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MultiQuark States

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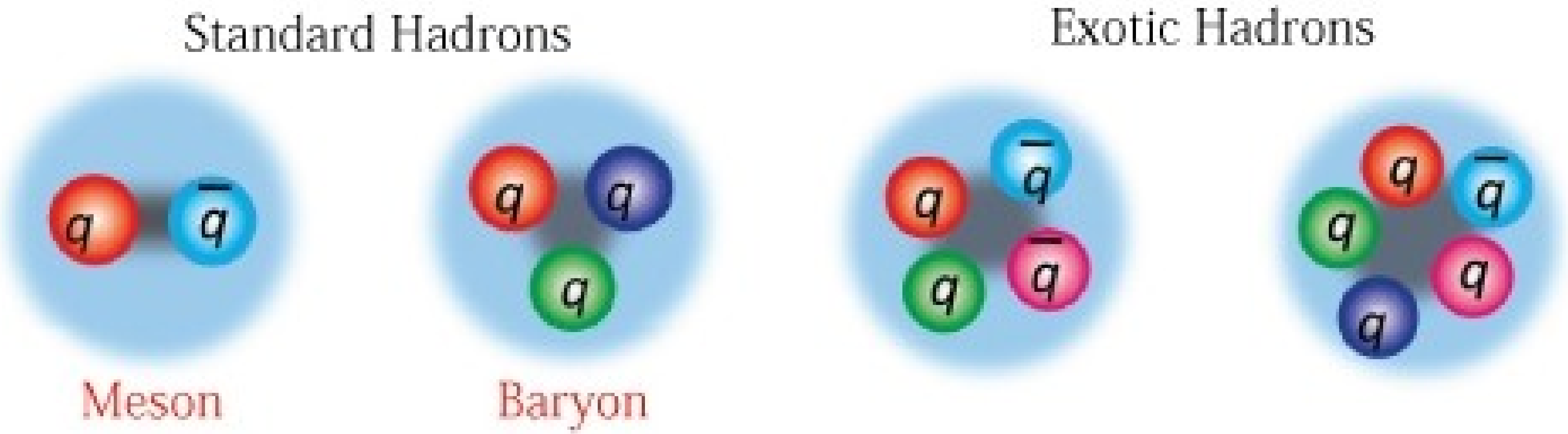
PRD91 (2015) 1, 014014 & PRD90 (2014) 9, 094007,
PRL 115,112001, PLB 752,329, arxiv:1601:00565 with Jon Rosner
JHEP 7,153(2013) with Shmuel Nussinov
arXiv:1611.00348 with Jon Rosner & Shmuel Nussinov
and a big intellectual debt to Harry Lipkin

UK HEP Forum, Nov 4, 2016


Standard Hadrons
Exotic Hadrons
Meson
Baryon

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 b 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 $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ 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 $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ 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 π-(s)

    $\Rightarrow$ very broad

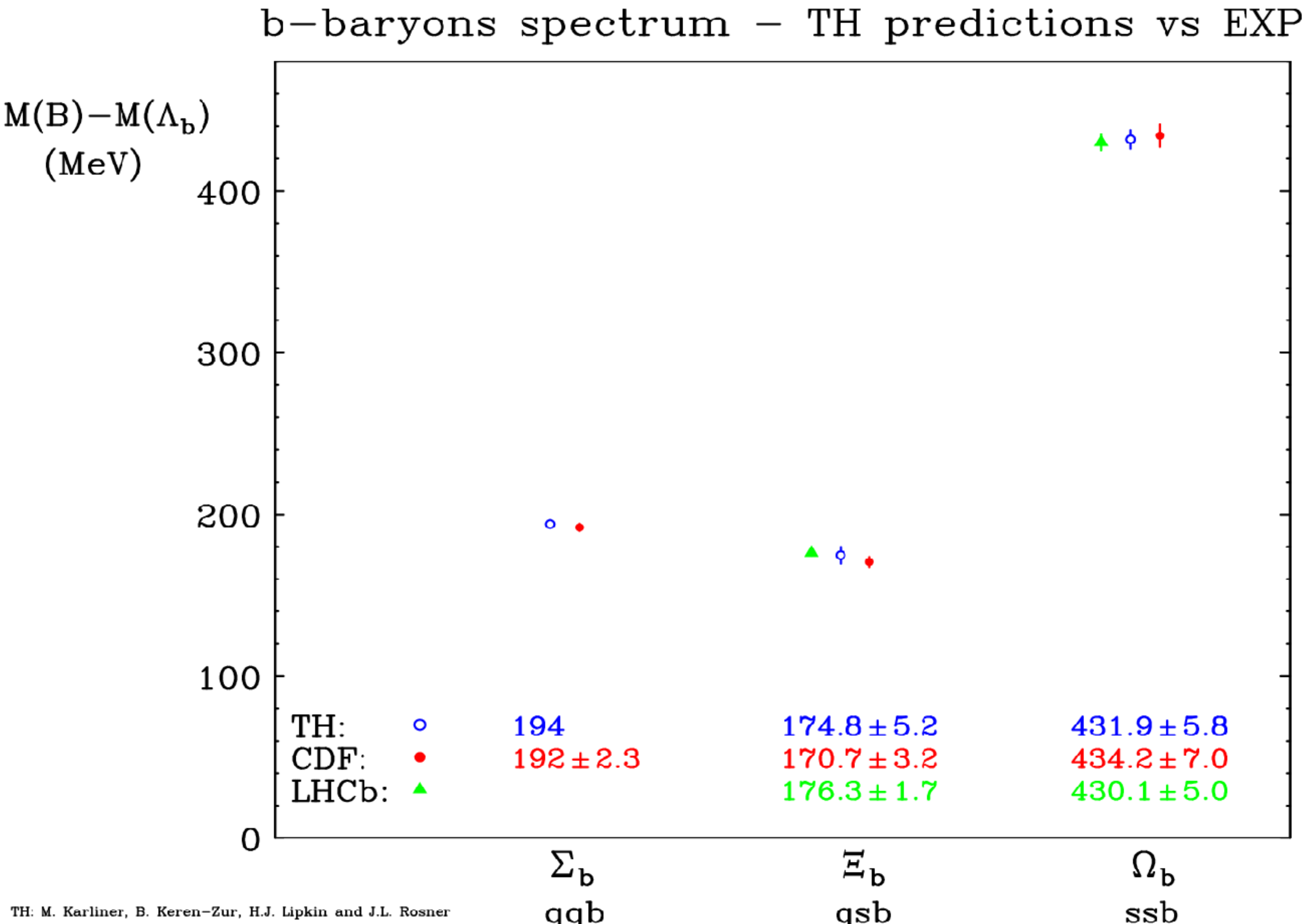
- explains why light exotics so hard to pin down
- situation very different for $\bar{Q}Q\bar{q}q$ exotics:
- $\bar{Q}Q$ hardly mix with light quarks
- decay into quarkonium and π-(s)
  or two heavy-light mesons:

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

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

$\Rightarrow$ 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:



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

arXiv:0802.0649v2 [hep-ph] 4 Mar 2008

Possibility of Exotic States in the Upsilon system

Marek Karliner [a*]
and
Harry J. Lipkin [a,b†]

Abstract

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

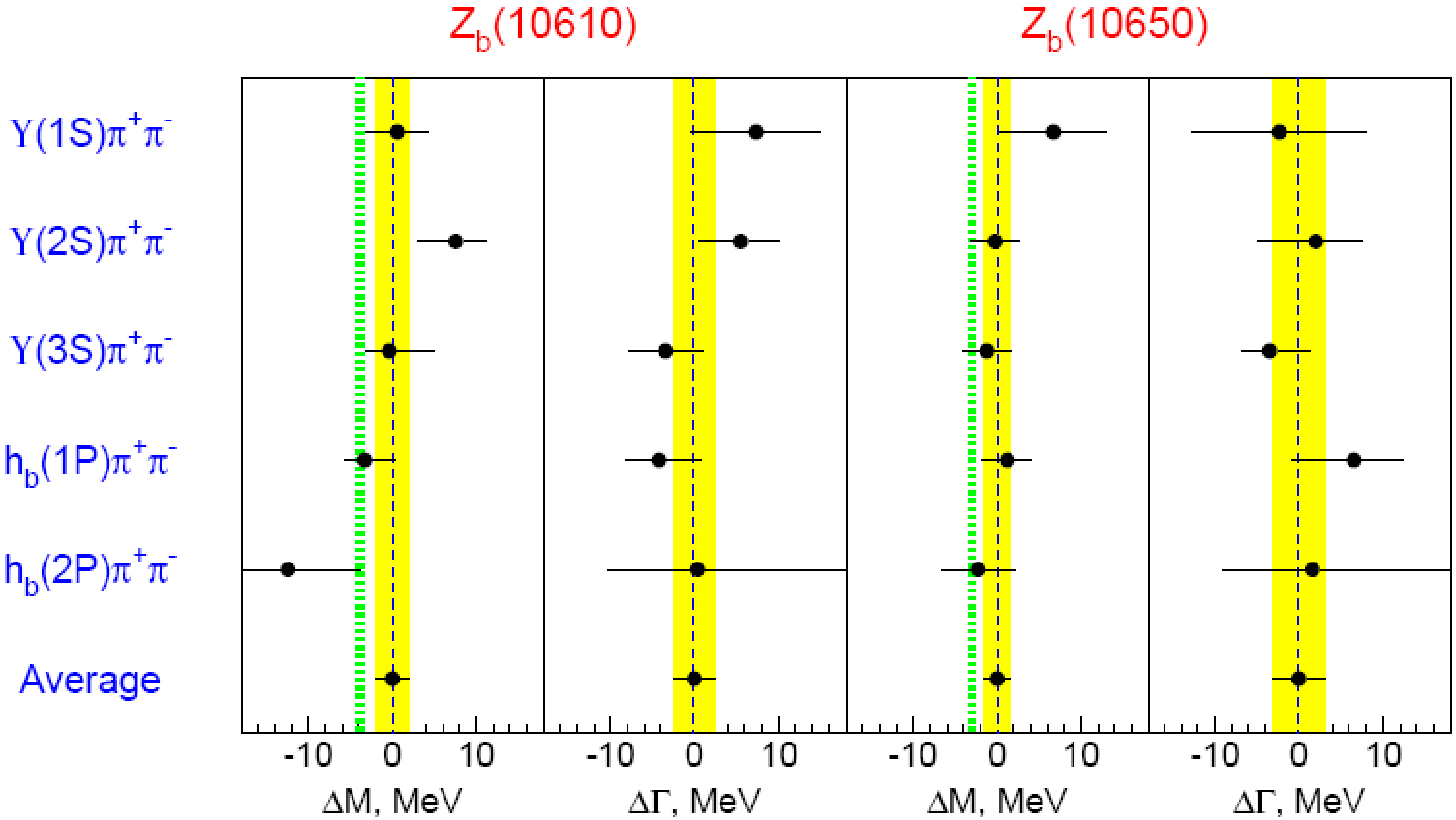
Observation of two charged bottomonium-like resonances

The Belle Collaboration

(Dated: May 24, 2011)

Abstract

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



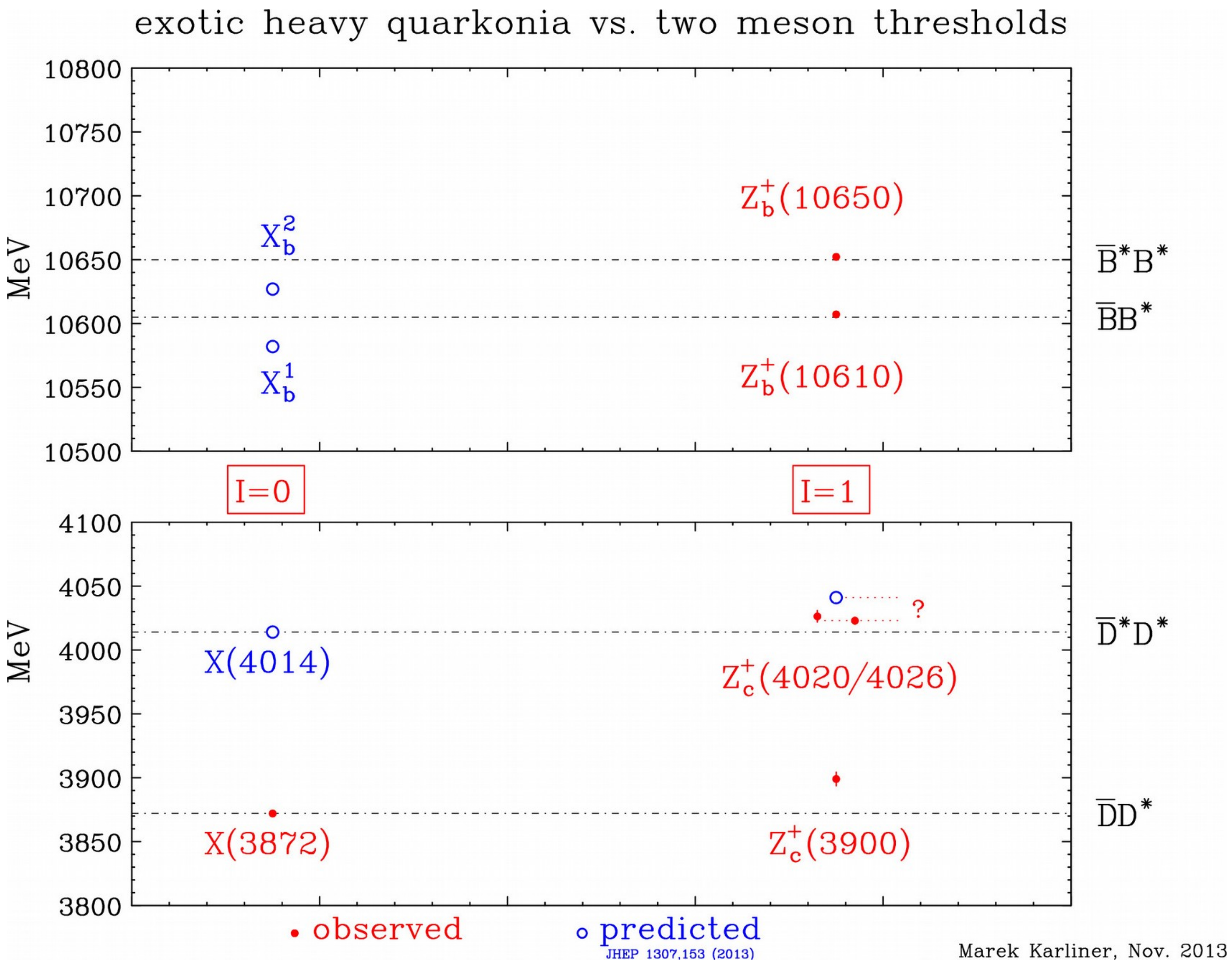
nels. The vertical dotted lines indicate $B^*\overline{B}$ and $B^*\overline{B}^*$ thresholds.

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

5 narrow exotic states close to meson-meson thresholds

state	mass MeV	width MeV	$\bar{Q}Q$ decay mode	phase space MeV	nearby threshold	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
$\times$					$\bar{D}D$	
$\times$					$\bar{B}B$	

- 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
MeV
10800
10750
10700
10650
10600
10550
10500
X_b^2
X_b^1
$Z_b^+(10650)$
$Z_b^+(10610)$
$\bar{B}^*B^*$
$\bar{B}B^*$
I=0
I=1
4100
4050
4000
3950
3900
3850
3800
X(4014)
X(3872)
?
$Z_c^+(4020/4026)$
$Z_c^+(3900)$
$\bar{D}^*D^*$
$\bar{D}D^*$
observed
predicted
JHEP 1307,153 (2013)
Marek Karliner, Nov. 2013

The Z_Q resonances decay into

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

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

$\Longrightarrow$ 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 $\bar{D}D$

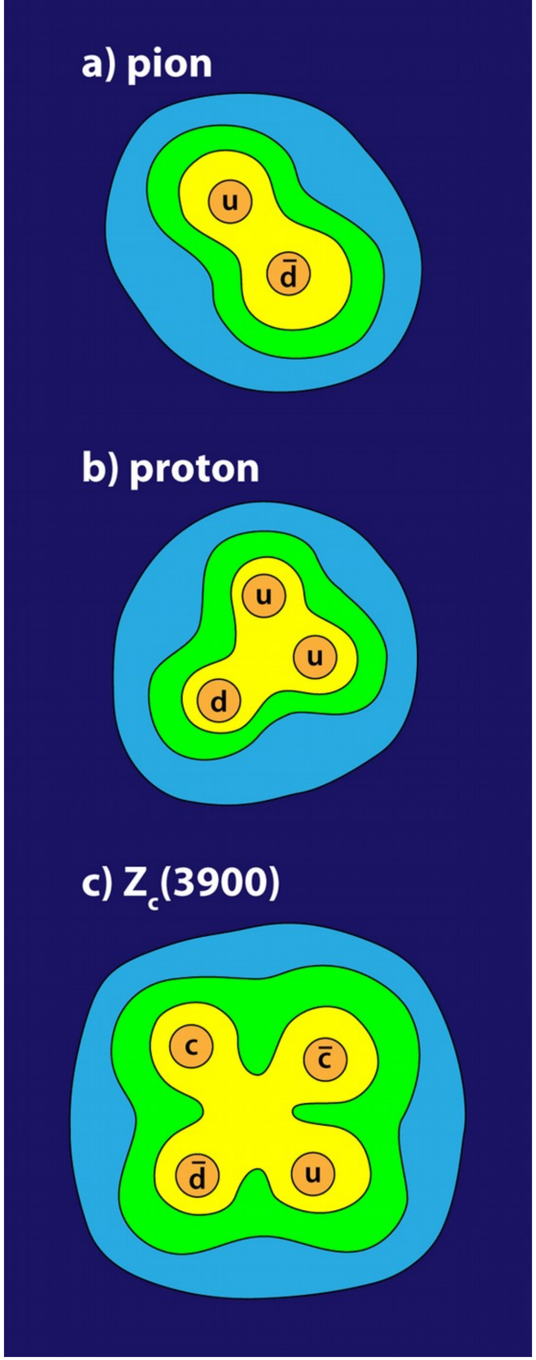
$\Rightarrow$ indicates an extended object

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 $\bar{B}B^*$!



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

$\text{BR}(\bar{D}D^*) \sim 10\times$ BR($\text{J}/\psi + X$)
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:

$D^* \to D^* + \pi, \quad P$-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-light $Q\bar{q}$ 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

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

$\Rightarrow$ LHCb !

an amusing paper from CMS: null result in search for

$$X_b \to \Upsilon(1S)\pi^+\pi^-$$

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 $\chi_b(3P)$

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

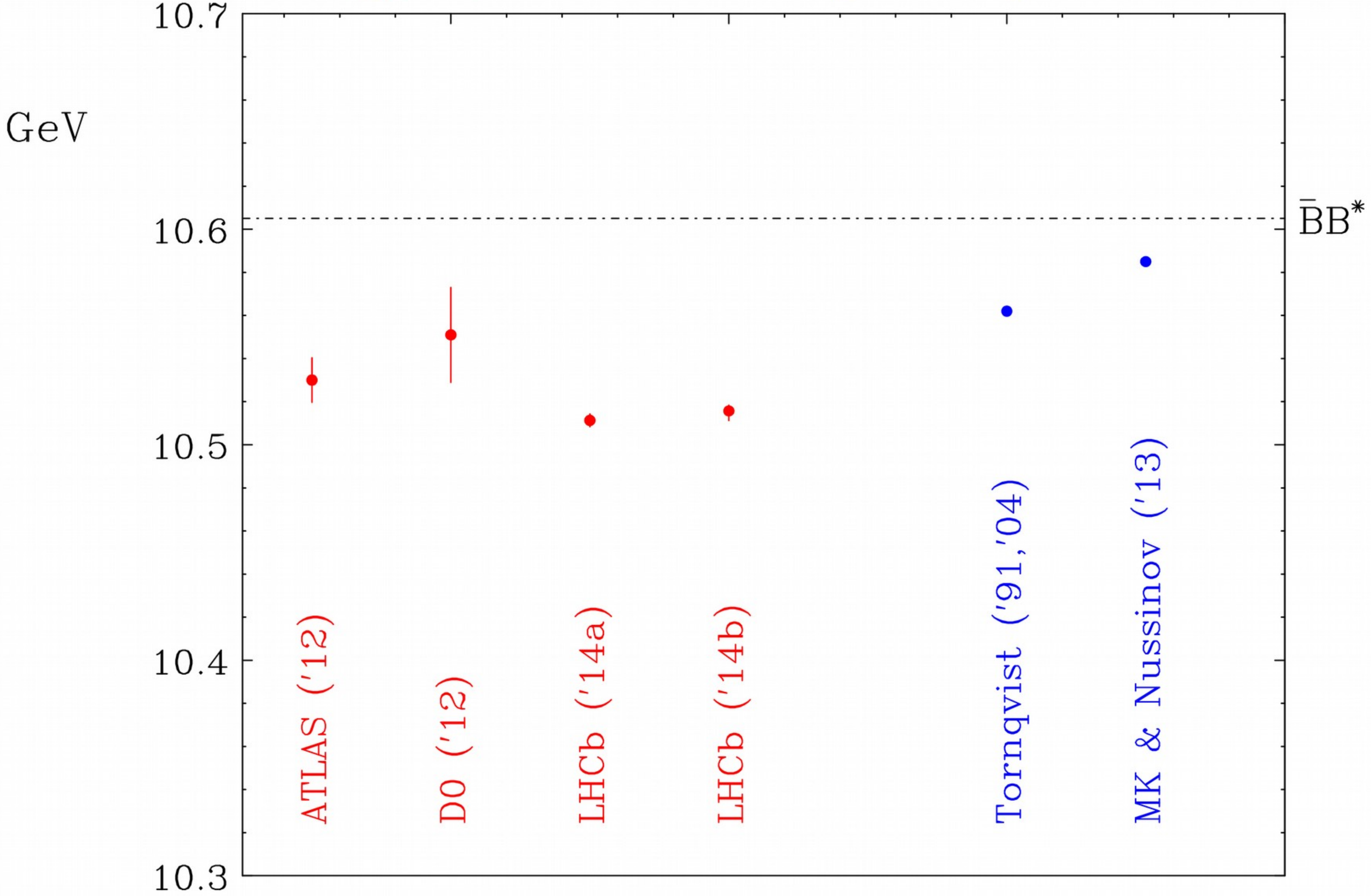
suggests that $X(3872)$ is a mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{*0}$

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*



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

(b) both couple to pions;
one of them can have $I = 0$, e.g.
$\Sigma_c \bar{\Lambda}_c \underset{\pi}{\longrightarrow} \Lambda_c \bar{\Sigma}_c$.

(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:

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

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

$\Sigma_c\bar{D}^*$, $\Sigma_c B^*$, $\Sigma_b\bar{D}^*$, $\Sigma_b B^*$, 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 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:

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

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

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University of Chicago, 5620 S. Ellis Avenue, Chicago, IL 60637, USA

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 $\bar{Q}\bar{Q}'$.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2015-153
LHCb-PAPER-2015-029
July 13, 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 $5/2$.

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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^*, $\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, 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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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

PRL **115,** 122001 (2015) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2015

New Exotic Meson and Baryon Resonances from Doubly Heavy Hadronic Molecules

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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 $\bar{Q}\bar{Q}'$.

DOI: 10.1103/PhysRevLett.115.122001 PACS numbers: 14.20.Pt, 12.39.Hg, 12.39.Jh, 14.40.Rt

Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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

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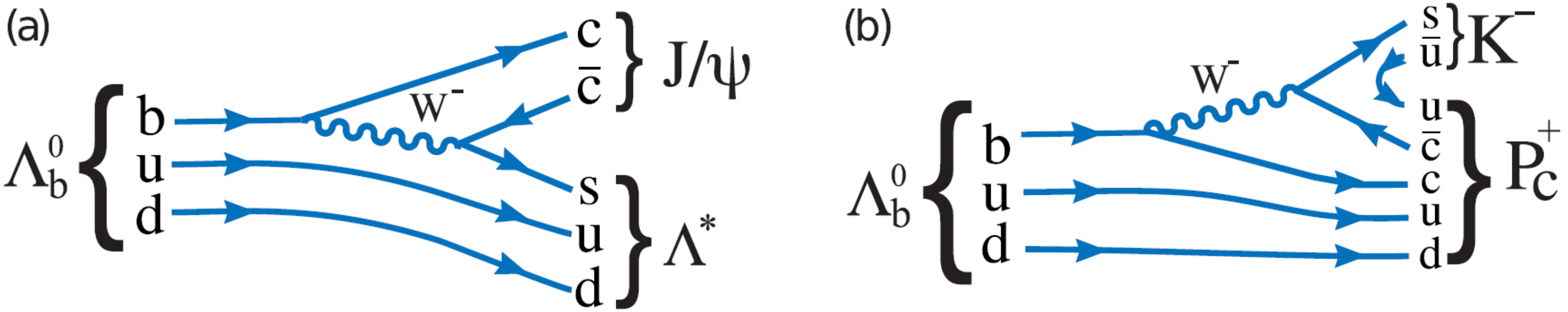
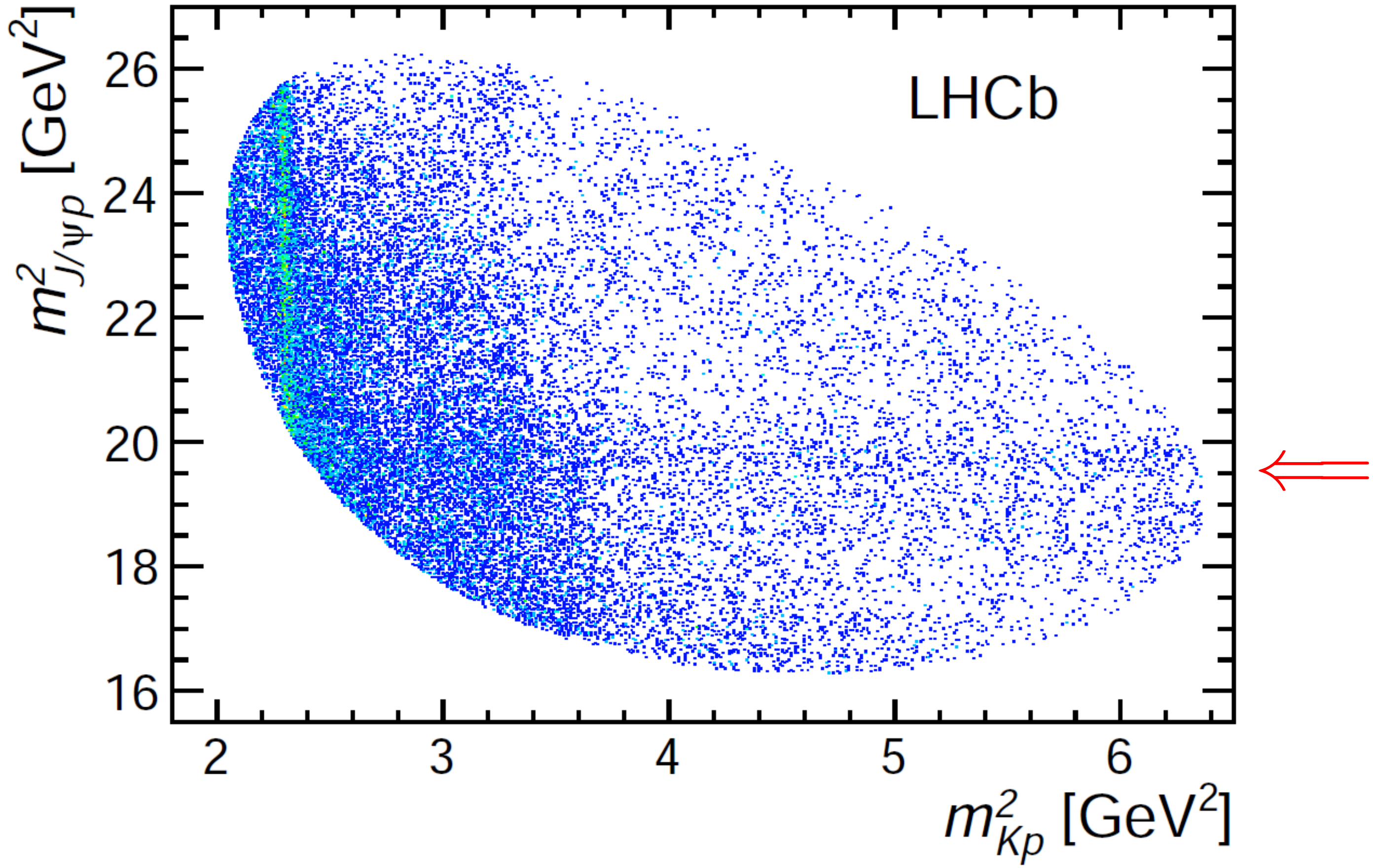
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)

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.

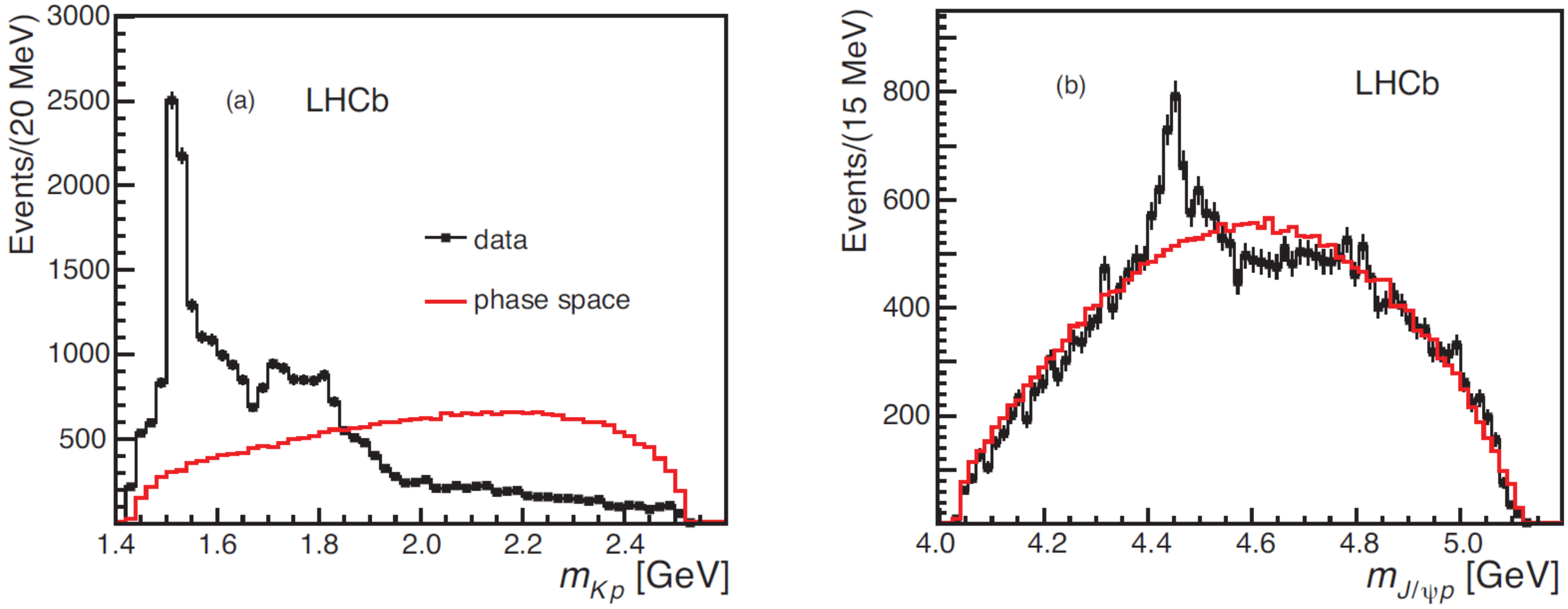
DOI: 10.1103/PhysRevLett.115.072001 PACS numbers: 14.40.Pq, 13.25.Gv



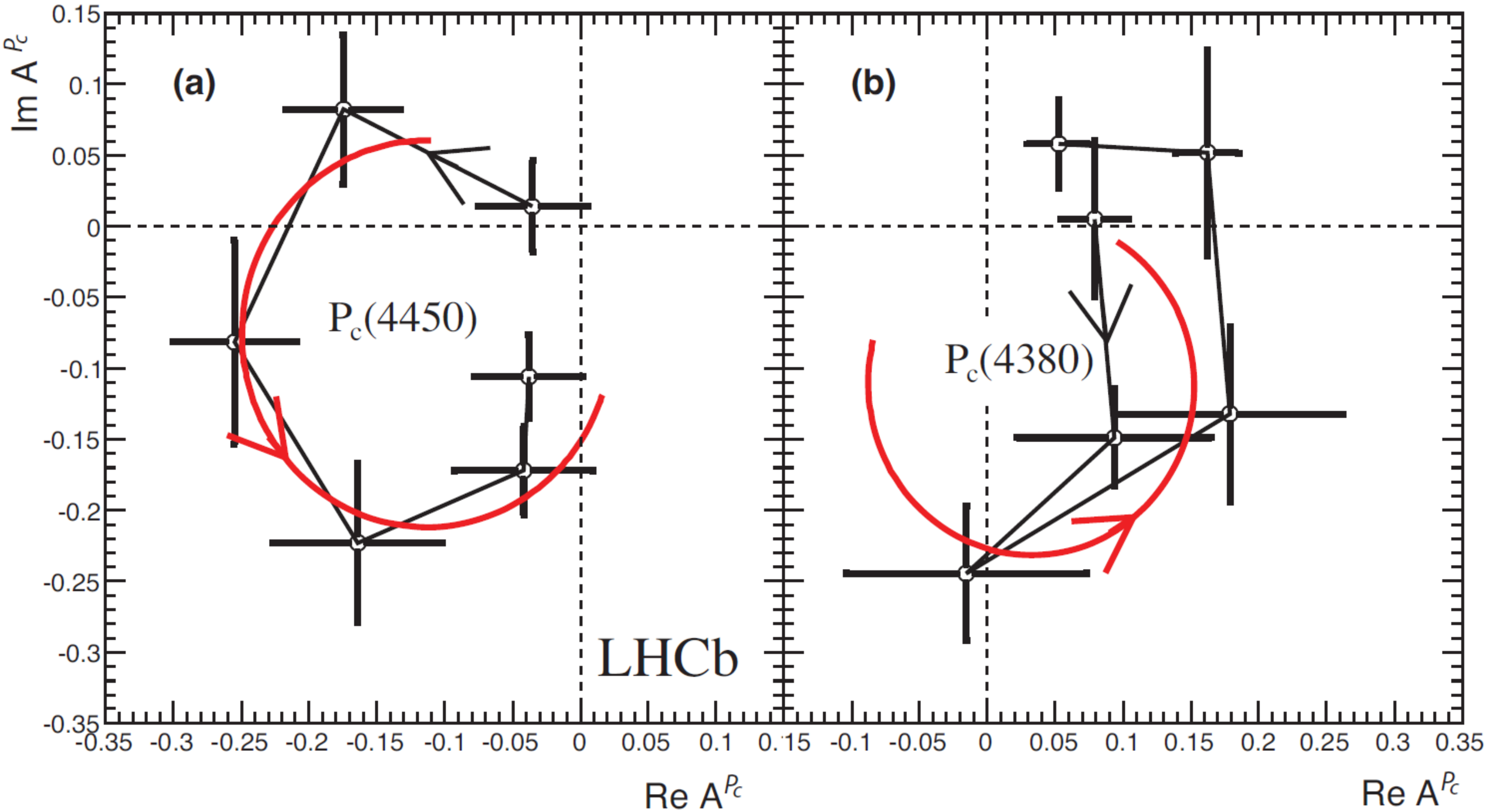
Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi\,\Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.



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.



$P_c(4450)$: 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

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

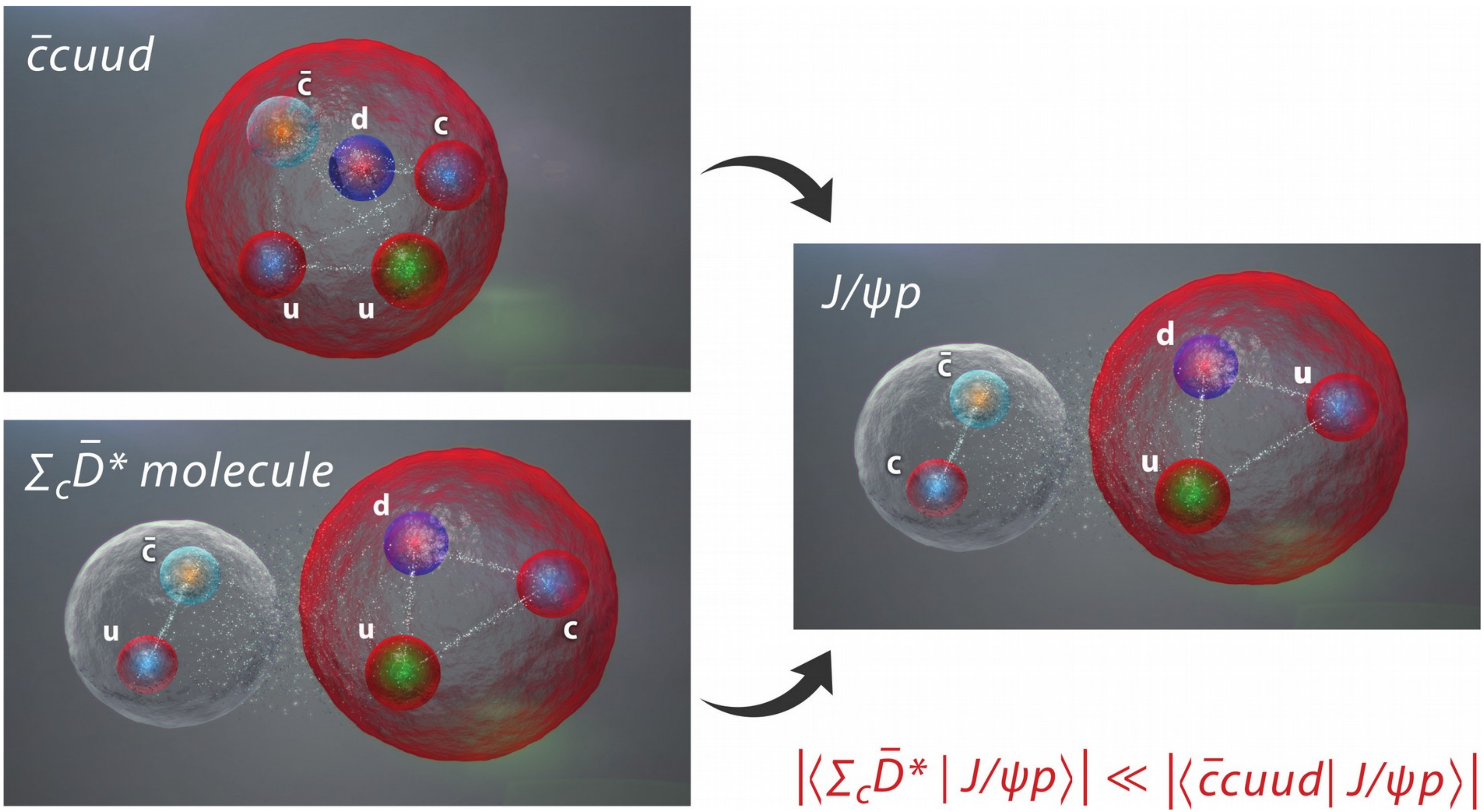
To get $\Gamma = 39$ MeV, the matrix element must be small .

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.

In a molecule narrow width is automatic:

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 $J/\psi p$



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"

$\Longrightarrow$ need a different production mechanism

radii of hadronic molecules

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

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

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

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

at 1.2 fm the two hadrons overlap a bit

relative importance of π-s?

how does it work in b analogues?

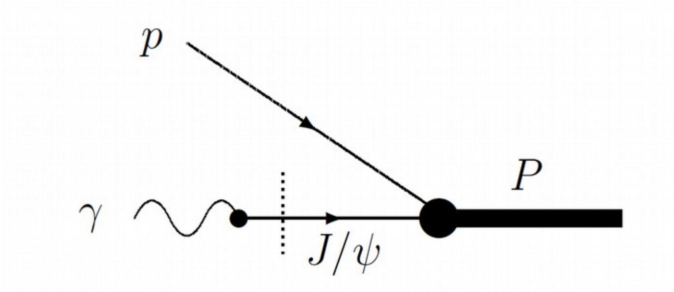
Photoproduction of exotic baryon resonances

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

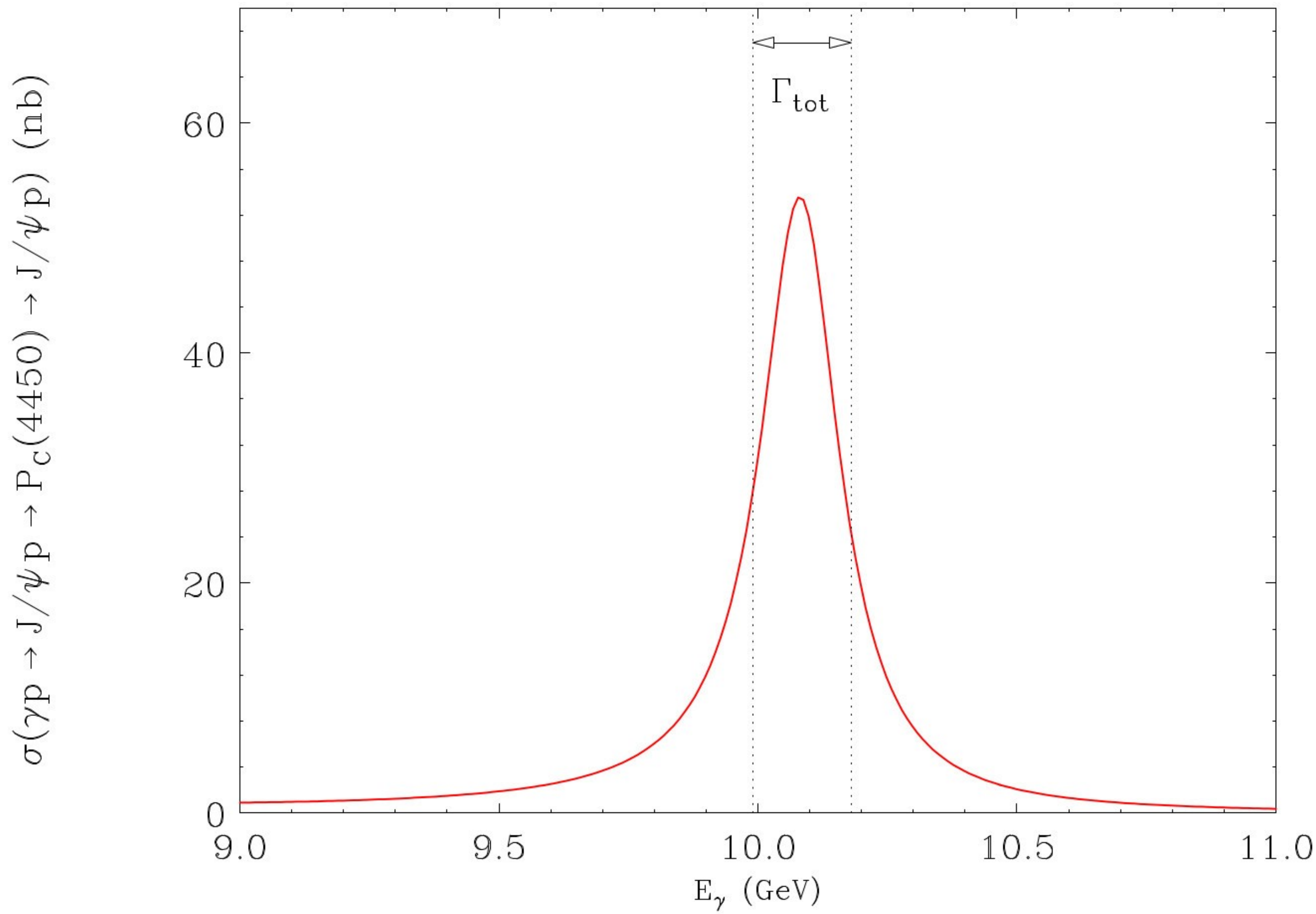
LHCb: new exotic resonances in $J/\psi\, p$ channel:

$\Longrightarrow$ 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 $B_{\rm out} = 0.1$, 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:

$\sigma(\gamma p \to J/\psi p) < 1$ nb for $10 < E_\gamma < 13$

Why P_c-s not seen in these data ?

a) smearing by photon energy spread

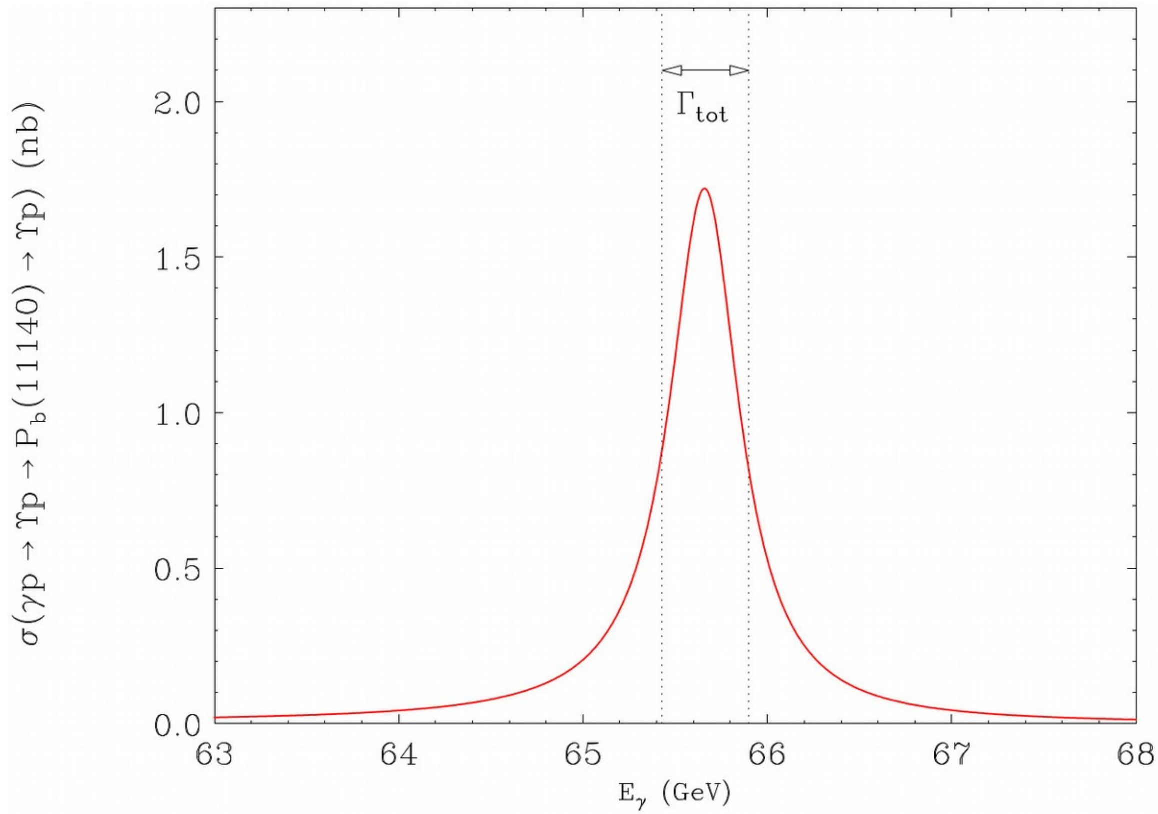
b) mostly forward scattering data

c) small branching fraction ?

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

$E_\gamma = 65.66$ GeV,

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



$X(3872) \to J/\psi\,\pi^+\pi^-$ seen in LHC exps,

$\sigma^{\text{prompt}}(pp \to X(3872) + \text{anything}) \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) \sim$ few nb

so perhaps LHC can also see

$P_c(4450) \to J/\psi\, p$

$P_b(11140) \to \Upsilon p$?

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

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

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

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

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 $\to J/\psi\, \Lambda$

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

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

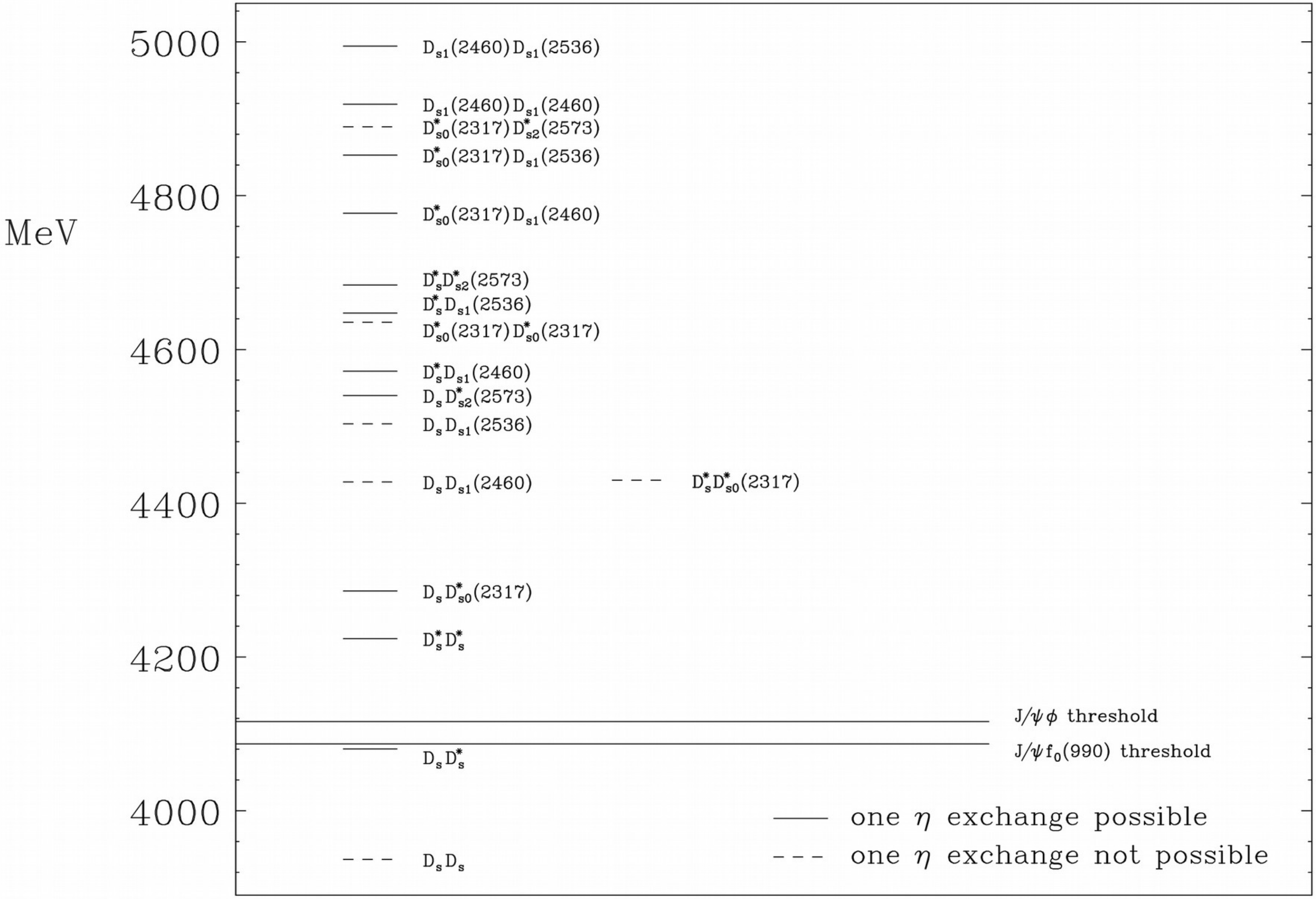
$\Rightarrow$ look for clear experimental signatures

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 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



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

10-30 MeV below threshold @4908 MeV

and

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

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

$\Longrightarrow$ should see bcq, ccq, etc.

QQq baryons are the simplest baryons:

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

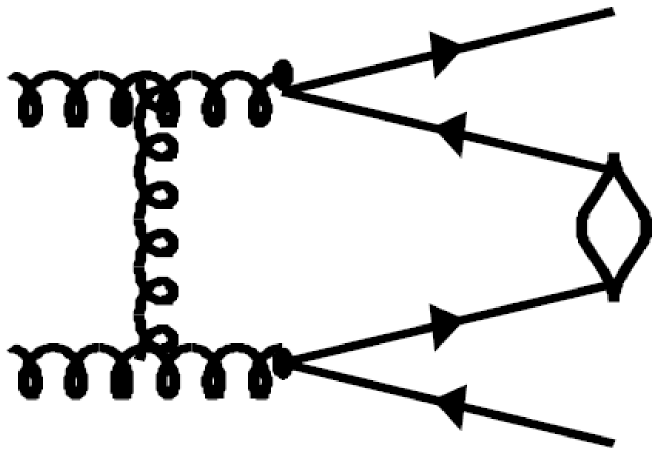
so QQq baryon $\sim \bar{Q}q$ meson

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

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

hydrogen atom of baryon physics!

B_c production in LHCb: gg fusion



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

Ξ_{bc} production: same diagram,

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

$\Longrightarrow \quad \sigma(pp \to \Xi_{bc} + X) \lesssim \sigma(pp \to B_c + X)$

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

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

$\sigma(pp \to \Xi_{cc} + X) \sim 40$ nb @ 7TeV

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

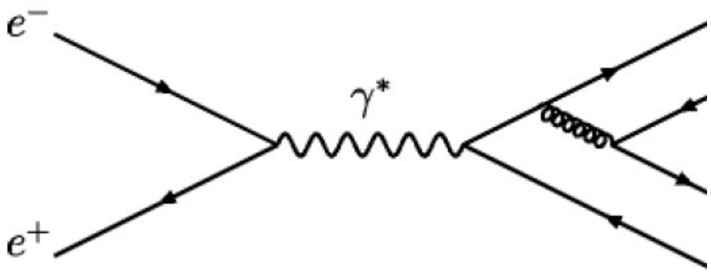
with sufficient E_{CM} may study
double heavy flavor production

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

$\Rightarrow$ a precondition for producing doubly heavy B_c, B_c^*,
and doubly heavy $\Xi_{bc} = bcq$, 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 Ξ_{bc}

same diagram
for B_c and Ξ_{bc}:



estimate $\sigma(e^+e^- \to \gamma B_c^+ B_c^- + X)$
$\sim$ 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.
$\Xi_{cc}^{++} \to 3\pi^+ \, \Xi^-$ (missed by CDF trigger)
$\Xi_{cc}^{++} \to \Lambda_c K^- 2\pi^+$

lifetime: each c quark can decay independently

$\Gamma(\Xi_{cc}^{++}) = 3.56 \times 10^{-12}$ GeV
$\tau(\Xi_{cc}^{++}) = 185$ fs

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

In addition to $c \to s u \bar{d}$, 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

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

the difference due to $cd \to su$

$\Longrightarrow \tau(\Xi_{bc}^{0}) = 93$ 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^0_{bb}, but
$\tau(\Xi^0_b)$ not much different from $\tau(\Xi^-_b)$
so treat Ξ^0_{bb} and Ξ^-_{bb} generically as Ξ_{bb}

$\Longrightarrow \quad \tau(\Xi_{bb}) \approx 376$ 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

$QQ\bar{Q}\bar{Q}$ States

arXiv:1611.00348 MK,J.L. Rosner, S.Nussinov

Toolbox borrowed from QQq baryons

$M_{(cc\bar{c}\bar{c})} = 6{,}192 \pm 25$ MeV, 225 ± 25 MeV above $\eta_c \eta_c$

unlikely to be narrow, nor to have significant non-hadronic decays

$M_{(bb\bar{b}\bar{b})} = 18{,}826 \pm 25$ MeV, 28 ± 25 MeV above $\eta_b \eta_b$

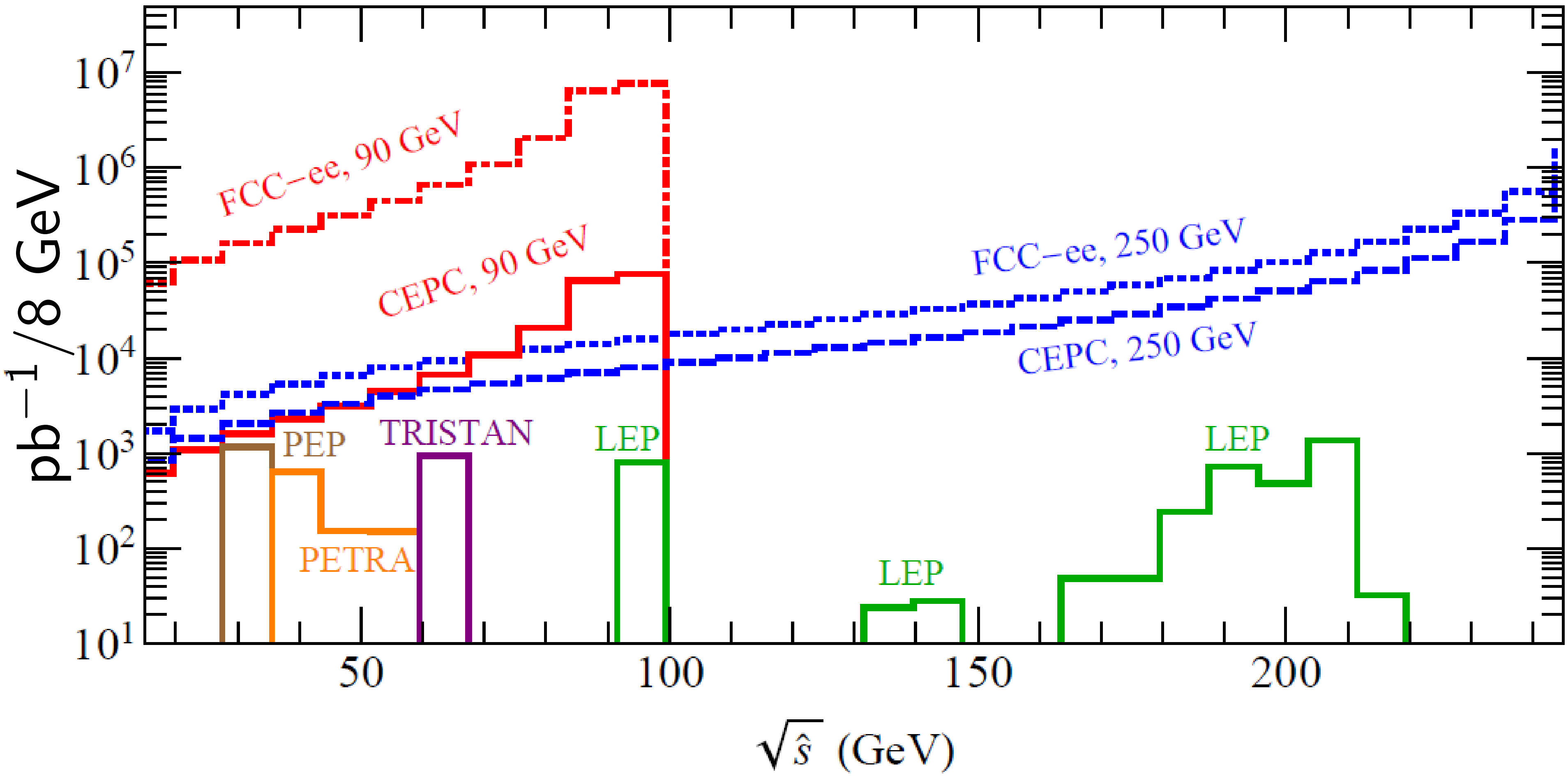
could be narrow & exhibit non-hadronic decays if estim. $> 1\sigma$ high

production of an extra $Q\bar{Q}$: probabillity $\sim 0.1\%$

CMS (arXiv:1610.07095) sees double $\Upsilon(1S)$; production;
38 events, each $\Upsilon \to \mu^+\mu^-$, in 20.7 fb^{-1} at $\sqrt{s} = 8$ TeV

$\Rightarrow$ Inspect neutral 4ℓ final states for possible evidence of $bb\bar{b}\bar{b}$ state; most likely $J^{PC} = 0^{++}$

integrated luminosity

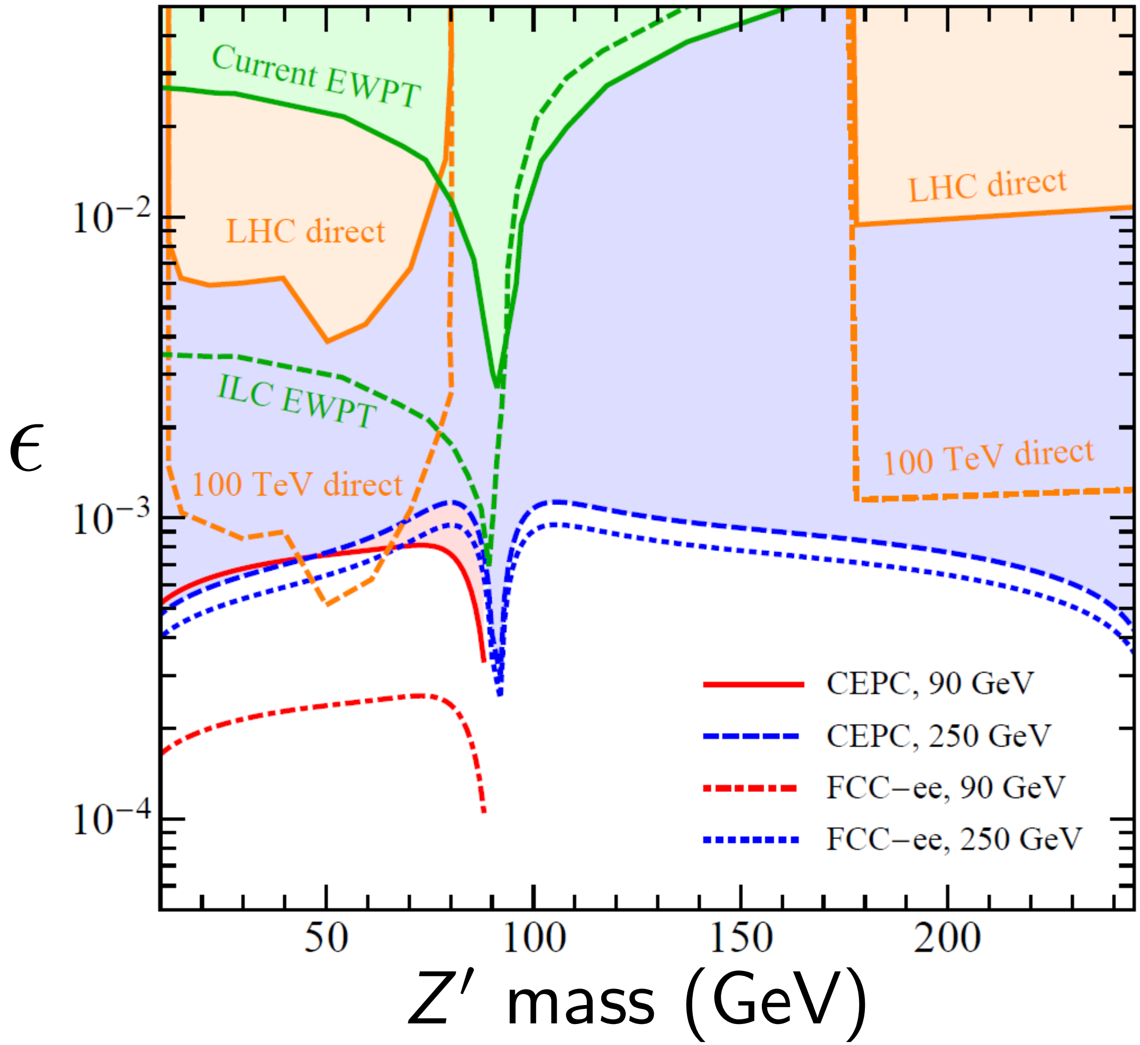


Integrated luminosity from past low energy e^+e^- colliders at their nominal center-of-mass energies compared to the effective luminosity through radiative return from future e^+e^- colliders at $\sqrt{s} = 90$ or 250 GeV

gaps filled in and much more

dark photon limits on ϵ at 95% C.L.

including $e^+e^- \to \gamma Z' \to \gamma \mu^+ \mu^-$



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

EWPT & direct searches from J. Fan, M. Reece, and L. T. Wang, arXiv:1411.1054

assume $\Delta m = m^2/(10^5 \text{ GeV})$

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) $QQ\bar{Q}\bar{Q}$ teteraquarks, esp. $bb\bar{b}\bar{b} \to 4\ell$ at $\sim$ 18.8 GeV

(e) 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; $\chi_{1b}(3P)$?

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

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

  – $cc\bar{c}\bar{c}$ @ 6,192±25 MeV and $bb\bar{b}\bar{b}$ @ 18,826±25 MeV $\Rightarrow 4\ell$

- exciting new spectroscopy in future e^+e^- high-$\mathcal{L}$ high-E colliders

Supplementary transparencies

discovery of isovector $Z_c(3900)$

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

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

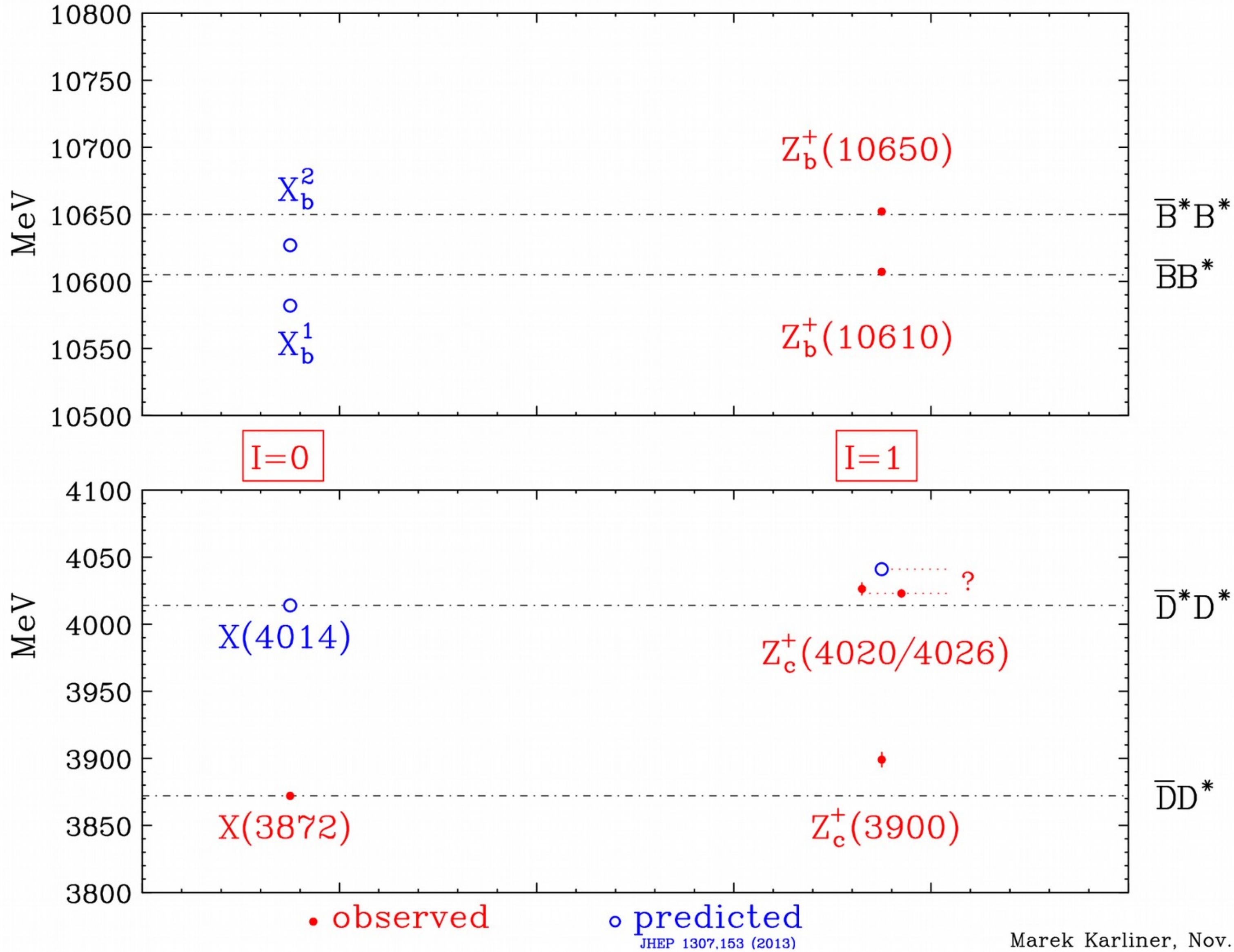
- $I = 0$ narrow resonance very close to $\bar{D}^*D^*$ threshold
- $I = 1$ narrow resonance a bit above $\bar{D}^*D^*$ threshold

did not have to wait long...

BESIII:

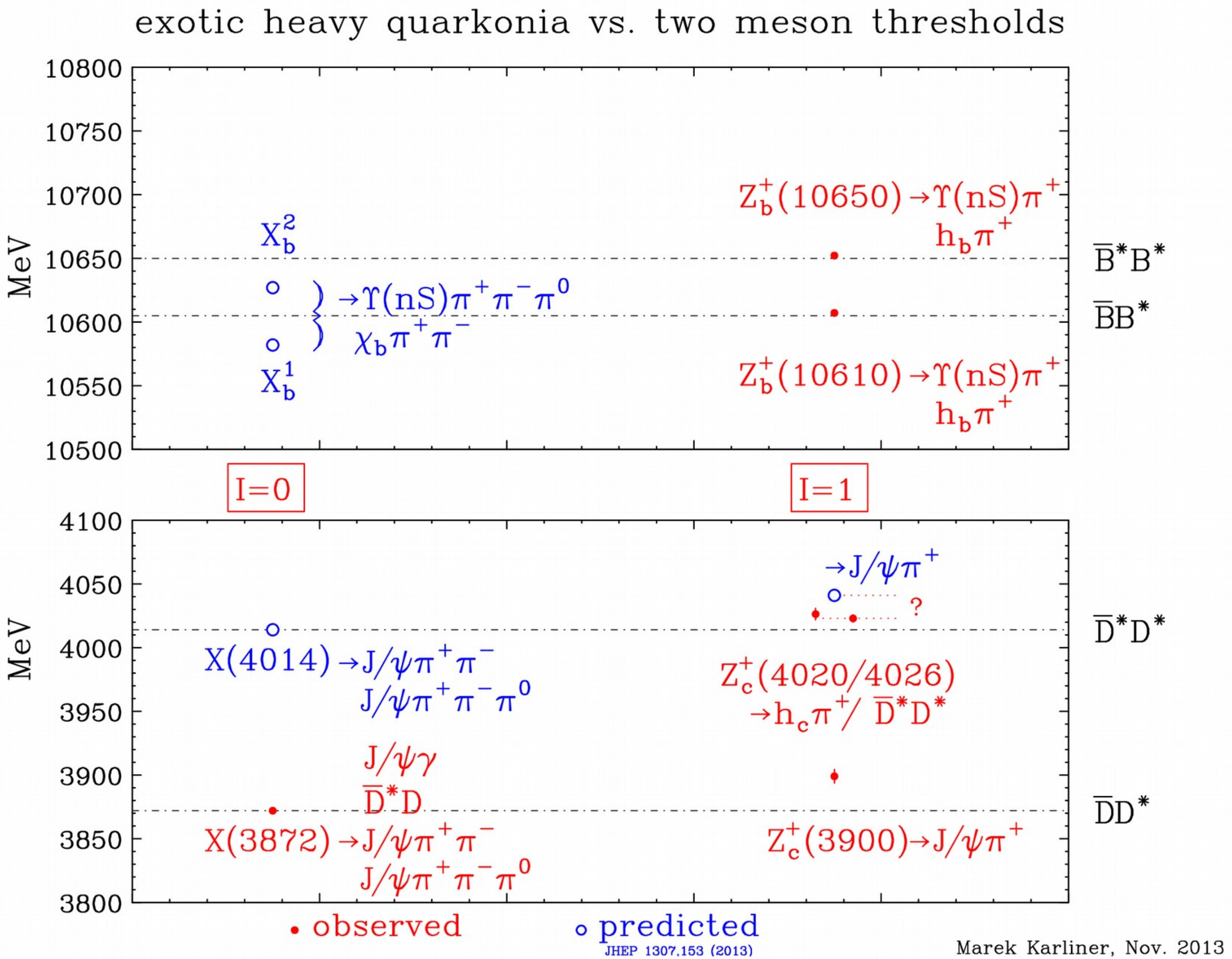
$Z_c^+(4025)$, arXiv:1308.2760, $\Gamma \approx 25$ MeV

$Z_c^+(4020)$, 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
MeV
10800
10750
10700
10650
10600
10550
10500
X_b^2
X_b^1
$\to \Upsilon(nS)\pi^+\pi^-\pi^0$
$\chi_b\pi^+\pi^-$
$Z_b^+(10650) \to \Upsilon(nS)\pi^+$
$h_b\pi^+$
$Z_b^+(10610) \to \Upsilon(nS)\pi^+$
$h_b\pi^+$
$\bar{B}^*B^*$
$\bar{B}B^*$
I=0
I=1
4100
4050
4000
3950
3900
3850
3800
$X(4014) \to J/\psi\pi^+\pi^-$
$J/\psi\pi^+\pi^-\pi^0$
$J/\psi\gamma$
$\bar{D}^*D$
$X(3872) \to J/\psi\pi^+\pi^-$
$J/\psi\pi^+\pi^-\pi^0$
$\to J/\psi\pi^+$
?
$Z_c^+(4020/4026)$
$\to h_c\pi^+/ \bar{D}^*D^*$
$Z_c^+(3900) \to J/\psi\pi^+$
$\bar{D}^*D^*$
$\bar{D}D^*$
• observed
○ predicted
JHEP 1307,153 (2013)
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 $\Upsilon(1S)\pi^+\pi^-$ 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 fb^{-1}. The search looks for the exclusive decay channel $X_b \to \Upsilon(1S)\pi^+\pi^-$ followed by $\Upsilon(1S) \to \mu^+\mu^-$. 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 $\Upsilon(1S)\pi^+\pi^-$ of the X_b and the $\Upsilon(2S)$. 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:

$m[D_{s0}(2317)] - m[D_s] = 345$ 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 η–π^0 mixing

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