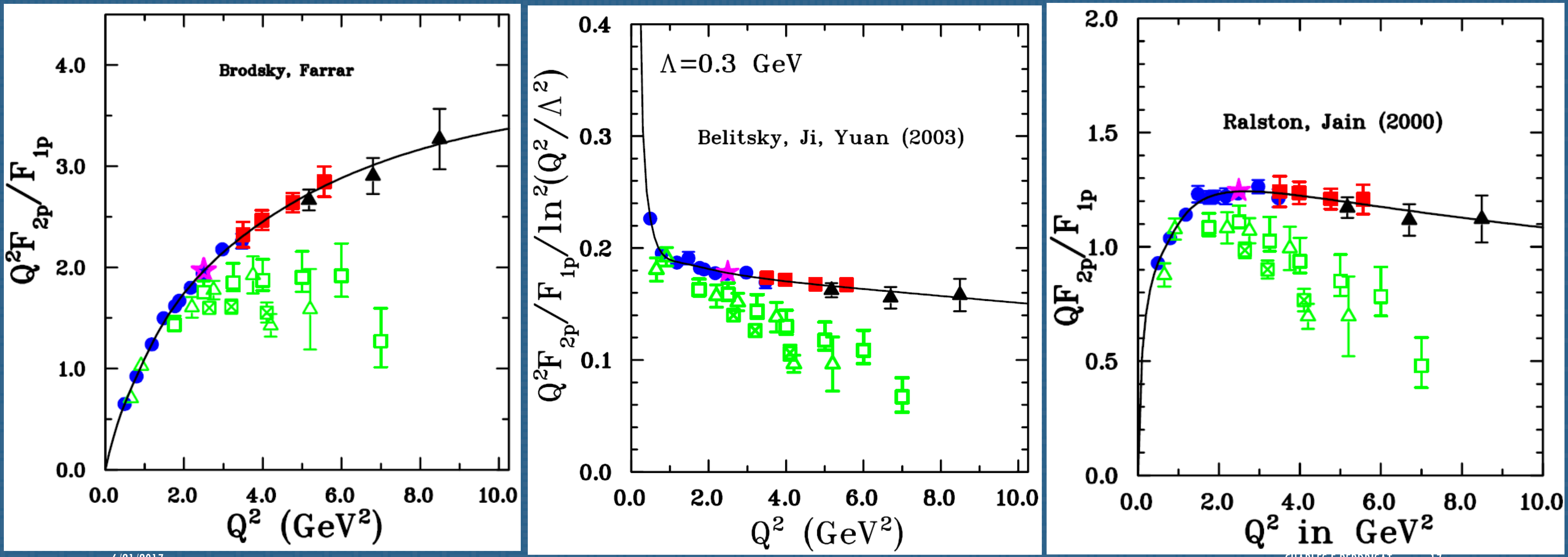
H and E are quark correlation functions; emission, re-absorption of a quark in non-perturbative realm

Curves shown from Regge parametrization for H and E from Guidal et al., (2005)

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

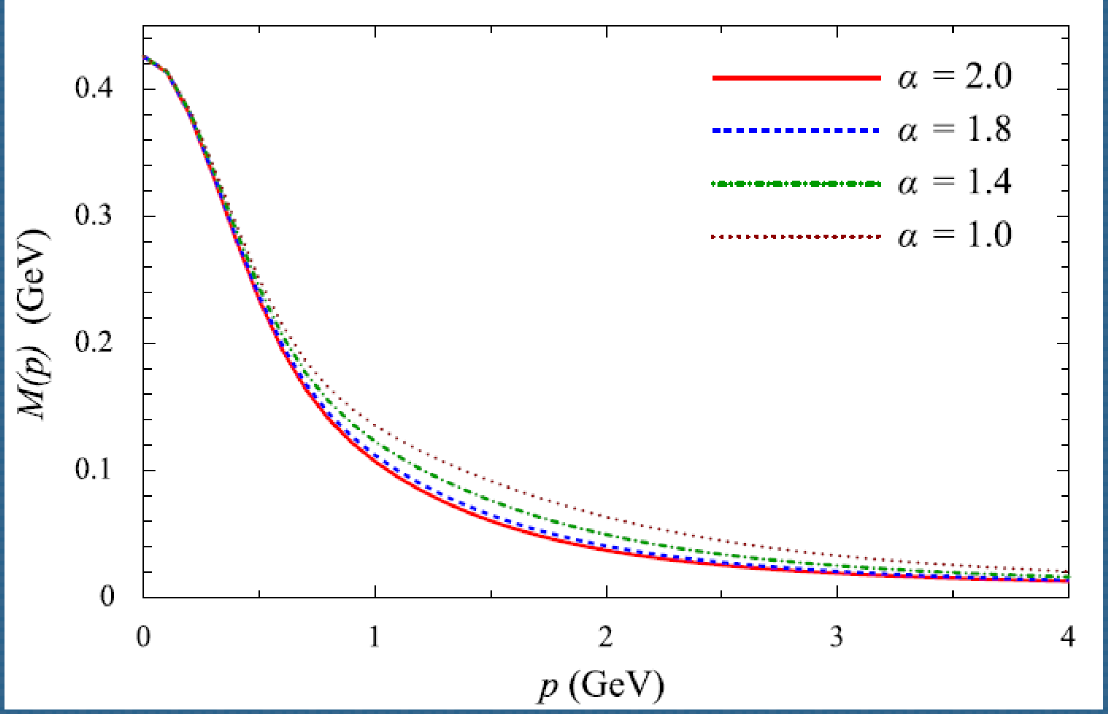
Perturbative QCD for F_2/F_1, Brodsky and Farrar (1973)

At high momentum transfer, 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 $\alpha\ 1/Q^2$: $F_1 \approx (1/Q^2)^2$. $F_2 \rightarrow$ helicity flip, $\approx 1/Q^2$, so $Q^2F_2/F_1 \approx$ constant. Polarization ratio data do not support this prediction.

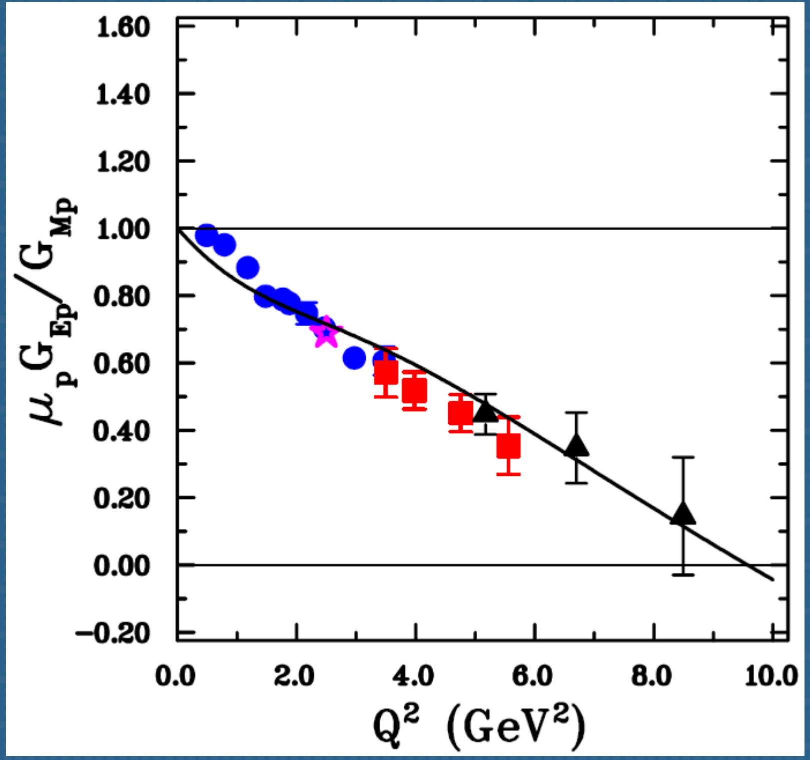


Elastic *ep* scattering in 1-10 GeV^2 Q^2 range is in domain of non-perturbative QCD. Dressed quarks are consequence of Dynamical Chiral Symmetry Breaking. (Craig Roberts e.a. PRL 111 (2013)) and described by Dyson-Schwinger equations.

The quarks-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. If mass evolution regulated by damping factor α in dressed quark propagator, then if $G_{Ep} \rightarrow 0$ near 10 GeV^2 then $\alpha \approx 2$.



C.D. Roberts, J. Segovia
arXiv 1408.2919
Private comm. 2017



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 *ff* obey

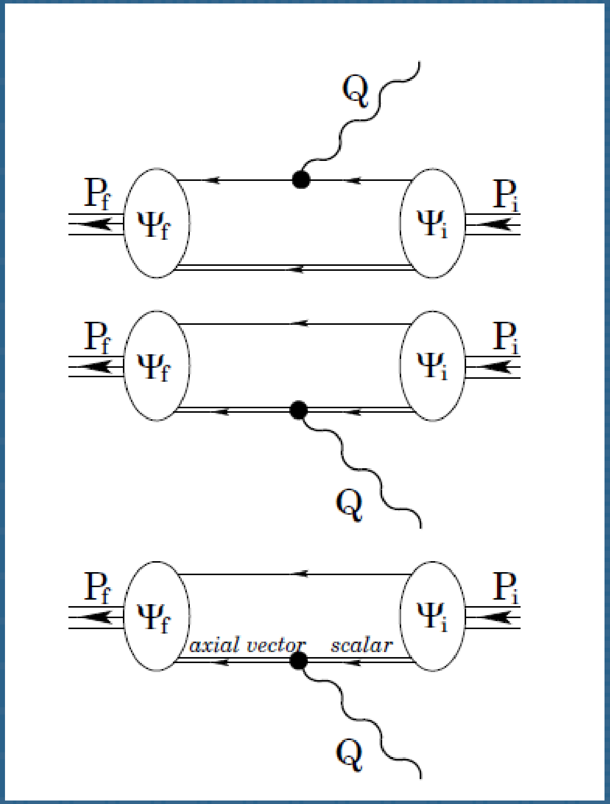
$$f^u_{1(2)p} = f^d_{1(2)n} \qquad f^d_{1(2)p} = f^u_{1(2)n}$$

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

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

See: 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

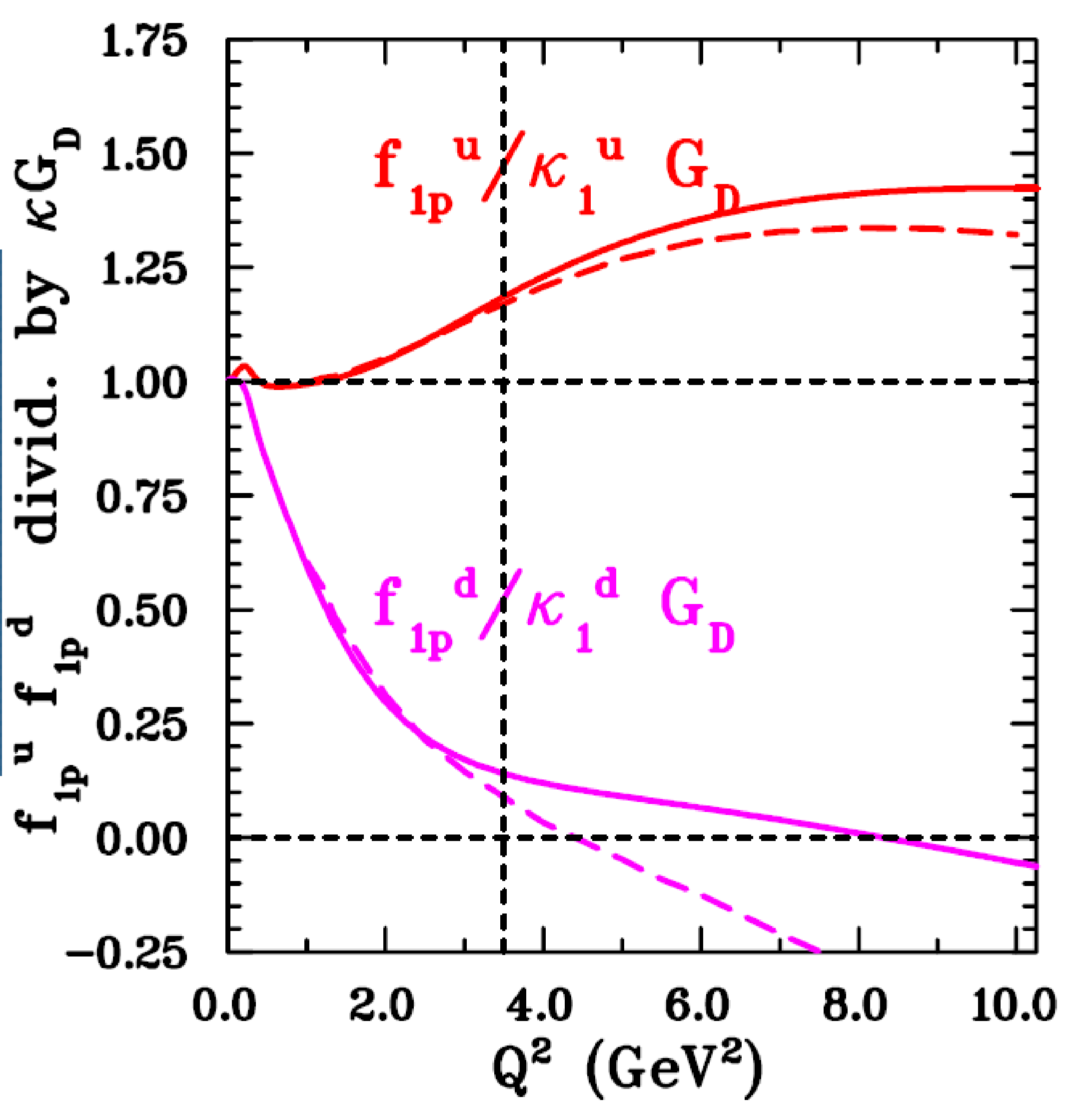


Wilson, Cloët, Chang, Roberts, Phys. Rev. C 85, 025205 (2012).

Solid lines for polynomial fits to nucleon FF

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

Dashed lines for Dynamical Chiral Sym. Breaking prediction



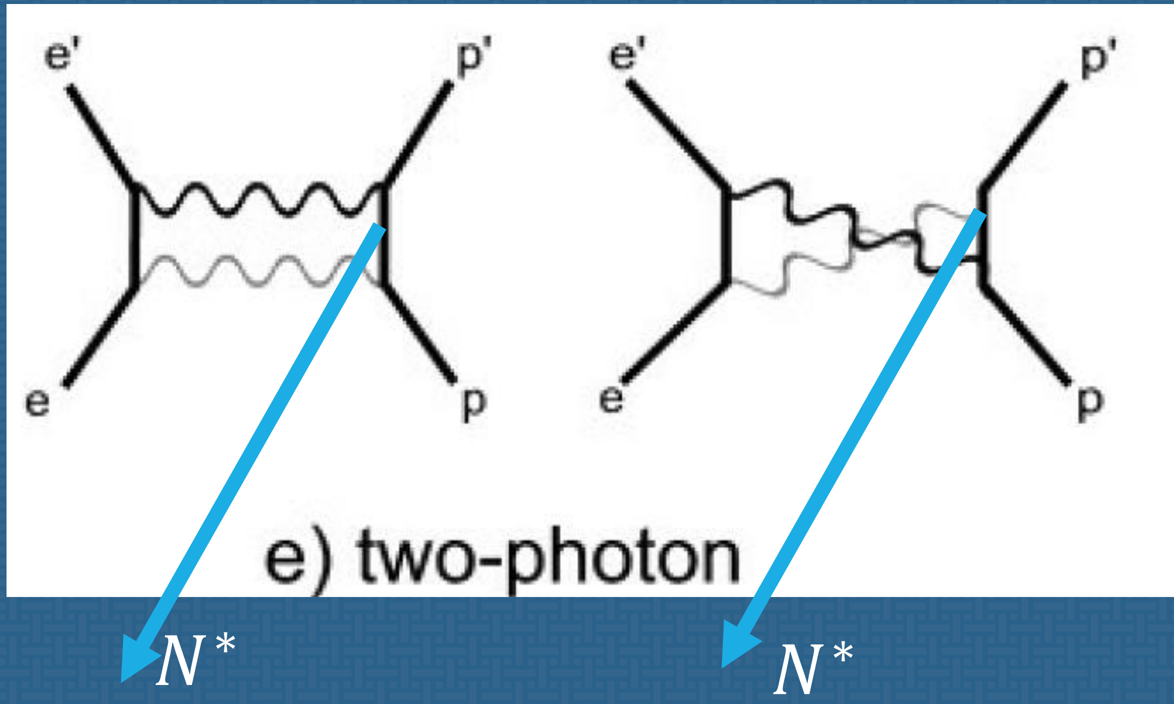
Is there an explanation for the "dramatic" difference between the results of the 2 types of experiments: Rosenbluth and Polarization?

Results of both types obtained within OPEX approximation.

Guichon and Vanderhaeghen, (2003)

Contribution of two-photon exchange, TPEX, must be evaluated, or better, measured.

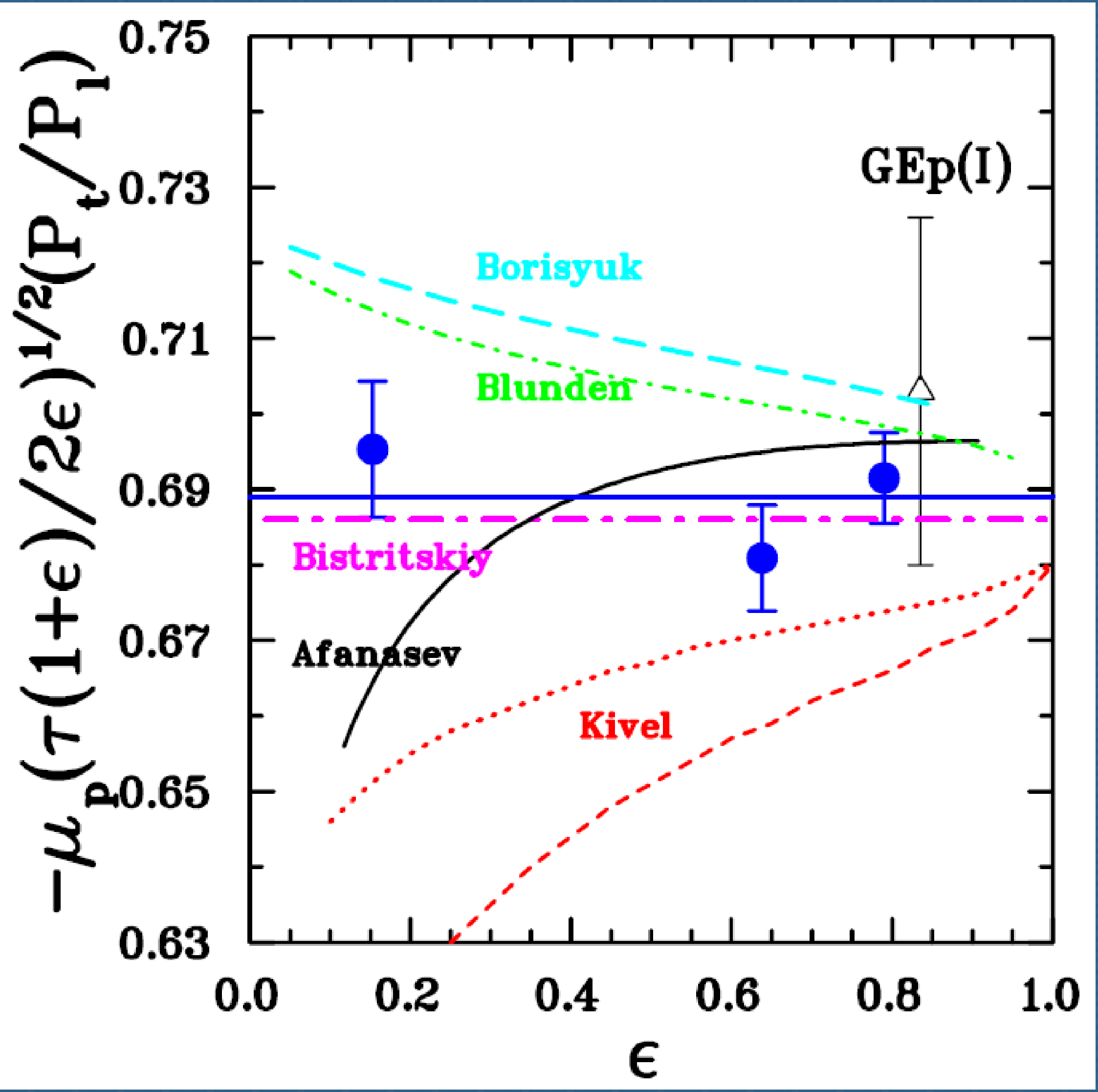
Difficult to calculate: virtual nucleon can be any excited baryon.



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

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

At Jefferson Lab the $G_{Ep}(2\gamma)$ 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 extremely small error bars (~1 %).



Average $\mu G_{Ep}/G_{Mp}$=0.6884±0.0041 (to better than 1%)

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 $\mu G_{Ep}/G_{Mp}$ in the absence of a 2-photon effect

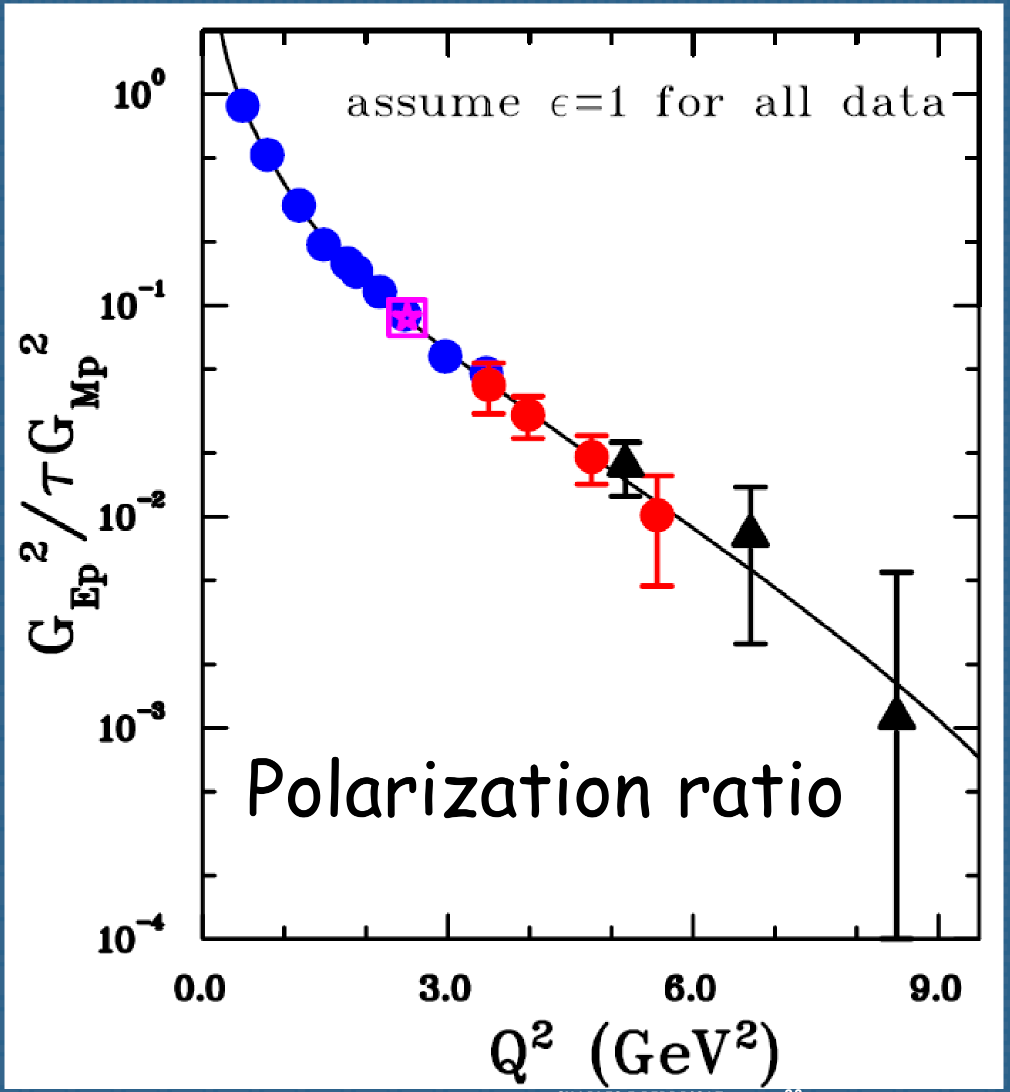
Is there a physical reason for the "difference", or are we seeing the limit of sensibility to G_{Ep} of cross section data?

Rewrite cross section in terms of G_{Mp}, assuming G_{Ep} a perturbation (exact):

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

Then plot $\frac{\varepsilon}{\tau}\frac{G_E^2}{G_M^2}$ versus Q^2.

$\tau = Q^2/4m_p^2$ and ε kinematic factor



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The relative contribution of Rosenbluth G_{Ep} to the cross section differs from polarization experiments values above $Q^2 \approx 2\text{-}3.0\ GeV^2$.

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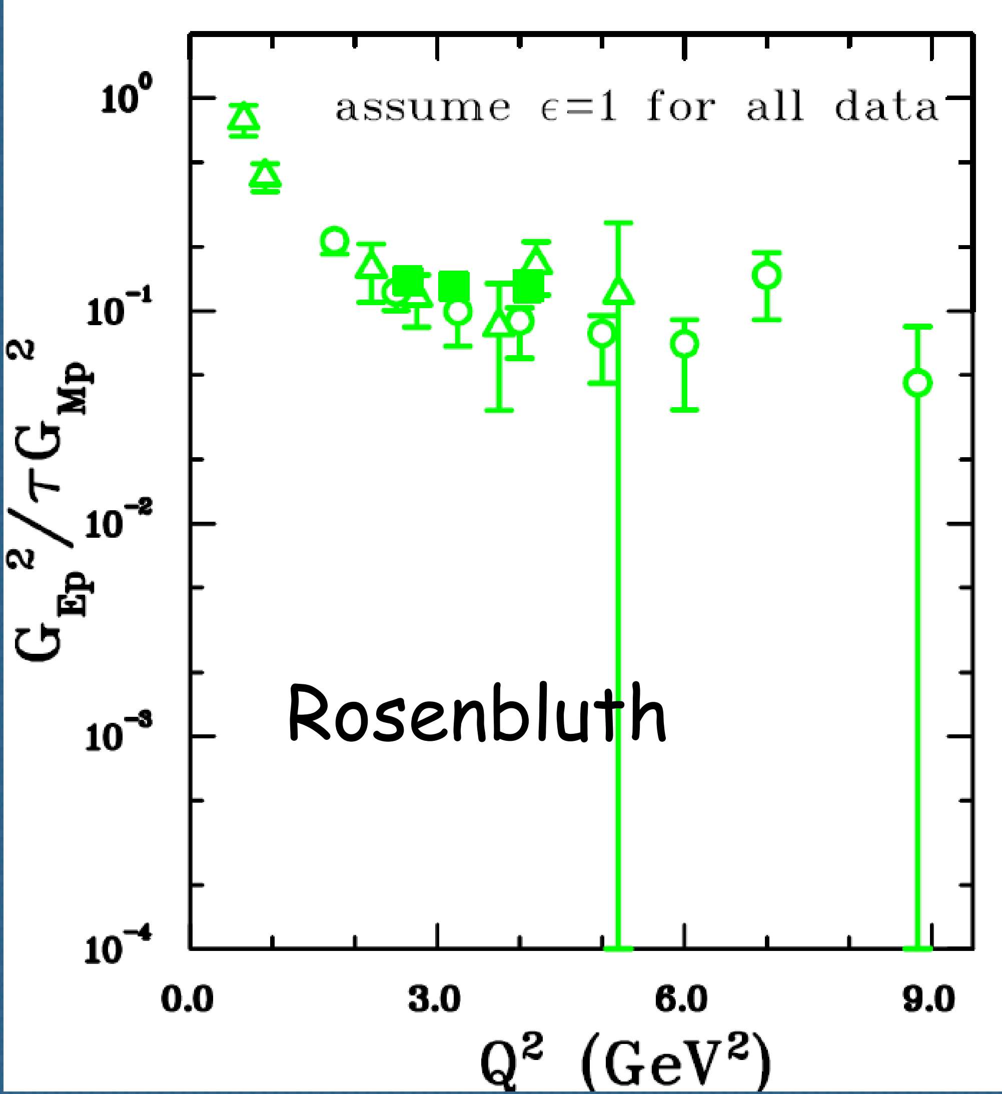
When $\frac{\varepsilon}{\tau}\frac{G_E^2}{G_M^2}$ plotted versus Q^2, cross section data stop decreasing for $\frac{\varepsilon}{\tau}\frac{G_E^2}{G_M^2}$ ~0.1.



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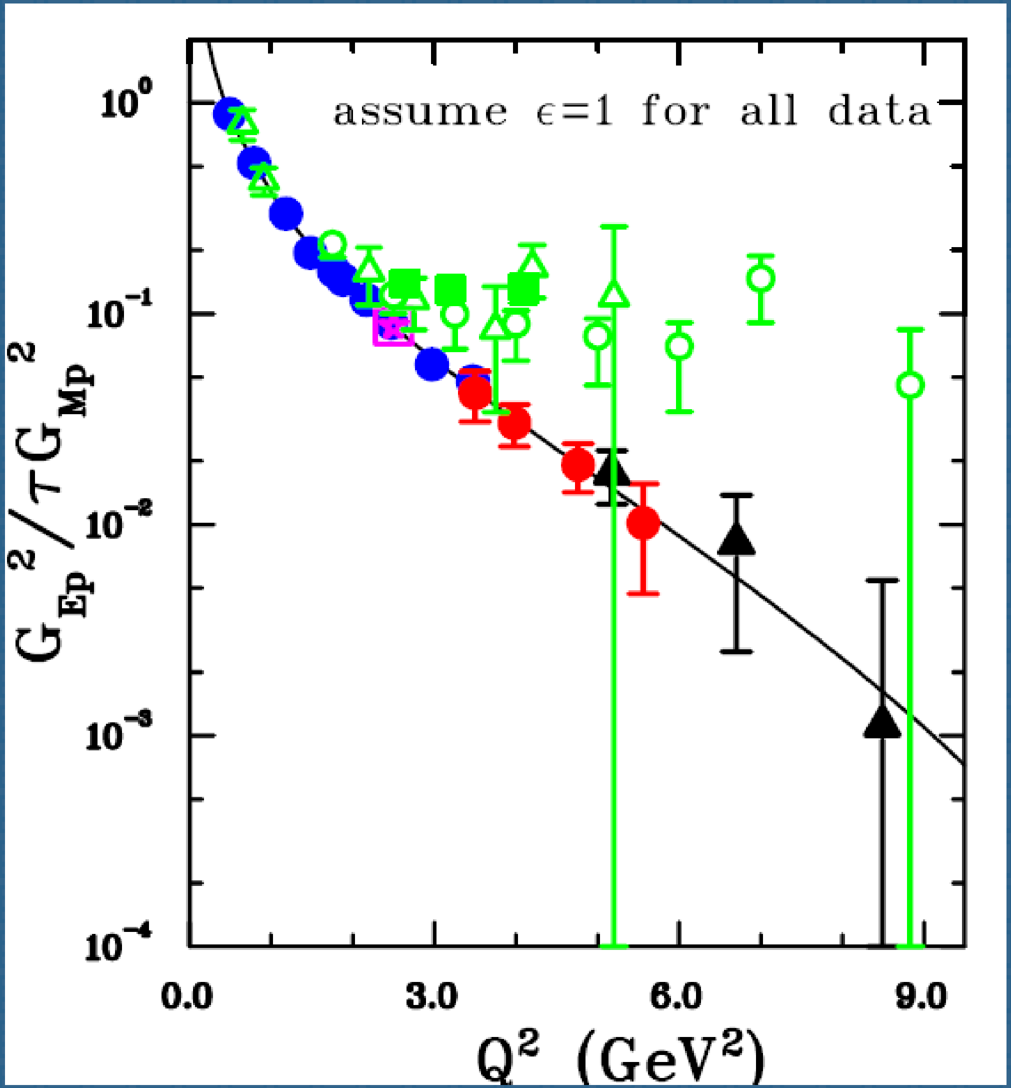

CONCLUSION

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 structure of the proton which resulted 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 it has been visited 35,754 times by June 20 2017

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.

The End

“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

Parametrization of Dirac and Pauli nucleon form factors

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

Notes: F_{1n} negative at Q^2~0 because G_{En}~0 and G_{Mn} is negative.
$F_{2n}/\kappa_n \sim F_{2p}/\kappa_p$,
neutron data are extrapolated beyond 3.5 GeV^2.

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

Alternately, can use prediction of Roberts et al for $\mu_n G_{En}/G_{Mn}$ shown next to "predict" the likely behavior of the dressed quark ff.