Proton Form Factor Measurements to Large Four Momentum Transfer Q^2 at Jefferson Lab

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Outline

- Introduction
- Nucleon Structure and Form Factors
- Rosenbluth separation of G^2_E and G^2_M
- Recoil Polarization in elastic ep: Born approx.
- Polarization transfer Measurements at JLab
- Comparison of G_{Ep}/G_{Mp} and F_{2p}/F_{1p} to Theoretical Model Predictions
- Measurements of G_{Ep}/G_{Mp} at 12 GeV.
- Conclusions

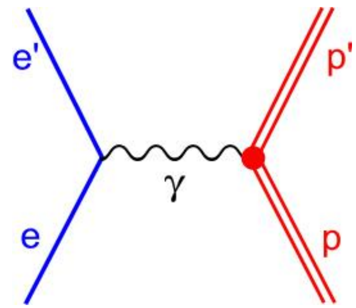
Introduction

- At large Q^2 electromagnetic Form Factors contain structure information on the many-body system of quarks and gluons of the nucleon. At low Q^2 they inform us about the pion cloud.

- When obtained from experiment, the Form Factors 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 might regain after applying a number of radiative corrections; the current status of these corrections is unsatisfactory.

ep elastic Scattering, Born term

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



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

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

F_1 helicity conserving Dirac FF

F_2 helicity non-conserving Pauli FF

Alternately, the Sachs form factors

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

$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2) \quad \text{with } \tau = Q^2/4M^2$$

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

Rosenbluth vs. Recoil Polarization

Cross section

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{Mott}} \left(G_{Ep}^2(Q^2) + \frac{\tau}{\varepsilon} G_{Mp}^2(Q^2) \right) / (1+\tau)$$

with

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

Reduced cross section:

$$\sigma_{reduced} = \varepsilon(1+\tau)\frac{d\sigma}{d\Omega} / \frac{d\sigma}{d\Omega_{Mott}} = \varepsilon G_{Ep}^2 + \tau G_{Mp}^2 = \tau G_{Mp}^2 \left(1 + \frac{\varepsilon}{\tau} \frac{G_{Ep}^2}{G_{Mp}^2} \right)$$

Recoil polarization components

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

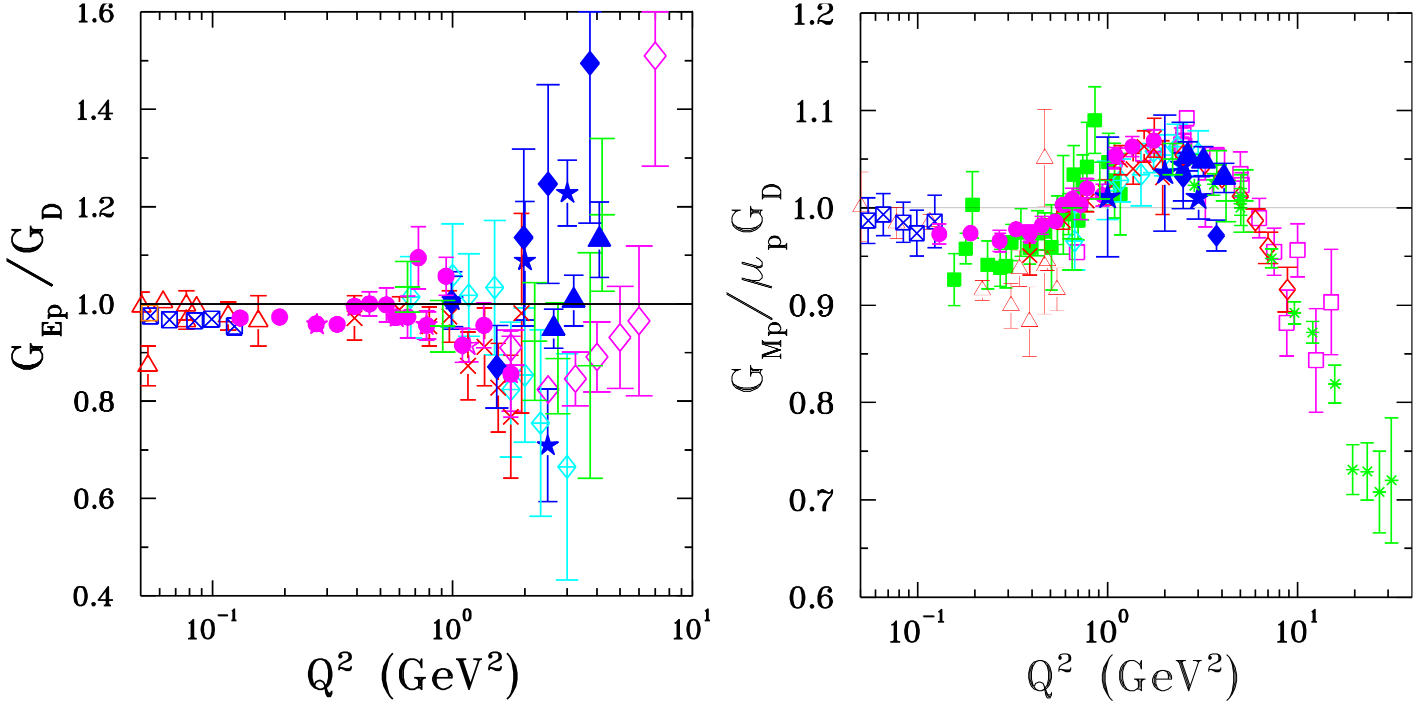
$$hP_e P_\ell = hP_e \frac{(E_e + E_{e'})}{M} G_{Mp}^2 \sqrt{\tau(1+\tau)} \tan^2\left(\frac{\theta_e}{2}\right) / I_0$$

Form Factor ratio:

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

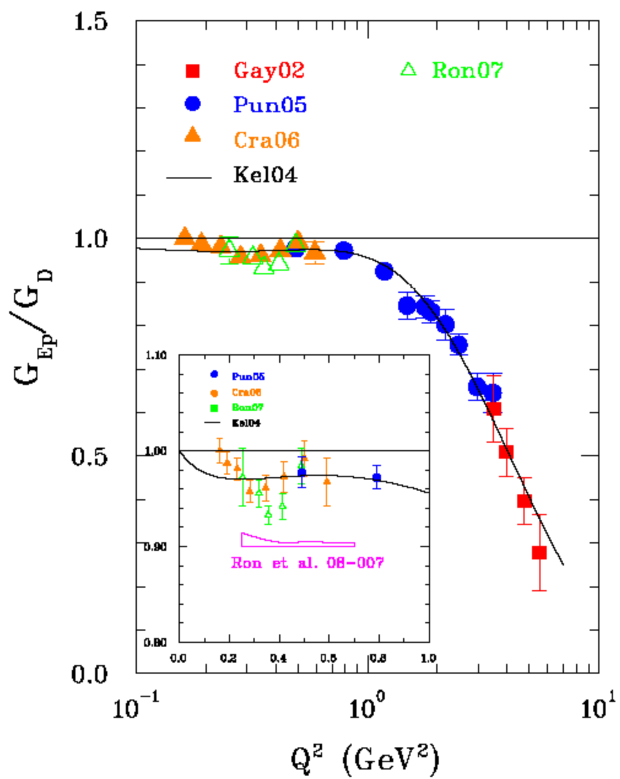
All Rosenbluth separation data above Q^2 of 0.05 GeV^2

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

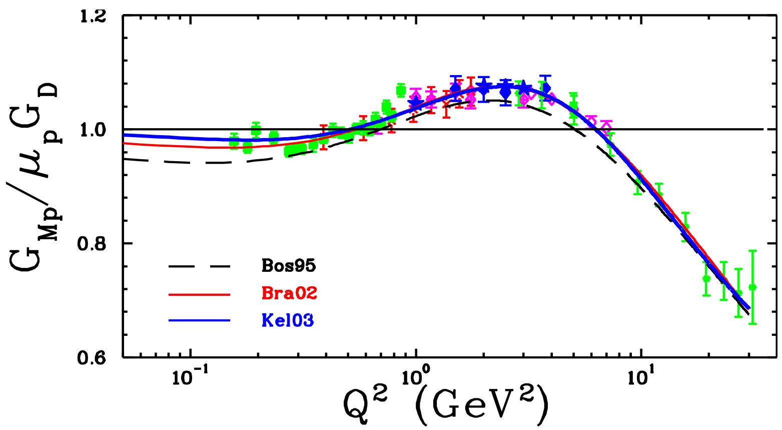


The form factors of the proton

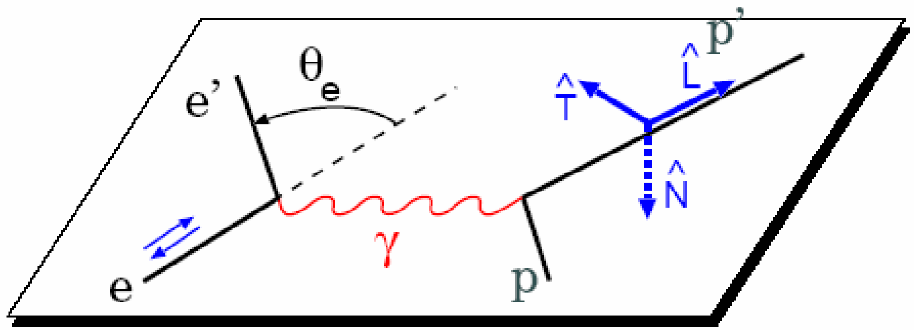
GEp/GD from selected polarization experiments, showing to the Kelly fit



GMp using GEp/GMp from polarization, (Brash et al)



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



Transferred polarization is: (Akhiezer & Rekalo)

$$P_n = 0$$

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

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

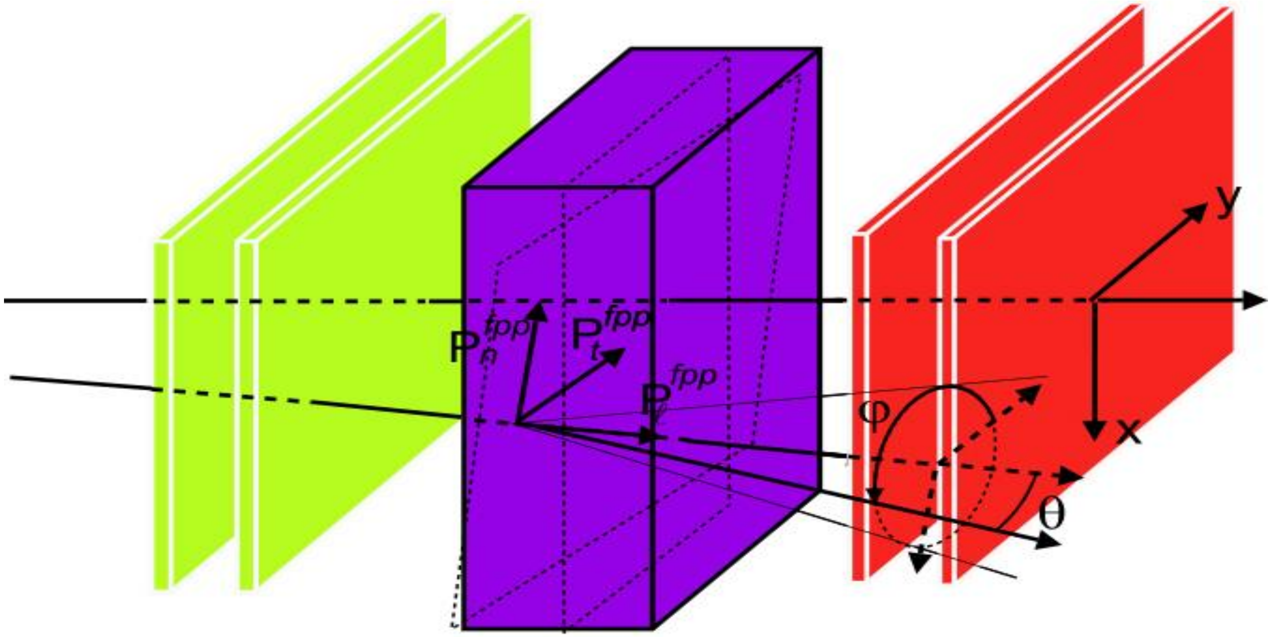
Where, $h = |h|$ is the beam helicity

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

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

No error contributions from analyzing power and beam polarization measurements

Focal Plane Polarimeter



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

P_t^{fpp} and P_n^{fpp} are the physical asymmetries at the FPP

φ Distribution and Physical Asymmetries

At Q^2 of 5.6 GeV^2, Proton Momentum 3.8 GeV/c

Physical Asymmetries are obtained from the helicity difference distributions

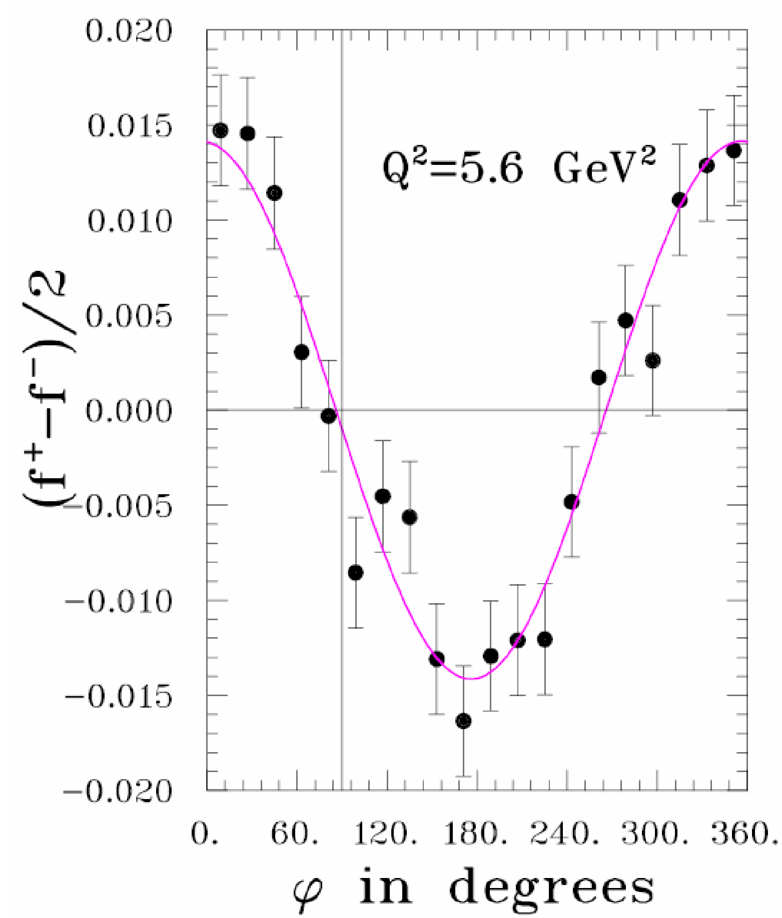
$$D_i = \left(f_i^{+} - f_i^{-} \right) / 2$$

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

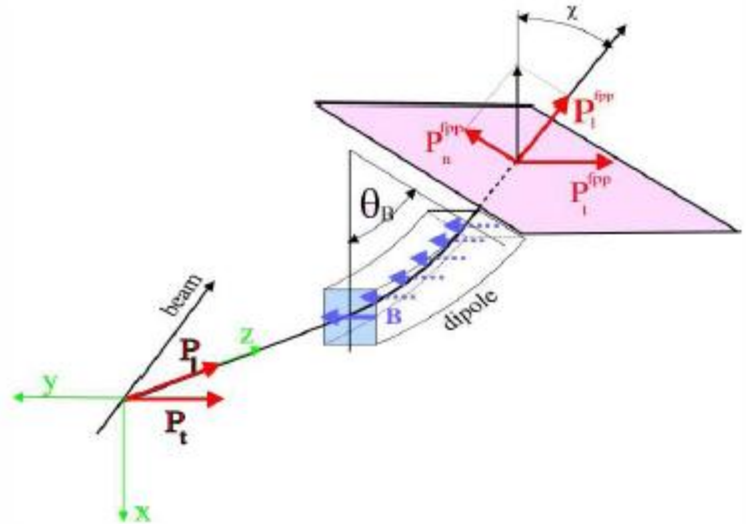
Sum distribution give instrumental asymmetries

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

$$E_i = \frac{i}{2}$$



Spin precession

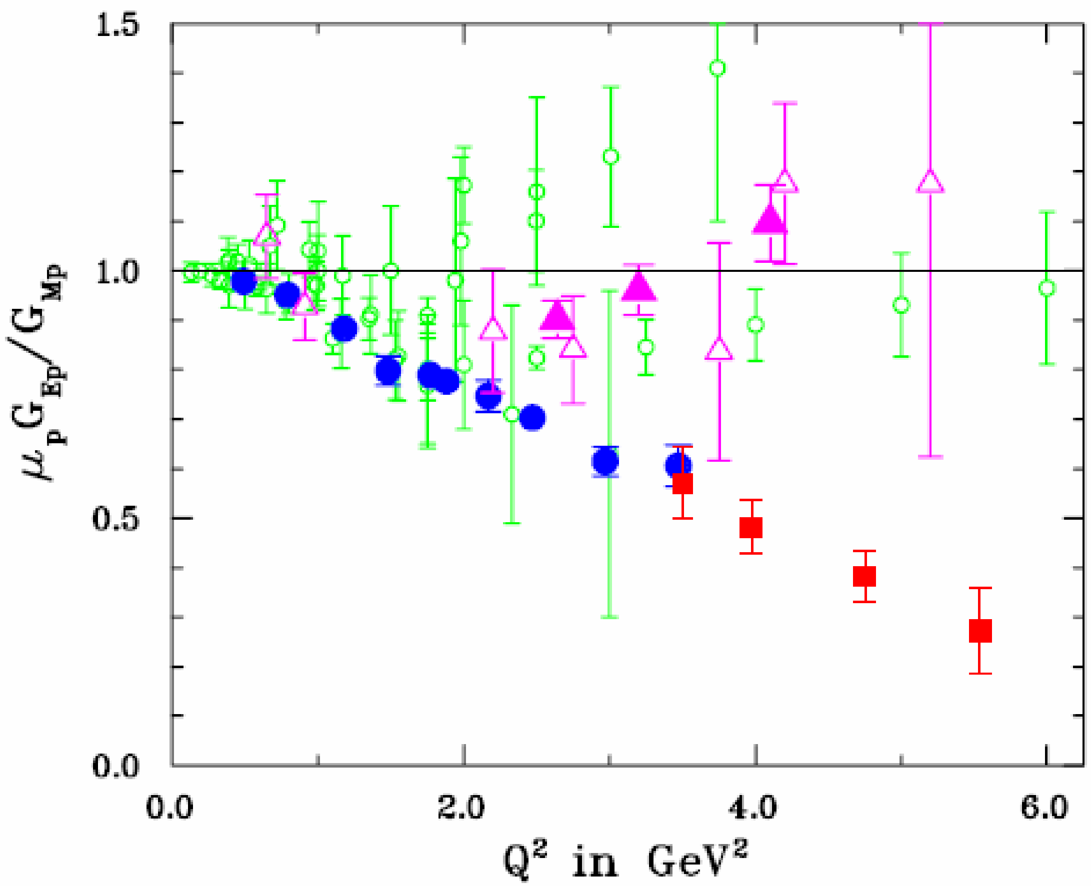


Precession angle, $\chi = \gamma \, \kappa_p \, \theta_{\text{bending}}$

$$\begin{pmatrix} P_n \\ P_t \\ P_l \end{pmatrix}_{\text{fpp}} = \begin{pmatrix} S_{nn} & S_{n't} & S_{nl} \\ S_{tn} & S_{tt} & S_{tl} \\ S_{ln} & S_{lt} & S_{ll} \end{pmatrix} \begin{pmatrix} P_n \\ P_t \\ P_l \end{pmatrix}_{\text{tgt}}$$

P_n^{tgt} is zero in one photon exchange approximation and P_ℓ^{fpp} cannot be measured

Data From First Two JLab Experiments



Results of both experiments are published: (Jones *et al.*, Phys. Rev. Lett. 84, 1398 (2000); Gayou *et al.*, Phys. Rev. Lett. 88, 092301 (2002); Punjabi, Perdrisat *et al.*, Phys. Rev. C 71, 055202 (2005); Perdrisat, Punjabi and Vanderhaeghen, Prog. Part. Nucl. Phys. 59, 694-764, 2007)

G_{Ep} – III Experiment at JLab

- The Ratio G_{Ep}/G_{Mp} was measured with the recoil polarization technique at Q^2 of 5.2, 6.8 and 8.54 GeV^2 in Hall C at JLab, between October 2007 and June 2008.

- The experiment used the high momentum spectrometer (HMS) to detect proton; a new double focal plane polarimeter (FPP) in the focal plane of the HMS measured the polarization of the recoil proton.

- A large area Electromagnetic Calorimeter (BigCal) was used to detect the elastically scattered electrons in coincidence with protons.

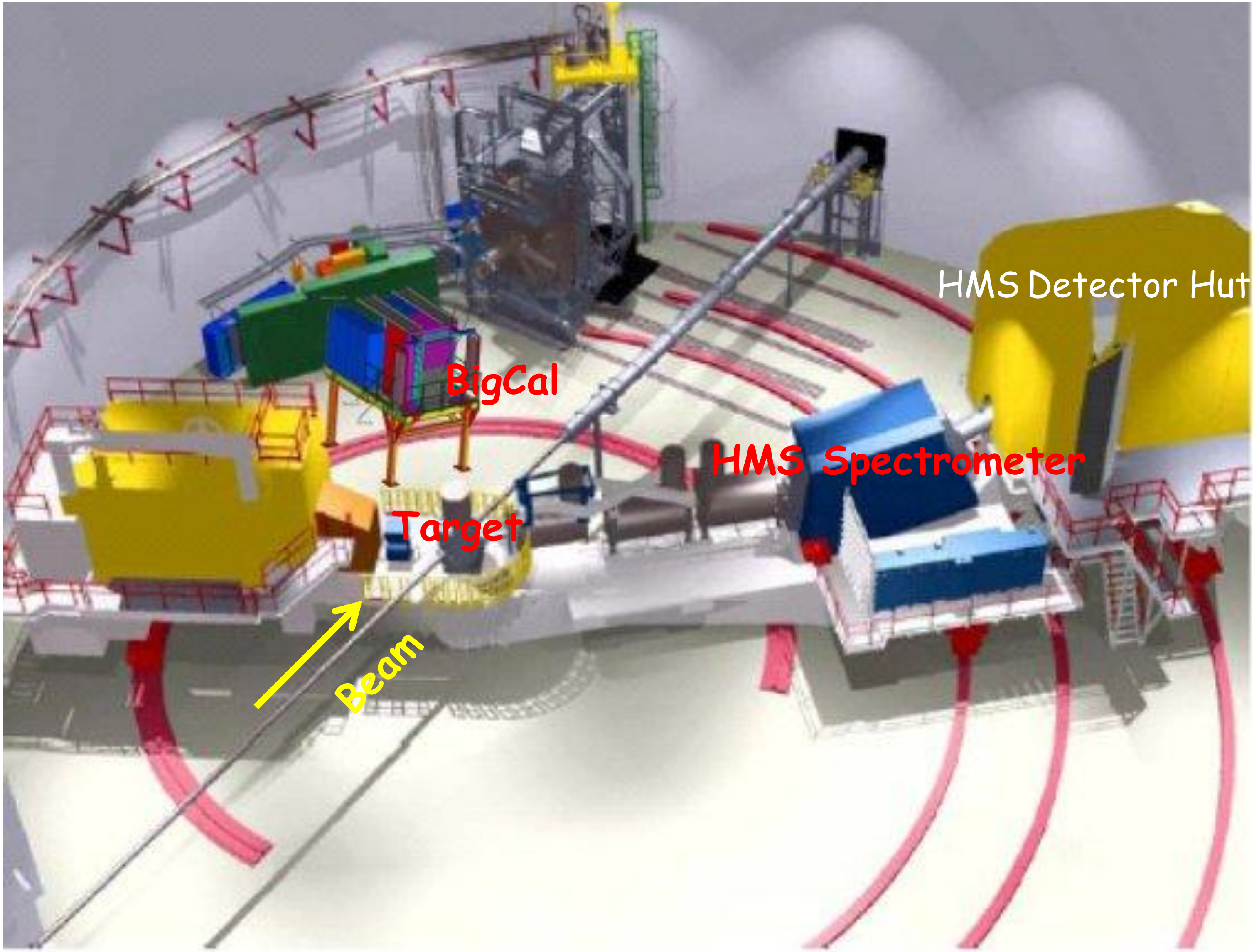
Recognition

A number of JINR physicists have helped make GEp(III) successful,
For the Focal Plane Polarimeter. In alphabetic order:

S. Chernenko,
D. Kirillov,
N. Piskunov,
S. Razin,
I. Sitnik,
L.Smykov†
Yu Zanevski

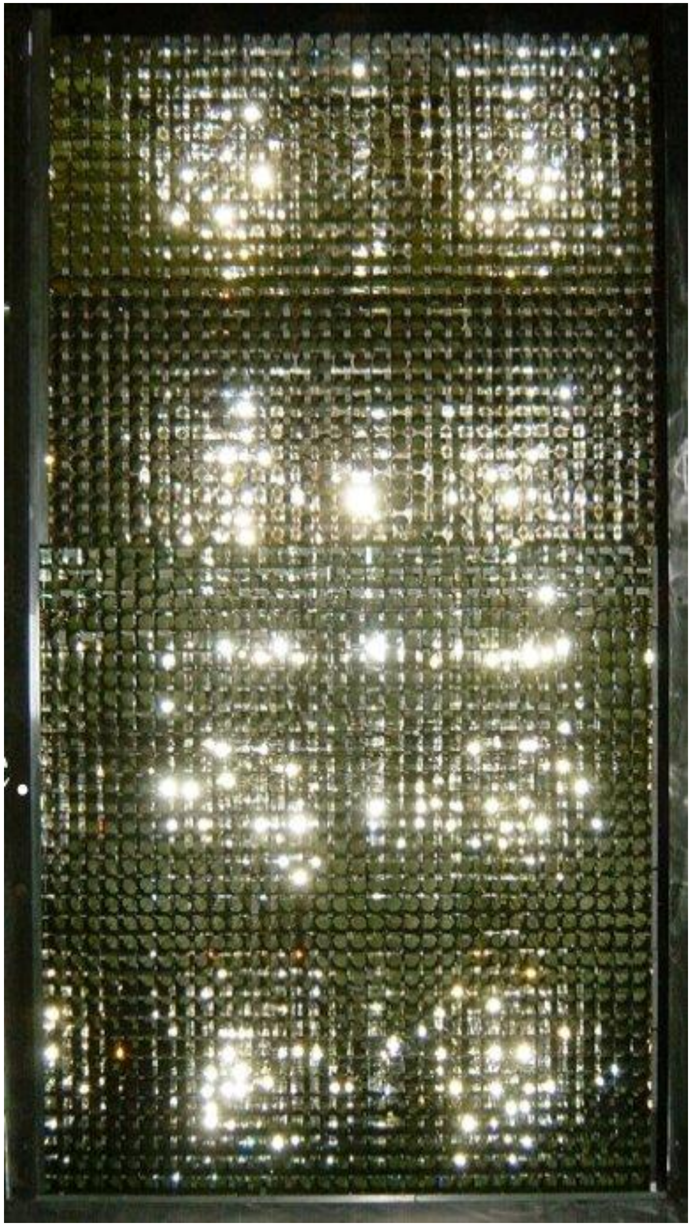
We also greatly beneficiated from the contribution o]from the Protvino group of Prof. Vasiliev for BigCal.

Hall C Layout



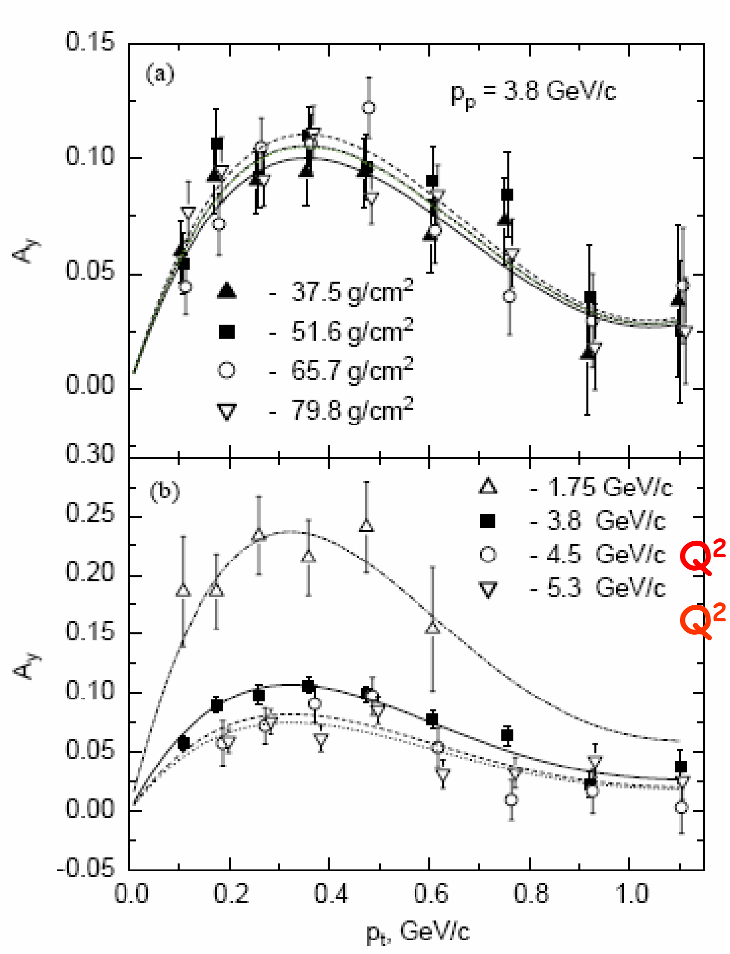
BigCal in Hall C

BigCal glass



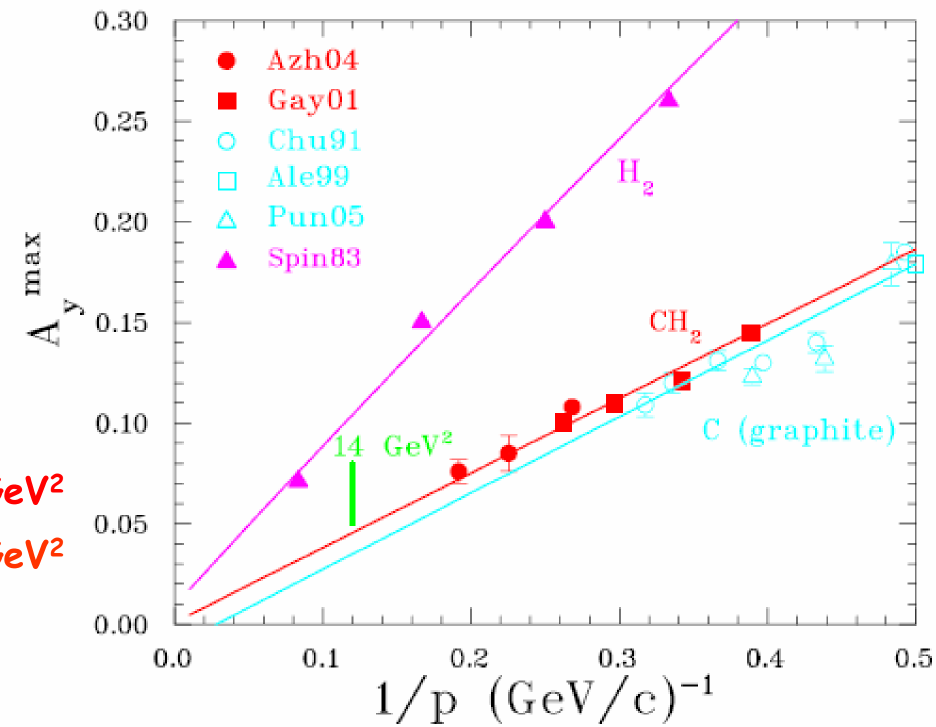
Double FPP in HMS

Carbon/CH_2/H_2 Analyzing Power Data



Q^2 =5.6 GeV^2

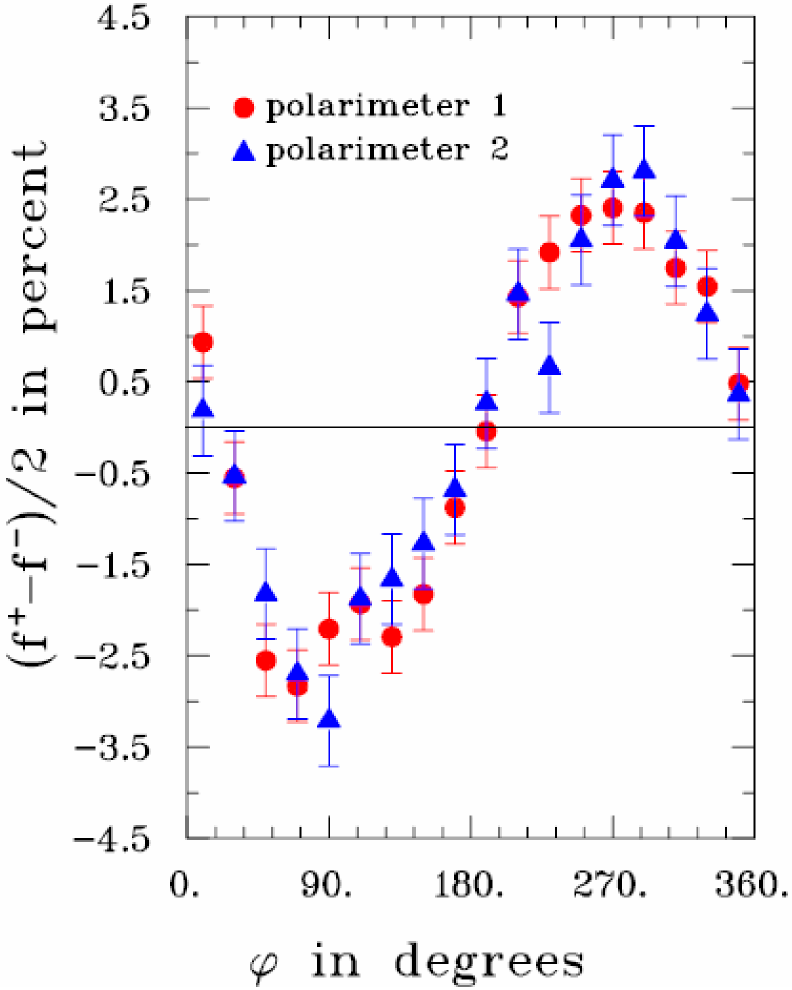
Q^2 =8.5 GeV^2

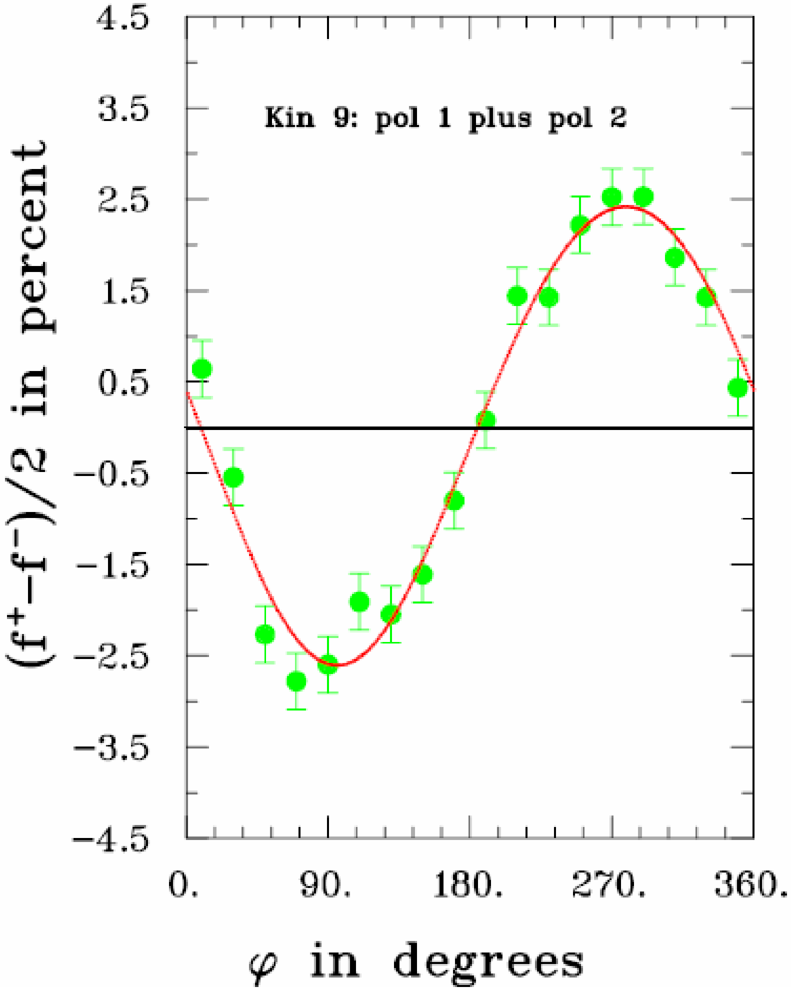


The Dubna polarimeter calibration campaign of 2001:

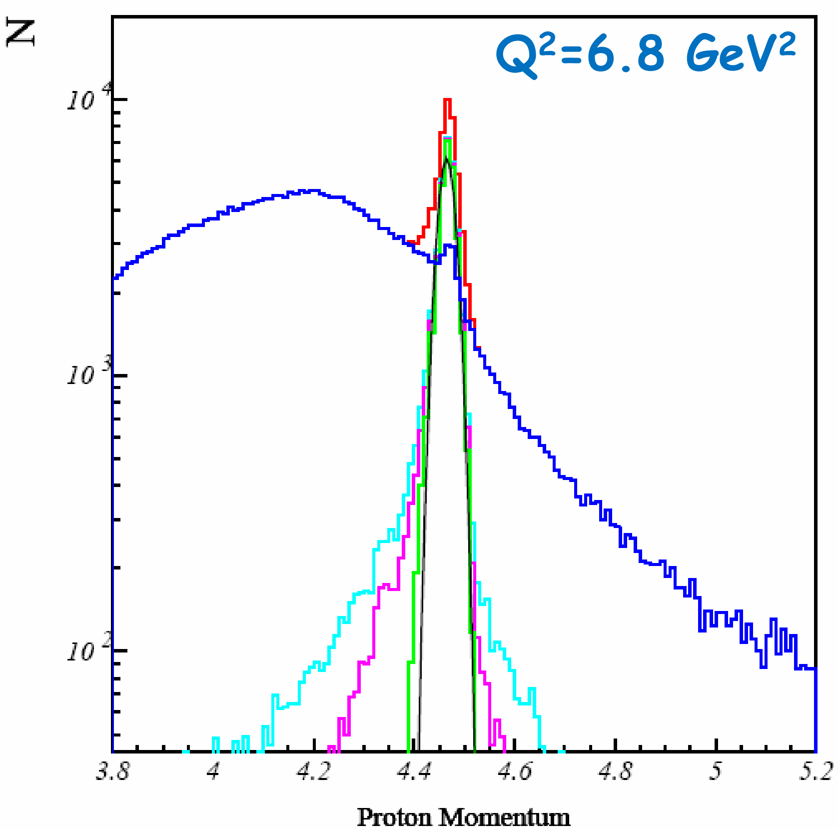
L. S. Azhgirey et al, Nucl. Instr. and Method A 538 (2005) 431

Sample of Physical Asymmetry at Q^2 of 8.5 GeV^2



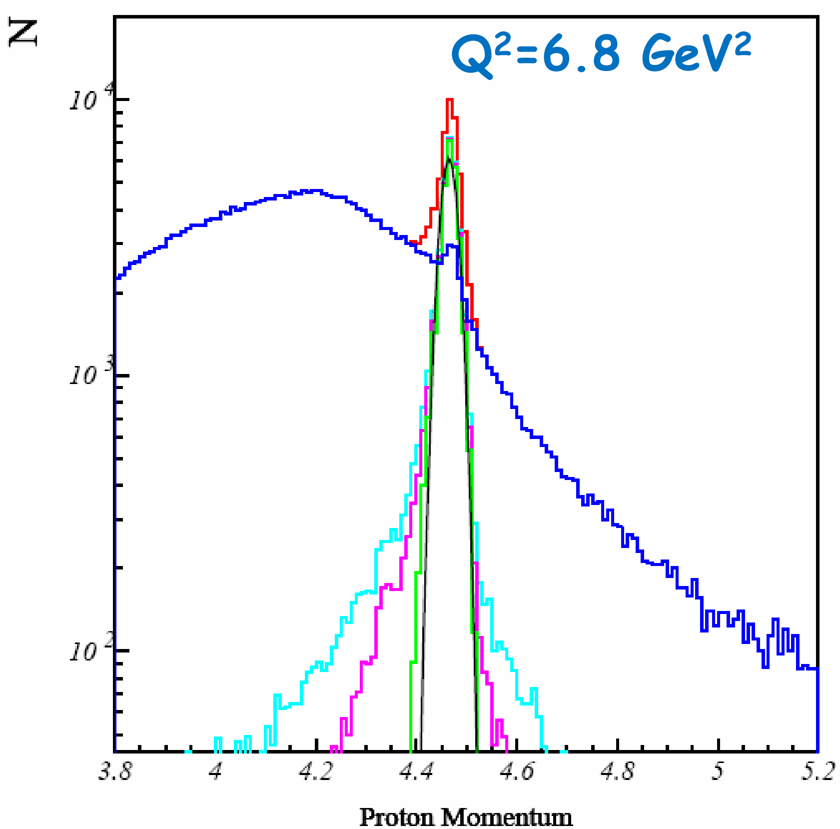


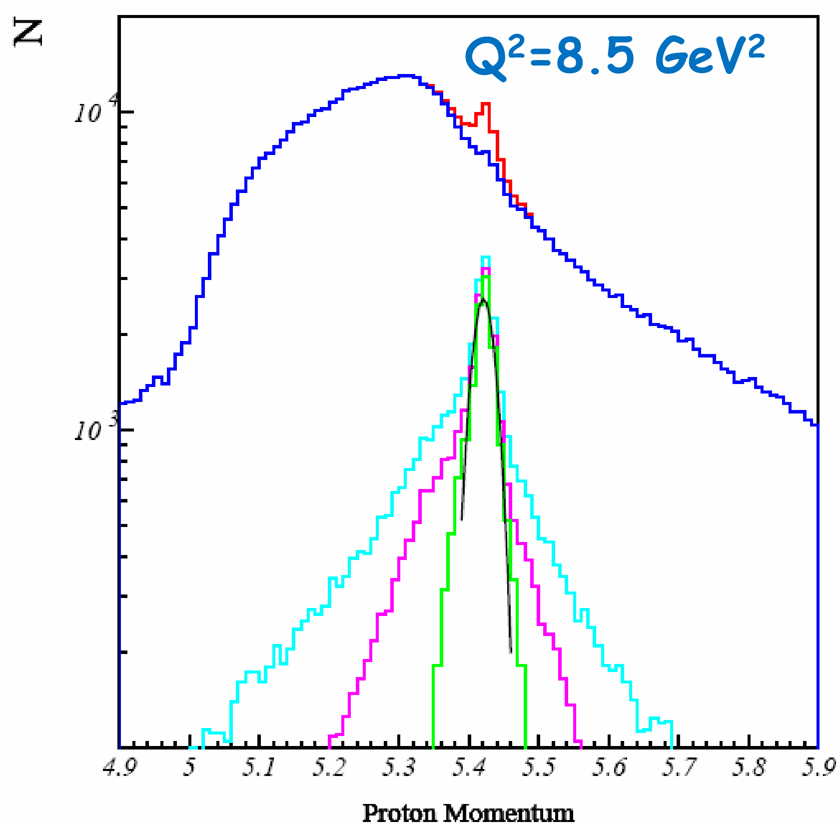
Proton Momentum Spectrum



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

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

Statistics and Preliminary Results from G_{Ep}(III)

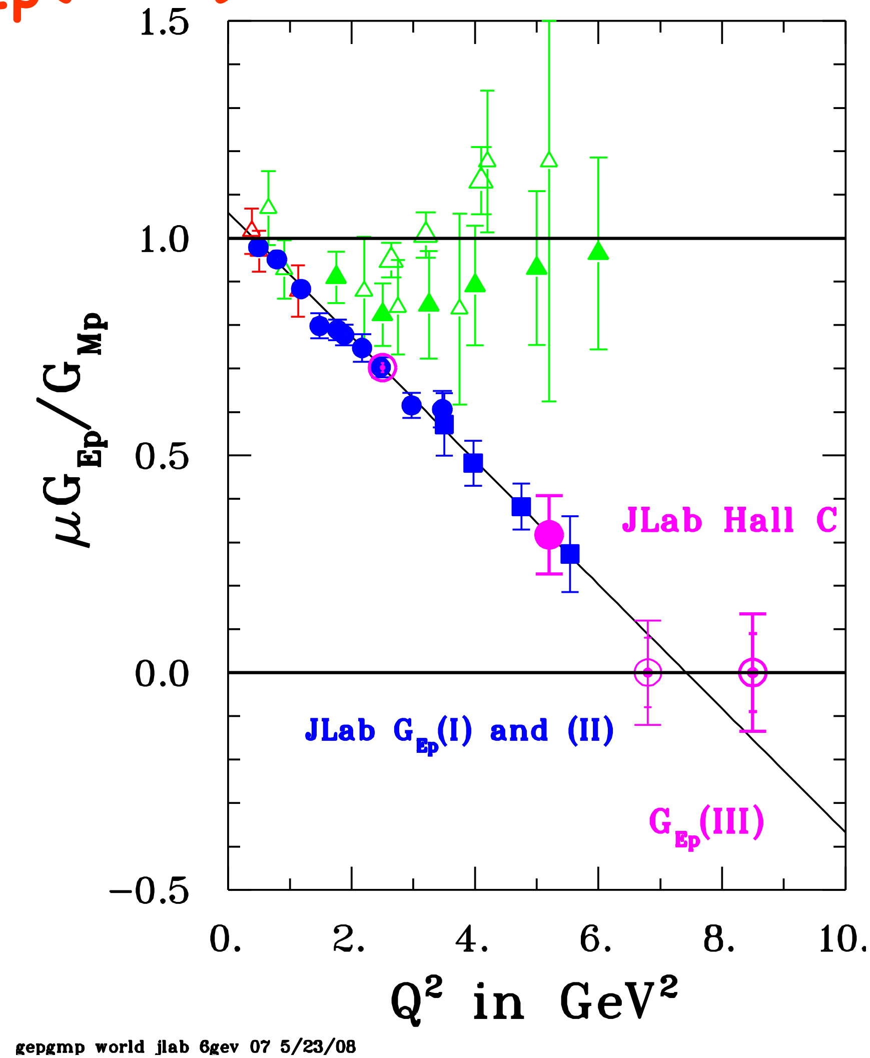
New equipment worked beautifully: BigCal and FPP

8.54 GeV^2 point: 1.63 billion triggers collected

Analyzing power at 5.4 GeV/c close to Dubna value

6.8 GeV^2 point: 160 million triggers

5.2 GeV^2 point: a test of the spin transport at 180°



— $\mu_p G_{Ep}/G_{Mp} = 1.056 - 0.1427 Q^2$

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.

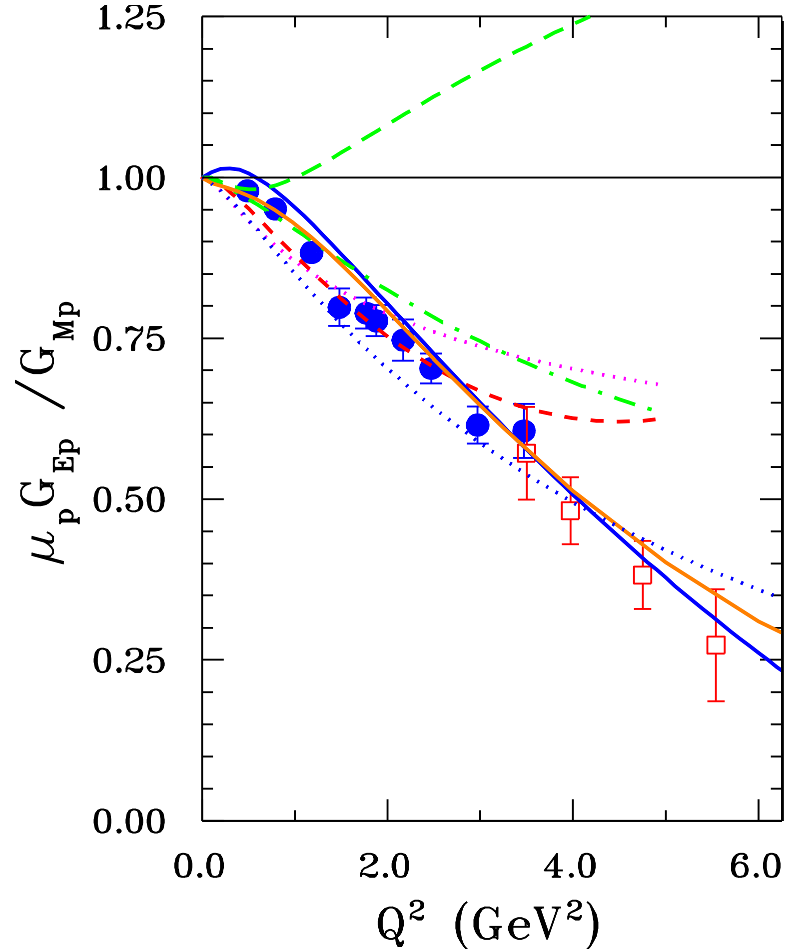
Early work of Höhler (76): ρ(770), ω(782),Φ(1020) and effective ρ'(1250)

Gary and Krumpelman (85) asympt. pQCD

Mergell, Meissner and Drechsel (96)

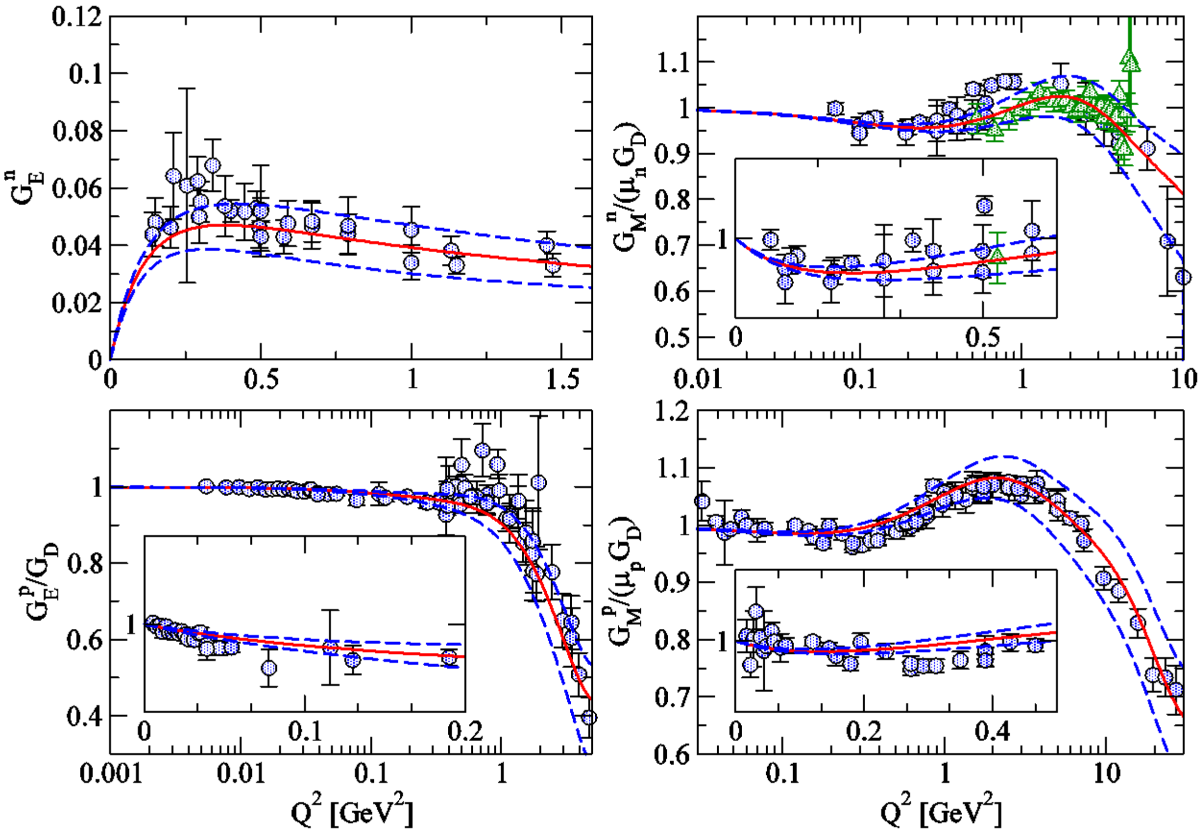
Lomon (01,02) used ρ(770),ω(782),Φ(1020) and ρ'(1450), ω'(1419), 11 parameters.
Lomon (06) revised fit better for G_{En}.

Bijker and Iachello (02)



Continue VMD

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



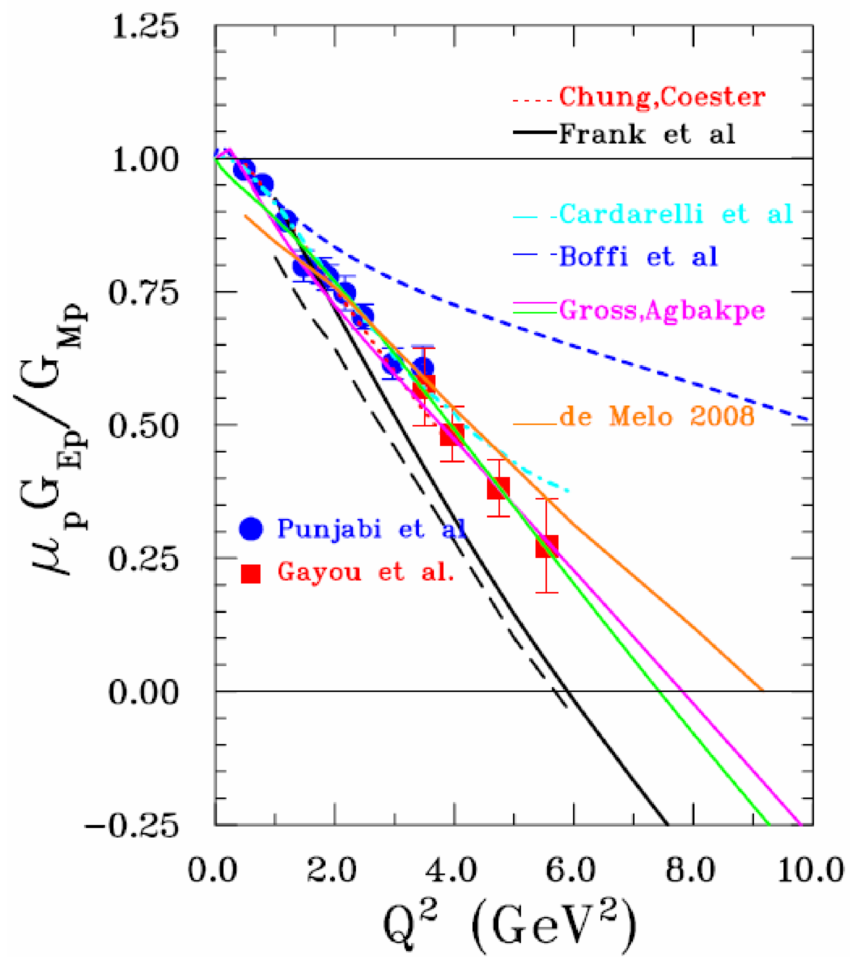
Constituent Quark Models

Initially proposed by Isgur and Karl (78) Non-relativistic CQM

Variety of q-q potentials (harmonic oscillator, hypercentral, linear)

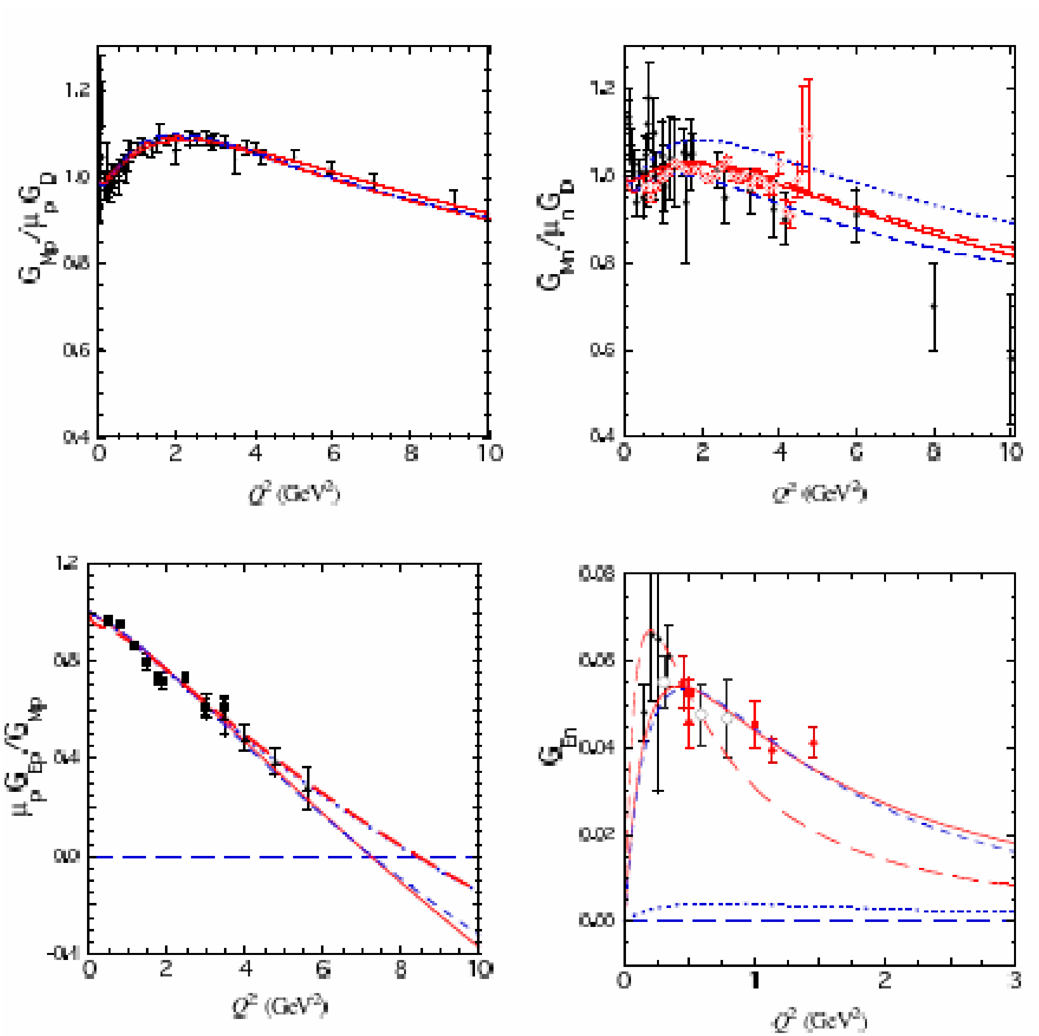
Non-relativistic treatment of quark dynamics, relativistic EM currents

Relativistic Constituent Quark Models (RCQM): Many different approaches: light-front formalism (Miller et al., Cardarelli et al.), point form (Boffi et al.), hypercentral potential (Giannini et al.) etc; *ad hoc* quark momentum wave function, or quark potential models wave function; relativistic treatment necessary: Parameters: m_q, confinement scale, κ_u κ_d.



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

Four different models
8 possible adjustable Parameters, four constants fixed by constraints.

Zero crossing of G_{Ep} is natural!

Argument of F. Gross and collaborator (Gross, Ramalho and Peňa, 2008), zero crossing is quite natural, unlike the defunct “scaling” behavior.

Simple argument: as long as F_{1p} and F_{2p} are positive, and Q^2F_{2p}/F_{1p} behavior supports that, $G_{Ep}=F_{1p}-\tau F_{2p}$ must become negative somewhere!

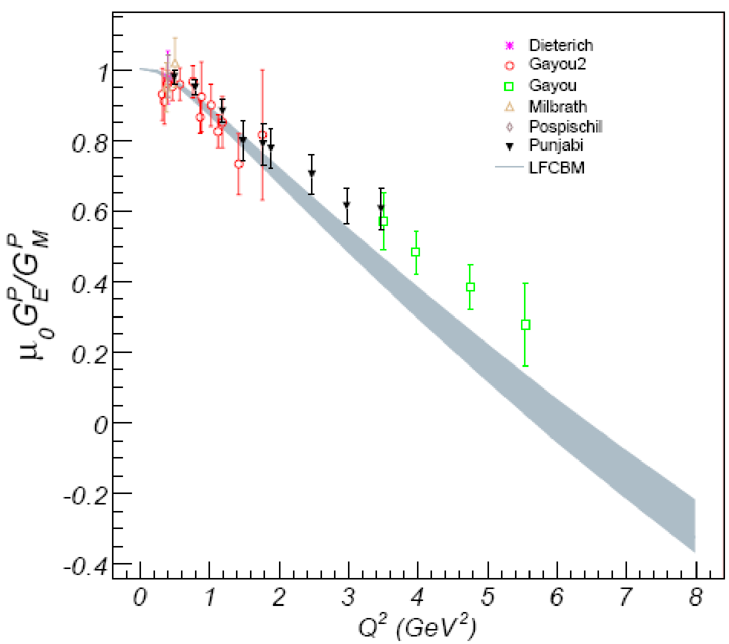
Gross al et al: oversimplifying
$G_{Ep}/G_{Mp} = (f_1 - \tau f_2)/(f_1 + f_2)= (1- \tau\kappa)/ (1 + \kappa)$.
f_1 and f_2 are quark Dirac and Pauli FF, κ is anomalous magnetic moment, approximately 2.

The zero crossing is then at Q^2=2 GeV^2!

Lattice QCD

FF from first principle, limited by computational power to pion mass larger than natural (and finite lattice size)

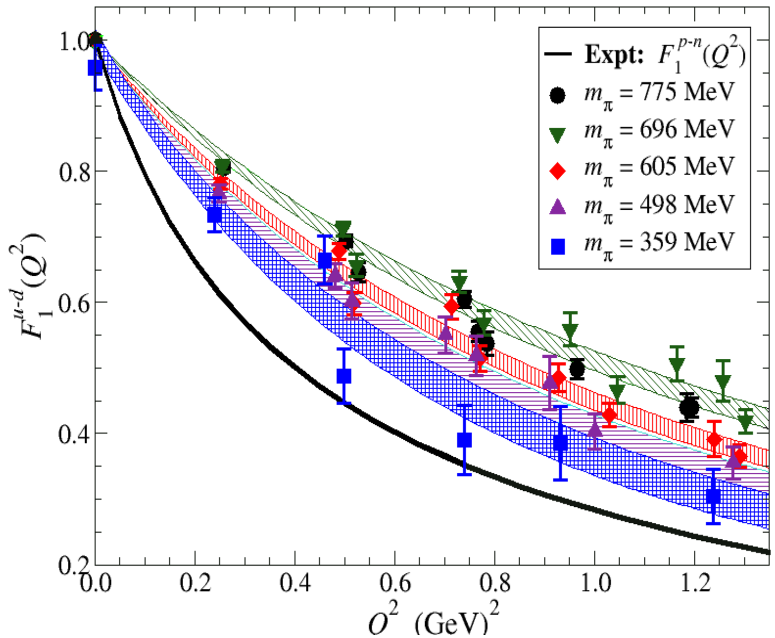
Matevosyan, Thomas, Miller(AIP 2005)
Use LFCBM (Light Front Cloudy Bag model, rCQM) to extrapolate QCDSF 'data' to physical pion mass, (Gloeckeler et al 2005)



H.H. Matevosyan - PANIC 2005

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

Vector $F_1V = F_1(I=1) = F_1p - F_1n$

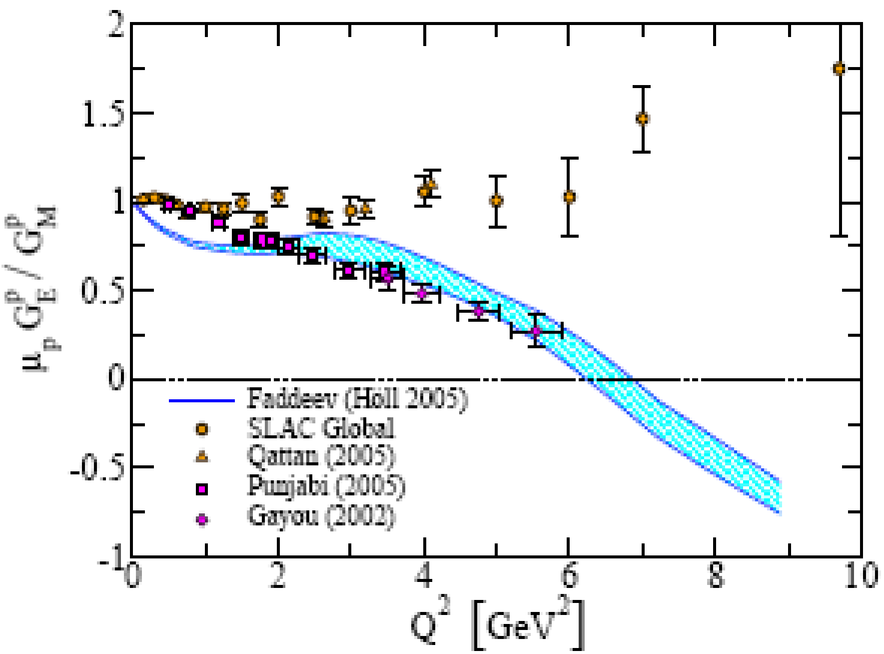


Eliminates need to calculate unconnected loops

Poincare invariant Faddeev equation solution

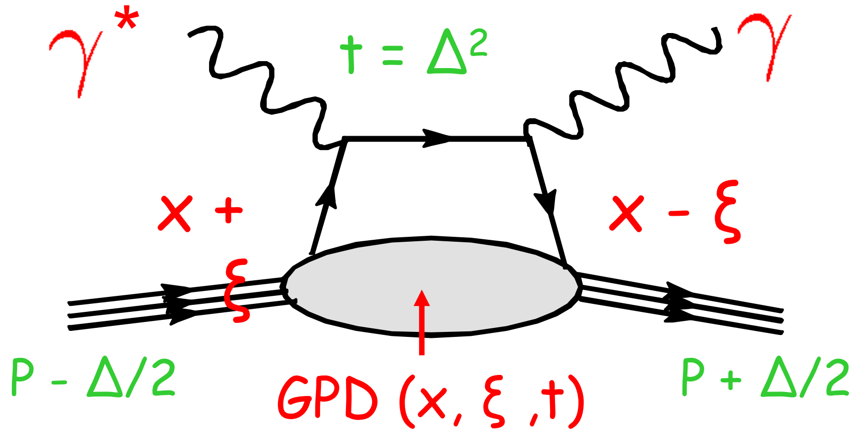
Arrington, Roberts and Zanetti, J. Phys. G34, S23 (2007)

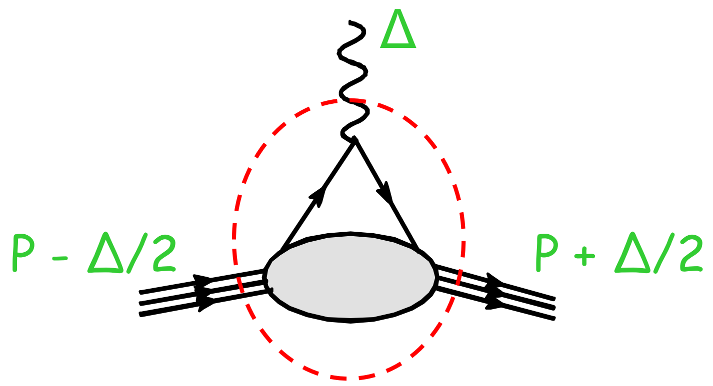
Based on Hoehl et al, N.P. A755:298 (2005)



Parameters:
diquark magnetic dipole and quadrupole moments, q_{1+} and χ_{1+} and scalar to vector EM transition strength, χ_T

Generalized parton distributions





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

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

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

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

In DIS

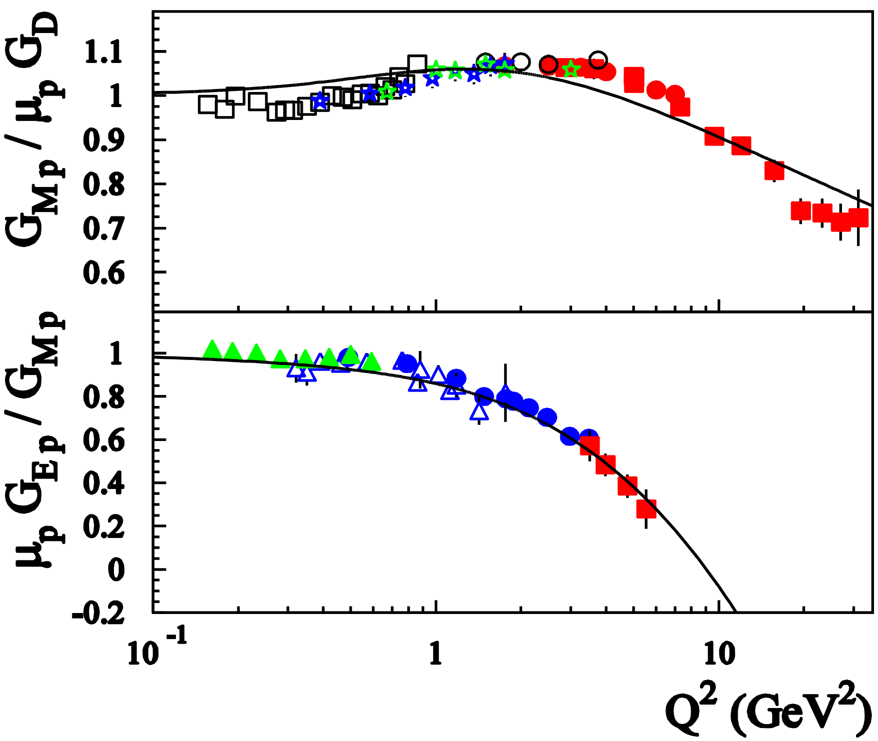
First moments are electroweak form factors: F_1^q, F_2^q, G_A^q and G_P^q; for example:

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

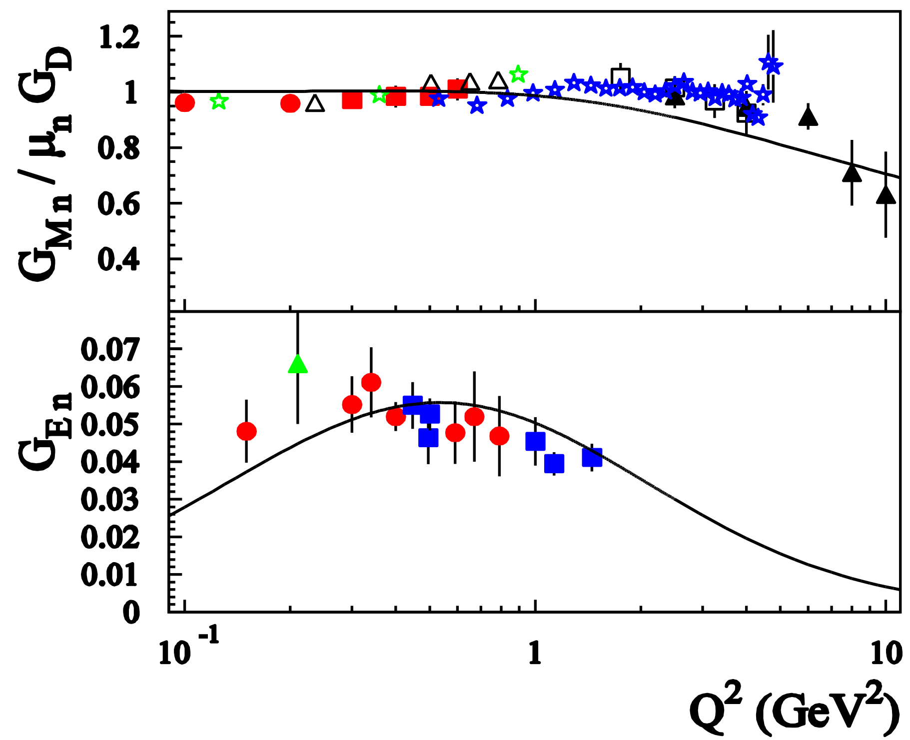
$$\int_{-1}^{1} dx\, E^q(x, \xi, t) = F_2^q(t) \quad \textit{Pauli}$$

Electromagnetic Form Factors

PROTON



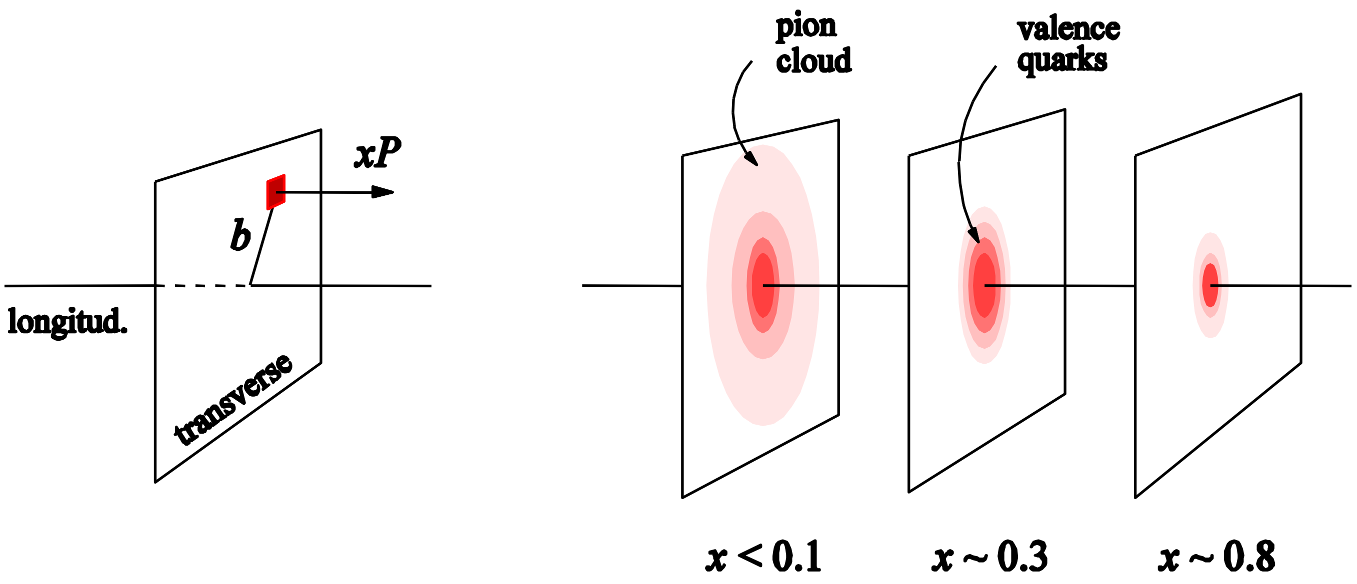
NEUTRON



modified Regge parameterization : Guidal, Polyakov, Radyushkin, Vanderhaeghen, Phys.Rev. D72 (2005) 054013

(Used to estimate the quark contribution to the spin)

GPDs : 3D quark/gluon imaging of nucleon

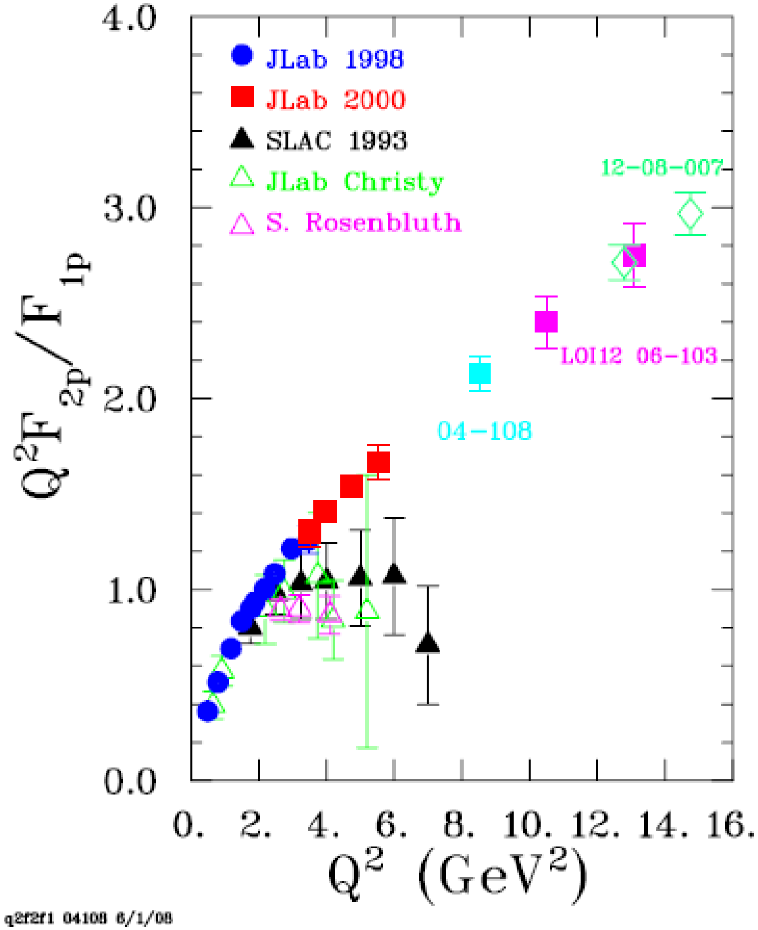


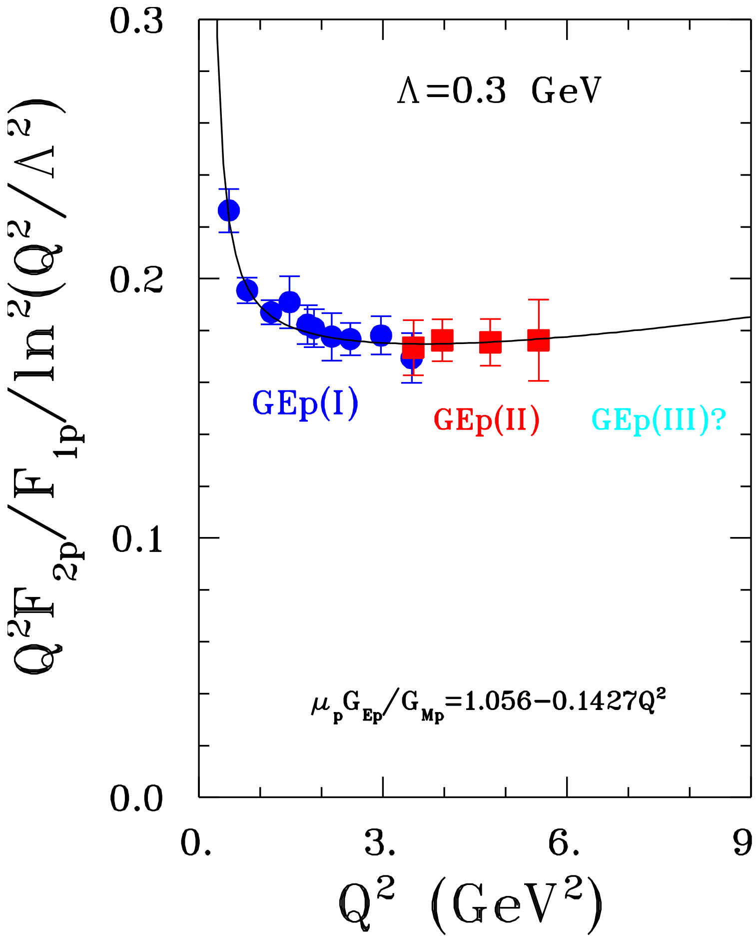
Fourier transform of t-dependence of GPDs, make it possible to access the spatial distributions of partons in the transverse plane, providing a 3-dimensional picture of the nucleon :

simultaneous distributions of quarks w.r.t. longitudinal momentum x and transverse position b

⇨ theoretical parameterization needed

Proton: F2 /F1 and pQCD



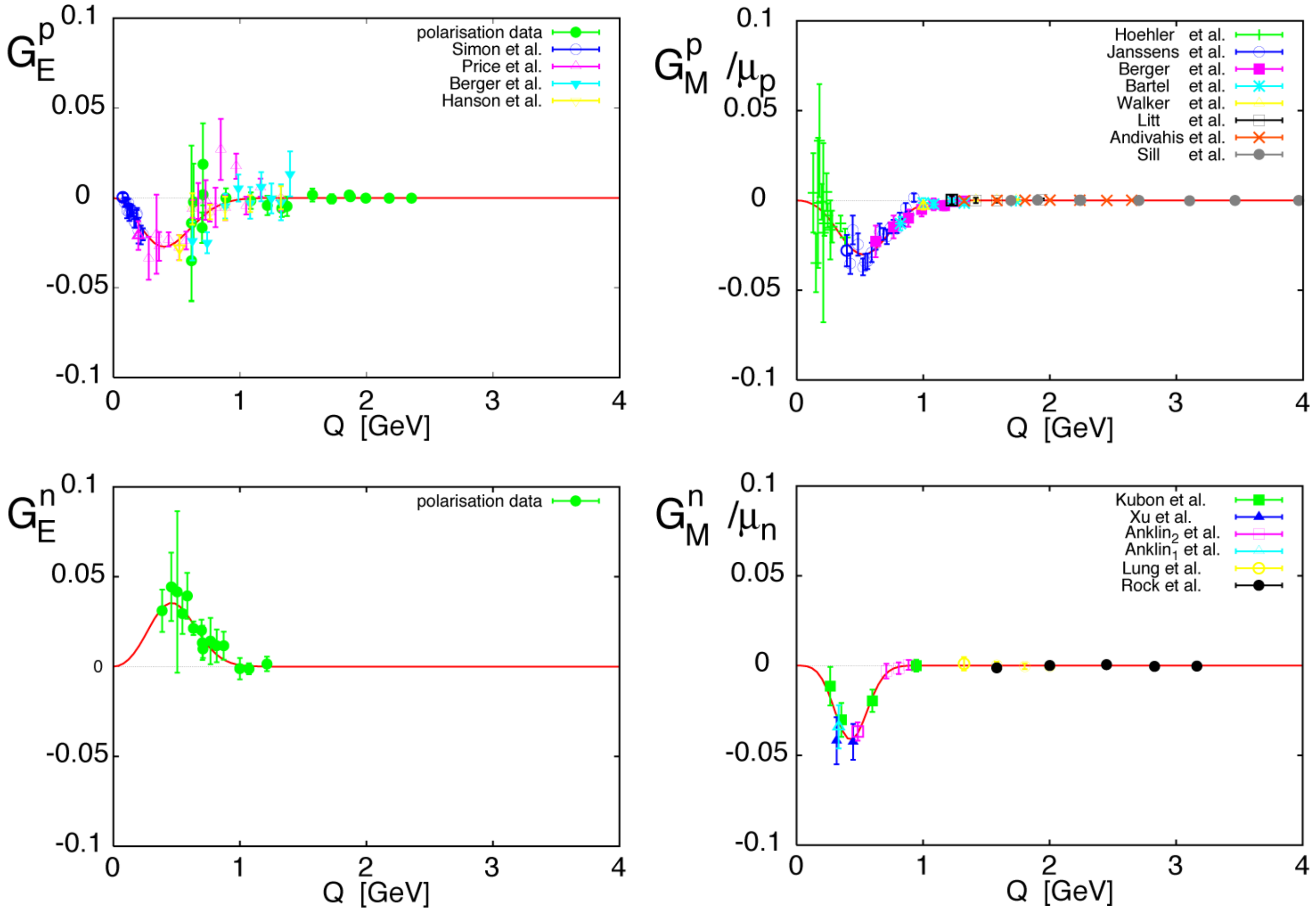


Brodsky and Farrar (75):
$Q^2F_2/F_1 \to$ constant

Belitsky, Ji and Yuan (03):
$Q^2F_2/F_1 \to \ln^2(Q^2/\Lambda^2)$

Low Q^2 Behavior of Nucleon FFs

Friedrich and Walcher, Eur. Phys. J. A17, 607. Emphasize the low Q^2 region to show the structure at 0.2 GeV^2



G_{Ep}, G_{Mp} and G_{Mn} show minimum and G_{En} show maximum at $Q^2 \approx 0.2$ GeV^2

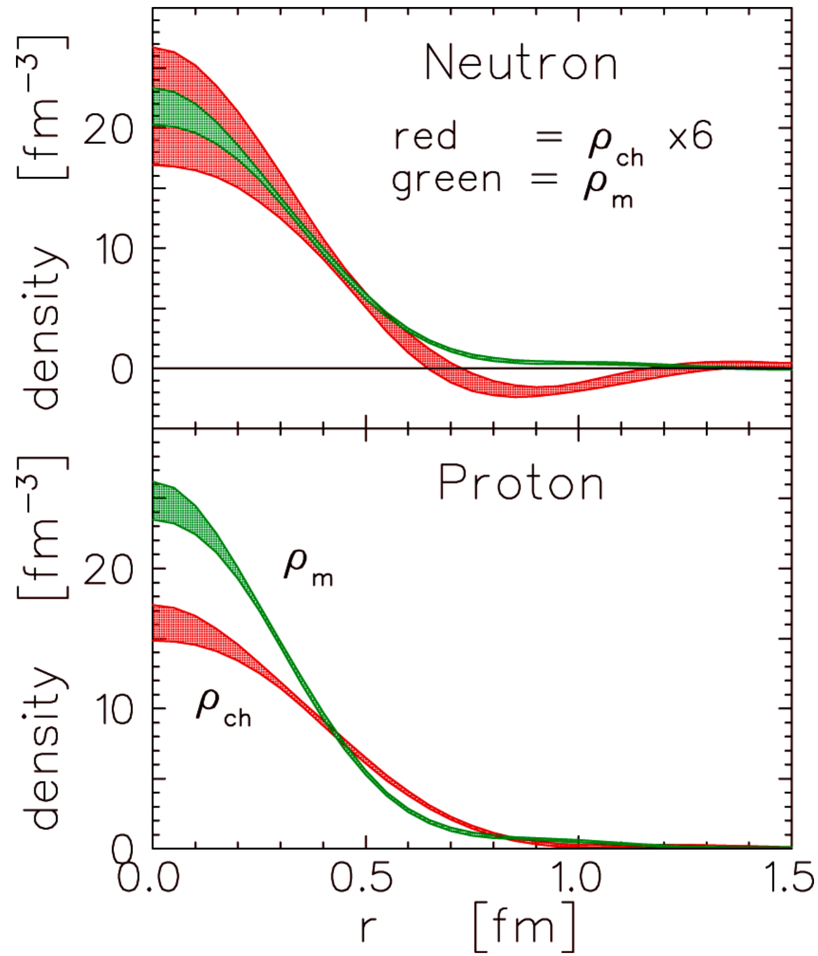
Charge density and Pion cloud

•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

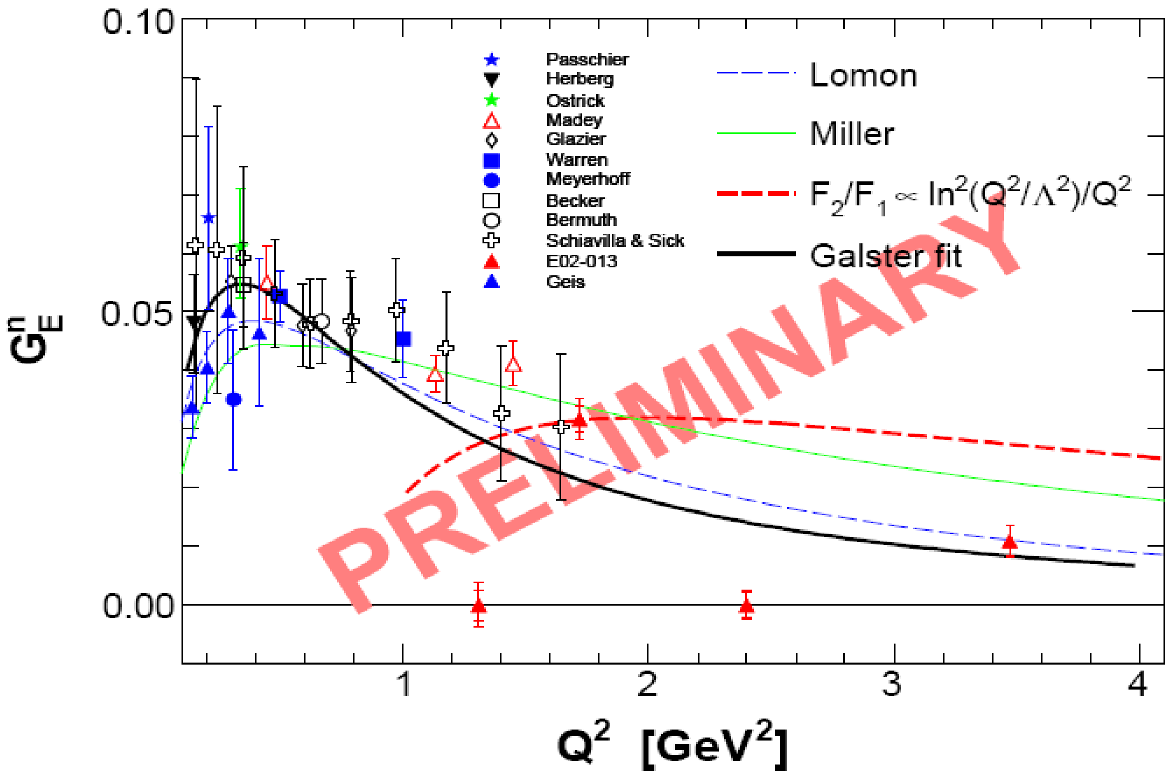
$$\tilde{G}_{E,M}(k) = G_{E,M}(Q^2)(1+\tau)^2 \quad \textbf{with } k^2 = \frac{Q^2}{1+\tau} \quad \textbf{and} \quad \tau = \left(\frac{Q}{2M}\right)^2$$

•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



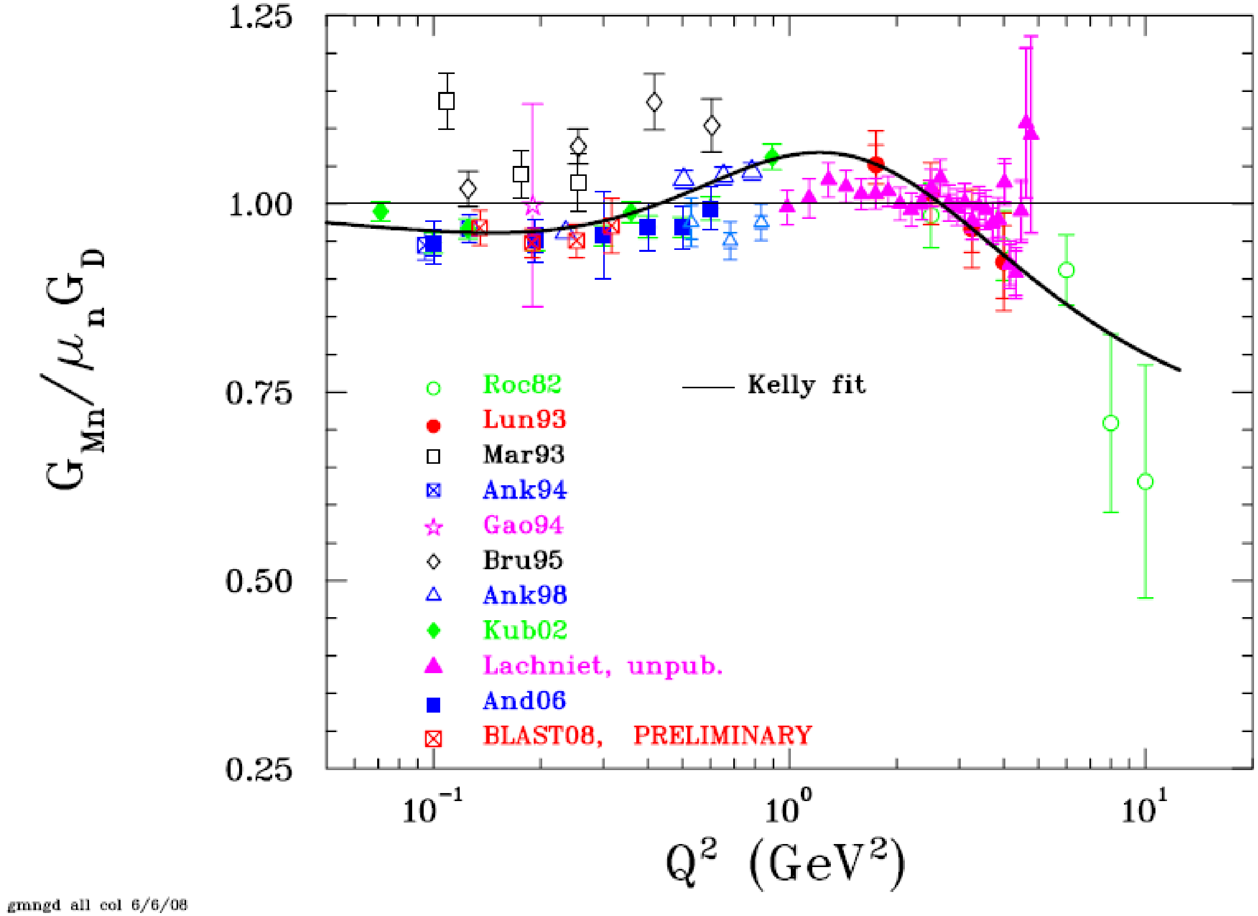
Electric Form Factor of the Neutron



All polarization results, including new Bates/BLAST data (Geis 2008)

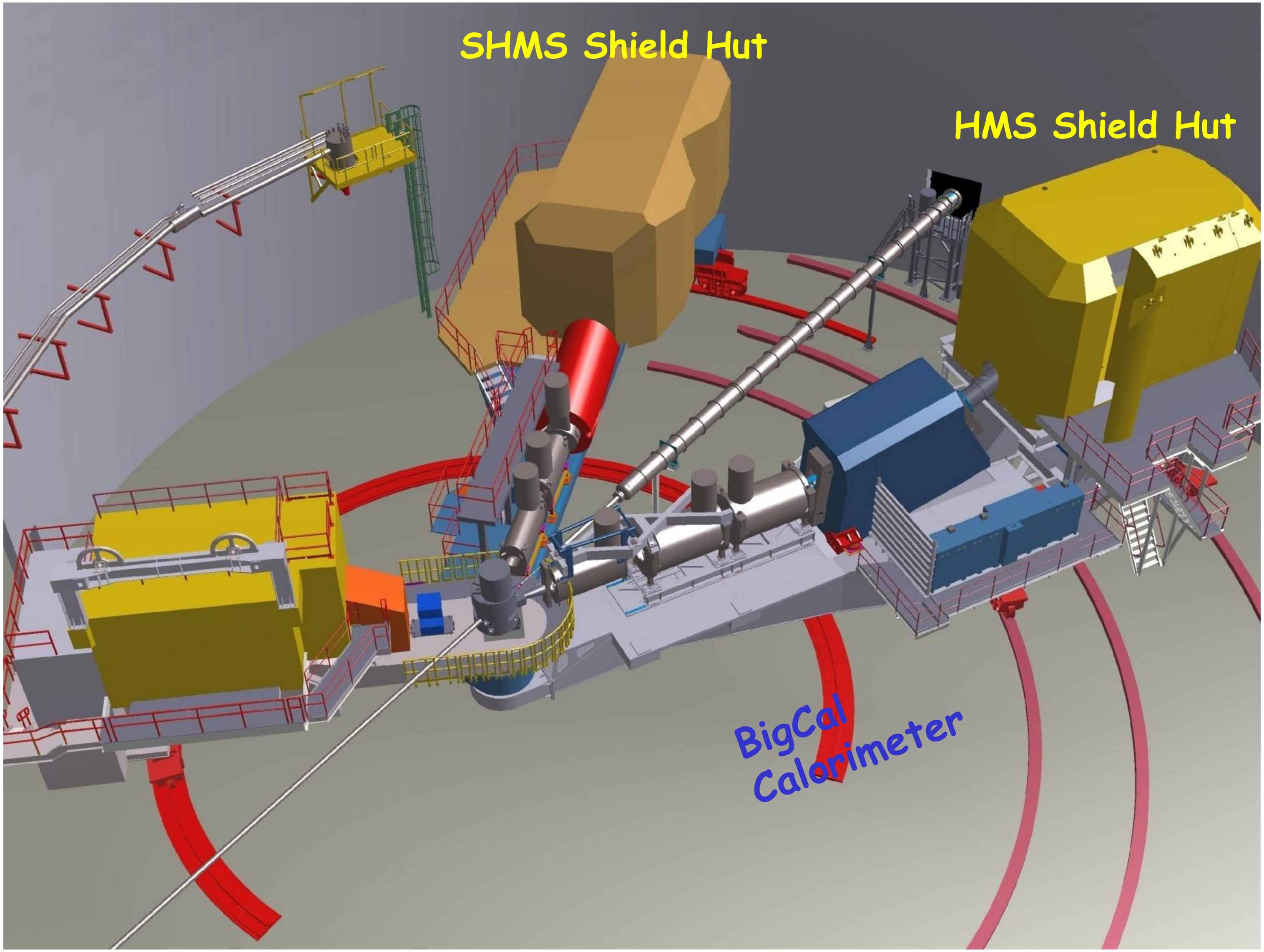
Two of the Hall A preliminary data shown (02-013), anticipated error for two more (5/2008)

Magnetic Form Factor of the Neutron

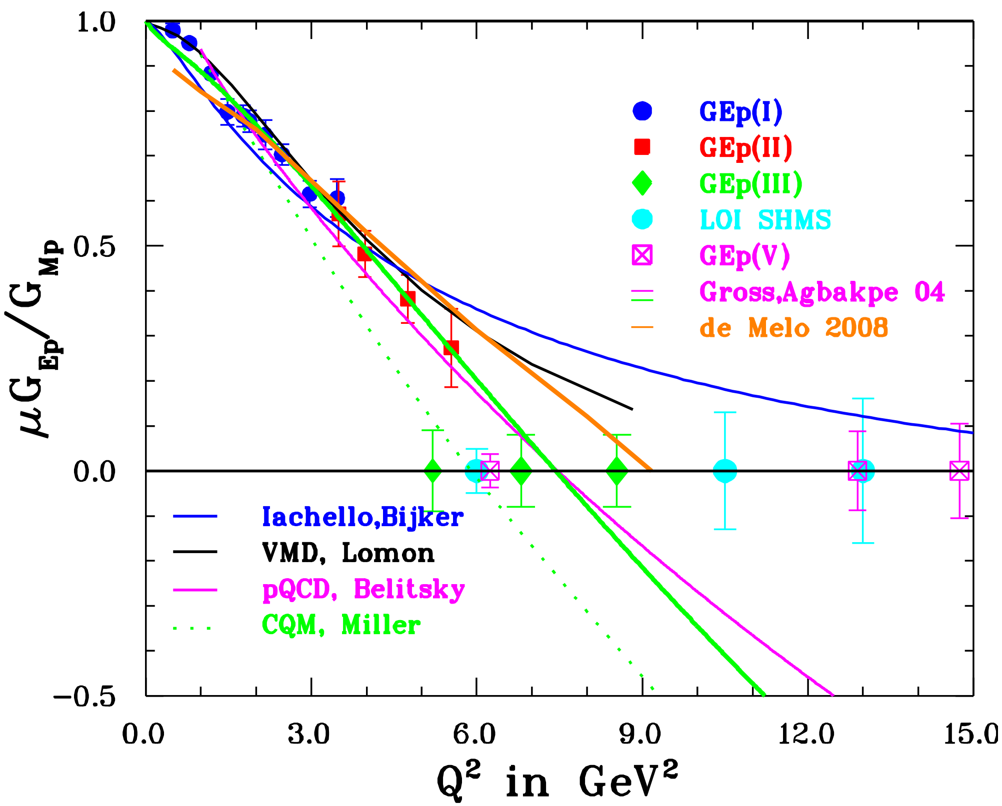


Preliminary Bates/BLAST results $\vec{d}(\vec{e},e')$, Meitanis et al

Measuring G_{Ep}/G_{Mp} in Hall C at 12 GeV



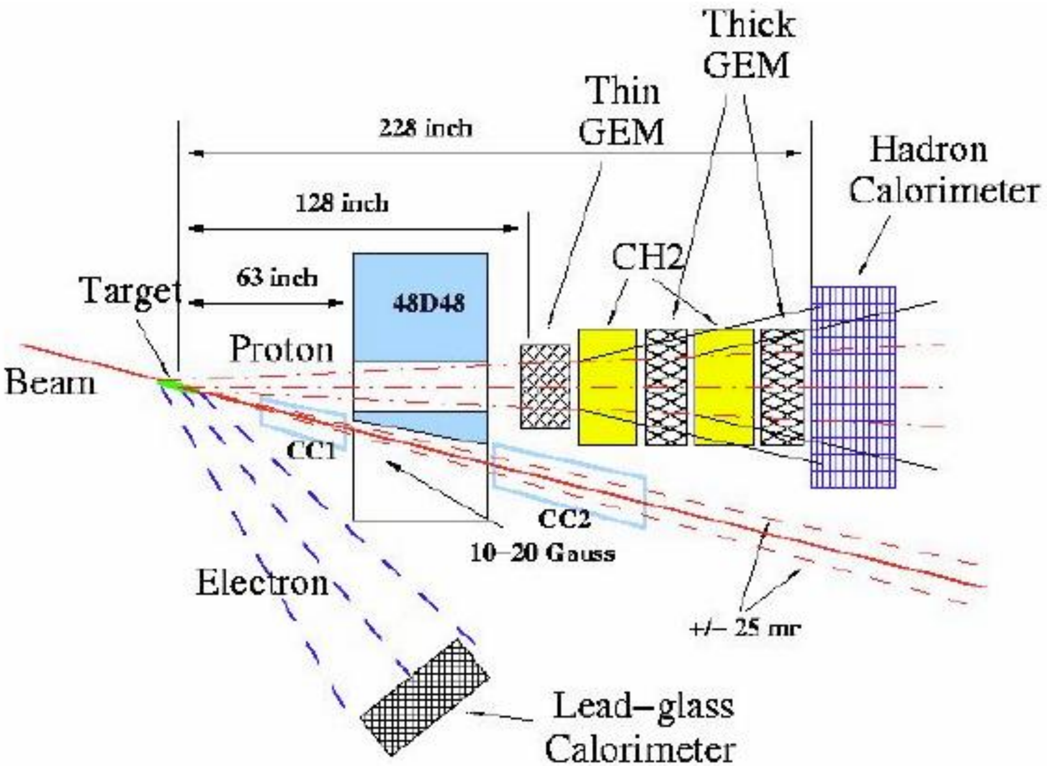
Gep/GMp with 12 GeV beam at JLab



gep he 12gev 8/26/08

Measurement of G_{Ep}/G_{Mp} in Hall A at 12 GeV

- BigCal at 37° detect electrons
- Large solid angle ~ 35 msr Dipole Magnet at 14° to detect protons
- Exit beam pipe through Dipole
- Hadron Calorimeter to trigger on > 4 GeV/c protons
- Angular correlation between proton and electron used in trigger



Conclusions

Discrepancy between Rosenbluth and polarization transfer real, not an experimental problem.

G_{Ep}(III) collaboration has taken data at Q^2 of 5.2, 6.8 and 8.45 GeV^2. Data are currently being analyzed.

Many new model calculations inspired by our results: VMD models give good parameterization of FF at low to intermediate Q^2. All relativistic constituent quark models predict decreasing ratio with increasing Q^2. A few lattice QCD and direct solution of Dyson Schwinger are now available.

pQCD prediction that asymptotically Q^2F_2/F_1 becomes constant is not seen. New pQCD prediction, include logarithmic corrections.

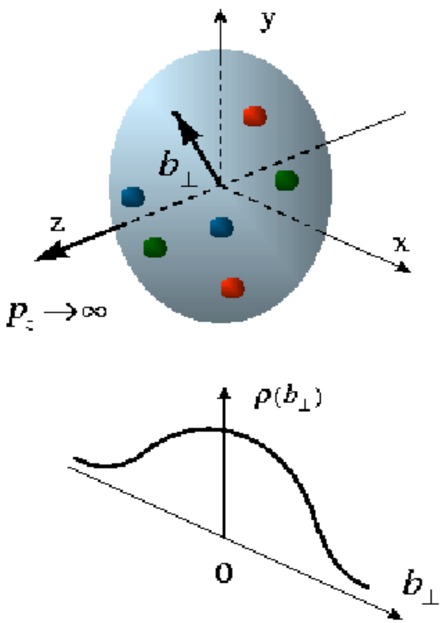
Starting in 2014, Jlab with 12 GeV beams will provide means for next step, In creasing Q^2 to 15 GeV^2. One experiment approved, another in preparation (LOI 2006).

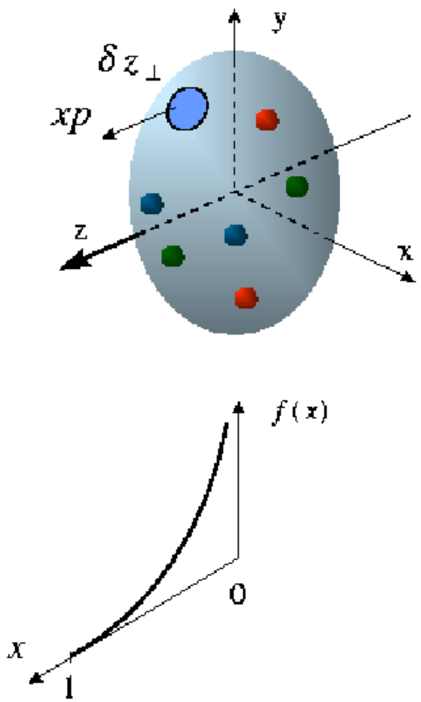
The END

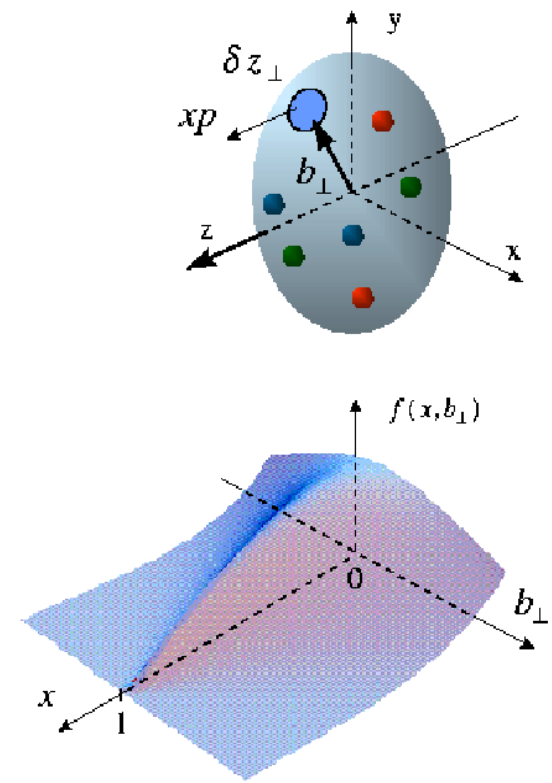
GPDs yield 3-dim quark structure of nucleon

Burkardt (2000, 2003)

Belitsky, Ji, Yuan (2004)







Elastic Scattering
transverse quark distribution in coordinate space

DIS
longitudinal quark distribution in momentum space

DES (GPDs)
fully-correlated quark distribution in both coordinate and momentum space

Spectrometer Pair in Hall A