RESTORATION OF CHIRAL AND $U(1)_A$ SYMMETRIES IN EXCITED HADRONS IN THE SEMICLASSICAL REGIME

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Contents of the Talk

- Chiral symmetry of QCD and its spontaneous breaking.
- Chiral symmetry restoration in excited hadrons.
- Chiral and $U(1)_A$ restorations in the semiclassical regime.
- Generalized NJL Model.
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Spontaneous breaking of chiral symmetry in QCD.

In QCD $m_u, m_d \ll \Lambda_{QCD}$. Hence to a good approximation.

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

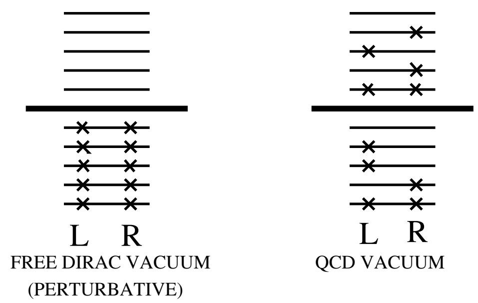
$U(1)_A$ is explicitly broken by the axial anomaly (quantum fluctuations).

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

Why? No chiral symmetry in the vacuum.

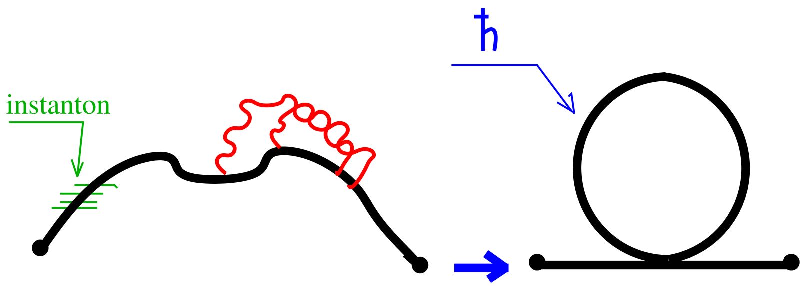
(i) No parity doublets low in the spectrum.

(ii) $\langle 0|\bar{q}q|0\rangle =\sim (-240\ MeV)^3$

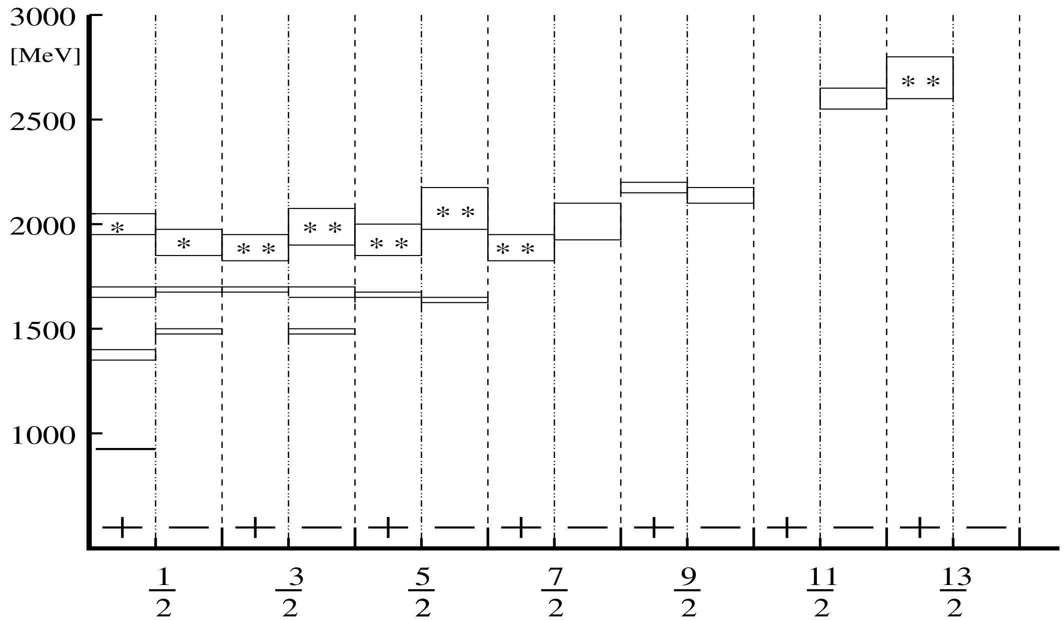


The most general origin are quantum fluctuations of quark fields.

$$< \bar{q}q >= -Tr\ lim_{x \to 0_+} < 0|T\{q(0)\bar{q}(x)\}|0 > \quad \longleftrightarrow \quad \hbar$$



Low and high lying baryon spectra.



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

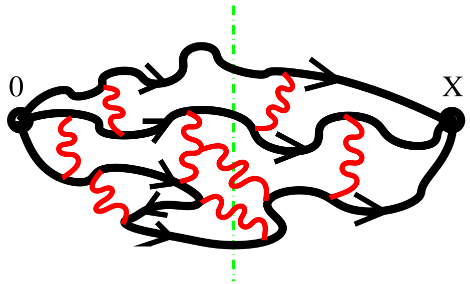
High-lying spectrum: parity doubling indicates the onset of the new physical regime - EFFECTIVE chiral symmetry restoration OR chiral symmetry restoration of the SECOND kind.

L.Ya.G., 2000 ; T.D. Cohen and L.Ya.G., 2002

Chiral symmetry restoration by definition.

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

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

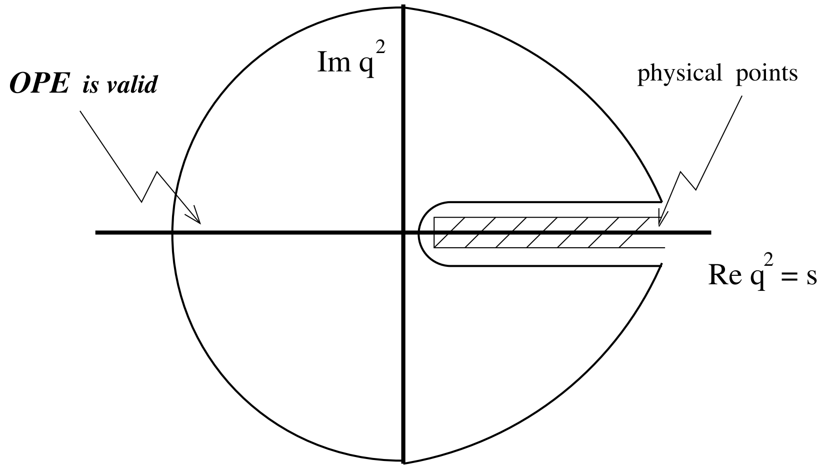


Consider two interpolators $J_1(x)$ and $J_2(x)$ such that $J_1(x) = U J_2(x) U^\dagger$where $U \in SU(2)_L \times SU(2)_R$. If $U|0\rangle = |0\rangle$, then spectra of hadrons with the quantum numbers 1 and 2 must be identical (Wigner-Weyl mode).

In the Nambu-Goldstone mode symmetry is broken in the vacuum, $U|0\rangle \neq |0\rangle$.Then the spectra of 1 and 2 are different. However, it happens that the noninvariance of the vacuum becomes irrelevant (unimportant) high in the spectrum, because hadrons mostly decouple from the quark condensates. Then chiral symmetry is approximately restored in the high-lying hadrons.

Chiral symmetry restoration and quark-hadron duality.

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



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:

$$\rho_1(s \rightarrow \infty) \rightarrow \rho_2(s \rightarrow \infty), \quad where \quad J_1(x) = UJ_2(x)U^\dagger$$

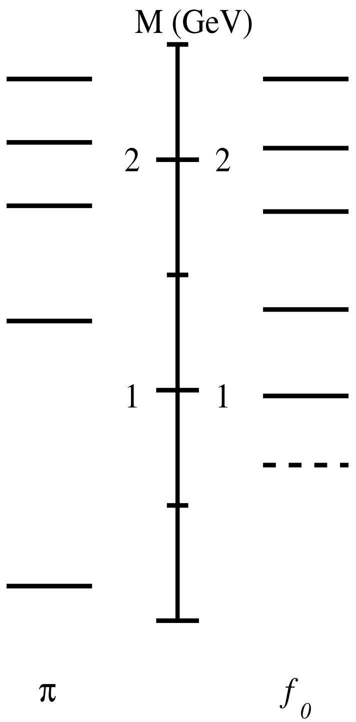
If the spectrum is quasidiscrete, then approximate chiral multiplets.
Shifman, 2005: OPE + some additional assumptions: the slowest possible rate of the symmetry restoration in large N_c mesons $\sim 1/n^{3/2}$.

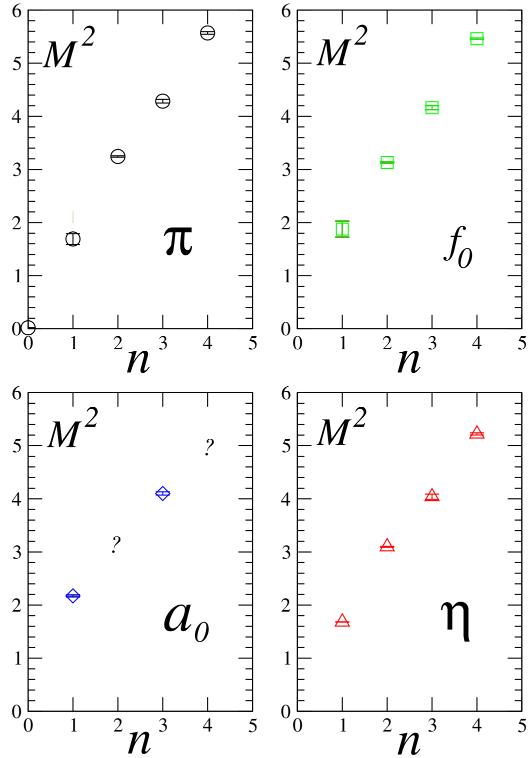
Chiral multiplets of excited mesons. L.Ya.G.,2002,2004

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 $\bar{p}p$ (Anisovich, 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

Chiral and $U(1)_A$ restorations in the semiclassical regime

What is the most fundamental reason of symmetry restoration? (L.Ya.G.,2004)

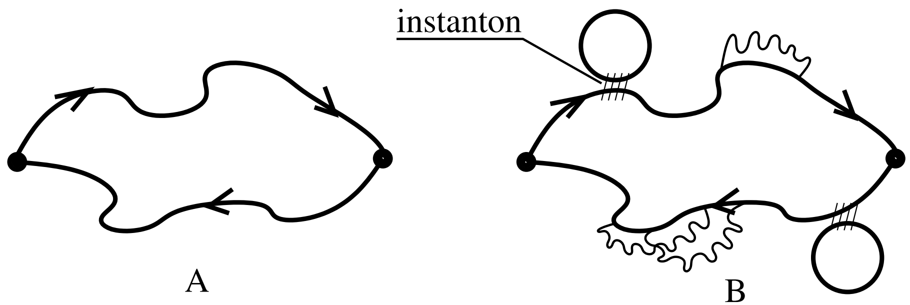
$$\Pi(x,y) = \frac{1}{Z}\int DA_\mu D\Psi D\bar{\Psi} e^{\frac{iS(\bar{\Psi},\Psi,A)}{\hbar}} J(x)J(y)^\dagger$$

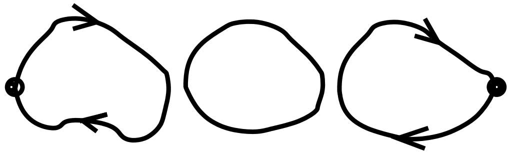
If $\hbar \to 0$, then only the CLASSICAL TRAJECTORY survives:

$$\delta S(\bar{\Psi}_{cl}, \Psi_{cl}, A_{cl}) = 0 \qquad \Longleftarrow CLASSICAL\ EQUATION\ OF\ MOTION$$

At the classical level both chiral and $U(1)_A$ symmetries are manifest.

Their breaking comes from the quantum fluctuations and starts from the one loop order .





Chiral and $U(1)_A$ restorations in the semiclassical regime

If $S \gg \hbar$, then the SEMICLASSICAL EXPANSION is valid:

- the classical contribution $\longrightarrow (\frac{\hbar}{S})^0$
- the one-loop contribution $\longrightarrow (\frac{\hbar}{S})^1$
- the two-loop contribution $\longrightarrow (\frac{\hbar}{S})^2$

Chiral and $U(1)_A$ breakings start from the one-loop order. If $S \gg \hbar$, the quantum fluctuations become suppressed and chiral and $U(1)_A$ symmetries get restored.

In hadrons with large n (radial quantum number) or large J , $S \gg \hbar$.

Do we reach a semiclassical regime? At $N_c = \infty$ it is an exact statement (for mesons).

- The mesons are narrow states and the two-point function is saturated by the bound states only.
- The spectrum is infinite.

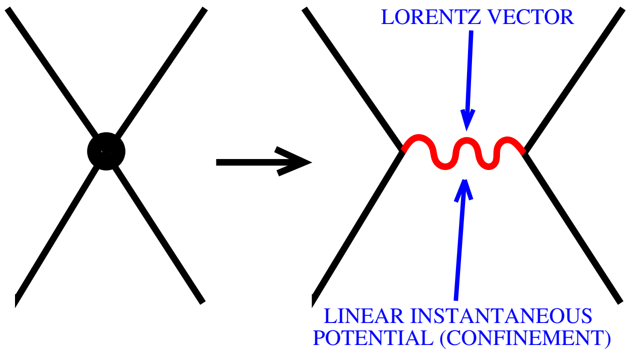
Then we can excite a meson with an arbitrary large action S .

For any large S there always exist such N_c that the isolated mesons with such an action do exist and can be described semiclassically.

Generalized NJL. L.Ya.G., A.Nefediev. 2005,2006

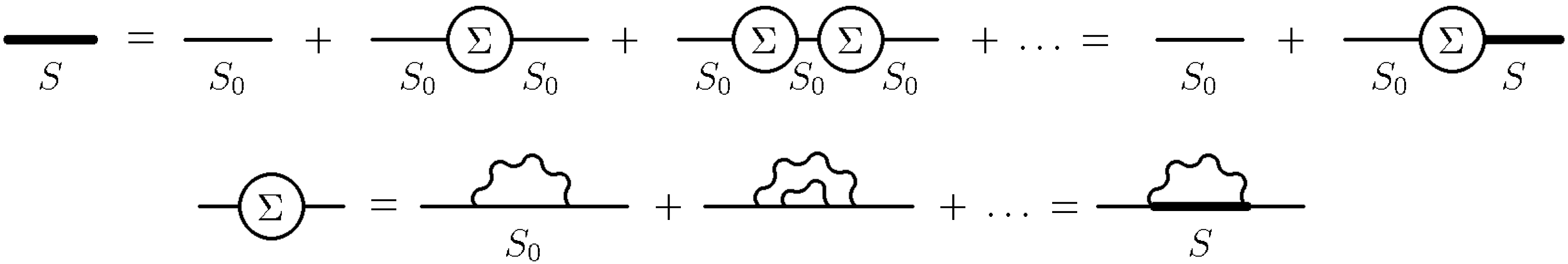
The only interaction between quarks is the instantaneous Lorentz-vector confinement potential.

Le Yaouanc, Oliver, Pene and Raunal, 1983



Chiral symmetry breaking is via the Schwinger-Dyson (gap) equation:

$$S = S_0 + S_0 \Sigma S$$



Generalized NJL. L.Ya.G., A.Nefediev. 2005,2006

The gap equation:

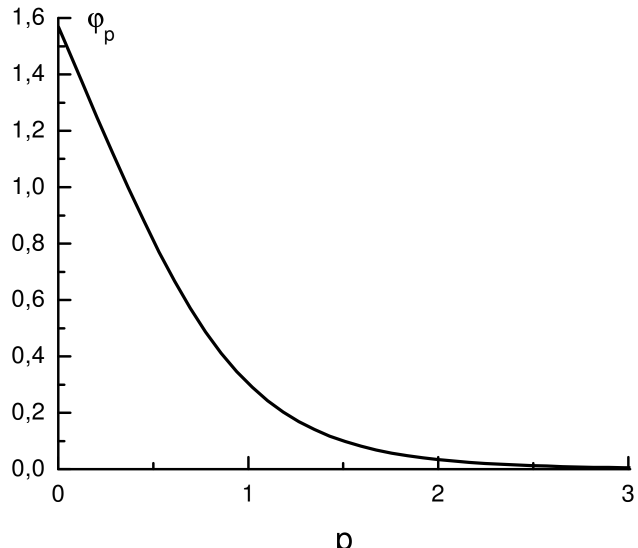
$$i\Sigma(\vec{p}) = \hbar \int \frac{d^4k}{(2\pi)^4} V_{CONF}(\vec{p}-\vec{k})\gamma_0 \frac{1}{S_0^{-1}(k_0,\vec{k}) - \Sigma(\vec{k})}\gamma_0.$$

The self-energy consists of the scalar (chiral symmetry breaking) and vector (chiral symmetric) parts: $\Sigma(\vec{p}) = [A_p - m] + (\vec{\gamma}\hat{\vec{p}})[B_p - p].$

They come entirely from quantum fluctuations - loops!

Then the dispersive law is: $E_p = A_p \sin\phi_p + B_p \cos\phi_p; \qquad \tan\phi_p = \frac{A_p}{B_p}$

The numerical solution of the gap equation:



Generalized NJL. L.Ya.G., A.Nefediev. 2005,2006

Given the quark Green function, mesons are obtained from the Bethe-Salpeter equation.

In the highly-excited hadrons TYPICAL momenta of valence quarks are large, hence $\phi_p \rightarrow 0$ and the chiral symmetry breaking Lorentz-scalar self-energy (dynamical mass) $\rightarrow 0$.

Quarks decouple from the chiral condensate.

Consequently chiral symmetry is approximately restored and the spectrum consists of approximate chiral multiplets..

Chiral symmetry breaking proceeds only near the turning points, where quarks are slow and condensate is important.

The Goldstone bosons decouple from the valence quarks:
GT relation: $g_\pi \sim m_q^{eff}; \qquad m_q^{eff} \rightarrow 0$

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 hadrons are strongly affected by the spontaneous breaking of chiral and $U(1)_A$ symmetries, while in the high-lying states these chiral symmetry breakings become irrelevant (chiral symmetry restoration).

2. While for the low-lying hadrons the idea of quasiparticles (constituent quarks) interacting strongly with the pion field is fruitful, in the high-lying hadrons, where the typical momenta of quarks are large, quarks decouple from the chiral condensate and have definite chirality.

3. A fundamental origin of this phenomenon is that effects of quantum fluctuations of the quark fields must vanish at large n and J and the semiclassical description becomes adequate.