Theoretical Overview of XYZ States

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2^{nd} International Workshop on
High Intensity Electron-Positron Accelerator (HIEPA) in China
Yangihu Campus UCAS

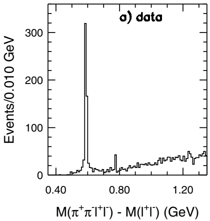
Beijing, China · 18-21 March, 2018

Outline

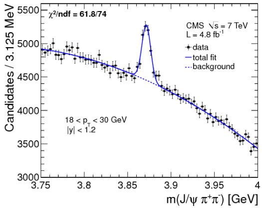
1. Renaissance in Quarkonium Spectroscopy
2. QCD in its Full Form - The XYZ states
   - Tetraquarks
   - Thresholds - Molecules and Cusps
   - Hybrids
3. Summary

Renaissance in Hadron Spectroscopy (2003)

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

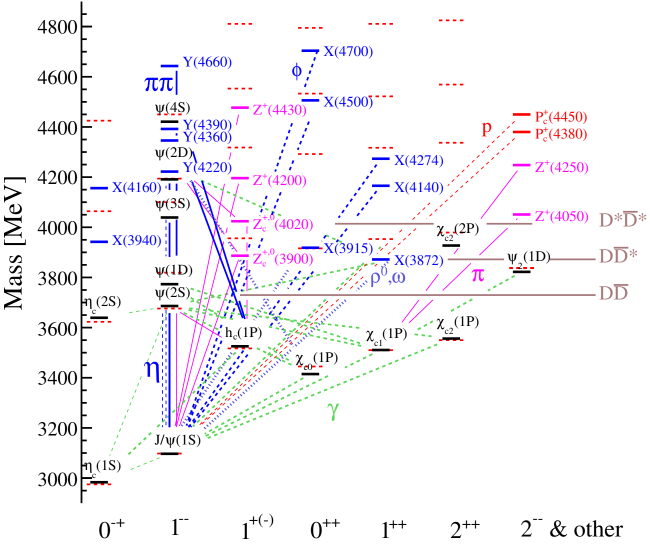


- Direct production observed CDF, DZero
- CMS, ATLAS, LHCb



XYZ States Today

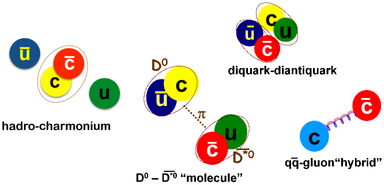
$c\bar{c}$



S. L. Olsen, T. Skwarnicki, D. Zieminska, Reviews of Modern Physics **90**, 1 (2018)

QCD dynamics - XYZ states

- For heavy quark-antiquark ($Q\bar{Q}$) systems the QCD effects of gluon excitations and light quark pairs become manifest above ($Q\bar{q} + q\bar{Q}$) threshold.
- Theoretical tools
  - Heavy Quark Symmetry (HQS)
  - Lattice QCD
- Model approaches:
  - tetraquark states with various dynamic models
  - molecules and cusp effects
  - hybrid states - excited gluonic degrees of freedom



Recent Reviews (Models)

- Tetraquark advocate: L. Maiani, “Exotic Hadrons,” CERN *Heavy-hadron Spectroscopy,* July 2017
- 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]
- R. F. Lebed, R. E. Mitchell, E. S. Swanson, “Heavy-Quark QCD Exotica,” Prog. Part. Nucl. Phys. **93**, 143 (2017) [arXiv:1610.04528].
- S. L. Olsen, T. Skwarnicki, D. Zieminska, "Nonstandard heavy mesons and baryons: Experimental evidence,” Reviews of Modern Physics **90**, 1 (2018)

Tetraquarks

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

- All the presumed tetraquark states observed so far have strong decays.
- Only stable ordinary mesons: π, K, D, D_s, D_s^*, B, B_s, B_s^*, B_c, B_c^*
- Are there any stable tetraquarks?

YES

Levels of stability for tetraquarks

A) Unstable
- Resonance with OZI allowed strong decays.
- Typically large width
- Analog in $Q\bar{Q}$ systems are states above two heavy light meson threshold

B) Metastable
- Narrow states with strong decays (but none OZI allowed).
- Analog in $Q\bar{Q}$ systems: states below heavy-light pair threshold

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

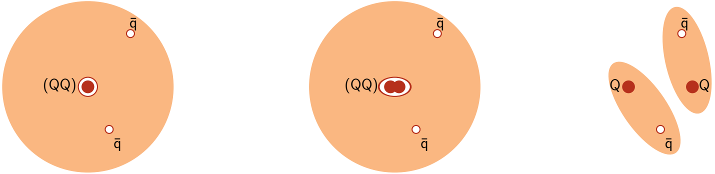
HQS implies stable heavy tetraquark mesons $Q_iQ_j\bar{q}_k\bar{q}_l$

- 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)
  - $\{Q_i Q_j\}$ 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

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

- 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

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

Estimating ground-state tetraquark masses

- Finite mass corrections
  - Use the splittings in observed heavy-light mesons and baryons to obtain the coefficients of the $1/\mathcal{M}$ corrections
- 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

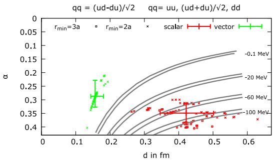
Expectations for ground-state tetraquark masses

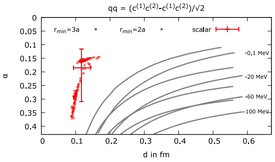
State	J^P	$m(Q_i Q_j \bar{q}_k \bar{q}_l)$	Decay Channel	$\mathcal{Q}$ [MeV]
$\{cc\}[\bar{u}\bar{d}]$	1^+	3978	$D^+ D^{*0}$ 3876	102
$\{cc\}[\bar{q}_k \bar{s}]$	1^+	4156	$D^+ D_s^{*-}$ 3977	179
$\{cc\}\{\bar{q}_k \bar{q}_l\}$	$0^+, 1^+, 2^+$	4146, 4167, 4210	$D^+ D^0$, $D^+ \bar{D}^{*0}$ 3734, 3876	412, 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	$B^* D / BD^*$ 7190/7290	249
$\{bc\}[\bar{u}\bar{d}]$	1^+	7272	$B^* D / BD^*$ 7190/7290	82
$\{bc\}[\bar{q}_k \bar{s}]$	1^+	7445	DB_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	**−121**
$\{bb\}[\bar{q}_k \bar{s}]$	1^+	10643	$\bar{B}\bar{B}_s^* / \bar{B}_s \bar{B}^*$ 10695/10691	**−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

- 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
- Karliner & Rosner model results, arXiv:1707.07666.
  $Q(\{bb\}[\bar{u}\bar{d}]) = -215$ MeV

Generalizing results for (meta)stable tetraquark states

- All heavy quarks implies perturbative QCD applies:
  $\{Q_iQ_j\}[\bar{Q}_k\bar{Q}_l]$, $\{Q_iQ_j\}\{\bar{Q}_k\bar{Q}_l\}$, $[Q_iQ_j][\bar{Q}_k\bar{Q}_l]$, $[Q_iQ_j]\{\bar{Q}_k\bar{Q}_l\}$ with
  $m(Q_i) = m(Q_j) = M_1 \geq m(Q_k) = m(Q_l) = M_2 >> \Lambda_{\rm QCD}$
  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 $p = 1.5...2$)





Implication for $Q_i\bar{Q}_j q_k\bar{q}_l$ systems

Ground states - S waves.

- $Q_i\bar{Q}_j$ color $(1,8)$ spin $(0,1)$ (Quarkonium-like)

By a similar argument as above applied to $Q_i Q_j \bar{q}_k \bar{q}_l$

- For small $Q_i - \bar{Q}_j$ separation the interaction is attractive in the color 1 and repulsive for the color 8.
- The effective potential for color 1 is given by $V_{Q\bar{Q}}(R)$. (LQCD)
- In a full-strength Cornell potential, rms core radii are small on tetraquark scale: $\langle r^2\rangle^{1/2} = 0.24\ \text{fm}\,(cc); 0.21\ \text{fm}\,(bc); 0.14\ \text{fm}\,(bb)$.
- For large $Q_i - \bar{Q}_j$ separation the light quarks mostly shield the color and the system rearranges into two heavy-light mesons.

Implication for $Q_i\bar{Q}_j q_k \bar{q}_l$ systems

As $m(Q_i), m(Q_j) \to \infty$ the ground state of $Q_i\bar{Q}_j q_k \bar{q}_l$ has the properties:

- The heavy-antiquark quarks are attracted close together in a color $\bar{1}$
- The tetraquark state becomes stable against decay into two heavy-light mesons.
  (eg. $m(Q_{ii} q_k \bar{q}_k) - 2m(Q_i \bar{q}_k) = \Delta - (\frac{2}{3}\alpha_s)^2 m(Q_i) + O(\frac{1}{m(Q_i)})$ with Δ fixed)
- But 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 FOR STABILITY.

Hence:

- A $c\bar{c}$ tetraquark resonance would have a corresponding state in the $b\bar{b}$ system significantly lower (relative to the associated heavy-light threshold.)

Threshold States

Why was the X(3872) so surprising?

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

After 15 years aspects of the X(3872)
are still not fully understood

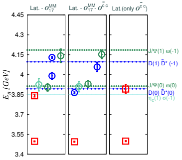
$c\bar{c}$ States (LQCD)

- Study elastic scattering using Luscher's LQCD finite size method.

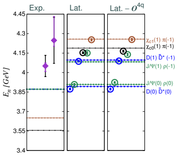
  Nucl. Phys B **339 (1990) 222**

- Padmanath, Lang and Prelovesek find:
  - A pole appears just below threshold in the $J^{PC} = 1^{++}$ $I = 0$ channel
  - But requires both the $(c\bar{c})$ and the $D\bar{D}^*$ components
  - Suggests there is a significant $(c\bar{c})$ component of the X(3872)
  - No pole observed in the $I = 1$ channel or the $I = 0$ $(D_s\bar{D}_s^*)$ channels

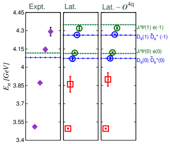
- Promising future method



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



(b) $I = 1$: $\bar{c}c\bar{u}d$



(c) $I = 0$: $\bar{c}c\bar{s}s$ & $\bar{c}c$

M. Padmanath, C.B. Lang, S.Prelovsek
Phys. Rev. D92 (2015) 034501

XYZ States and the $2^3P_J(c\bar{c})$ States

- The $\chi_{c2}(2P)$ has $I^G(J^{PC}) = 0^+(2^{++})$

  $M = 3927.2 \pm 2.6$ and $\Gamma = 24 \pm 6$ (MeV)

- Possible $\chi_{c0}(2P)$ seen in $J/\psi D\bar{D}$

  $M = 3862^{+26}_{-32}{}^{+40}_{-13}$ and $\Gamma = 201^{+154}_{-67}{}^{+88}_{-22}$ (MeV)

  K. Chilikin, el al. (Belle Collaboration), [arXiv:1704.01872]

- Supports the charmonium view that the $X(3872)$ has a large $\chi_c1(2P)$ component.
- What about the X(3915)?
- Count states. Dynamics is complicate. No simple model is adequate.
  - Possible true tetraquark states
  - Many thresholds in e^+e^- opening in region below 4.0 GeV [total 8]
    - ★ $D^0\bar{D}^0$, $(D^0\bar{D}^{0*} + D^{0*}\bar{D}^0)$,

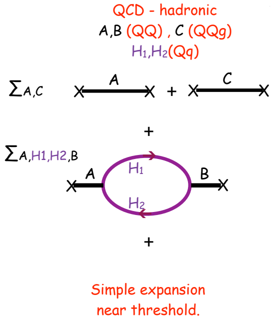
      D^+D^-, $(D^\pm D^{\mp *} + D^{\pm *}D^\mp)$,

      $D_s\bar{D}_s$, $(D_s\bar{D}_s^* + D_s^*\bar{D}_s)$

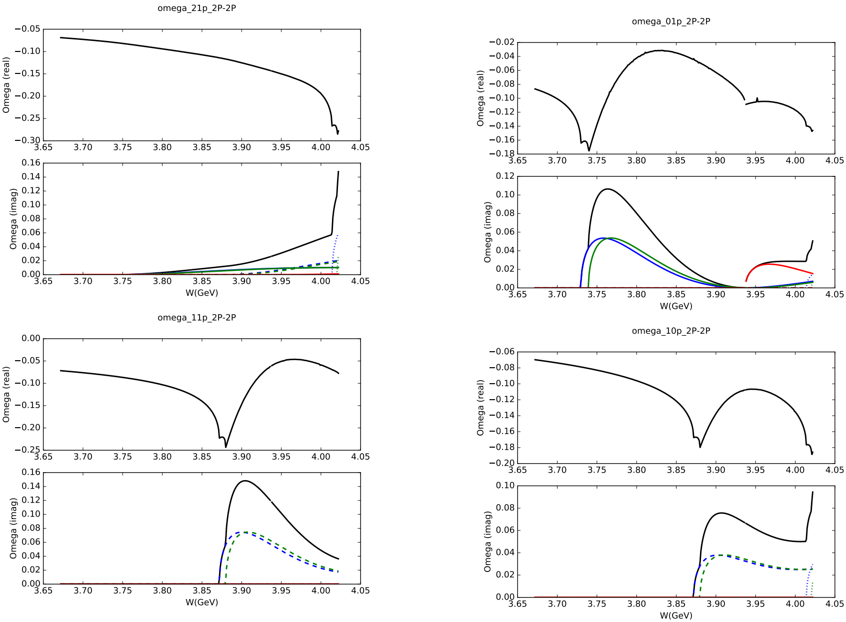
      solid dashed

State	EFG		DLGZ		BGS		LQCD	
2^3P_2	3949	3927	3937	3927	3979	3927	4048	3927
2^1P_1	3926	3904	3916	3906	3956	3904	4024	3904
2^3P_1	3906	3884	3914	3904	3953	3901	4021	3900
2^3P_0	3870	3848	3848	3838	3916	3864	3972	3881

Sample calculations of 2P states: (EFG [1111.0454], DLGZ [1609.00287], BGS[hep-ph/0505002] and LQCD[1610.01073])



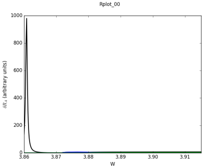
$2P(c\bar{c})$ Shifts :$\Omega(W)$

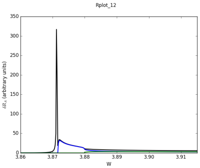


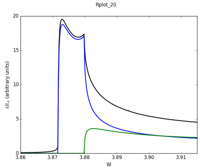
X(3872)

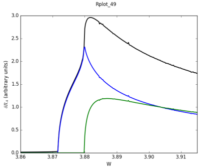
$$R_A = Im([W - M - \Omega(W)]^{-1})$$

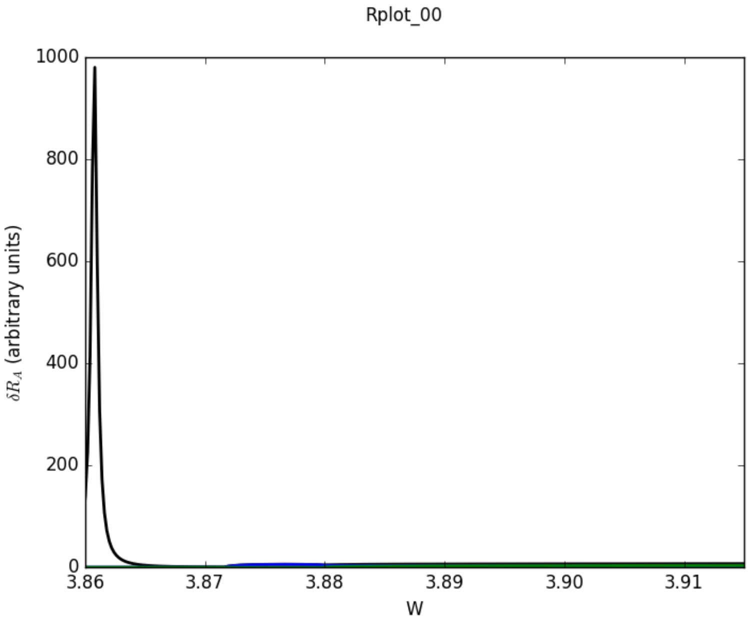
- Add a small intrinsic decay width (1 MeV) for non-OZI decays
- Vary the bare mass M in 50 steps of 5 MeV/step.
- First step has pole below threshold (3.8618 GeV).










Rplot_00
1000
800
600
400
200
0
δR_A (arbitrary units)
3.86
3.87
3.88
3.89
3.90
3.91
W

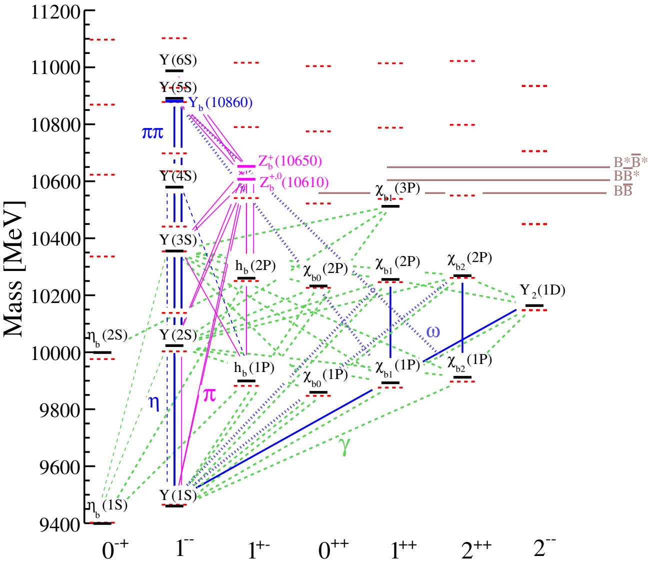
Expectations for the $X_b(10,604)$: If $X_c(3872)$ is a molecular state:

- State at threshold as in $c\bar{c}$
- $I = 0$

If $X_c(3872)$ is only associated with the nearby 2^3P_1 and free heavy-light loops:

- The 2^3P_1 is more than 70 MeV below threshold.
- No state will be observed at BB^* threshold

$b\bar{b}$



S. L. Olsen, T. Skwarnicki, D. Zieminska, Reviews of Modern Physics **90**, 1 (2018)

Charged States

$Z_b^\pm(10610), Z_b^\pm(10650) \quad I^G(J^P) = 1^-(1^+)$

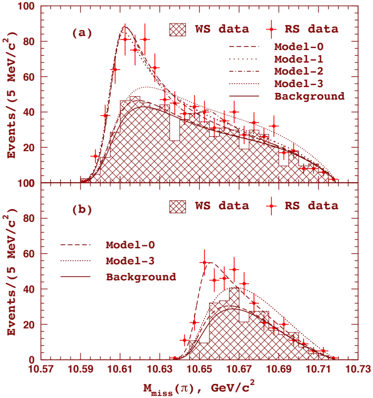
- $Z_b^\pm(10610)$: $M = 10607.2 \pm 2.0, \Gamma = 18.4 \pm 2.4$

Channel	BR(%)
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$82.6 \pm 2.9 \pm 2.3$
$\Upsilon(1S)\pi^+$	$0.60 \pm 0.17 \pm 0.07$
$\Upsilon(2S)\pi^+$	$4.05 \pm 0.81 \pm 0.58$
$\Upsilon(3S)\pi^+$	$2.40 \pm 0.58 \pm 0.36$
$h_b(1P)\pi^+$	$4.26 \pm 1.28 \pm 1.10$
$h_b(2P)\pi^+$	$6.08 \pm 2.15 \pm 1.63$

- $Z_b^\pm(10650)$: $M = 10652.2 \pm 1.5, \Gamma = 11.5 \pm 2.2$

Channel	BR(%)
$B^{*+}\bar{B}^{*0} + \bar{B}^{*0} B^{*+}$	$82.6 \pm 2.9 \pm 2.3$
$\Upsilon(1S)\pi^+$	$0.60 \pm 0.17 \pm 0.07$
$\Upsilon(2S)\pi^+$	$4.05 \pm 0.81 \pm 0.58$
$\Upsilon(3S)\pi^+$	$2.40 \pm 0.58 \pm 0.36$
$h_b(1P)\pi^+$	$4.26 \pm 1.28 \pm 1.10$
$h_b(2P)\pi^+$	$6.08 \pm 2.15 \pm 1.63$

- Comments:
  - States only 3 MeV above threshold.
  - Isopsin violation effects tiny
  - HQS guarantees the analogy states $c\bar{c}$ and $b\bar{b}$ at the same thresholds.



$Z_c^{\pm}(3885), Z_c^{\pm,0}(4020) \quad I^G(J^P) = 1^-(1^+)$

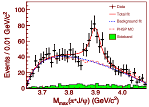
- $Z_c^{\pm}(3885)$: $M = 3886.6 \pm 2.4, \Gamma = 28.1 \pm 2.6$

Channel	Ratio $D\bar{D}^*/X$
$D^+\bar{D}^{*0} + \bar{D}^0 D^{*+}$	1
$J/\psi\pi^+$	$6.2 \pm 1.1 \pm 2.7$
$h_c(1P)\pi^+$	not yet observed

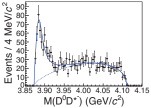
- $Z_c^{\pm,0}(4020)$: $M = 4024.1 \pm 1.9, \Gamma = 13 \pm 5$

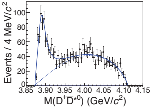
Channel	Ratio $D^*\bar{D}^*/X$
$D^{*+}\bar{D}^{*0} + \bar{D}^{*0} D^{*+}$	1
$J/\psi\pi^+$	12 ± 5
$h_c(1P)\pi^+$	not yet observed
$\psi(2S)\pi^+$	not yet observed

- Comments:
  - States less than 10 MeV above threshold.
  - Small isopsin violation effects.

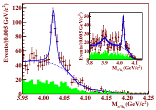


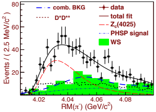
M(D^0+D^{*-}) = 3.8752





$M_{\rm pole} = 3883.9 \pm 1.5 \pm 4.2$ MeV
$\Gamma_{\rm pole} = 24.8 \pm 3.3 \pm 11.0$ MeV





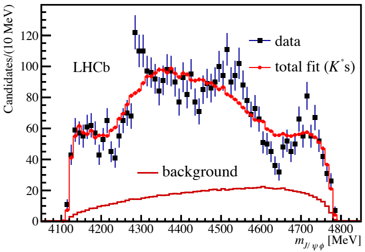
$M = 4022.9 \pm 0.8 \pm 2.7$ MeV
$\Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV

M(D^{*0}+D^{*-}) = 4.0178

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



- 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

The Y(4260) and Y(4360) System

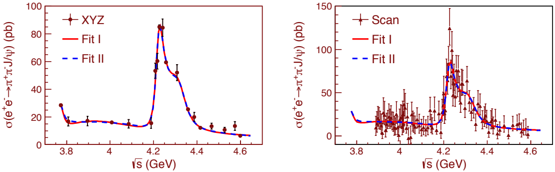


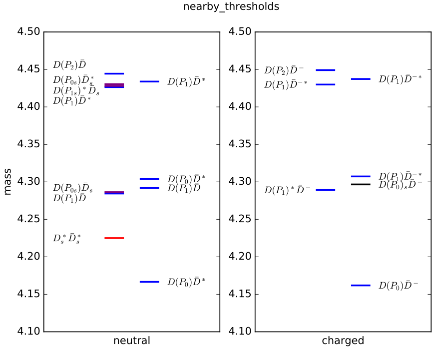
TABLE I: The measured masses and widths of the resonances from the fit to the $e^+e^- \to \pi^+\pi^- J/\psi$ cross section with three coherent Breit-Wigner functions. The numbers in the brackets correspond to a fit by replacing R_1 with an exponential describing the continuum. The errors are statistical only.

Parameters	Fit result
$M(R_1)$	$3812.6^{+61.9}_{-96.6}$ $(\cdots)$
$\Gamma_{\rm tot}(R_1)$	$476.9^{+78.4}_{-64.8}$ $(\cdots)$
$M(R_2)$	4222.0 ± 3.1 (4220.9 ± 2.9)
$\Gamma_{\rm tot}(R_2)$	44.1 ± 4.3 (44.1 ± 3.8)
$M(R_3)$	4320.0 ± 10.4 (4326.8 ± 10.0)
$\Gamma_{\rm tot}(R_3)$	$101.4^{+25.3}_{-19.7}$ $(98.2^{+25.4}_{-19.6})$

Ablikim, M., el al. (BESIII Collaboration), PRL 118,092001, 2017

- $J^{PC} = 1^{--}$ but no signal in ΔR_c
  - $\psi(4415)$ conventionally identified as $4S$ state
  - not a conventional $(c\bar{c})$ charmonium state
- Lattice calculations suggest a possible hybrid state $(c\bar{c}g)$ in this mass region

Nearby Thresholds
There are many heavy-light meson pair channels opening in region 4.2 – 4.4

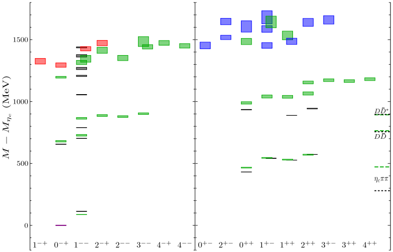


$c\bar{c}$ States (LQCD)

- Lattice calculations ($m_\pi = 240$ MeV)

J^{PC}	$M - M_{\eta_c}$ (MeV)					
0^{-+}	0	679(6)	1197(7)	1295(18)		
1^{--}	88(1)	728(7)	865(7)	1316(17)	1345(27)	1427(17)
2^{--}	879(7)	1352(21)				
2^{-+}	888(7)	1414(24)	1472(21)			
3^{--}	902(6)	1442(18)	1484(40)			
4^{-+}	1474(19)					
4^{--}	1450(18)					
0^{++}	466(3)	989(10)	1485(25)	1607(46)		
1^{++}	531(4)	1038(12)	1486(25)	1534(35)		
1^{+-}	545(4)	1041(12)	1454(23)	1587(27)	1643(47)	1681(53)
2^{++}	571(4)	1065(13)	1154(11)	1173(11)	1639(32)	
3^{++}	1166(11)					
3^{+-}	1173(11)	1660(34)				
4^{++}	1181(12)					
1^{-+}	1326(23)					
0^{+-}	1453(27)					
2^{+-}	1518(18)	1647(26)				

G. Cheung, et al., arXiv:1610.0107



- No $c\bar{c}g$ (1^{--}) hybrid state below $\psi(4160)[2^3D_1(c\bar{c})]$
- The ordering of hybrids states in a spin multiplet is stable as $m_\pi = 392 \to 240$ MeV

Low-lying multiplet:

- $(S=0)$ 1^{--}; $(S=1)$ $0^{-+}, 1^{-+}, 2^{-+}$
- So if we identify the Y(4260) as a hybrid:

State	Shift	Mass (MeV)
1^{--}	0	4260
0^{-+}	-132	4128
1^{-+}	-101	4159
2^{-+}	45	4305

- Expect photon transitions.
  (Very small branching fractions).

To do list:

- Y(4660) 5S state or radially excited Y(4260)?
- Measure R in the highest energy region (4.6-4.7) in detail.
- The corresponding states in the $b\bar{b}$ system await a detailed lattice calculation

Summary

Many puzzles of the XYZ states remain but:

- HQS summetry gives insight into scaling between ($c\bar{c}$) and ($b\bar{b}$) for tetraquark states. Stable $bb\bar{u}\bar{d}$, $bb\bar{u}\bar{s}$, and $bb\bar{d}\bar{s}$ tetraquarks exist.
- Lattice QCD identifies where to expect hybrid states in the $c\bar{c}$.

BESIII , Belle2, LHCb will provide critical data for disentangling the nature of the XYZ states:

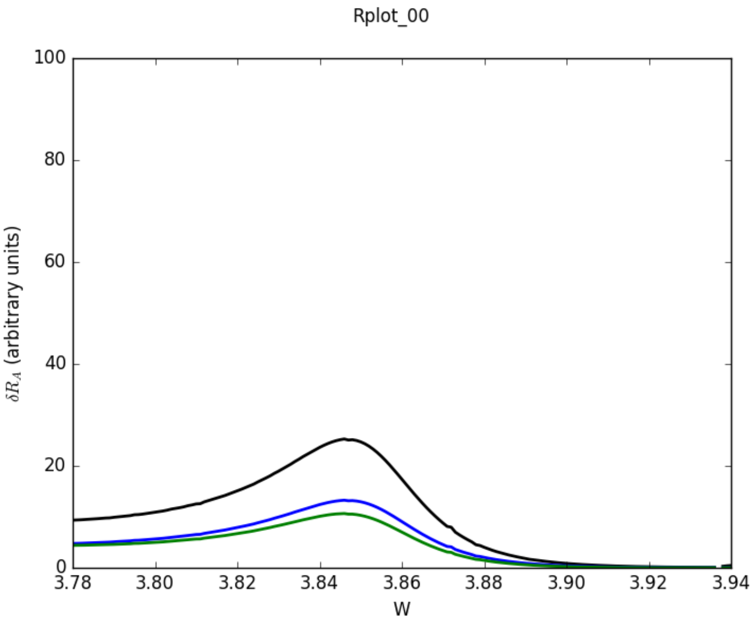
- Detailed studies of transitions from higher mass states in the ($c\bar{c}$) that greatly increased luminosity will make possible.
- Observing(or not) HQS partners of the ($c\bar{c}$) XYZ states in the ($b\bar{b}$).

Challenges for theory:

- Lattice QCD calculation of the ($b\bar{b}$) spectrum (with hybrids).
- Continued LQCD progress on identifying XYZ states by the Luscher method.
- A better model of line shapes for resonances in the threshold region.
- Model builders - Make your predictions for XYZ states in the ($b\bar{b}$).

Backup

2^3P_0 Toy model



Possible quarkonium-like tetraquark mesons

$c\bar{c}$

TABLE II. See the caption of Table I.

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$Z_c^{+,0}(3900)$	3886.6 ± 2.4	28.1 ± 2.6	1^{+-}	$e^+e^- \to \pi^{-,0}(J/\psi\pi^{+,0})$	BESIII (Ablikim *et al.*, 2013a, 2015f), Belle (Liu *et al.*, 2013)
				$e^+e^- \to \pi^{-,0}(D\bar{D}^*)^{+,0}$	BESIII (Ablikim *et al.*, 2014b, 2015e)
$Z_c^{+,0}(4020)$	4024.1 ± 1.9	13 ± 5	$1^{+-}(?)$	$e^+e- \to \pi^{-,0}(h_c\pi^{+,0})$	BESIII (Ablikim *et al.*, 2013b, 2014c)
				$e^+e^- \to \pi^{-,0}(D^*\bar{D}^*)^{+,0}$	BESIII (Ablikim *et al.*, 2014a, 2015d)
$Z^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K(\chi_{c1}\pi^+)$	Belle (Mizuk *et al.*, 2008), *BABAR* (Lees *et al.*, 2012a)
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^+	$B \to K(J/\psi\pi^+)$	Belle (Chilikin *et al.*, 2014)
				$B \to K(\psi'\pi^+)$	LHCb (Aaij *et al.*, 2014b)
$Z^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B \to K(\chi_{c1}\pi^+)$	Belle (Mizuk *et al.*, 2008), *BABAR* (Lees *et al.*, 2012a)
$Z^+(4430)$	4477 ± 20	181 ± 31	1^+	$B \to K(\psi'\pi^+)$	Belle (Choi *et al.*, 2008; Mizuk *et al.*, 2009), Belle (Chilikin *et al.*, 2013), LHCb (Aaij *et al.*, 2014b, 2015b)
				$B \to K(J\psi\pi^+)$	Belle (Chilikin *et al.*, 2014)
$P_c^+(4380)$	4380 ± 30	205 ± 88	$(\frac{3}{2}/\frac{5}{2})^\mp$	$\Lambda_b^0 \to K(J/\psi p)$	LHCb (Aaij *et al.*, 2015c)
$P_c^+(4450)$	4450 ± 3	39 ± 20	$(\frac{5}{2}/\frac{3}{2})^\pm$	$\Lambda_b^0 \to K(J/\psi p)$	LHCb (Aaij *et al.*, 2015c)
$Y_b(10860)$	$10891.1^{+3.4}_{-3.8}$	$53.7^{+7.2}_{-7.8}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\pi^+\pi^-)$	Belle (Chen *et al.*, 2008; Santel *et al.*, 2016)
$Z_b^{+,0}(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$Y_b(10860) \to \pi^{-,0}(\Upsilon(nS)\pi^{+,0})$	Belle (Bondar *et al.*, 2012; Garmash *et al.*, 2015), Belle (Krokovny *et al.*, 2013)
				$Y_b(10860) \to \pi^-(h_b(nP)\pi^+)$	Belle (Bondar *et al.*, 2012)
				$Y_b(10860) \to \pi^-(B\bar{B}^*)^+$	Belle (Garmash *et al.*, 2016)
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$Y_b(10860) \to \pi^-(\Upsilon(nS)\pi^+)$	Belle (Bondar *et al.*, 2012; Garmash *et al.*, 2015)
				$Y_b(10860) \to \pi^-(h_b(nP)\pi^+)$	Belle (Bondar *et al.*, 2012)
				$Y_b(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle (Garmash *et al.*, 2016)

Olsen, Skwarnicki, and Zieminska: Nonstandard heavy mesons and baryons: …

TABLE I. Recently discovered nonstandard hadron candidates with hidden charm or beauty. The masses M and widths Γ are averages of measurements with uncertainties added in quadrature, except for $X(4140)$, $X(4274)$ [$Z^+(4200)$], where Aaij *et al.* (2017a, 2017d) (Chilikin *et al.*, 2014) values are listed. See Sec. V.D (Sec. VI.A) for more detailed discussion. The errors on the average values include scale factors in case of tensions between individual measurements (Patrignani *et al.*, 2016). We do not quote a mass or width for the $Y(4260)$ structure, since the latest precision data revealed its double-peak composition (Ablikim *et al.*, 2017c), with the main component listed under $Y(4220)$ and its high-mass shoulder under $Y(4360)$. The results from single-peak fits to the $Y(4260)$ structure are not included when determining the $Y(4220)$ parameters. For $X(3872)$, only $\pi^+\pi^-J/\psi$ decays are used in the mass average. Ellipses indicate an inclusive reaction. Question marks indicate informed guesses at J^{PC} values or no information. For charged states, C refers to the neutral isospin partner. See Table II for a continuation.

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.69 ± 0.17	< 1.2	1^{++}	$B \to K(J/\psi\pi^+\pi^-)$	Belle (Choi *et al.*, 2003, 2011), *BABAR* (Aubert *et al.*, 2005c), LHCb (Aaij *et al.*, 2013a, 2015d)
				$p\bar{p} \to (J/\psi\pi^+\pi^-) + \cdots$	CDF (Acosta *et al.*, 2004; Abulencia *et al.*, 2006; Aaltonen *et al.*, 2009b), D0 (Abazov *et al.*, 2004)
				$B \to K(J/\psi\pi^+\pi^-\pi^0)$	Belle (Abe *et al.*, 2005), *BABAR* (del Amo Sanchez *et al.*, 2010a)
				$B \to K(D^0\bar{D}^0\pi^0)$	Belle (Gokhroo *et al.*, 2006; Aushev *et al.*, 2010b), *BABAR* (Aubert *et al.*, 2008c)
				$B \to K(J/\psi\gamma)$	*BABAR* (del Amo Sanchez *et al.*, 2010a), Belle (Bhardwaj *et al.*, 2011), LHCb (Aaij *et al.*, 2012a)
				$B \to K(\psi'\gamma)$	*BABAR* (Aubert *et al.*, 2009b), Belle (Bhardwaj *et al.*, 2011), LHCb (Aaij *et al.*, 2014a)
				$pp \to (J/\psi\pi^+\pi^-) + \cdots$	LHCb (Aaij *et al.*, 2012a), CMS (Chatrchyan *et al.*, 2013a), ATLAS (Aaboud *et al.*, 2017)
				$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$	BESIII (Ablikim *et al.*, 2014d)
$X(3915)$	3918.4 ± 1.9	20 ± 5	0^{++}	$B \to K(J/\psi\omega)$	Belle (Choi *et al.*, 2005), *BABAR* (Aubert *et al.*, 2008b; del Amo Sanchez *et al.*, 2010a)
				$e^+e^- \to e^+e^-(J/\psi\omega)$	Belle (Uehara *et al.*, 2010), *BABAR* (Lees *et al.*, 2012c)
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0^{-+}(?)$	$e^+e^- \to J/\psi(D^*\bar{D})$	Belle (Pakhlov *et al.*, 2008)
				$e^+e^- \to J/\psi(\cdots)$	Belle (Abe *et al.*, 2007)
$X(4140)$	$4146.5^{+6.4}_{-5.3}$	83^{+27}_{-25}	1^{++}	$B \to K(J/\psi\phi)$	CDF (Aaltonen *et al.*, 2009a), CMS (Chatrchyan *et al.*, 2014), D0 (Abazov *et al.*, 2014), LHCb (Aaij *et al.*, 2017a, 2017d)
				$p\bar{p} \to (J/\psi\phi) + \cdots$	D0 (Abazov *et al.*, 2015)
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0^{-+}(?)$	$e^+e^- \to J/\psi(D^*\bar{D}^*)$	Belle (Pakhlov *et al.*, 2008)
$Y(4260)$	See $Y(4220)$ entry		1^{--}	$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$	*BABAR* (Aubert *et al.*, 2005a; Lees *et al.*, 2012b), CLEO (He *et al.*, 2006), Belle (Yuan *et al.*, 2007; Liu *et al.*, 2013)
$Y(4220)$	4222 ± 3	48 ± 7	1^{--}	$e^+e^- \to (J/\psi\pi^+\pi^-)$	BESIII (Ablikim *et al.*, 2017c)
				$e^+e^- \to (h_c\pi^+\pi^-)$	BESIII (Ablikim *et al.*, 2017a)
				$e^+e^- \to (\chi_{c0}\omega)$	BESIII (Ablikim *et al.*, 2015g)
				$e^+e^- \to (J/\psi\eta)$	BESIII (Ablikim *et al.*, 2015c)
				$e^+e^- \to (\gamma X(3872))$	BESIII (Ablikim *et al.*, 2014d)
				$e^+e^- \to (\pi^-Z_c^+(3900))$	BESIII (Ablikim *et al.*, 2013a), Belle (Liu *et al.*, 2013)
				$e^+e^- \to (\pi^-Z_c^+(4020))$	BESIII (Ablikim *et al.*, 2013b)
$X(4274)$	4273^{+19}_{-9}	56^{+14}_{-16}	1^{++}	$B \to K(J/\psi\phi)$	CDF (Aaltonen *et al.*, 2017), CMS (Chatrchyan *et al.*, 2014), LHCb (Aaij *et al.*, 2017a, 2017d)
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$(0/2)^{++}$	$e^+e^- \to e^+e^-(J/\psi\phi)$	Belle (Shen *et al.*, 2010)
$Y(4360)$	4341 ± 8	102 ± 9	1^{--}	$e^+e^- \to \gamma(\psi'\pi^+\pi^-)$	*BABAR* (Aubert *et al.*, 2007; Lees *et al.*, 2014), Belle (Wang *et al.*, 2007, 2015)
				$e^+e^- \to (J/\psi\pi^+\pi^-)$	BESIII (Ablikim *et al.*, 2017c)
$Y(4390)$	4392 ± 6	140 ± 16	1^{--}	$e^+e^- \to (h_c\pi^+\pi^-)$	BESIII (Ablikim *et al.*, 2017a)
$X(4500)$	4506^{+16}_{-19}	92^{+30}_{-21}	0^{++}	$B \to K(J/\psi\phi)$	LHCb (Aaij *et al.*, 2017a, 2017d)
$X(4700)$	4704^{+17}_{-26}	120^{+52}_{-45}	0^{++}	$B \to K(J/\psi\phi)$	LHCb (Aaij *et al.*, 2017a, 2017d)
$Y(4660)$	4643 ± 9	72 ± 11	1^{--}	$e^+e^- \to \gamma(\psi'\pi^+\pi^-)$	Belle (Wang *et al.*, 2007, 2015), *BABAR* (Aubert *et al.*, 2007; Lees *et al.*, 2014)
				$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle (Pakhlova *et al.*, 2008)

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*

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	**−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	**−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**

$J^P = 1^+$ $\{bb\}[\bar{u}\bar{d}]$ 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 $BB_s\gamma$)

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