Nucleon Form Factor Measurements and Interpretation

C.F. Perdrisat

the College of William and Mary, Williamsburg, VA 23187

Exclusive Reactions at High Momentum Transfer

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dedicated to the memory of

James J. Kelly

Outline

- Introduction
- FF from Rosenbluth and recoil polarization (or beam-target asymmetry)
- Form factors of the Proton
- Form factors of the Neutron
- The "discrepancy"
- Recent progress in calculating FF
- Forthcoming experiments
- Conclusions

(see also review in "Progress in Particle and Nuclear Physics", to be published, C.F.P., V. Punjabi and M. Vanderhaeghen, Dec. 1, 2006, arXiv:hep-ph/0612014)

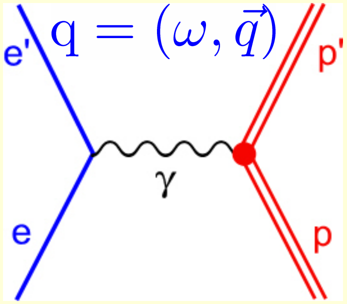
and previous reviews by H. Gao (03)), C. Hyde-Wright and K. de Jaeger (04) and J. Arrington et al.(06

Introduction

- Electromagnetic Form Factors contain structure information on the many-body system of quarks and gluons of the nucleon.
- When obtained from experiment, they are relativistic invariants only to the extent that the probe is a single virtual photon exchanged between electron and nucleon; higher order contributions destroy this invariance, which one should regain after applying a number of radiative corrections.

ep elastic in Born approximation

j_μ=<e'|γ_μ|e>



J_μ=<p'|Γ_μ|p>

$$Q^2 = -q^2 = \vec{q}^{\,2} - \omega^2$$

Nucleon vertex: $$\Gamma_\mu(p, p^0) = \underbrace{\gamma_\mu F_1(Q^2)}_{Dirac} + \underbrace{\frac{i\sigma_{\mu\nu}}{2M} q^\nu F_2(Q^2)}_{\text{Pauli}}$$

F_1 is helicity conserving, F_2 helicity non-conserving form factor

In common usage are the electric- and magnetic form factors

$$G_E(Q^2)=F_1(Q^2)-\tau\, F_2(Q^2)$$
$$G_M(Q^2)=F_1(Q^2)+F_2(Q^2)$$

In the Breit frame, and for small Q^2, G_E and G_M are Fourier transforms of charge- and current distributions

Rosenbluth vs. Recoil Polarization

Cross section $$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{Mott}(G_{Ep}^2 + \frac{\tau}{\epsilon}G_{Mp}^2)/(1+\tau)$$

with $$\tau = \frac{Q^2}{4M^2} \text{ and } \epsilon = \frac{1}{1+2(1+\tau)\tan^2(\frac{\theta_e}{2})}$$

Reduced cross section:

$$\sigma_{reduced} = \epsilon(1+\tau)\frac{d\sigma}{d\Omega}/\frac{d\sigma}{d\Omega}_{Mott}$$
$$= \epsilon G_{Ep}^2 + \tau G_{Mp}^2 = I_0$$

Recoil polarization components

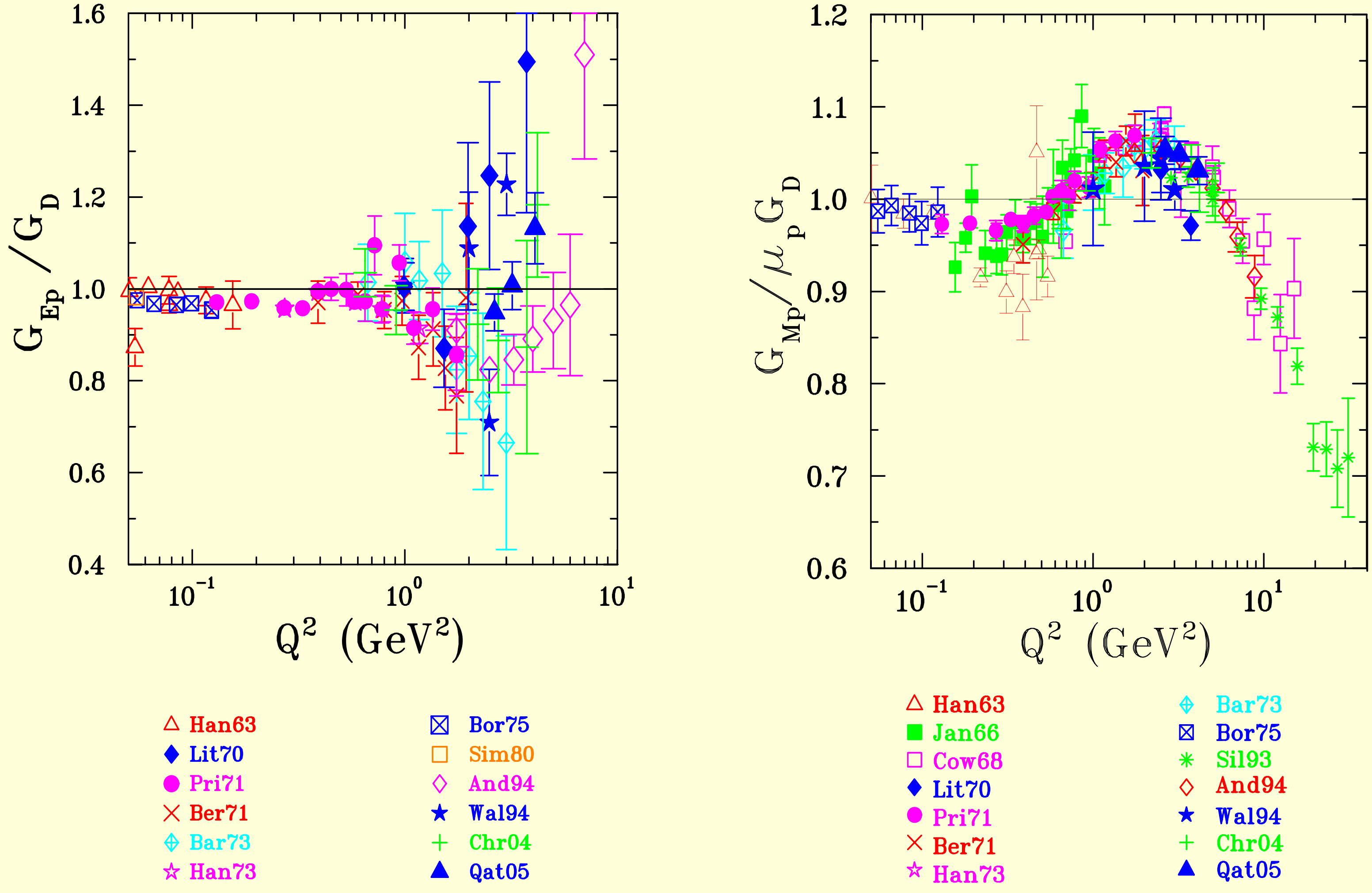
$$hP_eP_t = -hP_e 2\sqrt{\tau(1+\tau)}G_{Ep}G_{Mp}\tan(\frac{\theta_e}{2})/I_0$$
$$hP_eP_\ell = hP_e\frac{(E_e+E_{e'})}{M}G_{Mp}^2\sqrt{\tau(1+\tau)}\tan^2(\frac{\theta_e}{2})/I_0$$

Form Factor ratio:

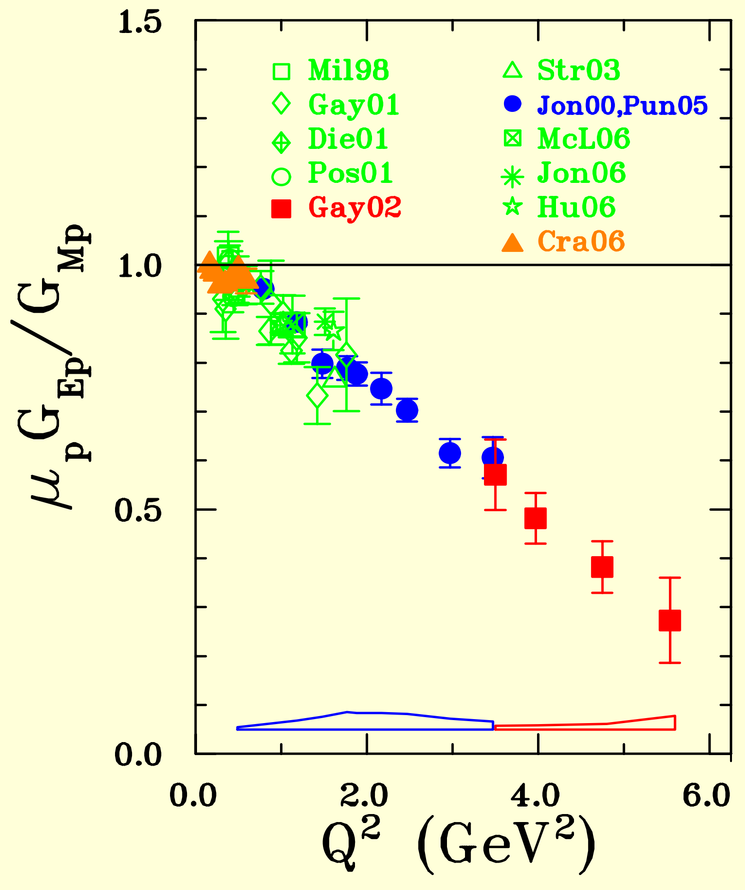
$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell}\frac{(E_e+E_{e'})}{2M}\tan(\frac{\theta_e}{2})$$

all Rosenbluth separation data above 0.05 GeV²

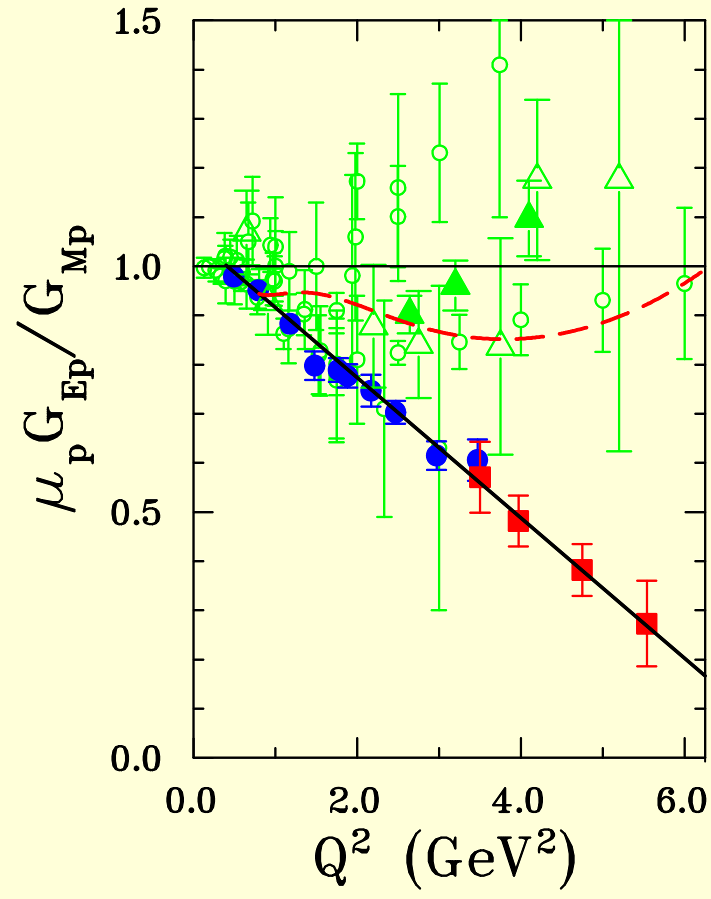
divided by the dipole for factor G_D



Double-polarization experiments, large Q^2



Polarization data only



All data, Arrington and Gayou fits

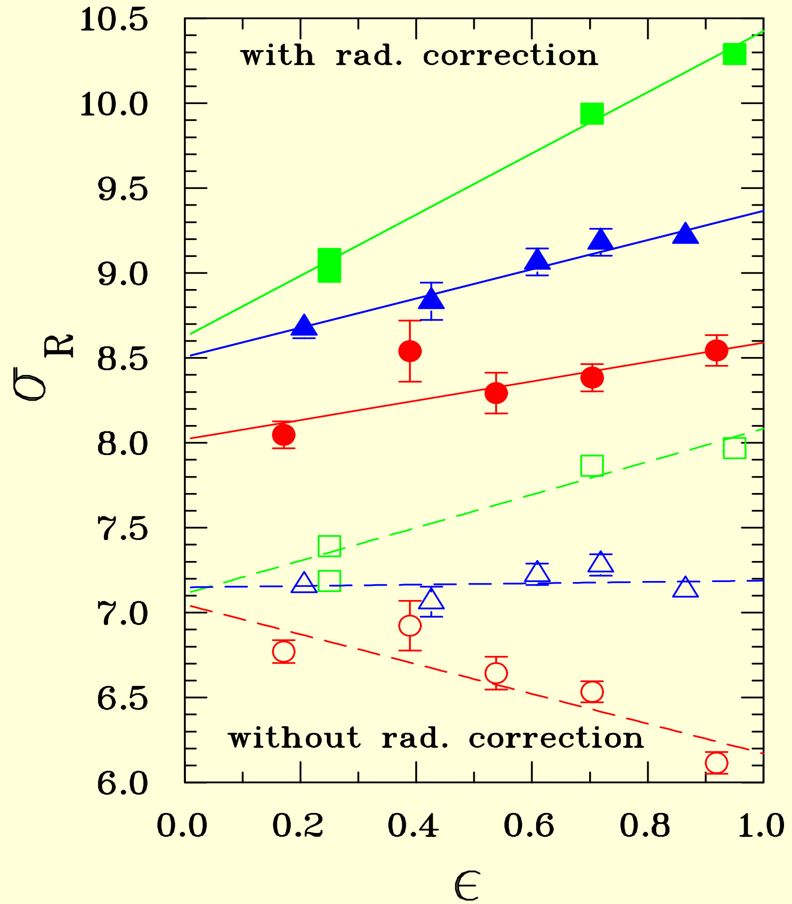
So what causes the different results?

First, radiative corrections at large Q^2 are large and strongly ε-dependent.

$$\sigma_R = [\varepsilon(1+\tau)/\tau][\sigma_{exp}/\sigma_{Mott}] =$$
$$= G^2_{Mp} + \varepsilon\, G^2_{Ep}/\tau$$

green for 1.75 GeV^2
blue for 3.75 GeV^2
red for 5 GeV^2

Data from Andivahis et al. (1994)



Second, there is a scatter in size of calculated corrections

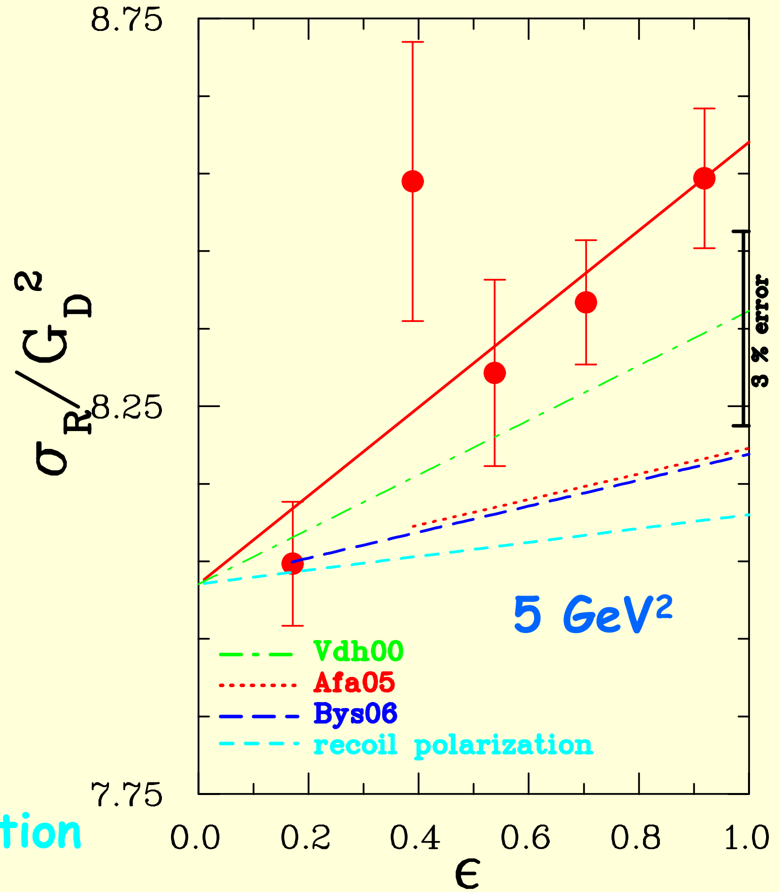
Andivahis et al: based on Mo and Tsai, with improvements from Walker et al.

Vdh: code similar to Maximon and Tjon: with realistic energy cut, external radiative correction included.

Bystritskiy, Kuraev and Tomasi-Gustafsson: with Drell-Yan structure function, fixed 3% energy cut, no external radiative correction.
Are these results right?

Afanasev et al: two-photon correction

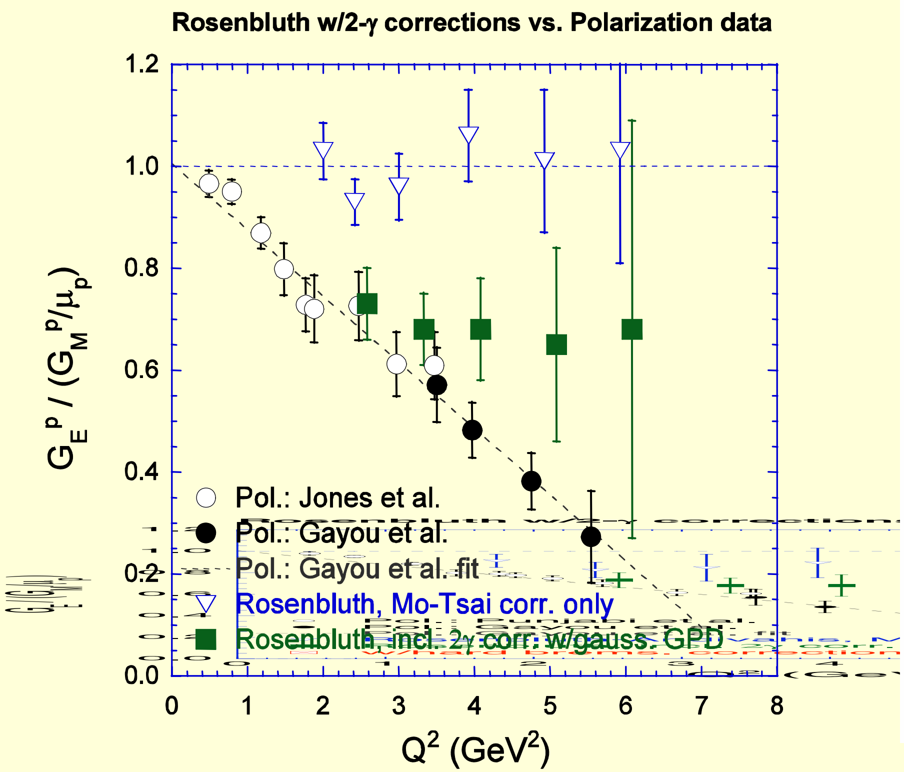
Extrapolation from Hall A recoil polarization

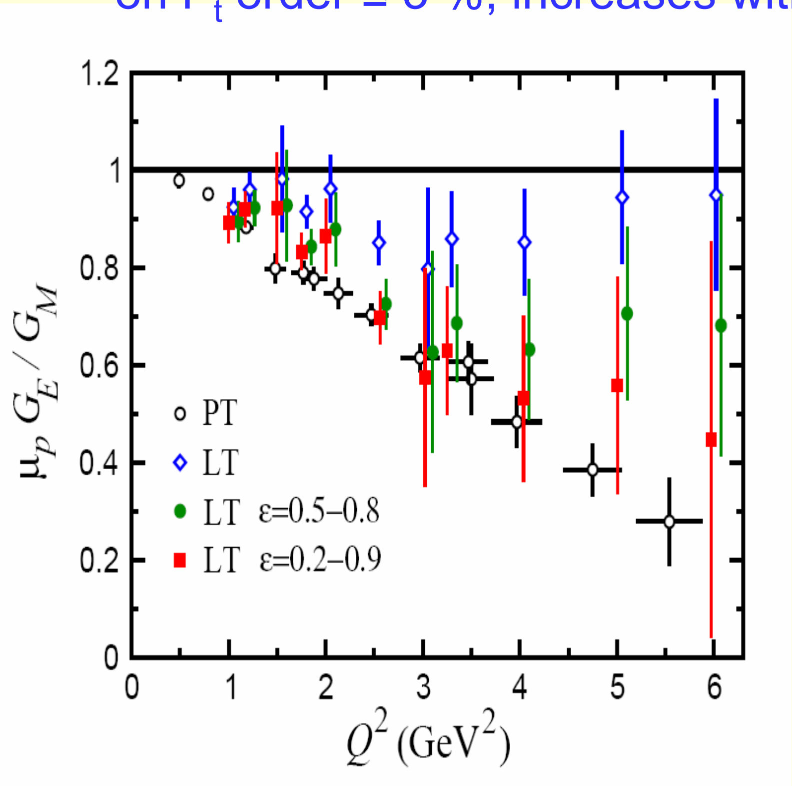


Third, two-(hard)photon exchange might explain it.

Afanasev, Brodsky,Carlson, Y.C. Chen, Vanderhaeghen, GPDs fitted to FF data, Guidal et al.(04)

Blunden Melnitchouk and Tjon (05): intermediate state a proton, includes finite size effects: effect on P_t order ≤ 3 %, increases with Q^2





See also P. Jain's paper on Wednsday

How will we find out which is which?

Answer: experimentally

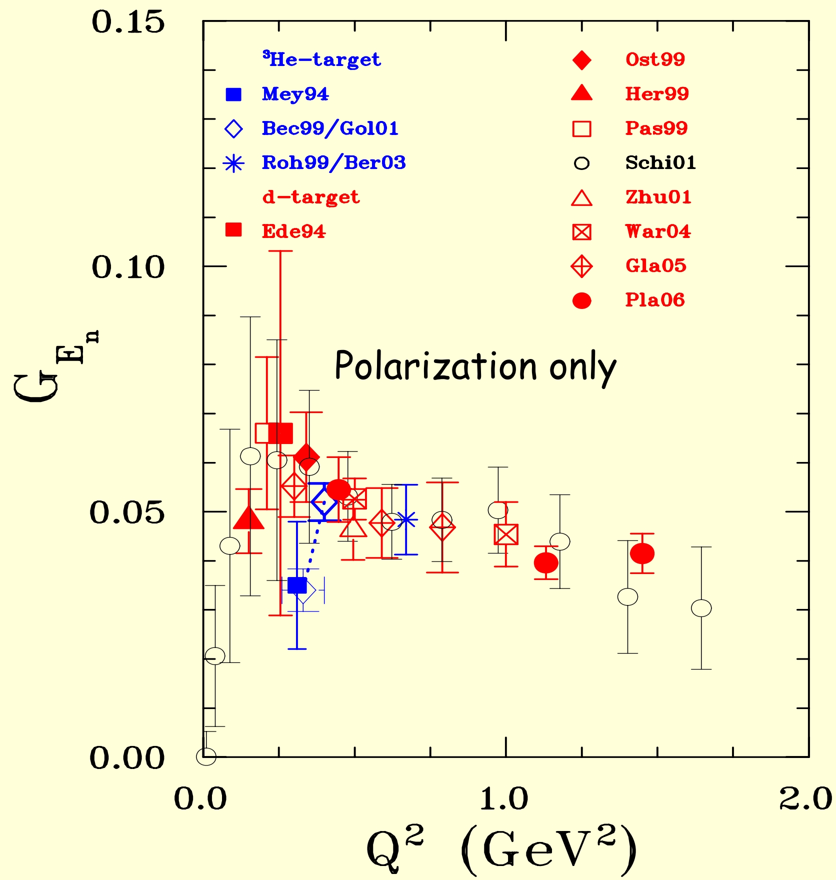
For example:

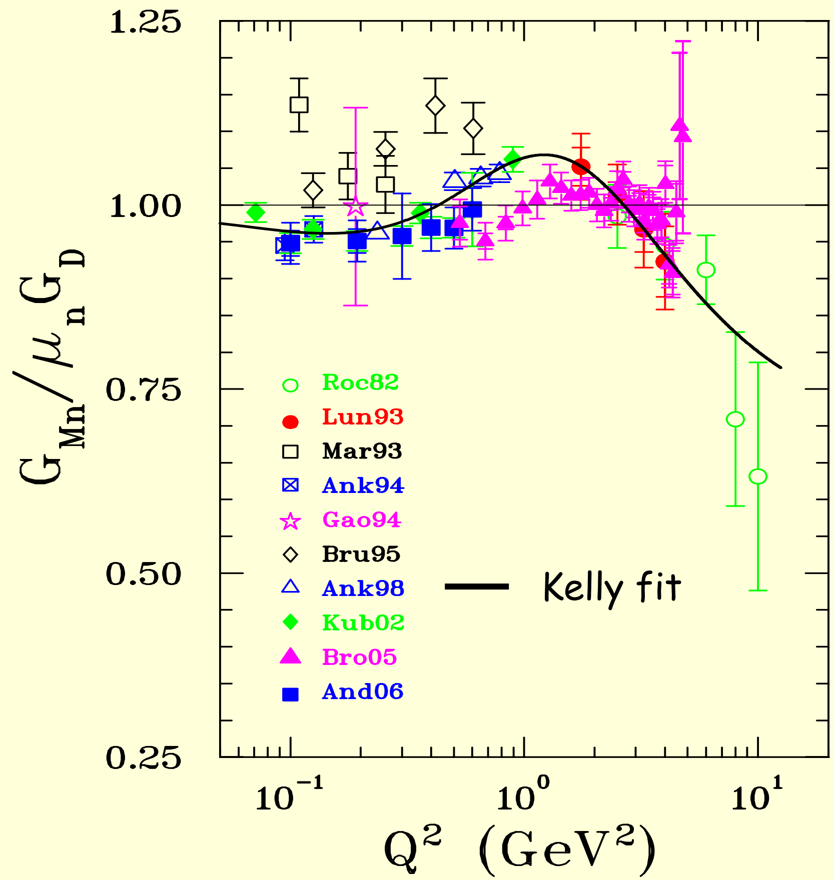
1) ε-independence of G_{Ep}/G_{Mp} in recoil polarization → Hall C expt 04-019, this Fall
2) cross section difference in e^+ and e^- proton scattering → Hall B expt 04-116
3) non-linearity of Rosenbluth plot → C Hall expt 05-017; ongoing

All above determine real part of 2-photon amplitude

4) Also imaginary part from induced out-of-plane polarization and single-spin target asymmetry → by-product of expt 04-019? → Hall A expt 05-015 (^3He↑)
5) Single-spin beam asymmetry at Bates, Mainz: ppm experiments

and what about the neutron?





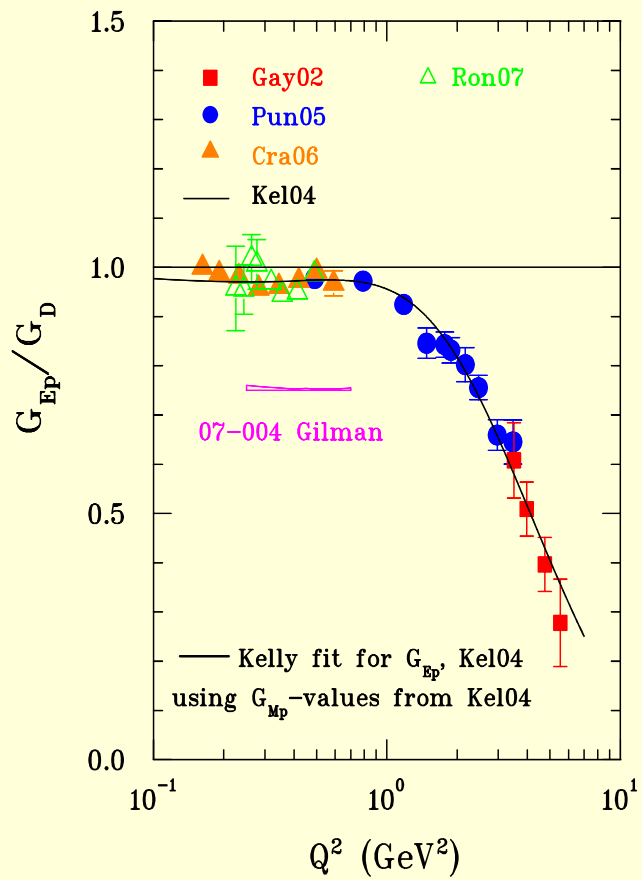
new data expected from Hall A soon: expt. 02-013 to 3.4 GeV^2

Hall B results (Brooks et al) still preliminary/unpublished

This is the proton!

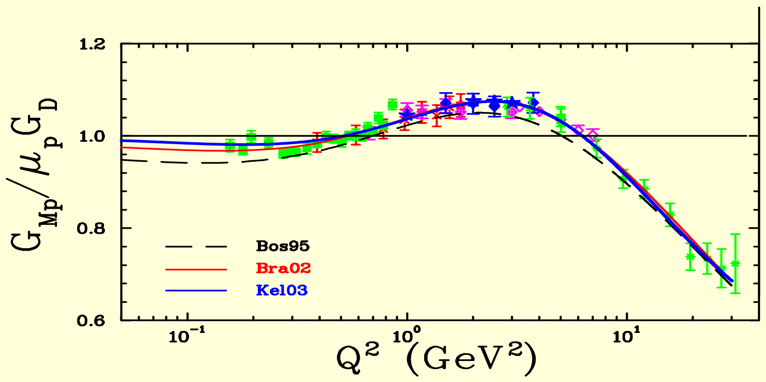
G_{Ep}/G_D from selected polarization experiments, compared to the Kelly fit (which does not include Crawford data)

JLab07-004 Gilman et al. cond. approved.



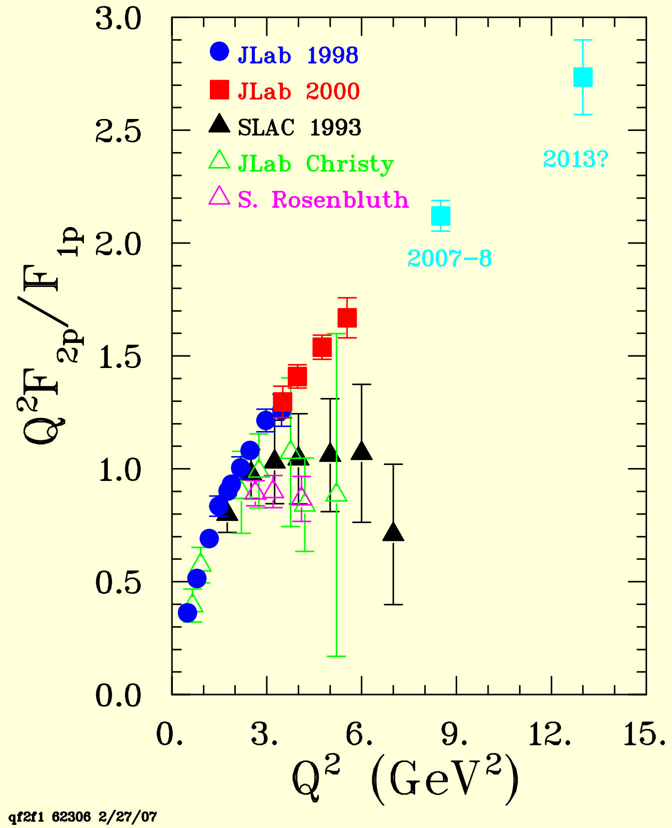
G_{Mp} assuming the ratio G_{Ep}/G_{Mp} from polarization, reanalysis of data base

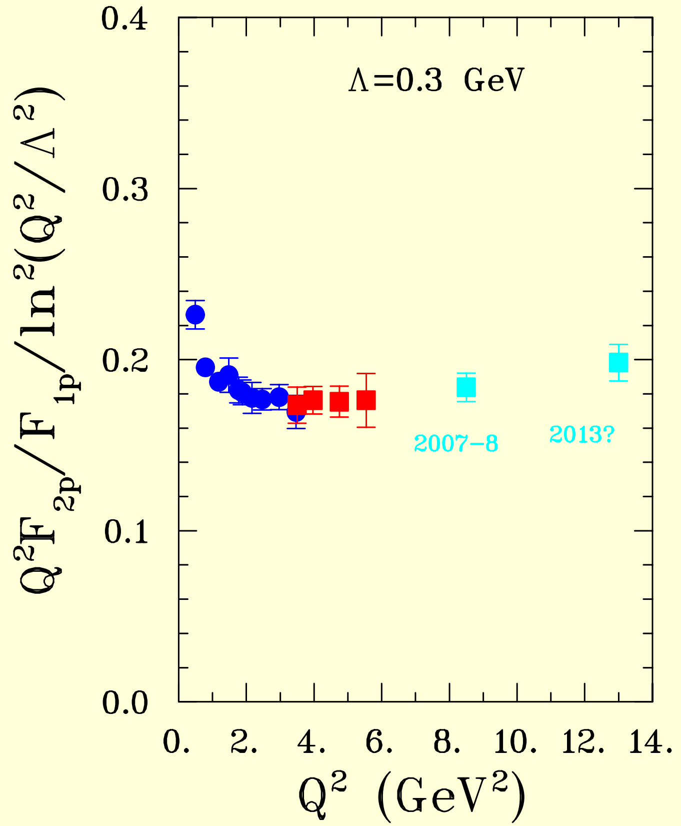
Brash, Kozlov, Li and Huber (02)



Note that both the Q^2 and the ratio scales in these figures are commensurate. Both deviations from G_D are now accurately mapped; they are very different.

F_2/F_1 and pQCD





Brodsky and Farrar (75):

$Q^2F_2/F_1 \rightarrow$ constant

Belitsky, Li and Yuan (03):

$Q^2F_2/F_1 \rightarrow \ln^2(Q^2/\Lambda^2)$

Assuming JLab fit for G_{Ep}/G_{Mp}: $R=1.0587-0.14265Q^2$

Dispersion Theory/VMD

VMD earliest model for nucleon
e.m. Form Factors

Virtual photon couples to nucleon
through exchange of a vector meson

Iachello's in 1973, first to predict
0 crossing of G_{Ep}: VMD+small structure.

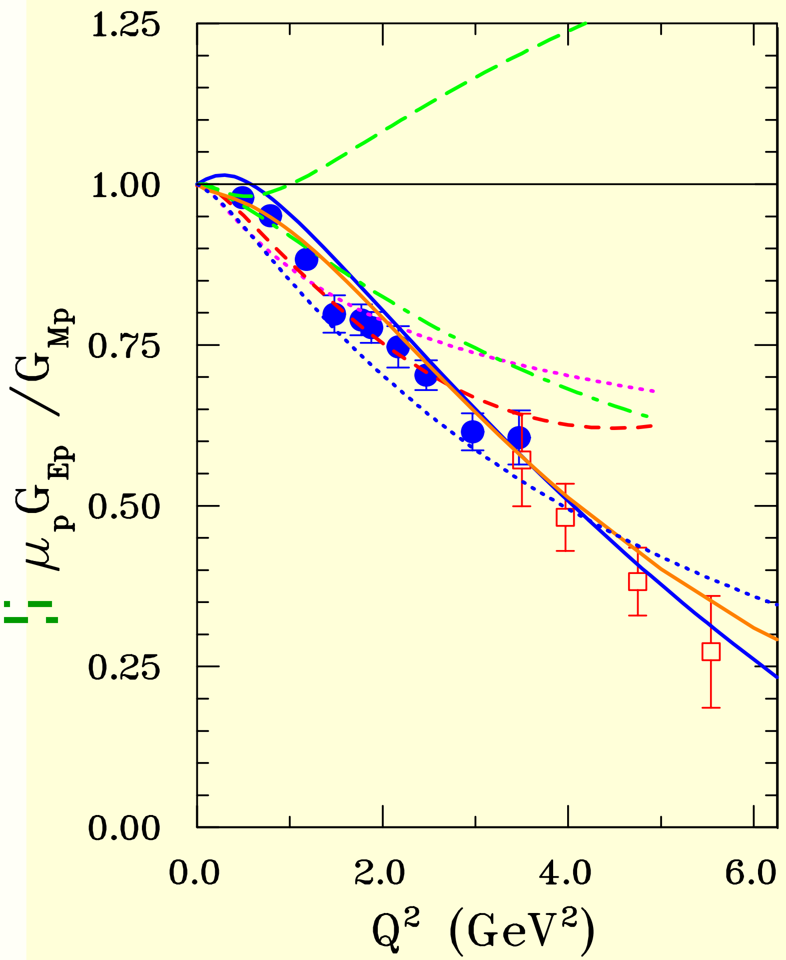
Early work of Höhler (76): ρ(770),
ω(782),Φ(1020) and effective ρ'(1250)

Gary and Krumpelman (85) asympt. pQCD

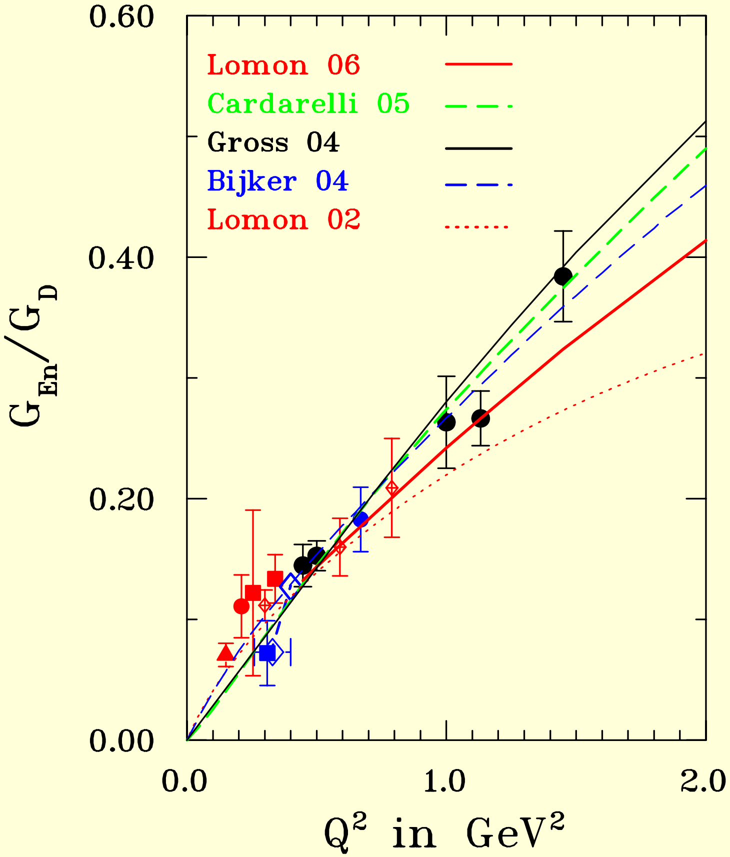
Mergell, Meissner and Drechsel (96)

Lomon (01,02) used ρ(770),ω(782),Φ(1020)
and ρ'(1450), ω'(1419), 11 parameters.
Lomon (06) revised fit better for G_{En}.

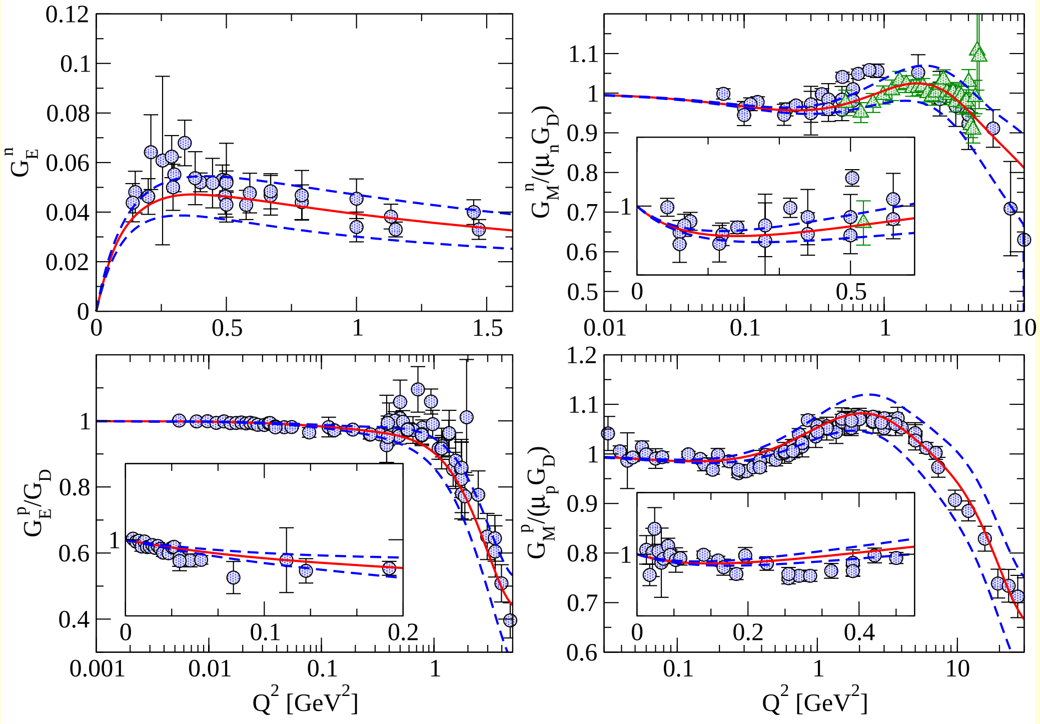
Bijker and Iachello (02)



Continue VMD



Belushkin et al. (06) with several more mesons, 2π and KK' continua. 15 parameter fit



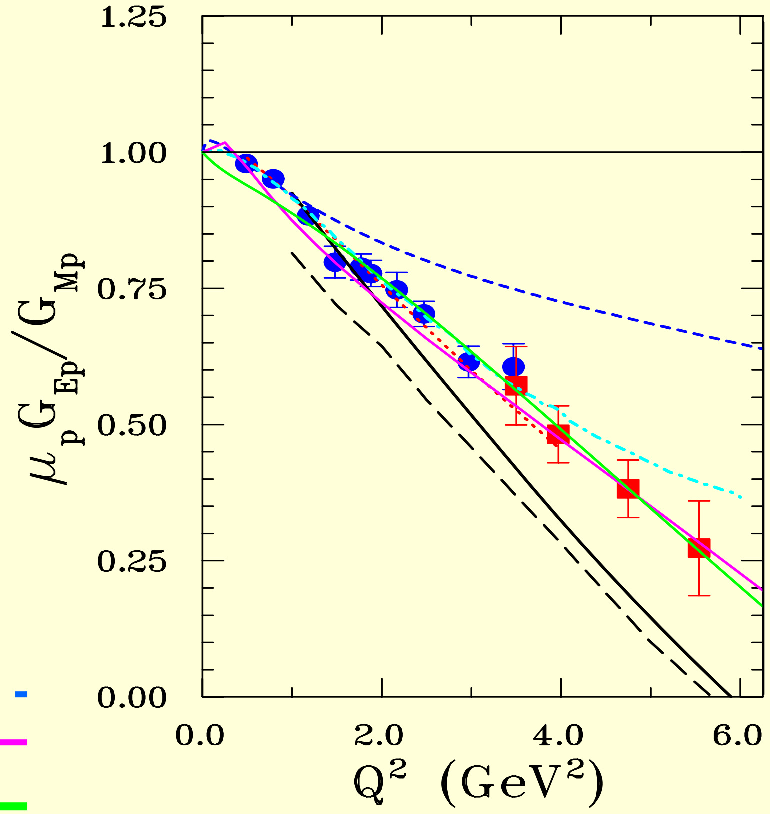
Question: does VMD have any predictive power beyond the Q^2 range of the data?

Belushkin,Hammer,Meissner (06)

Constituent Quarks

Initially proposed by Isgur & Karl (78)
Early non-relativistic CQM
Relativistic CQM: 3 forms of dynamics: instant, point like and light-front [Dirac(49)] , + impulse approximation (interaction with one quark assumed)

Point-like: Chung & Coester (91) ....
Front form:
Frank,Jennings, Miller (96), - - - - -
and G.A. Miller, Frank (02) ———
Point-like: Cardarelli et al (00) - · -
Goldstone boson: Boffi et al (01) - - -
Cov. spectator: Gross,Agbakpe (04) ———
Gross,Ramalho,Pena (06) ———



p1

Is the Nucleon non-spherical?

- A spin-orientation dependent quark density, depending upon spin direction of 1 quark relative to nucleon spin, defined by G.A. Miller, lead to conclusion that nucleon can be deformed, with shape and "deformity" depending on relative direction of spin of that 1 quark, relative to nucleon spin.
- After averaging over all spin directions one retrieves the spherical shape, as discussed by F. Gross. Currently controversial!
- Question: are the JLab G_{Ep} results having a direct bearing on the question of (non-) sphericity: would "scaling" (i.e. $G_{Ep} \sim G_{Mp}/\mu_p$) result in sphericity?

Slide 19

p1 perdrisa, 4/17/2007

Lattice QCD

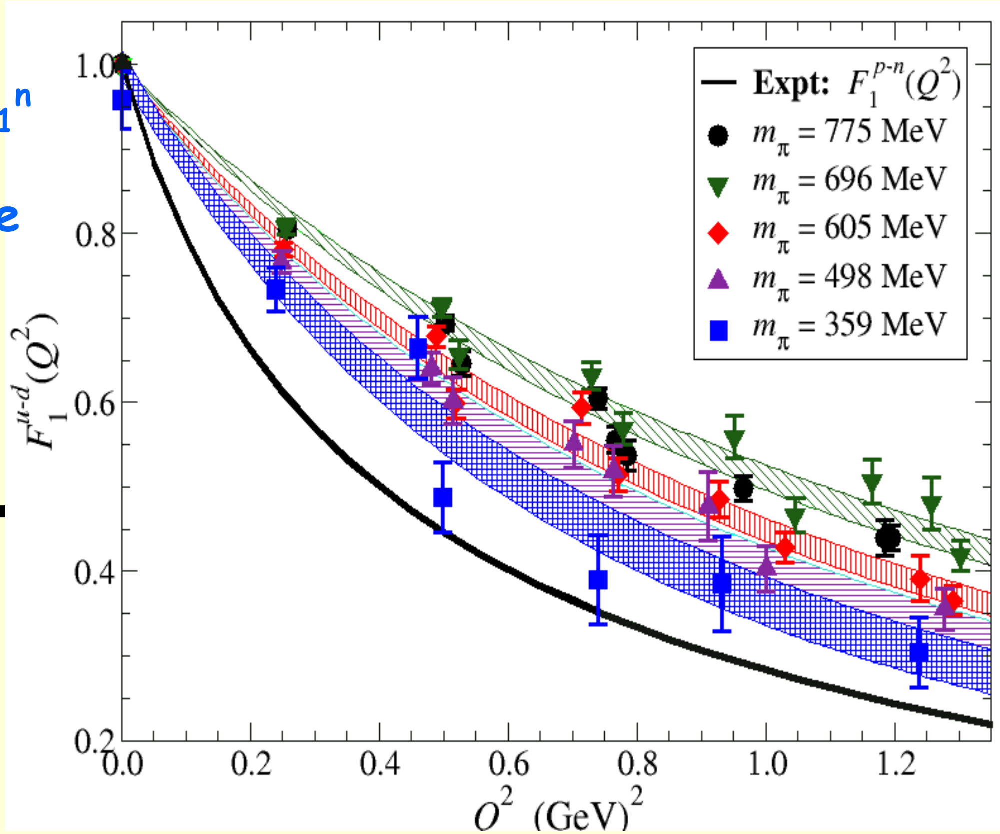
FF from first principle
Limited by computational power to pion mass larger than natural

Vector $F_1^V = F_1^{(I=1)} = F_1^p - F_1^n$

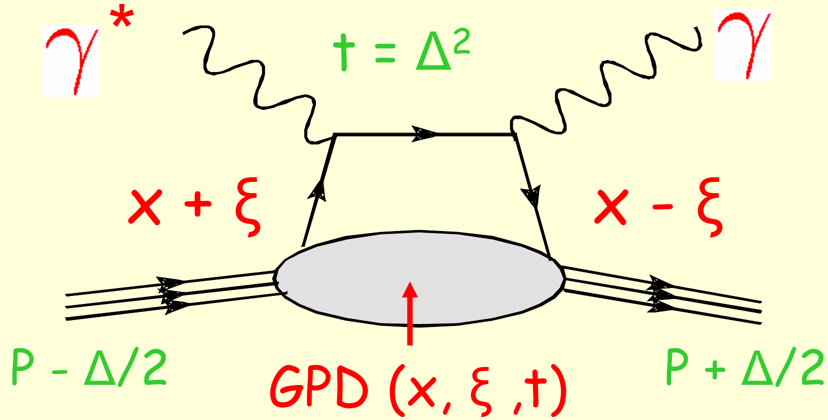
Eliminates need to calculate unconnected loops

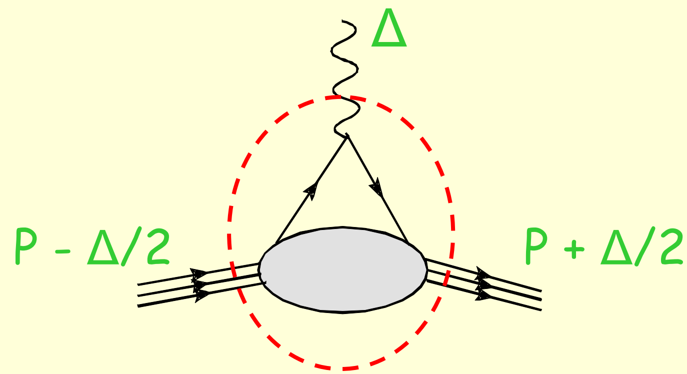
Fair agreement with data (shown from Kelly fit) at lowest π mass

LHPC collaboration (Edward et al, 06)
unquenched, hybrid action, versus π mass



Generalized parton distributions





Ji , Radyushkin(1996): for large Q^2 hard exclusive process can be described by 4 transitions (GPDs); QCD factorization theorem.

V : H (x, ξ t), **T** : E (x, ξ ,t), **AV** : $\tilde{H}$ (x, ξ ,t), **PS** : $\tilde{E}$ (x, ξ ,t)

$$\begin{aligned} H^q(x,\xi=0,t=0) &= q(x) \\ \tilde{H}^q(x,\xi=0,t=0) &= \Delta q(x) \end{aligned}$$

unpolarized quark distribution
polarized quark distribution

In DIS

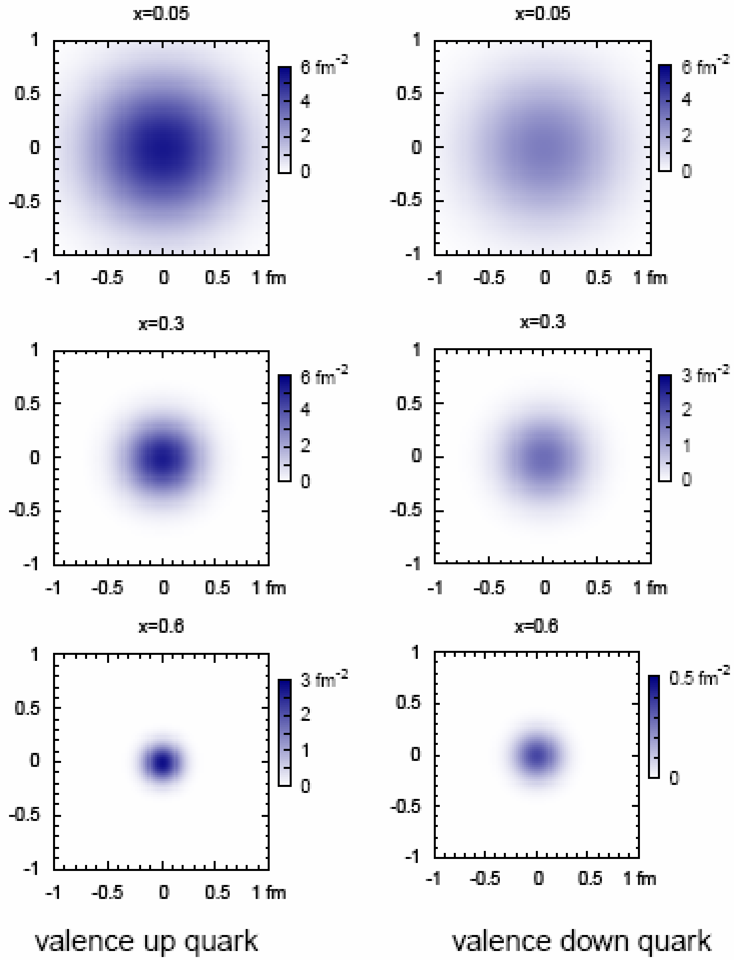
First moments are electroweak form factors: F_1^q, F_2^q, G_A^q and G_P^q; for example:

$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t) \text{ Dirac}$$

$$\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t) \text{ Pauli}$$

GPDs from Form Factor Data

- Valence quark GPDs extracted from experimental $F_1^p, F_2^p, F_1^n, F_2^n$, using Regge phenomenology at small x and reasonable assumptions at large x. Provide information on GPD higher moments, axial form factors, as well as tomography, (M.Diehl et al., Euro Phys. J. 39,1 (2005))

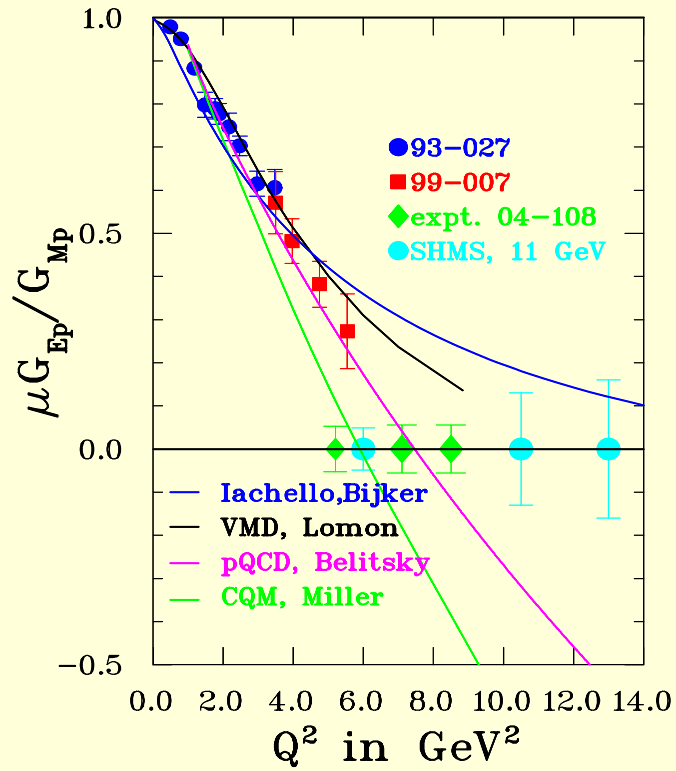


GEp(III) and beyond

Expt. 04-108 will run in October.
may be limited to 8.6 GeV^2 by
insufficient beam energy

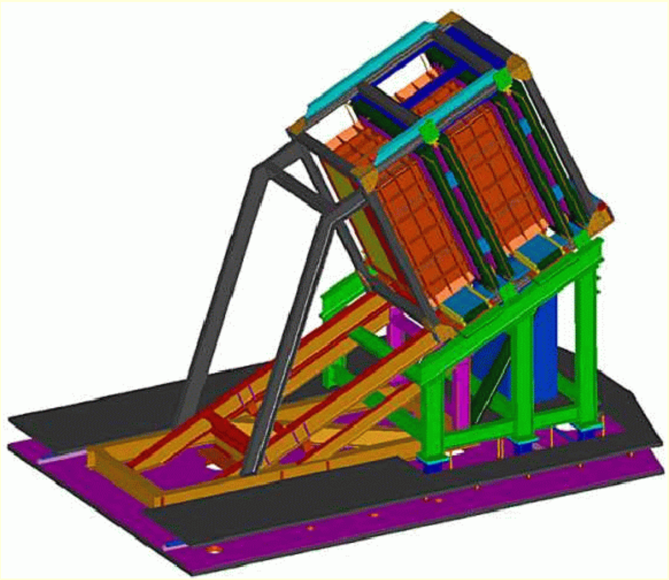
LOI 07-013 proposed
to use the SHMS with
BigCal to 13 GeV^2

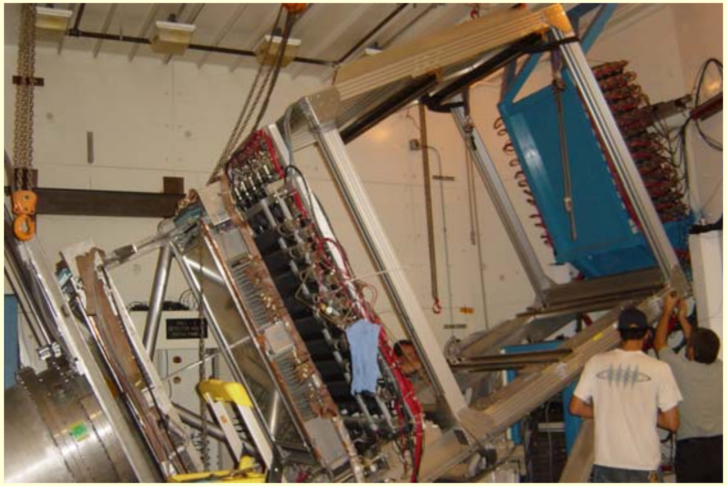
L. Pentchev proposes
to replace SHMS by dipole
to increase solid angle
by factor of ~8

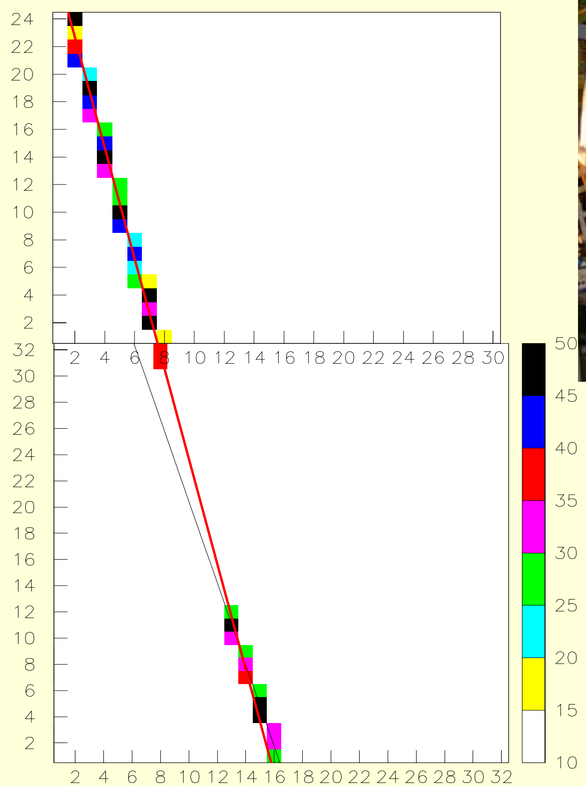


FPP and BigCal in Hall C

2001….2007+







Conclusion, Perspective

Experimental characterization, and phenomenological understanding of the structure of the proton, have changed drastically since 1998, year of the first recoil polarization experiment in Hall A.

Rapid decrease of G_{Ep} with Q^2 was not complete surprise: had been predicted (but ignored by experimentalists 10 years ago) in at least 3 papers: Iachello Jackson and Lande (73) based on VMD, Frank, Jennings and Miller (96) based on CQM, and Holzwarth (96) based on chiral soliton.

Full understanding of implications of the JLab finding may not be in yet. Where does the pQCD behavior kick in? are the nucleons spherical in their ground state? Are we "really" seeing the effect of quark orbital angular momentum? If the shape of the FF not diffractive, what does $G_{Ep}=0$ or $G_{Ep}<0$ mean?

Also to come is full understanding of two-photon effects, and revision of standard radiative correction calculation codes.

Some of forthcoming experiments will address these questions.

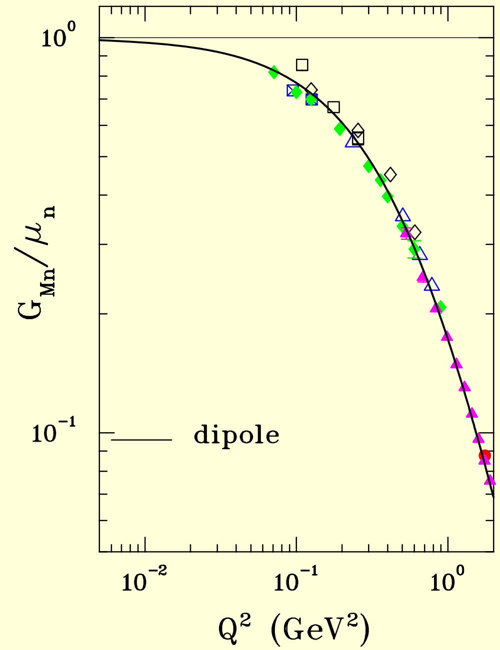
Why is the dipole form factor so prevalent?

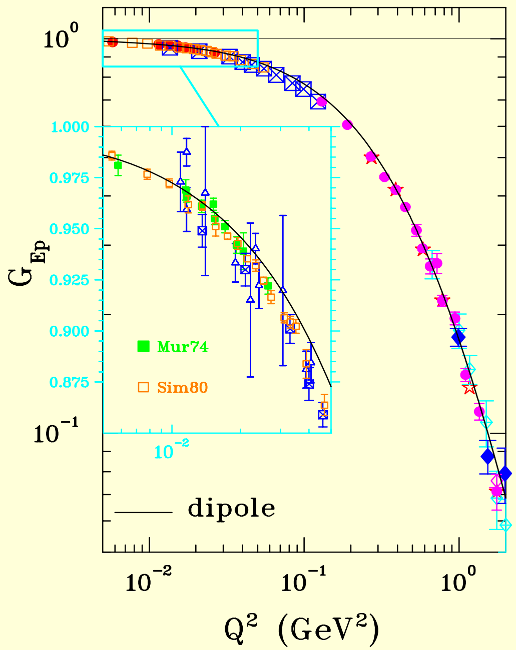
$G_D = 1/(1+Q^2/0.71)^2$ and $G_{Ep} = G_D$, $G_{MN} = \mu_N G_D$

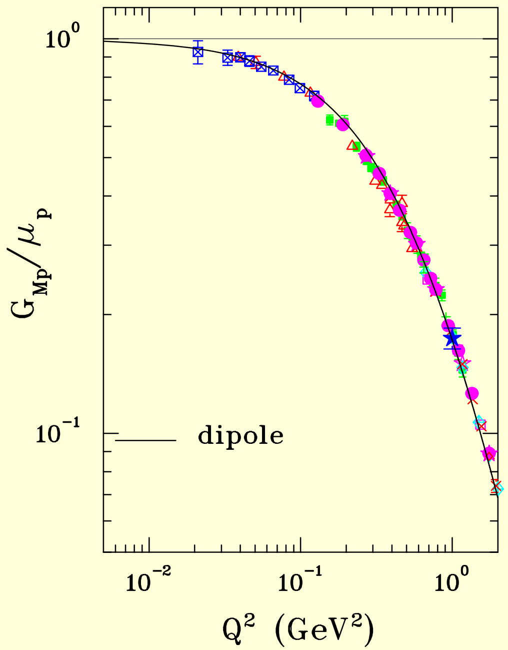
provides excellent "fits" to 3 of the nucleon form factors, below 2 GeV^2

"Explained" in Vector Dominance Model: near cancellation of two isoscalar or isovector, vector mesons with similar masses and coupling

Rosenbluth data only.





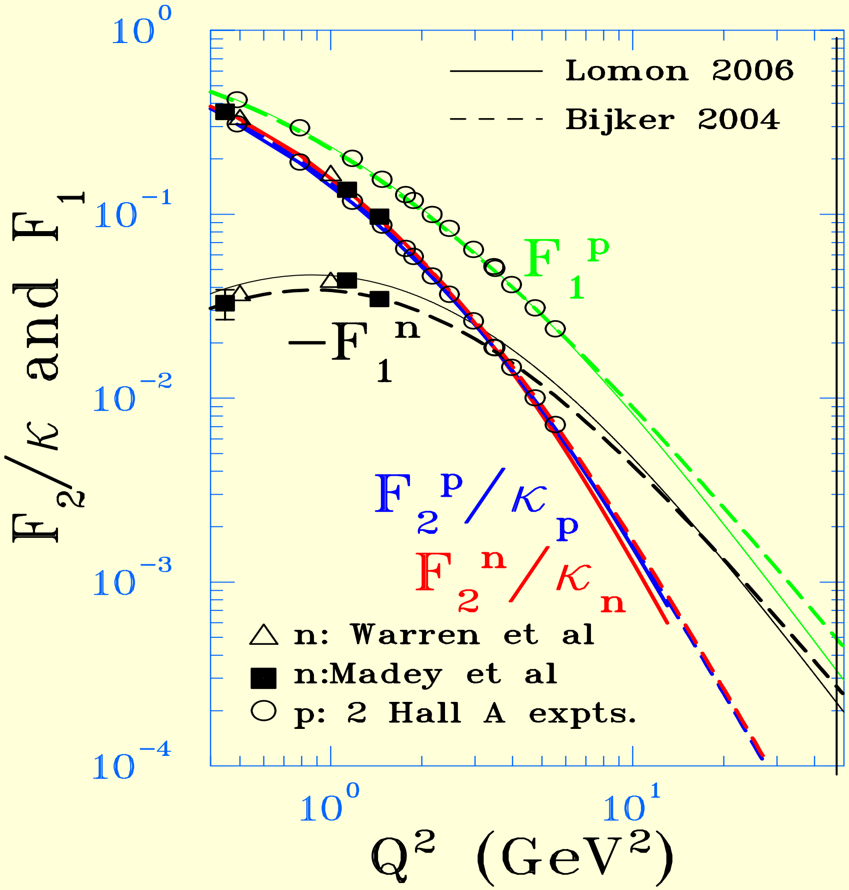


VMD/continued

Modified versions of VMD model (Lomon, 06) and (Bijker, 04), fit data base well.

and "predict" that at large Q^2
$F_{1p} \rightarrow -F_{1n}$
(even though as $Q^2 \rightarrow 0$ $F_{1n} \rightarrow 0$),
and $F_{2p} \rightarrow F_{2n}$

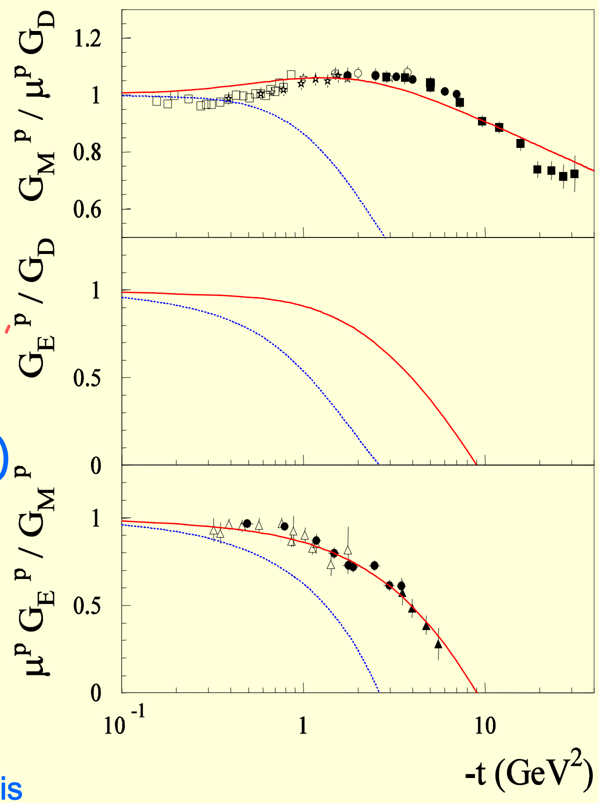
Fact that $F_2^p/\kappa_p \sim F_2^n/\kappa_n$ at large Q^2 reflects dominance of isoscalar mesons for F_2.



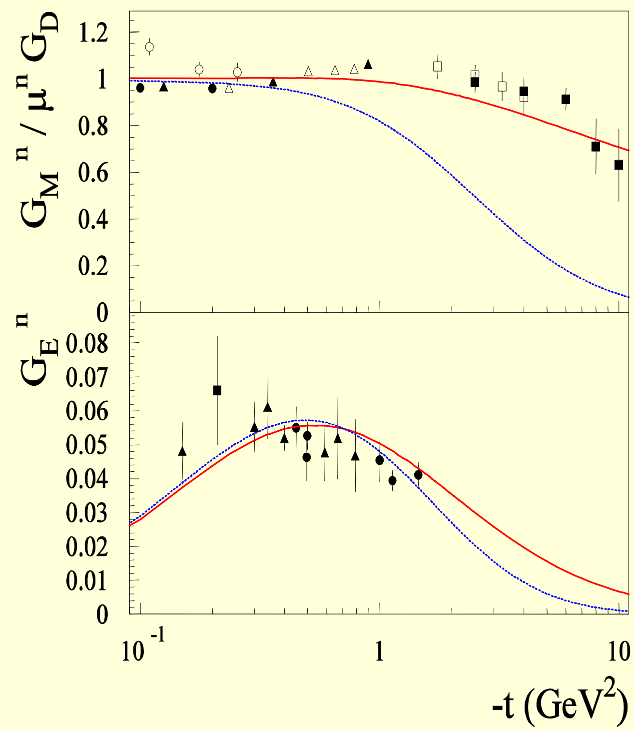
Nucleon GPD parametrizations

Used for two-gamma calculation of
Afanasev, Brodsksy, Carlson, Chen and Vanderhaeghen (05)
From Guidal et al.(05)

PROTON



NEUTRON



To the extent that interaction is with single quark, remaining "soup" described by GPDs hand-bag model; factorization. Still at lower end of domain of applicability

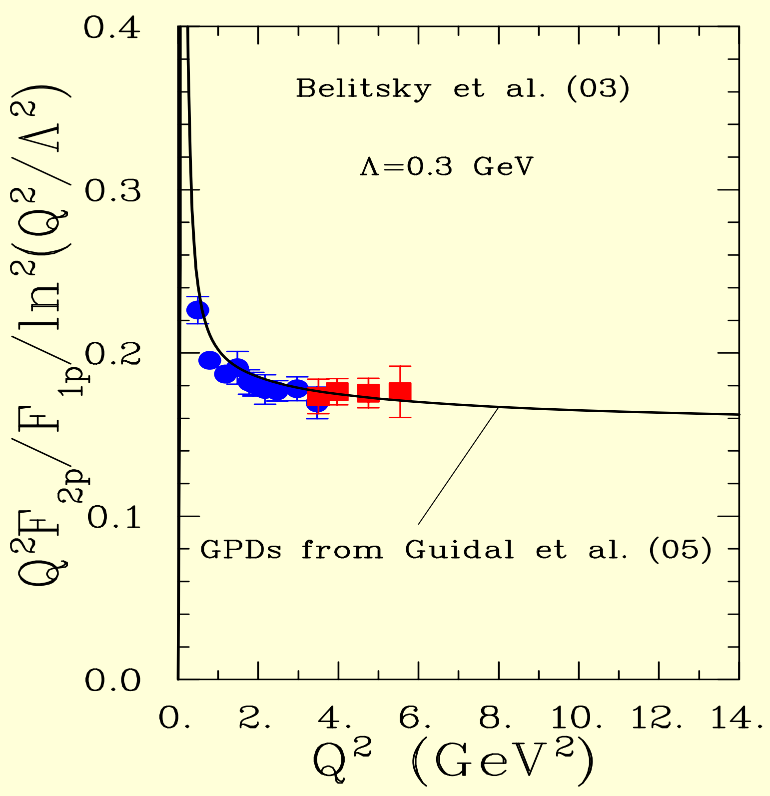
Modified Regge parametrization

Regge parametrization

End GPDs

The empirical GPDs show an asymptotical behavior similar to that of Belitsky's modified pQCD

F_1 and F_2 from GPD's
Guidal et al.(05)



New Experiments: FF

Recent G_{En} In Hall A,
Q^2 of 1.20, 2.48 and 3.43 GeV^2; data are currently being analyzed!

Next is G_{Ep}/G_{Mp} in Hall C, scheduled to start Oct. 1 (yes, this year)
Q^2 of 5.20, 7.1 and 8.6 GeV^2 ; nominally 9 GeV^2, depends on available beam energy.

Conditionally approved in Hall A: G_{Ep}/G_{Mp} by recoil in range $0.3<Q^2<0.7$ GeV^2, with exquisitely small statistical uncertainty (Gilman et al. expt. 07-004)
This is the presumed "pion cloud" region, not discussed here.