Search for Two-Hard-Photon Exchange in Elastic *ep*

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Introduction

How we "visualize" the proton has changed remarkably in the last 12 years.

A trigger to this change of "worldview" of the proton has been a series of experiments at Jlab, which established that the ratio of the elastic form factors, G_{Ep} and G_{Mp}, was not constant, but decreased systematically with the invariant mass squared, Q^2, of the virtual photon in *ep* scattering.

Why the different results?

…..Introduction

Cross sections are subject to large radiative corrections; these may not be accurate enough, or incomplete, having missed the two hard photon contribution in the past. Or may be not.

Radiative corrections are weak when the ratio G_{Ep}/G_{Mp} is measured directly, as in double polarization experiments. This is in contrast to cross section measurements, where G_{Ep}^2 and G_{Mp}^2 are measured.

Here will discuss aspects of elastic *ep* scattering, emphasizing need to determine experimentally the role of higher order radiative corrections and "what we know" we need to know.

The two methods to measure G_E/G_M

Cross section

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

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

$\tau=Q^2/4m_p^2$ with $Q^2=-m_\gamma^2$ $\quad \varepsilon=\dfrac{1}{1+2(1+\tau)\tan^2(\frac{\vartheta_e}{2})}$

Recoil polarization

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

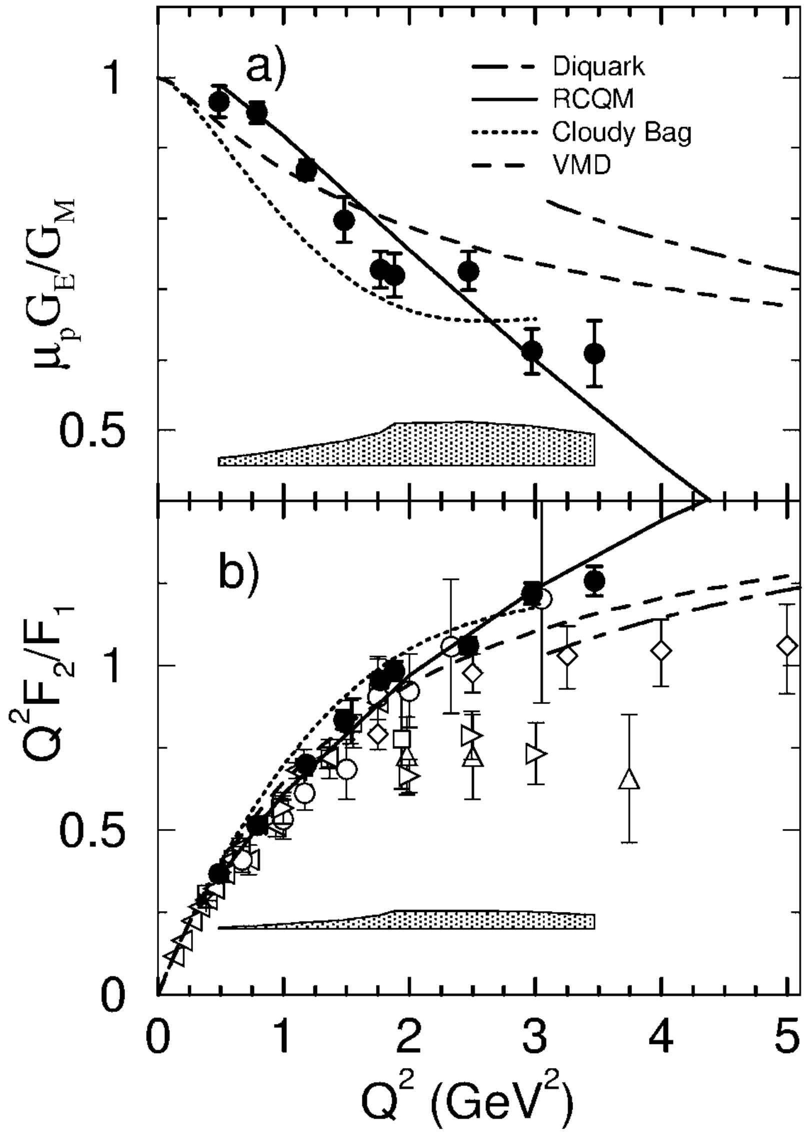
P_t and P_ℓ are the proton polarizations, transverse and longitudinal to the proton momentum, and in the reaction plane.

The first measurement of the proton's G_{Ep}/G_{Mp} ratio for $Q^2 > 0.5$ GeV^2 in a double-polarization experiment ran at Jefferson Lab (then known as CEBAF) in 1998.

M.K. Jones et al. PRL 84, 1398 (2000),

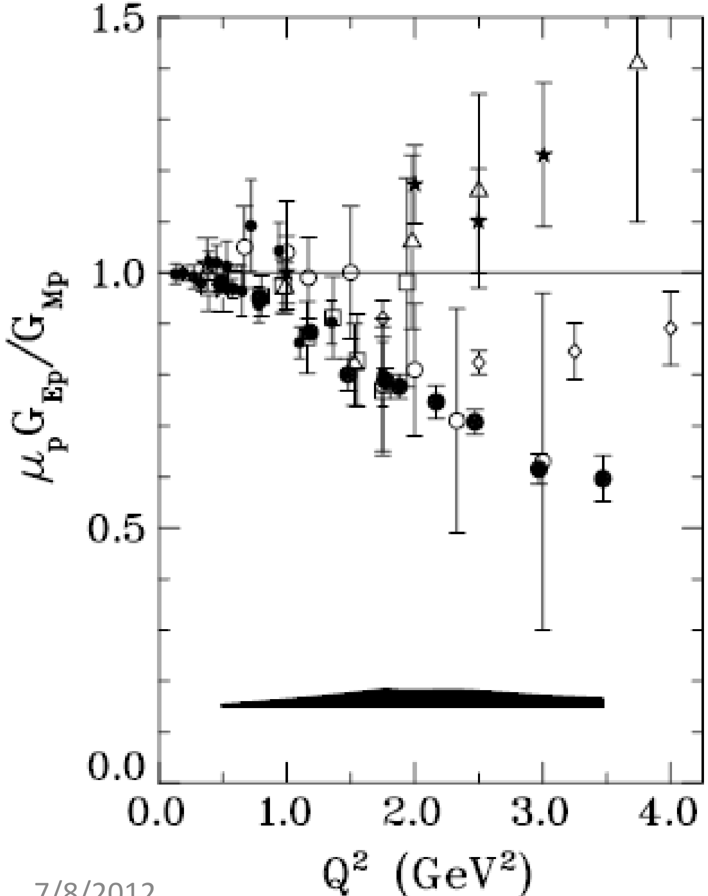
The results seemed to disagree with the LT-separation (or Rosenbluth) cross section data available at the time (shown in lower graph only, open symbols).

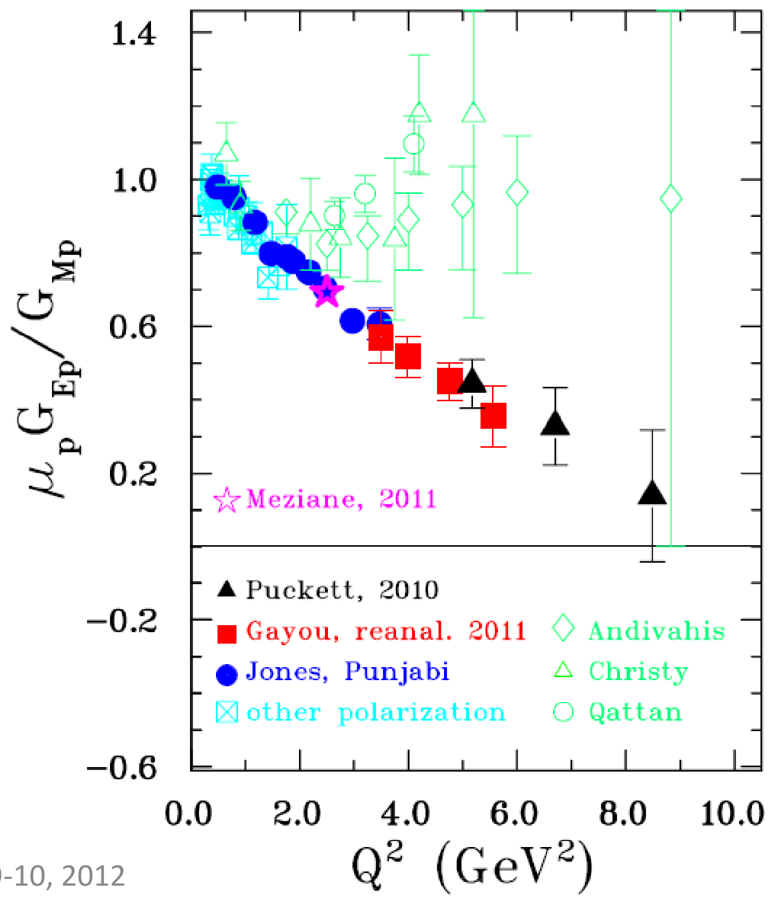
J. Litt et al. PL B 31 (1970),
L. Andivahis et al. PR D 50 5491 (1994)



The data of GEp(I) have been reanalyzed since
Punjabi et al, PR C71 055202 (05)
Here compared with the LT separation data of the time.

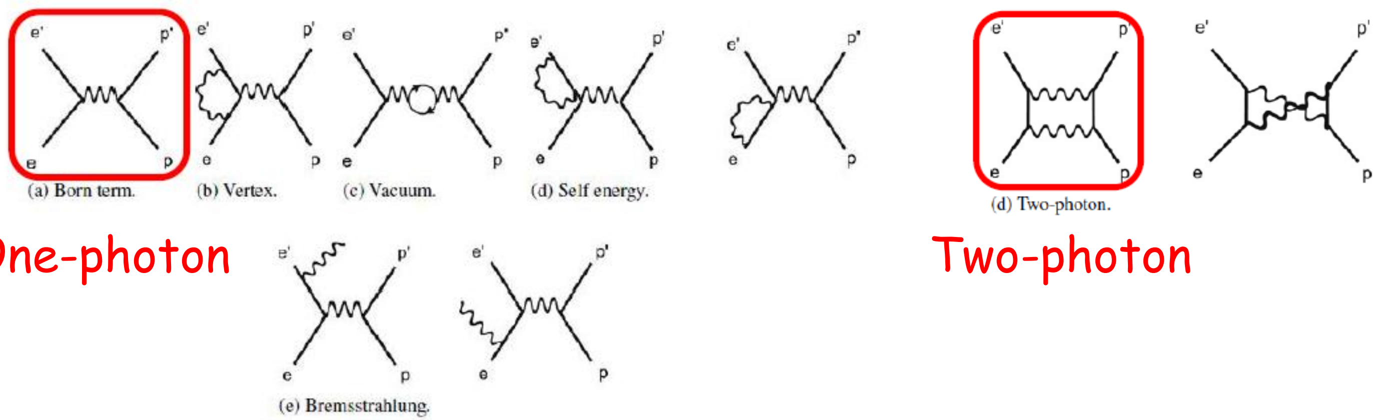
Since 2010 we have the results of GEp(III), as well as the reanalyzed data of GEp(II),
Puckett et al. PRL, 104, 242307 (2010),
Puckett et al. PR C85 045203 (2012),
respectively.





Possible causes for the discrepancy

The firsts to suggest that the difference may be to the hitherto neglected two-photon exchange were P.A.M. Guichon and M.Vanderhaeghen, PRL 91, 142303 (2003), and Blunden, Melnitchouk and Tjon, PRL 91, 142304 (2003).: in the same issue of PRL!
Cross section data require radiative corrections; polarization data for G_{Ep}/G_{Mp} in first approximation do not.



One-photon

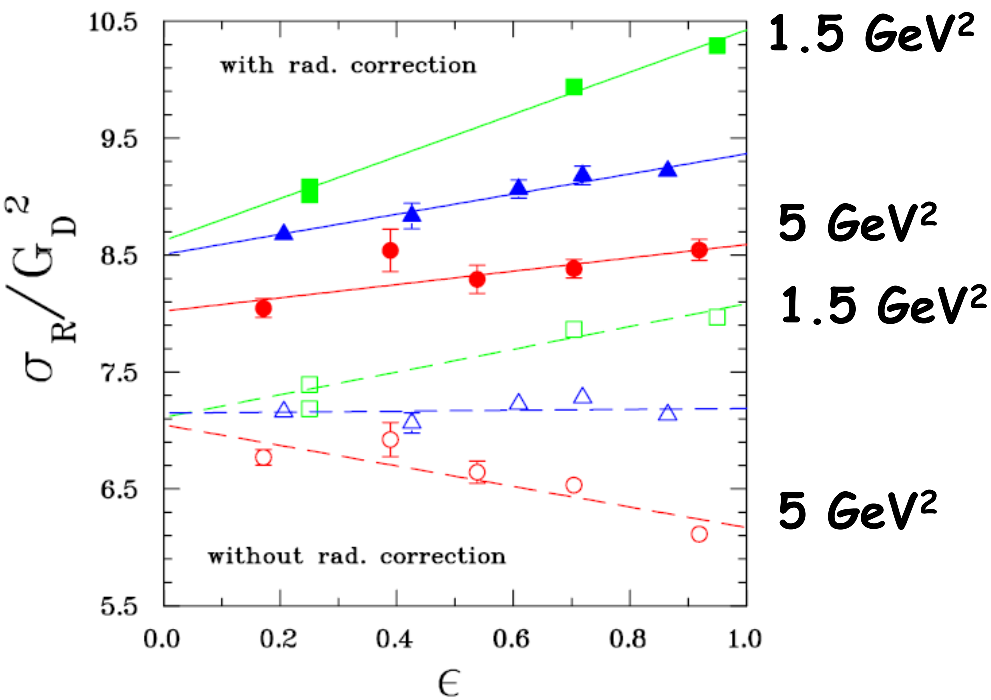
Two-photon

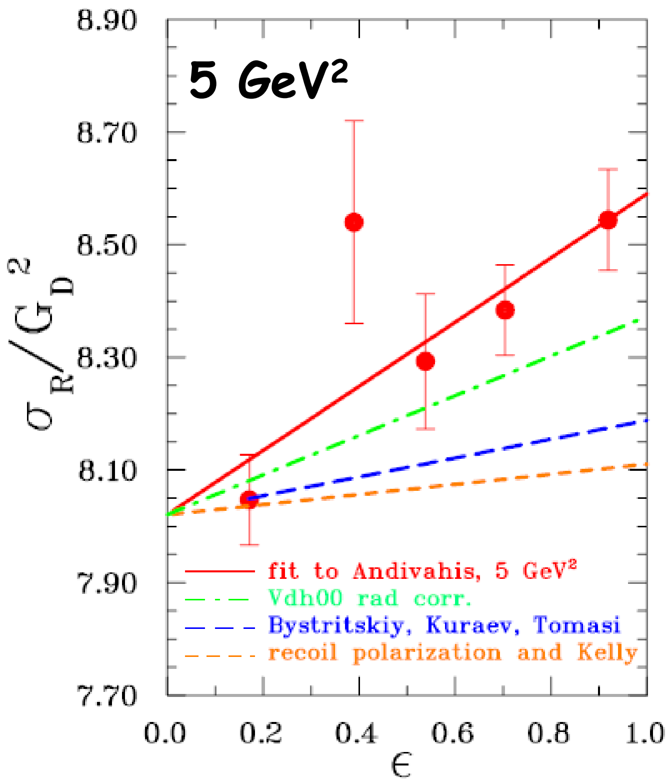
J. Arrington, Phys. Rev. C 69, 032201 (2004).
A.V. Afanasev, et Phys. Rev. D 72, 013008 (2005).
S. Kondratyuk, P. G. Blunden, et al, Phys. Rev. Lett. 95, 172503 (2005).
Y. M. Bystritskiy et al, Phys. Rev. C 75, 015207 (2007)
C.E. Carlson, M.Vanderhaeghen, Ann. Rev. Nucl. Part. Sci. 57, 171 (2007)

Radiative corrections not accurate enough?

The difference between LT separation (Rosenbluth) and double-polarization is drastic, and it is real. New Rosenbluth separation in Hall A agree with older data. Overlap points in G_E/G_M show that polarization results are independent of spectrometer used to rotate longitudinal polarization.

Review articles: PPNP, 59, 694-764 (2007), Perdrisat, Punjabi,Vanderhaeghen.

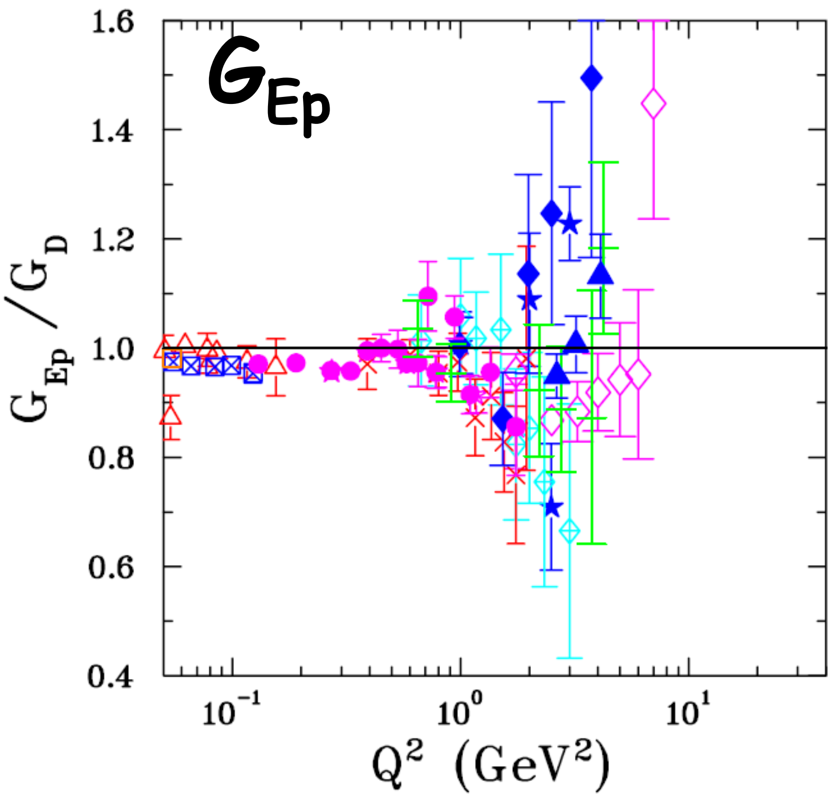


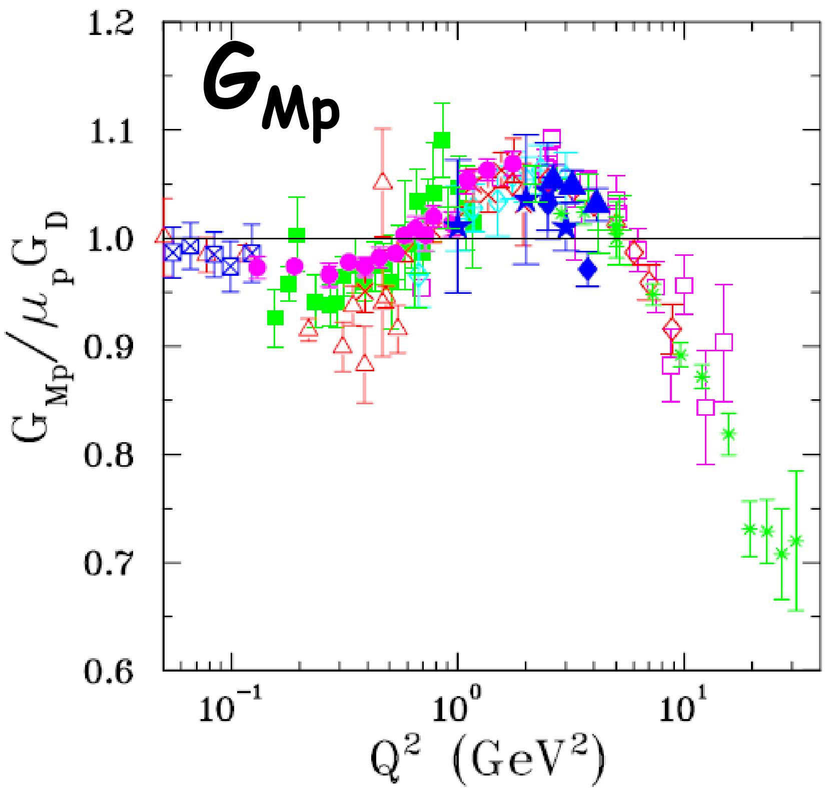


Data: Andivahis et al, PR D 50 (1994) 5491, **modified** Mo and Tsai (1969) **corrections**

Rosenbluth results

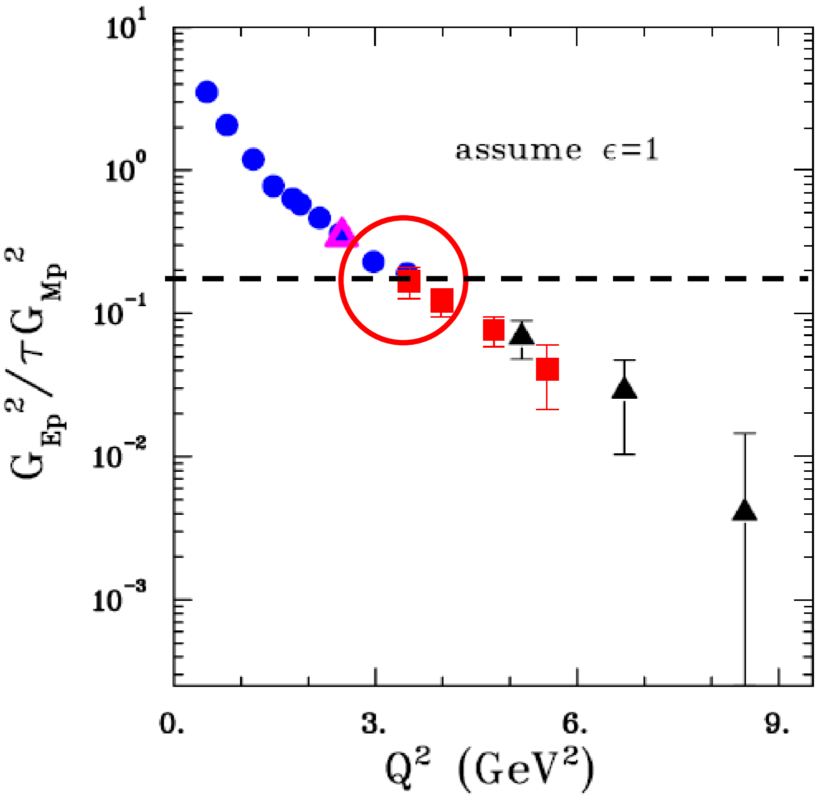
Information for G_{Ep} starts to become fuzzy at $Q^2=1$ GeV^2, and has completely disappeared by $Q^2=3$ GeV^2.
Nothing like that for G_{Mp}.
No direct or obvious evidence for a "so far neglected" two-gamma contribution!

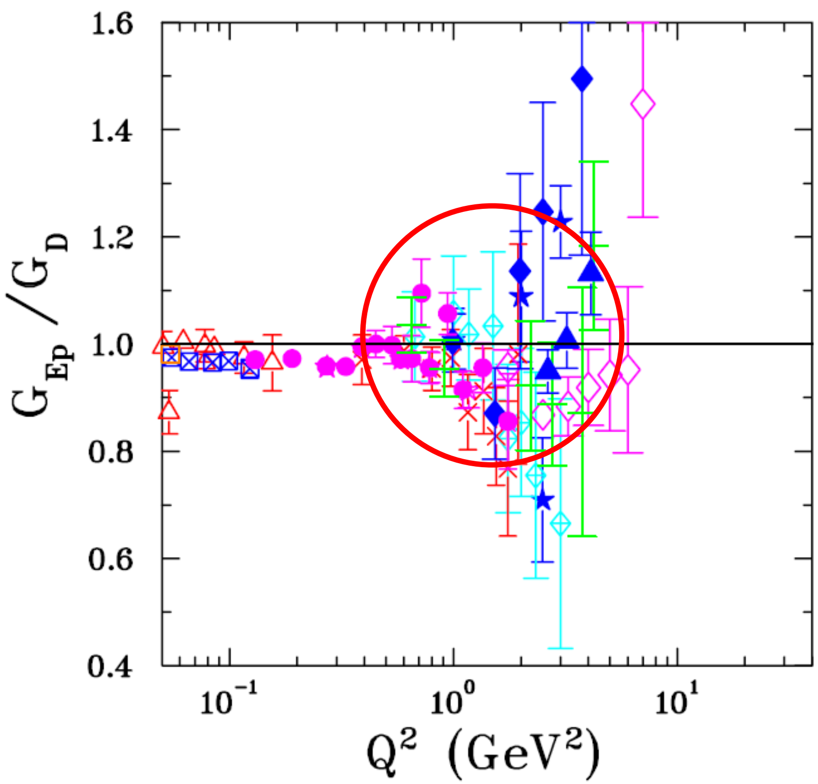




The relative contribution of G_{Ep} to the cross section becomes of order of the experimental uncertainty (10-20%) by $Q^2 \approx 3.5$ GeV^2. Which is where the LT data for G_{Ep} seem to loose track of G_{Ep}! Coincidence?

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





In Fact…

If G_{Ep} approaches zero, or the error bar on the cross section becomes large, then G_{Ep}/G_D becomes 1, (to the extend that GM≈GD).

Hence the behavior of the G_{Ep}/G_D ratio obtained from cross section measurements does not necessarily imply inaccurate or incomplete radiative corrections, in particular does not *a priori* require a significant two-photon contribution.

Never-the-less, of course relevant data will provide the final answer, as to whether two-photon exchange is an important effect in proton form factor measurements.

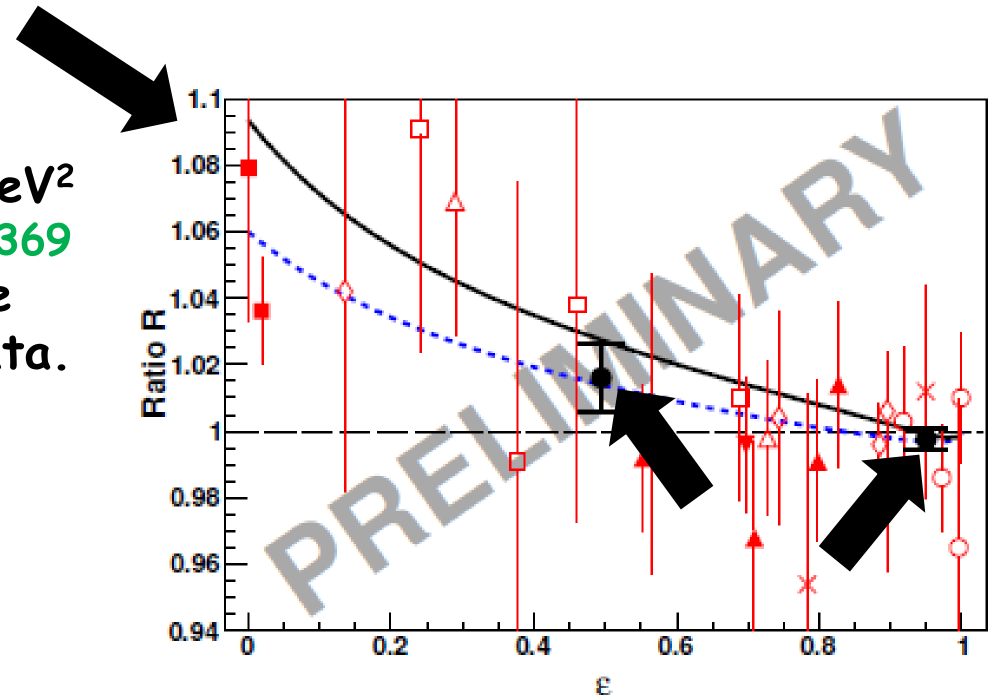
Currently a large effort is being invested in direct detection of two-photon effects from the ratio $d\sigma^+/d\sigma^-$.

Current attempts to determine the two-gamma contribution from the e^+p/e^-p cross section ratio

$$(d\sigma^+ - d\,\sigma^-)/(d\sigma^+ + d\sigma^-) = 1 - 2\, d\sigma_{2\gamma}/(d\sigma^+ + d\sigma^-)$$

1) Novosibirsk has preliminary results:
   This is run I: Q^2=2.0 GeV^2;
   Run II at Q^2=1.6 GeV^2 and
   ε<0.5 yet to come.
   Older data shown with Q^2<2 GeV^2
   A.V. Gramolin et al, arXiv:1112.5369

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



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

3) Olympus at DESY, currently in data taking mode

Two-photon term introduces 3^d Form Factor, F_3

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

and modifies the G_M and G_E form factors:

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

Define

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

Then polarization ratio is G_E/G_M with 3 additional terms:

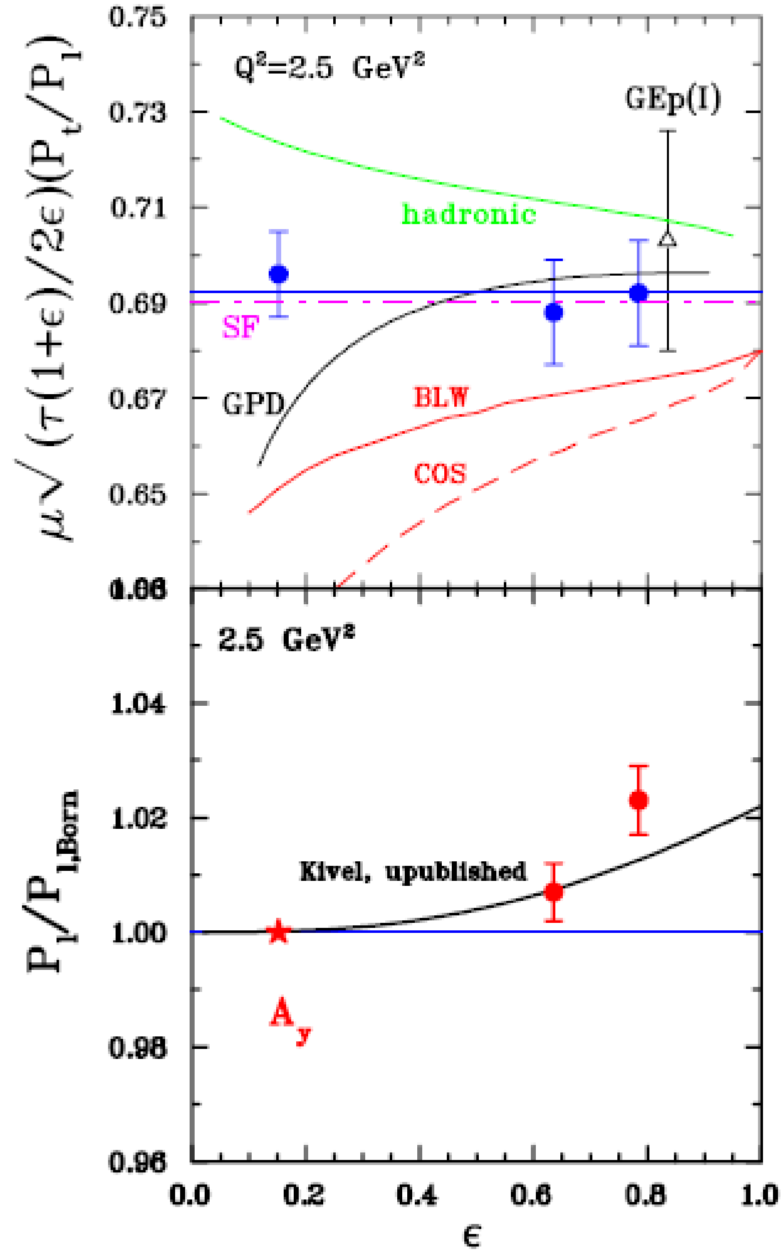
$$P_t/P_l = -\sqrt{\frac{2\varepsilon}{\tau(1+\varepsilon)}}\left\{\frac{G_E}{G_M} + Y_E - \left(\frac{G_E}{G_M}\right)Y_M + \left(1 - \frac{2\varepsilon}{1+\varepsilon}\right)\left(\frac{G_E}{G_M}\right)Y_3\right\}$$

Double-polarization Jlab 2-gamma expt.

Measured G_{Ep}/G_{Mp} at Q^2=2.5 GeV2
3 values of ε, unprecedentedly small error bars. $R=\mu\sqrt{[\tau(1+\varepsilon)/2\varepsilon]}(P_t/P_\ell)$.

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.

Soft-colinear effective field theory: Kivel, unpub. 2012

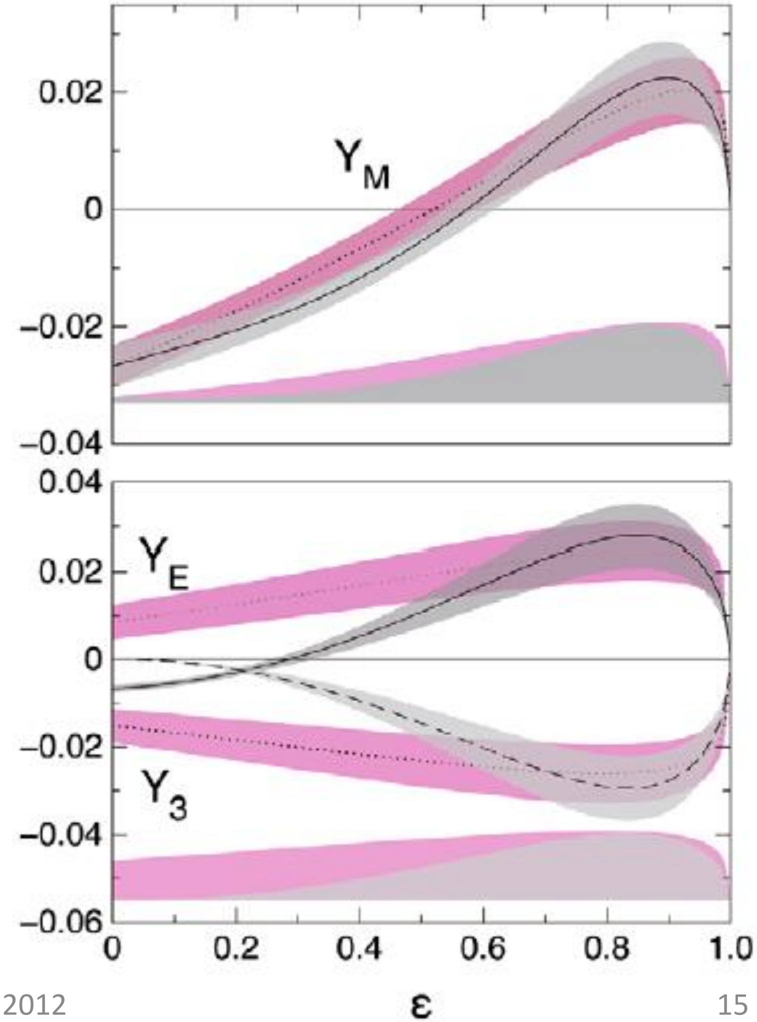


One interpretation for the two-gamma results

The data fitted are cross section at 2.64 GeV^2, the Hall C G_{Ep}/G_{Mp} ratio and P_ℓ at 2.50 GeV^2.

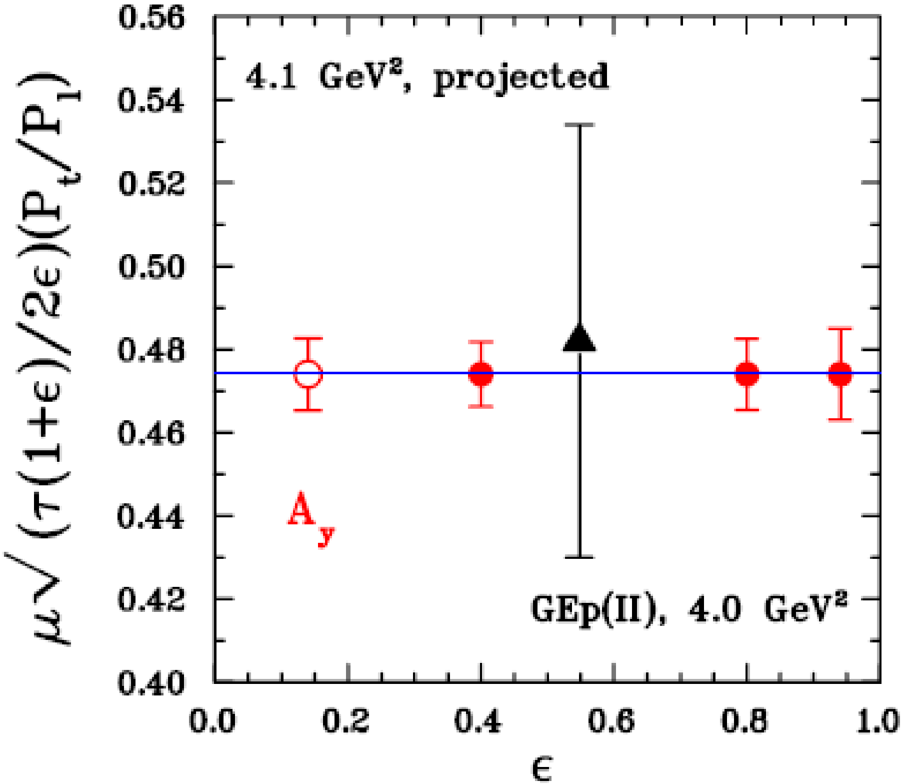
The two colors correspond to two different parameterizations of the fit to the G_{Ep}/G_{Mp} and P_ℓ ratio.

J. Guttmann, N. Kivel, M. Meziane,
and M. Vanderhaeghen
Eur. Phys. J. A (2011) 47: 77



A second two-gamma experiment at Jlab 12 GeV?

Choose 4.1 GeV^2 because 0.01 statistics possible in 10 days per point.



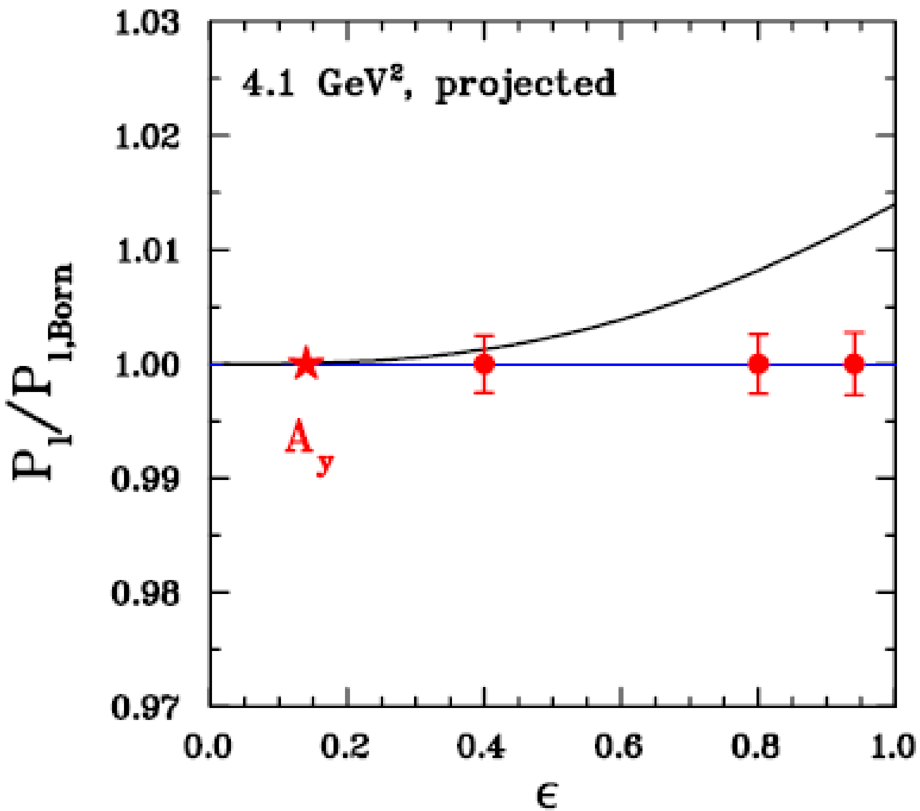
Cross section with small uncertainty at 4.1 GeV^2 available: I.A. Qattan et al, PRL 94 (2005), 142301.

Radiative corrections (including two-gamma) tend to get suppressed in the double ratio $r=G_{Ep}/G_{Mp}$, but not in the simple ratio P_ℓ:

$$P_{\ell,Born}=\sqrt{(1-\varepsilon^2)}\ /(1+\varepsilon r^2/\tau)$$

Curve from N. Kivel and M. Vanderhaeghen (priv. comm. 2012) soft-collinear effective field theory approach.

P_ℓ required for determination of the 3 two-photon amplitudes, Y_E, Y_M and Y_3, together with R, e+/e- and the cross section.



A possible scenario for a second GEp(2γ) at JLab

Assumes that $R=\mu_p G_{Ep}/G_{Mp} \approx 0.474$

Q^2 (p_p) GeV^2	ε	E_e GeV	θ_e	θ_p	ΔR	$\Delta P_\ell / P_{\ell Born}$	time in days
4.1	0.14	2.81	100.	11.9	0.009	used for A_y	10
4.1	0.40	3.37	61.0	20.3	0.008	0.0025&	10
4.1	0.80	5.56	26.9	31.0	0.008	0.0026&	10
4.1	0.94	9.56	13.8	36.4	0.012	0.0028&	10

Conclusions

There is still a need to understand the disagreement between cross section (Rosenbluth) data and double polarization data:

a) Higher order graphs like two-hard photon exchange are of intrinsic interest. Standard radiative corrections may need one more revision.
   But by itself the discrepancy between cross section and polarization results would not be of major physical importance, provided the polarization data gives us the true Form Factor ratio.

b) Whether double polarization data truly determines the invariant Born Form Factors F_1 and F_2 is the question that must be checked experimentally. The 2007-8 Hall C Jlab test was at relatively low Q^2. It should be repeated at larger Q^2.

c) A test can be done with good accuracy at Jlab, at Q^2=4.1 GeV^2, once the 11 GeV beam becomes available.

Thank you!

"Experiments are the only means of knowledge at our disposal. The rest is poetry, imagination".

Max Planck