Artificial chiral restoration and mass generation in QCD

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Key questions to QCD

- How is the hadron mass generated in the light quark sector?
- How important is 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?

Reminder: chiral symmetry

When neglecting the two lightest quark masses, the QCD Lagrangian becomes invariant under the symmetry group

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

- the axial vector part of the $SU(2)_L \times SU(2)_R$ symmetry is broken spontaneously in the vacuum
- the vector part is (approximately) preserved
- the $U(1)_A$ axial symmetry is not only broken spontaneously but also explicitly (axial anomaly)

The Banks–Casher relation

The lowest eigenmodes of the Dirac operator are related to the quark condensate of the vacuum:

$$\langle \overline{\psi}\psi \rangle = -\pi\rho(0)$$

$\rho(0)$ is the density of the lowest quasi-zero eigenmodes of the Dirac operator. Here the sequence of limits is important: $V \to \infty$ then $m_q \to 0$.

Unbreaking chiral symmetry

We perform a lattice hadron spectroscopy using reduced quark propagators which exclude a variable number k of the lowest Dirac eigenmodes. We split the quark propagator $S \equiv D^{-1}$ into a low mode (lm) part and a *reduced* part

$$S = \sum_{i \leq k} \mu_i^{-1} |v_i\rangle \langle v_i| \gamma_5 + \sum_{i>k} \mu_i^{-1} |v_i\rangle \langle v_i| \gamma_5$$
$$= S_{\text{lm}(k)} + S_{\text{red}(k)}$$

In our study we use

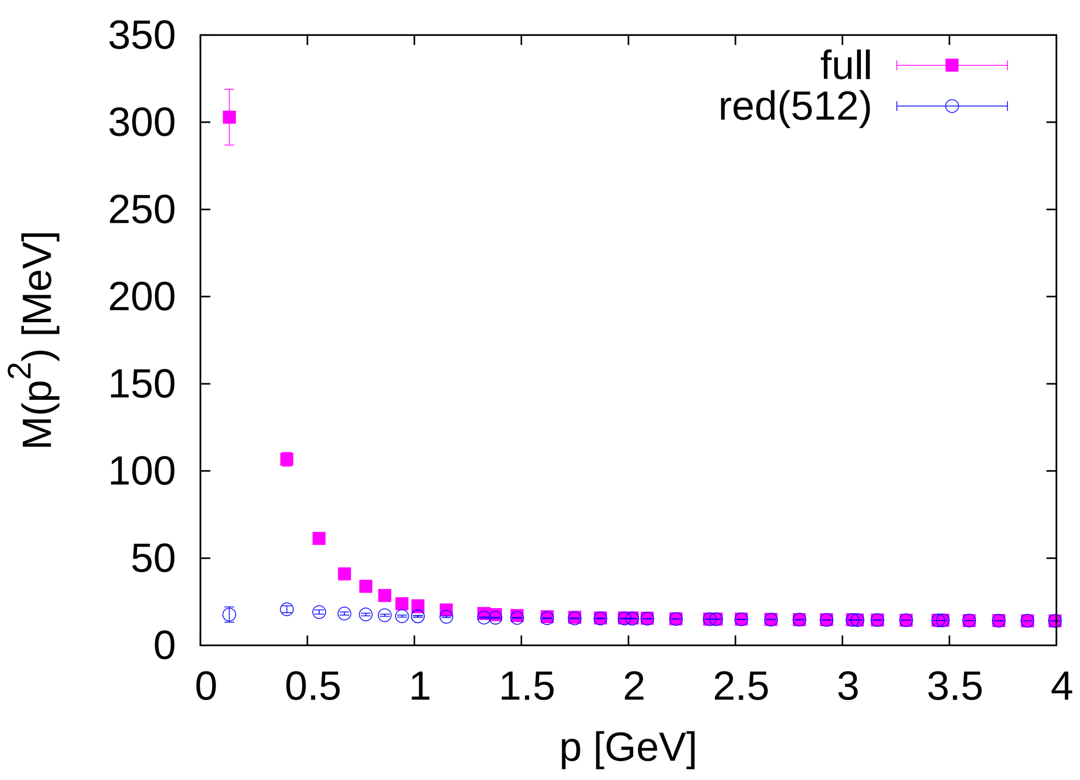
$$\Rightarrow S_{\text{red}(k)} = S - S_{\text{lm}(k)}.$$

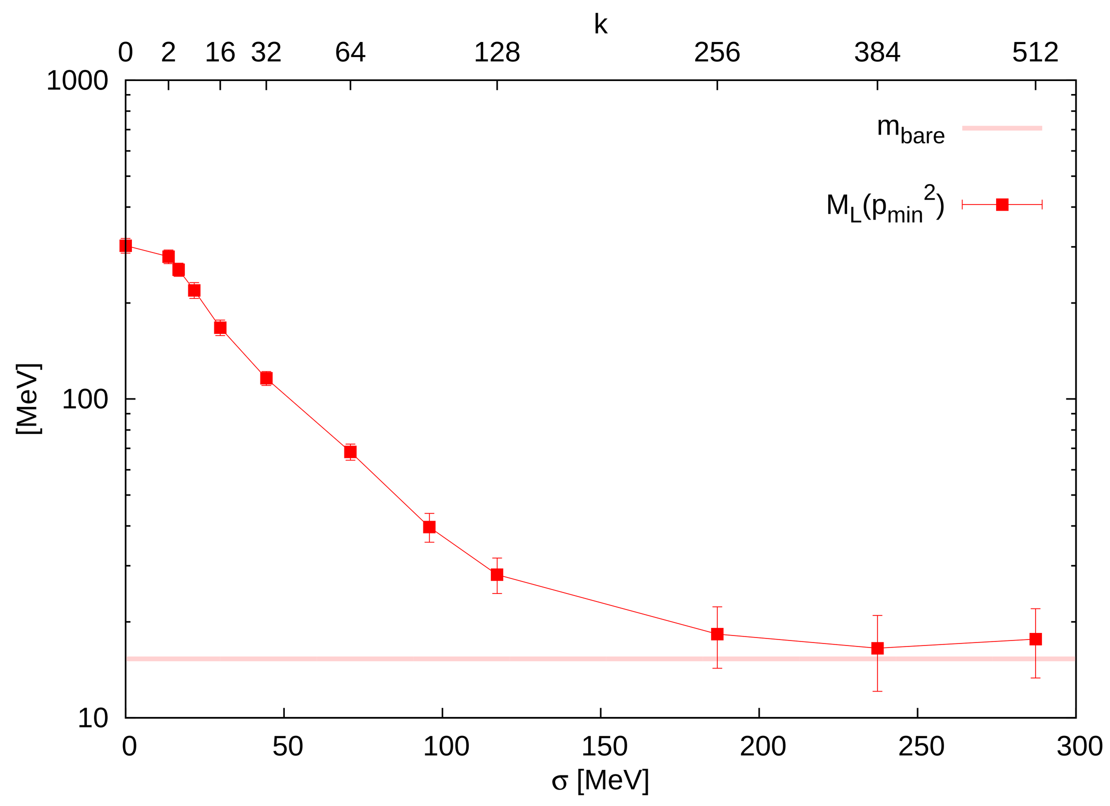
The setup

- 161 configurations [1, 2] of lattice size $16^3 \times 32$ and lattice spacing $a = 0.1440(12)$ fm
- two degenerate flavors of light CI fermions, $m_\pi = 322(5)$ MeV
- three different kinds of quark sources: Jacobi smeared narrow (0.27 fm) and wide (0.55 fm) sources and a derivative source to serve a large operator basis for the variational method.

Valence quark mass

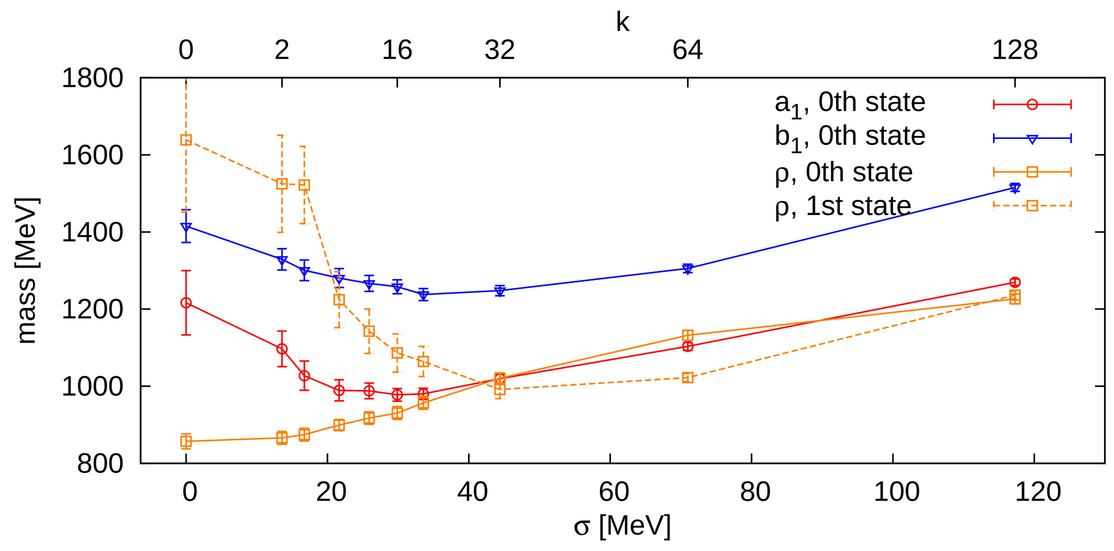
We explore the infrared mass of the mass function $M(p^2)$ of the CI quark propagator $S(\mu;p) = Z(\mu;p^2)/\left(i\not{p} + M(p^2)\right)$ as a function of the Dirac mode truncation level k. For this study [3] we fixed the gauge of the configurations to Landau gauge. Lattice gauge fixing on multi-GPUs, see [6].





Meson masses

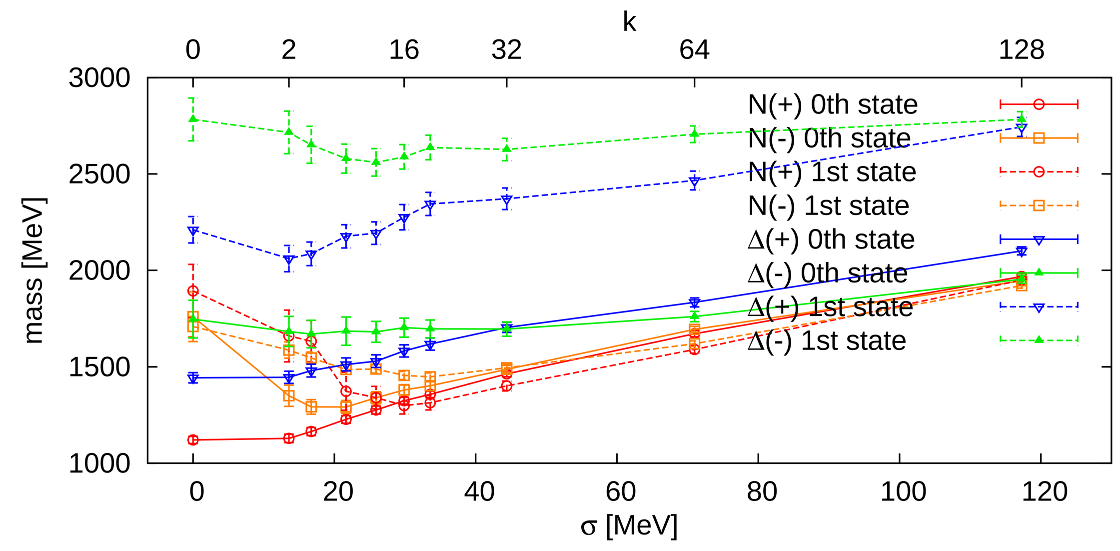
Here we show the evolution of the masses of light isovector mesons as a function of the Dirac mode truncation level k. For details see [4, 5].



- heavy ρ meson: mass not due to dynamical chiral symmetry breaking
- degeneracy of ρ and a_1: restoration of the $SU(2)_L \times SU(2)_R$ chiral symmetry
- degeneracy of ρ and ρ': hint to a higher symmetry which includes $SU(2)_L \times SU(2)_R$ as a subgroup
- nondegeneracy of ρ and b_1: $U(1)_A$ remains broken, still existence of confined states.

Baryon masses

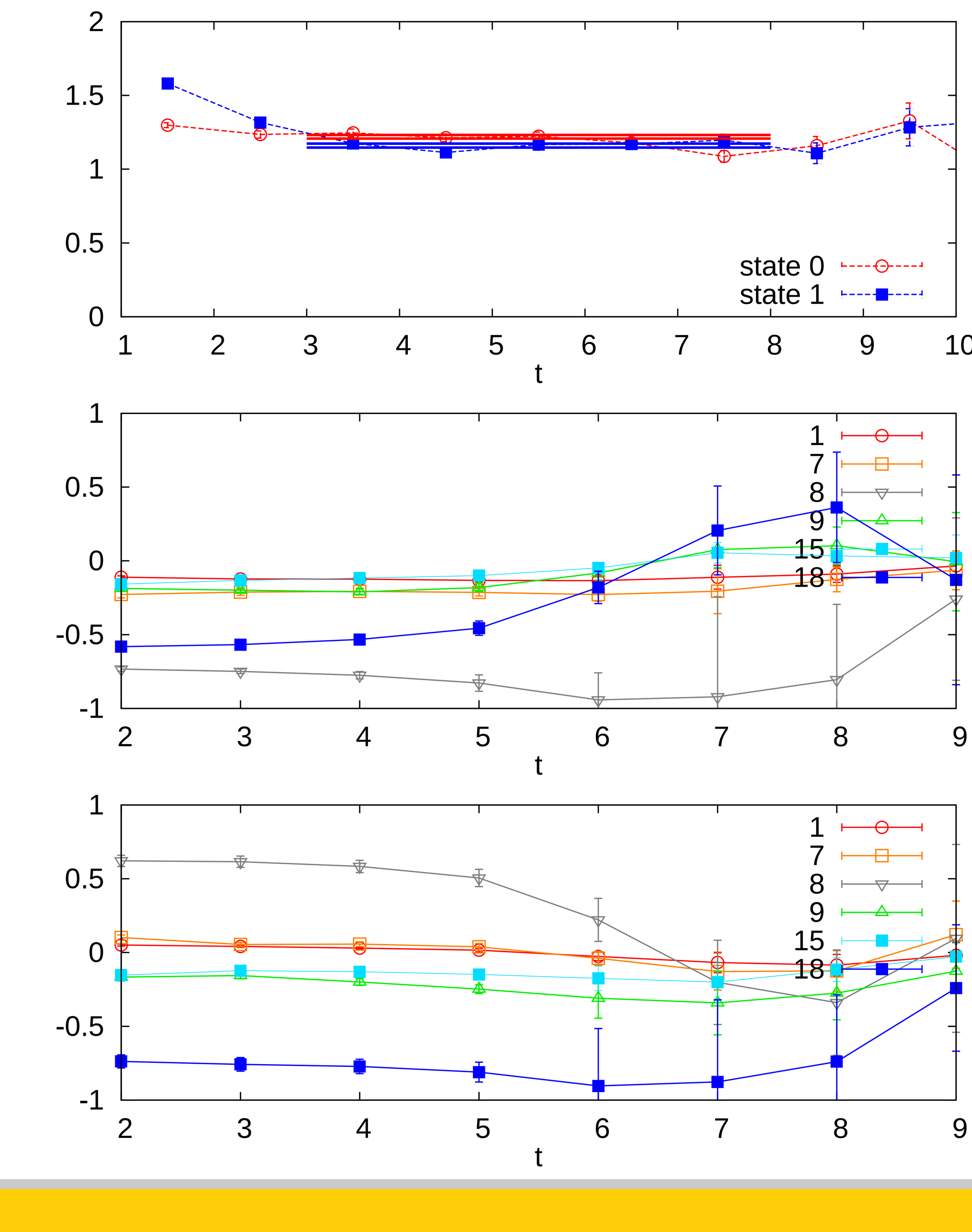
The evolution of the masses of the ground and first excited states of the nucleon and Δ, both with positive and negative parity is shown below [5]



- heavy $N(+)$: mass not due to dynamical chiral symmetry breaking
- parity doubling of $N(+)$ and $N(-)$
- degeneracy of two $N(+)$ and $N(-)$ states: hint to a higher symmetry which includes $SU(2)_L \times SU(2)_R$ as a subgroup
- distinguished excited states of $\Delta(+)$ and $\Delta(-)$: confinement persists
- Δ-N splitting reduces to $\approx 50\%$

Details: example nucleon

$N(+)$ with 64 eigenmodes subtracted: effective mass plot for the two lowest states (top), eigenvectors corresponding to the ground state (middle) and first excited state (bottom).



References

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More

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