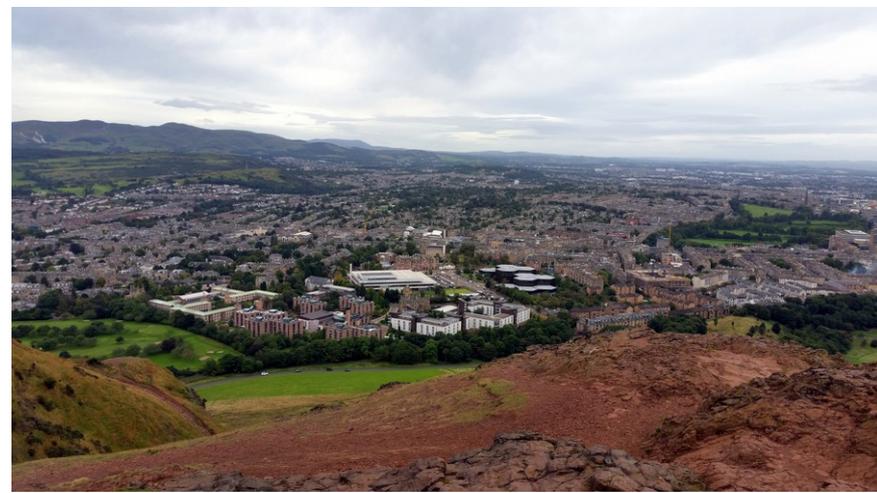




Tel Aviv University



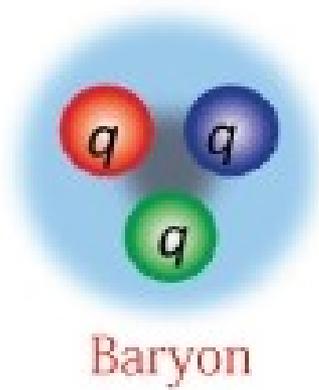
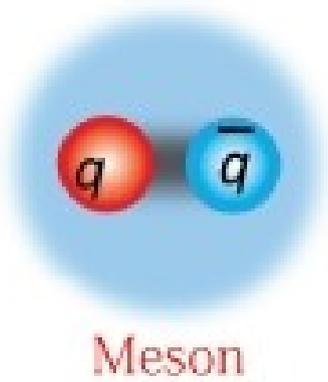
# Exotic baryons and mesons with two heavy quarks

Marek Karliner  
Tel Aviv University

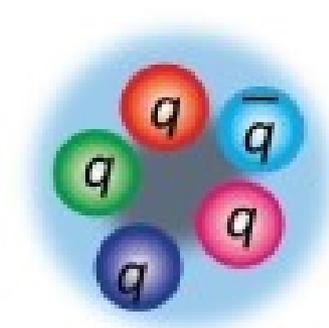
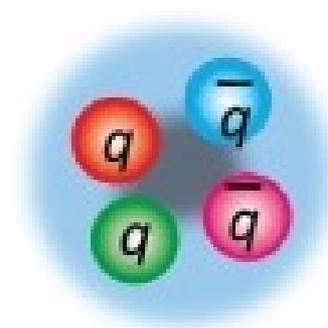
PRD91 (2015) 1, 014014 & PRD90 (2014) 9, 094007,  
PRL 115,112001, PLB 752,329, arxiv:1601:00565 with Jon Rosner  
JHEP 7,153(2013) with Shmuel Nussinov  
and a big intellectual debt to Harry Lipkin

Edinburgh, Sep. 27, 2016

## Standard Hadrons



## Exotic Hadrons



# exotic hadrons – tetra and pentaquarks – discussed right from the start of the quark model

Volume 8, number 3

PHYSICS LETTERS

1 February 1964

## A SCHEMATIC MODEL OF BARYONS AND MESONS \*

M. GELL-MANN

*California Institute of Technology, Pasadena, California*

Received 4 January 1964

...

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon  $\Lambda$  if we assign to the triplet  $t$  the following properties: spin  $\frac{1}{2}$ ,  $z = -\frac{1}{3}$ , and baryon number  $\frac{1}{3}$ . We then refer to the members  $u\frac{1}{3}$ ,  $d^{-\frac{1}{3}}$ , and  $s^{-\frac{1}{3}}$  of the triplet as "quarks"  $q$  and the members of the anti-triplet as anti-quarks  $\bar{q}$ . Baryons can now be constructed from quarks by using the combinations  $(qqq)$ ,  $(qqq\bar{q})$ , etc., while mesons are made out of  $(q\bar{q})$ ,  $(q\bar{q}\bar{q})$ , etc. It is assumed that the lowest baryon configuration  $(qqq)$  gives just the representations  $1$ ,  $8$ , and  $10$  that have been observed, while

8419/TH.412

21 February 1964

AN  $SU_3$  MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II \*)

G. Zweig

CERN---Geneva

\*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

...

6) In general, we would expect that baryons are built not only from the product of three aces,  $AAA$ , but also from  $\bar{A}AAAA$ ,  $\bar{A}AAAAA$ , etc., where  $\bar{A}$  denotes an anti-ace. Similarly, mesons could be formed from  $\bar{A}A$ ,  $AAAA$  etc. For the low mass mesons and baryons we will assume the simplest possibilities,  $\bar{A}A$  and  $AAA$ , that is, "deuces and treys".

> 50 years of searches for exotics made from light (u,d,s) quarks, but no unambiguous exp. evidence

**but recently clearcut evidence in heavy-light exotics**

# The big questions about exotic hadrons:

- do they exist ?
- if yes, which ones ?
- what is their internal structure ?
- how best to look for them ?

# 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  $\pi$ -(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  $\pi$ -(s) or two heavy-light mesons:

$$\bar{Q}Q\bar{q}q \rightarrow \bar{Q}Q \pi$$

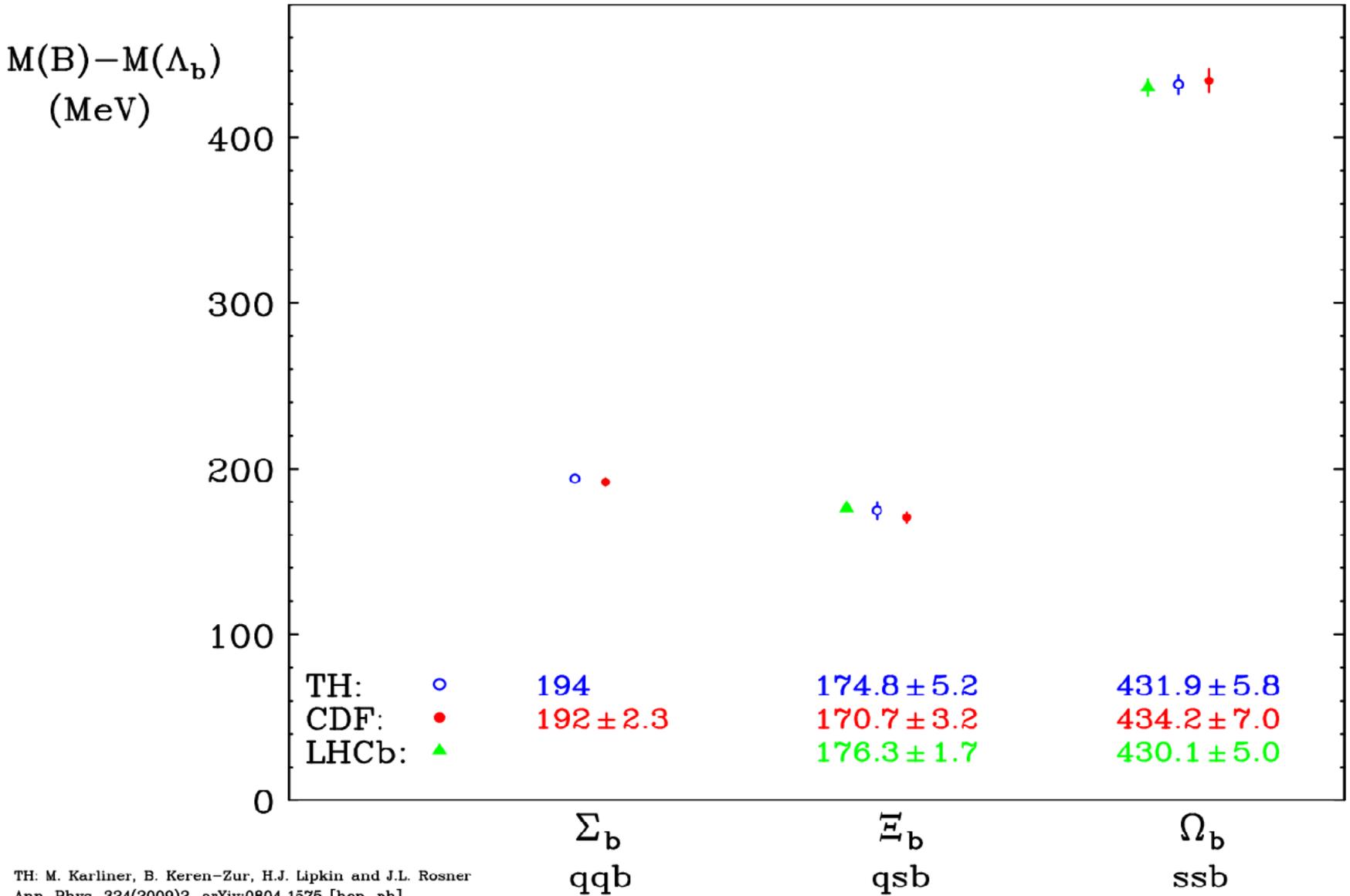
$$\bar{Q}Q\bar{q}q \rightarrow (\bar{Q}q) (Q\bar{q})$$

$\Rightarrow$  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



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<sup>a\*</sup>  
and  
Harry J. Lipkin<sup>a,b†</sup>

## Abstract

Recent data from Belle show unusually large partial widths  $\Upsilon(5S) \rightarrow \Upsilon(1S) \pi^+ \pi^-$  and  $\Upsilon(5S) \rightarrow \Upsilon(2S) \pi^+ \pi^-$ . The  $Z(4430)$  narrow resonance also reported by Belle in  $\psi' \pi^+$  spectrum has the properties expected of a  $\bar{c}c u \bar{d}$  charged isovector tetraquark  $T_{cc}^\pm$ . The analogous state  $T_{bb}^\pm$  in the bottom sector might mediate anomalously large cascade decays in the Upsilon system,  $\Upsilon(mS) \rightarrow T_{bb}^\pm \pi^\mp \rightarrow \Upsilon(nS) \pi^+ \pi^-$ , with a tetraquark-pion intermediate state. We suggest looking for the  $\bar{b}b u \bar{d}$  tetraquark in these decays as peaks in the invariant mass of  $\Upsilon(1S) \pi$  or  $\Upsilon(2S) \pi$  systems. The  $\bar{b}b u \bar{s}$  tetraquark can appear in the observed decays  $\Upsilon(5S) \rightarrow \Upsilon(1S) K^+ K^-$  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.

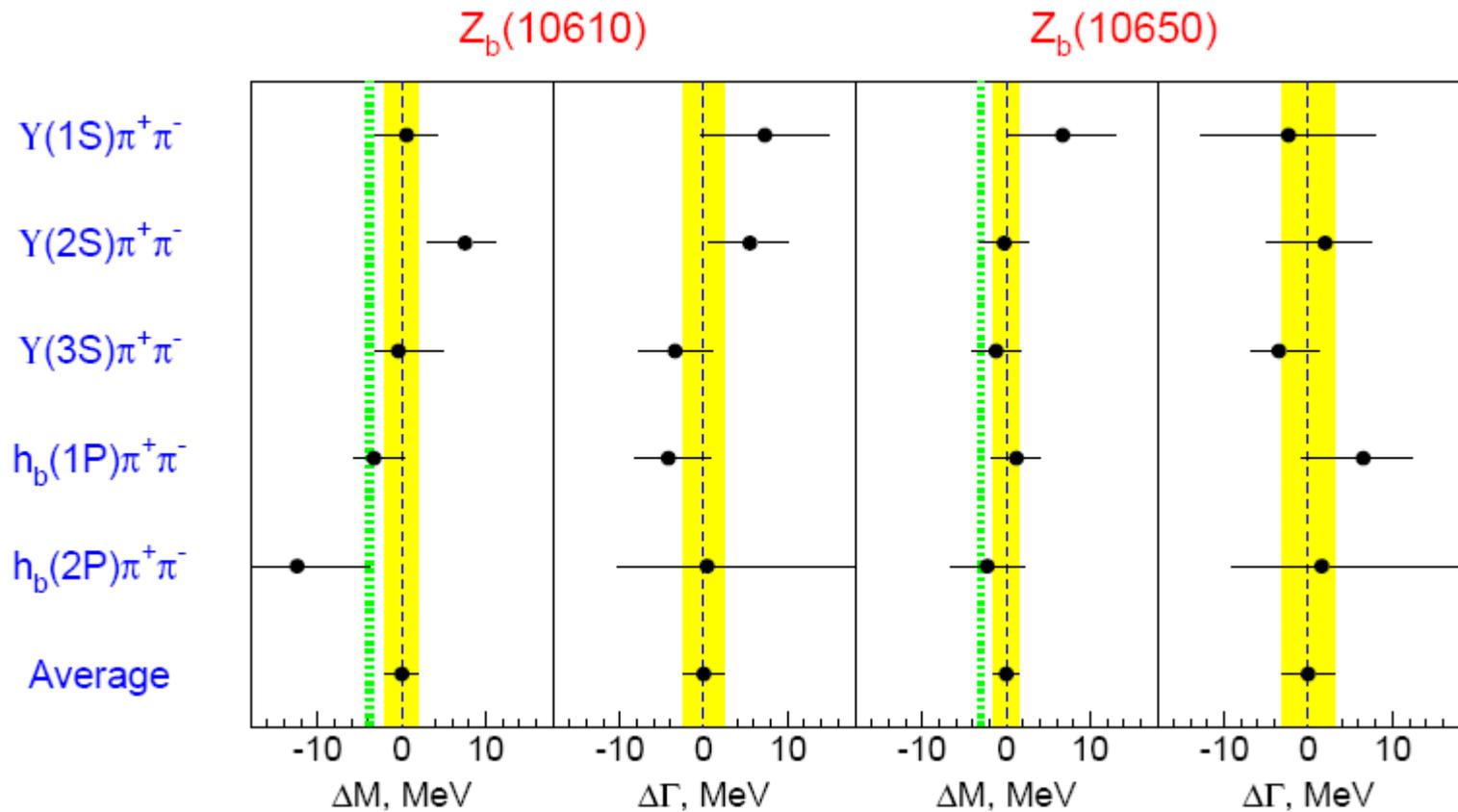
# Observation of two charged bottomonium-like resonances

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  $121.4\text{ fb}^{-1}$  data sample collected with the Belle detector near the  $\Upsilon(5S)$  resonance at the KEKB asymmetric-energy  $e^+e^-$  collider.



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

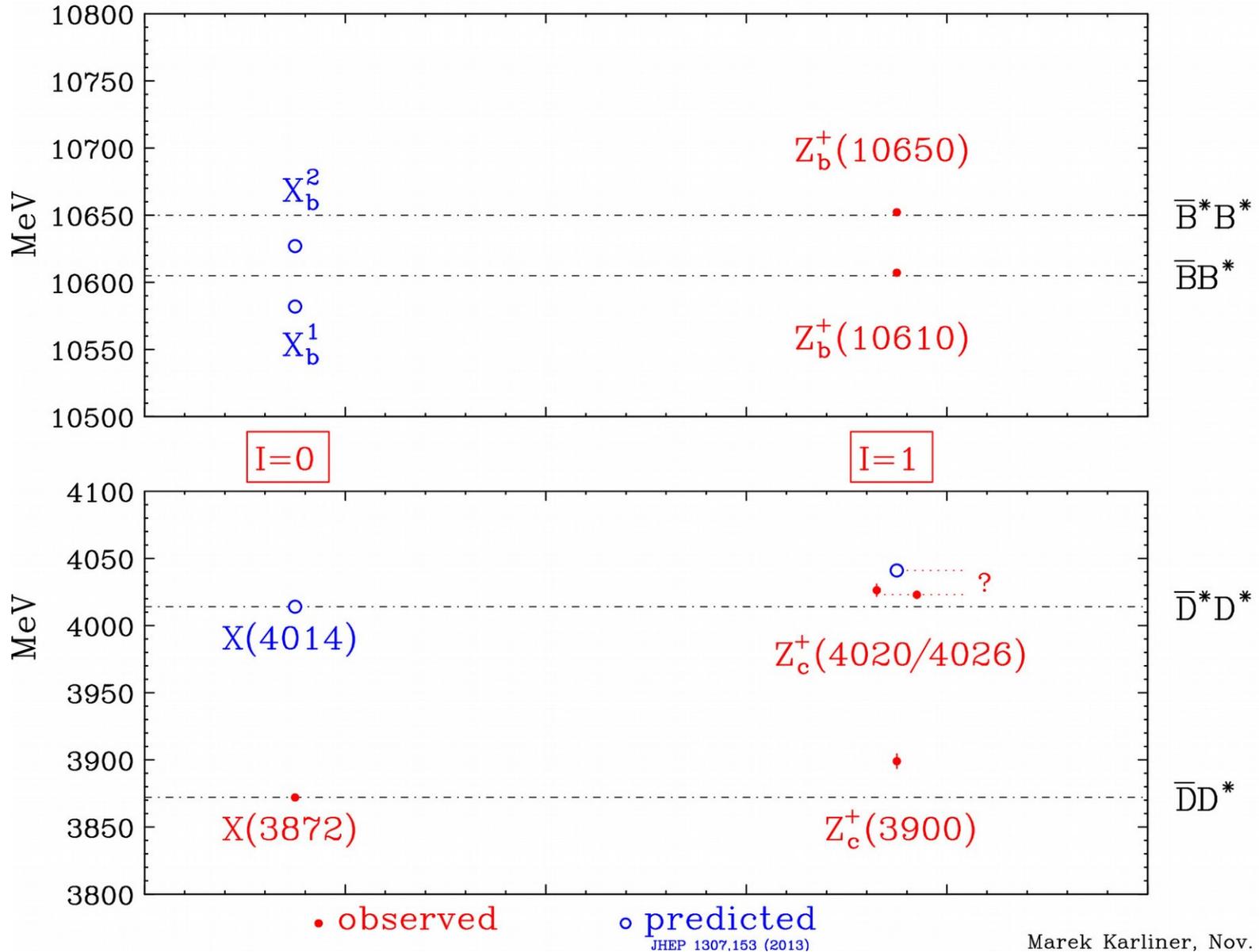
$$J^P = 1^+ \quad \text{for both } Z_b(10610) \text{ and } Z_b(10650)$$

## 5 narrow exotic states close to meson-meson thresholds

state	mass MeV	width MeV	$\bar{Q}Q$ decay mode	phase space MeV	nearby threshold	$\Delta E$ MeV
$X(3872)$	3872	$< 1.2$	$J/\psi \pi^+ \pi^-$	495	$\bar{D}D^*$	$< 1$
$Z_b(10610)$	10608	21	$\Upsilon \pi$	1008	$\bar{B}B^*$	$2 \pm 2$
$Z_b(10650)$	10651	10	$\Upsilon \pi$	1051	$\bar{B}^*B^*$	$2 \pm 2$
$Z_c(3900)$	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
$\times$					$\bar{D}D$	
$\times$					$\bar{B}B$	

- 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



Marek Karliner, Nov. 2013

The  $Z_Q$  resonances decay into

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

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

$\implies$  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  $\bar{Q}Q\pi$

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

strong hint in favor of molecular interpretation

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

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

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

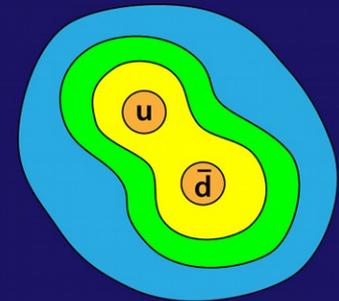
$\Rightarrow$  indicates an extended object

new result from Belle  
(analysis by Alexei Garmash):

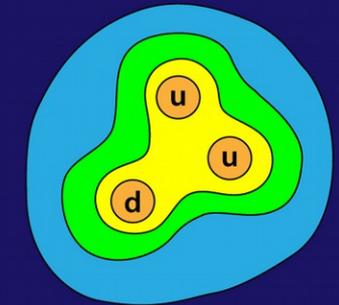
$$\frac{\Gamma(Z_b(10610) \rightarrow \bar{B}B)}{\Gamma(Z_b(10610) \rightarrow \Upsilon(1S)\pi)} \approx \frac{83\%}{0.6\%} = \mathcal{O}(100)$$

despite 1000 MeV of phase space  
for  $\Upsilon(1S)\pi$  vs few MeV for  $\bar{B}B^*$  !

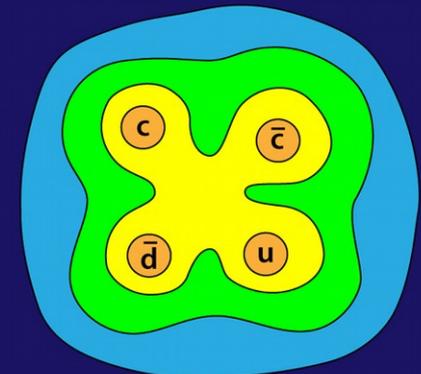
a) pion



b) proton



c)  $Z_c(3900)$



BR-s of  $X(3872)$  to  $J/\psi$  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 ( $\Gamma_i/\Gamma$ )
$\Gamma_1$	$e^+ e^-$	
$\Gamma_2$	$\pi^+ \pi^- J/\psi(1S)$	$> 2.6 \%$
$\Gamma_3$	$\rho^0 J/\psi(1S)$	
$\Gamma_4$	$\omega J/\psi(1S)$	$> 1.9 \%$
$\Gamma_5$	$D^0 \bar{D}^0 \pi^0$	$> 32 \%$
$\Gamma_6$	$\bar{D}^{*0} D^0$	$> 24 \%$
-		

## 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.  $\text{BR}(\text{fall apart mode}) \gg \text{BR}(\text{quarkonium} + X)$
4. no states which require binding through 3 pseudoscalar coupling

## binding two hadrons through $\pi$ exchange<sup>†</sup>:

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

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

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

---

$\pi$  = shorthand for a light pseudoscalar, not necessarily physical pion

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

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

$$D^* + \pi \rightarrow D$$

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

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

goes into itself under  $\pi$  exchange

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

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

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

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

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

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

$\Rightarrow$  deuteron-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 below thresholds

EXP signature:

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

perhaps also

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

$\Rightarrow$  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  $\chi_b(3P)$

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

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

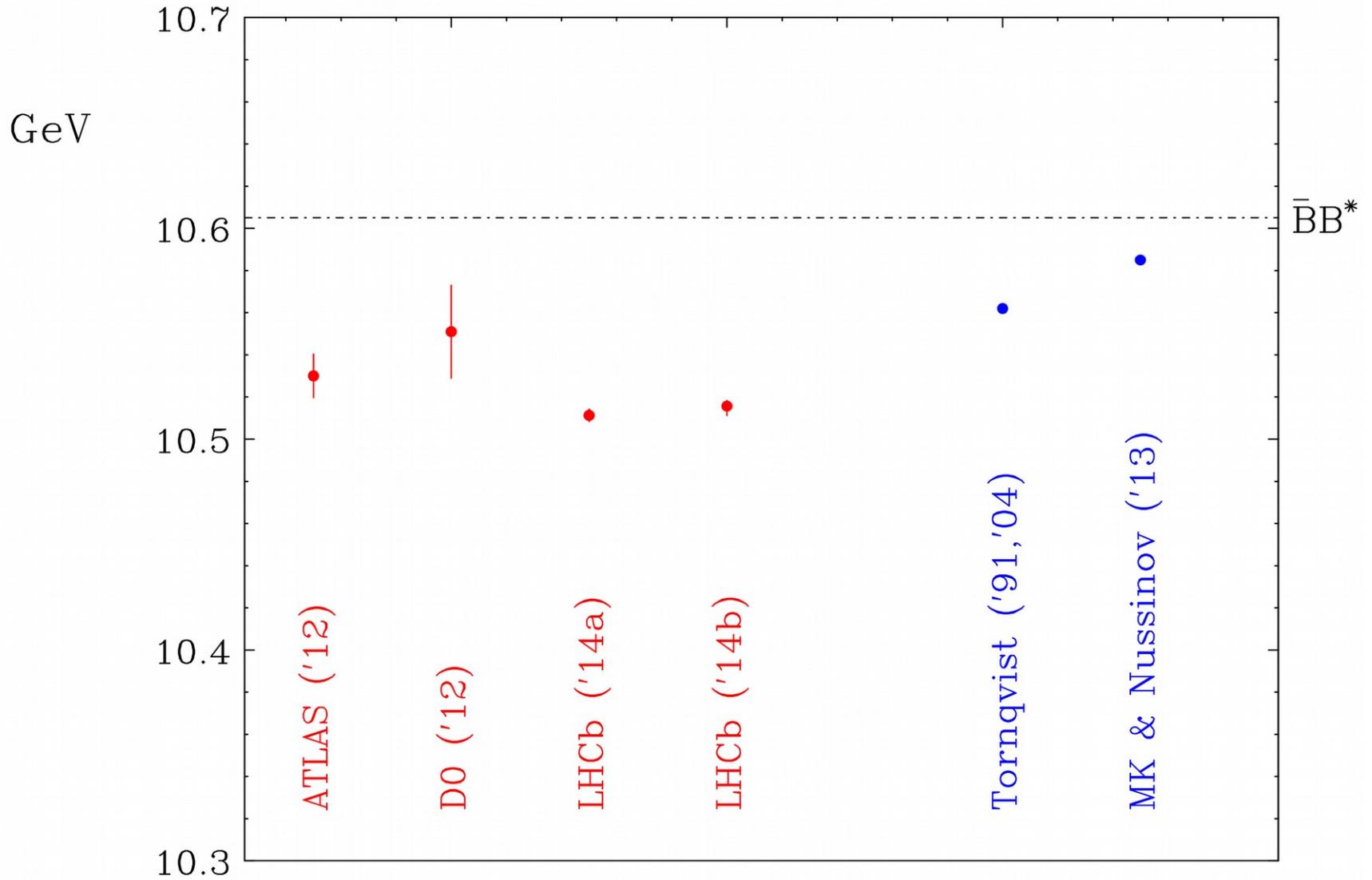
In the bottomonium system  $\chi_{b1}(2P)$  is much too light, but  $\chi_{b1}(3P)$  is near the expected  $X_b$  mass.

Seen in  $\chi_{b1}(3P) \rightarrow \Upsilon(mS)\gamma$ ,  $m = 1, 2, 3$

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]	$10515.7_{-3.9-2.1}^{+2.2+1.5}$

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



\* a biased sample

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

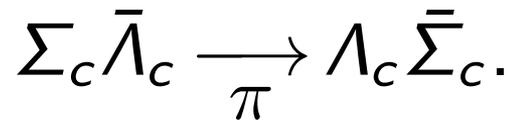
⇒ mixing is inevitable

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

necessary\* conditions for existence of a resonance

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

(b) both couple to pions;  
one of them can have  $l = 0$ , e.g.



(c) spin & parity which allow the state  
go into itself under one  $\pi$  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*

$\pi$  exchange between two states with  $l_1, l_2$  and  $S_1, S_2$ :

$$V_{\text{eff}} \sim \pm(l_1 \cdot l_2)(S_1 \cdot S_2) \quad \text{for } (qq, q\bar{q}) ,$$

$q$  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  $D^*$ ,  $B^*$ ,  $\Sigma_c$ , and  $\Sigma_b$

doubly-heavy hadronic molecules:

most likely candidates with  $Q\bar{Q}'$ ,  $Q = c, b$ ,  $\bar{Q}' = \bar{c}, \bar{b}$ :

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

$\Sigma_c\bar{D}^*$ ,  $\Sigma_c B^*$ ,  $\Sigma_b\bar{D}^*$ ,  $\Sigma_b B^*$ , 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  $\pi^-(s)$

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

$QQ'$  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:  $\Theta_{cc} \rightarrow J/\psi p$

$(S_1 \cdot S_2) (l_1 \cdot l_2)$  interaction:  $l = 1/2 \rightarrow J = 3/2$

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

small overlap of molecular state with  $J/\psi p$

$\Rightarrow$  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 <sup>a,b</sup>	Threshold (MeV) <sup>c</sup>	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	$J/\psi p$
$\Sigma_c B^*$	1/2	$c\bar{b}qqq'$	7779.5	$B_c^+ p$
$\Sigma_b\bar{D}^*$	1/2	$b\bar{c}qqq'$	7823.0	$B_c^- p$
$\Sigma_b B^*$	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 <sup>d</sup>	$B_c^+ \pi$
$\Sigma_b\bar{\Lambda}_c$	1	$b\bar{c}qq' \bar{u}\bar{d}$	8100.9 <sup>d</sup>	$B_c^- \pi$
$\Sigma_b\bar{\Lambda}_b$	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	$\Upsilon(nS)\pi\pi$

<sup>a</sup>Ignoring annihilation of quarks.

<sup>b</sup>Plus other charge states when  $I \neq 0$ .

<sup>c</sup>Based on isospin-averaged masses.

<sup>d</sup>Thresholds differ by 27.6 MeV.



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

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Raymond and Beverly Sackler Faculty of Exact Sciences  
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<sup>b</sup> *Enrico Fermi Institute and Department of Physics  
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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  $D\bar{D}^*$ ,  $D^*\bar{D}^*$ ,  $D^*B^*$ ,  $\bar{B}B^*$ ,  $\bar{B}^*B^*$ ,  $\Sigma_c\bar{D}^*$ ,  $\Sigma_c B^*$ ,  $\Sigma_b\bar{D}^*$ ,  $\Sigma_b B^*$ ,  $\Sigma_c\bar{\Sigma}_c$ ,  $\Sigma_c\bar{\Lambda}_c$ ,  $\Sigma_c\bar{\Lambda}_b$ ,  $\Sigma_b\bar{\Sigma}_b$ ,  $\Sigma_b\bar{\Lambda}_b$ , and  $\Sigma_b\bar{\Lambda}_c$ , as well as corresponding S-wave states giving rise to  $QQ'$  or  $\bar{Q}\bar{Q}'$ .

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



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

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

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narrow resonance at  
 $4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$

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DOI: 10.1103/PhysRevLett.115.122001

PACS numbers: 14.20.Pt, 12.39.Hg, 12.39.Jh, 14.40.Rt

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

R. Aaij *et al.*\*

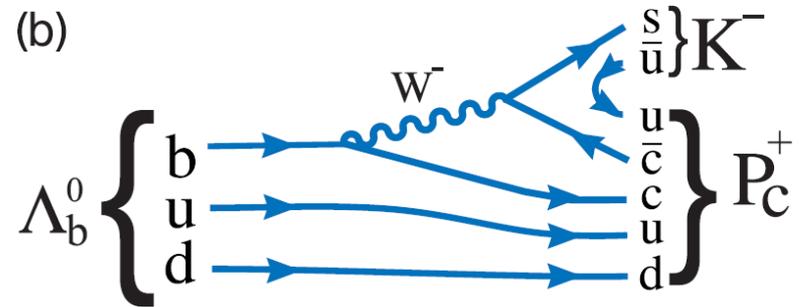
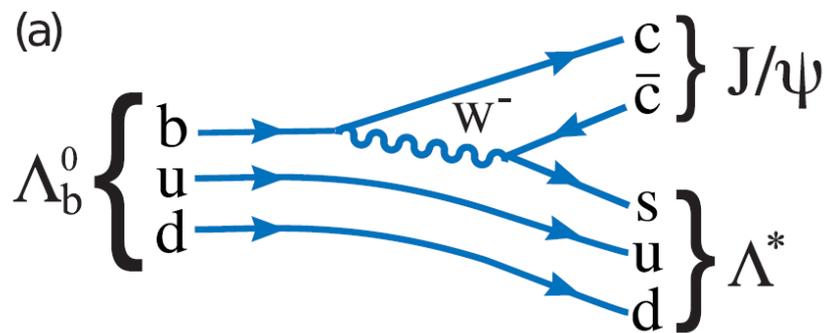
(LHCb Collaboration)

(Received 13 July 2015; published 12 August 2015)

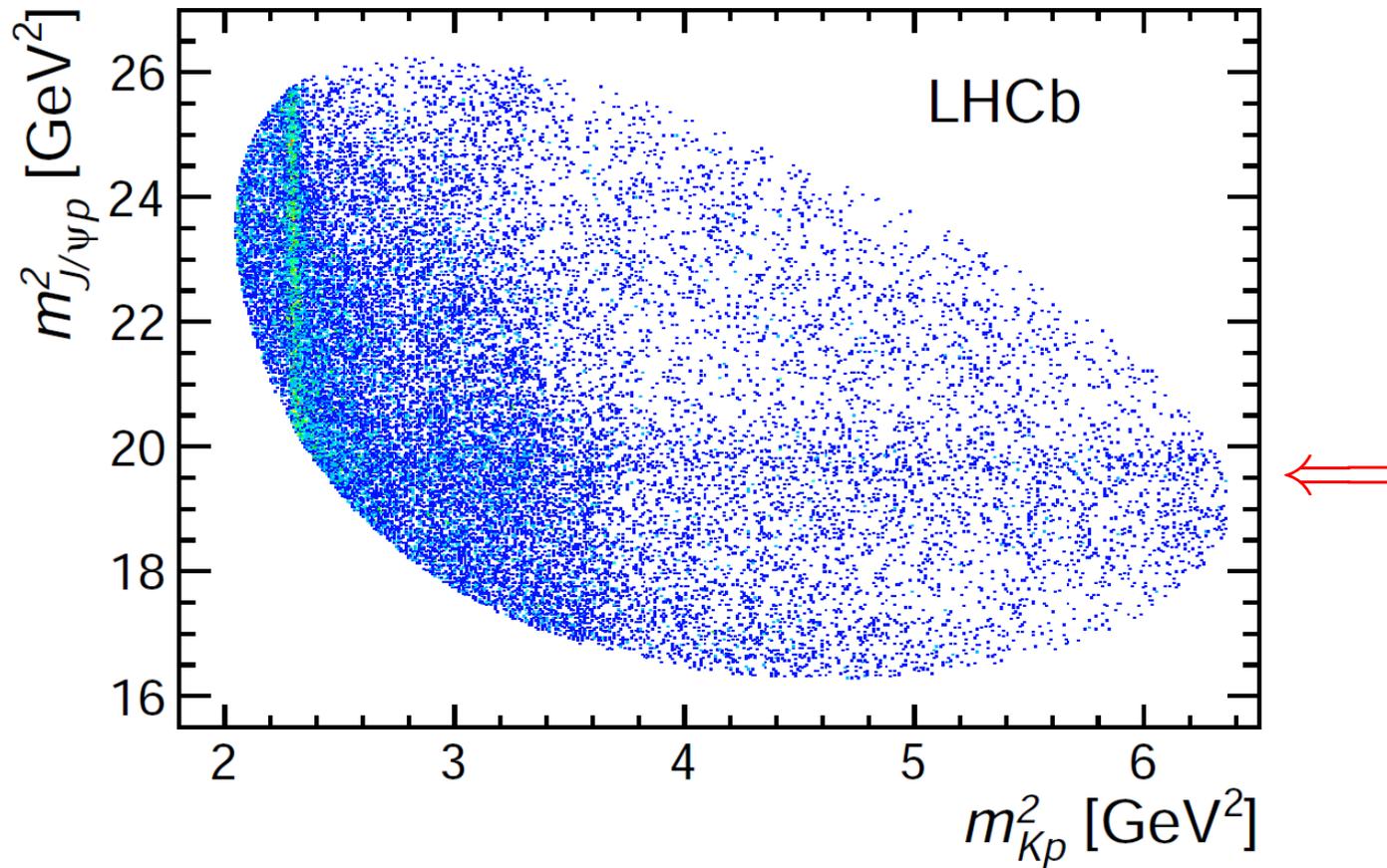
Observations of exotic structures in the  $J/\psi p$  channel, which we refer to as charmonium-pentaquark states, in  $\Lambda_b^0 \rightarrow J/\psi K^- p$  decays are presented. The data sample corresponds to an integrated luminosity of  $3 \text{ fb}^{-1}$  acquired with the LHCb detector from 7 and 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  $4380 \pm 8 \pm 29 \text{ MeV}$  and a width of  $205 \pm 18 \pm 86 \text{ MeV}$ , while the second is narrower, with a mass of  $4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$  and a width of  $39 \pm 5 \pm 19 \text{ MeV}$ . The preferred  $J^P$  assignments are of opposite parity, with one state having spin  $3/2$  and the other  $5/2$ .

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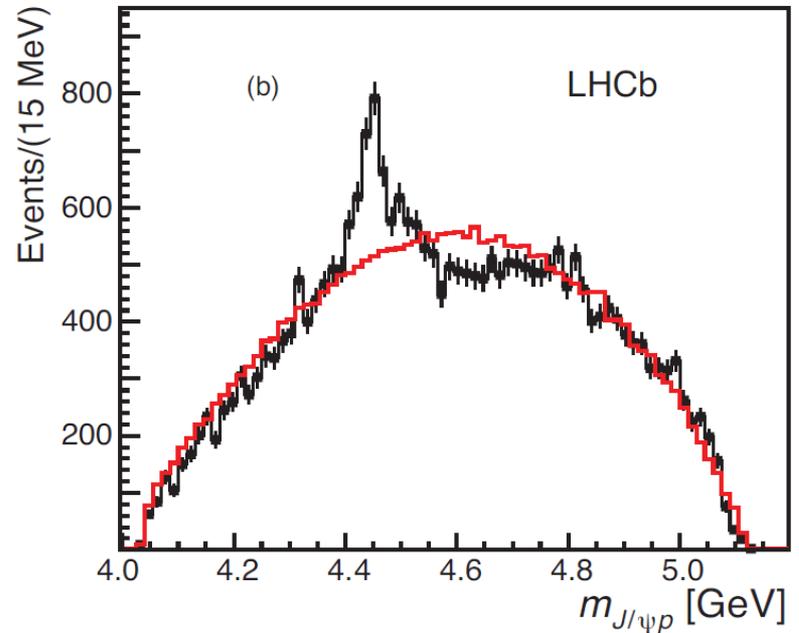
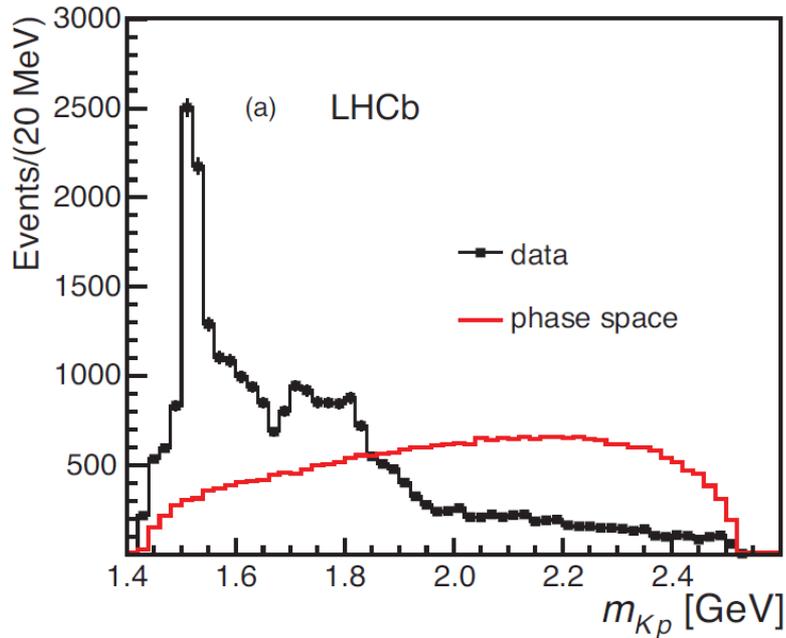
PACS numbers: 14.40.Pq, 13.25.Gv



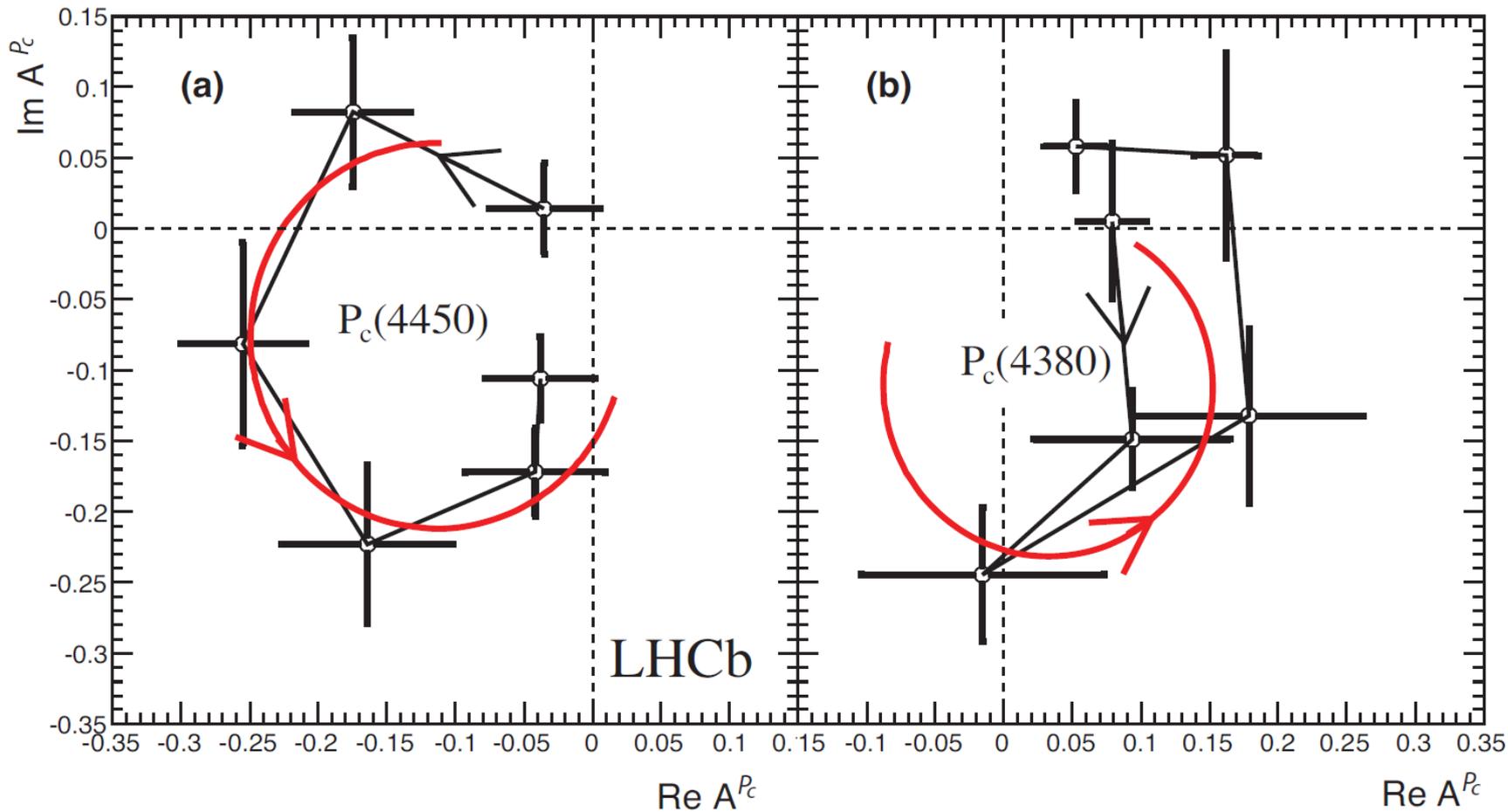
Feynman diagrams for (a)  $\Lambda_b^0 \rightarrow J/\psi \Lambda^*$  and (b)  $\Lambda_b^0 \rightarrow P_c^+ K^-$  decay.



Invariant mass squared of  $K^-p$  versus  $J/\psi p$  for candidates within  $\pm 15$  MeV of the  $\Lambda_b^0$



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



$P_c(4450)$ : 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 problem for pentaquark interpretation, given the large phase space of 400 MeV

$$\Gamma (P_c(4450) \rightarrow J/\psi p) = \left| \langle P_c(4450) | J/\psi p \rangle \right|^2 \times (\text{phase space})$$

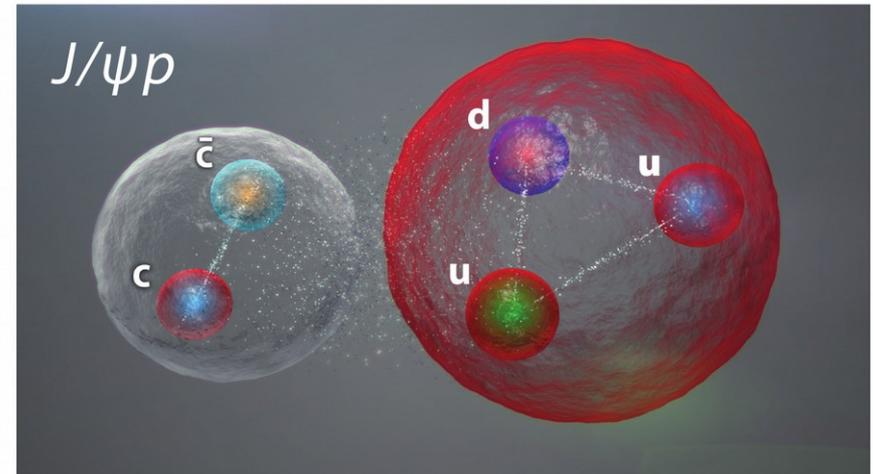
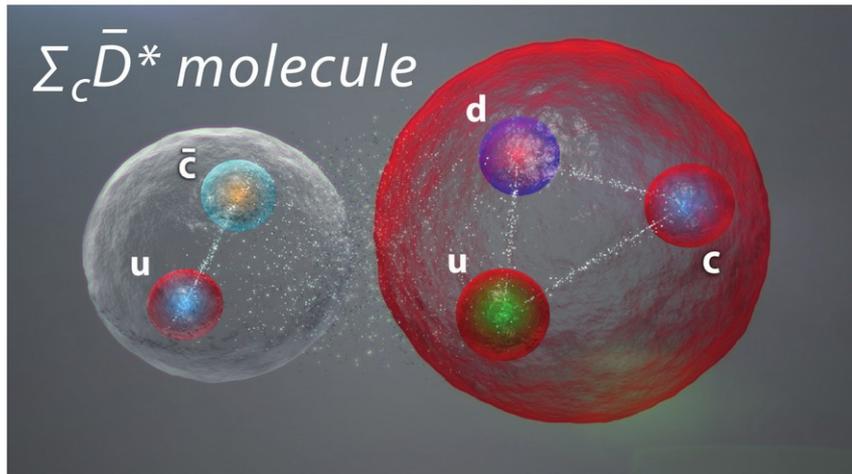
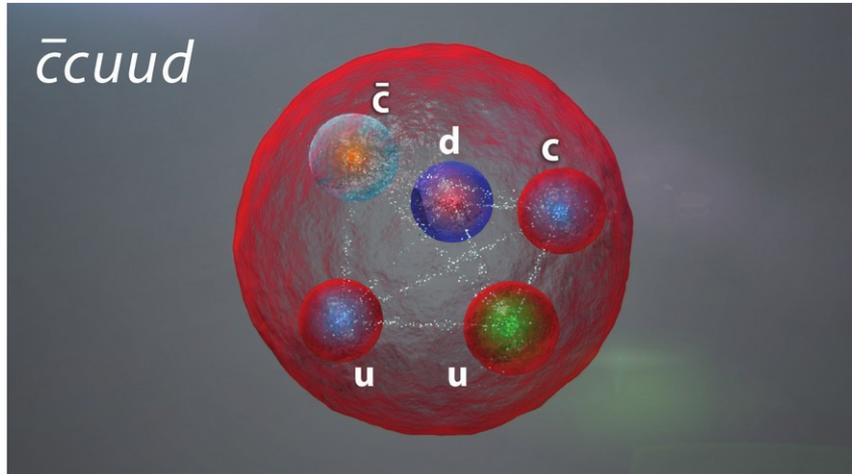
To get  $\Gamma = 39$  MeV, the matrix element must be small .

But in a pentaquark  $c$  and  $\bar{c}$  are close to each other within the same confinement volume, so overlap with  $J/\psi$  is generically large.

In a molecule narrow width is automatic:

$c$  is in  $\Sigma_c$ ,  $\bar{c}$  is in  $\bar{D}^*$ ; they are from each other, so overlap with  $J/\psi$  is generically small.

# Decay of a tightly bound pentaquark vs. hadronic molecule to $J/\psi p$



$$|\langle \Sigma_c \bar{D}^* | J/\psi p \rangle| \ll |\langle \bar{c}cuud | J/\psi p \rangle|$$

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

$P_c(4450)$  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

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

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

$$\Rightarrow r(X(3872)) \approx 4.4 \text{ fm} \quad \text{v. large, } \pi\text{-s dominate?}$$

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

at 1.2 fm the two hadrons overlap a bit

relative importance of  $\pi$ -s?

how does it work in  $b$  analogues?

# Photoproduction of exotic baryon resonances

MK & J. Rosner, arXiv:1508.01496

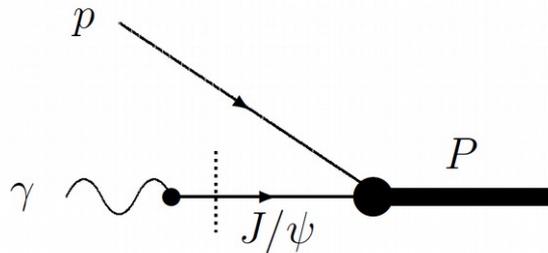
Q. Wang, X. H. Liu and Q. Zhao, arXiv:1508.00339

V. Kubarovsky and M. B. Voloshin, arXiv:1508.00888

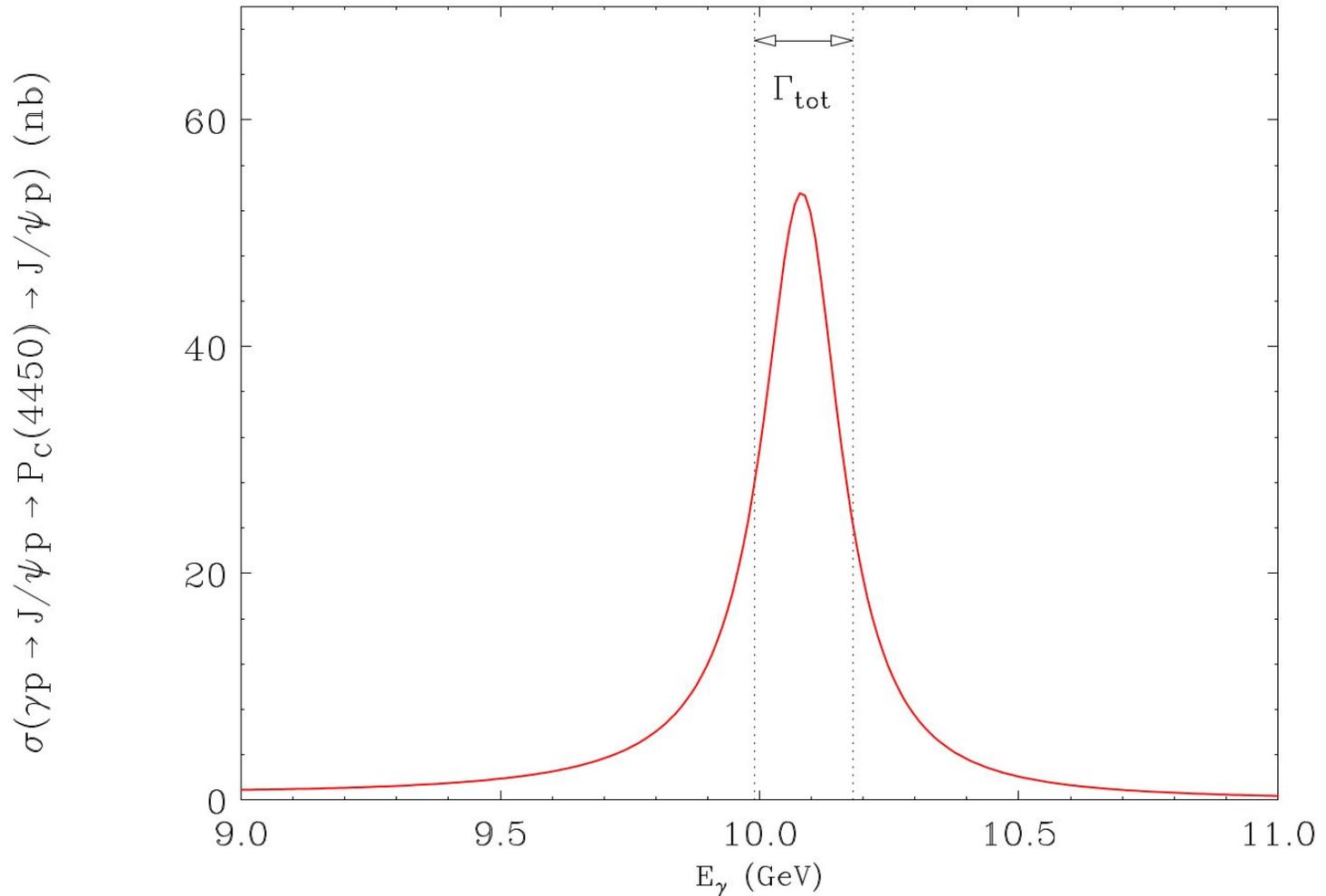
LHCb: new exotic resonances in  $J/\psi p$  channel:

$\implies$  excellent candidates for photoproduction

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



- $E_\gamma = 10 \text{ GeV} \implies \text{CLAS12 \& GlueX @JLab \& ...}$
- $\sigma \sim 50 \text{ nb} \gg \sigma_{\text{diffractive}} \sim 1 \text{ nb}$



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

SLAC and Cornell, 1975:

$$\sigma(\gamma p \rightarrow J/\psi p) < 1 \text{ nb for } 10 < E_\gamma < 13$$

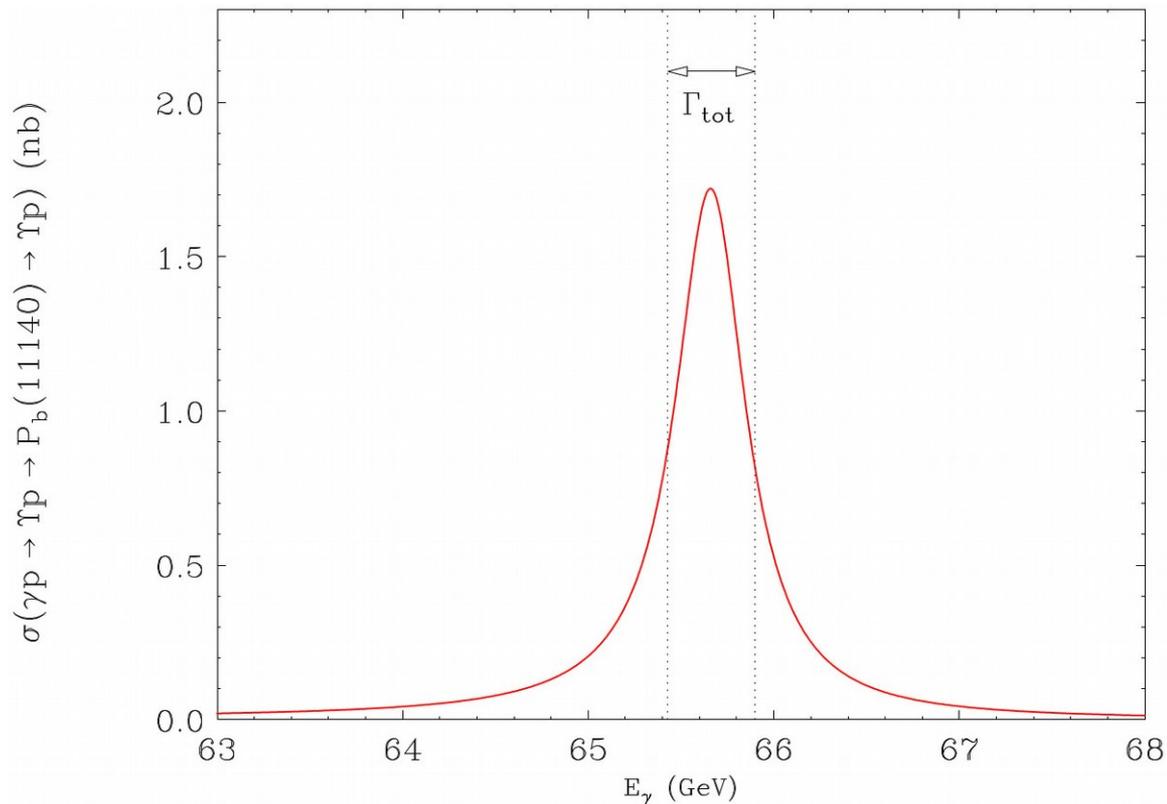
Why  $P_c$ -s not seen in these data ?

- 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

$$E_\gamma = 65.66 \text{ GeV},$$

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



detailed analysis needed to determine  
if  $\pi$  exchange suffices to bind two  
hadrons in each of these channels,  
and in corresponding  $QQ'$  channels.

but

- relevant  $\pi$ -hadron couplings yet unknown
- exchanges other than  $\pi$ , e.g. must have short-distance repulsion to stabilize the potential
- possible contributions beyond  $S$ -waves  
c.f.  $D$ -wave in deuteron

⇒ too early to calculate the binding in most cases

# Exotic resonances due to $\eta$ exchange

arXiv:1106.00565

- Mesons w/o  $u$  and  $d$  light quarks, e.g.  $D_s$  :
- cannot exchange  $\pi$
- but under suitable circumstances can bind as a result of  $\eta$  exchange.

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

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New results from LHCb  
on  $J/\psi \phi$  resonances  
talk by T. Skwarnicki

# exotic baryons due to $\eta$ exchange:

if  $\eta$  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

new  $J/\psi \phi$  LHCb resonances:  
molecules or tightly bound tetraquarks

if  $\bar{c}c\bar{s}s$  tetraquarks

$\bar{c}c\bar{c}c$  very likely to exist

$\Rightarrow$  look for clear experimental signatures

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

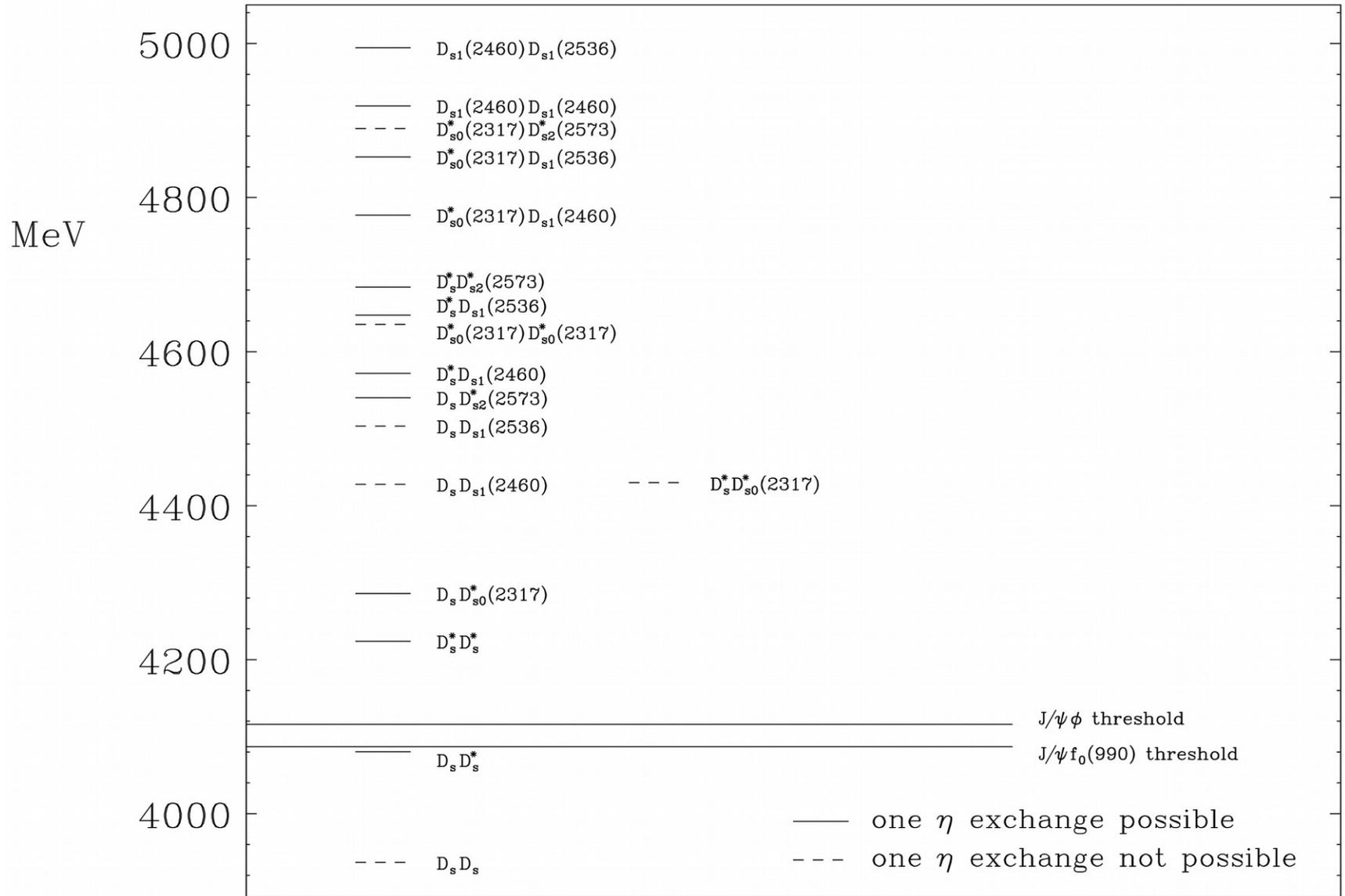
States ( $J^P$ )	$M$ (MeV)	$M - M(J/\psi)$ $-M(\phi)$	Binding by $\eta$ ?	Allowed $J^P$
$D_s^+(0^-) D_s^-(0^-)$	3936.6	-179.8	No	-
$D_s^+(0^-) D_s^{*-}(1^-)$	4080.4	-36.0	Yes	$1^+$
$D_s^{*+}(1^-) D_s^{*-}(1^-)$	4224.2	107.8	Yes	$0^+, 2^+{}^a$
$D_s^+(0^-) D_{s0}^{*-}(2317)(0^+)$	4286.0	169.6	Yes	$0^-$
$D_s^+(0^-) D_{s1}^-(2460)(1^+)$	4427.8	311.4	No <sup>b</sup>	$[1^-]{}^b$
$D_s^{*+}(1^-) D_{s0}^{*-}(2317)(0^+)$	4429.8	313.4	No <sup>b</sup>	$[1^-]{}^b$
$D_s^+(0^-) D_{s1}^-(2536)(1^+)$	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 <sup>c</sup>	736.4	Yes	$1^+$
$D_{s0}^{*+}(2317)(0^+) D_{s2}^{*-}(2573)(2^+)$	4889.6 <sup>c</sup>	773.2	No	-
$D_{s1}^+(2460)(1^+) D_{s1}^-(2460)(1^+)$	4919.0 <sup>c</sup>	802.6	Yes	$0^+, 2^+{}^a$
$D_{s1}^+(2460)(1^+) D_{s1}^-(2536)(1^+)$	4994.6 <sup>c</sup>	878.2	Yes	$0^+, 1^+, 2^+$

<sup>a</sup>  $J^P = 1^+$  forbidden by symmetry.

<sup>b</sup> Proximity of these two channels may lead to binding. See text.

<sup>c</sup> Cannot be produced in  $B \rightarrow KX$  because of kinematic mass limit.

# Thresholds involving two $D_s$ mesons



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

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

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

$\Rightarrow$  deuteron-like  $J = 1$ ,  $l = 0$  bound state, “*beautron*”

extra  $\sim 3$  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  $bcq, ccq, \text{ etc.}$

$QQq$  baryons are the simplest baryons:

when  $m_Q \rightarrow \infty$ ,  $QQ$  form a static  $\bar{3}_c$  diquark

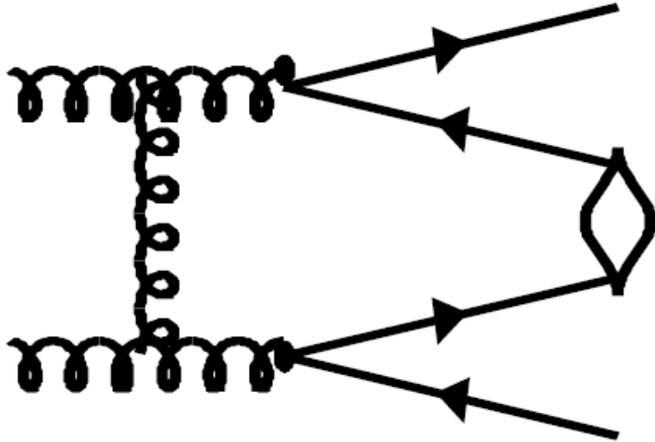
so  $QQq$  baryon  $\sim \bar{Q}q$  meson

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

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

hydrogen atom of baryon physics!

## $B_c$ production in LHCb: $gg$ fusion



v. hard to compute reliably from first principles, but...

$\Xi_{bc}$  production: same diagram,

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

$$\implies \sigma(pp \rightarrow \Xi_{bc} + X) \lesssim \sigma(pp \rightarrow B_c + X)$$

LHCb is making a lot of  $B_c$ -s  $\sigma \approx 0.4 \mu\text{b}$

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

$\Xi_{cc}$  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),

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

$$\text{vs. } \tau(\Lambda_c) \approx 0.2 \times 10^{-12} \text{ sec.}$$

verified by detailed lifetime calculation

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

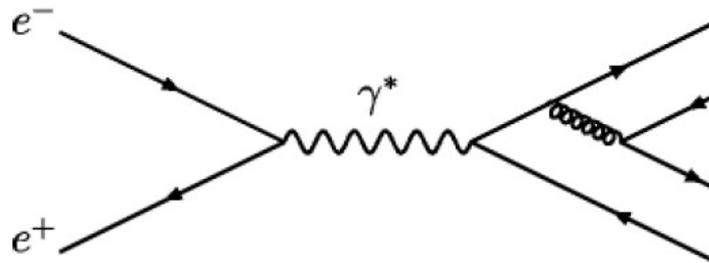
$$e^+ e^- \rightarrow b\bar{b}c\bar{c} + X ,$$

$$e^+ e^- \rightarrow b\bar{b}b\bar{b} + X$$

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

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

same diagram  
for  $B_c$  and  $\Xi_{bc}$ :



estimate  $\sigma(e^+ e^- \rightarrow \gamma B_c^+ B_c^- + X)$

$\sim 1.7 \text{ fb @90 GeV, } 0.24 \text{ fb @250 GeV}$

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	$M(J = 1/2)$	$M(J = 3/2)$
$\Xi_{cc}^{(*)}$	$ccq$	$3627 \pm 12$	$3690 \pm 12$
$\Xi_{bc}^{(*)}$	$b[cq]$	$6914 \pm 13$	$6969 \pm 14$
$\Xi'_{bc}$	$b(cq)$	$6933 \pm 12$	—
$\Xi_{bb}^{(*)}$	$bbq$	$10162 \pm 12$	$10184 \pm 12$

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	$430 \pm 100$	$460 \pm 50$	500	$\sim 200$
$\Xi_{cc}^{+} = ccd$	53	$120 \pm 100$	$160 \pm 50$	150	$\sim 100$
$\Xi_{bc}^{+} = bcu$	244	$330 \pm 80$	$300 \pm 30$	200	—
$\Xi_{bc}^{0} = bcd$	93	$280 \pm 70$	$270 \pm 30$	150	—
$\Xi_{bb}^{0} = bbu$	370	—	$790 \pm 20$	—	—
$\Xi_{bb}^{-} = bbd$	370	—	$800 \pm 20$	—	—

# 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 <sup>a</sup>
$\Lambda_b\bar{\Lambda}_b$	11239
$B_c\bar{B}_c$	12551
$B_c\bar{B}_c^*$	12619–12635 <sup>b</sup>
$B_c^*\bar{B}_c^*$	12687–12719 <sup>b</sup>
$\Xi_{bc}\bar{\Xi}_{bc}$	13842–13890 <sup>c</sup>
$\Xi_{bb}\bar{\Xi}_{bb}$	20300–20348 <sup>c</sup>

<sup>a</sup>analogue of the very narrow  $D_{s0}(2317)$

<sup>b</sup>With estimated  $B_c^* B_c$  splitting 68–84 MeV

<sup>c</sup>estimate, MK&Rosner (2014)

# Likely decay modes of $QQq$ baryons

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

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

e.g.

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

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

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  $c \rightarrow sud$ , have  $cd \rightarrow su$

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

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

$b \rightarrow cdu$  and  $c \rightarrow sud$

e.g.  $\Xi_{bc}^+ \rightarrow J/\psi \Xi_c^+$

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

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

$$\tau(\Xi_c^+) = (4.42 \pm 0.26) \times 10^{-13} \text{ s}$$

the difference due to  $cd \rightarrow su$

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

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

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

- $\Xi_{bb} = bbq$

$bu \rightarrow cd$  possible for  $\Xi_{bb}^0$ , but

$\tau(\Xi_b^0)$  not much different from  $\tau(\Xi_b^-)$   
 so treat  $\Xi_{bb}^0$  and  $\Xi_{bb}^-$  generically as  $\Xi_{bb}$

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

rare but spectacular decay mode:

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

rough estimate of  $\Xi_{cc}$  production rate

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

$\Xi_{cc}$  suppressed vs.  $\Xi_c$  as  $\Xi_c$  vs.  $\Xi$ :

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

perhaps can generalize to  $\Xi_{bc}$  and  $\Xi_{bb}$  production rate

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

or

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

and

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

a possible way to check if  $\Xi_{bc}$  and  $B_c$

production rates are comparable:

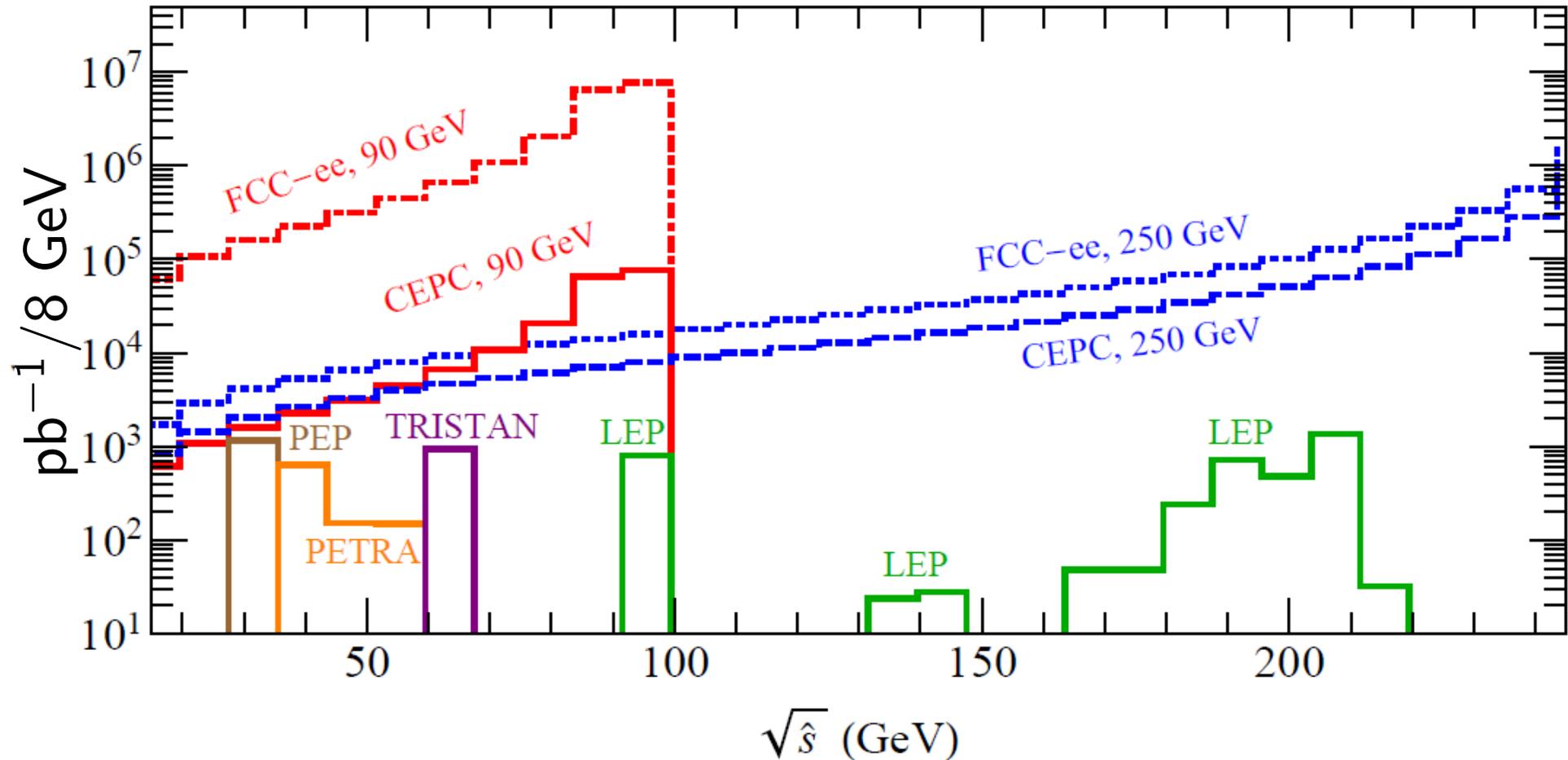
compare analogous prod. rates of  $\Xi_c$  and  $D_s$

(or  $\Xi_b$  and  $B_s$ ) in the same setup,

and large enough  $E_{CM}$

be it  $e^+e^-$ ,  $\bar{p}p$  or  $pp$

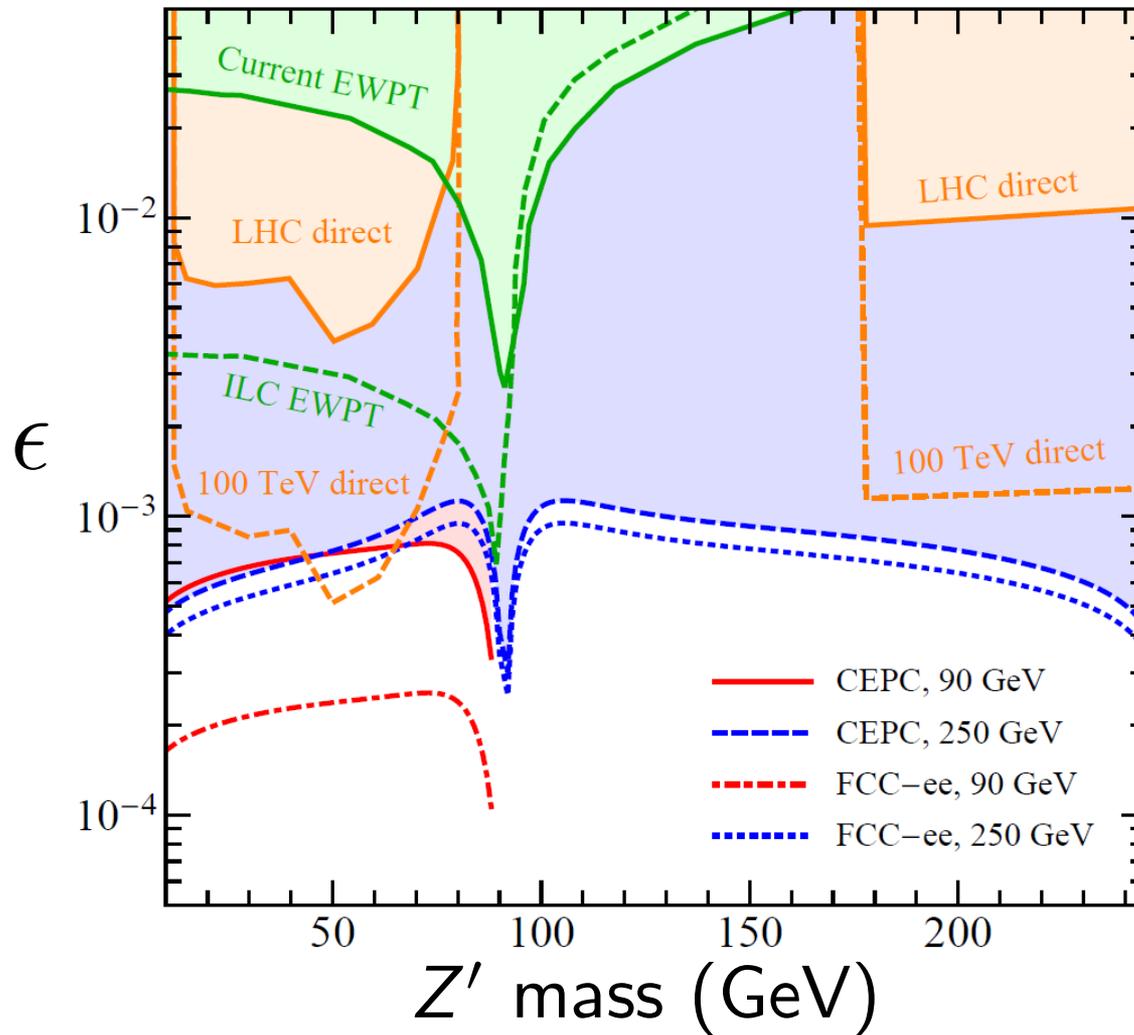
# integrated luminosity



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**

# dark photon limits on $\epsilon$ at 95% C.L. including $e^+e^- \rightarrow \gamma Z' \rightarrow \gamma \mu^+ \mu^-$



EWPT = electroweak precision constraints  
100 TeV projection assumes  $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$

EWPT & direct searches from J. Fan, M. Reece, and L. T. Wang,<sup>5</sup> assume  $\Delta m = m^2 / (10^5 \text{ GeV})$   
arXiv:1411.1054

# 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  
 $\Sigma_c B^*$ ,  $\Sigma_b \bar{D}^*$ ,  $\Sigma_b B^*$ ,  $\Sigma_Q \bar{\Lambda}_{Q'}$ ,  $\Sigma_Q^+ \Sigma_Q^-$ , ...  
 $\eta$ -mediated:  $D_s \bar{D}_s^*$ ,  $\Lambda_c \bar{D}_s^*$ , ...
- doubly & triply heavy baryons  $QQq$ ,  $QQQ$  @  $pp$  &  $e^+e^-$
- exciting new spectroscopy in future  $e^+e^-$  high- $\mathcal{L}$  high- $E$  colliders

# Supplementary transparencies

discovery of isovector  $Z_c(3900)$

⇒ 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

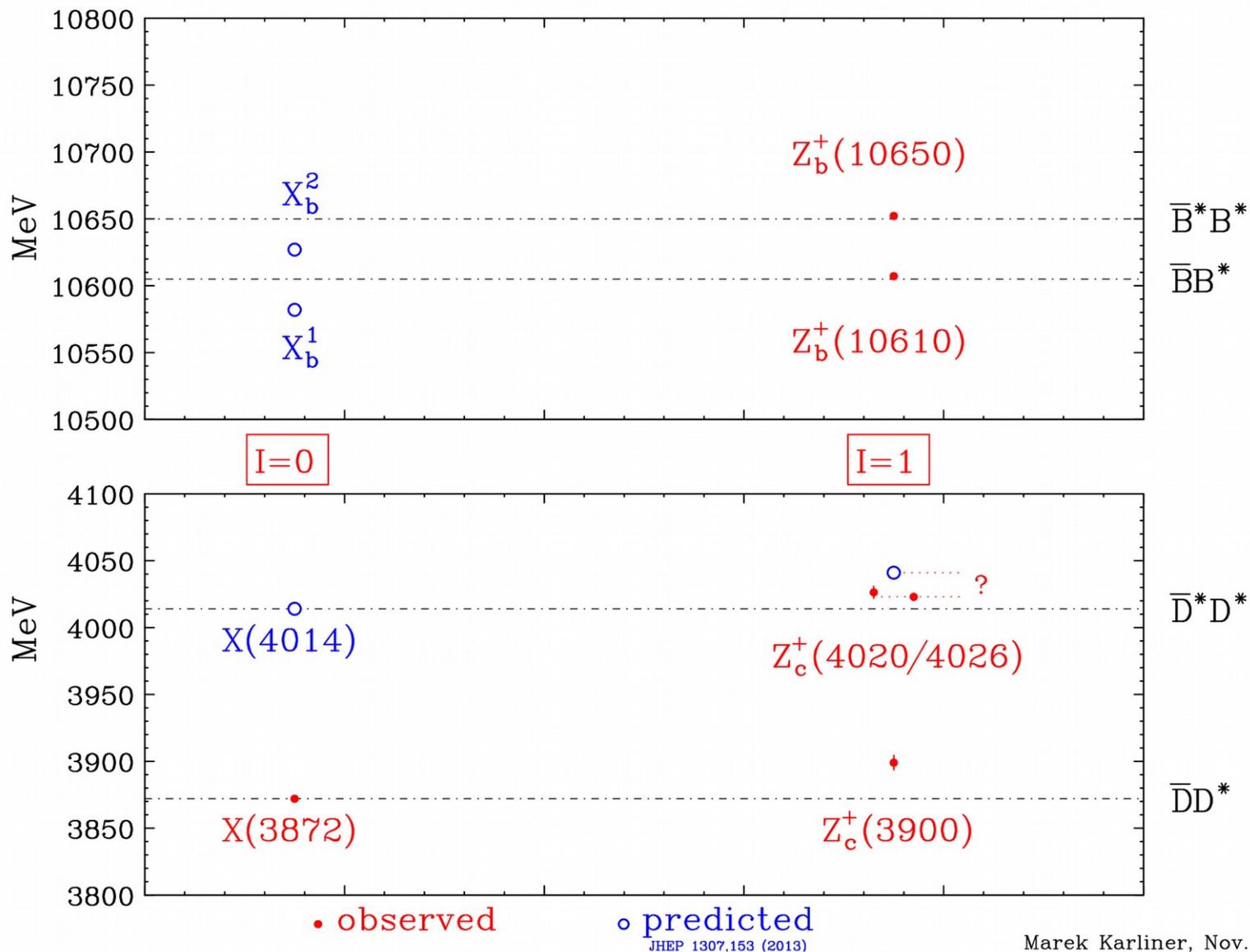
did not have to wait long...

BESIII:

$Z_c^+(4025)$ , arXiv:1308.2760,  $\Gamma \approx 25$  MeV

$Z_c^+(4020)$ , arXiv:1309.1896;  $\Gamma \approx 8$  MeV

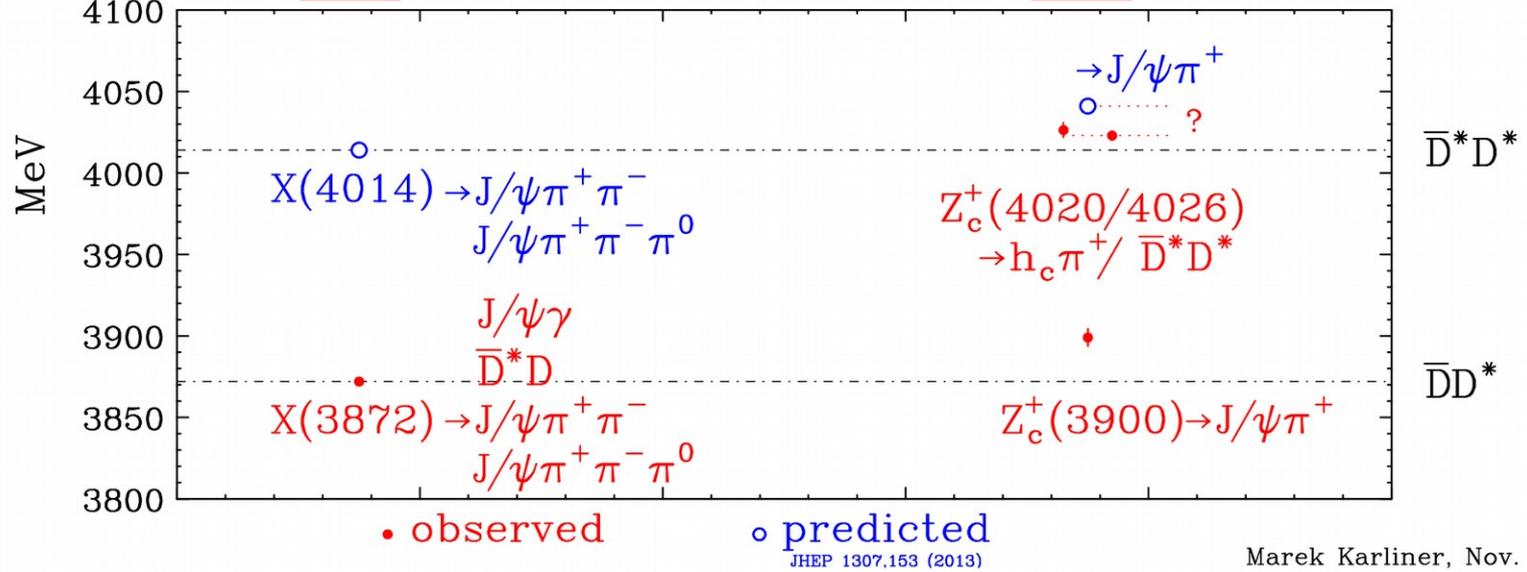
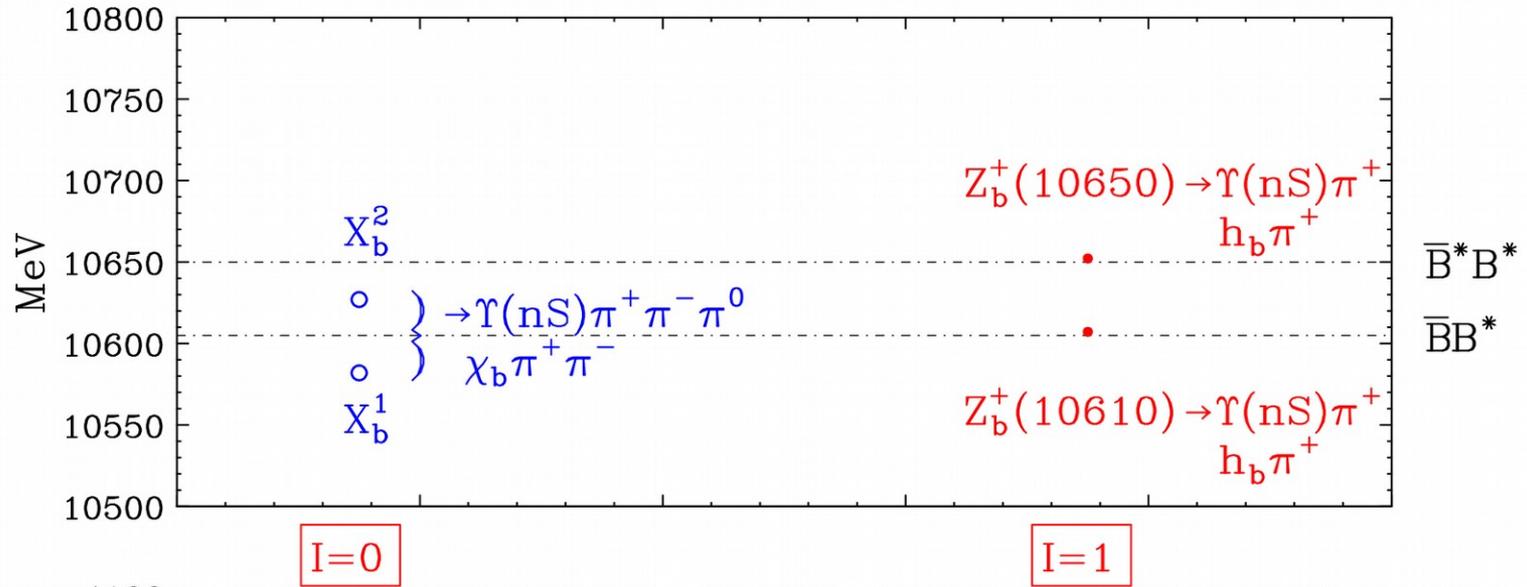
# exotic heavy quarkonia vs. two meson thresholds



Marek Karliner, Nov. 2013

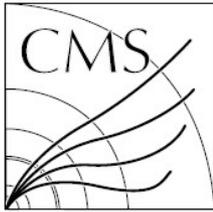
caveat: some masses = peak positions,  
with interference  $\neq$  pole mass

# exotic heavy quarkonia vs. two meson thresholds



Marek Karliner, Nov. 2013

# Null result from 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 $\sqrt{s} = 8$ 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  $\sqrt{s} = 8$  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  $X_b \rightarrow Y(1S)\pi^+\pi^-$  followed by  $Y(1S) \rightarrow \mu^+\mu^-$ . 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

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

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,  $\Gamma < 3.8 \text{ MeV}$ ,

decay:  $D_{s0}(2317) \rightarrow D_s^+ \pi^0$

through v. small isospin-violating  $\eta - \pi^0$  mixing

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