Charm tetraquarks in lattice QCD

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[GC, C.E.Thomas, J.J.Dudek, R.G.Edwards, arXiv:1709.01417]

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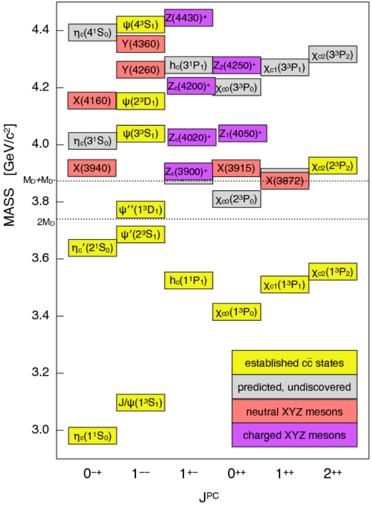
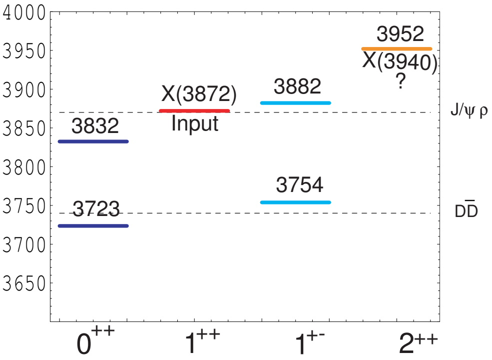
Introduction

- Large number of X, Y, Z states have been seen.
- Charged Z states suggest $c\bar{c}q\bar{q}$ structure. Molecules? Compact tetraquarks?



S. Olsen, arxiv:1511.01589

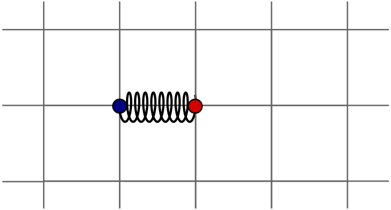
Tetraquarks



Maiani, Piccinini, Polosa, Riquer Phys.Rev.D71:014028,2005

Large multiplet of states predicted by tetraquark models. Does QCD predict such states? Calculations from first principles are desirable.

Lattice QCD



$$S = \int d^4x \left(-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \sum_f \bar{q}_f (i\gamma^\mu D_\mu - m_f) q_f \right)$$

- Path integral $Z = \int \prod_i d\psi_i d\bar{\psi}_i dU_i \; e^{-S_{latt}[\psi,\bar{\psi},U]}$ can be evaluated numerically on a Euclidean lattice.
- Lattice QCD is the only ab-initio systematically improvable method at low energy.
- Can we see signs of a bound state or narrow resonance in exotic flavour channels?
- Can we see signs of a tetraquark multiplet in spectrum calculations?

Calculating Observables

- Two-point correlation functions are calculated numerically on the lattice where operators $\mathcal{O}$ are constructed with definite quantum numbers.

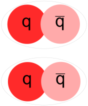
$$\begin{aligned} \langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle &= \langle 0|\mathcal{O}(t)\mathcal{O}^\dagger(0)|0\rangle \\ &= \sum_n |\langle 0|\mathcal{O}|n\rangle|^2 e^{-M_n t}. \end{aligned}$$

- The spectrum is contained in the two-point correlation function. We can extract the spectrum by calculating a matrix of two-point correlation functions for many operators. What about $\mathcal{O}$?

Four-quark Operators

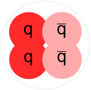
- Meson-meson operators (M)

$$\mathcal{O}(\vec{p}=0,t) \sim (\bar{c}\Gamma q')(\bar{q}\Gamma' c).$$



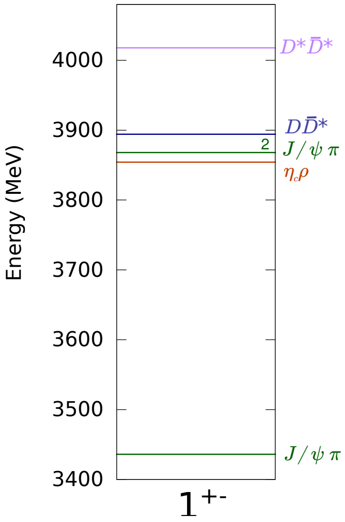
- Tetraquark operators (T)

$$\mathcal{O}(\vec{p}=0,t) \sim G_{ad} \underbrace{\left(g_{abc} c_b (C\Gamma_1) q_c^T\right)}_{\text{Diquark}} \underbrace{\left(g_{def} \bar{c}_e^T (\Gamma_2 C) \bar{q}_f\right)}_{\text{Anti-diquark}}.$$



- We construct these operators to transform irreducibly under lattice symmetries, have a range of colour-flavour-spin structures and respect other relevant symmetries.

Finite-volume Spectrum ($c\bar{c}q\bar{q}$)

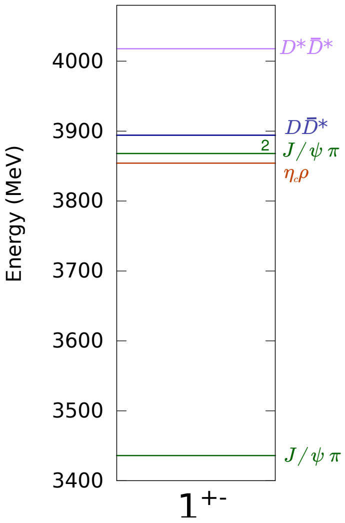


- The energy levels are discrete in a finite volume. Momentum is quantised.
- We can plot the non-interacting meson-meson levels in this channel.
- Interactions cause deviations from the non-interacting levels. Forms the basis of the Lüscher formalism to determine scattering amplitudes from a Euclidean field theory.

[C. Thomas, 25 Sep 2017, 15:15]

[R. Briceno, 26 Sep 2017, 10:10]

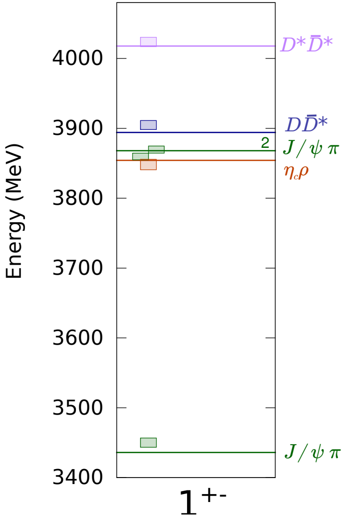
Finite-volume Spectrum ($c\bar{c}q\bar{q}$)



- In the non-interacting limit, we know how many meson-meson levels are in this channel. Will we see an 'extra' energy level of tetraquark origin?
- Will there be large shifts from the non-interacting levels suggesting a strong interaction? Hints of bound states or narrow resonances?

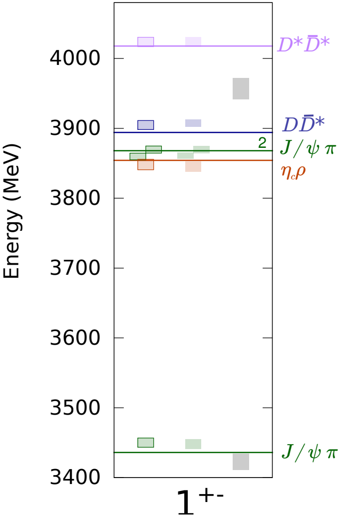
Results

Isospin-1 $c\bar{c}q\bar{q}$ Spectrum at $m_\pi \sim 400$ MeV



- The number of energy levels we find is equal to the number of expected non-interacting meson-mesons.
- Finite-volume spectrum lies close to non-interacting meson-meson levels suggesting there are weak meson-meson interactions.
- There is no strong indication for a bound state or narrow resonance in this channel. $Z_C(3900)$?
- Tetraquark operators do not have a significant effect on calculating the spectrum.

Isospin-1 $c\bar{c}q\bar{q}$ Spectrum at $m_\pi \sim 400$ MeV



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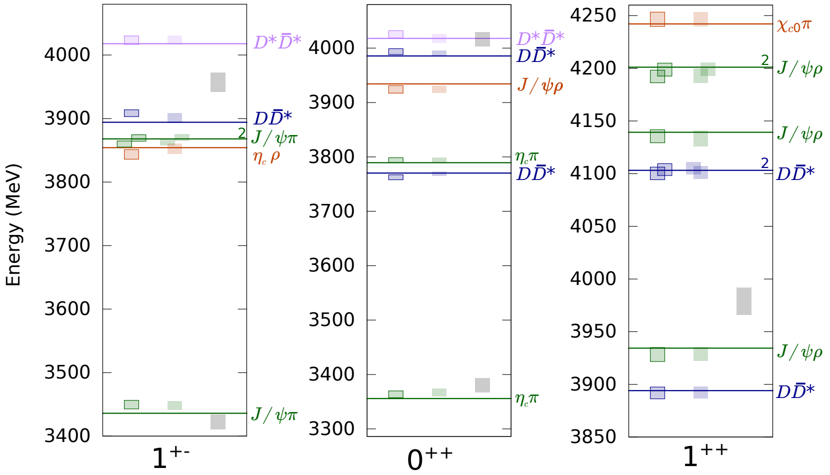
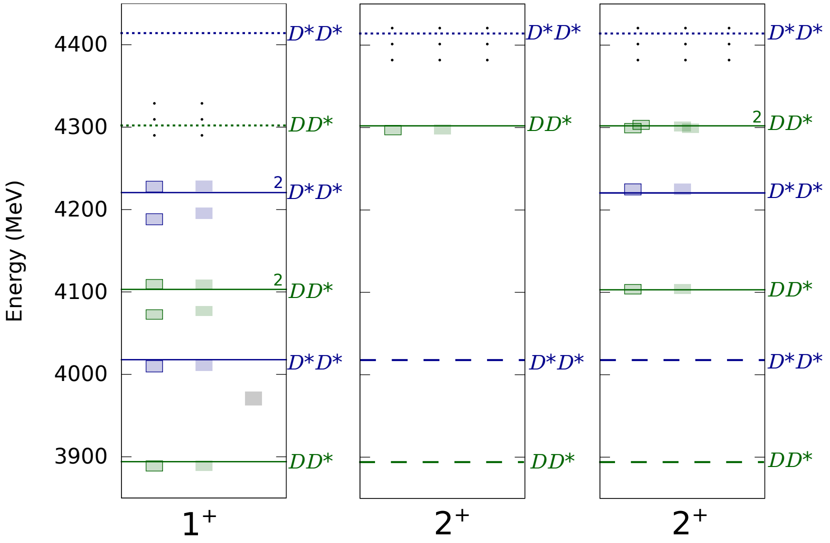
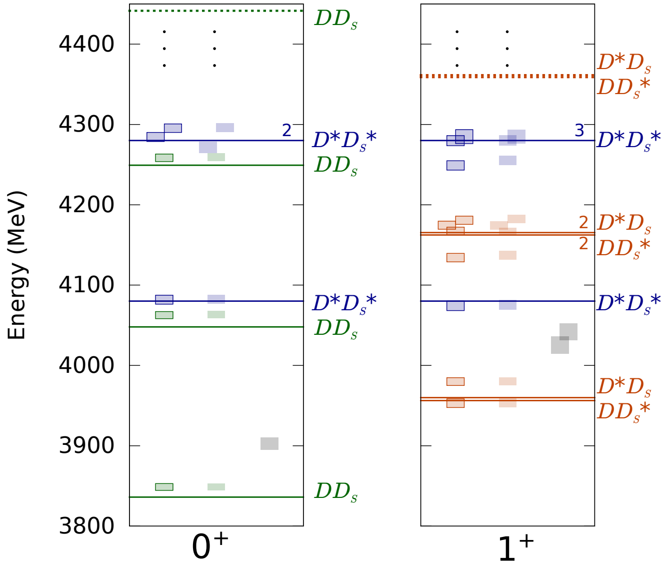


Isospin-0 doubly charmed spectrum ($cc\bar{q}\bar{q}$)



Isospin-1/2 doubly charmed spectrum ($cc\bar{q}\bar{s}$)



Other lattice studies

- Our results are consistent with some recent lattice studies.
  Prelovsek et al. arXiv:1405.7623 - $Z_C(3900)$
  Guerrieri et al. arXiv:1411.2247 - $cc\bar{q}q$
  Padmanath et al. arXiv:1503.03257 - $X(3872), \ldots$
- Other recent lattice studies in other channels.
  Alexandrou et al. arXiv:1212.1418 - Light sector
  Francis et al. arXiv:1607.05214 - Signs of a $bb\bar{q}\bar{q}$ tetraquark

Conclusions and outlook

- Majority of energies lie close to non-interacting energy levels and the number of energy levels is as expected. Therefore, there are no strong indications for any bound states or narrow resonances in the channels we've studied.
- Addition of a class of tetraquark operators to calculations does not significantly affect the extracted spectrum.
- To rigorously quantify the interaction, next steps are to relate the discrete finite volume spectrum to scattering phenomena using the Lüscher formalism. This would require more spectra in moving frames and different volumes.
- $m_\pi \sim 400$ MeV lattice is an efficient test bed for tetraquark operators. Calculations towards physical point are desirable but more expensive.