STRUCTURE OF THE NUCLEON FROM ELECTROMAGNETIC FORM FACTORS

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1. Historical background
2. Analysis of form factors
3. High-Q^2 behavior: scaling laws
4. Low-Q^2 behavior
5. Stability against perturbations
6. Time-like form factors
7. Consequences and implications
8. Conclusions

1. Historical background

~1960's Hofstadter

⇒Nucleon not point-like

$\langle r_p^2 \rangle^{1/2} \sim 0.75$ fm

~1970's Many experiments

⇒Neutron very complex

$\frac{dG_{En}}{d(Q^2)} \sim 0.50$ (GeV/c)^2

1973 IJL

⇒Nucleon has a two component structure:

1. Intrinsic structure, $g(Q^2)$
2. Meson cloud, (ρ, ω, φ)

1970's Non-relativistic quark model (Isgur-Karl)

⇒Unable to describe form factors in a consistent way

1980's Perturbative QCD (Lepage-Brodsky-Farrar)

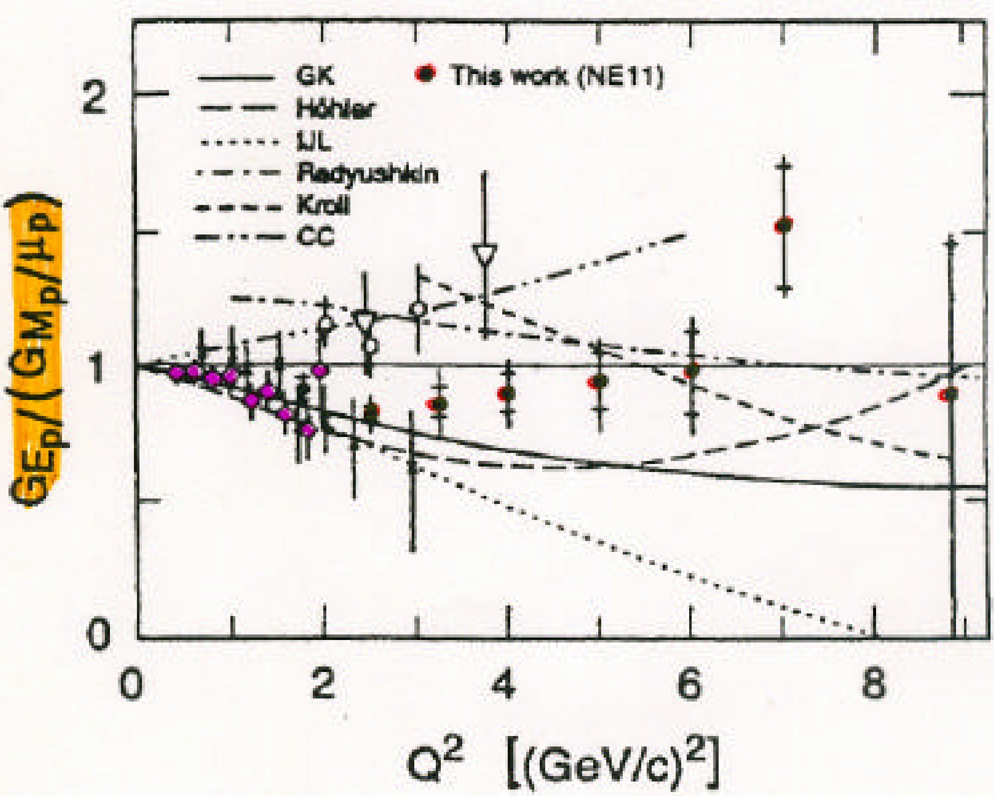
⇒Large Q^2 behavior $\propto \frac{1}{Q^4}$

1980's Empirical dipole form

⇒Scaling $G(Q^2) \propto \frac{1}{\left(1+\frac{Q^2}{0.71}\right)^2}$

1995 SLAC (Rosenbluth separation)

⇒Consistent with p-QCD and scaling



GK
Höhler
IJL
Radyushkin
Kroll
CC
This work (NE11)
2
1
0
0
2
4
6
8
$G_{E_p}/(G_{M_p}/\mu_p)$
Q^2 [(GeV/c)^2]

2000-2002 TJNAF

Recoil polarization method

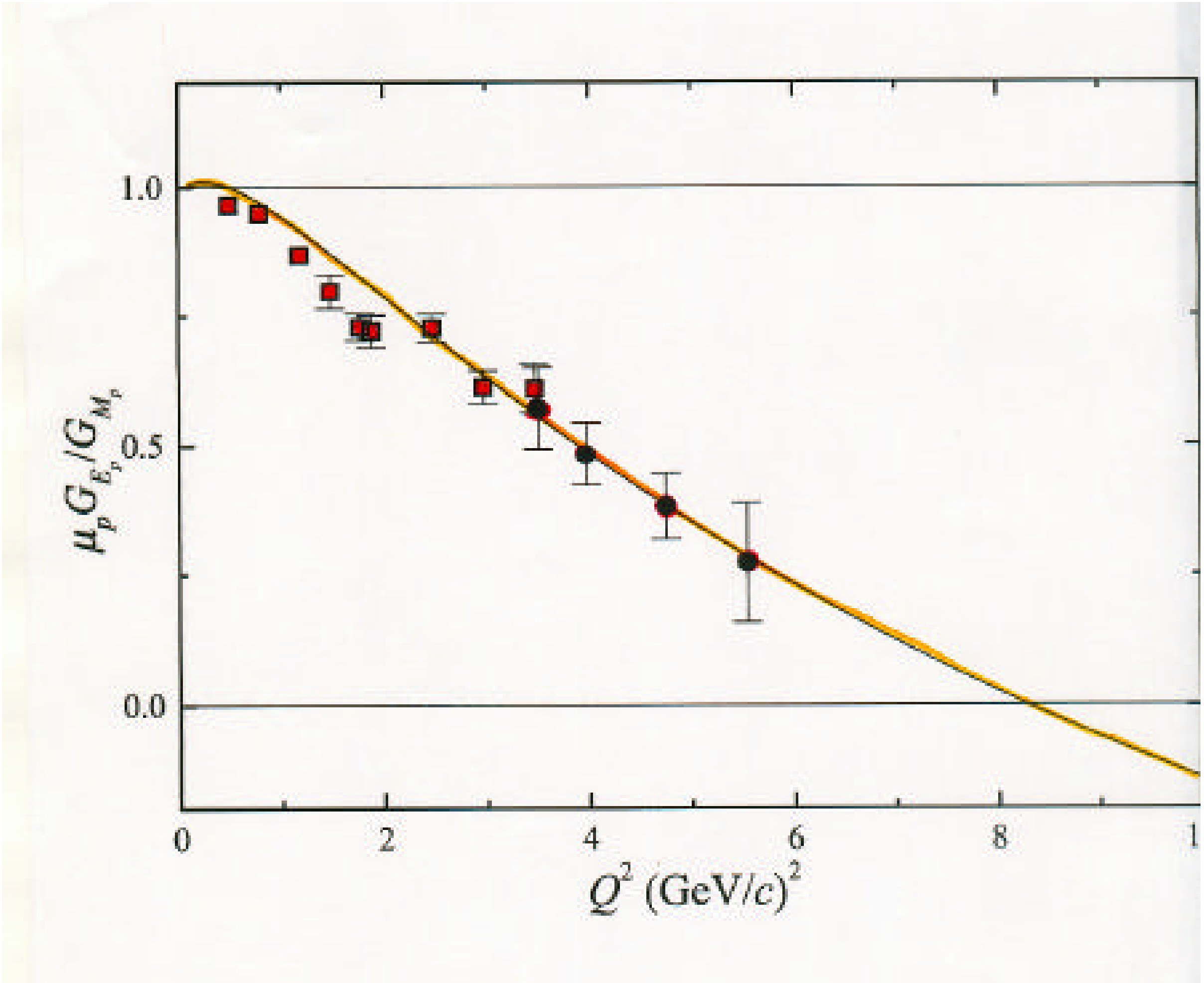
(no Rosenbluth separation)

⇒Astounding result

Proton electric form factor

decreases dramatically with Q^2

Inconsistent with scaling



1.0
0.5
0.0
0
2
4
6
8
1
$\mu_p G_{E_p}/G_{M_p}$
Q^2 (GeV/c)^2

2. Analysis of form factors

Basic principles:

(i) Relativistic invariance (exact)

⇒Electromagnetic current

$$J^{\mu} = F_1(Q^2)\gamma^{\mu} + \frac{\kappa}{2M_N^2} F_2(Q^2) i\sigma^{\mu\nu} q_{\nu}$$

$F_1(Q^2)$	Dirac form factor
$F_2(Q^2)$	Pauli form factor
κ	Anomalous magnetic moment

(ii) Isospin invariance (slightly broken)

⇒Isoscalar, F_1^S, F_2^S, and isovector, F_1^V, F_2^V, form factors

Observed Sachs form factors

$$G_{M_p} = (F_1^S + F_1^V) + (F_2^S + F_2^V)$$
$$G_{E_p} = (F_1^S + F_1^V) - \tau(F_2^S + F_2^V)$$
$$G_{M_n} = (F_1^S - F_1^V) + (F_2^S - F_2^V)$$
$$G_{E_n} = (F_1^S - F_1^V) - \tau(F_2^S - F_2^V)$$

with

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

[Sachs form factors satisfy also the kinematical constraint

$$G_E(-4M_N^2) = G_M(-4M_N^2)$$

of crucial importance in the time-like region ($Q^2 < 0$).]

Different models of the nucleon correspond to different assumptions for the Dirac and Pauli form factors

1973 IJL

Two-component nucleon:

(i)Intrinsic structure and (ii) meson cloud

SEMI-PHENOMENOLOGICAL FITS TO NUCLEON ELECTROMAGNETIC FORM FACTORS

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Several theoretically interesting forms of the nucleon EM form factor have been considered and found to provide quantitative descriptions of available data with as few as three adjustable parameters.

Attempts towards understanding the nucleon electromagnetic form factors by fitting theoretically suggested forms to data have frequently been restricted to a consideration of the proton magnetic form factor $G_M^p(t)$ which is well-known experimentally over a wide range of t. The drawback of such fits is that the underlying physical models often admit predictions for the remaining three nucleon electromagnetic form factors which are in gross disagreement with experimental data. This is not the case in the work of Massam and Zichichi [1] and of Ng [2]. These authors perform simultaneous fits to all four form factors following an idea of Kroll et al. [3]. Both works describe the interaction of nucleons with the EM field in terms of vector meson dominance plus an intrinsic form factor at the nucleon-vector meson-vertex having a monopole form with one adjustable parameter. In ref. [1] SU(3) estimates were used to determine the vector meson coupling constants and a common intrinsic form factor was used for all data. The resulting one parameter fit to the data then available resulted in a $\chi^2 = 3.98$ per datum. In ref. [2] two vector meson coupling constants were left as parameters and three intrinsic form factors (i.e., hypercharge, isospin and baryon number form factors) were fit to the data. The resulting five parameter fit yielded a $\chi^2 = 1.47$ per datum. These fits were obtained without the benefit of recent large-t measurements of $G_M^p(t)$ [4] and the precise small-t data recently obtained for $G_M^p(t)$ and $G_E^p(t)$

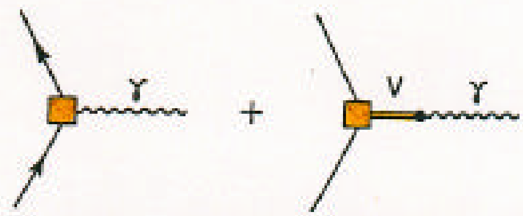

Fig. 1. Diagrams describing the interaction of nucleons with the EM field. The square box represents the intrinsic form factor $g(t)$ and V includes (ρ, ω, ϕ) mesons.

[5]. In this note we shall report several similar fits to the currently available data. In addition to using more data our fits differ from those of refs. [1] and [2] in two points. First, we have incorporated some of the effects of the large ρ-meson width using the techniques of Frazer and Fulco [6]. This is seen to allow a better description of the somewhat complicated deviations from the empirical dipole fit of $G_M^p(t)$ at small t. Second, wehave considered additional forms of the intrinsic nucleon form factors which are currently of some theoretical interest.

We describe all four nucleon form factors as the product of an intrinsic nucleon form factor $g(t)$ and a term describing the interaction of the bare nucleon with the EM field as shown in fig. 1. In addition to

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$$F_1^S(Q^2) = \frac{1}{2} g(Q^2) [(1 - \beta_\omega - \beta_\varphi)$$

$$+ \beta_\omega \frac{m_\omega^2}{m_\omega^2 + Q^2} + \beta_\varphi \frac{m_\varphi^2}{m_\varphi^2 + Q^2}]$$

$$F_1^V(Q^2) = \frac{1}{2} g(Q^2) \left[(1 - \beta_\rho) + \beta_\rho \frac{m_\rho^2}{m_\rho^2 + Q^2} \right]$$

$$F_2^S(Q^2) = \frac{1}{2} g(Q^2) [(-0.120 - \alpha_\varphi) \frac{m_\omega^2}{m_\omega^2 + Q^2}$$

$$+ \alpha_\varphi \frac{m_\varphi^2}{m_\varphi^2 + Q^2}]$$

$$F_2^V(Q^2) = \frac{1}{2} g(Q^2) \left[3.706 \frac{m_\rho^2}{m_\rho^2 + Q^2} \right]$$

Three forms of the intrinsic form factor, $g(Q^2)$, were used. Best fit for

$$g(Q^2) = \frac{1}{(1 + \gamma Q^2)^2}$$

Additional modification: non-negligible width of the ρ meson

$$\frac{m_\rho^2}{m_\rho^2 + Q^2}$$

replaced by

$$\frac{m_\rho^2 + 8\Gamma_\rho m_\pi/\pi}{m_\rho^2 + Q^2 + (4m_\pi^2 + Q^2)\Gamma_\rho \alpha(Q^2)/m_\pi}$$

where

$$\alpha(Q^2) = \frac{2}{\pi}\left[\frac{4m_\pi^2 + Q^2}{Q^2}\right] \times \ln\left(\frac{\sqrt{4m_\pi^2 + Q^2} + \sqrt{Q^2}}{2m_\pi}\right)$$

A. The ratio of electric to magnetic form factors of the proton

Using $\beta_\rho = 0.672$, $\beta_\omega = 1.102$, $\beta_\varphi = 0.112$, $\alpha_\varphi = -0.052$

and $\gamma = 0.25$ (GeV/c)$^{-2}$ and standard values of the masses

⇒Astonishing agreement of (1973) IJL with the new (2002) data

Electric form factor of the proton crosses zero at

$Q^2 \sim 8$ (GeV/c)^2 !!!

Of the utmost importance:

Measure the ratio $\mu_p G_{E_p}/G_{M_p}$ at $Q^2 > 6$ (GeV/c)^2

[Jlab experiment E01-109]

⇒The proton appears to be rather complex with at least two components:

(i) an intrinsic structure (presumably three valence quarks, q^3)

[estimate of the r.m.s. of the intrinsic structure ~ 0.34 fm]

(ii) a meson component (presumably $q\bar{q}$ sea pairs)

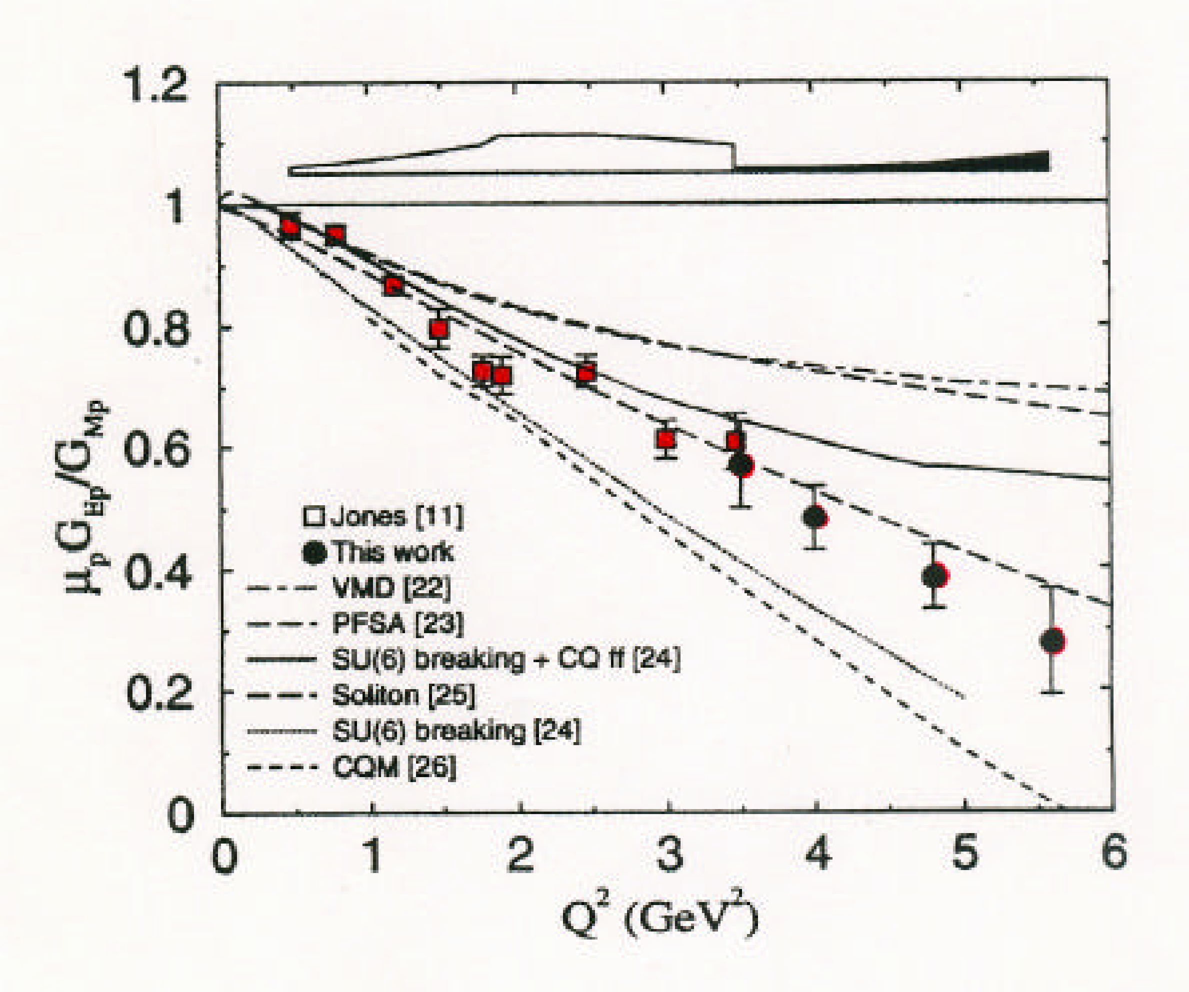
[Complex nature of the nucleon in accord with EMC collaboration where additional components were attributed to gluons.]

The vanishing of the electric form factor of the proton is due to the two term structure of the form factor (relativistic invariance). Any model with a two term structure will produce results in qualitative agreement with data.

Two models particularly interesting:

(i) Soliton model (Holzwarth, 1996)

(ii) Relativistic constituent quark model (Frank, Jennings and Miller, 1996)



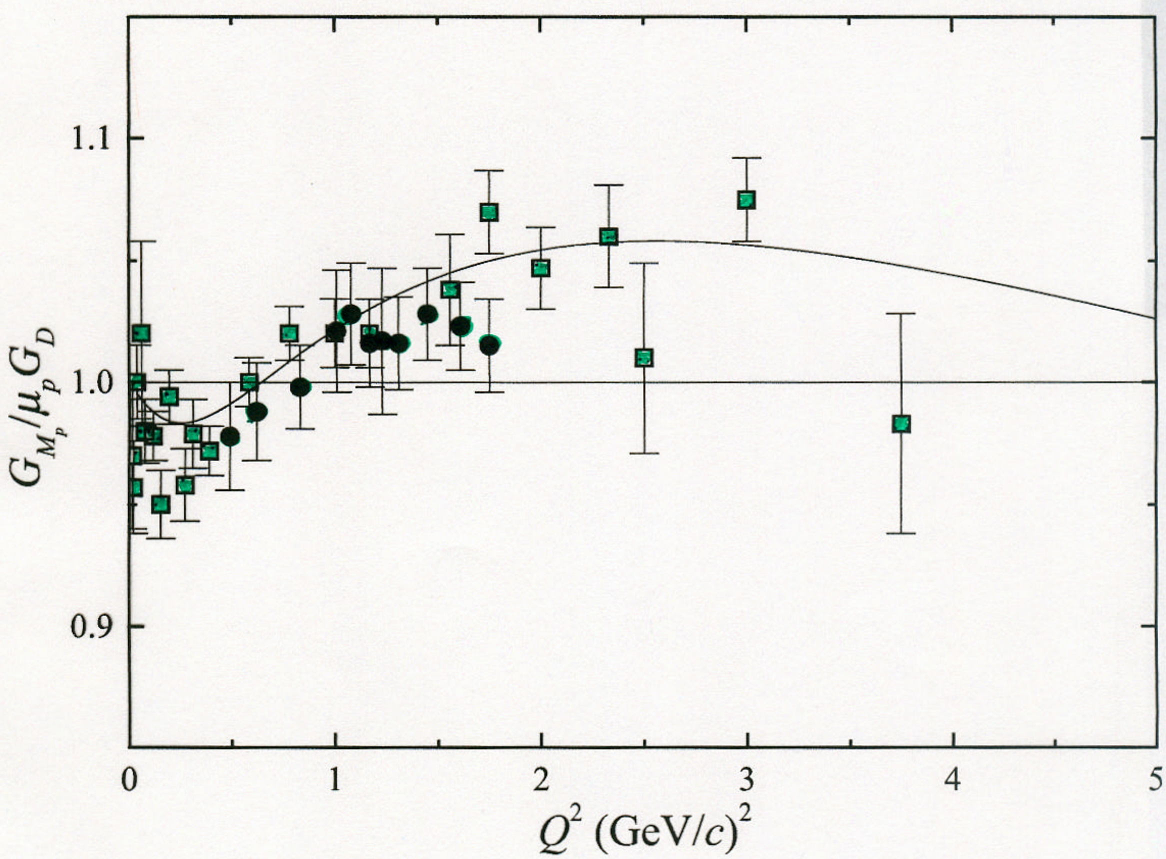
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
$\mu_p G_{Ep}/G_{Mp}$
Q^2 (GeV^2)
□ Jones [11]
● This work
VMD [22]
PFSA [23]
SU(6) breaking + CQ ff [24]
Soliton [25]
SU(6) breaking [24]
CQM [26]

B. The magnetic form factor of the proton

Also here agreement between 1973 IJL and experiment astonishing.

Ondulation with crossing points at ~ 0.6 and 6 $(\mathrm{GeV/c})^2$

⇒Proof that vector meson components with masses $m^2 \sim 0.5 - 1.0$ $(\mathrm{GeV/c})^2$ are important



1.1
1.0
0.9
$G_{M_p}/\mu_p G_D$
0
1
2
3
4
5
Q^2 (GeV/c)^2

C. The magnetic form factor of the neutron

⇒Dictated by isospin invariance

Measurements obscured by knowledge of wave functions of deuterons or ${}^3He$.

Older measurements in disagreement with 1973 IJL

Situation similar to proton form factors?

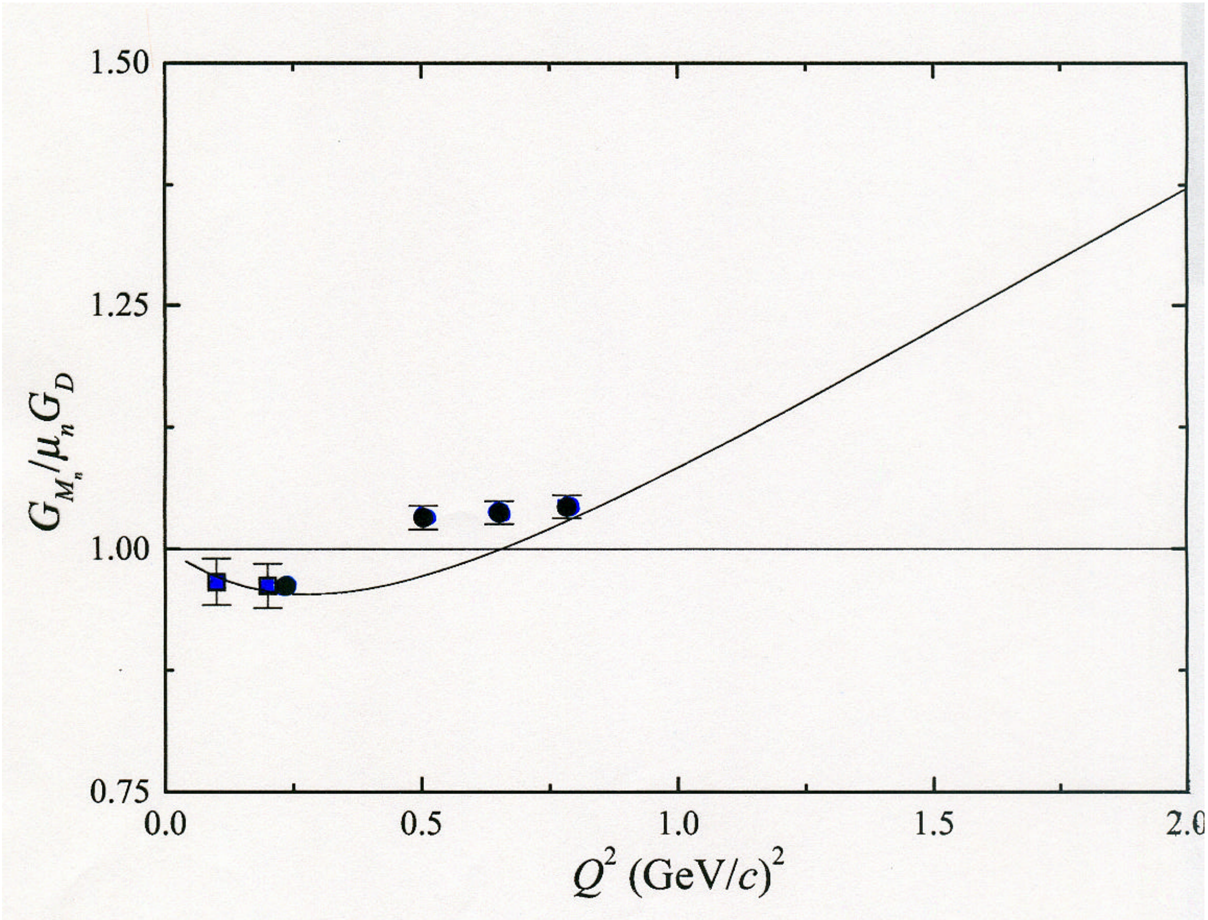
New analysis

Golak et al (2001)

Anklin et al (2001)

Ondulation at low Q^2 observed!

Isospin invariance satisfied at $Q^2 < 1$ (GeV/c)^2.



1.50
1.25
1.00
0.75
$G_{M_n}/\mu_n G_D$
0.0
0.5
1.0
1.5
2.0
Q^2 (GeV/c)^2

D. The electric form factor of the neutron

Same situation as for the magnetic form factor

New measurements:

Herberg et al (1999)

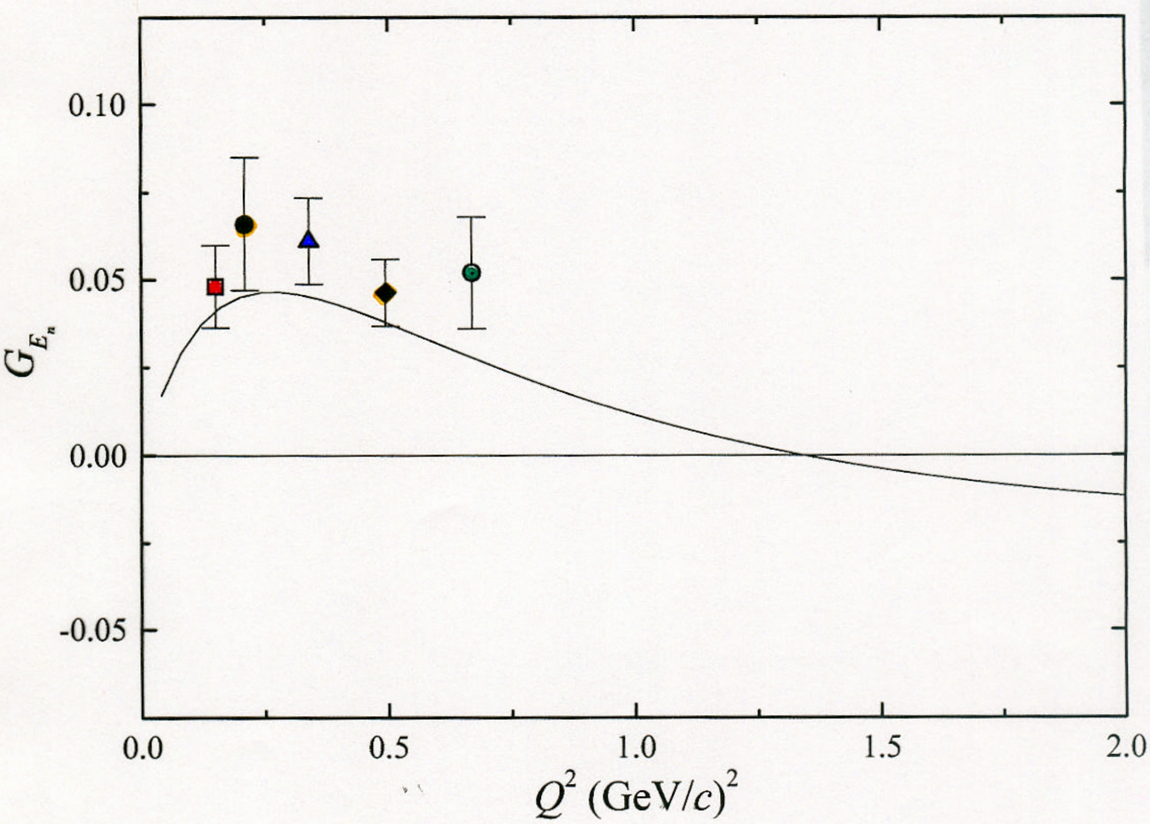
Passchier et al (1999)

Ostrick et al (1999)

Rohe et al (1999)

Zhu et al (2001)

In agreement with 1973 model


0.10
0.05
0.00
-0.05
G_{E_n}
0.0
0.5
1.0
1.5
2.0
Q^2 (GeV/c)^2

3. Scaling laws

Extent to which new data support scaling laws.

1973 IJL Consistent with scaling laws expected from p-QCD

Lepage-Brodsky (1979)

$$F_1 \sim 1/Q^4$$

$$F_2 \sim 1/Q^6$$

except for F_2^V that has a weak logarithm dependence on top of $1/Q^6$ due to the ρ width.

C. Another p-QCD scaling prediction: the ratio G_{M_p}/G_{M_n}

The ratio goes to zero

$$\frac{G_{M_p}}{G_{M_n}} \to 0^-$$

as a power of $\ln(Q^2/\Lambda^2)$

1973 model

$$\frac{G_{M_p}}{G_{M_n}} \to -0.21$$

at $Q^2 = 100$(GeV/c)^2. Consistent with p-QCD!

Both are in violation of the $SU(6)$ value $-3/2$.

Data?

Of utmost importance: Measure the magnetic form factor of the neutron in a model independent way at large Q^2

5. Stability against perturbations

(i) Additional vector mesons

$\rho(1450), \omega(1390), \varphi(1680)$

(Lomon, 2001)

(ii) Addition of an intrinsic piece to Pauli form factor F_2^V

$$\rightarrow (3.706 - \alpha_\rho)\frac{1}{(1+\gamma Q^2)} + \alpha_\rho \frac{m_\rho^2}{m_\rho^2 + Q^2}$$

(iii) Logarithm dependence of perturbative QCD

$$Q^2 \rightarrow Q^2 \frac{\ln[(\Lambda^2 + Q^2)/\Lambda_{QCD}^2]}{\ln[\Lambda^2/\Lambda_{QCD}^2]}$$

⇒Qualitative features not affected by these changes

6. Time-like form factors

Related by analytic continuation to the space-like form factors

A. Proton

Measured experimentally by

$e^+e^- \rightarrow p\bar{p}$ and $p\bar{p} \rightarrow e^+e^-$ [Fermilab E760-E835]

Physical region $-\infty \leq Q^2 \leq -4M_N^2$

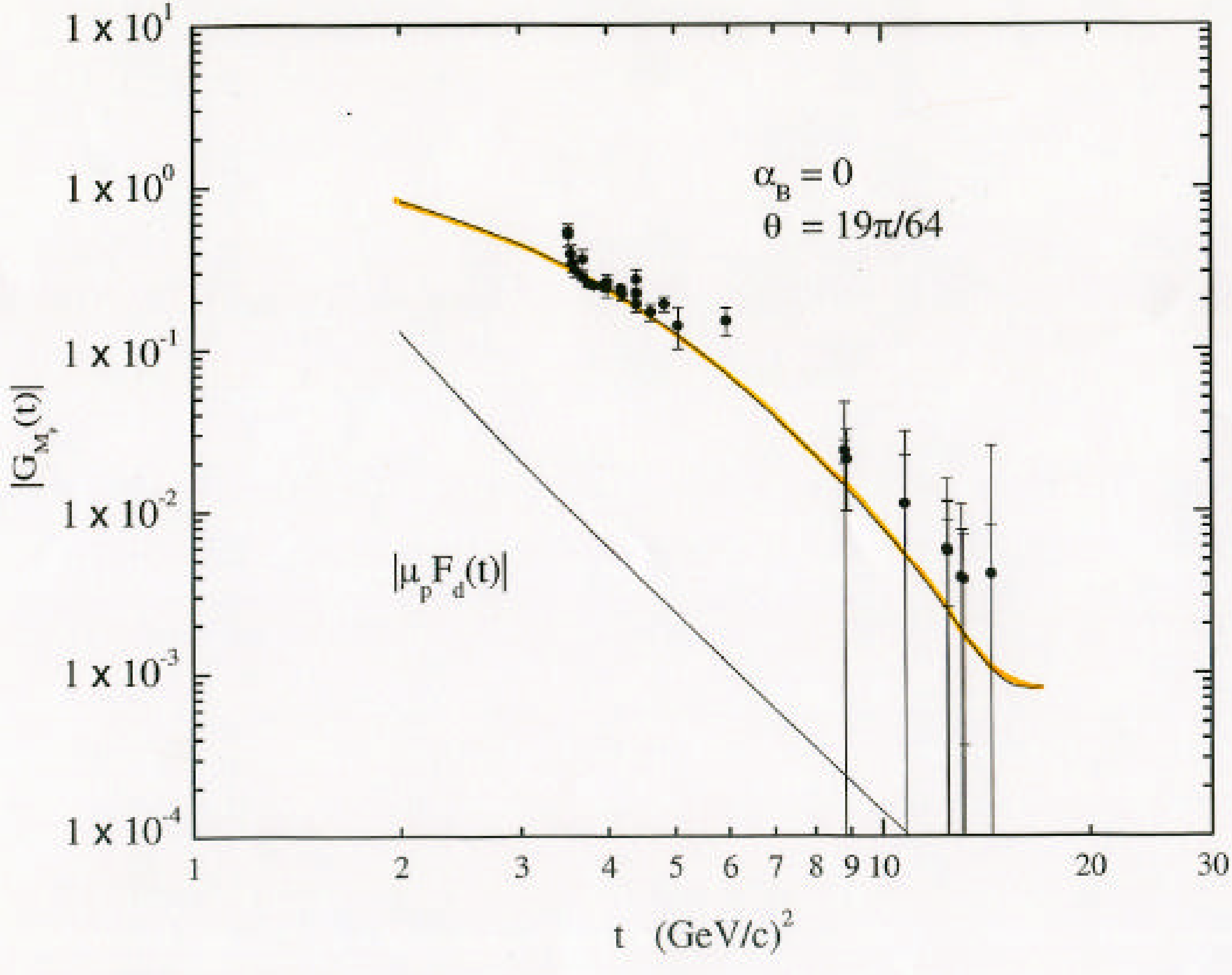
Straigthforward analytic continuation of the 1973 model (except for the ρ width)

$$g(Q^2) = \frac{1}{(1+\gamma e^{i\theta}Q^2)^2}$$

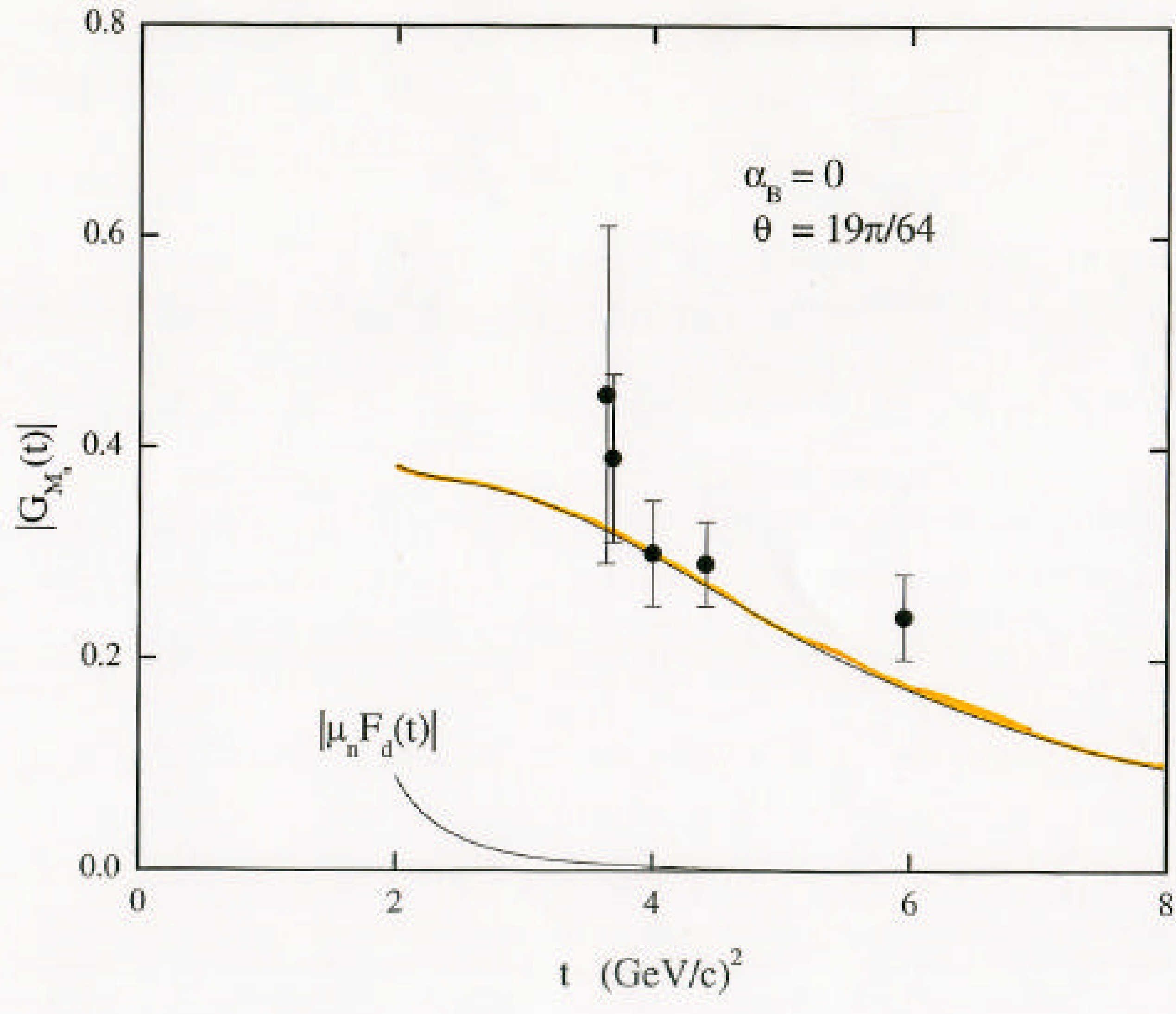
with $\theta \simeq \pi/4$ (Iachello and Wan, 2003)

In good agreement with data! (Ambrogiani et al., 1999)

Analytic continuation of the dipole form (dimensional scaling) in major disagreement with experiment



$\alpha_B = 0$
$\theta = 19\pi/64$
$|\mu_p F_d(t)|$
$|G_{M_\Lambda}(t)|$
t (GeV/c)^2
1 x 10^1
1 x 10^0
1 x 10^{-1}
1 x 10^{-2}
1 x 10^{-3}
1 x 10^{-4}
1 2 3 4 5 6 7 8 9 10 20 30



$\alpha_B = 0$
$\theta = 19\pi/64$
$|G_{M_s}(t)|$
$|\mu_n F_d(t)|$
t (GeV/c)^2
0.0
0.2
0.4
0.6
0.8
0
2
4
6
8

C. Ratio G_M^n/G_M^p

This ratio is predicted to be $-\frac{2}{3}$ by SU(6) symmetry

IJL predicts

$$\frac{G_M^n}{G_M^p} \sim -2$$

in the Q^2 range of the FENICE experiment

p-QCD predicts

$$\frac{G_M^n}{G_M^p} \rightarrow -\infty$$

IJL in excellent agreement with FENICE

Of utmost importance: measure G_M^n/G_M^p accurately

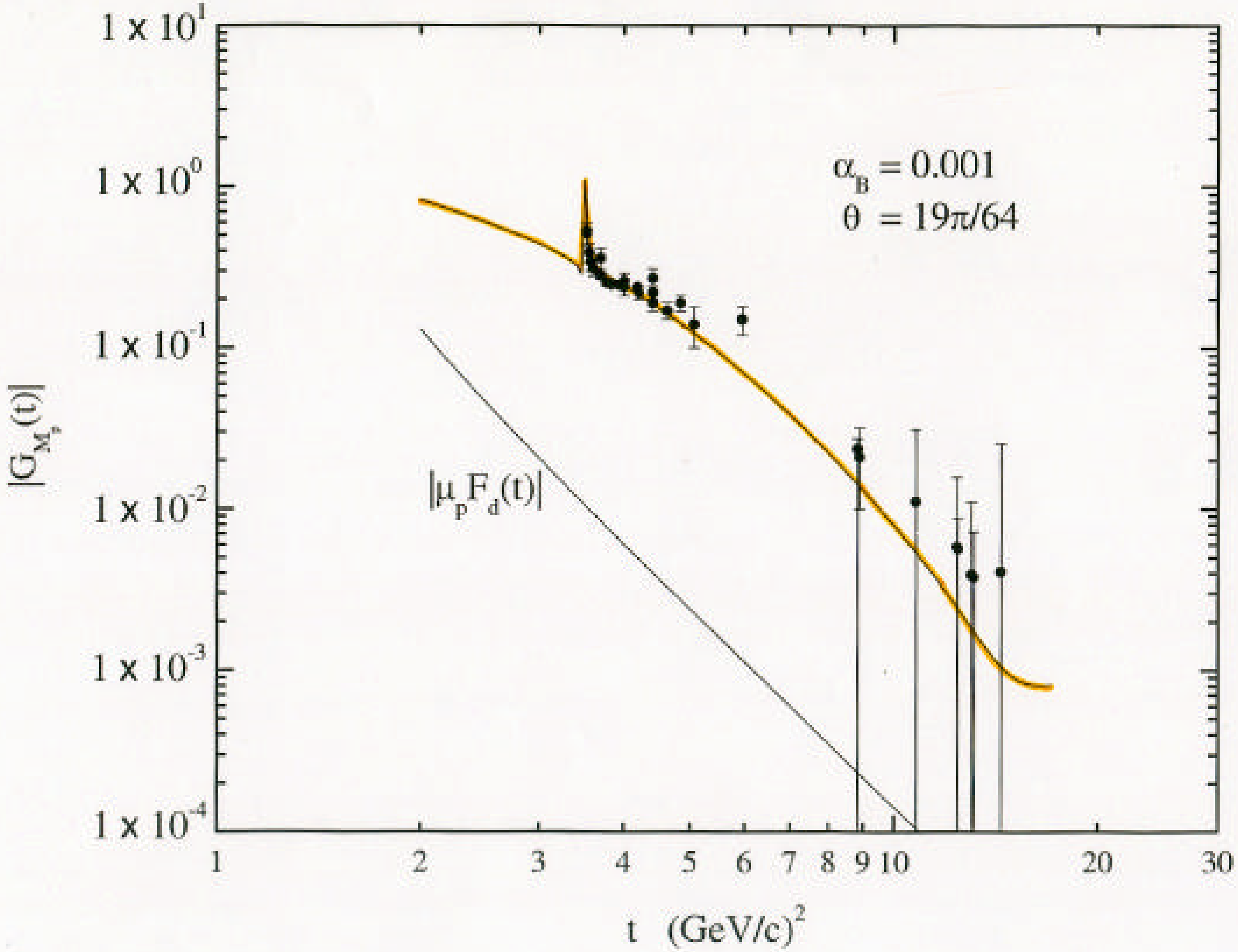
D. Subthreshold resonances

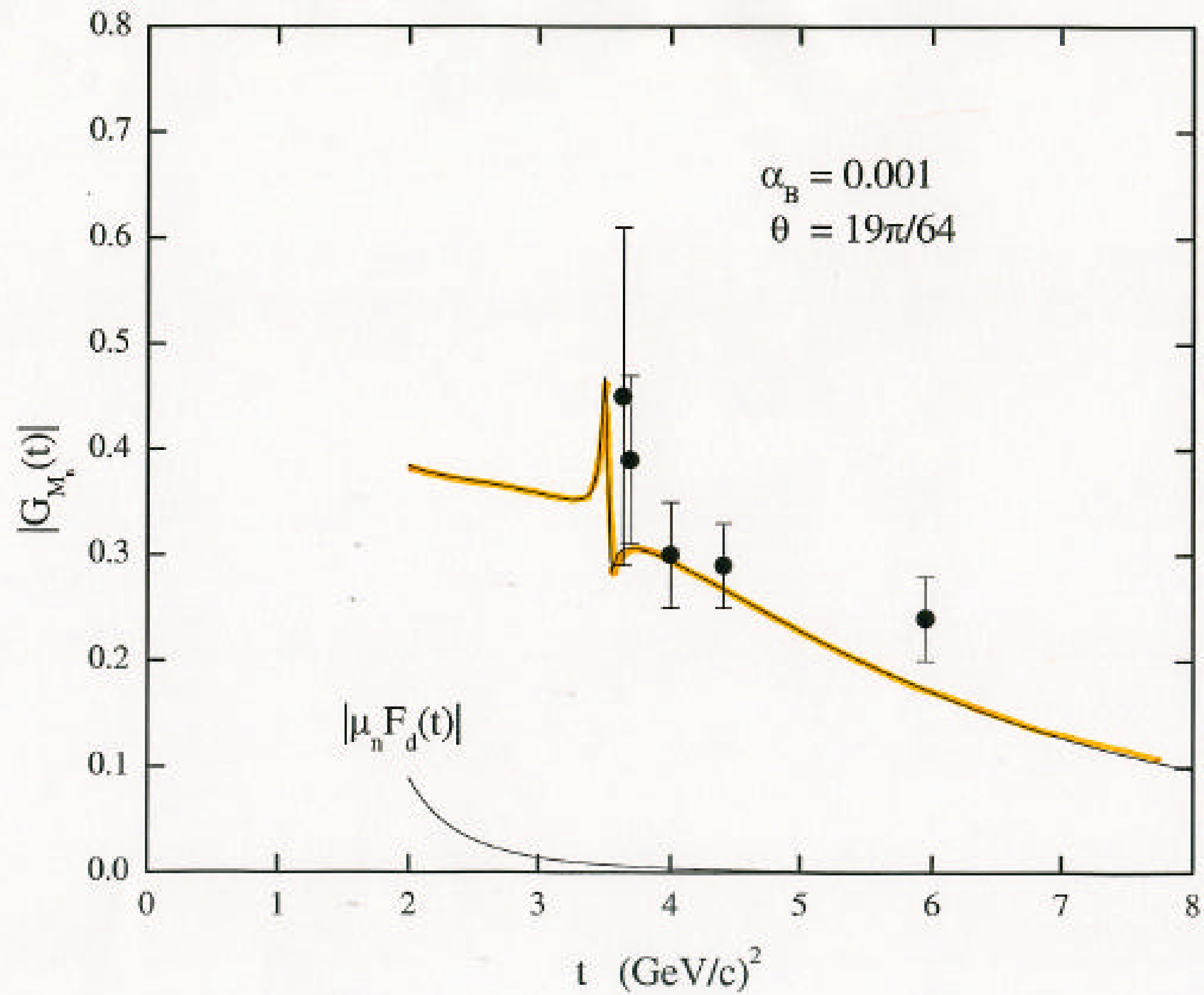
From proton data

⇒ Indication of a subthreshold resonance

Excellent fit with subthreshold resonance at $M_X \simeq 1870$MeV

⇒ Of utmost importance: measure G_M^n close to threshold


$\alpha_B = 0.001$
$\theta = 19\pi/64$
$|\mu_p F_d(t)|$
$|G_{M_s}(t)|$
t (GeV/c)^2
1 x 10^1
1 x 10^0
1 x 10^{-1}
1 x 10^{-2}
1 x 10^{-3}
1 x 10^{-4}
1
2
3
4
5
6
7
8
9
10
20
30



α_B = 0.001
θ = 19π/64
|G_{M_e}(t)|
|μ_n F_d(t)|
t (GeV/c)^2
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7
8

7. Conclusions

A.

Hofstadter (1960): Nucleon not point-like.

Gayou et al (2002): Complex structure of the nucleon: intrinsic (valence quarks)+ meson cloud ($q\bar{q}$ pairs).

B.

Size of the intrinsic structure r.m.s.~ 0.34 fm

C.

p-QCD not reached at 10 $(GeV/c)^2$. Physics up to this scale dominated by a mixture of hadronic and quark components.

D.

Symmetry, rather than detailed dynamics, appears to be the determining factor in the structure of the nucleon.

The nucleon: the basic building block of matter

Not yet completely understood

⇒New experiments needed both in the space-like and time-like region of the form factors

In the quest for the structure of the nucleon (QCD in the non-perturbative regime) DAFNE-2 could play a crucial role in

(i) testing the breaking of the effective $SU(6)$ symmetry through measurements of G_M^n/G_M^p

(ii) testing deviations from dimensional scaling of the ratio G_E/G_M, as shown dramatically by recent TJNAF experiments in the space-like region. (Requires a separation of G_E from G_M).

(iii) prove the existence of subthreshold resonances, hinted by presently available data on the proton