doubly heavy tetraquarks and baryons

Marek Karliner

JHEP 7,153(2013) – arXiv:1304.0345, with S. Nussinov
JHEP 8,96(2013) – arXiv:1305.6457, with Y. Frishman

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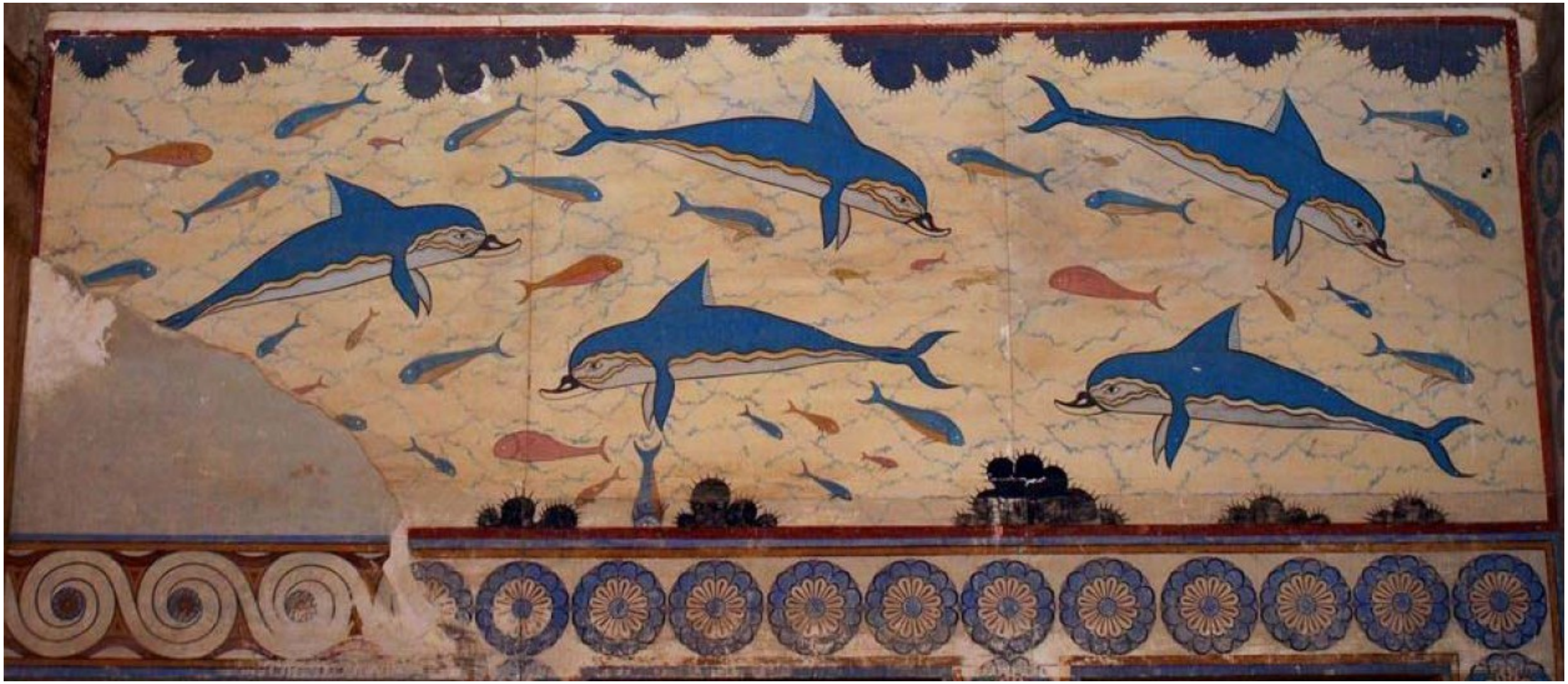

ICNFP 2013, OAC, Kolymbari, Crete

Possibility of Exotic States in the Upsilon system

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and
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Abstract

Recent data from Belle show unusually large partial widths $\Upsilon(5S) \to \Upsilon(1S)\,\pi^+\pi^-$ and $\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\pi^-$. The $Z(4430)$ narrow resonance also reported by Belle in $\psi'\pi^+$ spectrum has the properties expected of a $\bar{c}cu\bar{d}$ charged isovector tetraquark $T^{\pm}_{\bar{c}c}$. The analogous state $T^{\pm}_{\bar{b}b}$ in the bottom sector might mediate anomalously large cascade decays in the Upsilon system, $\Upsilon(mS) \to T^{\pm}_{\bar{b}b}\pi^{\mp} \to \Upsilon(nS)\,\pi^+\pi^-$, with a tetraquark-pion intermediate state. We suggest looking for the $\bar{b}bu\bar{d}$ tetraquark in these decays as peaks in the invariant mass of $\Upsilon(1S)\,\pi$ or $\Upsilon(2S)\,\pi$ systems. The $\bar{b}bu\bar{s}$ tetraquark can appear in the observed decays $\Upsilon(5S) \to \Upsilon(1S)\,K^+K^-$ as a peak in the invariant mass of $\Upsilon(1S)\,K$ system. We review the model showing that these tetraquarks are below the two heavy meson threshold, but respectively above the $\Upsilon\,\pi\pi$ and $\Upsilon\,K\bar{K}$ thresholds.

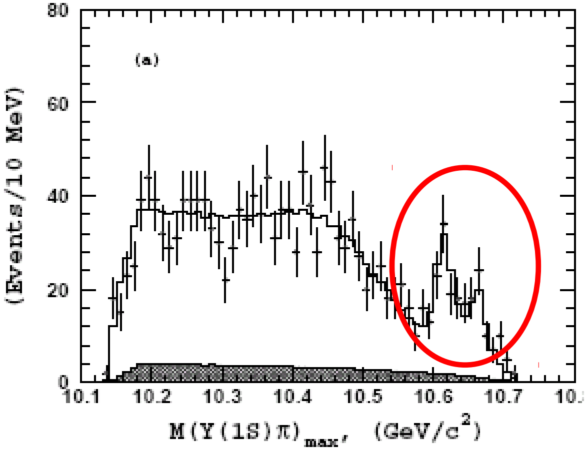
Observation of two charged bottomonium-like resonances

The Belle Collaboration

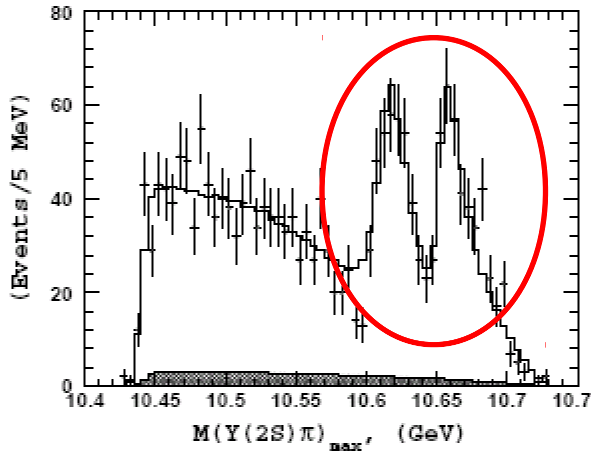
(Dated: May 24, 2011)

Abstract

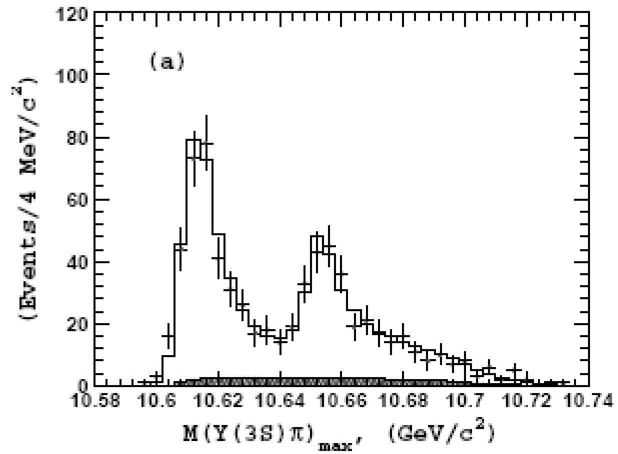
We report the observation of two narrow structures at 10610 MeV/c^2 and 10650 MeV/c^2 in the $\pi^{\pm}\Upsilon(nS)$ ($n = 1, 2, 3$) and $\pi^{\pm}h_b(mP)$ ($m = 1, 2$) mass spectra that are produced in association with a single charged pion in $\Upsilon(5S)$ decays. The measured masses and widths of the two structures averaged over the five final states are $M_1 = 10608.4 \pm 2.0$ MeV/c^2, $\Gamma_1 = 15.6 \pm 2.5$ MeV and $M_2 = 10653.2 \pm 1.5$ MeV/c^2, $\Gamma_2 = 14.4 \pm 3.2$ MeV. Analysis favors quantum numbers of $I^G(J^P)=1^+(1^+)$ for both states. The results are obtained with a 121.4 fb^{-1} data sample collected with the Belle detector near the $\Upsilon(5S)$ resonance at the KEKB asymmetric-energy e^+e^- collider.



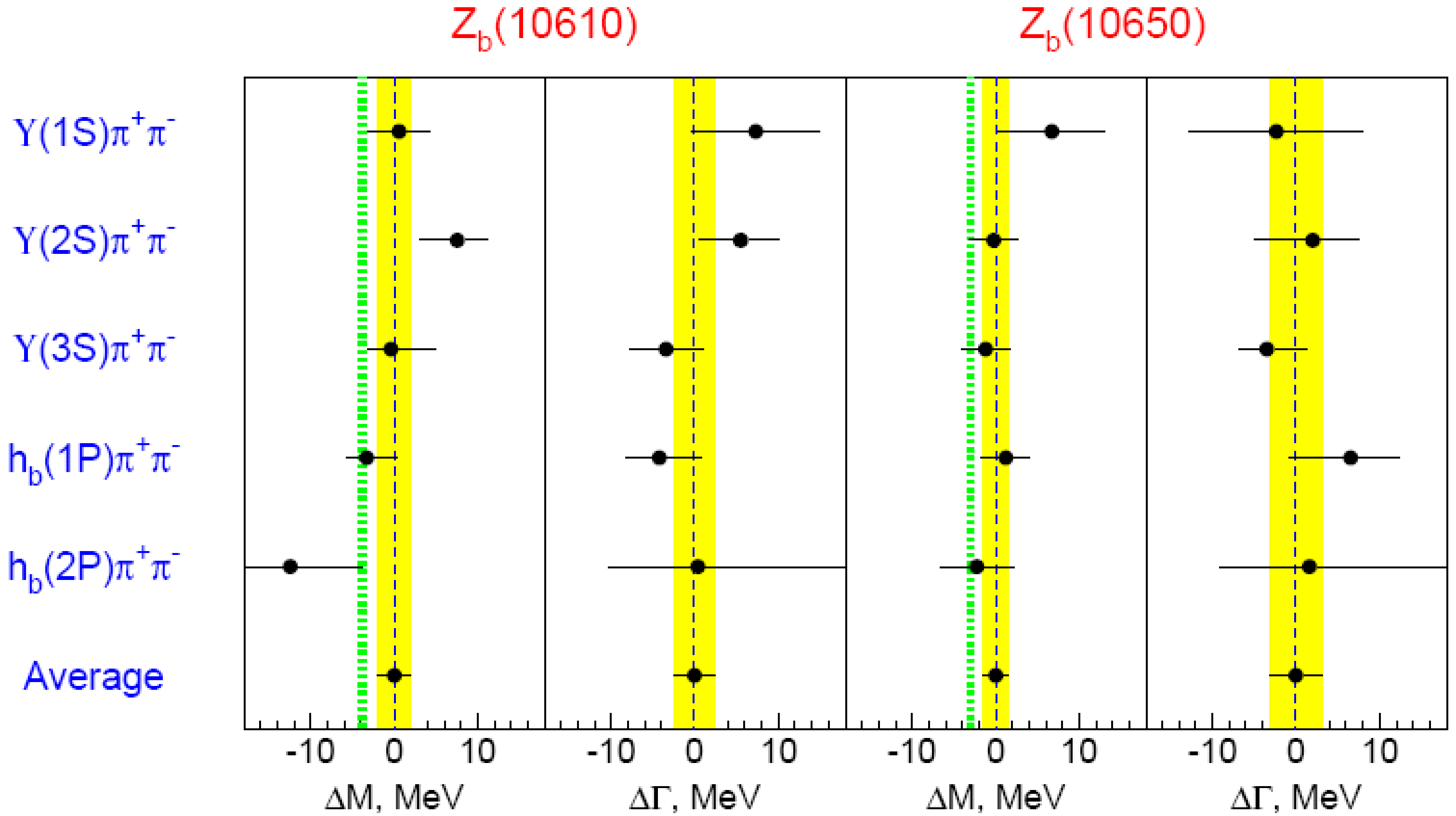
$$\Upsilon(3S)\pi^+$$



$$\Upsilon(2S)\pi^+$$



$$\Upsilon(1S)\pi^+$$



Comparison of $Z_b(10610)$ and $Z_b(10650)$ parameters obtained from different decay channels. The vertical dotted lines indicate $B^*\overline{B}$ and $B^*\overline{B}^*$ thresholds.

$$J^P = 1^+ \quad \text{for both } Z_b(10610) \text{ and } Z_b(10650)$$

The Z_b resonances decay into

Υ(nS) and a charged pion

→ must contain both bb* and ud*

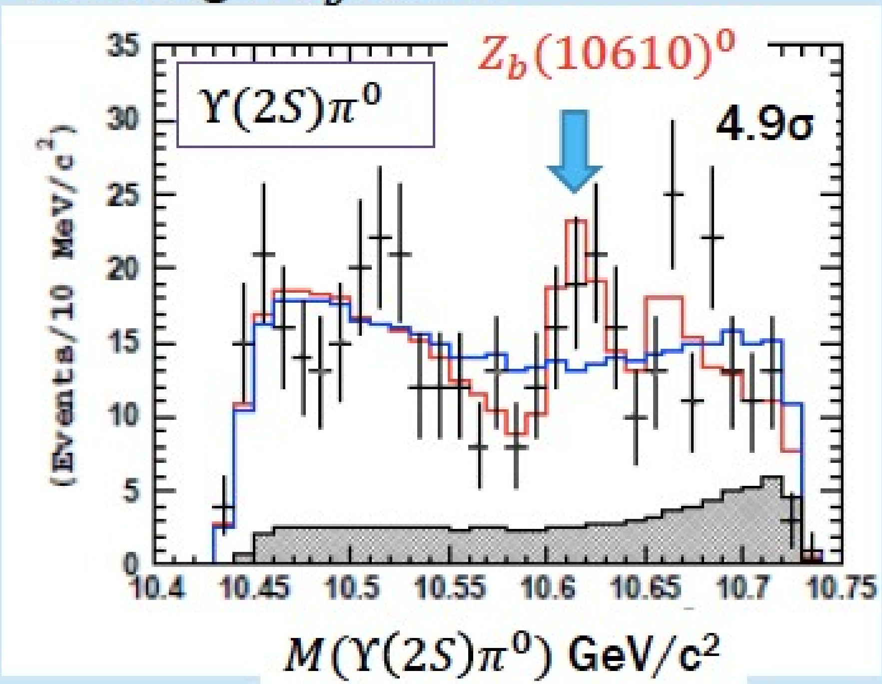
→ manifestly exotic

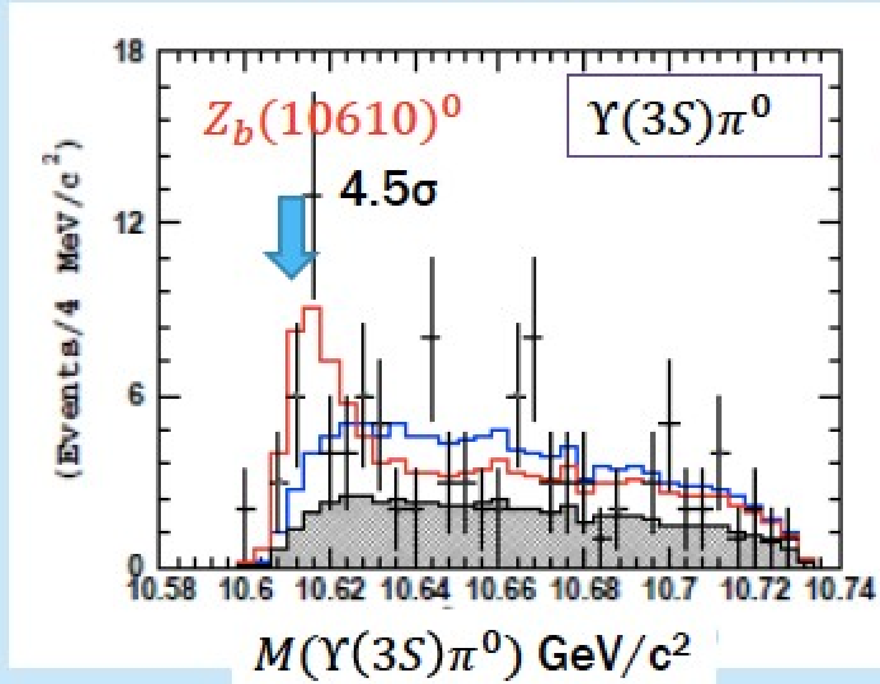
Neutral member of the I=1 multiplet very recently also observed by Belle in Dalitz plot analysis

$\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ decay

In this fit mass and width are fixed from the charged Z_b result.

fit result with Z_b
fit result without Z_b





Simultaneous fit gives 6.3 σ for $Z_b(10610)^0$

arXiv:1207.4345

After the discovery of Z_b-s by Belle,
natural to expect analogous states
in the charm system

one caveat:
a priori unknown whether charmed quarks
are heavy enough to allow for binding

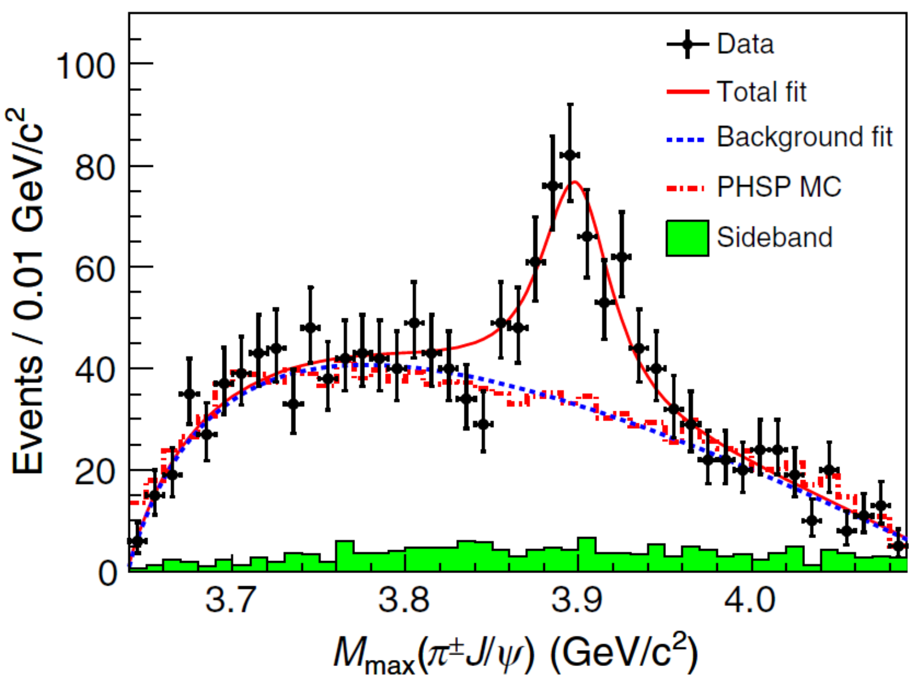
encouraging indications from toy model
of QCD in D=1+1
[JHEP 8,96(2013) – arXiv:1305.6457]

in March 2013 BES in Beijing
and Belle in KEK provided the answer:

Selected for a Viewpoint in *Physics*
PRL **110,** 252001 (2013) PHYSICAL REVIEW LETTERS week ending 21 JUNE 2013

Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV

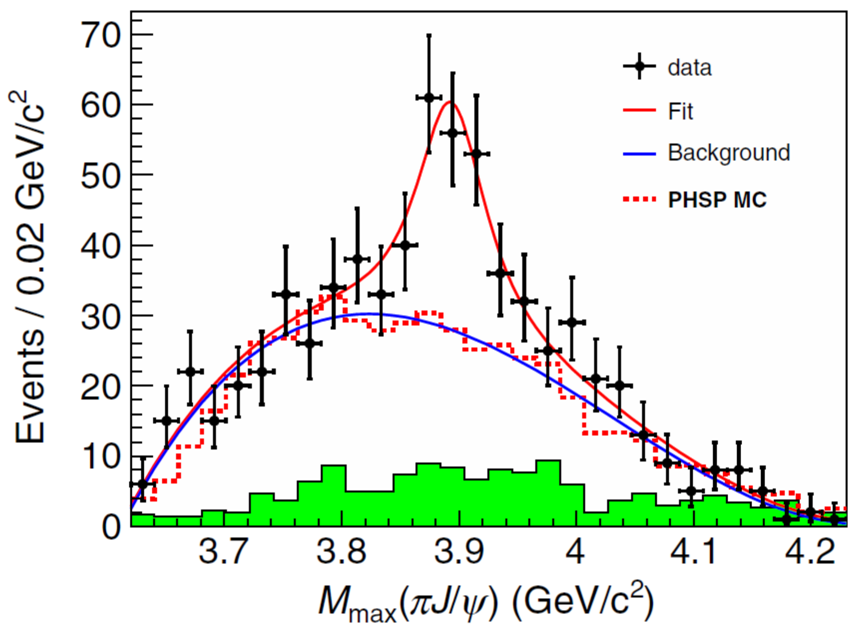
We study the process $e^+e^- \to \pi^+\pi^- J/\psi$ at a center-of-mass energy of 4.260 GeV using a 525 pb^{-1} data sample collected with the BESIII detector operating at the Beijing Electron Positron Collider. The Born cross section is measured to be $(62.9 \pm 1.9 \pm 3.7)$ pb, consistent with the production of the $Y(4260)$. We observe a structure at around 3.9 GeV/c^2 in the $\pi^\pm J/\psi$ mass spectrum, which we refer to as the $Z_c(3900)$. If interpreted as a new particle, it is unusual in that it carries an electric charge and couples to charmonium. A fit to the $\pi^\pm J/\psi$ invariant mass spectrum, neglecting interference, results in a mass of $(3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2 and a width of $(46 \pm 10 \pm 20)$ MeV. Its production ratio is measured to be $R = (\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- J/\psi)/\sigma(e^+e^- \to \pi^+\pi^- J/\psi)) = (21.5 \pm 3.3 \pm 7.5)\%$. In all measurements the first errors are statistical and the second are systematic.



Selected for a Viewpoint in *Physics*
PRL **110,** 252002 (2013) PHYSICAL REVIEW LETTERS week ending 21 JUNE 2013

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

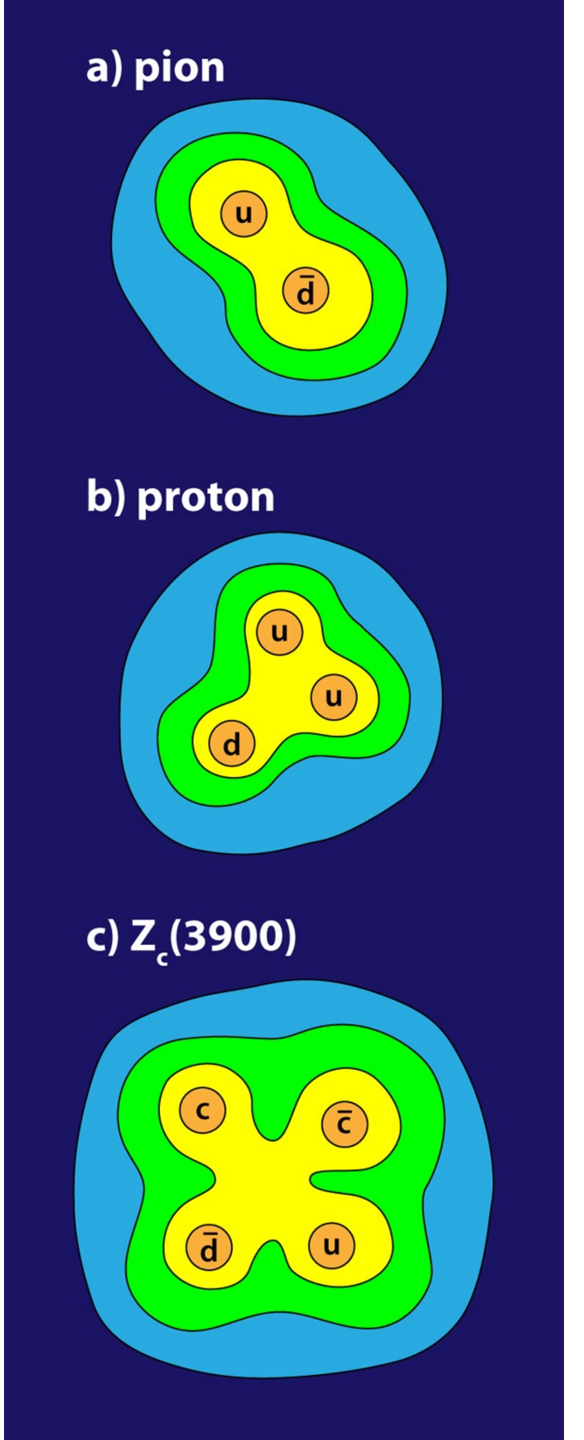
The cross section for $e^+e^- \to \pi^+\pi^- J/\psi$ between 3.8 and 5.5 GeV is measured with a 967 fb^{-1} data sample collected by the Belle detector at or near the $\Upsilon(nS)$ ($n = 1, 2, \ldots, 5$) resonances. The $Y(4260)$ state is observed, and its resonance parameters are determined. In addition, an excess of $\pi^+\pi^- J/\psi$ production around 4 GeV is observed. This feature can be described by a Breit-Wigner parametrization with properties that are consistent with the $Y(4008)$ state that was previously reported by Belle. In a study of $Y(4260) \to \pi^+\pi^- J/\psi$ decays, a structure is observed in the $M(\pi^\pm J/\psi)$ mass spectrum with 5.2σ significance, with mass $M = (3894.5 \pm 6.6 \pm 4.5)$ MeV/c^2 and width $\Gamma = (63 \pm 24 \pm 26)$ MeV/c^2, where the errors are statistical and systematic, respectively. This structure can be interpreted as a new charged charmoniumlike state.



$$M_{Z_c} = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV}$$

$$\Gamma_{Z_c} = 46 \pm 10 \pm 20 \text{ MeV}$$

$Z_c^+(3900)$ decays to $J/\psi\,\pi^+$



tetraquark or a “molecule” ?

The molecule idea has a long history:
Voloshin & Okun 1976,
de Rujula, Georgi & Glashow 1977
Tornqvist, Z. Phys. C61,525 (1993)

Z_b-s sit 3 MeV above the BB* and B*B* thresholds

X(3872) sits at the DD* threshold

strong hints in favor of the molecular interpretation

what about the Z_c(3900)?

Heavy-light Qq mesons have I=1/2

→ they couple to pions

→ deuteron-like meson-meson bound states, "deusons"

via pion exchange – no D Dbar, only D Dbar*

$D\bar{D}^*$ (I=0) at threshold ←→ X(3872) !

S-wave → $J^P = 1^+$

I=1 attraction x3 weaker than I=0

→ I=1 expected well above threshold

What about B B-bar* analogue ?...

B B* vs D D*:
-- same attractive potential
-- much heavier, so smaller kinetic energy
→ expect $B\bar{B}^*$ and $B^*\bar{B}^*$ I=1 states near threshold

→ $Z_b(10610)$ and $Z_b(10650)$ seen by Belle !!!

I=0 binding much stronger
→I=0 states expected well <u>below</u> threshold

EXP signature:
Z_b(I=0) → Υ(ns) $\pi_+ \pi_-$
Z_b(I=0) → B B-bar γ via EM B* → B γ, E(γ)=46 MeV → **LHCb!**

in the M_Q → ∞ limit attractive potential between the two heavy mesons becomes universal

Kinetic E ~ p^2/M_Q → 0

→ treat kinetic E as perturbation

$$H = a \cdot p^2 + V(r) \qquad \text{where } a \equiv 1/2\mu_{\rm red}$$

convert the parameter $a \sim 1/M_Q$ into a dimensionless parameter $\tilde{a}$

"natural" unit of $\sim$ 0.8 Fermi $\sim$ 4.0 GeV^{-1}

With $m_D \sim 2\,\mathrm{GeV}$ and $m_B \sim 5.3\,\mathrm{GeV}$

$\tilde{a}(D) = 1/8$ $\tilde{a}(B) = 1/21$

→ small: can use 1-st order P.T.

for I=1 potential have 2 data points:

$Z_c(3900)$ at $\tilde{a}(D)$ approximately $27\,\mathrm{MeV}$ above $\bar{D}D^*$ threshold

$Z_b(10610)$ at $\tilde{a}(B)$ approximately $3\,\mathrm{MeV}$ above $\bar{B}B^*$ threshold

Linear extrapolation to $\tilde{a} = 0$ yields

$$E_b^{I=1}(\tilde{a}=0) \approx -11.7\,\text{MeV}$$

In view of the convexity, the actual binding energy likely to slightly exceed this linear extrapolation

→ use this result for the isovector channel to estimate the $\bar{B}B^*$ binding in the isoscalar channel

Assuming that the isoscalar binding energy in the $m_Q \to \infty$ limit is 3 times larger than for the isovector,

$$E_b^{I=0}(\tilde{a}=0) \approx 3 \cdot (-11.7) = -35\,\text{MeV}$$

$X(3872)$ at $\bar{D}D^*$ threshold → $E_b^{I=0}(\tilde{a}(D)) \approx 0$

Linear extrapolation to $\tilde{a}(B)$ yields $\bar{B}B^*$ binding energy in the isoscalar channel $\approx -20\,\text{MeV}$

Heavy Quark Nuclear Physics!

the newly discovered $Z_c(3900)$ isovector resonance confirms and refines the estimates for the mass of the putative $\bar{B}B^*$ isoscalar bound state.

immediately leads to several predictions:

– two I=0 narrow resonances in bottomonium system, ~23 MeV below Z_b(10610) and Z_b(10650), i.e. ~20 MeV below BB* and B*B* thresholds

– I=0 resonance near D* Dbar* threshold

– I=1 resonance slightly above D* Dbar* threshold the newly discovered $Z_c(3900)$ isovector resonance confirms and refines the estimates for the mass of the putative $\bar{B}B^*$ isoscalar bound state.

immediately leads to several predictions:

– two I=0 narrow resonances in bottomonium system,
~23 MeV below Z_b(10610) and Z_b(10650), i.e.
~20 MeV below BB* and B*B* thresholds

– I=0 resonance near D* Dbar* threshold

– I=1 resonance slightly above D* Dbar* threshold
reported Aug 13 by BES, arXiv:1308.2760
Z_c{+-}(4025): M=4026.3+-2.6+-3.7 MeV,
Γ=24.8+-5.6+-7.7

Likely observable at LHC and Tevatron:

Guo, Meißner & Wang, arXiv:1308.0193

~ nb x-section for Z_b(10610) and Z_b(10650)

x-section for Z_c(3900) and Z_c(4020)
larger by a factor of 20-30

large enough to be observed

x-section for neutral exotic states ?

$\Sigma_b^+ \Sigma_b^-$ dibaryon ?

Σ_b heavier, with I=1 → stronger binding via π

→ deuteron-like J=1, I=0 bound state: "beautron"

exp. signature:

(Σ_b Σ_b) → Λ_b Λ_b π π

Γ(Σ_b) = 4.3+-3 MeV, Γ(Σ_b) = 9.2+-3 MeV

- +

so might be visible

should be seen in lattice QCD

doubly heavy baryons QQq (bbq,ccq, bcq)

– not exotic, must exist

– excellent challenge for EXP (LHCb!)
  (bbq) → (cc*s) (cc*s) q → J/Ψ J/Ψ Ξ
  unique signature, w/o background

– QQq and QQq*q* have the same color structure

→ once QQq mass is known, can immediately
  predict QQq*q* mass:

$$m(cc\bar{u}\bar{d}) = m(\Xi_{ccu}) + m(\Lambda_c) - m(D^0) - \frac{1}{4}[m(D^*) - m(D)]$$

Summary

- a simple and consistent picture emerges from Belle and BES data:
- the new exotic resonances are loosely bound states of DD*, D*D*, BB* and BB*
- prediction: $\bar{D}^* D^*$ resonances in I=0 and I=1 channels seen!
- predictions: new I=0 BB* and B*B* states below threshold
- heavy “deuteron”: $\Sigma_b \Sigma_b$
- challenge for EXP: doubly heavy baryons QQq (LHCb?)
- QQq → accurate prediction for QQq*q* tetraquark
- challenge for TH: derive from QCD