Tetraquark Interpretation of Charged Bottomonium-like States and Implications

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Based on work in collaboration with A.Ali and C.Hambrock

9th International Workshop on Heavy Quarkonium 2013

Outline

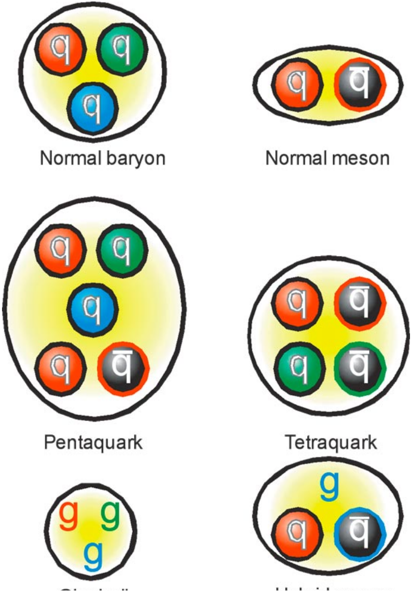
- Motivation
- Tetraquark vs Hadronic Molecules
- $Z_b(10610)$ and $Z_b(10650)$ as Tetraquarks

  Can these two states be accommodated in the tetraquark model (diquark-antidiquark)?
- Implications
- Summary

Motivation

Quark model:
Hadrons are composed of 2 or 3 quarks (meson, baryon)

However QCD allows hadrons with $N_{\text{quarks}} \neq 2, 3$.



Exotica Candidates

[Zupanc et al. 09] , [Bondar et al., PRL 12] , [Liu et al., 13] , [Ablikim et al., 13]

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes	date
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \to \eta Y_s(2175)$	2006
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi, D\bar{D}^*$	$B \to KX(3872), p\bar{p}$	2003
$Z_c(3900)$	3899 ± 6	46 ± 22	1^+	$\pi^\pm J/\psi$	$Y(4260) \to Z_c(3900)\pi$	2013
$X(3915)$	3914 ± 4	28^{+12}_{-14}	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$	2009
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$	2009
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$	2005
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)	$B \to KY(3940)$	
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	2005
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)	$e^+e^- \to J/\psi X(4160)$	2008
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	2005
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)	2007
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+ \Lambda_c^-$	e^+e^- (ISR)	2008
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)	2007
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4050)$	2008
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4250)$	2008
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$	2007
$Z_b(10610)$	$10,607 \pm 2$	18.4 ± 2.4	1^+	$\pi^\pm h_b(1,2P), \pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10610)\pi$	2011
$Z_b(10650)$	$10,652 \pm 2$	11.5 ± 2.2	1^+	$\pi^\pm h_b(1,2P), \pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10650)\pi$	2011
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$	$e^+e^- \to Y_b$	2008

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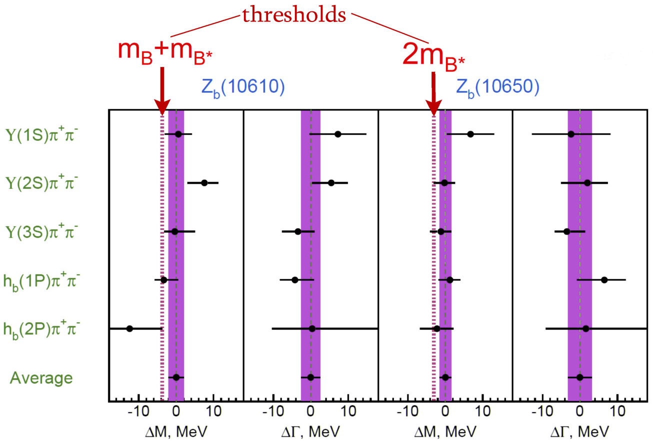
$Z_b(10610)$
$Z_b(10650)$

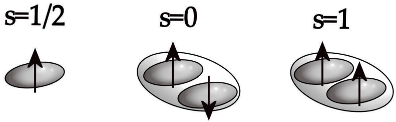


$Z_b(10610)$ **M=10607.2±2.0 MeV** **$Z_b(10650)$** **M=10652.2±1.5 MeV**

Belle arXiv:1110.2251

Tetraquark building blocks: diquarks

For heavy quarks, the spin decouples. Heavy diquark building blocks:



Using these blocks, we construct the lowest-lying tetra-quarks:

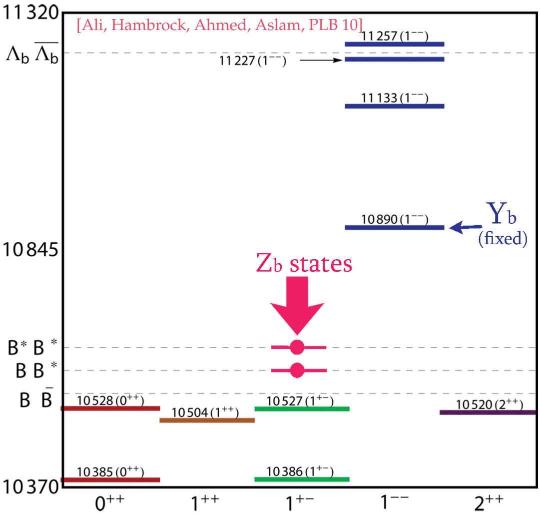
Two states with $J^{PC} = 0^{++}$:

$$\begin{aligned} |0^{++}\rangle &= |0_Q, 0_{\bar{Q}};\ 0_J\rangle \\ |0^{++\prime}\rangle &= |1_Q, 1_{\bar{Q}};\ 0_J\rangle \end{aligned}$$

Three states with $J = 1$:

$$\begin{aligned} |1^{++}\rangle &= \frac{1}{\sqrt{2}}\left(|0_Q, 1_{\bar{Q}};\ 1_J\rangle + |1_Q, 0_{\bar{Q}};\ 1_J\rangle\right) \\ |1^{+-}\rangle &= \frac{1}{\sqrt{2}}\left(|0_Q, 1_{\bar{Q}};\ 1_J\rangle - |1_Q, 0_{\bar{Q}};\ 1_J\rangle\right) \\ |1^{+-\prime}\rangle &= |1_Q, 1_{\bar{Q}};\ 1_J\rangle \end{aligned}$$

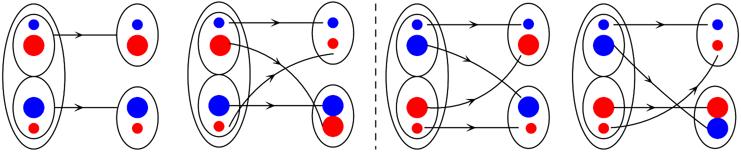
$[bq][\bar{b}\bar{q}]$ Constituent Model Spectrum



- HQ symmetry motivates fixing
- states are iso-doublets $q = u, d$
- tetraquark $Z_b$masses do not agree with Belle
- However tetraquarks with mixing & self energy corrections in principle allowed in parts of parameter space [Ali, Hambrock, WW, PRD 11]

What are the distinctive features of a tetraquark?

Mesonic Molecules vs Tetraquarks



Mesonic Molecules

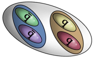
- Mass: close to meson-meson threshold.
- $\Gamma(Z_b \to BB^*) \gg \Gamma(Z_b \to \Upsilon\pi)$ if kinematically allowed.
  See C.Hanhart's talk for more remarks on hadronic molecules.

Tetraquark based on Diquark-anti-diquark

- Diquarks will be broke off in both cases: $\Gamma(Z_b \to BB^*) \sim \Gamma(Z_b \to \Upsilon\pi)$ if kinematically allowed.

Z_b States: Molecule or Tetraquark?

Molecule 

Tetraquark 

$$|Z_{b(10610)}\rangle = (0_{b\bar{q}} \otimes 1_{\bar{b}q} + 1_{b\bar{q}} \otimes 0_{\bar{b}q})/\sqrt{2}$$

$$|Z_{b(10650)}\rangle = 1_{b\bar{q}} \otimes 1_{\bar{b}q}$$

$$|Z_{b(10610)}\rangle = (0_{[bq]} \otimes 1_{[\bar{b}\bar{q}]} - 1_{[bq]} \otimes 0_{[\bar{b}\bar{q}]})/\sqrt{2}$$

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Z_b States: Molecule or Tetraquark?

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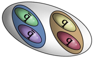
Tetraquark 

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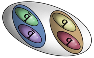
$\downarrow$ Fierz $\downarrow$

$$|Z_{b(10610)}\rangle = 1^-_{b\bar{q}} \otimes 1^-_{q\bar{b}}$$

$$|Z_{b(10650)}\rangle = (1^-_{b\bar{q}} \otimes 0^-_{q\bar{b}} + 0^-_{b\bar{q}} \otimes 1^-_{q\bar{b}})/\sqrt{2}$$

Z_b States: Molecule or Tetraquark?

Molecule 

Tetraquark 

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$Z_{b(10610)} \to B\bar{B}^* + B^*\bar{B}$

$Z_{b(10650)} \to B^*\bar{B}^*$

$Z_{b(10610)} \to B^*\bar{B}^*$

$Z_{b(10650)} \to B\bar{B}^* + B^*\bar{B}$

Z_b States: Molecule or Tetraquark?

[Belle Collaboration (2012)]

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

Molecule

$|Z_{b(10610)}\rangle$ = ... $\otimes 0_{[\bar{b}\bar{q}]}) / \sqrt{2}$

$|Z_{b(10650)}\rangle$ = ...

$|Z_{b(10650)}\rangle = (1^-_{b\bar{q}} \otimes 0^-_{q\bar{b}} + 0^-_{b\bar{q}} \otimes 1^-_{q\bar{b}}) / \sqrt{2}$

$Z_{b(10610)} \to B\bar{B}^* + B^*\bar{B}$

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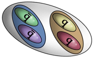
Z_b Concluding Remarks

Tetraquark 

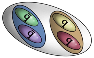
PRO:
Fails to explain the decay pattern for $B\bar{B}^*$ channels

Molecule 

PRO:
Close to thresholds
Explains $B^{(*)}\bar{B}^{(*)}$ decay pattern

Z_b Concluding Remarks

Tetraquark



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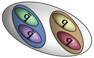
Z_b Concluding Remarks

Tetraquark



PRO:
Fails to explain the decay pattern for $B\bar{B}^*$ channels

Molecule

PRO:
Close to thresholds
Explains $B^{(*)}\bar{B}^{(*)}$ decay pattern

…but…

Z_b Concluding Remarks

PHYSICAL REVIEW D **85**, 054011 (2012)

Tetraquark interpretation of the charged bottomonium-like states $Z_b^{\pm}(10610)$ and $Z_b^{\pm}(10650)$ and implications

Ahmed Ali,* Christian Hambrock,† and Wei Wang‡
Deutsches Elektronen-Synchrotron DESY, D-22607 Hamburg, Germany
(Received 21 October 2011; published 16 March 2012)

As already remarked, the 1^{+-} relatives of the Z_b and Z_b' states in the charm sector, Z_c and Z_c', in our model are expected to be produced in the decays of a 1^{--} hidden-charm tetraquark. The state $Y(4260)$ fits the bill. The enhancement of the cross sections for $e^+e^- \to J/\psi\pi^+\pi^-$ and $e^+e^- \to h_c\pi^+\pi^-$ seen by the CLEO Collaboration at the center-of-mass energy around 4.26 GeV [29] is very likely a signature of their existence. In order to confirm or negate this scanrio, we suggest our experimental colleagues to scan over this mass region more precisely.

$Z_c(3900)$ Discovered!

Observation of a charged charmoniumlike structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV

BESIII arXiv:1303.5949

Study of $e^+e^- \to \pi^+\pi^- J/\psi$ and Observation of a Charged Charmonium-like State at Belle

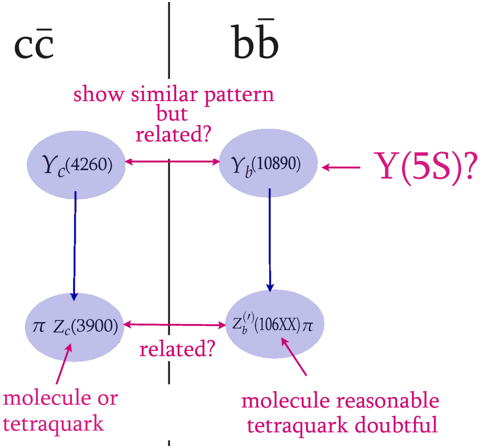
Belle arXiv:1304.0121

Observation of the Charged Hadron $Z_c^\pm(3900)$ at $\sqrt{s} = 4170$ MeV

Xiao et al arXiv:1304.3036

For theoretical discussion on the nature of $Z_c(3900)$, See A.Pilloni's talk (tetraquark interpretation along the same line with this work) and Q. Zhao's talk (hadronic $D\bar{D}^*$ molecules).

Exotic Heavy Quarkonia



$Y_b(10890)$ and $\Upsilon(5S)$?

PHYSICAL REVIEW D **82,** 091106(R) (2010)

Observation of an enhancement in $e^+e^- \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, and $\Upsilon(3S)\pi^+\pi^-$ production near $\sqrt{s} = 10.89$ GeV

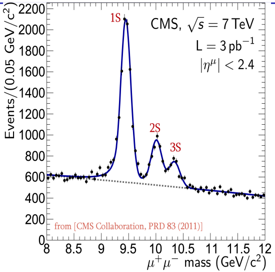
We measure the production cross sections for $e^+e^- \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, and $\Upsilon(3S)\pi^+\pi^-$ as a function of $\sqrt{s}$ between 10.83 GeV and 11.02 GeV. The data consist of 8.1 fb^{-1} collected with the Belle detector at the KEKB e^+e^- collider. We observe enhanced production in all three final states that does not agree well with the conventional $\Upsilon(10860)$ line shape. A fit using a Breit-Wigner resonance shape yields a peak mass of $[10\,888.4^{+2.7}_{-2.6}(\mathrm{stat}) \pm 1.2(\mathrm{syst})]\ \mathrm{MeV}/c^2$ and a width of $[30.7^{+8.3}_{-7.0}(\mathrm{stat}) \pm 3.1(\mathrm{syst})]\ \mathrm{MeV}/c^2$.

DOI: 10.1103/PhysRevD.82.091106 PACS numbers: 13.25.Gv, 14.40.Pq

PRL **108,** 122001 (2012) PHYSICAL REVIEW LETTERS week ending 23 MARCH 2012

Observation of Two Charged Bottomoniumlike Resonances in $\Upsilon(5S)$ Decays

Hadroproduction of Bottomonia



- $\mu^+\mu^-$ channel: Common particle detection for bottomonia

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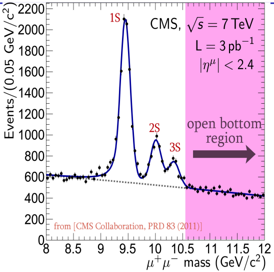

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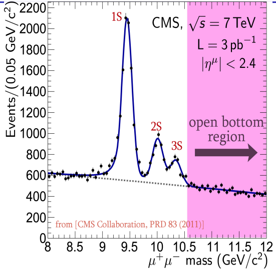
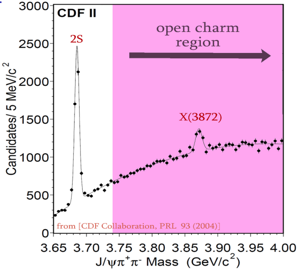
- Above threshold difficult ($BR(\mu^+\mu^-)$drops)
  - ↪ present research focused on $1S, 2S, 3S$

Hadroproduction of Bottomonia





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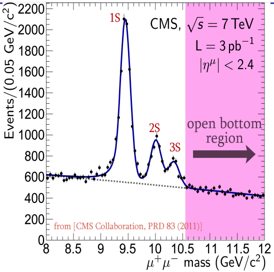
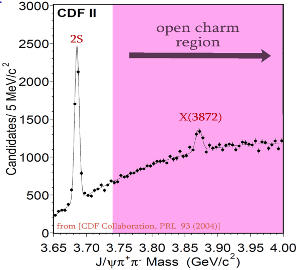
Hadroproduction of Bottomonia





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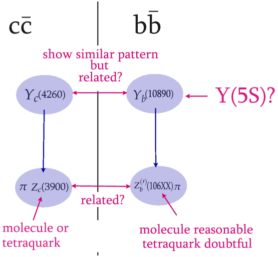
Acquire knowledge of bottomonia above hadronic thresholds. On LHC, we use NRQCD to derive:
$\sigma(pp \to \Upsilon(5S)(\to \mu^+\mu^-\pi^+\pi^-)X) \sim (1-10)pb$. VERY PRELIMINARY! Ali, Hambrock, WW, in preparation.

↪ Non-prompt production of $Z_b(106XX)$, clarify nature of observed states

Conclusions

- The Fock state description of the four-quark states possibly admits admixture of tetraquark (diquark-antidiquark) and hadronic molecular states. Data on $Z_b(10610)$ and $Z_b(10650)$ decays favors a substantial hadronic molecular component.
- Our anticipation to observe Z_c via $Y(4260) \to J/\psi\pi^+\pi^-$ is confirmed by experiments.
- Important puzzle remains:



To understand the composition of the four-quark states, it is essential to measure their hadronic production cross sections, and to have more precise data on their decays.

Outlook

- Hadroproduction of bottomonia and tetraquarks very interesting in the near future!

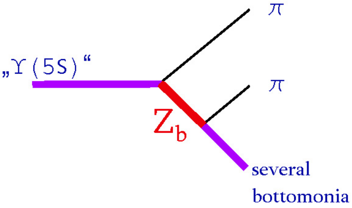
  ↪ heaps of new states to be discovered/re-discovered.

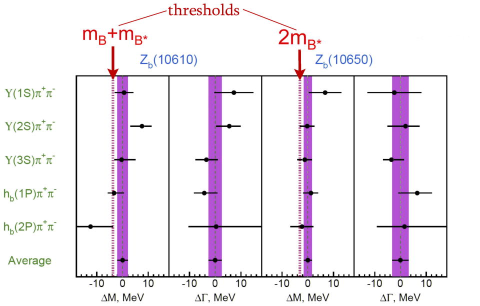
Backup: STOP

Z_b Masses by Belle

[Belle Collaboration, PRL 12]

measured in:





$Z_b(10610)$ M=10607.2±2.0 MeV **$Z_b(10650)$** M=10652.2±1.5 MeV

- Masses close to threshold:
No need for tetraquark scenario

- However tetraquarks with mixing & self energy corrections
[Ali, Hambrock, WW, PRD 11]
→ in principle allowed in parts of parameter space