Stable Tetraquarks and their Observation

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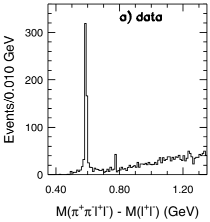
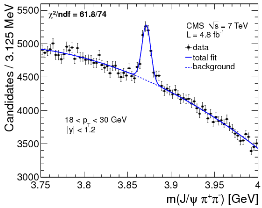
Outline

Renaissance in Hadron Spectroscopy (2003)

- BELLE observed $X(3872)$ in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$.
  PRL 91 (26), 2003
- BABAR



- Direct production observed CDF, DZero
- CMS, ATLAS, LHCb

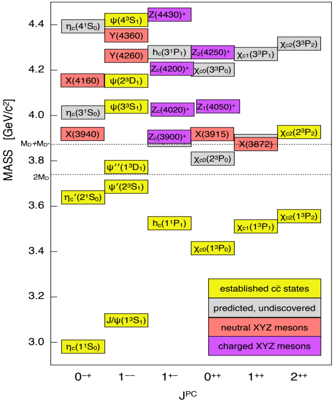


Why was the X(3872) so surprising?

- $J^{PC} = 1^{++}$ suggests it could be the $2^3P_1(c\bar{c})$ charmonium state
- $[m(D^0) + m(\bar{D}^{0*})] - m(X(3872)) \approx 0$ [to O(0.1 MeV)]
- Narrow: $\Gamma < 1.2$ MeV
- Decay $X(3872) \rightarrow J/\psi + \pi + \pi$ is dominated by $J/\psi + \rho$. Large isospin violation.
- $\frac{X(3872) \rightarrow \psi' + \gamma}{X(3872) \rightarrow J/\psi + \gamma} = 2.6 \pm 0.6$

The XYZ states

- $Q\bar{Q}q_i\bar{q}_j$
  - X(3872)
  - $Z_c^{\pm}(3885)$, $Z_c^{\pm}(4025)$, $Z_b^{\pm}(10610)$, $Z_b^{\pm}(10650)$
  - ...
- All these states at or above the associated heavy-light meson pair threshold.



Possible quarkonium-like tetraquark mesons PDG(2017)

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Stat.
$X(3872)$	3871.68 ± 0.17	<1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [51,52] (10.3),	2003	OK
					BaBar [53] (8.6)	2003	OK
				$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [54–56] (np),		
					D0 [57] (5.2)		
				$B \to K\,(\omega J/\psi)$	Belle [58] (4.3),		
					BaBar [59] (4.9)		
				$B \to K\,(D^{*0}\overline{D}^0)$	Belle [60,61] (6.4),		
					BaBar [62] (4.9)		
				$B \to K\,(\gamma J/\psi)$	Belle [63] (4.0),		
					BaBar [64,65] (3.6),		
					LHCb [66] (>10)		
				$B \to K\,(\gamma\psi(2S))$	BaBar [65] (3.5),		
					Belle [63] (0.4),		
					LHCb [66] (4.4)		
				$pp \to (\pi^+\pi^- J/\psi) + ...$	LHCb [67,68,69] (np)		
$Z_c(3900)$	3891.2 ± 3.3	40 ± 8	1^{+-}	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BESIII [70](> 8),	2013	OK
					Belle [71](5.2)	2013	OK
					CLEO [72](>5)		
				$Y(4260) \to \pi^0(\pi^0 J/\psi)$	BESIII [73](10.4)		
					CLEO [72](3.5)		
				$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BESIII [74](18)		
				$Y(4260) \to \pi^0(D\bar{D}^*)^0$	BESIII [75](> 10)		
$X(4020)^\pm$	4022.9 ± 2.8	7.9 ± 3.7	1^{+-}	$Y(4260, 4360) \to \pi^-(\pi^+ h_c)$	BESIII [76](8.9)	2013	NC!
				$Y(4260, 4360) \to \pi^0(\pi^0 h_c)$	BESIII [77](> 5)		
				$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BESIII [78](10)		
				$Y(4260) \to \pi^0(D^*\bar{D}^*)^0$	BESIII [79](5.9)		
$Z_b(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(10860) \to \pi^-(\pi^+\Upsilon(1S, 2S, 3S))$	Belle [80](> 10)		
					Belle [81]	2011	NC!
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [80](16)		
				$\Upsilon(10860) \to \pi^0(\pi^0\Upsilon(1S, 2S, 3S))$	Belle [82](6.5)		
				$\Upsilon(10860) \to \pi^-(B\bar{B}^*)^+$	Belle [83](> 8)		
$Z_b(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(10860) \to \pi^-(\pi^+\Upsilon(1S, 2S, 3S))$	Belle [80](>10)	2011	OK
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [80](16)		
				$\Upsilon(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle [83](6.8)		

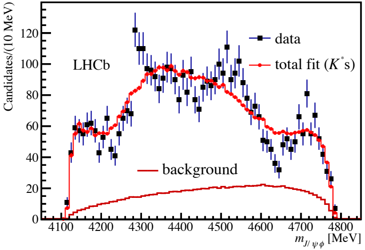
$c\bar{c}$

$b\bar{b}$

More $c\bar{c}q_i\bar{q}_j$ states

$c\bar{c}s\bar{s}$: $X \to J/\psi + \phi$ observed at LHCb

Particle	J^P	Significance	Mass (MeV)	Γ (MeV)	Fit Fraction (%)
X(4140)	1^+	$8.4\,\sigma$	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$13.0 \pm 3.2^{+4.8}_{-2.0}$
X(4274)	1^+	$6.0\,\sigma$	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	$7.1 \pm 2.5^{+3.5}_{-2.4}$
X(4500)	0^+	$6.1\,\sigma$	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$6.6 \pm 2.4^{+3.5}_{-2.3}$
X(4700)	0^+	$5.6\,\sigma$	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$12 \pm 5^{+9}_{-5}$



- Thresholds: $D_s\bar{D}_s^*$ (4081), $D_s^*\bar{D}_s^*$ (4225), $D_s(1P_0)\bar{D}_s(1P_0)(4636)$
- SU(3) symmetry $\to$ $c\bar{c}u\bar{s}$, $c\bar{c}d\bar{s}$ states

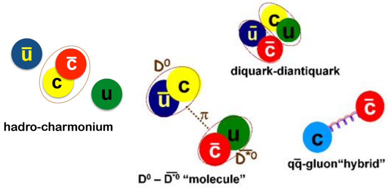
more tetraquarks ?

$c\bar{c}$

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	$0/2^{++}$	$B \to K\,(\omega J/\psi)$	Belle [85] (8.1),	2004	OK
					BaBar [59] (np)	2004	OK
				$e^+e^- \to e^+e^-\omega J/\psi$	Belle [86] (7.7),		
					BaBar [87] (19)		
$\chi_{c2}(3930)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [88] (5.3),		
					BaBar [89]	2005	OK
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\overline{D}^*)$	Belle [90] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\,(...)$	Belle [27] (5.0)		
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-J/\psi)$	Belle [91] (7.4)	2007	NC!
$X(4050)^\pm$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K\,(\pi^+\chi_{c1}(1P))$	Belle [92] (5.0),		
					BaBar [93] (1.1)	2008	NC!
$\chi_{c1}(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [96,97] (5.0)	2009	NC!
					D0 [98] (3.1),		
					CMS [99](>5)		
					Belle [100] (1.9),		
					LHCb [101](1.4),		
					BaBar [102]		
				$e^+e^- \to e^+e^-\,(\phi J/\psi)$	Belle [103] (3.2)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\overline{D}^*)$	Belle [90] (5.5)	2007	NC!
$Z_c(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^+	$\bar{B}^0 \to K^-(J/\psi\pi^+)$	Belle [106] (6.2)	2014	NC!
$X(4250)^\pm$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K\,(\pi^+\chi_{c1}(1P))$	Belle [92] (5.0),		
					BaBar [93] (2.0)	2008	NC!
$\psi(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \to \gamma\,(\pi^+\pi^-J/\psi)$	BaBar [107,108] (8.0)	2005	OK
					CLEO [109] (5.4),		
					Belle [91] (15)		
				$e^+e^- \to (\pi^+\pi^-J/\psi)$	CLEO [110] (11)		
				$e^+e^- \to (\pi^0\pi^0J/\psi)$	CLEO [110] (5.1)		
				$e^+e^- \to (f_0(980)J/\psi)$	BaBar [111](np),		
					Belle [71] (np)		
				$e^+e^- \to (\pi^-Z_c(3900)^+)$	BESIII [70] (8),		
					Belle [71] (5.2)		
				$e^+e^- \to (\gamma\,X(3872))$	BESIII [112] (5.3)		
$\chi_{c1}(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [97](3.1),		
					LHCb [101](1.0),	2011	NC!
					CMS [99](>3),		
					D0 [98](np)		
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(\phi J/\psi)$	Belle [103](3.2)	2009	NC!
$\psi(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma\,(\pi^+\pi^-\psi(2S))$	BaBar [113,114](np),		
					Belle [119,120] (8.0)	2007	OK
$Z_c(4430)$	4458 ± 15	166^{+37}_{-32}	1^+	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [121,122,123] (6.4),		
					BaBar [124] (2.4),	2007	OK
					LHCb [125] (13.9)		
				$\bar{B}^o \to (J/\psi\pi^+)K^-$	Belle [106] (4.0)		
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [126] (8.2)	2007	NC!
$\psi(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma\,(\pi^+\pi^-\psi(2S))$	Belle [119,120] (5.8),		
					BaBar [114] (np)	2007	NC!

QCD dynamics of charmonium-like states

- Many models
  - diquark-diantiquark
  - molecule
  - hadro-charmonium
  - hybrid
  - cusp effect



- Complicated dynamics
- LQCD approaches
- The systematic variation with heavy quark mass may help to distinguish models. $(c\bar{c}), (c\bar{b}), (b\bar{b})$

Some Reviews

- S. L. Olsen, “A New Hadron Spectroscopy,”’ Front. Phys. (Beijing) **10**, 121 (2015) [arXiv:1411.7738].
- R. F. Lebed, R. E. Mitchell, E. S. Swanson, “Heavy-Quark QCD Exotica,” Prog. Part. Nucl. Phys. **93**, 143 (2017) [arXiv:1610.04528].
- A. Esposito, A. Pilloni. A. D. Polosa, “Multiquark Resonances,” Phys. Rept. **668**, 1 (2016) [arXiv:1611.07920].
- A. Ali, J. S. Lange, S. Stone, “Exotics: Heavy Pentaquarks and Tetraquarks,” Prog. Part. Nucl. Phys. **97**, 123 (2017) [arXiv:1706.00610]
- Tetraquark advocate: L. Maiani, “Exotic Hadrons,” CERN *Heavy-hadron Spectroscopy*, July 2017

Consider tetraquarks of the following forms:

- $Q\bar{Q}q\bar{q}$
- $QQ\bar{q}\bar{q}$
- $Q\bar{Q}Q\bar{Q}$

where $Q = (c \text{ or } b)$ and $q = (u, d, \text{ or } s)$

Consider only ground states of given quantum numbers.

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.

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

Here we are only interested in B) and C).

Only stable ordinary mesons:

π, K, D, D_s, D_s^*, B, B_s, B_s^*, B_c, B_c^*

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

Are there any stable tetraquarks?

YES

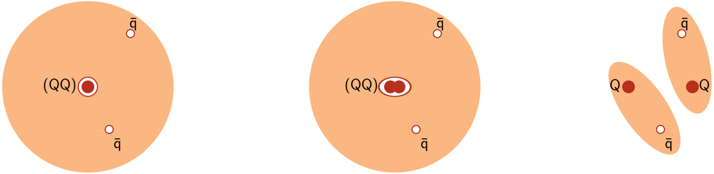
HQS implies stable heavy tetraquark mesons $Q_i Q_j \bar{q}_k \bar{q}_l$

- 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, arXiv:1707.09575

Systematics of doubly heavy tetraquarks

- Ground states - S waves.
  - $Q_i\bar{Q}_j$ color $(1,8)$ spin $(0,1)$ (Quarkonium-like)
  - $\{Q_iQ_j\}$ color $\bar{3}$ spin 1 or color 6 spin 0 (flavor symmetic)
  - $[Q_iQ_j]$ 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 $Q_iQ_j\bar{q}_k\bar{q}_l$ 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. $m(Q_iQ_i\bar{q}_k\bar{q}_k) - 2m(Q_i\bar{q}_k) = \Delta - \frac{1}{2}(\frac{2}{3}\alpha_s)^2 m(Q_i) + O(\frac{1}{m(Q_i)})$ with Δ fixed)

Heavy quark symmetry mass relations

- In the heavy limit, the color of the core Q_iQ_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

$$\begin{aligned}
m(\{Q_iQ_j\}\{\bar{q}_k\bar{q}_l\}) - m(\{Q_iQ_j\}q_y) &= m(Q_x\{q_kq_l\}) - m(Q_x\bar{q}_y) \\
m(\{Q_iQ_j\}[\bar{q}_k\bar{q}_l]) - m(\{Q_iQ_j\}q_y) &= m(Q_x[q_kq_l]) - m(Q_x\bar{q}_y) \\
m([Q_iQ_j]\{\bar{q}_k\bar{q}_l\}) - m([Q_iQ_j]q_y) &= m(Q_x\{q_kq_l\}) - m(Q_x\bar{q}_y) \\
m([Q_iQ_j][\bar{q}_k\bar{q}_l]) - m([Q_iQ_j]q_y) &= m(Q_x[q_kq_l]) - m(Q_x\bar{q}_y) \,.
\end{aligned}$$

- 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)

Expectations for ground-state tetraquark masses

State	J^P	j_ℓ	$m(Q_iQ_jq_m)$	HQS relation	$m(Q_iQ_j\bar{q}_k\bar{q}_l)$	Decay Channel	$\mathcal{Q}$ [MeV]
$\{cc\}[\bar{u}\bar{d}]$	1^+	0	3663	$m(\{cc\}u) + 315$	3978	D^+D^{*0} 3876	102
$\{cc\}[\bar{q}_k\bar{s}]$	1^+	0	3764	$m(\{cc\}s) + 392$	4156	$D^+D_s^{*-}$ 3977	179
$\{cc\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	1	3663	$m(\{cc\}u) + 526$	4146, 4167, 4210	D^+D^0, D^+D^{*0} 3734, 3876	412, 292, 476
$[bc][\bar{u}\bar{d}]$	0^+	0	6914	$m([bc]u) + 315$	7229	B^-D^+/B^0D^0 7146	83
$[bc][\bar{q}_k\bar{s}]$	0^+	0	7010	$m([bc]s) + 392$	7406	B_sD 7236	170
$[bc]\{\bar{q}_k\bar{q}_l\}$	1^+	1	6914	$m([bc]u) + 526$	7439	B^*D/BD^* 7190/7290	249
$\{bc\}[\bar{u}\bar{d}]$	1^+	0	6957	$m(\{bc\}u) + 315$	7272	B^*D/BD^* 7190/7290	82
$\{bc\}[\bar{q}_k\bar{s}]$	1^+	0	7053	$m(\{bc\}s) + 392$	7445	DB_s^* 7282	163
$\{bc\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	1	6957	$m(\{bc\}u) + 526$	7461, 7472, 7493	BD/B^*D 7146/7190	317, 282, 349
$\{bb\}[\bar{u}\bar{d}]$	1^+	0	10176	$m(\{bb\}u) + 306$	10482	$B^-\bar{B}^{*0}$ 10603	$\boxed{-121}$
$\{bb\}[\bar{q}_k\bar{s}]$	1^+	0	10252	$m(\{bb\}s) + 391$	10643	$\bar{B}\bar{B}_s^*/\bar{B}_s\bar{B}^*$ 10695/10691	$\boxed{-48}$
$\{bb\}\{\bar{q}_k\bar{q}_l\}$	$0^+, 1^+, 2^+$	1	10176	$m(\{bb\}u) + 512$	10674, 10681, 10695	B^-B^0, B^-B^{*0} 10559, 10603	115, 78, 136

RHS+all shifts

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	$B D / B^* D$ 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 $B^-\bar{B}^0\gamma$)

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

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

(3 MeV below $BB_s\gamma$)

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

Heavy quark limit for other systems

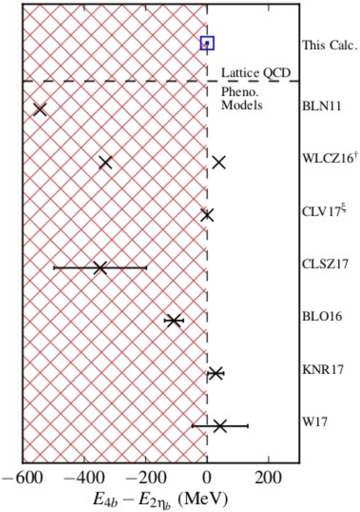
Likely no other stable states in the heavy-quark limit (or for $Q = c, b$)

- $Q_i \bar{Q}_j q_k \bar{q}_l$
  - By a similar argument as applied to $Q_i Q_j \bar{q}_k \bar{q}_l$
    Can't decay to a pair of heavy flavor hadrons.
  - Stability would requires $m(Q_i \bar{Q}_j q_k \bar{q}_l) < m(Q_i \bar{Q}_j) + m(q_k \bar{q}_l)$.
    No argument.
- $Q_i Q_j \bar{Q}_k \bar{q}_l$. Same as above.
- $Q_i q_k \bar{q}_l \bar{q}_n$
  - Stability would requires $m(Q_i q_j \bar{q}_k \bar{q}_l) < m(Q_i \bar{q}_k) + m(q_j \bar{q}_l)$.
    No argument.

Possible Tetraquarks with Four Heavy Quarks

- Many phenomenological models predicted that the ground state with four heavy quarks could be metastable.
- All expect that the $bb\bar{b}\bar{b}$ with $J^{PC} = 0^{++}$ is the most likely to be stable (i.e. below threshold for decay into $\eta_b\eta_b$)
- Recent LQCD calculations do not confirm these expectations.

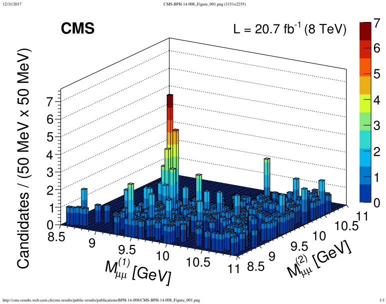
  C. Hughes, EE & C. Davies, arXiv:1710.03236



Upsilon Pair Production

- CMS 2Υ production
  - $\sigma_{fid} = 68.8 \pm 12.7(stat) \pm 7.4(syst) \pm 2.8(BR)pb$
  - Fraction of DPS $\approx 30\%$
- Encouraging for observation of possible $bb\bar{b}\bar{b}$ tetraquarks as well as bbq baryons and $bb\bar{q}\bar{q}'$ tetraquarks.

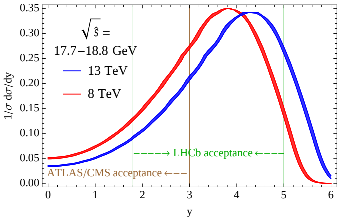
[arXiv:1610.07095]



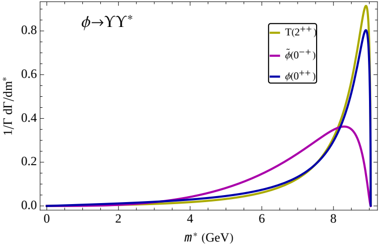
Observing a $\phi = bb\bar{b}\bar{b}$ tetraquark ground state at the LHC

Zhen Liu & EE, arXiv:1709.09605

- Production ϕ with $J^{PC} = O^{++}$ via gluon fusion
- Peaked forward in rapidity.
  - Assume VMD
  - $\Delta\mathcal{L} = \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}\Lambda\phi\Upsilon^\mu\Upsilon_\mu + \ldots$
  - $\sigma(pp \to \phi \to 4\ell) \sim$
    - $3\left(\frac{\Lambda}{0.2\ \mathrm{GeV}}\right)^2$ fb for 8 TeV
    - $5\left(\frac{\Lambda}{0.2\ \mathrm{GeV}}\right)^2$ fb for 13 TeV



- Invariant mass distribution for $m(\phi) = 18.5$ GeV: $\phi \to \Upsilon\Upsilon^* \to l^+l^-l^+l^-$



Observing a $\phi = bb\bar{b}\bar{b}$ tetraquark ground state at the LHC

Compare cross section $H \to ZZ^* \to l^+l^-l^+l^-$.

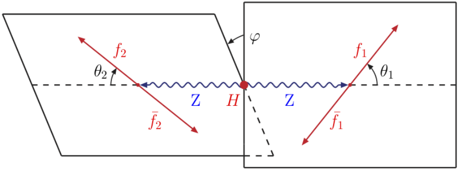
$$\frac{d\Gamma_H}{d\cos\theta_1 d\cos\theta_2} \sim \sin^2\theta_1 \sin^2\theta_2 + \frac{1}{2\gamma_1^2\gamma_2^2(1+\beta_1\beta_2)^2}\left[(1+\cos^2\theta_1)(1+\cos^2\theta_2) + 4\,\eta_1\eta_2\,\cos\theta_1\cos\theta_2\right] \tag{21}$$

and

$$\frac{d\Gamma_H}{d\varphi} \sim 1 - \eta_1\eta_2\frac{1}{2}\left(\frac{3\pi}{4}\right)^2 \frac{\gamma_1\gamma_2(1+\beta_1\beta_2)}{\gamma_1^2\gamma_2^2(1+\beta_1\beta_2)^2+2}\cos\varphi + \frac{1}{2}\frac{1}{\gamma_1^2\gamma_2^2(1+\beta_1\beta_2)^2+2}\cos 2\varphi \tag{22}$$

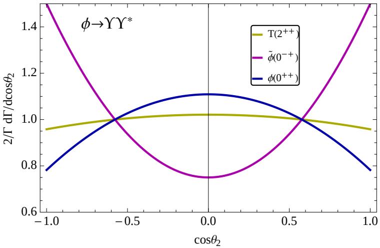
S.Choi, D. Miller, M. Muhlleitner, &P. Zerwas, [arXiv:hep-ph/0210066]

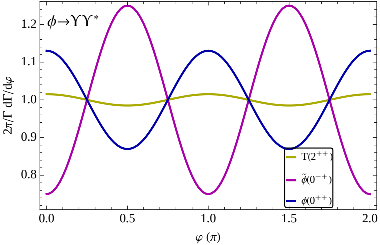
ϕ decays to $4l$ has only the vector contribution ($\eta_i = 0$).



Observing a $\phi = bb\bar{b}\bar{b}$ tetraquark ground state at the LHC

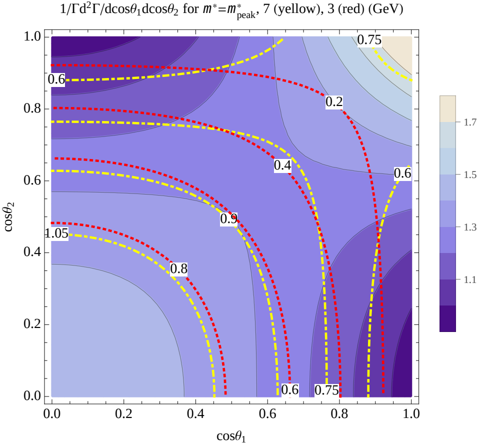
- Expected angular distributions: $\phi \to \Upsilon\Upsilon^{(*)} \to l^+l^-l^+l^-$
  - Can determine J^{PC} from the angular distributions





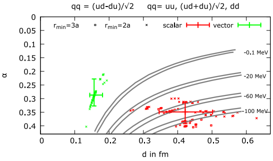
Observing a $\phi = bb\bar{b}\bar{b}$ tetraquark ground state at the LHC

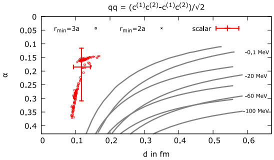
Double differential angular distributions of the tetraquark state $\phi(0^{++})$ for different values of the off-shell Υ^* dilepton invariant masses.



Generalizing results for (meta)stable tetraquark states

- All heavy quarks implies perturbative QCD applies:
  $\{Q_i Q_j\}[\bar{Q}_k \bar{Q}_l]$, $\{Q_i Q_j\}\{\bar{Q}_k \bar{Q}_l\}$, $[Q_i Q_j][\bar{Q}_k \bar{Q}_l]$, $[Q_i Q_j]\{\bar{Q}_k \bar{Q}_l\}$ with
  $m(Q_i) = m(Q_j) = M_1 \geq m(Q_k) = m(Q_l) = M_2 >> \Lambda_{\mathrm{QCD}}$
  A. Czarnecki, B. Leng & M. Voloshin model results, arXiv:1708.04595
  One state (w_{++}) bound for $M_2/M_1 < 0.152$
- $bb\bar{b}\bar{b}$ not bound.
  C. Hughes, E. E., & C. Davies LQCD calculation arXiv:1710.03236
- Can one map out the general region of stability using LQCD?
  Calculate the static energy of the heavier quarks and then use the SE.
  P. Bicudo, K. Cichy, A. Peters, B. Wagenbach &M. Wagner PRD.92.014507
  Fitted $V(r) = -\frac{\alpha}{r}\exp\left(-(\frac{r}{d})^p\right) + V_0$ (with $p = 1.5\ldots2$)





Summary

- 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.
- Other stable or metastable tetraquark states may exist (e.g. $bb\bar{b}\bar{b}$) that aren't guaranteed by the heavy quark limit.