Chiral and angular momentum content of rho and rho' mesons from dynamical lattice calculations

L. Ya. Glozman

Institut für Physik, FB Theoretische Physik, Universität Graz

With Christian Lang and Markus Limmer .

PRL 103 (2009) 121601

Few Body Systems 47 (2010) 91

1007.1346 [hep-lat] - submitted to PRL

Contents of the Talk

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

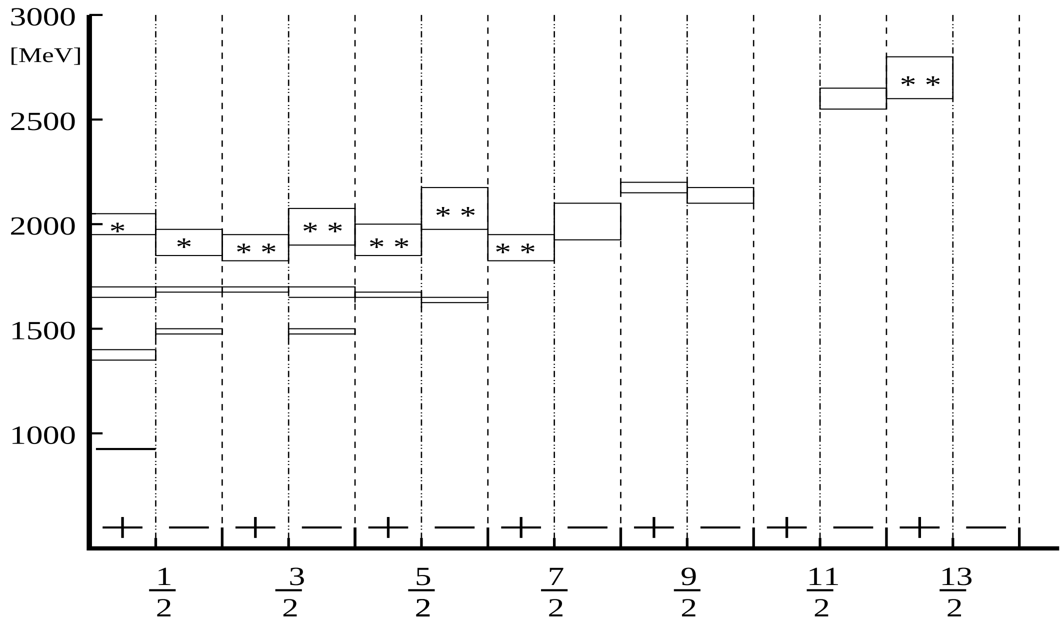
What is a hadron mass origin in QCD?

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

Dynamical chiral symmetry breaking 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.



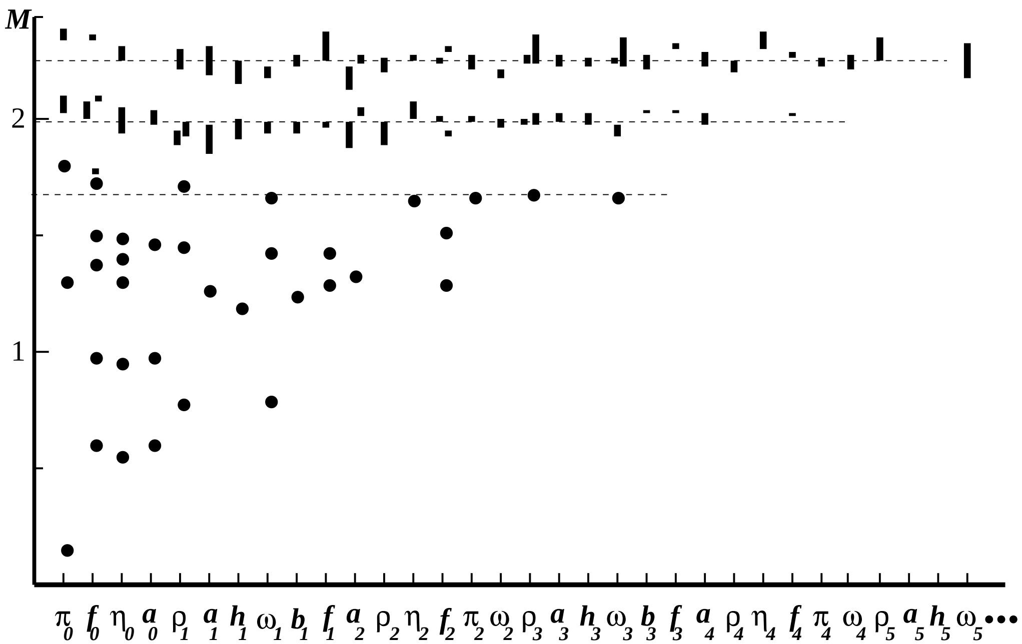
Low-lying spectrum: spontaneous breaking of chiral symmetry dominates physics.

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

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.



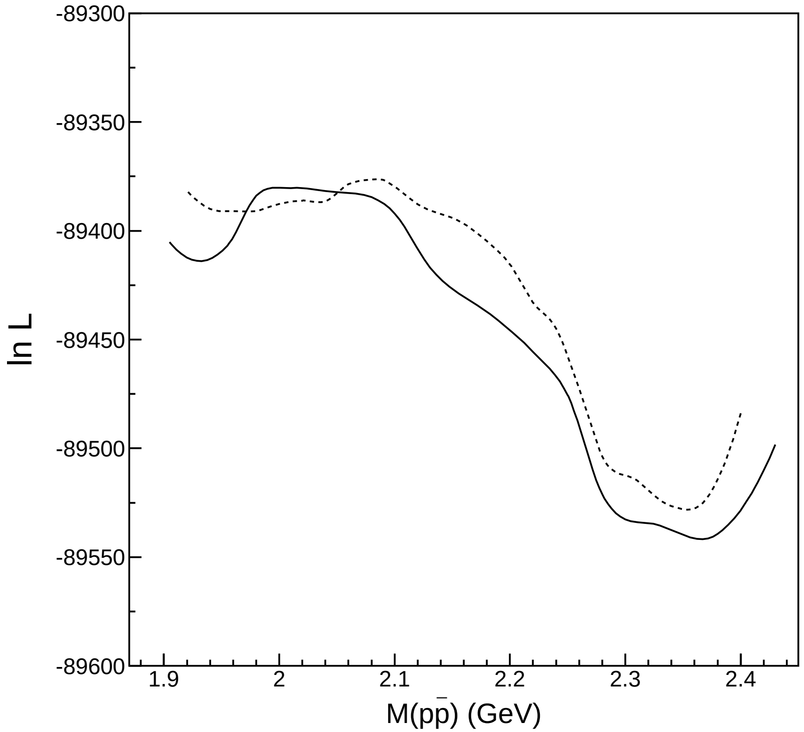
The high-lying mesons are from LEAR. Systematic appearance of $SU(2)_L \times SU(2)_R$ and $U(1)_A$ multiplets (L.Ya.G., 2002, 2004). Missing chiral partners for highest spins. Large symmetry: $N = n + J$ plus chiral symmetry(L.Ya.G. and A.V. Nefediev, 2007).

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. Requires L,S to be separately conserved quantum numbers !

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)

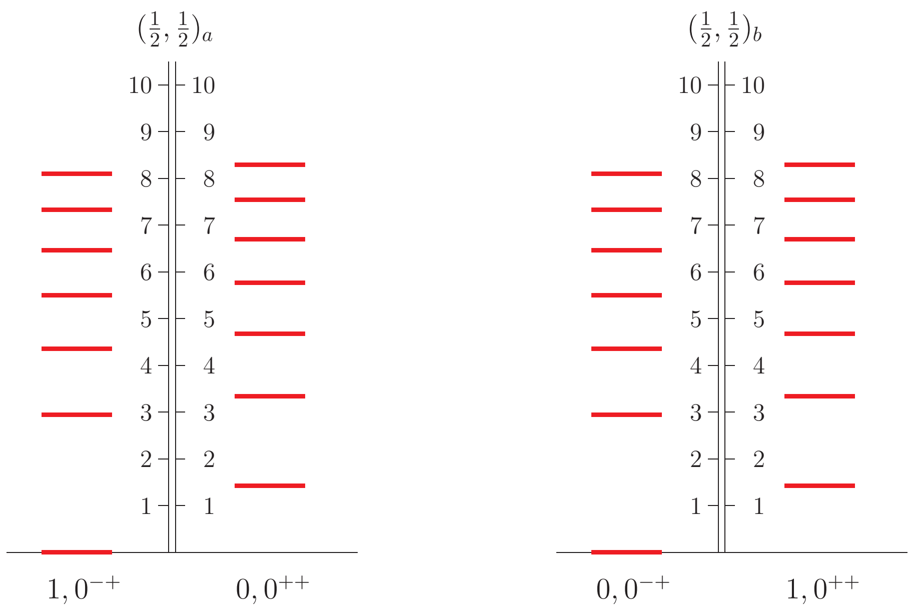
If a baryon is a member of an approximate chiral multiplet, then its decay into $N\pi$ must be suppressed, $(f_{BN\pi}/f_{NN\pi})^2 \ll 1$. If, on the contrary, this excited nucleon has no chiral partner and hence its mass is due to chiral symmetry breaking in the vacuum, then it should strongly decay 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	$N_+(?) - N_-(2600)$	?	?	0.00000064
3/2	$N_-(1520)$	no chiral partner		2.5

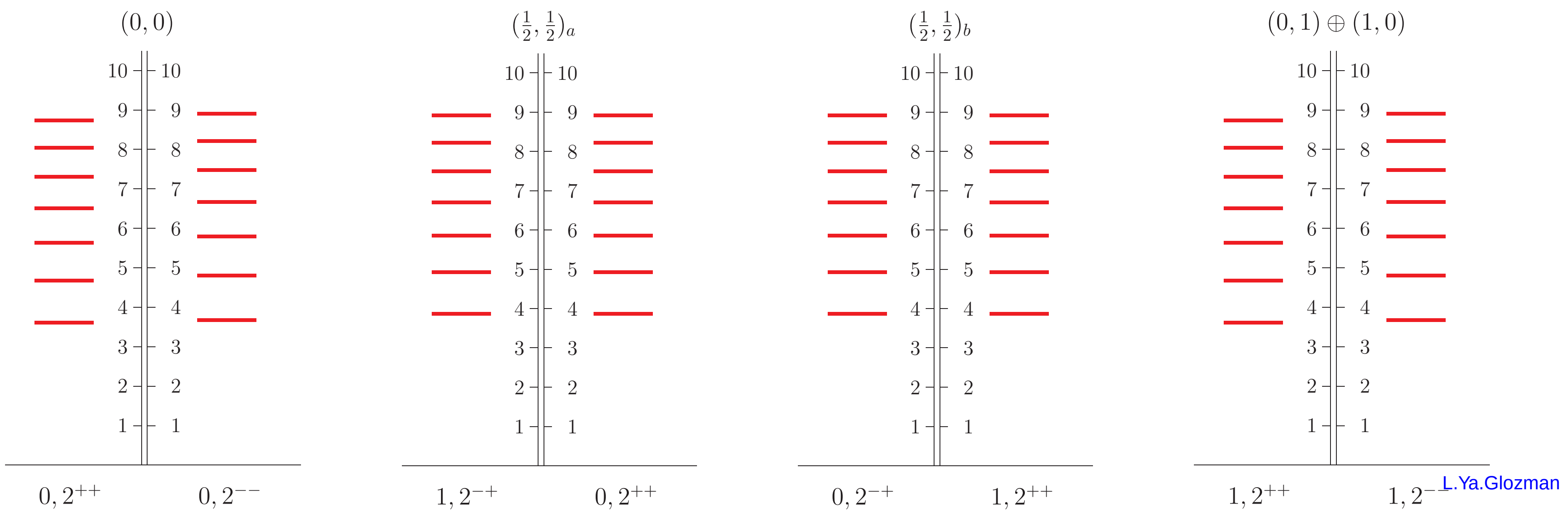
A 100% correlation of decays with the parity doublet patterns

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

$J = 0$



$J = 2$



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

One needs a complete and orthogonal basis for the $\bar{q}q$ component in mesons.
Representations of $SU(2)_L \times SU(2)_R$ is such a basis.

$$J = 0$$

$$\begin{aligned}
(1/2,1/2)_a &\quad : \quad 1, 0^{-+} \longleftrightarrow 0, 0^{++} \\
(1/2,1/2)_b &\quad : \quad 1, 0^{++} \longleftrightarrow 0, 0^{-+},
\end{aligned}$$

Even $J > 0$

$$\begin{aligned}
(0,0) &\quad : \quad 0, J^{--} \longleftrightarrow 0, J^{++} \\
(1/2,1/2)_a &\quad : \quad 1, J^{-+} \longleftrightarrow 0, J^{++} \\
(1/2,1/2)_b &\quad : \quad 1, J^{++} \longleftrightarrow 0, J^{-+} \\
(0,1) \oplus (1,0) &\quad : \quad 1, J^{++} \longleftrightarrow 1, J^{--}
\end{aligned}$$

Odd $J > 0$

$$\begin{aligned}
(0,0) &\quad : \quad 0, J^{++} \longleftrightarrow 0, J^{--} \\
(1/2,1/2)_a &\quad : \quad 1, J^{+-} \longleftrightarrow 0, J^{--} \\
(1/2,1/2)_b &\quad : \quad 1, J^{--} \longleftrightarrow 0, J^{+-} \\
(0,1) \oplus (1,0) &\quad : \quad 1, J^{--} \longleftrightarrow 1, J^{++}
\end{aligned}$$

L.Ya.G., Phys. Lett. B 587 (2004) 69

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:

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

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

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

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:

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

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

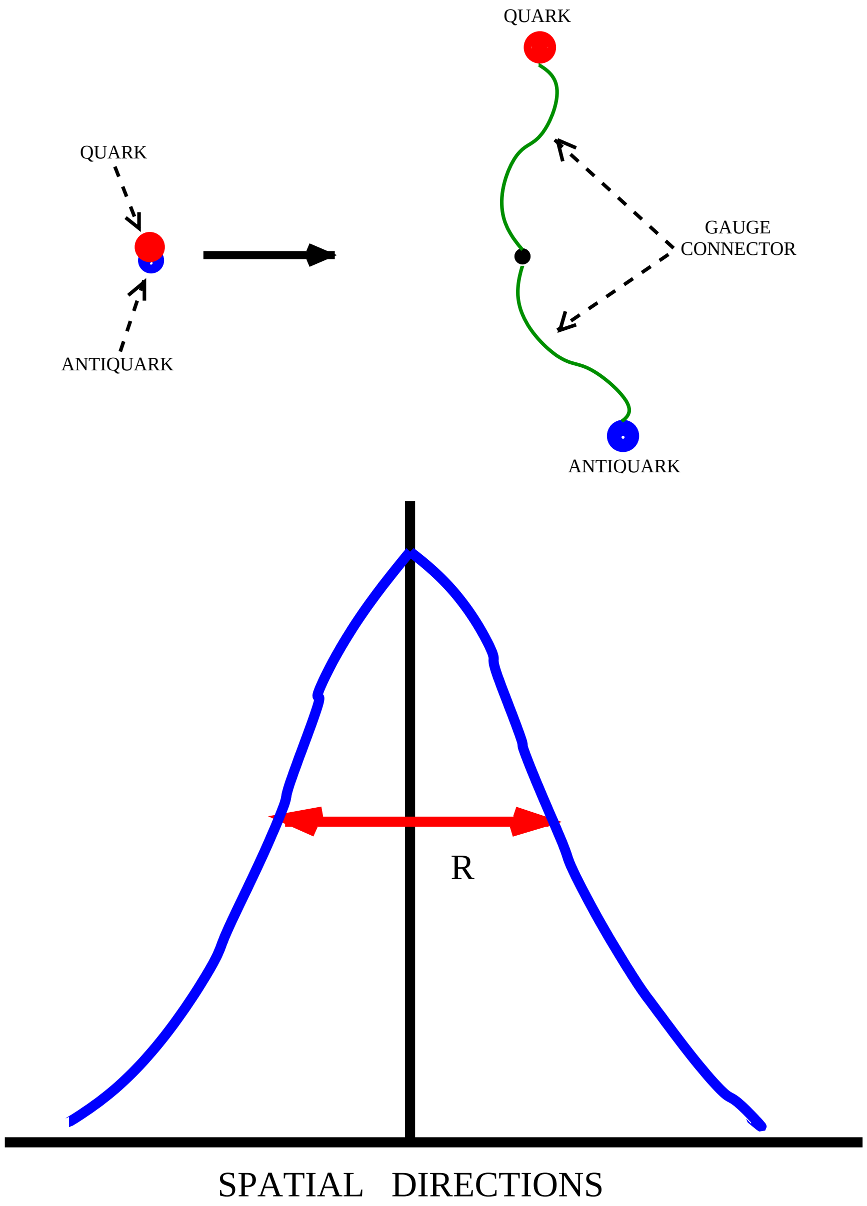
If local interpolators are used, then we extract the "wave functions" at the origin (more exactly, at the scale $\mu \sim (lattice\ spacing)^{-1}$ fixed by the lattice spacing):

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

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.

Gauge-invariant Gaussian smearing and resolution scale R definition.

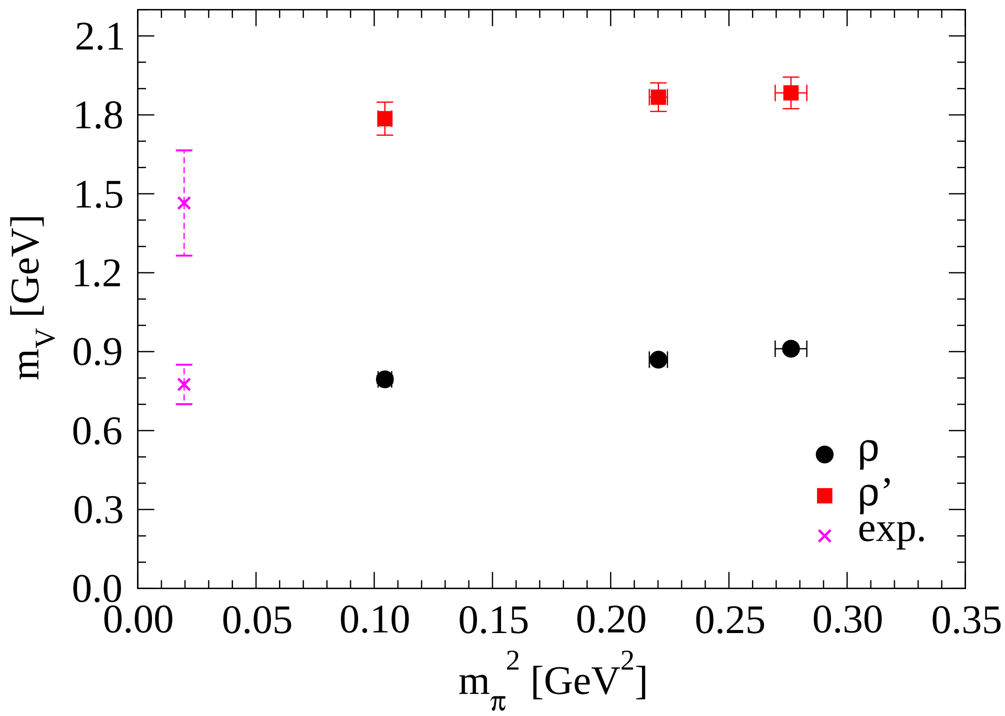


Chiral and $^{2S+1}L_J$ content of mesons on lattice

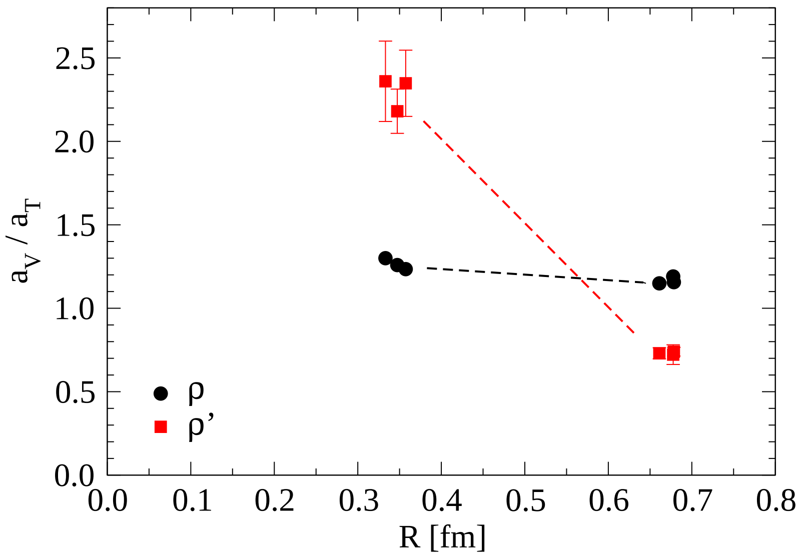
Lattice size 2.4 fm. Two light sea flavors. Lüscher-Weisz gauge action. Chirally Improved Dirac operator (C.Gattringer - 2001; C. Gattringer, I. Hip, C. Lang - 2001). Two smearings sizes: $n = 0.34$ fm and $w = 0.67$ fm. Four interpolating operators.

$$\mathcal{O}_V^n = \overline{u}_n \gamma^i d_n \ , \qquad \mathcal{O}_V^w = \overline{u}_w \gamma^i d_w \ , \tag{4}$$

$$\mathcal{O}_T^n = \overline{u}_n \gamma^t \gamma^i d_n \ , \qquad \mathcal{O}_T^w = \overline{u}_w \gamma^t \gamma^i d_w \ . \tag{5}$$



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



ρ: at the scale of the ρ size - strong chiral symmetry breaking: $\frac{(0,1)+(1,0)}{(1/2,1/2)_b} \sim 1.2$

$\rho \simeq 0.997|^3S_1\rangle - 0.073|^3D_1\rangle \approx |^3S_1\rangle$

ρ': at the scale of the ρ' size (1 fm) - weak chiral symmetry breaking: $\frac{(0,1)+(1,0)}{(1/2,1/2)_b} \to 0$.

$\rho(1450)$ in the infrared is mostly $(1/2,1/2)_b$. Its chiral partner likely is $h_1(1380)$.

$\rho' \sim \sqrt{1/3}|^3S_1\rangle - \sqrt{2/3}|^3D_1\rangle$

ρ' is not a radial excitation of ρ $(^3S_1)$.

The quark model and similar pictures are ruled out for ρ'.