The spectrum of mesons and structure of tetraquark candidates from lattice QCD

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Motivation

- **Mesons** are bound states of quarks and antiquarks with integer spin $J = 0, 1, 2, \ldots$
- Most mesons are predominantly **quark-antiquark states** ($\bar{q}q$).
- In principle mesons could also be composed of **two quarks and two antiquarks** ("**tetraquarks**", $\bar{q}\bar{q}qq$); in particular for mesons, which are theoretically not well understood, this might be the case.
- The **PANDA** experiment at **FAIR** will investigate many different mesons (different spin J, parity P, quark content u, d, s, c, including several tetraquark candidates), in particular D mesons, D_s mesons and charmonium.
- The theoretical framework to discribe and understand mesons is **QCD**, the quantum field theory of quarks and gluons,

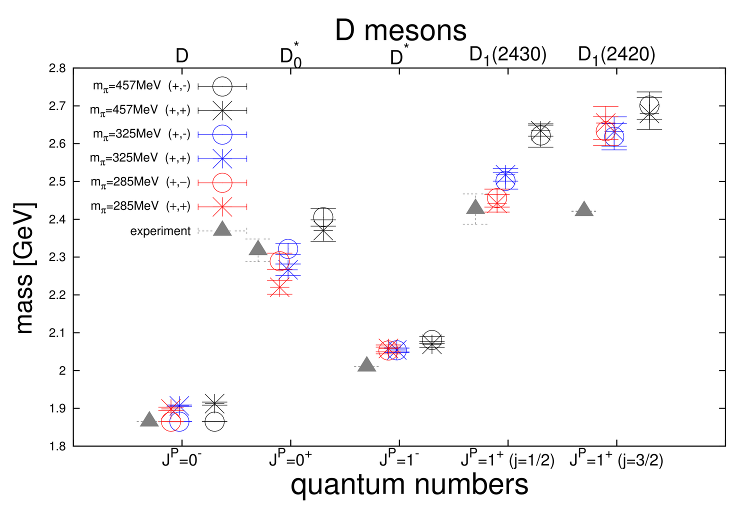
$$\mathcal{L}_{\mathrm{QCD}} = \sum_{q \in \{u,d,s,c,t,b\}} \bar{q}\Big(\gamma_\mu\Big(\partial_\mu - iA_\mu\Big) + m^{(q)}\Big)q + \frac{1}{2g^2}\mathrm{Tr}\Big(F_{\mu\nu}F_{\mu\nu}\Big);$$

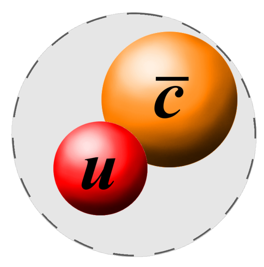
the numerical method to solve corresponding equations is **lattice QCD**.

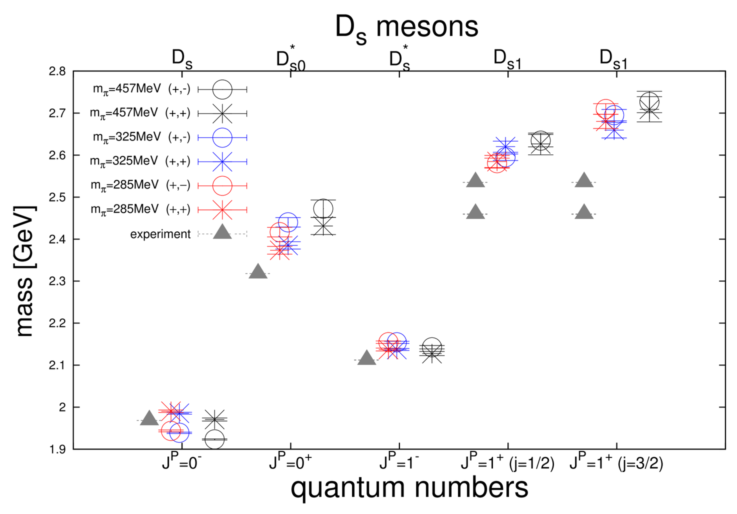
The spectrum of D mesons, D_s mesons and charmonium using $\bar{q}q$ operators

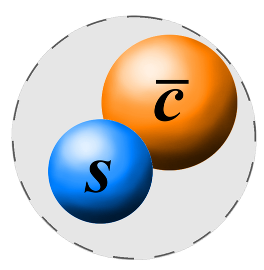
- Computations at
  - different values of the light u/d quark mass ($m_\pi \approx 285 \ldots 457$ MeV),
  - different lattice discretizations,
  - different values of the lattice spacing (ongoing),

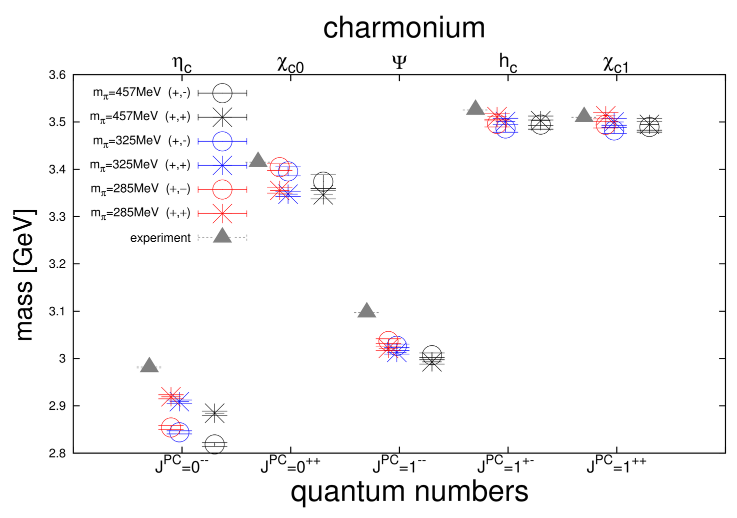
  to extrapolate to the physical point and to eliminate systematic errors.

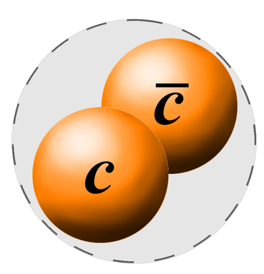












- For the majority of mesons agreement with experimental results.
- Disagreement might indicate a non-$\bar{q}q$ state (perhaps a tetraquark, a strong gluonic contribution, an unstable resonance; cf. the right column).
- Employing a variety of different operators allowed to distinguish and to investigate e.g. the two $J^P = 1^+$ D meson states:
  - $D_1(2430)$, light spin $j = 1/2$, $J = 1$ predominantly, due to quark spin (no strong angular momentum contribution).
  - $D_1(2420)$, light spin $j = 3/2$, $J = 1$, due to quark spin and angular momentum.
  - Important for a study of the decay $B \to D^{**}$ (there is a persistent conflict between experiment and theory, "1/2 versus 3/2 puzzle").

[1] M. Kalinowski and M. Wagner, PoS ConfinementX (2012) 303 [arXiv:1212.0403 [hep-lat]].

[2] M. Kalinowski and M. Wagner, Acta Phys. Polon. Supp. 6 (2013) 3, 991 [arXiv:1304.7974 [hep-lat]].

[3] M. Wagner and M. Kalinowski, PoS Lattice2013 (2012) 241 [arXiv:1310.5513 [hep-lat]].

Why tetraquarks? (example $a_0(980)$)

- The masses of light scalar mesons are inverted compared to expectation,
  - $\kappa \equiv K_0^*(800)$, $I = 1/2$, 682 ± 29 MeV ($\bar{s}u, \bar{s}d, \bar{u}s, \bar{d}s, \ldots$?),
  - $a_0(980)$, $I = 1$, 980 ± 20 MeV ($\bar{u}d, \bar{d}u, \bar{u}u - \bar{d}d, \ldots$?)

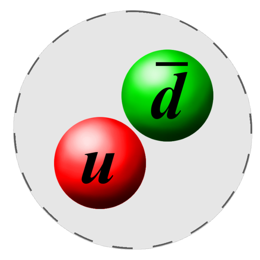
  (due to $m_s > m_{u/d}$, one would expect $m(\kappa) > m(a_0(980))$).
- Tetraquark picture:
  - $\kappa \equiv \bar{s}u(\bar{u}u + \bar{d}d)$,
  - $a_0(980) \equiv \bar{s}u\bar{d}s$

  (explains the experimentally measured meson masses as well as certain decays, e.g. $a_0(980) \longrightarrow K + \bar{K}$).

Creation operators for $a_0(980)$

- For our study of $a_0(980)$ we use several operators with identical quantum numbers, which are of rather different structure:
  - Quark-antiquark operator:

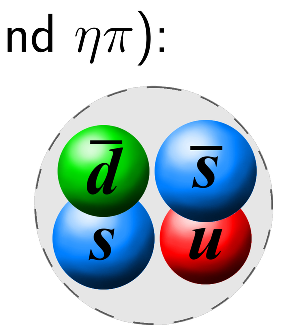
$$\mathcal{O}^{q\bar{q}} = \sum_{\mathbf{x}} \Big(\bar{d}_{\mathbf{x}} u_{\mathbf{x}}\Big).$$

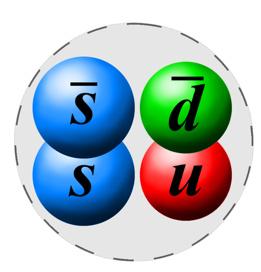


  - Mesonic molecule operators (both $K\bar{K}$ and $\eta\pi$):

$$\mathcal{O}^{K\bar{K}\text{ molecule}} = \sum_{\mathbf{x}} \Big(\bar{s}_{\mathbf{x}}\gamma_5 u_{\mathbf{x}}\Big)\Big(\bar{d}_{\mathbf{x}}\gamma_5 s_{\mathbf{x}}\Big)$$

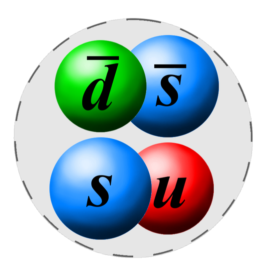
$$\mathcal{O}^{\eta\pi\text{ molecule}} = \sum_{\mathbf{x}} \Big(\bar{s}_{\mathbf{x}}\gamma_5 s_{\mathbf{x}}\Big)\Big(\bar{d}_{\mathbf{x}}\gamma_5 u_{\mathbf{x}}\Big).$$





  - Diquark-antidiquark operator:

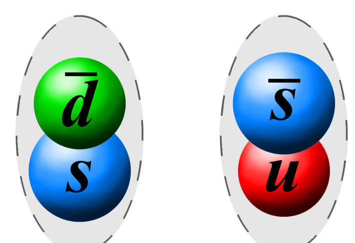
$$\mathcal{O}^{\text{diquark}} = \sum_{\mathbf{x}} \epsilon_{abc}\Big(\bar{s}_{\mathbf{x},b}(C\gamma_5)\bar{d}^T_{\mathbf{x},c}\Big)\epsilon_{ade}\Big(u^T_{\mathbf{x},d}(C\gamma_5)s_{\mathbf{x},e}\Big).$$

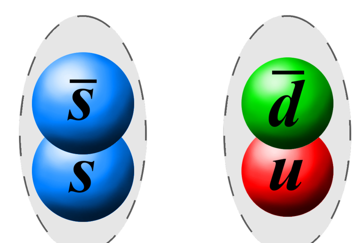


  - Two-meson operators (both $K + \bar{K}$ and $\eta + \pi$):

$$\mathcal{O}^{K+\bar{K}\text{ 2-meson}} = \sum_{\mathbf{x},\mathbf{y}} \Big(\bar{s}_{\mathbf{x}}\gamma_5 u_{\mathbf{x}}\Big)\Big(\bar{d}_{\mathbf{y}}\gamma_5 s_{\mathbf{y}}\Big)$$

$$\mathcal{O}^{\eta+\pi\text{ 2-meson}} = \sum_{\mathbf{x},\mathbf{y}} \Big(\bar{s}_{\mathbf{x}}\gamma_5 s_{\mathbf{x}}\Big)\Big(\bar{d}_{\mathbf{y}}\gamma_5 u_{\mathbf{y}}\Big).$$

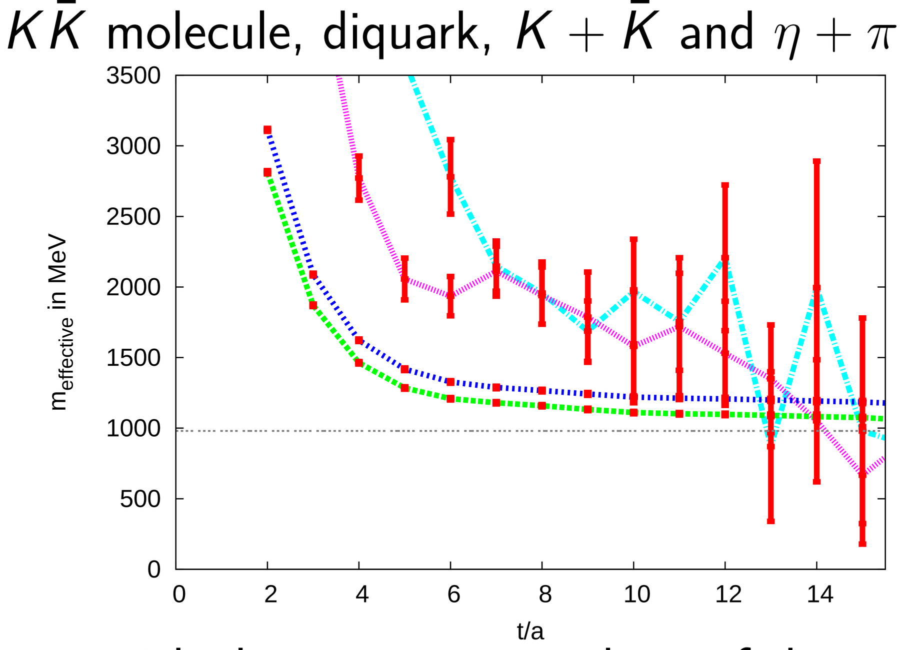




- Such a variety of operators allows not only to determine the mass of a meson, but also to obtain information about its internal structure.

First numerical results for $a_0(980)$

- Four operators ($K\bar{K}$ molecule, diquark, $K + \bar{K}$ and $\eta + \pi$ 2-meson).



- Two low lying states with the quantum numbers of the $a_0(980)$ and the expected mass (≈ 1000 MeV) can clearly be identified; these states are two-meson states, $K + \bar{K}$ and $\eta + \pi$.
- There is no third low lying state ≈ 1000 MeV, even though we employed operators of tetraquark structure.

  $\to$ $a_0(980)$ **does not seem to be a strongly bound tetraquark**.

  $\to$ $a_0(980)$ **could be a rather unstable resonance or a quark-antiquark state** (work in progress).
- Future plans include
  - similar investigations for heavier tetraquark candidates (D_{s0}^*, D_{s1}, $X(3872)$, charged Z states),
  - investigation of a theoretically predicted $\bar{c}\bar{c}cc$ tetraquark (in collaboration with expert group 2, cf. C. Fischer and collaborators).

[4] C. Alexandrou, J. O. Daldrop, M. Dalla Brida, M. Gravina, L. Scorzato, C. Urbach and M. Wagner, JHEP 1304 (2013) 137 [arXiv:1212.1418].

[5] J. Berlin, D. Palao and M. Wagner, PoS Lattice2013 (2012) 441 [arXiv:1308.4916 [hep-lat]].

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