New Measurements of G_{Ep}/G_{Mp} to High Q^2 at Jefferson Lab

Vina Punjabi
Norfolk State University

XX International Baldin Seminar on High Energy Physics Problems
Dubna, October 4-9, 2010

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

Nucleon Elastic Form Factors

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

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

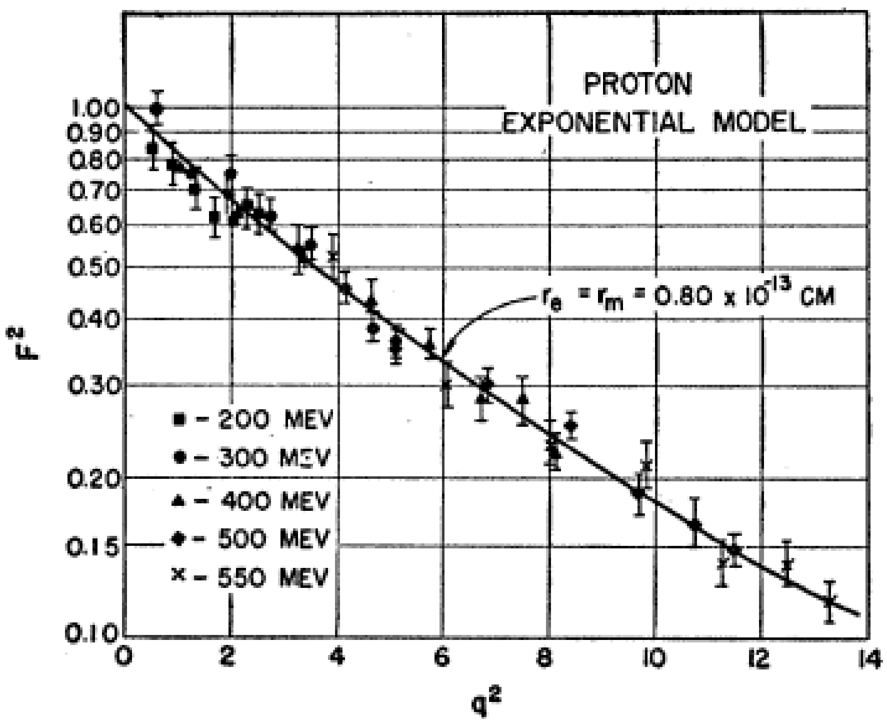
Investigation of FFs provide a powerful tool toward understanding
of non-perturbative QCD and confinement

Spectacular experimental progress in past decade using
New techniques / polarization experiments
Unexpected results that inspired theoretical progress

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

It all started in the 1950's



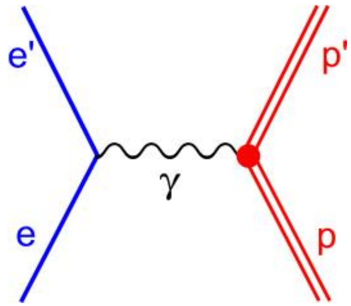
Robert Hofstadter
Nobel prize 1961

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

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

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

For $Q^2 \to 0$, 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

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

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

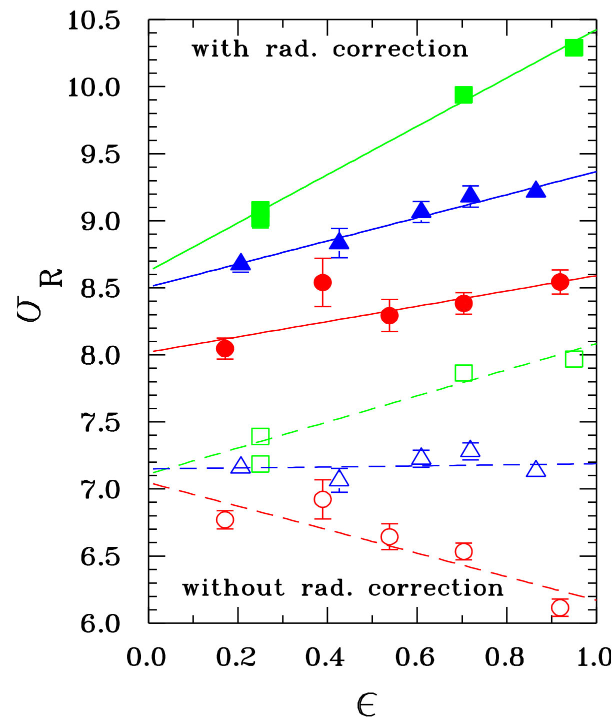
$$\tau = \frac{Q^2}{4m_p^2}$$

- 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.

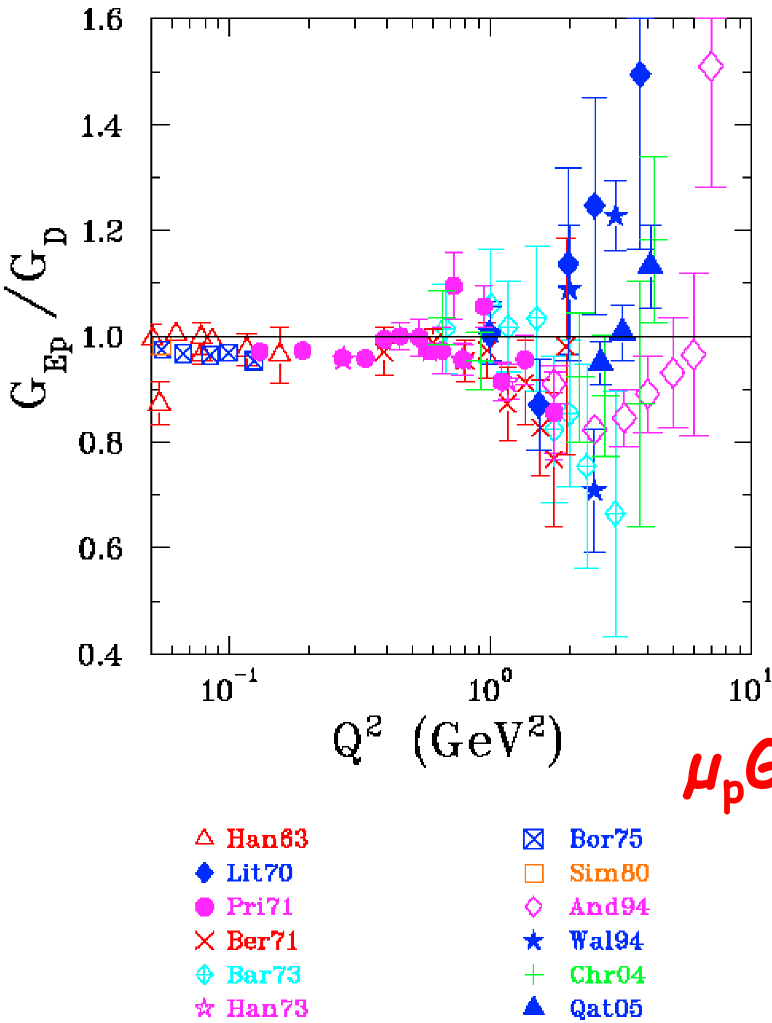
- Radiative corrections are crucial to obtain G_{Ep} from slope of σ_R



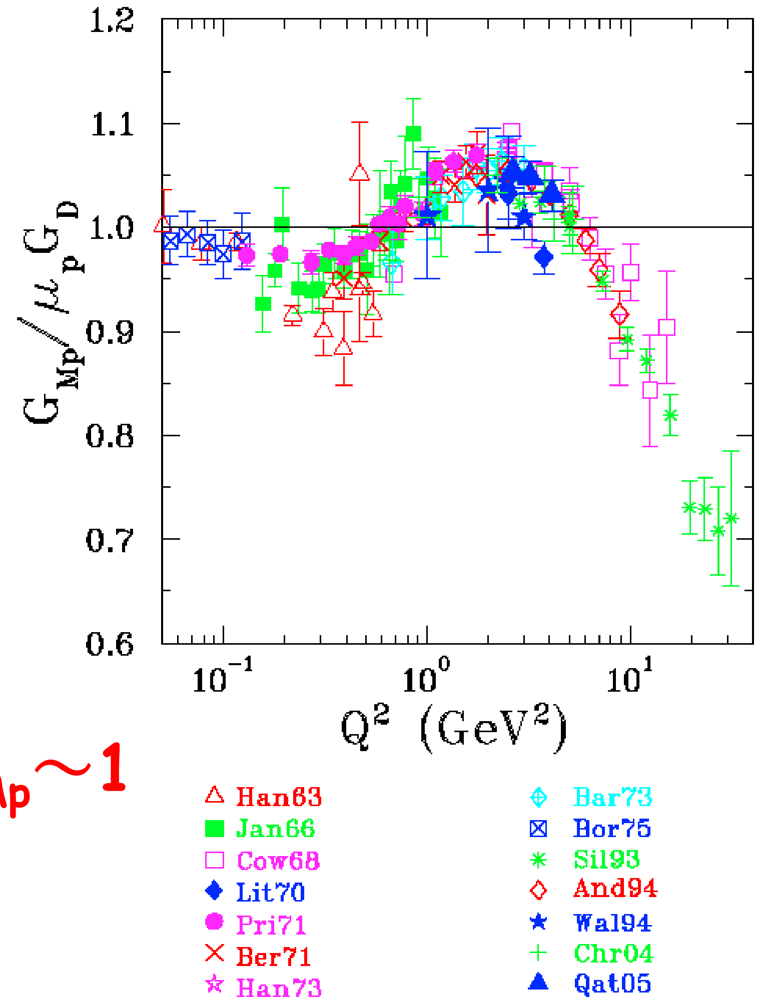
green for 1.75 GeV²
blue for 3.75 GeV²
red for 5 GeV²

Summary of Rosenbluth Data for Proton

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



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



Double polarization experiments

Polarization transfer in $\vec{e}N \rightarrow e\vec{N}$ or spin-target asymmetry $\vec{e}\vec{N} \rightarrow eN$, (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))

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

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

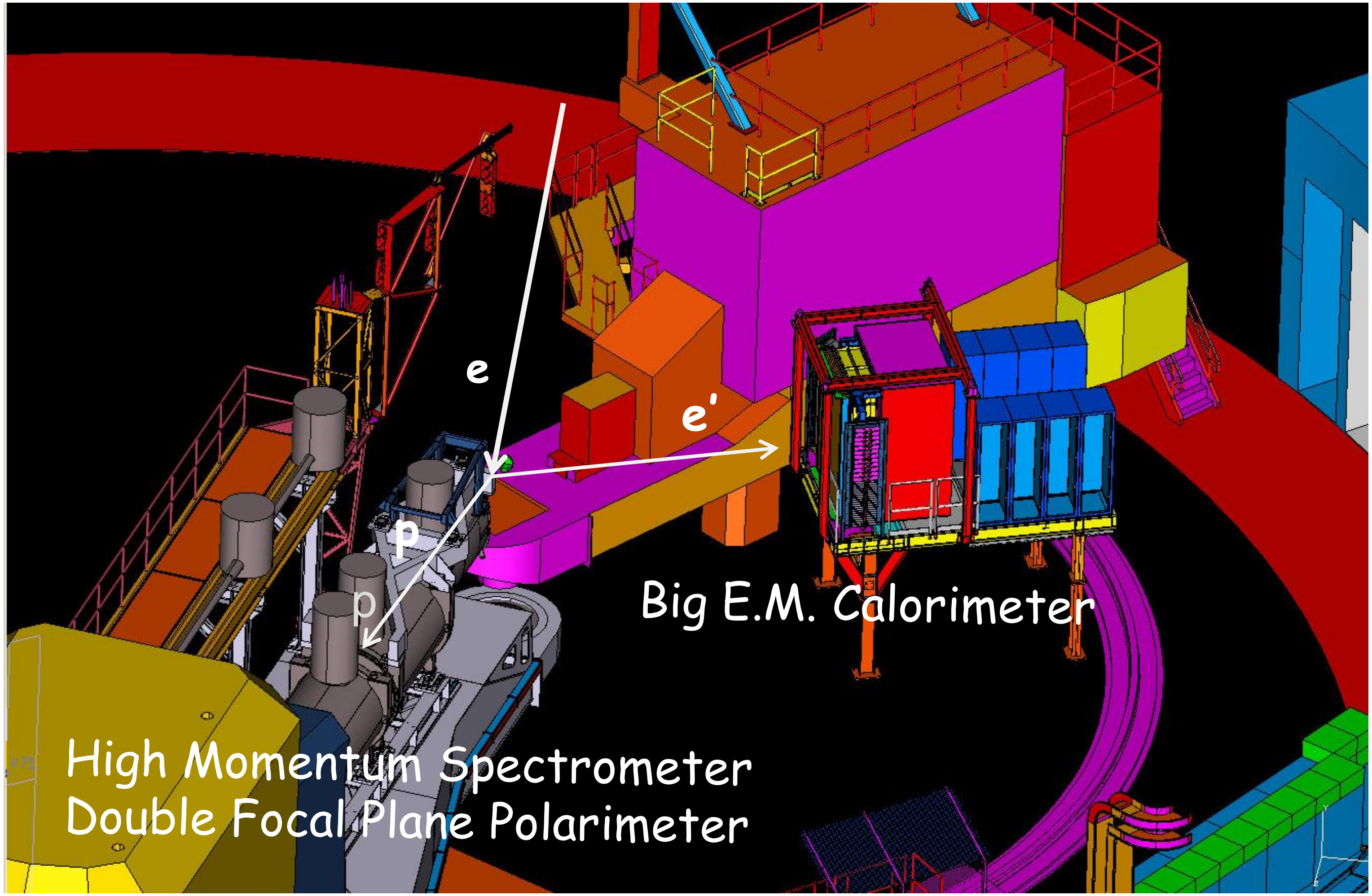
$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell}\frac{(E_e+E_{e'})}{2M}\tan\left(\frac{\theta_e}{2}\right) \quad or \quad -\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}$$

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

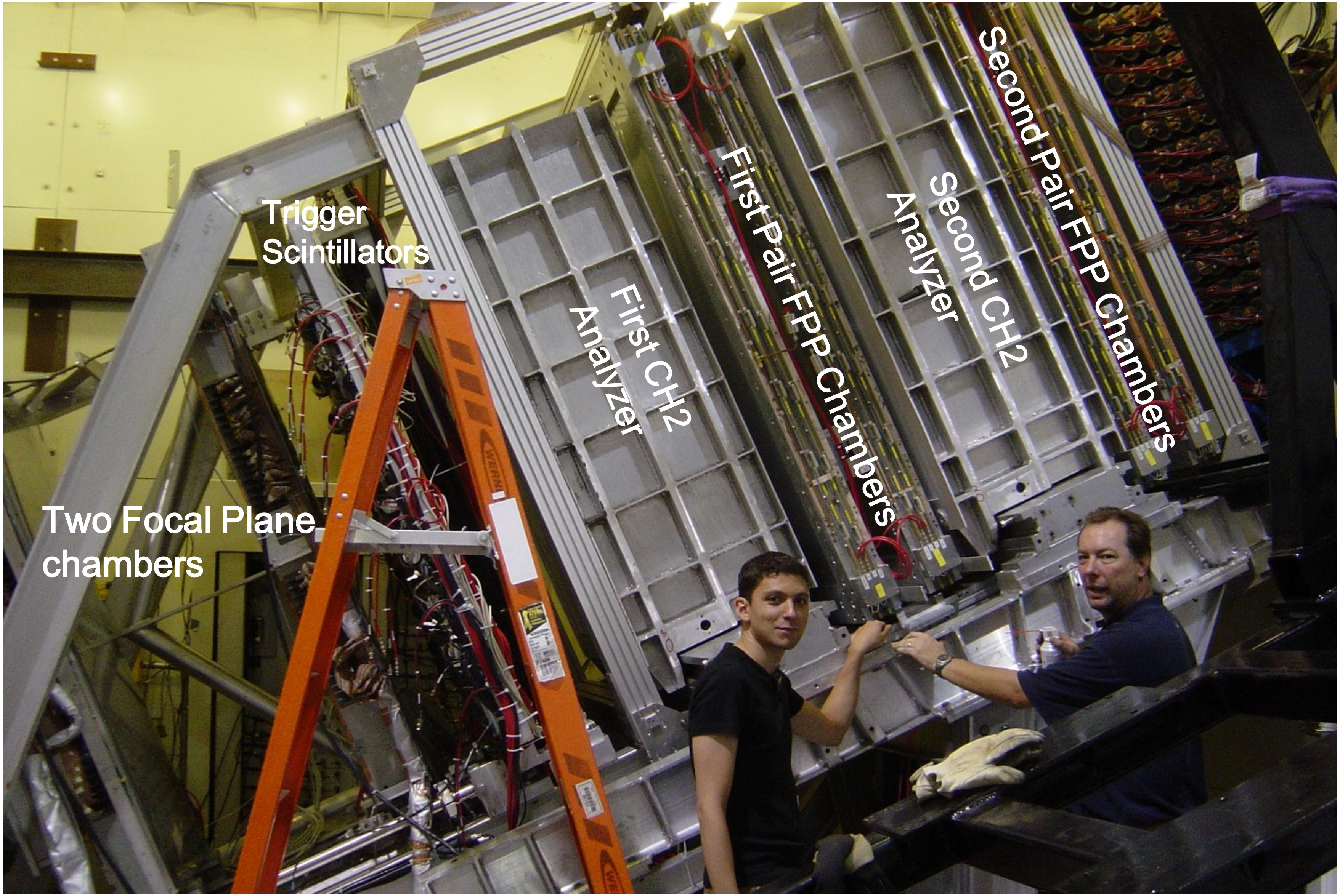


1.87- 5.71 GeV beam
80-100 μA beam current
80-85% polarization
20cm LH_2 target

BigCal in Hall C

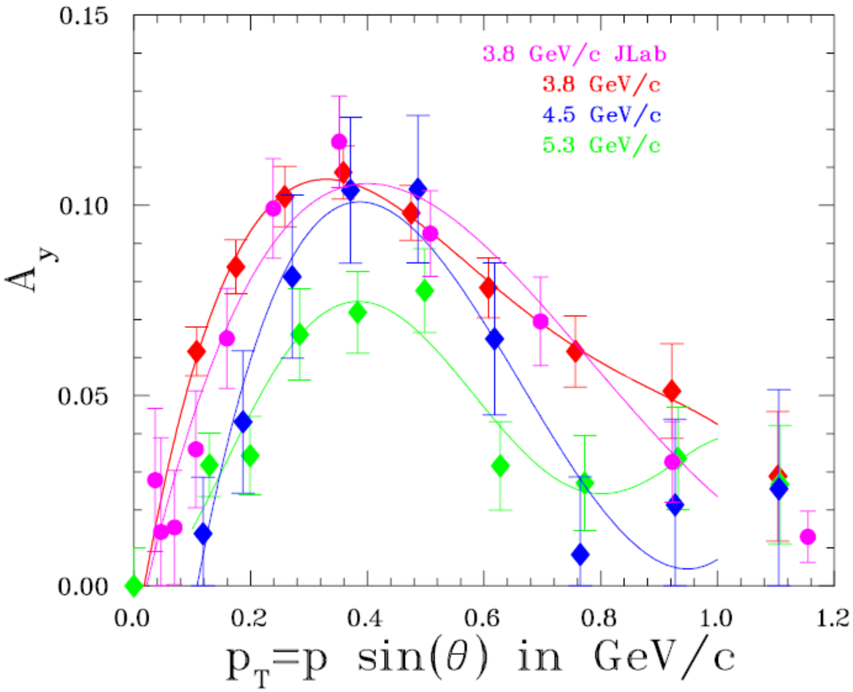
- Measure electron angles, energy
- Separate elastic from inelastic using angular correlation
- Large Jacobian in elastic *ep* scattering—large acceptance to match proton arm
- For Q2 = 8.5 GeV^2
  Ω_e = 143 msr to Ω_p = 6.7 msr

Double FPP in HMS

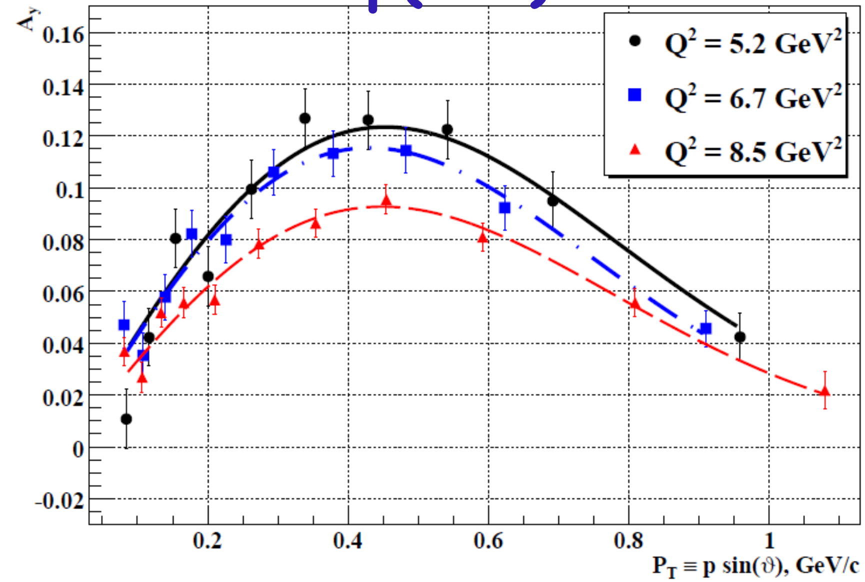


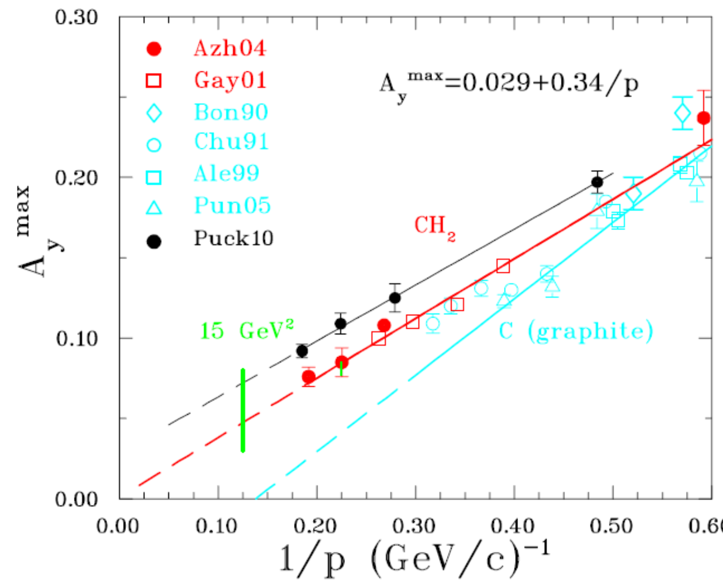
CH_2 Analyzing Power Data

Dubna Data



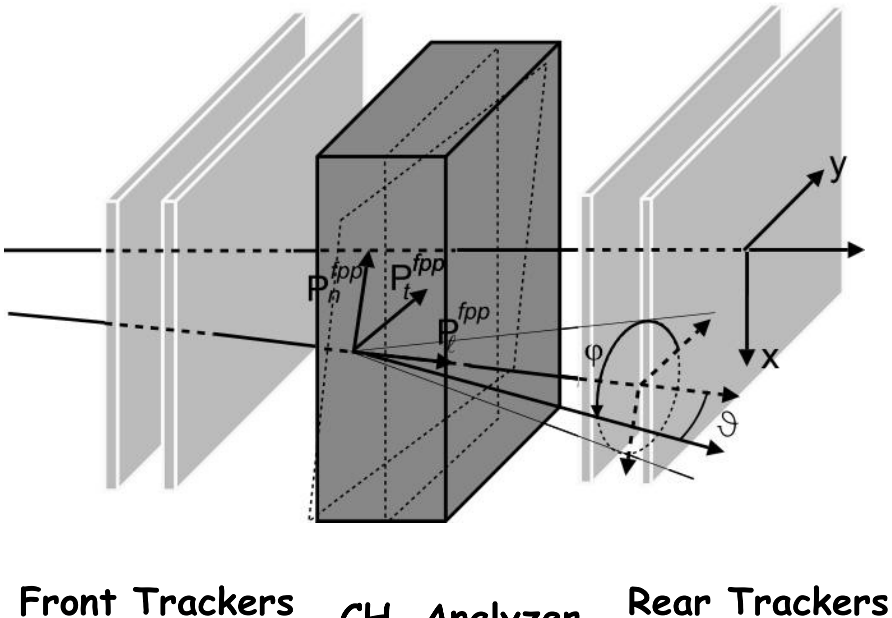
GEp(III) Data

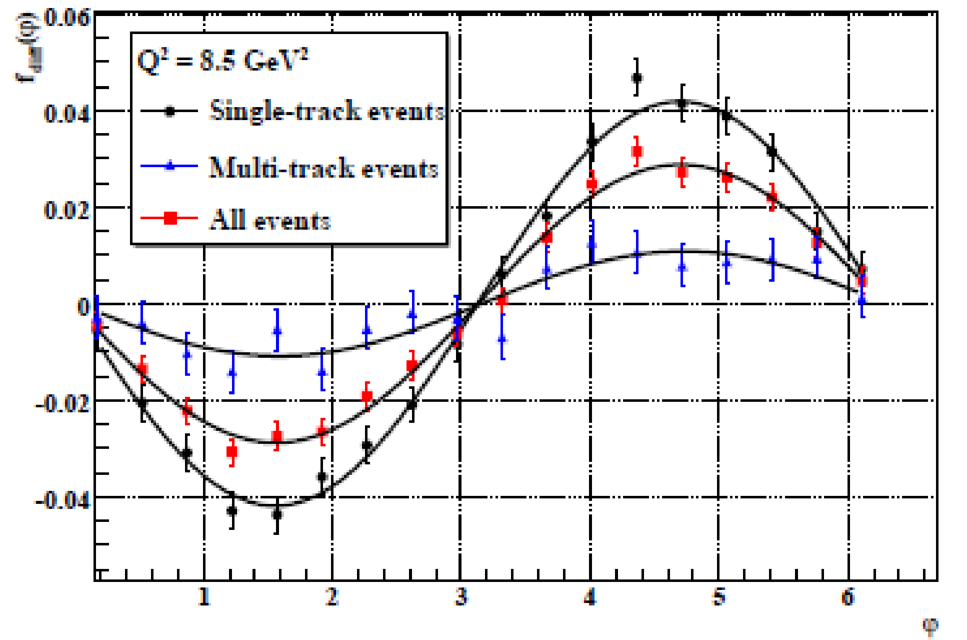




Empirical relation between A_y and proton momentum (A_y ~1/p) discovered at JINR

Focal Plane Polarimeter





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

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

Physical Asymmetries are obtained from difference distributions

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

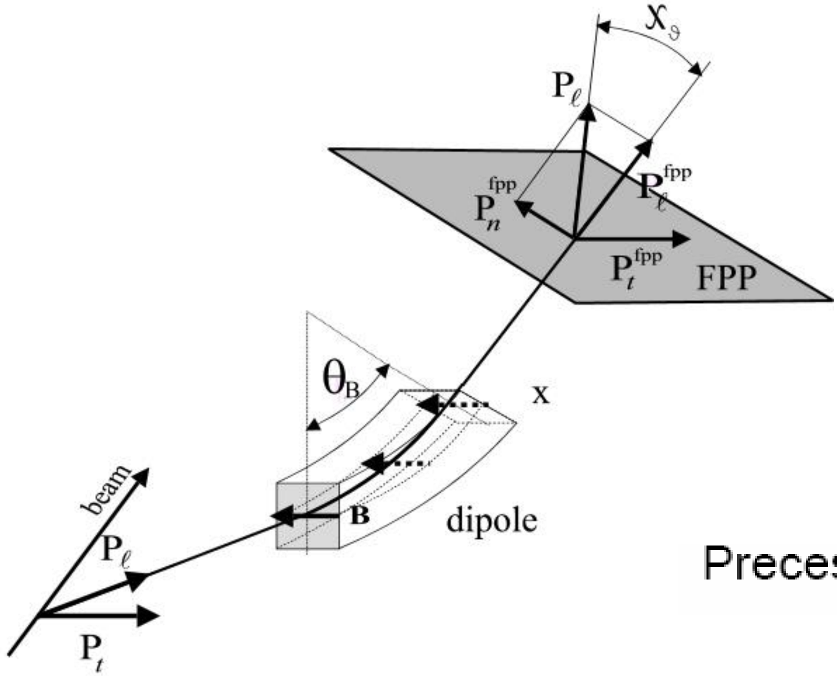
$$D_i = \frac{1}{2\pi}\left[A_y P_t^{fpp}\sin\varphi - A_y P_n^{fpp}\cos\varphi\right]$$

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

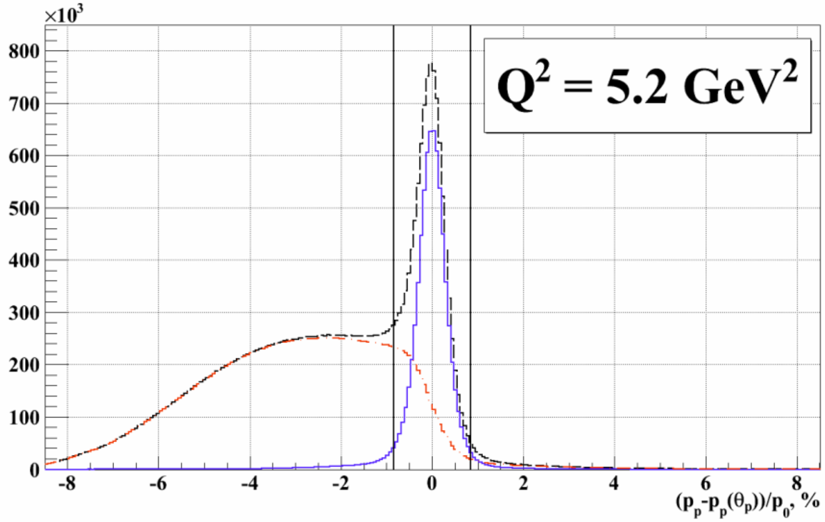
$$\begin{pmatrix} P_N \\ P_T \\ P_L \end{pmatrix}_{\text{fp}} = \begin{pmatrix} S_{n'n} & S_{n't} & S_{n'l} \\ S_{t'n} & S_{t't} & S_{t'l} \\ S_{l'n} & S_{l't} & S_{l'l} \end{pmatrix} \begin{pmatrix} P_N \\ P_T \\ P_L \end{pmatrix}_{\text{tgt}}$$

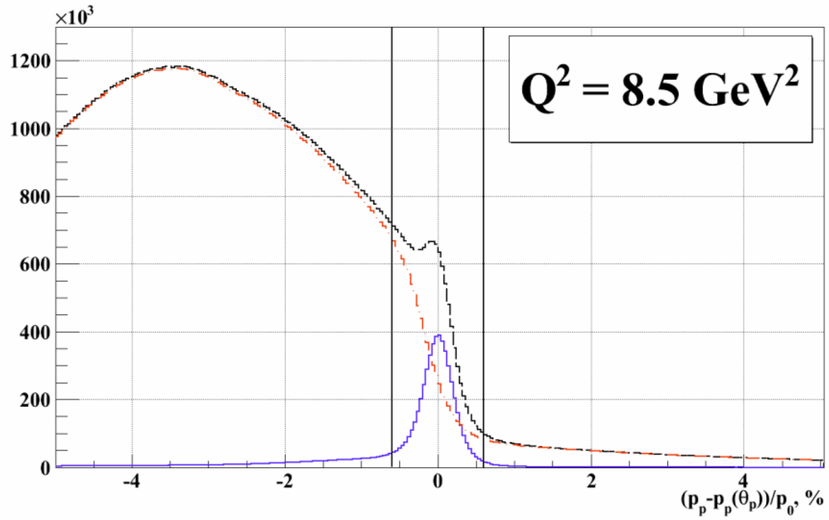
If only dipole field: $S_{t't} = 1$ and $S_{n'l} = -\sin\chi$

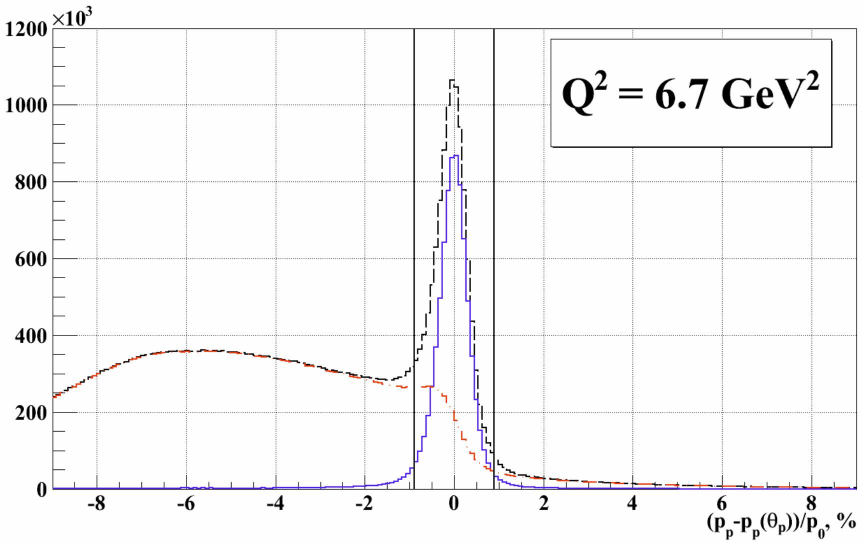
$S_{t'l} = S_{n't} = 0$

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

Proton Momentum Spectrum



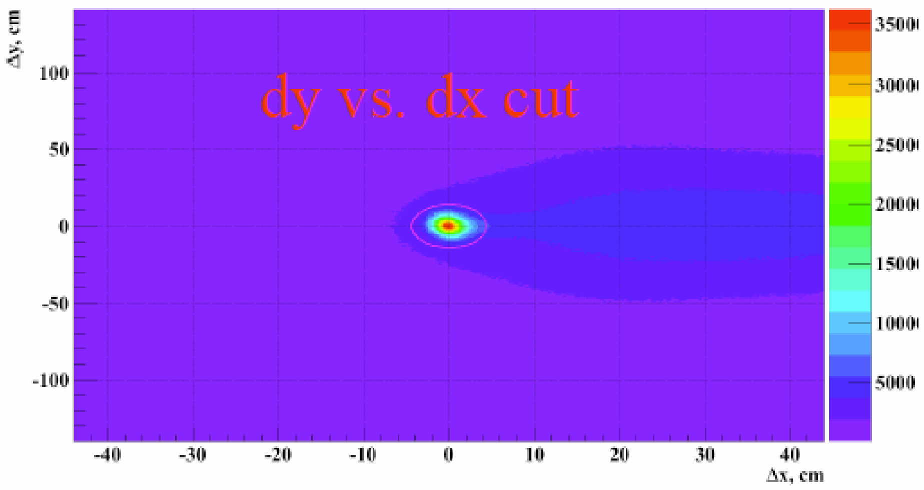


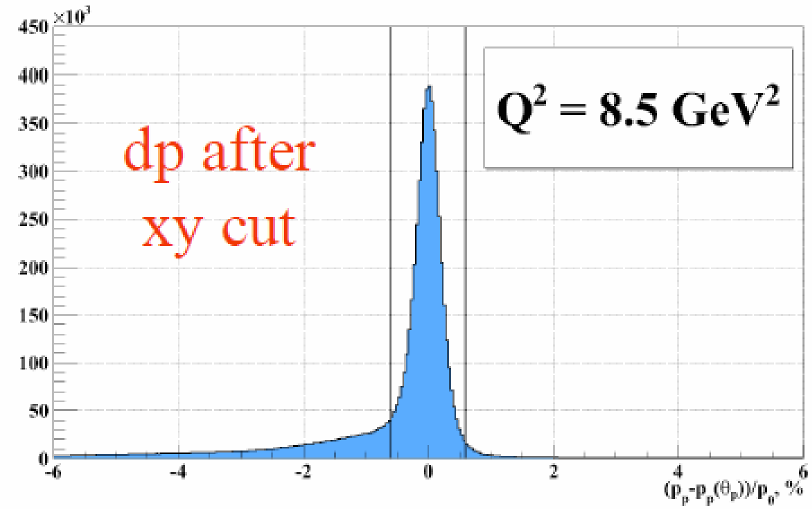


$$p_p(\theta_p) = \frac{2M_p E_e (E_e + M_p)\cos\theta_p}{M_p^2 + 2M_p E_e + E_e^2 \sin^2\theta_p}$$

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

Elastic Event Selection

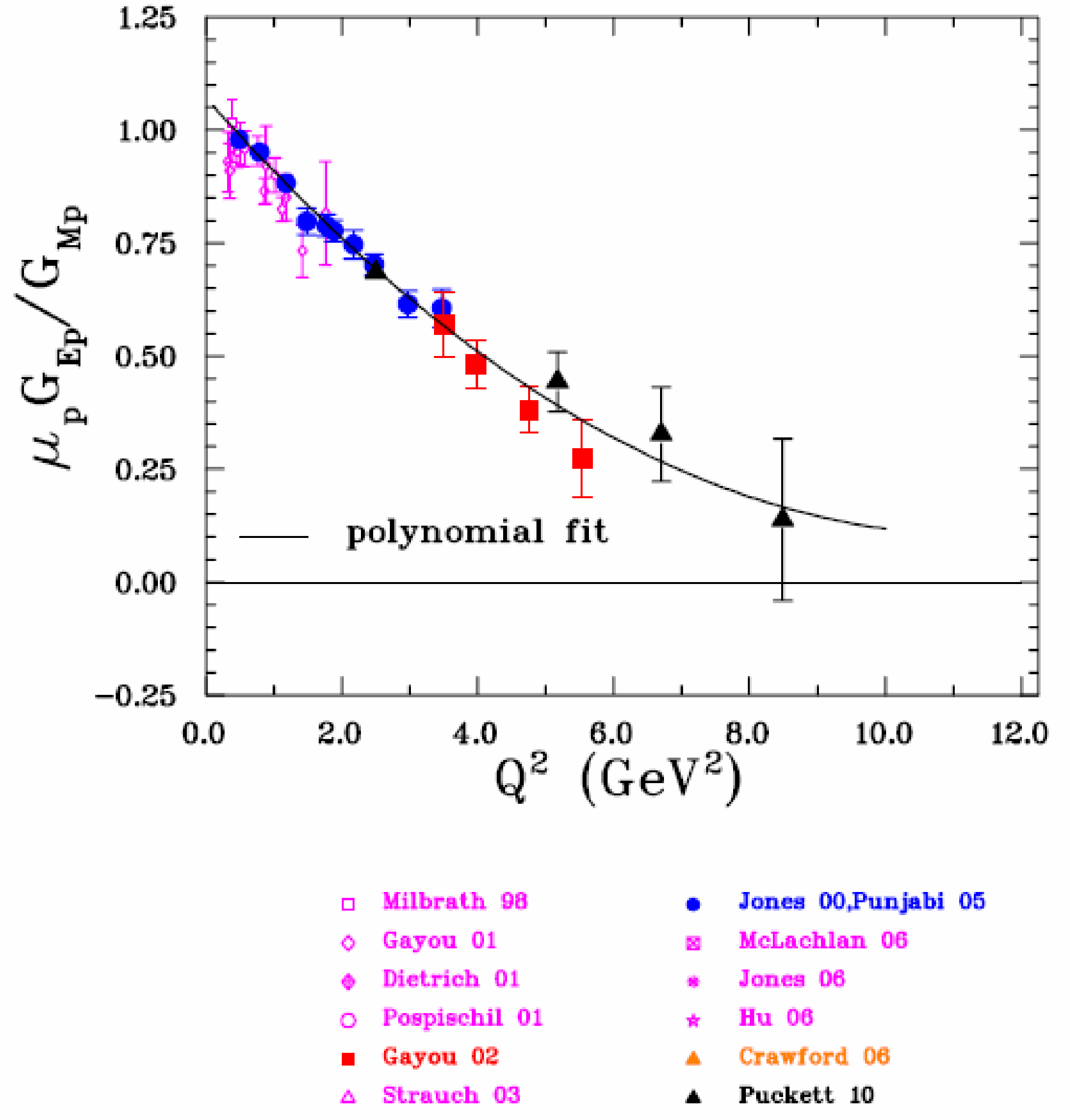




$$\left(\frac{\Delta x}{x_{\max}}\right)^2 + \left(\frac{\Delta y}{y_{\max}}\right)^2 \leq 1$$

- 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

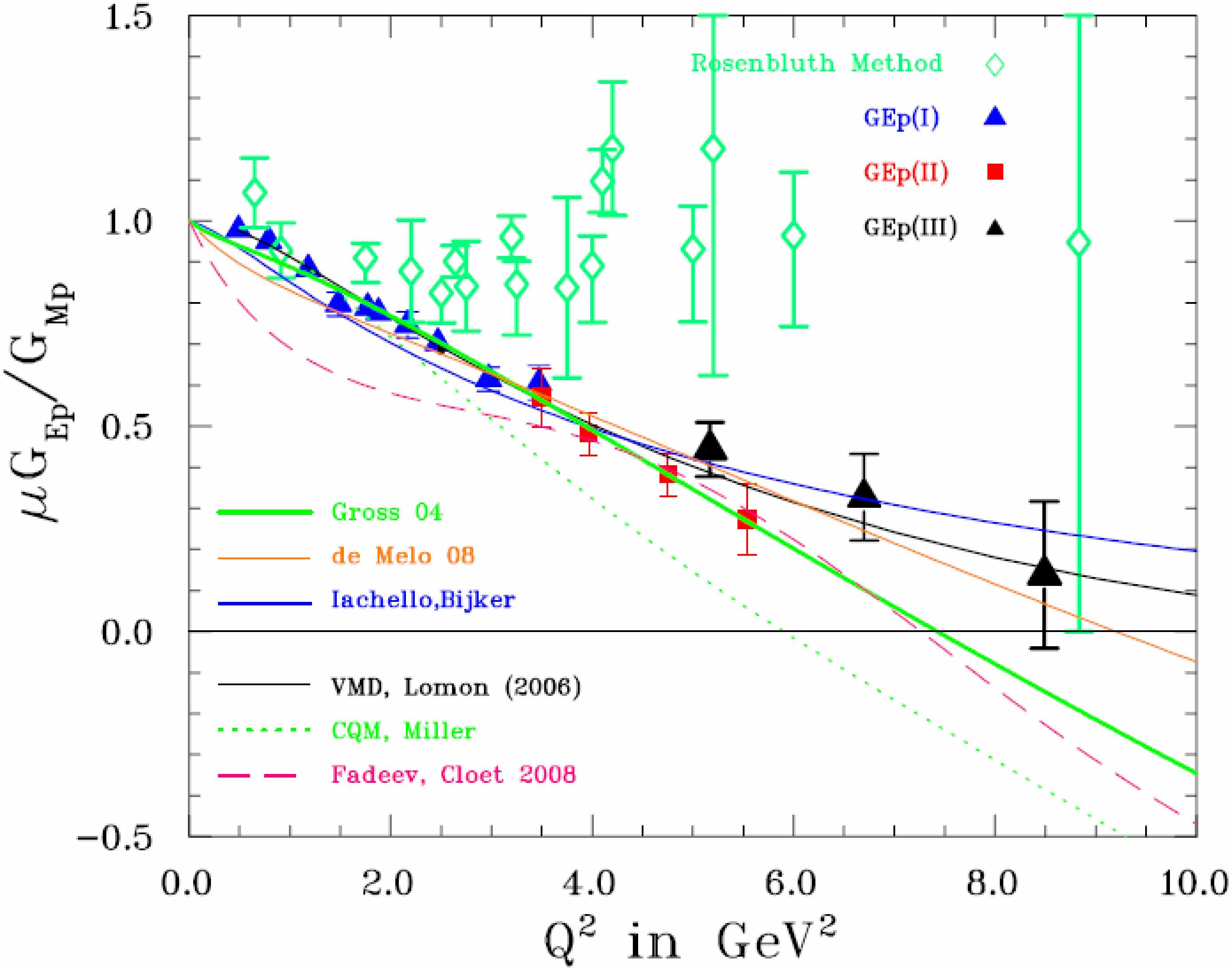
All data for the ratio G_{Ep}/G_{Mp} from Double Polarization



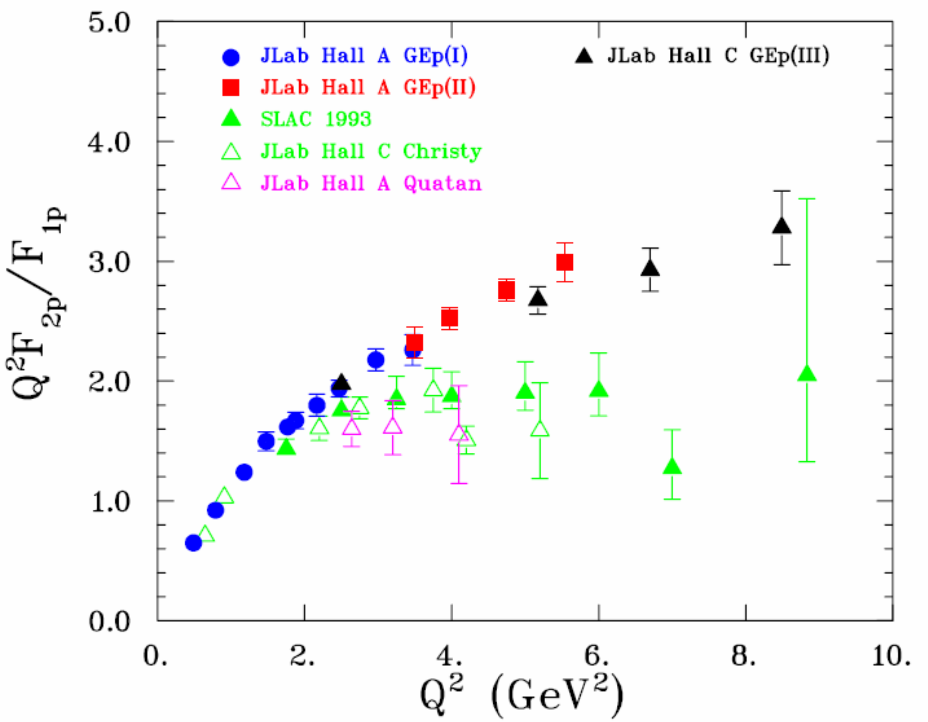
Theoretical Progress

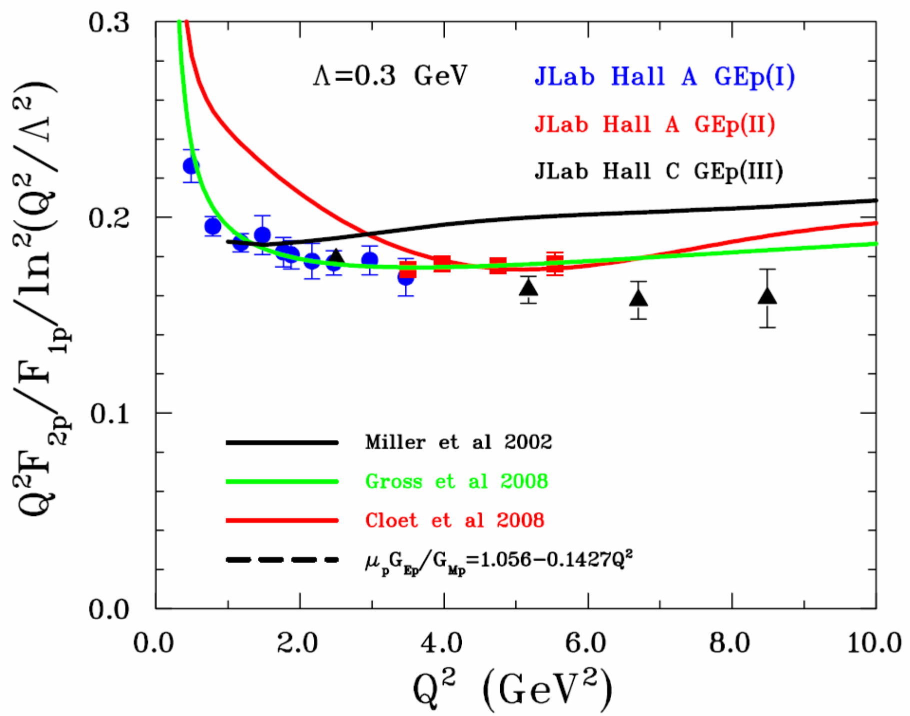
- VMD-based models
  - Describe all four nucleon FF's well
  - Tend to favor ratio reaching a constant value at intermediate Q^2
- rCQM
  - Show the importance of relativistic dynamics
- pQCD-inspired models
  - Predict logarithmic scaling behavior of F_2/F_1 at intermediate Q^2 (Belitsky and Ji) ->related 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
  - Behavior of G_{Ep}/G_{Mp} at intermediate Q^2 related to u/d ratio at small distances (Miller)
- Dyson-Schwinger Equations
  - Continuum approach to QCD, Hadrons as Composites of Quarks and Gluons
- Lattice QCD Models
    - Good progress already, and will get much better in the future

Theoretical predictions



Proton: F_2/F_1 and pQCD





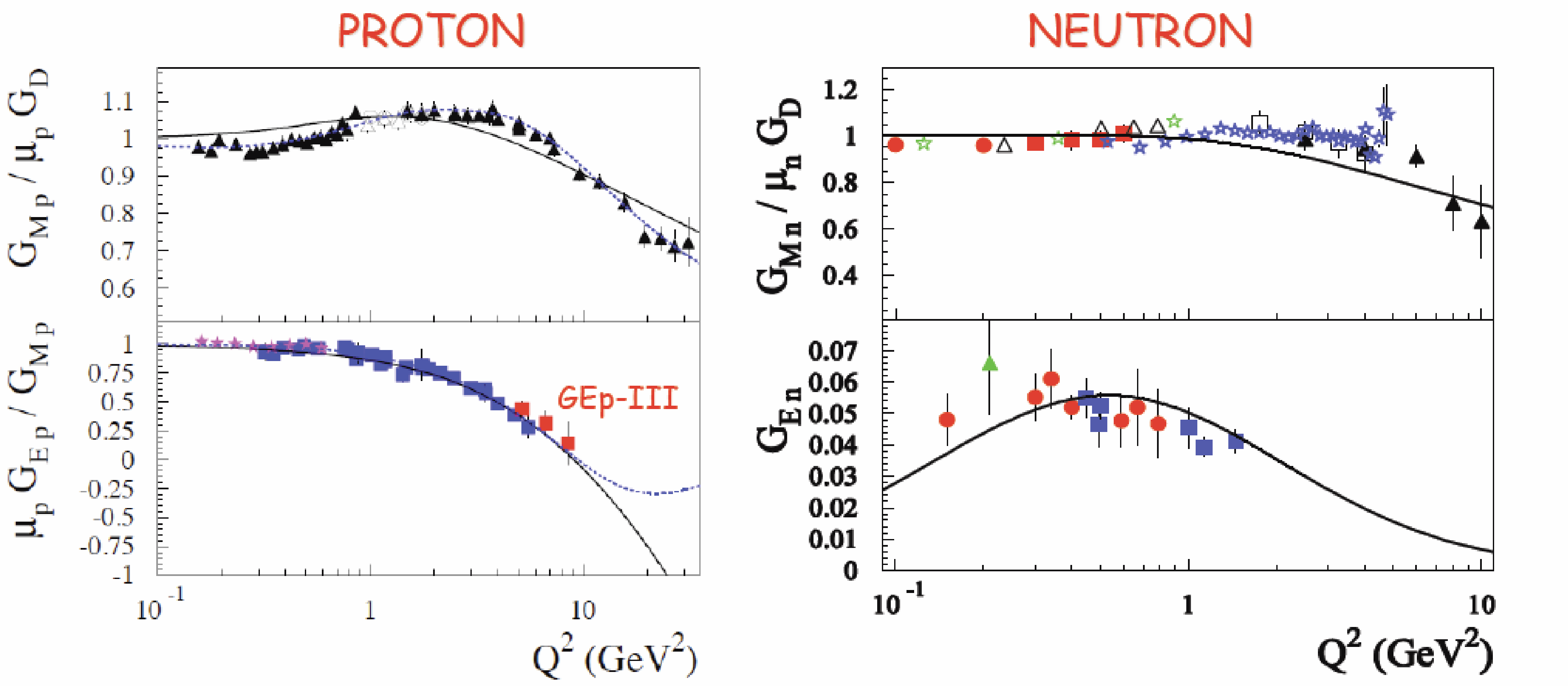
Brodsky and Farrar (75):

Q^2F_2/F_1 constant

Belitsky, Ji and Yuan (03):

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

GPD parametrization of Nucleon FF



- The first moments of GPDS are related to the elastic FF (Ji, 97)

$$\int_{-1}^{+1} dx\, H^q(x, \xi, Q^2) = F_1^q(Q^2), \qquad \int_{-1}^{+1} dx\, E^q(x, \xi, Q^2) = F_2^q(Q^2),$$

- Modified Regge Parametrization for H and E (Guidal et al., (2005)

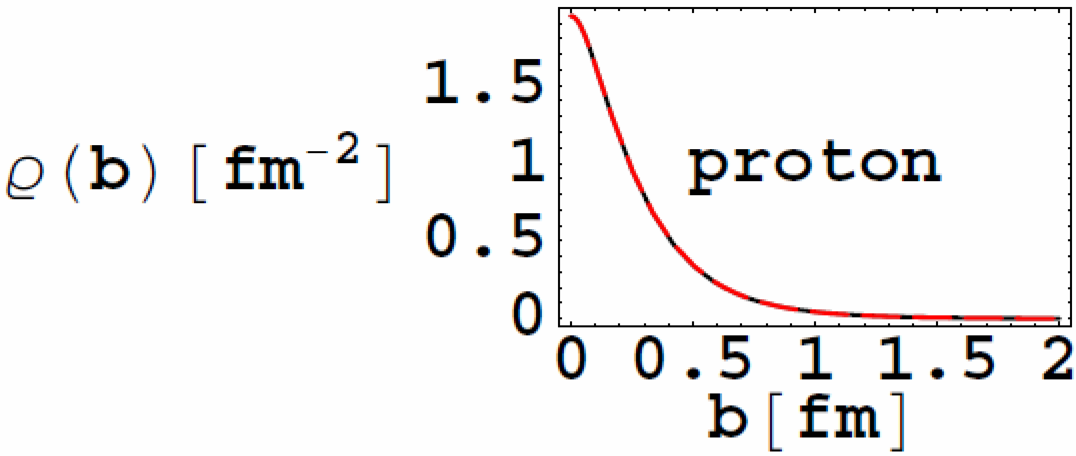
$$H^q(x, 0, Q^2) = q_v(x) x^{\alpha'(1-x)Q^2}, \qquad E^q(x, 0, Q^2) = \frac{\kappa^q}{N^q}(1-x)^{\eta^q} q_v(x) x^{\alpha'(1-x)Q^2}$$

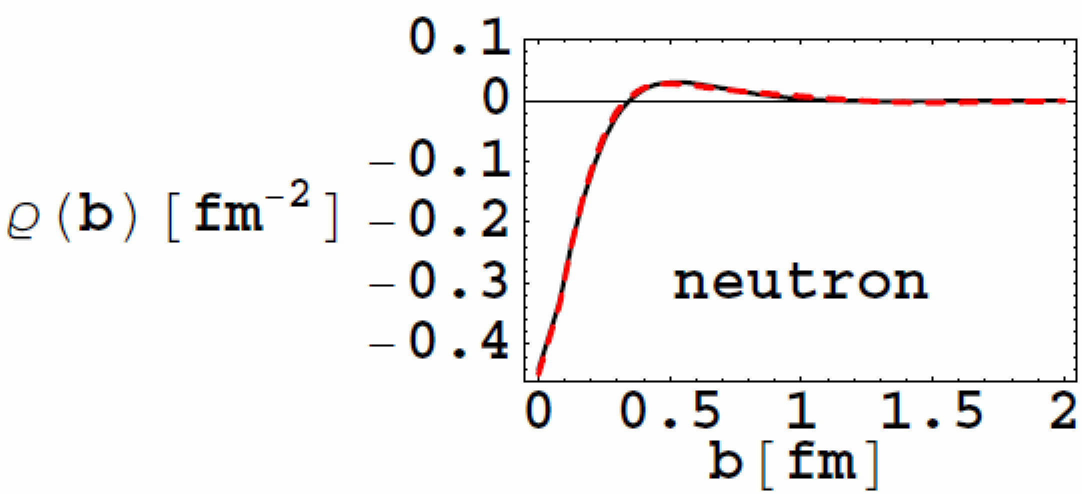
Transverse Charge Densities for Proton and Neutron

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

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

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

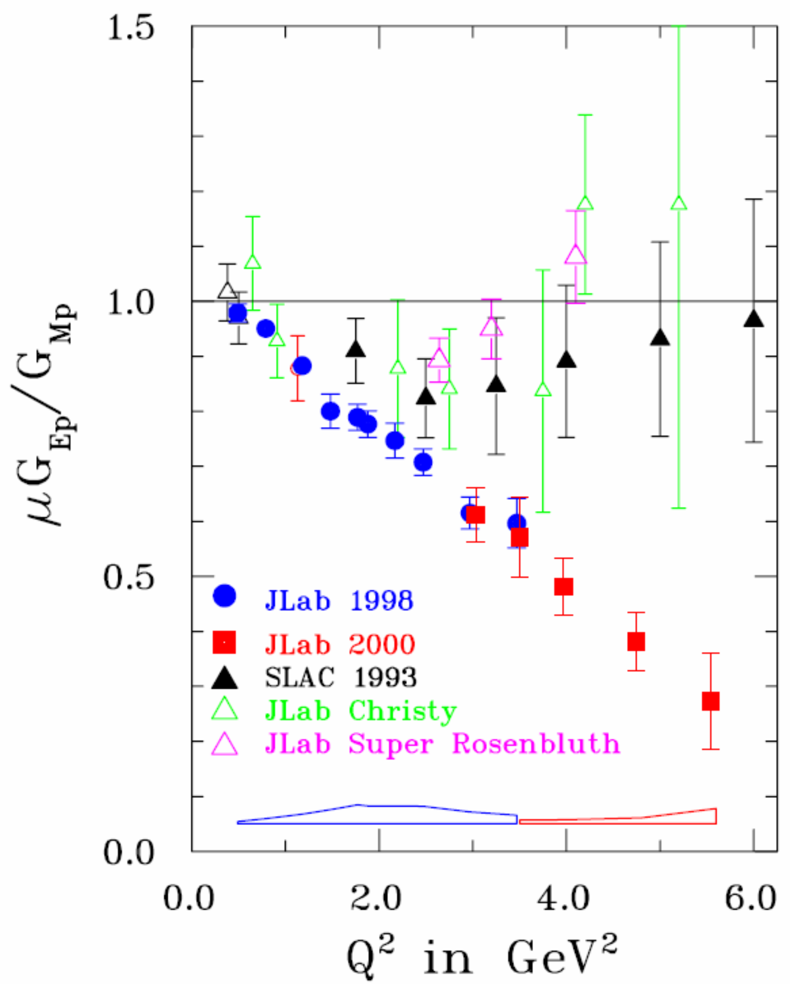




Charge density $\rho(b)$ of partons in the transverse plane is a two-dimensional Fourier transform of the F_1 form factor

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

G_{Ep}/G_{Mp} Crisis ?



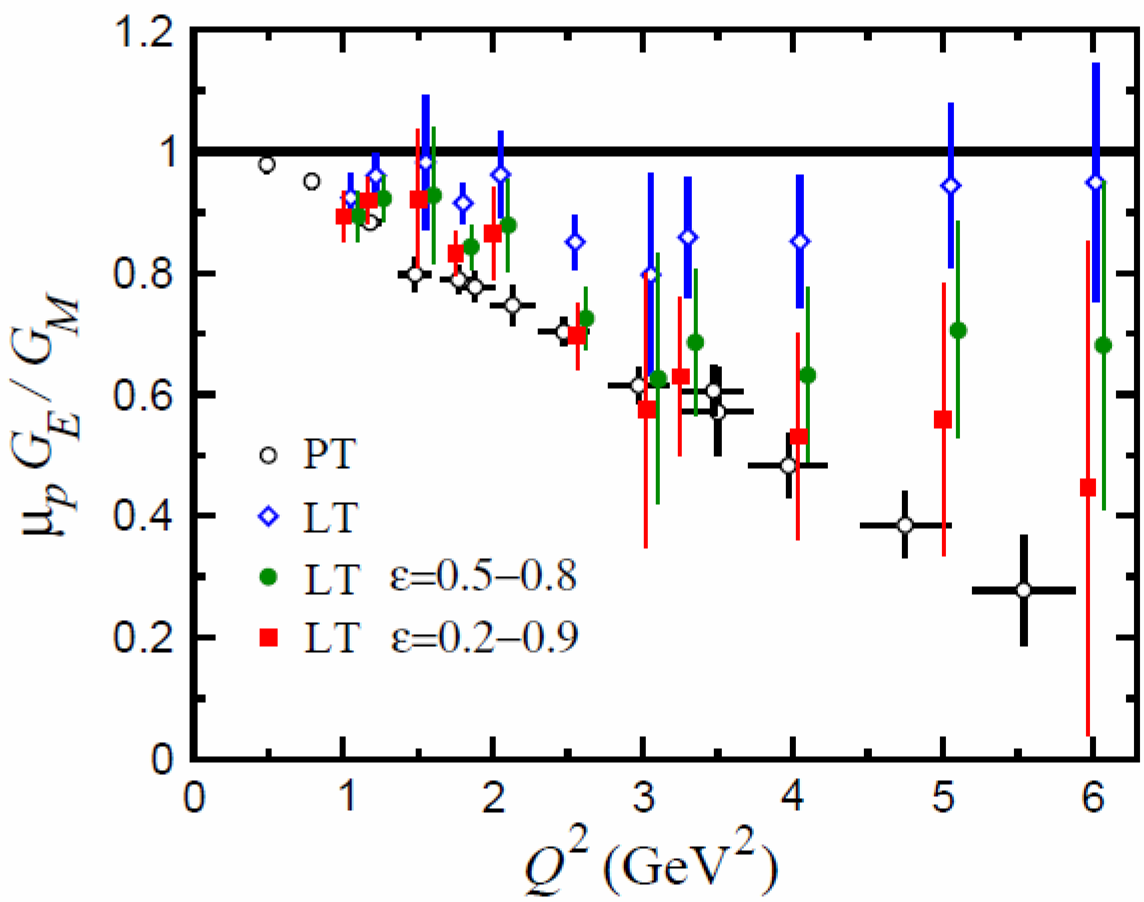
"The discrepancy is a serious problem as it generates confusion and doubt about the whole methodology of lepton scattering experiments"

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?

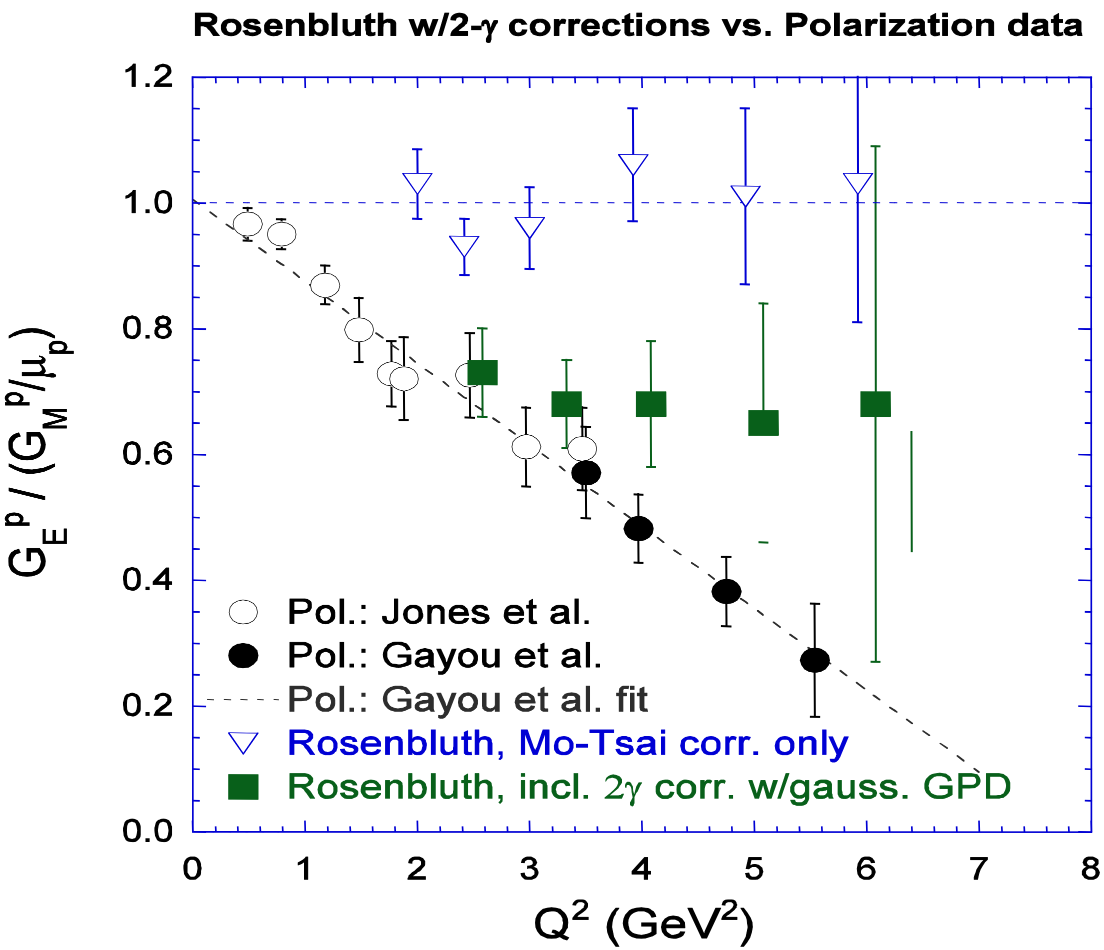
Two-Photon exchange

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



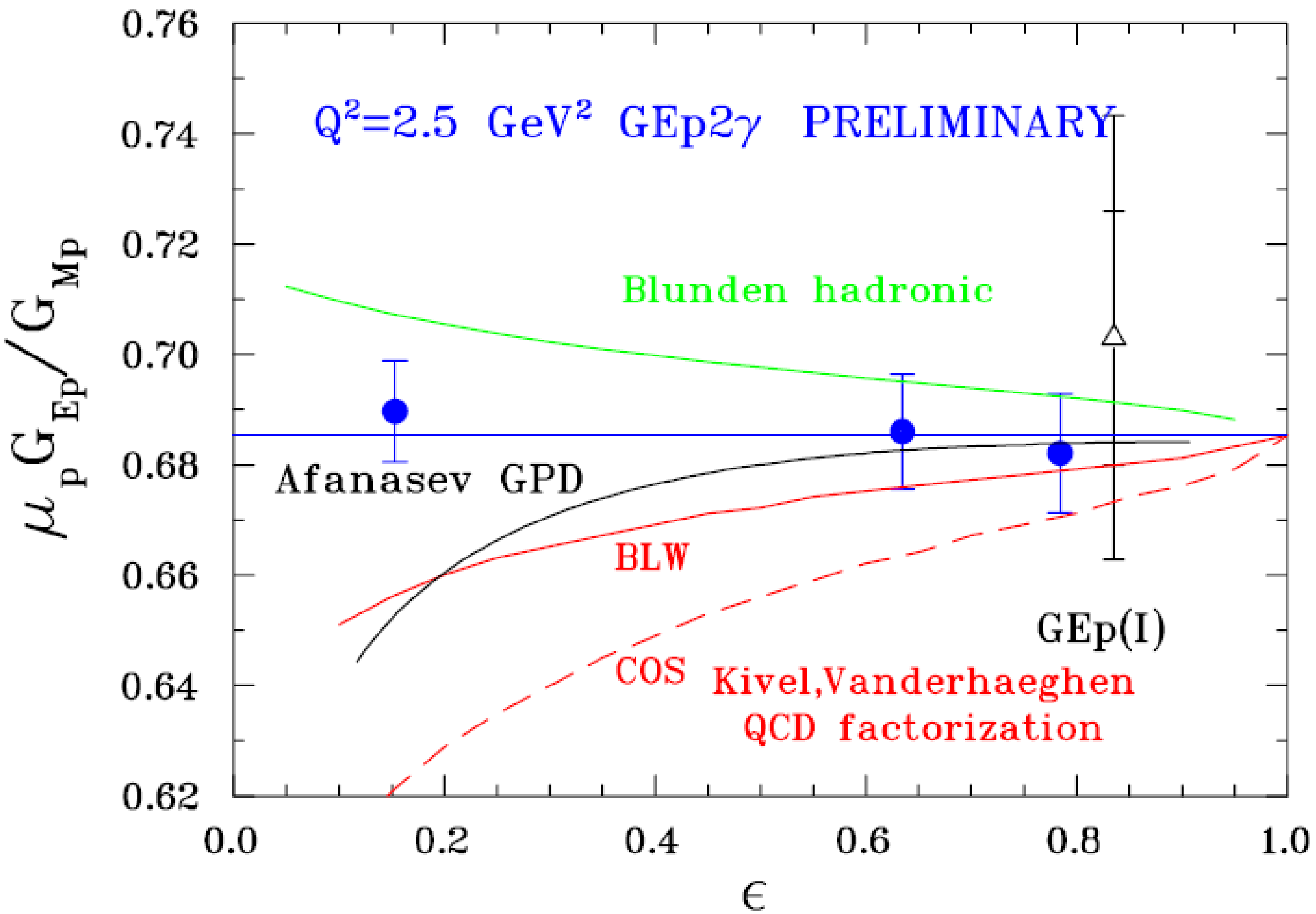
Blunden et al., PR *C* 72 (2005) 034612

Two-Photon Exchange: GPD predictions



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

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



Theoretical predictions are with respect to the Born approximation that is not known Except from experiment, which do not separate one γ from two γ

No radiative corrections applied, Less than 1%
(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}, has led to a fundamental change in picture of the internal structure of the proton,

  strong impact on theoretical progress,

  no evidence for two-photon exchange effects in ratio obtained from polarization observables.

- 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