LIGHT HADRON SPECTRA

L. Ya. Glozman

Institut für Physik, FB Theoretische Physik, Universität Graz

Contents of the Talk

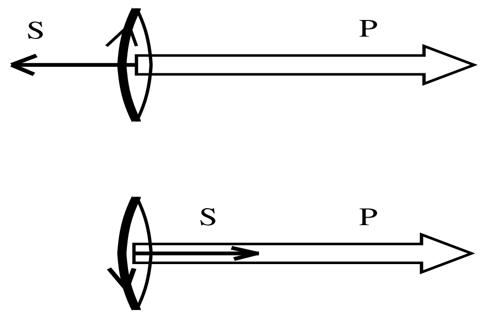
- Chiral symmetry of QCD and its spontaneous breaking.
- Low lying baryon spectrum.
- Chiral symmetry restoration in excited hadrons.
- Chiral symmetry restoration and the string picture.
- Hadrons on the lattice.
- Summary.

Massless fermions. Chiral symmetry.

Consider 1-flavor free massless fermion theory: $L_0 = i\bar{\Psi}\gamma_\mu\partial^\mu\Psi$. Define:

$$\Psi_L = \frac{1-\gamma_5}{2}\Psi$$

$$\Psi_R = \frac{1+\gamma_5}{2}\Psi$$

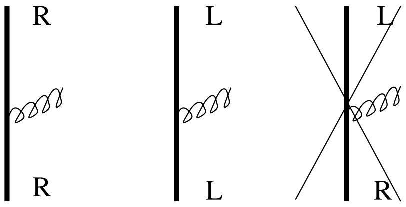


$$L_0 = i\bar{\Psi}_L\gamma_\mu\partial^\mu\Psi_L + i\bar{\Psi}_R\gamma_\mu\partial^\mu\Psi_R \ .$$

This Lagrangian is invariant with respect to independent variation of phases of Ψ_L and Ψ_R .

Symmetry group: $U(1)_L \times U(1)_R = U(1)_V \times U(1)_A$.

Consider vectorial interaction of the fermion field with the external gauge field (QED,QCD,...). The symmetry is preserved .



Spontaneous breaking of chiral symmetry in QCD.

In QCD $m_u, m_d \ll \Lambda_{QCD}$. Hence to a good approximation one can put $m_u, m_d = 0$.

$$u_L \to \alpha_L u_L + \beta_L d_L \qquad u_R \to \alpha_R u_R + \beta_R d_R$$
$$d_L \to \gamma_L u_L + \delta_L d_L \qquad u_R \to \gamma_R u_R + \delta_R d_R$$

$$U(2)_L \times U(2)_R = SU(2)_L \times SU(2)_R \times U(1)_V \times U(1)_A$$

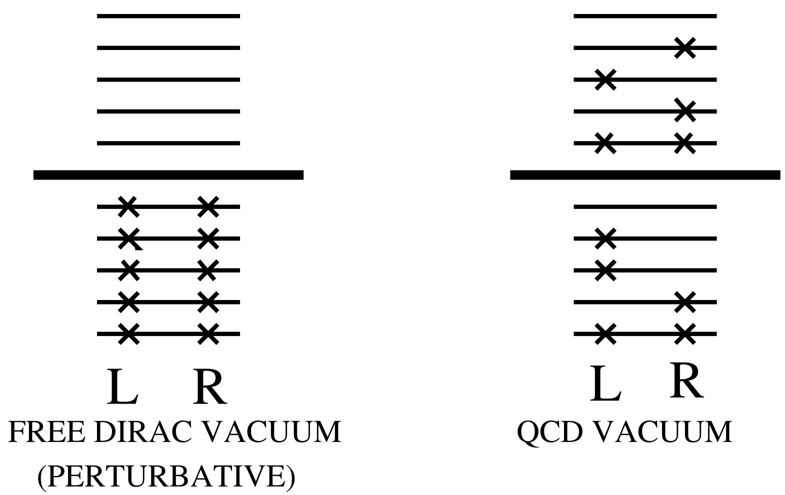
$U(1)_A$ is explicitly broken by the axial anomaly (quantum fluctuations).

$$SU(2)_L \times SU(2)_R \to SU(2)_V .$$

Why? The ground state of the theory (vacuum) does not have chiral symmetry.

(i) No parity doublets through the whole hadron spectrum.

(ii) Condensate of the left-right pairs $\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_R q_L + \bar{q}_L q_R|0\rangle \sim (-240\ MeV)^3$

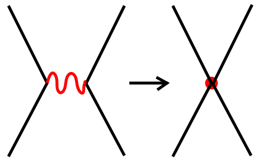


$$\langle QCD\ vacuum|H_{QCD}|QCD\ vacuum\rangle < \langle Dirac\ vacuum|H_0|Dirac\ vacuum\rangle$$

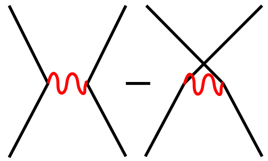
Chiral symmetry breaking microscopically. NJL.

Consider *chiral invariant* 4-fermion interaction motivated by gluon exchange (one ignores isospin for simplicity!)

$$L = \bar{\Psi} i \gamma_\mu \partial^\mu \Psi - G \bar{\Psi} \gamma_\mu \Psi \bar{\Psi} \gamma^\mu \Psi$$



Fermi-nature of quarks requires antisymmetrization:



$$-\bar{\Psi}\gamma_\mu\Psi\bar{\Psi}\gamma^\mu\Psi \rightarrow (\bar{\Psi}\Psi\bar{\Psi}\Psi + \bar{\Psi}i\gamma_5\Psi\bar{\Psi}i\gamma_5\Psi) - \frac{3}{2}\bar{\Psi}\gamma_\mu\Psi\bar{\Psi}\gamma^\mu\Psi - \frac{1}{2}\bar{\Psi}\gamma_\mu\gamma_5\Psi\bar{\Psi}\gamma^\mu\gamma_5\Psi$$

In the mean field approximation (quantum fluctuations are small)

$$\bar{\Psi}\Gamma\Psi\bar{\Psi}\Gamma\Psi \rightarrow 2\bar{\Psi}\Gamma\Psi\langle 0|\bar{\Psi}\Gamma\Psi|0\rangle - const^2, \qquad \Gamma = 1, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5$$

Vacuum: $|0\rangle : J^{PC} = 0^{++}$. Hence $\langle 0|\bar{\Psi}\gamma_5\Psi|0\rangle$ = $\langle 0|\bar{\Psi}\gamma_\mu\Psi|0\rangle$ = $\langle 0|\bar{\Psi}\gamma_\mu\gamma_5\Psi|0\rangle$ = 0 .

$$\bar{\Psi}\gamma_\mu\Psi\bar{\Psi}\gamma^\mu\Psi \rightarrow 2\bar{\Psi}\Psi\langle 0|\bar{\Psi}\Psi|0\rangle$$

Only Lorentz scalar quark pairs can condense in the vacuum! What is it?

$\bar{\Psi}\Psi = \bar{\Psi}_R\Psi_L + \bar{\Psi}_L\Psi_R$. It is not invariant under chiral transformation!

Chiral symmetry breaking microscopically. NJL.

$\langle 0|\bar{\Psi}\Psi|0\rangle \sim (-240MeV)^3 \Longrightarrow$ Quark condensate of the QCD vacuum.

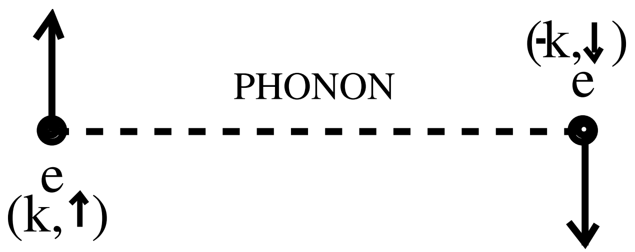
$L = \bar{\Psi} i\gamma_\mu \partial^\mu \Psi - G\bar{\Psi}\gamma_\mu \Psi \bar{\Psi}\gamma^\mu \Psi \Longrightarrow L = \bar{\Psi} i\gamma_\mu \partial^\mu \Psi + 2G\langle 0|\bar{\Psi}\Psi|0\rangle \bar{\Psi}\Psi$

It is a Lagrangian for a free Dirac particle with the mass M :

$$L = \bar{\Psi}(i\gamma_\mu \partial^\mu - M)\Psi \Longrightarrow M = -2G\langle 0|\bar{\Psi}\Psi|0\rangle$$

Lorentz scalar attractive part of any interaction in QCD is absorbed into a mass of a quasiparticle (constituent quark)!

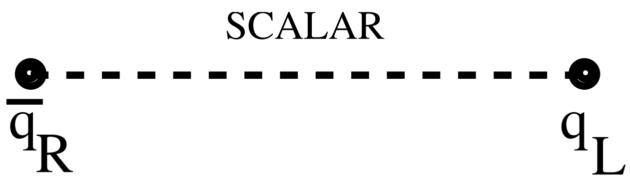
Analogy with superconductivity.



$V \sim -\sum V_{kk'} c^\dagger_{k'\uparrow} c^\dagger_{-k'\downarrow} c_{k\uparrow} c_{-k\downarrow}$

$\langle 0|c_{k\uparrow} c_{-k\downarrow}|0\rangle \neq 0$

Formation of a quasiparticle



$V \sim -G\bar{\Psi}\Psi\bar{\Psi}\Psi$

$\langle 0|\bar{\Psi}_R\Psi_L + \bar{\Psi}_L\Psi_R|0\rangle \neq 0$

Formation of a quasiparticle

Chiral symmetry breaking microscopically. NJL.

Transition from the bare massless particles to quasiparticles (Bogoliubov transformation):

$$a_M^{(\lambda)}(\vec{p}) = \gamma(\vec{p}) a_0^{(\lambda)}(\vec{p}) + \delta(\vec{p}) b_0^{(\lambda)^\dagger}(-\vec{p})$$

$$b_M^{(\lambda)^\dagger}(-\vec{p}) = -\delta(\vec{p}) a_0^{(\lambda)}(\vec{p}) + \gamma(\vec{p}) b_0^{(\lambda)^\dagger}(-\vec{p})$$

$$\gamma(\vec{p})^2 + \delta(\vec{p})^2 = 1$$

For bare (massless) particles:
chirality = + helicity (for quarks)
chirality = - helicity (for antiquarks)

Bare particles have both well-defined helicity and chirality, while quasiparticles (dressed particles) have only definite helicity and contain a mixture of bare particles and antiparticles with opposite chirality.

Chiral symmetry breaking microscopically. NJL.

In terms of the (almost) massless current quarks the axial current is (almost) conserved:

$$A_\mu = \bar{\Psi}\gamma_\mu\gamma_5\Psi; \quad \partial^\mu A_\mu = 0.$$

If one works in terms of *massive* quasiparticles (constituent quarks), then

$$\partial^\mu A_\mu = 2iM\bar{\Psi}\gamma_5\Psi.$$

How to reconcile this? The only solution is that the full axial current (which is conserved !) in the symmetry broken phase must contain a term which exactly cancels $2iM\bar{\Psi}\gamma_5\Psi$:

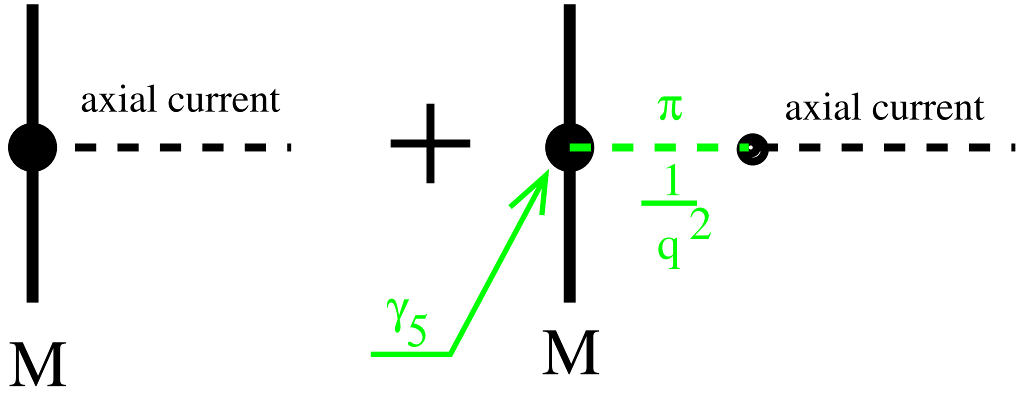
$$A_\mu = \bar{\Psi}\left(\gamma_\mu\gamma_5 + q_\mu\gamma_5 F(q^2)\right)\Psi.$$

$$\partial^\mu A_\mu = 0 \Longrightarrow A_\mu = \bar{\Psi}\left(\gamma_\mu\gamma_5 + \frac{2Mq_\mu}{q^2}\gamma_5\right)\Psi.$$

$1/q^2$ - propagator of massless particle!

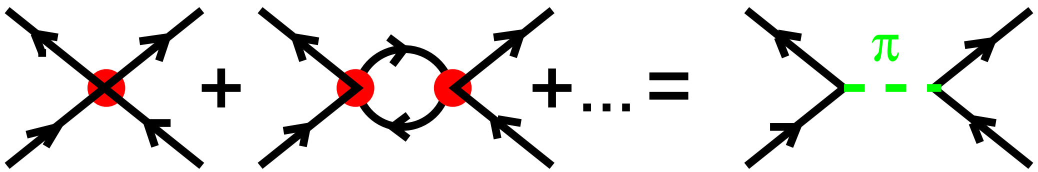
Once chiral symmetry is broken it is necessary to have a pseudoscalar zero-mass meson coupled with the massive fermion quasiparticle (constituent quark).

Chiral symmetry breaking microscopically. NJL.



How does all this come out microscopically?

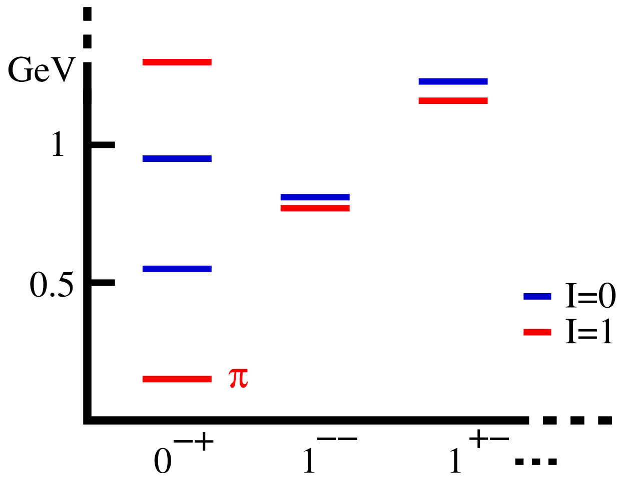
$$L = G[(\bar{\Psi}\Psi)^2 + (\bar{\Psi} i\gamma_5 \Psi)^2.$$



● *gluon exchange, or instanton−induced int, or ...*

There appears a pole with exactly zero mass in the pseudoscalar channel. Pion is a *relativistic* bound state. It contains $\bar{Q}Q$, $\bar{Q}Q\bar{Q}Q$,... Fock components. Pion is a highly collective excitation in terms of original (current) quarks q and $\bar{q}$ because quasiparticles Q and $\bar{Q}$ are *coherent collective* excitations of bare (current) quarks.

Low lying meson spectrum.

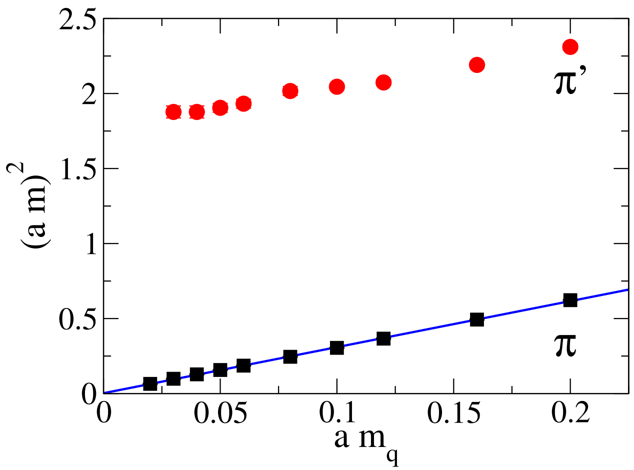


Why pion has a nonzero mass? If $m_u = m_d = 0$, then $m_\pi = 0$. In reality $m_u \sim 3 \div 5\ MeV,\ m_d =\sim 5 \div 9\ MeV\ \ll \Lambda_{QCD}$.

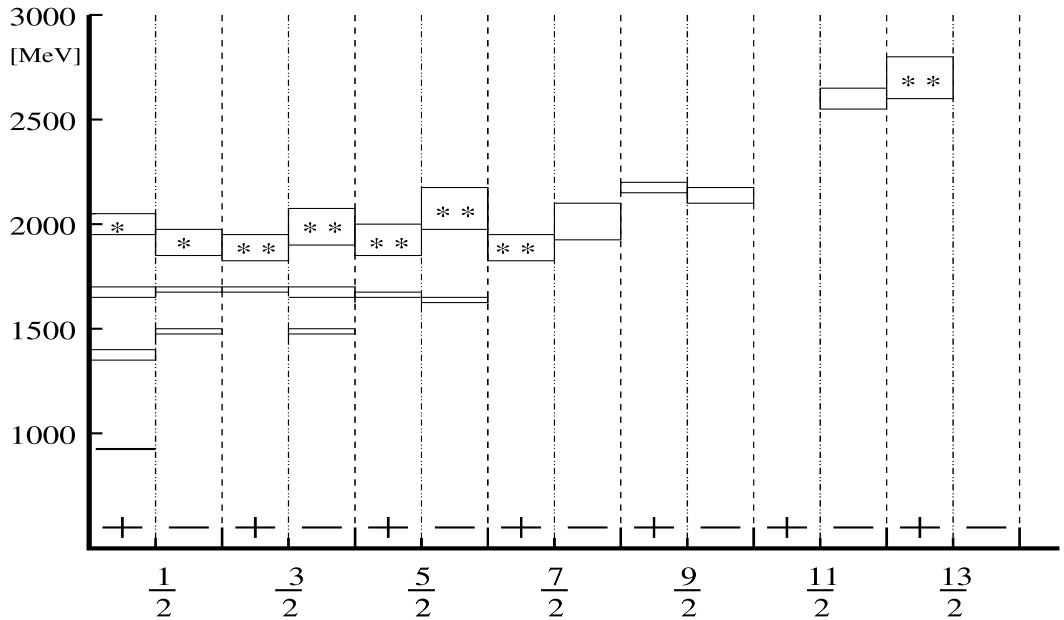
Gell -Mann, Oakes, Renner:

$$m^2_{\pi^{+,-}} = -\frac{1}{f_\pi^2}\frac{m_u+m_d}{2}(\langle 0|\bar{u}u|0\rangle + \langle 0|\bar{d}d|0\rangle),$$

$$m^2_{\pi^0} = -\frac{1}{f_\pi^2}(m_u\langle 0|\bar{u}u|0\rangle m_d\langle 0|\bar{d}d|0\rangle).$$



Low and high lying baryon spectra.

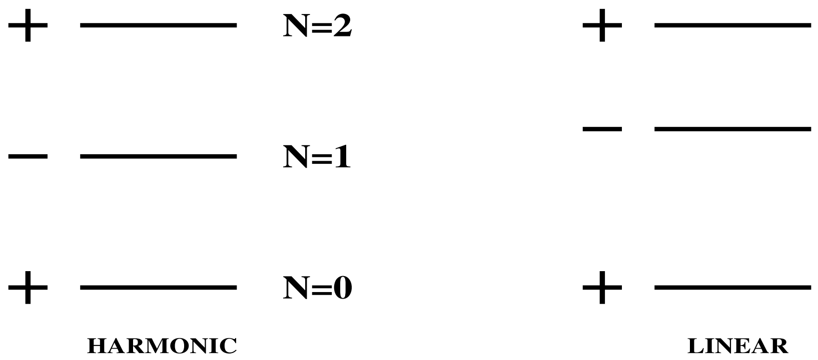


Low-lying spectrum: spontaneous breaking of chiral symmetry dominates physics.

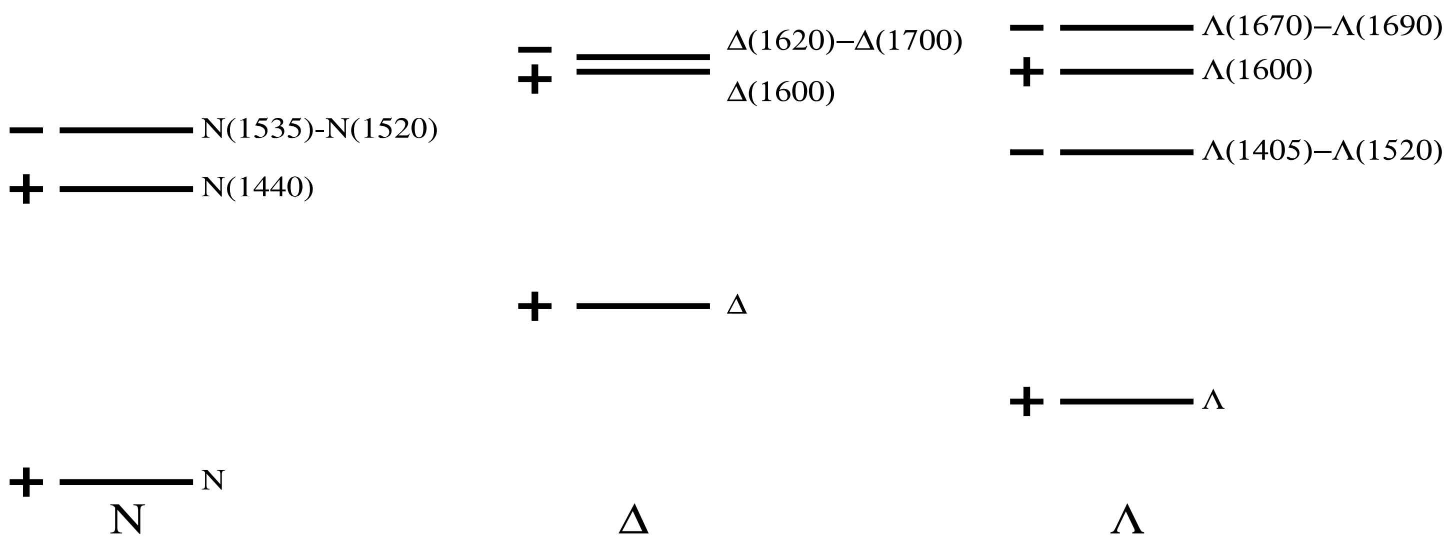
High-lying spectrum: parity doubling indicates the onset of the new physical regime - chiral symmetry restoration in excited hadrons.

L.Ya.G., PLB, 2000 ; T.D. Cohen and L.Ya.G.,PRD, 2002 ; review in T.D. Cohen and L.Ya.G.,IJMP A, 2002.

Where is a key problem for low-lying baryons?



A sequence of positive and negative parity levels with confining interaction.



Low-lying spectra of nucleon, Δ-resonance and Λ-hyperon.

The chiral constituent quark model.

Consequences of SBχS, $\langle \bar{q}q \rangle = -(240MeV)^3$:
(i) Valence quarks acquire dynamical (constituent) mass through their coupling to the quark condensate;
(ii) Practically massless Goldstone bosons (pion,...) appear as a collective quark-antiquark mode.

Physical insight from Nambu and Jona-Lasinio .

The axial current conservation requires a coupling of the constituent quark with the pion field - Weinberg, Manohar and Georgi, Ripka and Soni, Birse and Banerjee, Diakonov and Petrov,...

The low-lying baryons can be approximated at low momenta as systems of three confined quasiparticles (constituent quarks) with the 'residual' interaction mediated by the Goldstone boson field - L.Ya.G. and D.O.Riska, Phys. Rep., 1996

$$-\sum_{i<j} V(r_{ij})\lambda_i^F \cdot \lambda_j^F \vec{\sigma}_i \cdot \vec{\sigma}_j$$

Output: correct low-lying baryon spectra.

The chiral constituent quark model.

$$-\sum_{i<j} V(r_{ij})\lambda_i^F \cdot \lambda_j^F \vec{\sigma}_i \cdot \vec{\sigma}_j \longrightarrow -\sum_{i<j} C\, \lambda_i^F \cdot \lambda_j^F \vec{\sigma}_i \cdot \vec{\sigma}_j$$

Positive parity states:

Octet (N,Λ,Σ,Ξ); Octet* ($N(1440)$,$\Lambda(1600)$,...): -14C

Decuplet (Δ,Σ^*,Ξ^*,Ω); Decuplet* ($\Delta(1600)$,...) : -4C

Negative parity states:

$N(1535) - N(1520)$: -2C

$\Lambda(1670) \;-\; \Lambda(1690)$: -2C

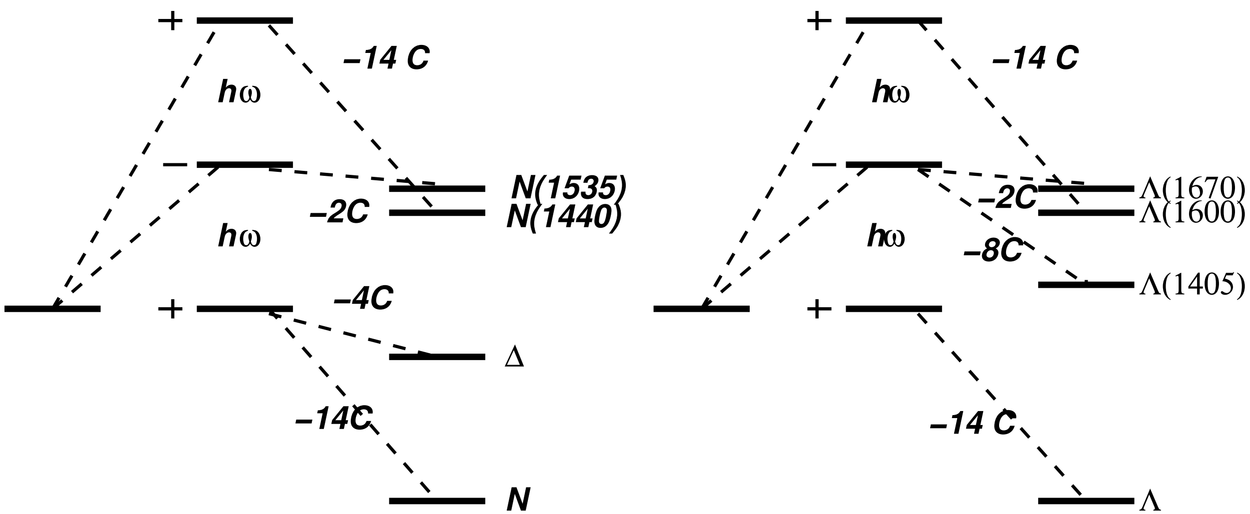
$\Lambda(1405) \;-\; \Lambda(1520)$: -8C

$\Delta - N$ splitting:

$C = 29.3\ MeV$

$N(1440) - N$ splitting:

$\hbar\omega = 250\ MeV$

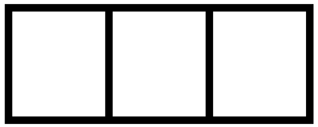


The chiral constituent quark model

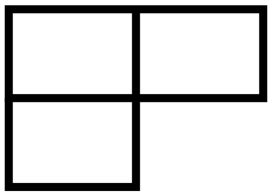
Why does the flavor-spin interaction shift the Roper states below the negative parity states? $\Longrightarrow$ Analyse symmetry properties of this interaction.

$$-\lambda_i^F \cdot \lambda_j^F \vec{\sigma}_i \cdot \vec{\sigma}_j$$

It is attractive if both spin and flavor wave functions are symmetric with respect to $i \leftrightarrow j$ or if both are antisymmetric. Hence it is attractive in those pairs where FS wave function is symmetric and repulsive in those pairs where it is antisymmetric . Roper states ($N(1440)$,$\Delta(1600)$,$\Lambda(1600)$,...) belong to 56 plet of $SU(6)_{FS}$. Their FS wave functions are completely symmetric:



Negative parity states belong to 70 plet of $SU(6)_{FS}$. Their FS wave functions are of mixed symmetry:



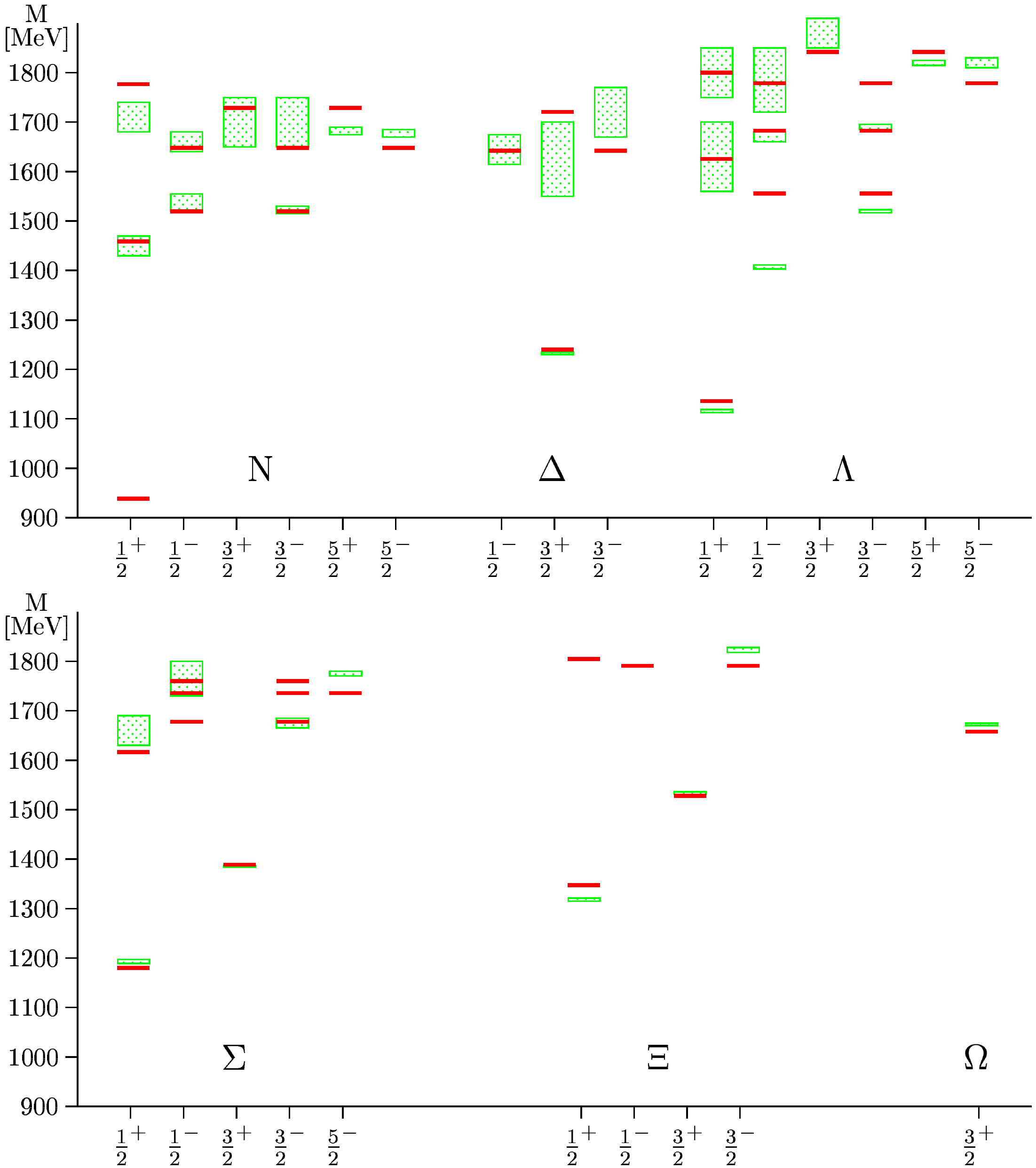
The chiral constituent quark model

Spectra have been obtained from the numerical solution of Faddeev equations

L.Ya.G., Z.Papp, W.Plessas, PLB, 1996

and stochastic variational approach

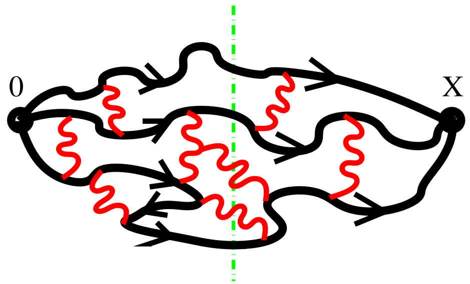
L.Ya.G., W.Plessas, K.Varga, R.F.Wagenbrunn, PRD, 1998



Chiral symmetry restoration by definition.

Hadrons can be seen as intermediate states in the two-point correlation function:

$$\Pi = i \int d^4x e^{iqx} \langle 0|T\left\{J_\alpha(x)J_\alpha(0)\right\}|0\rangle.$$

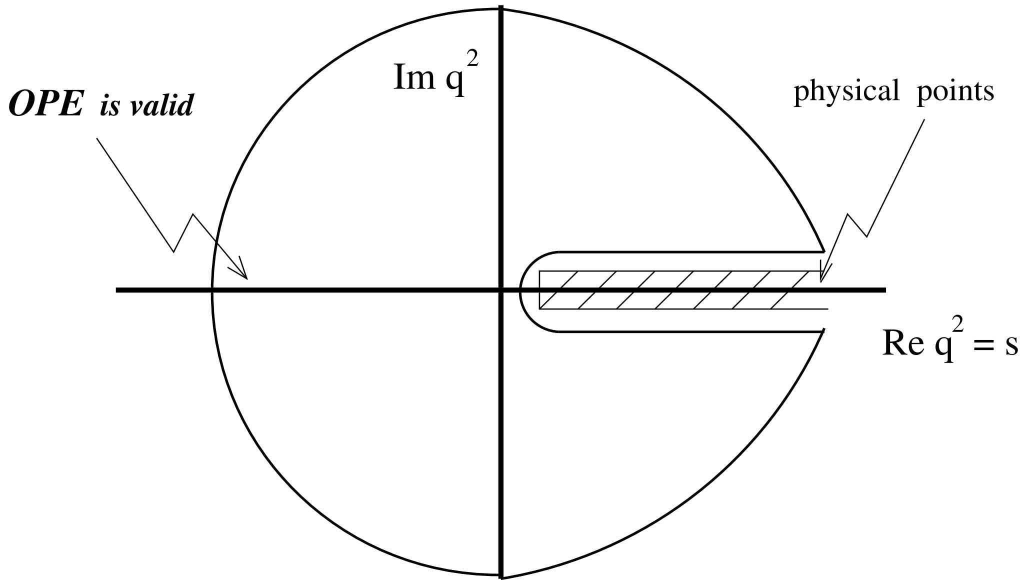


Consider two interpolators $J_1(x)$ and $J_2(x)$ such that $J_1(x) = UJ_2(x)U^\dagger$ where $U \in SU(2)_L \times SU(2)_R$. If $U|0\rangle = |0\rangle$, then spectra of hadrons with the quantum numbers 1 and 2 must be identical (Wigner-Weyl mode).

Spontaneous breaking of chiral symmetry in the vacuum implies that the spectra of 1 and 2 are different (Nambu - Goldstone mode). However, it may happen that the noninvariance of the vacuum becomes irrelevant (unimportant) high in the spectrum. Then the chiral symmetry will be restored in the high-lying hadrons. Effective chiral symmetry restoration or chiral symmetry restoration of the second kind .

Chiral symmetry restoration in excited spectra.

Causality → analyticity → $\Pi(q^2) = \frac{1}{\pi} \int ds \frac{\rho(s)}{s - q^2 - i\epsilon}$



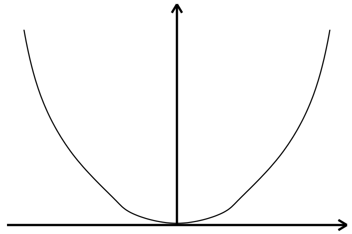
At unphysical points the OPE guarantees that the effects of the spontaneous breaking of chiral symmetry (quark condensates of different dimensions) are suppressed by $1/q^n, n > 0$. The same must be true in the physical region at large s:

$$\rho_1(s \to \infty) \to \rho_2(s \to \infty), \quad \textit{where} \quad J_1(x) = U J_2(x) U^\dagger$$

If the spectrum is quasidiscrete, then hadrons must fall into chiral multiplets.

A simple pedagogical example.

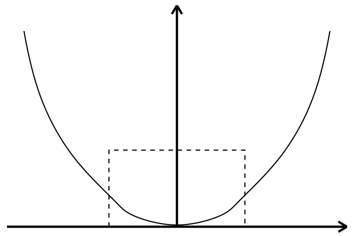
2-dim harm. osc.: $H = a_x^\dagger a_x + a_y^\dagger a_y + 1$.



Symmetry: $SU(2) \times U(1)$

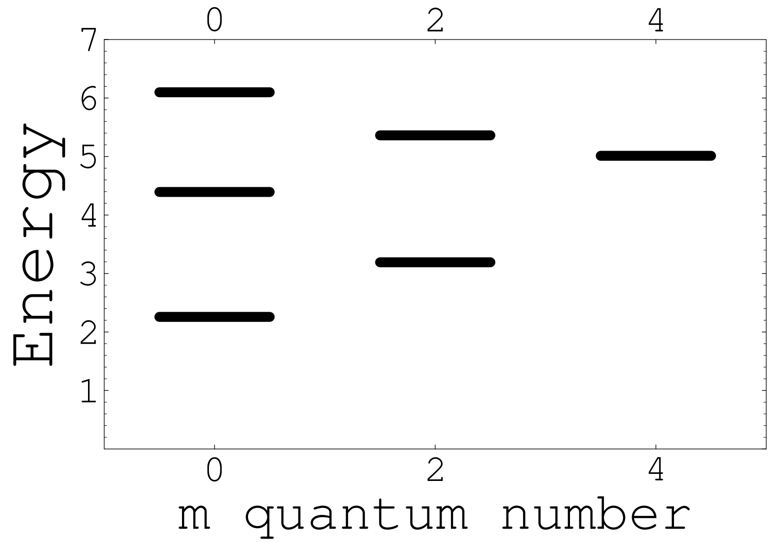
$E_{N,m} = (N + 1); m = N, N - 2, ..., -N$.

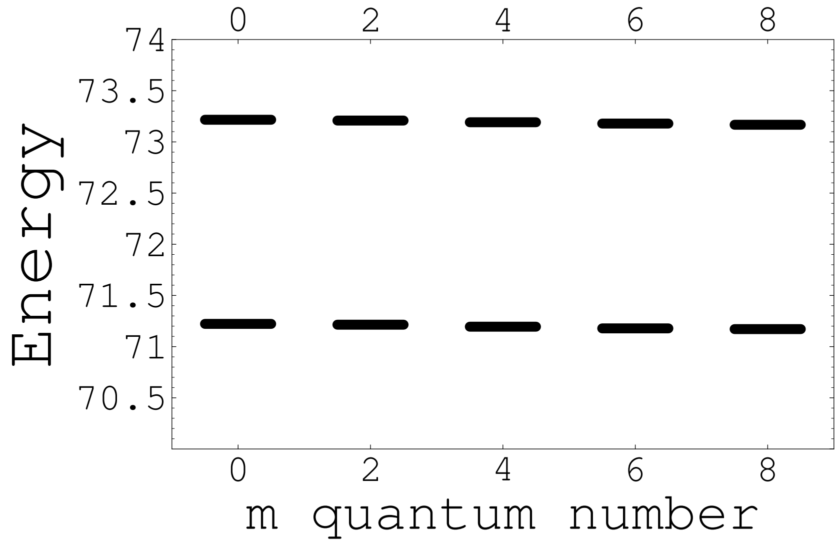
Add a symmetry breaking interaction:



$V_{SB} = A\Theta(r - R)$.

No $SU(2)$ symmetry.





Chiral classification of excited baryons.

$$SU(2)_L \times SU(2)_R$$

Irreducible representation: (I_L, I_R)

Parity operation: $L \longleftrightarrow R$. Hence $(I_L, I_R) \longleftrightarrow (I_R, I_L)$.

Irreducible representation of the parity-chiral group: $(I_L, I_R) \oplus (I_R, I_L)$.

It contains states with isospins $I = |I_L - I_R|, ..., I_L + I_R$ of both parities.

For $I \leq 3/2$ there are 3 possibilities:

(i) $(1/2, 0) \oplus (0, 1/2)$: doublets in N $(I^P = 1/2^+, 1/2^-)$.

(ii) $(3/2, 0) \oplus (0, 3/2)$: doublets in Δ $(I^P = 3/2^+, 3/2^-)$.

(iii) $(1/2, 1) \oplus (1, 1/2)$: quartets in $N\ and\ \Delta$ $(I^P = 1/2^+, 1/2^-, 3/2^+, 3/2^-)$.

Chiral classification of excited baryons.

$\mathbf{J = \frac{1}{2}}$:	$N^+(2100)(*)$	$N^-(2090)(*)$	$\Delta^+(1910)$	$\Delta^-(1900)$
$\mathbf{J = \frac{3}{2}}$:	$N^+(1900)$	$N^-(2080)$	$\Delta^+(1920)$	$\Delta^-(1940)(*)$
$\mathbf{J = \frac{5}{2}}$:	$N^+(2000)$	$N^-(2200)$	$\Delta^+(1905)$	$\Delta^-(1930)$
$\mathbf{J = \frac{7}{2}}$:	$N^+(1990)$	$N^-(2190)$	$\Delta^+(1950)$	$\Delta^-(2200)(*)$
$\mathbf{J = \frac{9}{2}}$:	$N^+(2220)$	$N^-(2250)$	$\Delta^+(2300)$	$\Delta^-(2400)$
$\mathbf{J = \frac{11}{2}}$:	?	$N^-(2600)$	$\Delta^+(2420)$	?
$\mathbf{J = \frac{13}{2}}$:	$N^+(2700)$	?	?	$\Delta^-(2750)$
$\mathbf{J = \frac{15}{2}}$:	?	?	$\Delta^+(2950)$	?

$(1/2,1) \oplus (1,1/2)$?? The parity doublets in the nucleon spectrum persist at ~ 1.7 GeV (no doublets yet in the delta spectrum). Then independent $(1/2,0) \oplus (0,1/2)$ and $(3/2,0) \oplus (0,3/2)$ doublets. If in addition $(1/2,1) \oplus (1,1/2)$, then there are still missing doublets.

Chiral classification of excited mesons. L.Ya.G., 2004

$U(2)_L \times U(2)_R = SU(2)_L \times SU(2)_R \times U(1)_V \times U(1)_A$.

Irreducible representations: (I_L, I_R) . Hence $I = |I_L - I_R|, ..., I_L + I_R$.

If $I_L \neq I_R$ then NO definite parity. $\Rightarrow (I_L, I_R) \oplus (I_R, I_L)$ (parity-chiral group).

For mesons with $I = 0, 1$ there are only three types of representations:

(i) $(0,0)$; $J \geq 1$.. The basis states of both parities are:

$$|(0,0); \pm; J\rangle = \frac{1}{\sqrt{2}}(\bar{R}R \pm \bar{L}L)_J.$$

(ii) $(1/2,1/2)_a$ and $(1/2,1/2)_b$. The basis states of both parities are:

a) $$|(1/2,1/2); +; I=0; J\rangle = \frac{1}{\sqrt{2}}(\bar{R}L + \bar{L}R)_J,$$
$$|(1/2,1/2); -; I=1; J\rangle = \frac{1}{\sqrt{2}}(\bar{R}\vec{\tau}L - \bar{L}\vec{\tau}R)_J.$$

b) $$|(1/2,1/2); -; I=0; J\rangle = \frac{1}{\sqrt{2}}(\bar{R}L - \bar{L}R)_J,$$
$$|(1/2,1/2); +; I=1; J\rangle = \frac{1}{\sqrt{2}}(\bar{R}\vec{\tau}L + \bar{L}\vec{\tau}R)_J.$$

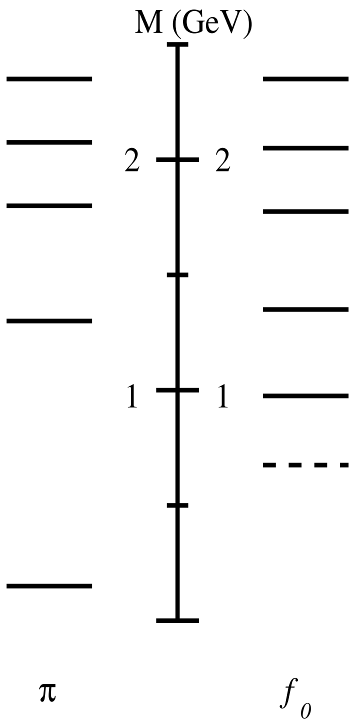
(iii) $(0,1) \oplus (1,0)$; $J \geq 1$.. The basis states of both parities are:

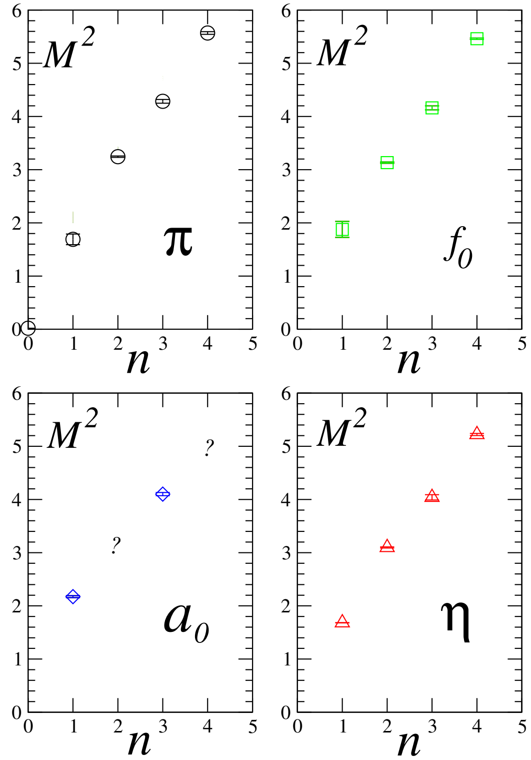
$$|(0,1) \oplus (1,0); \pm; J\rangle = \frac{1}{\sqrt{2}}(\bar{R}\vec{\tau}R \pm \bar{L}\vec{\tau}L)_J.$$

Chiral partners ($(1/2, 1/2)$ representation of $SU(2)_L \times SU(2)_R$):

$$\pi(I, J^{PC} = 1, 0^{-+}) \text{ and } f_0(I, J^{PC} = 0, 0^{++}),$$
$$a_0(I, J^{PC} = 1, 0^{++}) \text{ and } \eta(I, J^{PC} = 0, 0^{-+}) .$$

$$j_\pi(x) = \bar{q}(x)\vec{\tau} i\gamma_5 q(x) \longleftrightarrow j_{f_0}(x) = \bar{q}(x)q(x),$$
$$j_{a_0}(x) = \bar{q}(x)\vec{\tau} q(x) \longleftrightarrow j_\eta(x) = \bar{q}(x)i\gamma_5 q(x).$$





Chiral multiplets of excited mesons.

Data are from the partial wave analysis of $\bar{p}p$ (Anisovitch, Bugg,...)

(0,0)

$\omega_2(0,2^{--})$	$f_2(0,2^{++})$
1975 ± 20	1934 ± 20
2195 ± 30	2240 ± 15

(1/2,1/2)

$\pi_2(1,2^{-+})$	$f_2(0,2^{++})$
2005 ± 15	2001 ± 10
2245 ± 60	2293 ± 13

(1/2,1/2)

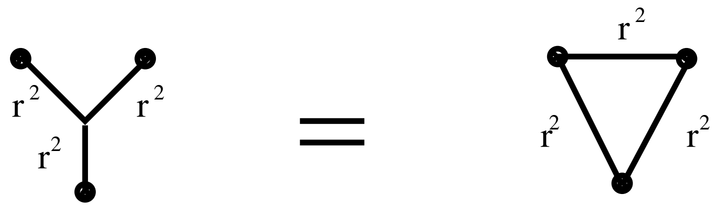
$a_2(1,2^{++})$	$\eta_2(0,2^{-+})$
2030 ± 20	$2030 \pm ?$
2255 ± 20	2267 ± 14

(0,1)+(1,0)

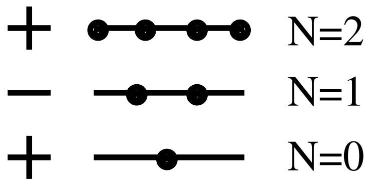
$a_2(1,2^{++})$	$\rho_2(1,2^{--})$
1950^{+30}_{-70}	1940 ± 40
2175 ± 40	2225 ± 35

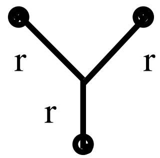
Can simple potential models explain doubling?

BARYONS



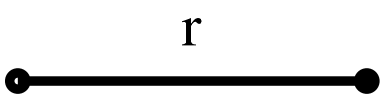
e.g. J=1/2





'Missing states'

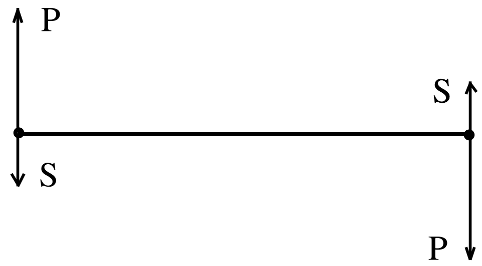
MESONS



$P = -(-1)^L$; e.g. $\pi \rightarrow^1 S_0$ $f_0 \rightarrow^3 P_0$

Chiral symmetry restoration and the string picture.

What is a model for excited hadrons? Assume :



(i) the field in the string is of pure color-electric origin

(ii)the valence quarks have a definite chirality

Then:

(i) The hadrons that belong to the same intrinsic quantum state of the string with quarks falling into the same parity-chiral multiplet must be degenerate.

(ii) The total parity of the hadron is a product of parity of the string in the given quantum state and the parity of the specific parity-chiral configuration of the quarks at the ends of the string.

Other implications:

(i) The spin-orbit interaction of quarks with the fixed chirality is absent (spin-orbit operator and chirality operator do not commute)

(ii) The tensor interaction is absent ($\vec{\sigma}(i) \cdot \vec{r}(i) = 0; \quad \vec{\sigma}(i) \cdot \vec{r}(j) = 0$)

Lattice strategy. Ab initio QCD computer calculations.

(i) Discretize space-time.

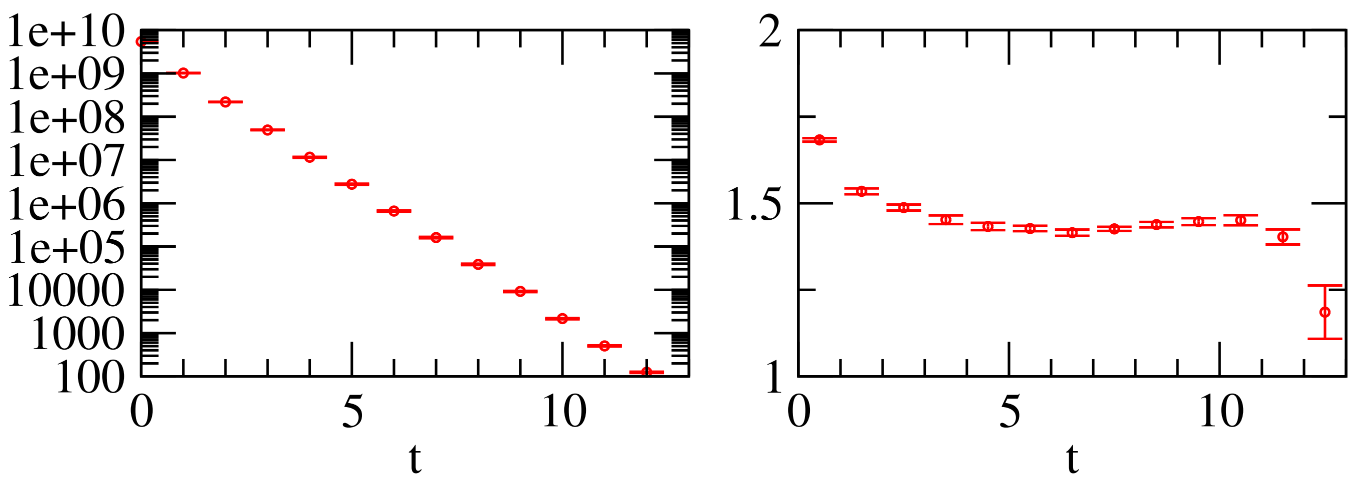
(ii) Create from the vacuum at some point 0 three quarks with required quantum numbers and annihilate them at some point x back into the vacuum.

(iii) Calculate by Monte Carlo path integral sum over all field configurations.

(iv) The required physical states will appear as intermediate states:

$$\langle 0| \left[\bar{\chi}(t)\chi(0)\right] |0\rangle = \sum_n \langle 0|\bar{\chi}|n\rangle e^{-E_n t} \langle n|\chi|0\rangle = C_0 e^{-E_0 t} + C_1 e^{-E_1 t} + ...$$

(v) Extract E_0 from the large t asymptotics; subtract it and try to extract E_1 at small times; ... If data are precise, it should work. Alas, in reality the data are not precise...



The low-lying baryons on the lattice.

Variational method (Michael,1985; Lüscher & Wolf,1990): Use several different interpolators χ_i and compute the cross-correlation matrix $C_{ij}(t) = \langle \bar{\chi}_i(t) \chi_j(0) \rangle$. Diagonalize matrix. Those eigenvalues $\lambda^k(t)$ which show exponential decay $\lambda^k(t) \sim e^{-E_k t}$ represent physical states.

D.Brömmel, P.Crompton, C.Gattringer, L.Ya.G., C.B.Lang, S.Schäfer, A. Schäfer, PRD, 2004.

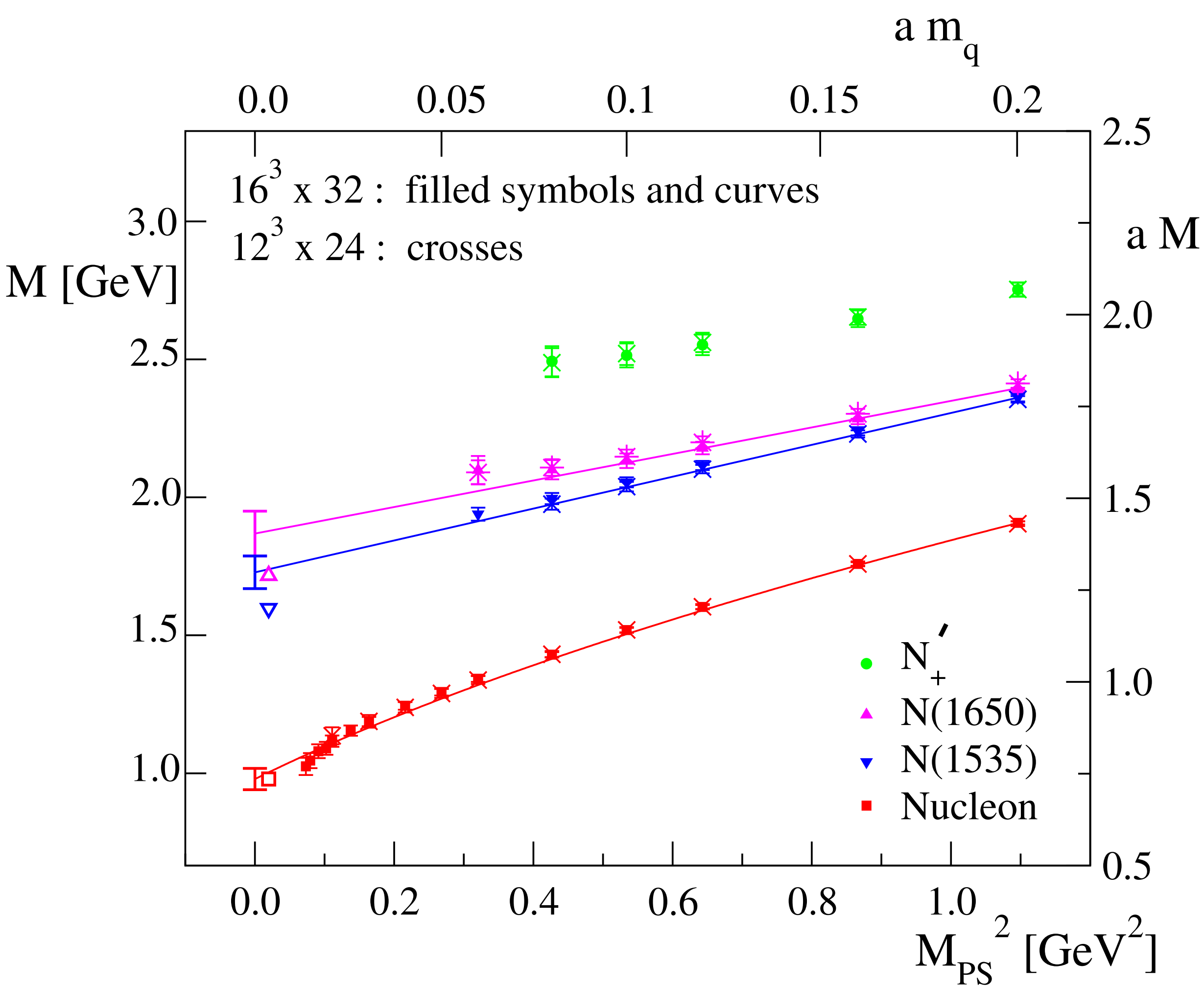
Chirally improved Dirac operator is used (Gattringer; Gattringer, Hip, Lang, 2001). Each quark is smeared (Gaussian shape). Interpolators:

$$\chi_1(x) = \epsilon_{abc} \left[u_a^T(x) C \gamma_5 d_b(x) \right] u_c(x),$$

$$\chi_2(x) = \epsilon_{abc} \left[u_a^T(x) C d_b(x) \right] \gamma_5 u_c(x),$$

$$\chi_3(x) = i\epsilon_{abc} \left[u_a^T(x) C \gamma_0 \gamma_5 d_b(x) \right] u_c(x).$$

The low-lying baryons on the lattice.



Where is the Roper?

What is the Roper?

Perhaps the Roper is not a 3q state but something else? Many speculations.

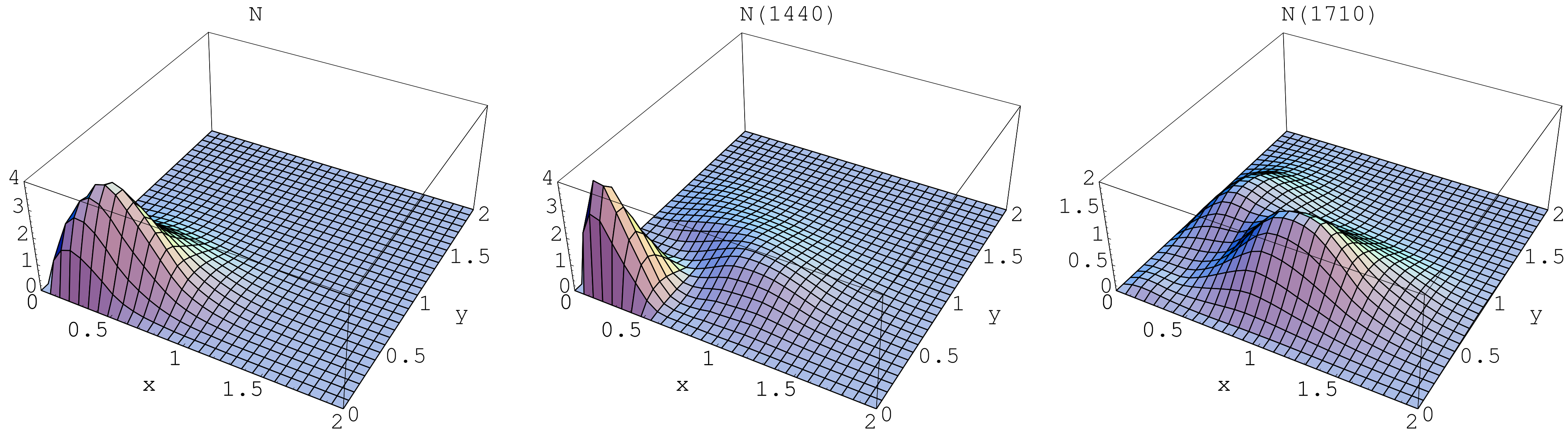
The most recent one: The Roper is a pentaquark with the scalar diquark - scalar diquark - antiquark structure, Jaffe and Wilczek, Phys. Rev. Lett., 2003, Physics Today, 2004, newspapers, press-conferences, ...

No - this scenario can be reliably ruled out, L.Ya.G., Phys. Rev. Lett., 2004

If the Roper has a leading $3q$ Fock component (Chiral constituent quark model) $\Longrightarrow$ it must be seen with the $3q$ interpolator. But how? The first Graz-Regensburg attempt and attempts of many others did not lead to success...
There are two lattice groups who claim have seen the Roper and the positive-negative parity level crossing. However, the methods they use can be shown to be problematic.

Any failure stimulates thinking ...

Lowest positive parity baryon wave functions



L.Ya.G, W.Plessas, K.Varga, R.F.Wagenbrunn, PRD, 1998

Spatially improved operators for excited hadrons.

Idea: to see the radially excited states $\Longrightarrow$ optimize quark fields in the source and sink in such a way that they would have a maximal overlap with the nodal wave function $\Longrightarrow$ two different types of gaussian smearings with different width. A linear combination of these two gaussians (with opposite signs) produces a nodal profile.

New method for excited hadrons on the lattice: 'Spatially improved operators'.

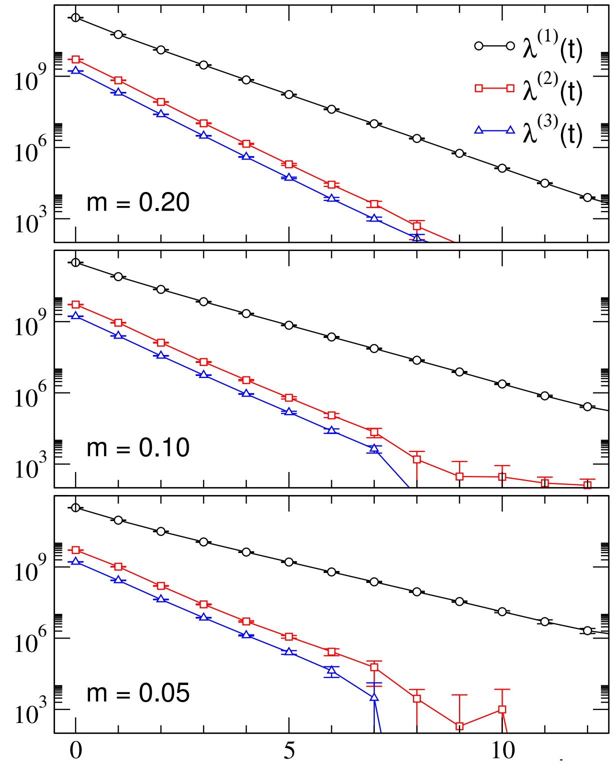
The second Graz - Regensburg attempt (T. Burch, C.Gattringer, L.Ya.G., R. Kleindl, C.B.Lang, A. Schäfer, 2004) - two different interpolators:

$$\chi_1(x) = \epsilon_{abc} \left[u_a^T(x) C \gamma_5 d_b(x) \right] u_c(x),$$

$$\chi_2(x) = \epsilon_{abc} \left[u_a^T(x) C d_b(x) \right] \gamma_5 u_c(x),$$

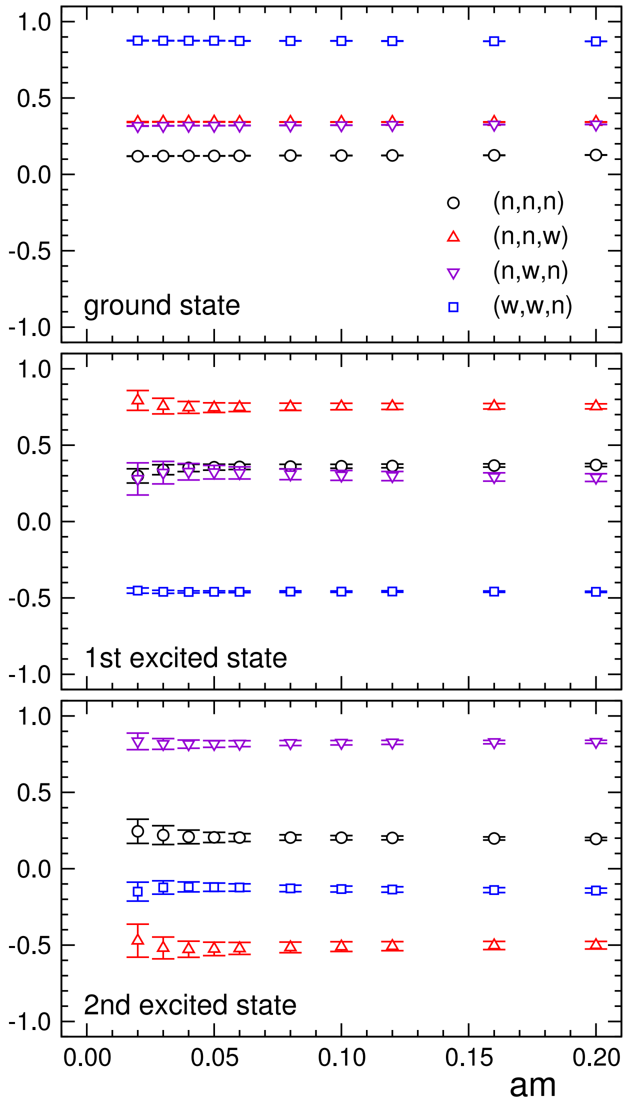
Each quark in the source and sink is smeared wide and narrow Gaussian shape. Then the cross-correlation matrix is computed and diagonalized.

Spatially improved operators for excited hadrons.



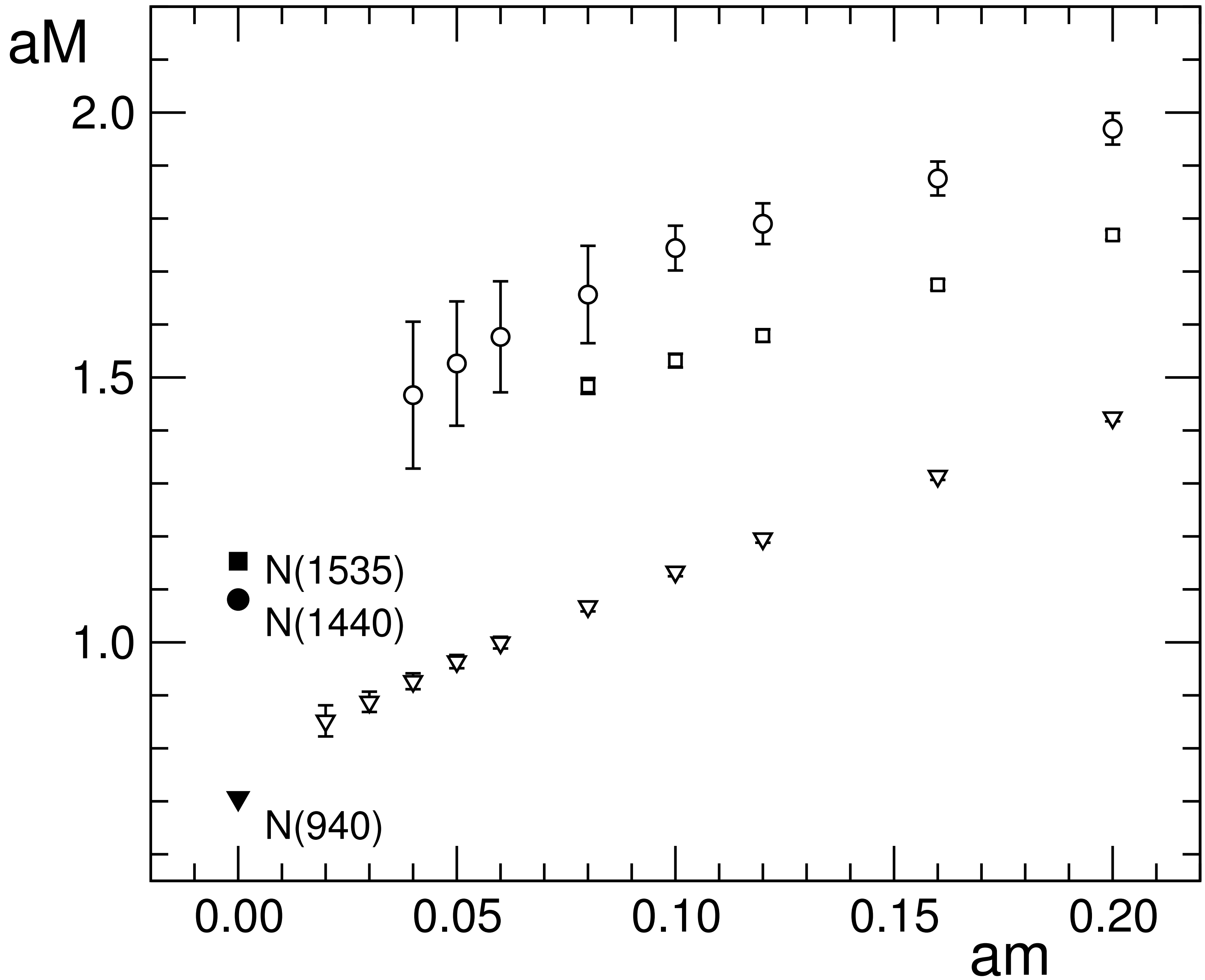
There is a clean exponential decay for three different eigenvalues. Hence they can be identified with the ground state, $N(939)$, the Roper state, $N(1440)$, and the next radial excitation $N(1710)$.

Spatially improved operators for excited hadrons.



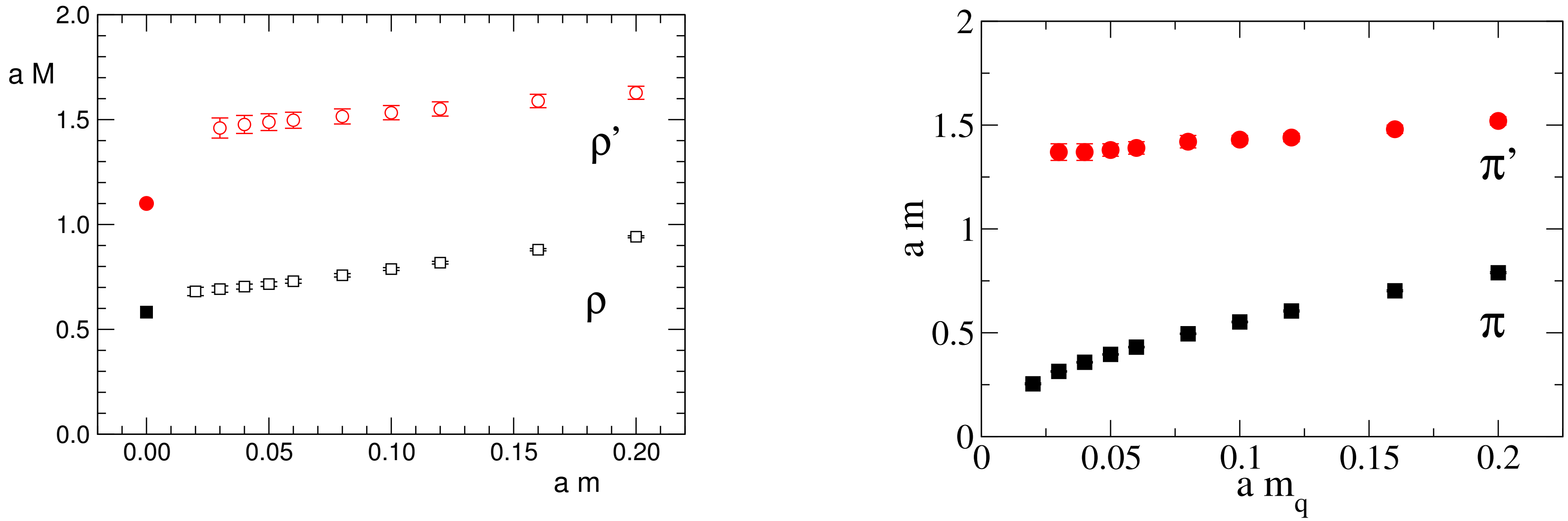
The ground state does not show a node while both excited states do show a node.

Spatially improved operators for excited hadrons.



DeGrand, 2003: Valence quarks in excited mesons decouple from the low-lying eigenmodes of the Dirac operator (i.e. decouple from the quark condensate).

Our lattice calculations:



Physics of the low-lying and high-lying states is very different and the high-lying states are not (or weakly) affected by spontaneous breaking of chiral symmetry.

Summary.

1. There are clear indications from phenomenology and theory that physics of the low-lying and the high-lying hadrons is rather different. The low-lying baryons and the pion are strongly affected by the spontaneous breaking of chiral symmetry, while in the high-lying states this chiral symmetry breaking becomes irrelevant (chiral symmetry restoration).

2. While for the low-lying baryons the idea of quasiparticles (constituent quarks) interacting strongly with the pion field is fruitful, in the high-lying hadrons a string (flux-tube) picture with valence quarks with definite chirality at the ends of the string is probably correct.

3. First lattice results support the idea of chiral symmetry restoration in excited hadrons.

4. Physics of the high-lying states is a pure physics of confinement. A vigorous and systematic experimental study of the high-lying hadrons is required (BEIJING, PANDA at GSI, JLAB, BONN, JPARC,...)