Proton Form Factors: Present and Prospects

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Outline

- Introduction
- Nucleon Form Factors: Born approximation
- Rosenbluth Separation
- Recoil Polarization in elastic ep: Born approx.
- Polarization transfer measurements
- JLab polarization results
- Why the difference?
- Radiative corrections? Two-photon exchange?
- Theoretical Predictions
- Next Experiments in Hall C and 11 GeV LOI
- Conclusions

Introduction

- The “traditional” method to obtain the separated form factors of the proton has been until the end of the 20th century the Rosenbluth separation of cross section data, which gives G^2_{Ep} and G^2_{Mp}
- G_{Ep}/G_{Mp} ratios have been measured in Hall A at JLab for Q^2 from 0.5 to 5.6 GeV^2 in 1998 and 2000, using the recoil polarization technique
- The results obtained from the 2 techniques are incompatible above an invariant four-momentum transfer squared Q^2 of 2-3 GeV^2
- Cross sections require large radiative corrections; affect separation of G^2_{Ep} and G^2_{Mp} significantly
- Form factor ratio G_{Ep}/G_{Mp} from recoil polarization affected by radiative corrections at percent level only.

Continue Introduction

- Current consensus: two-photon exchange, deemed negligible until recently, might explain difference, although several refinements of the calculation of the "usual" radiative correction terms have been shown to require re-examination

- Meanwhile the characterization of the 4 form factors of the nucleon, G_{Ep}, G_{Mp}, G_{En} and G_{Mn}, is slowly improving. There are interesting similarities (and differences) among the 4 form factors data; will not be covered here

- Recent lattice calculations show progress. While waiting for the next level of accuracy in lattice results of the proton form factors, the generalized parton distributions, or GPDs, are increasingly the way to describe the ep data in this non-perturbative range of Q^2

Rosenbluth Separation

- Cross section: $\frac{d\sigma}{d\Omega} = (\frac{d\sigma}{d\Omega})_{Mott} \times$
  $\left\{F_1^2(Q^2) + \tau\left[F_2^2(Q^2) + 2(F_1(Q^2) + F_2(Q^2))^2 \tan^2\frac{\theta}{2}\right]\right\}$
- F_1 and F_2 relativistic invariants depending on Q^2 only.

  $G_E = F_1 - \tau\kappa_p F_2$, and $G_M = F_1 + \kappa_p F_2$.
- $\frac{d\sigma}{d\Omega} = (\frac{d\sigma}{d\Omega})_{Mott}\left\{G_E^2 + \frac{\tau}{\epsilon}G_M^2\right\}/(1+\tau)$,
  with $\tau = \frac{Q^2}{4M_p^2}$ and $\epsilon = \frac{1}{1+2(1+\tau)\tan^2\frac{\theta}{2}}$
- Modern extraction of G_E and G_M from differential cross section data by Rosenbluth separation method.

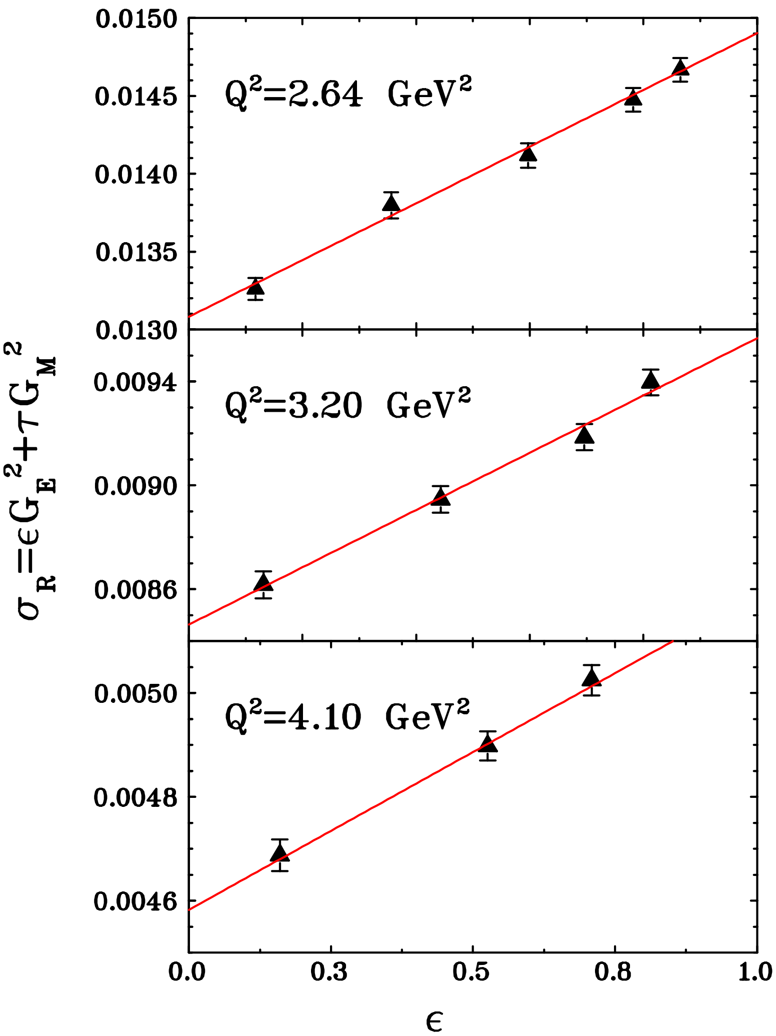
$$\boxed{\sigma_R = \epsilon(1+\tau)\frac{d\sigma}{d\Omega}/(\frac{d\sigma}{d\Omega})_{Mott} = \epsilon G_E^2 + \tau G_M^2}$$

at fixed τ.

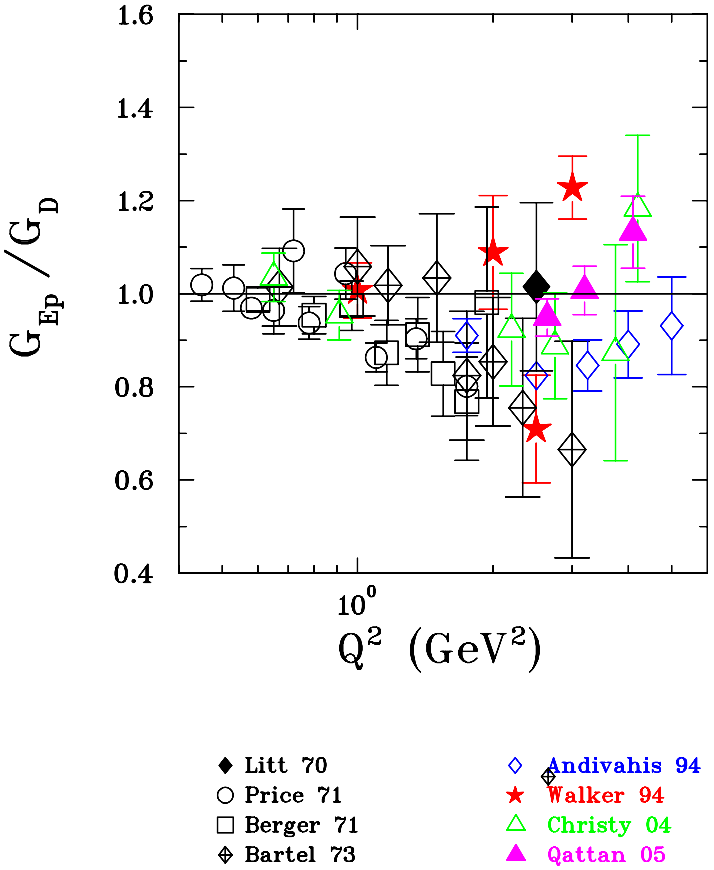
Separated FF by Rosenbluth method

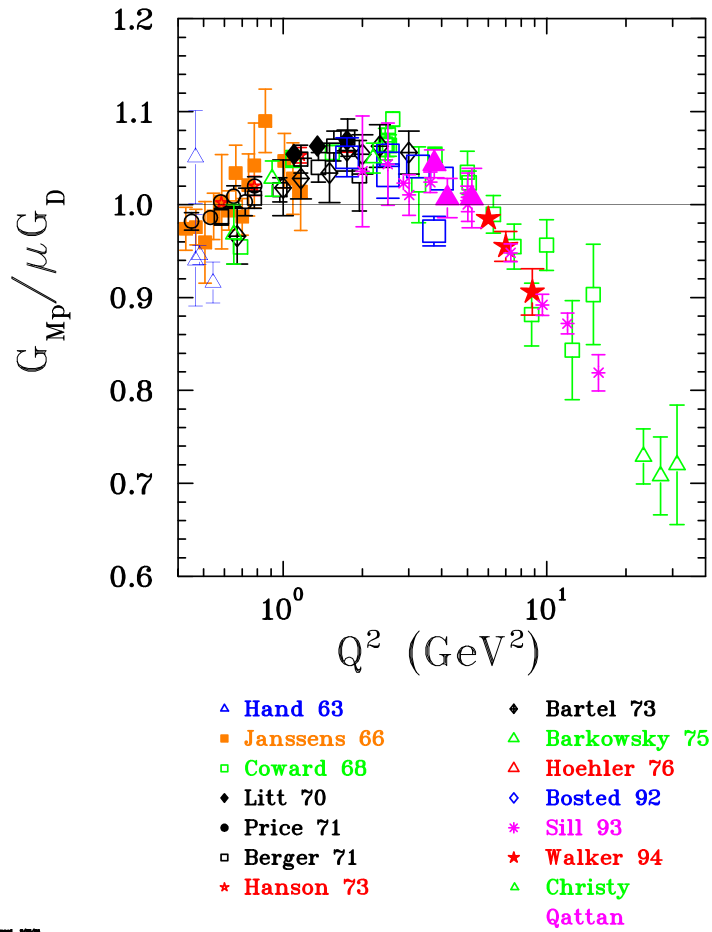
Jlab experiment 01-001:

I. A. Qattan *et al.*, Phys. Rev. Lett. **94**, 142301 (2005).

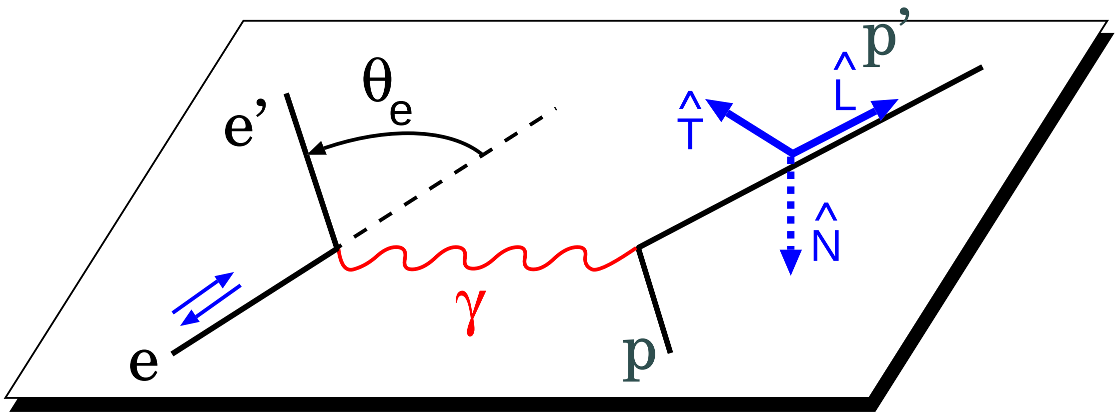


Rosenbluth World data





Spin Transfer Reaction ^{1}H$(\vec{e}, e' \vec{p})$



Transferred polarization is: (Akhiezer & Rekalo, 1968)

$$P_n = 0$$

$$hP_eP_t = -hP_e\, 2\sqrt{\tau(1+\tau)}G_{Ep}G_{Mp}\tan\left(\frac{\theta_e}{2}\right)/I_0$$

$$hP_eP_l = hP_e\frac{(E_e + E_{e'})}{M}G^2_{Mp}\sqrt{\tau(1+\tau)}\tan^2\left(\frac{\theta_e}{2}\right)/I_0$$

P_e beam polarization, $h = \pm 1$ beam helicity

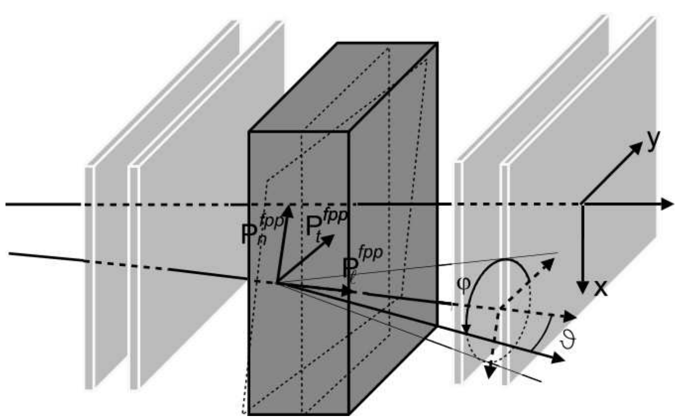
$$I_0 = G^2_{Ep}(Q^2) + \frac{\tau}{\epsilon}G^2_{Mp}(Q^2)$$

$$\Longrightarrow \frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

No error contributions from analyzing power and beam polarization

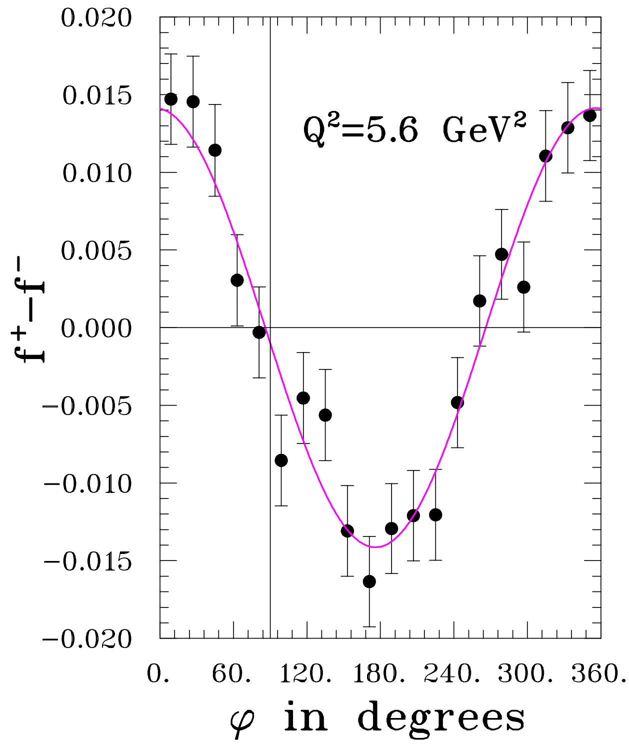
Polarization Transfer Experiments

- Measure asymmetry distribution after rescattering in analyzer.
- For two helicities of beam with polarization P_e, relative asymmetry in polarimeter is:
- $f^{\pm}(\varphi) = \frac{1}{2\pi}\left(1 \pm A_y|P_e|(P_t^{fpp} sin\varphi - P_n^{fpp} cos\varphi)\right)$
- P_n^{fpp} and P_t^{fpp} the physical asymmetries at the FPP
- A_y is analyzing power and φ azimuthal scattering angle



φ Distribution and Physical Asymmetries

- At the largest Q^2 of 5.6 GeV^2, proton momentum of 3.8 GeV/c



Physical asymmetries are obtained from difference distribution

$$D_i = (f_i^+ - f_i^-)/2$$
$$D_i = \frac{1}{2\pi}\left(A_y P_t^{fpp} \sin\varphi_i - A_y P_n^{fpp} \cos\varphi_i\right)$$

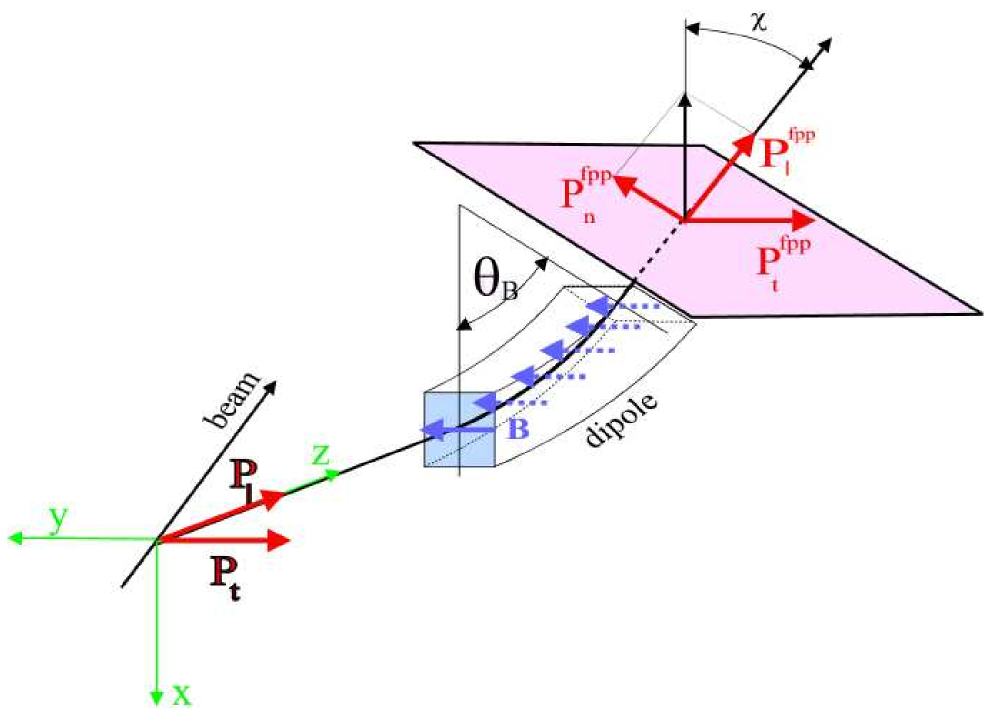
sum distribution gives instrumental asymmetries

$$E_i = (f_i^+ + f_i^-)/2$$
$$E_i = \frac{\epsilon_i}{2\pi}$$

Spin Precession

- The method requires accurate reconstruction of the polarization rotation occurring in the spectrometer magnetic elements.
- Code COSY to calculate 3×3 spin transfer matrix (S)

$$P^{fpp} = (S)P \tag{1}$$

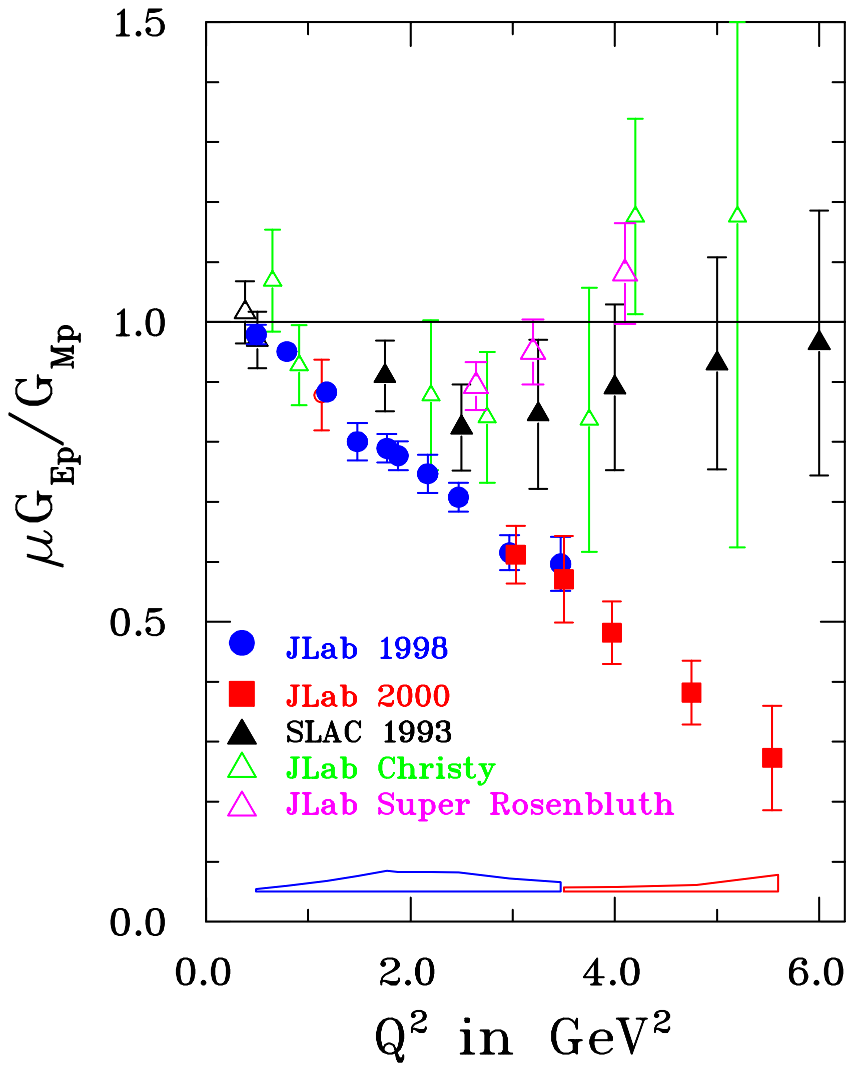


$$\boxed{\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell}\frac{E_e + E'_e}{2m_p} tan\frac{\theta_e}{2}}$$

- where now P_t and P_ℓ are reaction polarization components.

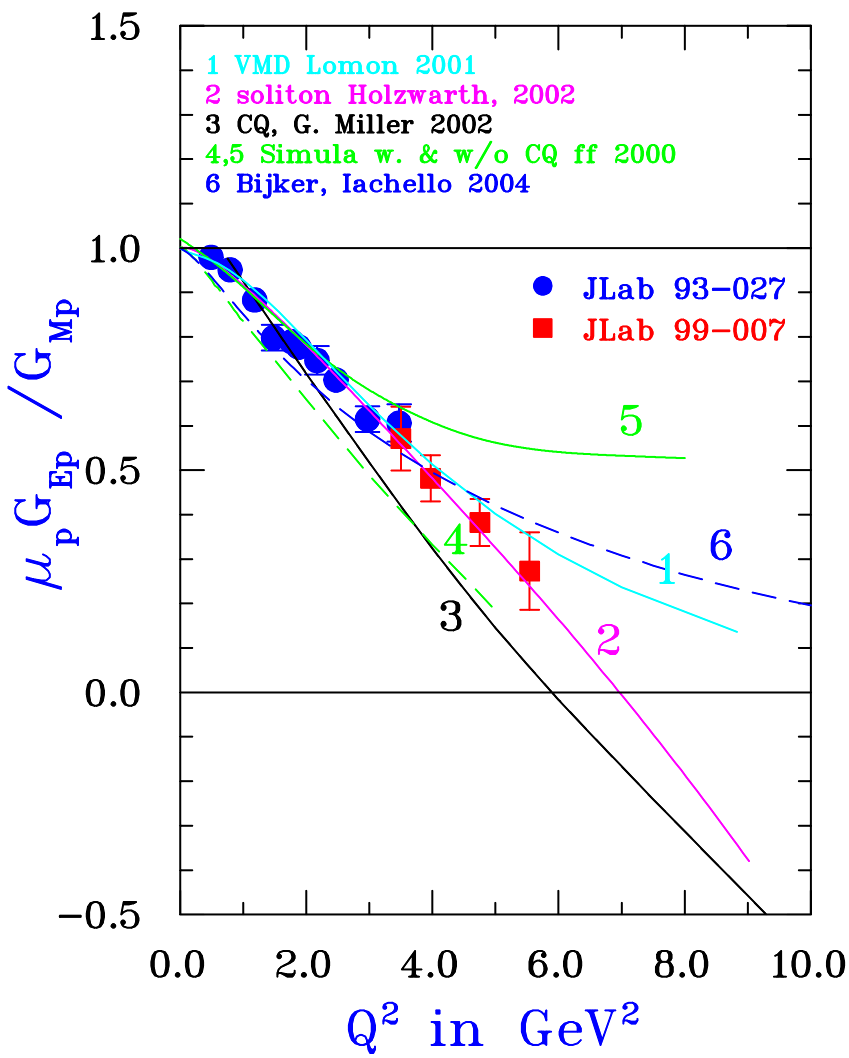
Current Results for G_{Ep}/G_{Mp}

Most recent Rosenbluth and JLab recoil polarization results.

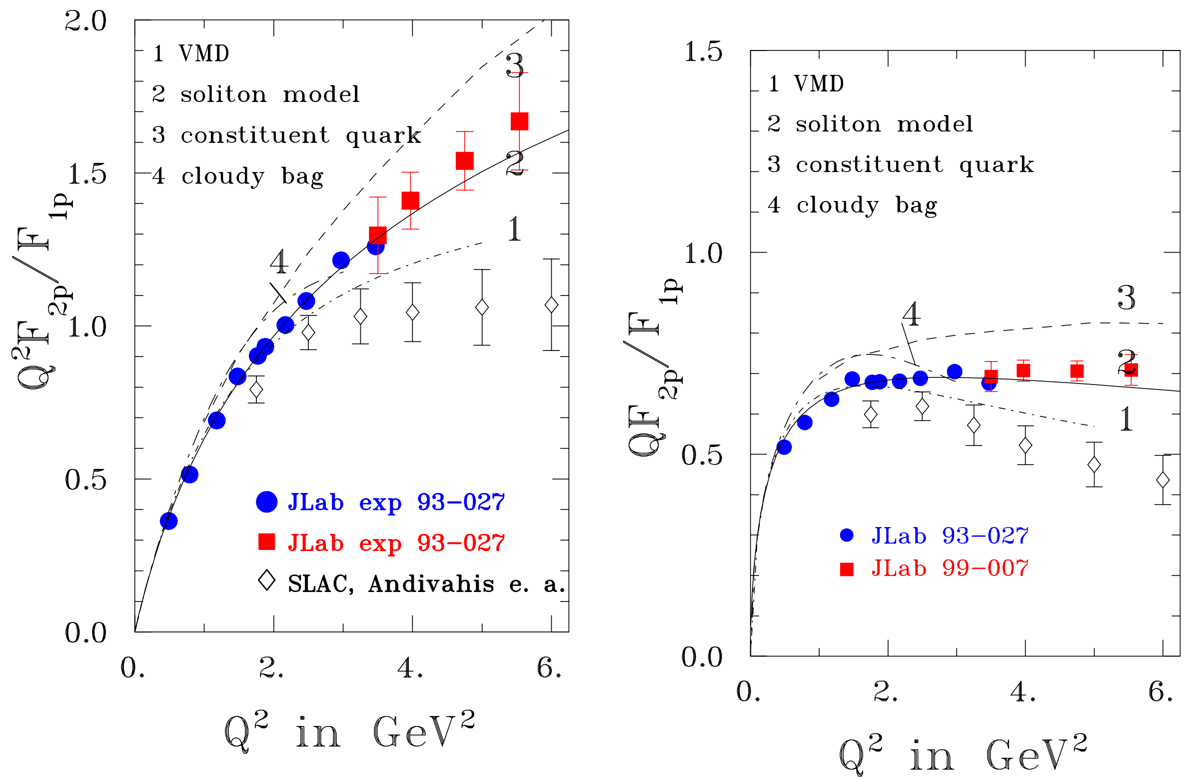


- M.K. Jones et al, P.R.L. **84**, 1398 (2000)
- O. Gayou et al, P.R.L. **88**, 092301 (2002)
- V. Punjabi et al, P. R. C **71**, 055202 (2005)

Sample of Theoretical Model Predictions

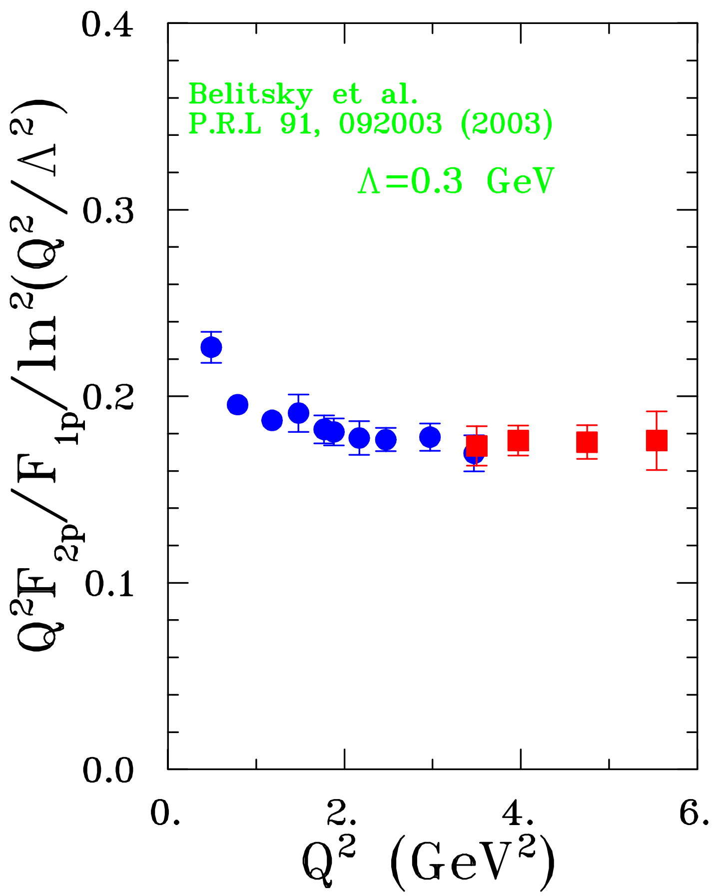


Comparison with early pQCD prediction



- perturbative QCD requires $F_2/F_1 \propto \frac{1}{Q^2}$ from counting rules (Brodsky and Farrar)
- data indicate $F_2/F_1 \propto \frac{1}{Q}$ in this range of Q^2

Recent pQCD forms

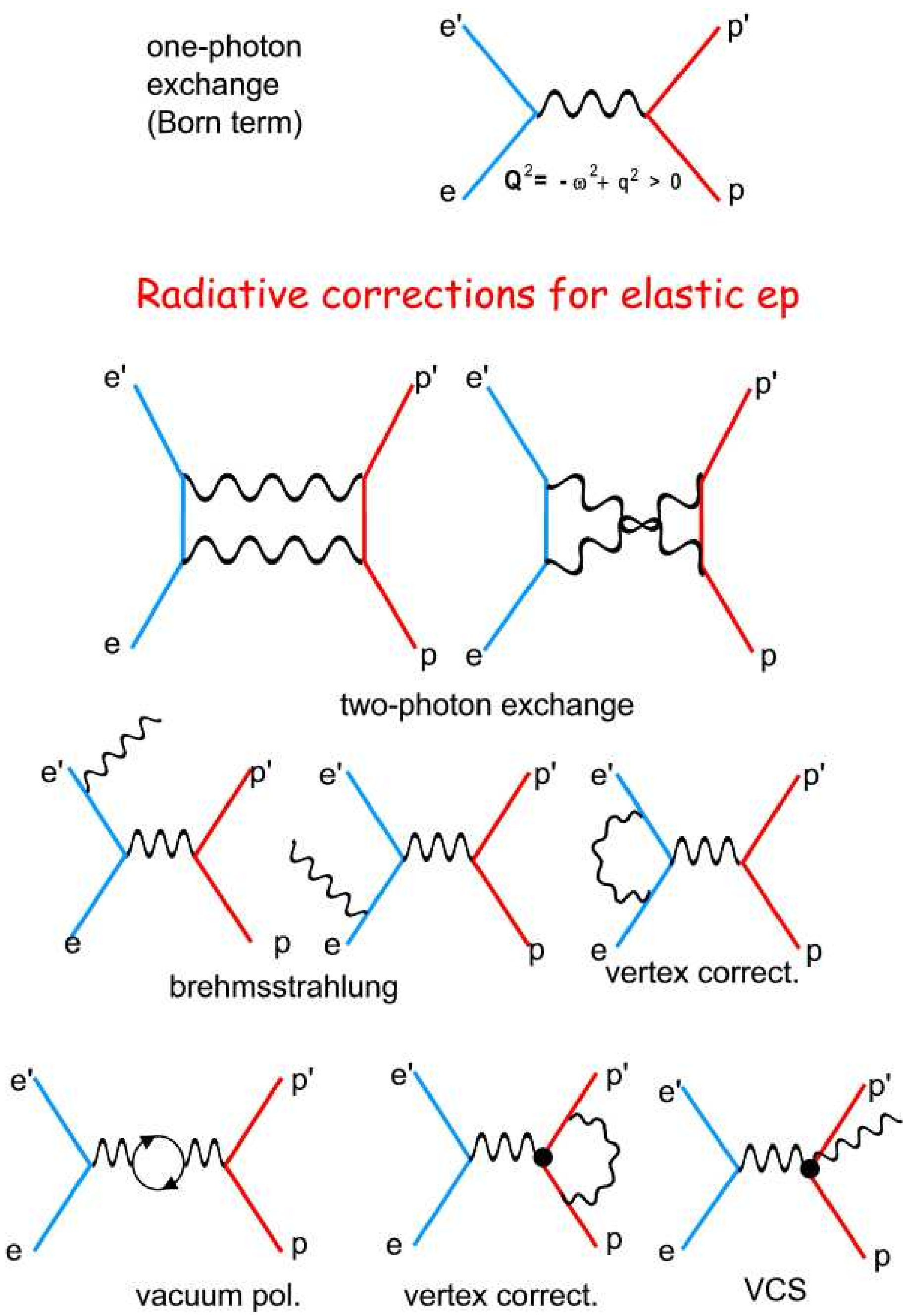


- pQCD motivated behavior of F_2 introduces logarithmic terms (Brodsky); not shown here
- Spin flip associated with F_2 requires quark in non-zero orbital angular momentum (Belitsky et al.).
  $\Lambda \sim 200 - 400 MeV \sim \Lambda_{QCD}$

Sources of the discrepancy

- Radiative corrections (RC) affect ep cross sections in single arm experiments $\sim$ by up to 30% and are ϵ-dependent. Slope of Rosenbluth plot affected, and therefore the value of G_{Ep}^2
- RC for SLAC data follow Mo, Mo and Tsai. Other calculations by Maximon and Tjon, Vanderhaeghen et al.
  None includes the inelastic contribution in proton vertex; may require additional revisions
- RC have $\sim$1% effect on the ratio G_{Ep}/G_{Mp} from polarization
- "Super" Rosenbluth separation in Hall A is first $^1H(e,p)e$ measurement; radiative corrections smaller; confirm older data. But is still a single arm experiment! radiative correction may not be final!

Radiative Corrections



Sources, continued

- two-(hard)photon contribution has been neglected until results of both Hall A polarization data; recent work on two-photon includes:

  Guichon and Vanderhaegen,

  Bluenden, Melnitchouk and Tjon

  Tomasi-Gustafsson and Rekalo

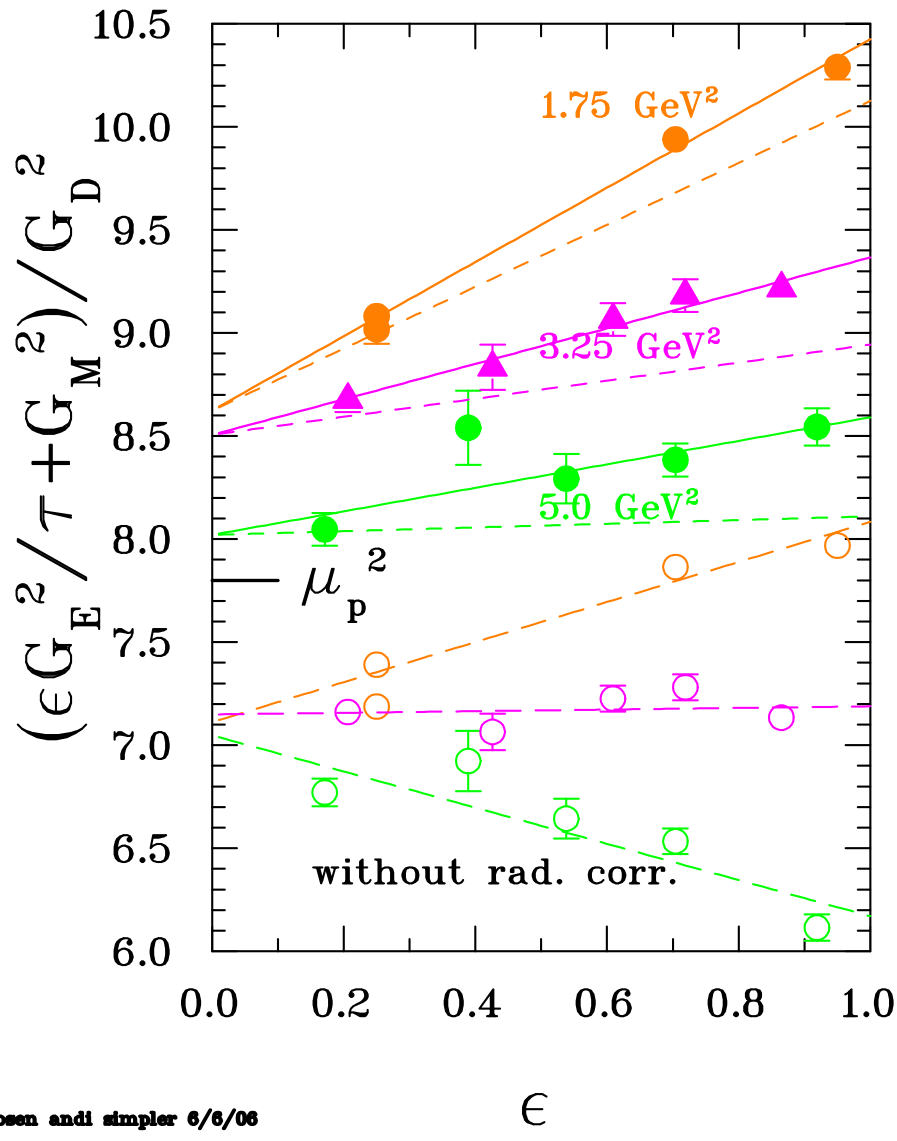
  Afanasev, Brodsky, Carlson, Chen and Vanderhaeghen (2)

  Bystritskiy, Kuraev and Tomasi-Gustafsson

  Jain and Mitra (2006)

- Two-photon exchange affects form factor observables as interference between the single- and two-photon processes

Radiative correction to 1994 SLAC data



For $Q^2 > 3$ GeV^2 the slope of σ_R is changed from negative for the raw data, to positive after radiative correction.

Two-(hard)photon contribution

- In Born term only 2 real form factors $G_M(Q^2)$ and $G_E(Q^2)$ or $F_1(Q^2)$ and $F_2(Q^2)$
- With two-photon term the T-matrix depends on 3 complex amplitudes, $\tilde{G}_M$, $\tilde{F}_2$ and $\tilde{F}_3$, functions of Q^2 and ϵ:

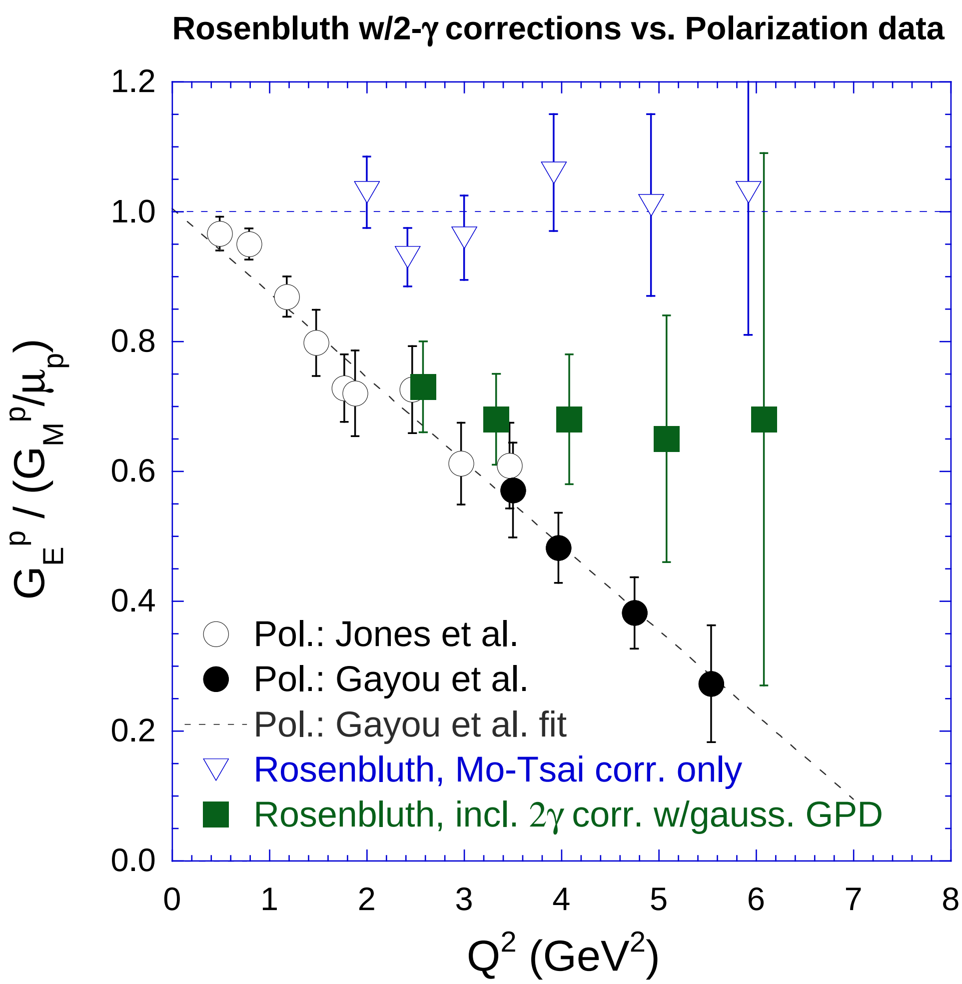
$$T = \frac{e^2}{Q^2}\overline{u}(k')\gamma_\mu u(k)\overline{u}_p(p')\left(\tilde{G}_M\gamma^\mu - \tilde{F}_2\frac{P^\mu}{M} + \tilde{F}_3\frac{\gamma\cdot KP^\mu}{M^2}\right)u(p)$$

- When two-photon contribution negligible: $\tilde{G}_M = G_M$, $\tilde{F}_2 = F_2$ and $\tilde{F}_3 = 0$
- The real part of $\tilde{F}_3$ contributes to the ep cross section and to the difference of the cross sections for e^+p and e^-p
- The imaginary part of $\tilde{F}_3$ determines the induced polarization in ep (not measured yet), and the asymmetry in $e\vec{p} \to ep$ (not measured yet) and $\vec{e}p \to ep$ (observed to be ~8 ppm).

Two-photon from GPDs

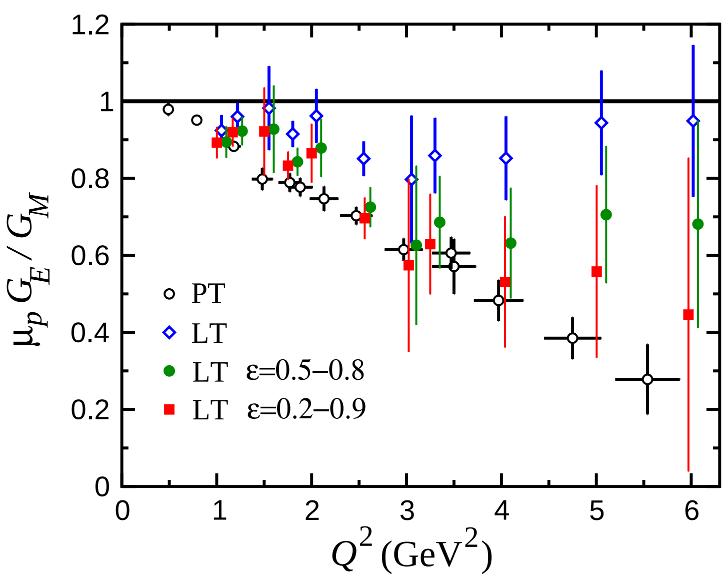
- Afanasev, Brodsky, Carlson, Chen and Vanderhaeghen: box diagram with GPDs
- GPDs from Guidal, Polyakov, Radyushkin and Vanderhaegen

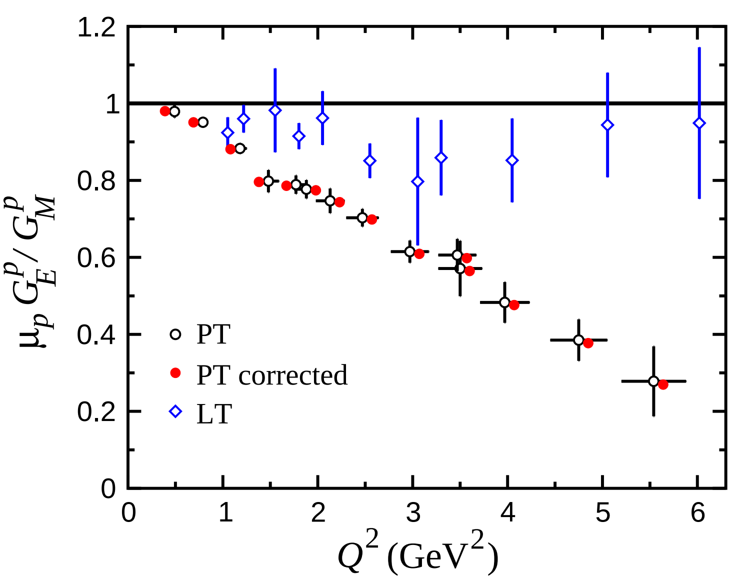
The result:



Two-photon from Blunden et al

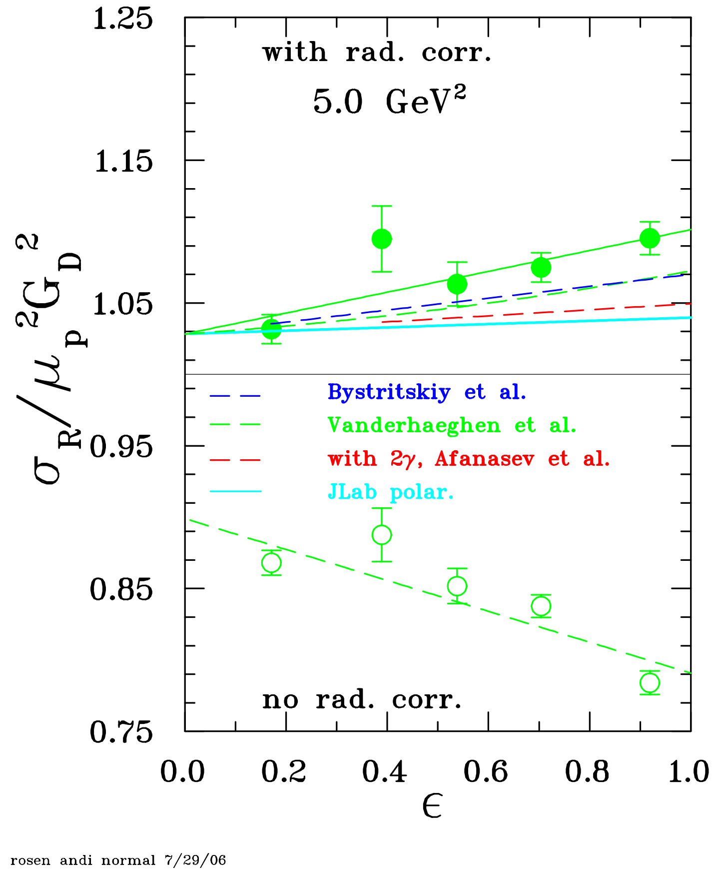
- Two-photon with intermediate state a proton, (including fi nite size effects): cross section and P_t and P_ℓ. Effect on polar. transfer data order ≤ 3%, increasing with Q^2
- Also replace proton by Δ-intermediate state. Effect smaller, of opposite sign, concentrated at small ϵ





PT$\rightarrow$ polarization transfer-, LT$\rightarrow$ L/T separation data

Different corrections to SLAC data



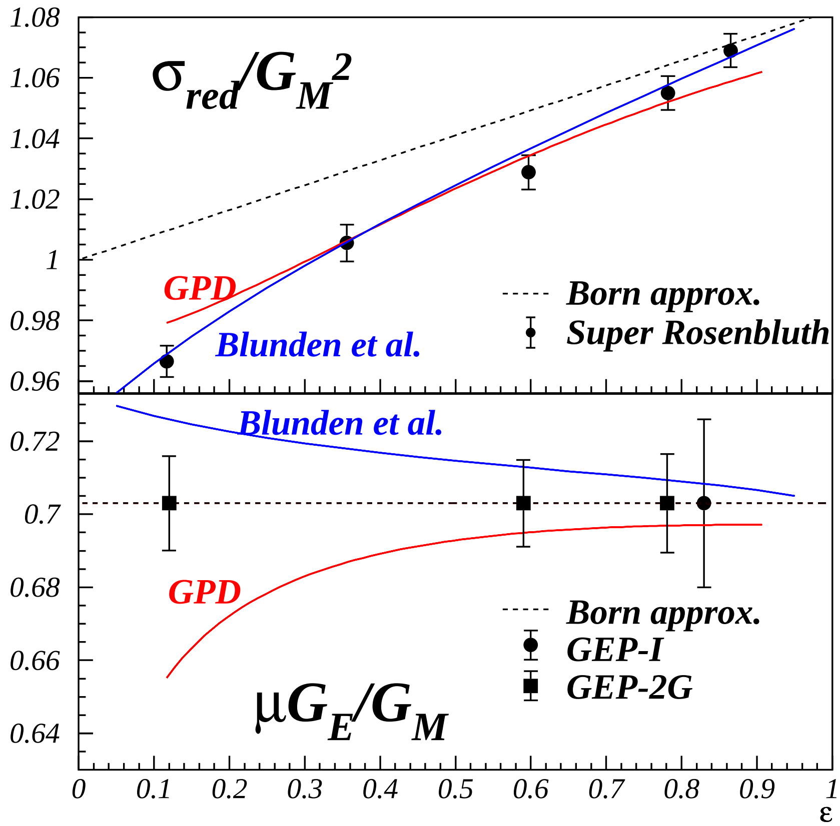
- JLab polar. shows the slope corresponding to the recoil polarization data
- with 2γ, after correction by Afanasev et al
- Vanderhaeghen et al. Radiative correction only, no 2γ term
- Bystritskiy et al. Radiative correction only, using structure function (Drell-Yang)

Two-photon Experiment in Hall C

- Experiment 04-019 in Hall C will measure G_{Ep}/G_{Mp} at fixed Q^2 of 2.6 GeV^2, one of Super Rosenbluth Q^2's.

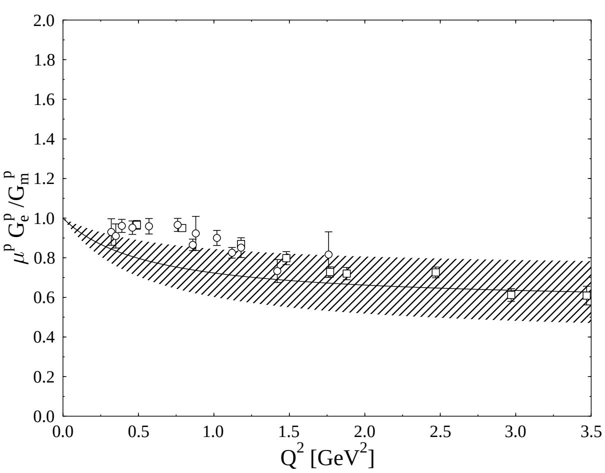
  with 1% statistics at 3 values of ϵ, 0.12, 0.6 and 0.78

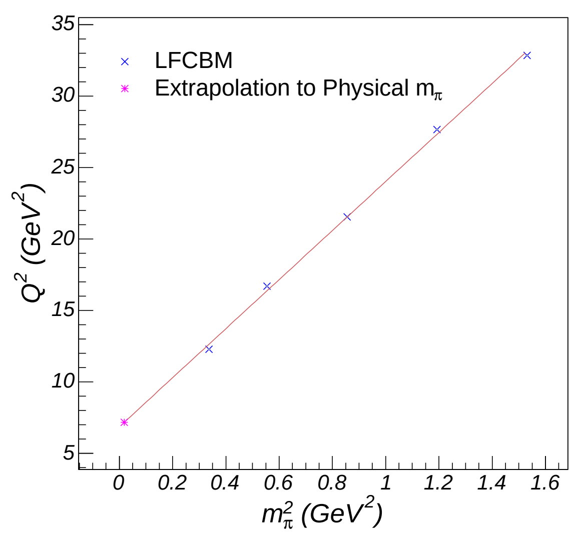
  (R. Suleiman, L. Pentchev, C.F. Perdrisat, R. Gilman)



Predictions from Lattice QCD

- Form factors from lattice QCDSF Collaboration results (Gockeler et al, 2005): lattice size 0.05 fm and π-mass in range 0.6 to 1.2 GeV, $Q^2 \leq 3.5$ GeV^2
- Matevosyan, Thomas and Miller: above results can be fi tted with parameterized form of Light Front Cloudy Bag Model (of G. Miller)
- Extrapolate LFCBM results to large Q^2 and to the physical π-mass

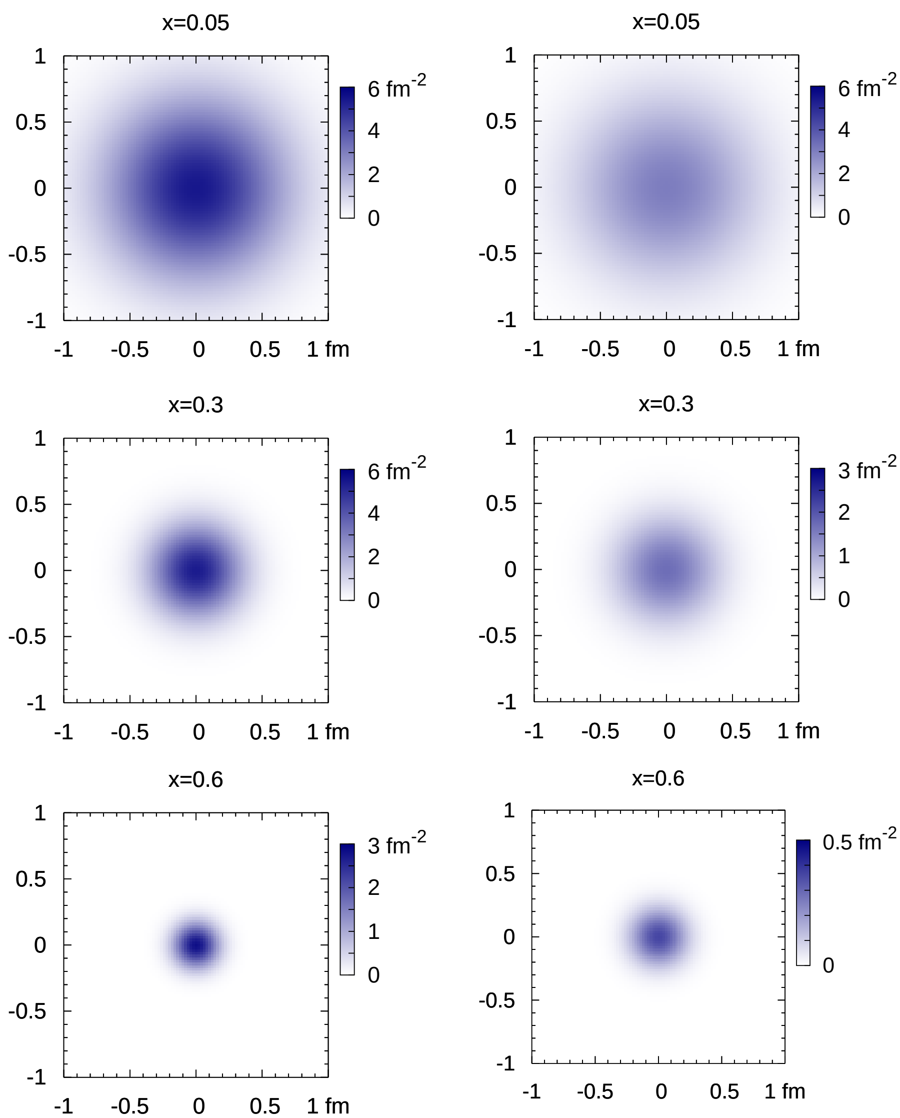




Even though neither form factors are reproduced separately with LFCBM, the zero of G_{Ep}/G_{Mp} appears reasonable!

GPDs from Form Factor Data

- Valence quark GPDs from form factors, Regge phenomenology at small x and reasonable assumptions at large x. $\longrightarrow$ higher moments of GPDs, axial form factors, and tomography



valence up quark valence down quark

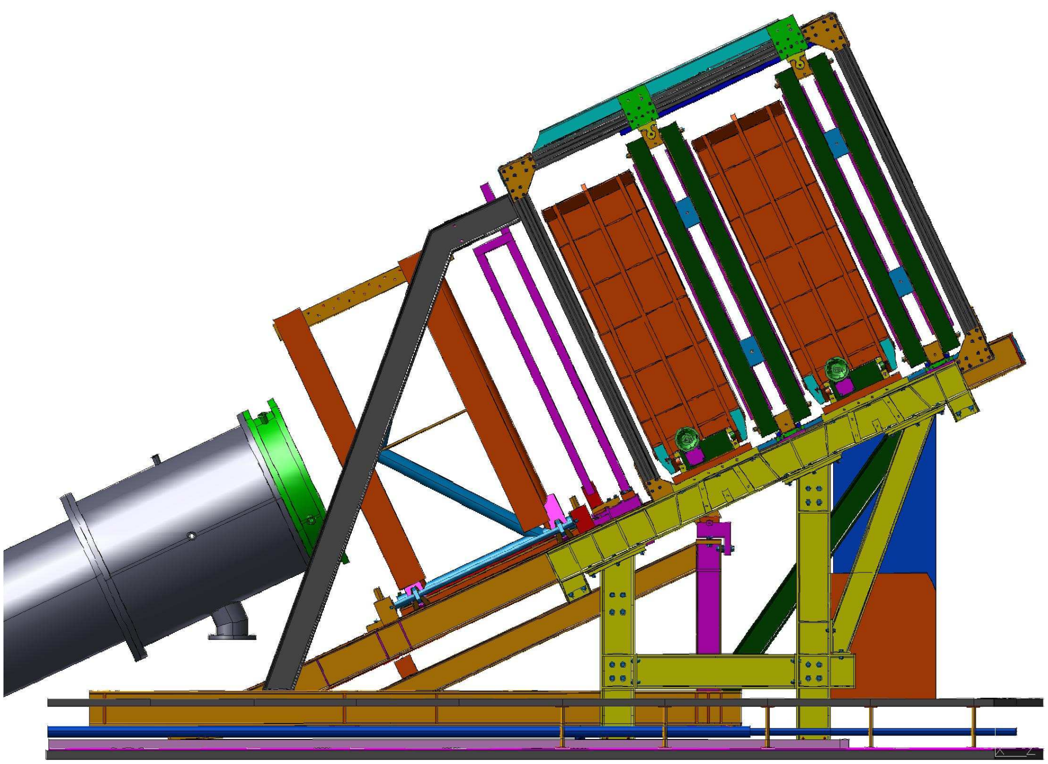
b_x and b_y for given x,Diehl, Feldmann, Jakob and Kroll (2005)

Next G_{Ep} Experiment in Hall C

- Experiment $GEp(III)$ will measure P_t/P_ℓ, and therefore G_{Ep}/G_{Mp} at Q^2=4.5, 7.5 and 9 GeV^2 if E$_{beam}$=6 GeV
- More likely beam energy in second half of 2007 is 5.7 GeV: then Q^2 $\sim$ 8.7 GeV^2
- At highest Q^2 proton momentum is 5.7 GeV/c, requiring the HMS spectrometer in Hall C which is rated to 7.5 GeV/c
- A new polarimeter will be installed in the HMS
- Analyzing power for pCH_2 was measured in Dubna in 2001, up to 5.3 GeV/c (Azhgirey et al, NIM A 538, 431 (2005))
- Detection of electron requires very large solid angle detector: lead-glass calorimeter

New Polarimeter in HMS

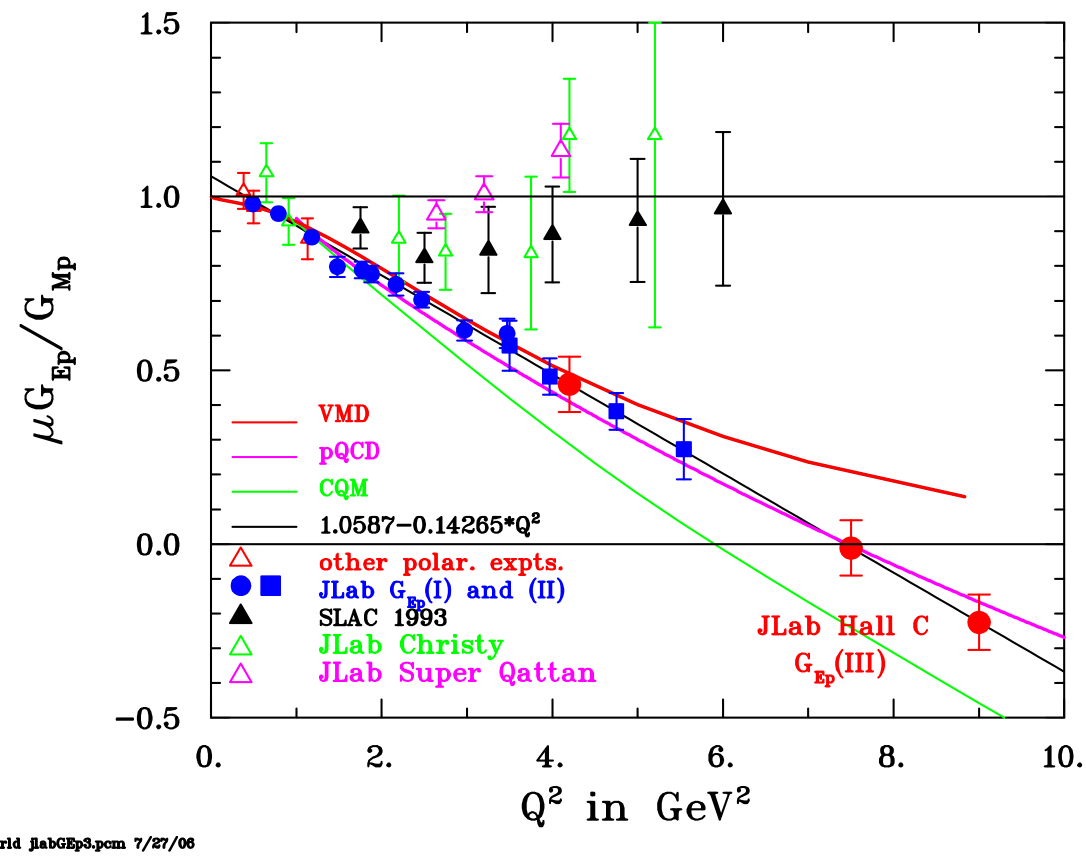
- New experiment to Q^2=9 GeV^2 requires better polarimeter
- Increasing analyzer thickness does not work
- Increasing the number of polarimeters in series does work
- Chose confi guration with two identical FPPs in series



Calorimeter BigCal

- Larger Q^2 only possible if electron detector solid angle matches spectrometer solid angle. At Q^2=9 GeV^2, requires $\Delta\Omega_e$=140 msr (HMS has 7 msr): lead glass calorimeter
- 1744 lead-glass bar calorimeter, 1024 from Protvino, 720 from Yerevan; 4x4 cm^2, length 45 and 40 cm.
- detect Čerenkov; insensitive to non-showering particles
- frontal area 2.8 m^2 or 30 square feet

Expected error bars

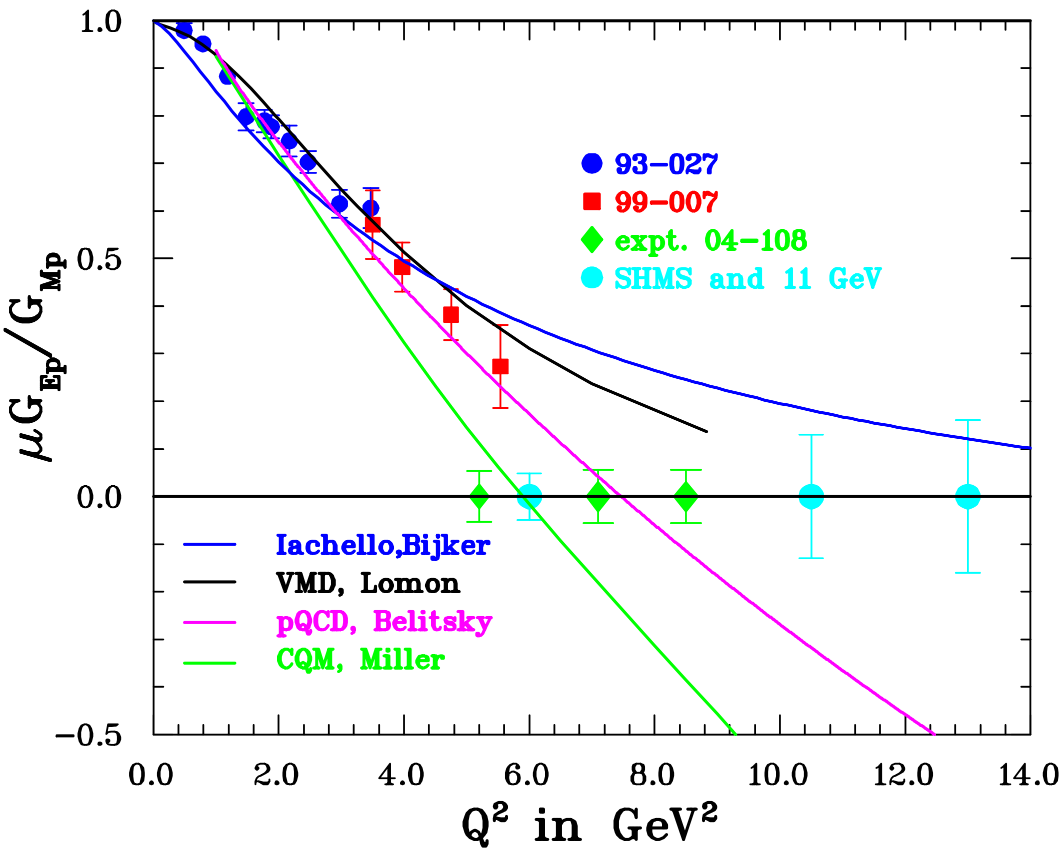


The 3 anticipated new data points are shown as ●, assuming 6 GeV beam energy.

LOI to PAC 30

- With the super HMS (SHMS) to be built for Hall C, Q^2 could be increased to 17 GeV^2.
- Based on current knowledge of analyzing power of CH_2 for protons, and with expected parameters of 11 GeV beam, natural limit is 13 GeV^2; may change after planned new calibration run in Dubna.
- Install polarimeter in SHMS, use BigCal calorimeter for electron as in GEp(III).
- GEp(IV) could take data on day 1 after commissioning of 11 GeV beam and SHMS.

LOI to PAC 30, continued



Conclusions

- The two JLab recoil polarization experiments have revealed that all previous Rosenbluth separation form factors data above Q^2=2-3 GeV^2 were incorrectly interpreted
- Uncertain at this point whether the physical cause for the difference between Rosenbluth and polarization results is incomplete radiative correction or interference of the two-photon process with the Born term, or both
- The history of proton form factor measurements, which has been started by R. Hofstaedter 50 years ago, illustrates the danger of using only one method to measure a given physical observable
- The next measurement, GE$_p$(III) will extend the Q^2 range to 9 GeV^2; the G_{Ep}/G_{Mp} ratio might have changed sign at this Q^2! GEp(IV) would extend measurements to 13 GeV^2 in 2013 (?)
- New neutron form factor measurements are forthcoming: they are very important: the nucleon must be characterized in its two isospin state forms