Doubly Heavy Tetraquarks in Lattice QCD

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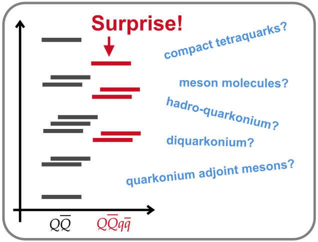
SnowMass2021
"Heavy-Quark Exotic Hadrons"

Virtual workshop, 16.09.2020



∘ Since 2003 $\mathcal{O}(12)$ new heavy flavor states discovered.

→ Some expected, bound & resonant.
→ Many unexpected, esp. 4-quark states.
→ Do not fit into conv. quark models.

∘ Multi-quark interactions are very complicated.
→ QCD origin, many models and interpretations exist.
→ Hard to find appropriate approximations for the relevant interactions.

∘ QCD calculations using LGT naturally include all interactions.
→ Approximations at the technical level.
→ Systematically improvable.

∘ We ask: What/how do quark combinations bind? What is their nature?

Four main lattice approaches:

1. Static quarks ($m_Q = \infty$)

Fitted potentials used to predict bound states and resonances.

◦ Allows for potential formulation.

◦ Ansatz fitted to lattice data.

◦ Plug into Schrödinger Eq. for E_n.

*$bb\bar{u}\bar{d}$, Bicudo et al. ('17,'19)

3. Finite volume energy levels

Lattice energies equated to (un)observed states.

◦ Operator matrix (GEVP) gives $\lambda_i \propto E_i \Rightarrow$ Finite volume states.

◦ Binding? Get $\Delta E = E_0 - E_{thresh}$.

◦ Mechanism? Vary quark masses.

*AF et al. ('17,'18, '20), Hughes et al. ('17), Junnarkar et al. ('18), Leskovec et al. ('19), Mohanta et al. ('20)

2. HAL QCD method

Lattice potentials studied for scattering properties.

◦ Expansion of energy dependent potential (systematics?).

◦ Method under debate, best motivated for heavy systems.

*HAL QCD ('16,'18)

4. Scattering analysis

Lattice energies studied in terms of scattering phase shifts.

◦ Excited state energies via GEVP.

◦ Analyse fvol spectrum $\Rightarrow$ Resonant, bound, virtual bound, free.

*Hadron Spectrum Coll. ('18,'20)

A case for doubly heavy tetraquarks $qq'\bar{Q}\bar{Q}'$ (especially $J^P = 1^+$)

∘ Hidden flavor $qQ\bar{q}'\bar{Q}$ are tetraquark candidates as excitations of $Q\bar{Q}'$.
→ technical difficulty for lattice calculations, resolve many f.vol states.
→ $qq'\bar{Q}\bar{Q}'$ candidates would be easier to handle on the lattice.

∘ Can tetraquarks exist as ground states? What would their binding mechanism/properties be?
→ Pheno. inspiration: Diquark dynamics and HQS could enable $J^P = 1^+$ **ground state doubly heavy tetraquarks** with flavor content $qq'\bar{Q}\bar{Q}'$.

In the following:

→ Tetraquarks with two heavy (c, b) and two light (ℓ, s) quarks.

→ Lattice evidence for $bb\bar{u}\bar{d}$, $bb\bar{\ell}\bar{s}$.

→ Recent updates on systematics.

→ Survey of candidates status.

→ Going further: $cs\bar{u}\bar{d}$ and all-heavies

Direct lattice calculations of doubly heavy tetraquarks

Step I) Set up a basis of operators

E.g. Diquark-Antidiquark (D) and Dimeson (M). *Most use ultra-local!

Step II) Solve the GEVP and extract finite volume energies

$$F(t) = \begin{pmatrix} G_{DD}(t) & G_{DM}(t) \\ G_{MD}(t) & G_{MM}(t) \end{pmatrix}, \quad F(t)\nu = \lambda(t)F(t_0)\nu \ , \ \lambda(t) = Ae^{-\Delta E(t-t_0)} \ .$$

*$\Delta E = E_{\text{tetra}} - E_{\text{thresh}}$ in case of binding correlator $(C_{\mathcal{O}_1\mathcal{O}_2}(t))/(C_{PP}(t)C_{VV}(t))$.

Step III) Finite volume corrections

Scenario I: Scattering state

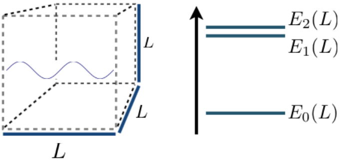
$$E_{b,L} \sim E_{b,\infty} \cdot \left[1 + \frac{a}{L^3} + \mathcal{O}(\frac{1}{L^4})\right]$$

Power law corrections.

Scenario II: Stable state

$$E_{b,L} \sim E_{b,\infty} \cdot \left[1 + Ae^{-\kappa L}\right]$$

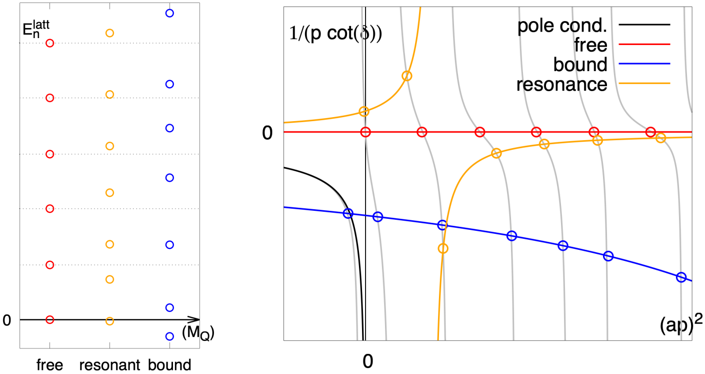
Exp. suppressed with $\kappa = \sqrt{E_{b,\infty}^2 + p^2}$.



*M. Hansen

Step IV) Finite volume / Scattering analysis

Limitation: Small GEVP without f.vol analysis ok for deeply bound states. Insufficient to tell apart free, resonant or virtual bd. states.

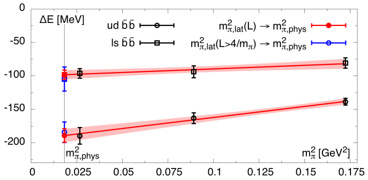


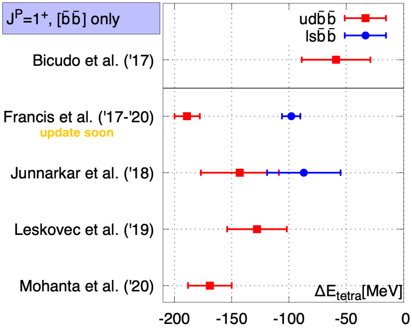
- ◦ map (many) finite volume states.
- ◦ understand in terms of scattering parameters (sketch: BW).
- ◦ resonance: extra state(s) appear, lowest state close to threshold.

What we know: Deeply bound $J^P = 1^+$ $bb\bar{u}\bar{d}$ and $bb\bar{\ell}\bar{s}$ tetraquarks

- $bb\bar{q}\bar{q}'$ are a focal point $\rightarrow$ All efforts observe deeply bound $bb\bar{u}\bar{d}$.

AF et al. ('17)





- Junnarkar, Mathur, Padmanath ('18)
- Leskovec, Meinel, Plaumer, Wagner ('19)
- HadronSpectrum Coll. ('17)
- Mohanta, Basak ('20)
- Colquhoun, AF, Hudspith, Lewis, Maltman ('17, '18, '20)

- Qualitative agreement with pheno.:

$\rightarrow$ $J^P = 1^+$ bound ground state.

$\rightarrow$ deeper binding with $m_Q \uparrow$.

$\rightarrow$ deeper binding with $m_q \downarrow$.

Recent updates

Chiral limit: ◦ Three studies have performed extrapolations to m_{phys}.

Continuum limit: ◦ Two studies have taken (partial) continuum limits.

Finite volume: ◦ Initial volume scaling in one study.
→ More work needed!

Operator choice: ◦ One study uses non-local sinks, but local sources.
◦ One study uses a basis with 5 operators in w-l approach.
→ More work needed!

Ground state systematics: Hudspith et al. ('20)
◦ The systematic due to the approach-from-below in w-l correlators is assessed through a box-sink construction.
→ We find corrections to ground state energies are significant $\propto$ 25MeV.

◦ For studies with w-l correlators, this puts pressure on the observation of shallow bound states. Immediate consequence:
→ $bc\bar{u}\bar{d}$ is no longer a strong bound candidate.
→ An updated study of the $cc\bar{u}\bar{d}$ is urgently required.

Survey of doubly heavy tetraquark candidates

observed (>1 group)
no deep binding
observed (1 group)
not confirmed (>1 group)

channel	deeply bound
$J^P = 1^+$	$bb\bar{u}\bar{d}$ $bc\bar{u}\bar{d}$
	$bb\bar{\ell}\bar{s}$ $bc\bar{\ell}\bar{s}$
	$bs\bar{u}\bar{d}$ $cs\bar{u}\bar{d}$
	$bb\bar{u}\bar{c}$ $bb\bar{s}\bar{c}$
	$cc\bar{u}\bar{d}$ $cc\bar{\ell}\bar{s}$
	$bb\bar{b}\bar{b}$
$J^P = 0^+$	$bb\bar{u}\bar{u}$ $cc\bar{u}\bar{u}$
	$bb\bar{u}\bar{d}$ $bc\bar{u}\bar{d}$
	$bb\bar{\ell}\bar{s}$ $bc\bar{\ell}\bar{s}$
	$bb\bar{s}\bar{s}$ $cc\bar{s}\bar{s}$
	$bs\bar{u}\bar{d}$ $cs\bar{u}\bar{d}$
	$bb\bar{u}\bar{c}$ $bb\bar{s}\bar{c}$
	$bb\bar{c}\bar{c}$ $cc\bar{u}\bar{d}$
	$bb\bar{b}\bar{b}$

∘ Searching for ground states significantly below threshold:

→ $bb\bar{u}\bar{d}$ and $bb\bar{\ell}\bar{s}$ in $J^P = 1^+$.
→ $cc\bar{q}\bar{q}'$ and $bc\bar{q}\bar{q}'$ not clear.
→ further candidates not observed.
→ not observed in $J^P = 0^+$.

*Bicudo et al. ('17), AF et al. ('17,'18, '20), *HadSpec Coll. ('18), Hughes et al. ('17), Junnarkar et al. ('18), Leskovec et al. ('19), Mohanta et al. ('20)

∘ States above threshold?

→ $bb\bar{u}\bar{d}$ in $J^P = 1^+$ /w static quarks find a resonance just above threshold. *Bicudo et al. ('19)
→ No results from other approaches.

∘ What about $cs\bar{u}\bar{d}$? → next slides.

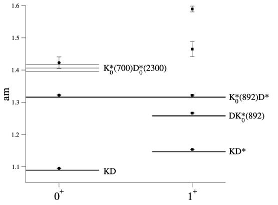
∘ Shallow binding? → Cannot be ruled out due to current limitations. (recall slide 6,9)

Opportunity together with experiment: Charm-strange $X(2900)$

◦ $X(2900)$, $cs\bar{u}\bar{d}$, is particularly interesting:
→ observed in experiment. *LHCb ('20)
→ within reach of lattice calculations.

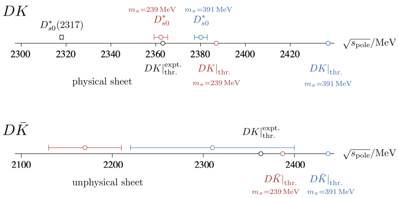
◦ Two existing lattice studies fall just short of the interesting region:

Hudspith, Coulqhoun, AF, Lewis, Maltman ('20)



(b) $ud\bar{s}\bar{c}$

Hadron Spectrum Coll. ('20)



◦ Close to D^*K^* threshold, but not enough operators to really probe.
◦ Currently no indication $X(2900)$, a quotable **statement is premature**.

◦ Focussed on DK and $D\bar{K}$ in the energy region < 2500MeV.

Extension studies required and eagerly awaited.

Opportunity together with experiment: All-heavy $cc\bar{c}\bar{c}$

◦ $cc\bar{c}\bar{c}$, is another interesting example:

→ observed in experiment. *LHCb ('20)

→ within reach of lattice calculations.

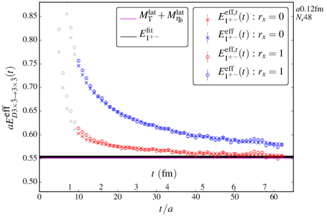
◦ One existing lattice study in $bb\bar{b}\bar{b}$, focussed below threshold:

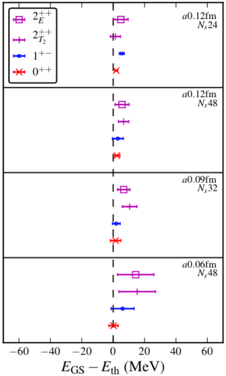
*Hughes et al. ('18)

Calculation using NRQCD in 0^{++}, 1^{+-} *and* 2^{++} *channels.*

⇒ No binding found.

Diquark-Antidiquark



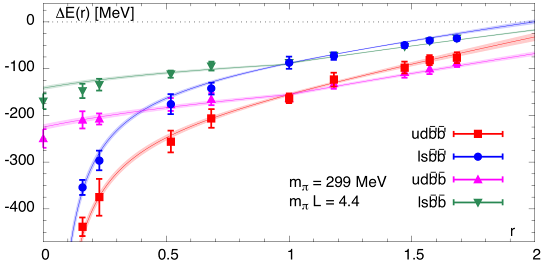


Extension study(?).

Opportunity together with pheno: A tunable system

AF et al. ('18)

*5 parameter pheno-Ansatz in Appendix



◦ E.g. scans in $m_{b'}$ map out the heavy quark mass dependence.

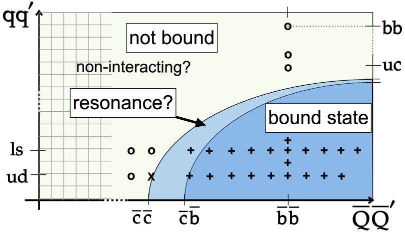
◦ Away from physical masses the binding mechanism can be probed.
→ Mass dependence can be confronted with model predictions.
→ System can be tuned continuously from the bound to the resonant or non-interacting regimes.

→ Requires robust control of finite volume spectrum.

Open: Are the diquark effect & HQS responsible for the binding?

◦ Mapping out the flavor/mass binding diagram.
→ (Un-)binding transition?
→ Connecting resonance?

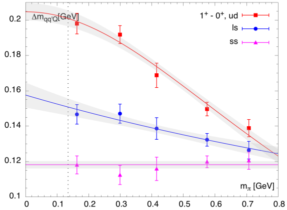
◦ Surveying more J^{PC} candidates
→ Other binding mechanisms?
→ More exotica? ($cs\bar{u}\bar{d}$, $cc\bar{c}\bar{c}$,. . .)



◦ Establish the finite volume spectra and perform scattering analysis
→ What is the resonant/bound nature of these tetraquarks?

◦ Study diquark dynamics (masses, radii)
→ Are these effects at play in the doubly heavy tetraquarks?

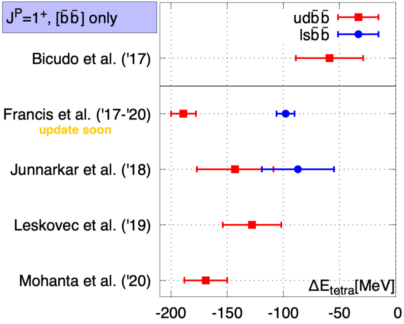
AF et al. (in prep)



Outlook

Lattice: Direct calculations reveal evidence of $bb\bar{u}\bar{d}$, $bb\bar{\ell}\bar{s}$ $J^P = 1^+$ tetraquarks.

◦ Clear path to improve systematics and extend applications, e.g. to $cs\bar{u}\bar{d}$, $cc\bar{c}\bar{c}$ or diquark studies.



Conjunction with experiment: $cs\bar{u}\bar{d}$ and $cc\bar{c}\bar{c}$ are a great opportunity. They can be accessed through experiments and (future) lattice calcs. Some methodological improvements are required though.

Conjunction with pheno: Doubly heavy tetraquarks present a tunable system that can be mutually beneficially confronted with pheno insights.

Doubly heavy tetraquarks are a new type of exotic predicted in QCD.

Exciting prospects and an interesting challenge!

Thank you for your attention.

Text summary

- Dozen of states that do not fit the conventional spectrum wisdom
- Lattice methods:
  - Lattice potential in systems w/ static quarks
  - HAL potential method
  - Finite volume energy levels
  - Scattering analysis
- Doubly heavy tetraquarks, a tunable system
- Candidate survey, status on the lattice:
  - $bb\bar{u}\bar{d}$ and $bb\bar{\ell}\bar{s}$ shift but still deeply bound, $bc\bar{u}\bar{d}$ not anymore
  - $cc\bar{u}\bar{d}$ tension? udcb shift puts pressure on $cc\bar{u}\bar{d}$ claim
  - Open: Are the HQS + diquark effect responsible? Study explicitly.
  - Above threshold: $cs\bar{u}\bar{d}$? Two studies, excited level not identified yet
  - All-heavy? $bb\bar{b}\bar{b}$ only ground state studied
- Future:
  - Above threshold: structures, resonances?
  - Shallow binding energies: free, virtual bound or resonant states?
  - Deep binding energies: Control all systematics, study binding mechanism.