Two-photon exchange: myth and history

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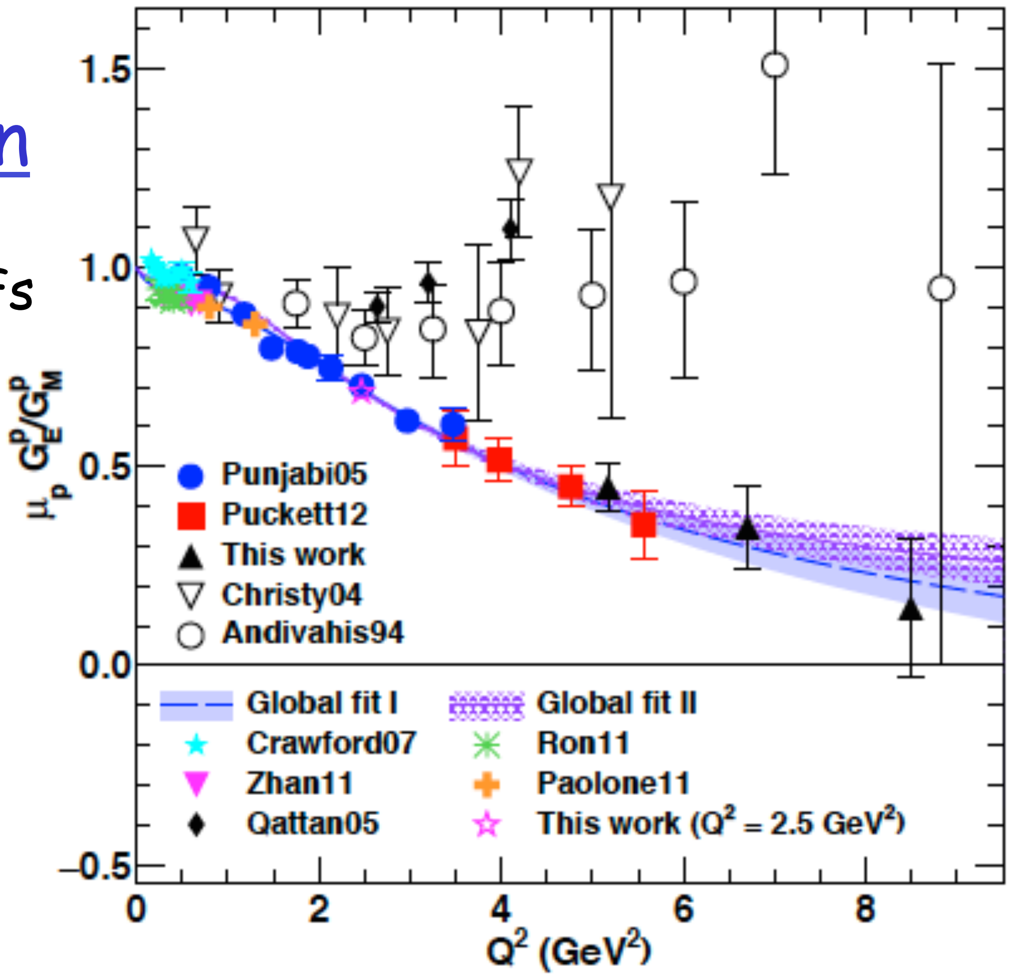
Polarization experiments

A.I. Akhiezer and M.P. Rekalo 1967

Jlab-GEp collaboration

1) "standard" dipole function for the nucleon magnetic FFs GMp and GMn
2) linear deviation from the dipole function for the electric proton FF Gep
3) QCD scaling not reached
3) Zero crossing of Gep?
4) ***contradiction between polarized and unpolarized measurements***



C. Perdrisat, V. Punjabi, M. Jones, E. Brash…

A.J.R. Puckett et al, PRL (2010), PRC (2012), arXiv:1707.08587 [nucl- ex]

Two photon exchange

- *1γ-2γ interference is of the order of $\alpha=e^2/4\pi=1/137$*

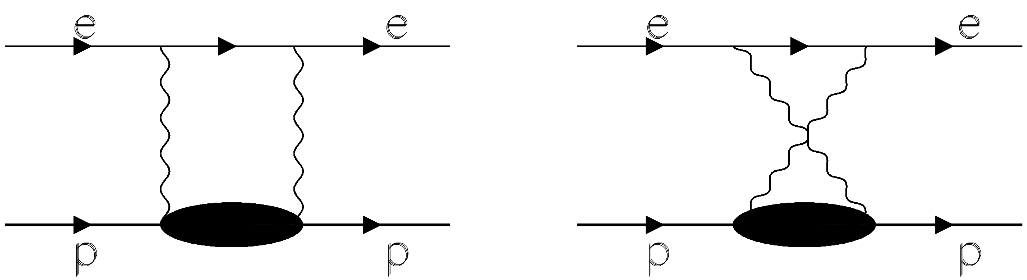
1. An idea from the 70's
2. Model (in)dependent calculations
3. Different calculations give quantitatively different results . Which physics mechanism to compensate this factor?
4. Model independent statements

No experimental evidence

Theory not enough constrained

Not a recent idea

- In the 70's it was shown [J. Gunion and L. Stodolsky, V. Franco, F.M. Lev, V.N. Boitsov, L. Kondratyuk and V.B. Kopeliovich, R. Blankenbecker...] that, at large momentum transfer, the sharp decrease of the FFs, if the if the momentum is shared between the two photons, may compensate the factor of $(Z\alpha)$ due to the steep decrease of FFs



$FF(Q^2) \rightarrow FF(Q^2/2)$

- In this case the effect should be larger
  - *At larger Z*
  - *At higher Q^2*

  -> Elastic scattering at zero degrees on Heavy Ions

MEASURING THE DEVIATION FROM THE RUTHERFORD FORMULA

- ***E.A. Kuraev, M. Shatnev, E.T-G.,*** ***Phys.Rev. C80 (2009) 018201***

Not a recent idea

VOLUME 91, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2003

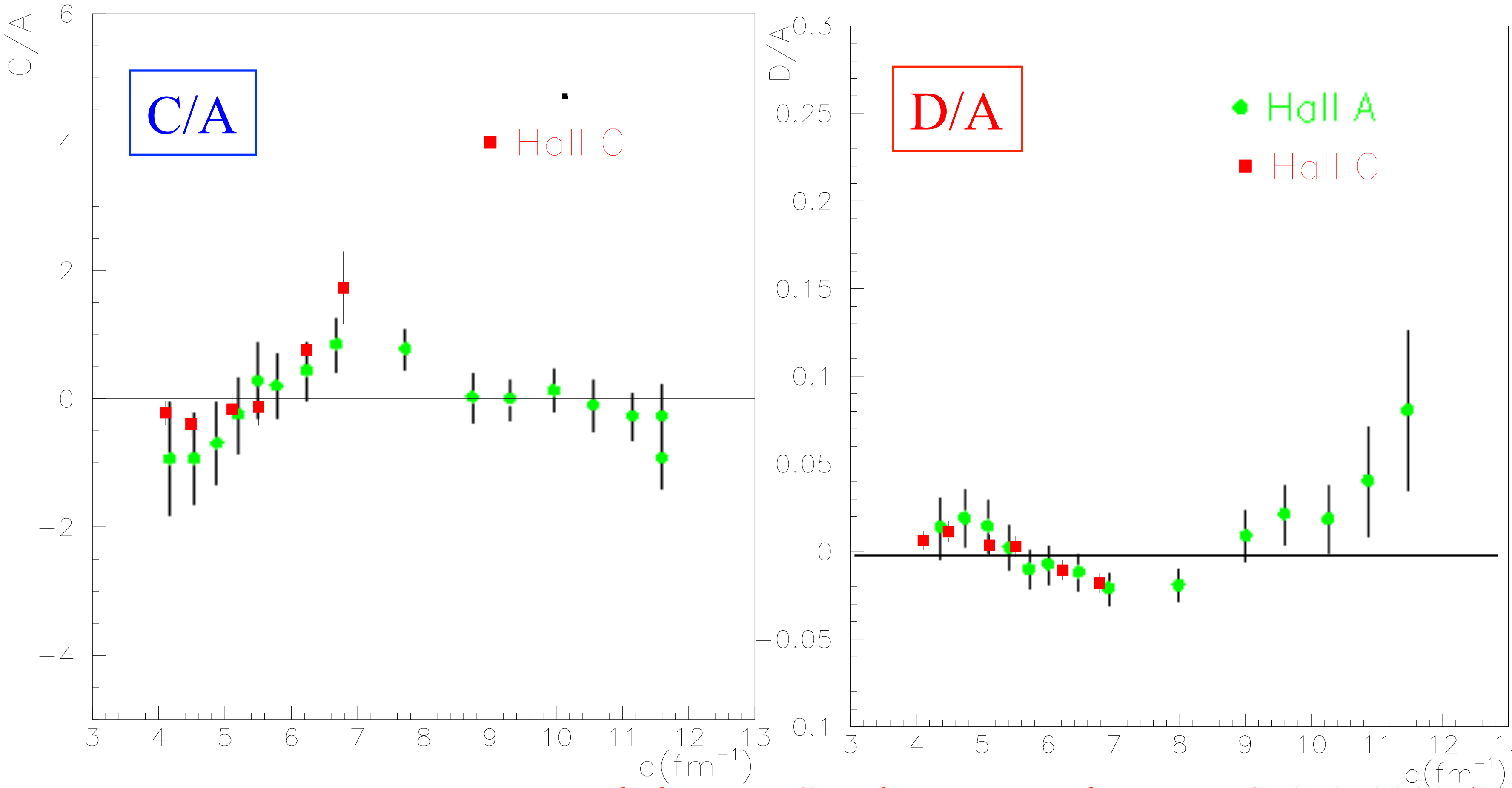
How to Reconcile the Rosenbluth and the Polarization Transfer Methods in the Measurement of the Proton Form Factors

P. A. M. Guichon[1] and M. Vanderhaeghen[2]

The apparent discrepancy between the Rosenbluth and the polarization transfer methods for the ratio of the electric to magnetic proton form factors can be explained by a two-photon exchange correction which does not destroy the linearity of the Rosenbluth plot. Though intrinsically small, of the order of a few percent of the cross section, this correction is accidentally amplified in the case of the Rosenbluth method.

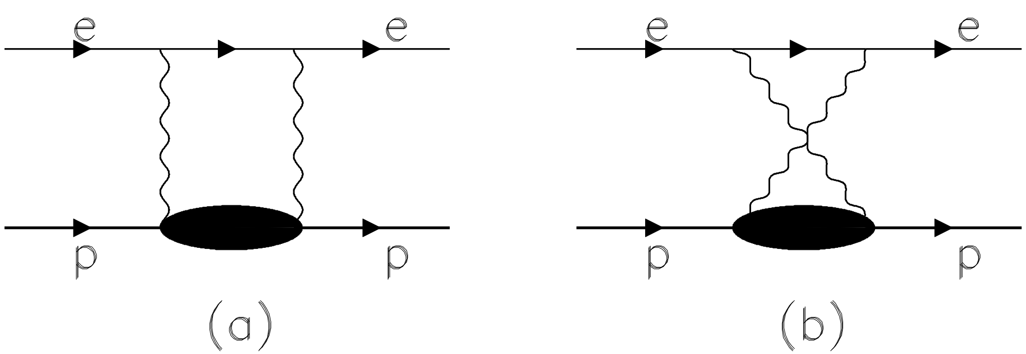
1γ-2γ interference (ed) (1999)

$$\frac{d\sigma}{d\Omega_e}(e^-h \to e^-h) = \sigma_0(\ A \cot^2\frac{\theta_e}{2} + B + \ C \cot\frac{\theta_e}{2} + D \cot^3\frac{\theta_e}{2} + ..)$$

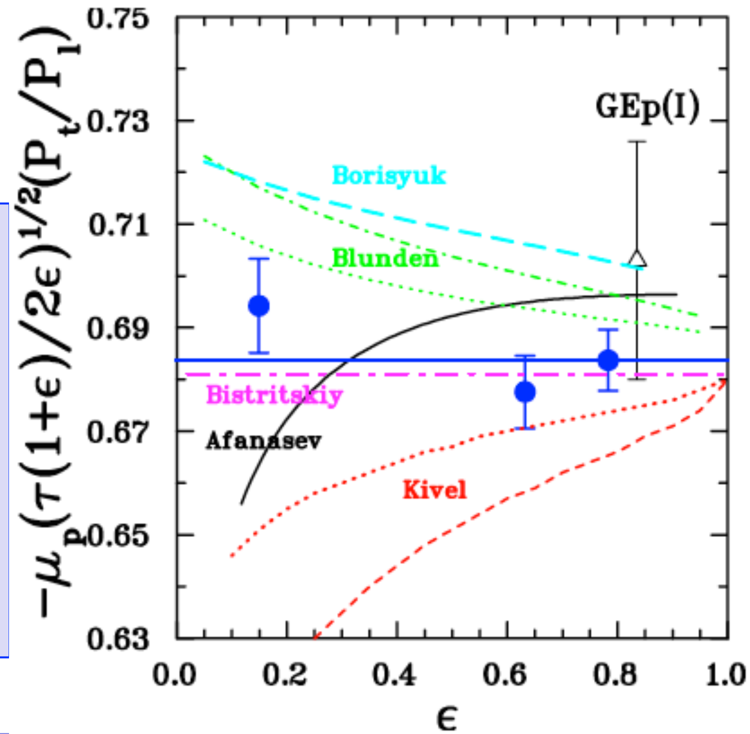


M. P. Rekalo, E. T-G and D. Prout, Phys. Rev. C60, 042202 (1999)

Model dependent calculations



The calculation of the box amplitude requires the description of intermediate nucleon excitation and of their FFs at any Q^2...



Different calculations give quantitatively different results

Theory not enough constrained

Model independent statements

Model Independent statements

Interaction of 4 spin ½ fermions: ep -> ep scattering or ppbar <-> e+e- annihilation

16 amplitudes in the general case.

- P- and T-invariance of EM interaction,
- helicity conservation,

- **One-photon exchange**
  - Two form factors (real in SL, complex in TL)
  - Functions of one variable

- **Two-photon exchange**
  - Three complex amplitudes
  - Functions of two variables

Model Independent statements

Non linearities in Rosenbluth plot

Charge asymmetry:

In SL : compare $\sigma(e^+p)$ and $\sigma(e^-p)$

In TL : asymmetry in the angular distribution

P-odd polarization observables

M.P. Rekalo, E.T-G. EPJA 22, 331 (2004); NPA740, 271 (2004); NPA742, 322 (2004); G.I. Gakh, E.T-G., NPA771, 169 (2006); S. Pacetti, R. Baldini-Ferroli, E.T-G.,Phys Rep.550, 1 (2015).

FACTA NON VERBA)

Model Independent statements

Non linearities in Rosenbluth plot

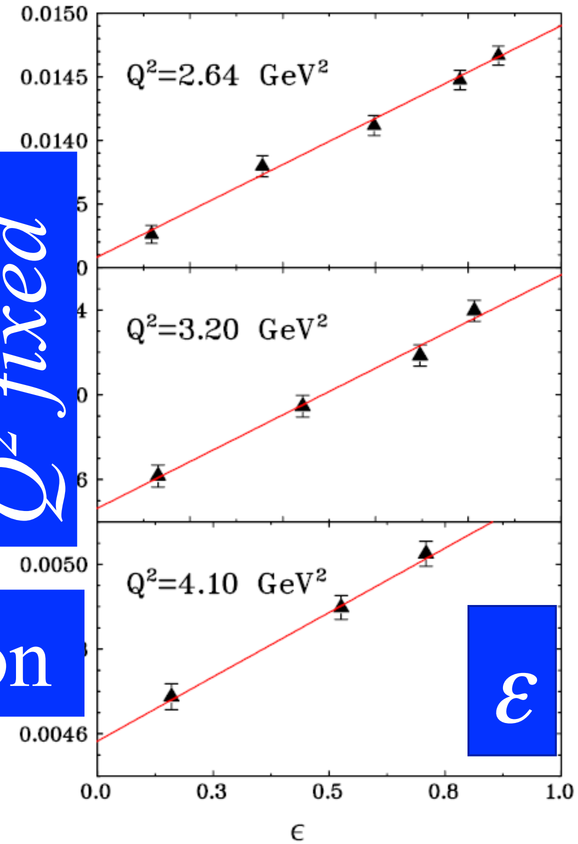
The Rosenbluth separation

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

$$\varepsilon = \left(1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right)^{-1}, \tau = \frac{Q^2}{4M^2}$$

$$\sigma_R = \varepsilon G_E^2 + \tau G_M^2$$

Q^2 fixed



ε

PRL 94, 142301 (2005)

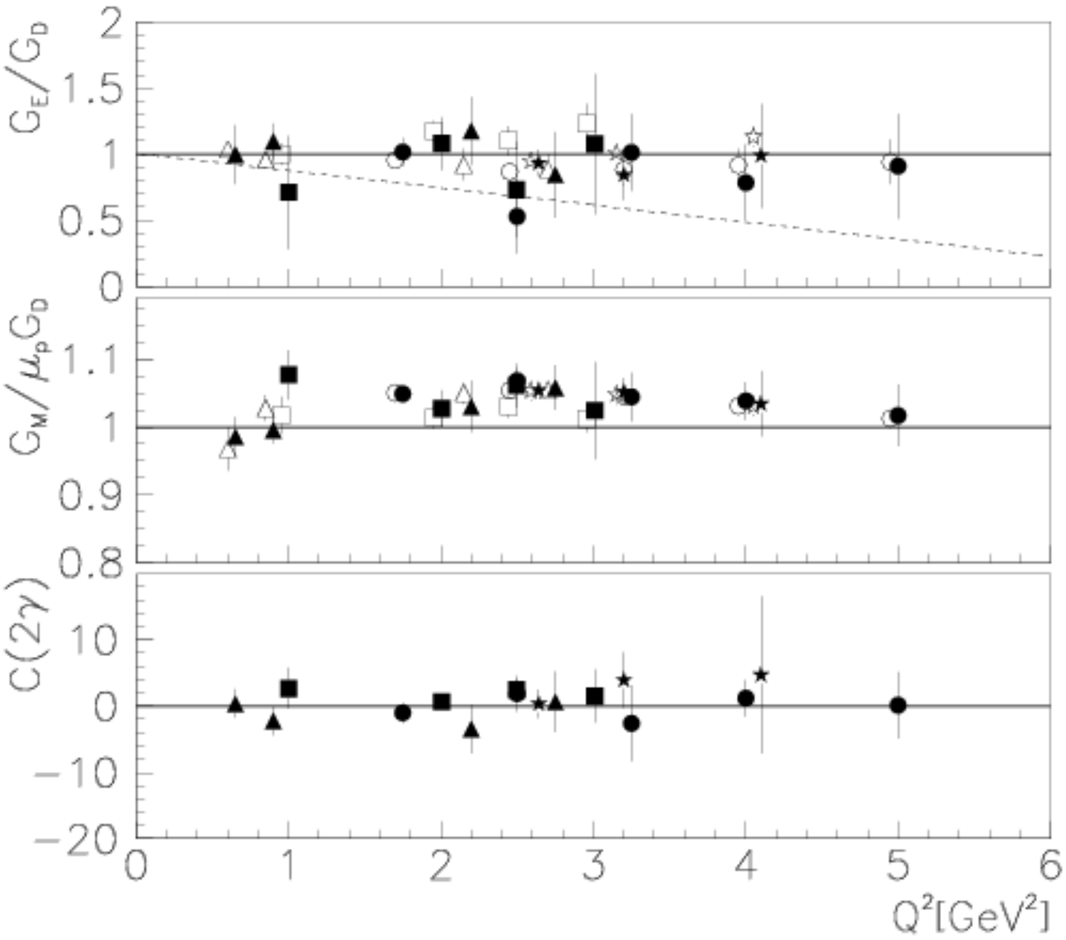
Linearity of the reduced cross section

→ $\tan^2\theta_e$ dependence

→ Holds for 1γ exchange only

Parametrization of 2γ-contribution for ep

$$\sigma^{red}(Q^2,\epsilon) = \epsilon G_E^2(Q^2) + \tau G_M^2(Q^2) + \alpha F(Q^2,\epsilon),$$



$$F(Q^2,\varepsilon) \to \sqrt{\frac{1+\varepsilon}{1-\varepsilon}} f^{(a)}(Q^2)$$

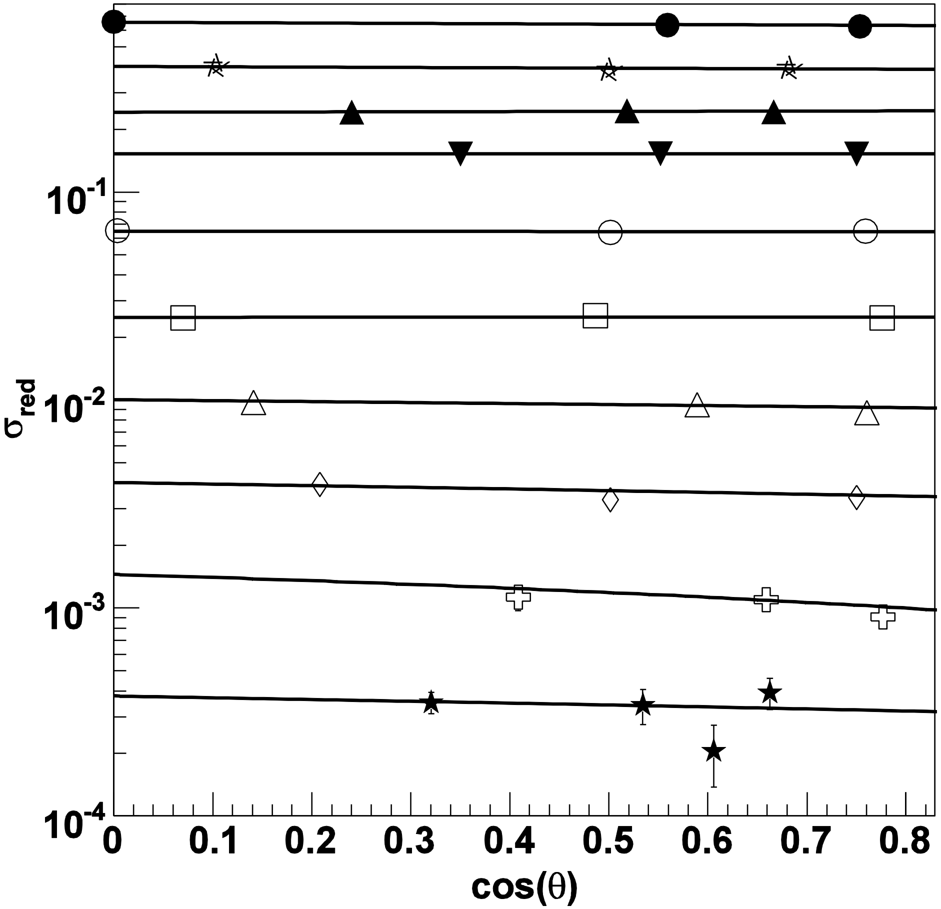
$$f^{(a)}(Q^2) = \frac{C_{2\gamma} G_D}{[1+Q^2[GeV]^2/m_a^2]^2}$$

From the data:
deviation from linearity
<< 1%!

E. T.-G., G. Gakh, Phys. Rev. C 72, 015209 (2005)

Linear fit to e+^{4}He scattering

$$\frac{d\sigma_{un}^{Born}}{d\Omega} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2\sin^4\frac{\theta}{2}}\left[1+2\frac{E}{M}\sin^2\frac{\theta}{2}\right]^{-1} F^2(q^2),$$



G.I. Gakh, E.T-G, NPA 838, 50 (2010)

$$\sigma_{red}|_{\bar{Q}^2}(\theta) = a + \alpha\ b\cos\theta$$

Q^2 [fm $^{-2}$]	a $\pm\Delta a$	b$\pm\Delta b$	χ^2
0.5	(66 ± 4) E-02	-6 ± 9	0.1
1	(0.40± 3) E-02	-3± 8	0.2
1.5	(0.24± 2) E-02	1.0 ± 0.1	0.1
2	(15 ± 2) E-03	0.0 ± 0.1	0.1
3	(65 ± 4) E-03	0.± 1	0.1
4	(25 ± 2) E-03	0.0± 0.4	0.1
5	(101± 8) E-04	-0.2± 0.2	0.5
6	(40± 5) E-04	-0.1± 0.1	0.6
7	(15± 3) E-04	-0.09± 0.07	1.0
8	(38± 9) E-05	-0.01± 0.03	1.0

Model Independent statements

Charge asymmetry:

In SL : compare $\sigma(e^+p)$ and $\sigma(e^-p)$

In TL : asymmetry in the angular distribution

Time-like region

In annihilation processes all information on the presence of 2γ is contained in a precise measurement of the angular distribution (simpler than Rosenbluth fit)

Differential cross section at complementary angles:

The SUM cancels the 2γ contribution:

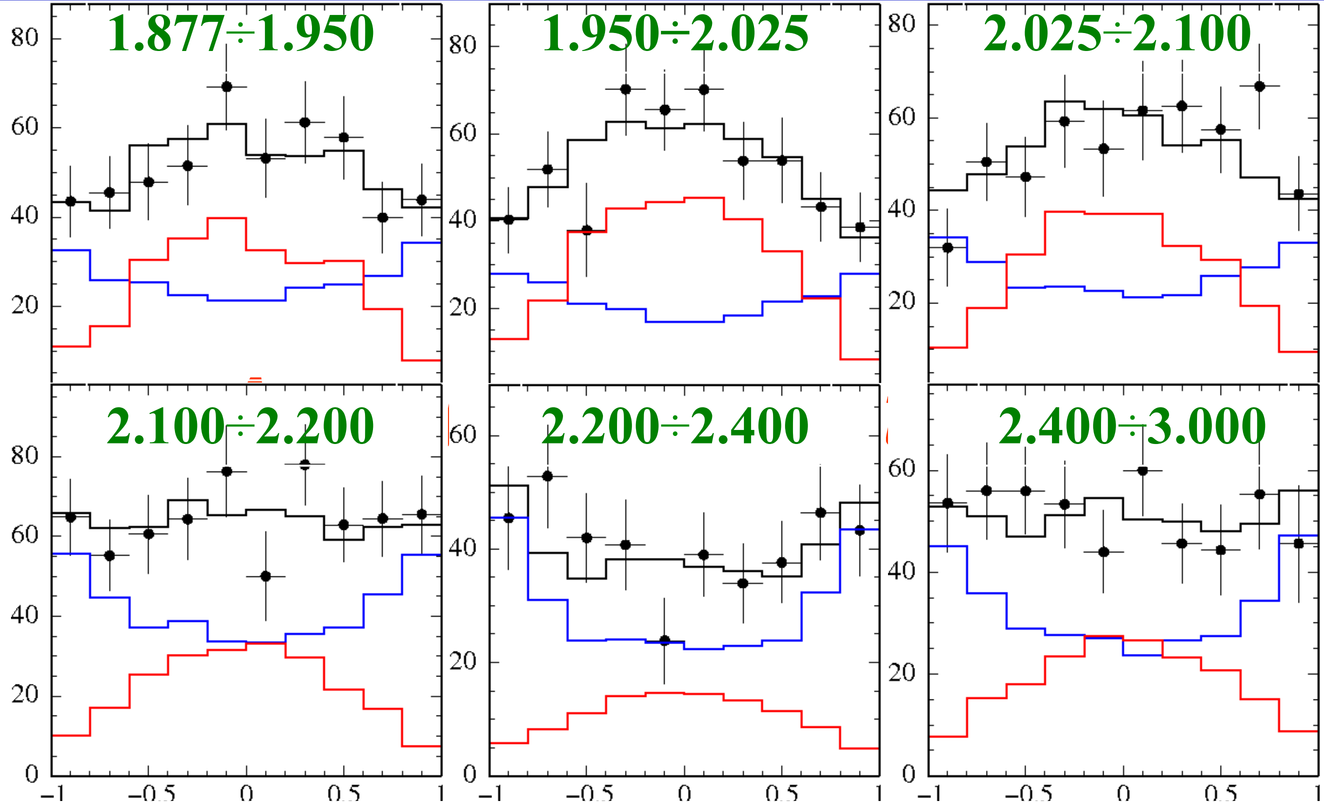
$$\frac{d\sigma_+}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(\theta) + \frac{d\sigma}{d\Omega}(\pi-\theta) = 2\frac{d\sigma^{Born}}{d\Omega}(\theta)$$

The DIFFERENCE enhances the 2γ contribution:

$$\frac{d\sigma_-}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(\theta) - \frac{d\sigma}{d\Omega}(\pi-\theta) = 4N\Big[(1+x^2)ReG_M\Delta G_M^* + \frac{1-x^2}{\tau}ReG_E\Delta G_E^* + \sqrt{\tau(\tau-1)}x(1-x^2)Re(\frac{1}{\tau}G_E - G_M)F_3^*\Big]$$

$$\tau = \frac{q^2}{4m^2}, \quad x = cos\theta$$

Angular Distributions $e^+e^- \to p\,\bar{p}$



Events/0.2 vs. cos θ

$$\frac{dN}{d\cos\theta_p} = A\left[H_M(\cos\theta, M_{p\bar{p}}) + \left|\frac{G_E}{G_M}\right|^2 H_E(\cos\theta, M_{p\bar{p}})\right]$$

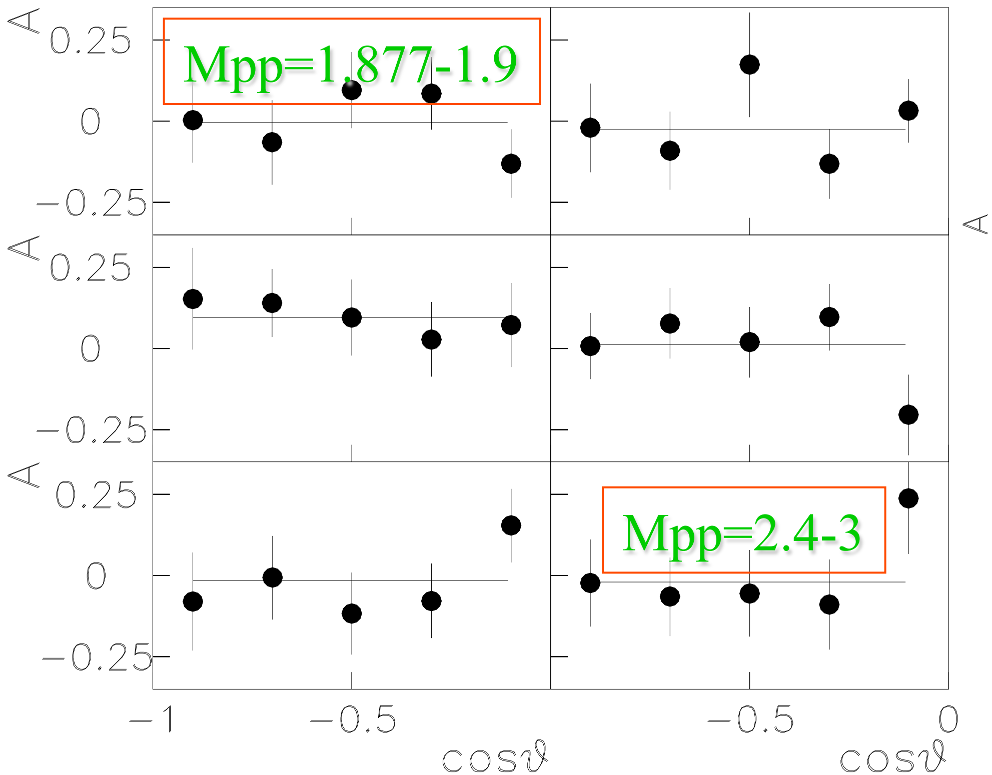
BABAR

2γ–exchange?

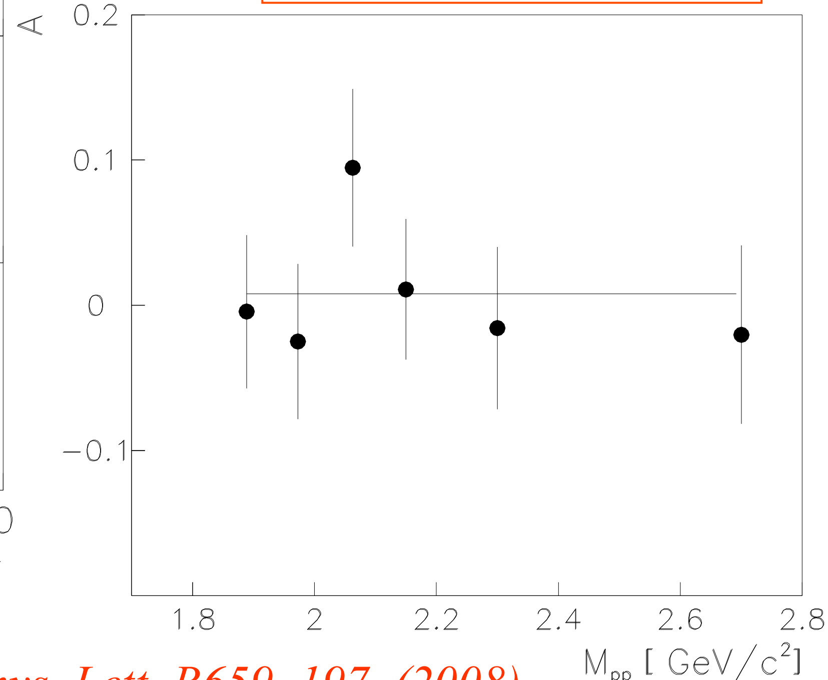
B. Aubert (BABAR Collaboration) Phys Rev. ***D73****, 012005 (2006)*

Angular Asymmetry : $e^+e^- \to p\,\bar{p}$

$$\mathcal{A}(c) = \frac{\frac{d\sigma}{d\Omega}(c) - \frac{d\sigma}{d\Omega}(-c)}{\frac{d\sigma}{d\Omega}(c) + \frac{d\sigma}{d\Omega}(-c)}$$



A=0.01±0.02

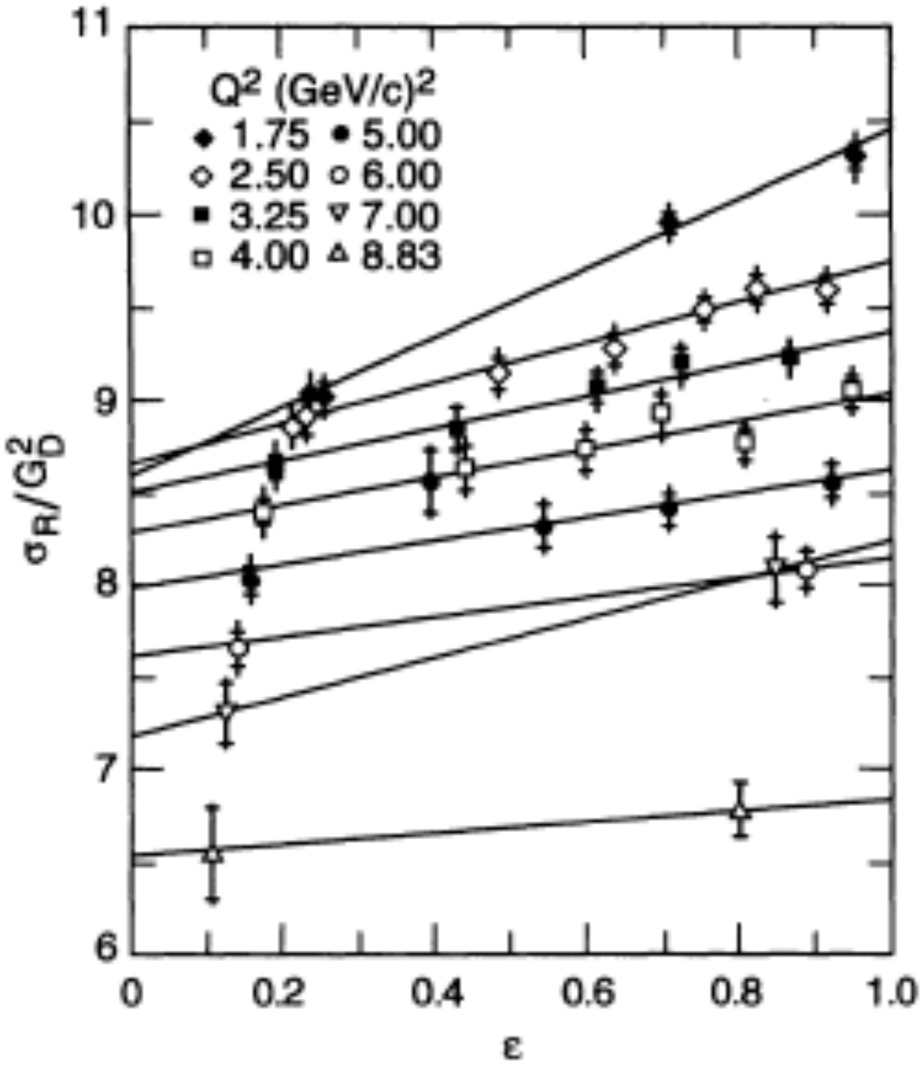


E. T.-G., E.A. Kuraev, S. Bakmaev, S. Pacetti, Phys. Lett. B659, 197 (2008) and if ….

normalization of Rosenbluth data

ep-elastic scattering: Normalization

Andivahis et al., PRD50, 5491 (1994)



Two spectrometers (8 and 1.6 GeV)

2 points at low ε

Fixed renormalization for the lowest ε point c=0.956 (acceptance correction)

Increases the slope!

$G_E \approx G_D$

Measurements of the electric and magnetic form factors of the proton from $Q^2 = 1.75$ to 8.83 $(\mathrm{GeV}/c)^2$

The 1.6 GeV reduced cross sections were normalized to the 8 GeV results by fitting the 8 GeV reduced cross sections versus the virtual photon polarization, ϵ, at each of the five lowest Q^2 values where a minimum of at least two 8 GeV data points existed such that a linear fit could be performed. The normalization factor was that needed at each Q^2 to place the 1.6 GeV reduced cross section on the fitted line. The five resulting normalization factors were found to be independent of Q^2, as expected, and the factor 0.958 ± 0.007, obtained for the lowest Q^2 point, was applied for all Q^2 points. The deviation of the normalization from unity by roughly 4% has been attributed to the uncertainty in the magnitude of the 1.6 GeV acceptance function. Because of the normalization, the 1.6 GeV reduced cross sections were assigned an additional point-to-point systematic error of $\pm 0.7\%$.

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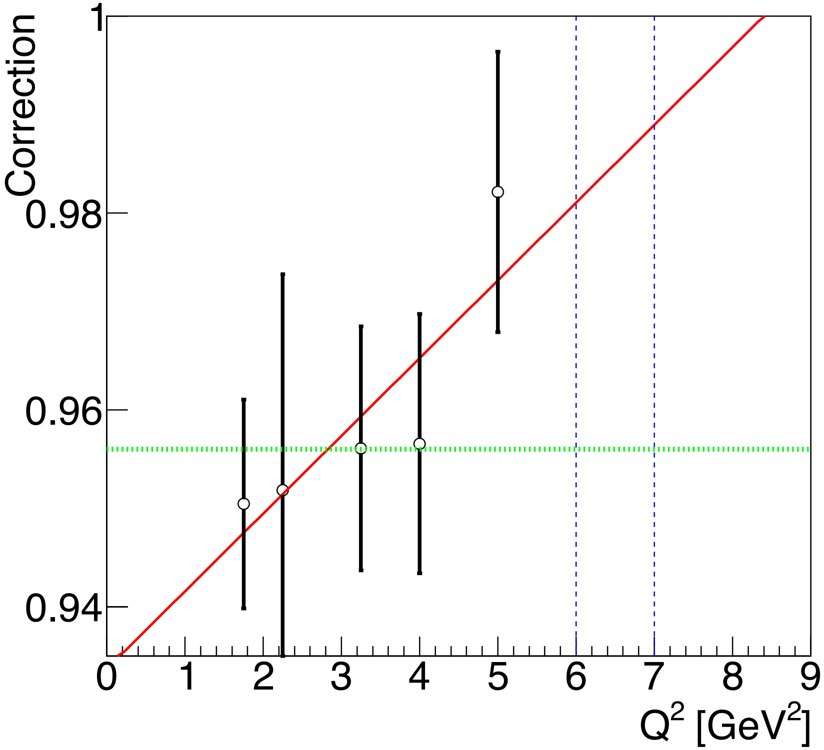
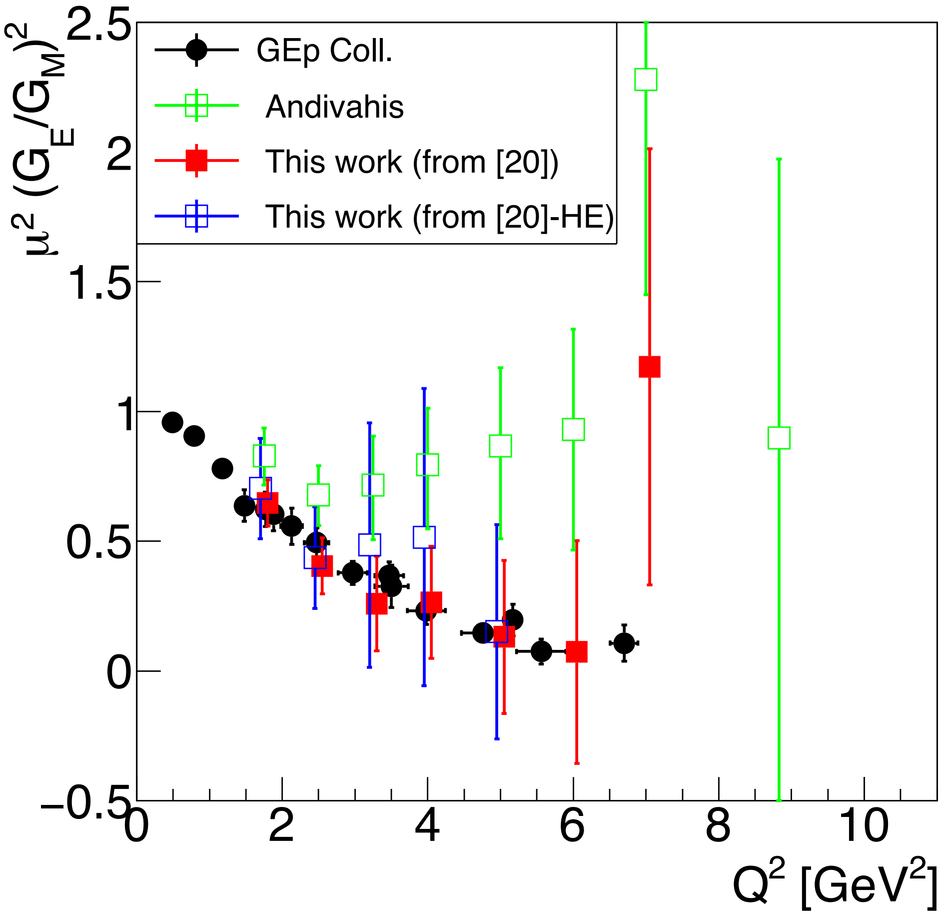
Direct extraction of the Ratio

Andivahis et al., PRD50, 5491 (1994)

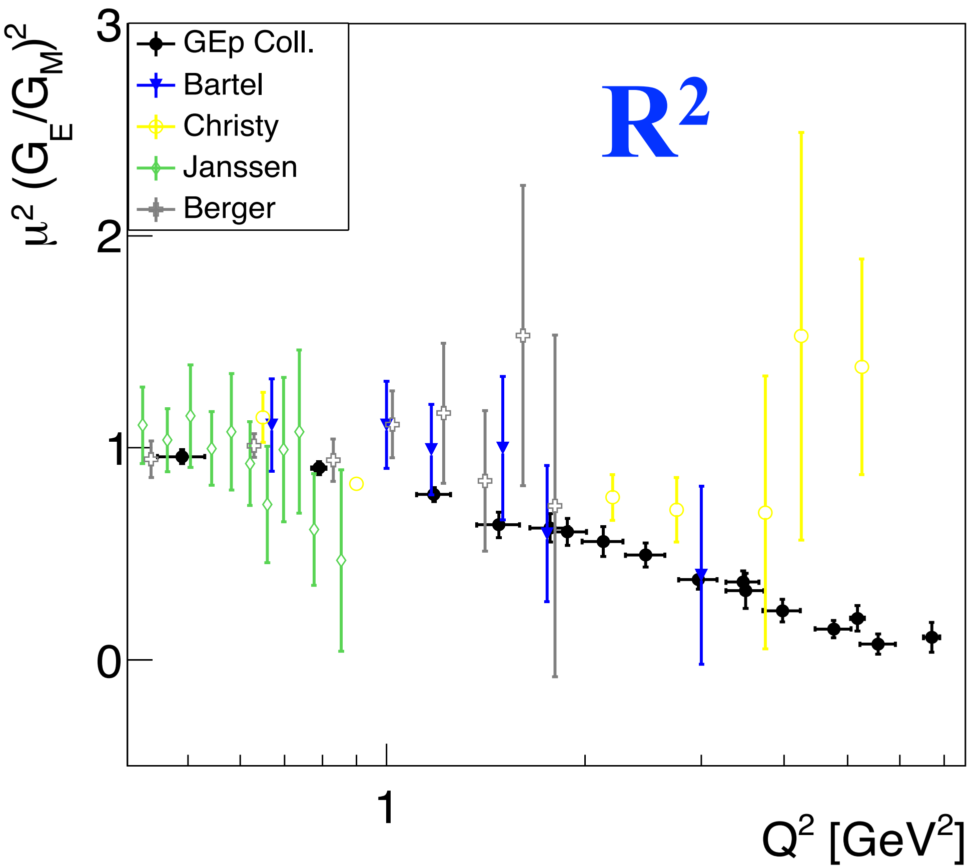


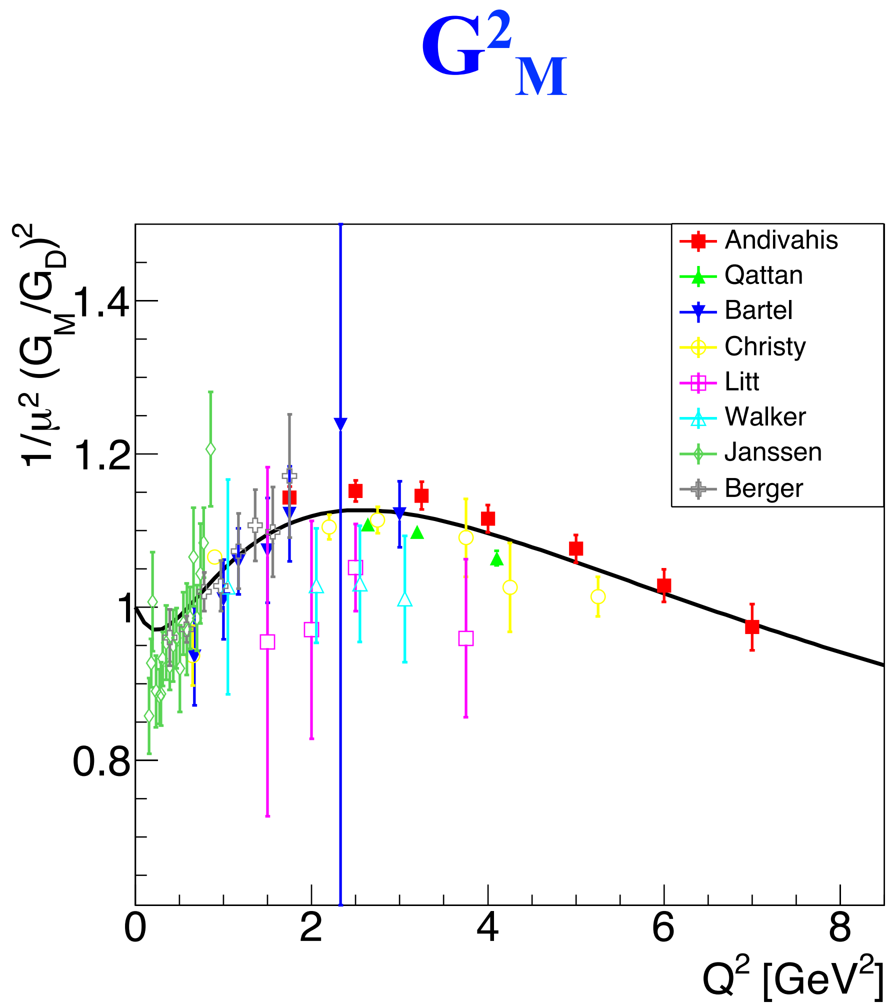
$$\sigma_{\text{red}} = G_M^2 (R^2 \epsilon + \tau),$$



S. Pacetti, E.T-G, PRC94, 055202 (2016)

Different Data Sets

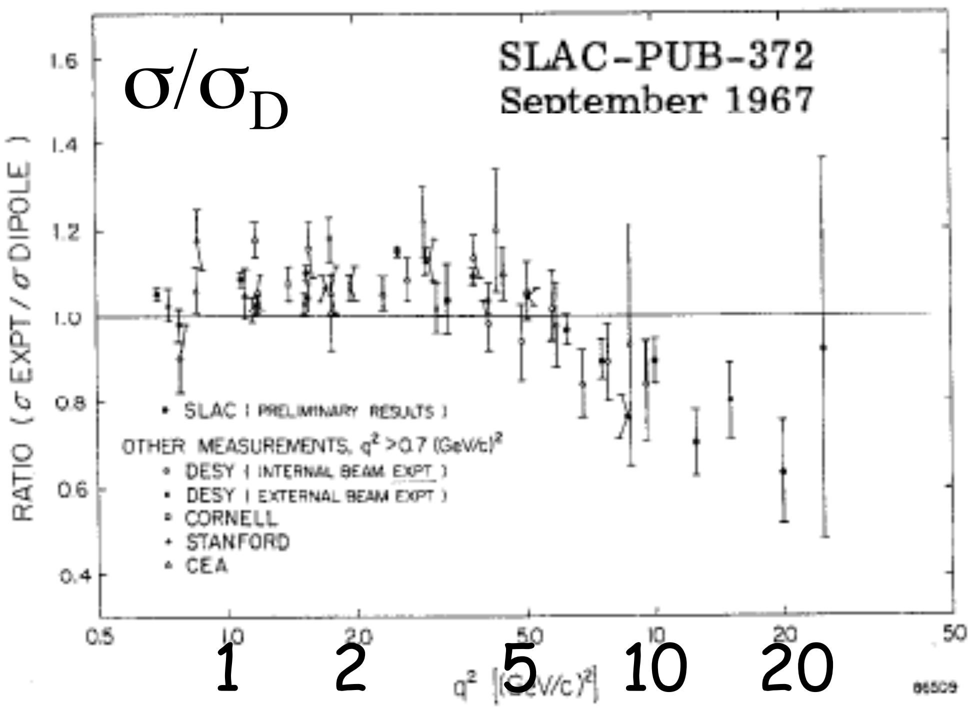




$$\sigma_{\rm red} = G_M^2(R^2\epsilon + \tau),$$

S. Pacetti, E.T-G, PRC94, 055202 (2016)

Nucleon FFs above 6 GeV



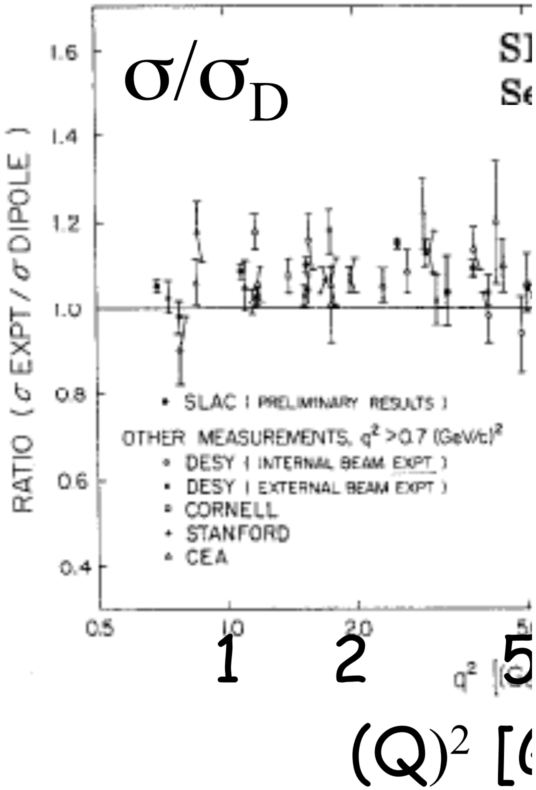
(Q)^2 [GeV^2]

…which makes evident any disagreement with the dipole prediction

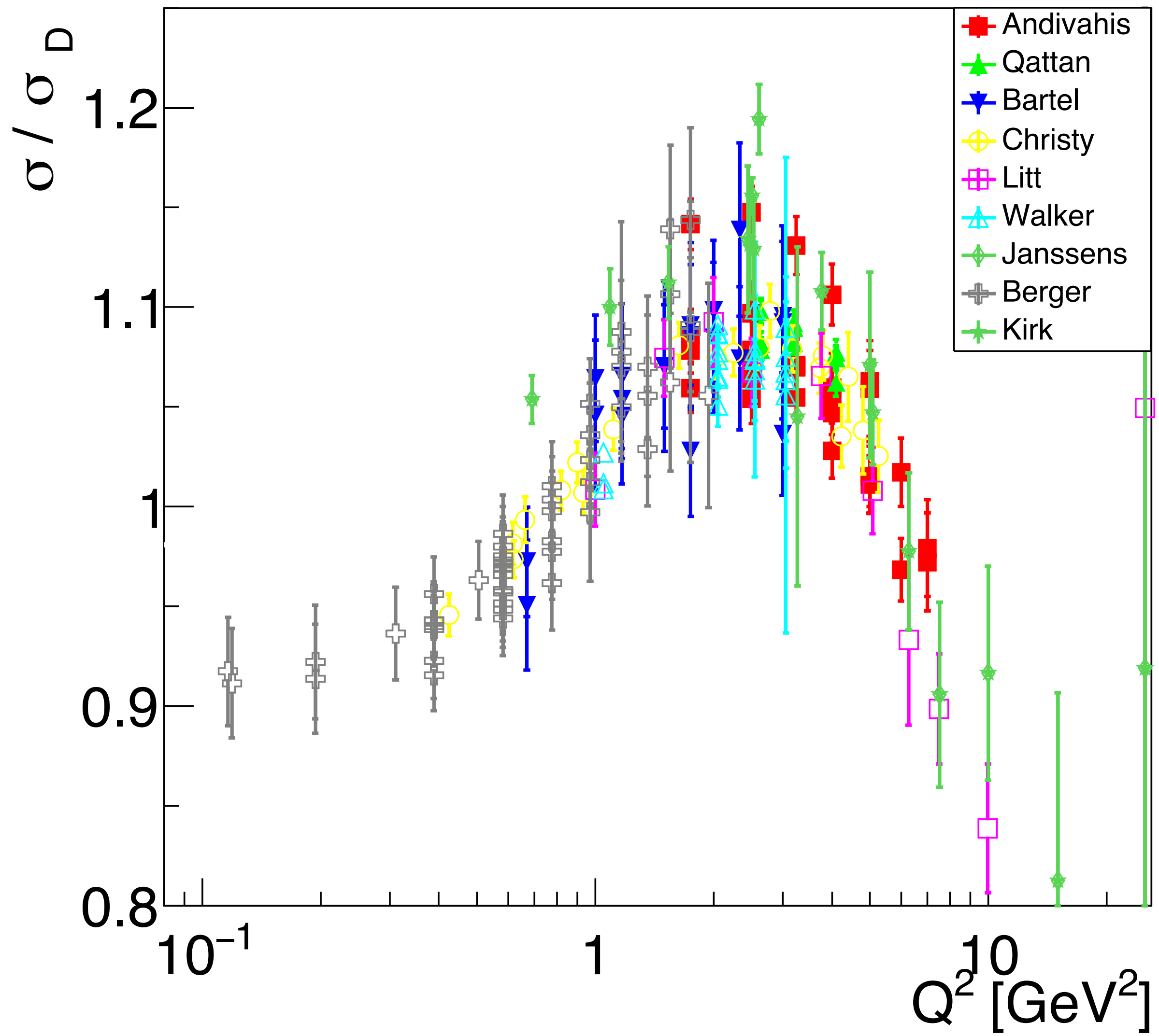
R. Taylor

(Q)^2 [GeV^2]

Nucleon FFs above 6 GeV



S. Pacetti, E.T-G, PRC94, 055202 (2016)



…which makes evide
with the dipole predic

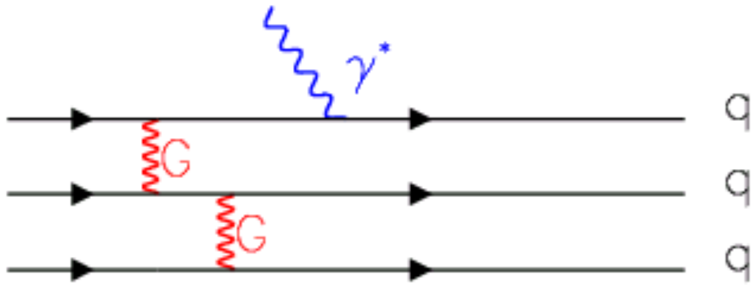
$(Q)^2$ [GeV²]

Conclusions

- Alternative explantions to the GEp discrepancy – <u>if any</u>
  - Radiative corrections
  - Normalization among/within sets of data
  - Parameter correlations : how to deconvoluate 100% correlated parameters ? *ill posed problem*
- Perspectives
  - Investigate the time-like region
  - Polarization observables
  - Eperimental check of radiative corrections: measurement of the four momenta of all particles

The discrepancy is NOT among observables (σ, PL and PT) but among derivatives(slope) similar to proton radius problem

Dipole Approximation and pQCD

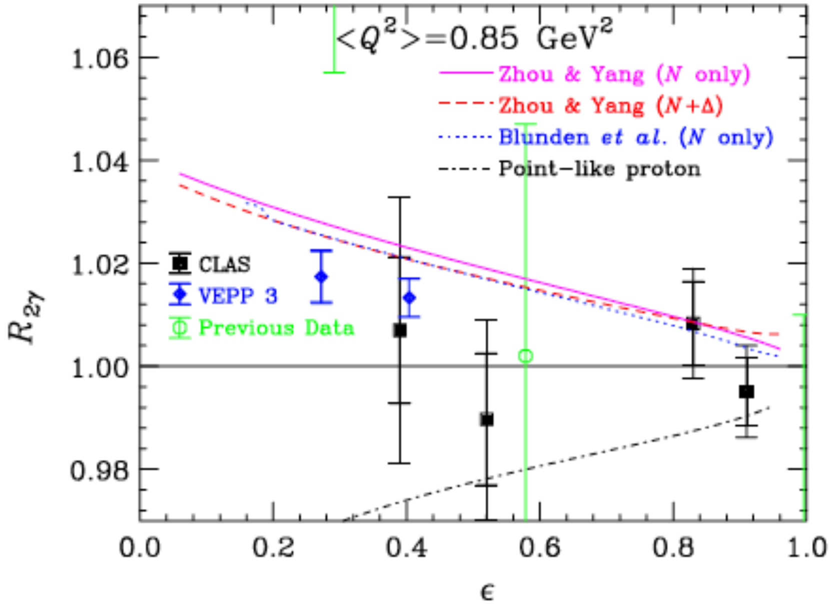


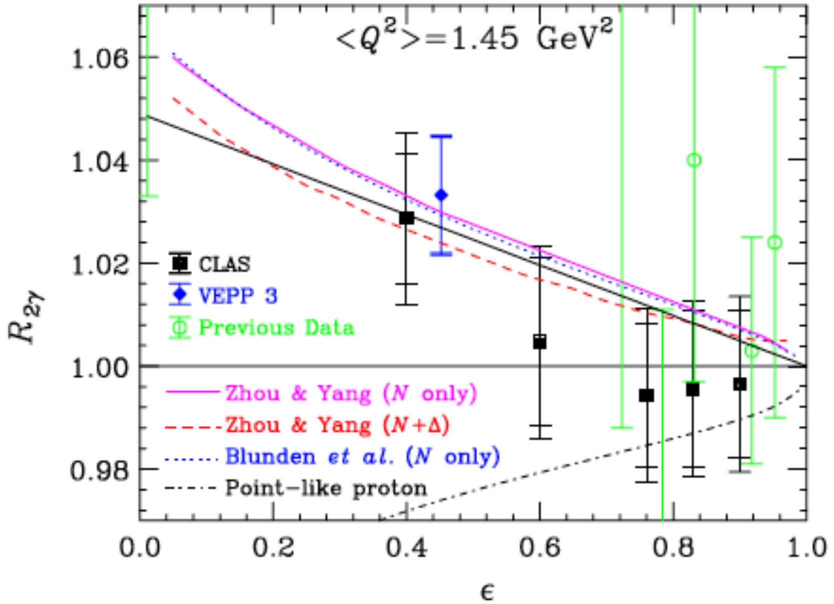
Dimensional scaling

- $F_n(Q^2) = C_n\, [1/(1+Q^2/m_n)^{n-1}]$,
  - $m_n = n\beta^2$, <quark momentum squared>
  - n is the number of constituent quarks
- Setting $\beta^2 = (0.471 \pm .010)$ GeV^2 *(fitting pion data)*
  - pion: $F_\pi(Q^2) = C_\pi\, [1/(1+Q^2/0.471\ \mathrm{GeV}^2)^1]$,
  - nucleon: $F_N(Q^2) = C_N\, [1/(1+Q^2/0.71\ \mathrm{GeV}^2)^2]$,
  - deuteron: $F_d(Q^2) = C_d\, [1/(1+Q^2/1.41\,\mathrm{GeV}^2)^5]$

V. A. Matveev, R. M. Muradian, and A. N. Tavkhelidze (1973), Brodsky and Farrar (1973), Politzer (1974), Chernyak & Zhitnisky (1984), Efremov & Radyuskin (1980)…

CLAS, VEPP, OLYMPUS….





V. Rimal, ArXiv 1603. 003151

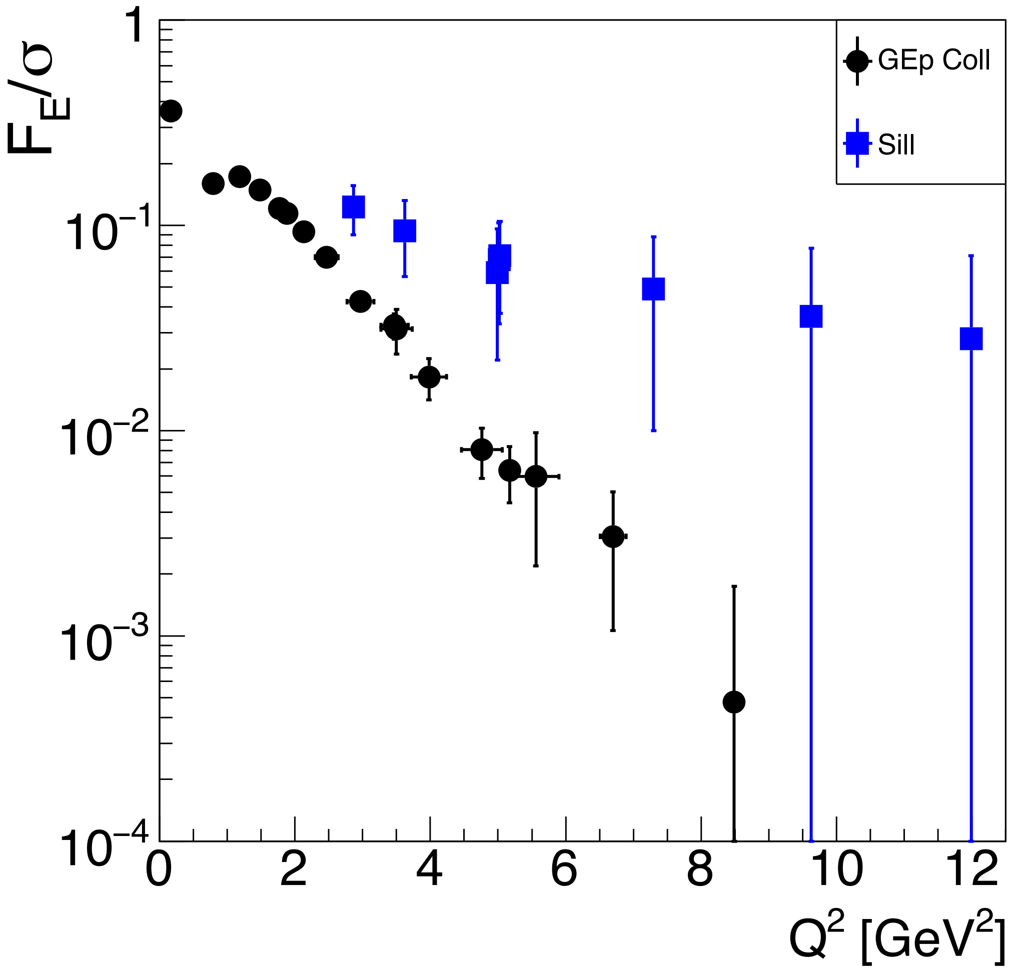
Q^2<2 GeV2

Effect < 2%

No evident increase with Q^2

Electric contribution to ep cross section

$$F_E = \frac{\epsilon G_E^2}{1+\tau/(\epsilon R^2)}.$$



$$\sigma_R = \varepsilon G_E^2 + \tau G_M^2$$

$G_E \approx G_D$

$G_E < G_D$

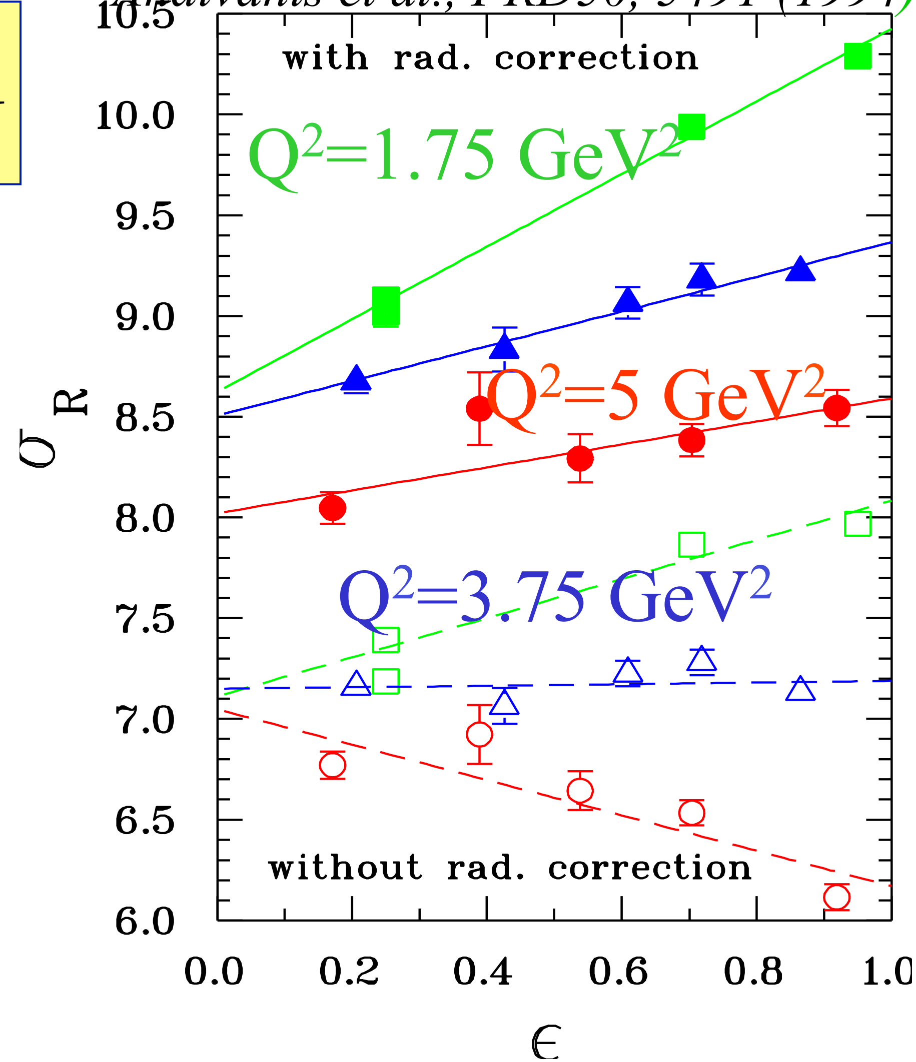
Radiative Corrections (ep)

$$\sigma_R = \varepsilon G_E^2 + \tau G_M^2$$

May change the slope of σ_R (and even the sign !!!)

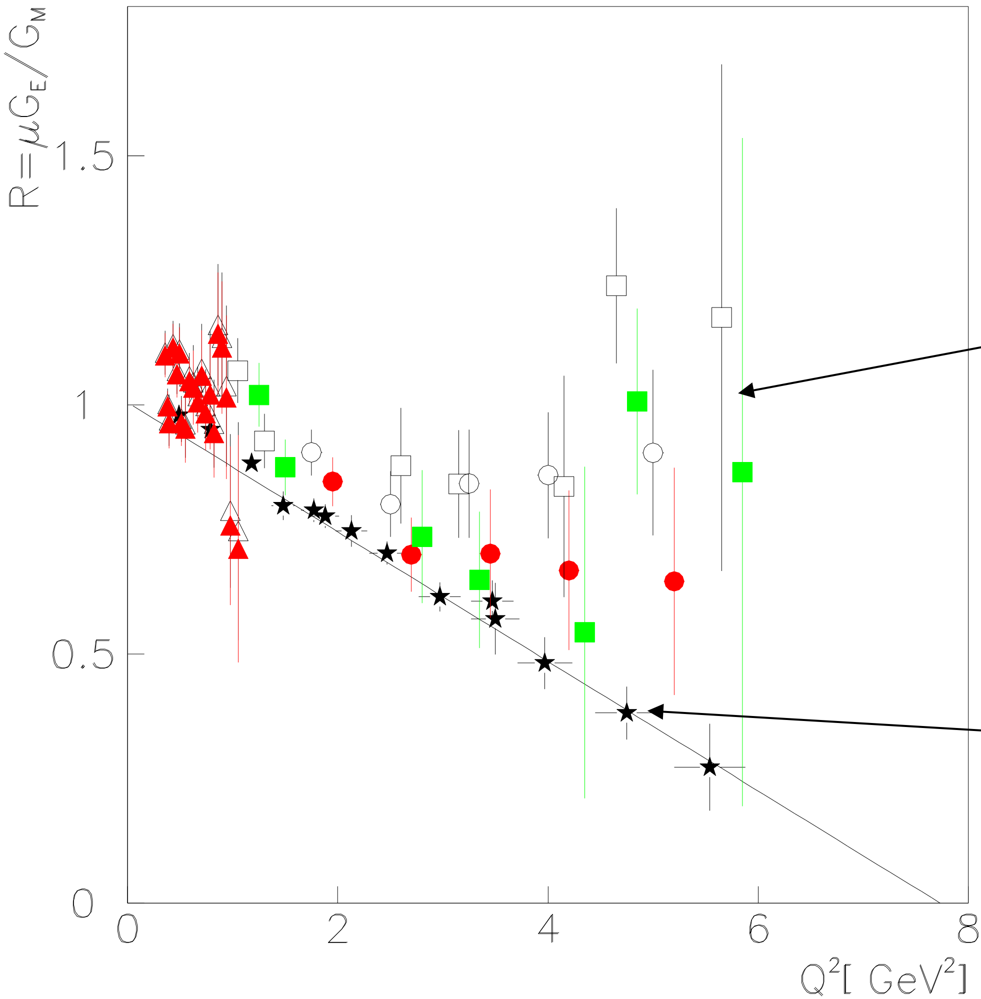
RC to the cross section:
- *large (may reach 40%)*
- *ε and Q^2 dependent*
- *calculated at first order*

Andivahis et al., PRD50, 5491 (1994)



E. T.-G., G. Gakh, PRC 72, 015209 (2005)

Radiative Corrections (SF method)



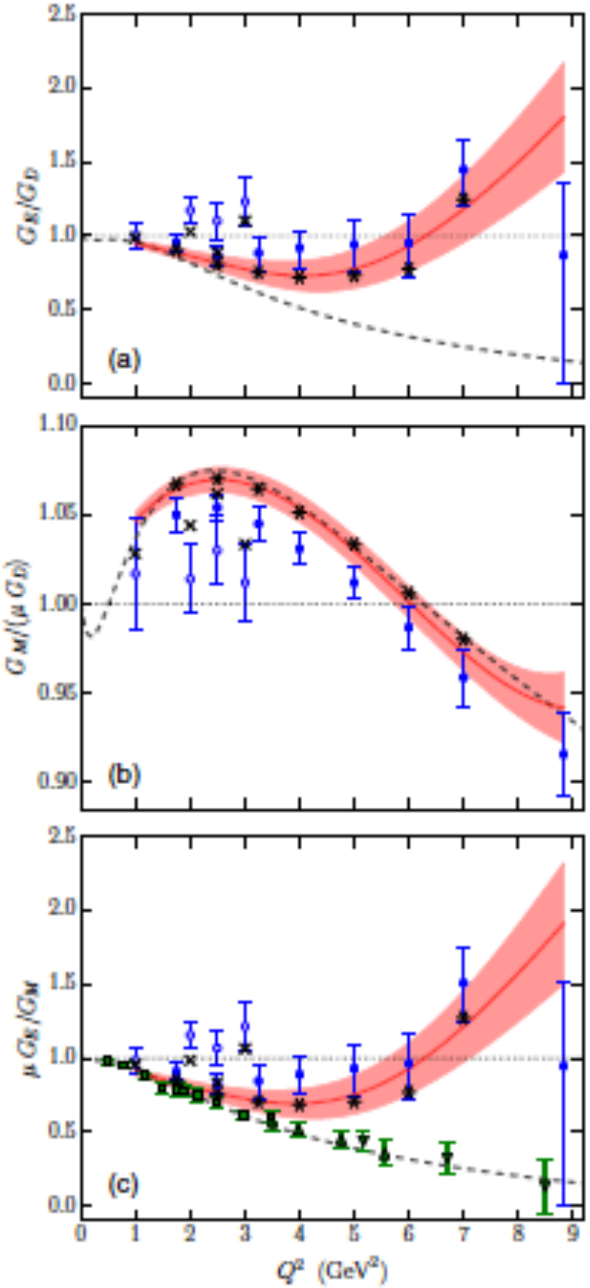
Andivahis et al., PRD50, 5491 (1994)

SLAC data

SLAC data
corrected by SF

Jlab Polarization data

Yu. Bystricky, E.A.Kuraev, E. T.-G, Phys. Rev. C 75, 015207 (2007)



PHYSICAL REVIEW C 93, 055201 (2016)

Reanalysis of Rosenbluth measurements of the proton form factors

A. V. Gramolin* and D. M. Nikolenko
Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia
(Received 28 March 2016; published 10 May 2016)

V. Fadin ,R.E.Gerasimov

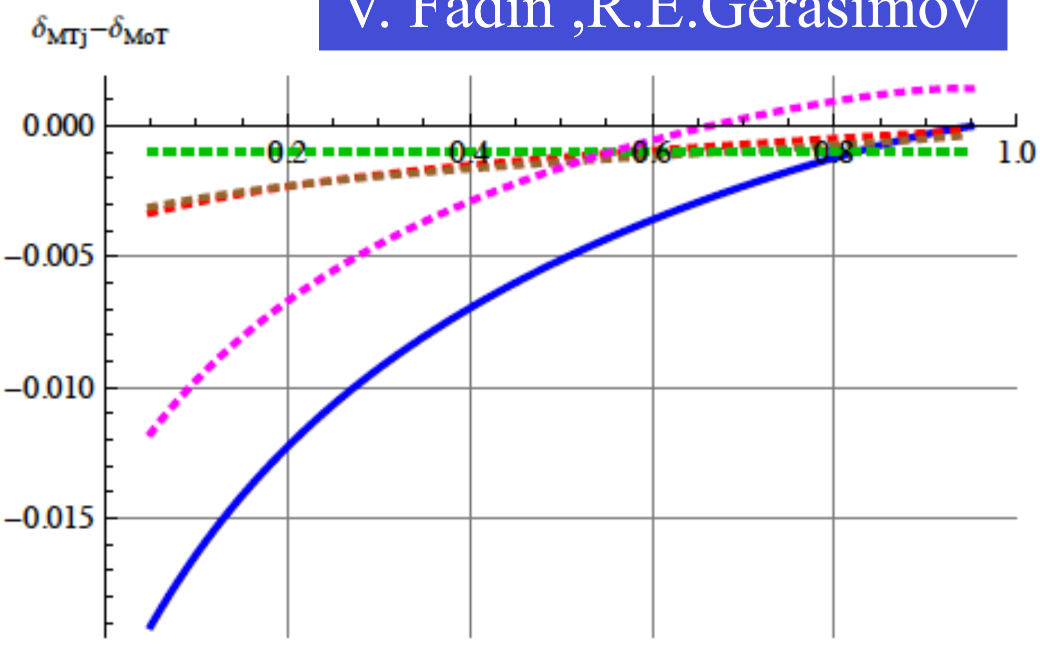
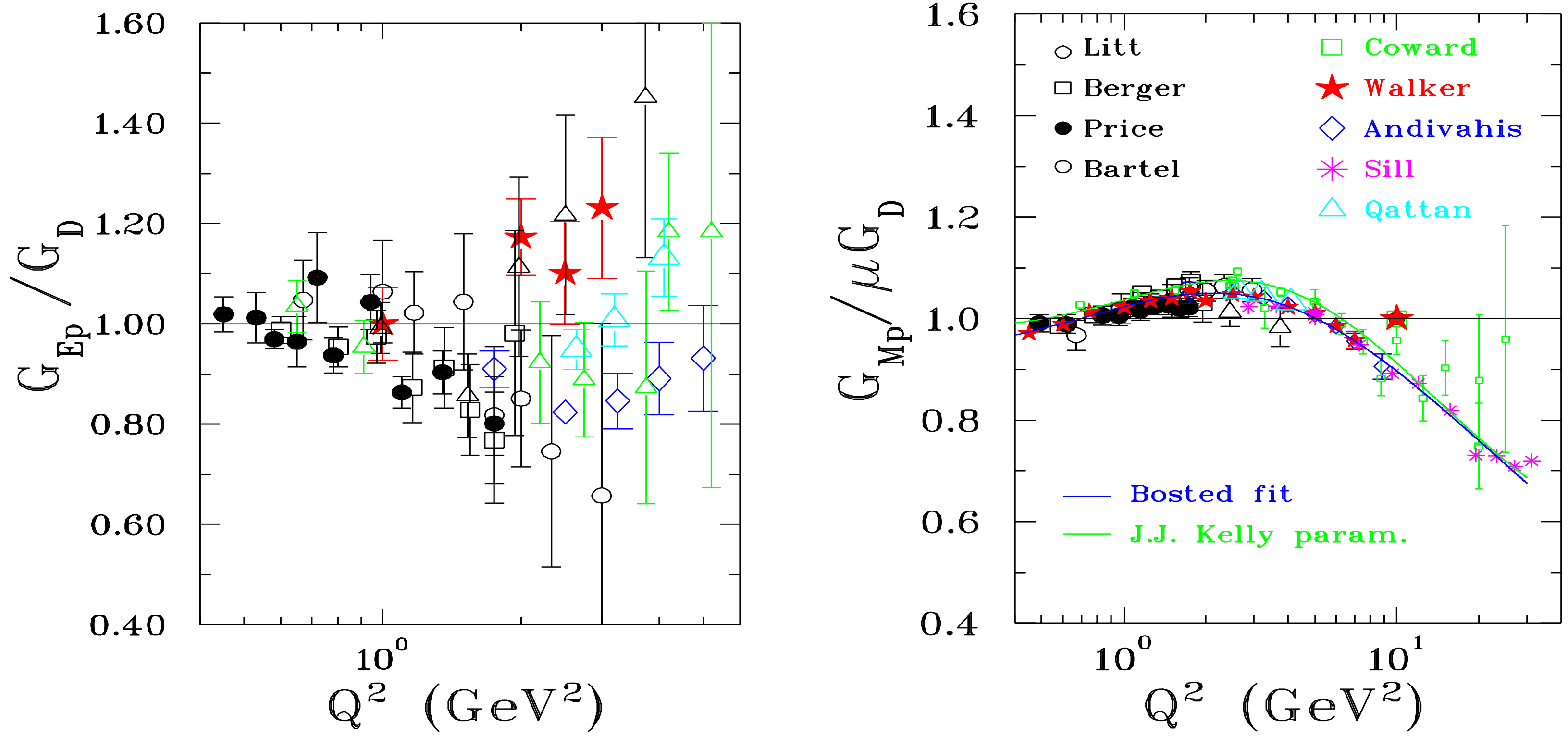


Figure 3: Difference at $Q^2 = 5\ GeV^2$.

Proton Form Factors ... before

Dipole approximation: $G_D=(1+Q^2/0.71\ GeV^2)^{-2}$



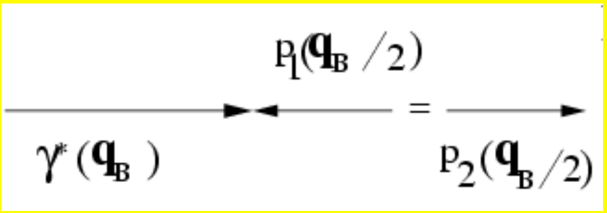
Rosenbluth separation/ Polarization observables

V. Punjabi, M. Jones,C. Perdrisat et al, JLab-GEp collaboration

Dipole Approximation

$$G_D=(1+Q^2 / 0.71\ GeV^2)^{-2}$$

- Classical approach
  - Nucleon FF (in non relativistic approximation or in the Breit system) are Fourier transform of the charge or magnetic distribution.



Breit system

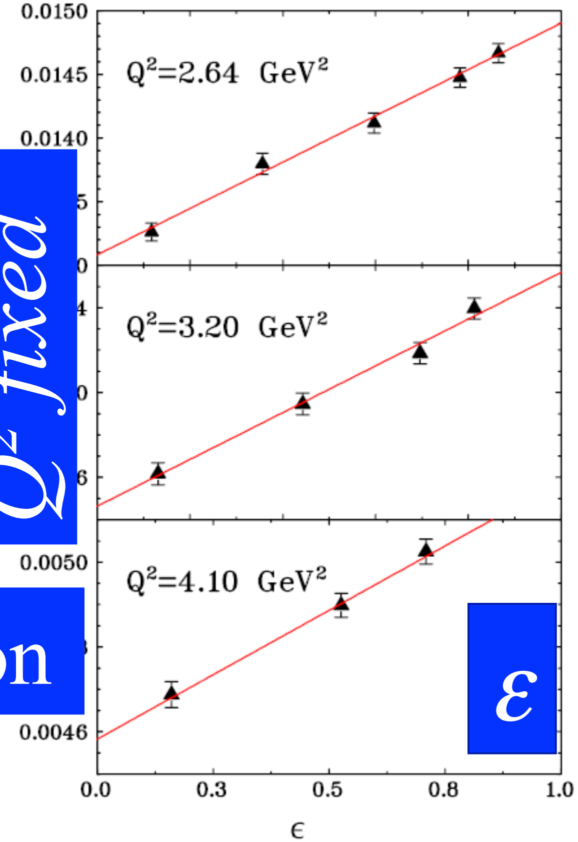
- The dipole approximation corresponds to **exponential density distribution.**
  - $\rho = \rho_0 \exp(-r/r_0)$,
  - $r_0^2 = (0.24\ fm)^2$, $<r^2> \sim (0.81\ fm)^2 \leftrightarrow m^2_D = 0.71\ GeV^2$

The Rosenbluth separation

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

$$\varepsilon = \left(1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right)^{-1}, \tau = \frac{Q^2}{4M^2}$$

$$\sigma_R = \varepsilon G_E^2 + \tau G_M^2$$



Q^2 *fixed*

ε

Linearity of the reduced cross section

→ $\tan^2\theta_e$ dependence

→ Holds for 1γ exchange only

PRL 94, 142301 (2005)

The Akhiezer-Rekalo method (1967)

SOVIET PHYSICS – DOKLADY VOL. 13, NO. 6 DECEMBER, 1968

PHYSICS

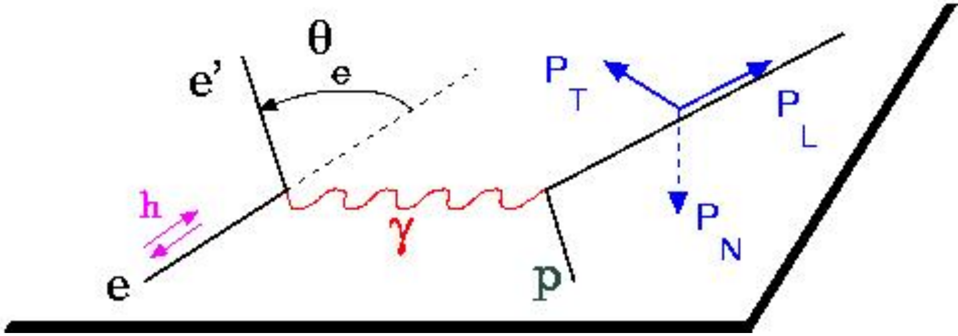
POLARIZATION PHENOMENA IN ELECTRON SCATTERING BY PROTONS IN THE HIGH-ENERGY REGION

Academician A. I. Akhiezer* and M. P. Rekalo

Physicotechnical Institute, Academy of Sciences of the Ukrainian SSR

Translated from Doklady Akademii Nauk SSSR, Vol. 180, No. 5, pp. 1081–1083, June, 1968
Original article submitted February 26,

$$s_2 \frac{d\sigma}{d\Omega_R} = 4p_2 \frac{(s\cdot q)}{1+\tau}\Gamma(\theta,\ \varepsilon_1)\left[\tau G_M (G_M + G_E) - \frac{1}{4\varepsilon_1} G_M (G_E - \tau G_M)\right],$$



The polarization induces a term in the cross section proportional to $G_E G_M$

Polarized beam and target or

polarized beam and recoil proton polarization

The polarization method (exp: 2000)

Transferred polarization is:

C. Perdrisat et al,
JLab-GEp collaboration

$$P_n = 0$$

$$\pm h P_t = \mp h\, 2\sqrt{\tau(1+\tau)} G_E^p G_M^p \tan\left(\frac{\theta_e}{2}\right) / I_0$$

$$\pm h P_l = \pm h (E_e + E_{e'}) (G_M^p)^2 \sqrt{\tau(1+\tau)} \tan^2\left(\frac{\theta_e}{2}\right) / M / I_0$$

Where, $h = |h|$ is the beam helicity

$$I_0 = (G_E^p(Q^2))^2 + \frac{\tau}{\epsilon}(G_M^p(Q^2))^2$$

$$\Longrightarrow \frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l} \frac{E_e + E_{e'}}{2M} \tan\left(\frac{\theta_e}{2}\right)$$

The simultaneous measurement of P_t and P_l reduces the systematic errors