CHIRAL SYMMETRY OF EXCITED HADRONS FROM PHENOMENOLOGY, THEORY AND LATTICE

L. Ya. Glozman

Institut für Physik, FB Theoretische Physik, Universität Graz

Contents of the Talk

- Chiral symmetry and origin of hadron mass
- Generalized 't Hooft Model
- Chiral symmetry, OPE, strings and holography
- Chiral and ${}^{2S+1}L_J$ content of mesons on lattice

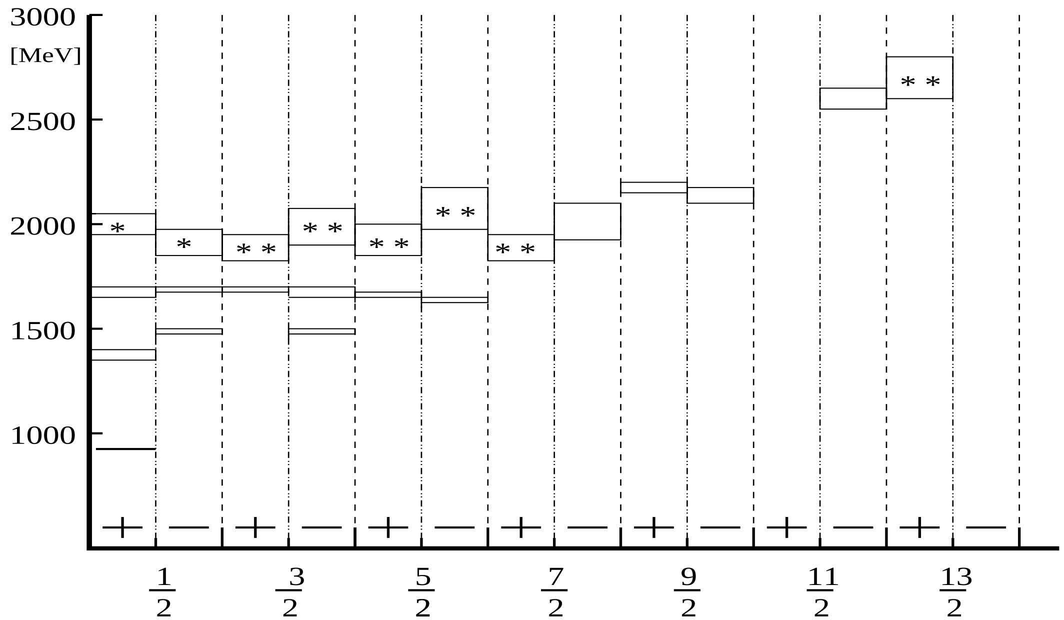
What is a hadron mass origin in QCD?

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

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

Is it true? Or, better to say, is it entirely true?

Low and high lying baryon spectra.



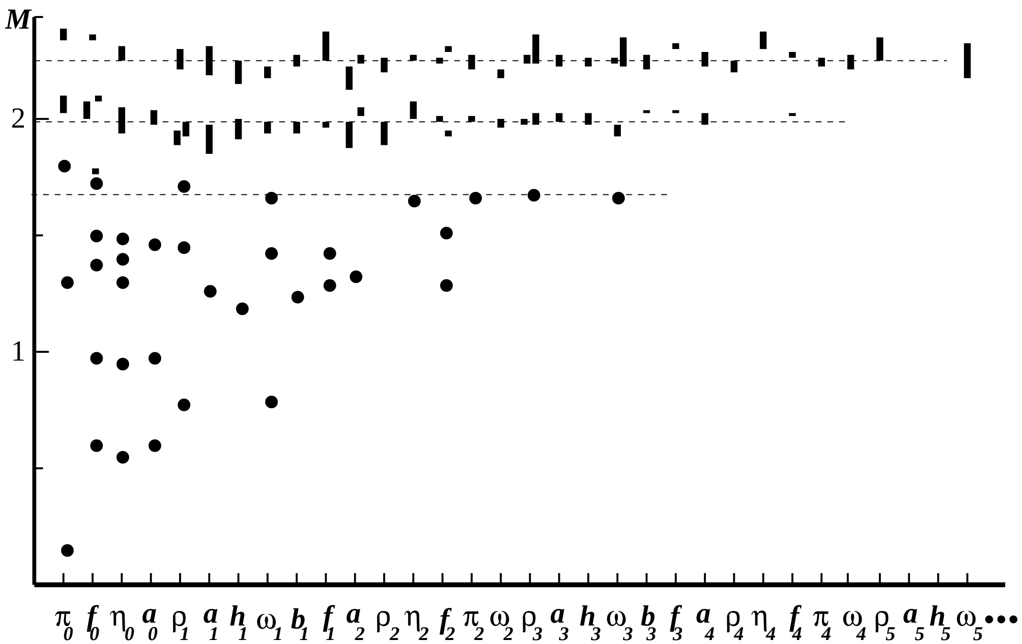
Low-lying spectrum: spontaneous breaking of chiral symmetry dominates physics.

High-lying spectrum: parity doubling is indicative of EFFECTIVE chiral symmetry restoration (a conjecture).

Mass of excited baryons comes mostly from the chirally symmetric dynamics; baryons decouple from the quark condensate of the vacuum.

L.Ya.G., 2000; T.D.Cohen and L.Ya.G., 2002; L.Ya.G., Phys. Rep. 444 (2007) 1

Low and high lying meson spectra.



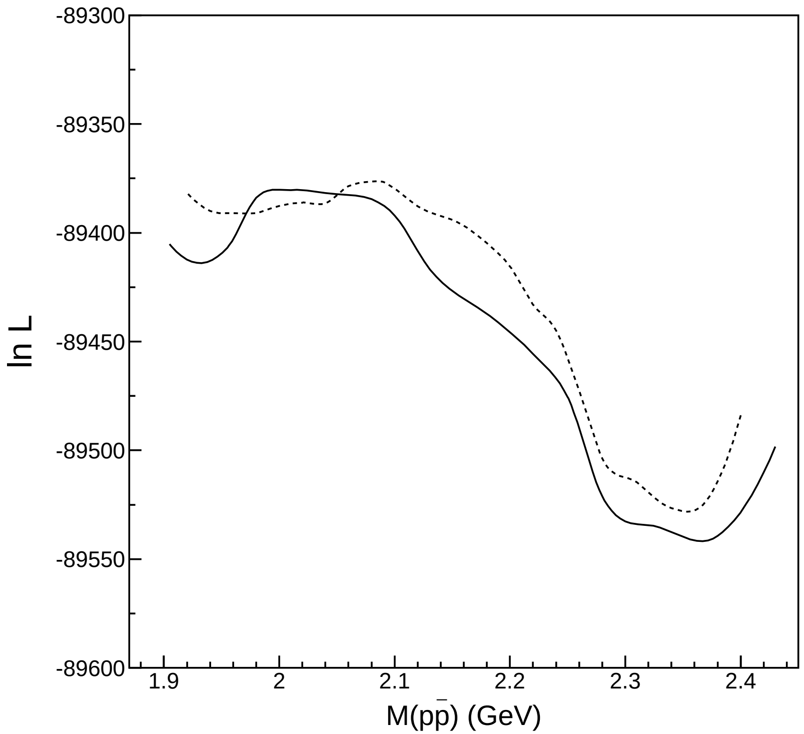
The high-lying mesons are from LEAR. Systematic appearance of $SU(2)_L \times SU(2)_R$ and $U(1)_A$ multiplets (L.Ya.G., 2002, 2004). Missing chiral partners for highest spins. Large symmetry: $N = n + J$ plus chiral symmetry(L.Ya.G. and A.V. Nefediev, 2007).

An alternative: $N = n + L$ without chiral symmetry (Afonin, 2006; Klempt and Zaitsev, 2007; Shifman and Vainshtein, 2008) Angular momenta ($^{2S+1}L_J$)- like in the nonrelativistic 2-body quantum mechanics. Conflict with the Poincare invariance and the renormalizability of QCD.

Do missing chiral partners exist?

If yes, why didn't Anisovich, Bugg, Sarantsev observe them in 2000-2002?

$\bar{p}p$ annihilation around 2 GeV. - Strong centrifugal repulsion! Observed states have positive parity, f_4 and a_4, and are produced in the $L = 3$ partial wave. All missing states,$\eta_4, \rho_4, \pi_4, \omega_4$, have negative parity and can be produced only in the $L = 4$ partial wave. Additional centrifugal suppression 10 - 100 times!



L.Ya.G., A. Sarantsev, PRD 82 (2010) 037501

$B_\pm \to N\pi$ decays (L.Ya.G., PRL 99 (2007) 191602)

If a baryon 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	$N_+(?) - N_-(2600)$	?	?	0.000000064
3/2	$N_-(1520)$	no chiral partner		2.5

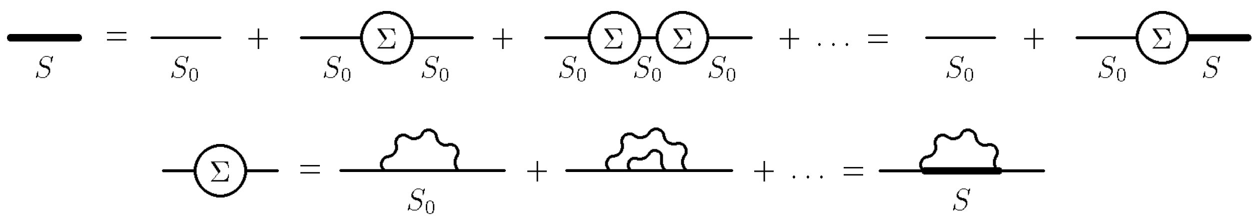
A 100% correlation of decays with the parity doublet patterns!

Generalized ’t Hooft model.

In 1+1 ’t Hooft model the only interaction is the Coulomb (linear) potential.

Le Yaouanc, Oliver, Pene and Raunal, 1983 : Postulate the confining instantaneous Coulomb-like potential in 3+1 dim (a la Gribov-Zwanziger). Seen in lattice Coulomb gauge.

Chiral symmetry breaking is via the Schwinger-Dyson (gap) equation. Infrared regularization is required.

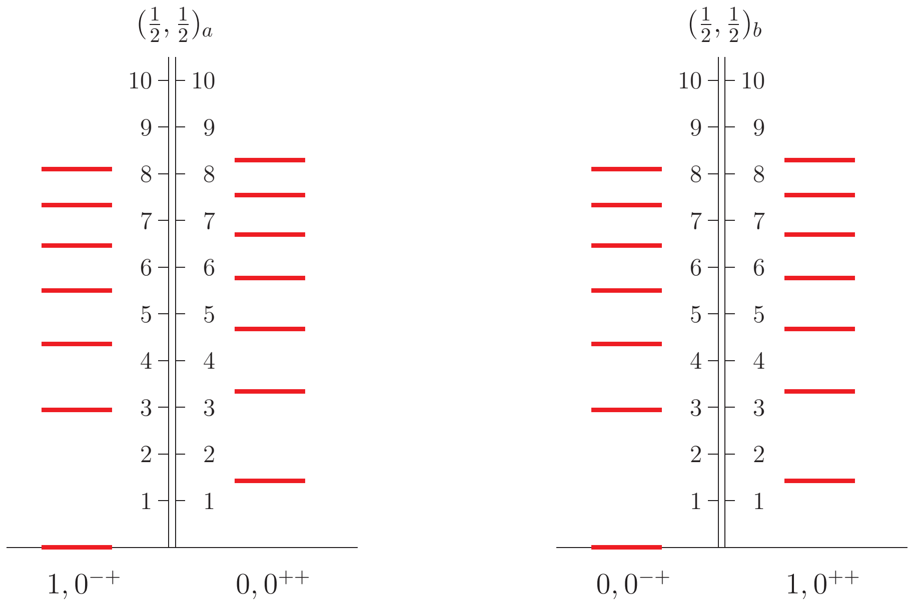


Given a quark Green function, obtain meson spectra fromthe Bethe-Salpeter equation.

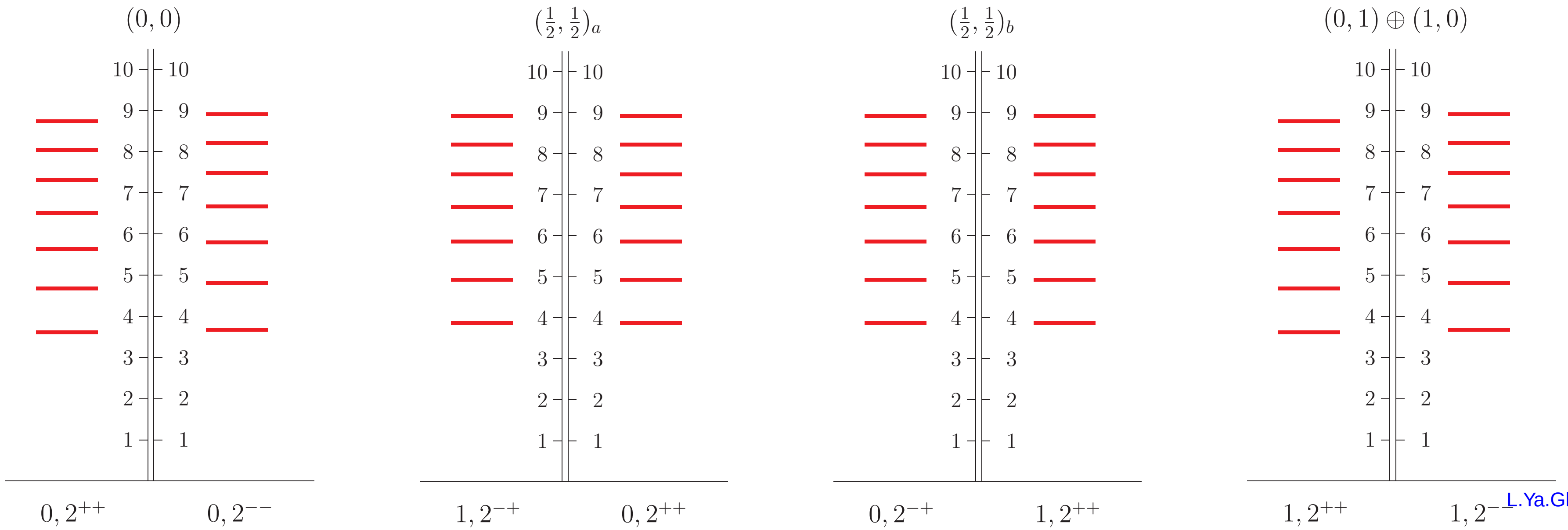
An important difference from the 1+1 ’t Hooft model: a rotational motion is possible; angular momenta exist.

Meson Spectra (R.F. Wagenbrunn and L.Ya.G., 2006)

$J = 0$

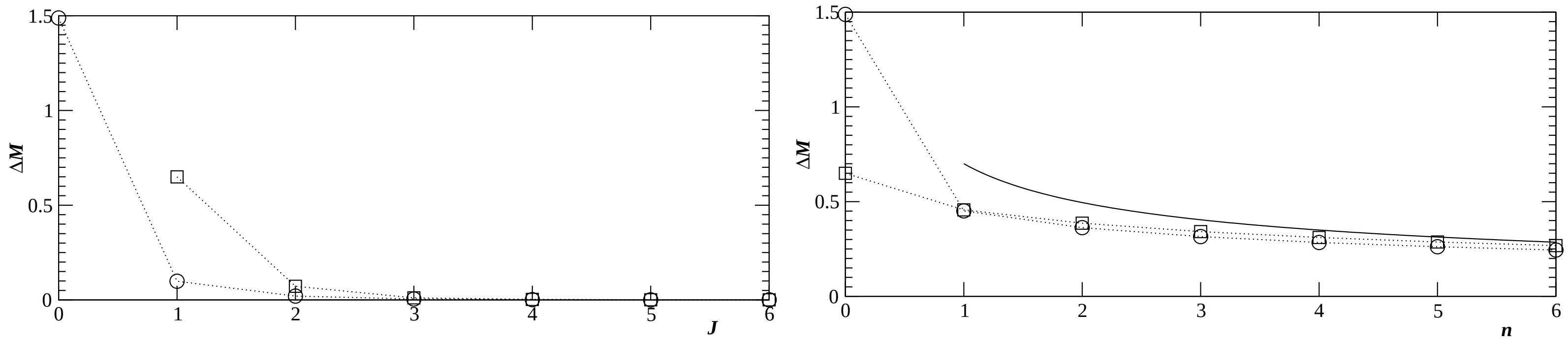


$J = 2$

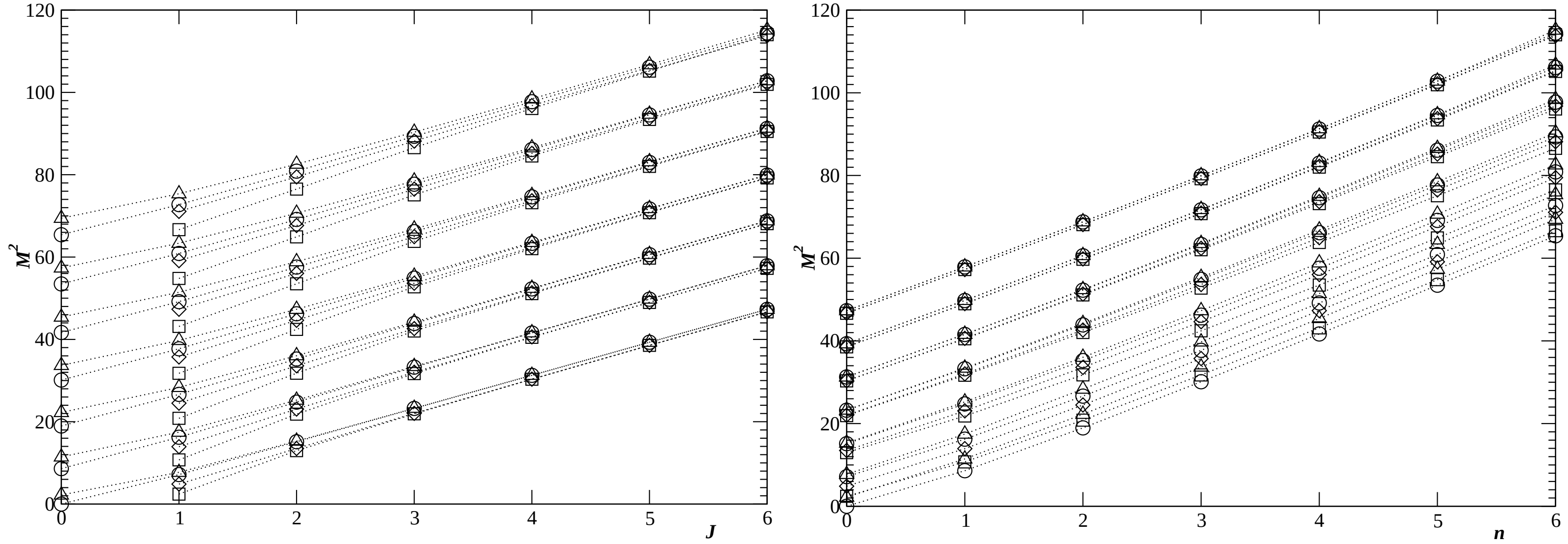


Meson Spectra (R.F. Wagenbrunn and L.Ya.G., 2006)

Rates of the symmetry restoration:



Regge trajectories:



$J \to \infty$: a complete degeneracy of all multiplets with the same J ; all states fall into $[(0,1/2) \oplus (1/2,0)] \times [(0,1/2) \oplus (1/2,0)]$. The loop effects disappear completely and the system becomes classical. No degeneracy of states with different J .

Chiral symmetry, OPE, strings and holography

L.Ya.G., A.V. Nefediev, PRD 76 (2007) 096004; 80 (2009) 057901

A unitary transformation from a chiral basis R in $\bar{q}q$ to the $\{I;{}^{2S+1}L_J\}$ basis :

$$|R;IJ^{PC}\rangle = \sum_{L}\sum_{\lambda_q\lambda_{\bar{q}}} \chi^{RPI}_{\lambda_q\lambda_{\bar{q}}} \times \sqrt{\frac{2L+1}{2J+1}} C^{S\Lambda}_{\frac{1}{2}\lambda_q\frac{1}{2}-\lambda_{\bar{q}}} C^{J\Lambda}_{L0S\Lambda}|I;{}^{2S+1}L_J\rangle.$$

Examples of fixed L :

$a_1\,:\,\,|(0,1)+(1,0);1\;1^{++}\rangle = |1;{}^3P_1\rangle$ $\qquad$ $h_1\,:\,\,|(1/2,1/2)_b;0\;1^{+-}\rangle = |0;{}^1P_1\rangle.$

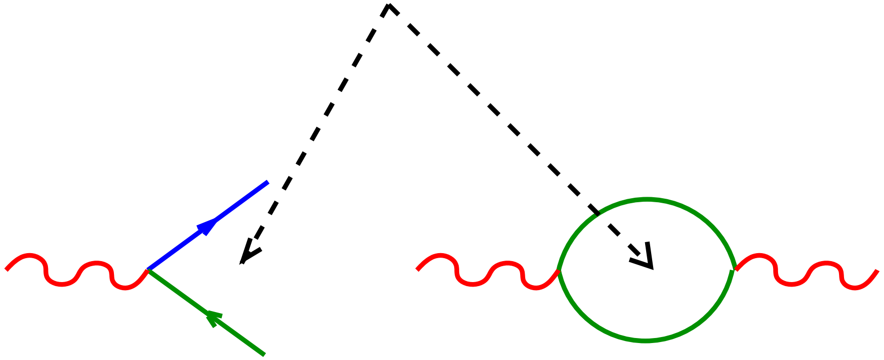
However, there are two kinds of ρ-mesons:

$$\begin{aligned} |(0,1)+(1,0);1\;1^{--}\rangle &= \sqrt{\frac{2}{3}}|1;{}^3S_1\rangle + \sqrt{\frac{1}{3}}|1;{}^3D_1\rangle, \\ |(1/2,1/2)_b;1\;1^{--}\rangle &= \sqrt{\frac{1}{3}}|1;{}^3S_1\rangle - \sqrt{\frac{2}{3}}|1;{}^3D_1\rangle. \end{aligned}$$

If chiral symmetry is unbroken, fixed L is impossible!

Chiral symmetry, angular content of mesons and OPE

$$\sqrt{\frac{2}{3}}\ {}^3S_1 + \sqrt{\frac{1}{3}}\ {}^3D_1$$



At the deep Euclidean momenta, the OPE is valid:

$$\Pi(Q^2) = -\frac{N_c}{12\pi^2} ln\ Q^2 + ...$$

In the time-like domain, along the cut, one has an infinite amount of excited ρ's:

$$\Pi(s) = -\sum_{n=1}^{\infty} \frac{f_n^2}{s - m_n^2}$$

It is not possible to match with the OPE if one assumes that all ρ's are radial excitations with the ${}^3S_1$ content.There must be ρ's that are orbital excitations. One cannot satisfy this with only one radial Regge trajectory.

AdS/QCD correspondence ?

QCD generating functional with the source $\phi_0(x)$ ($= J(x)$ in usual notation):

$$Z_{QCD}[\phi_0(x)] = \int \mathcal{D}[\bar{q}, q, A] \;\; exp\{iS_{QCD} + i \int d^4x \; \phi_0 \cdot \mathcal{O} \; \}$$

is to be matched with the 5dim gravity partition function for field $\phi_(x, z)$:

$$Z_5[\phi_(x, z)] = \int \mathcal{D}[\phi] \;\; exp\{iS[\phi]\}$$

so that $$Z_5[\phi_(x, z = 0) = \phi_0(x)] = Z_{QCD}[\phi_0(x)].$$

1 step: Identify hadron by its interpolating operator $\mathcal{O}$ in 4D and the corresponding 5D field $\phi_(x, z)$ in the bulk.

Unique for AdS/CFT. Is it true in QCD? Not: An infinite amount of different QCD operators sizebly contribute to the hadron mass with the given quantum numbers.

Example: ρ - meson.

$$\mathcal{O}_1 = \bar{q}\tau\gamma^\mu q; \quad \mathcal{O}_2 = \bar{q}\tau\sigma^{\mu\nu} q; \quad \mathcal{O}_3 = \bar{q}\tau D^\mu q; \ldots$$

AdS/QCD correspondence ?

2 step: (most explicit in Brodsky - deTeramond) Identify hadron quantum numbers L, S via the conformal (scaling) dimension Δ :
(i) Identify L as a relative angular momentum of two scalar partons: $\Delta = 2 + L$

(ii) Identify S via substitution of Δ by Twist = Dimension - Spin

$$\Delta \longrightarrow Twist = \Delta \; - \; S; \qquad S = \sum \sigma_i$$

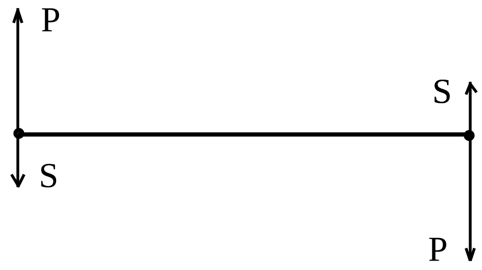
3 step: Given a field in the bulk with fixed $L; S$ solve a wave equation in the bulk with some boundary condition in the infrared that similates breaking of conformal invariance and appearance of confinement (hard wall or soft wall). From the eigenvalues and eigenvectors extract masses, wave functions, ...

Our comment: Then it is impossible to provide a proper matching at the ultraviolet boundary $z = 0$, where chiral symmetry is NOT broken (i.e. to satisfy the prescriptions of the AdS/CFT dictionary, that is a basic assumption of AdS/QCD):

$$\bar{q}\tau\gamma^\mu q = \sqrt{\frac{2}{3}}|1;{}^3S_1\rangle + \sqrt{\frac{1}{3}}|1;{}^3D_1\rangle.$$

Is Nambu-Goto string consistent with chiral symmetry?

What is the ASYMPTOTIC picture for excited hadrons? :



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

(ii)the ends of the string move at a speed of light

It is a classical Nambu-Goto string without spinning quarks at the ends of the string. Energy is determined by L and n . Consequence: Regge trajectories $M^2 \sim L$.

In reality there are quarks with SPIN at the ends. What are consequences?

(i) The quarks must have a definite chirality.

(ii) Hadrons that belong to the same intrinsic quantum state of the string can be of both parities, depending on the right-left combinations of the quarks at the ends. These hadrons must be degenerate.

(iii) There is no definite spin-orbit interaction of quarks (the spin-orbit operator and the chirality operator do not commute)

IS IT A CONSISTENT PICTURE?

Chiral and $^{2S+1}L_J$ content of mesons on lattice

L.Ya.G, C.B. Lang, M. Limmer

PRL 103 (2009) 121601

PRD 82 (2010) 097501

Chiral and ${}^{2S+1}L_J$ content of mesons on lattice

Example: $\rho(I, J^{PC} = 1, 1^{--})$

$$(1,0)+(0,1): \quad \mathcal{O}_V = \bar{q}\tau\gamma^i q = \bar{R}\tau\gamma^i R + \bar{L}\tau\gamma^i L$$

$$(1/2,1/2)_b: \quad \mathcal{O}_T = \bar{q}\tau\sigma^{0i} q = \bar{R}\tau\sigma^{0i} L + \bar{L}\tau\sigma^{0i} R$$

Chiral partners:

$$(1,0)+(0,1): \quad \rho(1,1^{--}) \longleftrightarrow a_1(1,1^{++})$$

$$(1/2,1/2)_b: \quad \rho(1,1^{--}) \longleftrightarrow h_1(0,1^{+-})$$

T. D. Cohen and X. Ji, PRD 55 (1997) 6870
L.Ya.G., Phys. Lett. B 587 (2004) 69

Chiral and ${}^{2S+1}L_J$ content of mesons on lattice

A unitary transformation exists from the chiral basis to the $\{I; {}^{2S+1}L_J\}$ basis (L.Ya.G. and A. V. Nefediev, PRD 76 (2007) 096004; PRD 80 (2009) 057901):

$$|R; IJ^{PC}\rangle = \sum_{LS} \sum_{\lambda_q \lambda_{\bar{q}}} \chi^{RPI}_{\lambda_q \lambda_{\bar{q}}} \times \sqrt{\frac{2L+1}{2J+1}} C^{S\Lambda}_{\frac{1}{2}\lambda_q \frac{1}{2} - \lambda_{\bar{q}}} C^{J\Lambda}_{L0S\Lambda} |I; {}^{2S+1}L_J\rangle.$$

$$\rho: \; |(0,1)+(1,0); 1\ 1^{--}\rangle = \sqrt{\frac{2}{3}}|1; {}^3S_1\rangle + \sqrt{\frac{1}{3}}|1; {}^3D_1\rangle,$$

$$\rho: \; |(1/2,1/2)_b; 1\ 1^{--}\rangle = \sqrt{\frac{1}{3}}|1; {}^3S_1\rangle - \sqrt{\frac{2}{3}}|1; {}^3D_1\rangle.$$

However:

$$a_1: \; |(0,1)+(1,0); 1\ 1^{++}\rangle = |1; {}^3P_1\rangle$$

$$h_1: \; |(1/2,1/2)_b; 0\ 1^{+-}\rangle = |0; {}^1P_1\rangle$$

Some elements of lattice technology.

Assume we have a hadron with excitation energies $n = 1, 2, 3, ...$

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

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.

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

Chiral and ${}^{2S+1}L_J$ content of mesons on lattice

We want to study $\rho = \rho(770)$ and its first excitation $\rho' = \rho(1450)$.We need energies, chiral as well as the angular momentum decomposition of the states.
Then a sufficient basis of interpolators:

$$(1,0)+(0,1): \quad \mathcal{O}_V = \bar{q}(x)\tau\gamma^i q(x) = \bar{R}(x)\tau\gamma^i R(x) + \bar{L}(x)\tau\gamma^i L(x)$$

$$(1/2,1/2)_b: \quad \mathcal{O}_T = \bar{q}(x)\tau\sigma^{0i} q(x) = \bar{R}(x)\tau\sigma^{0i} L(x) + \bar{L}(x)\tau\sigma^{0i} R(x)$$

If local interpolators are used, then we extract the "wave functions" at the origin (more exactly, at the scale $\mu \sim (lattice\ spacing)^{-1}$ fixed by the lattice spacing):

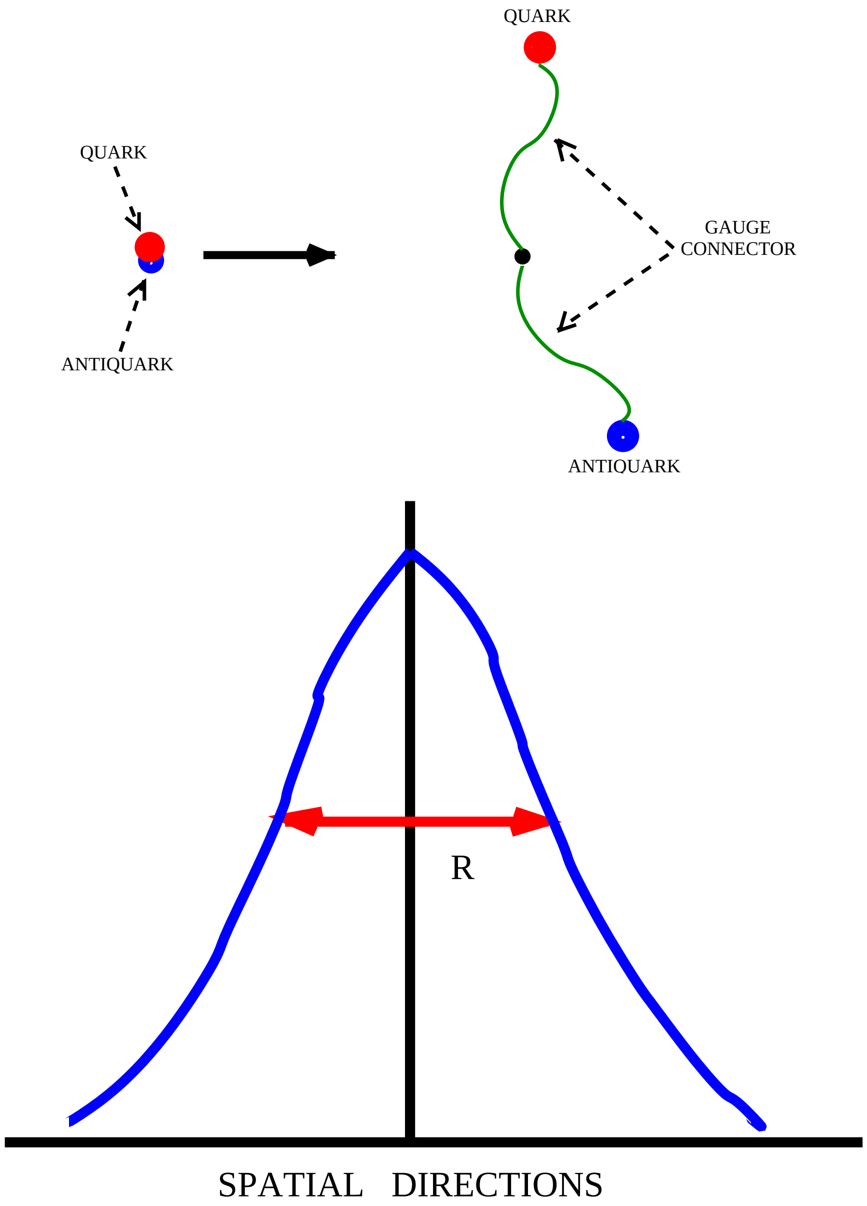
$$a_i^{(n)} = \langle 0 \mid \mathcal{O}_i(\mu) \mid n \rangle \; .$$

But we want to know the "wave functions" at the infrared scales, where mass is generated! What to do?

Smear the local interpolators in spatial directions over the range R in a gauge-invariant way. Then you will study a hadron "wave function" at the resolution scale fixed by R.

Chiral and ${}^{2S+1}L_J$ content of mesons on lattice

Gauge-invariant Gaussian smearing and resolution scale R definition.

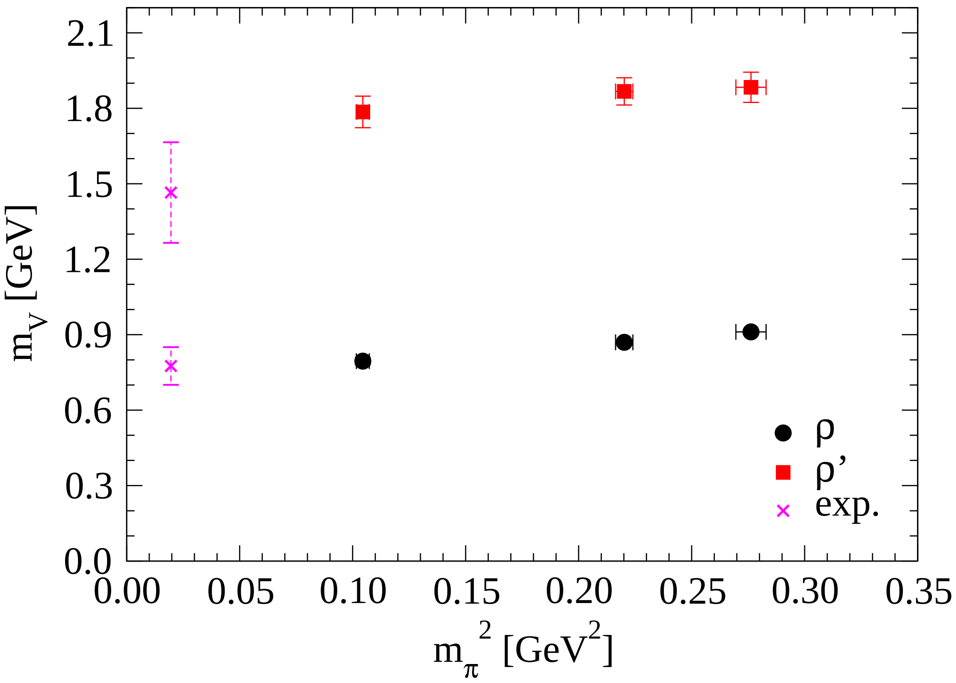


Chiral and ${}^{2S+1}L_J$ content of mesons on lattice

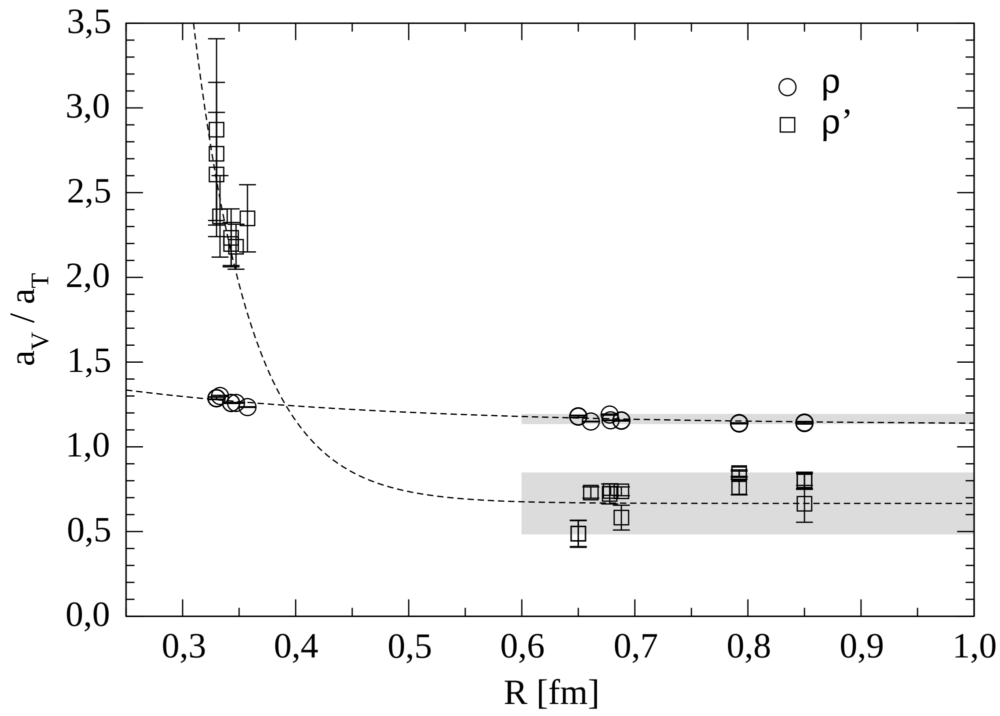
Lattice size 2.4 fm. Two light sea flavors. Lüscher-Weisz gauge action. Chirally Improved Dirac operator. A few smearings sizes (resolution scales) R: 0.35 fm – 0.85 fm. A few different 6×6 and 4×4 correlation matrices (for different matrices the results are consistent!)

$$\mathcal{O}_V^{R_1} = \overline{u}_{R_1}\gamma^i d_{R_1} \ , \qquad \mathcal{O}_V^{R_2} = \overline{u}_{R_2}\gamma^i d_{R_2} \ , \ldots \tag{4}$$

$$\mathcal{O}_T^{R_1} = \overline{u}_{R_1}\gamma^t\gamma^i d_{R_1} \ , \qquad \mathcal{O}_T^{R_2} = \overline{u}_{R_2}\gamma^t\gamma^i d_{R_2} \ , \ldots \tag{5}$$



Chiral and ${}^{2S+1}L_J$ content of mesons on lattice



ρ: at the scale $R \sim 1$ fm $\frac{(0,1)+(1,0)}{(1/2,1/2)_b} \sim 1.16 \pm 0.03$

$\rho \approx |{}^3S_1\rangle$

ρ': at the scale $R \sim 1$ fm - weaker chiral symmetry breaking: $\frac{(0,1)+(1,0)}{(1/2,1/2)_b} \sim 0.65 \pm 0.15$

$\rho(1450)$ in the infrared is dominated by $(1/2, 1/2)_b$.

$\rho' \sim 0.9|{}^3S_1\rangle - 0.4|{}^3D_1\rangle$

ρ' is not a radial excitation of ρ