Status and Results of Nucleon Form Factors

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Outline

Introduction

Elastic form factors of the Nucleon

Rosenbluth separation and double polarization, two methods to obtain G_E and G_M

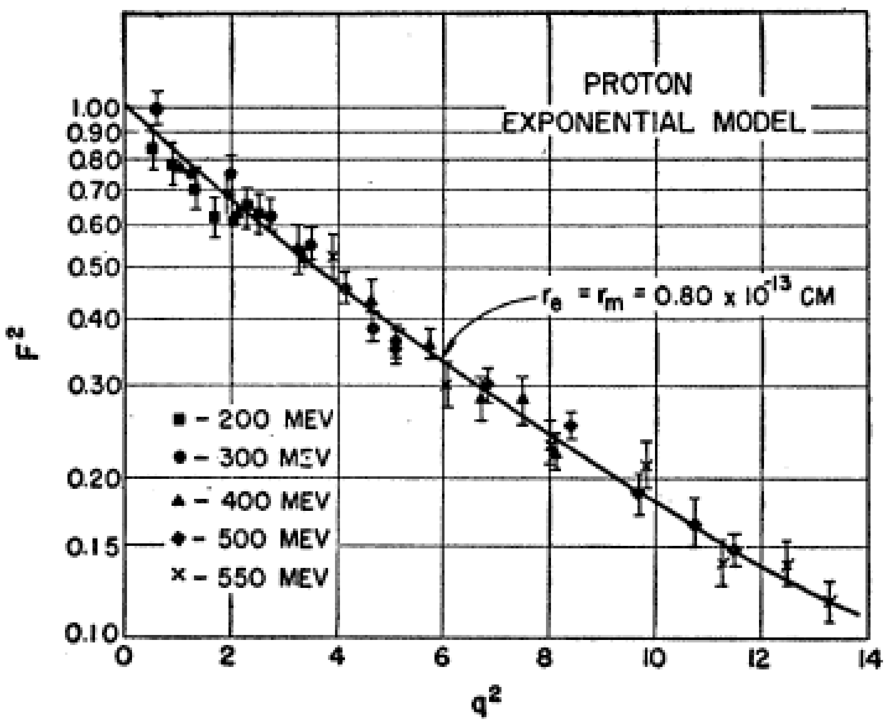
Old and new results for G_E and G_M

New results from theoretical calculations

The proton form factor "Discrepancy" and possible interpretation of the "Discrepancy"

Conclusions

It all started in the 1950's



Robert Hofstadter
Nobel prize 1961

For his Pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons

ep-elastic
Finite size of the proton

Nucleon Elastic Form Factors

The Form Factors (FF) are fundamental quantities
defined in context of single-photon exchange

FF Describe internal structure of the nucleons
related to charge and magnetization distributions

Investigation of FFs provide a powerful tool toward understanding
of non-perturbative QCD and confinement

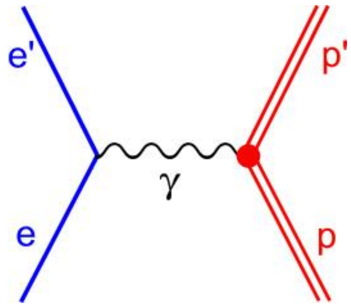
Spectacular experimental progress in past decade using high energy
continuous beam of CEBAF with high polarization,
double polarization method
Unexpected results that inspired theoretical progress

Precise knowledge of FF is essential,
rigorous tests of nucleon models
input to nuclear structure and parity violation experiments

New information on basic hadron structure, such as role of quark
Orbital angular momentum

ep Elastic in Born approximation

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



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

using parity conservation and current conservation, the hadron current is parameterized by two form factors

Nucleon vertex: $$\Gamma_\mu(p,p') = \gamma_\mu F_1(Q^2) + \frac{i\sigma_{\mu\nu}}{2M} q^\nu F_2(Q^2)$$

Dirac　　　Pauli

F_1 helicity conserving , F_2 helicity non-conserving form factors. In electron scattering $Q^2 = -(p_e - p_{e'})^2 > 0$ (space like region).

Alternately, the Sachs form factors

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

For $Q^2 \rightarrow 0$, G_E and G_M are Fourier transforms of charge and current distributions in the Breit frame.

Rosenbluth separation of G_E^2 and G_M^2

Rosenbluth cross section in terms of F_1, F_2 and G_E, G_M

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{Mott} \times \left\{ F_1^2(Q^2) + \tau\kappa^2 F_2^2(Q^2) + 2\tau\left(F_1(Q^2) + \kappa F_2(Q^2)\right)^2 \tan^2\frac{\theta_e}{2} \right\}$$

$$\frac{d\sigma}{d\Omega_{\exp}} = \frac{d\sigma}{d\Omega_{mott}} \left\{ G_{Ep}^{\;\;2} + \tau \left[\underbrace{1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}}_{1/\varepsilon} \right] G_{Mp}^{\;\;2} \right\} \frac{1}{1+\tau} \qquad \tau = \frac{Q^2}{4m_p^2}$$

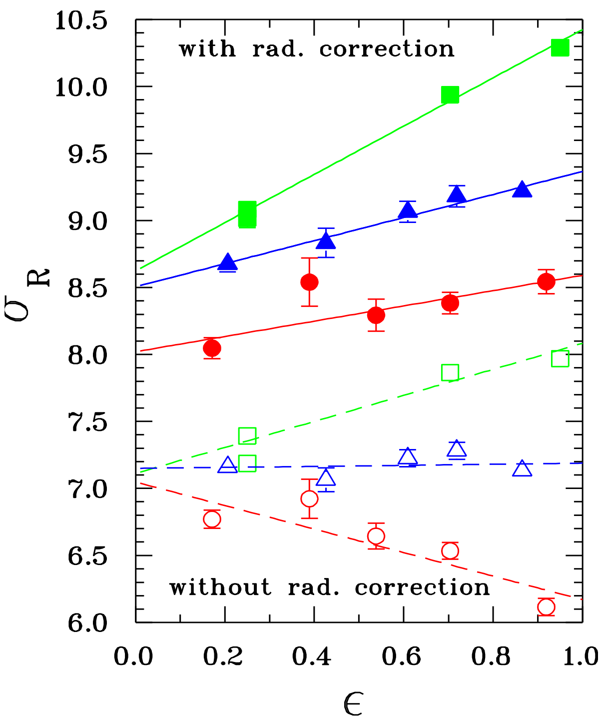
- this form leads to the Rosenbluth separation method:

$$\sigma_R \equiv \left\{ \left(\frac{d\sigma}{d\Omega}\right)_{\exp} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{mott} \right\} \frac{\varepsilon(1+\tau)}{\tau} = \frac{\varepsilon}{\tau} G_{Ep}^2 + G_{Mp}^2$$

- where ε is the virtual photon polarization.

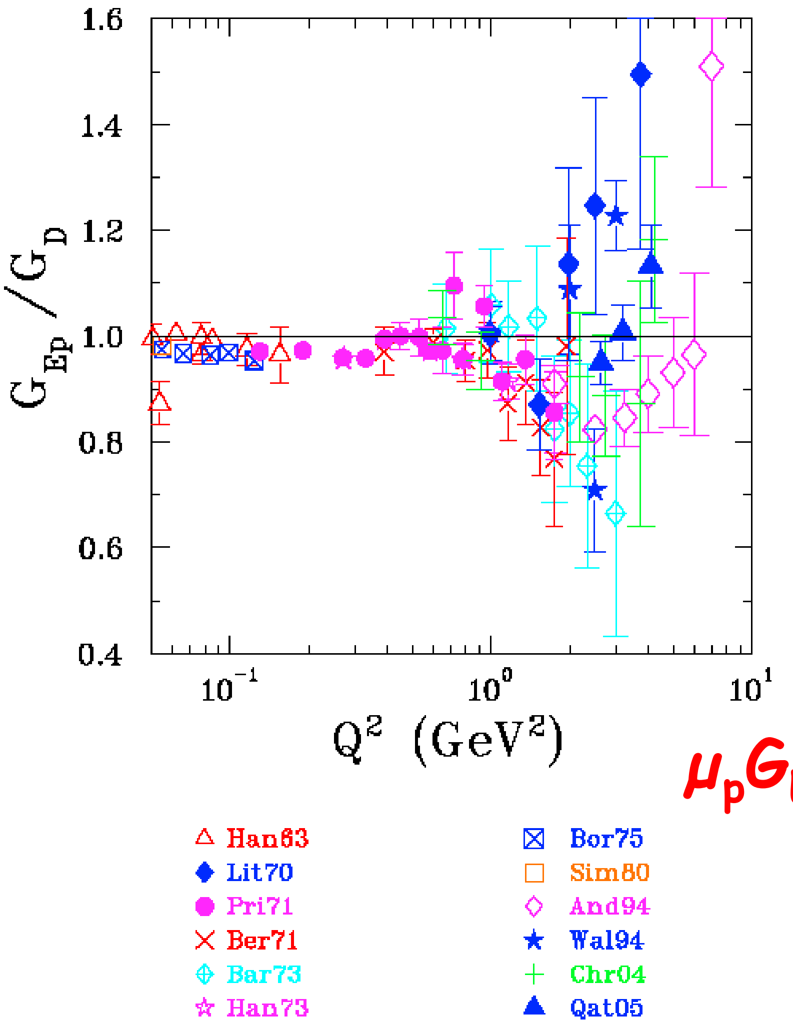
- Radiative corrections are crucial to obtain G_{Ep} from slope of σ_R

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

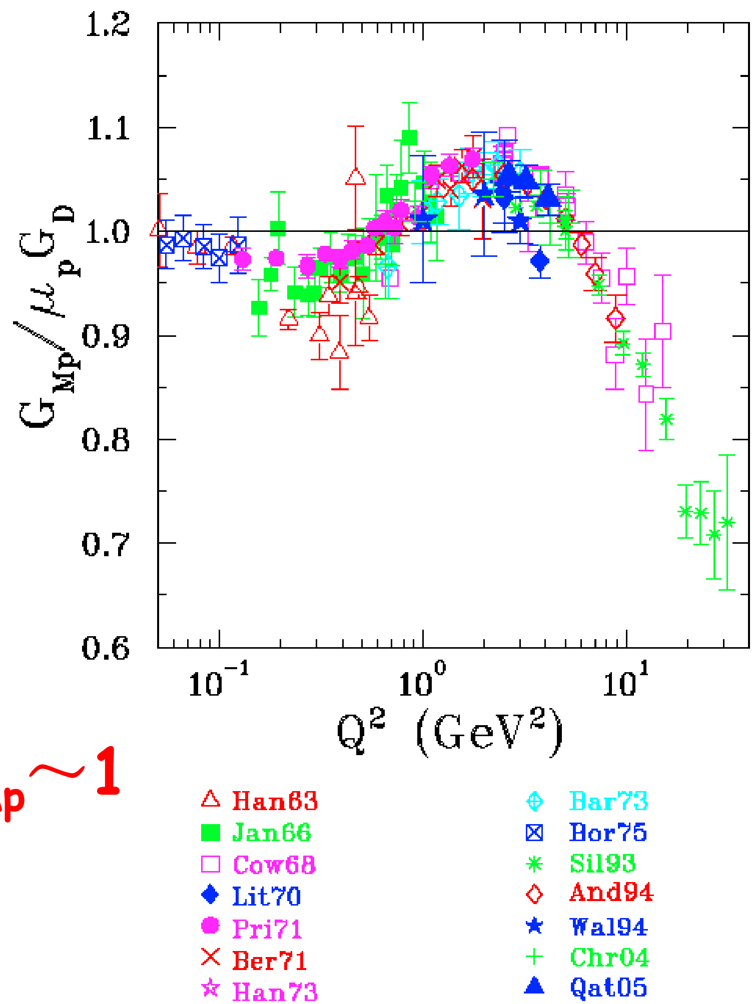


All Rosenbluth Separation Data for Proton

Divided by the dipole form factor $G_D=(1-Q^2/0.71)^{-2}$:



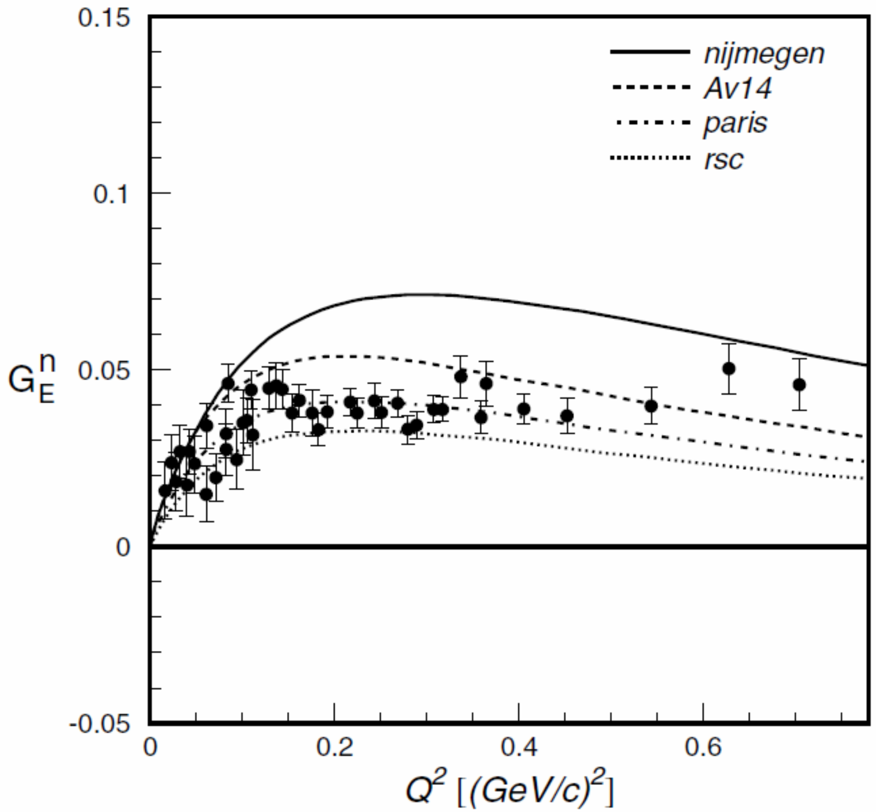
$\mu_p G_{Ep}/G_{Mp} \sim 1$

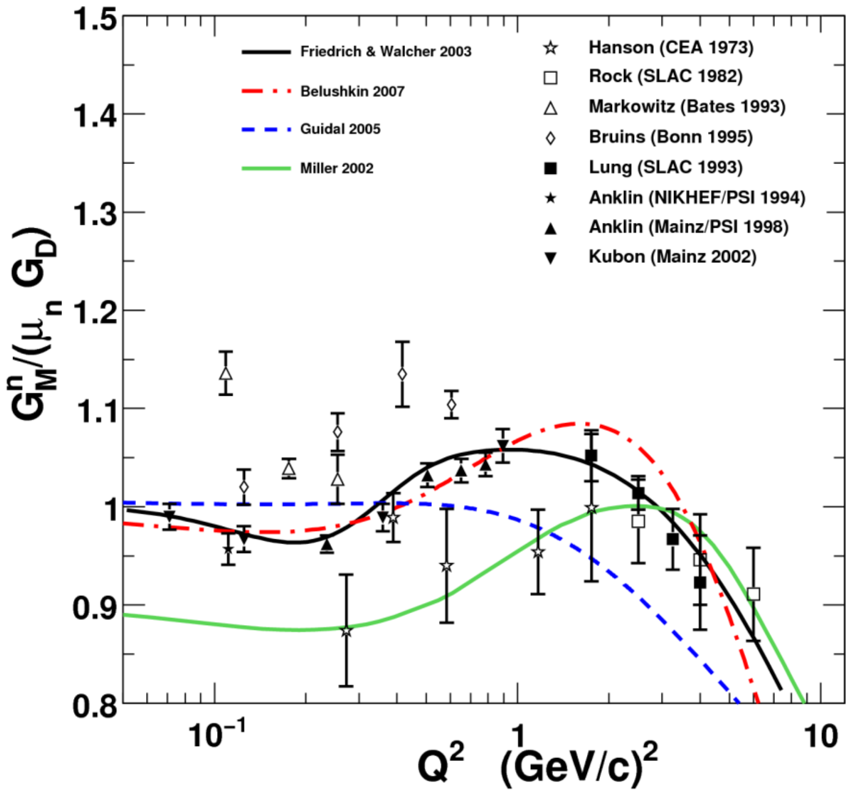


Neutron Form Factors

From elastic and quasi elastic electron-deuteron scattering cross sections

Interpretation model dependent, requires d-wave function.





Double polarization experiments

Polarization transfer in $\vec{e}N \to e\vec{N}$ or spin-target asymmetry $\vec{e}\vec{N} \to eN$, (N=p or n) are two different techniques, but give same information

For recoil polarization, the two polarization components are in the reaction plane, no normal component: (Akhiezer and Rekalo, Sov. J. Part. Nucl. 4, 277 (1974)); (Arnold, Carlson and Gross, Phys. Rev. C 23, 363 (1981))

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

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

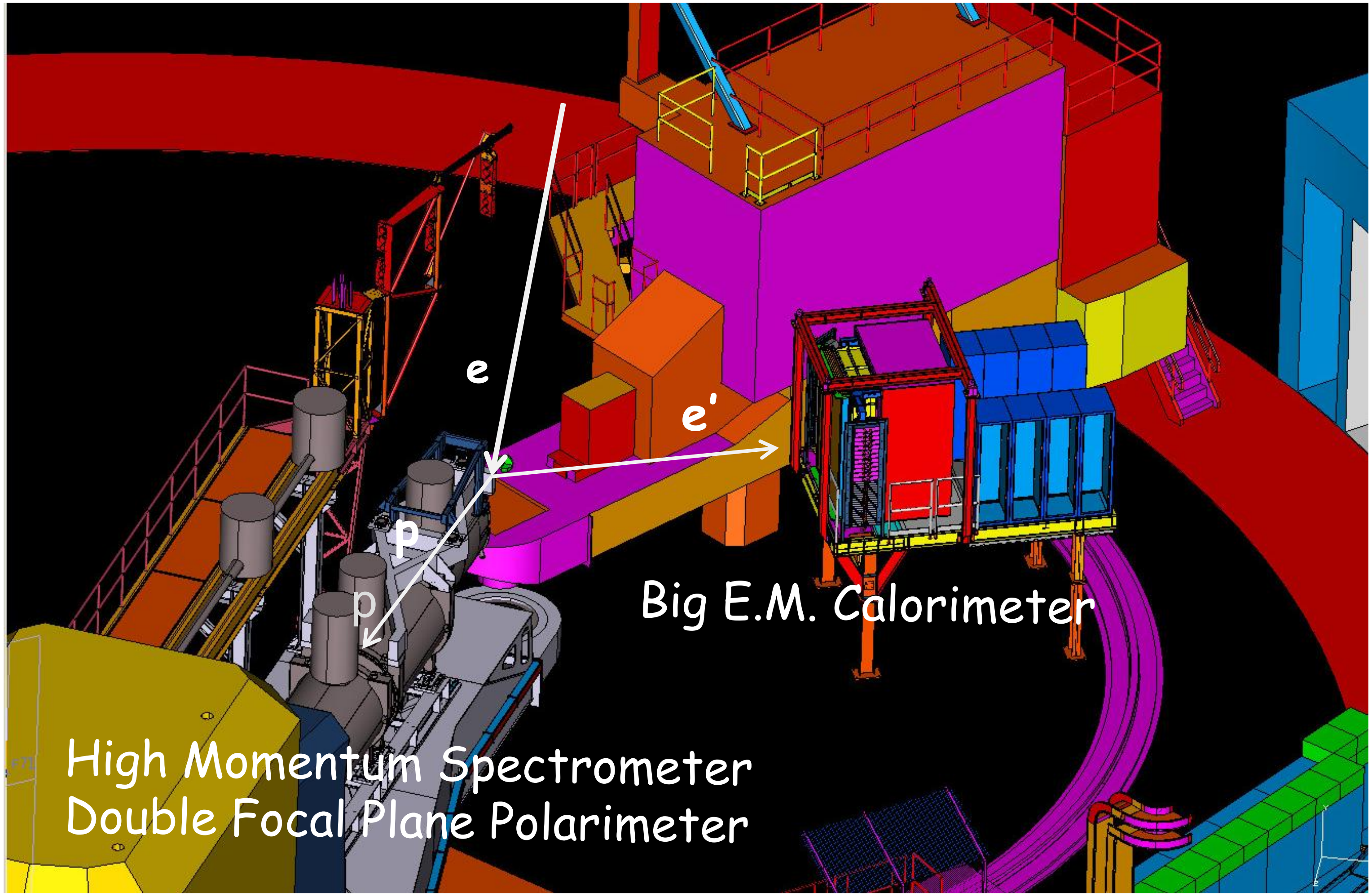
$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell}\frac{(E_e+E_{e'})}{2M}\tan\left(\frac{\theta_e}{2}\right) \quad or \quad -\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}$$

The method superior because of smaller systematics: the Form Factor ratio is independent of the electron polarization P_e and of the polarimeter analyzing power A_y (h is beam helicity ±1).

Statistical uncertainty depends directly on both P_e and A_y.

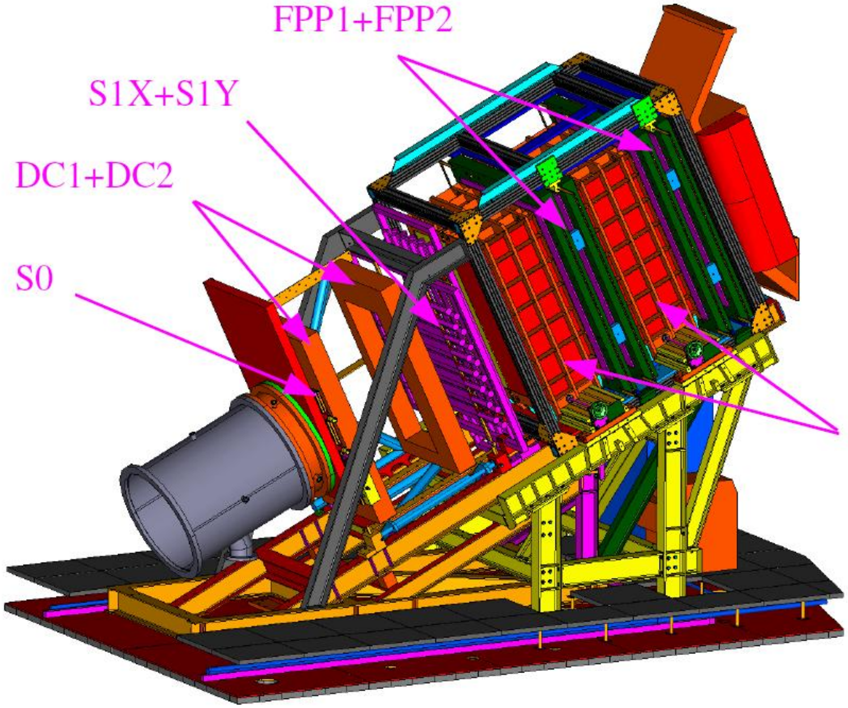
Remaining systematics mostly from spin precession

GEp(III) Setup



1.87- 5.71 GeV beam
80-100 μA beam current
80-85% polarization
20cm LH_2 target

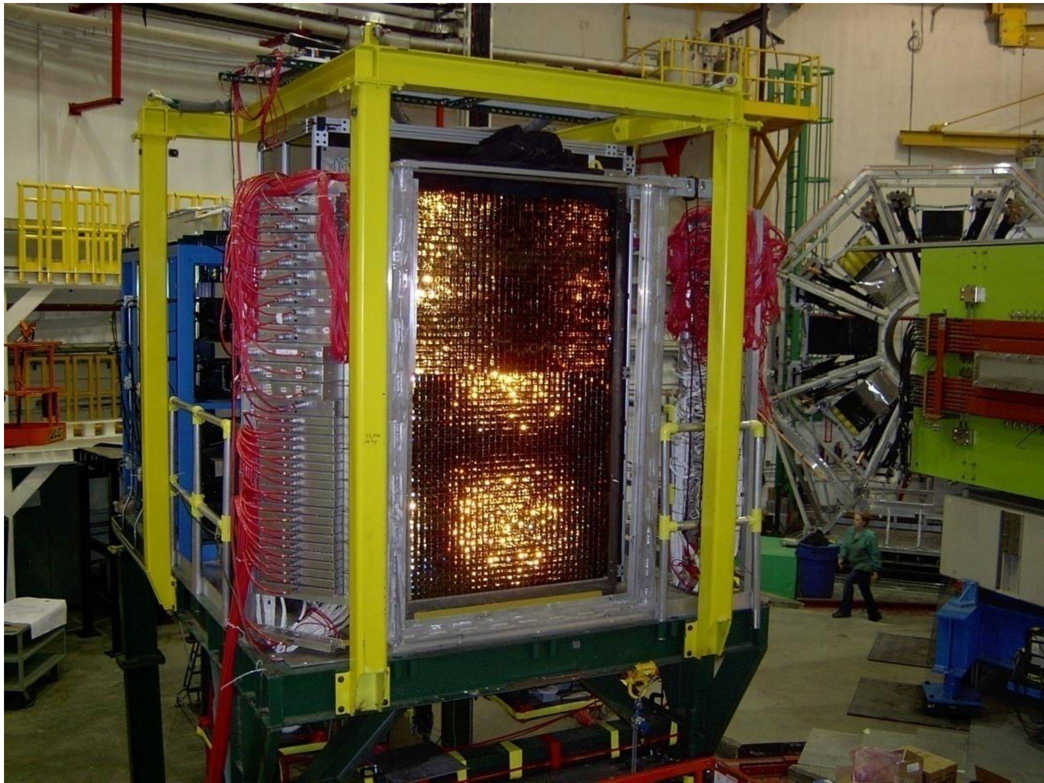
Detectors



Changes in standard HMS detector package:

·Focal Plane Polarimeter with Double Analyzer:
-> 70% increased efficiency

· Scintillator plane S0 in front of drift chambers needed for triggering

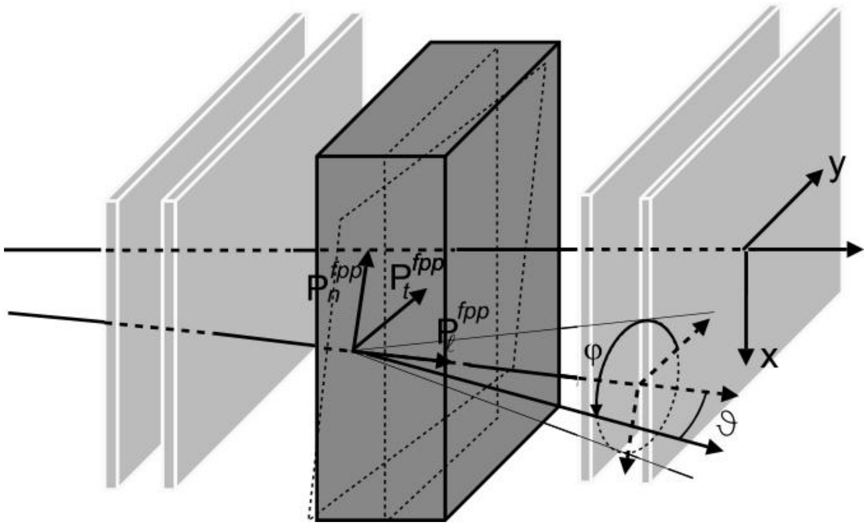


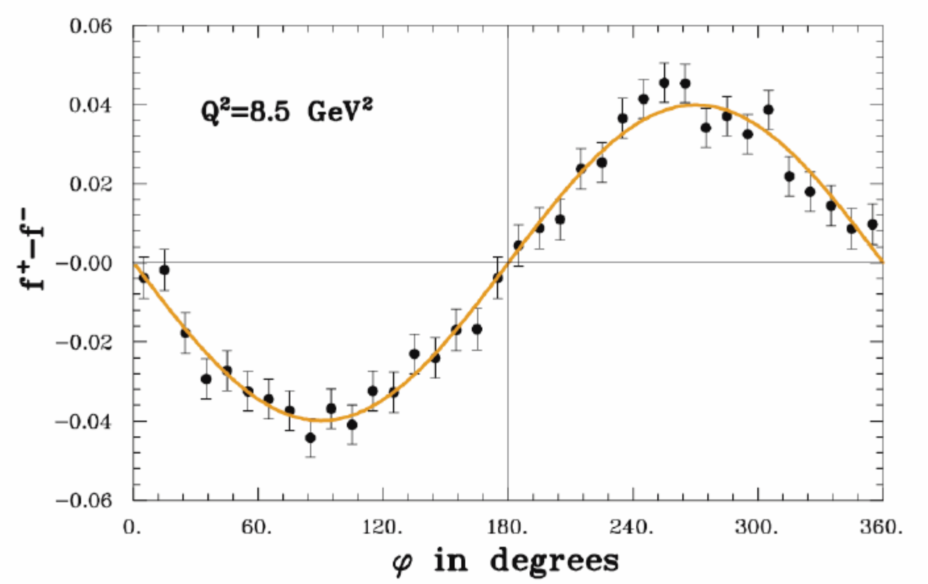
1744 channel E.M. Calorimeter (BigCal):

· from $\frac{6.8\%}{\sqrt{E}}$ to $\frac{23\%}{\sqrt{E}}$ (due to radiation damage) needed for triggering

· position resolution ~5 mm – most important parameter for elastic separation

Focal Plane Polarimeter





Front Trackers **CH_2 Analyzer** **Rear Trackers**

$$f^{\pm}(\theta,\varphi)=\frac{\varepsilon(\theta,\varphi)}{2\pi}\left(1\pm A_y(\theta)P_t^{fpp}\sin\varphi - A_y(\theta)P_n^{fpp}\cos\varphi\right)$$

P_t^{fpp} and P_n^{fpp} are the polarization components at the FPP

Physical Asymmetries are obtained from difference distributions

$$D_i=\left(f_i^{+}-f_i^{-}\right)/2$$

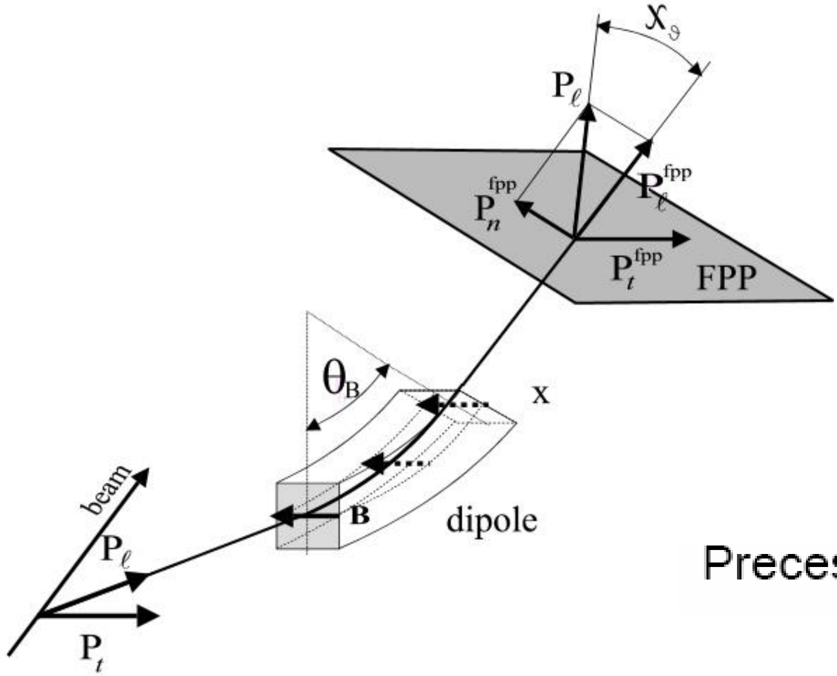
$$D_i=\frac{1}{2\pi}\left[A_y P_t^{fpp}\sin\varphi - A_y P_n^{fpp}\cos\varphi\right]$$

Sum distribution give instrumental asymmetries

$$E_i = f_i^{+} + f_i^{-}/2$$

$$E_i=\varepsilon_i/2$$

Spin Precession



$$p_l^{fp} = 0 \quad and \quad P_n^{tgt} = 0$$

Precession angle, $\chi = \gamma \kappa_p \theta_{\text{bending}}$

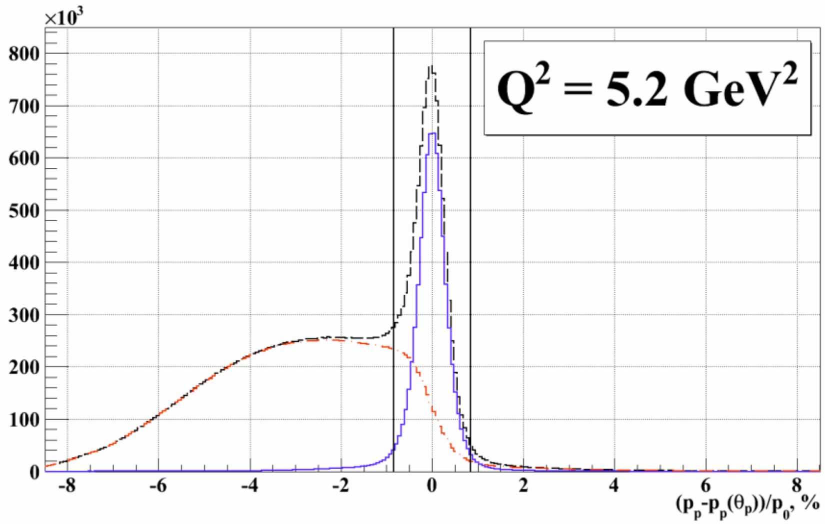
$$\begin{pmatrix} P_N \\ P_T \\ P_L \end{pmatrix}_{\text{fp}} = \begin{pmatrix} S_{n'n} & S_{n't} & S_{n'l} \\ S_{t'n} & S_{t't} & S_{t'l} \\ S_{l'n} & S_{l't} & S_{l'l} \end{pmatrix} \begin{pmatrix} P_N \\ P_T \\ P_L \end{pmatrix}_{\text{tgt}}$$

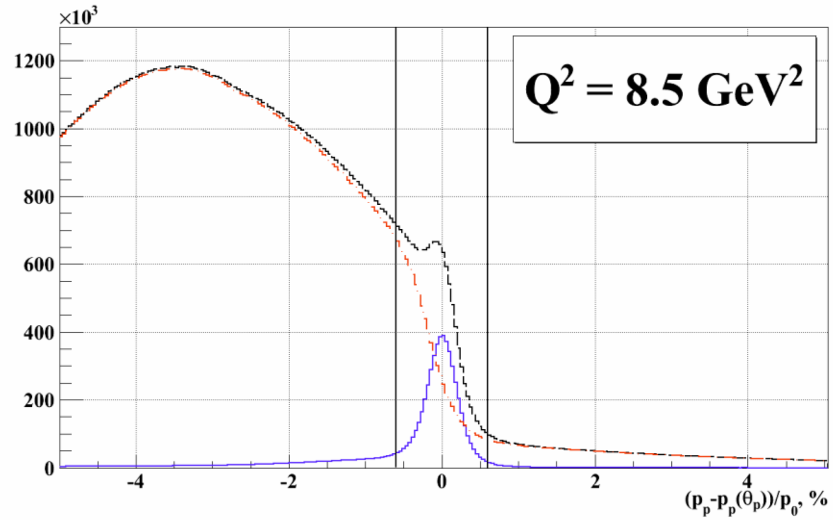
If only dipole field: $S_{t't} = 1$ and $S_{n'l} = -\sin\chi$

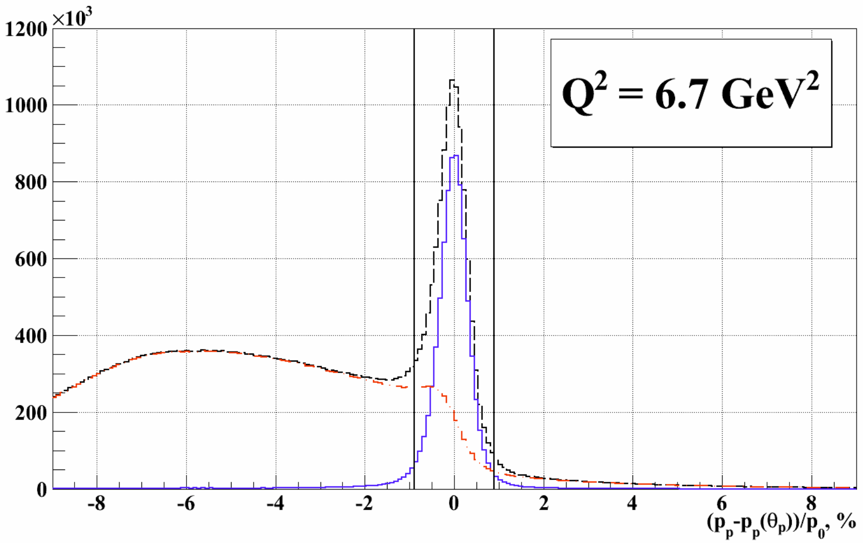
$S_{t'l} = S_{n't} = 0$

$P_T^{fp} = P_T$ and $P_N^{fp} = -P_L \sin(\chi)$

Proton Momentum Spectrum



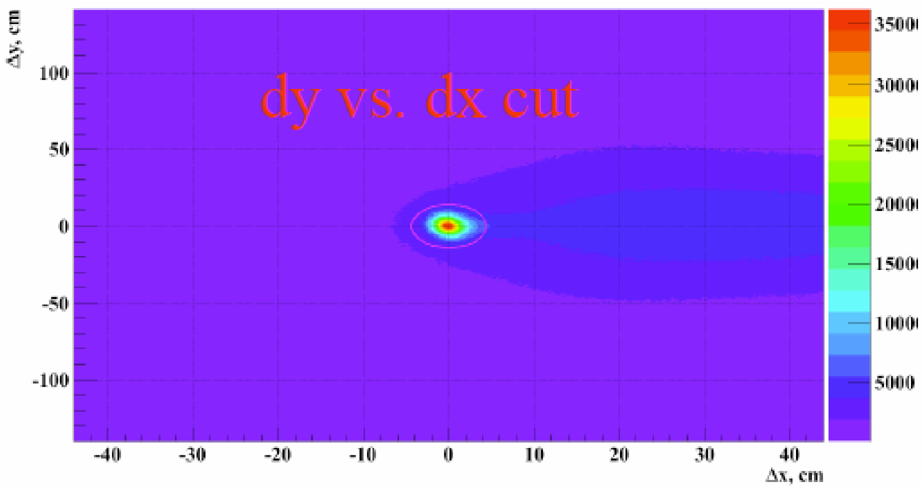


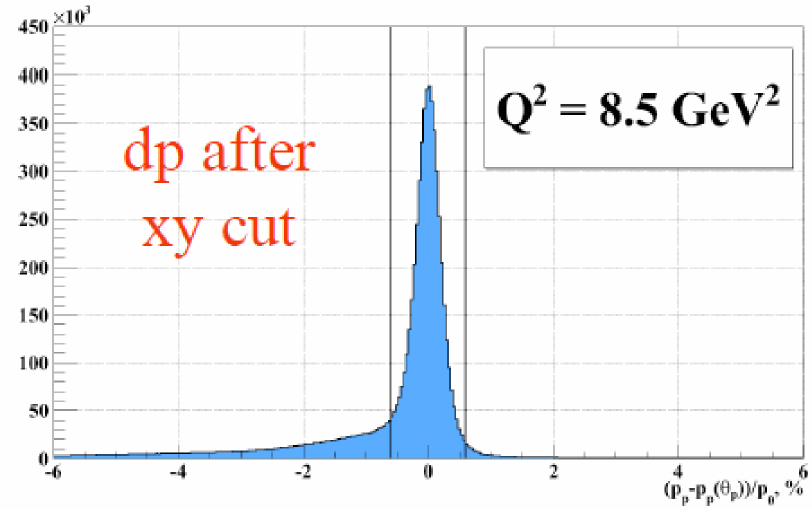


$$p_p(\theta_p) = \frac{2M_p E_e (E_e + M_p)\cos\theta_p}{M_p^2 + 2M_p E_e + E_e^2 \sin^2\theta_p}$$

- Proton angle-momentum correlation in elastic scattering
- p-p(θ) spectra:
- ALL/PASS/FAIL cuts

Elastic Event Selection

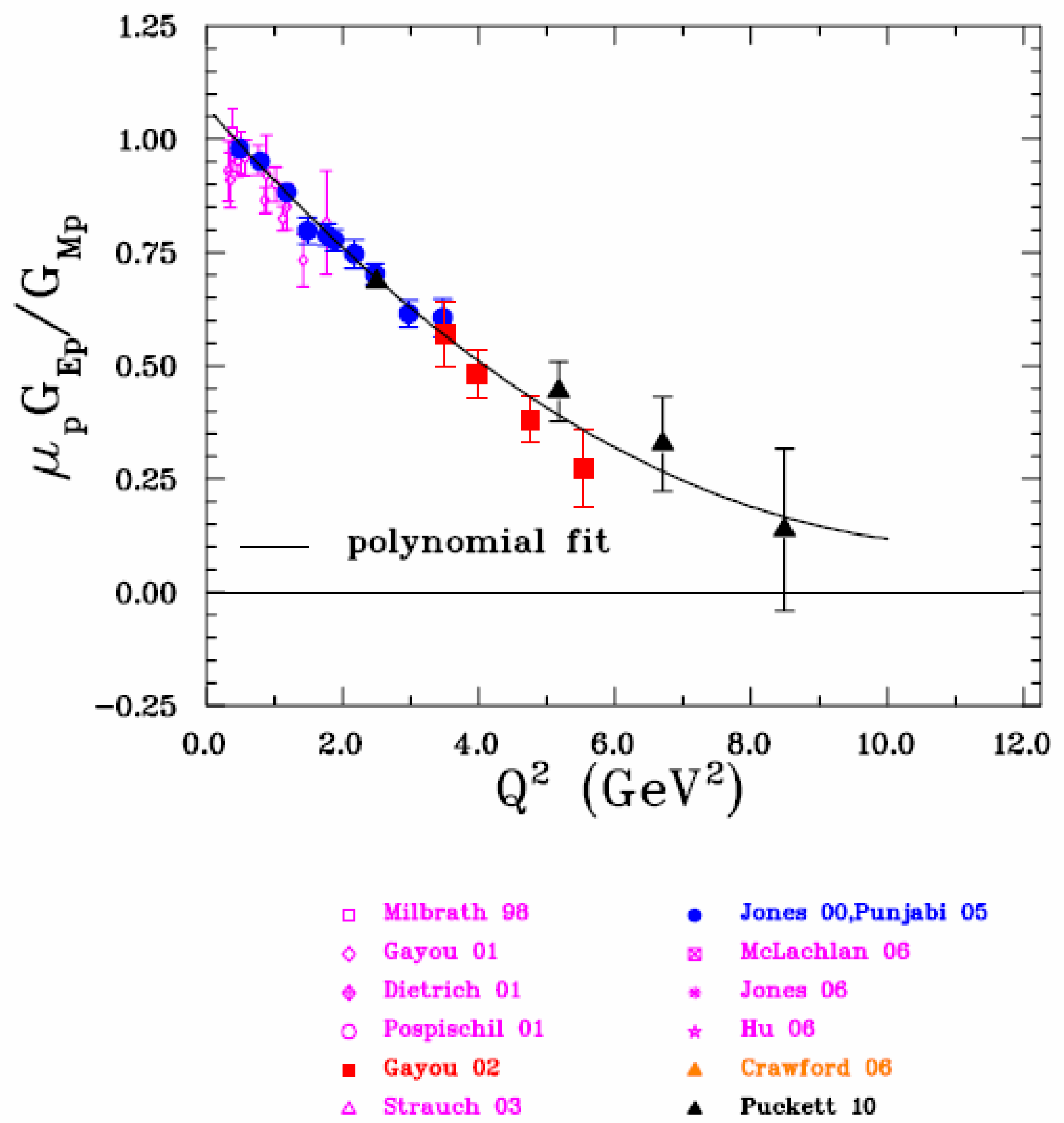




$$\left(\frac{\Delta x}{x_{max}}\right)^2 + \left(\frac{\Delta y}{y_{max}}\right)^2 \leq 1$$

- Elliptical cut at BigCal cleans up "dp" spectrum rather efficiently
- Fat tail on inelastic side of peak indicates "leftover" background
- Tight cuts to dx, dy, dp needed
- Still ~6% background for final cuts at Q^2=8.5 GeV^2

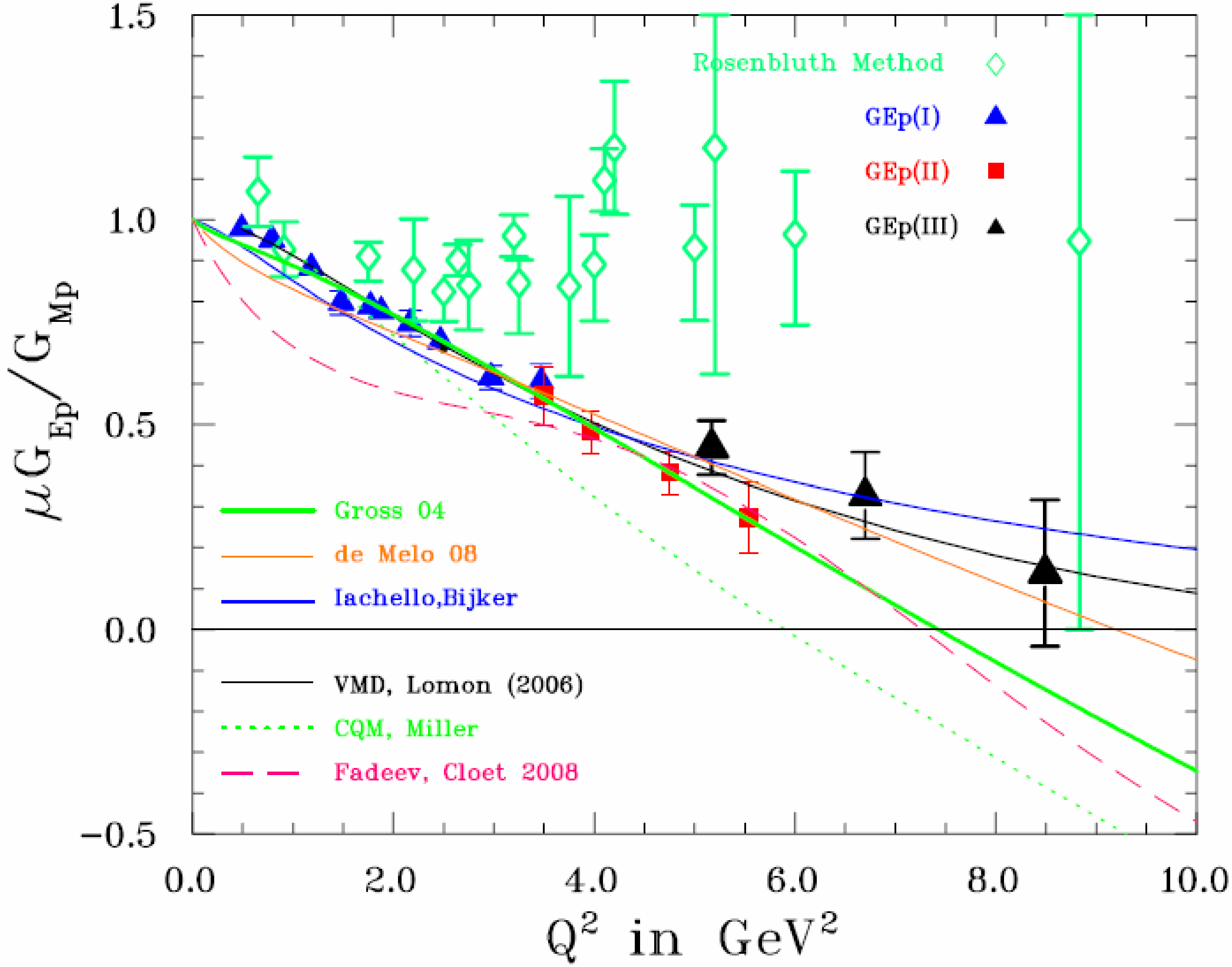
All data for the ratio G_{Ep}/G_{Mp} from Double Polarization



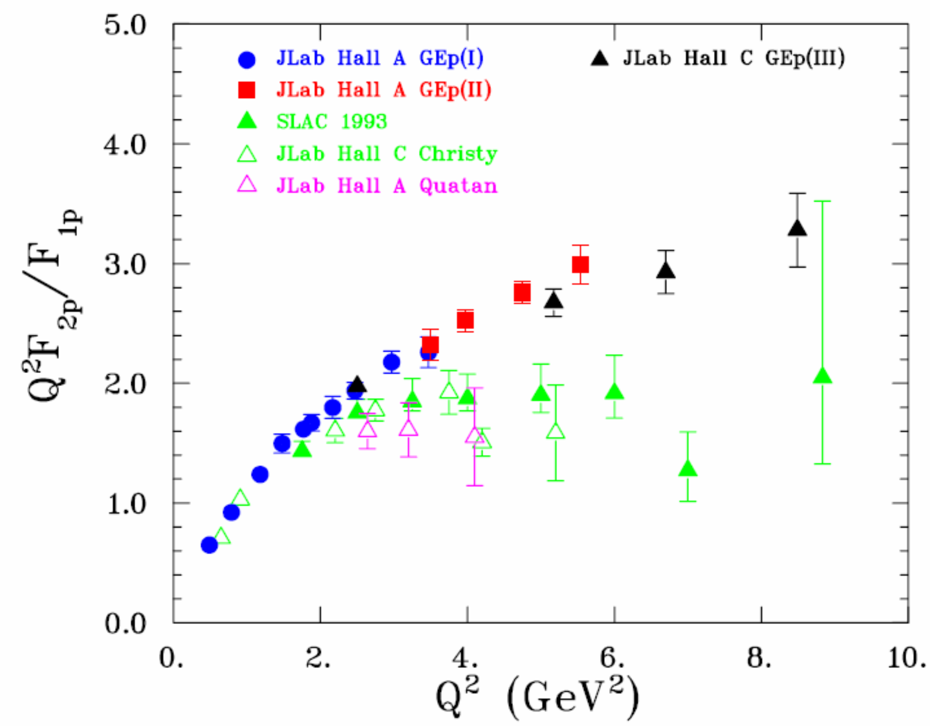
Theoretical Progress

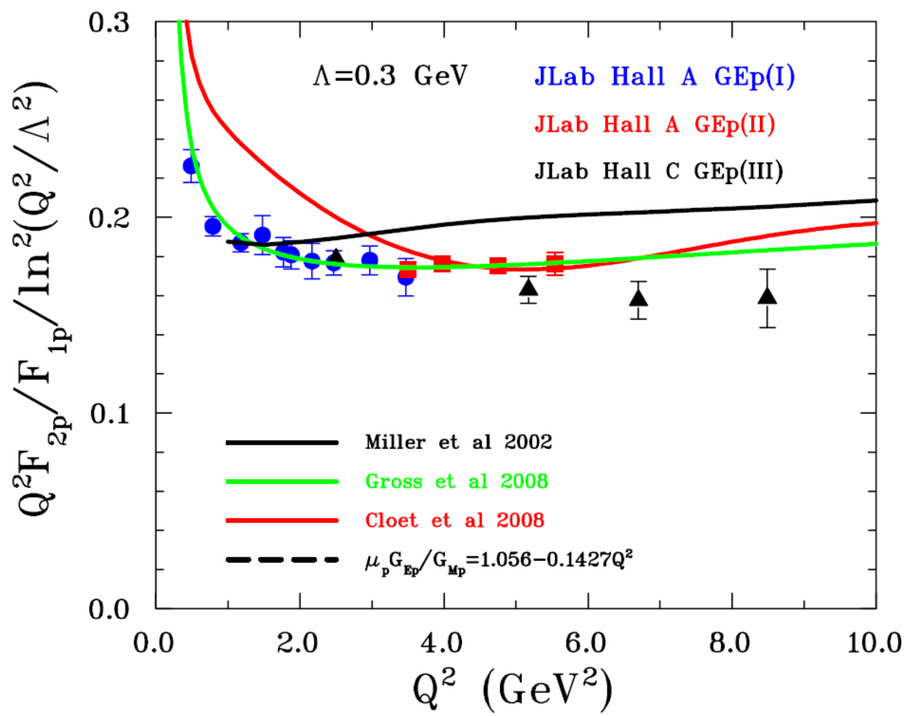
- VMD-based models
  - Describe all four nucleon FF's well
  - Tend to favor ratio reaching a constant value at intermediate Q^2
- rCQM
  - Show the importance of relativistic dynamics
- pQCD-inspired models
  - Predict logarithmic scaling behavior of F_2/F_1 at intermediate Q^2 (Belitsky and Ji) ->related to quark Orbital angular momentum (OAM)
- GPD-inspired models
  - Show a connection with OAM of the quarks in the nucleon
  - FF's provide important constraints on GPD's
- Dyson-Schwinger Equations
  - Dressed quarks are fundamental degrees of freedom, diquark correlations, Solution of Poincare-covariant Faddeev equations based on rainbow-ladder truncation of DSEs of QCD. photon-nucleon vertex depends on a single parameter: diquark charge radius.
- Lattice QCD Models
  - Good progress already, and will get much better in the future

Theoretical predictions



Proton: F_2/F_1 and pQCD





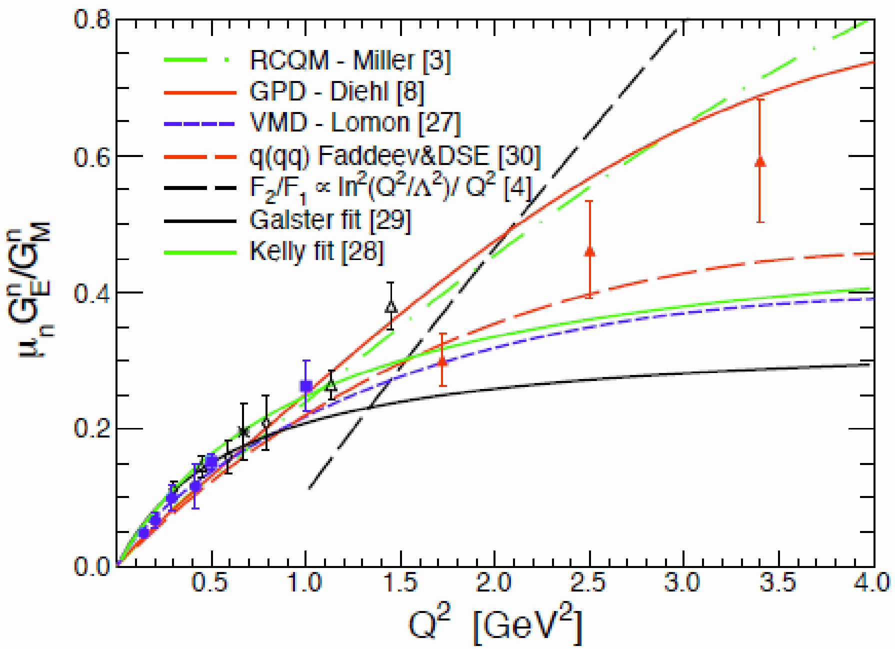
Brodsky and Farrar (75):

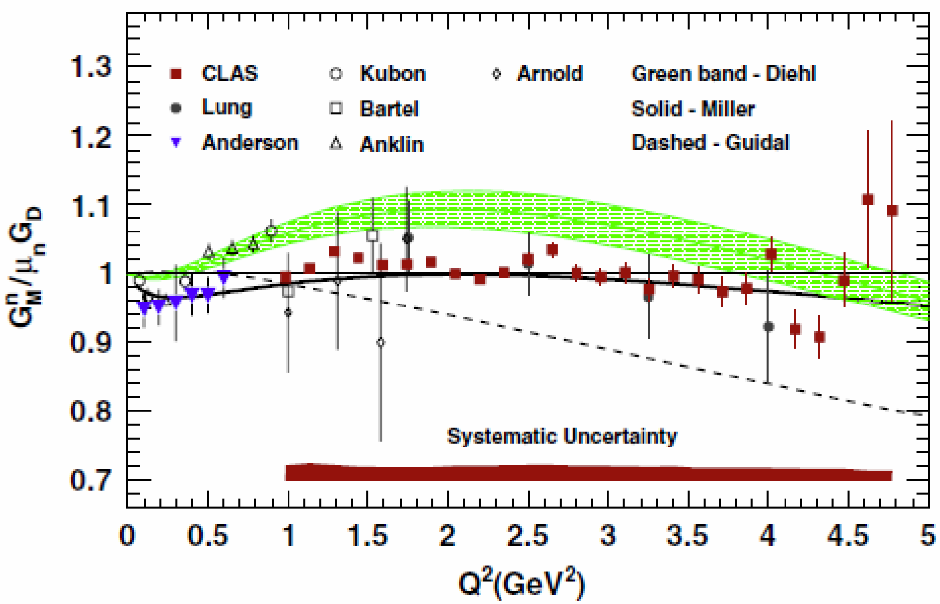
Q^2F_2/F_1 constant

Belitsky, Ji and Yuan (03):

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

Neutron form factor data compared to theoretical estimates

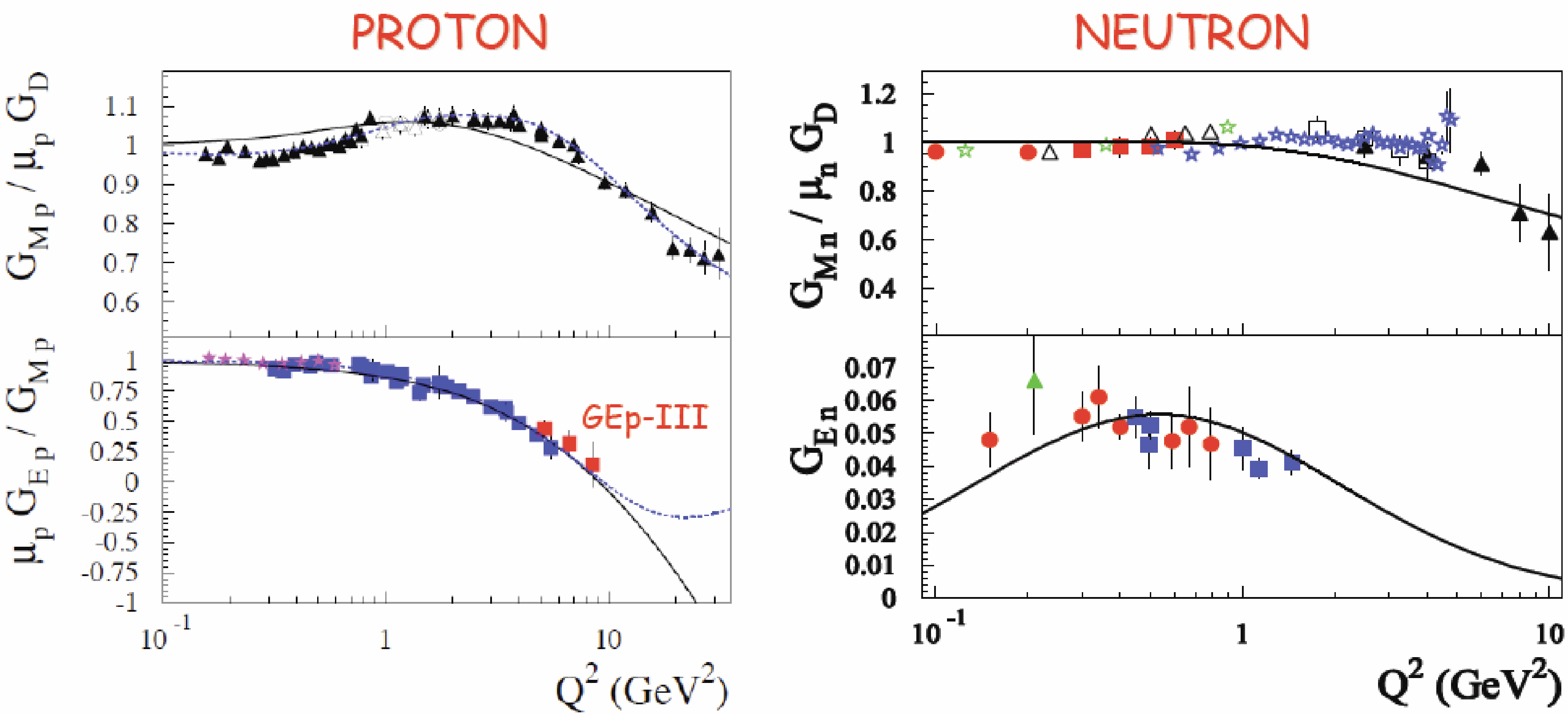




Preliminary, Riordan *et al.*

Lachniet *et al.*, Phys. Rev. Lett. 102 192001 (2009).

GPD parametrization of Nucleon FF



Guidal *et al.*, (2005)

3-parameter fit

modified Regge GPD parameterization:
1 : Regge slope -> proton Dirac (Pauli) radius
2, 3 : large x behavior of GPD E^u, E^d -> large Q^2 behavior of F_{2p}, F_{2n}

- Form factors constrain GPDs through sum rules: 0th moments of vector (H) and tensor(E) GPDs equal e.m. form factors

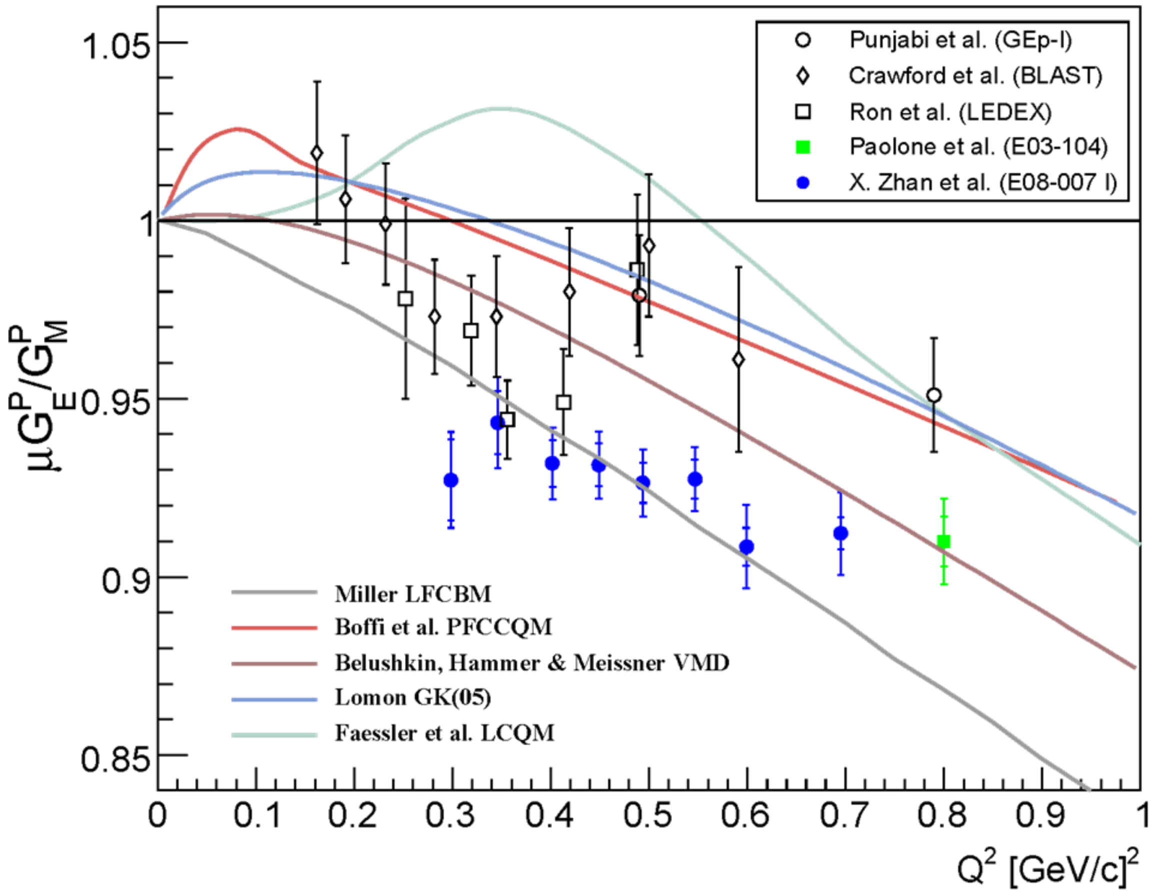
$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$$

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

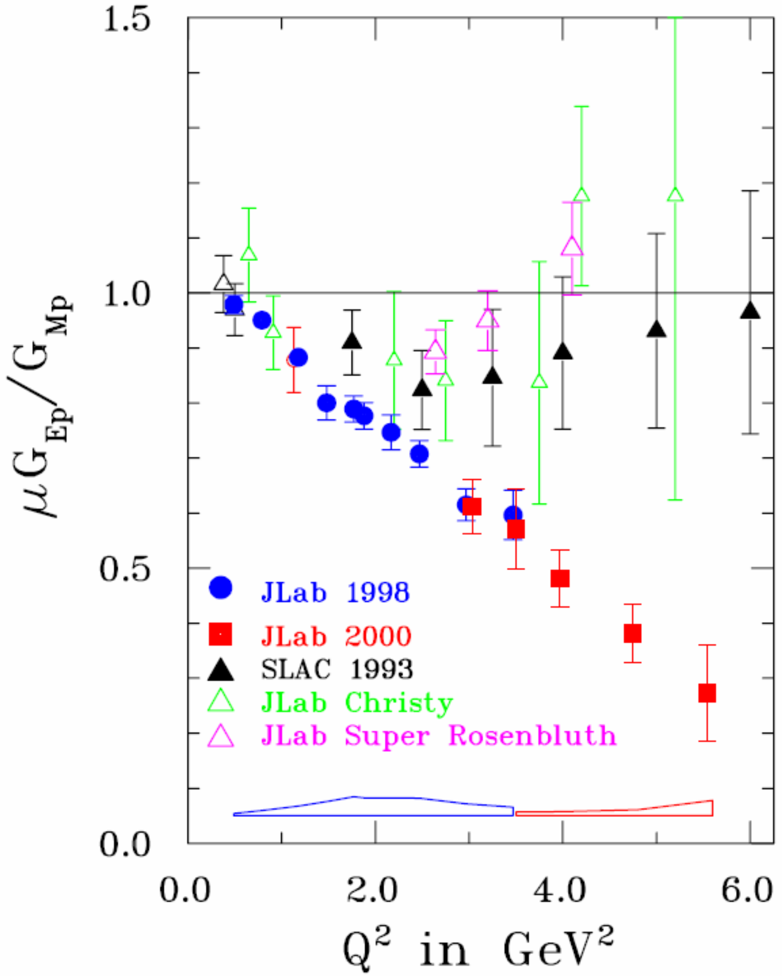
Low Q^2 Region

New results from JLab for G_{Ep}/G_{Mp} in low Q^2 region

Preliminary



G_{Ep}/G_{Mp} Crisis ?



"The discrepancy is a serious problem as it generates confusion and doubt about the whole methodology of lepton scattering experiments"

P.A.M. Guichon and
M. Vanderhaeghen, PRL 91, 142303 (2003)

So what are the causes for the different results for $\mu G_{Ep}/G_{Mp}$, from cross section and polarization measurements?

Source(s?) of the discrepancy

Radiative corrections (RC) to *ep* cross sections can be as large as ~30 % and ε-dependent. Slope of Rosenbluth plot changed by the correction

RC follow Mo and Tsai, or Maximon and Tjon; do not include the inelastic contribution in proton vertex; may require additional revisions

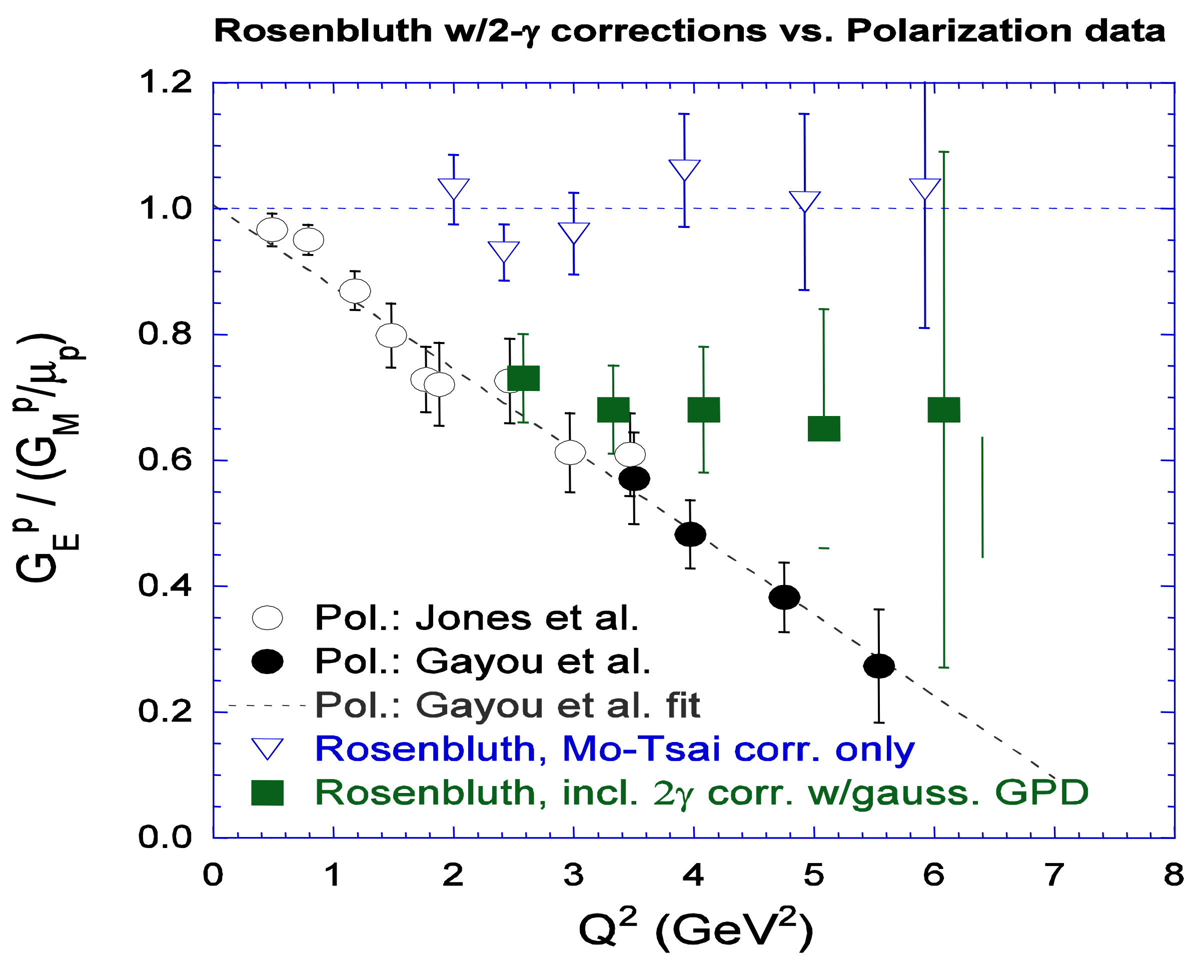
RC to P_t/P_l for double polarization data are about 1 to 2 % in Q^2 range up to ~ 6 GeV^2

``Super'' Rosenbluth separation in Hall A first $^1H(e,p)e$ measurement; radiative corrections smaller; "confirms" older data

Two-(hard) photon contribution has been neglected until results of the two Hall A polarization experiments; Recent work on two-photon include: Guichon and Vanderhaegen, Blunden, Melnitchouk and Tjon, Tomasi-Gustafsson and Rekalo, Afanasev, Brodsky, Carlson, Chen and Vanderhaeghen

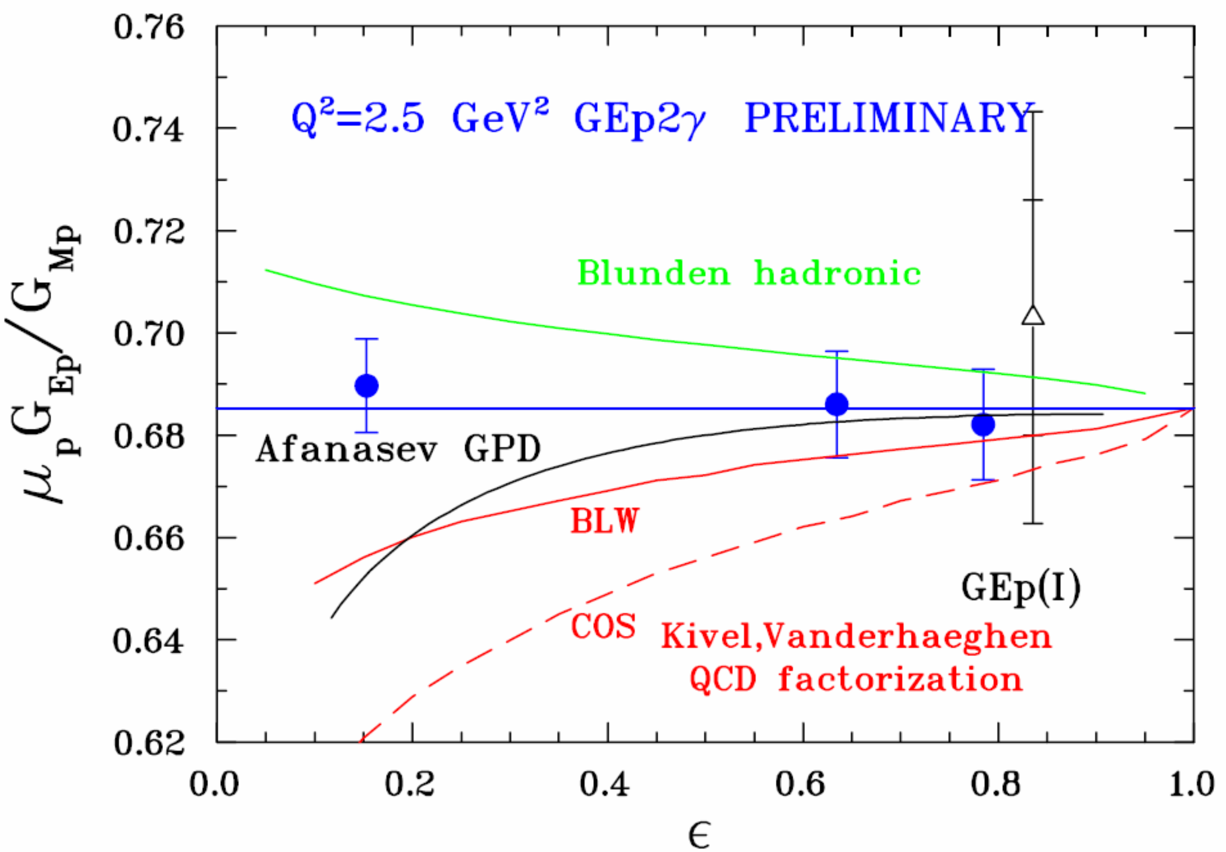
Two-photon exchange affects form factor observables as interference between the single- and two-photon processes

Two-Photon Exchange: GPD predictions



A. Afanasev et al., Phys. Rev. D 72:013008 (2005)

Results of $G_{Ep}(2\gamma)$ Experiment from JLab



The predictions are normalized to converge at the fitted value of ε = 1.

radiative corrections applied, they are negligible
(Afanasev et.al, Phys.Rev. D64 (2001) 113009)

Concluding Remarks

- Since Hofstadter's first experiments 50 years ago, we have discovered many new features about the structure of the proton and neutron.

- High-Q^2 surprise in G_{Ep}/G_{Mp}, have led to a fundamental change in picture of the internal structure of the proton, strong impact on theoretical progress, evidence for two-photon exchange effects.

- The new results from double polarization method for proton and neutron, together with further results following the 12 GeV upgrade, will provide answers to a number of open questions crucial to our understanding of fundamental nucleon properties, and the nature of QCD in the confinement regime

Thank you for your attention

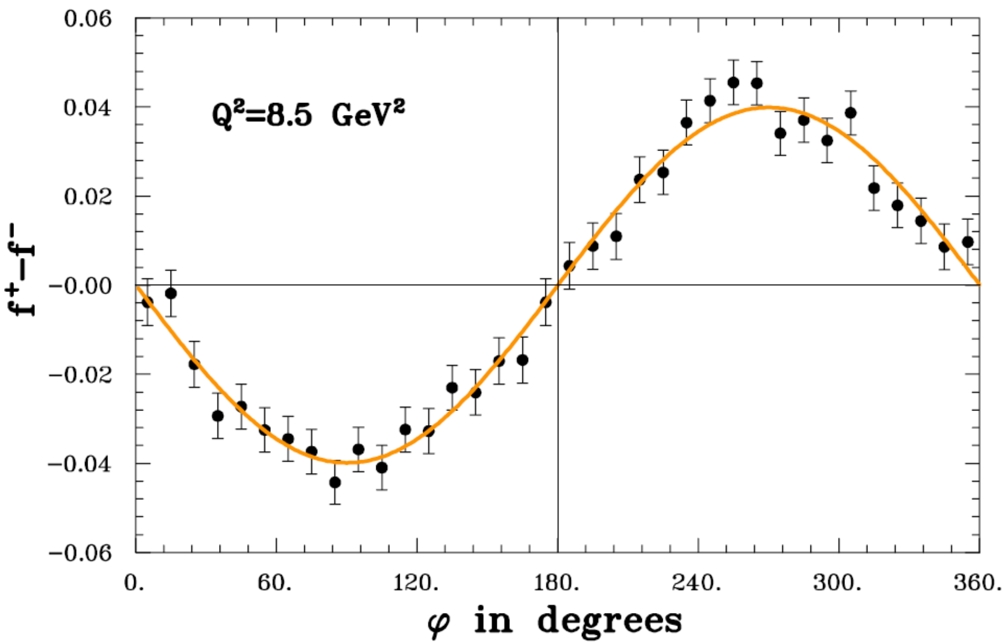
Extra slides

Systematic Uncertainties

Q^2, GeV^2	5.2	6.7	8.5
ϕ_{bend} (±.5 mrad)	.0162	.0202	.0378
θ_{bend} (±2 mrad)	.0009	.0006	.0002
δ (±0.3%)	.0029	.0027	.0024
φ_{fpp} (±.14 mrad/ sin(ϑ_{fpp}))	.0003	.0057	.0178
E_{beam} (±.05%)	.00027	.00009	.00025
False asym.	.0069	.0057	.0018
Background	.0015	.0013	.0130
Rad. Corr. (% of R)	0.05% ($\Delta R \approx$ -.0002)	0.12% ($\Delta R \approx$ -.0004)	0.13% ($\Delta R \approx$ -.0002)
Total ΔR_{syst}	.018	.022	.043

- Non-dispersive precession uncertainty dominates the systematic uncertainty in R
- Ay, h cancel, no uncertainty for R
- Standard radiative corrections (not applied) negligible compared to other uncertainties

FPP Asymmetry



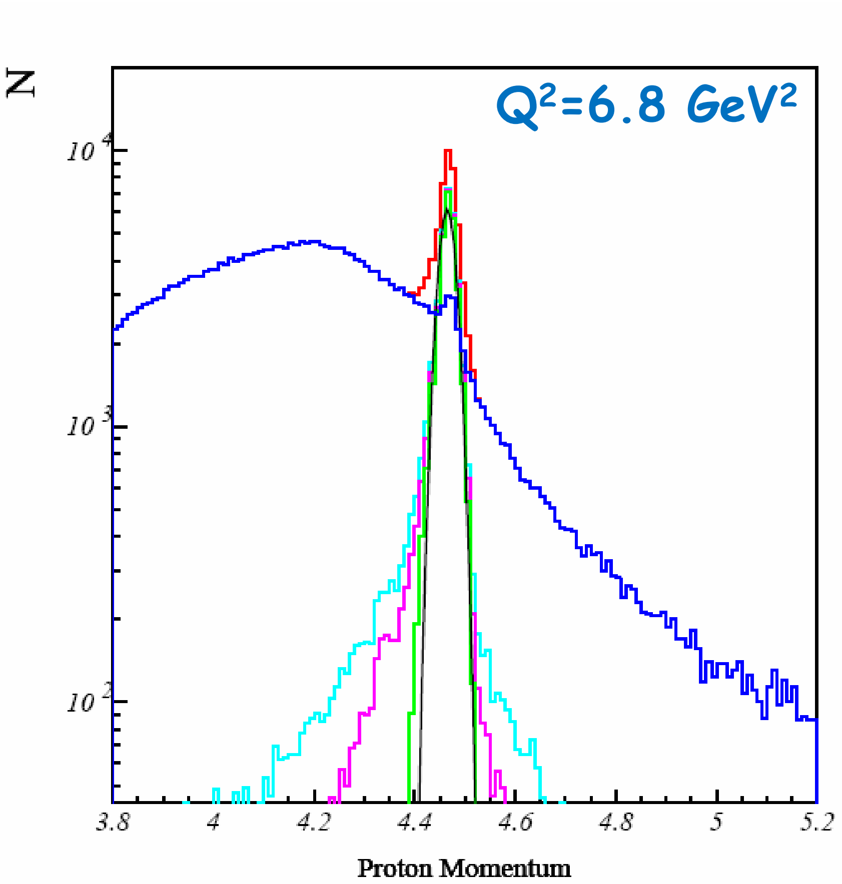
$$f_+ - f_- = A\sin(\varphi + \delta)$$

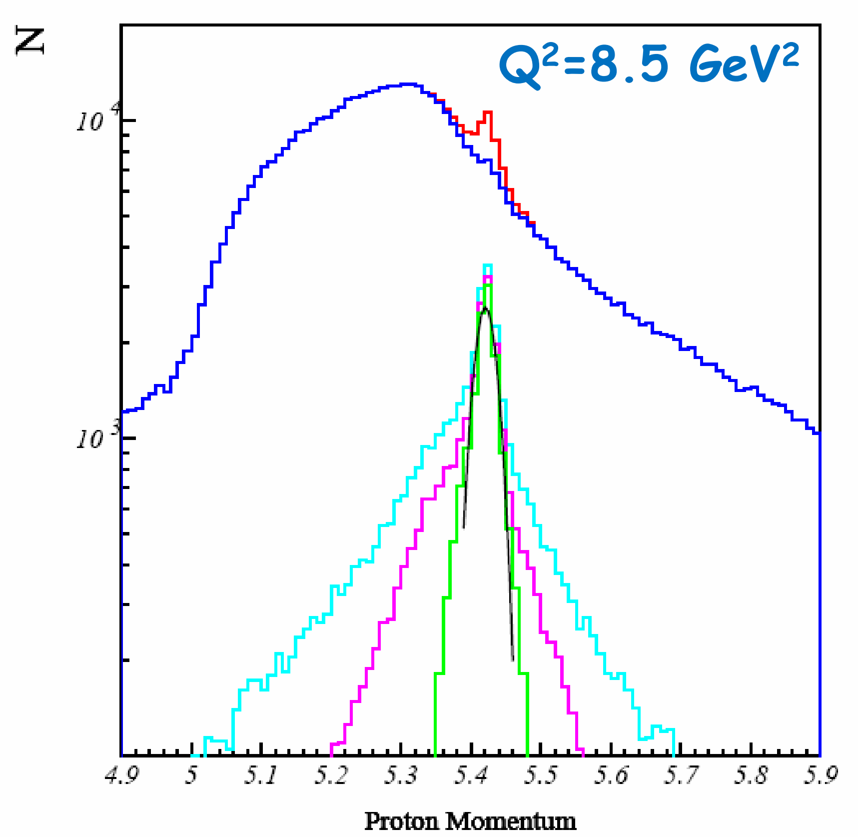
$$A = \overline{A}_y \sqrt{\left(P_x^{fpp}\right)^2 + \left(P_y^{fpp}\right)^2}$$

$$\tan\delta = \frac{P_y^{fpp}}{P_x^{fpp}}$$

Helicity difference asymmetry, Q2 = 8.5 GeV2, 0.5° ≤ θ ≤ 14.0°

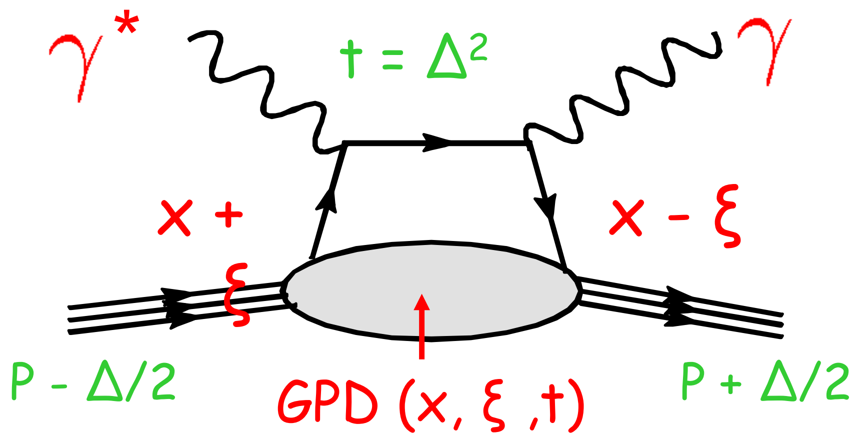
Proton Momentum Spectrum

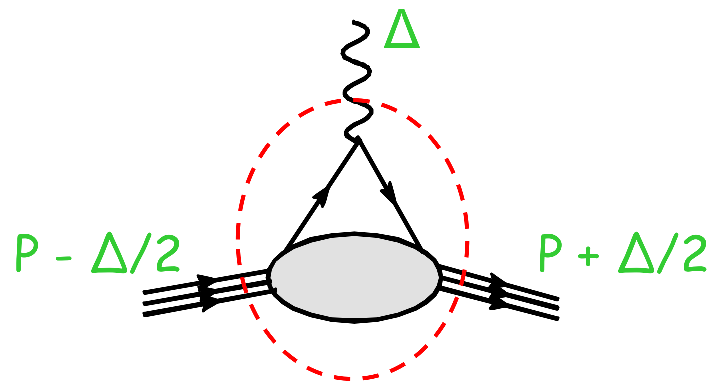




Red : all events, Cyan: with δ-θ cut, Magenta: requiring co-planarity,
Green: localization in BigCal and polar angle correlation with fit in Black
Blue: the background

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)

$$H^q(x, \xi = 0, t = 0) = q(x)$$ unpolarized quark distribution

$$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$$ polarized quark distribution

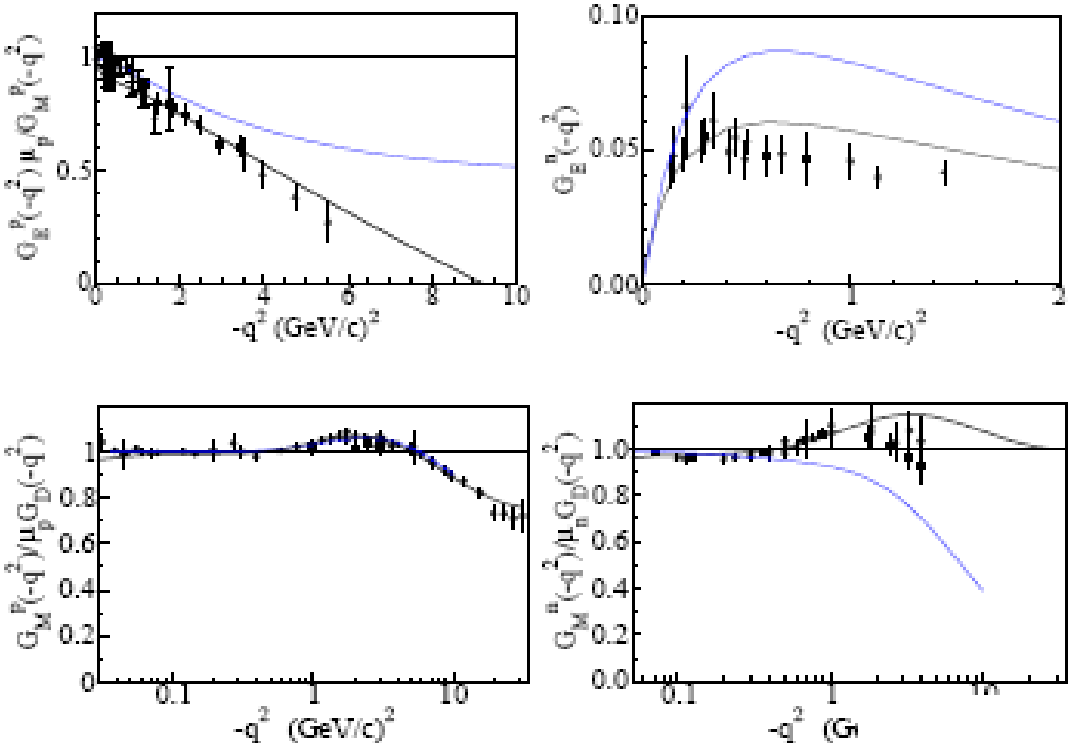
In DIS

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

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

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

New Theoretical Results

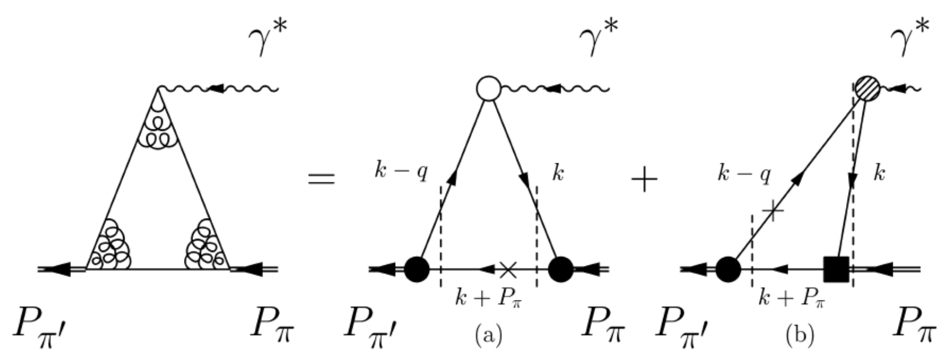


Solid line: LF Nucleon ff's

Solid line: Gari-Krümpelman

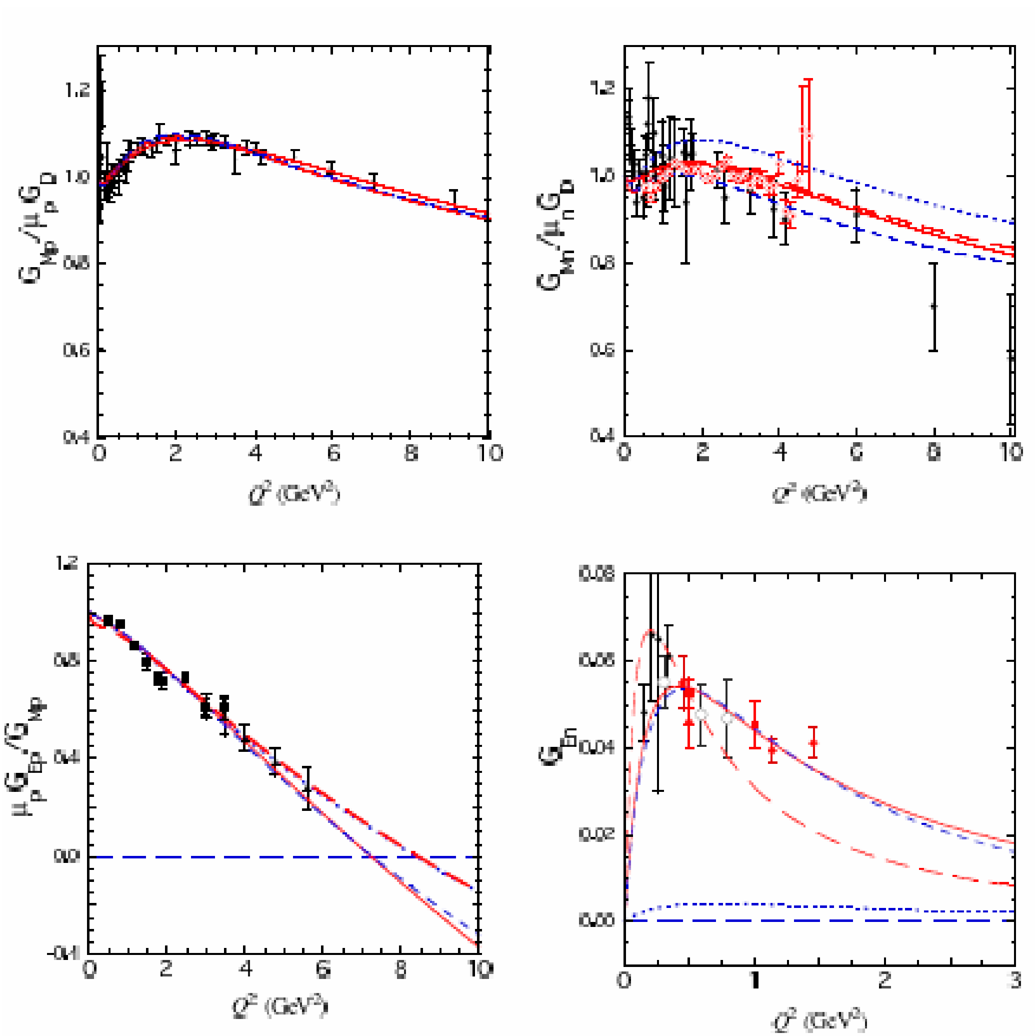
De Melo, Frederico, Pace, Pisano, Salmè light front CQM with qqbar from Z-diagram, the source of the zero crossing. Zero crossing still near 9 GeV² when GEp data taken out of fit

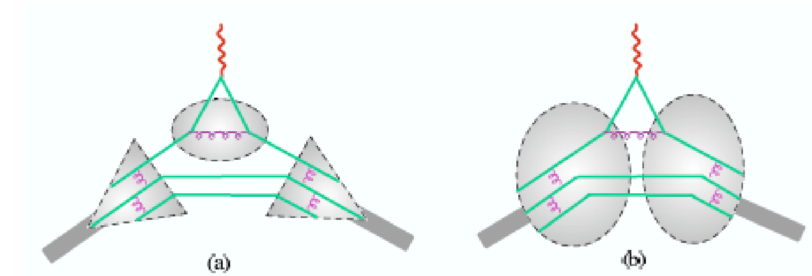
Spacelike region



A Pure S-Wave Covariant Model for the Nucleon

Franz Gross et al., Phys. Rev. C 77, 015202 (2008)





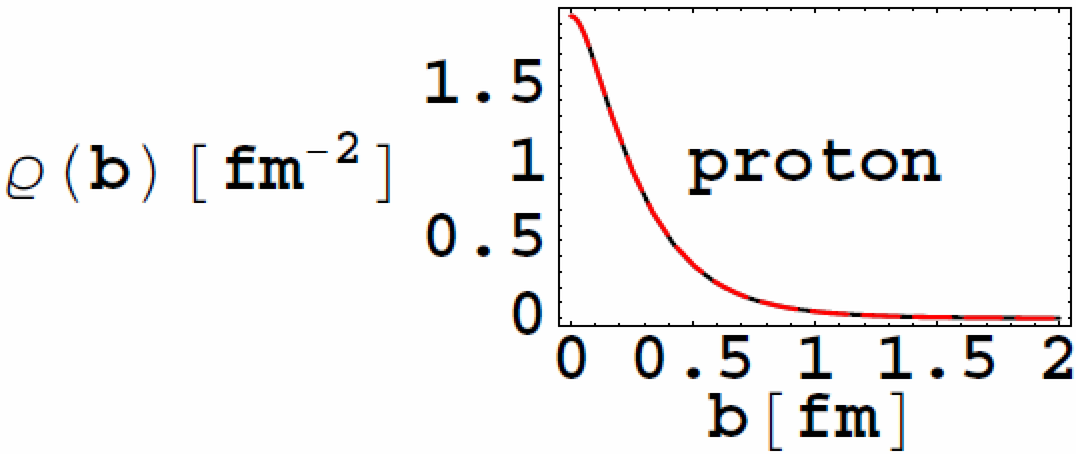
Covariant spectator theory modeling nucleon as a system of three valence Constituent Quarks with their own form factors

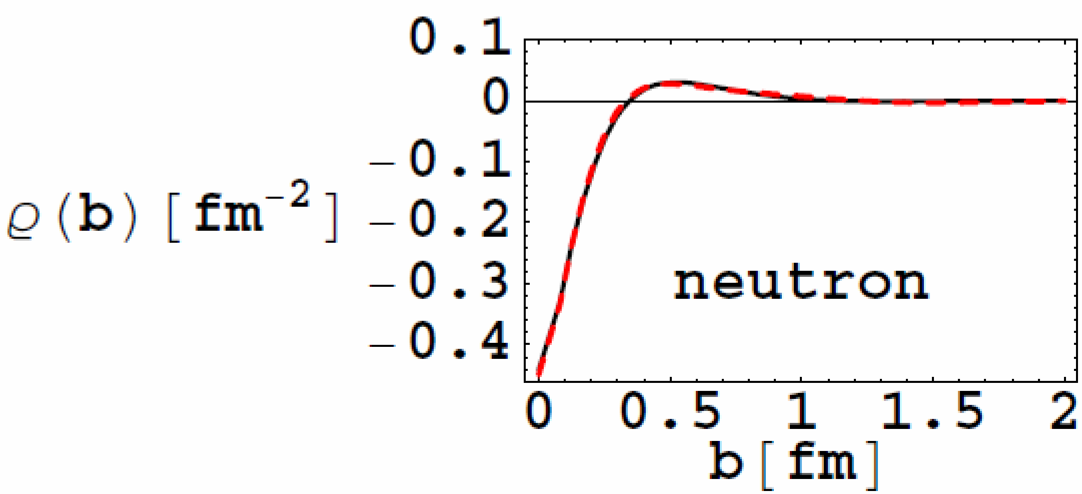
Transverse Charge densities for proton and Neutron

$$q(x, \mathbf{b}) = \int \frac{d^2q}{(2\pi)^2} e^{i\mathbf{q}\cdot\mathbf{b}} H_q(x, t = -\mathbf{q}^2)$$

$$\rho(b) \equiv \sum_q e_q \int dx q(x, \mathbf{b}) = \int \frac{d^2q}{(2\pi)^2} F_1(Q^2 = \mathbf{q}^2) e^{i\mathbf{q}\cdot\mathbf{b}}.$$

G. A. Miller, PRL 99, 112001 (2007)





Charge density ρ(b) of partons in the transverse plane is a two-dimensional Fourier transform of the F_1 form factor

It is calculated in the infinite momentum frame, from the measured FF

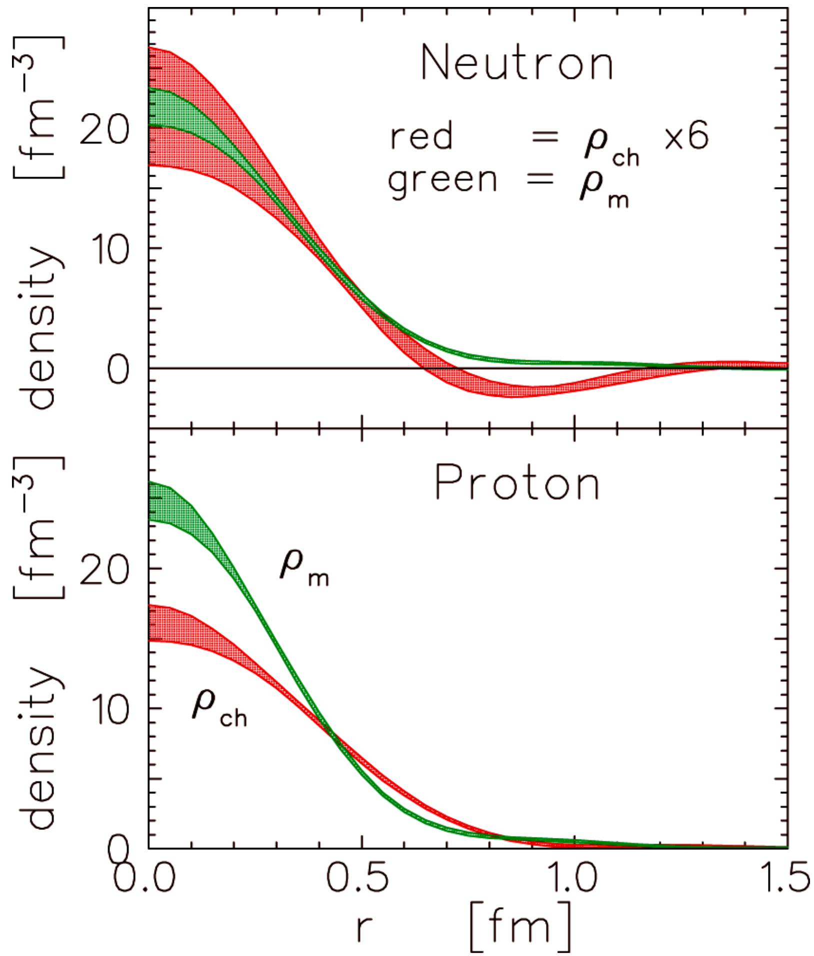
Charge density and Pion cloud

•Kelly has performed simultaneous fit to all four EMFF in coordinate space using Laguerre-Gaussian expansion and first-order approximation for Lorentz contraction of local Breit frame

$$\tilde{G}_{E,M}(k) = G_{E,M}(Q^2)(1+\tau)^2 \quad \textbf{with} \quad k^2 = \frac{Q^2}{1+\tau} \quad \textbf{and} \quad \tau = \left(\frac{Q}{2M}\right)^2$$

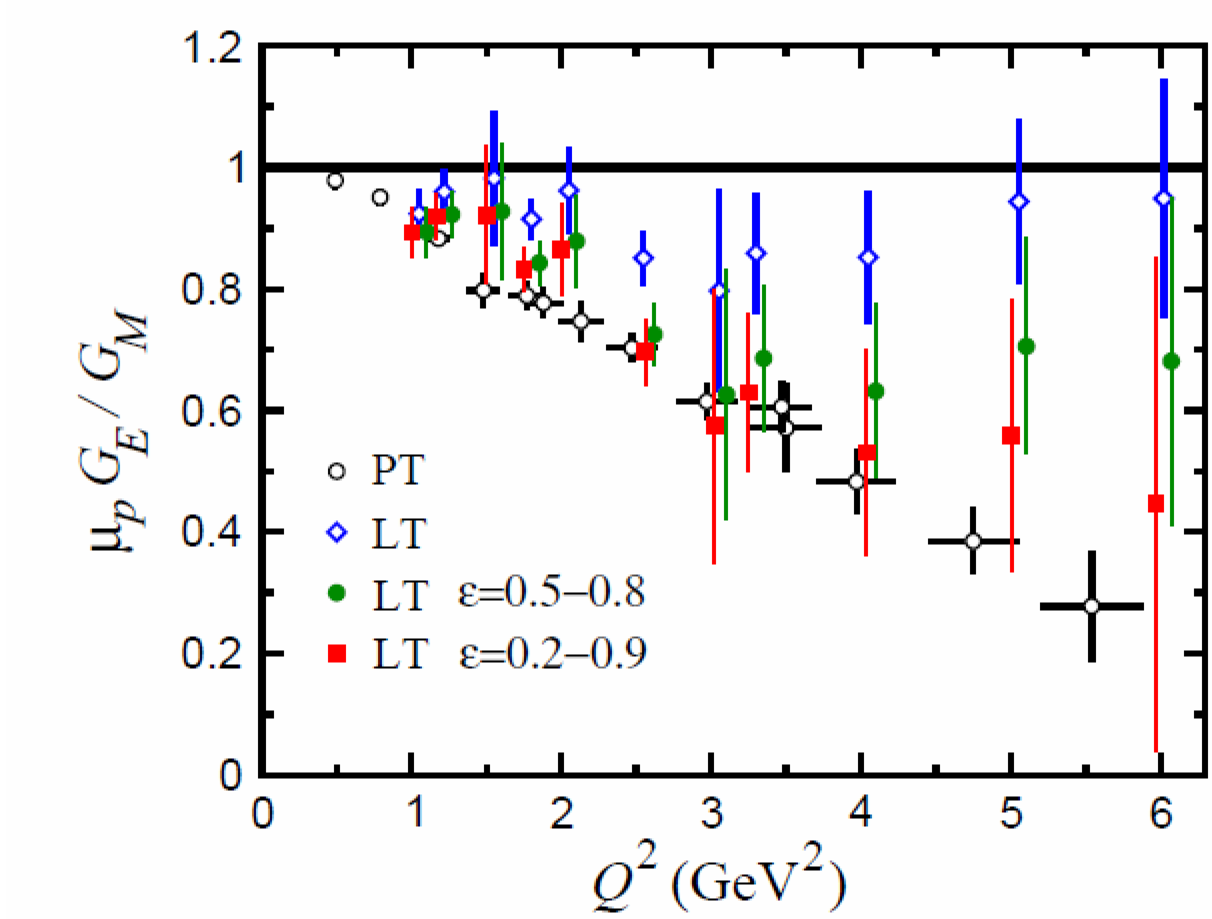
•Friedrich and Walcher have performed a similar analysis using a sum of dipole FF for valence quarks but neglecting the Lorentz contraction

•Both observe a structure in the proton and neutron densities at ~0.9 fm which they assign to the pion cloud



Two-Photon exchange

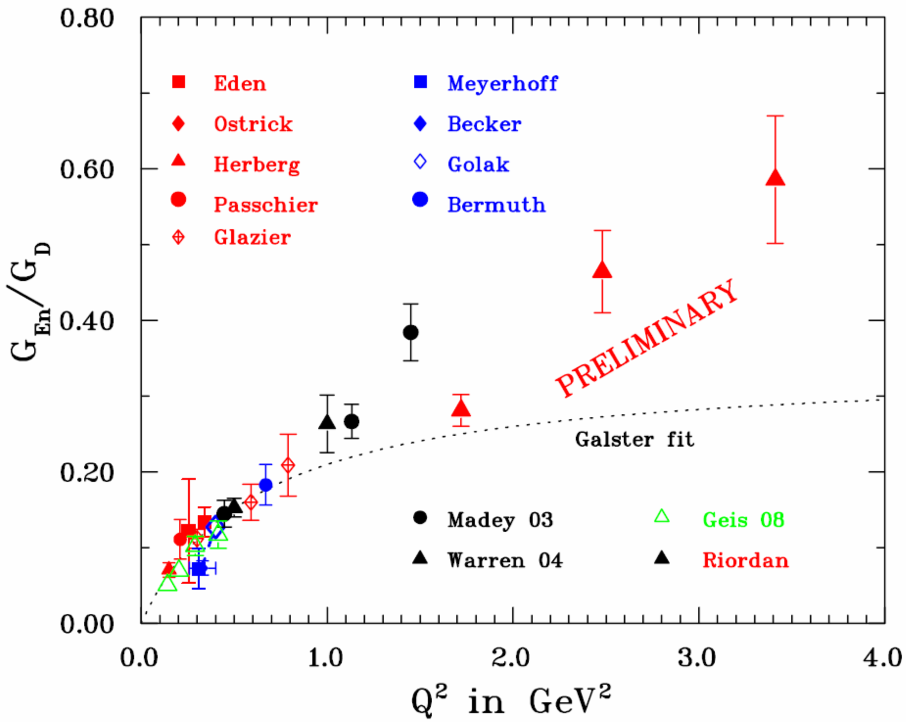
Two-photon with intermediate state a proton, including finite size effects: cross section and P_t and P_ℓ. Effect on P_t order ≤ 3 %, increasing with Q^2



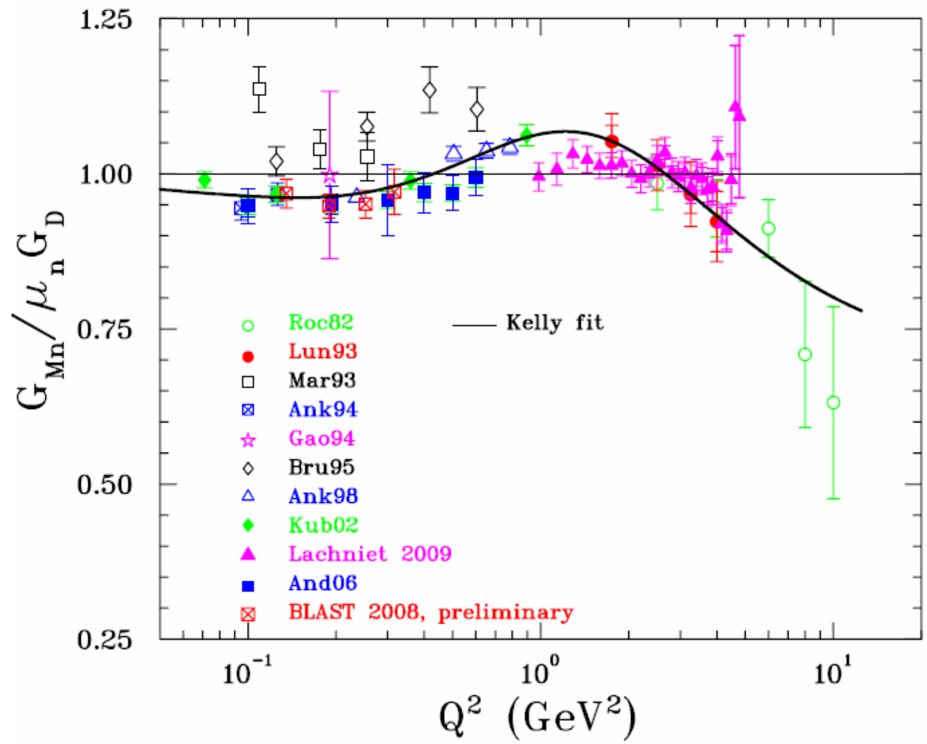
Blunden et al., PR C 72 (2005) 034612

Neutron Form Factors

From recent experiments at JLab



All polarization data



Polarization and cross section Data, ratio method e,e'n/e,e'p on deuteron; wave function dependence very small