Baldin ISHEPP XXI (2012)

QUARK AND HADRON DEGREES OF FREEDOM IN THE ROPER RESONANCE ELECTROPRODUCTION

IgorT. Obukhovsky

Institute of Nuclear Physics
Moscow State University

Dubna 11.09.2012

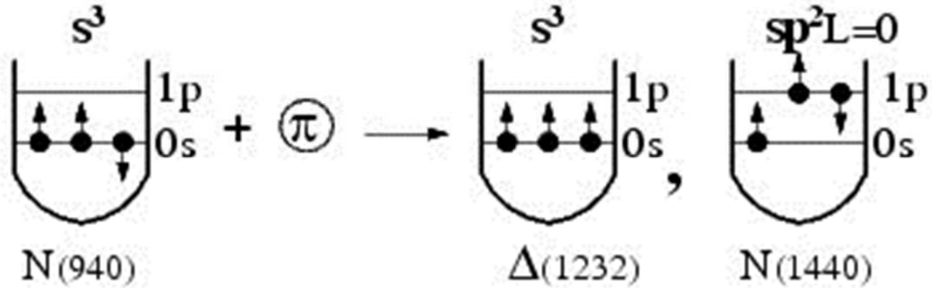
MSU: D.K. Fedorov
I.T. Obukhovsky
Tuebingen: A. Faessler
Th. Gutsche
V.E. Lyubovitskij

1. Introduction

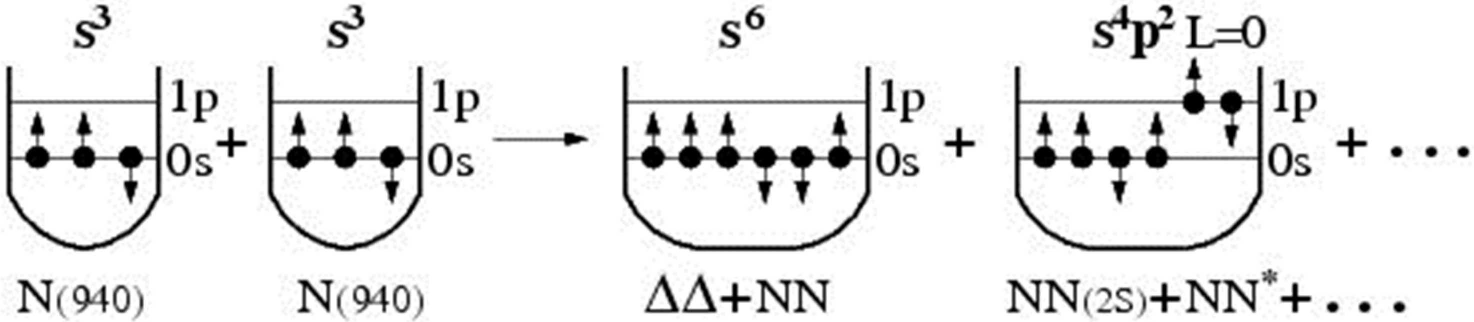
Motivation: a study of the Roper resonance can shed light on short range NN correlations in nuclei and the NN scattering at intermediate energies.

It follows from a trivial quark shell-model consideration:

The lightest baryon resonances can be described by the most simple S-wave configurations $s^3[3]_X$ and $sp^2[3]_X$ $(L=0)$,



and the same configurations appear in the six-quark short-range NN wave function — as $3q$ parts of the S-wave configurations $s^6[6]_X$ and $s^4p^2[42]_X$:



In both cases the Pauli principle plays a key role.

However, the description of the Roper resonance with the $\boxed{sp^2[3]_X\, L=0}$ configuration, i.e. as the radial two-quanta ($2S$) excitation, fails to explain the large decay width and branching ratios for πN and $2\pi(\sigma)N$ channels

$$\Gamma_R \approx 300\, MeV, \quad \Gamma_{\pi N} \approx 200\, MeV, \quad \Gamma_{2\pi(\sigma)N} \approx 15 - 30\, MeV.$$

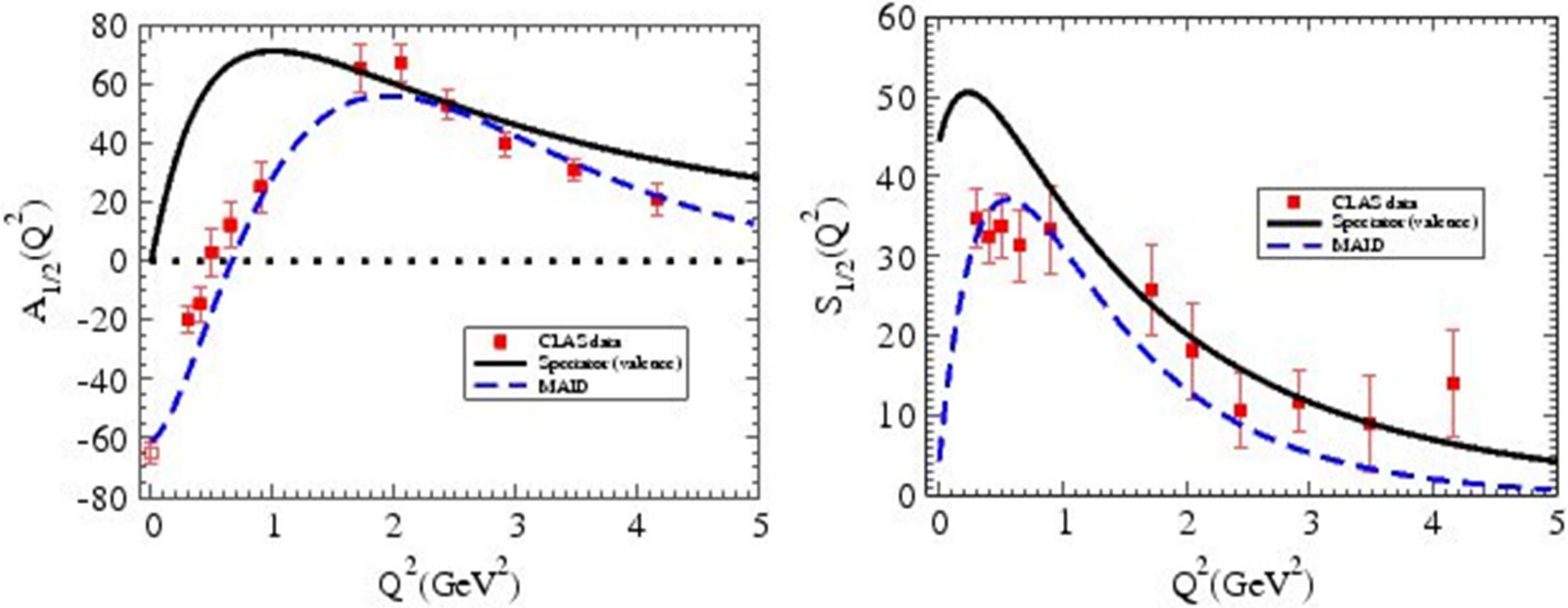
The observed widths are too large when compared to the predicted value of the constituent quark model (CQM) $\boxed{\Gamma_{\pi N}^{CQM} \approx 4\, MeV}$, while the observed mass $M_R \approx$1440 MeV is much too low.

****

While the simplest theoretical model fails (many other simple theoretical approaches also fail), on the experimental side there has been noticeable progress in the last decade.

The Roper resonance has been studied in π and $\pi\pi$ electroproduction processes on the proton at the JLab (collaboration CLAS: I.G.Aznauryan et al., Ph.R.C80, 055203; V.I. Mokeev et al., 045212) followed by combine analisys of π- and γ-induced reactions made by CB-ELSA and A2-TAPS collaborations: A.V. Sarantsev et al., Ph.L.B659, 94.

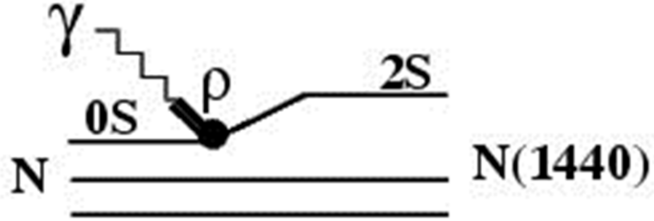
These data present new possibilities for the study of baryon resonances. We consider the transverse and longitudinal helicity amplitudes A1/2 and S1/2 for the Roper electroproduction off nucleon on the basis of recent CLAS data.



Adapted from G. Ramalho, K.Tsushima, Ph.R. D81, 074020 (2010)
CLAS: $A_{1/2}$ and $S_{1/2}$ in units of 10^{-3} GeV$^{1/2}$
Dashed: MAID fit, solid: Gross model.

Only the data at $Q^2 \gtrsim$1-2 GeV^2 correlate well with the quark model predictions. At low Q^2 the $A_{1/2}$ is in rather poor agreement with the data. It is typical of quark-model predictions:

the transverse helicity amplitude $A_{1/2} \sim \langle R, +\frac{1}{2}|j^\mu \epsilon_\mu^{(+)}|N, -\frac{1}{2}\rangle$ is given by the spin-flip transition $\lambda = -\frac{1}{2} \to +\frac{1}{2}$



and in QCM the transition operator $j^\mu \epsilon_\mu^{(+)}$ acts on quark spins and does not act on quark coordinates. Then orthogonality of the <u>coordinate</u> parts of R and N wave functions $\boxed{\langle R|N\rangle_X = 0}$ brings the value of $A_{1/2}$ to zero at the 'real photon' point Q^2 =0.

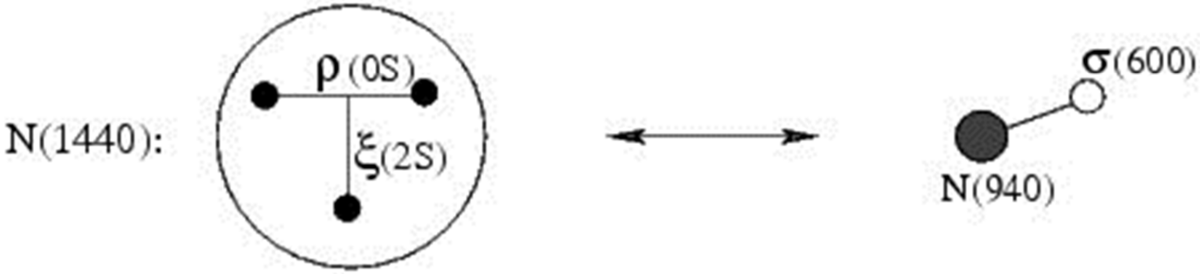
To avoid this

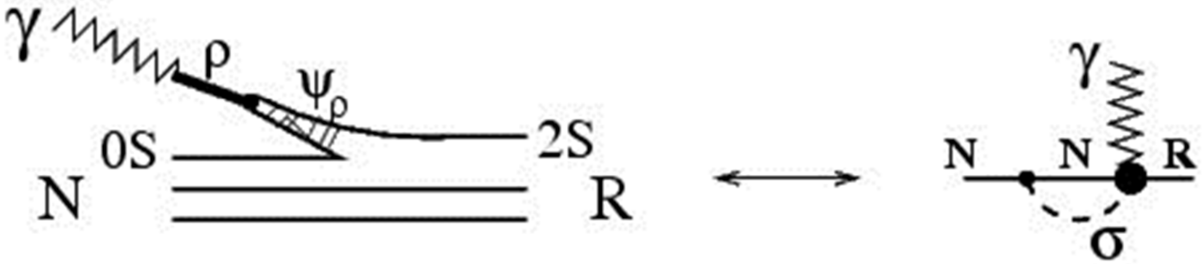
1) a <u>nonlocal</u> γqq operator in the $\gamma N(3q)R(3q)$ vertex can be used;
2) one can take into account a possible <u>hadron 'molecular'</u> <u>state</u> $N + \sigma$ as a component of Roper wave function.

Two ways for solution of low-Q^2 problem

1) Generalization of CQM:
CQM+$^3P_0$+VMD

2) N+σ molecule:
The resonance pole 1365-i95 MeV is rather close to the N+σ threshold



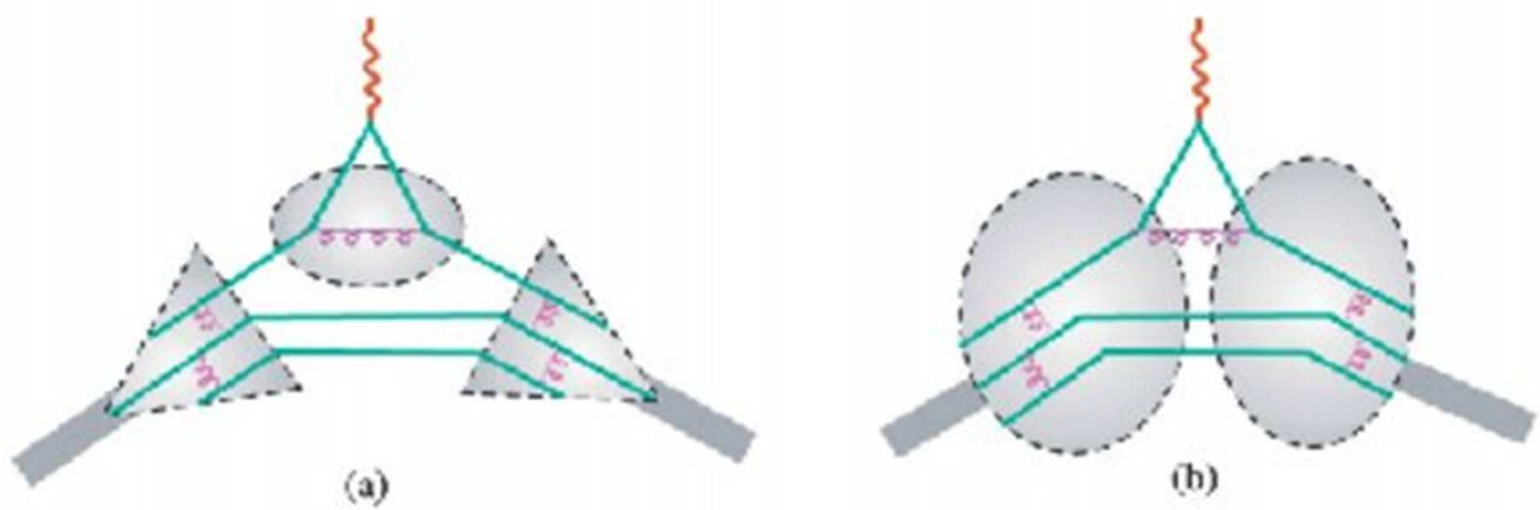


Nonlocality of e.-m. operator: in spite of orthogonality of coordinate parts of wave functions $\langle R|N\rangle_X$ =0 the spin-dependent magnetic matrix element does not go to zero when $Q^2 \to 0$.

2. CQM+3P0: a nonlocal e-m vertex

In both regions of Q^2 we are dealing with the same diagrams but differently broken into blocks (because of the running constant α_{QCD}):

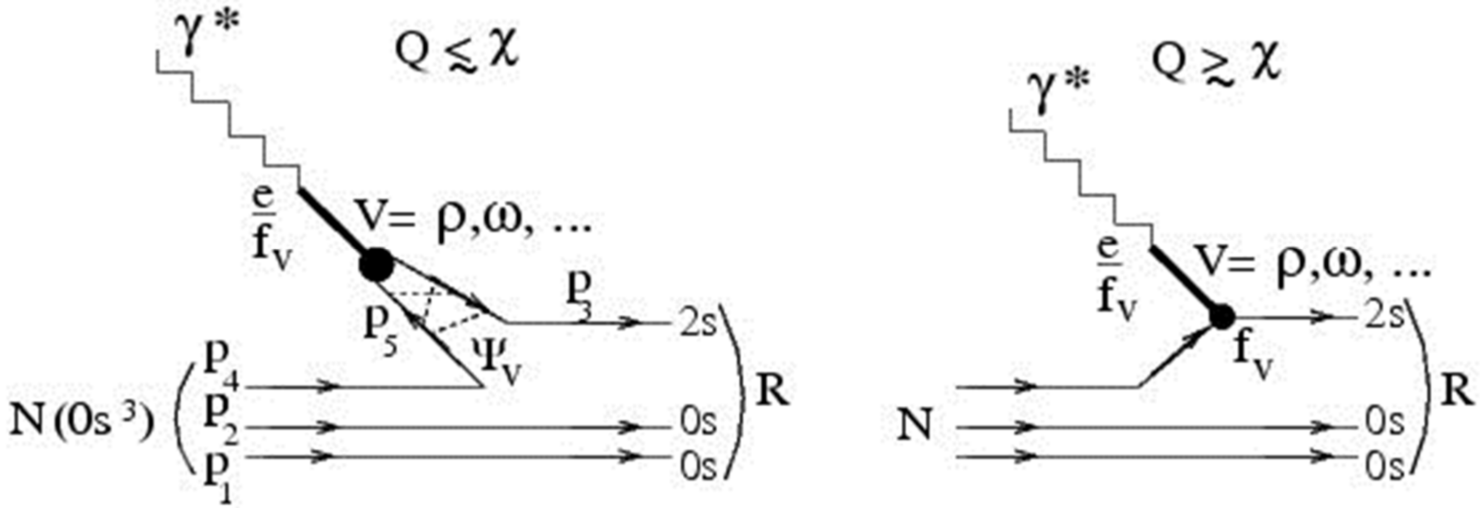
FRANZ GROSS, G. RAMALHO, AND M. T. PEÑA



(a) at low Q^2 the unknown large-distanse physics described by a phenomenological model (QCM, $^3P_0$, etc.) adjusted to low-energy data;
(b) at $Q^2 \gtrsim$ 1-2 GeV^2 the unknown short-range physics is encoded by adjusted parameters of a parton model.

We should sew these two models, (a) and (b), using some simple procedure.

(a) At low Q^2 a nonlocal γqq vertex could be derived from VMD and the $^3P_0$ $q\bar{q}$ pair creation model:



In this case the ρ-meson radius b_ρ defines the size of region of nonlocality.

(b) At high Q^2 a parton-like behavior of amplitudes $N+\gamma^* \to N$, and $N+\gamma^* \to R$ may be realized with the same h.o. basis in the limit $b_\rho \to 0$,.

Then the nonlocal γqq amplitude is turn to the point-like vertex.

To sew the (a) and (b) models we use a smooth suppression of b_ρ with

$$b_\rho(Q^2) = b_\rho e^{-Q^2/\chi}, \ \chi \approx 1\text{-}2\,\text{GeV}^2.$$

For quantitative estimations we use the h.o. wave functions (0S and 2S radial states) for the ρ-meson and baryons B=N,R:

$$\Psi_\rho(\varkappa,\lambda,t)\sim\varphi_{0S}(\varkappa,b_\rho),\quad \Psi_N\sim\varphi_{0S}(\mathcal{K}_N,b),\quad \Psi_R\sim\varphi_{2S}(\mathcal{K}_R,b)$$

with $\quad \varphi_{0S}\sim e^{-\varkappa^2 b_\rho^2},\quad e^{-3\mathcal{K}^2b^2/4},\quad \varphi_{2S}\sim(1-\mathcal{K}^2b^2)e^{-3\mathcal{K}^2b^2/4},$

dependent only on relative momenta

$$\varkappa=\tfrac{1}{2}(p_3-p_5),\quad \mathcal{K}_N=\tfrac{1}{3}(p_1+p_2)-\tfrac{2}{3}p_4,\quad \mathcal{K}_R=\tfrac{1}{3}(p_1+p_2)-\tfrac{2}{3}p_3,$$

and the $^3P_0$ $q\bar{q}$-pair creation model $\quad \mathcal{L}^{eff}_{q\bar{q}}(x)=g_{q\bar{q}}\,\bar{\psi}_q(x)\psi_q(x).$

The amplitude of "back-to-back" pairs created in the vacuum

$$V^{eff}_{q\bar{q}}=\langle p_4,\mu_4|\langle\widetilde{p_5,\mu_5}|\int d^3x\mathcal{L}^{eff}_{q\bar{q}}(x)|0\rangle$$
$$=g_{q\bar{q}}\langle-\mu_5|\sigma\cdot(p_4-p_5)|\mu_4\rangle\delta^{(3)}(p_4-p_5)$$

is further used for construction of nonlocal γqq and Mqq vertices.

$$VMD: \qquad \langle R|\epsilon_\mu^{(\lambda)} j^\mu|N\rangle = \sum_{V=\rho,\omega} \frac{\mathcal{M}^{(\lambda)}_{N+V\to R}}{g_{VNN}} \frac{M_V^2}{Q^2+M_V^2}$$

The transition matrix element of the effective pair-creation operator

$$\mathcal{M}^{(\lambda)}_{N+V\to R} = 3\langle R, 0, S'_z|V^{eff}_{q\bar{q}}|N, -\vec{q}, S_z\rangle|V, \vec{q}, \lambda\rangle$$

defines the transverse amplitude proportional to a nonlocal overlap

$$\boxed{\langle R|\epsilon_\mu^{(+)} j^\mu|N\rangle \sim \langle S'_z|i[\vec{\sigma}\times\vec{q}]|S_z\rangle \left[\frac{y^2}{n} - \left(\frac{1+y^2}{n}\right)^2 \frac{\vec{q}^{\,2}b^2}{6}\right] exp(-\frac{\vec{q}^{\,2}b^2}{6}),}$$

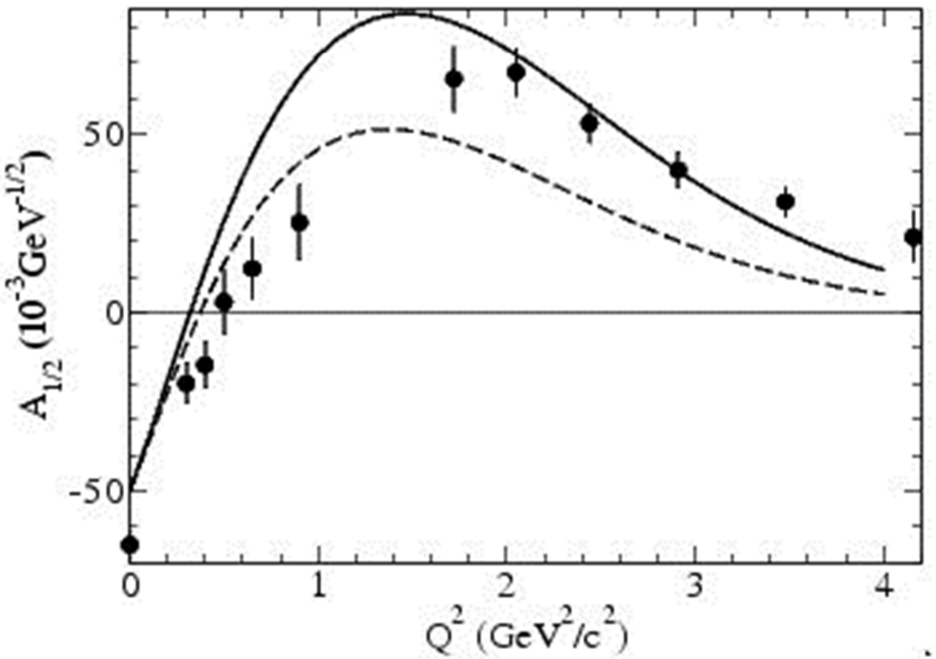
$$\text{where} \qquad \boxed{y = \frac{b_\rho}{b}}, \qquad n = 1 + \frac{2}{3}y^2.$$

If $b_\rho \neq 0$, the transverse helicity amplitude $A_{1/2}$ has got a nonzero value at the photon point $Q^2 = 0$ and correlates well with the data at low Q^2.

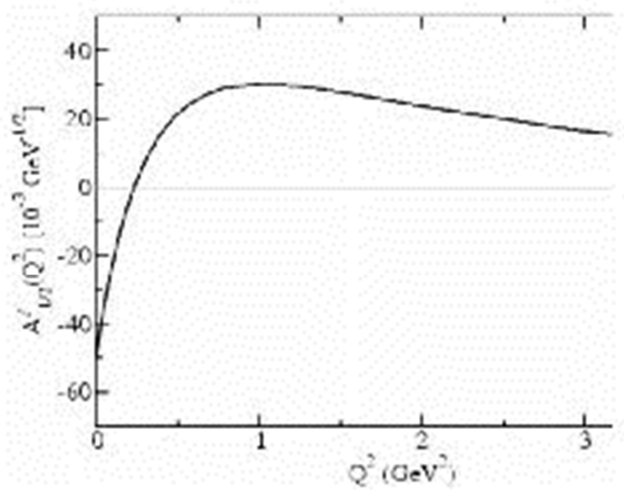
In the lab. system $\vec{q}^{\,2} = Q^2 + \left(\frac{Q^2+m_N^2-m_R^2}{2m_N}\right)^2$

QCM (with suppression):
$b_\rho = b\, e^{-Q^2/\chi}$,
$\chi = 1.5 m_N^2$, $b = 0.48$ fm

LF (without suppression):
S.Capstick, J.Phys. Conf. 69,012016 (2007)



- - - - b_ρ =const

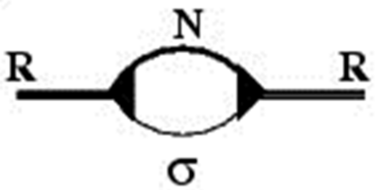


3. Composite structure of N(1440)

We consider the Roper resonance as a superposition of the radially excited three-quark configuration $|3q^*\rangle = |sp^2[3]_X\, L=0\rangle$ and the hadron molecule component $N+\sigma$

$$|R\rangle = \cos\theta|3q^*\rangle + \sin\theta|N+\sigma\rangle$$

The parameter θ is adjusted to optimize the description of the helicity amplitude $A_{1/2}$ only.

The hadron loop 

gives a negative contribution $\Sigma_{N\sigma}$ to the mass of the Roper resonance, and the $RM\sigma$ coupling constant $g_{RN\sigma}$ is defined by the 'compositness condition'

$$Z_R \equiv 1 - \frac{d}{d\not{p}}\Sigma_{N\sigma}(\not{p})\,|_{\not{p}=m_R} = 0,$$

i.e. the elementary particle R has a zero weight in the hadron molecule.

We use effective Lagrangians (Dubna group: G. Efimov, M. Ivanov, V. Lyubovitskij) for description of nonlocal RNσ and NNσ interactions, e.g.

$$\mathcal{L}_{str}(x) = g_{_{RN\sigma}}\bar{R}(x)\int d^4y\,\Phi_R(y^2)N(x+\alpha y)\sigma(x-(1-\alpha)y), \quad \alpha = \frac{M_\sigma}{m_{_N}+M_\sigma},$$

and h.o. Gaussians as Fourier transforms of $\Phi_N(y^2)$ and $\Phi_R(y^2)$

$$\tilde{\Phi}_N(k_{_E}^2) = exp(-\frac{k_{_E}^2}{\Lambda^2}) \quad \text{and} \quad \tilde{\Phi}_R(k_{_E}^2) = (1-\lambda\frac{k_{_E}^2}{\Lambda^2})exp(-\frac{k_{_E}^2}{\Lambda^2})$$

with the orthogonality condition $\int\tilde{\Phi}_R(^2k_{_E})\tilde{\Phi}_N(k_{_E}^2)d^4k_{_E} = 0$.

The electromagnetic interaction term for this nonlocal vertex

$$\mathcal{L}_{em}^{(1)} = g_{_{RN\sigma}} \bar{R}(x) \int dy\, e^{-ieI(x+\alpha y, x, P)} N(x+\alpha y)\sigma(x-(1-\alpha)y) + h.c.$$

is generated when the nonlocal Lagrangian are gauged with a gauge field exponential $e^{-ieI(x+\alpha y, x, P)}$ where

$$I(y, x, P) = \int_x^y dz_\mu A^\mu(z), \quad P \text{ is the path of integration}$$

S.Mandelstam, Ann.Phys. 19, 1 (1963); J.Terning, Ph.Rev. D44, 887 (1991)

The full Lagrangian of electromagnetic interaction

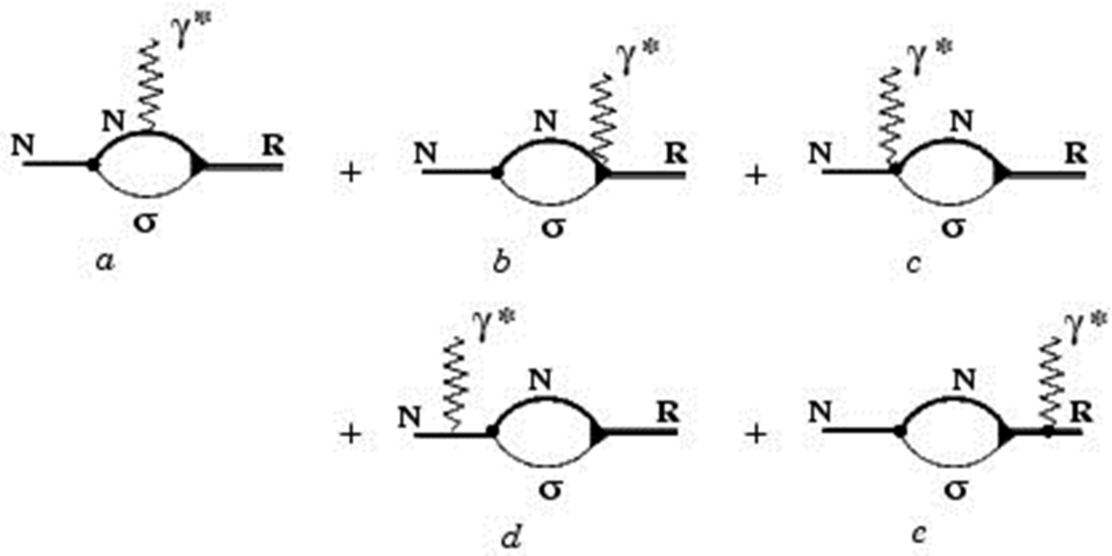
$$\mathcal{L}_{em} = \mathcal{L}_{em}^{(1)} + \mathcal{L}_{em}^{(2)}$$

includes also the standard term

$$\mathcal{L}_{em}^{(2)} = e_{B} \bar{B}(x) \not{A}(x) B(x), \quad B = N, R$$

obtained by minimal substitution $\partial^\mu B \rightarrow (\partial^\mu - e_{B} A^\mu) B$

Only the total sum of the first order diagrams (including the contact terms $\mathcal{L}_{em}^{(1)}$) satisfies the gauge invariance

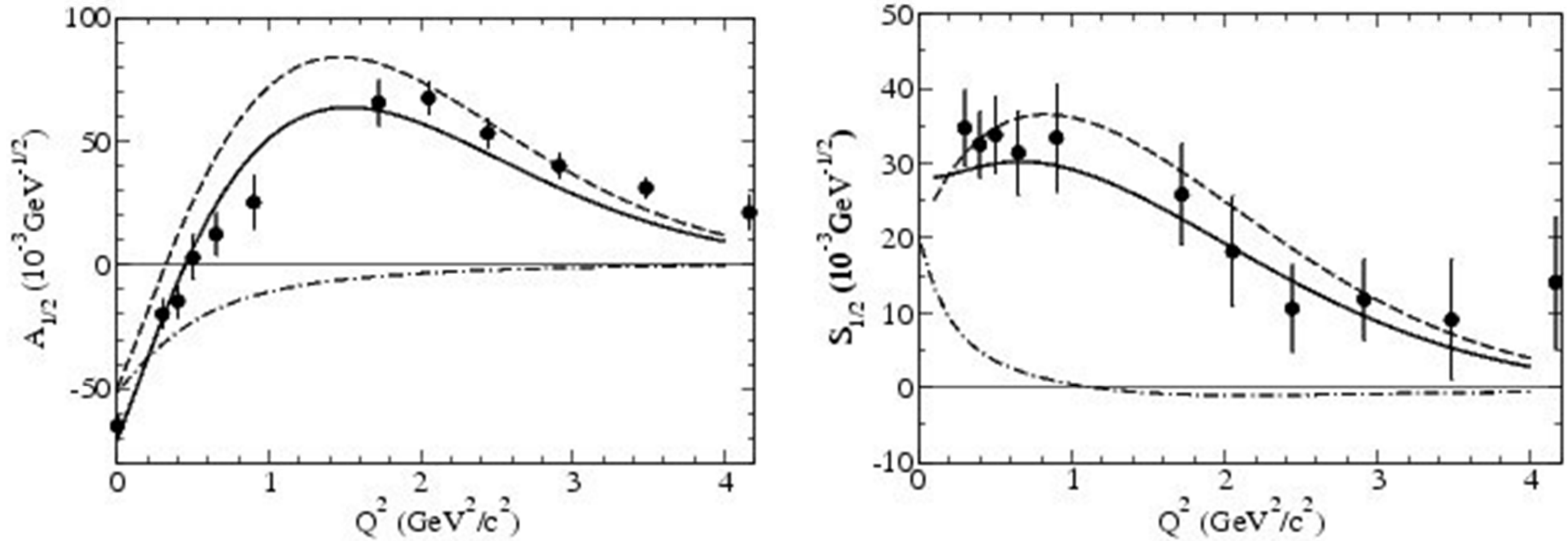


4. Results

PHYSICAL REVIEW D 84, 014004 (2011)

Electroproduction of the Roper resonance on the proton: The role of the three-quark core and the molecular $N\sigma$ component

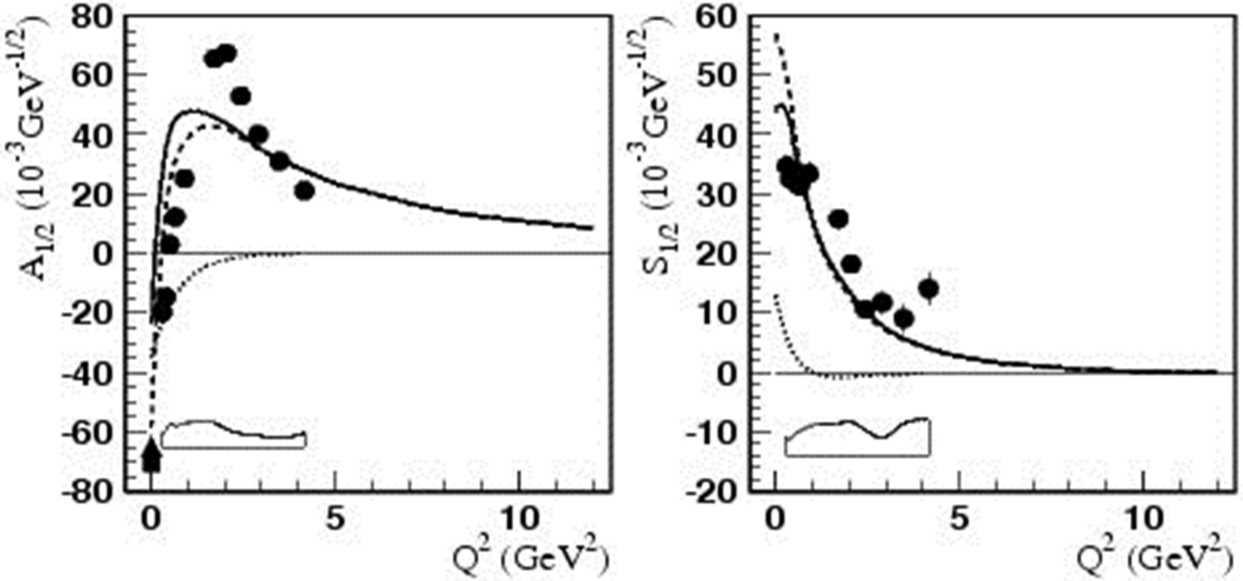
Igor T. Obukhovsky,[1] Amand Faessler,[2] Dimitry K. Fedorov,[1] Thomas Gutsche,[2] and Valery E. Lyubovitskij[2,*]



Free parameters: $b = 0.48$ fm, $b_\rho = 0.9\, b$, $\chi = 1.5\, m_N^2$, $\Lambda = 1$ GeV

$|R\rangle = \cos\theta|3q^*\rangle + \sin\theta|N+\sigma\rangle$, **the mixing angle (our fit):** $\boxed{\cos\theta = 0.8}$

Similar results were recently obtained in a LF approach
A.G. Aznauryan, V.D. Burkert, Ph.Rev. C85, 055202 (2012)
with the 3q weight $\cos\theta$ =0.77 and with the Q^2-dependent constituent quark mass.



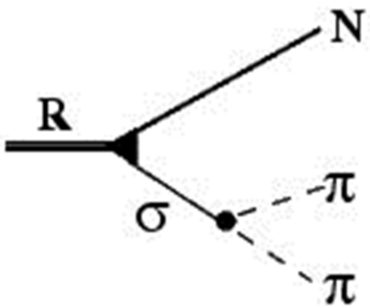
Decay widths

1) The standard QCM evaluations ($\Gamma^q_{R\to N\pi} \simeq 4\,\text{MeV}$, $\Gamma^q_{R\to N\sigma(\pi\pi)} \ll 1\,\text{MeV}$) are not consistent with the data

$$\Gamma_{R\to N\pi} \simeq 165 - 225\,MeV, \quad \Gamma_{R\to N\sigma(\pi\pi)} \simeq 15 - 30\,MeV$$

2) Moreover, in our improved quark model (QCM+$^3P_0$+VMD) the decay widths are also too small: $\Gamma^q_{R\to N\pi} \simeq$ 36 MeV, $\Gamma^q_{R\to N\sigma(\pi\pi)} \ll 1$ MeV.

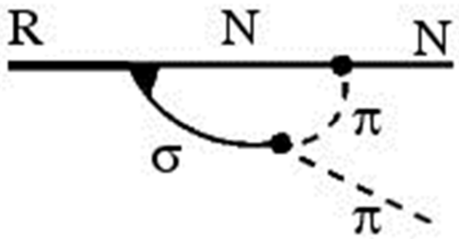
3) The hadron molecule: the weight of the $N+\sigma$ component in the Roper resonance $\sim \sin^2\theta$ =0.36 leads to a realistic branching for the channel of decay $R \to N + (\pi\pi)^{I=0}_{S\,wave}$:



$$\boxed{\Gamma^{mol}_{R\to N\sigma(\pi\pi)} = 19 - 27\,\text{MeV}} \text{ at } \Gamma_\sigma = \textbf{0.5-1 GeV}$$

$$|M_{fi}|^2 = g^2_{R\sigma N}\, g^2_{\sigma\pi\pi}\, \tilde{\Phi}^2_R(k^2) \frac{(m_N+m_R)^2 - s_{\pi\pi}}{(m^2_\sigma - s_{\pi\pi})^2 + m^2_\sigma\,\Gamma^2_\sigma(s_{\pi\pi})}$$

4) The pion cloud was not taken into account. Nevertheless, the hadron molecule component can be used to enhance the $R \to \pi + N$ decay width.



The contribution of the loop diagram to the πN decay width should be considerable (in our simple model it is about 100 MeV).

However, in order to carry out the necessary numerical estimates a dynamical model of the pion cloud should be developed.

5. Conclusions

1. It is suggested a two-component model of N(1440) as a combined state of the quark configuration $sp^2[3]_X$ and the hadron molecule N+σ.
2. The weight of the N+σ component in the Roper with $\sin^2\theta \approx$0.36 is compatible with the CLAS data at low and moderate Q^2.
3. This weight is also compatible with the value of the helicity amplitude $A_{1/2}$ at the photon point and with the data on the $R \to N + (\pi\pi)^{I=0}_{Swave}$ decay width.

We tried to show that the description of transition amplitudes in terms of partonlike models, which is very good at hight Q^2, can be naturally transformed into a good description at low Q^2 in terms of the soft vector-meson cloud by 'switching on' a nonzero radius of the intermediate vector meson. However, for gaining a complete understanding of low-Q^2 behaviour of amplitudes the soft π- and σ-meson clouds should also be taken into consideration.