Open bottom tetraquarks

and their relation to doubly charmed baryons

- Doubly bottom tetraquarks and charmed bottom tetraquarks will be discussed through the combined lens of lattice QCD and effective field theories.

- Existing experimental input from heavy mesons, heavy baryons, and a doubly charmed baryon will provide valuable insight.

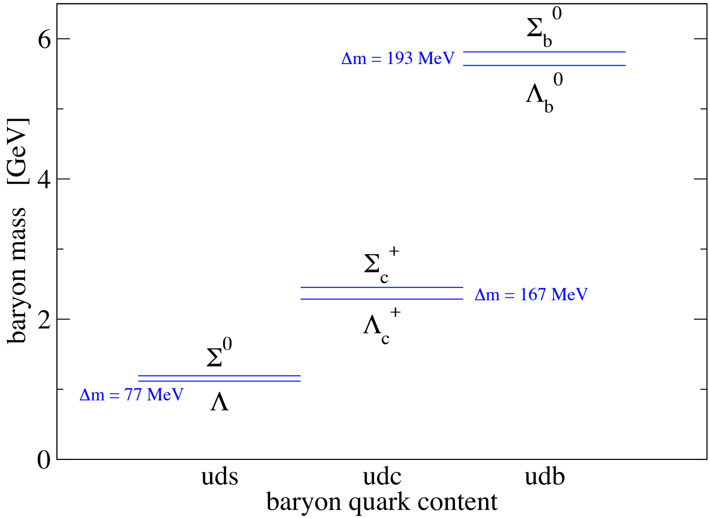
- Prospects for experimental observation of open bottom tetraquarks will be considered.

randy.lewis@yorku.ca

Binding in a light diquark

The strong force within qq is more attractive with $I = 0$ than with $I = 1$.

Known baryon masses show the difference:



To make a tetraquark, replace the heavy quark Q with a heavy anti-diquark $\bar{Q}\bar{Q}$.

What is the binding within $\bar{Q}\bar{Q}$?...

Lattice QCD and lattice NRQCD

Lattice QCD is a first-principles approach to strong interactions.
Statistical and systematic errors can be quantified and managed.

Typical lattice spacings are too large to handle a dynamical bottom quark.
This is no problem because there is an effective field theory: lattice NRQCD.

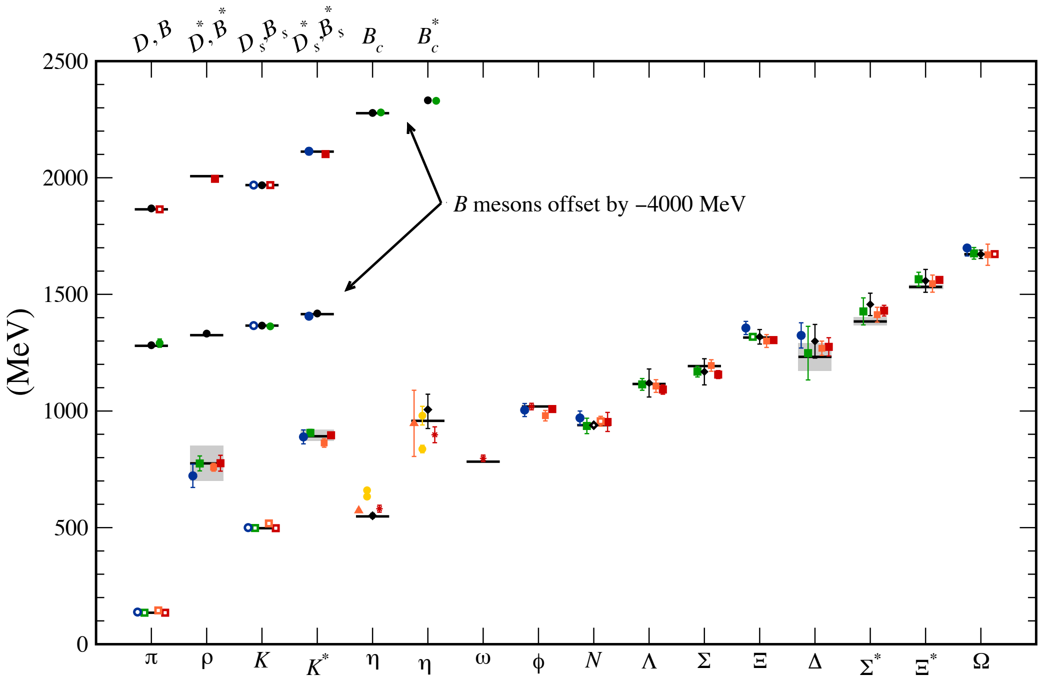
The lattice NRQCD Hamiltonian is a familiar non-relativistic expansion:

$$
\begin{aligned}
H = & -\frac{\Delta^{(2)}}{2M_0} - c_1\frac{(\Delta^{(2)})^2}{8M_0^3} + \frac{c_2}{U_0^4}\frac{ig}{8M_0^2}(\tilde{\boldsymbol{\Delta}}\cdot\tilde{\boldsymbol{E}} - \tilde{\boldsymbol{E}}\cdot\tilde{\boldsymbol{\Delta}}) \\
& - \frac{c_3}{U_0^4}\frac{g}{8M_0^2}\boldsymbol{\sigma}\cdot(\tilde{\boldsymbol{\Delta}}\times\tilde{\boldsymbol{E}} - \tilde{\boldsymbol{E}}\times\tilde{\boldsymbol{\Delta}}) \\
& - \frac{c_4}{U_0^4}\frac{g}{2M_0}\boldsymbol{\sigma}\cdot\tilde{\boldsymbol{B}} + c_5\frac{a^2\Delta^{(4)}}{24M_0} - c_6\frac{a(\Delta^{(2)})^2}{16nM_0^2}
\end{aligned}
$$

Lepage,Magnea,Nakleh,Magnea,Hornbostel,PRD46(1992)4052

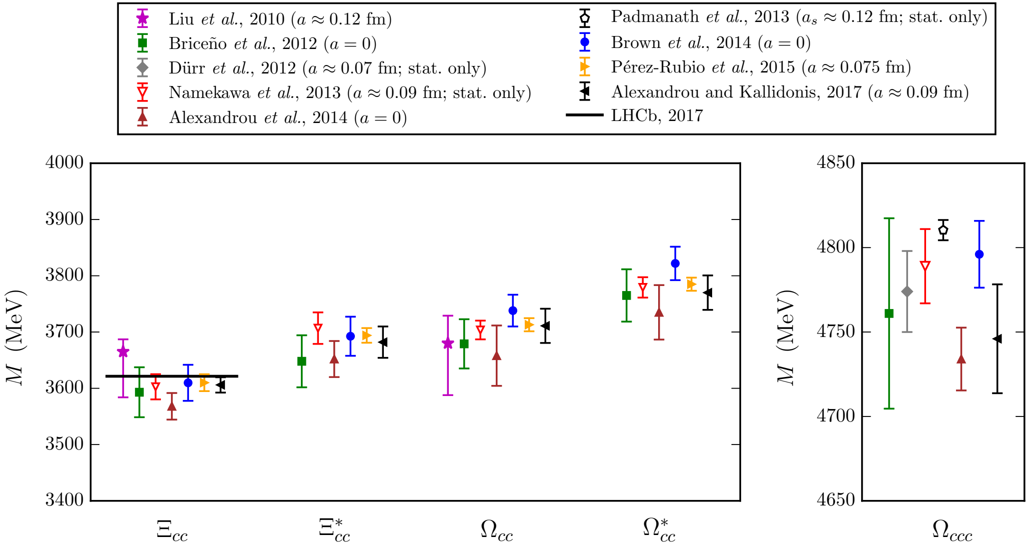
Interactions with gluons (and thus light quarks) come through $\tilde{\boldsymbol{E}}$, $\tilde{\boldsymbol{B}}$ and $\tilde{\boldsymbol{\Delta}}$.

Hadron spectrum from lattice QCD



Particle Data Group, 2017

ccq and ccc baryons from lattice QCD



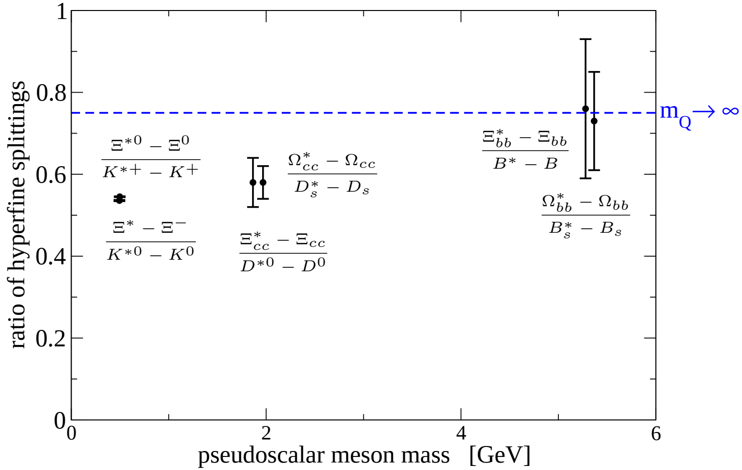
Particle Data Group, 2017

Note: The LHCb Ξ_{cc} measurement came after the lattice predictions above.

The original quenched lattice QCD predictions also agree: Lewis,Mathur,Woloshyn,PRD64(2001)094509
Mathur,Lewis,Woloshyn,PRD66(2002)014502

$\bar{Q}\bar{Q}$ binding energy

Lattice QCD shows the approach toward $m_Q \to \infty$ for $QQ = ss$, cc, bb.



The cc baryon mass differences are from lattice QCD.
The bb baryon mass differences are from lattice NRQCD.

Data from Brown,Detmold,Meinel,Orginos,PRD90(2014)094507

Stability of $qq'\bar{Q}\bar{Q}$ tetraquarks

For sufficiently heavy Q, there is a strong-interaction stable $qq'\bar{Q}\bar{Q}$ tetraquark.

- Consider decay into two mesons:

$$E(q\bar{Q}) + E(q'\bar{Q}) - E(qq'\bar{Q}\bar{Q}) = \frac{2}{9} m_Q \alpha_s^2 \quad \text{(which is positive)}$$

Therefore this tetraquark cannot decay to two mesons.

Carlson,Heller,Tjon,PRD37(1988)744

- Consider decay into two baryons:

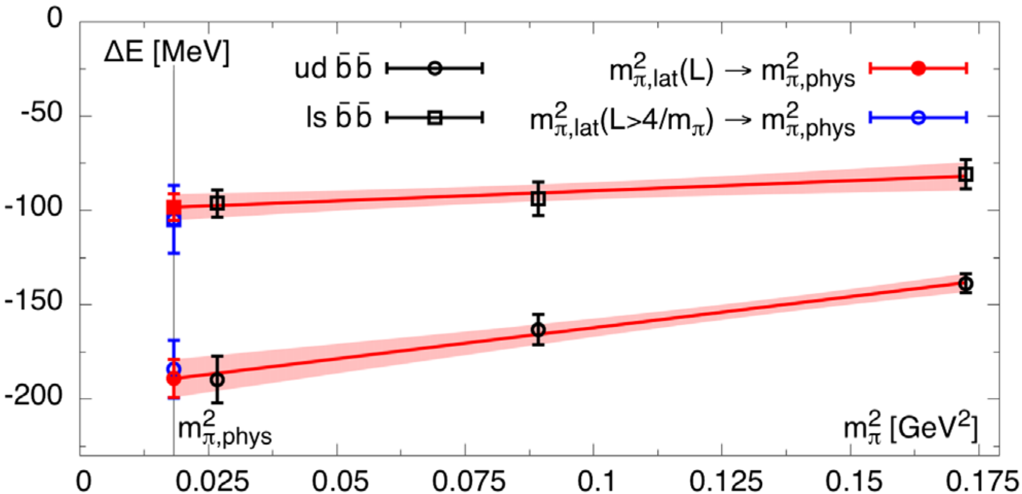
$$\begin{aligned} E(qq'q'') + E(\bar{q}''\bar{Q}\bar{Q}) - E(qq'\bar{Q}\bar{Q}) &= E(qq'q'') + E(\bar{q}''Q) - E(qq'Q) \\ &\geq E(\text{proton}) + E(\bar{q}''Q) - E(qq'Q) \end{aligned}$$

Known masses for charm and bottom confirm that the right-hand side is positive.
Therefore this tetraquark cannot decay into two baryons.

Eichten,Quigg,PRL119(2017)202002

Is the bottom quark sufficiently heavy?...

Lattice results for $ud\bar{b}\bar{b}$ and $\ell s\bar{b}\bar{b}$ tetraquarks

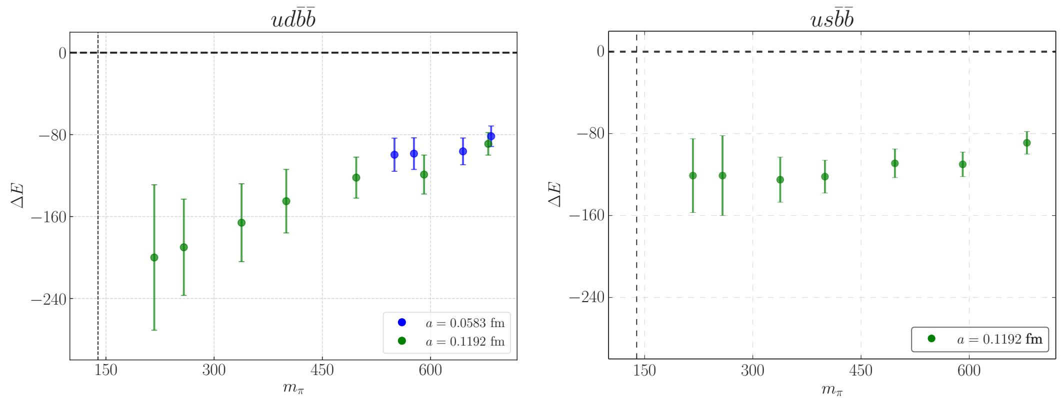


Results are from a correlation matrix of two $I(J^P) = 0(1^+)$ operators:

$$(u_a^T C\gamma_5 d_b)(\bar{b}_a C\gamma_i \bar{b}_b^T) \qquad \text{and} \qquad (\bar{b}_a\gamma_5 u_a)(\bar{b}_b\gamma_i d_b) - (\bar{b}_a\gamma_5 d_a)(\bar{b}_b\gamma_i u_b)$$

Francis,Hudspith,Lewis,Maltman,PRL118(2017)142001

Independent confirmation

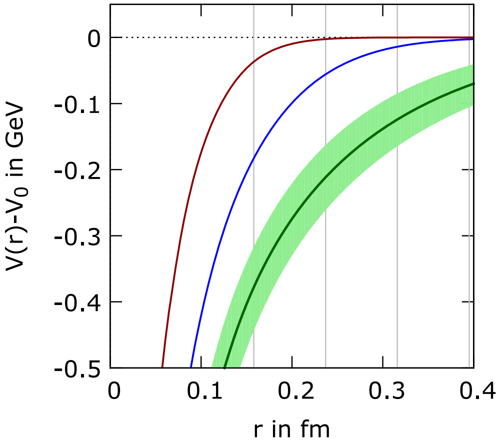


Junnarkar,Padmanath,Mathur,EPJWebConf175(2018)05014

Compared to our study, these authors
- use the same two operators,
- use the same lattice NRQCD action,
- use a different light quark action.
- use a coarser lattice and a finer lattice,
- include some heavier values for m_π.

Lattice QCD and the Born-Oppenheimer approximation

1. Lattice QCD gives the static $\bar{Q}\bar{Q}$ potential, $V(r)$. (2 light quarks are present.)
2. $V(r)$ is fit to a phenomenologically motivated continuous function.
3. Solve the Schrödinger equation with $H_{\bar{b}\bar{b}} = \frac{\boldsymbol{p}^2}{2\mu} + 2m_H + V(r)$.



The resulting binding energy for a $0(1^+)$ $ud\bar{b}\bar{b}$ tetraquark is

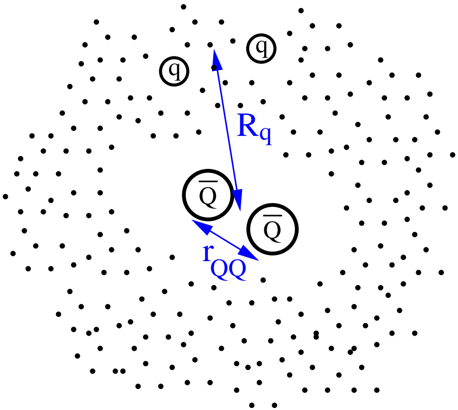
$-90^{+46}_{-42}\,\mathrm{MeV}$ for $m_H = m_B$

$-93^{+47}_{-43}\,\mathrm{MeV}$ for $m_H = m_b$

Others are found to be unbound, including $ss\bar{b}\bar{b}$ and $cc\bar{b}\bar{b}$.

Bicudo,Cichy,Peters,Wagenbach,Wagner,PRD92(2015)014507

A phenomenological picture



The $\bar{Q}\bar{Q}$ acts like a single heavy object.

It is surrounded by light d.o.f of QCD.

$r_{QQ} \sim \frac{1}{M_Q}$ and $R_q \sim \frac{1}{\Lambda_{\text{QCD}}}$

(M_Q is the reduced mass of the pair.)

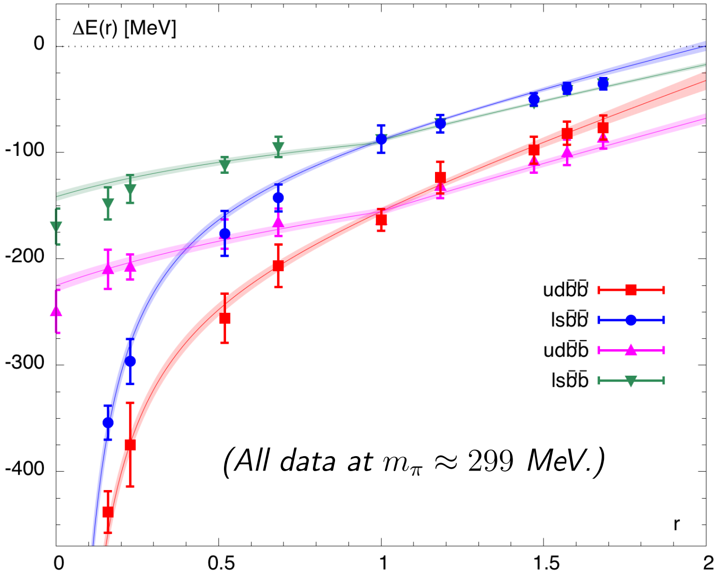
Expand in $\frac{\Lambda_{\text{QCD}}}{M_Q}$. (Recall lattice NRQCD.)

Various models incorporate this idea and find (a) $ud\bar{b}\bar{b}$ is bound,
(b) $ud\bar{c}\bar{c}$ is unbound,
and (c) $ud\bar{c}\bar{b}$ is unbound or barely bound.

Ader,Richard,Taxil,PRD25(1982)2270
Lipkin,PLB172(1986)242
Manohar,Wise,NPB399(1993)17
Karliner,Rosner,PRL119(2017)202001
Eichten,Quigg,PRL119(2017)202002
Czarnecki,Leng,Voloshin,PLB778(2018)233

Lattice study of $\bar{Q}\bar{Q}$ and $\bar{b}\bar{Q}$ tetraquarks

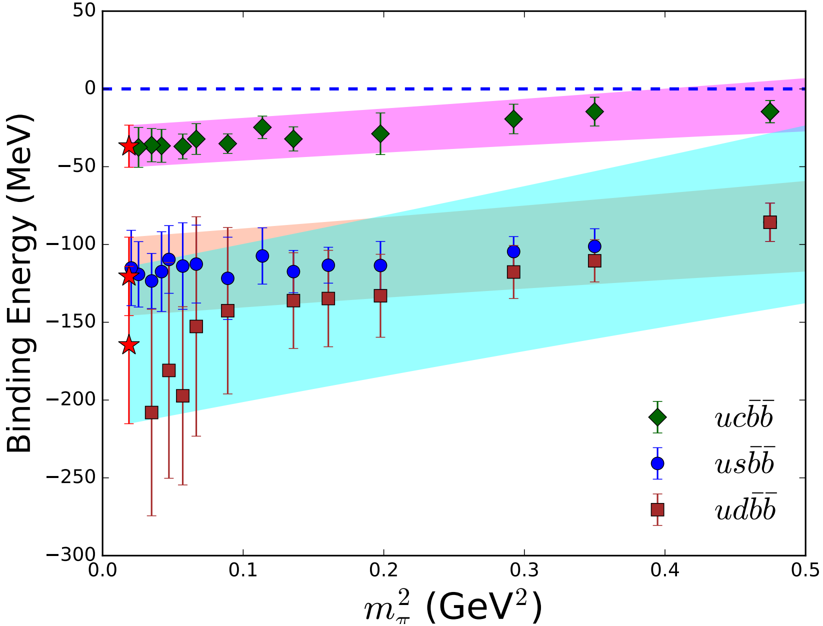
The $\bar{Q}$ mass is varied to see how the tetraquark binding is affected.



$r = \frac{m_b}{m_Q}$

Francis,Hudspith,Lewis,Maltman, work in progress

An exploration of $uc\bar{b}\bar{b}$ (preliminary)

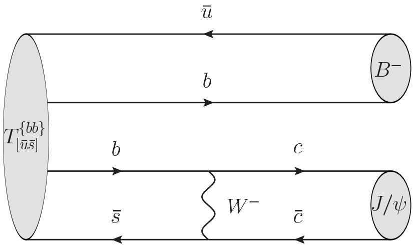


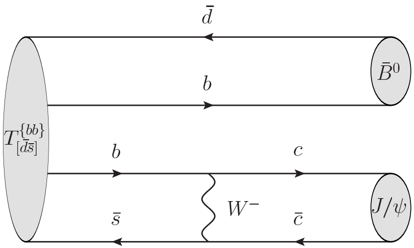
Junnarkar, Padmanath, Mathur, work in progress

Ideas for $\bar{b}\bar{b}$ tetraquark decays

The lifetime of a $ud\bar{b}\bar{b}$ tetraquark is O(half the B meson lifetime) ~ 0.8 ps
because either $\bar{b}$ can decay.

The $\ell s\bar{b}\bar{b}$ tetraquarks have interesting two-body decays:





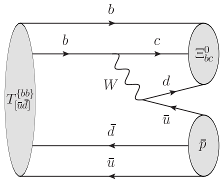
branching fraction: $\mathcal{B} \sim O(10^{-3})$?

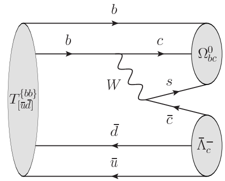
(Similar decays for the $ud\bar{b}\bar{b}$ tetraquark are CKM suppressed by $V_{cd}^2 \approx 0.05$.)

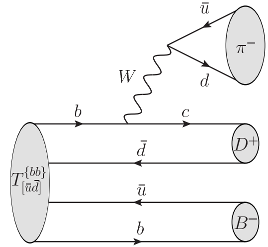
Ali,Parkhomenko,Qin,Wang,arXiv:1805.02535

Some $\bar{b}\bar{b}$ tetraquark decay channels

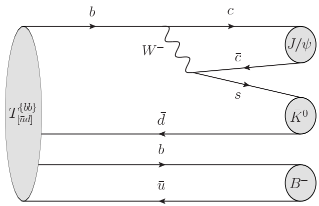
$\mathcal{B} \sim O(10^{-3})$:







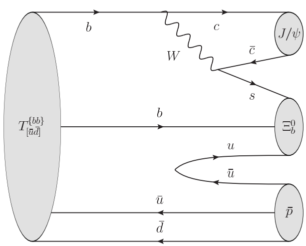
$\mathcal{B} \sim O(10^{-4})$:



Similar diagrams arise from

- interchanging $u \leftrightarrow d$.
- using an s quark.

$\mathcal{B} \sim ???$:



Ali, Parkhomenko, Qin, Wang, arXiv:1805.02535

Excited $\bar{b}\bar{b}$ tetraquark states?

- Compare spin-averaged $I = 1$ and $I = 0$ baryon masses:
$$\begin{aligned}\bar{\Sigma} - \Lambda &= 205 \text{ MeV} \\ \bar{\Sigma}_c - \Lambda_c &= 210 \text{ MeV} \\ \bar{\Sigma}_b - \Lambda_b &= 207 \text{ MeV}\end{aligned}$$

From this, quark-diquark symmetry predicts a similar splitting for tetraquarks.

We already saw lattice evidence for $I = 0$ $ud\bar{b}\bar{b}$ binding near 200 MeV.
Therefore the $I = 1$ $ud\bar{b}\bar{b}$ could be near threshold. Mehen,PRD96(2017)094028

- Notice that distinguishable heavy quarks allow more tetraquark options.
In particular, $ud\bar{c}\bar{b}$ tetraquarks can be $I(J^P) = 0(0^+)$ or $0(1^+)$.

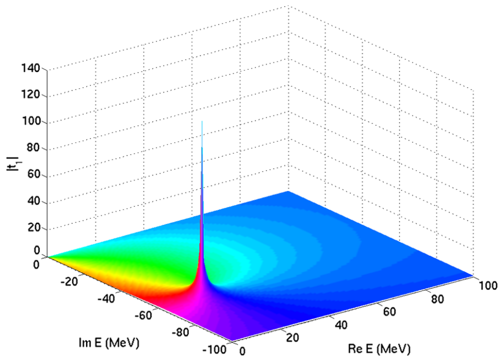
Some predictions put them both near threshold, but there is no consensus yet.

Karliner,Rosner,PRL119(2017)202001
Eichten,Quigg,PRL119(2017)202002
Francis,Hudspith,Lewis,Maltman,EPJWebConf175(2018)05023

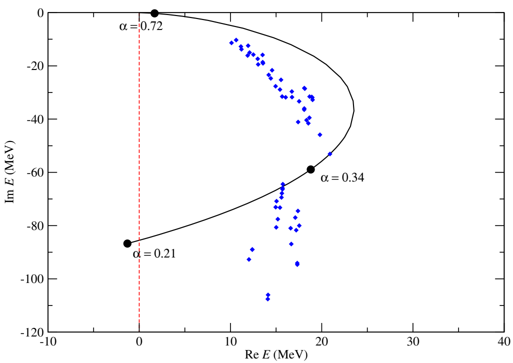
$ud\bar{b}\bar{b}$ tetraquark resonances

$V(r)$ is obtained from lattice QCD and the Born-Oppenheimer approximation.
A resonance appears as a pole on the second Riemann sheet at $m - i\Gamma/2$.

Eigenvalue of the T matrix.



A study of systematic errors.



This resonance has $I(J^P) = 0(1^-)$, $m = 2m_B + 17 \pm 4$ MeV, and $\Gamma = 112^{+90}_{-103}$ MeV.

Bicudo,Cardoso,Peters,Pfaumer,Wagner,PRD96(2017)054510

Summary

To work in QCD directly, use lattice calculations and effective field theories.

- Consistency is observed among various approaches.
- The recent measurement of the Ξ_{cc} mass provides useful input.
- The $I(J^P)$=$0(1^+)$ $ud\bar{b}\bar{b}$ and $\ell s\bar{b}\bar{b}$ tetraquarks decay only weakly.
- Tetraquark excited states and resonances are being studied.
- The possibility of open charmed tetraquarks is also being pursued.

Model approaches have also been used to study open bottom tetraquarks.

- There are too many to describe in this brief presentation.
  For example, see the references in Luo,Chen,Liu,Liu,Zhu,EPJC77(2017)709.
- Here too, the recent measurement of the Ξ_{cc} mass provides useful input.

randy.lewis@yorku.ca