Quark models of N* electrocouplings at high Q^2 and their *connection to QCD*

Nucleon Resonance Structure in Exclusive Electroproduction at High Photon Virtualities with the CLAS 12 Detector

Jefferson Lab, May 16th, 2011

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Some observations

CQMs

- not **derived** from QCD (at least for the moment)
- **approximated** approaches to QCD dynamics
- **necessary** (as other models) QCD equations not yet solved
- LQCD results: very important, not yet systematic
- evolution of CQMs: benefits from QCD aspects

quark models before QCD

First formulation of Quark Model (Gell-Mann, Zweig 1964)

- realizations of SU(3) symmetry
- internal indexes useful for quantum numbers

Constituent Quark (Morpurgo 1965)

- hadrons as bound states of quarks
- binding from a potential
- high quark mass (up to 10 GeV)

Non Relativistic model

Excited baryon wave function with h.o.
symmetric model working well (Horgan-Dalitz 1973)

Birth of QCD

Quarks have been observed

Bjorken scaling:

Proton composed of **pointlike** objects

spin 1/2 (partons)

confined

asymptotically free

QCD

Colour **SU(3) gauge theory**

quark and gluons

current quarks

massless

≠ Constituent Quarks

Some immediate benefits for CQM

$$\Psi_{3q} = \theta_{colour} \times \chi_{spin} \times \phi_{fl} \times \psi_{space}$$

$SU(3)_c$ **$SU(2)$** **$SU(3)_f$** **$O(3)$**

θ_{colour} is antisymmetric the rest is SYMMETRIC

Confinement

h.o. is acceptable

but non realistic

spectrum degeneracy of levels

Q^2 behavior of ff strongly damped

Proton (and baryon) structure

quarks ,gluons, quark-antiquark pairs

the interaction increases at low Q^2

Two types of quarks

valence quarks (determine quantum numbers)

sea quarks

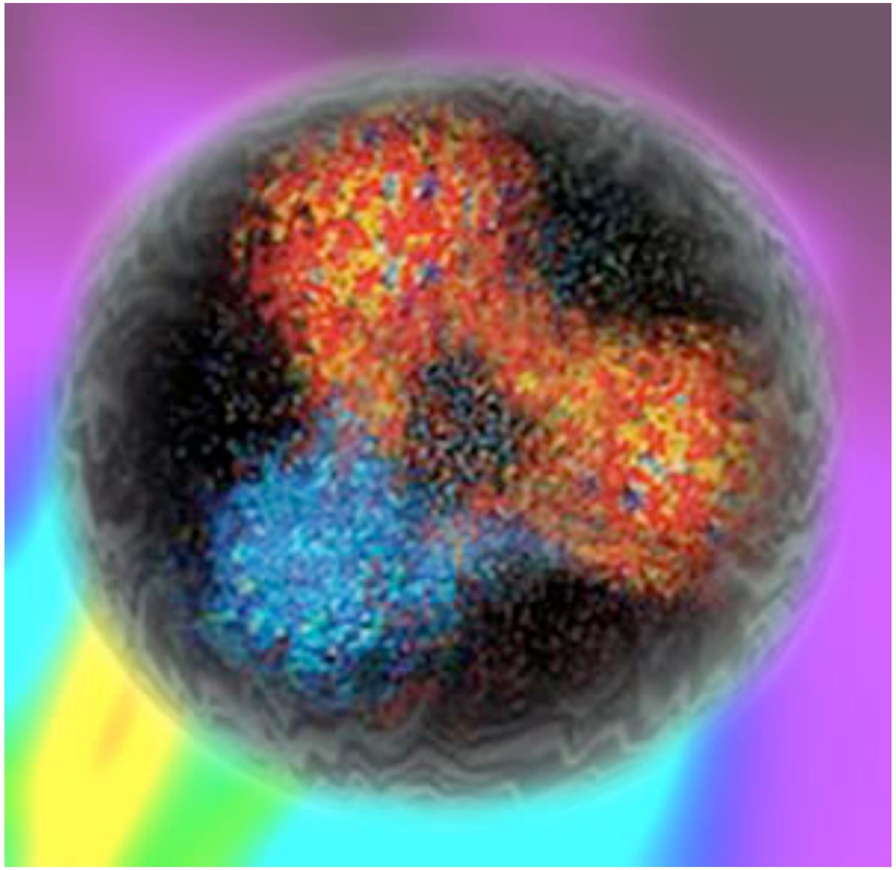
High Q^2 regime

Possible picture for proton structure

three valence quarks,

each surrounded by quark-antiquark pairs and gluons

plus …



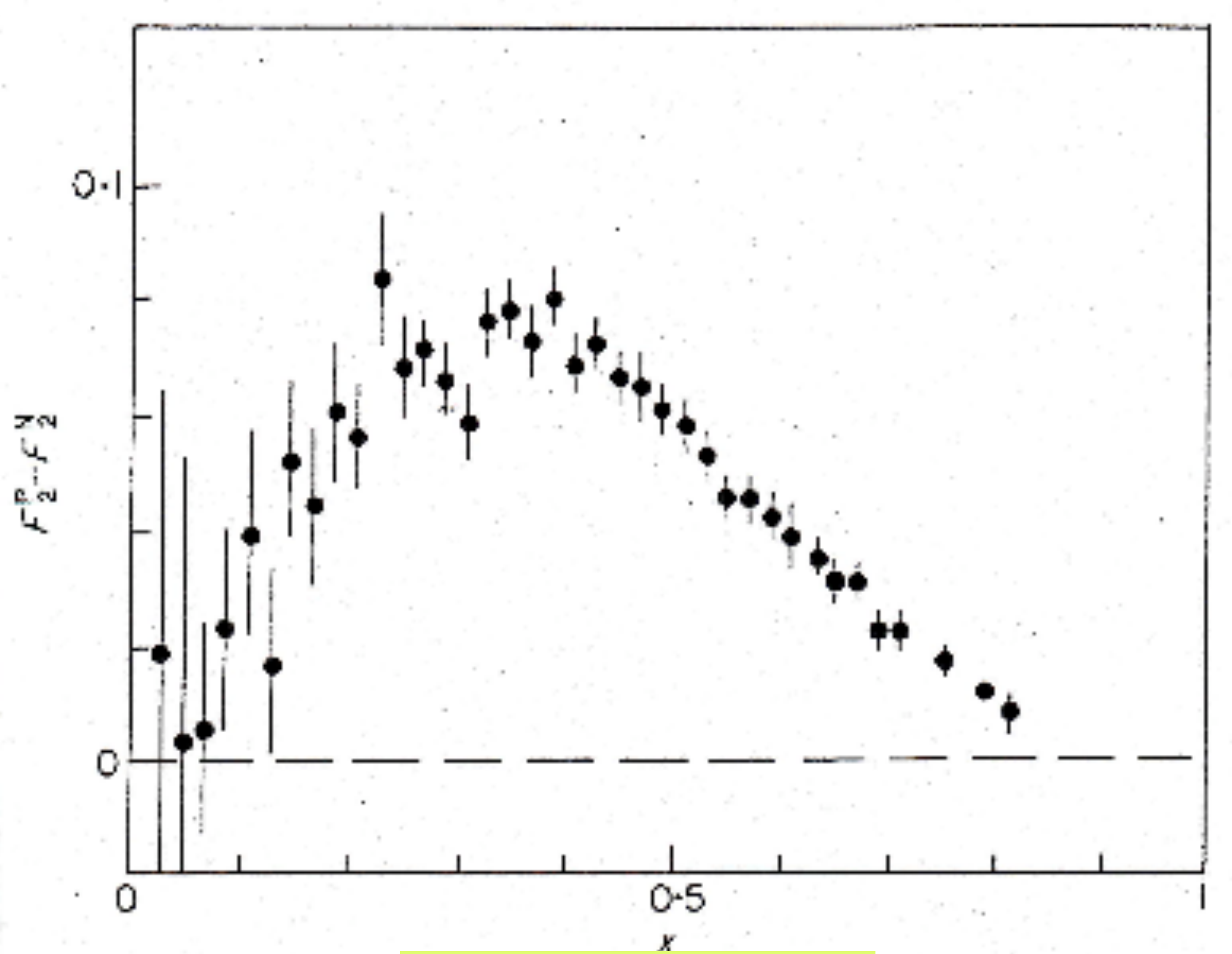
Constituent Quarks

At variance with QCD quarks:

CQ acquire mass &
size
carrier of the proton sin

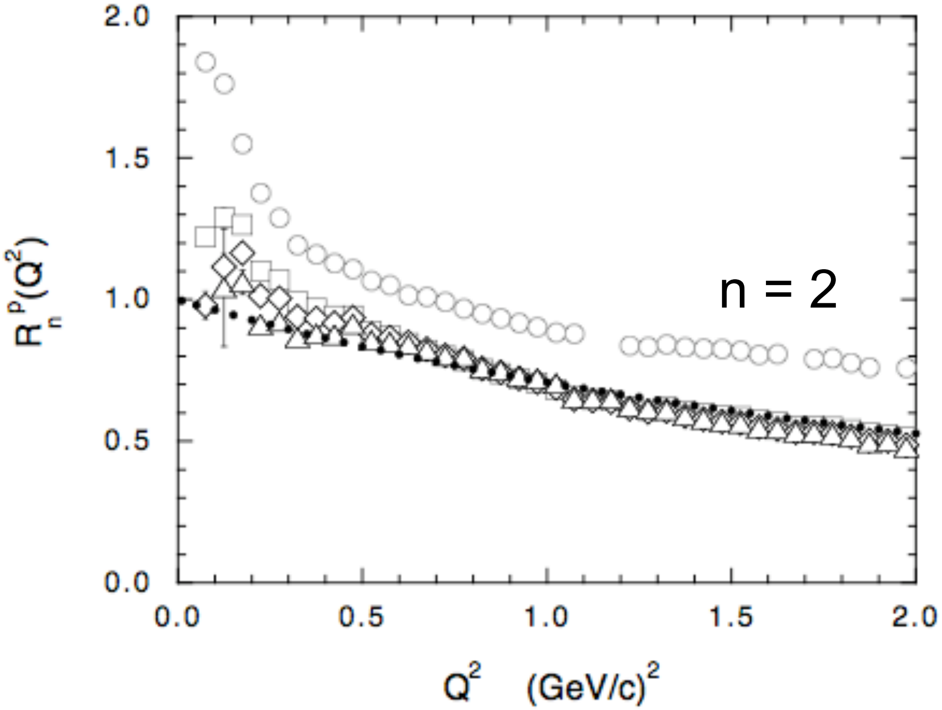
Medium-low Q^2

Further support 1



Peak at x » 1/3

Further support 2



Ratio between
proton Nachtmann moments &
CQ distribution

Bloom-Gilman duality

Inelastic proton scattering as elastic scattering on CQ

(approximate) scaling function ⟶ square of CQ ff

$F(Q^2) = 1/(1+ 1/6\, r_{CQ}^2\, Q^2)$

$r_{CQ} \cong$ **0.2 fm**

Ricco et al., PR **D67,** 094004 (2003)

Emerging picture

At medium-low Q^2 CQ are suitable internal degrees of freedom
they have mass, size and account for all quantum numbers

Including SPIN spin crisis?

Consistent inclusion of quark-antiquark pairs in the Unquenched quark model

	val	sea	total
$\Delta\Sigma$	0.378	0.298	0.676
ΔL	0.000	0.324	0.324
2J	0.378	0.622	1.000

Bijker-Santopinto
Phys.Rev. C80 (2009) 065210

main contribution coming from quark-antiquark pairs and their orbital angular momentum

Introducing dynamics

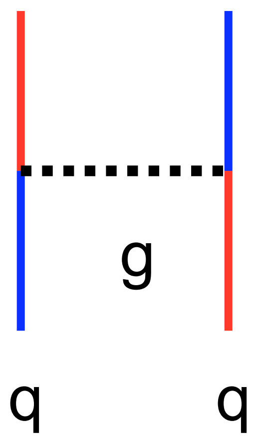
LQCD (De Rújula, Georgi, Glashow, 1975)

the quark interaction contains

- a long range spin-independent confinement

  $\longrightarrow$ SU(6) configurations

- a short range spin dependent term



One Gluon Exchange

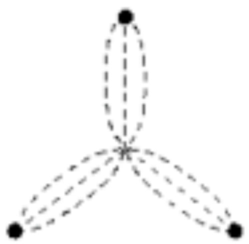
V_{OGE} = -a/r + Hyperfine interaction

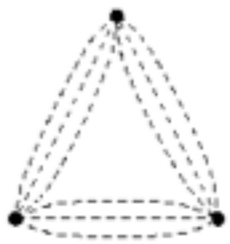
- QCD fundamental mechanism

3-body forces

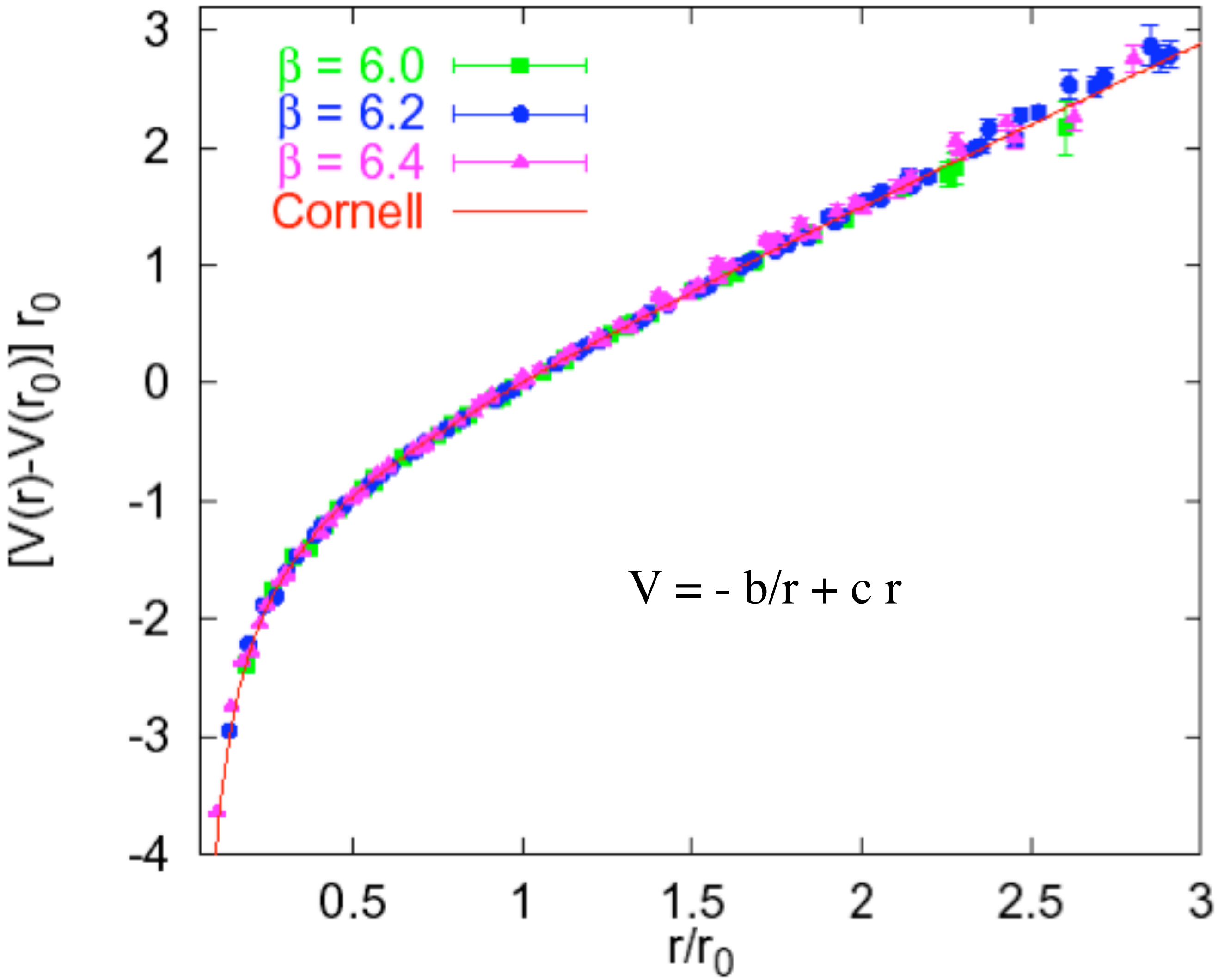
Carlson et al, 1983
Capstick-Isgur 1986
hCQM 1995

- Flux tube model

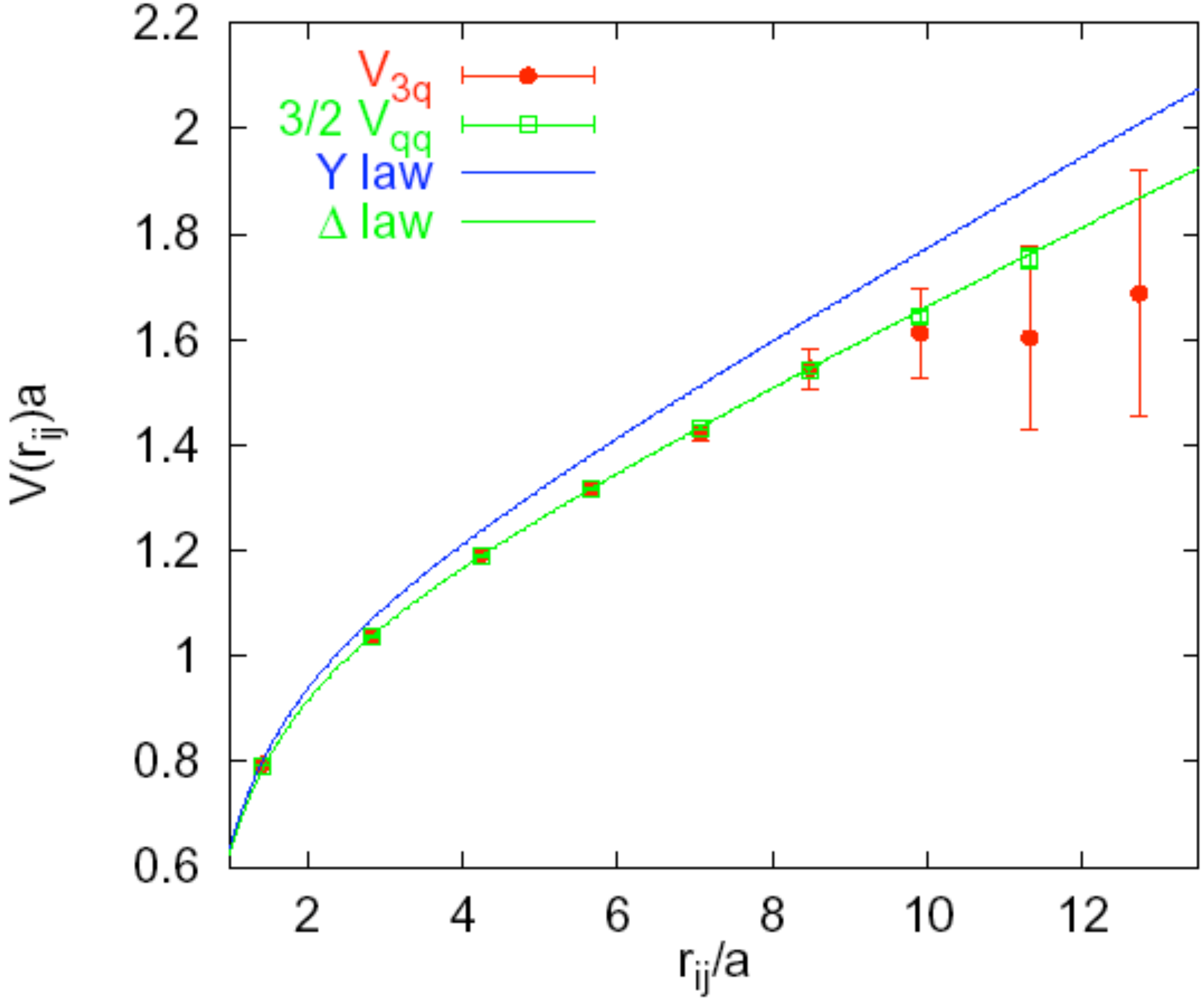




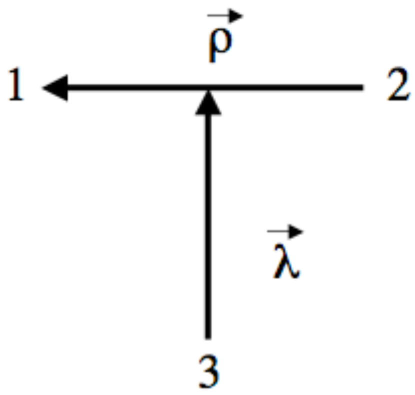
Quark-antiquark lattice potential G.S. Bali Phys. Rep. 343, 1 (2001)



3-quark lattice potential G.S. Bali Phys. Rep. 343, 1 (2001)



Jacobi coordinates



Hyperspherical Coordinates

$$(\rho, \Omega_\rho, \lambda, \Omega_\lambda) \Rightarrow (x, t, \Omega_\rho, \Omega_\lambda)$$

$$x = \sqrt{\rho^2 + \lambda^2}$$

$$t = arctg\frac{\rho}{\lambda}$$

$$L^2(\Omega)Y_{[\gamma]}(\Omega) = -\gamma(\gamma+4)Y_{[\gamma]}(\Omega)$$

$$L^2(\Omega) \Leftrightarrow C_2(O(6))$$

γ grand angular quantum number

$Y_{[\gamma]}(\Omega)$ Hyperspherical harmonics

$$\sum_{i<j} V(\mathbf{r}_{ij}) \approx V(x) + \dots$$

Hasenfratz et al. 1980:
$\Sigma\, V(r_i,r_j)$ is approximately hypercentral

Hypercentral Hypothesis $V = V(x)$

Factorization

$$\psi(x, t, \Omega_\rho, \Omega_\lambda) = \psi_{\nu\gamma}(x) \quad Y_{[\gamma, l_\rho, l_\lambda]}$$

("dynamics") ("geometry")

Only one differential equation in x (hyperradial equation)

Hypercentral Model

Genoa group, 1995

$V(x) = -\tau/x + \alpha\, x$

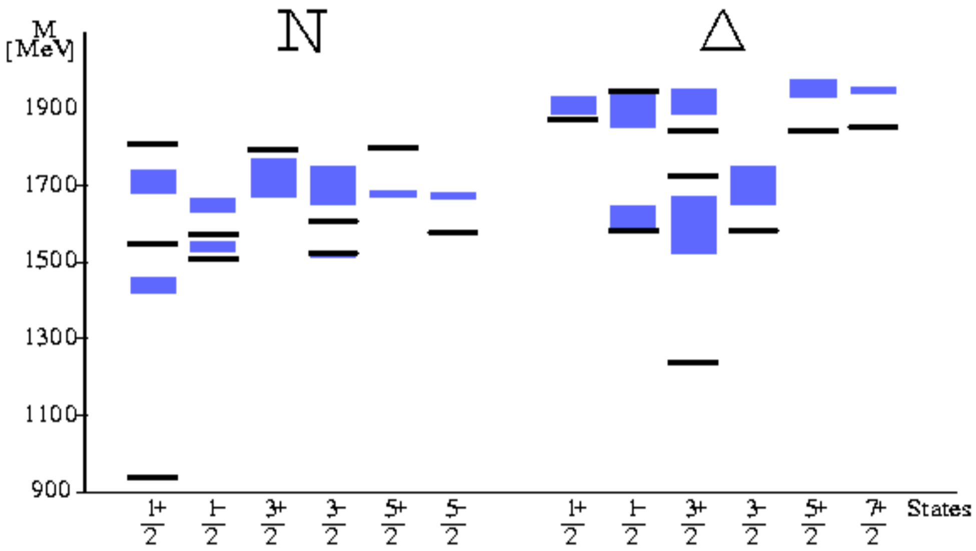
Hypercentral approximation of $V = - b/r + c\, r$

Hypercentral Model (1)

$$H_{3q} = 3m + \sum_{i=1}^{3} \frac{\mathbf{p}_i^2}{2m} + V(x) + H_{hyp}$$

M. Ferraris, M. M. Giannini, M. Pizzo, E. Santopinto, L. Tiator, Phys. Lett. B364 (1995), 231

- $V(x) = -\frac{\tau}{x} + \alpha x;$ $\qquad H_{hyp} = A \left[\sum_{i<j} V^S(\mathbf{r}_i, \mathbf{r}_j) \;\; \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j + \text{tensor} \right]$
- 3 parameters τ α A $\leftarrow$ fixed to the spectrum, $m = \frac{M}{3}$



$\tau = 4.59$

$\alpha = 1.61 \text{ fm}^{-1}$

$A \Leftarrow (N - \Delta)$

$$x = \sqrt{\rho^2 + \lambda^2}$$

hyperradius

Results (predictions) with the Hypercentral Constituent Quark Model

for

- Helicity amplitudes
- Elastic nucleon form factors

HELICITY AMPLITUDES

Definition

$A_{1/2} = < N^* \; J_z = 1/2 \mid H^T{}_{em} \mid N \; J_z = -1/2 > * \zeta$ §

$A_{3/2} = < N^* \; J_z = 3/2 \mid H^T{}_{em} \mid N \; J_z = 1/2 > * \zeta$ §

$S_{1/2} = < N^* \; J_z = 1/2 \mid H^L{}_{em} \mid N \; J_z = 1/2 > * \zeta$

N, N* nucleon and resonance as 3q states

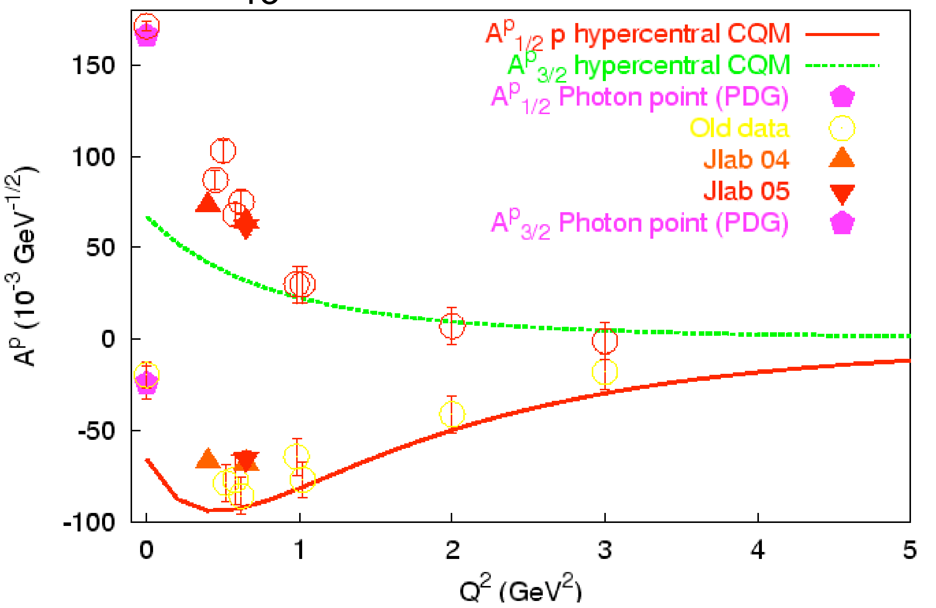
$H^T{}_{em}$ $H^l{}_{em}$ model transition operator

ζ overall sign -> problem

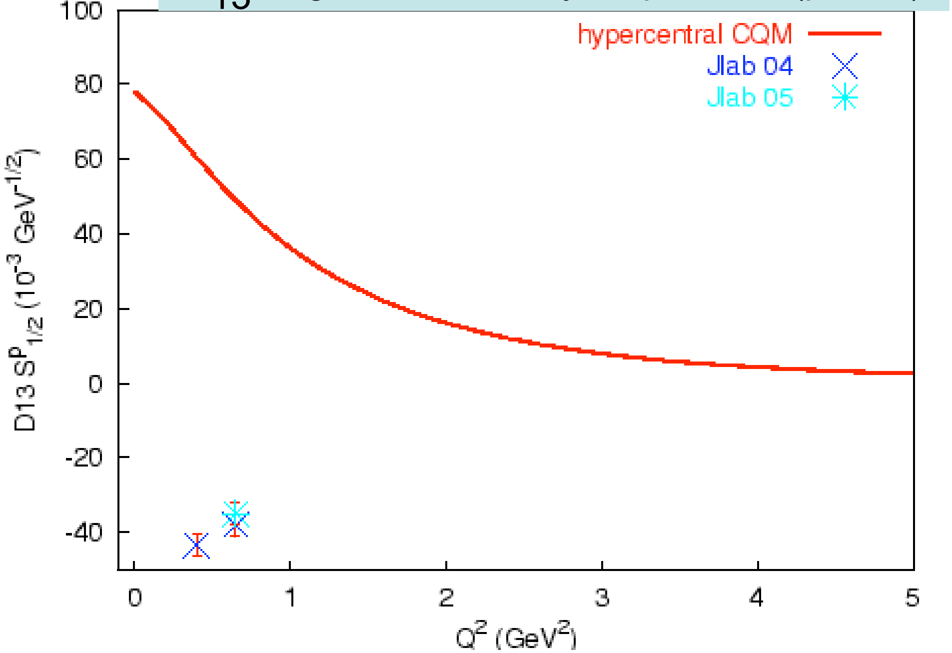
§ results for the negative parity resonances:
M. Aiello et al. J. Phys. G24, 753 (1998)

D_{13}

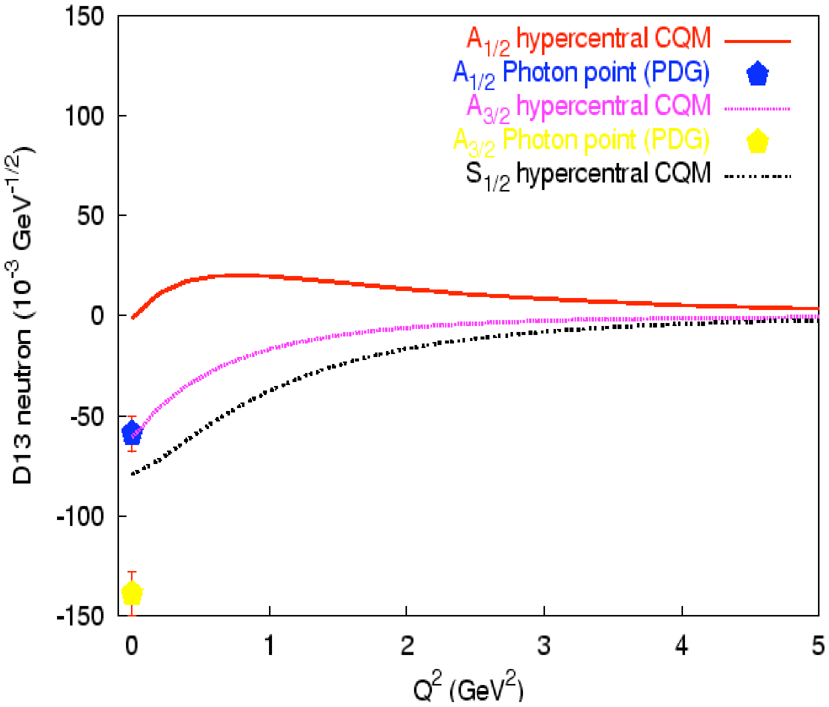
D_{13} transverse helicity amplitudes (proton)

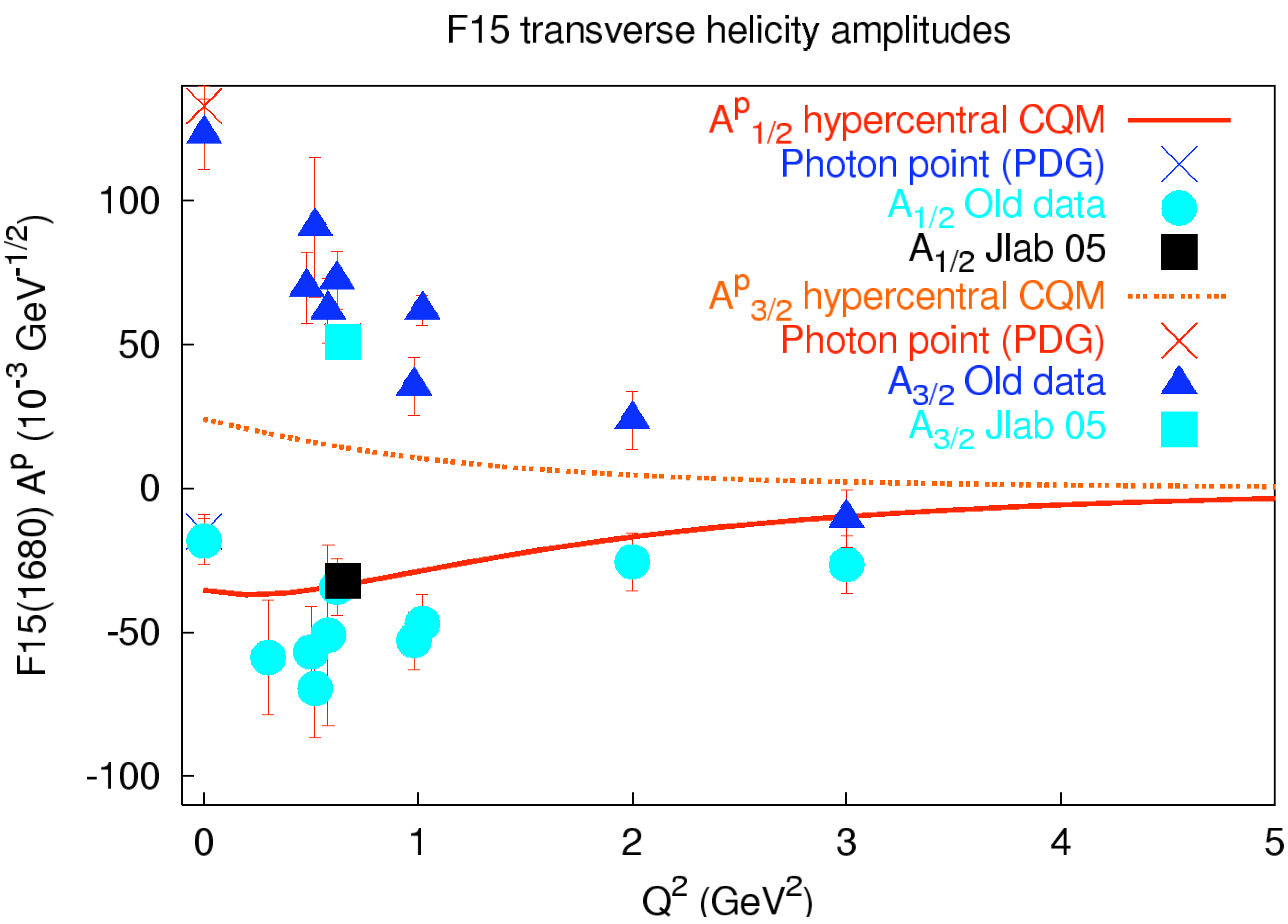


D_{13} longitudinal helicity amplitudes (proton)



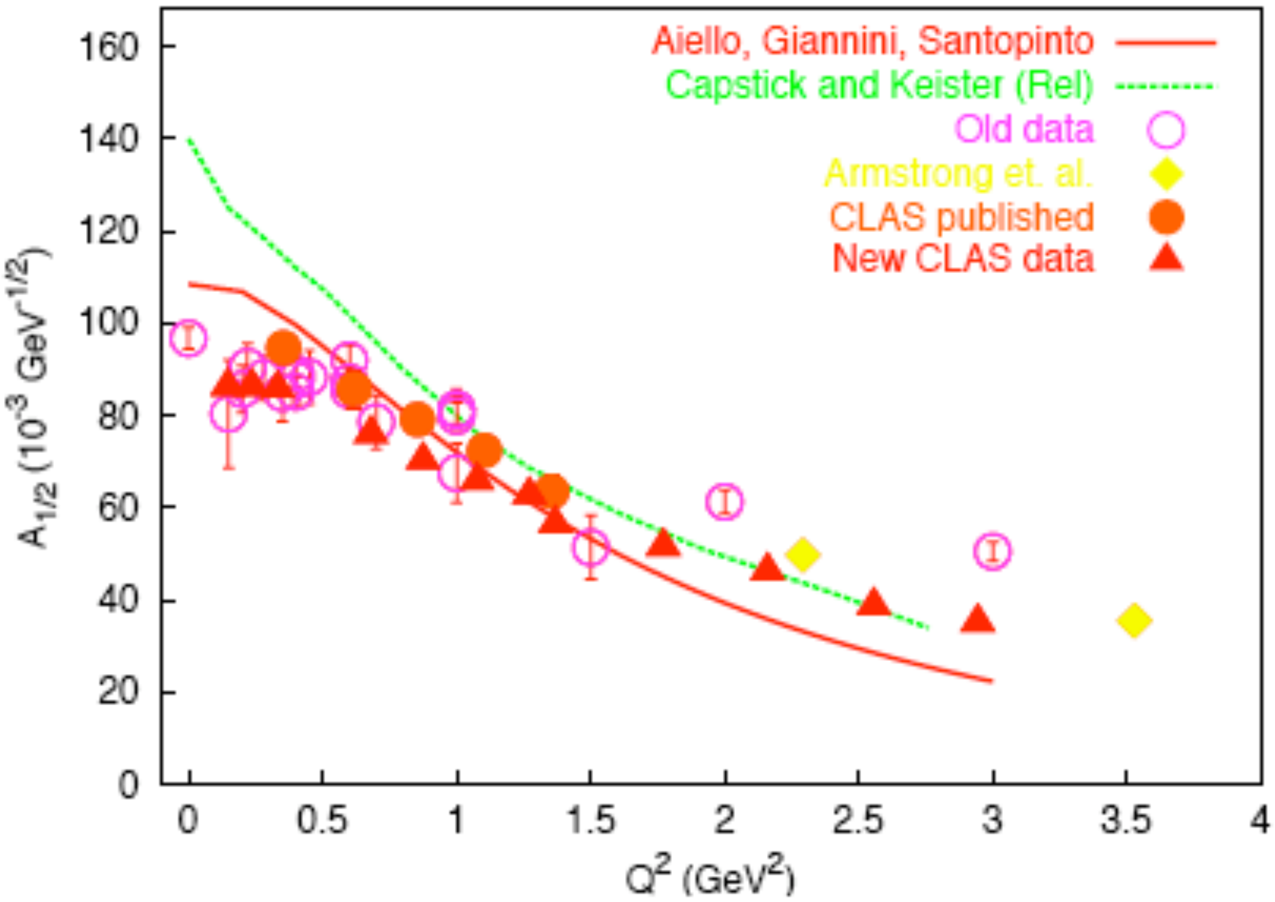
D_{13} helicity amplitudes (neutron)





F15 transverse helicity amplitudes
A^p_1/2 hypercentral CQM
Photon point (PDG)
A_1/2 Old data
A_1/2 Jlab 05
A^p_3/2 hypercentral CQM
Photon point (PDG)
A_3/2 Old data
A_3/2 Jlab 05
F15(1680) A^p (10^-3 GeV^-1/2)
Q^2 (GeV^2)
100
50
0
-50
-100
0
1
2
3
4
5

S11(1535)

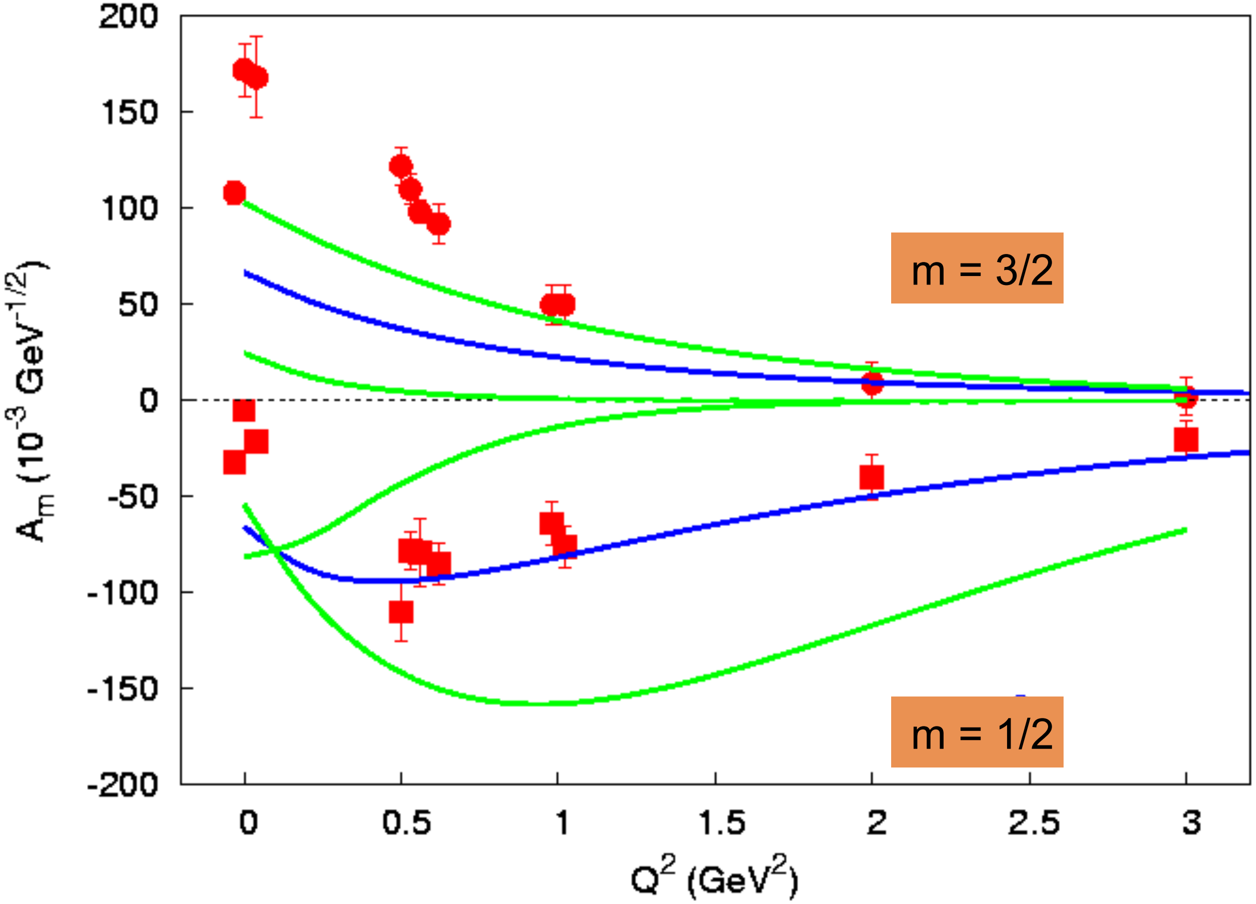


Aiello, Giannini, Santopinto
Capstick and Keister (Rel)
Old data
Armstrong et. al.
CLAS published
New CLAS data
$A_{1/2}$ (10^{-3} GeV$^{-1/2}$)
Q^2 (GeV^2)
0
20
40
60
80
100
120
140
160
0
0.5
1
1.5
2
2.5
3
3.5
4

A^p_m $N(1520)D13$

r_p 0.5 fm

r_p 0.86 fm

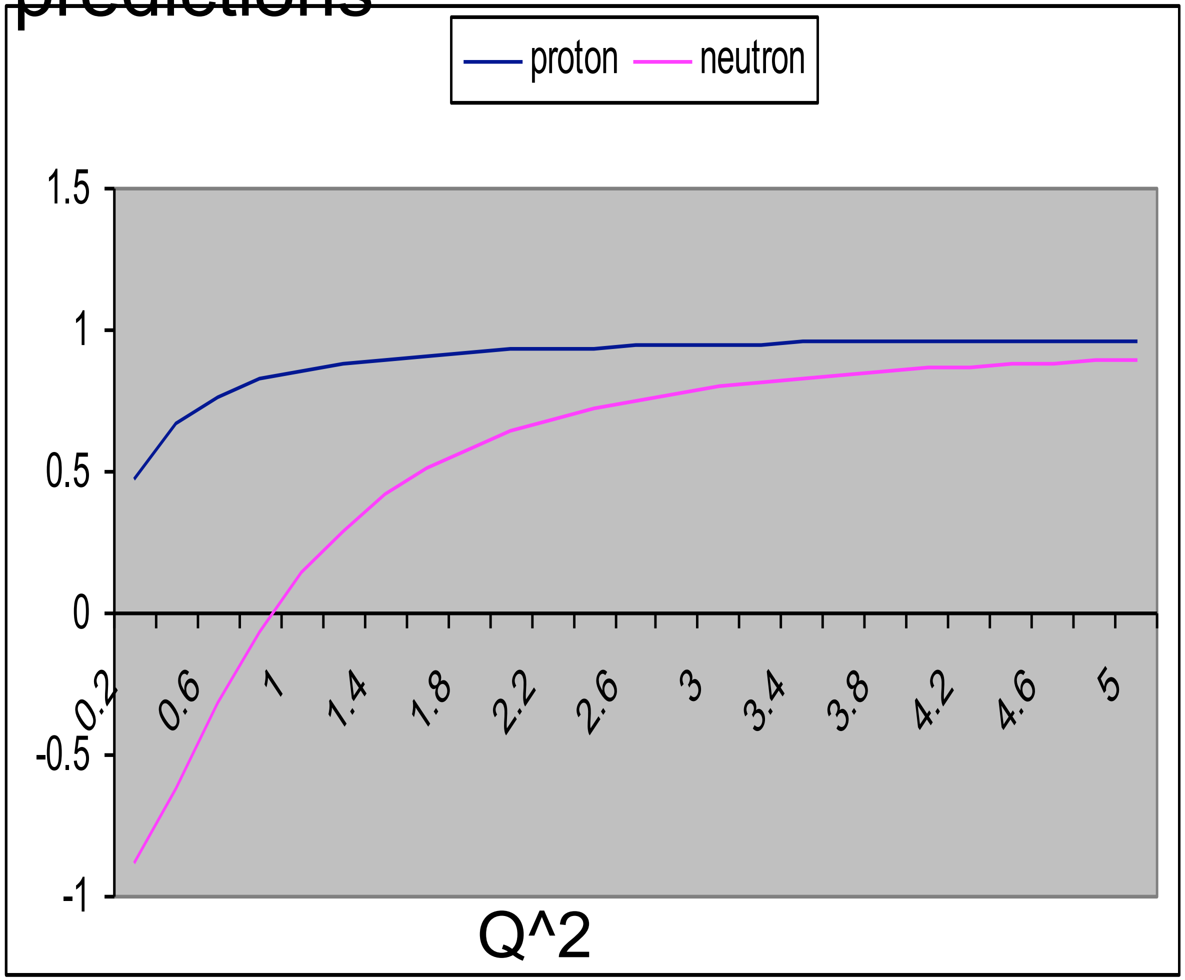


Green curves H.O.

Blue curves hCQM

D13 hCQM

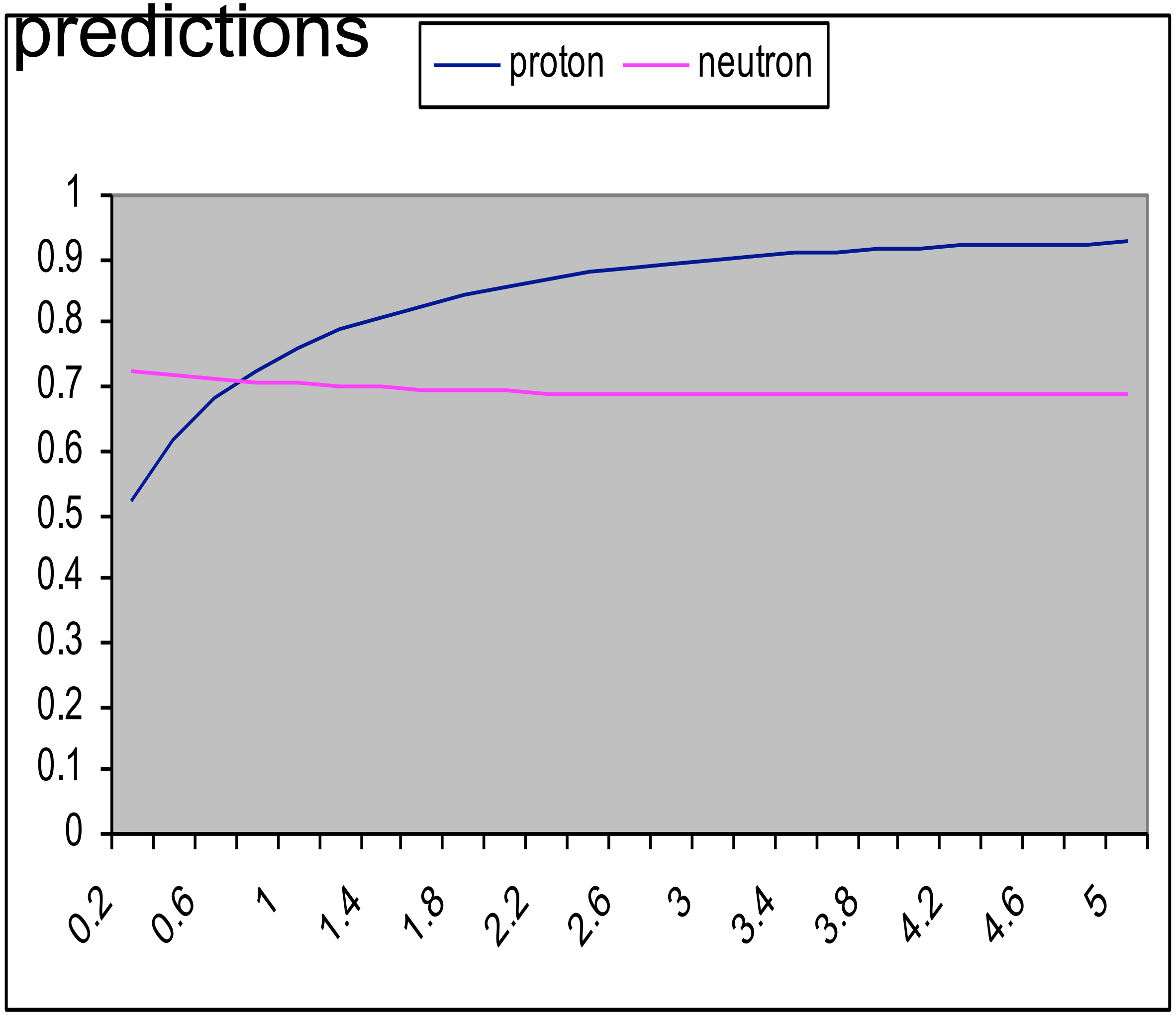
predictions



GeV^2

F15 predictions

hCQM



Q^2 GeV^2

Helicity ratio

	proton	neutron
P33	≈ -0.5	
D13	ok	ok
F15	ok	≈ 0.7
D13*	ok	0.96
D33	ok	
D15	1/3	≈ 0.32
F35	-0.82	
F37	-0.32	
P13	ok	ok

Structure effects ?

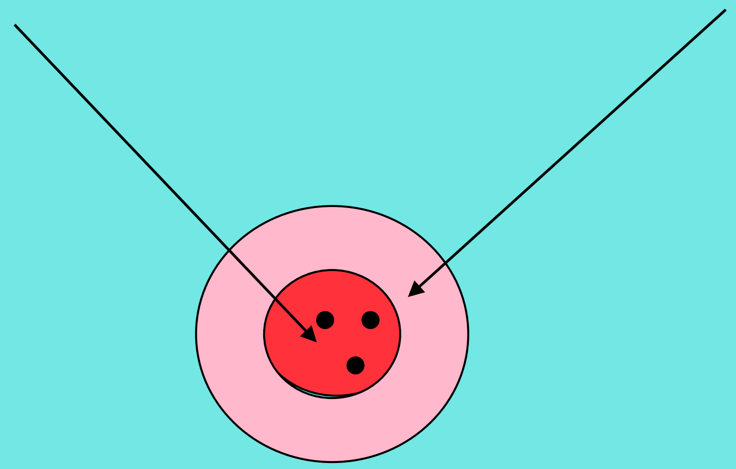
observations

- the calculated proton radius is about 0.5 fm

  (value previously obtained by fitting the helicity amplitudes)
- the medium Q^2 behaviour is fairly well reproduced (1/x potential)
- there is lack of strength at low Q^2 (outer region) in the e.m. transitions

  specially for the A 3/2 amplitudes
- emerging picture: quark core (0.5 fm) plus (meson or sea-quark) cloud

Quark-antiquark pairs effects are important for the low Q^2 behavior



Elastic form factors

The non relativistic calculation gives values higher than data since the calculated radius is 0.5 fm

a relativistic calculation is needed

Performed by variuos groups

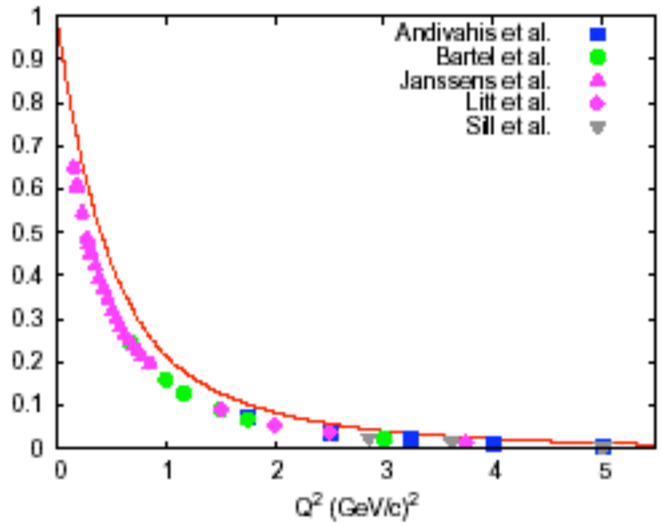
Rome,	Pavia-Graz,	Bonn,	Genova
LF	PF	BS	PF

Calculated values!

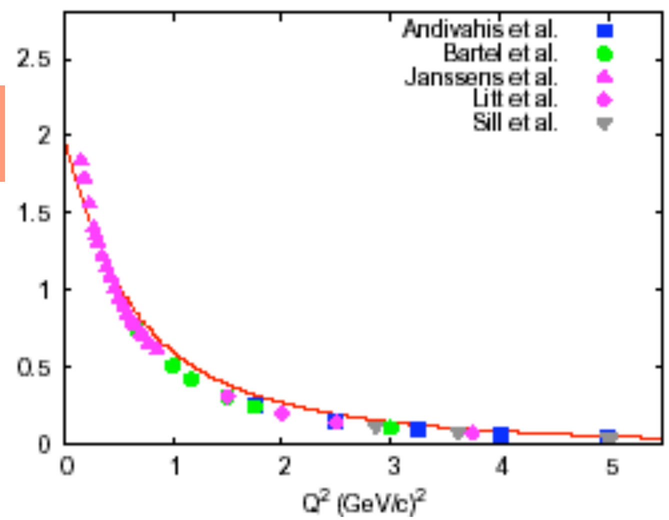
- Boosts to initial and final states
- Expansion of current to any order
- Conserved current

Relativistic theory in point form

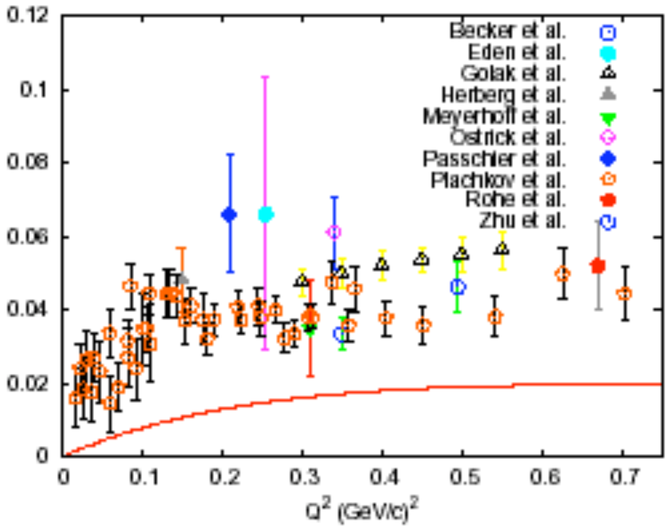
G_E^p



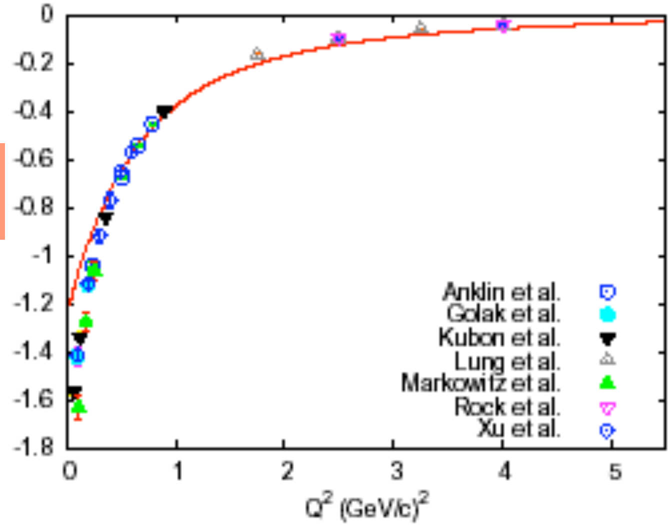
G_M^p



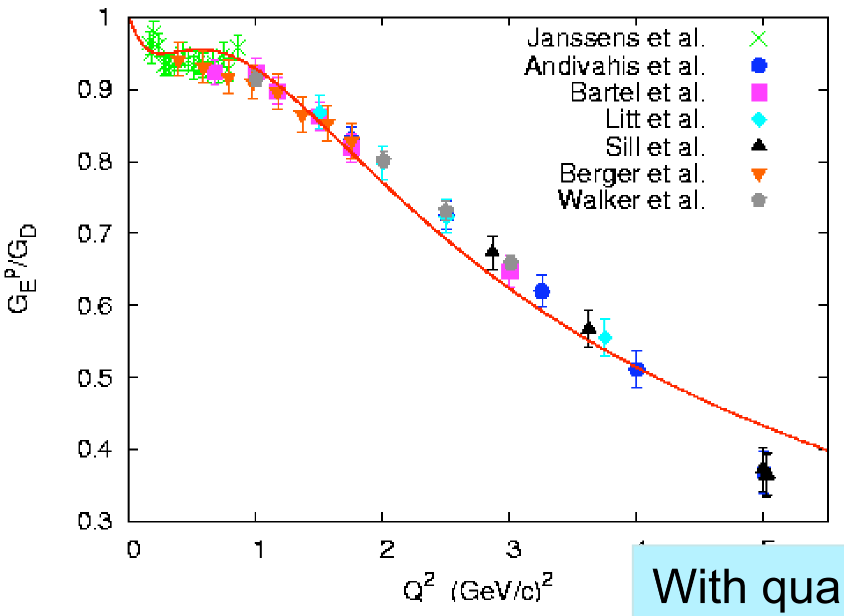
G_E^n

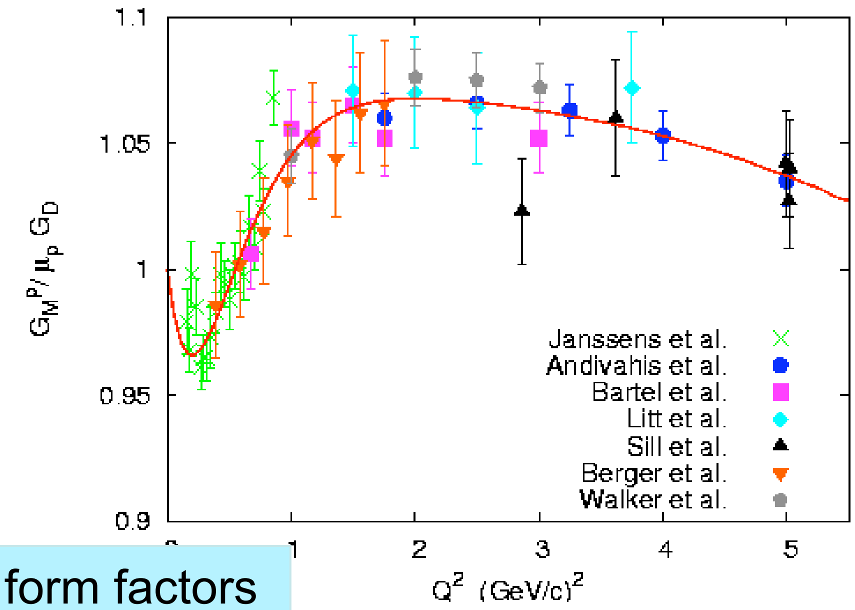


G_M^n

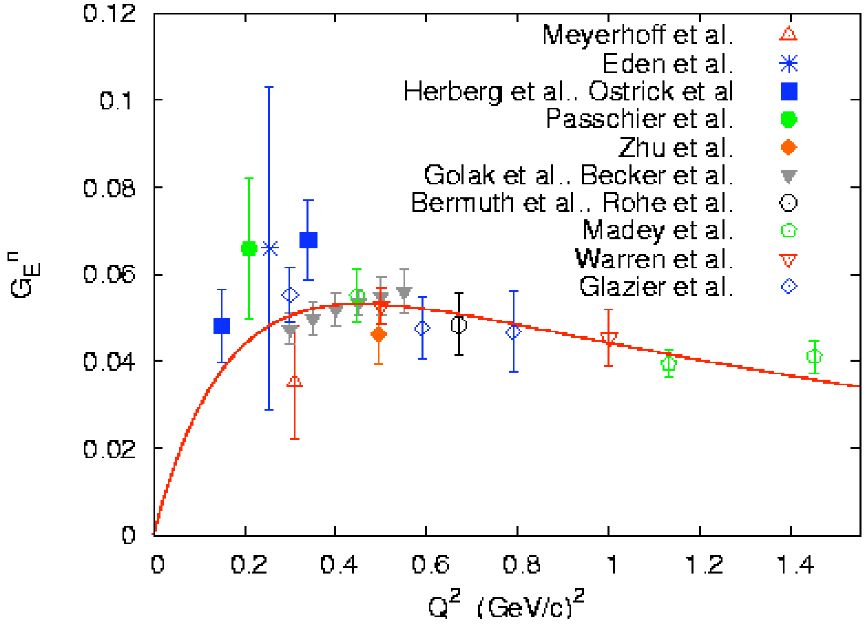


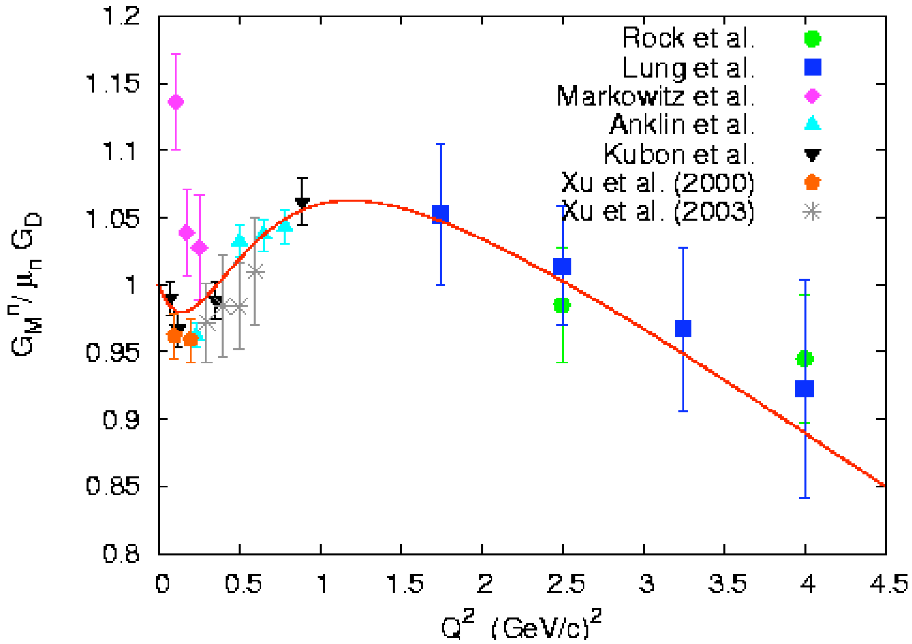
M. De Sanctis, M.G., E. Santopinto, A. Vassallo, PR C **76**, 062201(R) (2007)



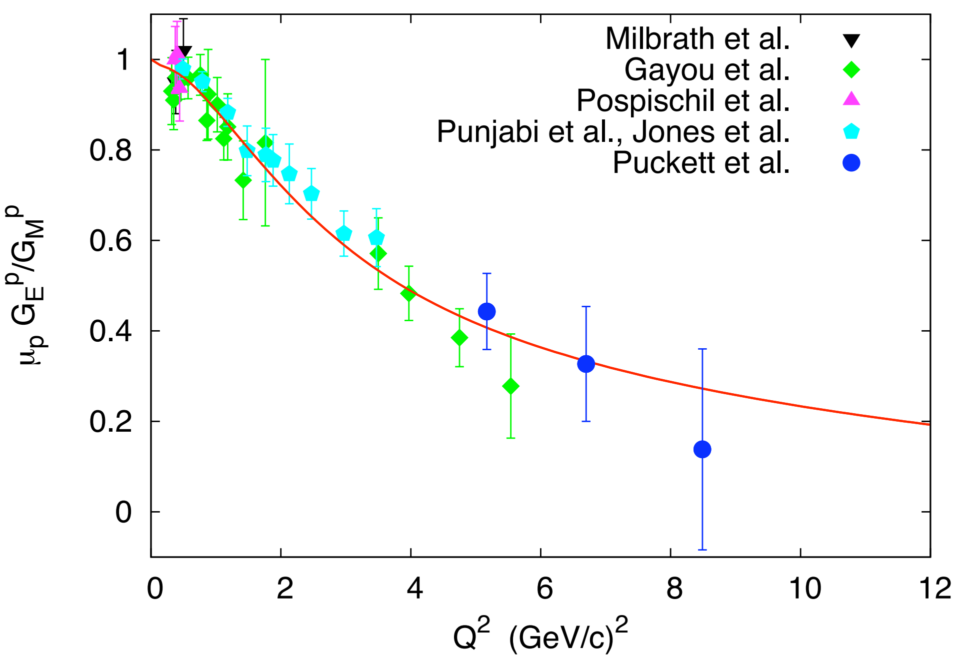


With quark form factors

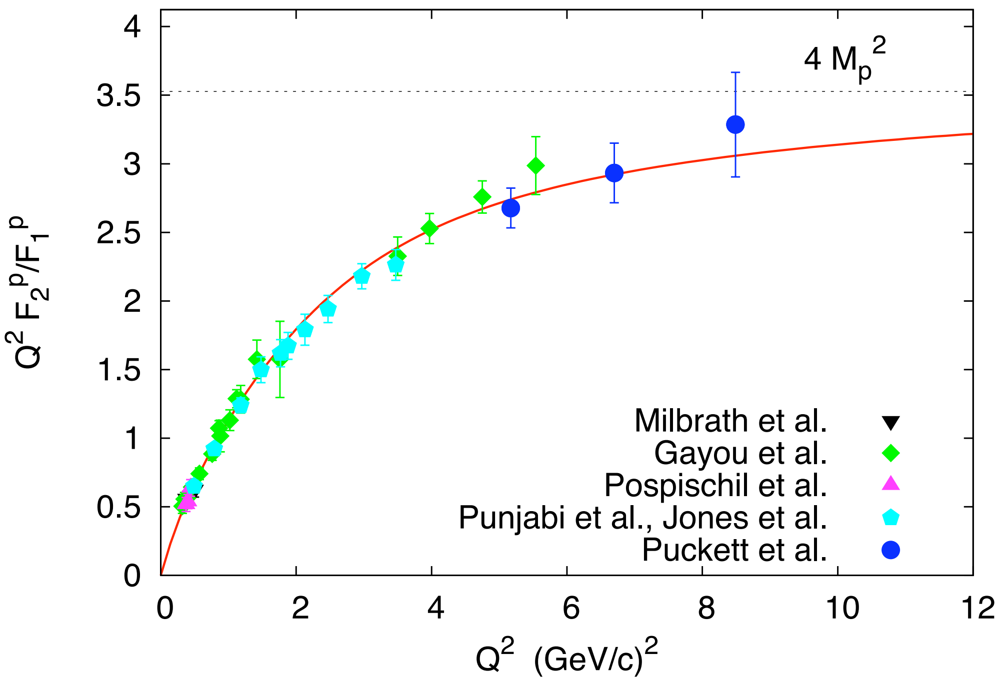




Genoa group, Phys. Rev. C76, 062201 (2007)



With quark form factors



Santopinto et al.
PR C **82**, 065204 (2010)

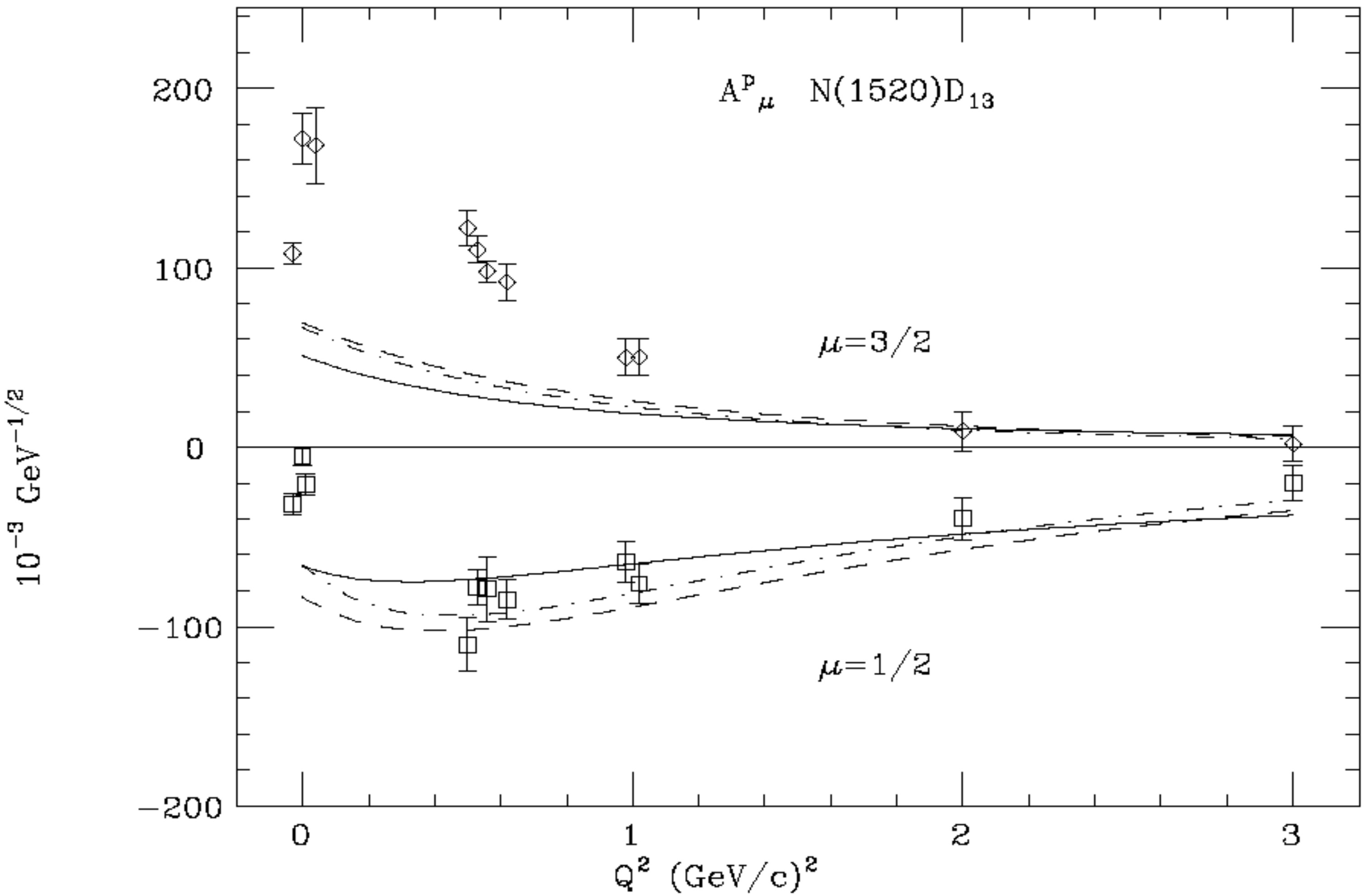
Relativistic corrections to form factors

- Breit frame
- Lorentz boosts applied to the initial and final state
- Expansion of current matrix elements up to first order in quark momentum
- Results

$$A_{rel}(Q^2) = F \; A_{n.rel}(Q^2_{eff})$$

F = kin factor $\quad Q^2_{eff} = Q^2 (M_N/E_N)^2$

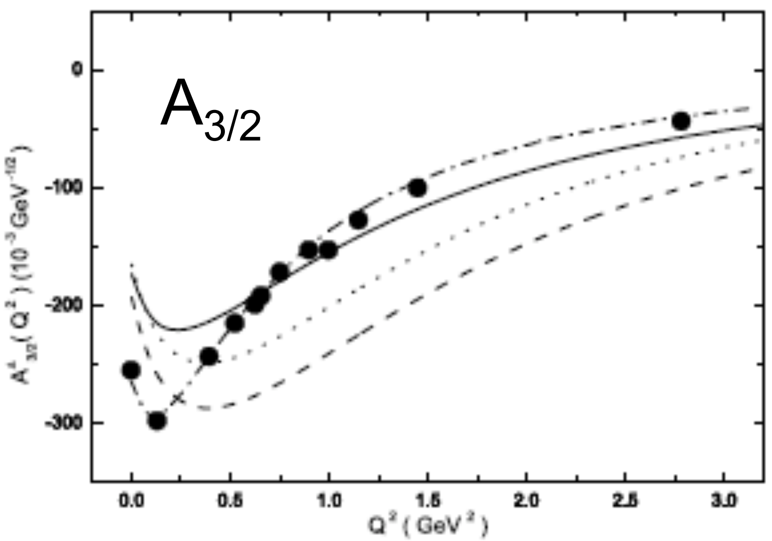
De Sanctis et al. EPJ 1998

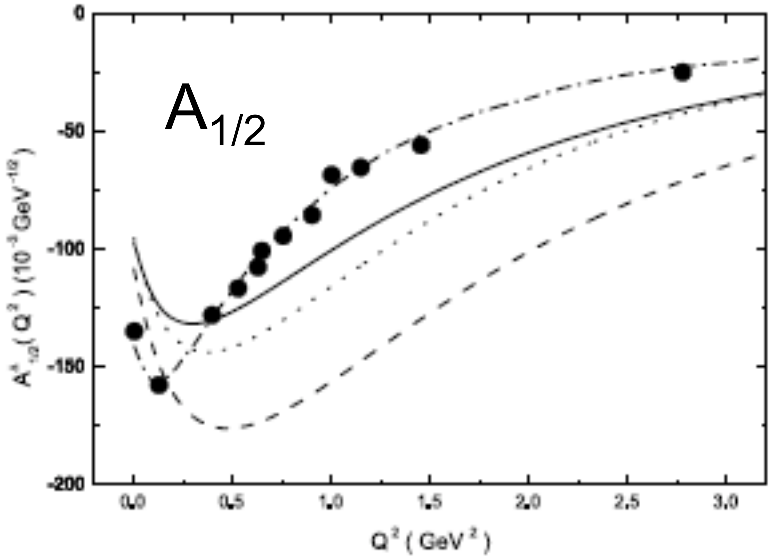


Full curves: hCQM with relativistic corrections

Dashed curves: hCQM in different frames

Chen, Dong, M.G., Santopinto, Trieste 2006





dot bare
dash dressed
full rel. corr (prelimnary calculation)
dash-dot MAID

Relativistic treatment

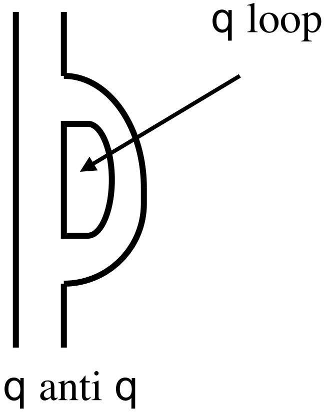
- elastic form factors: necessary
- helicity amplitudes: probably necessary
  exciting higher resonances the recoil is smaller
- Delta excitation: g.s. in the SU(6) limit
  probably more important

Relativity is an important issue for the description of elastic and inelastic form factors

but it is not the only important issue

Unquenching the quark model

Mesons P. Geiger, N. Isgur, Phys. Rev. D41, 1595 (1990)
D44, 799 (1991)

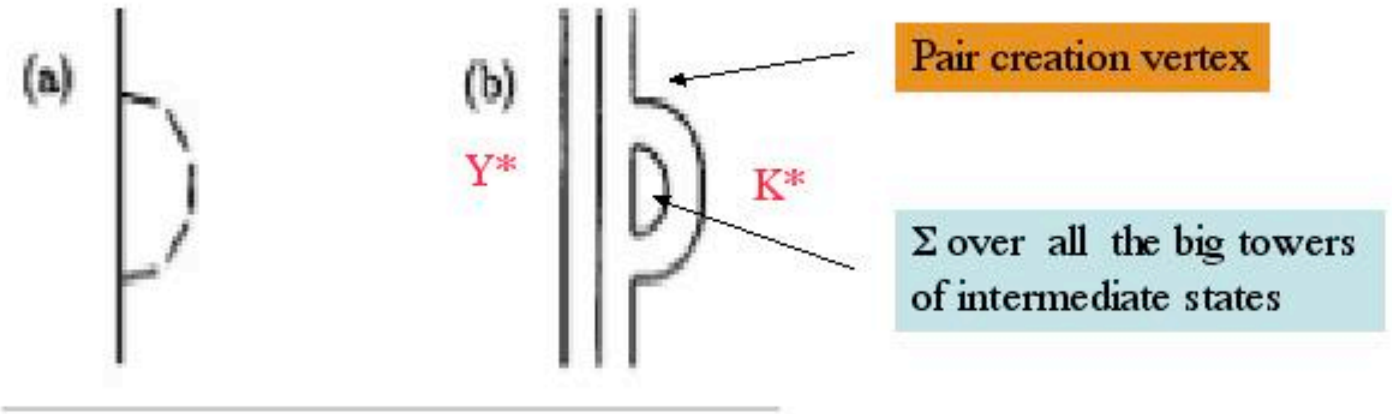


Note:

- sum over all intermediate states
  necessary for OZI rule
- linear interaction is preserved
  renormalization of the string constant

baryons

The qq-pair creation mechanism is introduced at the microscopical level
→ string-like qq pair creation mechanism

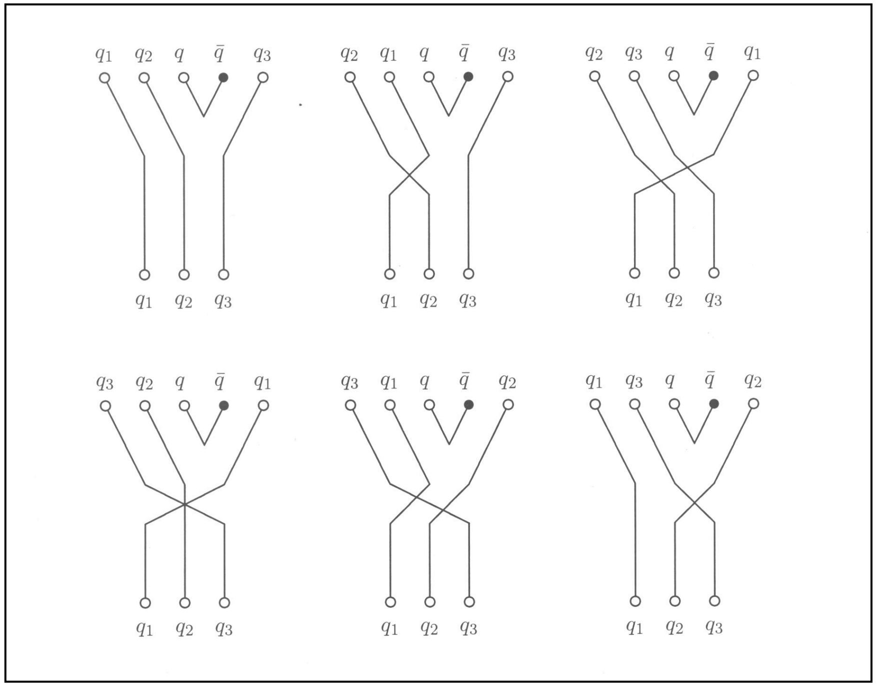


R. Bijker, E. Santopinto,
Phys.Rev.C80:065210,2009

Problems that have been solved for baryons:

- sum over the big tower of intermediate states
- permutational symmetry

(both with group theoretical methods)



- find a quark QCD inspired pair creation mechanism $^3P_0$
- implementation of the mechanism in such a way to do not destroy the good CQMs results

The good magnetic moment results of the CQM are preserved by the UCQM

Bijker, Santopinto,Phys.Rev.C80:065210,2009.

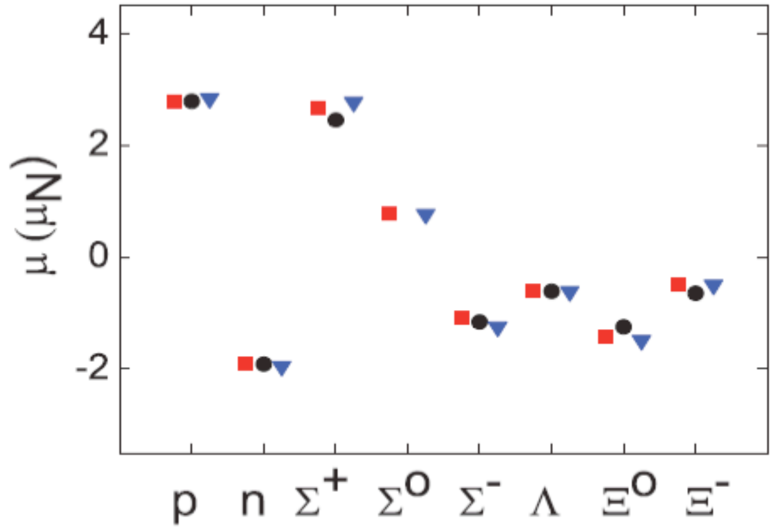
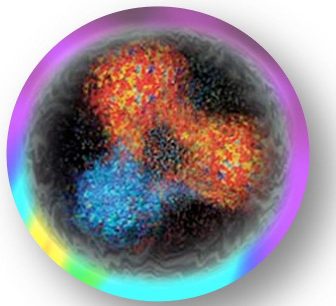


FIG. 3. (Color online) Magnetic moments of octet baryons: experimental values from the Particle Data Group [34] (circles), CQM (squares), and unquenched quark model (triangles).

Possible structure of the nucleon



3-quark core (about 0.5 fm)
+
quark-antiquark pairs
outside and inside the core

Unquenching the CQM:

effects on spectrum
e.m. excitation
consistent evaluation of electroproduction

conclusions

- QCD has affected CQM formulation at various stages
- Important issues for N* high Q2 electrocouplings:
  - Relativity: mainly for ground state

    affects Q^2 behaviour
  - Quark-antiquark pairs

    to be introduced consistently (unquenching)

    modify both low and high Q^2 behaviour
  - Quark from factors

    introduce a Q^2 behaviour of quite different origin

    (connected to fundamental dynamics?)