Heavy and light spectroscopy near the physical point, Part II: Tetraquarks

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Motivation

Lattice QCD provides precise calculations of the hadron spectrum.

Building on successes for conventional mesons and baryons, we are exploring a particular tetraquark possibility.

Quark content $qq\bar{Q}\bar{Q}$ avoids two major lattice difficulties:

- It needs no disconnected diagrams.
- A tetraquark would be the lightest state in this channel.

NOTE:

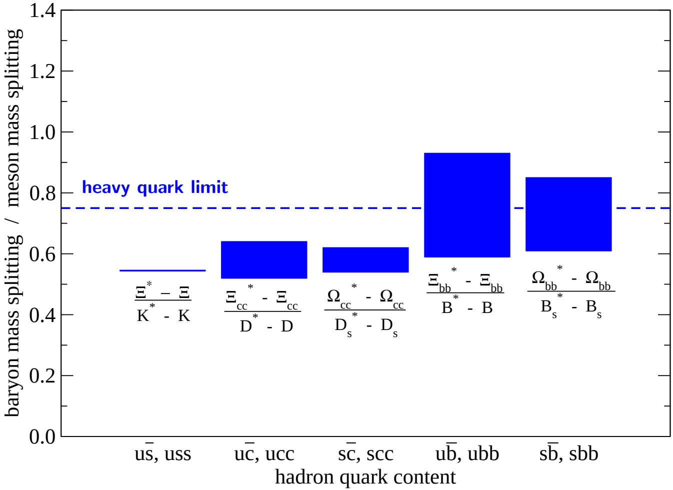
$\bar{Q}\bar{Q}$ can be $\bar{b}\bar{b}, \bar{c}\bar{c}, \bar{b}\bar{c}$ or $\bar{b}\bar{s}$.

qq can be uu, dd, ss, ud, us or ds .

http://arxiv.org/abs/1607.05214

Heavy diquarks are quark-like

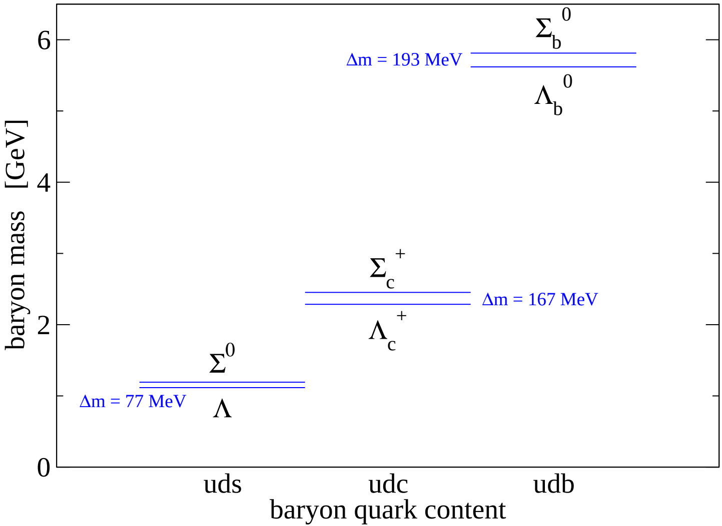
Heavy quark symmetry relates a baryon's QQ to a meson's $\bar{Q}$. This is observed in experiment and lattice data.



Numbers from PDG and Brown,Detmold,Meinel,Orginos,PRD90(2014)094507

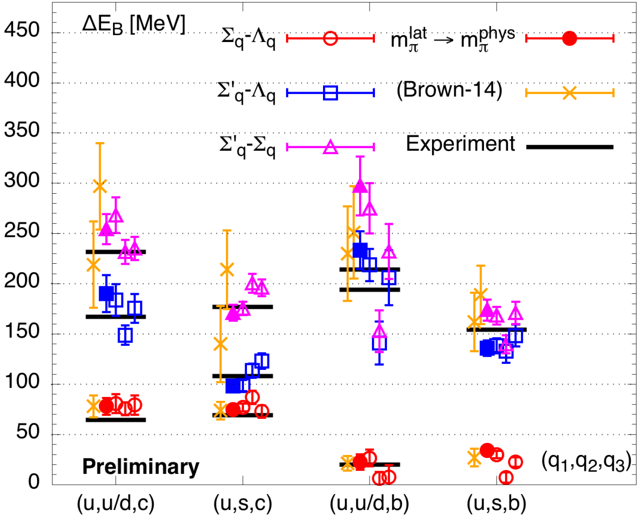
Light diquarks prefer spin zero

The *ud* diquark binds more strongly in spin 0 (Λ) than spin 1 (Σ).



Light diquarks prefer spin zero

The *ud* diquark binds more strongly in spin 0 (Λ) than spin 1 (Σ). $\rightarrow$ also seen in our (incomplete) baryon analysis, previous talk (Hudspith, 14:15).



A diquark-anti diquark operator

For definiteness, begin with quark content $ud\bar{b}\bar{b}$.

The ud portion should be Λ-like, not Σ-like. ud is antisymmetric in both color and flavor:

$$L_a(x) = \epsilon_{abc}(u_b^{\alpha})^T(x)(C\gamma_5)^{\alpha\beta}d_c^{\beta}(x) \ .$$

The $\bar{b}\bar{b}$ portion will be quark-like. To join with ud, it must be color antisymmetric but flavor symmetric:

$$H_a(x) = \epsilon_{ade}\bar{b}_d^{\kappa}(x)(C\gamma_i)^{\kappa\rho}(\bar{b}_e^{\rho})^T(x) \ .$$

The total (diquark-anti diquark) operator is,

$$D(x) = L_a(x)H_a(x) \ .$$

The lightest state will therefore be $\boxed{J^P = 1^+}$.

A meson-meson operator

Again, consider quark content $ud\bar{b}\bar{b}$ with $J^P = 1^+$.

The lightest conventional state would be a meson pair:

$$B(5279) \quad (J^P = 0^-), \quad B^*(5325) \quad (J^P = 1^-) \, .$$

A (meson-meson) operator with definite isospin is,

$$\begin{aligned} M(x) = & \, \bar{b}_a^\alpha(x)\gamma_5^{\alpha\beta} u_a^\beta(x) \; \bar{b}_b^\kappa(x)\gamma_i^{\kappa\rho} d_b^\rho(x) \\ & - \bar{b}_a^\alpha(x)\gamma_5^{\alpha\beta} d_a^\beta(x) \; \bar{b}_b^\kappa(x)\gamma_i^{\kappa\rho} u_b^\rho(x) \, . \end{aligned}$$

It mixes with $D(x)$ but differs in its internal color structure.

Since $D(x)$ and $M(x)$ have the same quantum numbers, they can propagate the same physical states, though the strength of their overlaps will differ.

GEVP analysis

We define the "binding correlator"

$$G_{\mathcal{O}_1\mathcal{O}_2} = \frac{C_{\mathcal{O}_1\mathcal{O}_2}(t)}{C_{PP}(t)C_{VV}(t)} \; .$$

Using a GEVP analysis we have the following matrix,

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

First eigenvalue is the ground state, second contains contaminations, fit to,

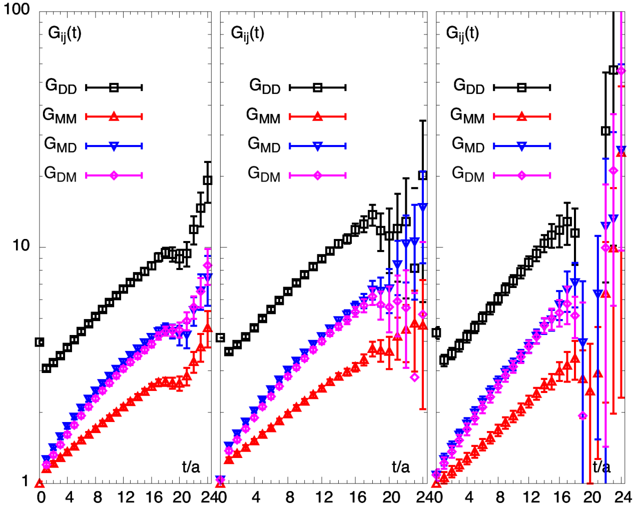
$$\lambda(t) = (1+\delta)e^{-\Delta E(t-t_0)} \; .$$

Lattice Setup

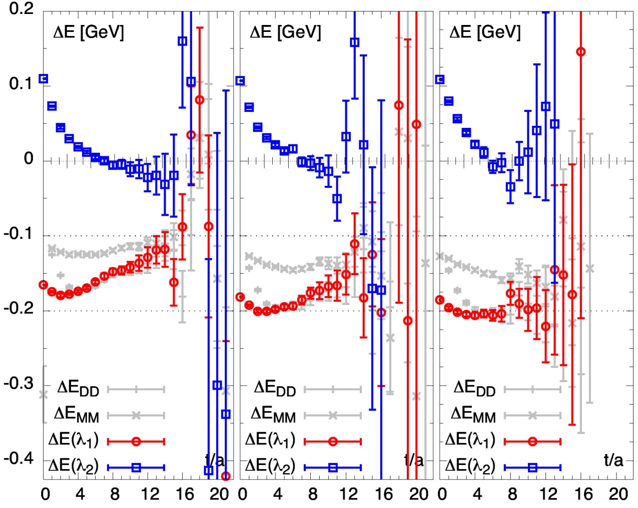
Our lattice setup was explained in the previous talk (Hudspith, 14:15), as reminder:

Basic-Setup	Iwasaki GA	Wilson-Clover FA	CG-wall props
β	1.9	1.9	1.9
c_{SW}	1.715	1.715	1.715
Label	E_H	E_M	E_L
Extent	$32^3 \times 64$	$32^3 \times 64$	$32^3 \times 64$
a^{-1} [GeV]	2.194(10)	2.194(10)	2.194(10)
κ_l	0.13754	0.13770	0.13781
κ_s	0.13666	0.13666	0.13666
am_π	0.18928(36)	0.13618(46)	0.07459(54)
am_K	0.27198(28)	0.25157(30)	0.23288(25)
$m_\pi L$	6.1	4.4	2.4
m_π [MeV]	415	299	164
M_Υ [GeV]	9.528(79)	9.488(71)	9.443(76)
Configurations	400	800	195
Measurements	800	800	3078

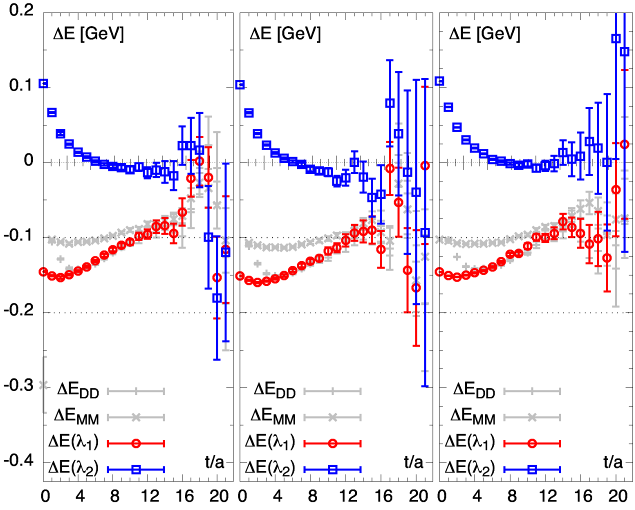
$ud\bar{b}\bar{b}$ tetraquark



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



$\ell s \bar{b} \bar{b}$ tetraquark



Chiral extrapolations and finite volume error

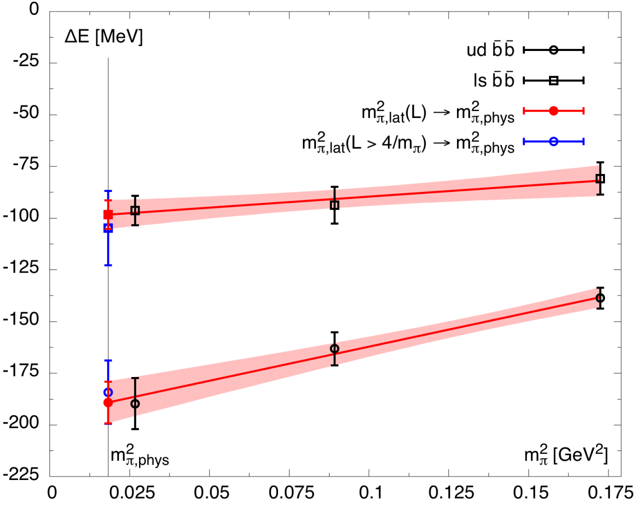


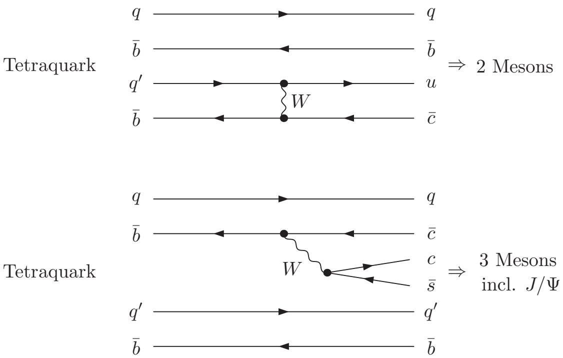
Table of results

Ensemble	$\Delta E_{ud\bar{b}\bar{b}}$ [MeV]	$\Delta E_{\ell s\bar{b}\bar{b}}$ [MeV]
E_H	-139(5)	-81(8)
E_M	-163(8)	-94(9)
E_L	-190(12)	-96(7)
Phys	-189(10)(3)	-98(7)(3)
	$M_{ud\bar{b}\bar{b}}$ [GeV]	$M_{\ell s\bar{b}\bar{b}}$ [GeV]
Predicted Mass	10.415(10)	10.594(8)

Ensemble and extrapolated physical-point (Phys) $ud\bar{b}\bar{b}$ and $\ell s\bar{b}\bar{b}$ binding energies from fitting all ensembles. Errors for the individual ensembles are statistical. For the extrapolated physical point entries, the first error is statistical and the second systematic. We provide a prediction for the physical masses of these states, errors have been added in quadrature.

Experimental search avenues

With such deep binding, both tetraquarks decay only weakly,



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

$$us\bar{b}\bar{b} \to J/\psi B^+ \phi$$
$$\to J/\psi B_s K^+$$

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

- Challenging for experiment, but favorable tags exist!

Summary

$J^P = 1^+$ tetraquark with flavor $qq\bar{Q}\bar{Q}$ is convenient for lattice:

- no disconnected diagrams.
- tetraquark appears as lightest state not as excited state.

This tetraquark has a favorable diquark structure for qq.
The $\bar{Q}\bar{Q}$ is related to known baryons by heavy quark symmetry.

Lattice results show deep binding for $ud\bar{b}\bar{b}$ and $\ell s\bar{b}\bar{b}$ with the first excitation at the two-meson threshold.

- Interpretation as tetraquark state
- Combined chiral-volume analysis shows extrapolation under control
- Binding energies at the physical point are:
  $\Delta E_{ud\bar{b}\bar{b}} = -189(10)(3)$ MeV and $\Delta E_{\ell s\bar{b}\bar{b}} = -98(7)(3)$ MeV

Expected decays: $ud\bar{b}\bar{b}$ and $\ell s\bar{b}\bar{b}$ will decay weakly.

$\ell s\bar{b}\bar{b}$ tetraquark