Charm-bottom and heavy-light tetraquarks from lattice QCD

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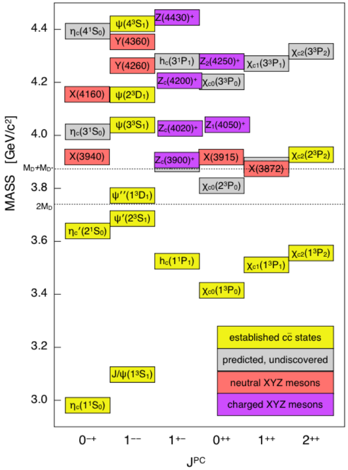
Heavy flavor tetraquarks - a challenge to theory

*Mitchell, Ohlsen

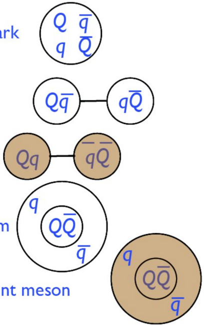
*Ali



Models for XYZ Mesons

Quarkonium Tetraquarks

- compact tetraquark
- meson molecule
- diquark-onium
- hadro-quarkonium
- quarkonium adjoint meson



Many models and interpretations exist.
Very difficult to address on the lattice due to $c\bar{c}$ or $b\bar{b}$ with $q\bar{q}$.

A case for doubly heavy tetraquarks:

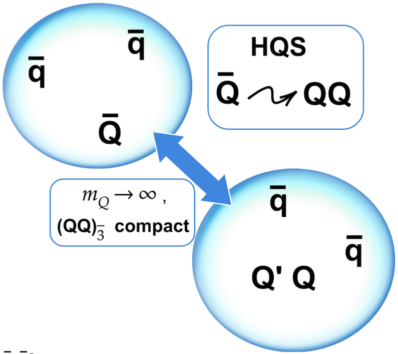
Away from the X, Y, Z states, the heavy hadron spectrum suggests a binding mechanism for ground state tetraquarks, $qq'\bar{Q}\bar{Q}'$ ($J^P = 1^+$).

Assumptions:

- Q-spin decouples, $[\bar{Q}\bar{Q}]_3 \leftrightarrow Q$ (good approx. for $Q = b$)
- q's prefer to be in $\{qq\}_{\bar{3}}$

Observations in Q and q:

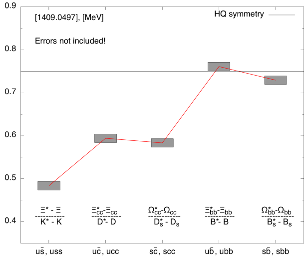
- $[\bar{Q}\bar{Q}]_3^{m_Q \to \infty}$ becomes compact
- HQS relates $qq'Q$ and $qq'\bar{Q}\bar{Q}'$
- $B(qqQ)$ with $(qC\gamma_5 q)$ lightest
- $m_B(\{ud\}) < m_B(\{us\})$

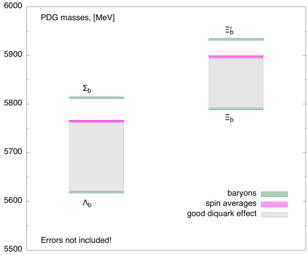


Question: Combining $\overbrace{(qC\gamma_5 q')}^{\{qq\}}\overbrace{(\bar{Q}C\gamma_i\bar{Q}')}^{[\bar{Q}\bar{Q}]}$ diquarks, do they form stable $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$, $ud\bar{c}\bar{b}$ tetraquarks?

Answer in the simple HQS-GDQ picture

$\rightarrow$ Single-b baryon as analogous system to tetraquark.





HQS: $[\bar{Q}\bar{Q}]$ behaves like single Q:

- Good approx. in $(\Xi^*_{bb} - \Xi_{bb})/(B^* - B)$ and $(\Omega^*_{bb} - \Omega_{bb})/(B^*_s - B_s)$

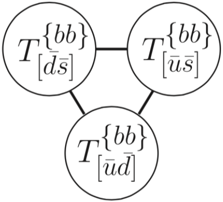
Spectrum as guide for diquark effect:

- $\{ud\}$: $\Lambda_b - B_{sp} \sim -145\text{MeV} \leftrightarrow [ud]$: $\Sigma_b - B_{sp} \sim 49\text{MeV}$
- $\{\ell s\}$: $\Xi_b - B_{sp} - \sim -106\text{MeV} \leftrightarrow [\ell s]$: $\Xi'_b - B_{sp} \sim 36\text{MeV}$

$B_{sp} = \frac{1}{4}[\,3B_{s=0} + B_{s=1}\,] \sim$ spin averaged "threshold"

Old idea: Stable multiquarks pointed out previously *Ader et al. ('82); *Manohar, Wise ('93); ...

Renewed interest from phenomenology
*Karliner, Rosner ('17); *Eichten, Quigg ('17); *Czarnecki, Leng, Voloshin ('18); *Mehen ('17); *Maiani ('19); ...



Lattice work *Guerrieri et al. ('15); *Bicudo, Wagner et al ('11-'19); Bali, Herzegger ('11); ...

$\Rightarrow$ These studies typically identify $ud\bar{b}\bar{b}$ as favorable channel.

HQS-GDQ picture, consequences for $qq'\bar{Q}'\bar{Q}$ tetraquarks:

- $J^P = 1^+$ *ground state* tetraquark below meson-meson threshold
- Deeper binding with heavier quarks in the $\bar{Q}'\bar{Q}$ diquark
- Deeper binding for lighter quarks in the qq' diquark

Goal: Determine $\Delta E = E_{\text{tetra}} - E_{\text{meson}-\text{meson}}$ for $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$ and $ud\bar{c}\bar{b}$
$\Rightarrow$ Verify, quantify predictions of binding mechanism in mind

Direct lattice calculation of doubly heavy $J^P = 1^+$ tetraquarks

Step I: Set up a basis of operators

Diquark-Diquark:

$$D = \left((q_a)^T (C\gamma_5) q'_b \right) \times \left[\bar{Q}_a (C\gamma_i) (\bar{Q}'_b)^T - a \leftrightarrow b \right]$$

Dimeson: $$M = (\bar{b}_a \gamma_5 u_a)\,(\bar{b}_b \gamma_i d_b) - (\bar{b}_a \gamma_5 d_a)\,(\bar{b}_b \gamma_i u_b)$$

Step II: Solve the GEVP and get the energies

$$F(t) = \begin{pmatrix} G_{DD}(t) & G_{DM}(t) \\ G_{MD}(t) & G_{MM}(t) \end{pmatrix}, \quad F(t)\nu = \lambda(t) F(t_0)\nu \,,$$

$$G_{\mathcal{O}_1\mathcal{O}_2} = \frac{C_{\mathcal{O}_1\mathcal{O}_2}(t)}{C_{PP}(t) C_{VV}(t)} \,,\ \lambda(t) = A e^{-\Delta E (t-t_0)} \,.$$

*3 $\times$ 3 GEVP for $\bar{Q}'\bar{Q}$; 2 $\times$ 2 for $\bar{Q}\bar{Q}$. More γ's possible but not beneficial in $\bar{b}\bar{b}$.

Further lattice energy levels studies:

- Similar set-up to this one *Junnarkar, Mathur, Padmanath ('18)
- Non-local sink operators *Leskovec, Meinel, Plaumer, Wagner ('19)
- Distillation ($ud\bar{c}\bar{c}$, $\ell s\bar{c}\bar{c}$) *HadronSpectrum Coll. ('17)

Roadmap:

- Determine ΔE_{tetra} $\Rightarrow$ Binding correlator $\sim e^{-\Delta E\, t}$
- Quark mass dependence qq', $\bar{Q}\bar{Q}'$ $\Rightarrow$ Verify, quantify predictions
- Finite volume effects$_*$ $\Rightarrow$ Scattering or stable state?
- Energy level systematics$_*$ $\Rightarrow$ Precision

*no binding correlator

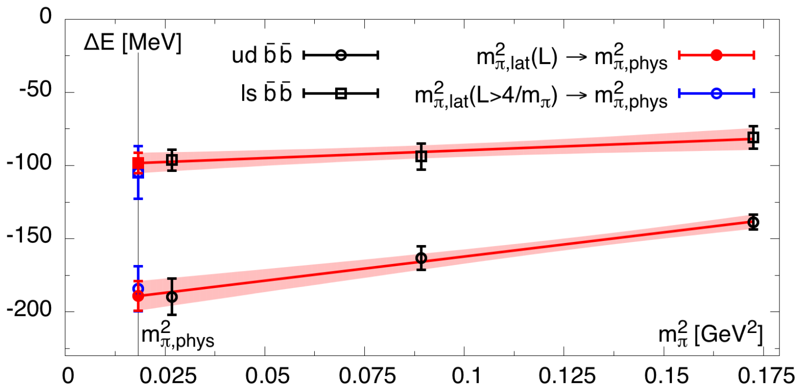
Lattice action:

- $N_f = 2 + 1$ Wilson-Clover fermions with Iwasaki gauge action

Valence-quarks:

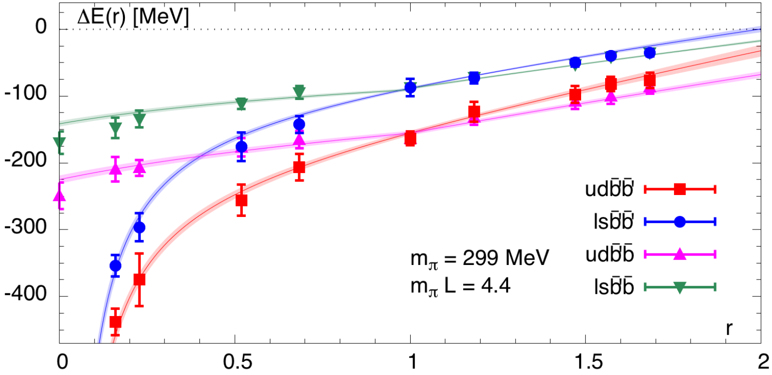
- Wilson-Clover quarks for $u = d, s$
- Fermilab/Tsukuba relativistic effective HQ action for c
- NRQCD for b and non-relativstic, unphysical $Q' = b'$

PACS-CS,'09	$32^3 \times 64$	$a^{-1} = 2.194$[GeV]	$m_{s,lat} = m_{s,phys}$
m_π[MeV]	415	299	163
$m_\pi L$	6.1	4.4	2.4
n_{conf}	400	800	187



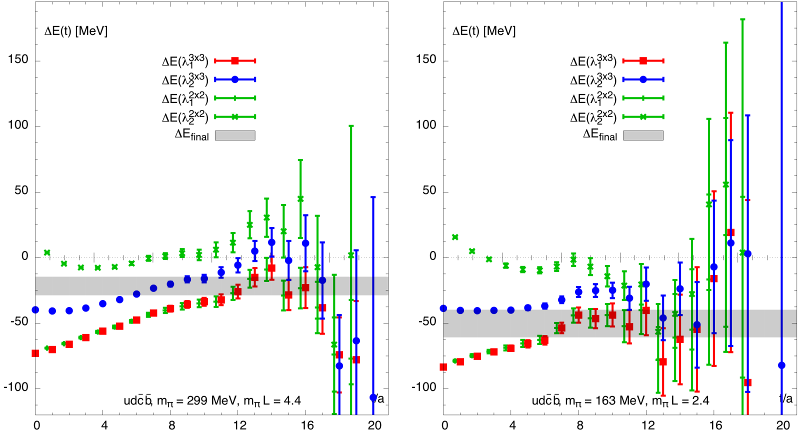
Physical point: $\Delta E_{ud\bar{b}\bar{b}} = 189(10)(3)$ MeV and $\Delta E_{ls\bar{b}\bar{b}} = 98(7)(3)$ MeV

- *Bound ground state* tetraquark below meson-meson threshold ✓
- Deeper binding with heavier $\bar{Q}'\bar{Q}$ diquarks, $\sim 1/m_Q$
- Deeper binding for lighter quarks in the qq' diquark ✓



Setting the heavy quark mass $m_{b'}$ to unphysical values we map out the heavy quark mass dependence of the binding energy.

- *Bound ground state* tetraquark below meson-meson threshold ✓
- Deeper binding with heavier $\bar{Q}'\bar{Q}$ diquarks, $\sim 1/m_Q$ ✓
- Deeper binding for lighter quarks in the qq' diquark ✓



Previously: Most likely bound tetraquark in charm quark region is $ud\bar{c}\bar{b}$

Calculation indeed reveals evidence for doubly heavy tetraquarks:

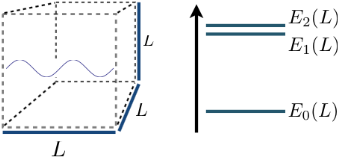
- $\Delta E_{ud\bar{b}\bar{b}} \simeq 190$ MeV and $\Delta E_{ls\bar{b}\bar{b}} \simeq 100$ MeV
- $\Delta E_{ud\bar{c}\bar{b}} \sim 15 - 61$ MeV (current status).

Finite volume corrections

Large energy shifts are possible due to the finite lattice volume.

Scenario I: Scattering state
The finite volume energy belongs to a scattering state, the corrections go as

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



*M. Hansen

Scenario II: Stable state
The corrections are exponentially suppressed with $\kappa = \sqrt{E_{b,\infty}^2 + p^2}$

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

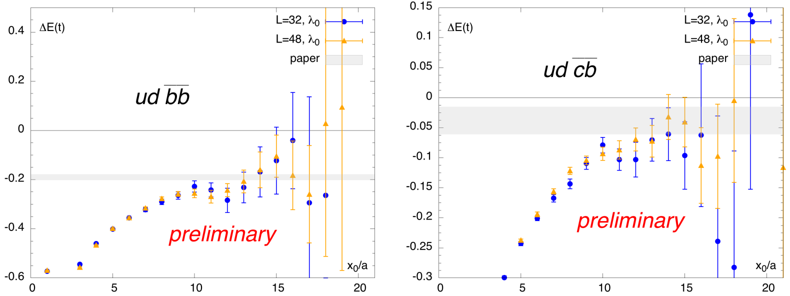
An in-depth study of volume effects is absolutely important and gives insight into the nature of the states observed.

*From now on: No more binding correlator

Signs of stability

κ_l	L	T	m_π[MeV]	$m_\pi L$	L[fm]	n_{conf}	status
0.13781	32	64	164	2.4	2.88	71	preliminary
	48	64		3.6	4.32	113	preliminary
	64	64		4.8	5.76	32	pending

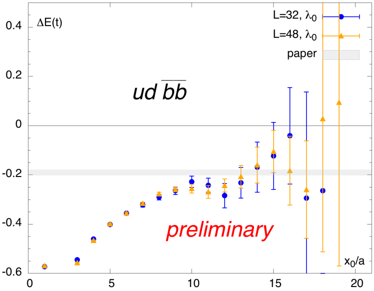
$\Rightarrow$ New volumes for a well understood/tuned setup. (add. $m_\pi \simeq 180, 200$MeV)

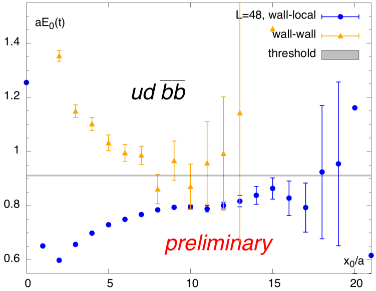


Short- and long-distance agreement are signs of the $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$ (not shown here) and $ud\bar{c}\bar{b}$ being stable states$_*$. **Further work needed!**

*See e.g. 1705.09239.

Solidifying conclusions





Finite volume scaling
→ stable states in QCD?

To Do: Further statistics and study is needed to firmly establish this conclusion

Wall-local correlators
→ approach to ground state from below. Systematic?

To Do: Extend and include correlator that approaches from above

Experimental detection possibilities

$J^P = 1^+$ doubly heavy tetraquarks are a new type of exotic predicted in QCD. Many possible decay channels exist, examples:

$ud\bar{b}\bar{b} \longrightarrow B^+ D^0$	$us\bar{b}\bar{b} \longrightarrow B^+ D_s^0$	$ud\bar{c}\bar{b} \longrightarrow \bar{D}^0 \bar{D}^0$
$\longrightarrow J/\psi B^+ K^0$	$\longrightarrow B_s \bar{D}^+$	$us\bar{c}\bar{b} \longrightarrow \pi^- K^+ B^0$
	$\longrightarrow J/\psi B_s K^+$	$ds\bar{c}\bar{b} \longrightarrow D^- B^+ \gamma$

Highest experimental detection probability at LHCb. *Gershon, Poluetkov

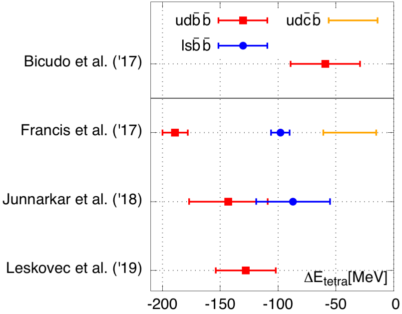
- Have presented an inclusive strategy to search for double beauty hadron production at the LHC through the signature of displaced B_c^- mesons
  - Well suited for search at LHCb
  - Still highly challenging, but seems to have better potential than exclusive searches
- More detailed study needed to understand LHCb sensitivity
  - Depends on bbx production cross-sections, inclusive branching fractions to final states containing B_c^- mesons, masses and lifetimes
  - More theory work on these would be welcome

arXiv:1810.06657

Project prospects and summary

Pheno. intuition hints at doubly heavy tetraquarks based on HQS and good diquarks.

In direct calculations we find evidence of $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$ and $ud\bar{c}\bar{b}$ $J^P = 1^+$ tetraquarks (single volume L[fm]=2.88)



Varying the quark masses in all $qq'\bar{Q}\bar{Q}'$ channels broad agreement with the intuitive binding mechanism is seen.

A *preliminary study* of volume scaling shows signs that $ud\bar{b}\bar{b}$, $\ell s\bar{b}\bar{b}$ and $ud\bar{c}\bar{b}$ are stable states in QCD. A clear statement is premature.

In our setup, currently ground states energies are reached from *below*. An extension to establish a firm upper bound is desirable.

Outlook for experimental detection (`1806.09288, 1810.06657`)

Exciting prospects. Let's hunt some exotica!

Thank you for your attention.

Appendix

Phenomenological model

$\bar{b}'\bar{b}'$:

$$\Delta E_{ud\bar{b}'\bar{b}'} = \frac{C_0}{2r} + C_1^{ud} + C_2^{ud}(2r) + (23\ \text{MeV})\, r,$$
$$\Delta E_{\ell s\bar{b}'\bar{b}'} = \frac{C_0}{2r} + C_1^{\ell s} + C_2^{\ell s}(2r) + (24\ \text{MeV})\, r$$

$\bar{b}'\bar{b}$, $r < 1$:

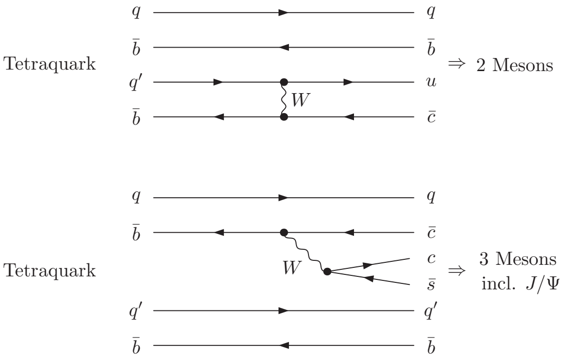
$$\Delta E_{ud\bar{b}'\bar{b}} = \frac{C_0}{1+r} + C_1^{ud} + C_2^{ud}(1+r) + (34\ \text{MeV} - 11\ \text{MeV}\, r)\,,$$
$$\Delta E_{\ell s\bar{b}'\bar{b}} = \frac{C_0}{1+r} + C_1^{\ell s} + C_2^{\ell s}(1+r) + (34\ \text{MeV} - 12\ \text{MeV} r)$$

$\bar{b}'\bar{b}$, $r > 1$:

$$\Delta E_{ud\bar{b}'\bar{b}} = \frac{C_0}{1+r} + C_1^{ud} + C_2^{ud}(1+r) + (34\ \text{MeV}\, r - 11\ \text{MeV})\,,$$
$$\Delta E_{\ell s\bar{b}'\bar{b}} = \frac{C_0}{1+r} + C_1^{\ell s} + C_2^{\ell s}(1+r) + (36\ \text{MeV}\, r - 11\ \text{MeV})$$

Detection possibilities in experiment: $ud\bar{b}\bar{b}$ and $\ell s\bar{b}\bar{b}$

With such deep ΔE, both $ud\bar{b}\bar{b}$ and $\ell s\bar{b}\bar{b}$ tetraquarks decay only weakly



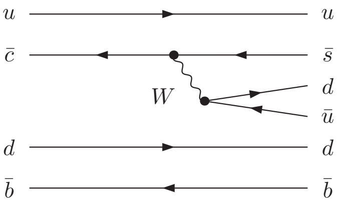
$ud\bar{b}\bar{b} \rightarrow B^+ D^0$
$\rightarrow J/\psi B^+ K^0$

$us\bar{b}\bar{b} \rightarrow B^+ D_s^0$
$\rightarrow B_s \bar{D}^+$
$\rightarrow J/\psi B^+ \phi$
$\rightarrow J/\psi B_s K^+$

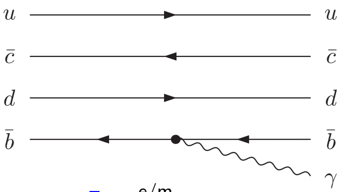
$ds\bar{b}\bar{b} \rightarrow B^+ D_s^-$
$\rightarrow B_s \bar{D}^0$
$\rightarrow J/\psi B^0 \phi$
$\rightarrow J/\psi B_s K^0$

Detection possibilities in experiment: $ud\bar{c}\bar{b}$

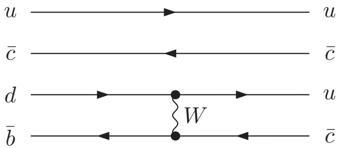
At this point $ud\bar{c}\bar{b}$ could decay only weakly or also electromagnetically



$us\bar{c}\bar{b} \stackrel{\text{weak}}{\Longrightarrow} (\pi^- K^+ B^0)$



$ds\bar{c}\bar{b} \stackrel{\text{e/m}}{\Longrightarrow} (D^- B^+ \gamma)$



$ud\bar{c}\bar{b} \stackrel{\text{weak}}{\Longrightarrow} (\bar{D}^0 \bar{D}^0)$

Energy of $ud\bar{c}\bar{b}$ at $m_\pi[\text{MeV}] = 164$