First observation of the QCD dynamical string

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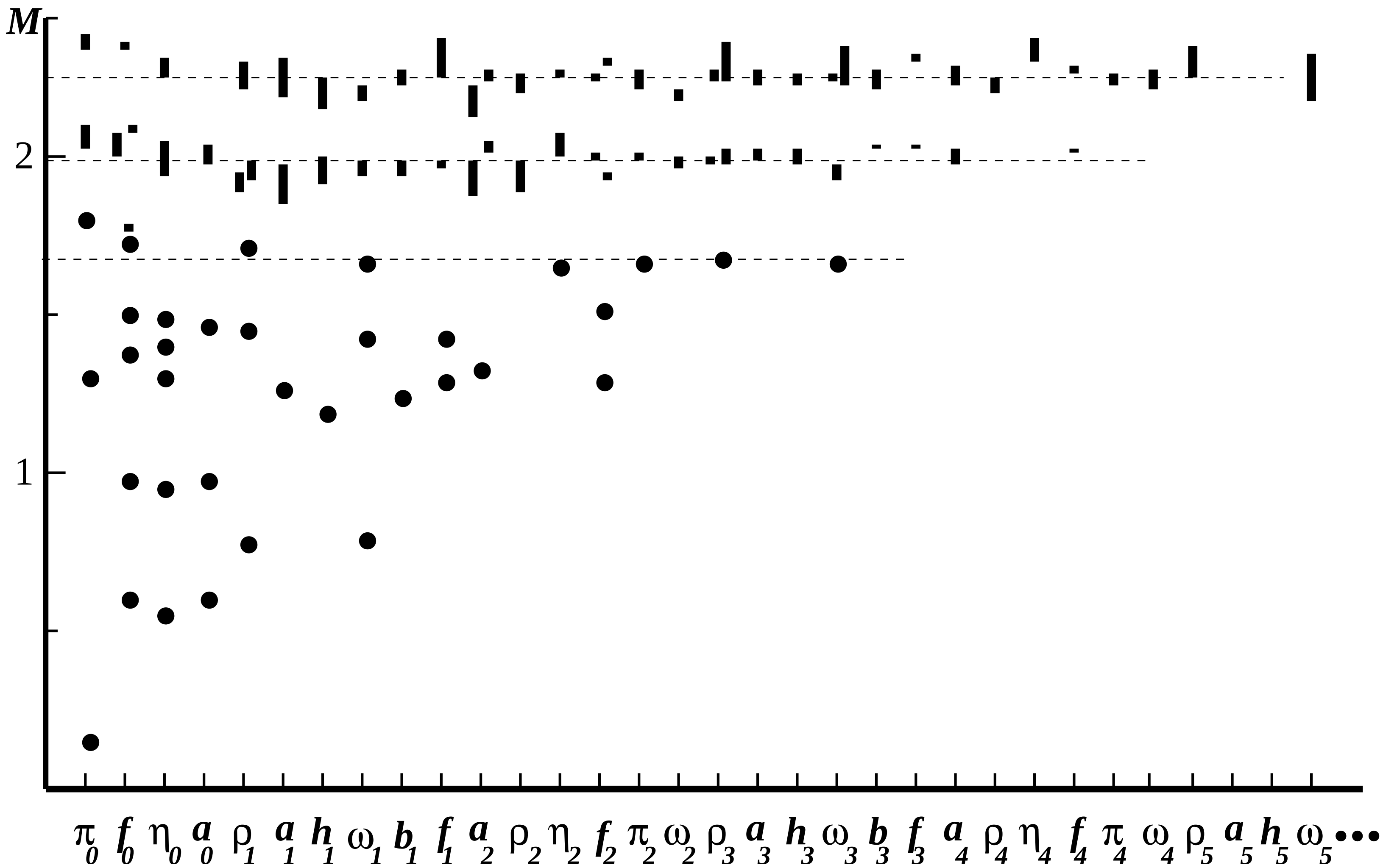
Low and high lying meson spectra.



The high-lying mesons are from $\bar{p}p$ annihilation at LEAR (Anisovich, Bugg, Sarantsev,...).

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.

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

S - standard quark propagator in a given gauge configuration;
μ_i are the eigenvalues of the manifestly chirally symmetric 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 the $\rho(I=1,1^{--})$ spectrum.
Then a basis of interpolators:

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

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

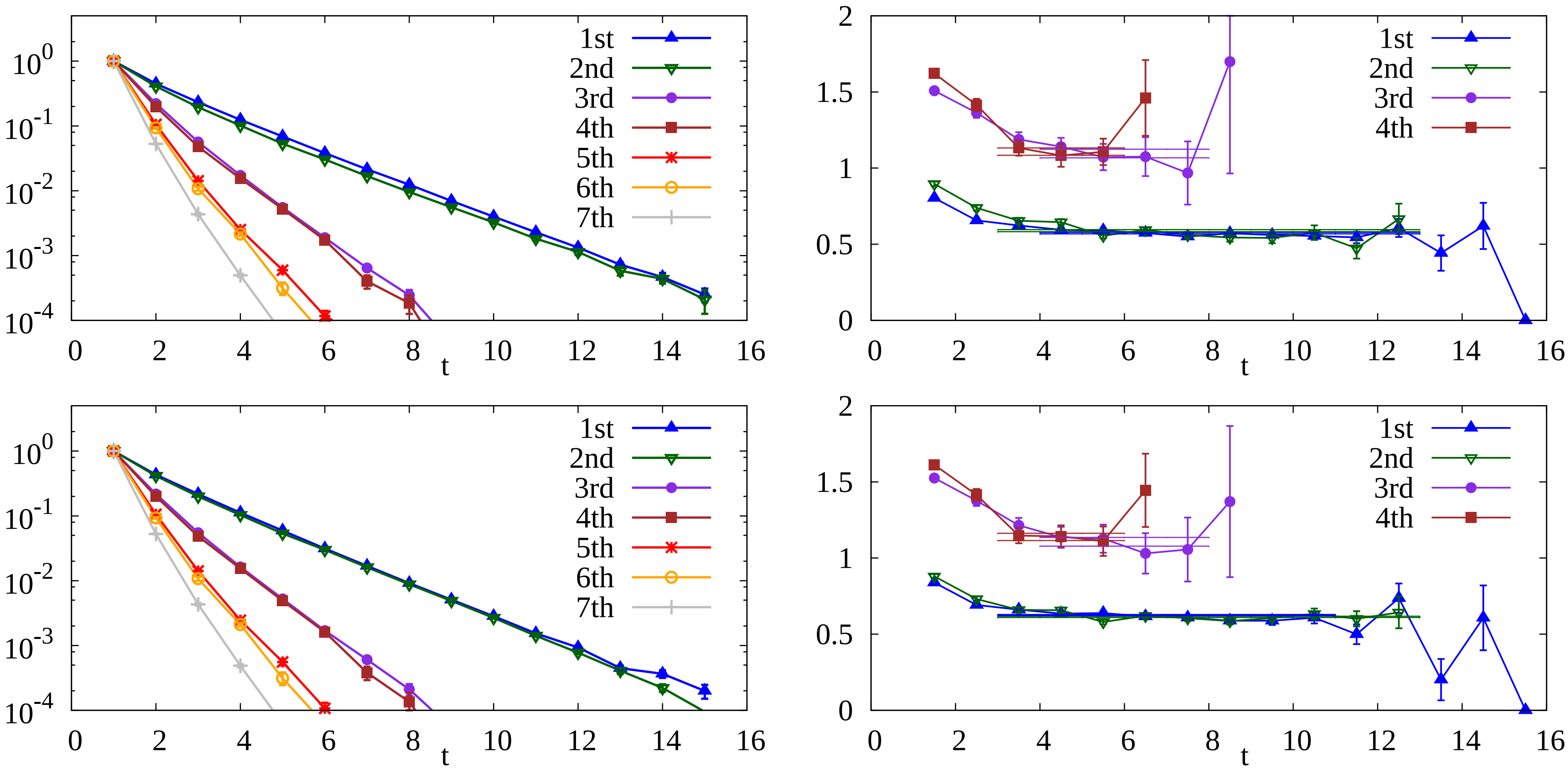
with a few different exponential smearings of the quark fields in spatial directions in the source and sink.

Some lattice details:

- 100 gauge configurations with 2 dynamical flavors with the overlap Dirac operator from JLQCD.
- $L = 1.9$ fm; $a = 0.12$ fm
- $m_\pi = 289$ MeV

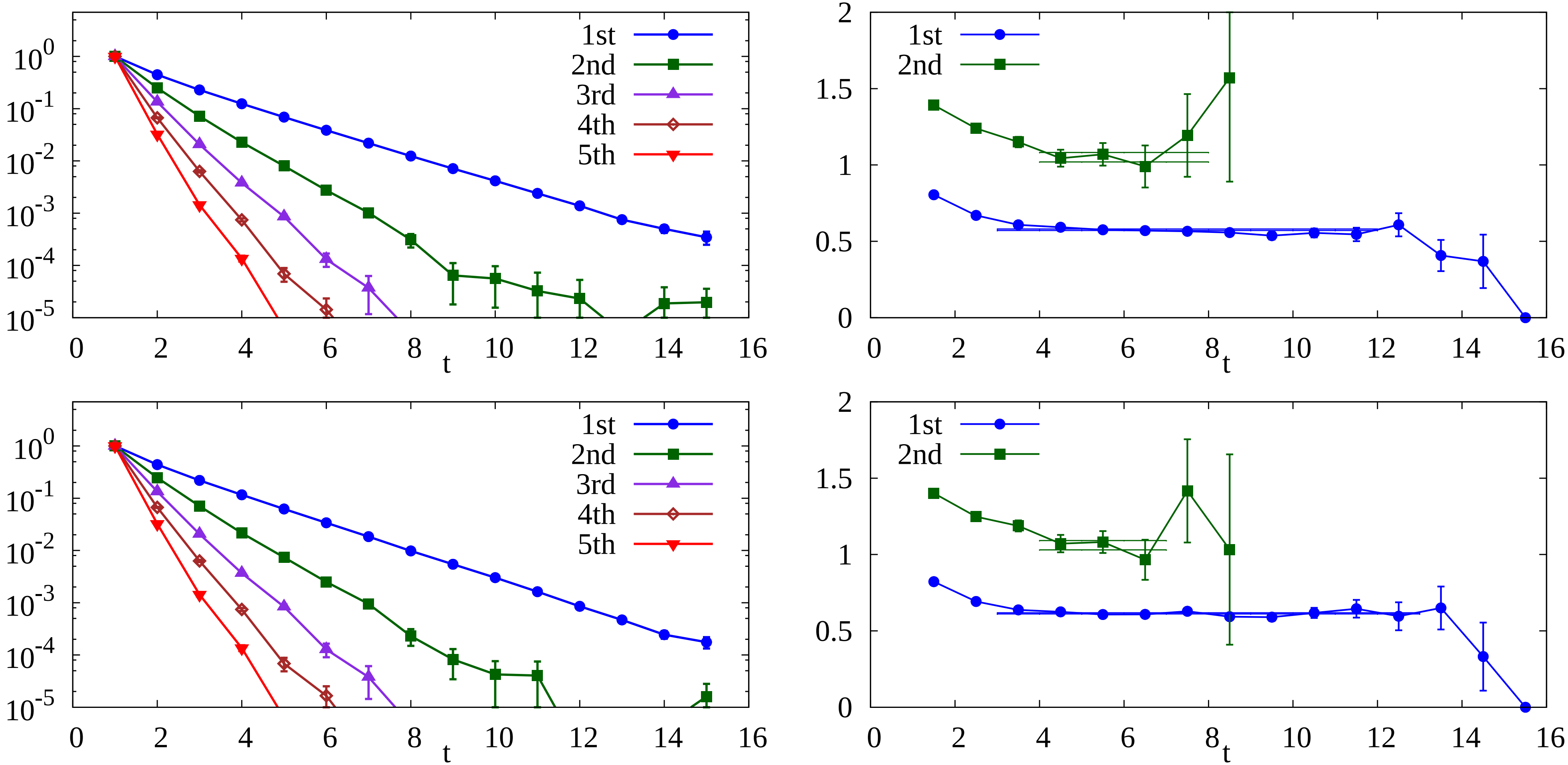
We subtract the low-lying chiral modes from the valence quarks.

$\rho(I=1,1^{--})$ with 10 and 20 eigenmodes subtracted



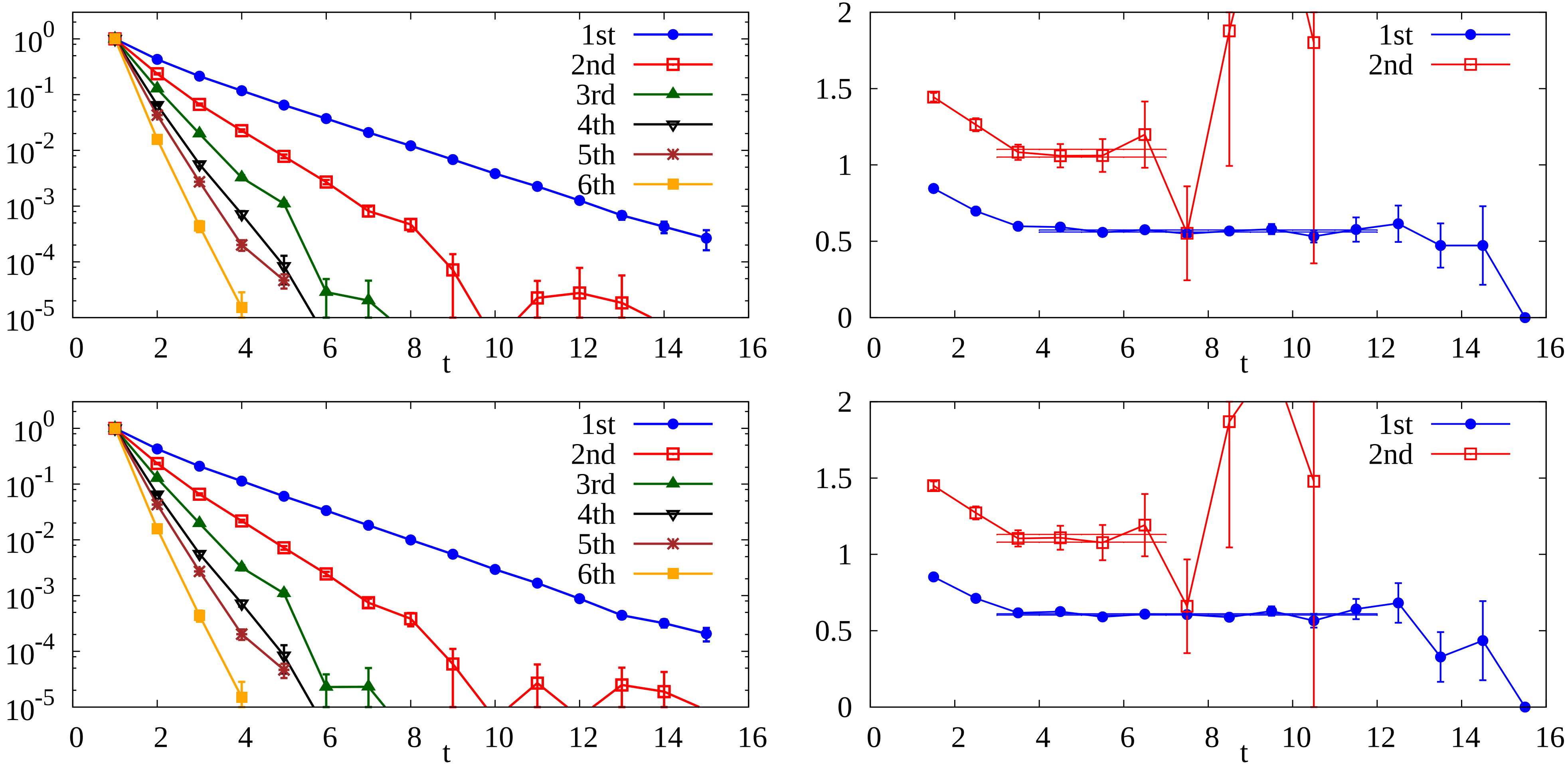
The correlators $\lambda_n(t) \sim \exp(-E_n t)$ for all eigenstates (left) and the effective mass plots $E_n(t) = \log(\lambda_n(t)/\lambda_n(t+1))$ for the two lowest four states (right).

$a_1(I = 1, 1^{++})$ with 10 and 20 eigenmodes subtructed



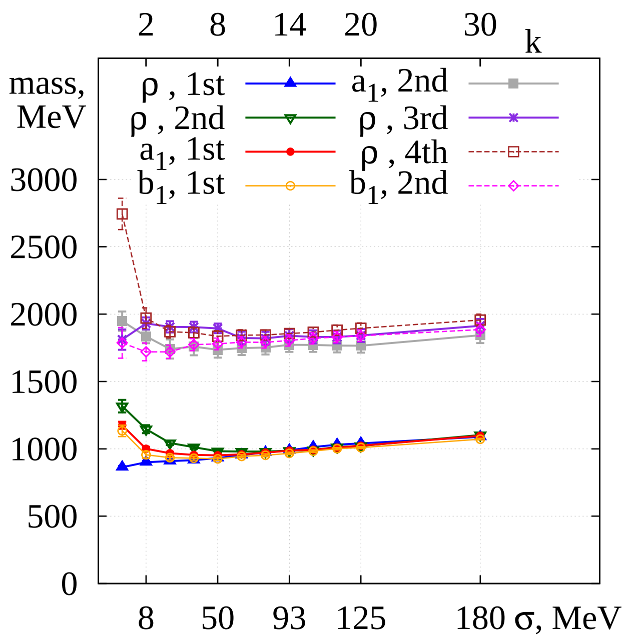
The correlators $\lambda_n(t) \sim \exp(-E_n t)$ for all eigenstates (left) and the effective mass plot $E_n(t) = \log(\lambda_n(t)/\lambda_n(t+1))$ for the lowest two states (right).

$b_1(I=1, 1^{+-})$ with 10 and 20 eigenmodes subtructed



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

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:

$$(0,0) \quad : \quad \omega(0,1^{--}) \quad f_1(0,1^{++})$$

$$(\tfrac{1}{2},\tfrac{1}{2})_a \quad : \quad h_1(0,1^{+-}) \quad \rho(1,1^{--})$$

$$(\tfrac{1}{2},\tfrac{1}{2})_b \quad : \quad \omega(0,1^{--}) \quad b_1(1,1^{+-})$$

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

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.

Radial spectrum of a dynamical string with J=1

Energy is independent on orientations of the quark spins and on their spatial and charge parities. These are the energy levels of a dynamical QCD string.

$$E_{n_r} = (n_r + 1)\hbar\omega$$

$$\hbar\omega = 900 \pm 70 MeV$$

What do meson degeneracies and splittings tell us?

- Chiral symmetry is restored but confinement is still there

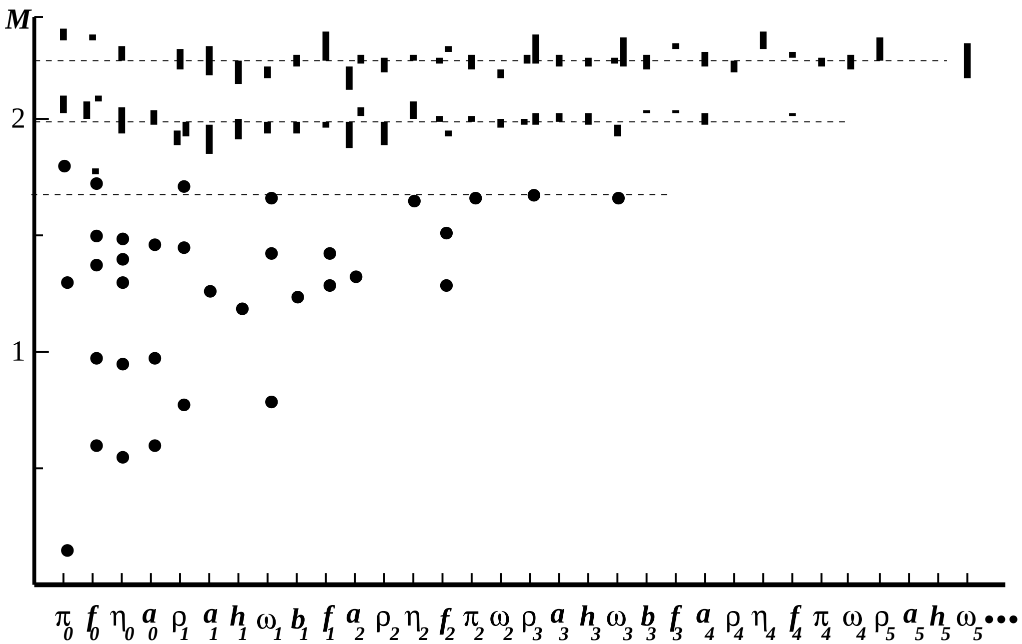
- Hadrons get their large chirally symmetric mass

- Both $SU(2)_L \times SU(2)_R$ and $U(1)_A$ get simultaneously restored (consistent with the instanton mechanism of both breakings)

- A symmetry of a dynamical chirally symmetric string includes $SU(2)_L \times SU(2)_R \times U(1)_A \times U(1)_V$ as a subgroup

- The radial spectrum of the string $E_{n_r} = (n_r + 1)\hbar\omega, \quad \hbar\omega = 900 \pm 70 MeV$

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.

Is Nambu-Goto string consistent with chiral symmetry?

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:

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

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

If chiral symmetry is unbroken, fixed L is impossible!