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

The static properties of the proton are well known: M, S, μ_p

A spin ½ point-like Dirac particle would have $\mu_p = e\hbar/2m_p$

μ_p was first measured by Otto Stern in 1933. He concluded from result $\mu_p = 2.7928$ that Proton - not a point particle

1950-1960: Does the proton have finite size?

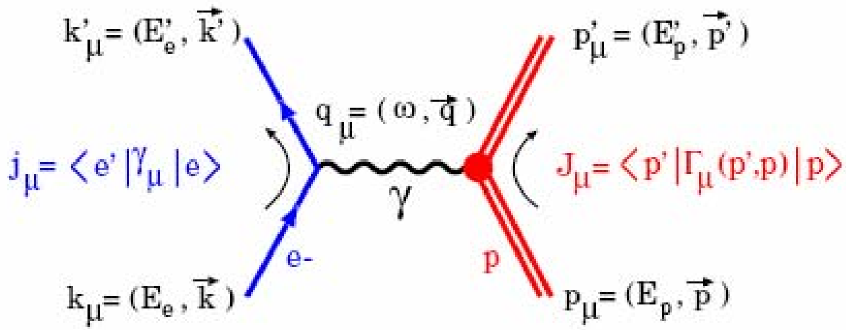
Earliest elastic electron-proton scattering experiments at Stanford, under leadership of Bob Hofstadter, determined proton charge radius ~ 0.8 fm, close to modern value 0.895 fm

1960-1990: What is the internal structure of the proton?

In DIS with electron-proton, Friedman, Kendall and Taylor, discovered partons/quarks in 'scaling' of structure function and measure their momentum and spin distributions

Today: How are the nucleon's charge & current distributions related to the quark's momentum & spin ?

Electron - Proton Elastic Scattering



Nucleon vertex:

$$\Gamma_\mu(p',p) \quad = \quad \underbrace{F_1(Q^2)}_{Dirac}\gamma_\mu + \frac{i\kappa_p}{2M_p}\underbrace{F_2(Q^2)}_{Pauli}\sigma_{\mu\nu}q^\nu$$

F_1 is the helicity conserving form factor

F_2 is the helicity non-conserving form factor

Relationship to Electric, G_E, and Magnetic, G_M, form factors:

$$G_E(Q^2) = F_1(Q^2) - \kappa_p \frac{Q^2}{4M_p^2} F_2(Q^2)$$

$$G_M(Q^2) = F_1(Q^2) + \kappa_p F_2(Q^2)$$

In Breit frame, $G_E(Q^2)$ and $G_M(Q^2)$ are the Fourier transforms of the charge and current distributions.

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

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

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

- **this form leads to the Rosenbluth separation method:**

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

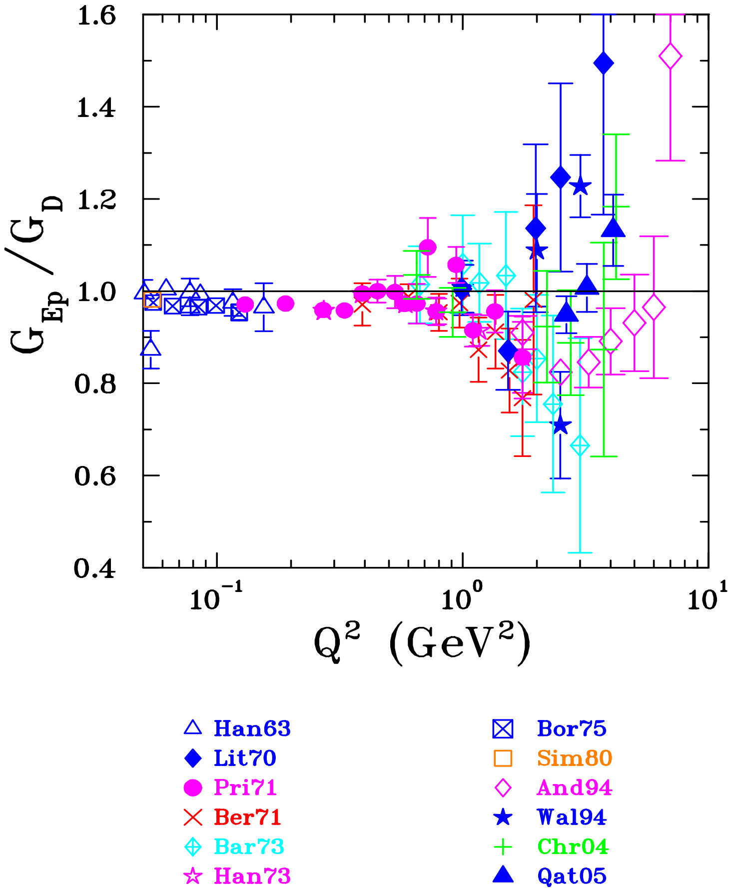
- **where ε is the virtual photon polarization.**

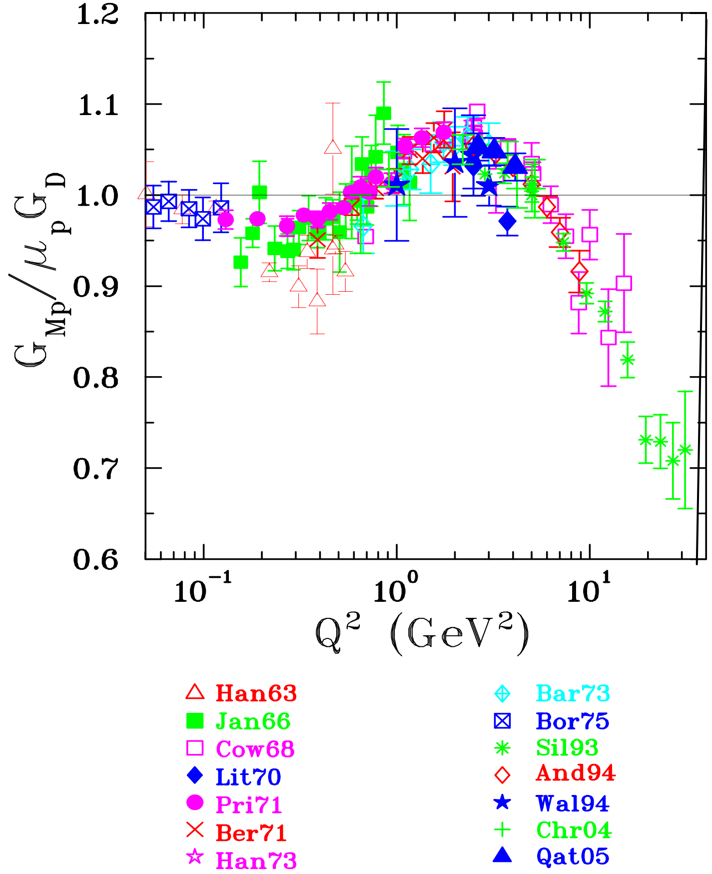
Empirically prior to our two experiments

$$G_{Ep} \sim G_{Mp}/\mu_p \sim G_{Dipole} = \frac{1}{(1+Q^2/0.71)^2}$$

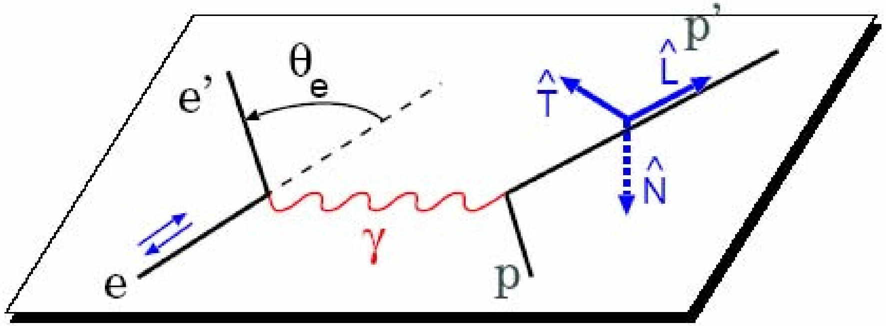
All Rosenbluth separation data above 0.05 GeV^2

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





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



Transferred polarization is: (Akhiezer & Rekalo)

$$P_n = 0$$

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

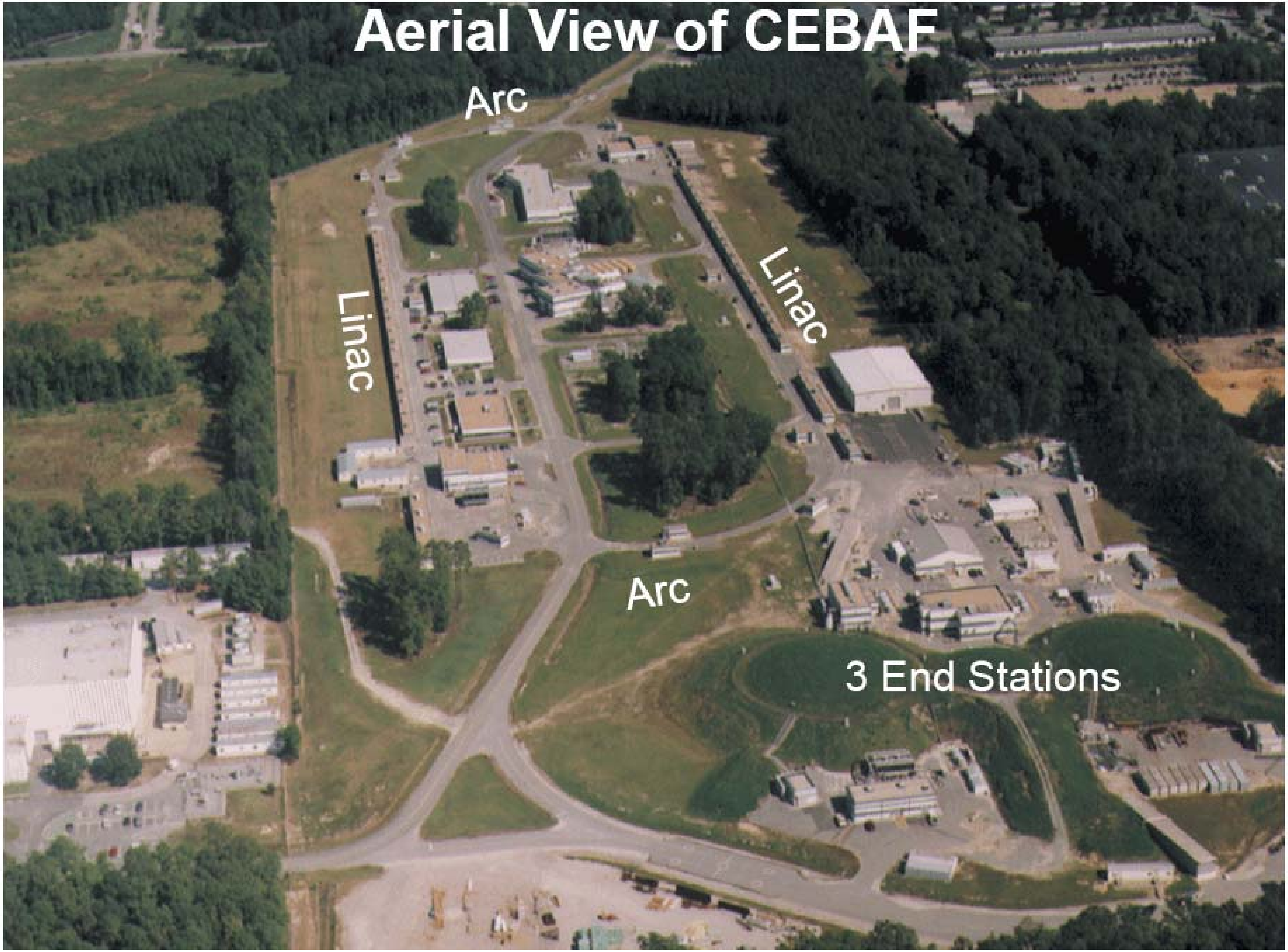
$$\pm h P_l = \pm h (E_e + E_{e'}) (G_M^p)^2 \sqrt{\tau(1+\tau)} \tan^2\left(\frac{\theta_e}{2}\right) / M / I_0$$

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

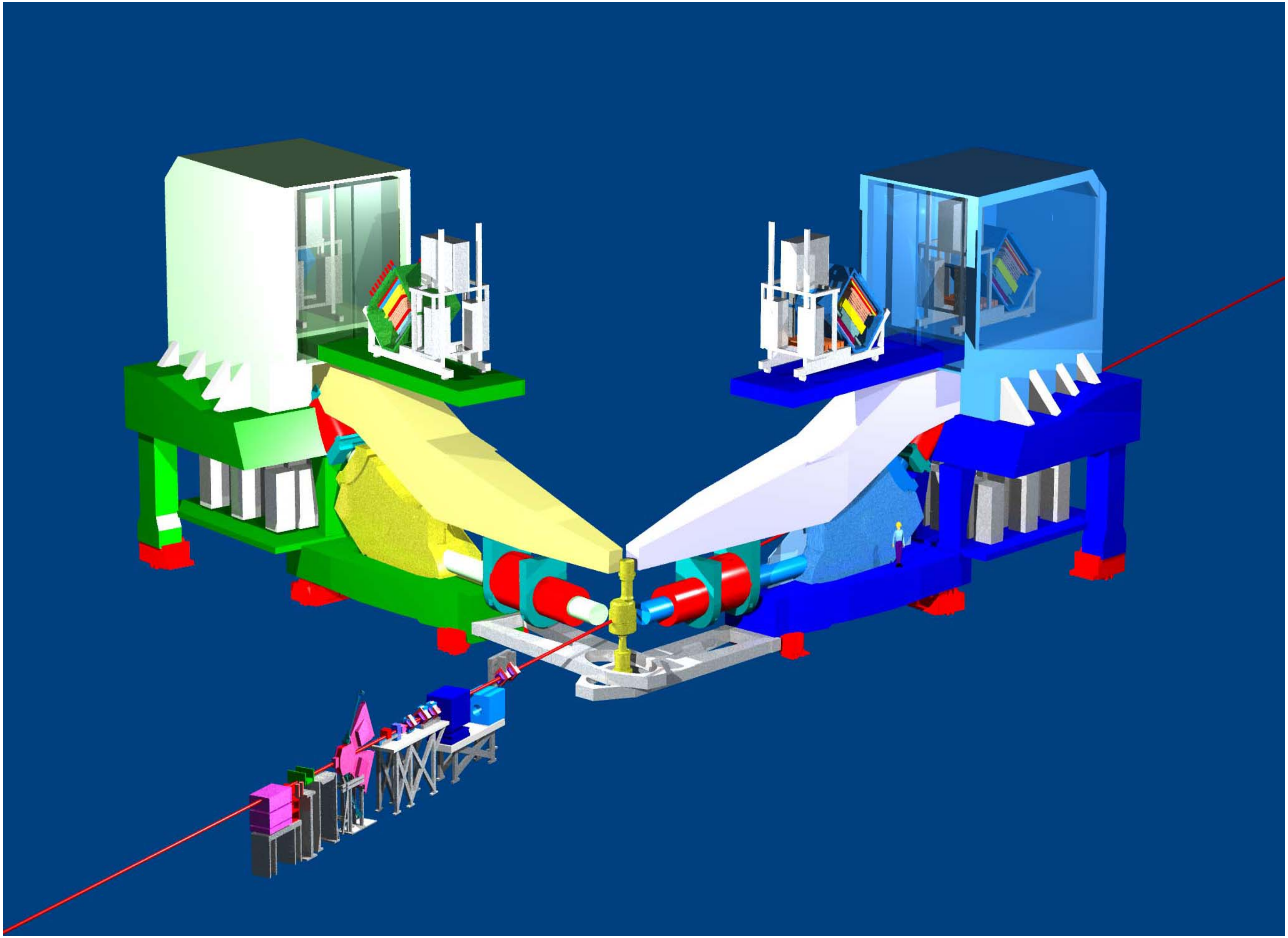
$$I_0 \;=\; (G_E^p(Q^2))^2 + \frac{\tau}{\epsilon}(G_M^p(Q^2))^2$$

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

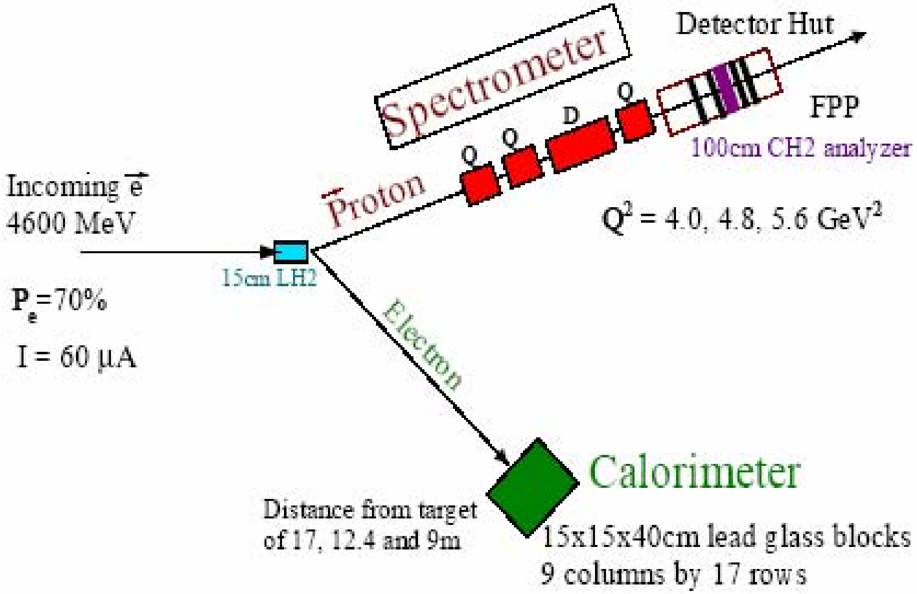
No error contributions from analyzing power and beam polarization measurements


Aerial View of CEBAF
Arc
Linac
Linac
Arc
3 End Stations

Spectrometer Pair in Hall A



Experimental Conditions



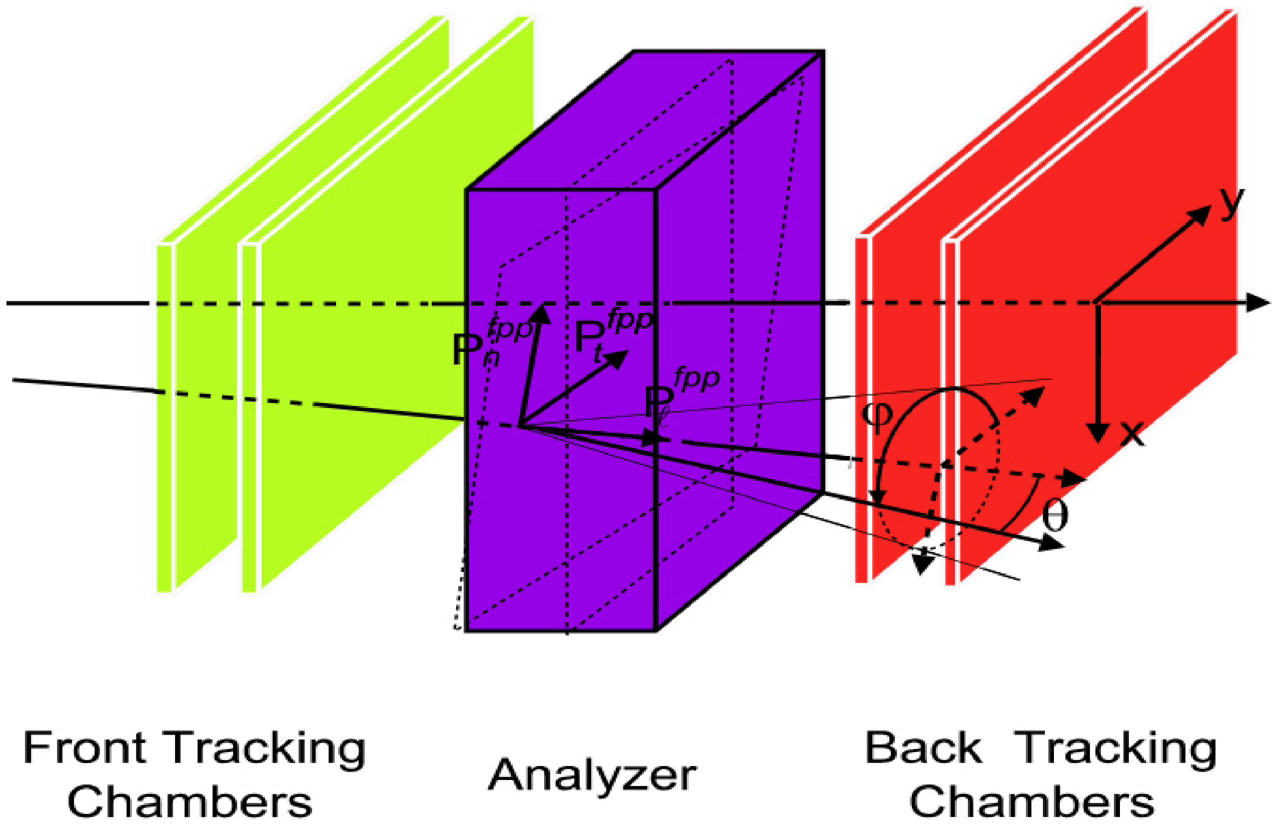
- Trigger on single proton in HRS, so background included (target walls and pion electro-production)

- Proton at forward angles so defines the solid angle.

Position the calorimeter to match proton solid angle.

At Q^2 = 5.6, $\Delta\Omega_e \approx 42\, msr$

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 difference distributions

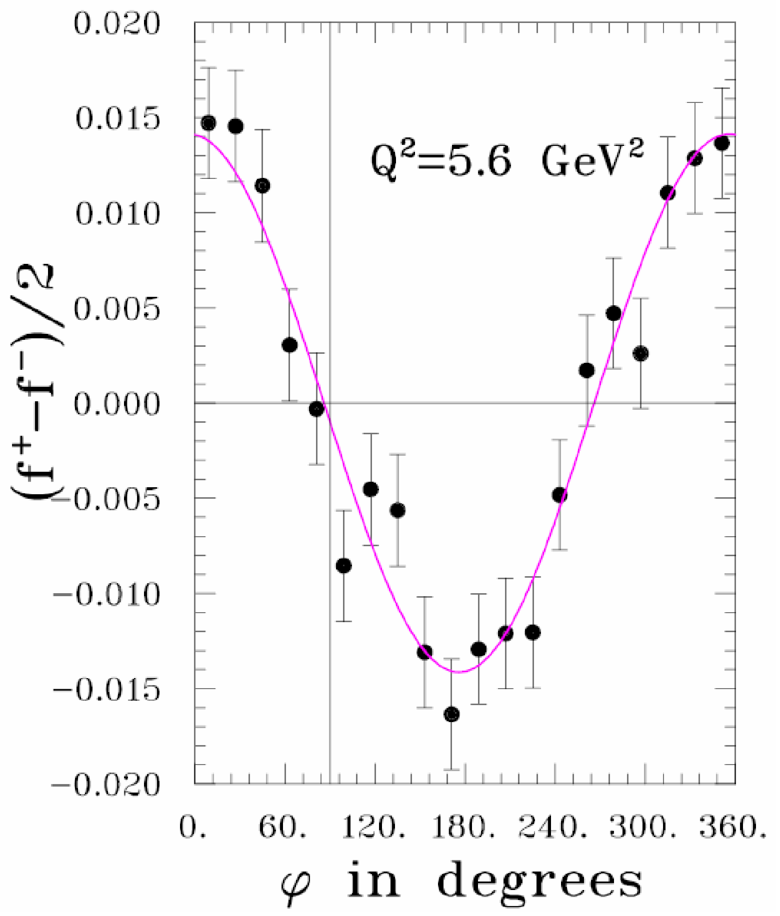
$$D_i = \left(f_i^+ - f_i^-\right)/2$$

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

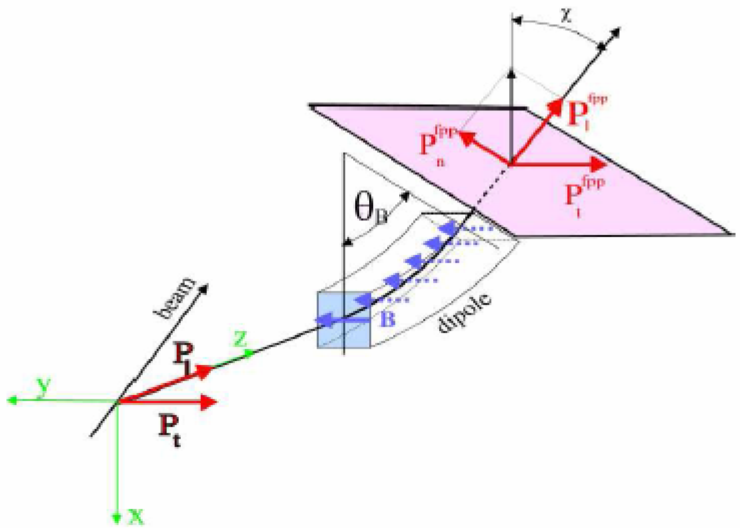
Sum distribution give instrumental asymmetries

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

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



Spin precession

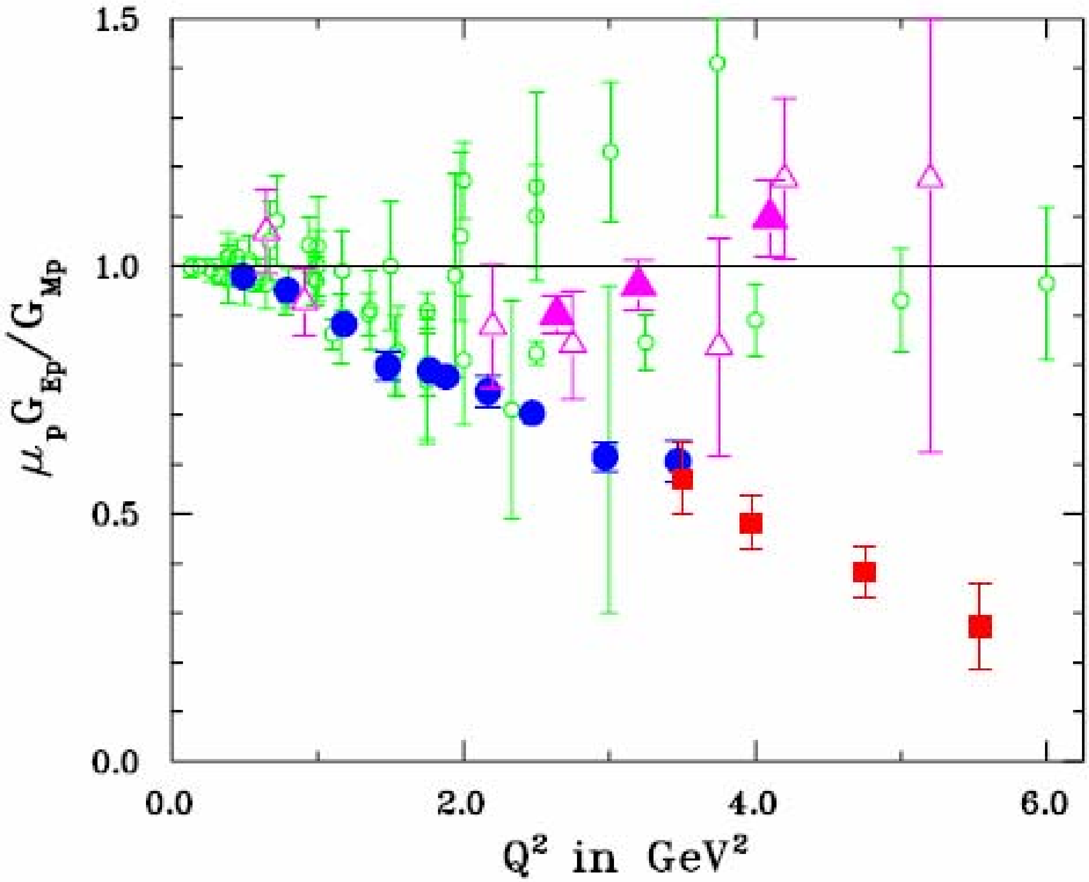


Precession angle, $\chi = \gamma \, \kappa_p \, \theta_{\text{bending}}$

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

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); and Punjabi, Perdrisat *et al.*, Phys. Rev. C 71, 055202 (2005))

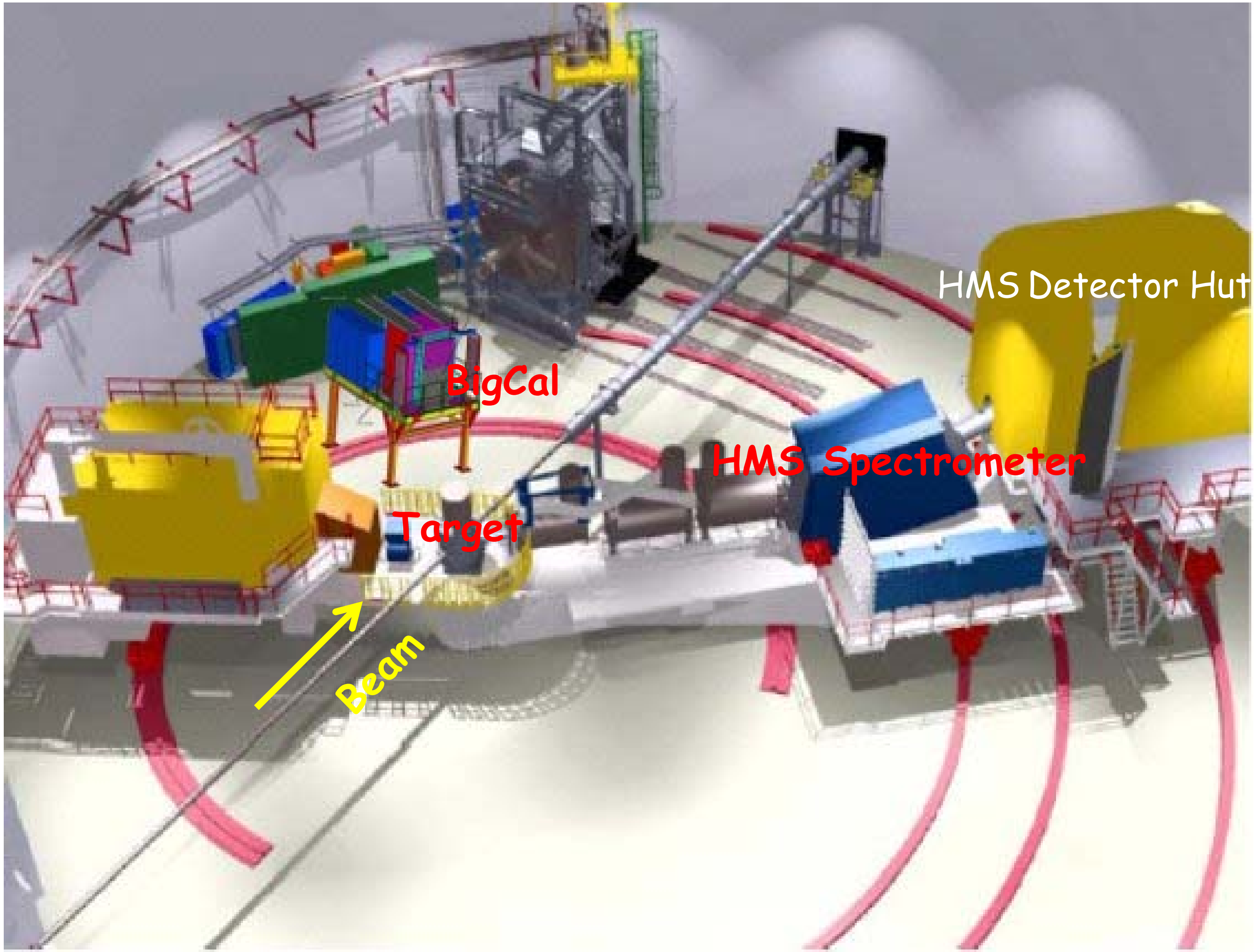
G_{Ep} – III Experiment at JLab

- 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 High Momentum Spectrometer (HMS) measured the polarization of the recoil proton.

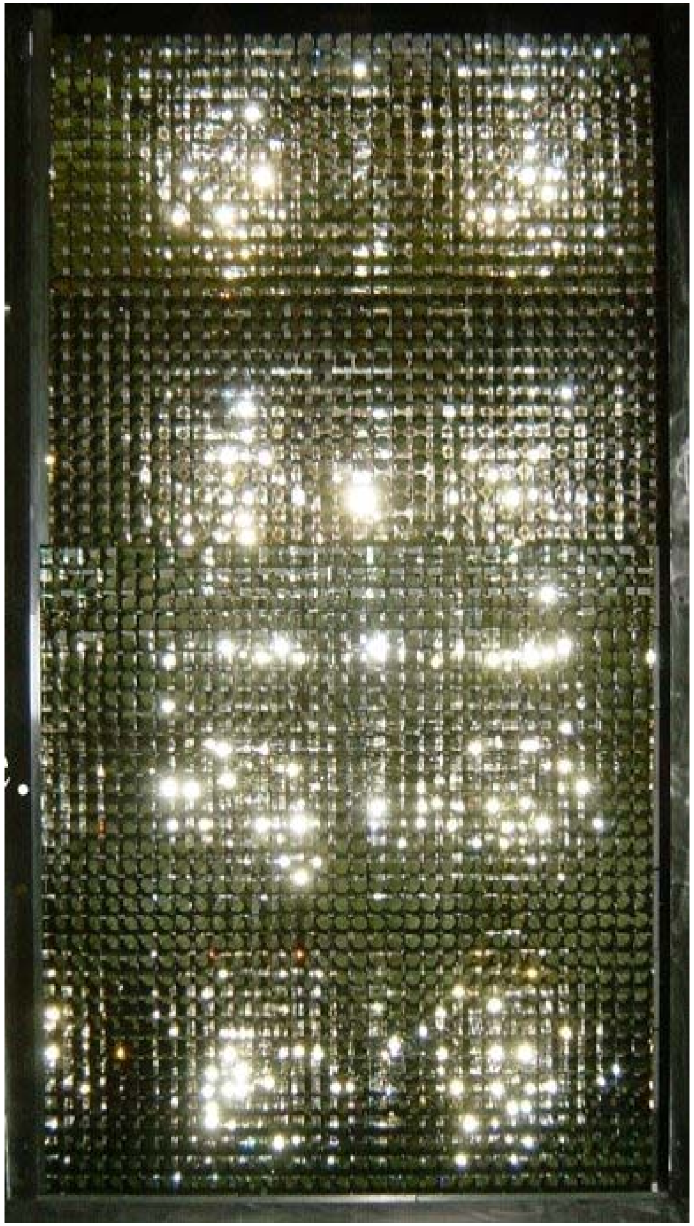
- A large area Electromagnetic Calorimeter (BigCal) was used to detect the elastically scattered electrons in coincidence with protons.

Hall C Layout

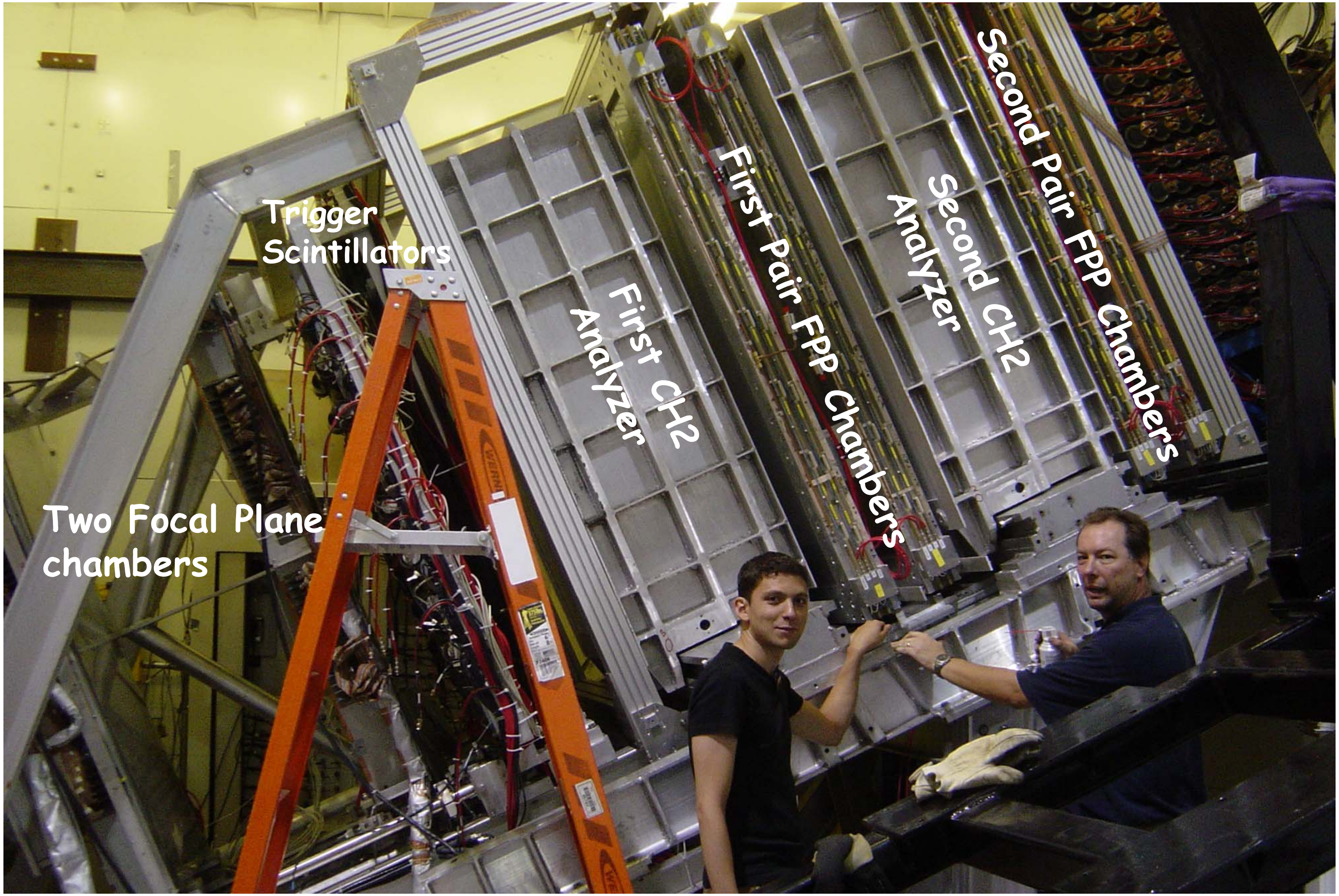


BigCal in Hall C

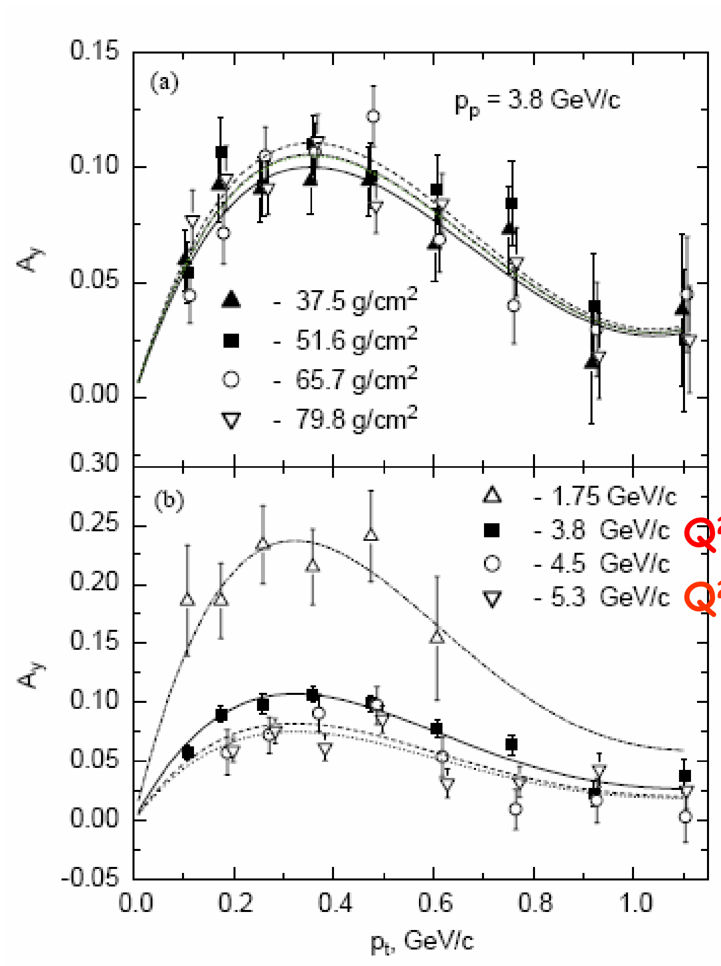
BigCal glass



Double FPP in HMS

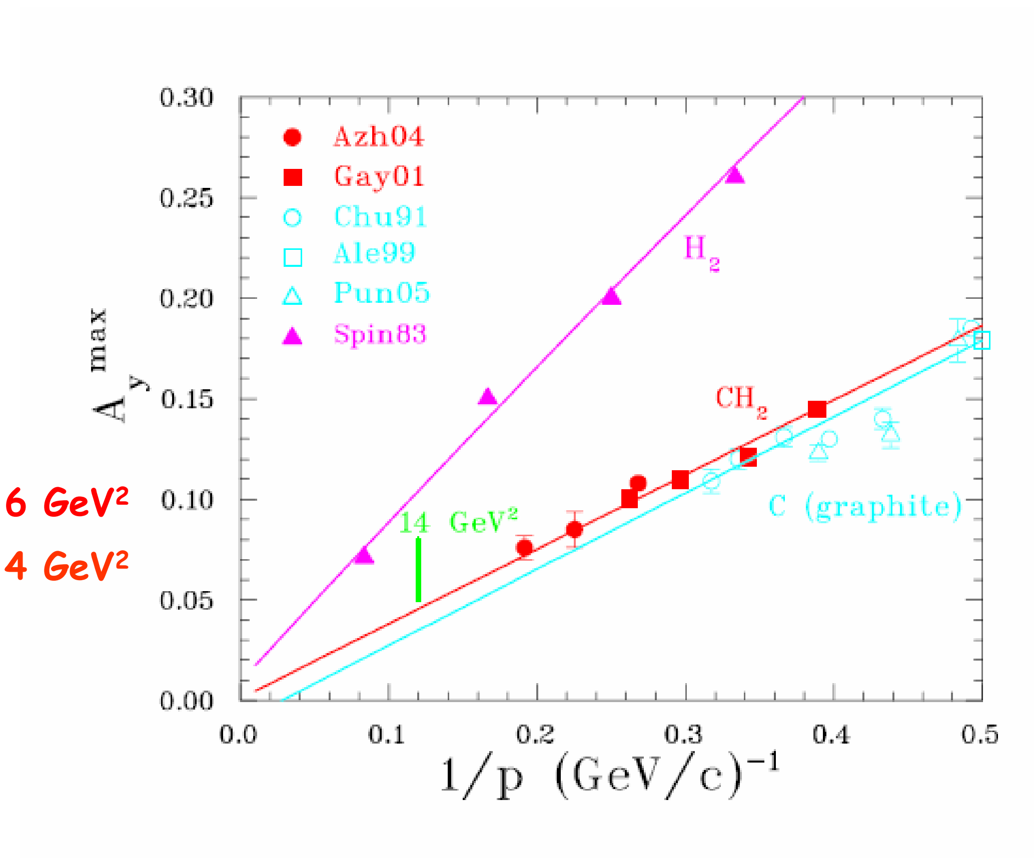


Carbon/CH_2/H_2 Analyzing Power Data

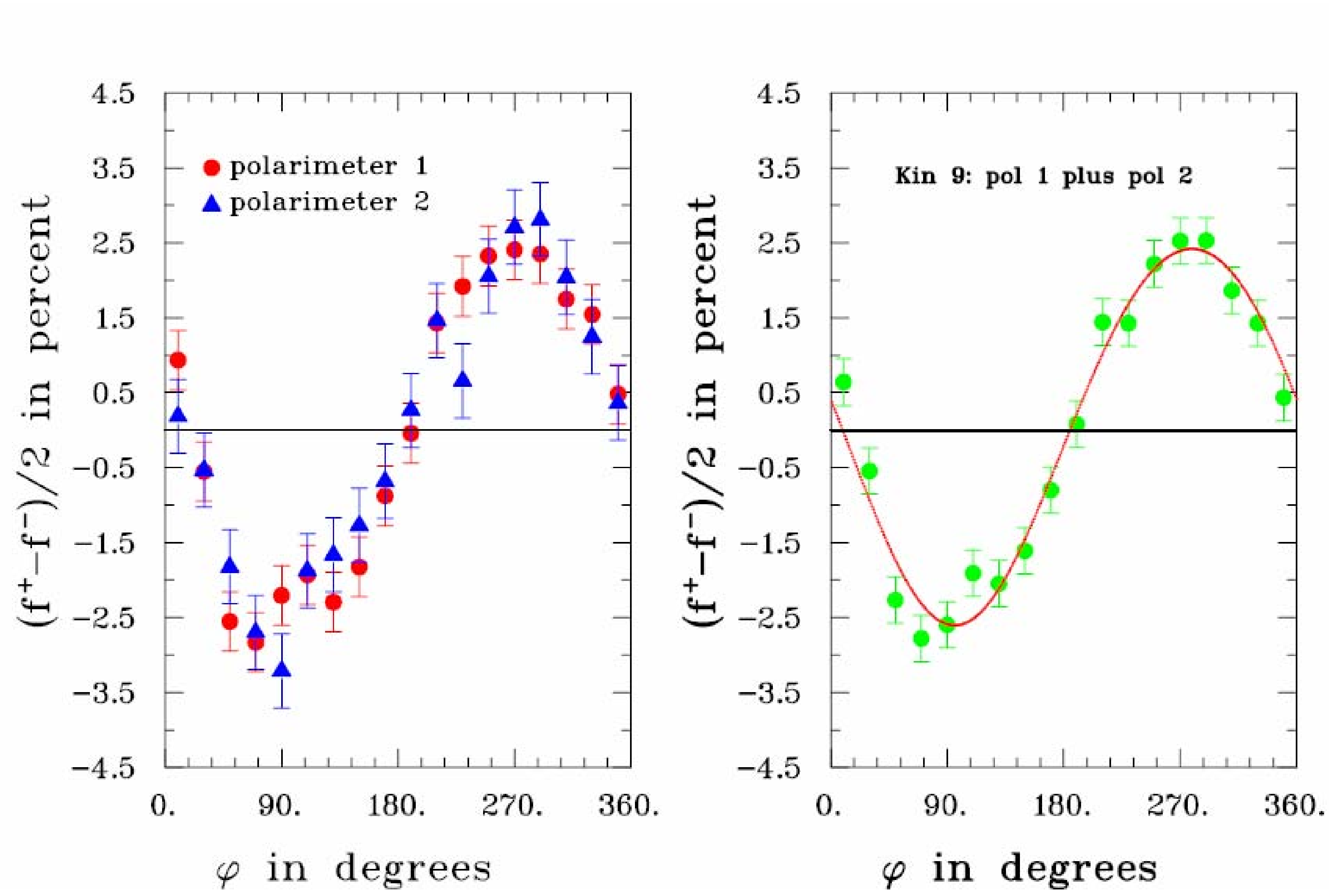


Q^2 =5.6 GeV²

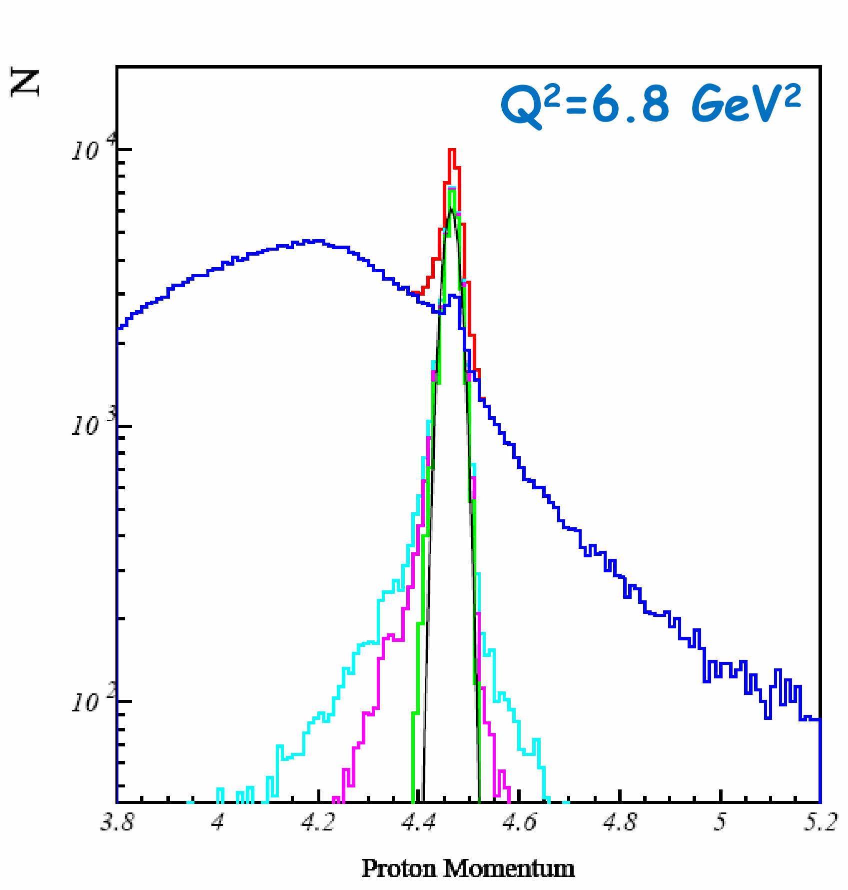
Q^2 =8.4 GeV²



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

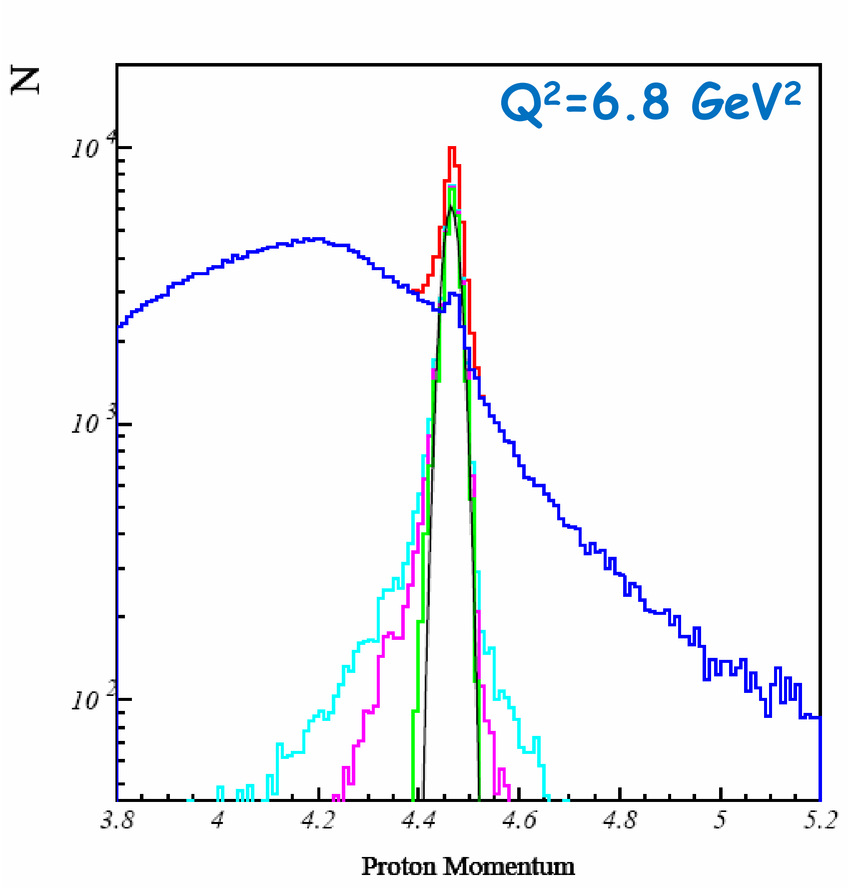


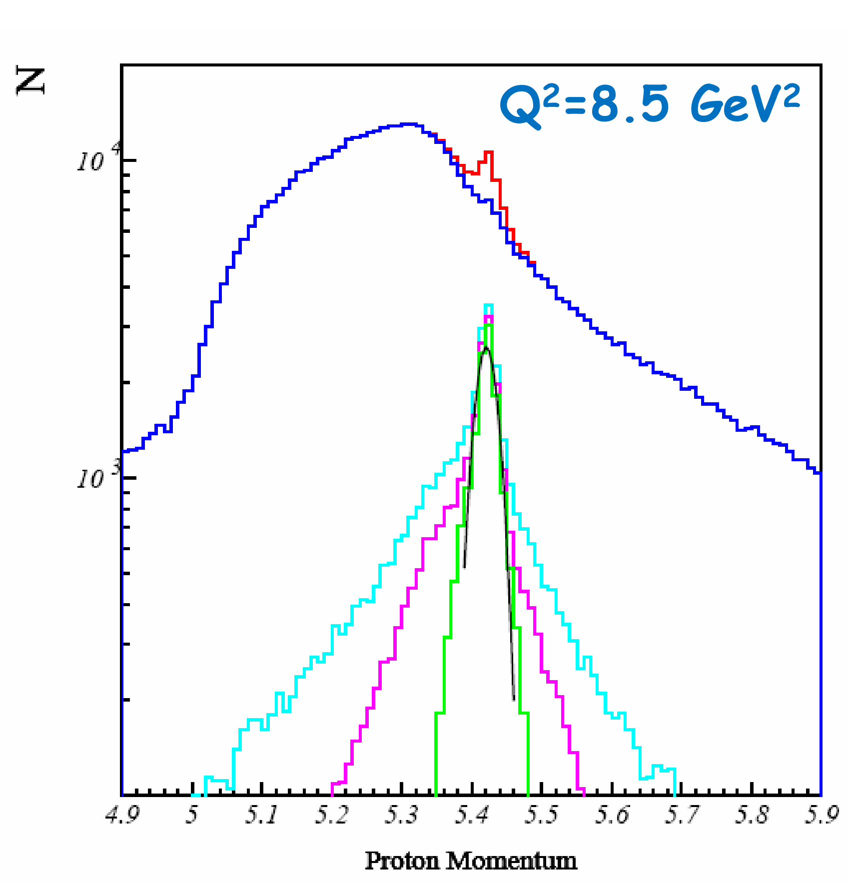
Proton Momentum Spectrum



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)

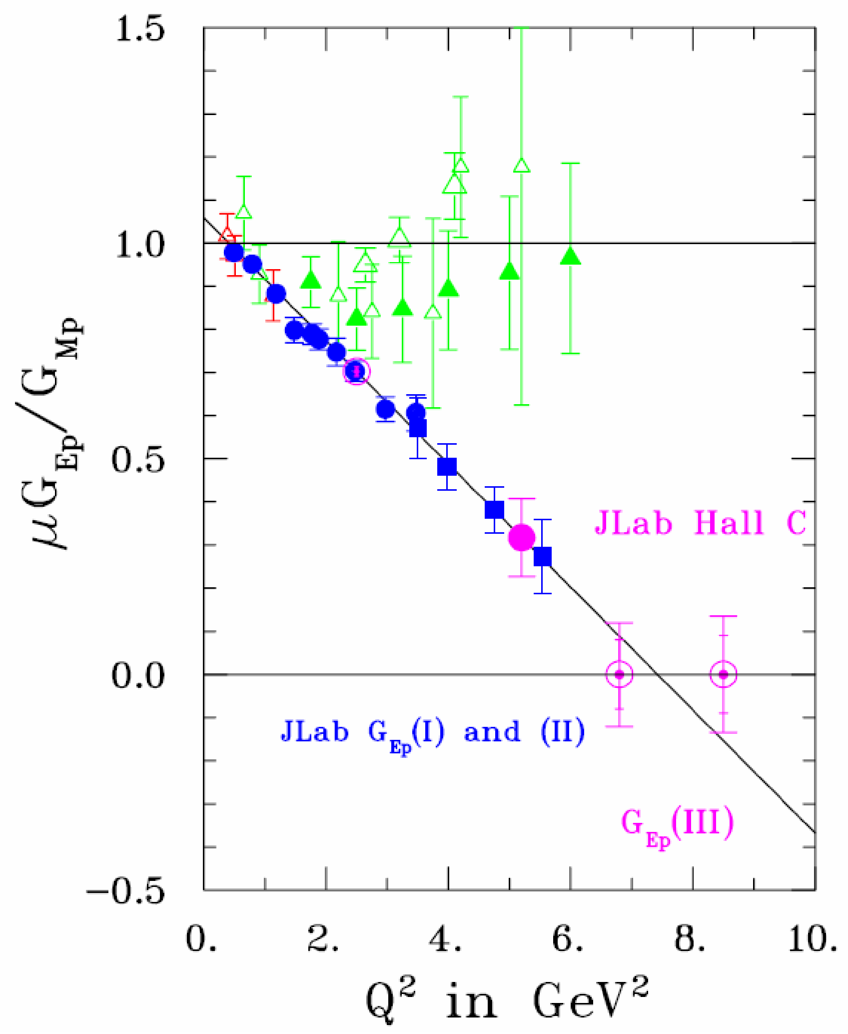
New equipment worked beautifully: BigCal and FPP

8.54 GeV² point: 1.63 billion triggers collected

Analyzing power at 5.4 GeV/c close to Dubna value

6.8 GeV² point: 160 million triggers

5.2 GeV² point: a test of the spin transport at X=180°



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.

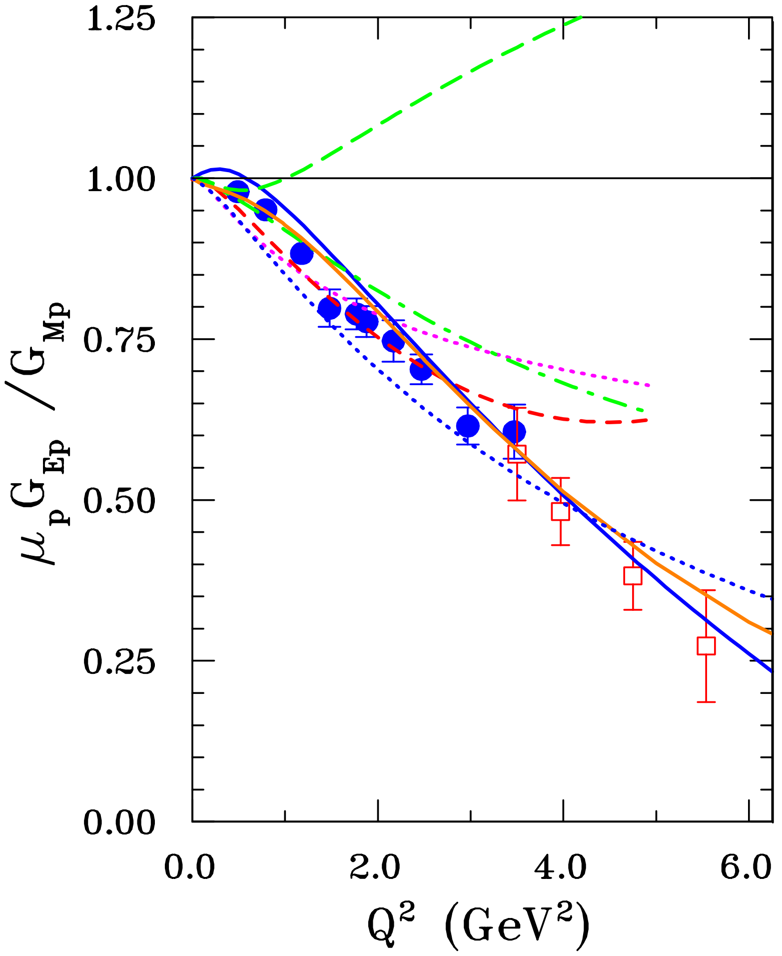
Early work of Höhler (76): ρ(770),
ω(782),Φ(1020) and effective ρ'(1250)

Gary and Krumpelman (85) asympt. pQCD

Mergell, Meissner and Drechsel (96)

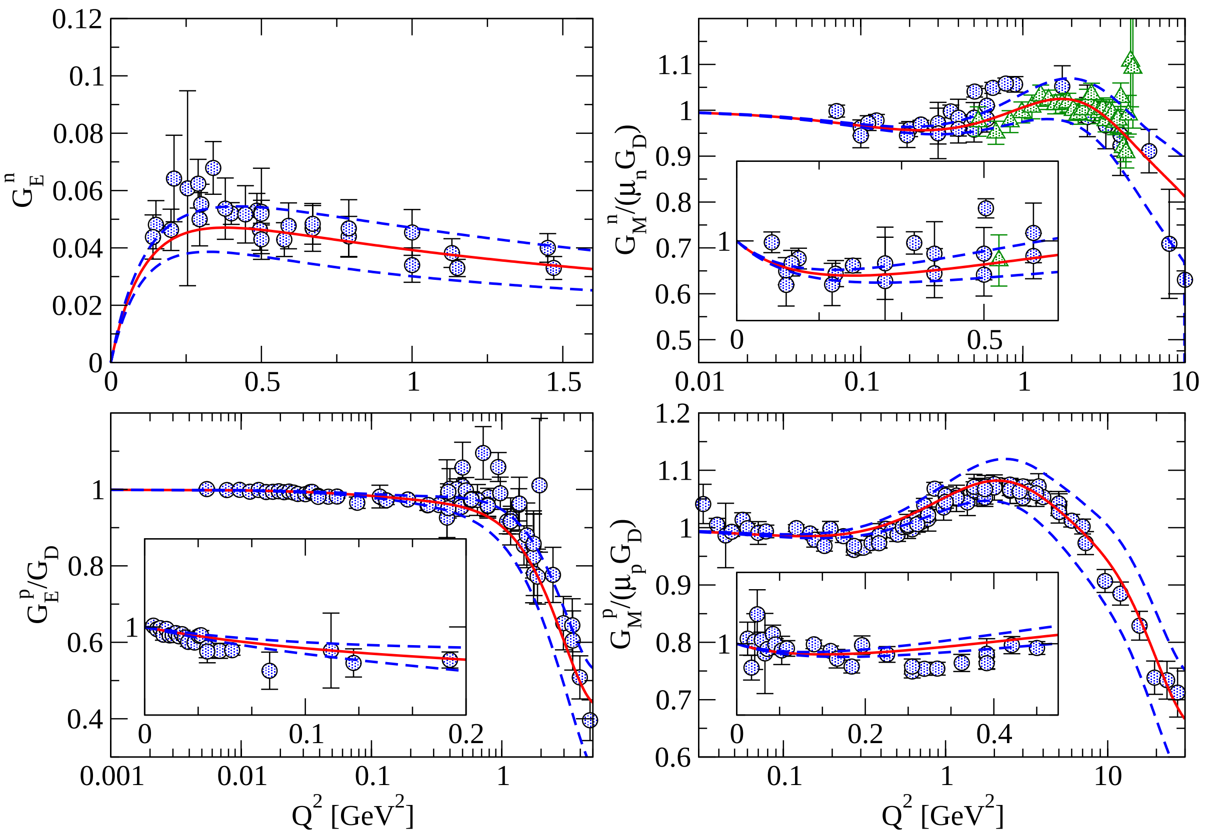
Lomon (01,02) used ρ(770),ω(782),Φ(1020)
and ρ'(1450), ω'(1419), 11 parameters.
Lomon (06) revised fit better for G_{En}.

Bijker and Iachello (02) ......



Continue VMD

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



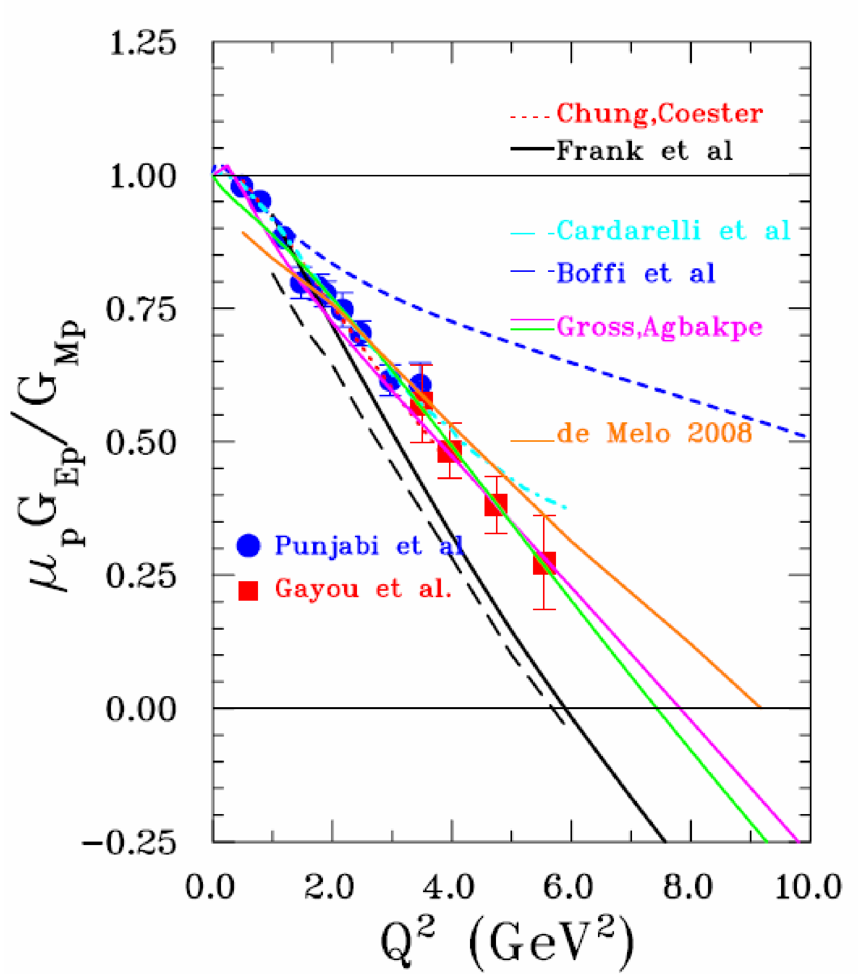
Constituent Quark Models

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

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

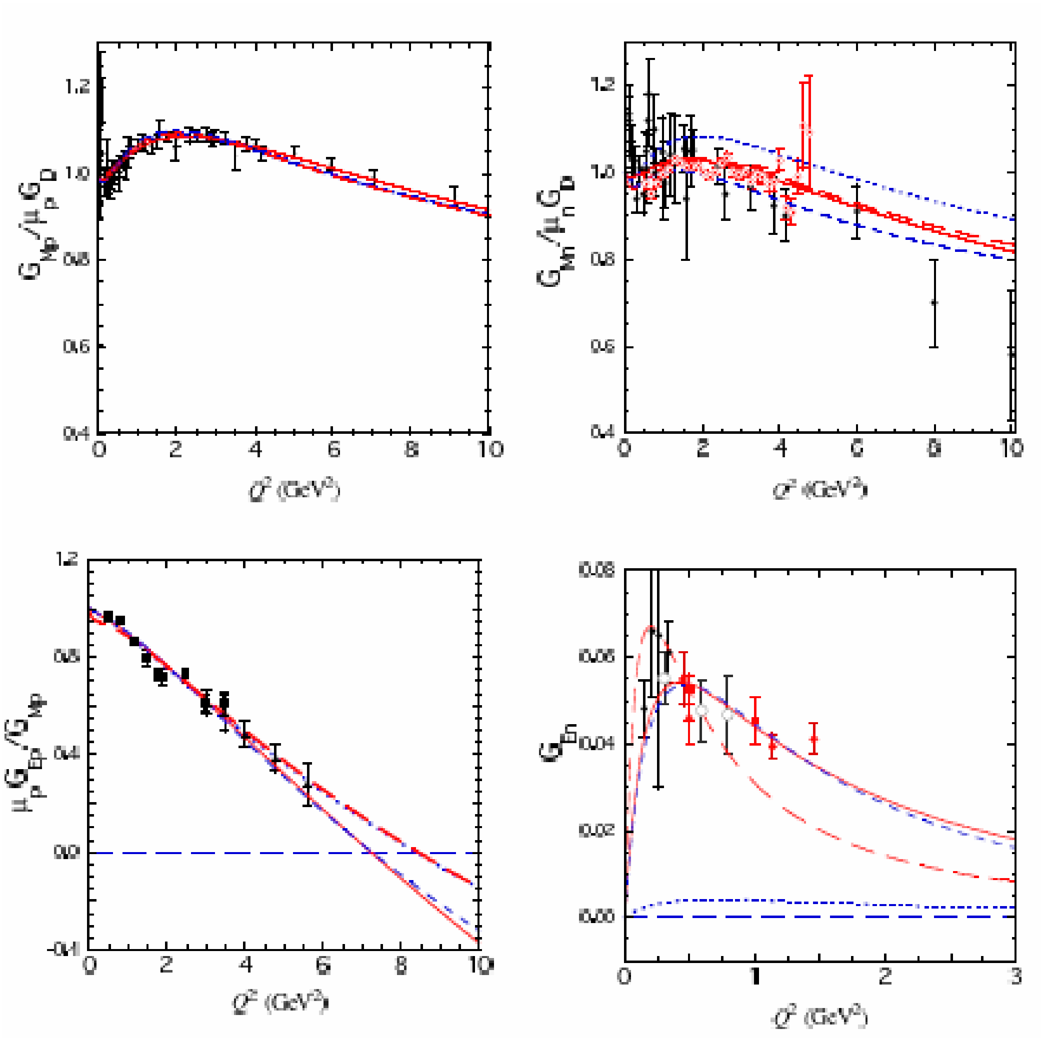
Non-relativistic treatment of quark dynamics, relativistic EM currents

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!

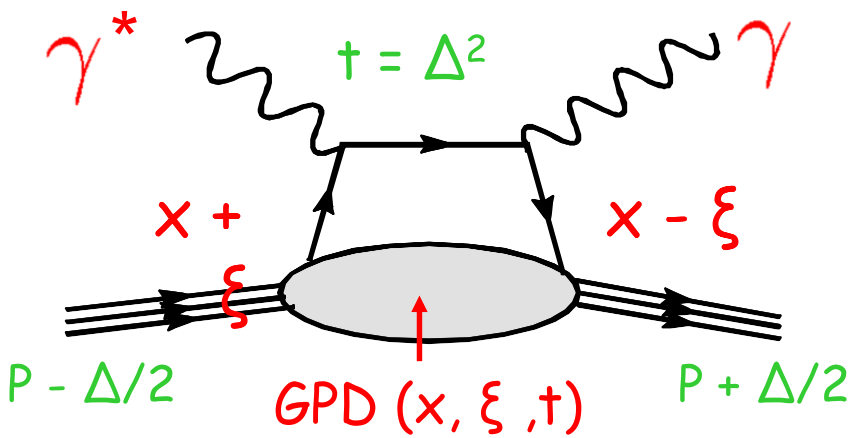
Argument of F. Gross and collaborator (Gross, Ramalho and Peňa, 2008), zero crossing is quite natural, unlike the defunct "scaling" behavior.

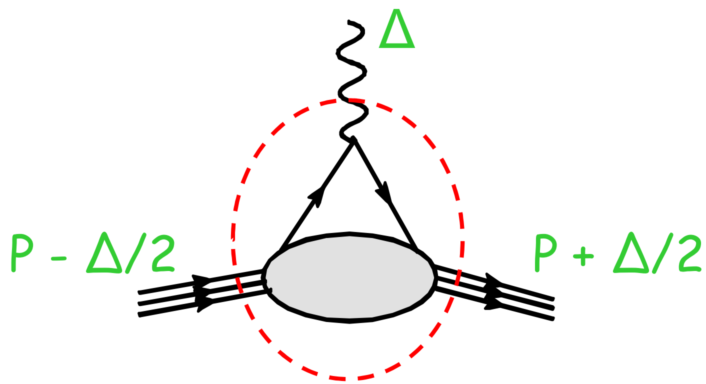
Simple argument: as long as F_{1p} and F_{2p} are positive, and Q^2F_{2p}/F_{1p} behavior supports that, $G_{Ep}=F_{1p}-\tau F_{2p}$ must become negative somewhere!

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!

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

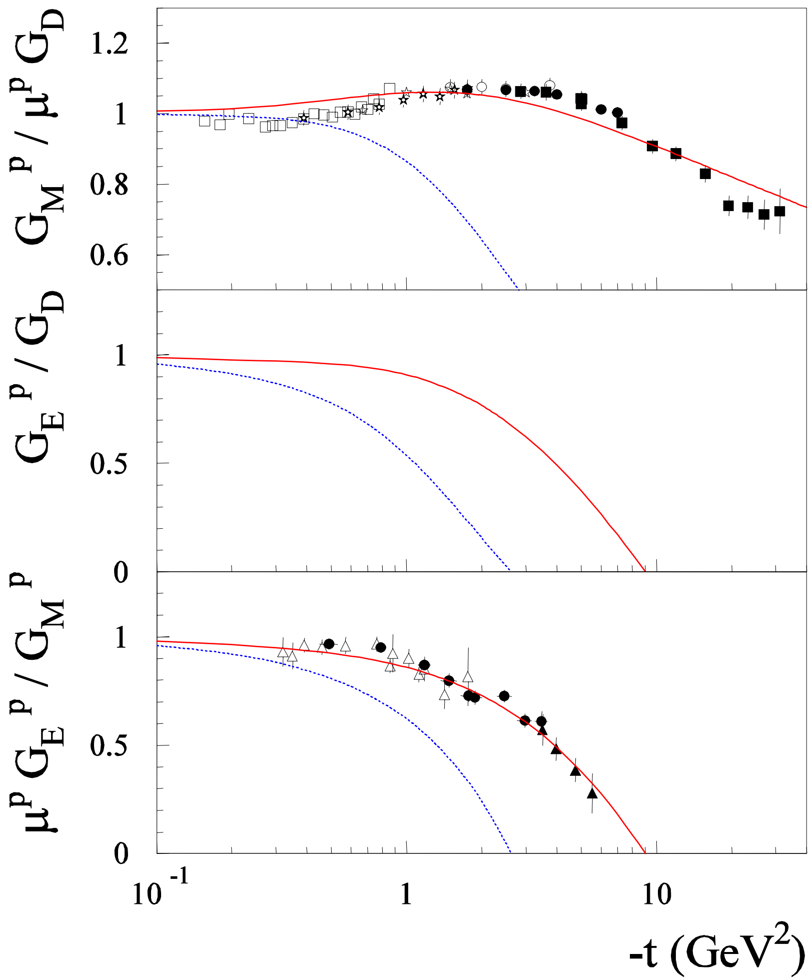
First moments are electroweak form factors: F_1^q, F_2^q, G_A^q and G_P^q; for example:

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

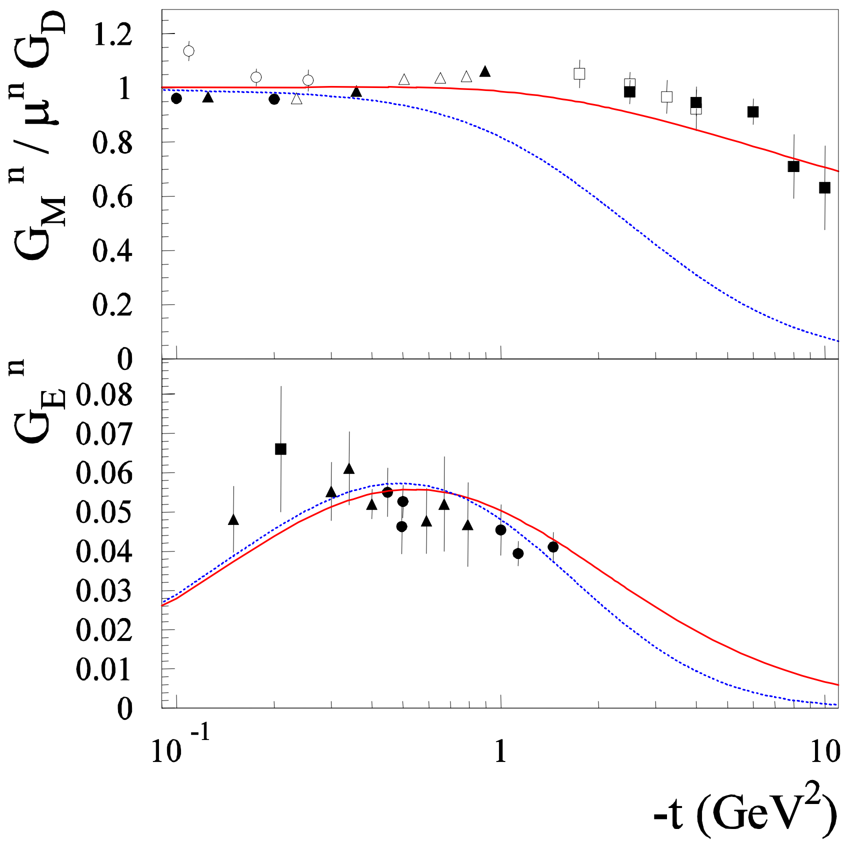
$$\int_{-1}^{1} dx\, E^q(x, \xi, t) = F_2^q(t) \quad \textit{Pauli}$$

Nucleon GPD Parametrizations

PROTON



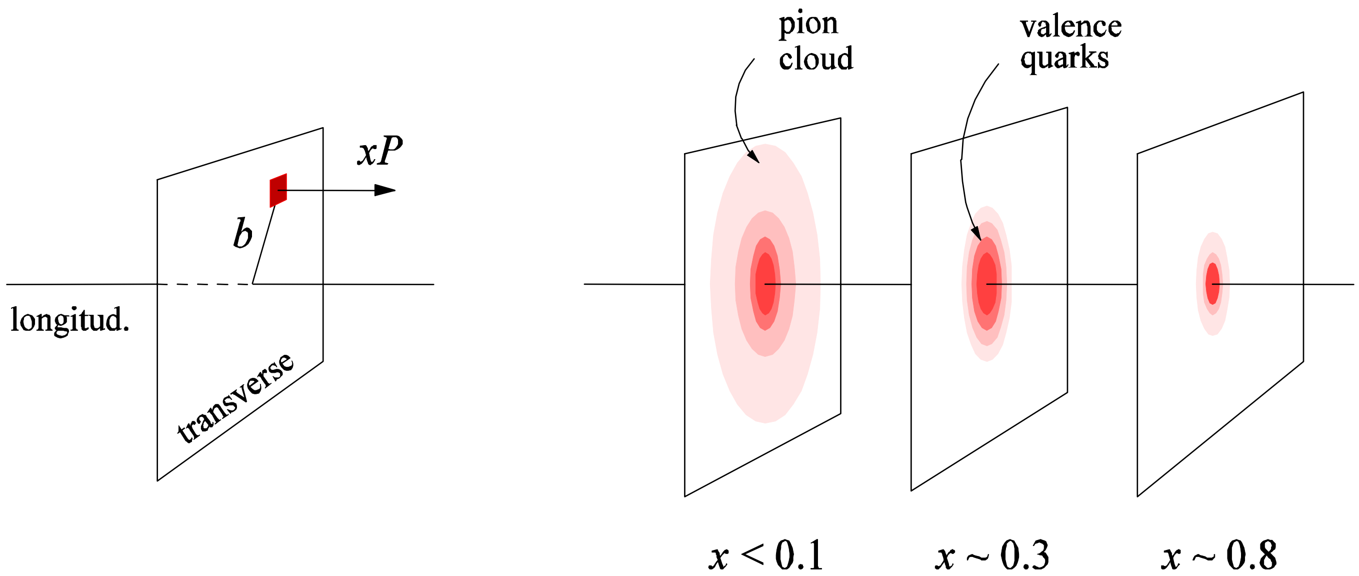
NEUTRON



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

→ Regge parametrization (Used to estimate the quark contribution to the spin)

GPDs : 3D quark/gluon imaging of nucleon

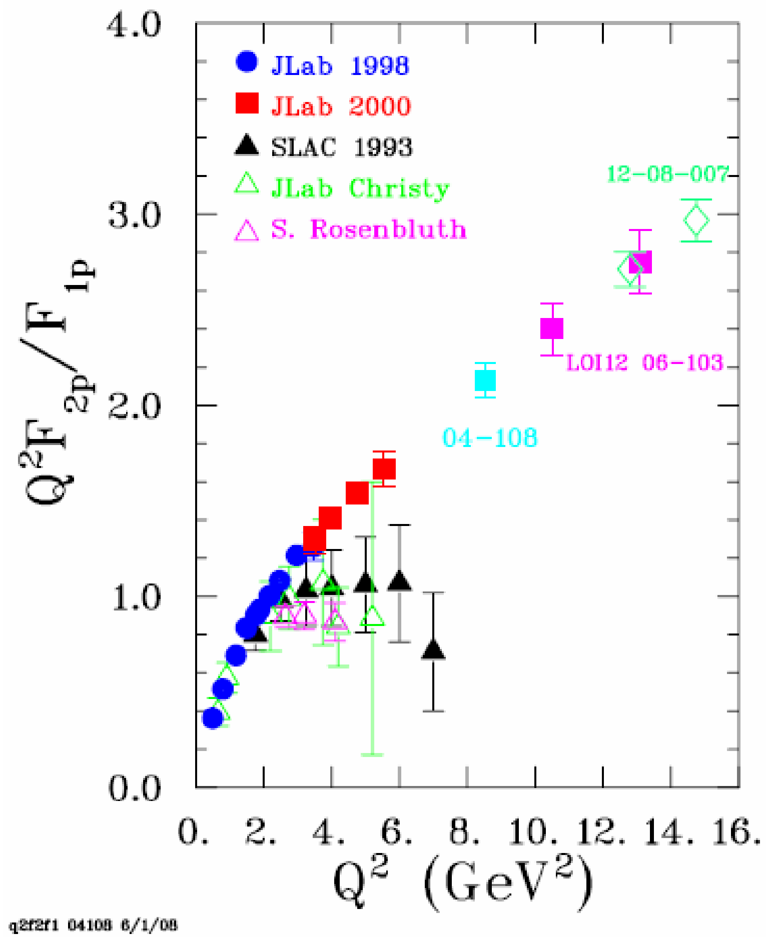


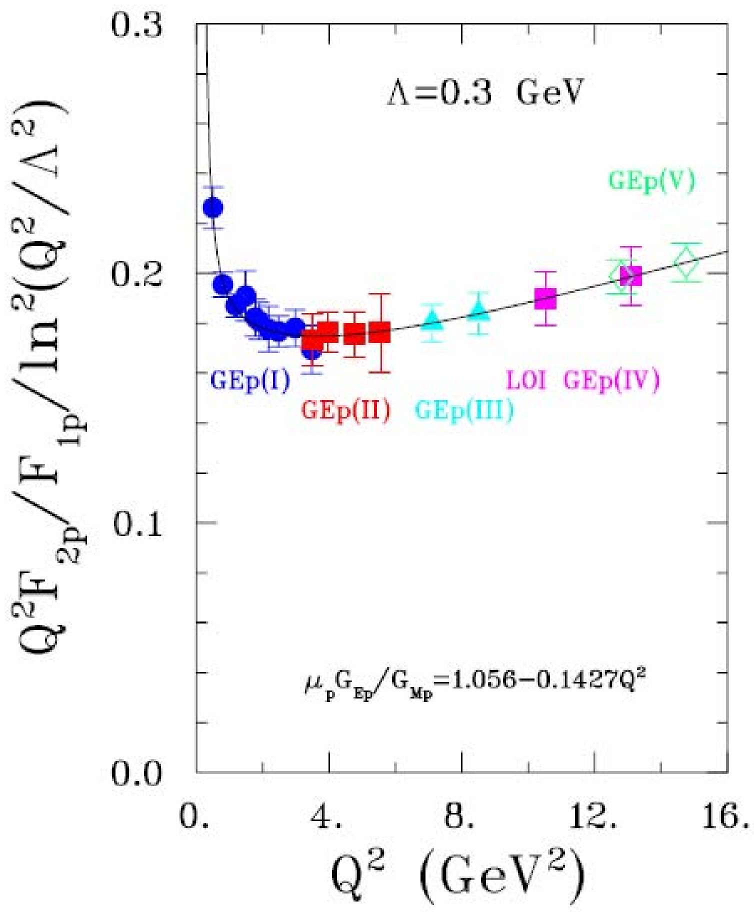
Fourier transform of t-dependence of GPDs, possible to access the spatial distributions of partons in the transverse plane, providing 3 dimensional picture of the nucleon :

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

⇨ theoretical parametrization needed

Proton: F2 /F1 and pQCD



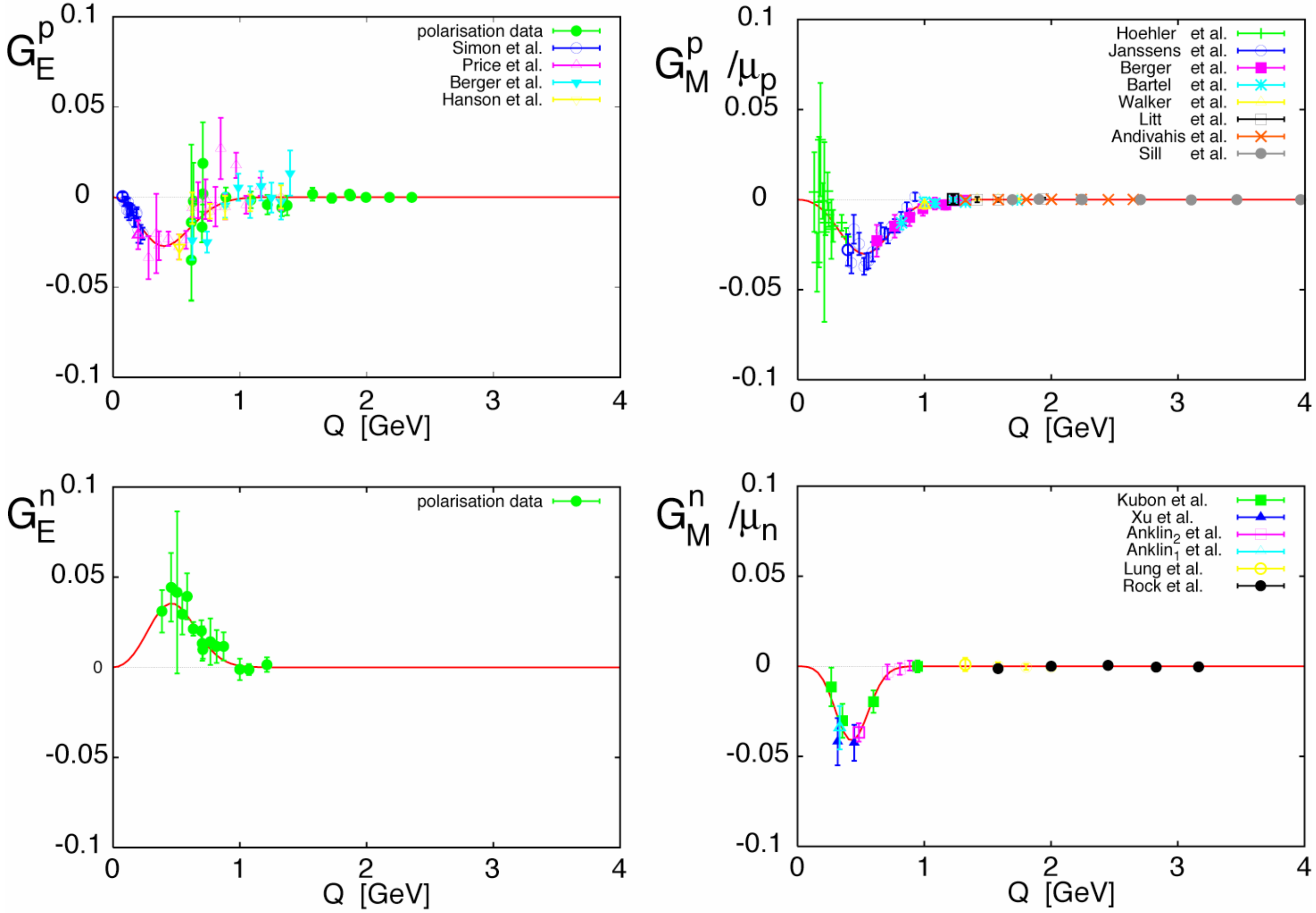


Brodsky and Farrar (75):
$Q^2F_2/F_1 \rightarrow$ **constant**

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

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 $Q^2 \approx 0.2\ GeV^2$

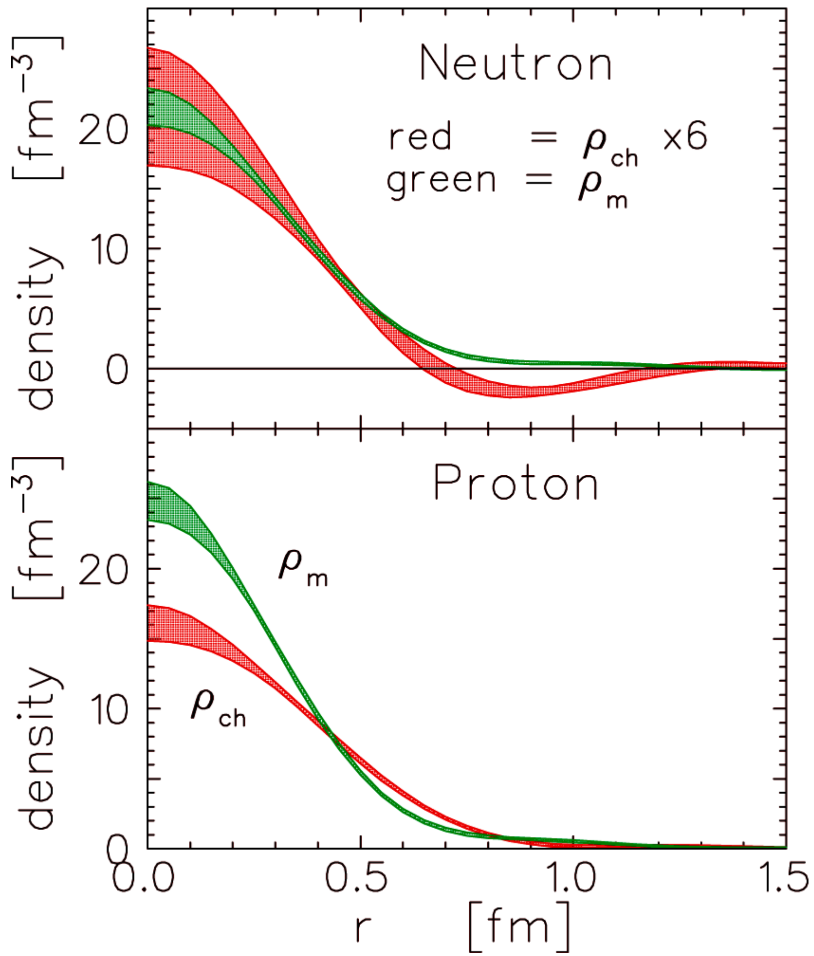
Charge density and Pion cloud

- 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

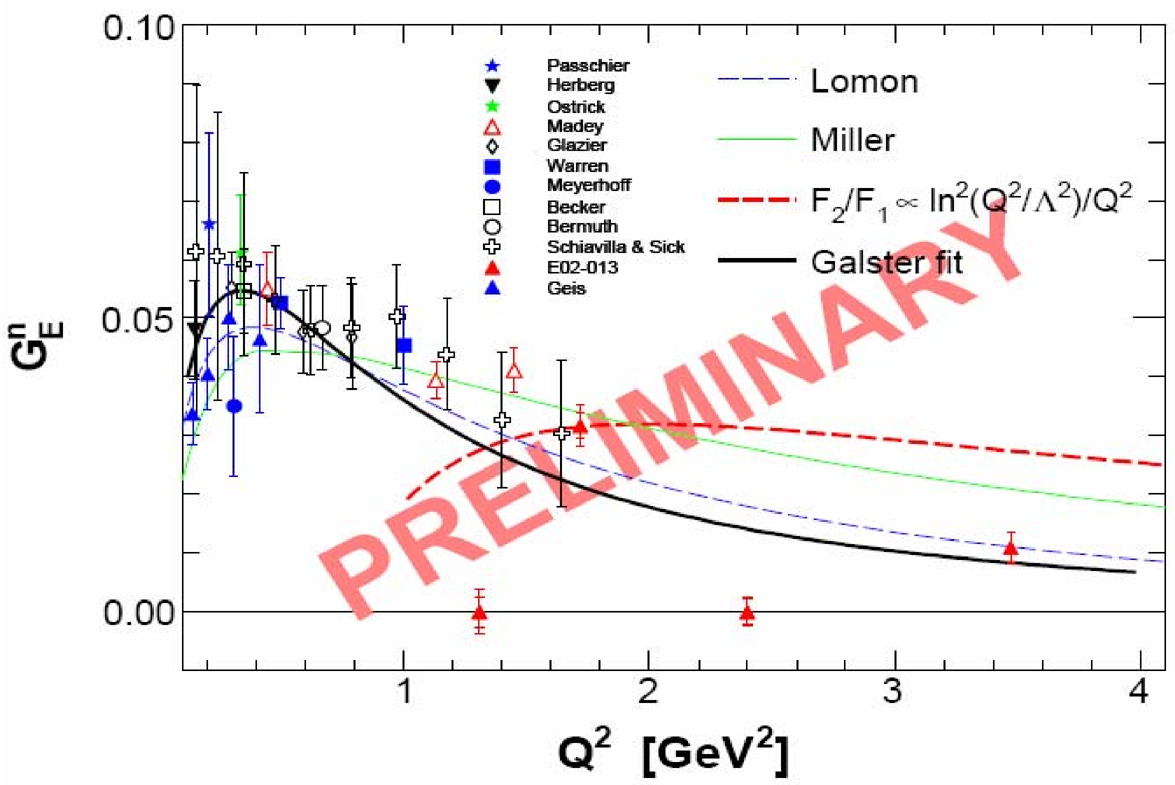
$$\tilde{G}_{E,M}(k) = G_{E,M}(Q^2)(1+\tau)^2 \quad \text{with } k^2 = \frac{Q^2}{1+\tau} \quad \text{and} \quad \tau = \left(\frac{Q}{2M}\right)^2$$

- 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



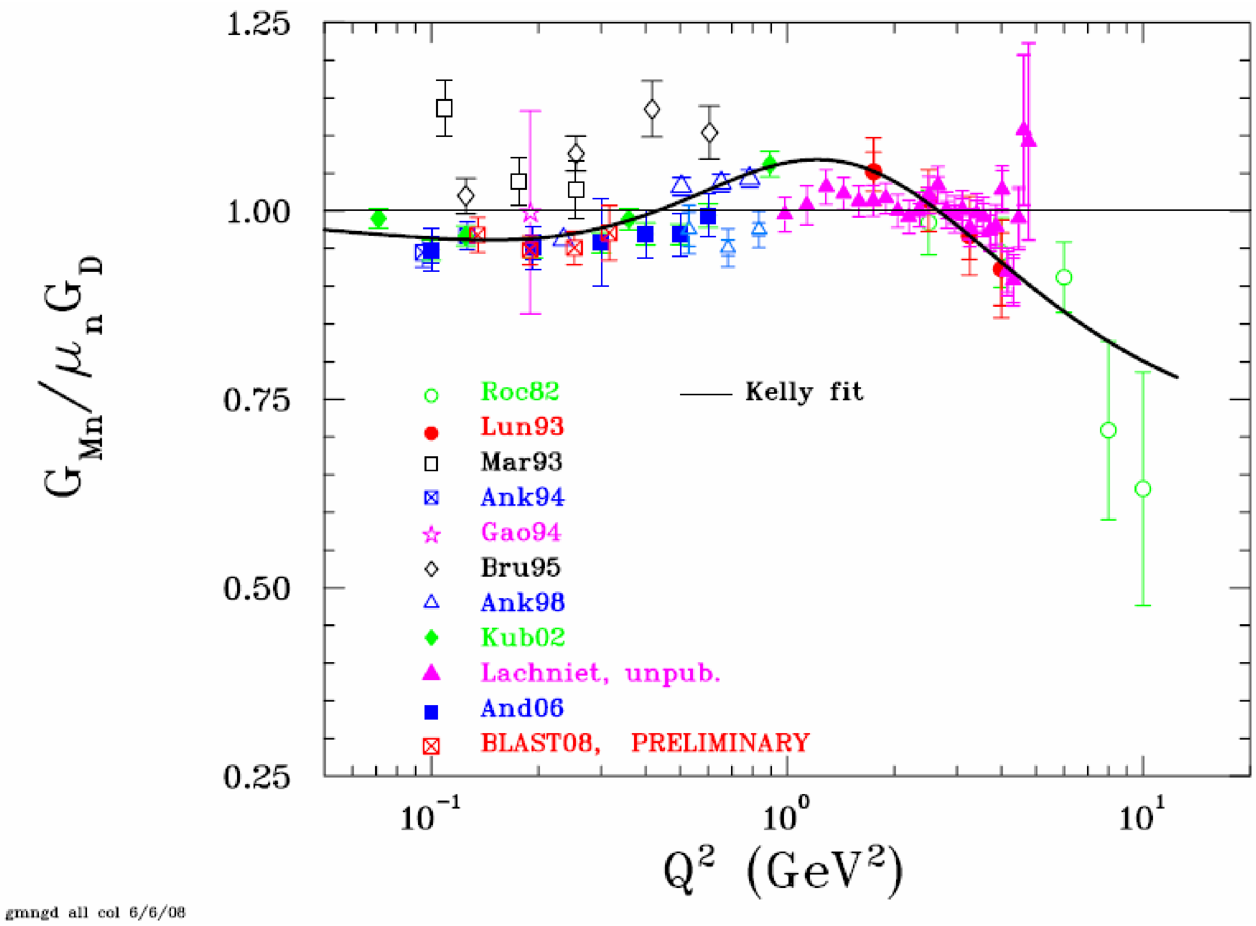
Electric Form Factor of the Neutron



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

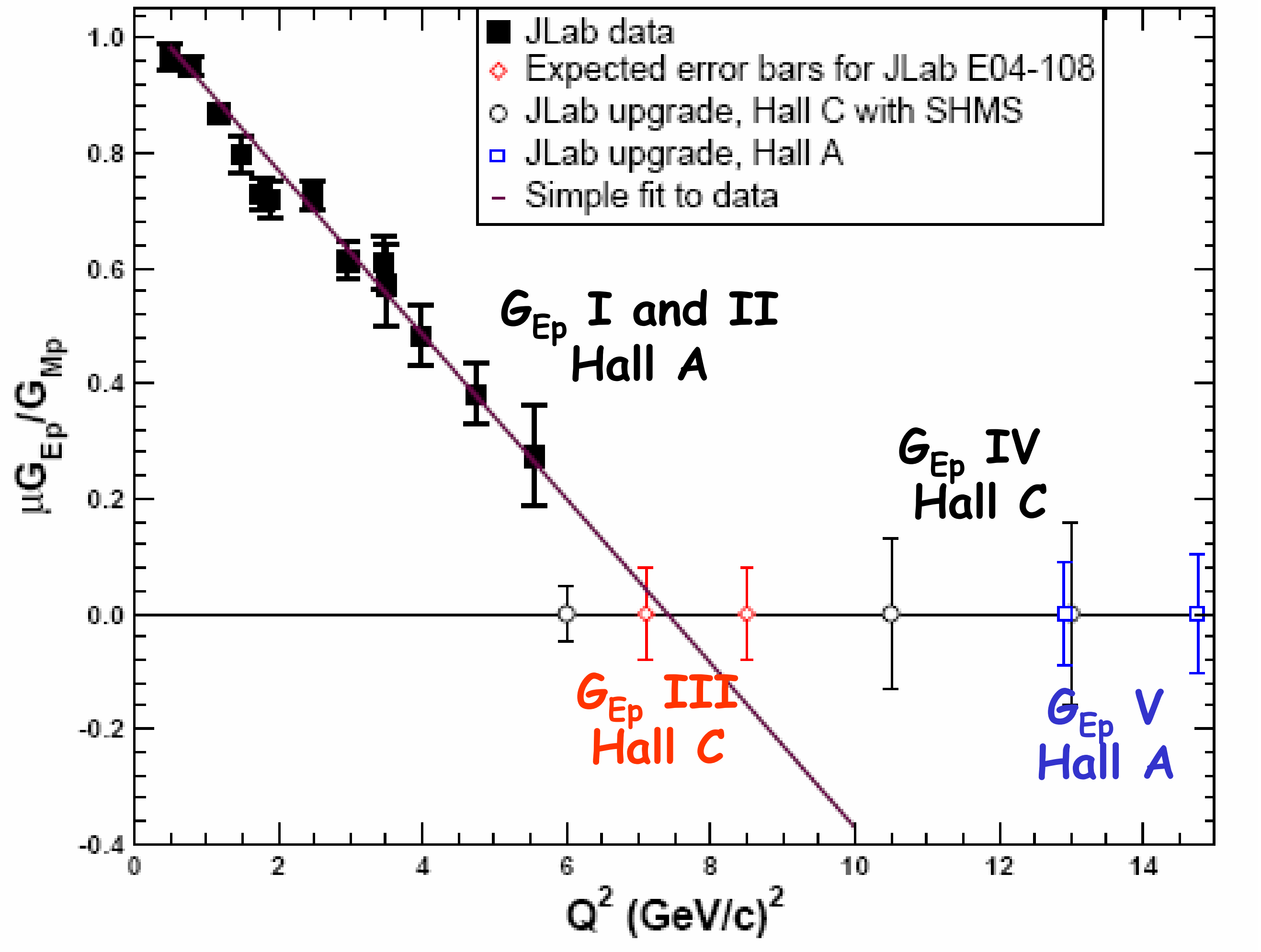
Two of the Hall A preliminary data shown (02-013), anticipated error for two more (5/2008)

Magnetic Form Factor of the Neutron

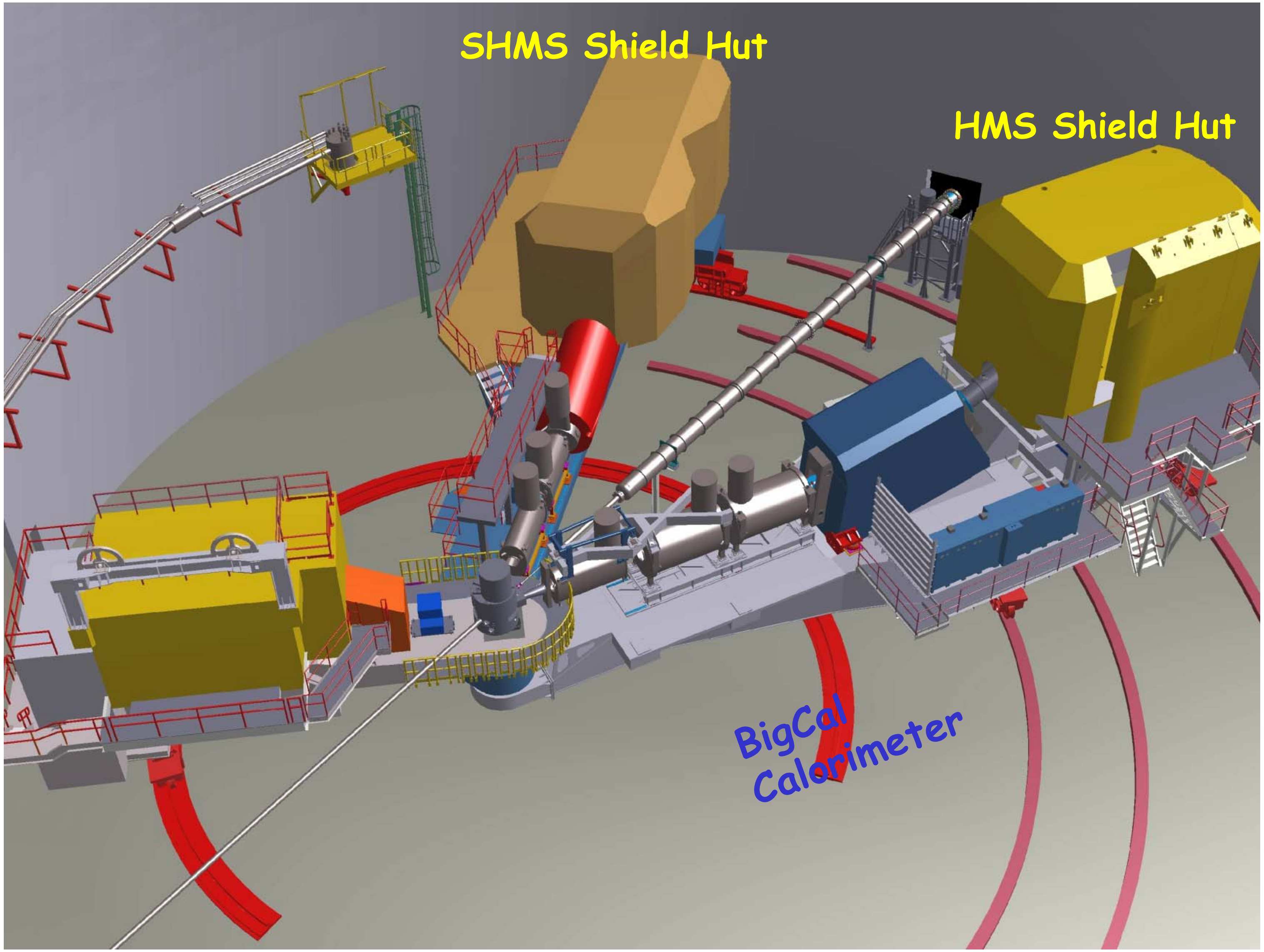


Preliminary Bates/BLAST results $\vec{d}(\vec{e},e')$, Meitanis et al

G_{Ep}/G_{Mp} with 12 GeV at JLab

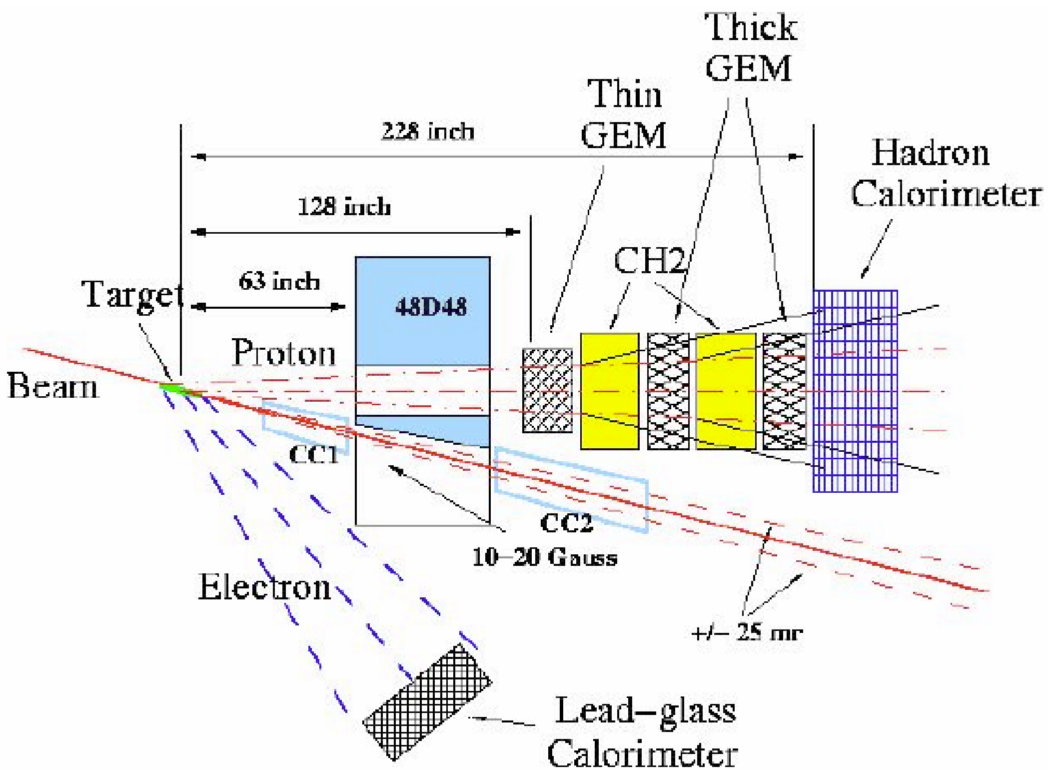


Measuring G_{Ep}/G_{Mp} in Hall C at 12 GeV



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 use in trigger



Conclusions

Discrepancy between Rosenbluth and polarization transfer well established, not an experimental problem, caused by TPE effects or incomplete radiative corrections (next talk by Prof. Perdrisat).

G_{Ep}(III) experiment very successfully took data at Q^2 of 5.2, 6.8 and 8.45 GeV^2. Initial analysis of the data shows strikingly good agreement with the Hall A polarization data.

Many new model calculations inspired by our experimental results: VMD models give good parametrization of FF at low to intermediate Q^2. All constituent quark models predict decreasing ratio with increasing Q^2 but relativistic treatment necessary.

GPDs describe hadrons in terms of quarks and gluons: combine features of FFs and parton densities and distribution amplitudes; elastic FF provide powerful constraint on parameterizations of GPDS; used to estimate quark orbital angular momentum and quark contribution to the spin.

Older pQCD prediction that asymptotically Q^2F_2 /F_1 becomes constant not seen. New pQCD, include logarithmic corrections in pQCD limit; Brodsky argues that F_2 must contain logarithmic term from higher twist contribution

G_{Ep}/G_{Mp} measurements to Q^2 = 15 GeV2 with JLab at 12 GeV.

The END

Thank you for your Attention