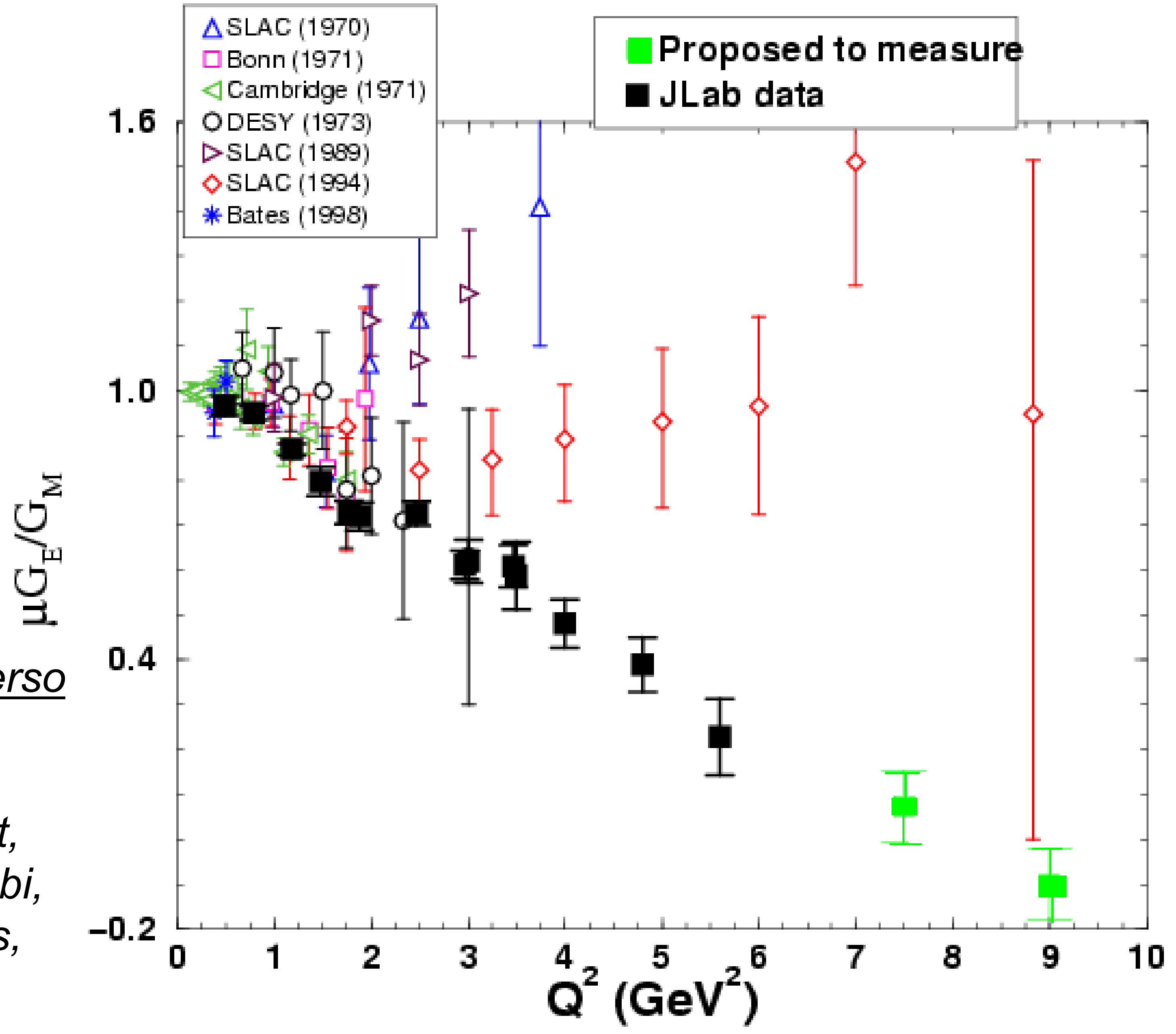
Recent developments in Electromagnetic Hadron Form Factors

Egle Tomasi-Gustafsson
DAPNIA/SPhN, Saclay

- *What* are Form Factors?
- *Why* to measure?
- *How* to measure?
- *What is new?*
- Consequences, Conclusions



Spokepersons:

Ch. Perdrisat, V. Punjabi, M. Jones, E. Brash

Hadron Electromagnetic Form factors

- Characterize the internal structure of a particle (≠ point-like)
- FFs are real in space-like region (scattering) and imaginary in time-like region (annihilation).
- Elastic form factors contain information on the hadron ground state.
- In a P- and T-invariant theory, the EM structure of a particle of spin S is defined by 2S+1 form factors.
- Neutron and proton form factors are different.
- Deuteron: 2 structure functions, but 3 form factors.
- Playground for theory and experiment.

MOTIVATIONS

- In the traditional view, the atom's nucleus appears as a cluster of nucleons - protons and neutrons. A deeper view reveals quarks and gluons inside the nucleons.

- CEBAF's continuous, energetic beams of probing electrons let physicists examine how the two view fit together. Ultimately, the process of bridging the views will yield a complete understanding of nuclear matter….

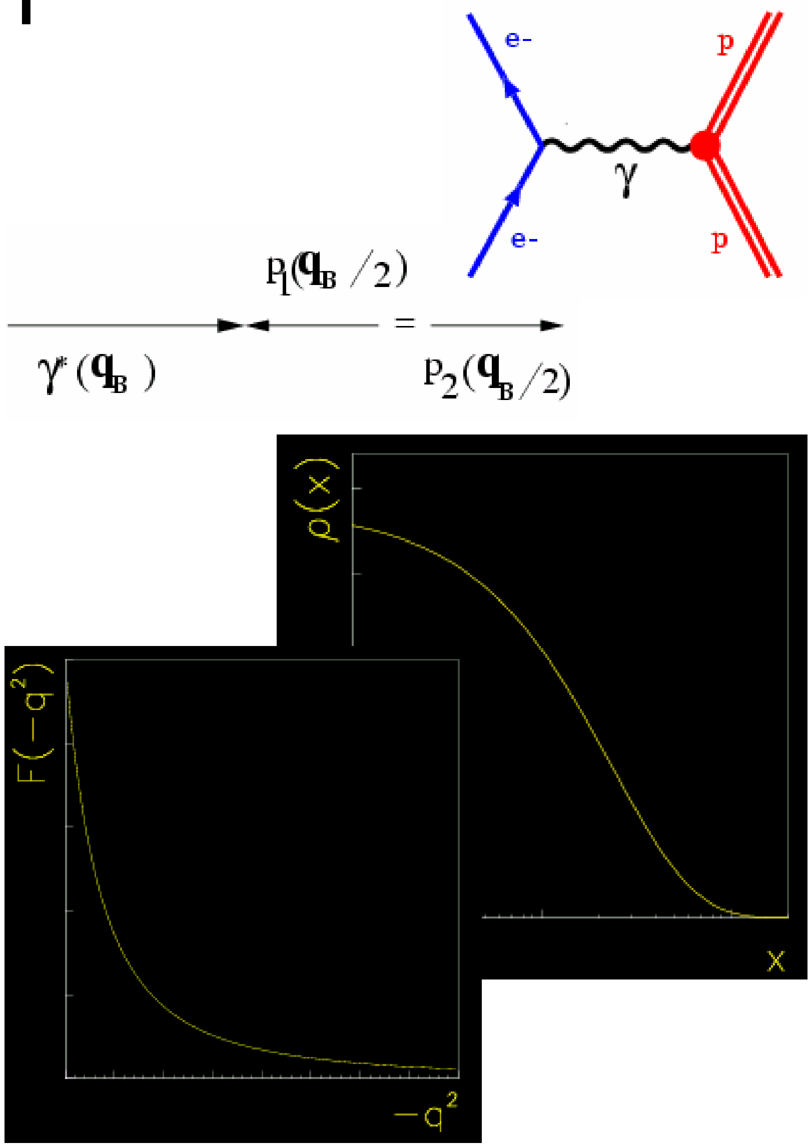
Istitutional plan (2000)

Jefferson Lab

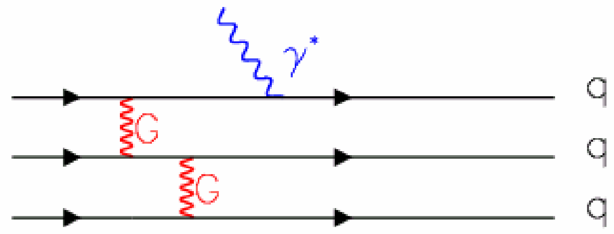
Dipole Approximation

$G_D=1/(1+Q^2/0.71\ \mathrm{GeV}^2)^2$

- Classical approach
  - Nucleon FF (in the Breit system) are Fourier transform of the charge or magnetic distribution.
- The dipole approximation corresponds to an exponential density distribution.
  - $\rho = \rho_0 \exp(-r/r_0)$,
  - $r_0^2= (0.24\ \mathrm{fm})^2$, $<r^2> \sim(0.81\ \mathrm{fm})^2$ $\leftrightarrow m^2_D = 0.71\ \mathrm{GeV}^2$

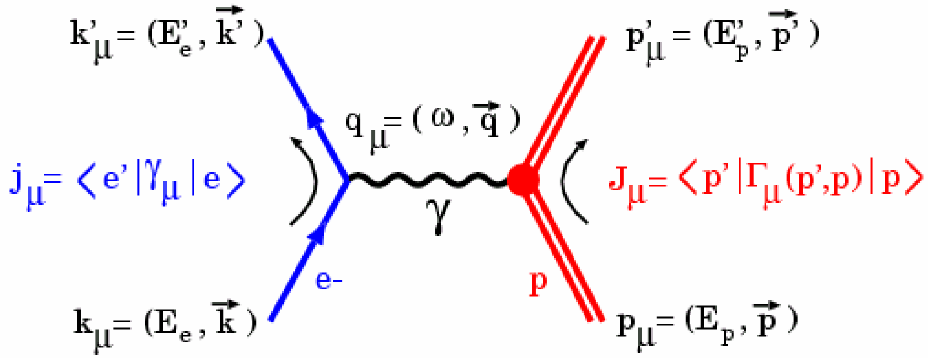


Dipole Approximation and pQCD



- Dimensional scaling
  - $F_n(Q^2) = C_n\, [1/(1+Q^2/m_n)^{n-1}]$,
    - $m_n = n\beta^2$, <quark momentum squared>
    - n is the number of constituent quarks
  - Setting $\beta^2 = (0.471 \pm .010)$ GeV *(fitting pion data)*
    - pion: $F_\pi(Q^2) = C_\pi\, [1/(1+Q^2/0.471\ \mathrm{GeV}^2)^1]$,
    - nucleon: $F_N(Q^2) = C_N\, [1/(1+Q^2/0.71\ \mathrm{GeV}^2)^2]$,
    - deuteron: $F_d(Q^2) = C_d\, [1/(1+Q^2/1.41\,\mathrm{GeV}^2)^5]$

The Pauli and Dirac Form Factors



- The electromagnetic current in terms of the Pauli and Dirac FFs:

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

- Normalization:
  $F_{1p}(0)=1$, $F_{2p}(0)=\kappa_p$

- Related to the Sachs FFs :

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

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

- Normalization:
  $G_{Ep}(0)=1$, $G_{Mp}(0)=\mu_p=2.79$

Proton Form Factors

The Nobel Prize in Physics 1961

"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the stucture of the nucleons"

Robert Hofstadter

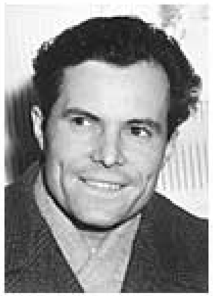
1/2 of the prize

USA

Stanford University
Stanford, CA, USA

b. 1915
d. 1990

"for his researches concerning the resonance absorption of gamma radiation and his discovery in this connection of the effect which bears his name"



Rudolf Ludwig Mössbauer

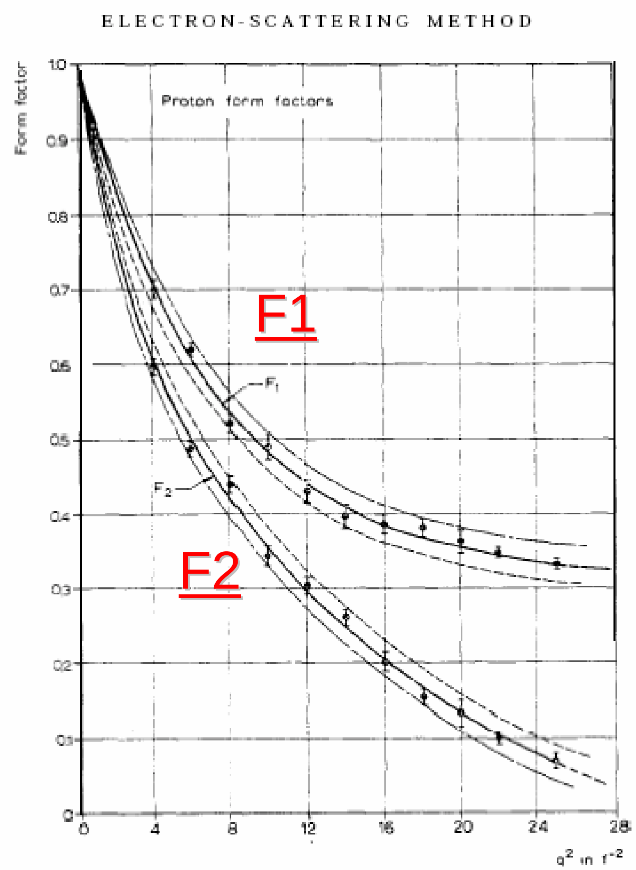
1/2 of the prize

Federal Republic of Germany

Technical University
Munich, Federal Republic of Germany; California Institute of Technology
Pasadena, CA, USA

b. 1929

Over a period of time lasting at least 2000 years, Man has puzzled over and sought an understanding of the composition of matter…

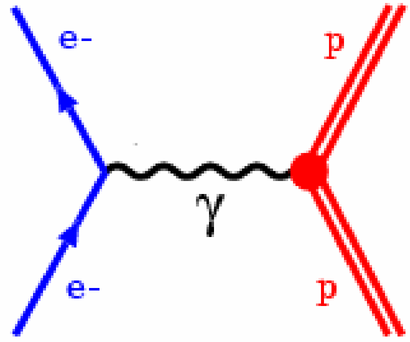


Q^2=1 GeV^2

The Rosenbluth separation

- Elastic ***ep*** cross section (1-γ exchange)

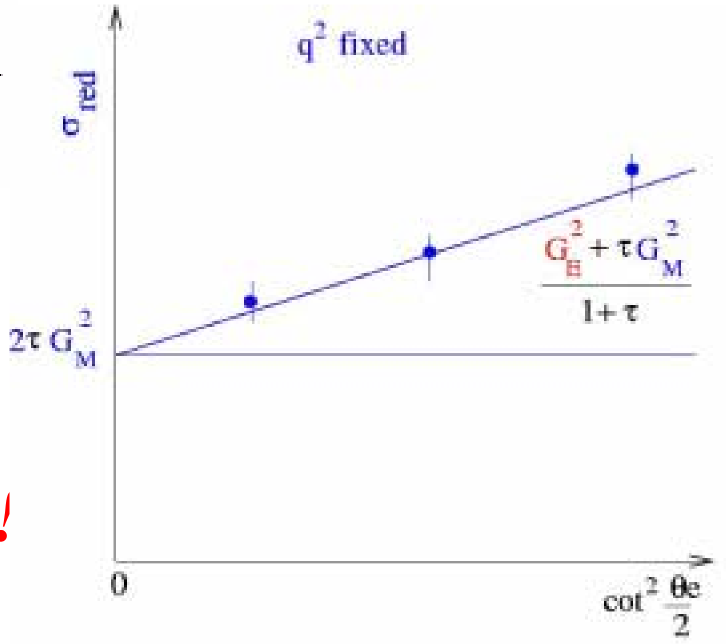
$$\frac{d\sigma}{d\Omega_e} = \sigma_M \left[2\tau G_M^2 \tan^2\frac{\theta_e}{2} + \frac{G_E^2 + \tau G_M^2}{1+\tau} \right]$$



- point-like particle: σ Mott

$$\sigma_M = \frac{4\alpha^2}{(-q^2)^2}\frac{\epsilon_2^3}{\epsilon_1}\cos^2\frac{\theta_e}{2} = \frac{4\alpha^2}{(-q^2)^2}\frac{\epsilon_2^2\cos^2\frac{\theta_e}{2}}{1+2\frac{\epsilon_1}{m}\sin^2\frac{\theta_e}{2}},\ \tau = \frac{Q^2}{4m^2}$$

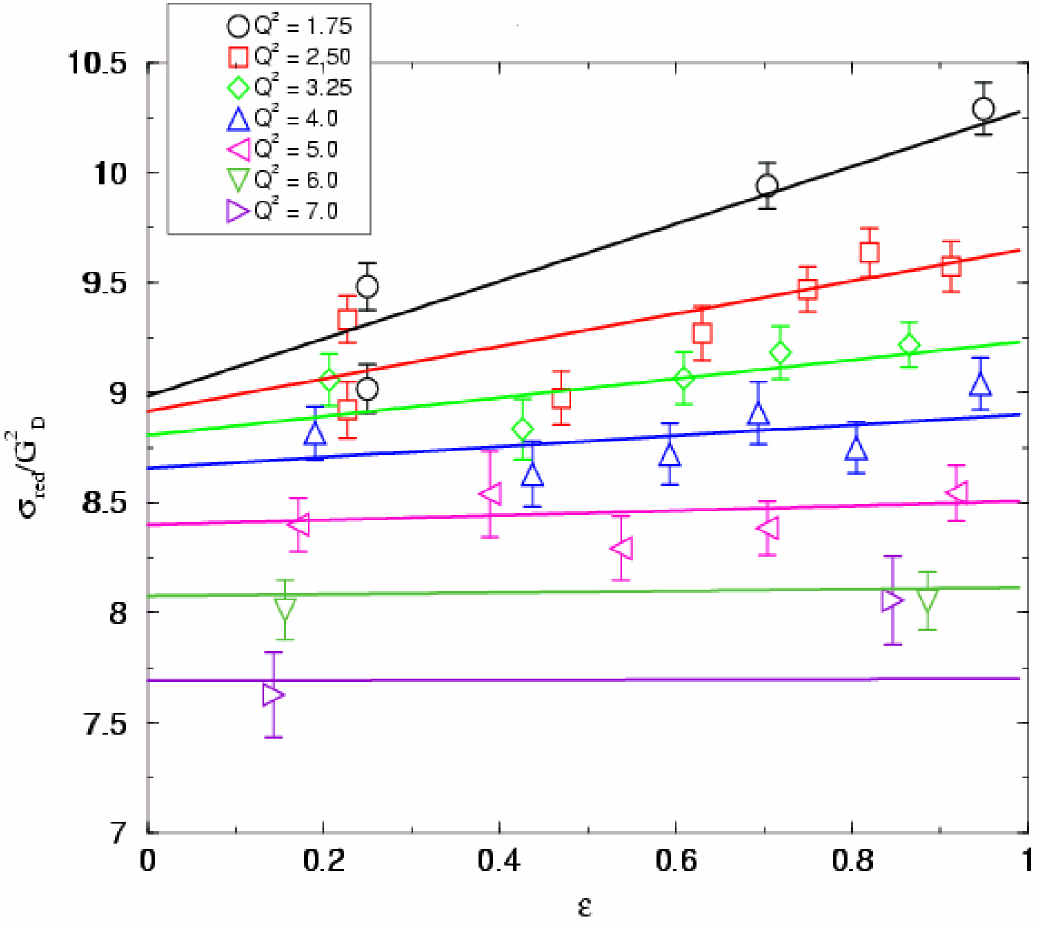
$$\sigma_{red} = \frac{\frac{d\sigma}{d\Omega_e}}{\frac{\alpha^2}{-q^2}\left(\frac{\epsilon_2}{\epsilon_1}\right)^2}$$



*Linearity of the **reduced cross section!***

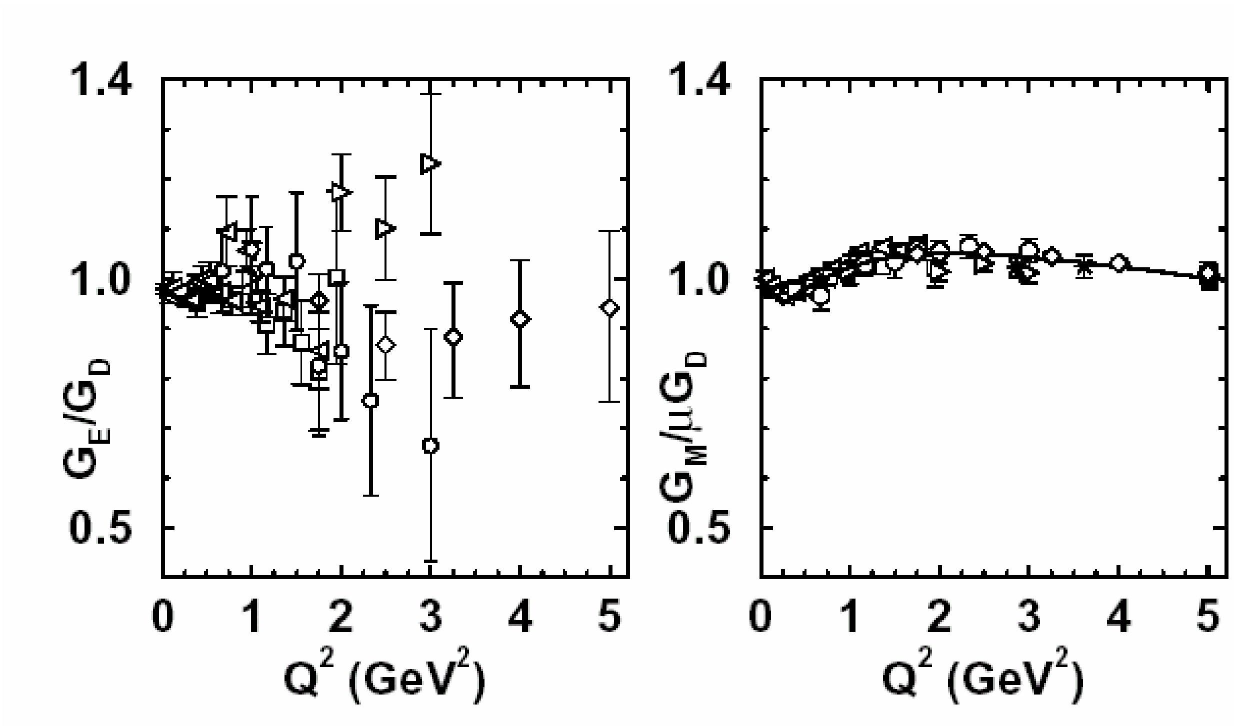
The Rosenbluth data (SLAC)

$$\sigma_{red} = \frac{d\sigma}{d\Omega}\frac{(1+\tau)\epsilon}{\tau\sigma_{Mott}} = G_M^2(1 + \frac{\epsilon}{\tau}\frac{G_E^2}{G_M^2})$$

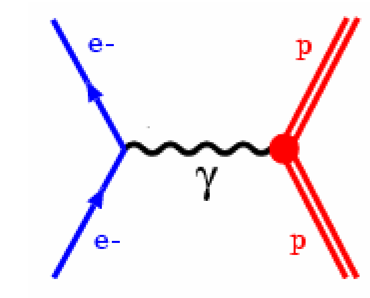


L. Andivahis et al. Phys. Rev. D 50, 5491 (1994)

Proton Form Factors ...before



One photon-exchange



L. Andivahis et al. Phys. Rev. D 50, 5491 (1994)

Dipole approximation:
$G_D=1/(1+Q^2/0.71\ \mathrm{GeV}^2)^{2}$

Rosenbluth separation/ Polarization observables

The polarization method (1968)

SOVIET PHYSICS – DOKLADY VOL. 13, NO. 6 DECEMBER, 1968

PHYSICS

POLARIZATION PHENOMENA IN ELECTRON SCATTERING BY PROTONS IN THE HIGH-ENERGY REGION

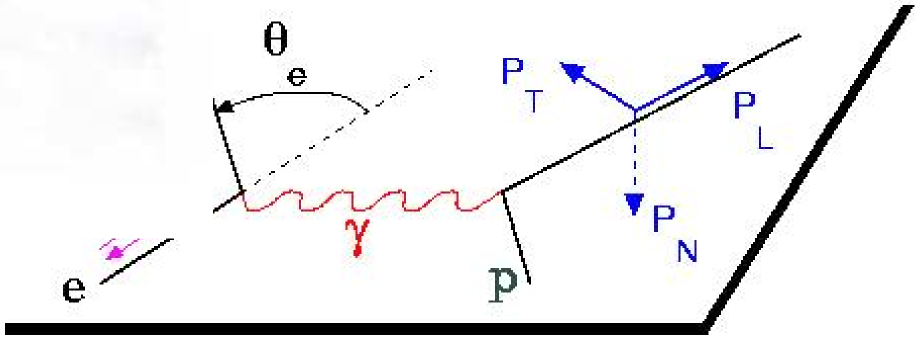
Academician A. I. Akhiezer* and M. P. Rekalo

Physicotechnical Institute, Academy of Sciences of the Ukrainian SSR

Translated from Doklady Akademii Nauk SSSR, Vol. 180, No. 5, pp. 1081–1083, June, 1968

Original article submitted February 28, 1967

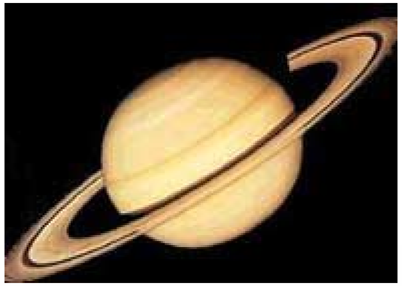
$$s_2 \frac{d\sigma}{d\Omega_R} = 4p_2 \frac{(s \cdot q)}{1+\tau} \Gamma(\theta, \varepsilon_1) \left[\tau G_M (G_M + G_E) - \frac{1}{4\varepsilon_1} G_M (G_E - \tau G_M) \right],$$



The polarization induces a term in the cross section proportional to $G_E G_M$

Polarized beam and target or polarized beam and recoil proton polarization

Proton polarimeter



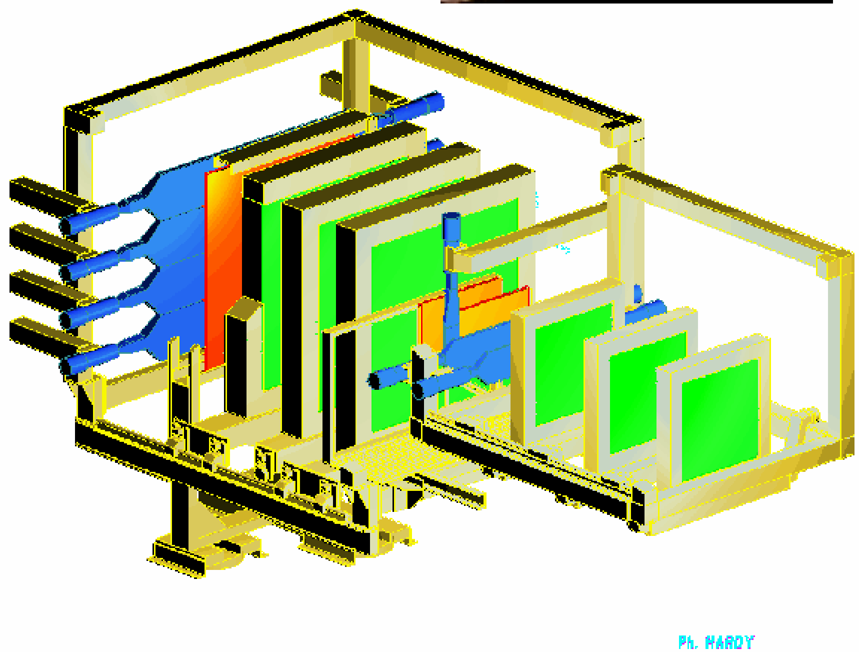
Inclusive reaction p+C → 1 Charged particle+X

•Analyzing powers:

$$N^{\pm}(\theta,\phi) = N_0(\theta)(1 \pm P_y A_y(\theta)\cos\phi),$$

$$R(\theta,\phi) = \frac{N^{+}(\theta,\phi) - N^{-}(\theta,\phi)}{N^{+}(\theta,\phi) + N^{-}(\theta,\phi)} = a_1(\theta)\cos\phi$$

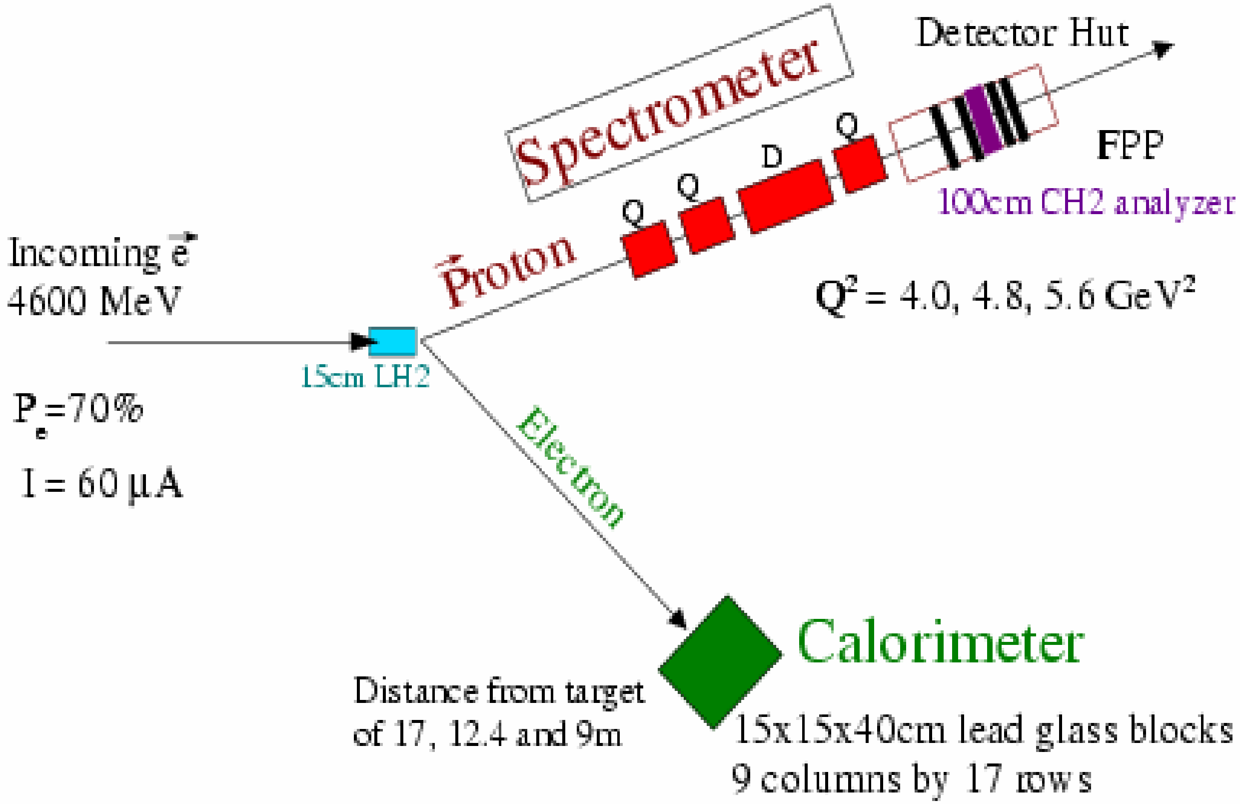
$$A_y(\theta) = \frac{a_1(\theta)}{P_y}, \quad \Delta A_y \simeq \frac{1}{P_y}\sqrt{\frac{1}{N_{Incident}}}.$$



•Figure of merit, efficiency, uncertainties:

$$F = \epsilon A_y^2, \quad \epsilon = \frac{N_{useful}}{N_{Incident}}, \quad \Delta P = \sqrt{\frac{2}{N_{Incident} F}}$$

The experimental set-up(JLab-E99007)



-Trigger on proton: background, target walls and pion electroproduction

-The solid angle is defined by the proton

The polarization method (exp)

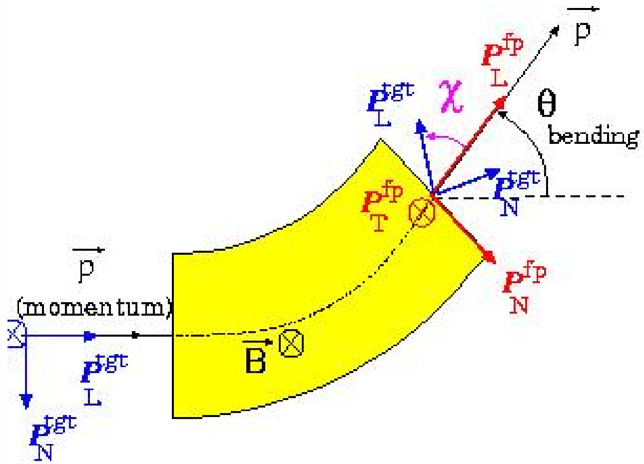
Transferred polarization is:

(Akhiezer & Rekalo and Arnold, Carlson & Gross):

$$P_n = 0$$

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

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



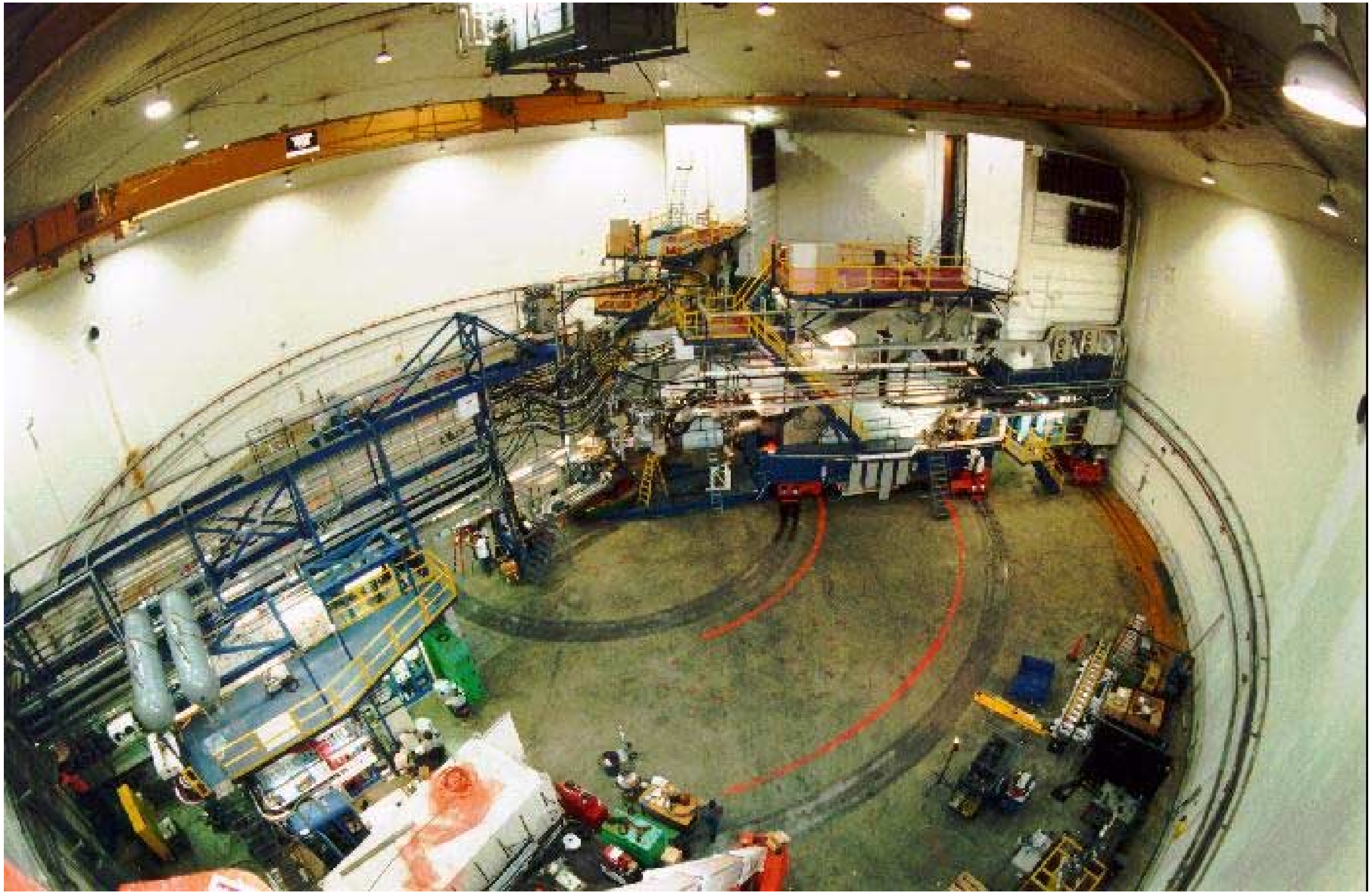
Where, $h = |h|$ is the beam helicity

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

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

The simultaneous measurement of P_t and P_l reduces the systematic errors !!

The HALL A at JLAB

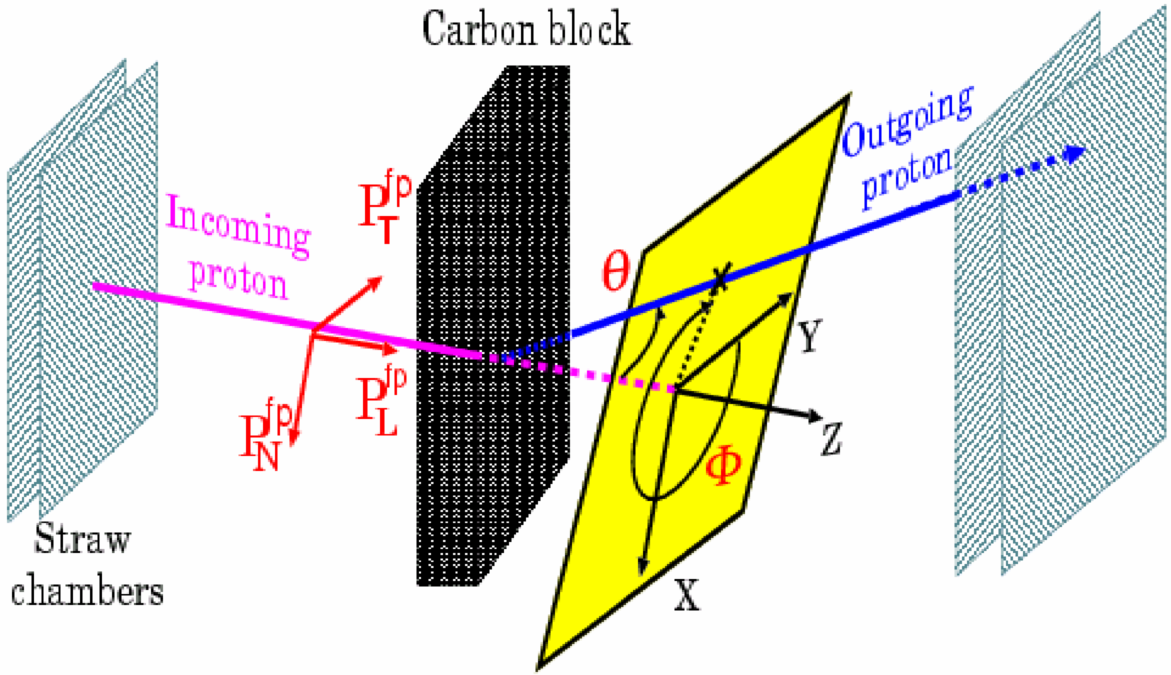


The HALL A-calorimeter

Electron detection

- Assembled a 1.35 x 2.55 m^2 calorimeter
- 17 rows and 9 columns of 15x15 lead-glass blocks

Focal plane polarimeter



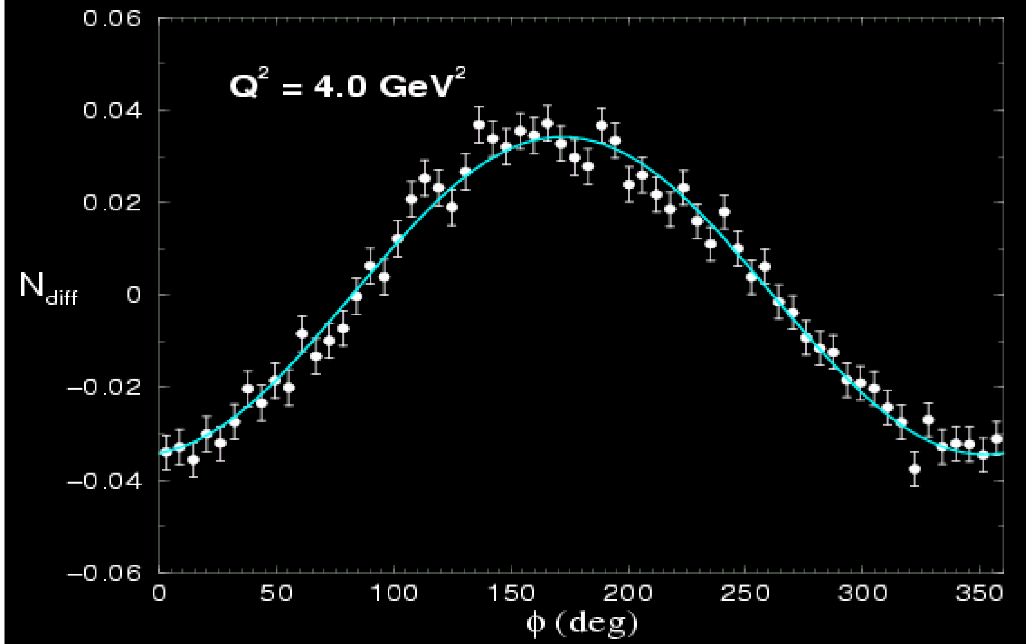
$$N^{\pm}(\theta,\phi) = N_0^{\pm}(\theta)\Big[1 \quad + \quad [\pm h A_c(\theta) P_n^{fp} + b_i] \cos\phi$$
$$+ \quad \Big[\pm h A_c(\theta) P_t^{fp} + a_i\Big] \sin\phi\Big]$$

- $P_n^{fp} = -P_l^{tgt}\sin(\chi)$ and $P_t^{fp} = P_t^{tgt}$
- a_i and b_i are the instrumental asymmetries which are eliminated

by subtracting N^- from N^+.

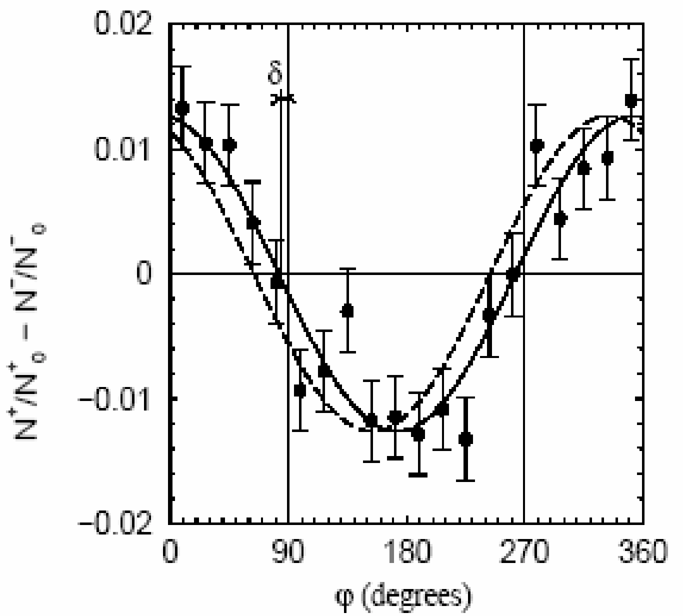
Azymuthal distribution

$$N_{diff}(\theta,\phi) = \frac{1}{2}\left[\frac{N^+(\theta,\phi)}{N_o^+(\theta)} - \frac{N^-(\theta,\phi)}{N_o^-(\theta)}\right]$$



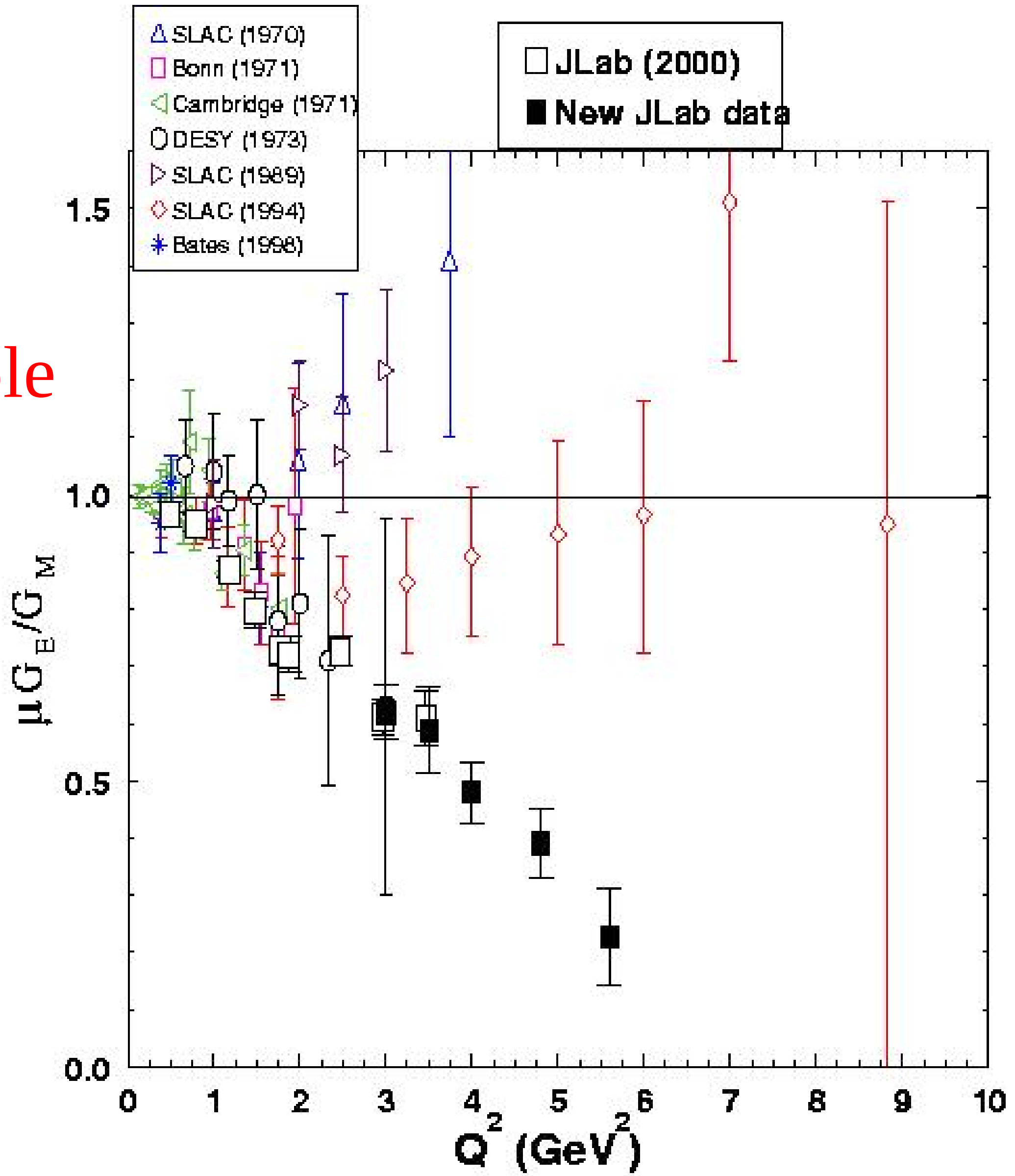
$$N_{diff}(\theta,\phi) = \overbrace{hA_c(\theta)P_n^{fp}}^{a}\cos\phi + \overbrace{hA_c(\theta)P_t^{fp}}^{b}\sin\phi$$

Q²=5.6 GeV/c²



THE RESULTS

- Linear deviation from dipole
- $G_{Ep} \neq G_{Mp}$



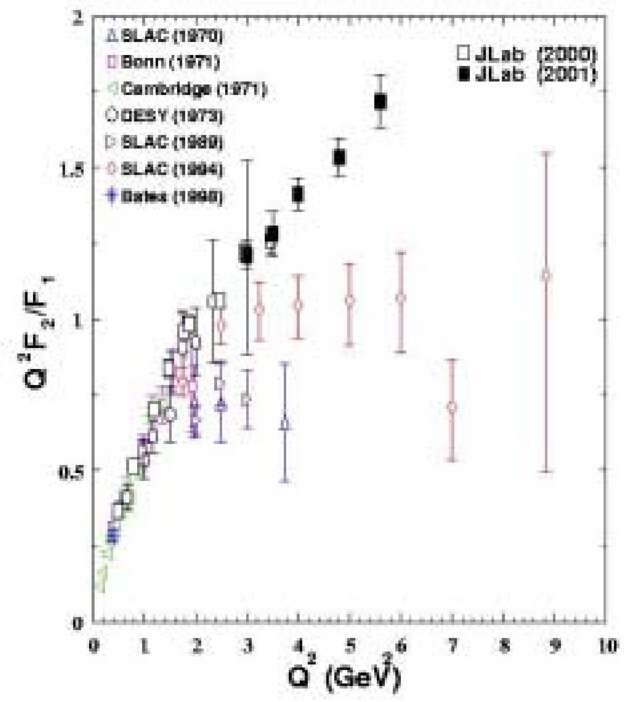
Jlab E93-027 , E99-007

Spokepersons:

Ch. Perdrisat, V. Punjabi, M. Jones, E. Brash

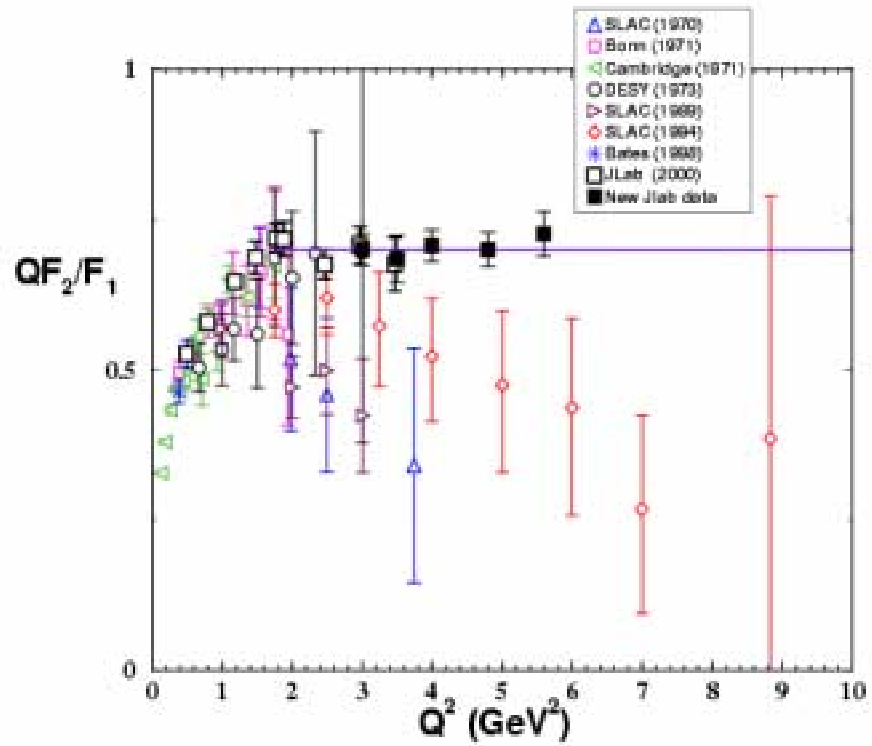
M. Jones et ql. Phys. Rev. Lett. 84,1398 (2000)
O. Gayou et al. Phys. Rev. Lett. 88:092301 (2002)

Scaling?



$$\text{pQCD: } F_1 \to 1/Q^4,\ F_2 \to 1/Q^6$$

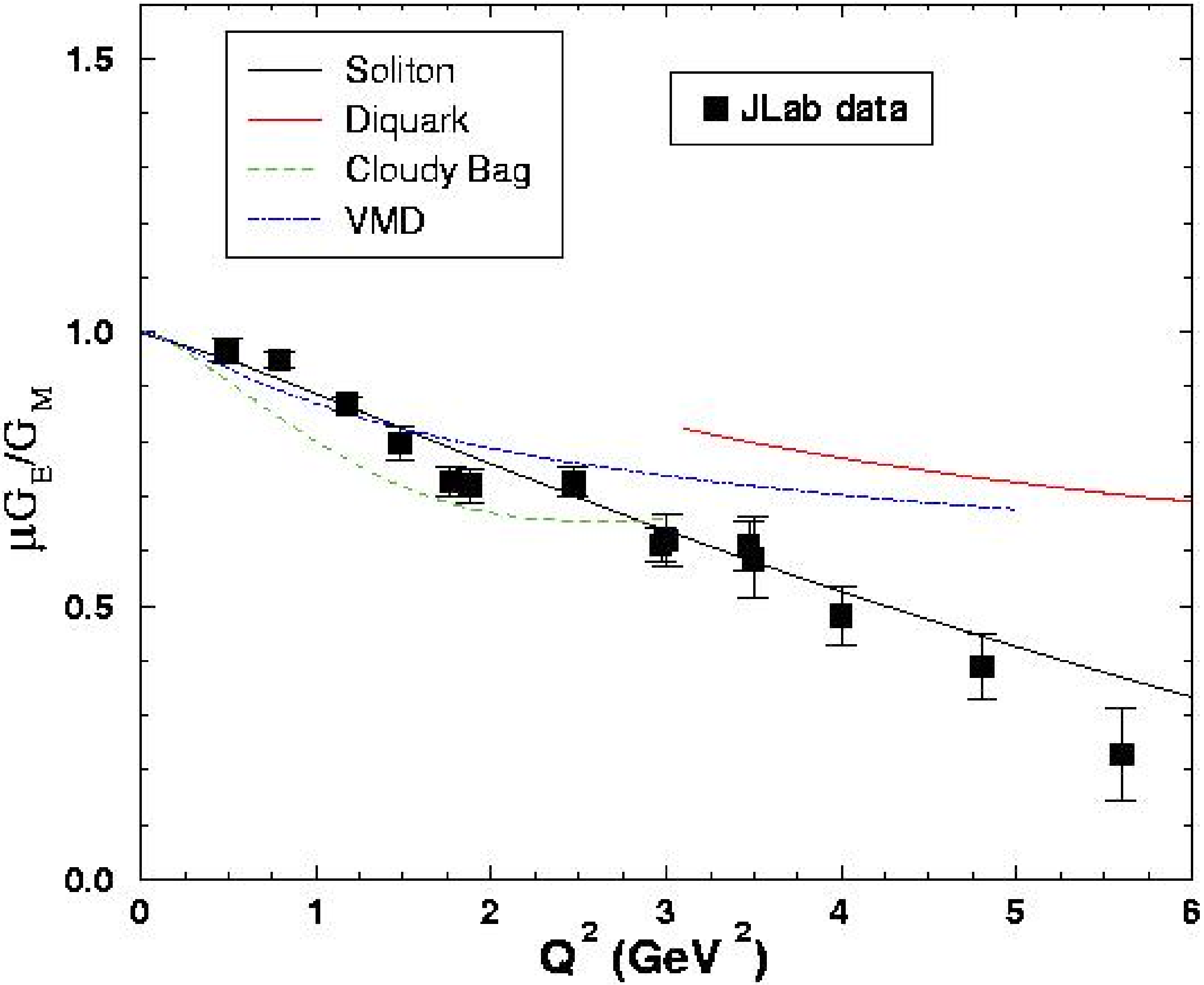
$$F_1 / F_2 \to Q^2$$



Models, models, models...

- Skyrme Models (Soliton)
- Vector Dominance Models (G-K, IJL…)
- Perturbative QCD
- (Relativistic) Constituent Quark Model
- Di-quark models
- SkPD

Comparison with theory



Issues

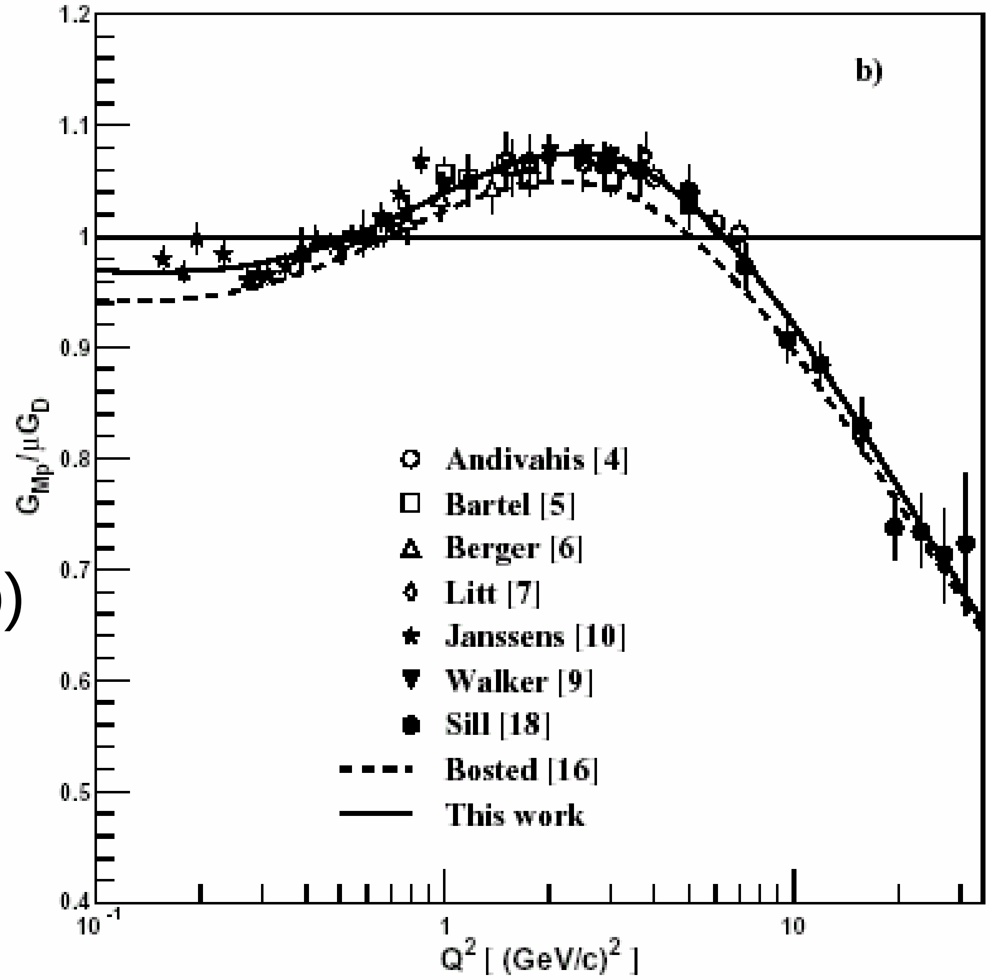
- When pQCD starts to apply?
- Simultaneous description of the four nucleon form factors...
- ...in the space-like and in the time-like regions
- Consequences for the light ions description

The proton magnetic form factor

The new results induce

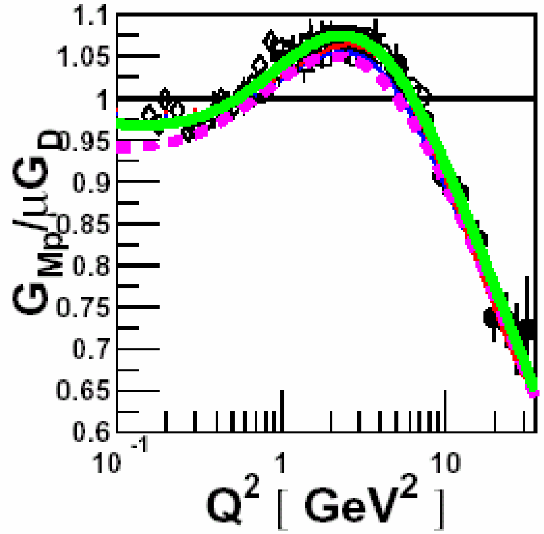
3% global effect

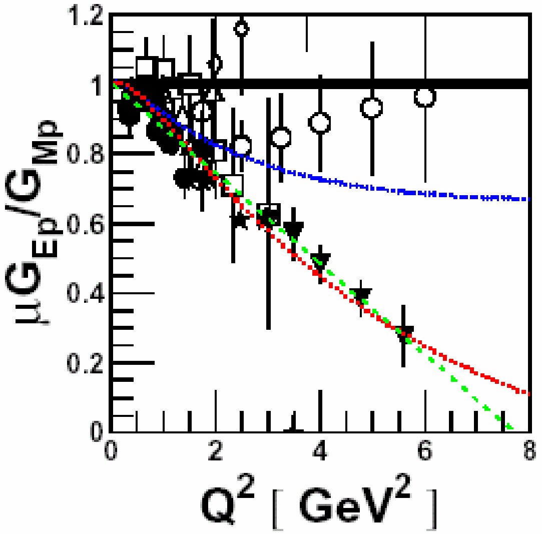
Radiative corrections on σ(ep) up to 30%!



E. Brash et al. Phys. Rev. C65:051001, 2002

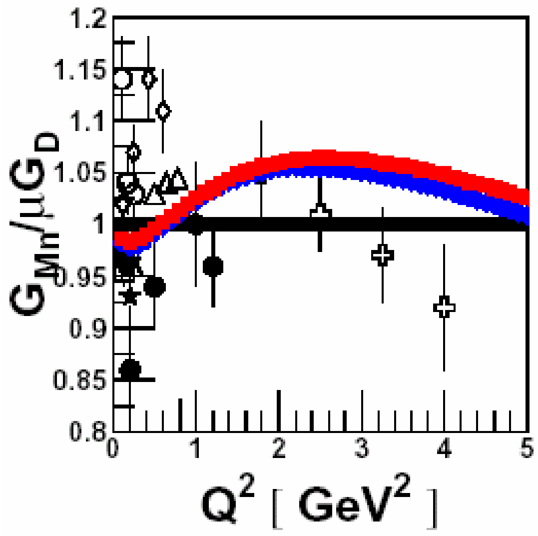
The nucleon form factors

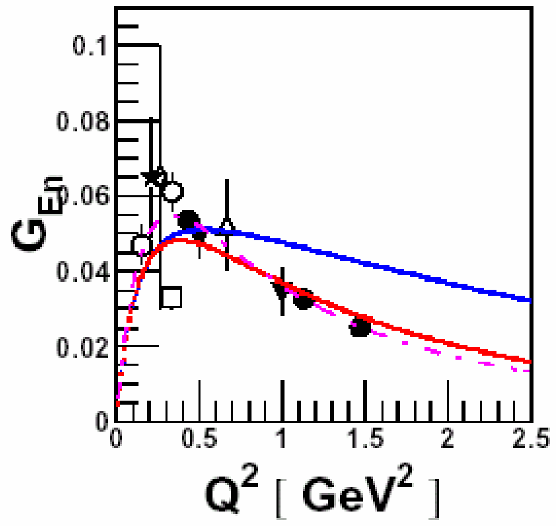




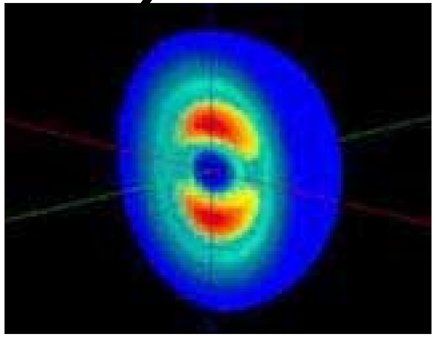
proton

neutron





The deuteron (S=1)



$$\frac{d\sigma}{d\Omega_e} = \sigma_0 \left[A(q^2) \cot^2 \frac{\theta_e}{2} + B(q^2) \right]$$

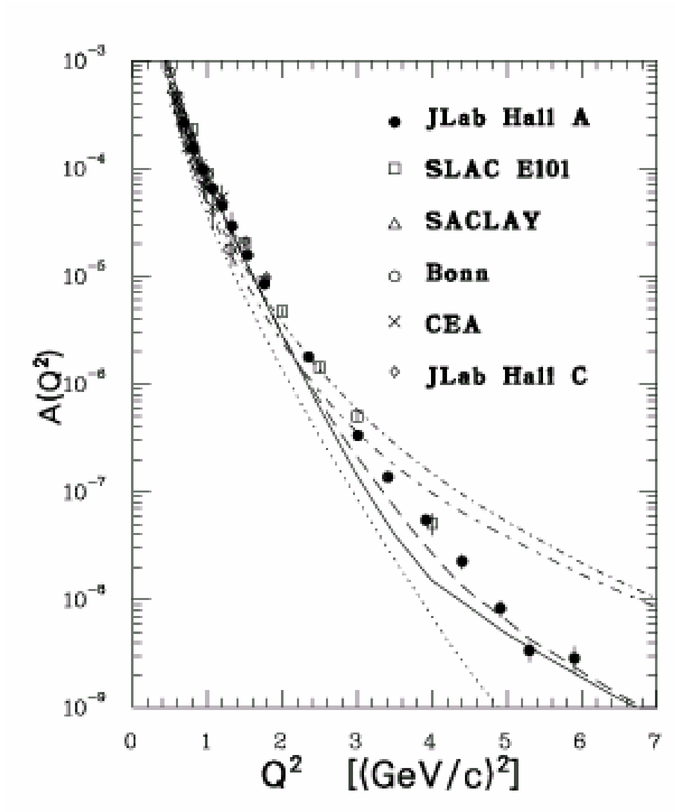
$$A(q^2) = G_C^2 + \frac{8}{9}\tau^2 G_Q^2 + \frac{2}{3}\tau G_M^2, \; B(q^2) = \frac{4}{3}\tau(1+\tau)G_M^2$$

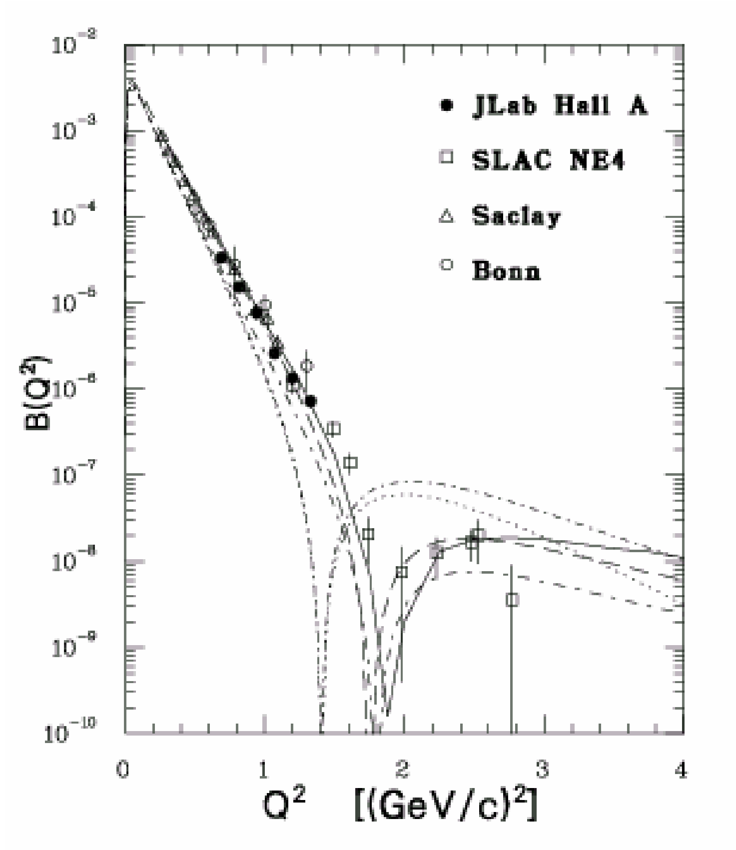
$$W t_{20} = \frac{1}{2}\left[\frac{8}{3}\tau G_C G_Q + \frac{8}{9}\tau^2 G_Q^2 + \frac{\tau}{3}(1 + 2(1+\tau)\tan^2\frac{\theta_e}{2})G_M^2\right]$$

The deuteron

Cross section

B(Q^2)

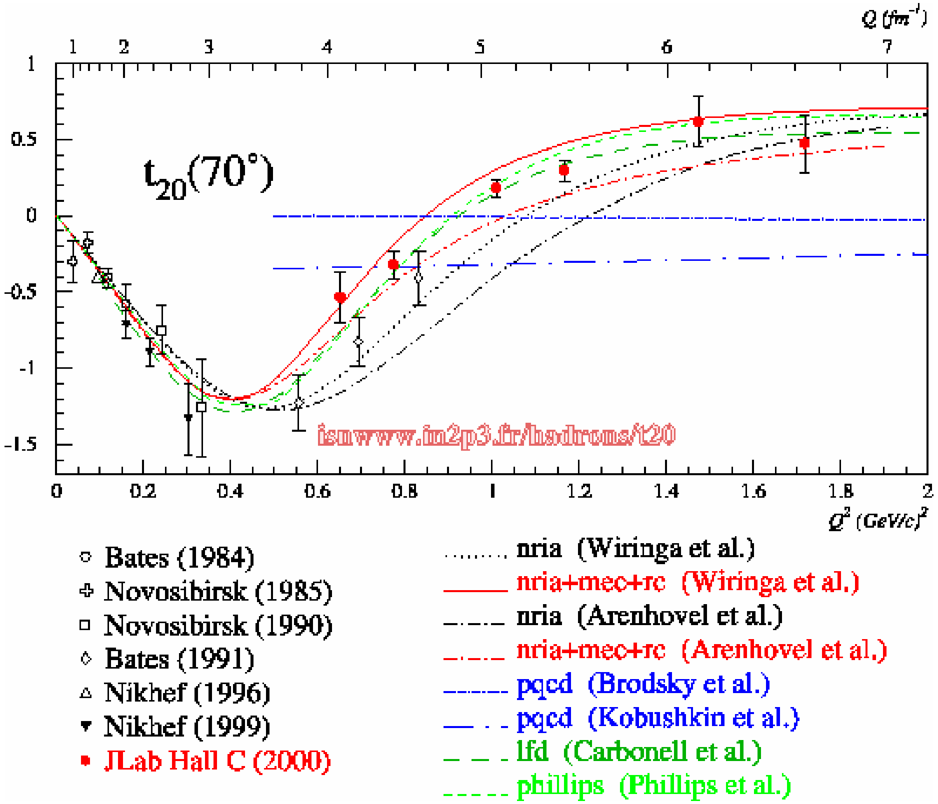


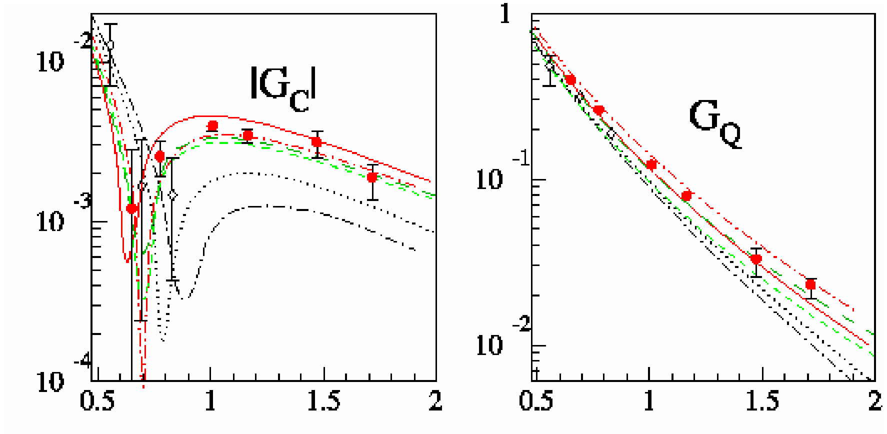


A(Q^2)

The deuteron

Polarization observables





Jlab E94-018

Spokepersons:

B. Beise, S. Kox

D. Abbott et ql. Phys. Rev. Lett. 84,5053 (2000)

The IA deuteron structure: S=1, T=0

$$G_c = G_{Es} C_E, \quad G_q = G_{Es} C_Q, \quad G_m = \frac{M_d}{M_p}\left(G_{Ms} C_S + \frac{1}{2} G_{Es} C_L\right)$$

1) The nucleon form factors:

$$G_{Ms} = G_{Mp} + G_{Mn}$$

$$G_{Es} = G_{Ep} + G_{En}$$

2) The S *(u)* and D *(w)* deuteron wave function

$$\int_0^\infty dr \ \left[u^2(r) + w^2(r)\right] = 1.$$

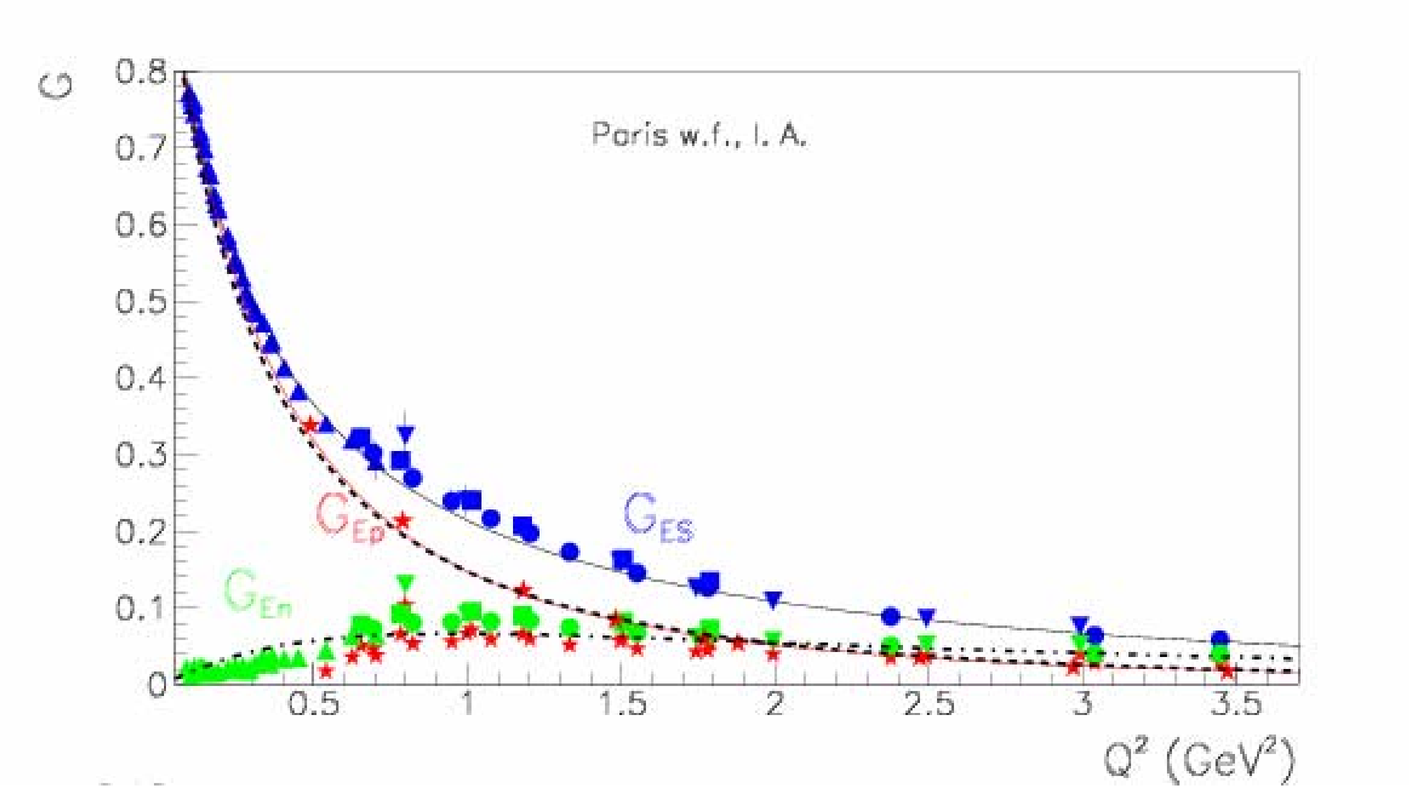
$$C_E = \int_0^\infty dr \ j_0\left(\frac{Qr}{2}\right)\left[u^2(r) + w^2(r)\right],$$

$$C_Q = \frac{3}{\sqrt{2}\tau}\int_0^\infty dr \ j_2\left(\frac{Qr}{2}\right)\left[u(r) - \frac{w(r)}{\sqrt{8}}\right] w(r),$$

$$C_S = \int_0^\infty dr \left[u^2(r) - \tfrac{1}{2} w^2(r)\right] j_0\left(\tfrac{Qr}{2}\right) + \tfrac{1}{2}\left[\sqrt{2} u(r) w(r) + w^2(r)\right] j_2\left(\tfrac{Qr}{2}\right),$$

$$C_L = \frac{3}{2}\int_0^\infty dr \ w^2(r)\left[j_0\left(\frac{Qr}{2}\right) + j_2\left(\frac{Qr}{2}\right)\right],$$

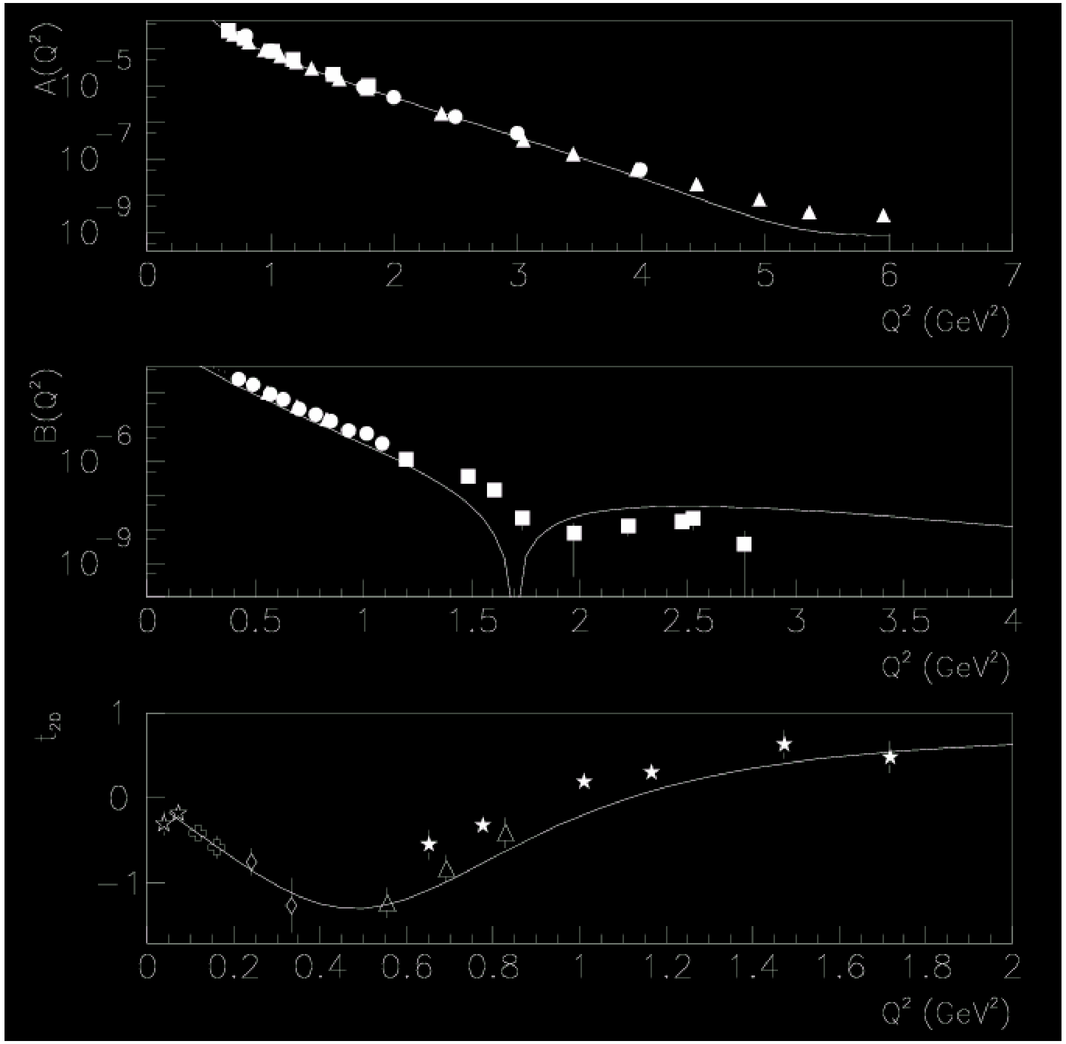
G_{En} from the deuteron



- $G_{En} > G_{Ep}$ starting from 2 GeV^2

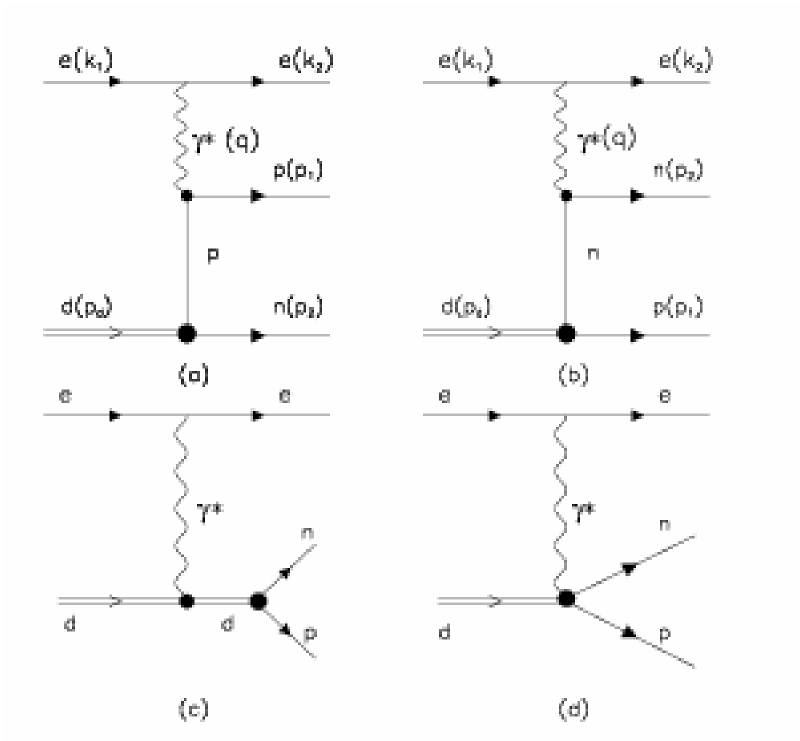
E. T-G. and M. P. Rekalo, Europhys. Lett. 55, 188 (2001)

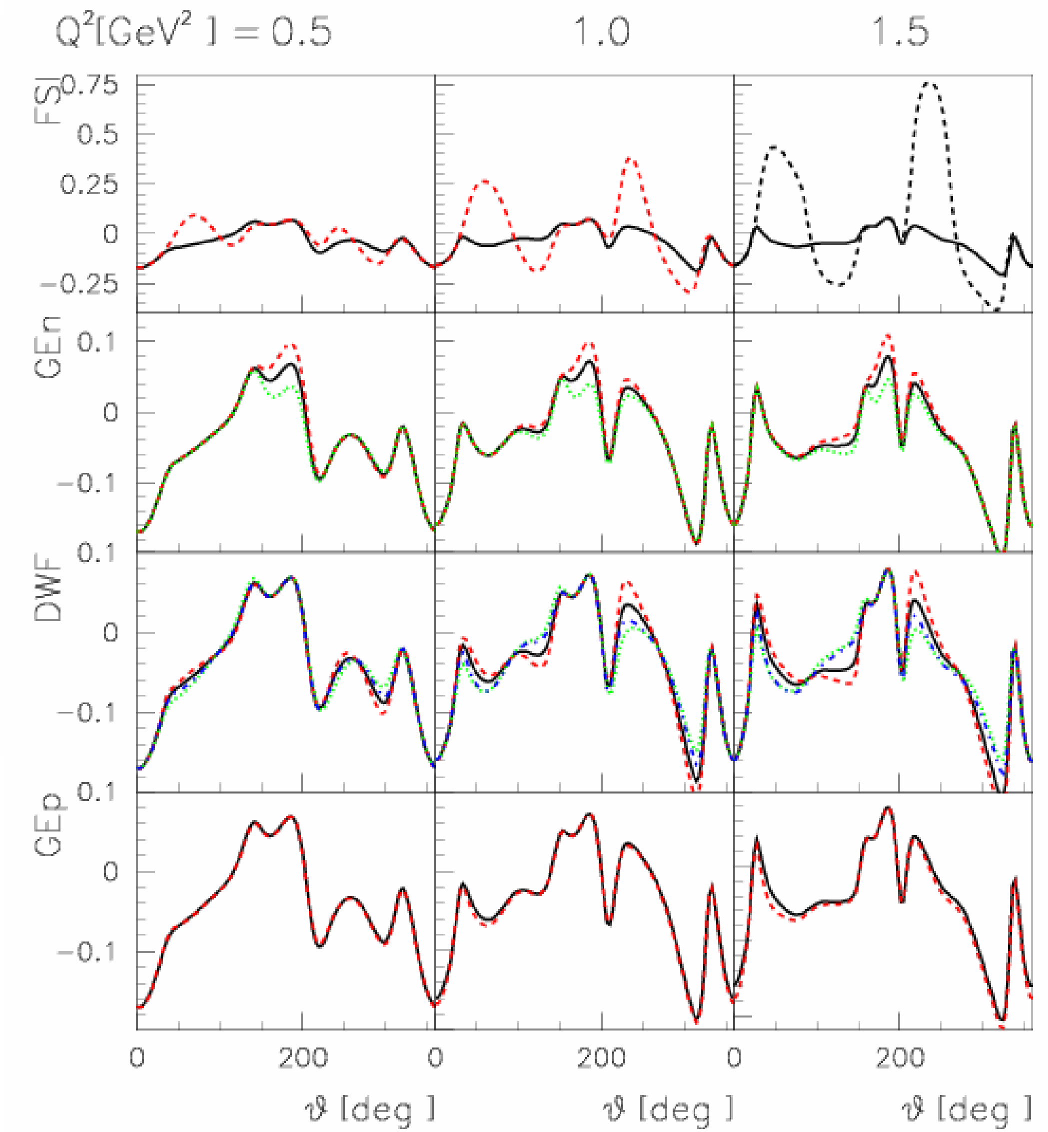
The IA deuteron structure



E. T-G. and M. P. Rekalo, Europhys. Lett. 55, 188 (2001)

The reaction d(e,e'n)p - A_x





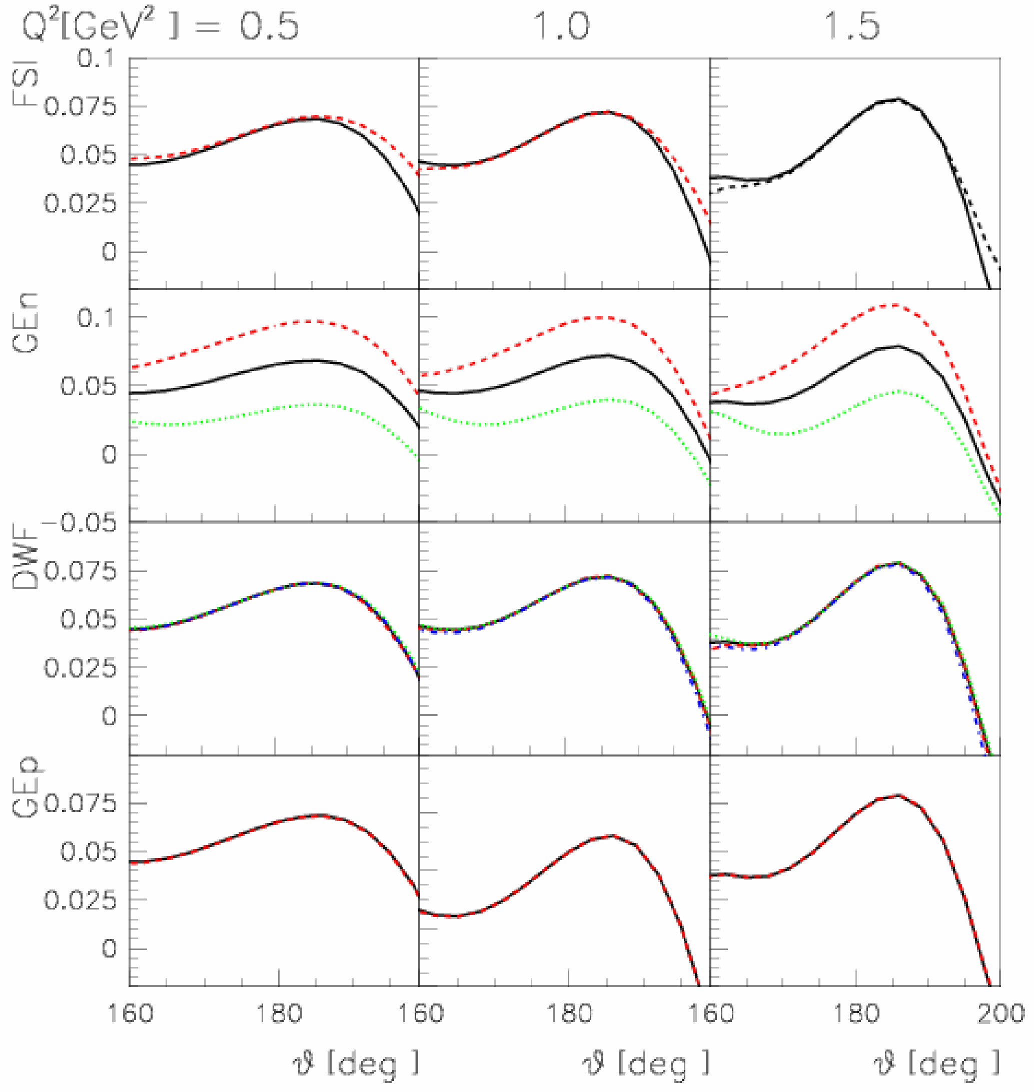
- The Impulse Approximation
- The deuteron structure
- Kinematics: proton spectator
- Polarization observables

The reaction d(e,e'n)p - A_x

Select the quasi-elastic Kinematics

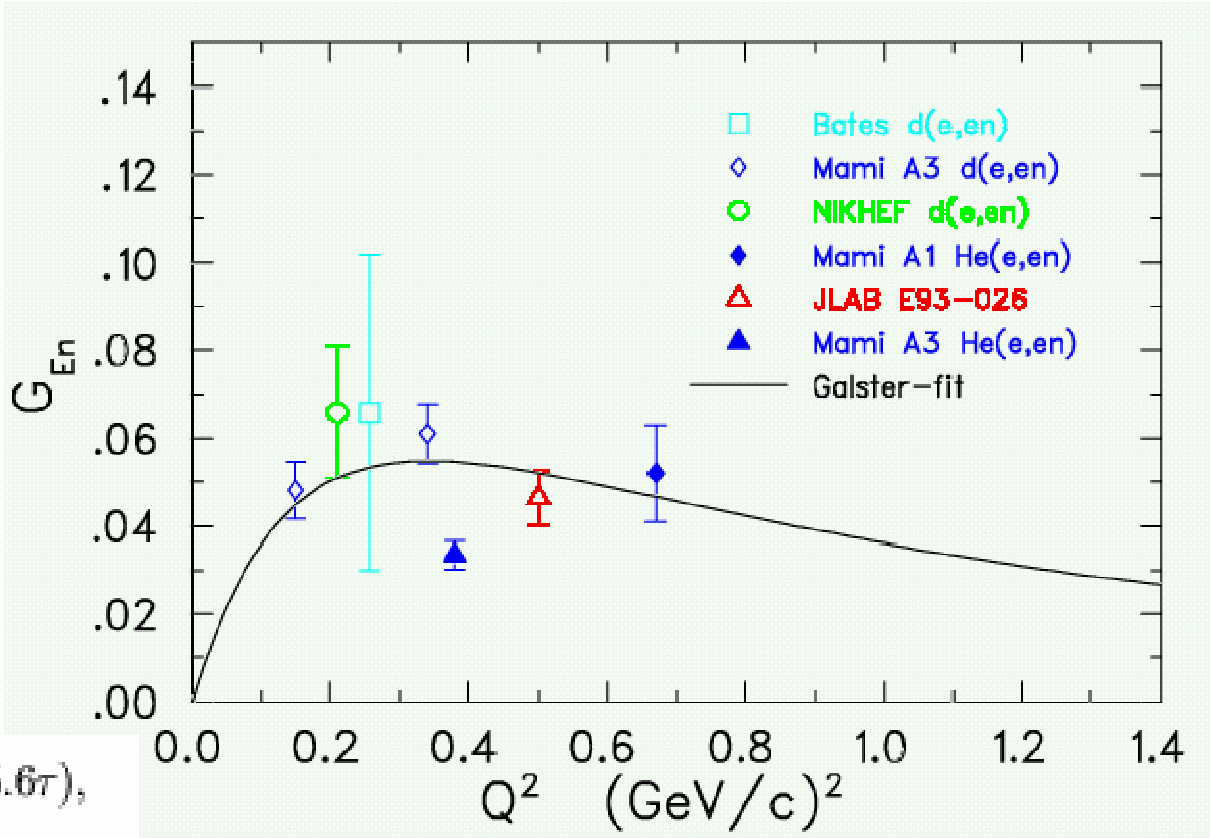
Large dependence of the asymmetry on Gen!

Polarized electron beam, polarized target or neutron polarimeter



The neutron electric form factor

- Polarization method
- Nuclear effects

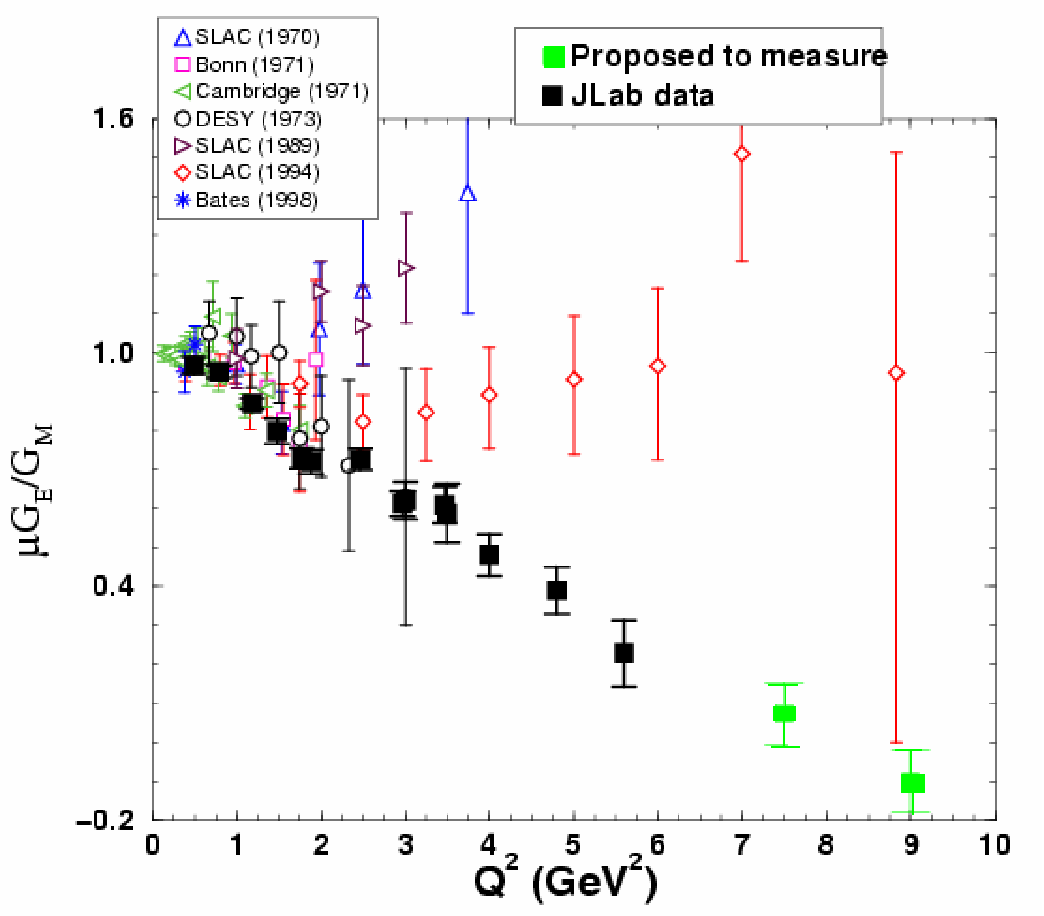


Galster parametrization:

$$G_{En} = G^G = -\tau\mu_n G_D/(1+5.6\tau),$$

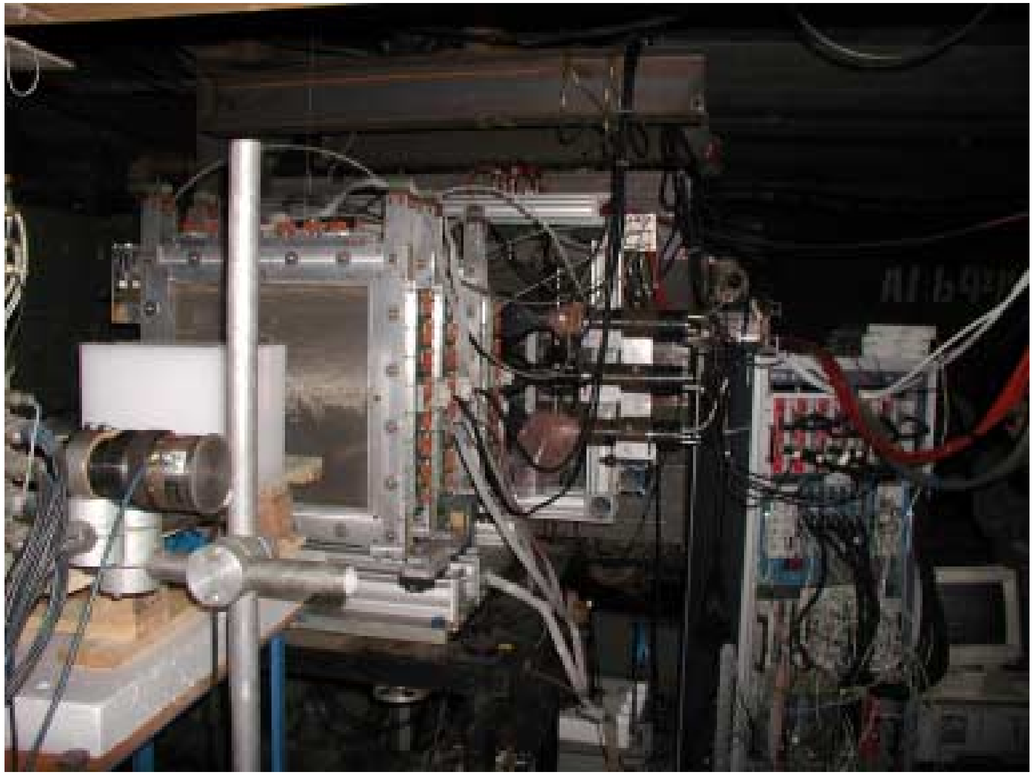
When G_E^p =0?

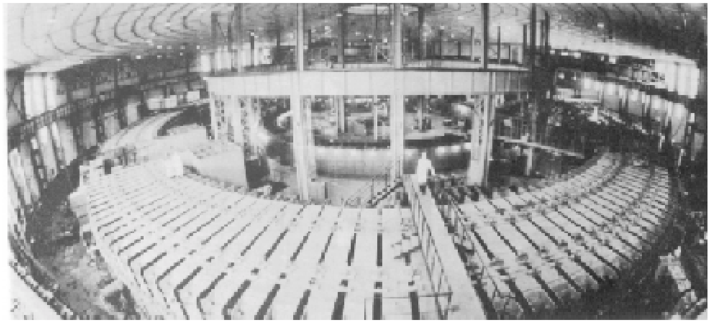
- Jlab E01-109
  - approved 07/2001
  - scheduled 2005
  - *Spokepersons: Ch. Perdrisat, V. Punjabi, M. Jones, E. Brash*
  - *20 Laboratories, 80 people*
- Hall A => Hall C
- New polarimeter
- New calorimeter
- G_e^p IV: up to 12 GeV^2, after the upgrade of Cebaf



Polarimetry at 4-5 GeV

- Pomme polarimeter ...





...JINR -LHE synchrophasotron

Analyzing powers

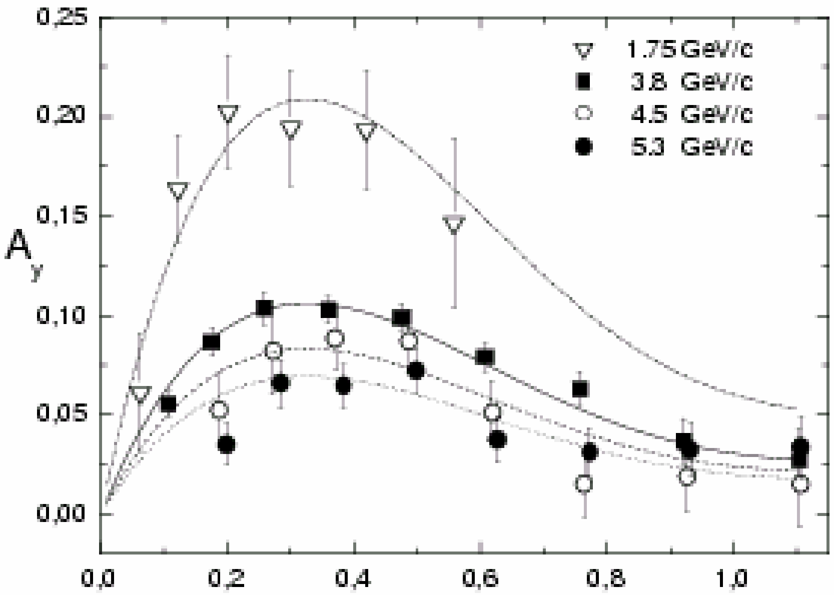
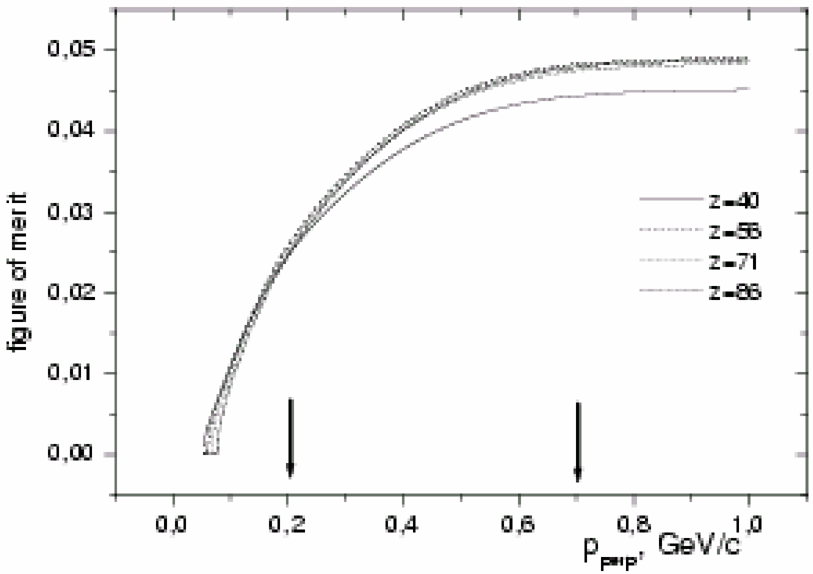


Figure of merit



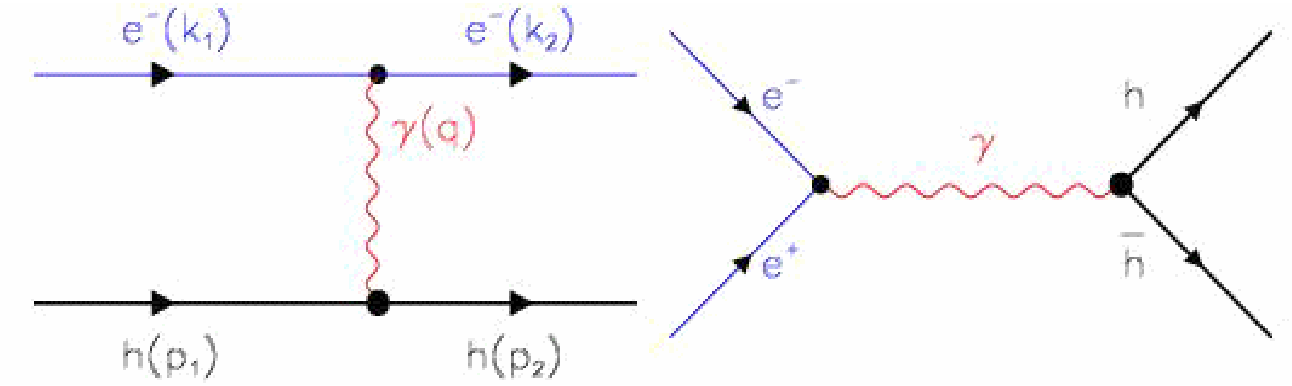
Collaboration:

JINR - MSU (Russia)
INRNE BAS (Bulgaria)
DAPNIA/SPhN - IPN (France)
W&M - NSU - TJNAF - RU (USA)
UR (Canada)

Time-like and space-like regions

- Form factors are *real in the space-like region* and *complex in the time-like region* .

Scattering *Annihilation*



$e^- + h \Rightarrow e^- + h$ $e^+ + e^- \Rightarrow h + \bar{h}$

Time-like and space-like regions

- T-L→ | G_M| ^{2}

-The cross section for $\overline{p}+p \to e^+ + e^-$ (1 γ-exchange):

$$\frac{d\sigma}{d(\cos\theta)} = \frac{\pi\alpha^2}{8m^2\sqrt{\tau-1}}\left[\tau|G_M|^2(1+\cos^2\theta) + |G_E|^2\sin^2\theta\right]$$

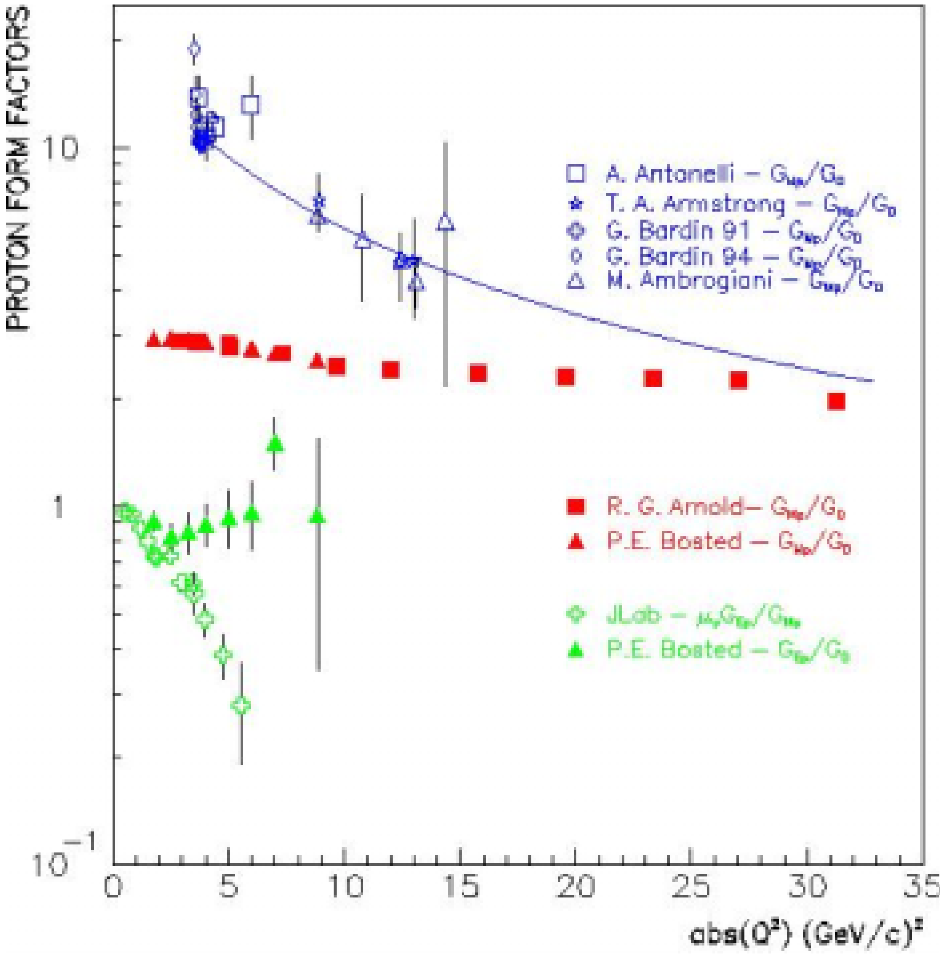
θ: angle between e^- and $\overline{p}$ in cms.

- Asymptotic properties from the Phragmèn-Lindelöf theorem

$$\lim_{q^2\to-\infty} F^{(SL)}(q^2) = \lim_{q^2\to\infty} F^{(TL)}(q^2)$$

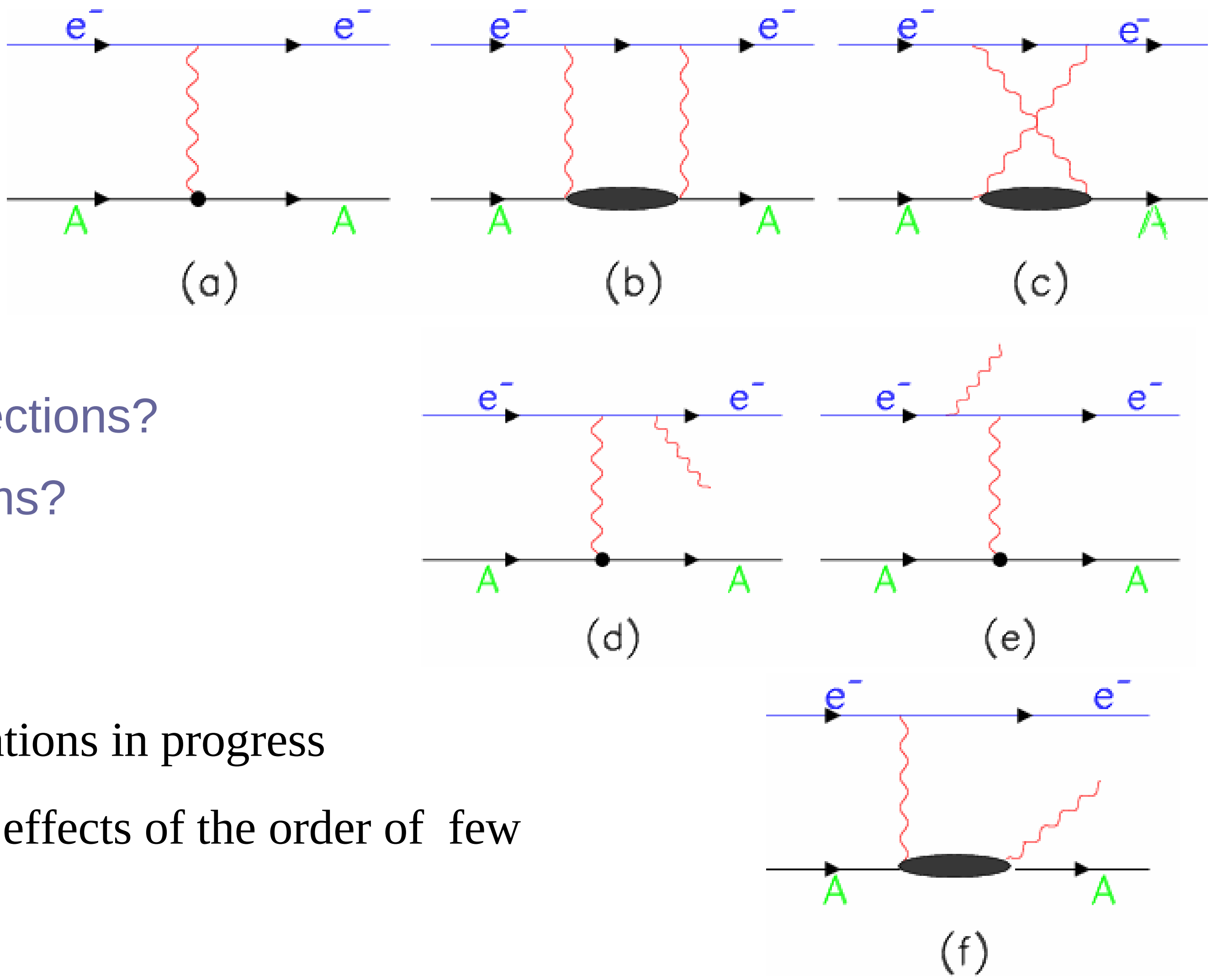
$$\begin{array}{cc} space-like & time-like \\ (e^- + p \to e^- + p) & (e^+ + e^- \leftrightarrow \overline{p}+p) \end{array}$$

$- F^{(TL)}(q^2) \ \to \ real$, if $q^2 \to \infty$



E. T-G. and M. P. Rekalo, Phys. Lett. B 504, 291 (2001)

Possible corrections

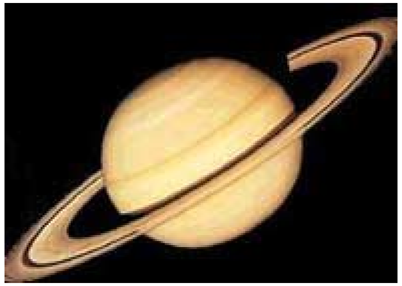


- 2-γ exchange?
- Radiative corrections?
- P-violating terms?

Complete calculations in progress

Estimations give effects of the order of few percent

Conclusions



- New precise results on proton electric form factor
    - Recoil polarization method
    - Polarimetry
    - Jlab polarized electron beam

- The electric and the magnetic distributions of the proton are different!
- The asymptotic region is far.
- The nucleon and light hadrons models have to be revisited.