Disentangling the Tetraquark States

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Outline

- Conventional QCD spectroscopy:
  - B_c system
  - Heavy Baryons: cqq, ccq, bqq, ...
- The zoo of tetraquarks - more to come
- Theory for tetraquarks involving heavy quarks
  - $Q_1 Q_2 \bar{q}_3 \bar{q}_4$
  - $Q_1 \bar{Q}_2 q_3 \bar{q}_4$
- Prospects

Convention QCD spectroscopy

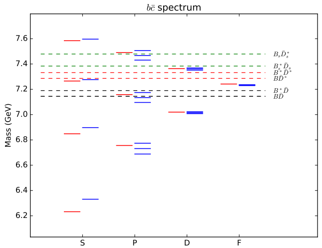
- Only the ground state B_c observed:

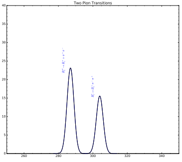
  $$m(B_c) = 6274.9 \pm 0.8 \text{ MeV}$$

  15 very narrow states.

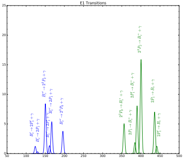
- All excited states below strong decay threshold make transitions $(\gamma, \pi\pi, \pi^0, \eta, ...)$ to the ground state B_c. (Figs LHC 14 TeV)

- Unequal quark masses allows additional tests of spin-orbit forces in QCD.





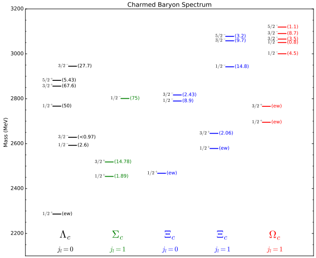
$m - m(B_c) - m(\pi^+) - m(\pi^-)$

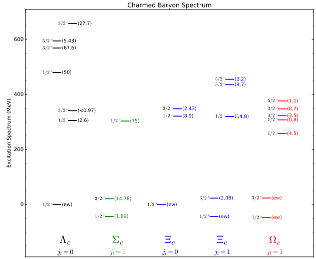


E_γ

Chris Quigg & EE (preliminary)

- Baryons with heavy quarks - Excitation spectrum cqq':
- The systematics of the baryons with one heavy quark is best illustrated by subtracting the ground state energy in each system.
- The discovery of the analogy bqq' systems will add to our understanding of the two light quark dynamics within the baryon
- Baryons with two heavy quarks - new insights into QCD dynamics





Tetraquark Candidate Zoo

PDG Name	Former/Common Name(s)	m (MeV)	Γ (MeV)	$I^G(J^{PC})$	Production	Decay	Discovery Year	Summary Table
$\chi_{c1}(3872)$	$X(3872)$	3871.69±0.17	< 1.2	$0^+(1^{++})$	$B \to KX$ $p\bar{p} \to X...$ $pp \to X...$ $e^+e^- \to \gamma X$	$\pi^+\pi^- J/\psi$ $3\pi J/\psi$ $D^{*0}\overline{D}^0$ $\gamma J/\psi$ $\gamma\psi(2S)$	2003	YES
$Z_c(3900)$		3886.6 ± 2.4	28.2 ± 2.6	$1^+(1^{+-})$	$\psi(4260) \to \pi^- X$ $\psi(4260) \to \pi^0 X$	$\pi^+ J/\psi$ $\pi^0 J/\psi$ $(D\bar{D}^*)^+$ $(D\bar{D}^*)^0$	2013	YES
$X(4020)$	$Z_c(4020)$	4024.1 ± 1.9	13 ± 5	$1^+(?^{?-})$	$\psi(4260, 4360) \to \pi^- X$ $\psi(4260, 4360) \to \pi^0 X$	$\pi^+ h_c$ $\pi^0 h_c$ $(D^*\bar{D}^*)^+$ $(D^*\bar{D}^*)^0$	2013	YES
$Z_b(10610)$		10607.2 ± 2.0	18.4 ± 2.4	$1^+(1^{+-})$	$\Upsilon(10860) \to \pi^- X$ $\Upsilon(10860) \to \pi^0 X$	$\pi^+\Upsilon(1S, 2S, 3S)$ $\pi^0\Upsilon(1S, 2S, 3S)$ $\pi^+ h_b(1P, 2P)$ $(B\bar{B}^*)^+$	2011	YES
$Z_b(10650)$		10652.2 ± 1.5	11.5 ± 2.2	$1^+(1^{+-})$	$\Upsilon(10860) \to \pi^- X$	$\pi^+\Upsilon(1S, 2S, 3S)$ $\pi^+ h_b(1P, 2P)$ $(B^*\bar{B}^*)^+$	2011	YES

PDG Name	Former/Common Name(s)	m (MeV)	Γ (MeV)	$I^G(J^{PC})$	Production	Decay	Discovery Year	Summary Table
$\chi_{c0}(3860)$		3862^{+48}_{-35}	201^{+177}_{-106}	$0^+(0^{++})$	$e^+e^- \to J/\psi X$	$D\overline{D}$	2017	NO
$X(3915)$	$\chi_{c0}(3915)$, $Y(3940)$	3918.4 ± 1.9	20 ± 5	$0^+(0/2^{++})$	$B \to KX$ $e^+e^- \to e^+e^-X$	$\omega J/\psi$	2004	YES
$\chi_{c2}(3930)$	$\chi_{c2}(2P)$, $Z(3930)$	3927.2 ± 2.6	$24{\pm}6$	$0^+(2^{++})$	$e^+e^- \to e^+e^-X$	$D\overline{D}$	2005	YES
$X(3940)$		3942^{+9}_{-8}	37^{+27}_{-17}	$?^?(?^{??})$	$e^+e^- \to J/\psi X$	$D\overline{D}^*$	2007	NO
$X(4050)^{\pm}$	$Z_1(4050)$	4051^{+24}_{-43}	82^{+51}_{-28}	$1^-(?^{?+})$	$B \to KX$	$\pi^+\chi_{c1}(1P)$	2008	NO
$X(4055)^{\pm}$	$Z_c(4055)$	4054 ± 3	45 ± 13	$1^+(?^{?-})$	$e^+e^- \to \pi^- X$	$\pi^+\psi(2S)$	2017	NO
$\chi_{c1}(4140)$	$Y(4140)$	4146.8 ± 2.4	22^{+8}_{-7}	$0^+(1^{++})$	$B^+ \to K^+X$ $e^+e^- \to e^+e^-X$	$\phi J/\psi$	2009	YES
$X(4160)$		4156^{+29}_{-25}	139^{+113}_{-65}	$?^?(?^{??})$	$e^+e^- \to J/\psi X$	$D\overline{D}^*$	2007	NO
$Z_c(4200)$		4196^{+35}_{-32}	370^{+99}_{-149}	$1^+(1^{+-})$	$\bar{B}^0 \to K^-X$	$J/\psi\pi^+$	2014	NO
$\psi(4230)$	$Y(4230)$	4218^{+5}_{-4}	59^{+12}_{-10}	$0^-(1^{--})$	$e^+e^- \to X$	$\omega\chi_{c0}(1P)$ $\pi^+\pi^-\psi(2S)$ $\pi^+\pi^-h_c(1P)$	2015	NO
$R_{c0}(4240)$	$Z_c(4240)$	4239^{+48}_{-21}	220^{+118}_{-88}	$1^+(0^{--})$	$\bar{B}^0 \to K^-X$	$\pi^+\psi(2S)$	2014	NO
$X(4250)^{\pm}$	$Z_2(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$1^-(?^{?+})$	$B \to KX$	$\pi^+\chi_{c1}(1P)$	2008	NO
$\psi(4260)$	$Y(4260)$	4230 ± 8	$55{\pm}19$	$0^-(1^{--})$	$e^+e^- \to X$	$\pi\pi J/\psi$ $\gamma\chi_{c0}(3872)$	2005	YES
$\chi_{c1}(4274)$	$Y(4274)$	4274^{+8}_{-6}	49 ± 12	$0^+(1^{++})$	$B^+ \to K^+X$	$\phi J/\psi$	2011	NO
$X(4350)$		$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0^+(?^{?+})$	$e^+e^- \to e^+e^-X$	$\phi J/\psi$	2009	NO
$\psi(4360)$	$Y(4360)$	4368 ± 13	$96{\pm}7$	$0^-(1^{--})$	$e^+e^- \to X$	$\pi^+\pi^-\psi(2S)$	2007	YES
$\psi(4390)$	$Y(4390)$	$4391.5^{+6.4}_{-6.9}$	$139.5^{+16.2}_{-20.6}$	$0^-(1^{--})$	$e^+e^- \to X$	$\pi^+\pi^-h_c(1P)$	2017	NO
$Z_c(4430)$		4478^{+15}_{-18}	181 ± 31	$1^+(1^{+-})$	$\bar{B}^0 \to K^-X$	$\pi^+\psi(2S)$ π^+J/ψ	2007	YES
$\chi_{c0}(4500)$	$X(4500)$	4506^{+16}_{-19}	92^{+30}_{-29}	$0^+(0^{++})$	$B^+ \to K^+X$	$\phi J/\psi$	2017	NO
$\psi(4660)$	$X(4630)$,$Y(4660)$	$4643{\pm}9$	$72{\pm}11$	$0^-(1^{--})$	$e^+e^- \to X$	$\pi^+\pi^-\psi(2S)$ $\Lambda_c^+\Lambda_c^-$	2007	YES
$\chi_{c0}(4700)$	$X(4700)$	4704^{+17}_{-26}	120^{+52}_{-45}	$0^+(0^{++})$	$B^+ \to K^+X$	$\phi J/\psi$	2017	NO
$\Upsilon(10860)$	$\Upsilon(5S)$	$10889.9^{+3.2}_{-2.6}$	51^{+6}_{-7}	$0^-(1^{--})$	$e^+e^- \to X$	$B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi)$ $\pi\pi\Upsilon(1S,2S,3S)$ $\pi^+\pi^-h_b(1P,2P)$ $\eta\Upsilon(1S,2S)$ $\pi^+\pi^-\Upsilon(1D)$	1985	YES
$\Upsilon(11020)$	$\Upsilon(6S)$	$10992.9^{+10.0}_{-3.1}$	49^{+9}_{-15}	$0^-(1^{--})$	$e^+e^- \to X$	$B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi)$ $\pi\pi\Upsilon(1S,2S,3S)$ $\pi^+\pi^-h_b(1P,2P)$	1985	YES

More tetraquark candidates assured:

- Analogs of the charmonium tetraquark candidates expected for the $b\bar{b}$ system. So far only seen the Z_b^+ states.
  HQS should dictate which states have analogs in any specific model.
- For the $b\bar{c}$ system we will see analogs of the Z_c^+ states for each of the thresholds BD^*, B^*D and B^*D^*.

Levels of stability for tetraquarks

A) Unstable

- Resonance with OZI (Okubo Zweig Iizuka) allowed strong decays.
- Typically large width
- Analog in $Q\bar{Q}$ systems are states above two heavy-light meson threshold
- All presently observed candidates for tetraquarks. [X(3872) ?]

B) Metastable

- Narrow states with strong decays (but none OZI allowed).
- Analog in $Q\bar{Q}$ systems are states below two heavy light meson threshold

C) Stable

- No strong decays.
- Analog in $Q\bar{Q}$ systems is B_c

All the potential tetraquark states observed so far have strong decays.

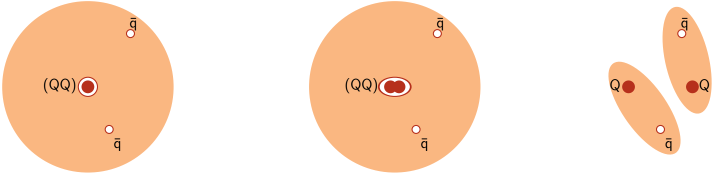
HQS implies stable heavy tetraquark mesons $Q_i Q_j \bar{q}_k \bar{q}_l$

- In the limit of very heavy quarks Q, novel narrow doubly heavy tetraquark states must exist.
- HQS relates the mass of a doubly heavy tetraquark state to combination of the masses of a doubly heavy baryon, a singly heavy baryon and a heavy-light meson.
- The lightest double-beauty states composed of $bb\bar{u}\bar{d}$, $bb\bar{u}\bar{s}$, and $bb\bar{d}\bar{s}$ will be stable against strong decays.
- Heavier $bb\bar{q}_k\bar{q}_l$ states, double-charm states $cc\bar{q}_k\bar{q}_l$, mixed $bc\bar{q}_k\bar{q}_l$ states, will dissociate into pairs of heavy-light mesons.
- Observing a weakly decaying double-beauty state would establish the existence of tetraquarks and illuminate the role of heavy color-antitriplet diquarks as hadron constituents.

EE & Chris Quigg, Phys. Rev. Lett. 119, 202002 (2017)

Systematics of doubly heavy tetraquarks

- Ground states - S waves.
  - $Q_i \bar{Q}_j$ color $(1, 8)$ spin $(0, 1)$ (Quarkonium-like)
  - $\{Q_i Q_j\}$ color $\bar{3}$ spin 1 or color 6 spin 0 (flavor symmetic)
  - $[Q_i Q_j]$ color $\bar{3}$ spin 0 or color 6 spin 1 (flavor antisymmetic)
- $m(Q_i) > \Lambda_{\mathrm{QCD}} > m(q_j)$
- The static energy between the heavy quarks is a $(2x2)$ matrix in color. As the separation, R, is varied:
  - Energy varies.
  - Color admixture varies.



Dynamics

- For small $Q_i - Q_j$ separation the interaction is attractive in the color $\bar{3}$ and repulsive for the color 6.
  - The effective potential for color $\bar{3}$ is given by $\frac{1}{2}V_{Q\bar{Q}}(R)$. (LQCD)
  - In a half-strength Cornell potential, rms core radii are small on tetraquark scale: $\langle r^2\rangle^{1/2} = 0.28$ fm (cc); 0.24 fm (bc); 0.19 fm (bb).
- For large $Q_i - Q_j$ separation the light quarks mostly shield the color and the system rearranges into two heavy-light mesons.
- As $m(Q_i), m(Q_j) \to \infty$ the ground state of $Q_i Q_j \bar{q}_k \bar{q}_l$ has the properties:
  - The two heavy quarks are attracted close together in a color $\bar{3}$
  - The tetraquark state becomes STABLE to decay into two heavy-light mesons.
    (eg. $m(Q_i Q_i \bar{q}_k \bar{q}_k) - 2m(Q_i \bar{q}_k) = \Delta - \frac{1}{2}(\frac{2}{3}\alpha_s)^2 m(Q_i) + O(\frac{1}{m(Q_i)})$ with Δ fixed)

Heavy quark symmetry mass relations

- In the heavy limit, the color of the core $Q_i Q_j$ is $\bar{3}$ the same as a $\bar{Q}_x$. Hence in leading order of $\mathcal{M}^{-1}$ the light degrees of freedom have the same dynamics in the two systems leading to the following mass relations

$$
\begin{aligned}
m(\{Q_i Q_j\}\{\bar{q}_k \bar{q}_l\}) - m(\{Q_i Q_j\} q_y) &= m(Q_x \{q_k q_l\}) - m(Q_x \bar{q}_y) \\
m(\{Q_i Q_j\}[\bar{q}_k \bar{q}_l]) - m(\{Q_i Q_j\} q_y) &= m(Q_x [q_k q_l]) - m(Q_x \bar{q}_y) \\
m([Q_i Q_j]\{\bar{q}_k \bar{q}_l\}) - m([Q_i Q_j] q_y) &= m(Q_x \{q_k q_l\}) - m(Q_x \bar{q}_y) \\
m([Q_i Q_j][\bar{q}_k \bar{q}_l]) - m([Q_i Q_j] q_y) &= m(Q_x [q_k q_l]) - m(Q_x \bar{q}_y) .
\end{aligned}
$$

- Finite mass corrections for all the states in these relations:

$$\delta m = \mathcal{S} \frac{\vec{S} \cdot \vec{j_\ell}}{2\mathcal{M}} + \frac{\mathcal{K}}{2\mathcal{M}}$$

Stability

- Stable against decay to two heavy-light mesons.
- Decay to doubly heavy baryon and light antibaryon?

$$(Q_i Q_j \bar{q}_k \bar{q}_l) \to (Q_i Q_j q_m) + (\bar{q}_k \bar{q}_l \bar{q}_m)$$

  - Starting from the HQS relation
    $$m(Q_i Q_j \bar{q}_k \bar{q}_l) - m(Q_i Q_j q_m) = m(Q_x q_k q_l) - m(Q_x \bar{q}_m)$$
    stability requires
    $$m(Q_x q_k q_l) - m(Q_x \bar{q}_m) < m(q_k q_l q_m)$$
  - $\mathcal{M} \to \infty$ does not systematically improve the stability.
  - $m(Q_x q_k q_l) - m(Q_x \bar{q}_m)$ has form $\Delta_0 + \Delta_1/M_{Q_x}$.
    $m(\Lambda_c) - m(D) = 416.87$ MeV and $m(\Lambda_b) - m(B) = 340.26$ MeV,
    $\Delta_0 \approx 330$ MeV
  - $m(q_k q_l q_m) > 938$ MeV

$$\boxed{\text{As } \overline{M} \to \infty, \text{ stable } Q_i Q_j \bar{q}_k \bar{q}_l \text{ mesons must exist}}$$

Known ground-state hadrons containing heavy quarks

- The spin dependent corrections can be directly calculated from the known mass spectrum.

State	j_ℓ	Mass ($j_\ell + \frac{1}{2}$)	Mass ($j_\ell - \frac{1}{2}$)	Centroid	Spin Splitting	$\mathcal{S}$ [GeV^2]
$D^{(*)}$ $(c\bar{d})$	$\frac{1}{2}$	2010.26	1869.59	1975.09	140.7	0.436
$D_s^{(*)}$ $(c\bar{s})$	$\frac{1}{2}$	2112.1	1968.28	2076.15	143.8	0.446
Λ_c $(cud)_{\bar{\mathbf{3}}}$	0	2286.46	–	–		–
Σ_c $(cud)_{\mathbf{6}}$	1	2518.41	2453.97	2496.93	64.44	0.132
Ξ_c $(cus)_{\bar{\mathbf{3}}}$	0	2467.87	–	–		–
Ξ_c' $(cus)_{\mathbf{6}}$	1	2645.53	2577.4	2622.82	68.13	0.141
Ω_c $(css)_{\mathbf{6}}$	1	2765.9	2695.2	2742.33	70.7	0.146
Ξ_{cc} $(ccu)_{\bar{\mathbf{3}}}$	0	3621.40	–		–	
$B^{(*)}$ $(b\bar{d})$	$\frac{1}{2}$	5324.65	5279.32	5313.32	45.33	0.427
$B_s^{(*)}$ $(b\bar{s})$	$\frac{1}{2}$	5415.4	5366.89	5403.3	48.5	0.459
Λ_b $(bud)_{\bar{\mathbf{3}}}$	0	5619.58	–		–	
Σ_b $(bud)_{\mathbf{6}}$	1	5832.1	5811.3	5825.2	20.8	0.131
Ξ_b $(bds)_{\bar{\mathbf{3}}}$	0	5794.5	–		–	
Ξ_b' $(bds)_{\mathbf{6}}$	1	5955.33	5935.02	5948.56	20.31	0.128
Ω_b $(bss)_{\mathbf{6}}$	1		6046.1			
B_c $(b\bar{c})$	$\frac{1}{2}$	*6329*	6274.9	*6315.4*	*54*	*0.340*

Determining $\mathcal{K}$

$$m = m_0 + \mathcal{S}\frac{\vec{S}\cdot\vec{j}_\ell}{2\mathcal{M}} + \frac{\mathcal{K}}{2\mathcal{M}} + O(\frac{1}{\mathcal{M}^2})$$

- Kinetic-energy shift differs in $Q\bar{q}$ mesons and Qqq baryons.

$$\delta\mathcal{K} \equiv \mathcal{K}_{(ud)} - \mathcal{K}_d$$

- Using known cog mass splittings:

$$\begin{aligned}[m((cud)_{\bar{\mathbf{3}}}) - m(c\bar{d})] - [m((bud)_{\bar{\mathbf{3}}}) - m(b\bar{d})] \\ = \delta\mathcal{K}\left(\frac{1}{2m_c} - \frac{1}{2m_b}\right) = 5.11 \text{ MeV}\end{aligned}$$

yields $\delta\mathcal{K} = 0.0235 \text{ GeV}^2$

($m_c = m(J/\psi)/2$ and $m_b = m(\Upsilon)/2$ used)

Putting it all together

1. The RHS of the HQS relation:

$$m(Q_i Q_j \bar{q}_k \bar{q}_l) - m(Q_i Q_j q_m) = m(Q_x q_k q_l) - m(Q_x \bar{q}_m)$$

   has been determined by data and $\mathcal{K}$ and $\mathcal{S}$ are known.

2. Knowing $\mathcal{K}$ allows determining the kinetic-energy shifts for the double heavy quark systems.

$$m(\{cc\}(\bar{u}\bar{d})) - m(\{cc\}d): \qquad \frac{\delta\mathcal{K}}{4m_c} = 2.80 \text{ MeV}$$

$$m(\{bc\}(\bar{u}\bar{d})) - m(\{bc\}d): \qquad \frac{\delta\mathcal{K}}{2(m_c + m_b)} = 1.87 \text{ MeV}$$

$$m(\{bb\}(\bar{u}\bar{d})) - m(\{bb\}d): \qquad \frac{\delta\mathcal{K}}{4m_b} = 1.24 \text{ MeV}$$

(only slightly larger than isospin-breaking effects we neglected)

Estimating ground-state tetraquark masses

- Decay thresholds
  - Strong decays $(Q_i Q_j \bar{q}_k \bar{q}_l) \not\to (Q_i Q_j q_m) + (\bar{q}_k \bar{q}_l \bar{q}_m)$
  - Must consider decays to a pair of heavy–light mesons case-by-case

- Doubly heavy baryons
  - One doubly heavy baryon observed, Ξ_{cc}

    LHC*b*: $M(\Xi_{cc}^{++}) = 3621.40 \pm 0.78$ MeV
  - At present others must come from model calculations:
    We adopt Karliner & Rosner, *PRD* **90**, 094007 (2014)
  - Future: Experiment or LQCD doubly heavy baryon calculations

Expectations for ground-state tetraquark masses

State	J^P	$m(Q_i Q_j \bar{q}_k \bar{q}_l)$	Decay Channel	$\mathcal{Q}$ [MeV]
$\{cc\}[\bar{u}\bar{d}]$	1^+	3978	$D^+ D^{*0}$ 3876	102
$\{cc\}[\bar{q}_k \bar{s}]$	1^+	4156	$D^+ D_s^{*-}$ 3977	179
$\{cc\}\{\bar{q}_k \bar{q}_l\}$	$0^+, 1^+, 2^+$	4146, 4167, 4210	$D^+ D^0$, $D^+ D^{*0}$ 3734, 3876	412, 292, 476
$[bc][\bar{u}\bar{d}]$	0^+	7229	$B^- D^+ / B^0 D^0$ 7146	83
$[bc][\bar{q}_k \bar{s}]$	0^+	7406	$B_s D$ 7236	170
$[bc]\{\bar{q}_k \bar{q}_l\}$	1^+	7439	$B^* D / B D^*$ 7190/7290	249
$\{bc\}[\bar{u}\bar{d}]$	1^+	7272	$B^* D / B D^*$ 7190/7290	82
$\{bc\}[\bar{q}_k \bar{s}]$	1^+	7445	$D B_s^*$ 7282	163
$\{bc\}\{\bar{q}_k \bar{q}_l\}$	$0^+, 1^+, 2^+$	7461, 7472, 7493	$BD / B^* D$ 7146/7190	317, 282, 349
$\{bb\}[\bar{u}\bar{d}]$	1^+	10482	$B^- \bar{B}^{*0}$ 10603	$\boxed{\mathbf{-121}}$
$\{bb\}[\bar{q}_k \bar{s}]$	1^+	10643	$\bar{B}\bar{B}_s^* / \bar{B}_s \bar{B}^*$ 10695/10691	$\boxed{\mathbf{-48}}$
$\{bb\}\{\bar{q}_k \bar{q}_l\}$	$0^+, 1^+, 2^+$	10674, 10681, 10695	$B^- B^0$, $B^- B^{*0}$ 10559, 10603	115, 78, 136

Comments

- Denote $\mathcal{T}$ for tetraquark states. So $\mathcal{T}^{\{bb\}}_{[\bar{u}\bar{d}]} = \{bb\}[\bar{u}\bar{d}]$.
- No excited states of doubly heavy tetraquark systems will be stable.
- The assumption of the core $Q_i Q_j$ being dominately a color $\bar{3}$, becomes less reliable as we approach the lowest two heavy-light meson threshold.
- Unstable doubly heavy tetraquarks near thresholds might be observable as resonances in wrong sign BB, BD, DD modes. Prime examples:
  - $\mathcal{T}^{\{bb\}}_{\{\bar{q}_k\bar{q}_l\}}(10681)$ $J^P = 1^+$ with $\mathcal{Q} = 78$ MeV
  - $\mathcal{T}^{[bc]}_{[\bar{q}_k\bar{s}]}(7272)$ $J^P = 1^+$ with $\mathcal{Q} = 82$ MeV
  - $\mathcal{T}^{\{bc\}}_{[\bar{u}\bar{d}]}(7229)$ $J^P = 0^+$ with $\mathcal{Q} = 83$ MeV
  - $\mathcal{T}^{\{cc\}}_{[\bar{u}\bar{d}]}(3978)$ $J^P = 1^+$ with $\mathcal{Q} = 102$ MeV
- Karliner & Rosner model results, arXiv:1707.07666.
  $Q(\{bb\}[\bar{u}\bar{d}]) = -215$ MeV

Observing stable tetraquarks

Opportunities at ATLAS, CMS, LHCb. Ideal for a Tera Z^0 factory.

$J^P = 1^+$ $\{bb\}[\bar{u}\bar{d}]$ meson, bound by 121 MeV

(77 MeV below $B^-\bar{B}^0\gamma$)

$$\mathcal{T}^{\{bb\}}_{[\bar{u}\bar{d}]}(10482)^- \to \Xi^0_{bc}\bar{p},\ B^-D^+\pi^-, \text{ and } \underbrace{B^-D^+\ell^-\bar{\nu}}_{\text{weak!}}$$

A study of the observability of these states at the LHC ($\sqrt{s} = 13$ TeV) has recently been carried out.

Ahmed Ali, Qin Qin, Wei Wang [arXiv:1806.09288]

$\sigma(pp \to \mathcal{T}^{\{bb\}}_{[\bar{u}\bar{d}]}) = 2.8^{+1.0}_{-0.7}$ nb

$J^P = 1^+$ $\{bb\}[\bar{u}\bar{s}]$ and $\{bb\}[\bar{d}\bar{s}]$ mesons, bound by 48 MeV

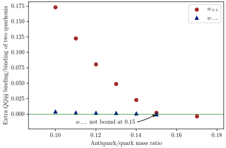
(3 MeV below $BB_s\gamma$)

$$\mathcal{T}^{\{bb\}}_{[\bar{u}\bar{s}]}(10643)^- \to \Xi^0_{bc}\overline{\Sigma}^- \qquad \mathcal{T}^{\{bb\}}_{[\bar{d}\bar{s}]}(10643)^0 \to \Xi^0_{bc}(\bar{\Lambda}, \overline{\Sigma}^0)$$

Other Stable Tetraquarks?

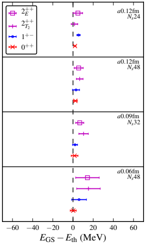
Tetraquarks - $(m(Q) >> \Lambda_{\mathrm{QCD}}) > (m(q) \approx \Lambda_{\mathrm{QCD}})$.

1. $Q_1 Q_1 \bar{Q}_2 \bar{Q}_2$
   $m_1 > m_2 >> \Lambda_{\mathrm{QCD}}$
   QCD - single gluon exchange.
   No stable tetraquarks for
   $m_2/m_1 > 0.152$



A. Czarnecki, B. Long, M. B. Voloshin [arXiv:1708.04594]

2. $bb\bar{b}\bar{b}$ - no stable tetraquarks.
   LQCD calculation
   no states $J^{PC} = 0^{++}, 1^{+-}, 2^{++}$
   below $\eta_b\eta_b$ treshhold.



C.Hughes, E. E. and C. Davies, PRD97 (2018), 054505

3 More general $Q_1 Q_2 \bar{q}_3 \bar{q}_4$

- Direct LQCD approach signal/noise problems.
- Three step approach looks attractive

  M. Pflaumer, el. al. [arXiv:1811.04724]

  and the references therein.

  ★ Construct the static potentials $Q_1 Q_2$ including gluons and light $\bar{q}_3 \bar{q}_4$

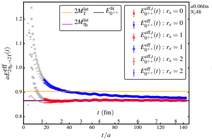
  ★ Solve the resulting SE (matrix)

  $$(-\tfrac{1}{2\mu}\nabla^2 + V_{QQ})\psi(r) = E\psi(r)$$

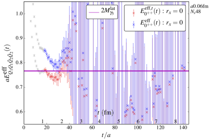
  for the energy levels and two meson scattering phase shifts.

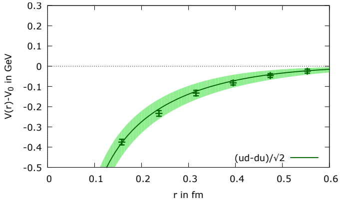
  ★ Include the relativistic corrections for heavy quarks.

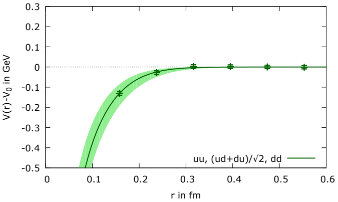
$m_1 = m_2 = m_b$



$m_1 = m_b, m_2 = m_c$

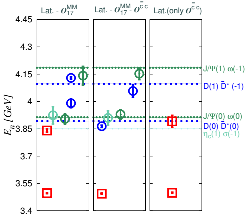




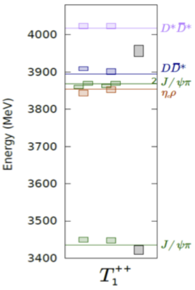


4 $Q_1\bar{Q}_2 q_3\bar{q}_4$

- All the observed tetraquark candidates of this form.
- Heavy quark limit
  $m(Q_1\bar{Q}_2 q_3\bar{q}_4) - m(Q_1\bar{Q}_2) - m(q_3\bar{q}_4) \to O(1)$
  No argument for stable tetraquarks
- LQCD studies of (eg. X(3872), X(3900)) are difficult.



(b) $I = 0: \; \bar{c}c(\bar{u}u + \bar{d}d)$ & $\bar{c}c$



Cheung *et al.* JHEP**1711** 033

- Lattice studies in search of X(3872) candidate assume $D\bar{D}^*$ elastic scattering.
  Prelovsek and Leskovec PRL**111** 192001 '13
  Lee *et al.* 1411.1389
- Admixture of $\bar{c}c$ and $D\bar{D}^*$. Pure molecule unlikely.
  No significant tetraquark Fock component!
  MP *et al.* PRD**92** 034501 '15
- No explanation for $Z_c(3900)^+$ as well.
  Prelovsek *et al.* PRD**91** 014504 '15
- Many systematics unaddressed.
  All are exploratory studies.
- Extensive and systematic investigation by HSC.
  Looking for candidates with tetraquark signatures.
  In isospin 0 and isospin 1 channel of charmonium-like spectrum.
  No conclusive evidence.
  ⇐ Cheung *et al.* JHEP**1711** 033

- Unstable doubly heavy tetraquarks near thresholds might be observable as resonances in wrong sign BB, BD, DD modes. Prime examples:
  - $\mathcal{T}^{\{bb\}}_{\{\bar{q}_k\bar{q}_l\}}(10681)$ $J^P = 1^+$ with $\mathcal{Q} = 78$ MeV
  - $\mathcal{T}^{[bc]}_{[\bar{q}_k\bar{s}]}(7272)$ $J^P = 1^+$ with $\mathcal{Q} = 82$ MeV
  - $\mathcal{T}^{\{bc\}}_{[\bar{u}\bar{d}]}(7229)$ $J^P = 0^+$ with $\mathcal{Q} = 83$ MeV

    $\sigma(pp \to \mathcal{T}^{[bc]}_{[\bar{u}\bar{d}]}) = 103^{+39}_{-25}$ nb [arXiv:1806.09288]
  - $\mathcal{T}^{\{cc\}}_{[\bar{u}\bar{d}]}(3978)$ $J^P = 1^+$ with $\mathcal{Q} = 102$ MeV
- These states are not far about the two meson ground state of these systems (in each channel). It is an ideal place to test the LQCD calculations against experimental observations for tetraquarks.

Summary

1. Much QCD spectroscopy remains to be explored.
   eg. the B_c and heavy baryon excitation spectra.

2. Stable $Q_1 Q_2 \bar{q}_3 \bar{q}_4$ tetraquarks exist.
   $[bb\bar{u}\bar{d}(I=0), bb\bar{u}\bar{s}, bb\bar{d}\bar{s}(I=1/2)](j_{qq}=0)$
   To observe these states high energy and luminosity
   and a dedicated search strategy are required.

3. $Q_1 \bar{Q}_2 q_3 \bar{q}_4$ tetraquarks are likely only metastable or unstable.
   HQS does not predict any stable tetraquarks.
   LQCD methods are being explored
   but quite difficult.