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Pentaquarks, doubly heavy exotic mesons and baryons and how to look for them

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outline

- exciting pentaquark results from LHCb

- to understand, view in wider context

→ exotic hadrons with two heavy quarks.

- QCD allows exotic states beyond qqq and $\bar{q}q$

- but:

  - mixing with ordinary excited hadrons

  - production rates often suppressed

  - rapid decay into f.s. with π-(s)

    $\Rightarrow$ very broad

- explains why light exotics so hard to pin down

- situation very different for $\bar{Q}Q\bar{q}q$ exotics:

- $\bar{Q}Q$ hardly mix with light quarks

- decay into quarkonium and π-(s) or two heavy-light mesons:

$$\bar{Q}Q\bar{q}q \to \bar{Q}Q\,\pi$$
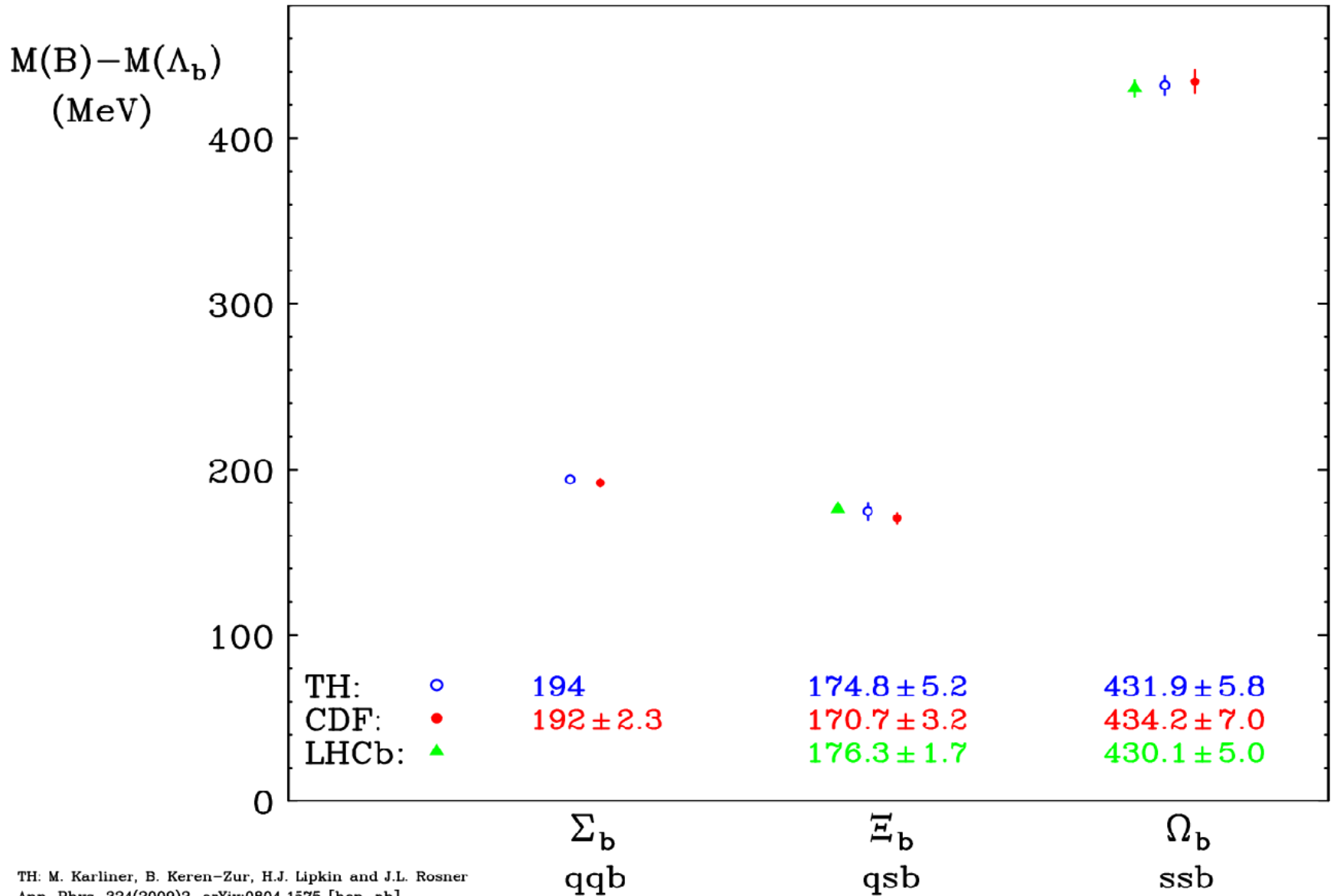
$$\bar{Q}Q\bar{q}q \to (\bar{Q}q)\,(Q\bar{q})$$

$\Rightarrow$ clear signature of exotic nature

hadrons w. heavy quarks are *much simpler:*

- heavy quarks almost static

- very small spin-dep. interaction $\propto 1/m_Q$

- key to accurate prediction of b quark baryons:

b−baryons spectrum − TH predictions vs EXP

$M(B)-M(\Lambda_b)$ (MeV)

400

300

200

100

0

		Σ_b	Ξ_b	Ω_b
TH:	○	194	174.8 ± 5.2	431.9 ± 5.8
CDF:	●	192 ± 2.3	170.7 ± 3.2	434.2 ± 7.0
LHCb:	▲		176.3 ± 1.7	430.1 ± 5.0

Σ_b Ξ_b Ω_b
qqb   qsb   ssb

TH: M. Karliner, B. Keren−Zur, H.J. Lipkin and J.L. Rosner
Ann. Phys. 324(2009)2, arXiv:0804.1575 [hep−ph]

Possibility of Exotic States in the Upsilon system

Marek Karliner[a*]
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 $T_{\bar{c}c}^{\pm}$. The analogous state $T_{\bar{b}b}^{\pm}$ in the bottom sector might mediate anomalously large cascade decays in the Upsilon system, $\Upsilon(mS) \to T_{\bar{b}b}^{\pm}\pi^{\mp} \to \Upsilon(nS)\,\pi^+\pi^-$, 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

Abstract

We report the observation of two narrow structures at $10610 \, \text{MeV}/c^2$ and $10650 \, \text{MeV}/c^2$ 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 $M_1 = 10608.4 \pm 2.0 \, \text{MeV}/c^2$, $\Gamma_1 = 15.6 \pm 2.5 \, \text{MeV}$ and $M_2 = 10653.2 \pm 1.5 \, \text{MeV}/c^2$, $\Gamma_2 = 14.4 \pm 3.2 \, \text{MeV}$. Analysis favors quantum numbers of $I^G(J^P)$=$1^+(1^+)$ for both states. The results are obtained with a $121.4 \, \text{fb}^{-1}$ data sample collected with the Belle detector near the $\Upsilon(5S)$ resonance at the KEKB asymmetric-energy e^+e^- collider.

5 narrow exotic states close to meson-meson thresholds

state	mass MeV	width MeV	$\bar{Q}Q$ decay mode	phase space MeV	nearby threshold	ΔE MeV
$X(3872)$	3872	< 1.2	$J/\psi\,\pi^+\pi^-$	495	$\bar{D}D^*$	< 1
$Z_b(10610)$	10608	21	$\Upsilon\pi$	1008	$\bar{B}B^*$	2 ± 2
$Z_b(10650)$	10651	10	$\Upsilon\pi$	1051	$\bar{B}^*B^*$	2 ± 2
$Z_c(3900)$	3900	$24 - 46$	$J/\psi\,\pi$	663	$\bar{D}D^*$	24
$Z_c(4020)$	4020	$8 - 25$	$J/\psi\,\pi$	783	$\bar{D}^*D^*$	6
×					$\bar{D}D$	
×					$\bar{B}B$	

- masses and widths approximate
- quarkonium decays mode listed have max phase space
- offset from threshold for orientation only, v. sensitive to exact mass

exotic heavy quarkonia vs. two meson thresholds
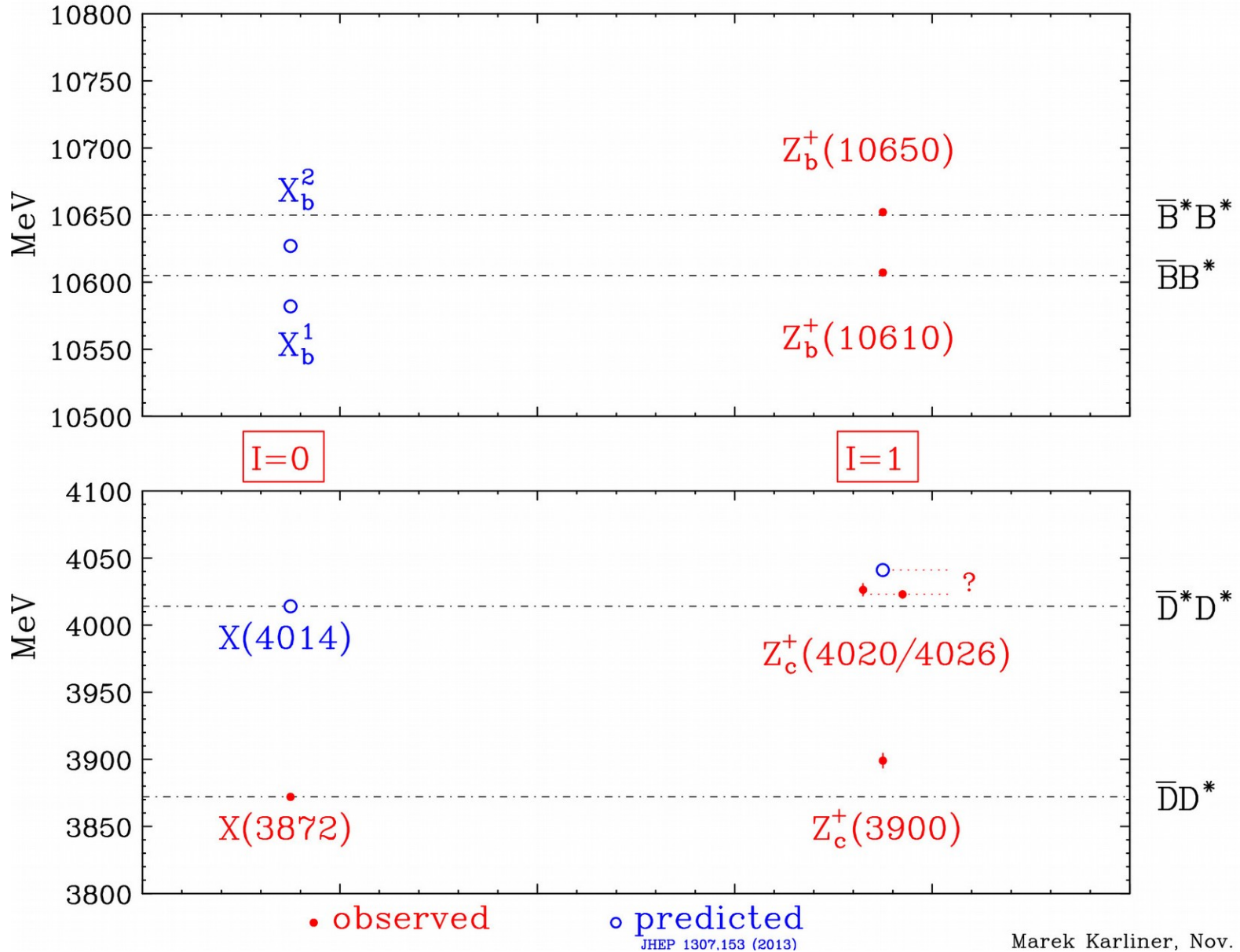
The Z_Q resonances decay into

$\bar{Q}Q\,\pi$

$\Longrightarrow$ must contain both $\bar{Q}Q$ and $\bar{q}q$, $\quad q = u, d$

$\Longrightarrow$ manifestly exotic

$X(3872)$: a mixture of $\bar{D}D^*$ and $\chi_{c1}(2P)$

tetraquarks or a "hadronic molecules" ?

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

all states close to two-meson thresholds

despite large phase space (hundreds of MeV)
narrow widths in decays into $\bar{Q}Q\,\pi$

$\Longrightarrow$ very small overlap of wave functions: $|\langle i|f\rangle|^2 \ll 1$

strong hint in favor of molecular interpretation

$$\frac{\Gamma(Z_c(3885) \to \bar{D}D^*)}{\Gamma(Z_c(3885) \to J/\psi\pi)} = 6.2 \pm 1.1 \pm 2.7$$

(BESIII/Yu-Ping Guo @EQCD, Jinan 6/2015)

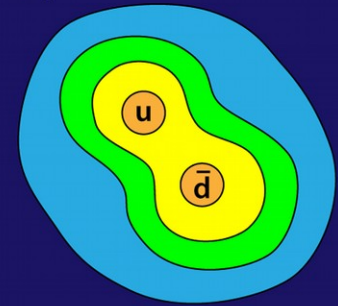overlap of Z_c wave function with $J/\psi\pi$ much smaller than with $\bar{D}D$

$\Rightarrow$ indicates an extended object

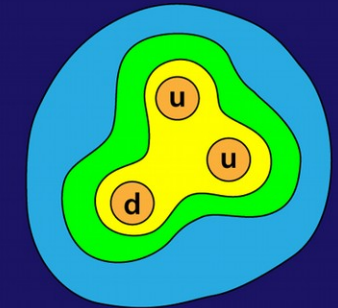new result from Belle
(analysis by Alexei Garmash):

$$\frac{\Gamma(Z_b(10610) \to \bar{B}B)}{\Gamma(Z_b(10610) \to \Upsilon(1S)\pi)} \approx \frac{83\%}{0.6\%} = \mathcal{O}(100)$$

despite 1000 MeV of phase space

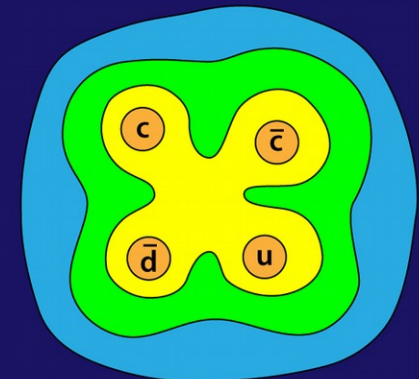for $\Upsilon(1S)\pi$ vs few MeV for $\bar{B}B^*$!

a) pion

b) proton

c) $Z_c(3900)$

BR-s of $X(3872)$ to J/ψ and pions vs "fall apart" mode $\bar{D}D^*$

$$\text{BR}(\bar{D}D^*) \sim 10\times \text{BR}(\,J/\psi + X)$$
despite -1 MeV vs $400-500$ MeV phase space

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

$X(3872)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$e^+ e^-$	
Γ_2	$\pi^+ \pi^- J/\psi(1S)$	$> 2.6\,\%$
Γ_3	$\rho^0 J/\psi(1S)$	
Γ_4	$\omega J/\psi(1S)$	$> 1.9\,\%$
Γ_5	$D^0 \overline{D}^0 \pi^0$	$>32\ \%$
Γ_6	$\overline{D}^{*0} D^0$	$>24\ \%$

4 pieces of experimental evidence in support of molecular interpretation of Z_Q and $X(3872)$:

1. masses near thresholds and J^P of S-wave

2. narrow width despite very large phase space

3. BR(fall apart mode) $\gg$ BR(quarkonium $+ X$)

4. no states which require binding through 3 pseudoscalar coupling

binding two hadrons through π exchange[†]:

explains conspicous absence of $\bar{D}D$ and $\bar{B}B$ resonances

e.g. $\bar{D}D$ resonance through π would require $DD\pi$ vertex. But 3-pseudoscalar vertex is forbidden in QCD by parity conservation.

another way to understand why no $D \to D\pi$: $J^P = 0^-$, so parity demands $D \to D\pi$ in P-wave; but D and π in P-wave give $J = 1$

π = shorthand for a light pseudoscalar, not necessarily physical pion

On the other hand, $\bar{D}D^*$ OK:

$\bar{D} \to \bar{D}^* + \pi$

$D^* + \pi \to D$

so $\bar{D}D^* \to \bar{D}^*D$ and $\bar{D}^*D \to \bar{D}D^*$

physical state $= (\bar{D}D^* + \bar{D}^*D)/\sqrt{2}$

goes into itself under π exchange

$\bar{D}*D^*$ also OK:

$D^* \to D^* + \pi$, P-wave

$L = 1$ can combine with $S = 1$ to give back $J = 1$;

same for D^*, so $\bar{D}^*D^* \to \bar{D}^*D^*$

Heavy-liqht $Q\bar{q}$ mesons have $I = 1$

$\Rightarrow$ they couple to pions; $m_{Q\bar{q}} \gg m_N$

$\Rightarrow$ deutron-like meson-meson bound states, "*deusons*"

pion exchange $\rightarrow$ no $\bar{D}D$, only $\bar{D}D^*$, $\bar{D}^*D^*$

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

S-wave $\rightarrow$ $J^P = 1^+$, confirmed by BESIII

$I = 1$: $3\times$ weaker than $I = 0$

$\Rightarrow$ $I = 1$ well above threshold

What about $\bar{B}B^*$ analogue ?....

$\bar{B}B*$ vs. $\bar{D}D^*$:

- same attractive potential
- much heavier, so smaller kinetic energy

$\Rightarrow$ expect $\bar{B}B^*$ and $\bar{B}^*B^*$ states near threshold

$\Rightarrow$ $Z_b(10610)$ and $Z_b(10650)$ seen by Belle !

- $I = 0$ much stronger than $I = 1$

$\Rightarrow$ $I = 0$ states expected well <u>below</u> thresholds

EXP signature:

$$X_b^{(*)}(I = 0) \to \Upsilon(nS)\,\omega, \quad \chi_b \pi^+ \pi^-$$

perhaps also

$$X_b^*(I = 0) \to \bar{B}B^*\gamma \quad \text{via } \bar{B}^* \to \bar{B}\gamma$$

$\Rightarrow$ LHCb !

an amusing paper from CMS: null result in search for

$$X_b \rightarrow Y(1S)\pi^+\pi^-$$

is excellent news for the molecular picture,

since isoscalar X_b with $J^{PC} = 1^{++}$

cannot decay into $\Upsilon(1S)\pi^+\pi^-$

It can decay into $\Upsilon(1S)\omega$ or $\chi_b\pi^+\pi^-$

X_b as mixture of $\bar{B}B^*$ (1^{++}) and $\chi_b(3P)$

$$R_{\psi\gamma} \equiv \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29 \text{ [LHCb]}$$

suggests that $X(3872)$ is a mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{*0}$

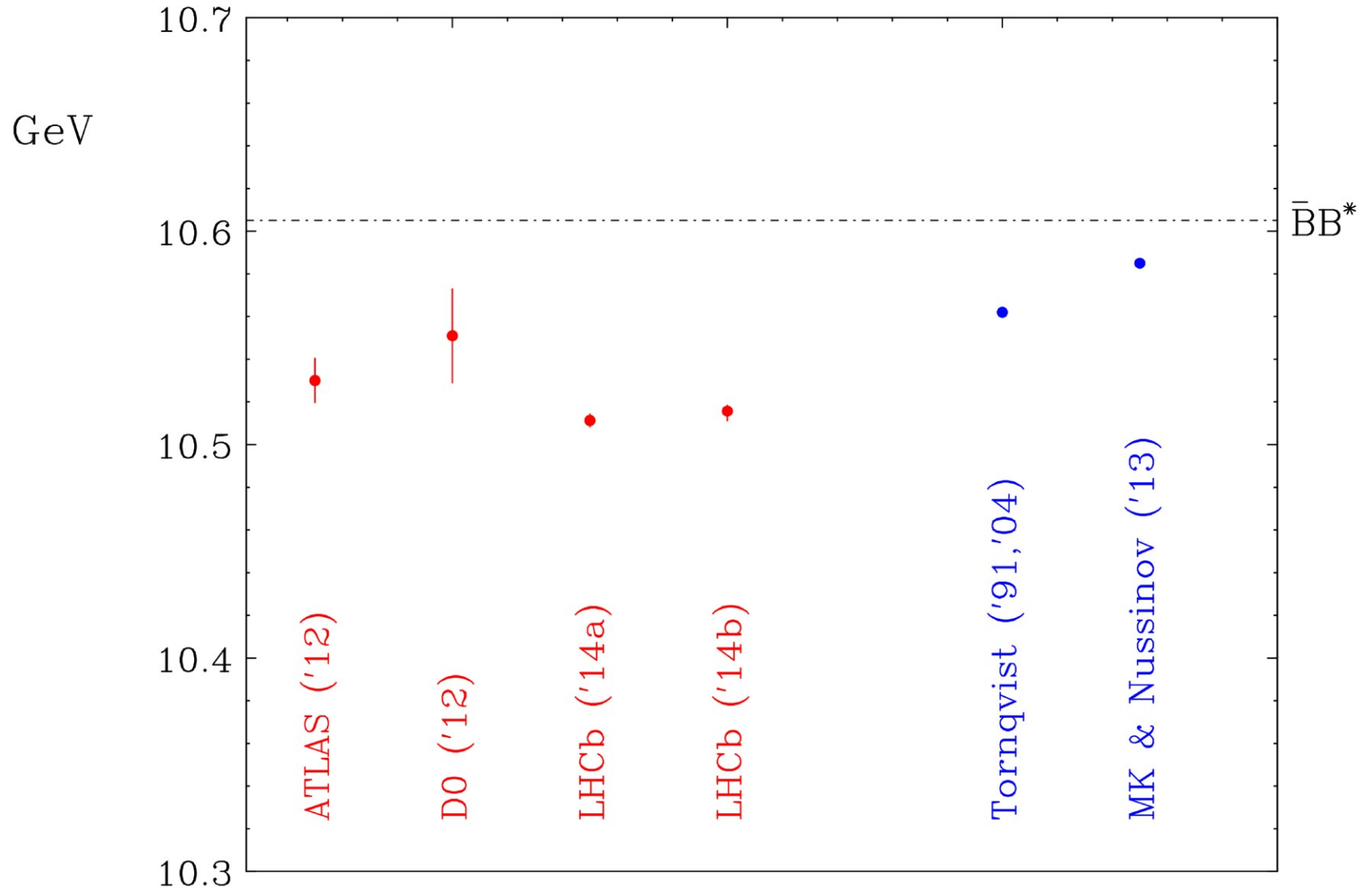In the bottomonium system $\chi_{b1}(2P)$ is much too light, but $\chi_{b1}(3P)$ is near the expected X_b mass.
Seen in $\chi_{b1}(3P) \to \Upsilon(mS)\gamma, \ m = 1, 2, 3$

Values of $M(\chi_{b1}(3P))$ observed in various experiments.

Collaboration	Reference	Value (MeV/c^2)
ATLAS	[17]	$10530 \pm 5 \pm 9$
D0	[18]	$10551 \pm 14 \pm 17$
LHCb (a)	[19]	$10511.3 \pm 1.7 \pm 2.5$
LHCb (b)	[20]	$10515.7^{+2.2+1.5}_{-3.9-2.1}$

$\chi_b(3P)$ mass   vs. X_b mass predictions*

GeV

10.7

10.6 — $\bar{B}B^*$

10.5

10.4

10.3

ATLAS ('12)   D0 ('12)   LHCb ('14a)   LHCb ('14b)   Tornqvist ('91,'04)   MK & Nussinov ('13)

*a biased sample

- X_b and $\chi_{1b}(3P)$ have the same quantum numbers

- their masses are close

$\Rightarrow$ mixing is inevitable

$\Longrightarrow$
X_b might have been seen already,
by ATLAS, D0 and LHCb,
camouflaging as $\chi_{1b}(3P)$

necessary[*] conditions for existence of a resonance

(a) <u>both</u> hadrons heavy, as $E_{kin} \sim 1/\mu_{RED}$

(b) both couple to pions;
     one of them can have $I = 0$, e.g.
     $$\Sigma_c \bar{\Lambda}_c \xrightarrow{\pi} \Lambda_c \bar{\Sigma}_c.$$
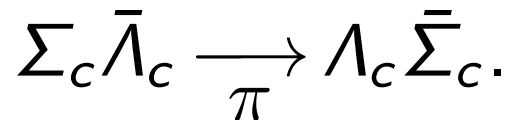
(c) spin & parity which allow the state
     go into itself under one π exchange

(d) $\Gamma(h_1) + \Gamma(h_2) \ll \Gamma(\text{molecule})$

---

[*]may not be sufficient

the binding mechanism can in principle

apply to any two heavy hadrons

which couple to isospin

and satisfy these conditions,

be they mesons or baryons

π exchange between two states with I_1, I_2 and S_1, S_2:

$$V_{\text{eff}} \sim \pm (I_1 \cdot I_2)(S_1 \cdot S_2) \qquad \text{for } (qq, q\bar{q}) \ ,$$

q or $\bar{q}$:
light quark(s) or antiquark(s) in hadrons 1 and 2,

- applies as long as the total spins S_i are correlated with the direction of the light-quark spins.

- true for D^*, B^*, Σ_c, and Σ_b

doubly-heavy hadronic molecules:
most likely candidates with $Q\bar{Q}'$, $Q = c, b$, $\bar{Q}' = \bar{c}, \bar{b}$:

$D\bar{D}^*$, $D^*\bar{D}^*$, D^*B^*, $\bar{B}B^*$, $\bar{B}^*B^*$,

$\Sigma_c\bar{D}^*$, Σ_cB^*, $\Sigma_b\bar{D}^*$, Σ_bB^*, the lightest of new kind

$\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, and $\Sigma_b\bar{\Lambda}_c$.

$c\bar{c}$ and $b\bar{b}$ states decay strongly to $\bar{c}c$ or $\bar{b}b$ and π-(s)
$b\bar{c}$ and $c\bar{b}$ states decay strongly to $B_c^{\pm}$ and π-(s)

QQ' candidates – dibaryons:

$\Sigma_c\Sigma_c$, $\Sigma_c\Lambda_c$, $\Sigma_c\Lambda_b$, $\Sigma_b\Sigma_b$, $\Sigma_b\Lambda_b$, and $\Sigma_b\Lambda_c$.

prediction of doubly heavy baryon with hidden charm:

$$\Sigma_c \bar{D}^* \equiv \Theta_{\bar{c}c}, \quad m_{\Theta_{\bar{c}c}} \approx 4460 \text{ MeV},$$

possible decay mode: $\Theta_{cc} \to J/\psi\, p$

$(S_1 \cdot S_2)\,(I_1 \cdot I_2)$ interaction: $I = 1/2 \to J = 3/2$

S-wave $\to J^P = 3/2^-$

small overlap of molecular state with $J/\psi p$
$\Longrightarrow$ narrow width $\lesssim$ few tens of MeV
despite > 400 MeV phase space

$\Theta_{\bar{c}c}$ minimal quark content: $\bar{c}c\, uud$

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$\Theta_{\bar{c}c}$ minimal quark content: $\bar{c}c\,uud \equiv P_c(4450)$

a molecule, not a tightly-bound pentaquark

Thresholds for $Q\bar{Q}'$ molecular states

Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	Example of decay mode
$D\bar{D}^*$	0	$c\bar{c}q\bar{q}$	3875.8	$J/\psi\,\pi\pi$
$D^*\bar{D}^*$	0	$c\bar{c}q\bar{q}$	4017.2	$J/\psi\,\pi\pi$
D^*B^*	0	$c\bar{b}q\bar{q}$	7333.8	$B_c^+\pi\pi$
$\bar{B}B^*$	0	$b\bar{b}q\bar{q}$	10604.6	$\Upsilon(nS)\pi\pi$
$\bar{B}^*B^*$	0	$b\bar{b}q\bar{q}$	10650.4	$\Upsilon(nS)\pi\pi$
$\Sigma_c\bar{D}^*$	1/2	$c\bar{c}qqq'$	4462.4	$J/\psi\,p$
Σ_cB^*	1/2	$c\bar{b}qqq'$	7779.5	B_c^+p
$\Sigma_b\bar{D}^*$	1/2	$b\bar{c}qqq'$	7823.0	B_c^-p
Σ_bB^*	1/2	$b\bar{b}qqq'$	11139.6	$\Upsilon(nS)p$
$\Sigma_c\bar{\Lambda}_c$	1	$c\bar{c}qq'\bar{u}\bar{d}$	4740.3	$J/\psi\,\pi$
$\Sigma_c\bar{\Sigma}_c$	0	$c\bar{c}qq'\bar{q}\bar{q}'$	4907.6	$J/\psi\,\pi\pi$
$\Sigma_c\bar{\Lambda}_b$	1	$c\bar{b}qq'\bar{u}\bar{d}$	8073.3[d]	$B_c^+\pi$
$\Sigma_b\bar{\Lambda}_c$	1	$b\bar{c}qq'\bar{u}\bar{d}$	8100.9[d]	$B_c^-\pi$
$\Sigma_b\bar{\Lambda}_b$	1	$b\bar{b}qq'\bar{u}\bar{d}$	11433.9	$\Upsilon(nS)\pi$
$\Sigma_b\bar{\Sigma}_b$	0	$b\bar{b}qq'\bar{q}\bar{q}'$	11628.8	$\Upsilon(nS)\pi\pi$

[a]Ignoring annihilation of quarks.   [b]Plus other charge states when $I \neq 0$.

[c]Based on isospin-averaged masses.   [d]Thresholds differ by 27.6 MeV.

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New Exotic Meson and Baryon Resonances from Doubly-Heavy Hadronic Molecules

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ABSTRACT

We predict several new exotic doubly-heavy hadronic resonances, inferring from the observed exotic bottomonium-like and charmonium-like narrow states $X(3872)$, $Z_b(10610)$, $Z_b(10650)$, $Z_c(3900)$, and $Z_c(4020/4025)$. We interpret the binding mechanism as mostly molecular-like isospin-exchange attraction between two heavy-light mesons in a relative S-wave state. We then generalize it to other systems containing two heavy hadrons which can couple through isospin exchange. The new predicted states include resonances in meson-meson, meson-baryon, baryon-baryon, and baryon-antibaryon channels. These include those giving rise to final states involving a heavy quark $Q = c, b$ and antiquark $\bar{Q}' = \bar{c}, \bar{b}$, namely $D\bar{D}^*$, $D^*\bar{D}^*$, D^*B^*, $\bar{B}B^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$, Σ_cB^*, $\Sigma_b\bar{D}^*$, Σ_bB^*, $\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, and $\Sigma_b\bar{\Lambda}_c$, as well as corresponding S-wave states giving rise to QQ' or $\bar{Q}\bar{Q}'$.

arXiv:1507.03414v1 [hep-ex] 13 Jul 2015

Observation of $J/\psi\, p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays

The LHCb collaboration[1]

Abstract

Observations of exotic structures in the $J/\psi p$ channel, that we refer to as pentaquark-charmonium states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions. An amplitude analysis is performed on the three-body final-state that reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

PHYSICAL REVIEW LETTERS

New Exotic Meson and Baryon Resonances from Doubly Heavy Hadronic Molecules

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(Received 13 July 2015; published 14 September 2015)

We predict several new exotic doubly heavy hadronic resonances, inferring from the observed exotic bottomoniumlike and charmoniumlike narrow states $X(3872)$, $Z_b(10610)$, $Z_b(10650)$, $Z_c(3900)$, and $Z_c(4020/4025)$. We interpret the binding mechanism as mostly molecularlike isospin-exchange attraction between two heavy-light mesons in a relative S-wave state. We then generalize it to other systems containing two heavy hadrons which can couple through isospin exchange. The new predicted states include resonances in meson-meson, meson-baryon, baryon-baryon, and baryon-antibaryon channels. These include those giving rise to final states involving a heavy quark $Q = c, b$ and antiquark $\bar{Q}' = \bar{c}, \bar{b}$, namely, $D\bar{D}^*$, $D^*\bar{D}^*$, D^*B^*, $\bar{B}B^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$, Σ_cB^*, $\Sigma_b\bar{D}^*$, Σ_bB^*, $\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, and $\Sigma_b\bar{\Lambda}_c$, as well as corresponding S-wave states giving rise to QQ' or $\bar{Q}\bar{Q}'$.

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)

Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions. An amplitude analysis of the three-body final state reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

M. Karliner, Doubly heavy hadrons & exotics   HEP2016, Jan 6

arXiv:1506.06386v1 [hep-ph] 21 Jun 2015

arXiv:1507.03414v1 [hep-ex] 13 Jul 2015

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ABSTRACT

We predict several new exotic doubly-heavy hadronic resonances, inferring from the observed exotic bottomonium-like and charmonium-like narrow states $X(3872)$, $Z_b(10610)$, $Z_b(10650)$, $Z_c(3900)$, and $Z_c(4020/4025)$. We interpret the binding mechanism as mostly molecular-like isospin-exchange attraction between two heavy-light mesons in a relative S-wave state. We then generalize it to other systems containing two heavy hadrons which can couple through isospin exchange. The new predicted states include resonances in meson-meson, meson-baryon, baryon-baryon, and baryon-antibaryon channels. These include those giving rise to final states involving a heavy quark $Q = c, b$ and antiquark $\bar{Q}' = \bar{c}, \bar{b}$, namely $D\bar{D}^*$, $D^*\bar{D}^*$, D^*B^*, $\bar{B}B^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$, Σ_cB^*, $\Sigma_b\bar{D}^*$, Σ_bB^*, $\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, and $\Sigma_b\bar{\Lambda}_c$, as well as corresponding S-wave states giving rise to QQ' or $\bar{Q}\bar{Q}'$.

Observation of $J/\psi\,p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays

The LHCb collaboration[1]

Abstract

Observations of exotic structures in the $J/\psi p$ channel, that we refer to as pentaquark-charmonium states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions. An amplitude analysis is performed on the three-body final-state that reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

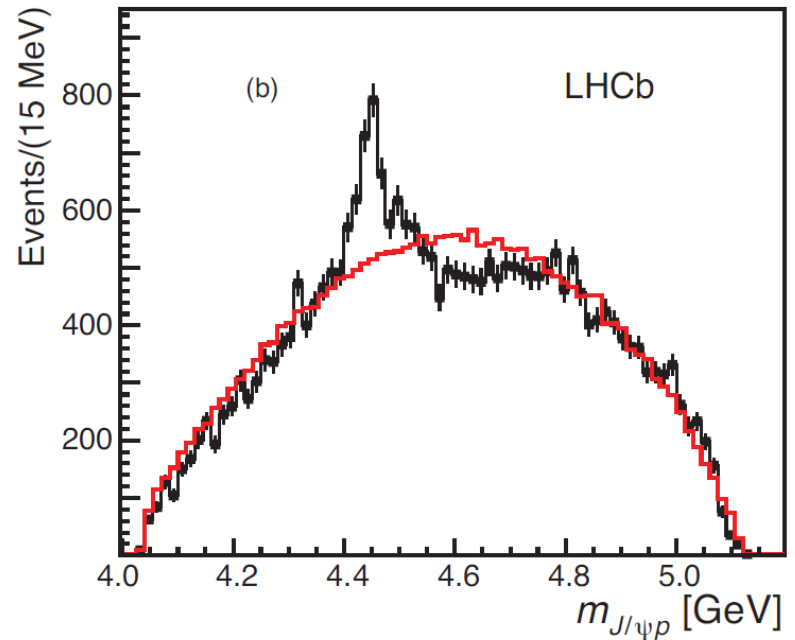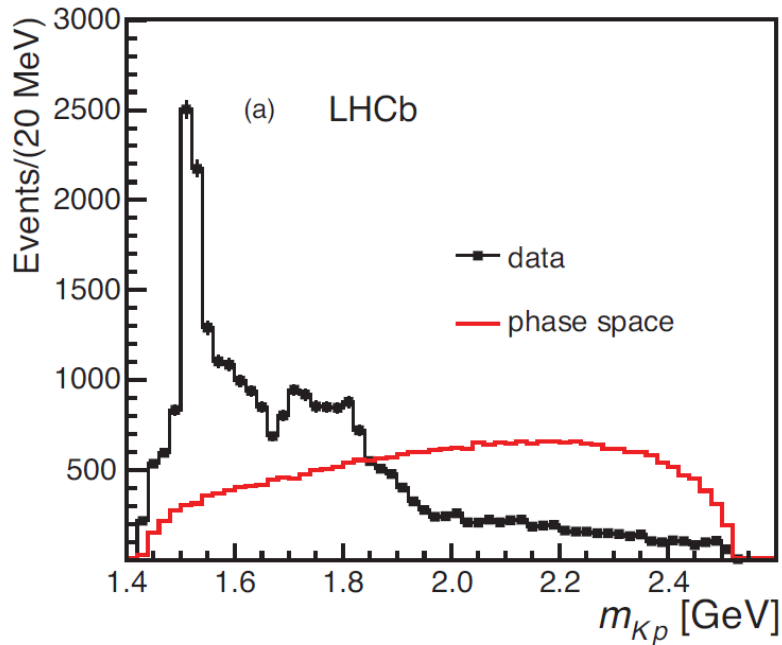Submitted to Phys. Rev. Lett.

$\Sigma_c\bar{D}^*$ threshold $= 4462$ MeV

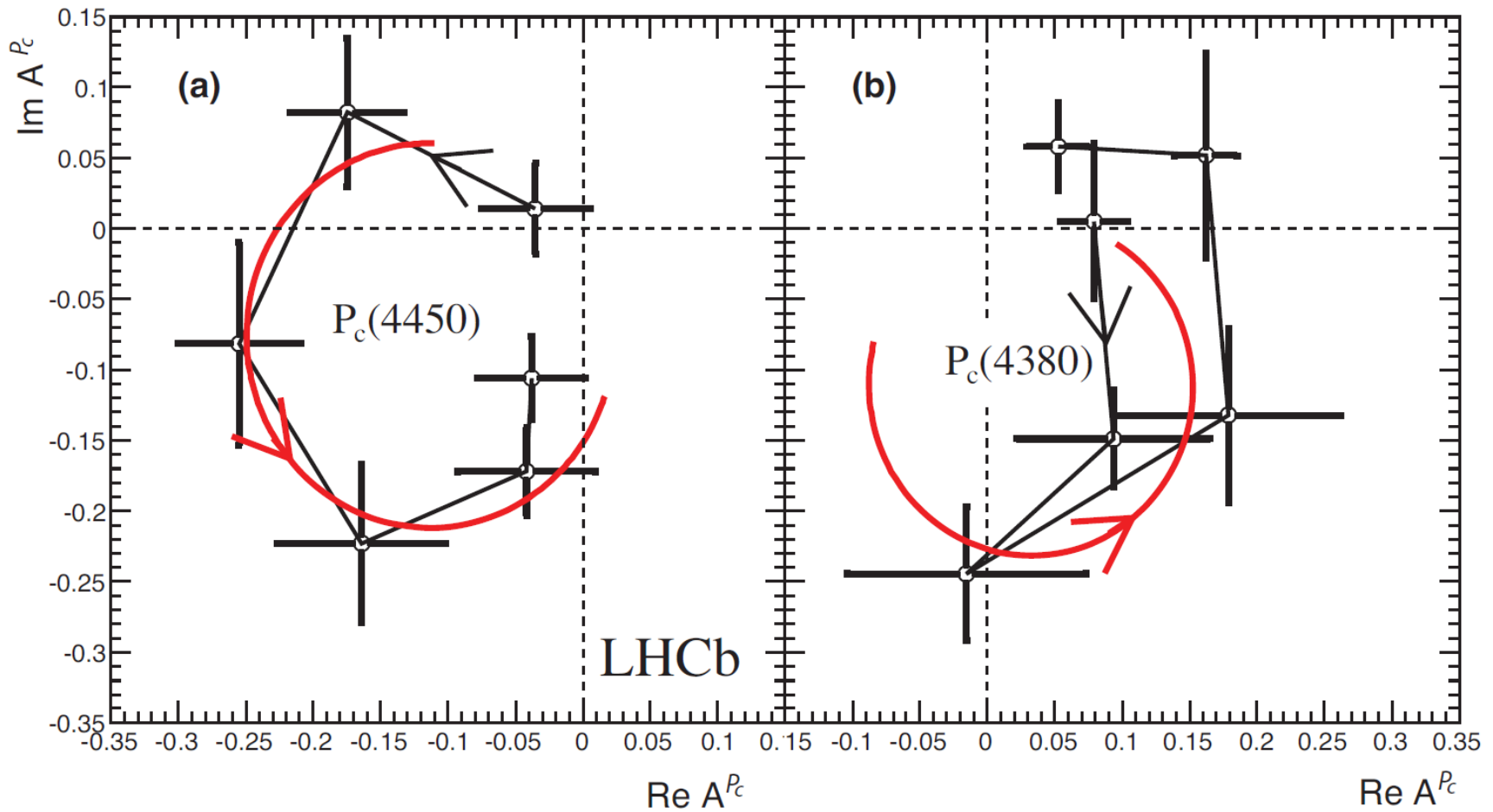narrow resonance at
$4449.8 \pm 1.7 \pm 2.5$ MeV
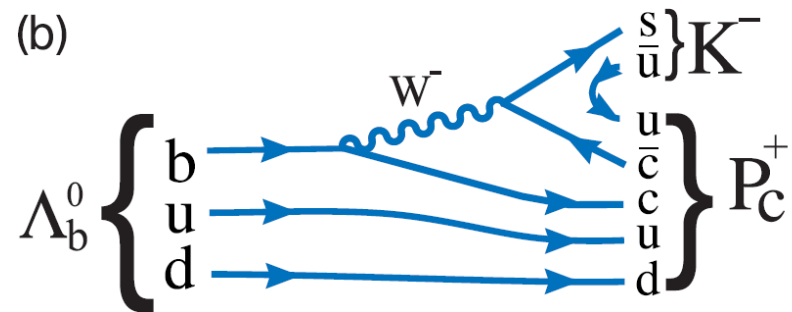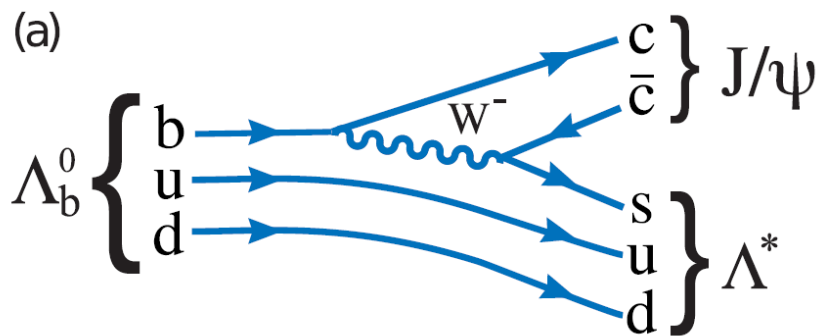
Feynman diagrams for (a) $\Lambda_b^0 \rightarrow J/\psi\, \Lambda^*$ and (b) $\Lambda_b^0 \rightarrow P_c^+ K^-$ decay.
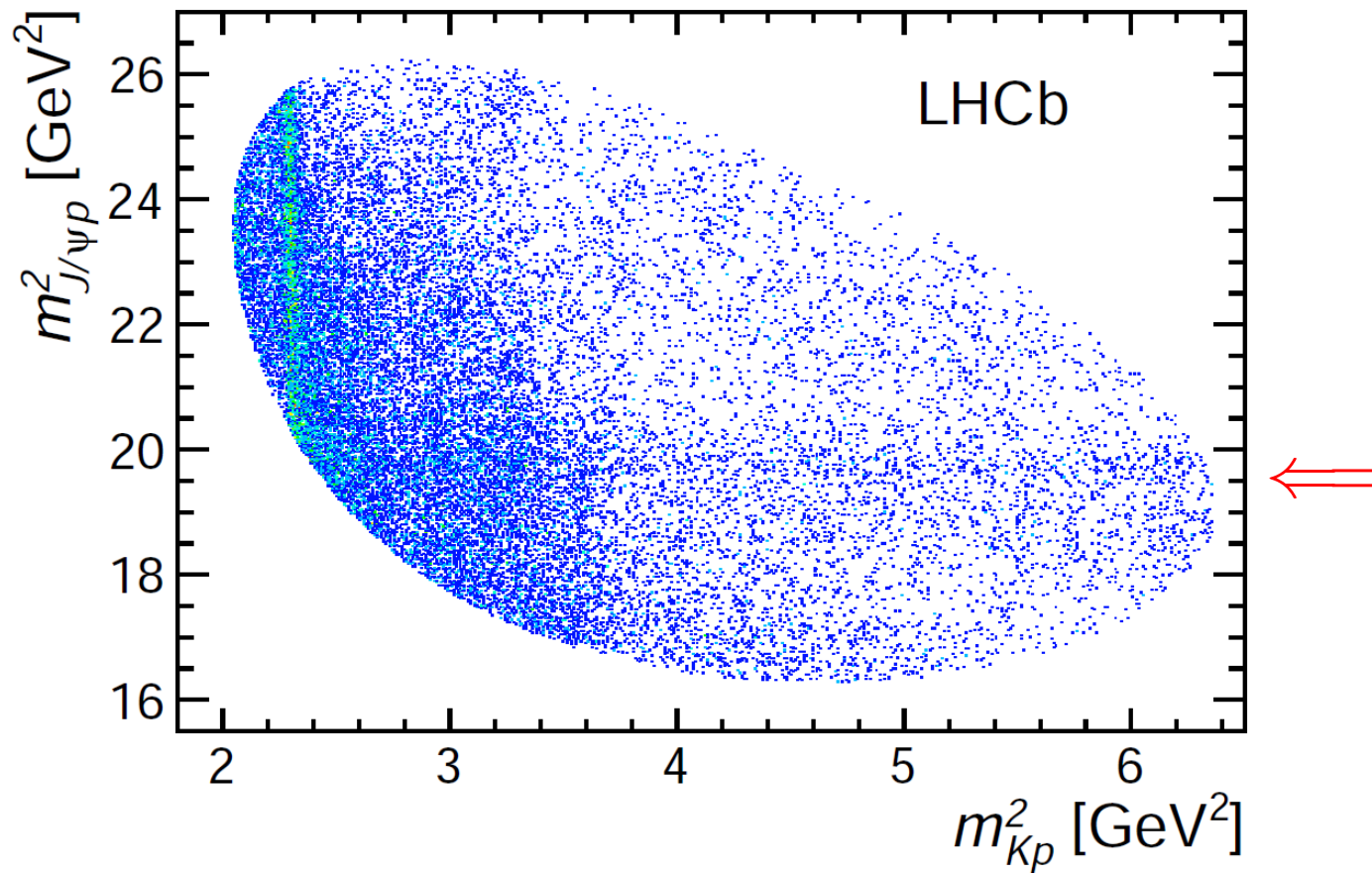
Invariant mass squared of $K^- p$ versus $J/\psi\, p$ for candidates within ± 15 MeV of the Λ_b^0

Invariant mass of (a) K^-p and (b) $J/\psi p$ combinations from $\Lambda_b^0 \to J/\psi K^- p$ decays. The solid (red) curve is the expectation from phase space. The background has been subtracted.

(a) $P_c(4450)$ LHCb

(b) $P_c(4380)$

$P_c(4450)$: predicted,
narrow: $\Gamma = 39 \pm 5 \pm 19$,
10 MeV from $\Sigma_c \bar{D}^*$ threshold
perfect Argand plot: a molecule

$P_c(4380)$: not predicted,
wide: $\Gamma = 205 \pm 18 \pm 86$ MeV,
Argand plot not resonance-like
???

The narrow width, 39 MeV, is a <u>problem for pentaquark</u>

interpretation, given the large phase space of 400 MeV

$$\Gamma\left(P_c(4450) \to J/\psi p\right) = \left|\langle P_c(4450)|J/\psi p\rangle\right|^2 \times (\text{phase space})$$
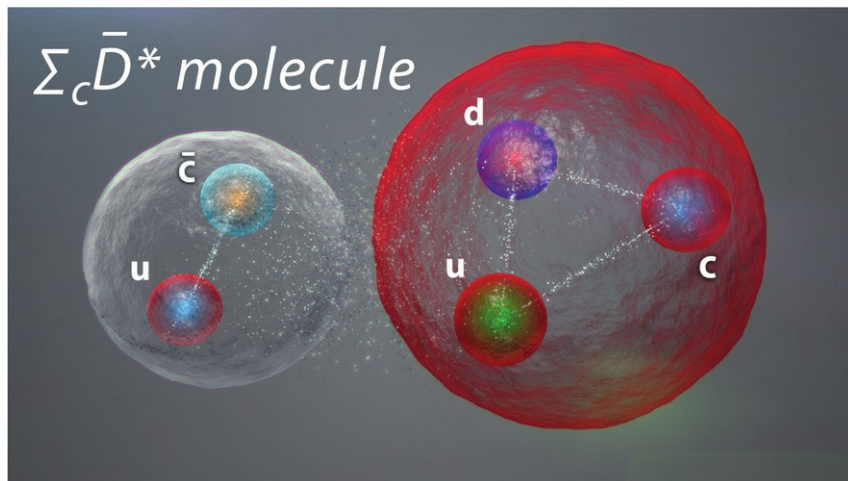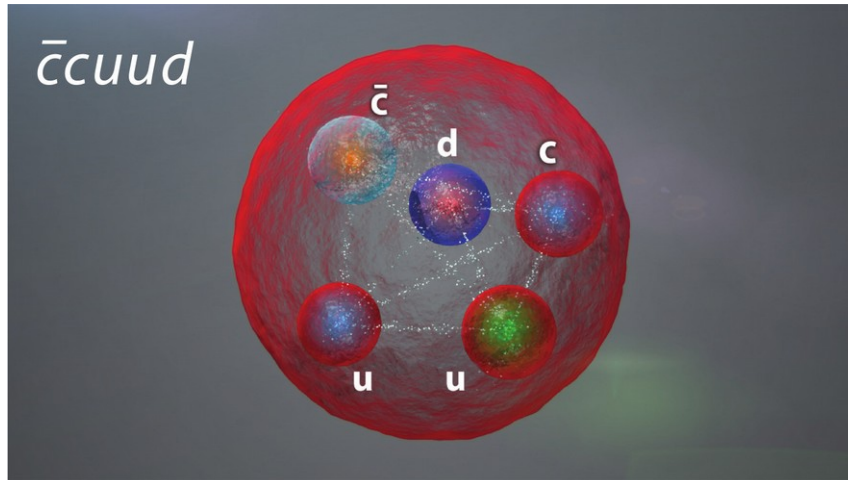
To get $\Gamma = 39$ MeV, the matrix element must be small .

But in a pentaquark c and $\bar{c}$ are close to each other

within the same confinement volume, so overlap with J/ψ

is generically large.

<u>In a molecule narrow width is automatic:</u>

c is in Σ_c, $\bar{c}$ is in $\bar{D}^*$; they are from each other,

so overlap with J/ψ is generically small.

Decay of a tightly bound pentaquark vs. hadronic molecule to $J/\psi p$
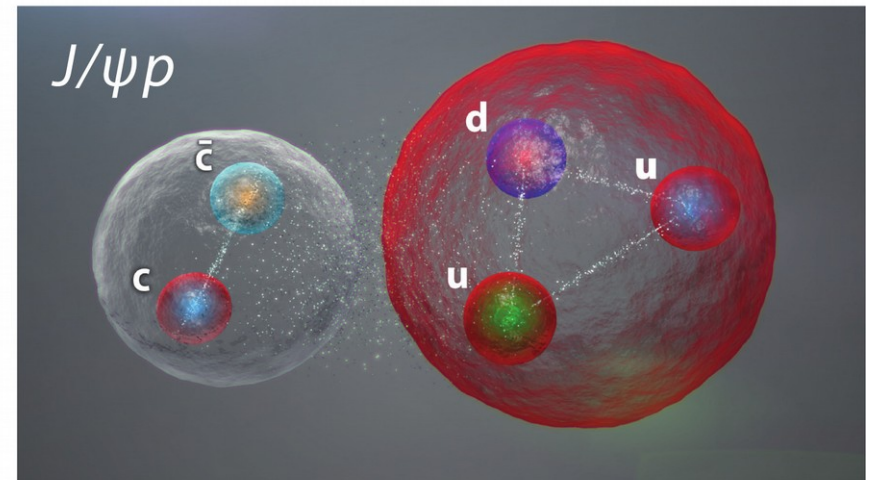
$$\left|\langle \Sigma_c \bar{D}^* \,|\, J/\psi p \rangle\right| \ll \left|\langle \bar{c}cuud \,|\, J/\psi p \rangle\right|$$

2 $J/\psi p$ resonances with $> 9\ \sigma$ in $\Lambda_b \to J/\psi p K^-$

$P_c(4450)$ very clean, but:

- $P_c(3380)$?

- J: $(3/2, 5/2)$ or $(5/2, 3/2)$?

- P: $(-, +)$ or $(+, -)$?

- $m(P_c(4450)) = m_p + m_{\chi_{c1}}$

- "triangle singularity"

$\implies$ need a different production mechanism

radii of hadronic molecules

$r(\Sigma_c \bar{D}^*) \ll r(X(3872))$:

in QM $r \approx 1/\sqrt{2\mu_{\mathrm{red}} \Delta E}$

$\Rightarrow r(X(3872)) \approx 4.4$ fm v. large, π-s dominate?

$\qquad r(\Sigma_c \bar{D}^*)\ \approx 1.2$ fm

at 1.2 fm the two hadrons overlap a bit

relative importance of π-s?

how does it work in b analogues?

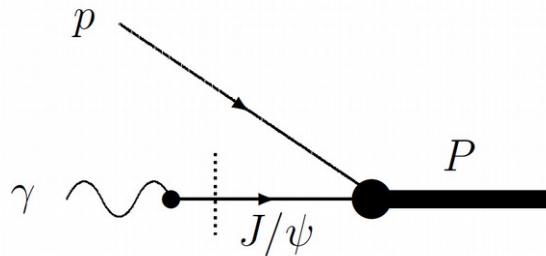# Photoproduction of exotic baryon resonances

MK & J. Rosner, arXiv:1508.01496
Q. Wang, X. H. Liu and Q. Zhao, arXiv:1508.00339
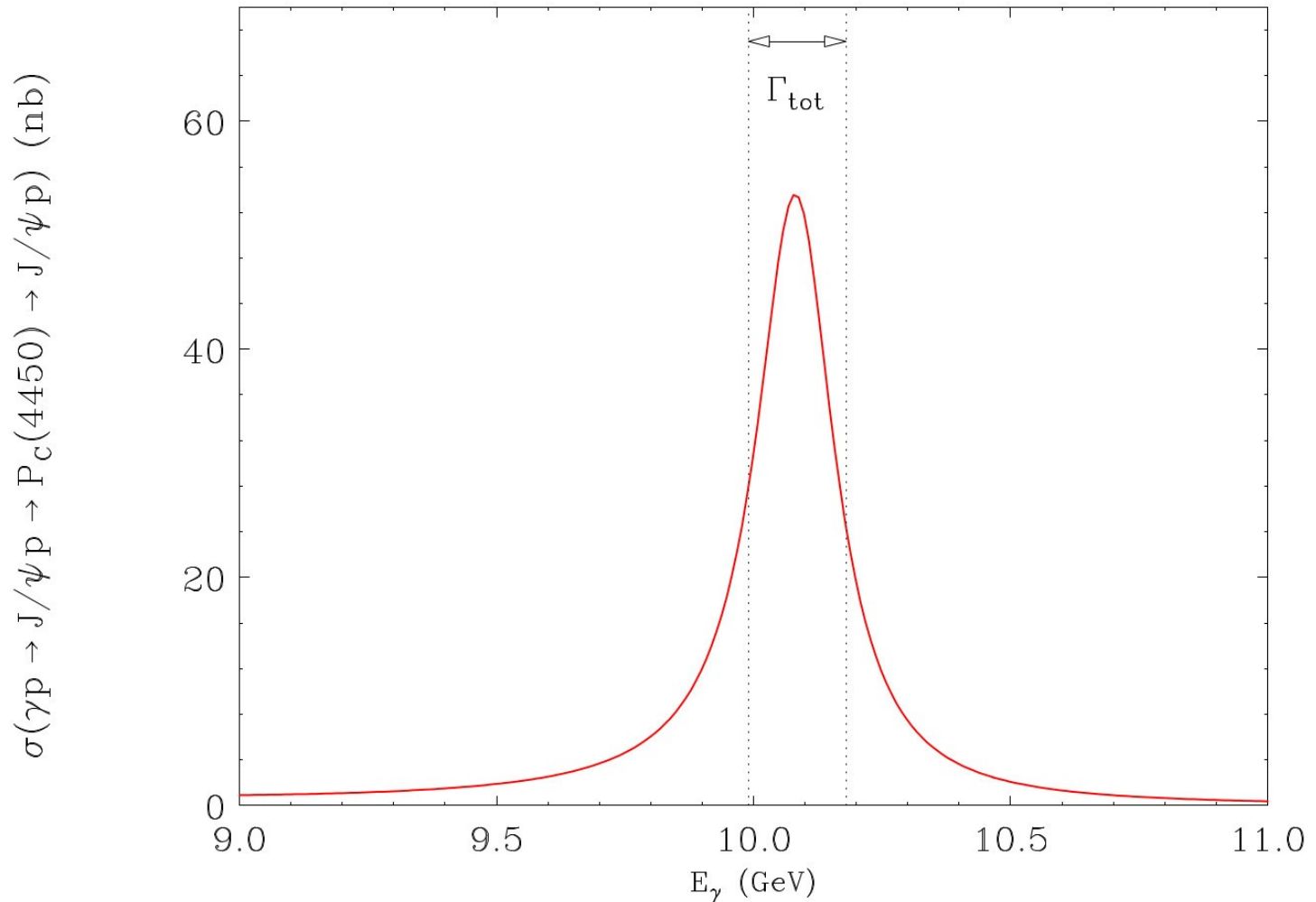V. Kubarovsky and M. B. Voloshin, arXiv:1508.00888

LHCb: new exotic resonances in $J/\psi\, p$ channel:

$\Longrightarrow$ excellent candidates for photoproduction

- estimate $\sigma(\gamma p \to P_c \to J/\psi p)$ from vector dominance:

- $E_\gamma = 10$ GeV $\Rightarrow$ CLAS12 & GlueX @JLab & ...

- $\sigma \sim 50$ nb $\gg \sigma_{\text{diffractive}} \sim 1$ nb

Cross section for resonant photoproduction $\gamma p \to J/\psi\, p \to P_c(4450) \to J/\psi\, p$, assuming $B_{\text{out}} = 0.1$, plotted as function of the incident photon energy E_γ. The vertical dotted lines indicate the width of the $P_c(4450)$ resonance.

SLAC and Cornell, 1975:

$$\sigma(\gamma p \to J/\psi p) < 1 \text{ nb} \ \text{ for } 10 < E_\gamma < 13$$
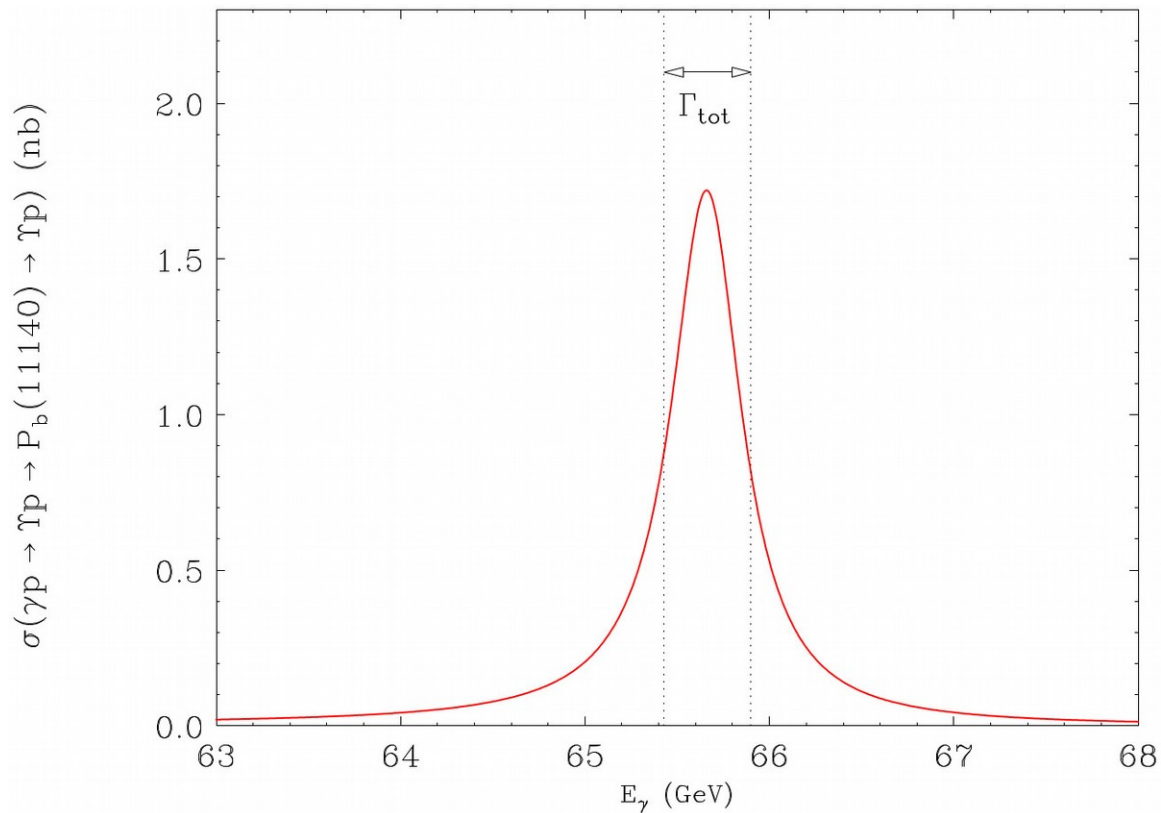
Why P_c-s not seen in these data ?

    a) smearing by photon energy spread

    b) mostly forward scattering data

    c) small branching fraction ?

bottomonium analogue:
$\Sigma_b B^*$ molecule at 11.14 GeV

$E_\gamma = 65.66$ GeV,

$\sigma \sim 1$ nb $\gg \sigma_{\text{diffractive}} \sim 50$ pb

detailed analysis needed to determine

if π exchange suffices to bind two

hadrons in each of these channels,

and in corresponding QQ' channels.

but

- relevant π-hadron couplings yet unknown

- exchanges other than π, e.g. must have
  short-distance repulsion to stabilize the potential

- possible contributions beyond S-waves
  c.f. D-wave in deuteron

$\implies$ too early to calculate the binding in most cases

Exotic resonances due to η exchange

arXiv:1106.00565

- Mesons w/o u and d light quarks, e.g. D_s :

- cannot exchange π

- but under suitable circumstances
  can bind as a result of η exchange.

$\Rightarrow$ exotic $D_s^{(*)} \bar{D}_s^{(*)}$ $(c\bar{s}\,\bar{c}s)$ mesons $\rightarrow J/\psi\,\phi$

   in $B \rightarrow XK \rightarrow J/\psi\,\phi\,K$

exotic baryons due to η exchange:

if η exchange generates $D_s \bar{D}_s^*$ resonances

then analogous baryon-meson resonances should exist

- a heavy baryon and a heavy meson

- at least one w/o light quarks

$\Rightarrow$ exotic $\Lambda_c \bar{D}_s^*$ ($cud\,\bar{c}s$) baryon $\rightarrow J/\psi\,\Lambda$

   in e.g. $\Lambda_b \rightarrow P_{\bar{c}cs}\,\pi^+\pi^- \rightarrow J/\psi\,\Lambda\,\pi^+\pi^-$

   a narrow $J/\psi\,\Lambda$ resonance $P_{\bar{c}cs}$ near 4400 MeV

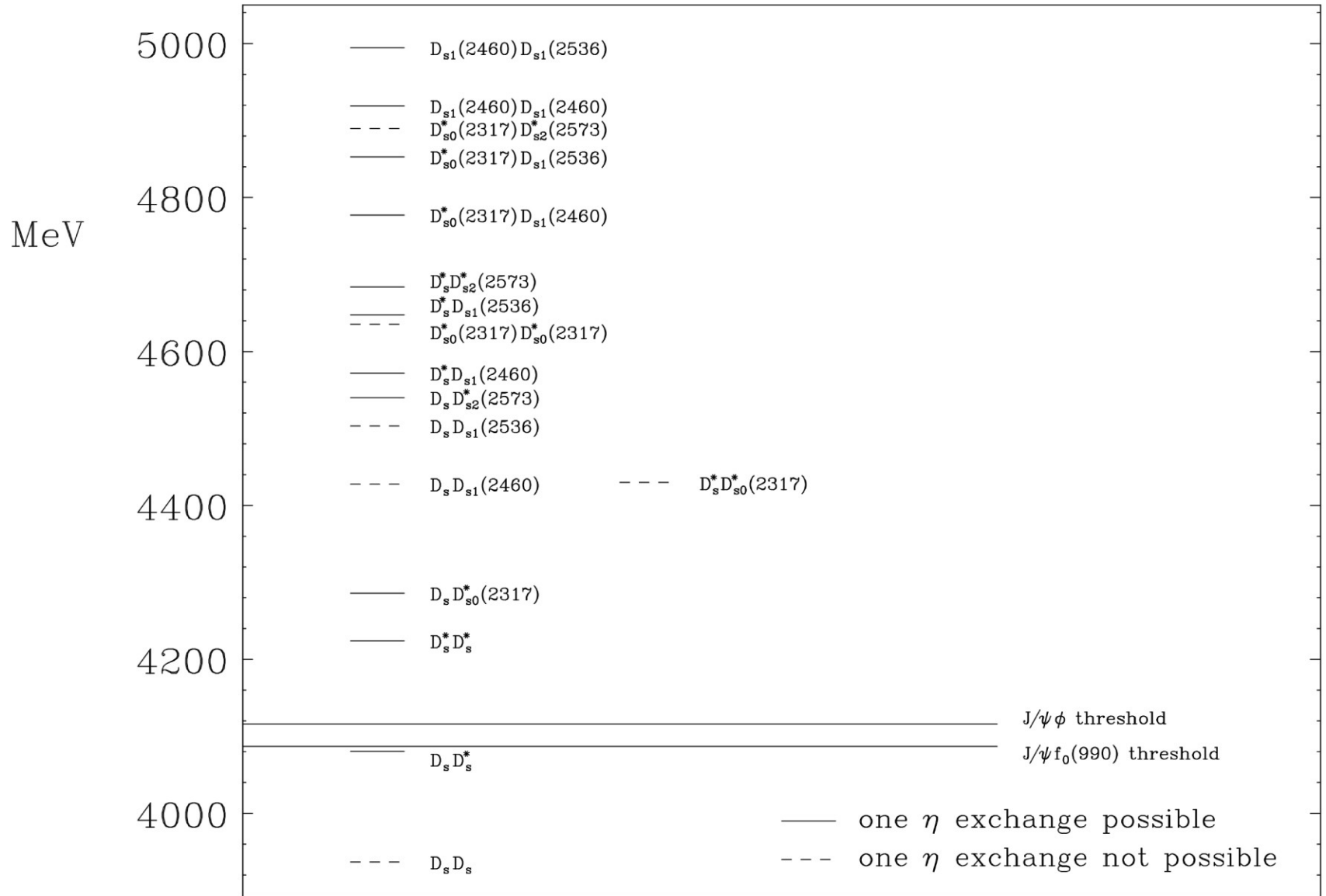Table 1: Possible S-wave resonances with two D_s mesons below 5 GeV.

States (J^P)	M (MeV)	$M - M(J/\psi)$ $- M(\phi)$	Binding by η?	Allowed J^P
$D_s^+(0^-)\, D_s^-(0^-)$	3936.6	−179.8	No	−
$D_s^+(0^-)\, D_s^{*-}(1^-)$	4080.4	−36.0	Yes	1^+
$D_s^{*+}(1^-)\, D_s^{*-}(1^-)$	4224.2	107.8	Yes	$0^+, 2^+$ [a]
$D_s^+(0^-)\, D_{s0}^{*-}(2317)(0^+)$	4286.0	169.6	Yes	0^-
$D_s^+(0^-)\, D_{s1}^-(2460)(1^+)$	4427.8	311.4	No[b]	$[1^-]$ [b]
$D_s^{*+}(1^-)\, D_{s0}^{*-}(2317)(0^+)$	4429.8	313.4	No[b]	$[1^-]$ [b]
$D_s^+(0^-)\, D_{s1}^-(2536)(1^+)$	4503.4	387.0	No	−
$D_s^+(0^-)\, D_{s2}^{*-}(2573)(2^+)$	4540.2	423.8	Yes	2^-
$D_s^{*+}(1^-)\, D_{s1}^-(2460)(1^+)$	4571.6	455.2	Yes	$0^-, 1^-, 2^-$
$D_{s0}^{*+}(2317)(0^+)\, D_{s0}^{*-}(2317)(0^+)$	4635.4	519.0	No	−
$D_s^{*+}(1^-)\, D_{s1}^-(2536)(1^+)$	4647.2	530.8	Yes	$0^-, 1^-, 2^-$
$D_s^{*+}(1^-)\, D_{s2}^{*-}(2573)(2^+)$	4684.0	567.6	Yes	$1^-, 2^-, 3^-$
$D_{s0}^{*+}(2317)(0^+)\, D_{s1}^-(2460)(1^+)$	4777.2	660.8	Yes	1^+
$D_{s0}^{*+}(2317)(0^+)\, D_{s1}^-(2536)(1^+)$	4852.8[c]	736.4	Yes	1^+
$D_{s0}^{*+}(2317)(0^+)\, D_{s2}^{*-}(2573)(2^+)$	4889.6[c]	773.2	No	−
$D_{s1}^+(2460)(1^+)\, D_{s1}^-(2460)(1^+)$	4919.0[c]	802.6	Yes	$0^+, 2^+$ [a]
$D_{s1}^+(2460)(1^+)\, D_{s1}^-(2536)(1^+)$	4994.6[c]	878.2	Yes	$0^+, 1^+, 2^+$

[a] $J^P = 1^+$ forbidden by symmetry.
[b] Proximity of these two channels may lead to binding. See text.
[c] Cannot be produced in $B \to KX$ because of kinematic mass limit.

Thresholds involving two D_s mesons

MeV

5000 — $D_{s1}(2460)D_{s1}(2536)$

4800 — $D_{s1}(2460)D_{s1}(2460)$
– – – $D_{s0}^*(2317)D_{s2}^*(2573)$
— $D_{s0}^*(2317)D_{s1}(2536)$

— $D_{s0}^*(2317)D_{s1}(2460)$

— $D_s^* D_{s2}^*(2573)$
— $D_s^* D_{s1}(2536)$
– – – $D_{s0}^*(2317)D_{s0}^*(2317)$

— $D_s^* D_{s1}(2460)$
— $D_s D_{s2}^*(2573)$
– – – $D_s D_{s1}(2536)$

4400 — – – – $D_s D_{s1}(2460)$ – – – $D_s^* D_{s0}^*(2317)$

— $D_s D_{s0}^*(2317)$

4200 — $D_s^* D_s^*$

$J/\psi\,\phi$ threshold

$J/\psi\,f_0(990)$ threshold

— $D_s D_s^*$

4000 —

— one η exchange possible

– – – one η exchange not possible

– – – $D_s D_s$

$$\bar{p}p \rightarrow (\Sigma_c \bar{\Sigma}_c)$$

10-30 MeV below threshold @4908 MeV

and

$$\bar{p}p \rightarrow (\Sigma_c \bar{\Lambda}_c)$$

10-30 MeV below threshold @4740 MeV

possibly accessible at PANDA

$\Sigma_b^+ \Sigma_b^-$ dibaryon:

$\Sigma_b^+ \Sigma_b^-$ vs. $\bar{B}B^*$:

$m_{\Sigma_b} > m_B$, $I = 1$ vs. $I = \frac{1}{2}$ $\rightarrow$ stronger binding via π

$\Rightarrow$ deuteron-like $J = 1$, $I = 0$ bound state, "*beautron*"

extra ~ 3 MeV binding from EM interaction

EXP signature: $\rightarrow \Lambda_b \Lambda_b \pi^+ \pi^-$

$\Gamma(\Sigma_b) \sim 5 \div 10$ MeV, so might be visible

should be seen in lattice QCD

also $\Sigma_c^+ \Sigma_c^-$, etc.

doubly heavy baryons QQq:

$ccq, \; bcq, \; bbq, \quad q = u, d$

must exist, but have never been seen

fascinating challenge for EXP & TH

LHCb sees thousands of B_c-s
$\implies$ should see $bcq, \; ccq,$ etc.

QQq baryons are the simplest baryons:

when $m_Q \to \infty$, QQ form a static $\overline{3}_c$ diquark

so QQq baryon $\sim \bar{Q}q$ meson

e.g. form factors: $F_{QQq}(q^2) = F_{\bar{Q}q}(q^2)$

corrections: $f\left(\dfrac{\Lambda_{QCD}}{m_Q}\right)$, calculable in QCD

hydrogen atom of baryon physics!

B_c production in LHCb: gg fusion
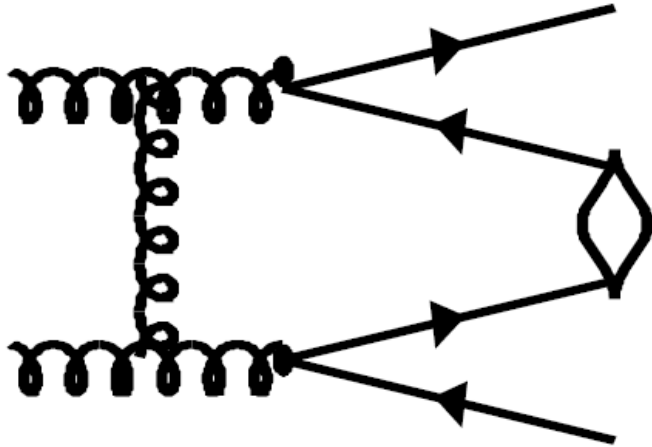
v. hard to compute reliably
from first principles, but. . .

Ξ_{bc} production: same diagram,

but b needs to pick up c, instead of c: $\quad \mathbf{3}_c \mathbf{3}_c$ vs. $\bar{\mathbf{3}}_c \mathbf{3}_c$

$$\implies \quad \sigma(pp \to \Xi_{bc} + X) \sim \sigma(pp \to B_c + X)$$

LHCb is making a lot of B_c-s
$\implies$ LHCb is making a lot of (QQq) baryons !!!

Ξ_{cc} is the lightest doubly-heavy baryon

is it LHCb's best bet for (QQq) ?

$$\sigma(\bar{c}c\,\bar{c}c) \gg \sigma(\bar{b}b\,\bar{c}c) \gg \sigma(\bar{b}b, \bar{b}b)$$

but $\tau(b) \sim 7\tau(c)$ (Cabibbo),

e.g. $\tau(\Lambda_b) \approx 1.4 \times 10^{-12}$ sec.
vs. $\tau(\Lambda_c) \approx 0.2 \times 10^{-12}$ sec.

verified by detailed lifetime calculation

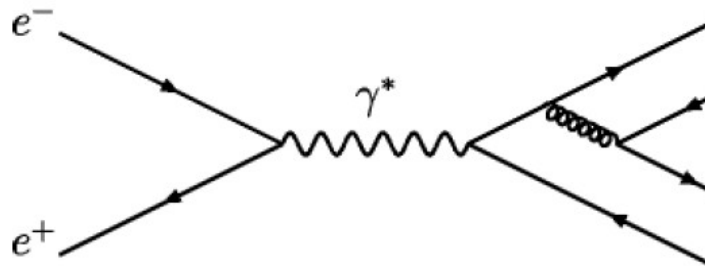with sufficient E_{CM} may study
double heavy flavor production

$$e^+ e^- \to b\bar{b}c\bar{c} + X \ ,$$
$$e^+ e^- \to b\bar{b}b\bar{b} + X$$

$\Rightarrow$ a precondition for producing doubly heavy B_c, B_c^*,
and doubly heavy $\bar{\Xi}_{bc} = bcq$, and $\bar{\Xi}_{bb} = bbq$, $q = u, d$.

must be able to see the (known) B_c state
if one expects to be able to detect $\bar{\Xi}_{bc}$

same diagram
for B_c and $\bar{\Xi}_{bc}$:

estimate $\sigma(e^+ e^- \to \gamma B_c^+ B_c^- + X)$
~ 1.7 fb @90 GeV, 0.24 fb @250 GeV

masses of doubly-heavy baryons:

use same toolbox that predicted

b baryon masses.

doubly heavy baryons: masses and lifetimes

our mass predictions (in MeV) for lowest-lying baryons with two heavy quarks. States without a star have $J = 1/2$; states with a star are their $J = 3/2$ hyperfine partners. The quark q can be either u or d. The square or curved brackets around cq denote coupling to spin 0 or 1.

State	Quark content	$M(J = 1/2)$	$M(J = 3/2)$
$\Xi_{cc}^{(*)}$	ccq	3627 ± 12	3690 ± 12
$\Xi_{bc}^{(*)}$	$b[cq]$	6914 ± 13	6969 ± 14
Ξ_{bc}'	$b(cq)$	6933 ± 12	–
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

summary of lifetime predictions for baryons containing two heavy quarks. Values given are in fs.

Baryon	This work	[27]	[51]	[70]	[71]
$\Xi_{cc}^{++} = ccu$	185	430±100	460±50	500	~ 200
$\Xi_{cc}^{+} = ccd$	53	120±100	160±50	150	~ 100
$\Xi_{bc}^{+} = bcu$	244	330±80	300±30	200	–
$\Xi_{bc}^{0} = bcd$	93	280±70	270±30	150	–
$\Xi_{bb}^{0} = bbu$	370	–	790±20	–	–
$\Xi_{bb}^{-} = bbd$	370	–	800±20	–	–

interesting thresholds for heavy flavor production in e^+e^-

Final state	Threshold (MeV)
$B\bar{B}$	10559
$B\bar{B}^*$	10605
$B^*\bar{B}^*$	10650
$B_s\bar{B}_s$	10734
$B_s\bar{B}_s^*$	10782
$B_s^*\bar{B}_s^*$	10831
$B_{s0}\bar{B}_s^*$	11132–11193[a]
$\Lambda_b\bar{\Lambda}_b$	11239
$B_c\bar{B}_c$	12551
$B_c\bar{B}_c^*$	12619–12635[b]
$B_c^*\bar{B}_c^*$	12687–12719[b]
$\Xi_{bc}\bar{\Xi}_{bc}$	13842–13890[c]
$\Xi_{bb}\bar{\Xi}_{bb}$	20300–20348[c]

[a] analogue of the very narrow $D_{s0}(2317)$
[b] With estimated B_c^* B_c splitting 68 84 MeV
[c] estimate, MK&Rosner (2014)

Likely decay modes of QQq baryons

- $\Xi_{cc}^{++} = ccu$

$$\Xi_{cc}^{++} \to (csu)\, W^+ \to (csu)\, (\pi^+, \rho^+, a_1^+)$$

e.g.

$$\Xi_{cc}^{++} \to 3\pi^+\, \Xi^- \quad \text{(missed by CDF trigger)}$$

$$\Xi_{cc}^{++} \to \Lambda_c K^- 2\pi^+$$

lifetime: each c quark can decay independently

$$\Gamma(\Xi_{cc}^{++}) = 3.56 \times 10^{-12} \text{ GeV}$$

$$\tau(\Xi_{cc}^{++}) = 185 \text{ fs}$$

- $\Xi_{cc}^+ = ccd$

In addition to $c \to su\bar{d}$, have $cd \to su$

$\Longrightarrow \quad \tau(\Xi_{cc}^+) = 50 \div 100$ fs

- $\Xi_{bc}^+ = bcu$

$b \to cdu$ and $c \to sud$

e.g. $\Xi_{bc} \to J/\psi\, \Xi_c$

$\tau(\Xi_{bc}^+) \approx 240$ fs

- $\Xi_{bc}^0 = bcd$

$\tau(\Xi_c^+) = (4.42 \pm 0.26) \times 10^{-13}$ s $\qquad$ the difference due to $cd \to su$

$\tau(\Xi_c^0) = (1.12^{+0.13)}_{0.10}) \times 10^{-13}$ s

$\Longrightarrow \tau(\Xi_{bc}^0) = 93$ fs

e.g. $\Xi_{bc}^0 \to j/\psi\, \Xi^0$ or $\Xi_{bc}^0 \to J/\psi\, \Xi^- \pi^+$

- $\Xi_{bb} = bbq$

$bu \to cd$ possible for Ξ_{bb}^0, but
$\tau(\Xi_b^{0)}$ not much different from $\tau(\Xi_b^-)$
so treat Ξ_{bb}^0 and Ξ_{bb}^- generically as Ξ_{bb}

$$\implies \quad \tau(\Xi_{bb}) \approx 376 \text{ fs}$$

rare but spectacular decay mode:

$$(bbq) \to (\bar{c}cs)\,(\bar{c}cs)q \to J/\psi\,J\psi\,\Xi$$

rough estimate of Ξ_{cc} production rate

assume suppression due to $s \to c$
indep. of spectators, i.e.

Ξ_{cc} suppressed vs. Ξ_c as Ξ_c vs. Ξ :

$$\sigma(pp \to \Xi_{cc} + X) \sim \sigma(pp \to \Xi_c + X) \cdot \frac{\sigma(pp \to \Xi_c + X)}{\sigma(pp \to \Xi + X)}$$

perhaps can generalize to Ξ_{bc} and Ξ_{bb} production rate

$$\sigma(pp \to \Xi_{bc} + X) \sim \sigma(pp \to \Xi_b + X) \cdot \frac{\sigma(pp \to \Xi_c + X)}{\sigma(pp \to \Xi + X)}$$

or

$$\sigma(pp \to \Xi_{bc} + X) \sim \sigma(pp \to \Xi_c + X) \cdot \frac{\sigma(pp \to \Xi_b + X)}{\sigma(pp \to \Xi + X)}$$

and

$$\sigma(pp \to \Xi_{bb} + X) \sim \sigma(pp \to \Xi_b + X) \cdot \frac{\sigma(pp \to \Xi_b + X)}{\sigma(pp \to \Xi + X)}$$

a possible way to check if Ξ_{bc} and B_c

production rates are comparable:

compare analogous prod. rates of Ξ_c and D_s

(or Ξ_b and B_s) in the same setup,

and large enough E_{CM}

be it e^+e^-, $\bar{p}p$ or pp
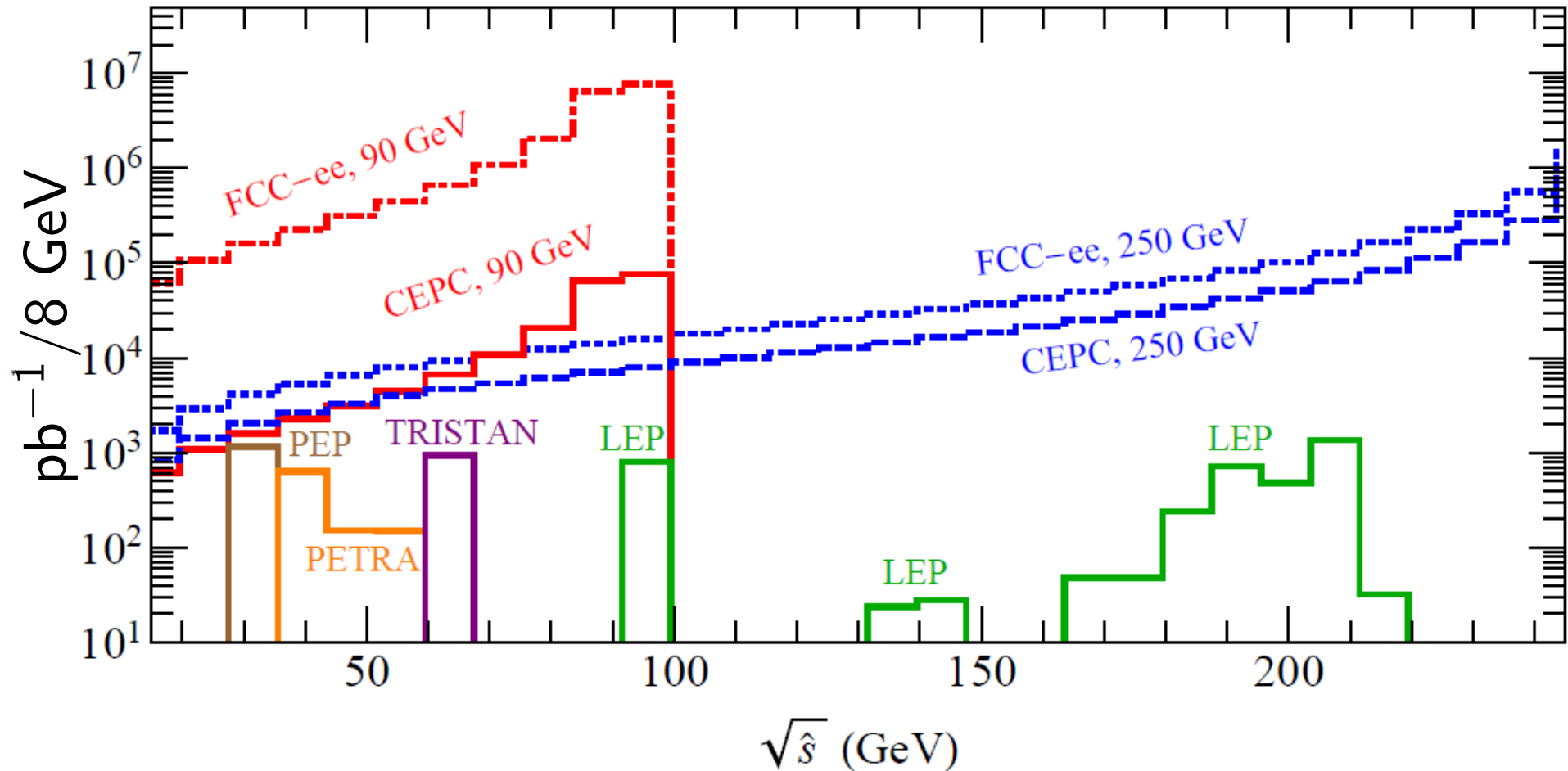
integrated luminosity
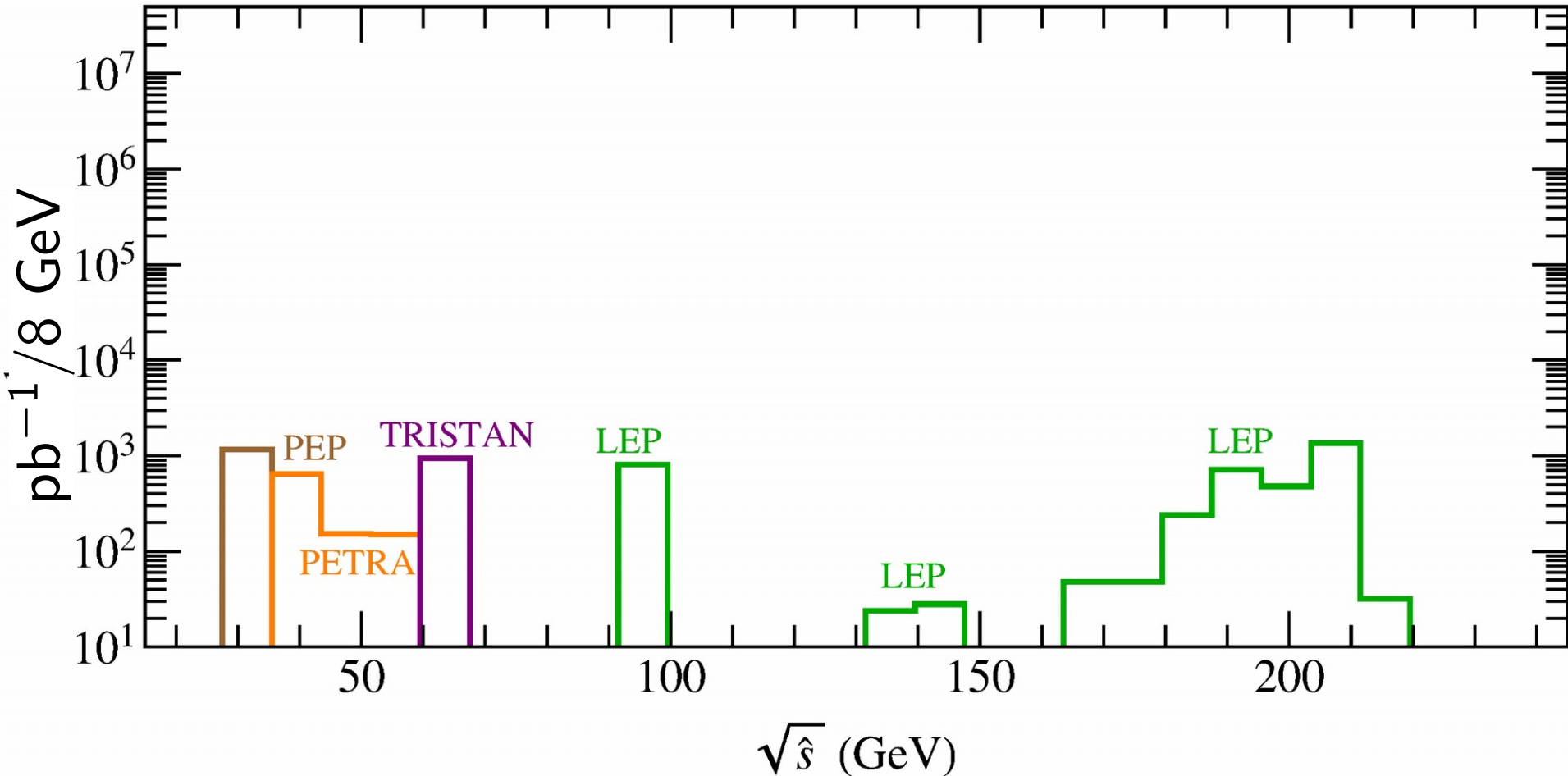
gaps left by PEP, PETRA, TRISTAN and LEP

integrated luminosity
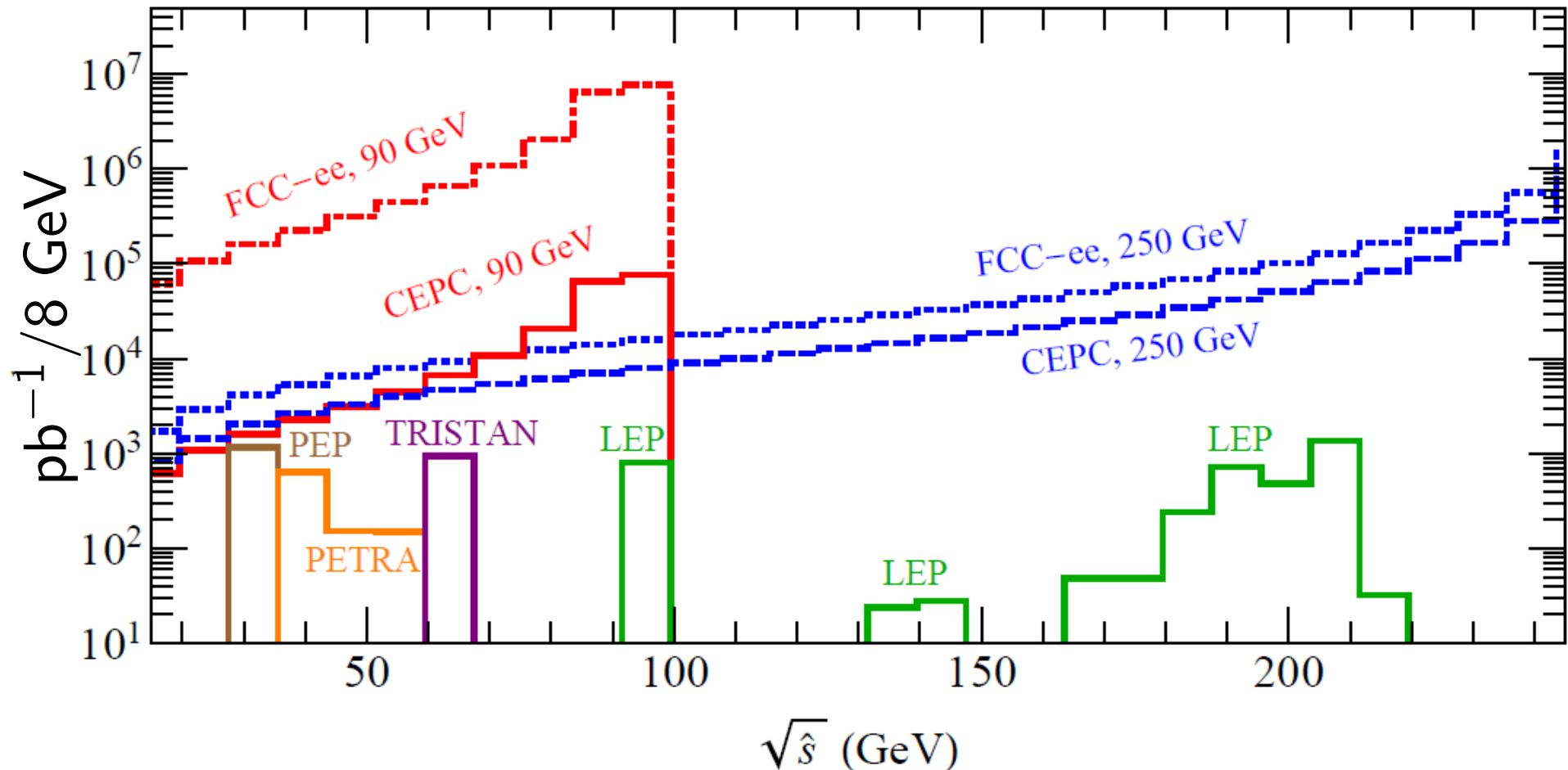
Integrated luminosity from past low energy e^+e^- colliders at their nominal center-of-mass energies compared to the effective luminosity through radiative return from future e^+e^- colliders at $\sqrt{s} = 90$ or 250 GeV

integrated luminosity

Integrated luminosity from past low energy e^+e^- colliders at their nominal center-of-mass energies compared to the effective luminosity through radiative return from future e^+e^- colliders at $\sqrt{s} = 90$ or 250 GeV

gaps filled in and much more

new rich heavy flavor QCD spectroscopy

(a) bottomonium analogues of charmonium X, Y, Z states

(b) new exotics – doubly-heavy hadronic molecules
  meson-meson, baryon-meson, baryon-baryon
  the lightest one:
  LHCb "pentaquark" $= \Sigma_c \bar{D}^* \, (\bar{c}cuud)$

(c) doubly heavy QQq baryons

(d) b analogues of $D_{s0}^*(2317)$ and $D_{s1}(2460)$:
 BK molecules or chiral partners of B_s, B_s^*

SUMMARY

- the new narrow exotic resonances are loosely bound
  states of $\bar{D}D^*$, $\bar{D}^*D^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$

  predictions:

- $\bar{D}^*D^*$ in $I = 0$ and $I = 1$ channels; $I = 1$ seen!

- new isosinglet $\bar{B}B^*$ and $\bar{B}^*B^*$ states below threshold;
  $\chi_1 b(3P)$?

- *heavy deuterons*: $\Sigma_c D^*$: LHCb $P_c(4450) \implies$ photoproduction
  $\Sigma_c B^*$, $\Sigma_b \bar{D}^*$, $\Sigma_b B^*$, $\Sigma_Q \bar{\Lambda}_{Q'}$, $\Sigma_Q^+ \Sigma_Q^-$, ...
  η-mediated: $D_s \bar{D}_s^*$, $\Lambda_c \bar{D}_s^*$, ...

- doubly & triply heavy baryons QQq, QQQ @pp & e^+e^-

- exciting new spectroscopy

Supplementary transparencies
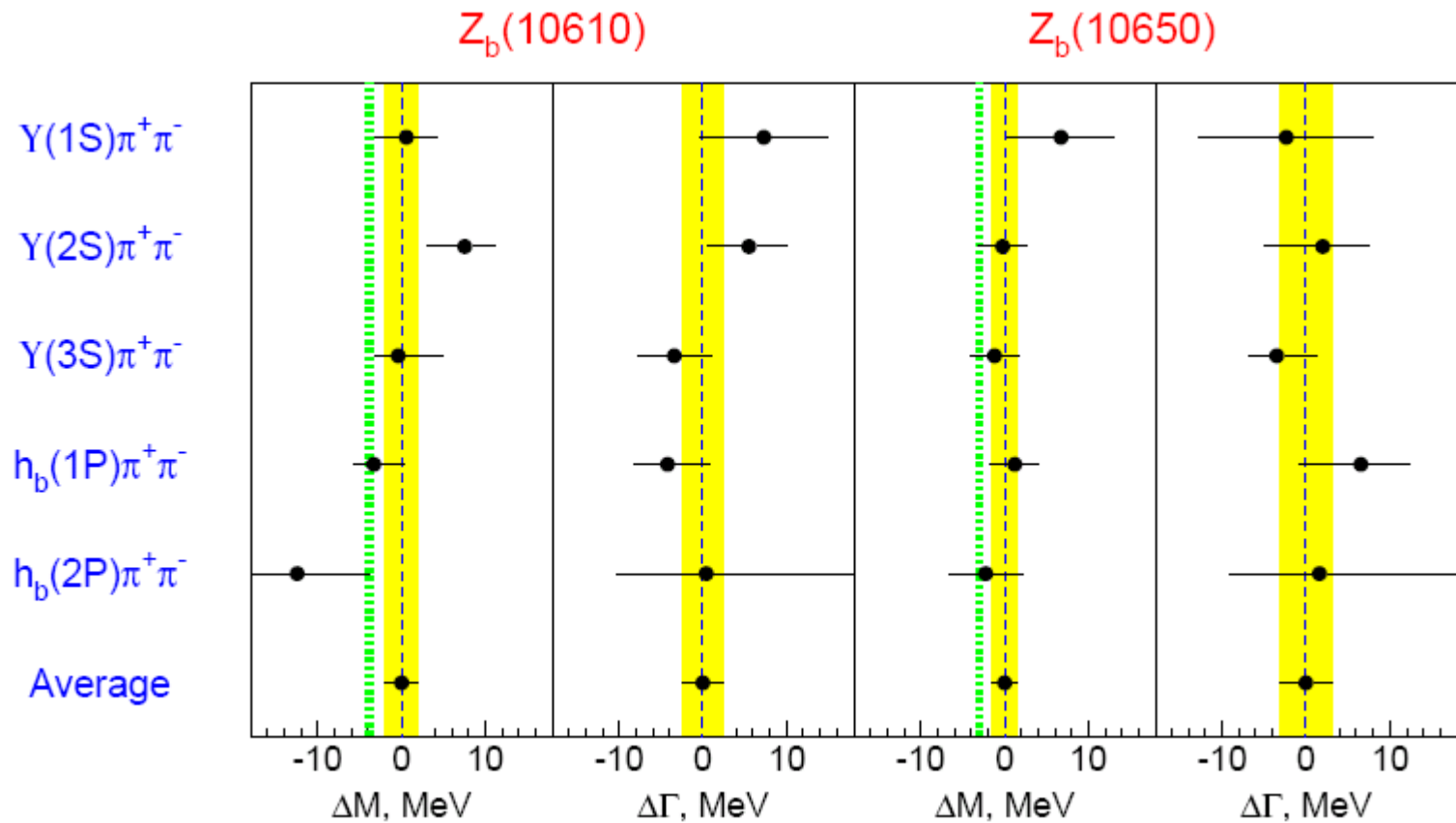
Z_b(10610)   Z_b(10650)

nels. The vertical dotted lines indicate $B^*\overline{B}$ and $B^*\overline{B}^*$ thresholds.

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

Full Amplitude Analysis with Full Statistics

Parameter	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
$f_{Z_b^\mp(10610)\pi^\pm}$, %	$4.8 \pm 1.2^{+1.5}_{-0.3}$	$18.1 \pm 3.1^{+4.2}_{-0.3}$	$30.0 \pm 6.3^{+5.4}_{-7.1}$
$M(Z_b(10610))$, MeV	$10608.5 \pm 3.4^{+3.7}_{-1.4}$	$10608.1 \pm 1.2^{+1.5}_{-0.2}$	$10607.4 \pm 1.5^{+0.8}_{-0.2}$
$\Gamma(Z_b(10610))$, MeV	$18.5 \pm 5.3^{+6.1}_{-2.3}$	$20.8 \pm 2.5^{+0.3}_{-2.1}$	$18.7 \pm 3.4^{+2.5}_{-1.3}$
$f_{Z_b^\mp(10650)\pi^\pm}$, %	$0.87 \pm 0.32^{+0.16}_{-0.12}$	$4.05 \pm 1.2^{+0.95}_{-0.15}$	$13.3 \pm 3.6^{+2.6}_{-1.4}$
$M(Z_b(10650))$, MeV	$10656.7 \pm 5.0^{+1.1}_{-3.1}$	$10650.7 \pm 1.5^{+0.5}_{-0.2}$	$10651.2 \pm 1.0^{+0.4}_{-0.3}$
$\Gamma(Z_b(10650))$, MeV	$12.1^{+11.3+2.7}_{-4.8-0.6}$	$14.2 \pm 3.7^{+0.9}_{-0.4}$	$9.3 \pm 2.2^{+0.3}_{-0.5}$

$J^P = 1^+$ for both Z_b is favored over 1^-, 2^- and 2^+ at more than 6σ
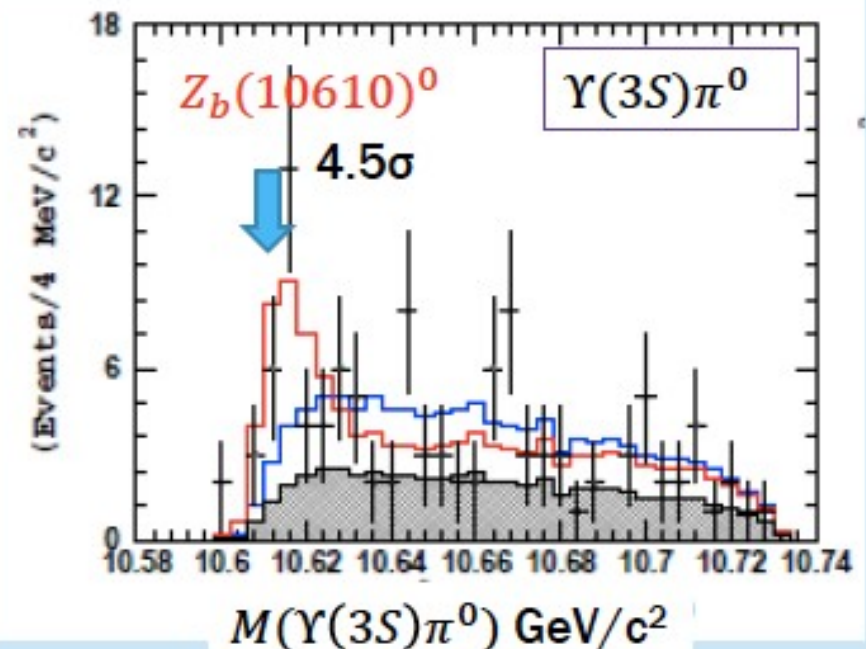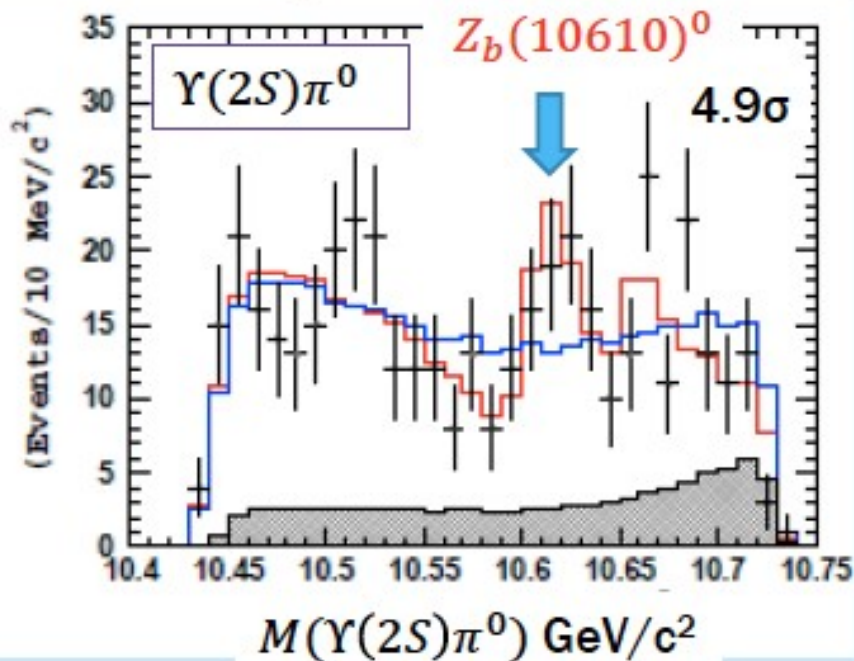
A. Garmash et al., Phys. Rev. D 91 (2015) 072003

$f_{Z_b(10610)}$ much bigger for $\Upsilon(3S)$, which has a large spatial extent.
$\implies Z_b(10610)$ is a large object.

Neutral member of the I=1 multiplet 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.

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

M. Karliner, Exotic quarkonia & QQq baryons

arXiv:1207.4345 11

discovery of isovector $Z_c(3900)$

$\Rightarrow$ several quantitative predictions, arXiv:1304.0345:

- two narrow $X_b(I = 0)$ bottomonium-like resonances
~ 23 MeV below $Z_b(10610)$ and $Z_b(10650)$, i.e.
~ 20 MeV below $\bar{B}B^*$ and $\bar{B}^*B^*$ thresholds

- $I = 0$ narrow resonance very close to $\bar{D}^*D^*$ threshold
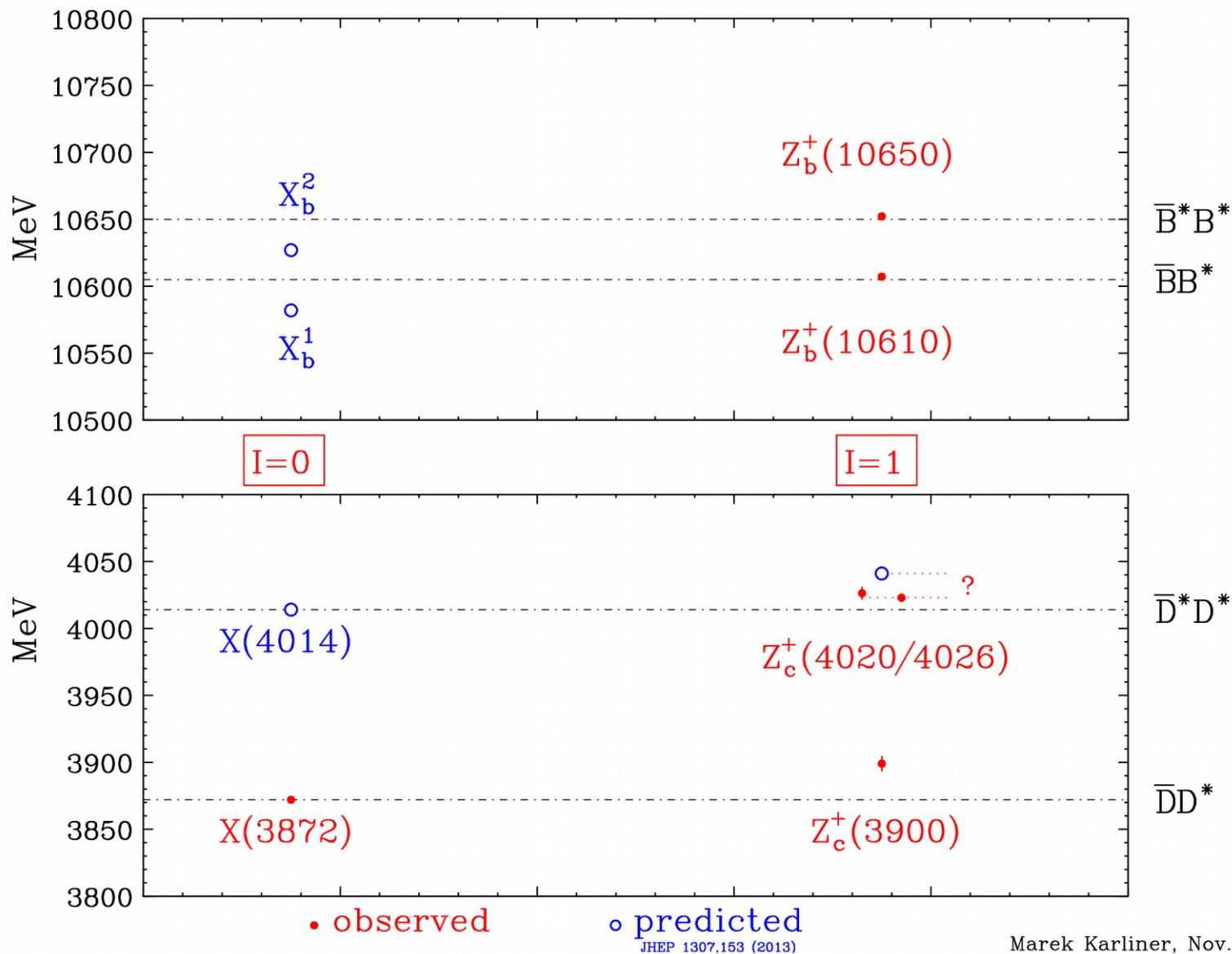- $I = 1$ narrow resonance a bit above $\bar{D}^*D^*$ threshold

did not have to wait long. . .
BESIII:
$Z_c^+(4025)$, arXiv:1308.2760, $\Gamma \approx 25$ MeV
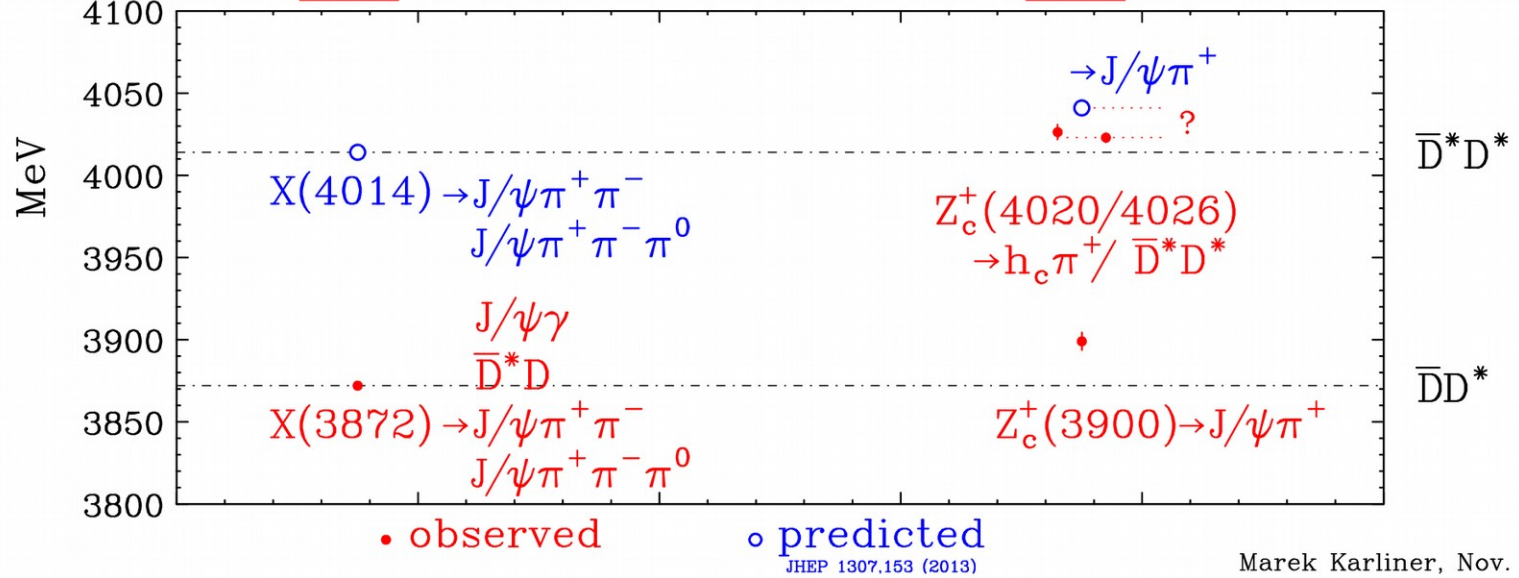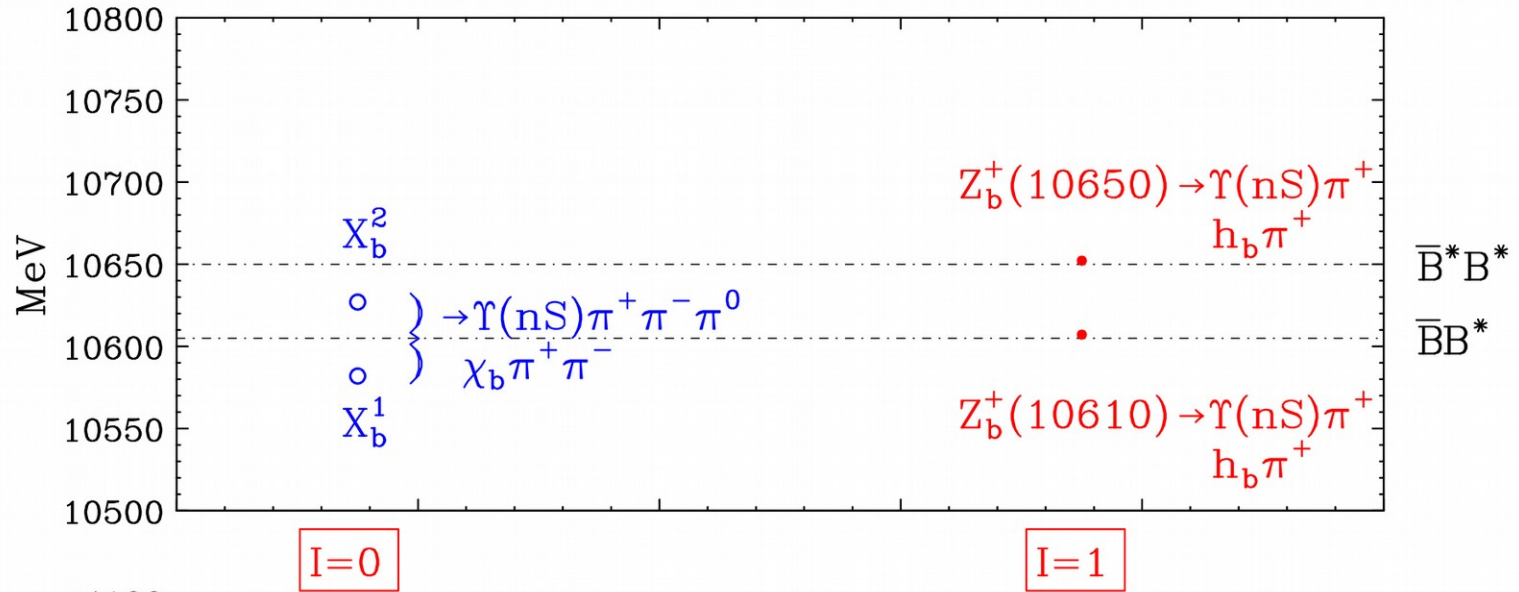$Z_c^+(4020)$, arXiv:1309.1896; $\Gamma \approx 8$ MeV

exotic heavy quarkonia vs. two meson thresholds

exotic heavy quarkonia vs. two meson thresholds

Null result from CMS:

CMS

CERN-PH-EP/2013-157
2013/09/03

CMS-BPH-11-016

Search for a new bottomonium state decaying to Y(1S)$\pi^+\pi^-$ in pp collisions at $\sqrt{s} = 8\,\text{TeV}$

The CMS Collaboration*

Abstract

The results of a search for the bottomonium counterpart, denoted as X_b, of the exotic charmonium state X(3872) is presented. The analysis is based on a sample of pp collisions at $\sqrt{s} = 8\,\text{TeV}$ collected by the CMS experiment at the LHC, corresponding to an integrated luminosity of $20.7\,\text{fb}^{-1}$. The search looks for the exclusive decay channel $X_b \to Y(1S)\pi^+\pi^-$ followed by $Y(1S) \to \mu^+\mu^-$. No evidence for an X_b signal is observed. Upper limits are set at the 95% confidence level on the ratio of the inclusive production cross sections times the branching fractions to $Y(1S)\pi^+\pi^-$ of the X_b and the $Y(2S)$. The upper limits on the ratio are in the range 0.9–5.4% for X_b masses between 10 and 11 GeV. These are the first upper limits on the production of a possible X_b at a hadron collider.

Pair production of narrow B_{sJ} states

$$e^+ e^- \to B_{sJ} + X$$

may be used to look for b-quark
analogues of the very narrow D_{sJ} states
seen by BaBar, CLEO and Belle

e.g. $D_{s0}(2317)$, $J^P = 0^+$, likely chiral partner of D_s:

$$m[D_{s0}(2317)] - m[D_s] = 345 \text{ MeV} \approx m_q^{\text{const.}}$$

below DK threshold $\Rightarrow$ very narrow, $\Gamma < 3.8$ MeV,

decay: $D_{s0}(2317) \to D_s^+ \pi^0$
through v. small isospin-violating $\eta - \pi^0$ mixing

detailed v. interesting predictions for b analogues
$\Rightarrow$ opportunity to test our understanding of χSB