Confinement, chiral symmetry breaking and the mass generation of hadrons

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Key questions to QCD

Key question to QCD: How is the hadron mass generated in the light quark sector?

- How important is the chiral symmetry breaking for the hadron mass?
- Are confinement and chiral symmetry breaking directly interrelated?
- Is there parity doubling and does chiral symmetry get effectively restored in high-lying hadrons?
- Is there some other symmetry?
- How is the angular momentum of hadrons connected to the chiral symmetry breaking?

What is the hadron mass origin in QCD?

Gell-Mann - Levy sigma model, Nambu - Jona-Lasinio mechanism, many "Bag-like" and microscopical models to QCD:

Chiral symmetry breaking in a vacuum is the source of the hadron mass in the light quark sector.

A typical implication: In a dense medium upon smooth chiral restoration the hadron (ρ,...) mass should drop off (the Brown-Rho scaling).

Is it true?

Is chiral symmetry breaking in QCD and confinement are uniquely interconnected? (A key question for the QCD phase diagram).

The quark condensate and the Dirac operator

Banks-Casher: A density of the lowest quasi-zero eigenmodes of the Dirac operator represents the quark condensate of the vacuum:

$$< 0|\bar{q}q|0 >= -\pi\rho(0).$$

Sequence of limits: $V \to \infty; m_q \to 0$.

The lattice volume is finite and the spectrum is descrete. We remove an increasing number of the lowest Dirac modes from the valence quark propagators and study the effects of the remaining chiral symmetry breaking on the masses of hadrons.

$$S(k) = S - \sum_{i \leq k} \mu^{-1} |v_i >< v_i| \gamma_5,$$

S - standard quark propagator in a given gauge configuration;

μ_i are the real eigenvalues of the Hermitian $D_5 = \gamma_5 D$ Dirac operator;

$|v_i >$ - eigenvectors;

k number of the removed lowest eigenmodes.

Extraction of the physical states on the lattice

Assume we have hadrons (states) with energies $n = 1, 2, 3, ...$ with fixed quantum numbers.

$$C(t)_{ij} = \langle \mathcal{O}_i(t) \mathcal{O}_j^\dagger(0) \rangle = \sum_n a_i^{(n)} a_j^{(n)*} \mathrm{e}^{-E^{(n)} t} \tag{1}$$

where

$$a_i^{(n)} = \langle 0 | \mathcal{O}_i | n \rangle \ .$$

The generalized eigenvalue problem:

$$\widehat{C}(t)_{ij} u_j^{(n)} = \lambda^{(n)}(t, t_0) \widehat{C}(t_0)_{ij} u_j^{(n)} . \tag{2}$$

Each eigenvalue and eigenvector corresponds to a given state. If a basis $\mathcal{O}_i$ is complete enough, one extracts energies and "wave functions" of all states.

$$\frac{C(t)_{ij} u_j^{(n)}}{C(t)_{kj} u_j^{(n)}} = \frac{a_i^{(n)}}{a_k^{(n)}} \ . \tag{3}$$

Extraction of the physical states on the lattice

E.g., we want to study $I = 1, 1^{--}$ states $\rho = \rho(770)$ and its excitations.
Then a basis of interpolators:

$$\mathcal{O}_V = \bar{q}(x)\tau\gamma^i q(x);$$

$$\mathcal{O}_T = \bar{q}(x)\tau\sigma^{0i} q(x);$$

$$\mathcal{O}_\partial = \bar{q}(x)\tau\partial^i q(x); \ldots$$

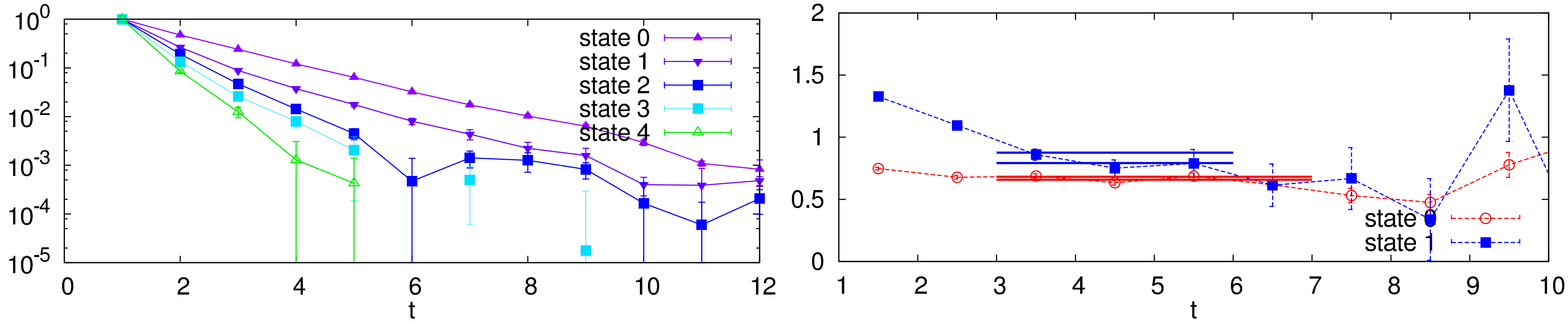
plus interpolators with a Gaussian smearing of the quark fields in spatial directions in the source and sink.

Some lattice details:

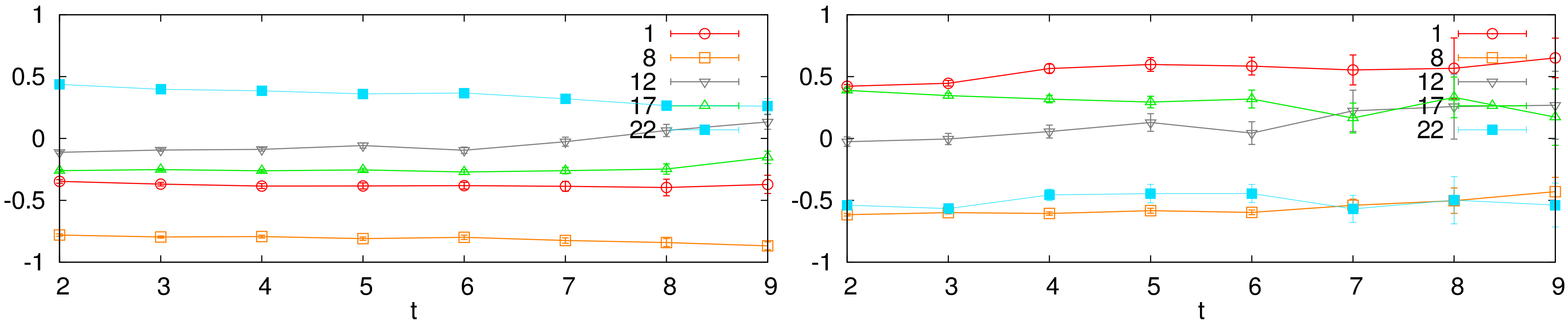
- Unquenched QCD with 2 dynamical flavors.
- $L = 2.4$ fm; $a = 0.144$ fm
- $m_\pi = 322$ MeV ($m_{u,d} \sim 15$ MeV)
- Chirally improved fermions

We subtract the low-lying chiral modes from the valence quarks.

$\rho(I=1,1^{--})$ with 12 eigenmodes subtracted

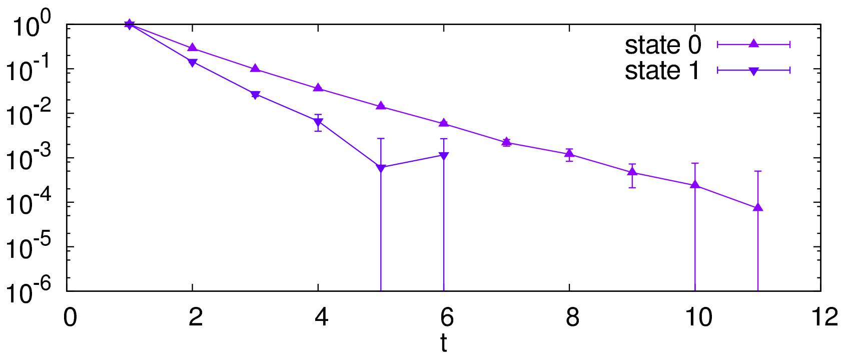


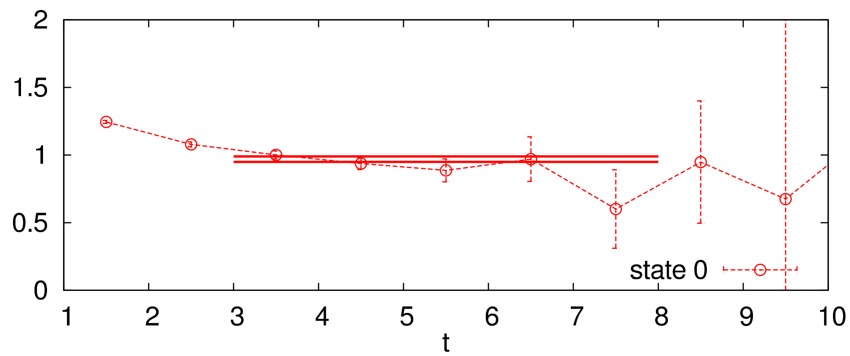
The correlators $\lambda_n(t) \sim \exp(-E_n t)$ for all eigenstates (left) and the effective mass plot $E_n(t) = \log(\lambda_n(t)/\lambda_n(t+1))$ for the two lowest states (right).



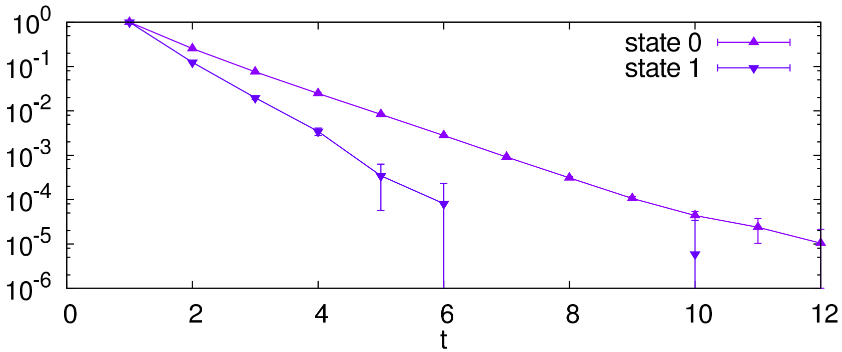
Eigenvectors corresponding to the ground state (left) and 1st excited state (right)

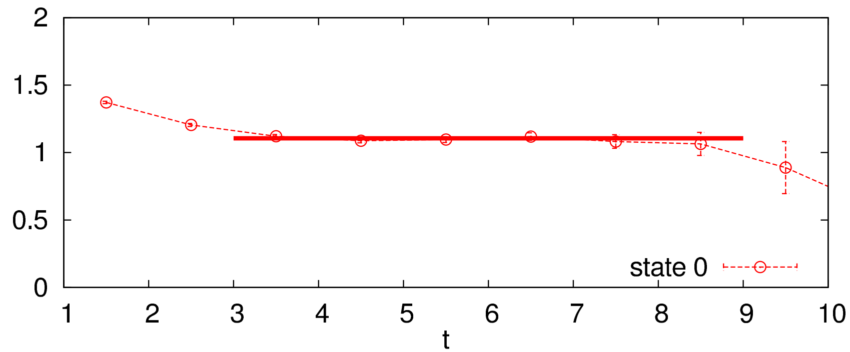
$b_1(I = 1, 1^{+-})$ states





The correlators $\lambda_n(t) \sim \exp\left(-E_n t\right)$ for all eigenstates with 2 eigenmodes subtracted and the effective mass plot $E_n(t) = \log(\lambda_n(t)/\lambda_n(t+1))$ for the lowest state.

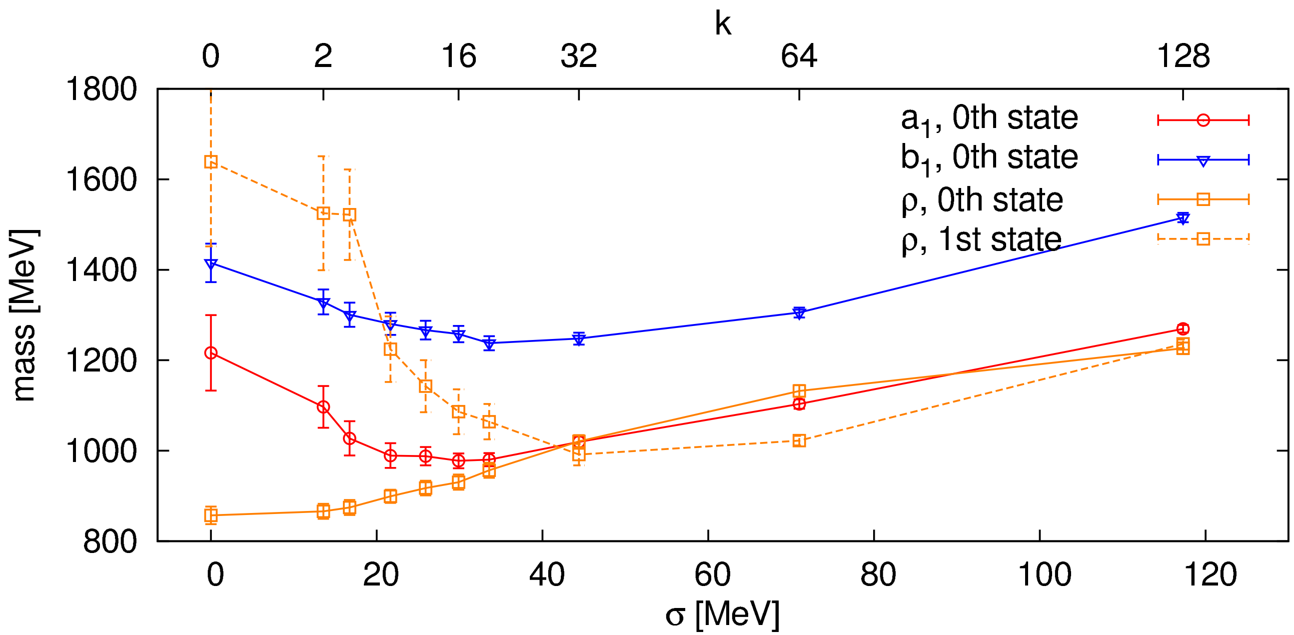




The same with 128 eigenmodes subtracted.

The quality of the exponential decay essentially improves with increasing the number of removed eigenmodes for ALL hadrons. By unbreaking the chiral symmetry we remove from the hadron its pion cloud and subtract all higher Fock components like πN, $\pi\Delta$, $\pi\pi$,...

What do meson degeneracies and splittings tell us?



The $SU(2)_L \times SU(2)_R \times C_i$ (chiral-parity) multiplets for $J = 1$ mesons:

$$\begin{array}{llll}
(0,0) & : & \omega(0,1^{--}) & f_1(0,1^{++}) \\
(\frac{1}{2},\frac{1}{2})_a & : & h_1(0,1^{+-}) & \rho(1,1^{--}) \\
(\frac{1}{2},\frac{1}{2})_b & : & \omega(0,1^{--}) & b_1(1,1^{+-}) \\
(0,1)+(1,0) & : & a_1(1,1^{++}) & \rho(1,1^{--})
\end{array}$$

The h_1, ρ, ω and b_1 states would form an irreducible multiplet of the $SU(2)_L \times SU(2)_R \times U(1)_A$ group.

What do meson degeneracies and splittings tell us?

- Chiral symmetry is restored but confinement is still there !

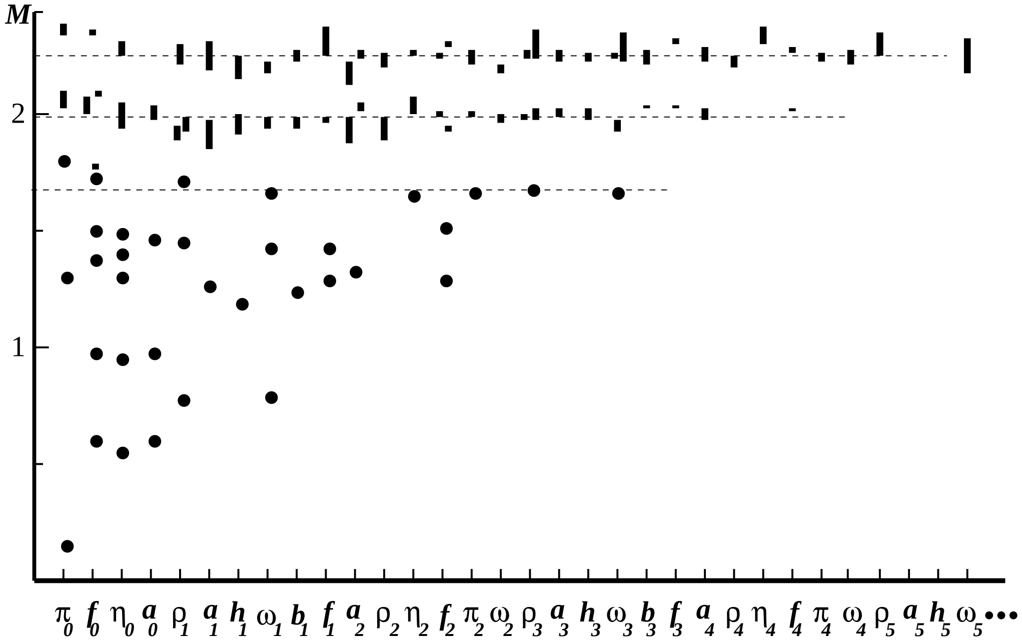
- Hadrons get their large chirally symmetric mass!

- The $SU(2)_L \times SU(2)_R$ gets restored while the $U(1)_A$ is still broken!

- The $U(1)_A$ explicit breaking comes not (not only) from the low-lying modes as the $SU(2)_L \times SU(2)_R$!

- $\rho - \rho'$ degeneracy indicates higher symmetry that includes $SU(2)_L \times SU(2)_R$ as a subgroup. What is this symmetry!? Is this symmetry related with the symmetry of the high-lying mesons?

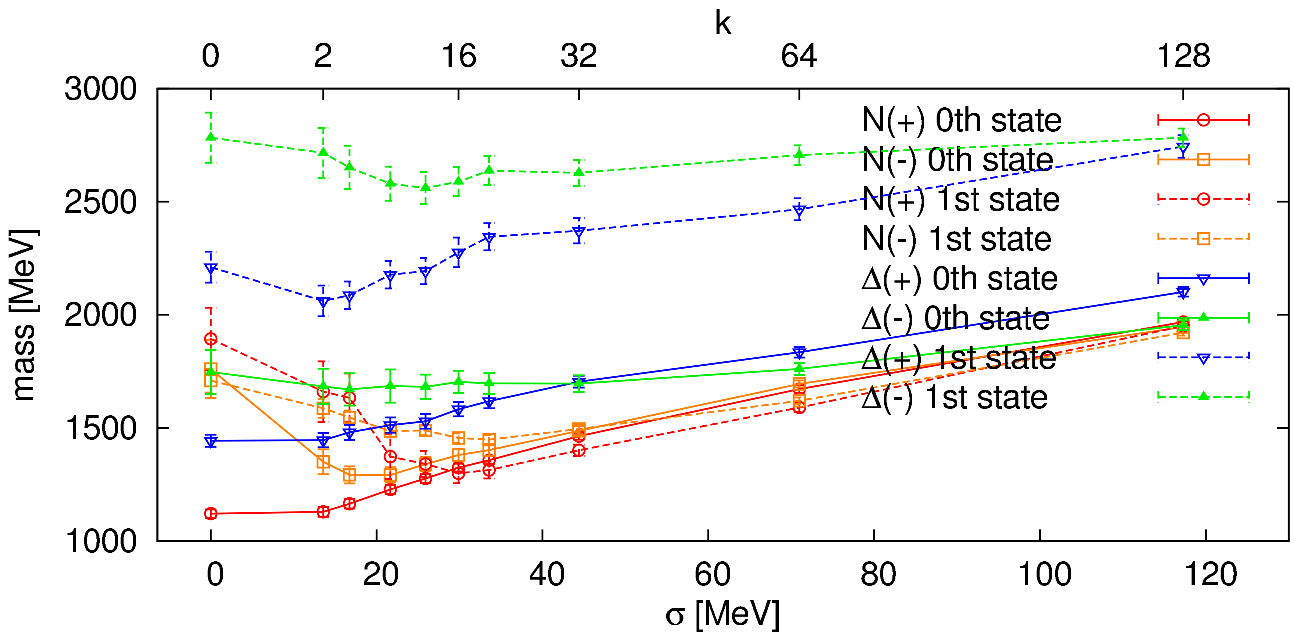
Low and high lying meson spectra.



The high-lying mesons are from $\bar{p}p$ annihilation at LEAR (Anisovich, Bugg, Sarantsev,...). Missing parity partners for highest spin states at each band. They ALL require higher partial wave in $\bar{p}p$ that is strongly (10-100 times) suppressed in $\bar{p}p$ near threshold. Cannot be seen in $\bar{p}p$?

Large symmetry: $N = n + J$ plus chiral symmetry.
An alternative: $N = n + L$ without chiral symmetry. (Afonin, Shifman-Vainshtein, Klempt-Zaitsev,...).L is a conserved quantum number ?! Naive string picture with quarks at the ends is intrinsically inconsistent.

Baryons



Three possible $SU(2)_L \times SU(2)_R \times C_i$ (chiral-parity) multiplets for any spin

$$(1/2, 0) + (0, 1/2); \quad (3/2, 0) + (0, 3/2); \quad (1/2, 1) + (1, 1/2)$$

Our interpolators have $J = 1/2$ for N and $J = 3/2$ for Δ, i.e. we cannot see $(1/2, 1) + (1, 1/2)$ quartets.

- Chiral symmetry is restored (all baryons are in doublets), while confinement is still there.
- Baryons have large CHIRALLY SYMMETRIC mass.
- Two $J = 1/2$ N doublets get degenerate - clear sign for a higher symmetry. No this higher symmetry for Δ's.

Chiral parity doublet

A free $I = 1/2$ chiral doublet B in the $(0, 1/2) + (1/2, 0)$ representation:

$$B = \begin{pmatrix} B_+ \\ B_- \end{pmatrix} . \tag{4}$$

The axial rotation mixes the positive and negative parity components:

$$B \to \exp\left(\imath \frac{\theta_A^a \tau^a}{2} \sigma_1\right) B. \tag{5}$$

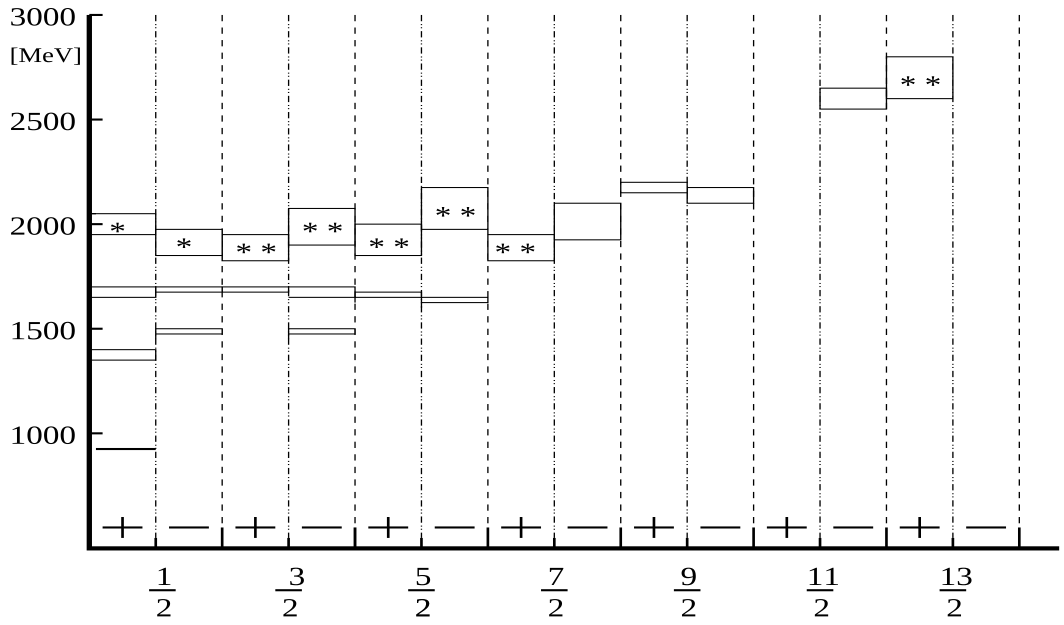
A chiral-invariant Lagrangian

$$\mathcal{L}_0 = i\bar{B}\gamma^\mu \partial_\mu B - m_0 \bar{B} B \tag{6}$$

- A nonzero chiral-invariant (!) mass m_0.
- $g_+^A = g_-^A = 0$, while the off-diagonal axial charge , $|g_{+-}^A| = |g_{-+}^A| = 1$.
- Pion decouples: $G_{\pi B_\pm B_\pm} = 0$.

B. W. Lee, 1972: "We dismiss this model as physically uninteresting"

Low and high lying baryon spectra.



Low-lying spectrum: spontaneous breaking of chiral symmetry is important for physics.

High-lying spectrum: parity doubling is suggestive of EFFECTIVE chiral symmetry restoration.

Recent and most complete analysis on highly excited nucleons (elastic πN and photoproduction data from Bonn and JLAB) reports evidence for some of the missing states and the parity doubling patterns look now better than before.

$B_\pm \to N\pi$ decays

If the state is a member of an approximate chiral multiplet, then its decay into $N\pi$ must be suppressed, $(f_{BN\pi}/f_{NN\pi})^2 \ll 1$. If, on the contrary, this excited nucleon has no chiral partner and hence its mass is due to chiral symmetry breaking in the vacuum, then it should strongly decay into $N\pi$, $(f_{BN\pi}/f_{NN\pi})^2 \sim 1$.

Spin	Chiral multiplet	Representation	$(f_{B_+N\pi}/f_{NN\pi})^2$	$(f_{B_-N\pi}/f_{NN\pi})^2$
1/2	$N_+(1440) - N_-(1535)$	$(1/2,0)\oplus(0,1/2)$	0.15	0.026
1/2	$N_+(1710) - N_-(1650)$	$(1/2,0)\oplus(0,1/2)$	0.0030	0.026
3/2	$N_+(1720) - N_-(1700)$	$(1/2,0)\oplus(0,1/2)$	0.023	0.13
5/2	$N_+(1680) - N_-(1675)$	$(1/2,0)\oplus(0,1/2)$	0.18	0.012
7/2	$N_+(?) - N_-(2190)$	?	?	0.00053
9/2	$N_+(2220) - N_-(2250)$	?	0.000022	0.0000020
11/2	$N_+(?) - N_-(2600)$	?	?	0.00000064
3/2	$N_-(1520)$	no chiral partner		2.5

A 100% correlation of decays with the parity doublet patterns!

Baryon axial charges

Key question: Baryon axial charges.

If small, « 1, then supports the chirally symmetric mass. If large, ~ 1, then chiral symmetry breaking is important.

Lattice results are available only for two lowest negative parity $I = 1/2; J^P = 1/2^-$ states.

- T. T. Takahashi, T. Kunihiro, PRD78 (2008) 011503

$m_q \sim 65$ MeV; $G_A^{(1)} \sim 0; G_A^{(2)} \sim 0.55$

- T. Mauer, T. Burch, L.Ya.G., C.B. Lang, D. Mohler, A. Scaefer

$m_q \sim 15$ MeV; $G_A^{(1)} \sim 0; G_A^{(2)} \sim 1.1$.

Conclusions

- After removal of the low-lying modes of the Dirac operator chiral symmetry is restored and signals from all hadrons survive (except for a pion).

- The quality of the signals from the hadrons after removal of the quark condensate become much better than with the untruncated quark propagators. Most probably this is related to the fact that we artificially remove the pion cloud of the hadrons.

- Chiral symmetry is artificially restored but confinement is there.

- There is a large chirally symmetric mass in this regime.

- All hadrons in this regime fall into different representations of the chiral group (parity doublets).

- We observe a higher degree of degeneracy than simply $SU(2)_L \times SU(2)_R$. I.e. there is a higher symmetry in this regime that includes chiral group as a subgroup.

- Removal of the low-lying modes of the Dirac operator does NOT restore the $U(1)_A$ symmetry.