The spectrum of charmed 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,

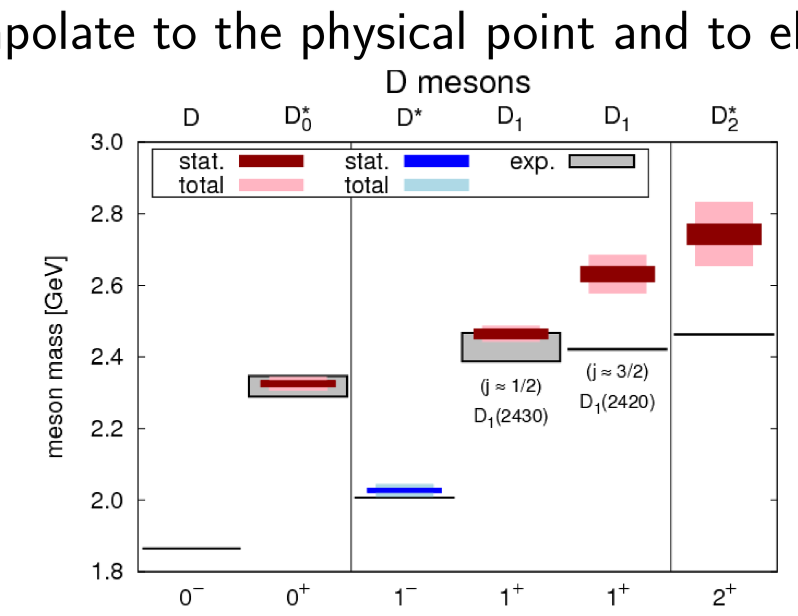
$$\mathcal{L}_{\text{QCD}} = \sum_{q \in \{u,d,s,c,t,b\}} \bar{q}\Big(\gamma_\mu\Big(\partial_\mu - iA_\mu\Big) + m^{(q)}\Big)q + \frac{1}{2g^2}\text{Tr}\Big(F_{\mu\nu}F_{\mu\nu}\Big);$$

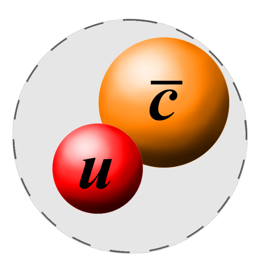
the numerical method to solve corresponding equations is **lattice QCD**.

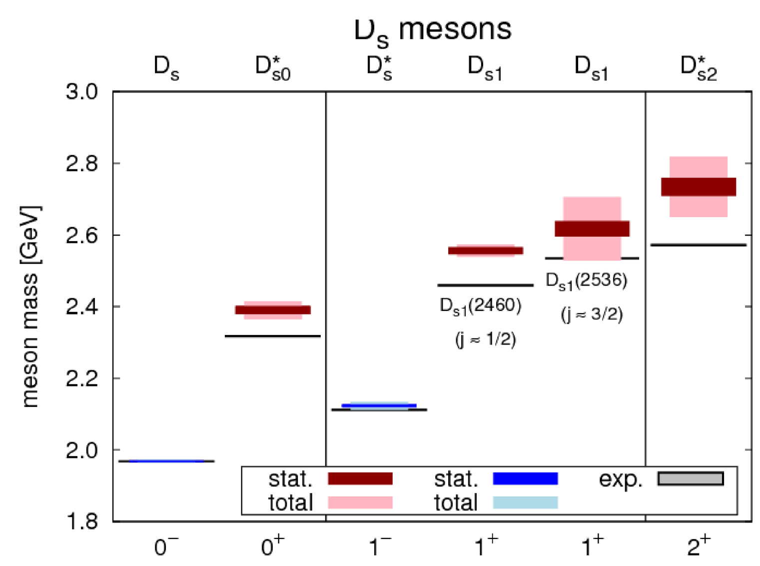
The spectrum of D mesons, D_s mesons and charmonium using $\bar{q}q$ operators

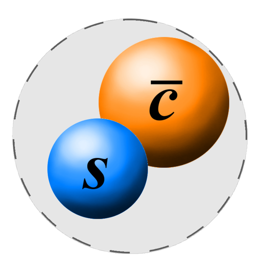
- Computations at
  - different values of the light u/d quark mass ($m_\pi \approx 225 \ldots 470\,\text{MeV}$),
  - different lattice discretizations,
  - different values of the lattice spacing,

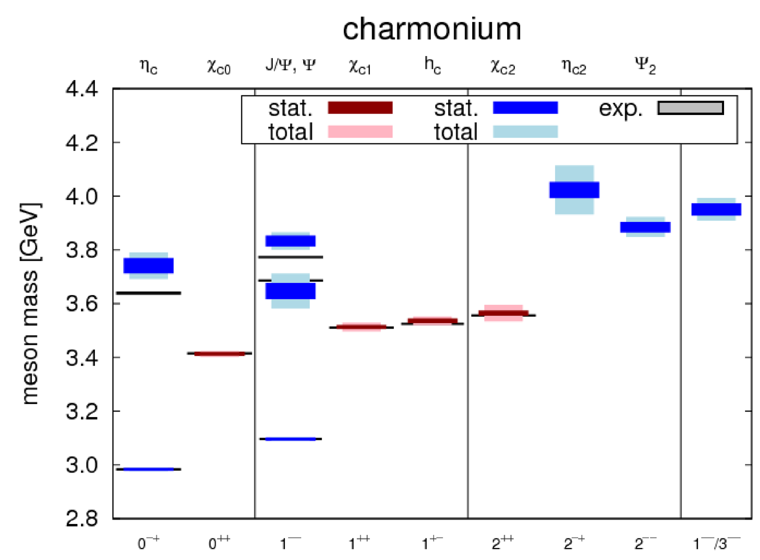
  to extrapolate to the physical point and to eliminate systematic errors.

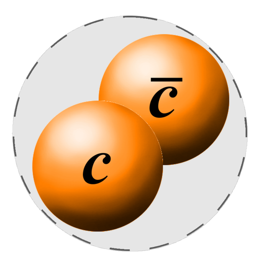












- For the majority of mesons agreement with experimental results.
- Disagreement might indicate a non-$\bar{q}q$ state (perhaps a tetraquark, a strong gluonic contribution, an unstable resonance; cf. the right column).
- Employing a variety of different operators allowed to distinguish and to investigate 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").

M. Kalinowski and M. Wagner, Phys. Rev. D **92**, no. 9, 094508 (2015) [arXiv:1509.02396 [hep-lat]].

K. Cichy, M. Kalinowski and M. Wagner, Phys. Rev. D **94**, no. 9, 094503 (2016) [arXiv:1603.06467 [hep-lat]].

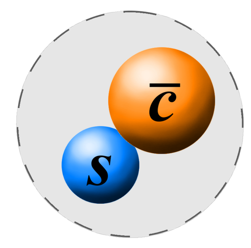
Why tetraquarks? (example $D_{s0}^*(2317)$)

- The masses of charmed scalar mesons D_{s0}^* and D_{s1} are below expectation of typical quark models and lattice computations, e.g. left column
- $D_{s0}^*(2317) - D_0^*(2400)$ mass difference is far too small to account for the s-u/d quark mass difference of 150 ± 30 MeV,
- $D_{s2}^*(2573)$ ist too light to be a radial excitation of the $D_{s0}^*(2317)$.
- Tetraquark interpretation:
  - explains states below the DK and D^*K thresholds naturally,
  - $D_{s2}^*(2573)$ may be a member of a scalar tetraquark multiplet.

Creation operators for $D_{s0}^*(2317)$

- For our study of $D_{s0}^*(2317)$ we use several operators with identical quantum numbers, which are of rather different structure:
  - Quark-antiquark operator:

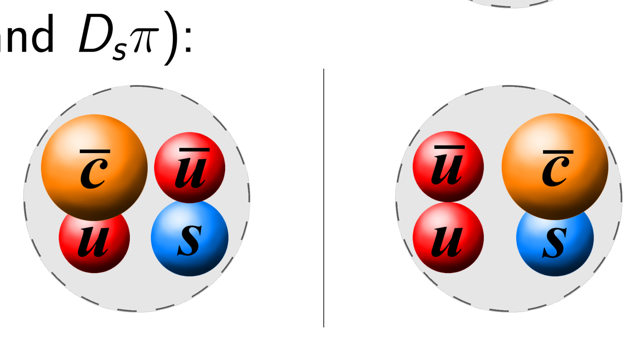
$$\mathcal{O}^{q\bar{q}} = \sum_{\mathbf{x}} \Big(\bar{c}_{\mathbf{x}} s_{\mathbf{x}}\Big).$$



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

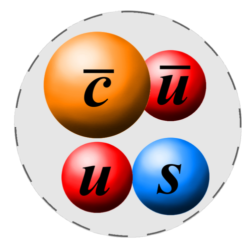
$$\mathcal{O}^{D\bar{K}\text{ molecule}} = \sum_{\mathbf{x}} \Big(\bar{u}_{\mathbf{x}}\gamma_5 s_{\mathbf{x}}\Big)\Big(\bar{c}_{\mathbf{x}}\gamma_5 u_{\mathbf{x}}\Big)$$

$$\mathcal{O}^{D_s\pi\text{ molecule}} = \sum_{\mathbf{x}} \Big(\bar{u}_{\mathbf{x}}\gamma_5 u_{\mathbf{x}}\Big)\Big(\bar{c}_{\mathbf{x}}\gamma_5 s_{\mathbf{x}}\Big).$$



  - Diquark-antidiquark operator:

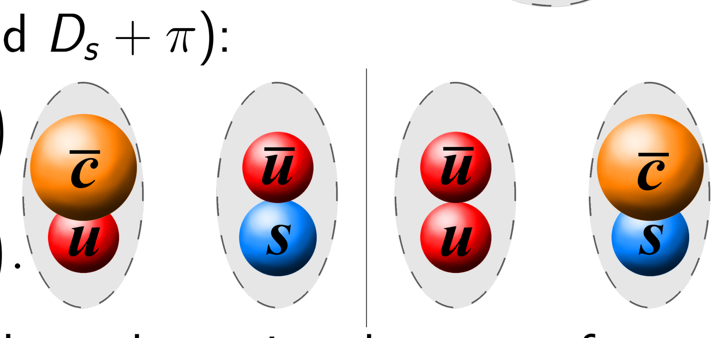
$$\mathcal{O}^{\text{diquark}} = \sum_{\mathbf{x}} \epsilon_{abc}\Big(\bar{u}_{\mathbf{x},b}(C\gamma_5)\bar{c}^T_{\mathbf{x},c}\Big)\epsilon_{ade}\Big(s^T_{\mathbf{x},d}(C\gamma_5)u_{\mathbf{x},e}\Big).$$



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

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

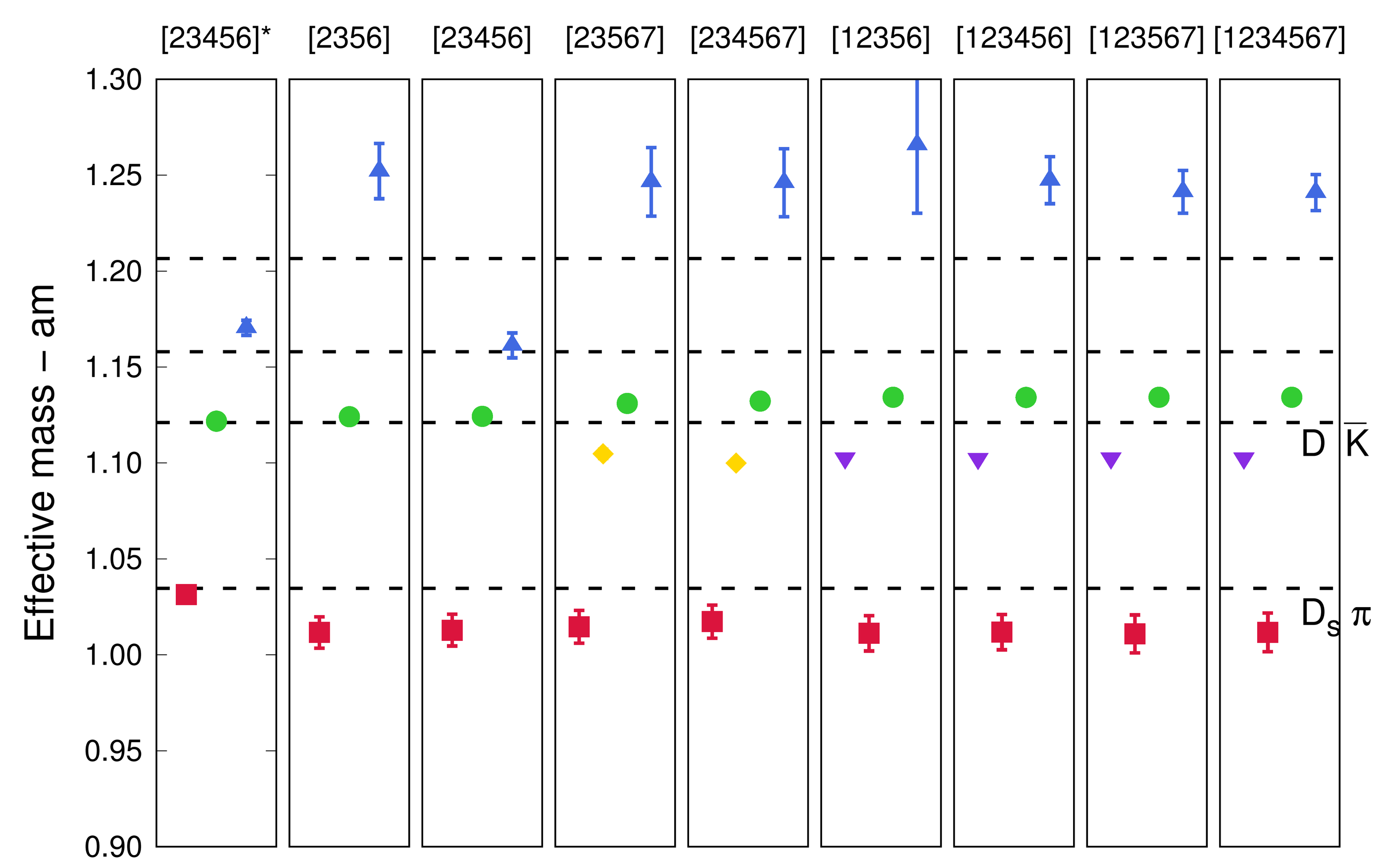
$$\mathcal{O}^{D_s+\pi\text{ 2-meson}} = \sum_{\mathbf{x},\mathbf{y}} \Big(\bar{s}_{\mathbf{x}}\gamma_5 u_{\mathbf{x}}\Big)\Big(\bar{c}_{\mathbf{y}}\gamma_5 s_{\mathbf{y}}\Big).$$



- 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 $D_{s0}^*(2317)$

- Varying operator bases ($q\bar{q} \equiv 1$; $D\bar{K}$, $D_s\pi$ molecule $\equiv 2, 3$; $D + \bar{K}$, $D_s + \pi$ 2-meson $\equiv 5, 6$; Diquark-antidiquark $\equiv 4, 7$).



- Only two-particle states are calculated in an analysis of a $\bar{c}s\bar{d}u$ structure.
- A third low lying state ≈ 2300 MeV occurs (states colored in yellow), although a conventional $q\bar{q}$ structure is not provided to the analysis.
  - If it is, it dominates the signal (states colored in violet), but competes with a non-trivial diquark-antidiquark structure
- This might suggests an internal structure beyond a conventional quark-antiquark pair
  - Future plans include varying pion masses, operators to resolve first momentum excitations, investigation of the states near thresholds, ...

A. Abdel-Rehim, C. Alexandrou, J. Berlin, M. Dalla Brida, J. Finkenrath and M. Wagner, arXiv:1701.07228 [hep-lat].

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