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

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arXiv:1506.06386, arXiv:1508.01496 with Jon Rosner
JHEP 7,153(2013) with Shmuel Nussinov

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outline

In order to understand the latest exciting pentaquark results from LHCb, one must view them in a wider context. This is a context of exotic hadrons containing two heavy quarks.

it has been realized early on that quark models and QCD sustain a much richer pattern of different multi-quark and/or color network configurations, beyond the "non-exotic" standard $\bar{q}q$ mesons and qqq baryons. Still, production rates of such particles are often suppressed and the light pions will in most cases allow rapid decays of the exotics into final states with pion(s) – turning them into very broad resonances.

This explains why the vast majority of known hadrons are simple mesons and baryons.

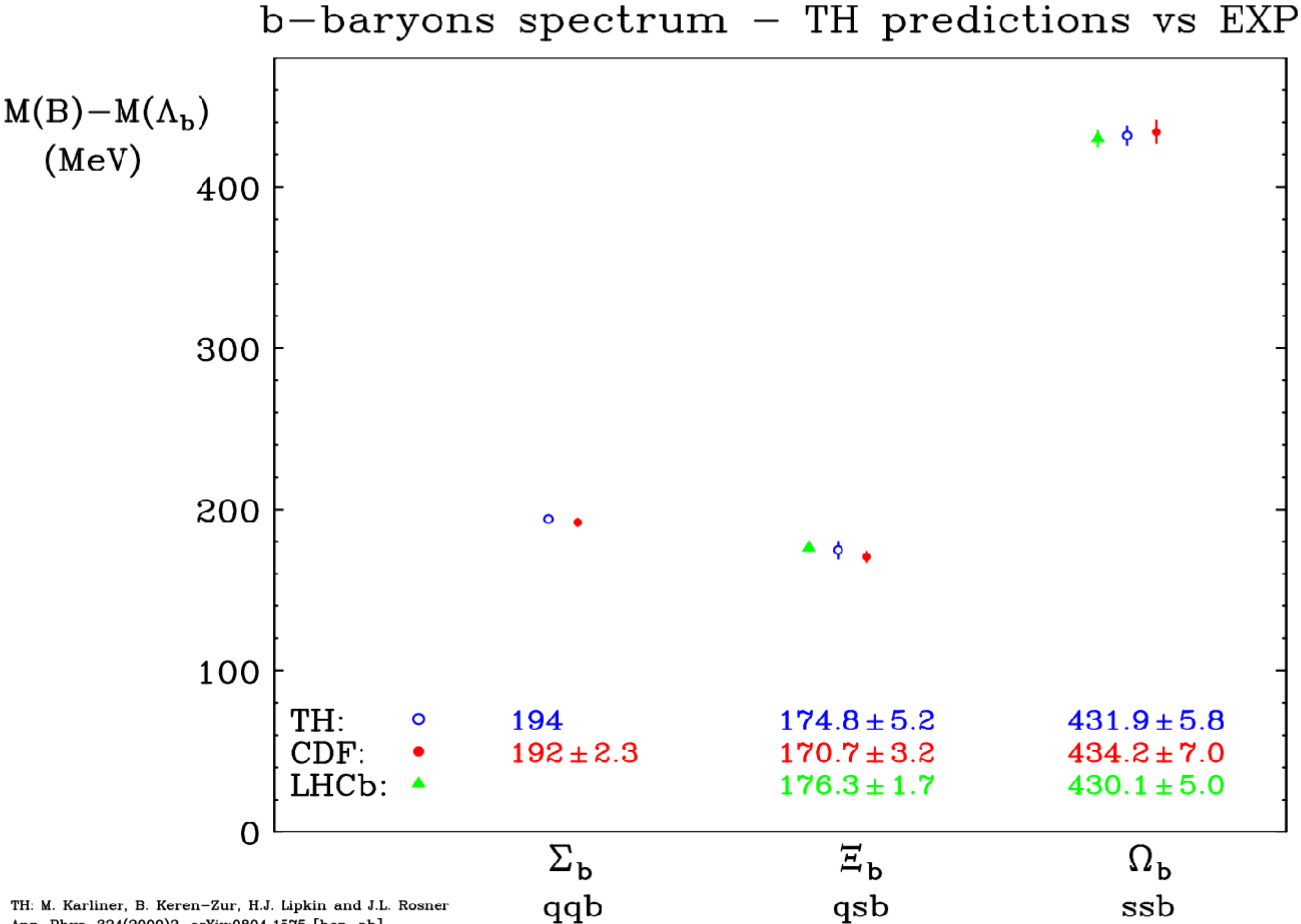
The situation is different for exotics which contain a heavy quark-antiquark pair and a light quark-antiquark pair: $\bar{Q}Q\bar{q}q$

The heavy quarks hardly mix with the light quarks, so such exotics decay into quarkonium and pion(s) or into two heavy-light mesons, providing clear signature of their exotic nature:

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

Hadrons containing heavy quarks are simpler than hadrons containing light quarks only, because the heavy quarks are almost static and have a very small spin-dependent interaction with other quarks.

This was the key to the accurate prediction of baryons containing the b quark:



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)

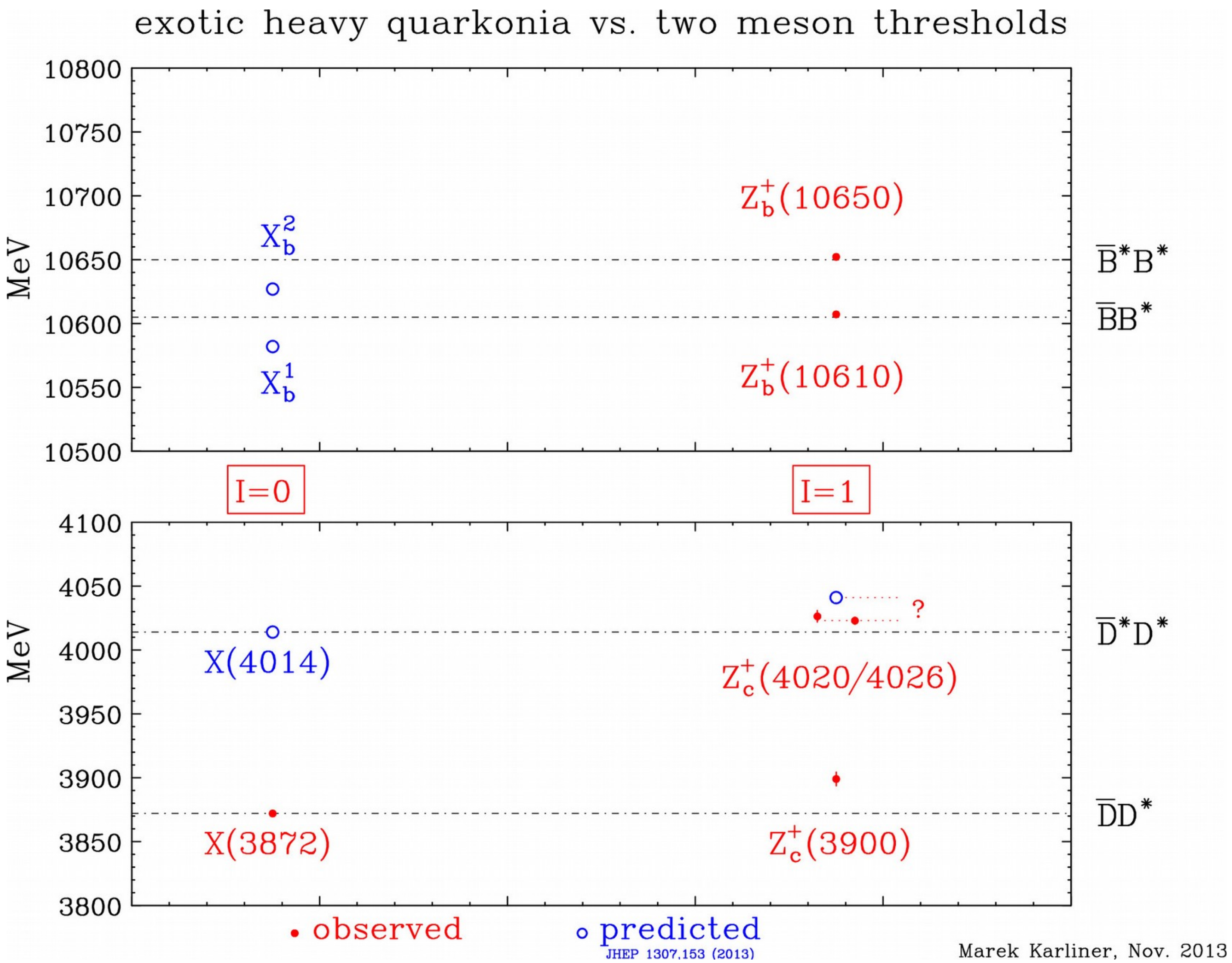
Abstract

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.

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
10800
10750
10700
10650
10600
10550
10500
MeV
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
MeV
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 $\bar{q}q$, $\quad q = u,d$

$\Longrightarrow$ <u>manifestly exotic</u>

$X(3872)$: 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 $\bar{D}D$

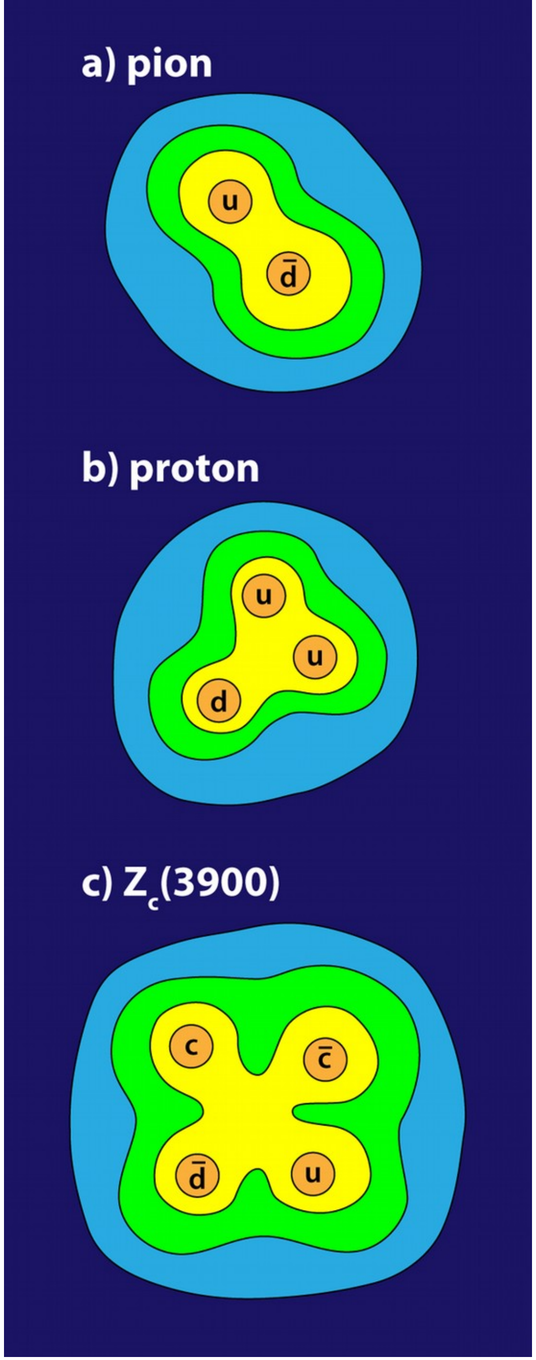
$\Rightarrow$ indicates an extended object

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 $\bar{D}D^*$

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

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

$X(3872)$ DECAY MODES

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

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

1. masses near thresholds and J^P of S-wave
2. narrow width despite very large phase space
3. BR(fall apart mode) $\gg$ BR(quarkonium $+ X$)
4. no states which require binding through 3 pseudoscalar coupling

binding two hadrons through π exchange[†]:

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

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

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

---

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

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

$\bar{D} \to \bar{D}^* + \pi$
$D^* + \pi \to D$
so $\bar{D}D^* \to \bar{D}^*D$ and $\bar{D}^*D \to \bar{D}D^*$
physical state $= (\bar{D}D^* + \bar{D}^*D)/\sqrt{2}$
goes into itself under π exchange

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

$D^* \to D^* + \pi, \quad P$-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-liqht $Q\bar{q}$ mesons have $I = 1$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

EXP signature:

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

perhaps also

$X_b^*(I = 0) \to \bar{B}B^*\gamma$ 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 $\chi_b(3P)$

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

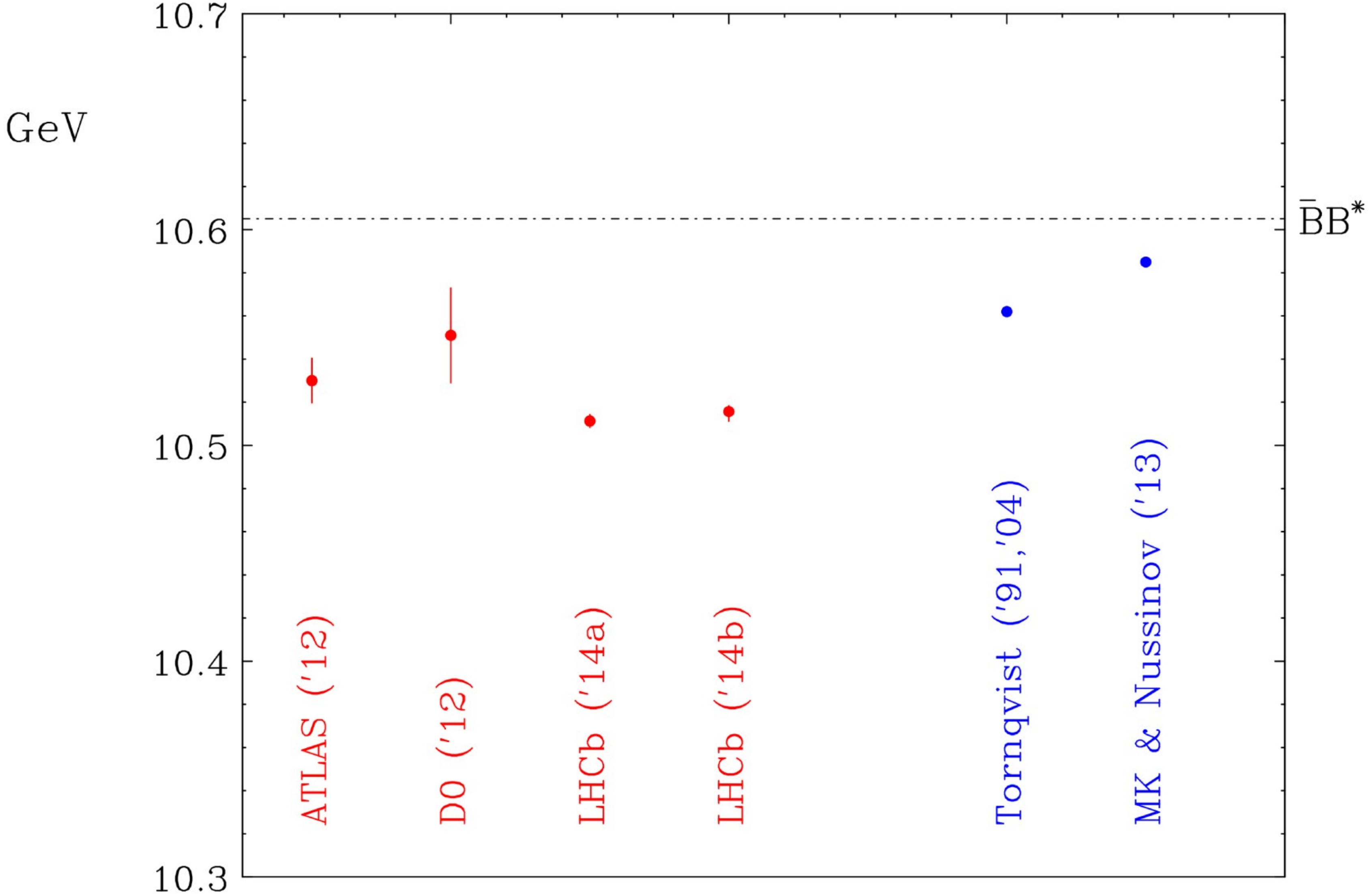
suggests that $X(3872)$ is a mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{*0}$

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.
$\Sigma_c \bar{\Lambda}_c \xrightarrow[\pi]{} \Lambda_c \bar{\Sigma}_c$.

(c) spin & parity which allow the state
go into itself under one π exchange

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

---

*may not be sufficient

the binding mechanism can in principle

apply to any two heavy hadrons

which couple to isospin

and satisfy these conditions,

be they mesons or baryons

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

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

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

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

- true for D^*, B^*, Σ_c, and Σ_b

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

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

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

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

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

QQ' candidates – dibaryons:

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

prediction of doubly heavy baryon with hidden charm:

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

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.

Submitted to Phys. Rev. Lett.

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

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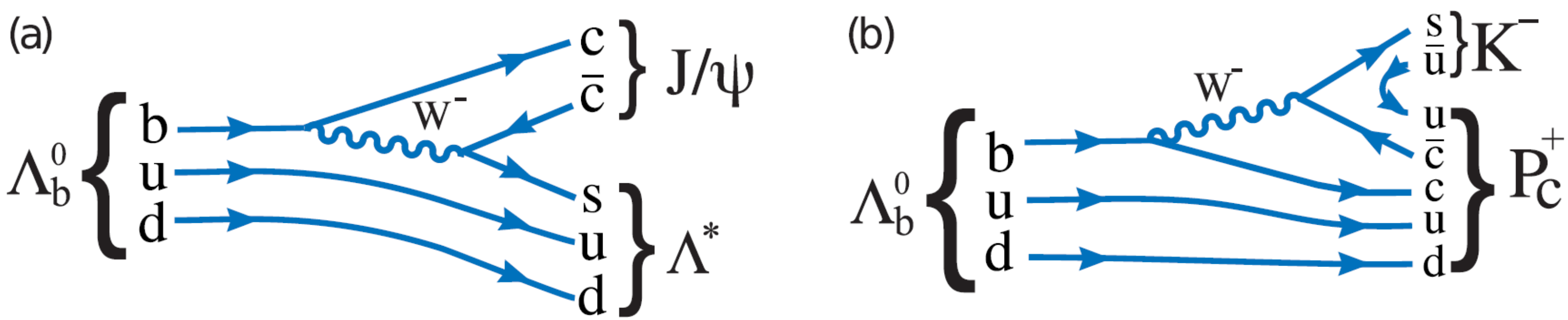
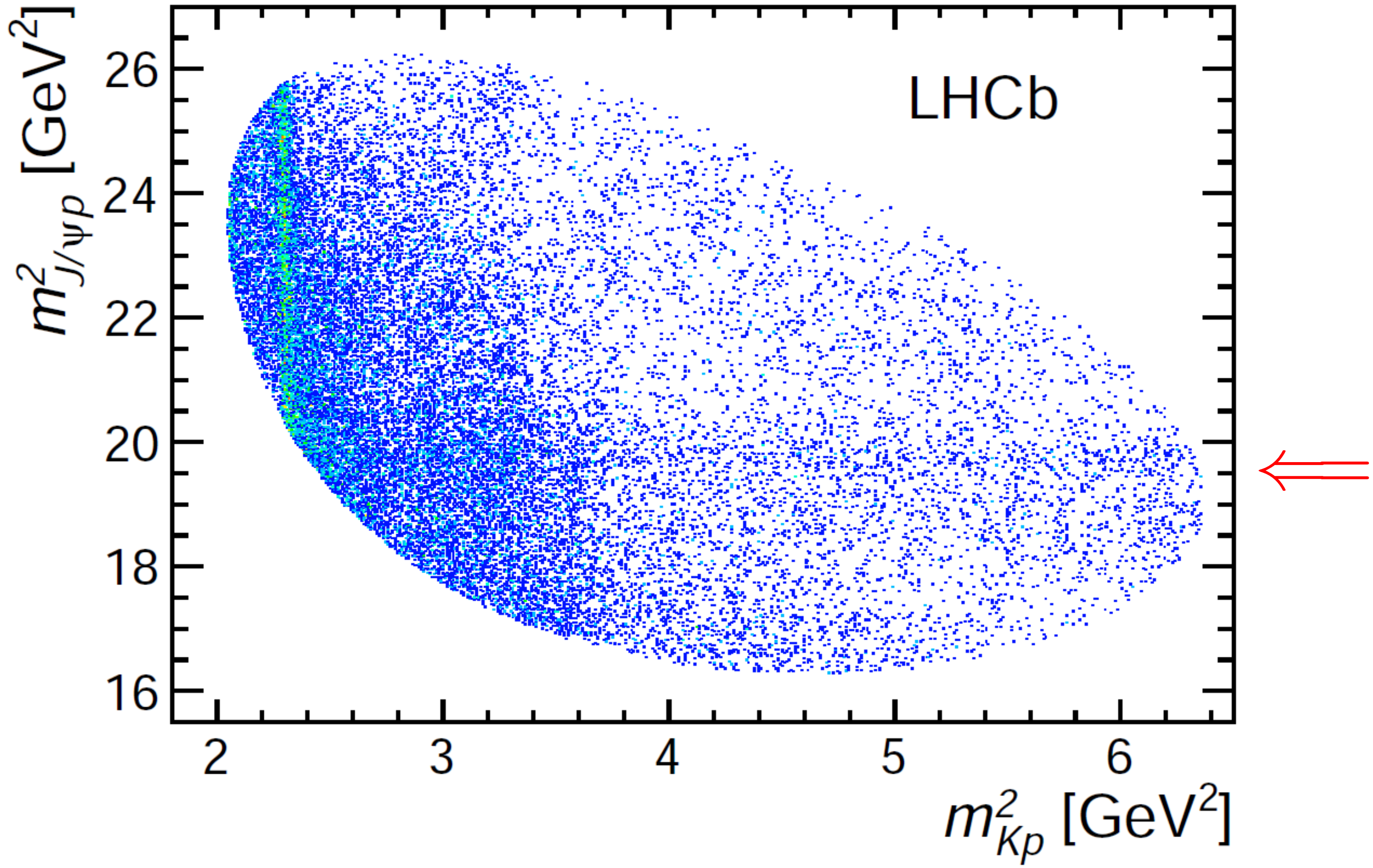
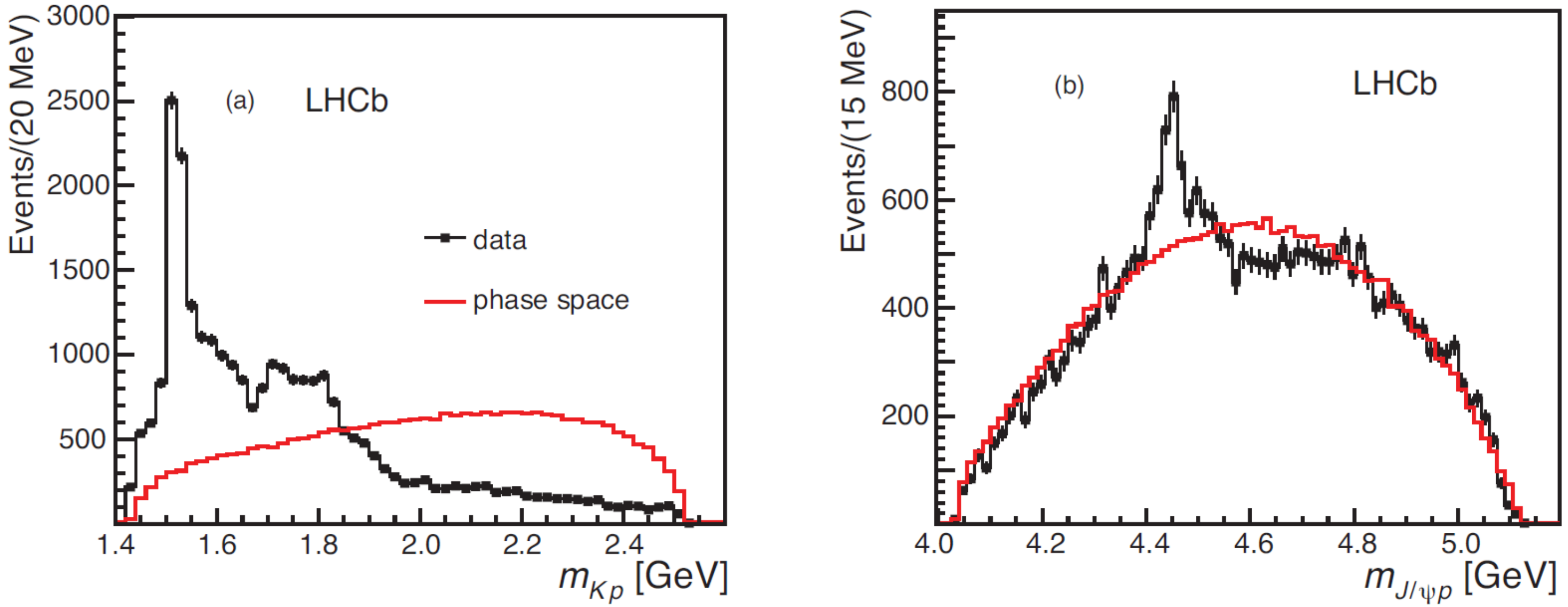
narrow resonance at
$4449.8 \pm 1.7 \pm 2.5$ MeV



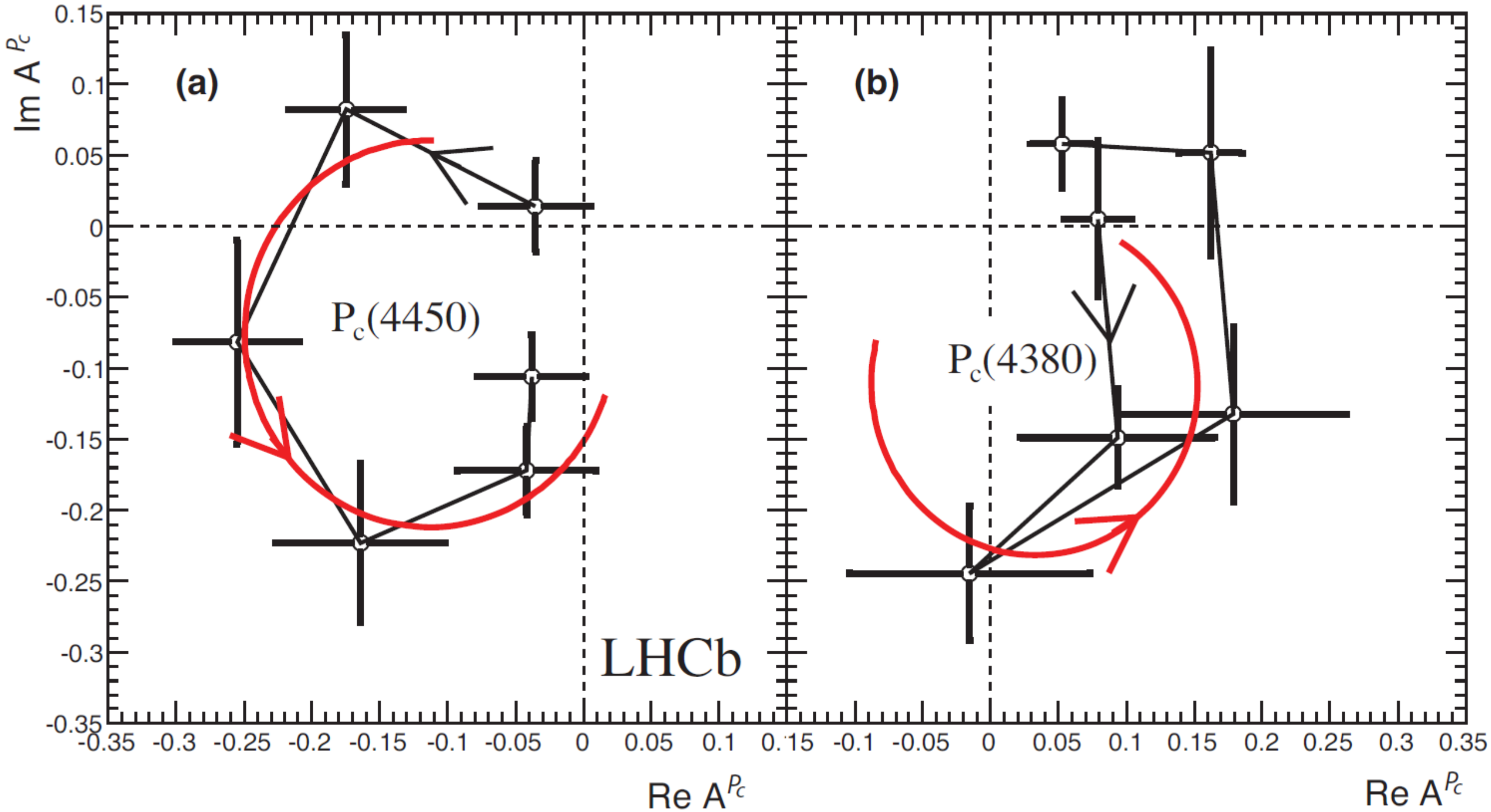
Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi\, \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.



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

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

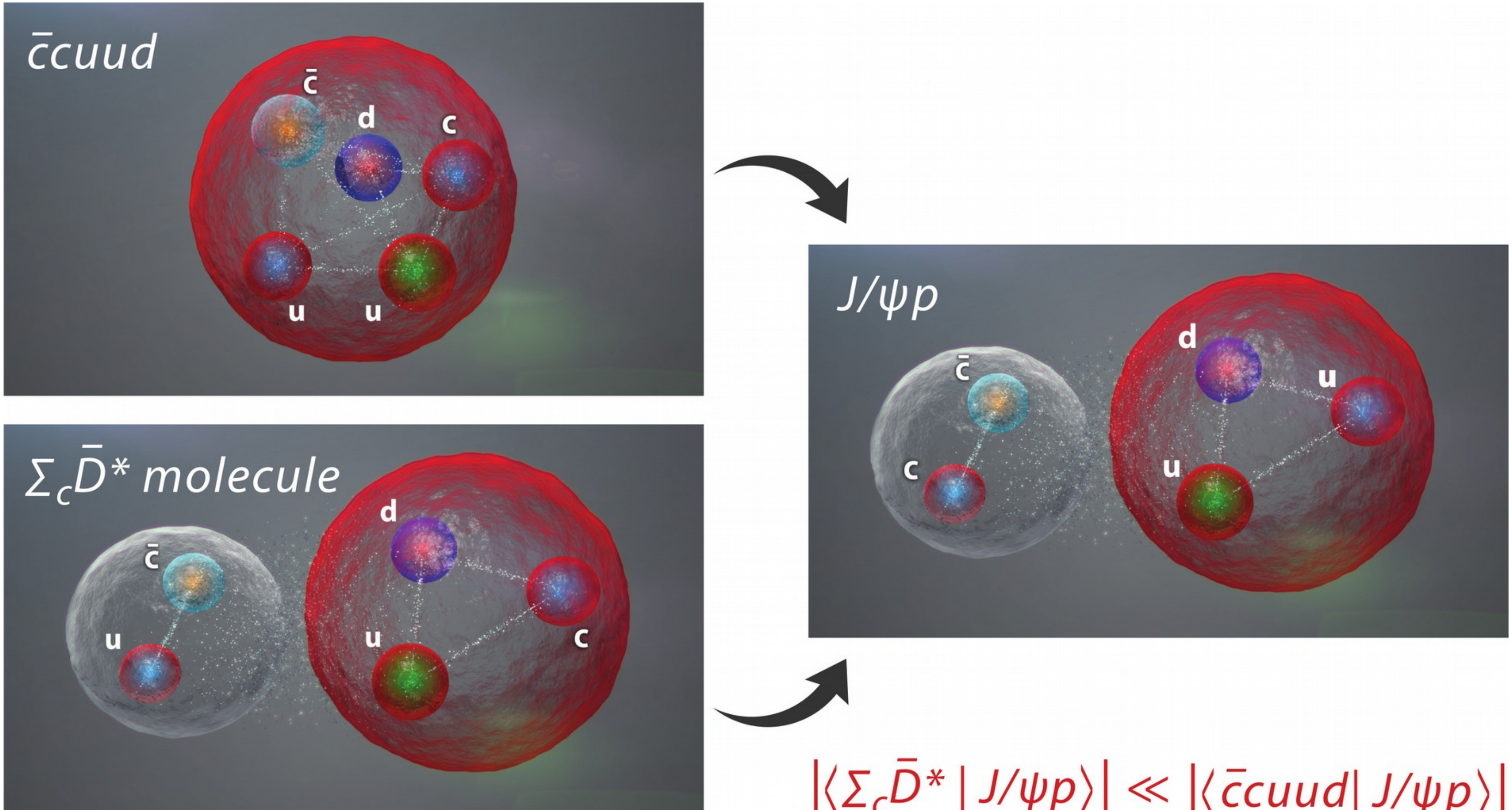
To get $\Gamma = 39$ MeV, the matrix element must be small .

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 $J/\psi p$



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

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

$P_c(4450)$ very clean, but:

- $P_c(3380)$?
- J: $(3/2, 5/2)$ or $(5/2, 3/2)$?
- P: $(-,+)$ or $(+,-)$?
- $m(P_c(4450)) = m_p + m_{\chi_{c1}}$
- "triangle singularity"

$\Longrightarrow$ need a different production mechanism

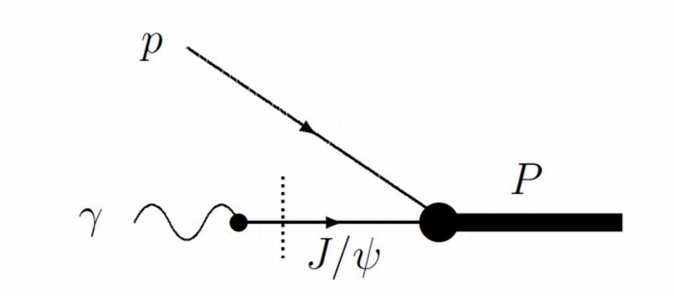
Photoproduction of exotic baryon resonances

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

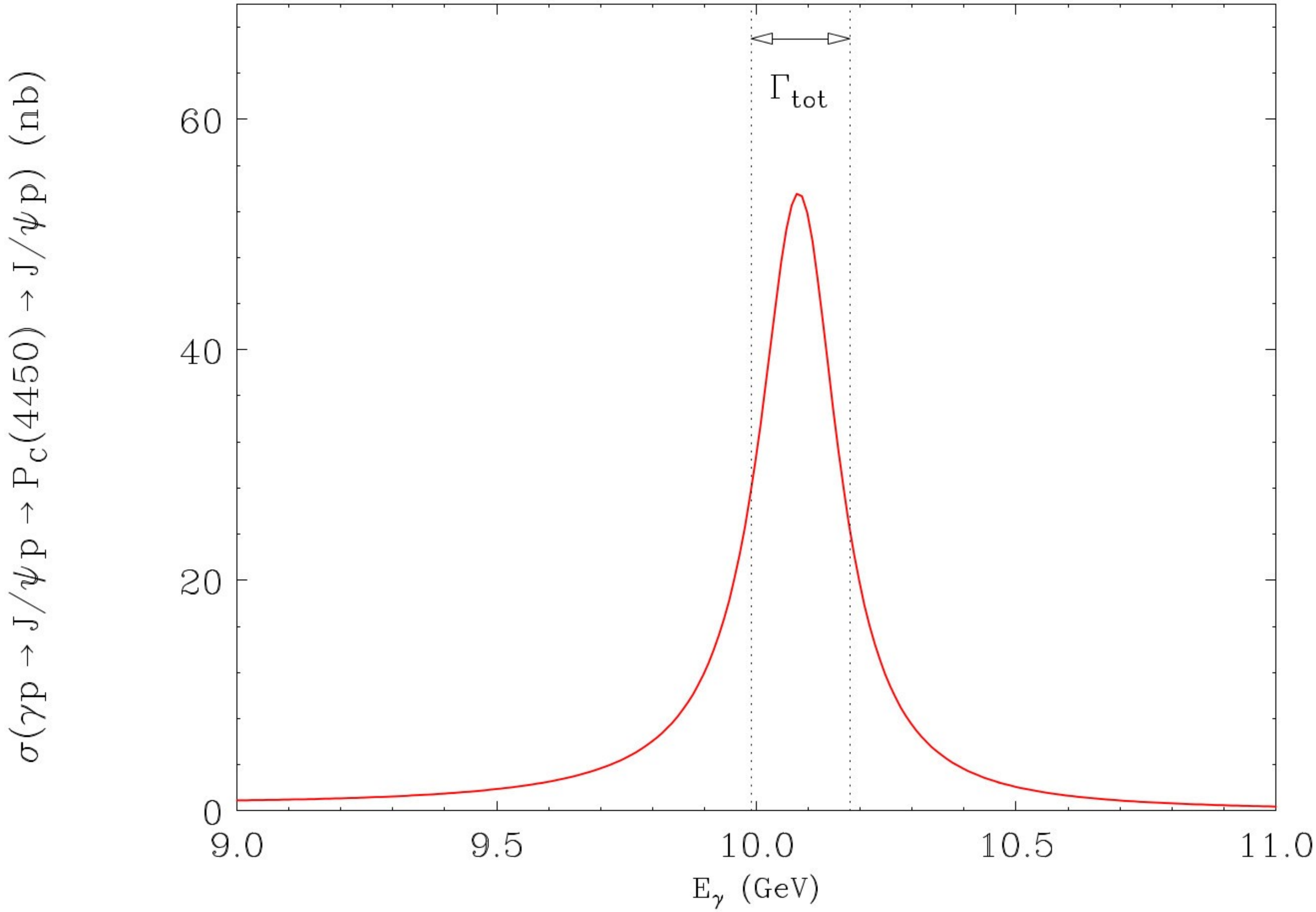
LHCb: new exotic resonances in $J/\psi\, p$ channel:

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

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

Why P_c-s not seen in these data ?

a) smearing by photon energy spread

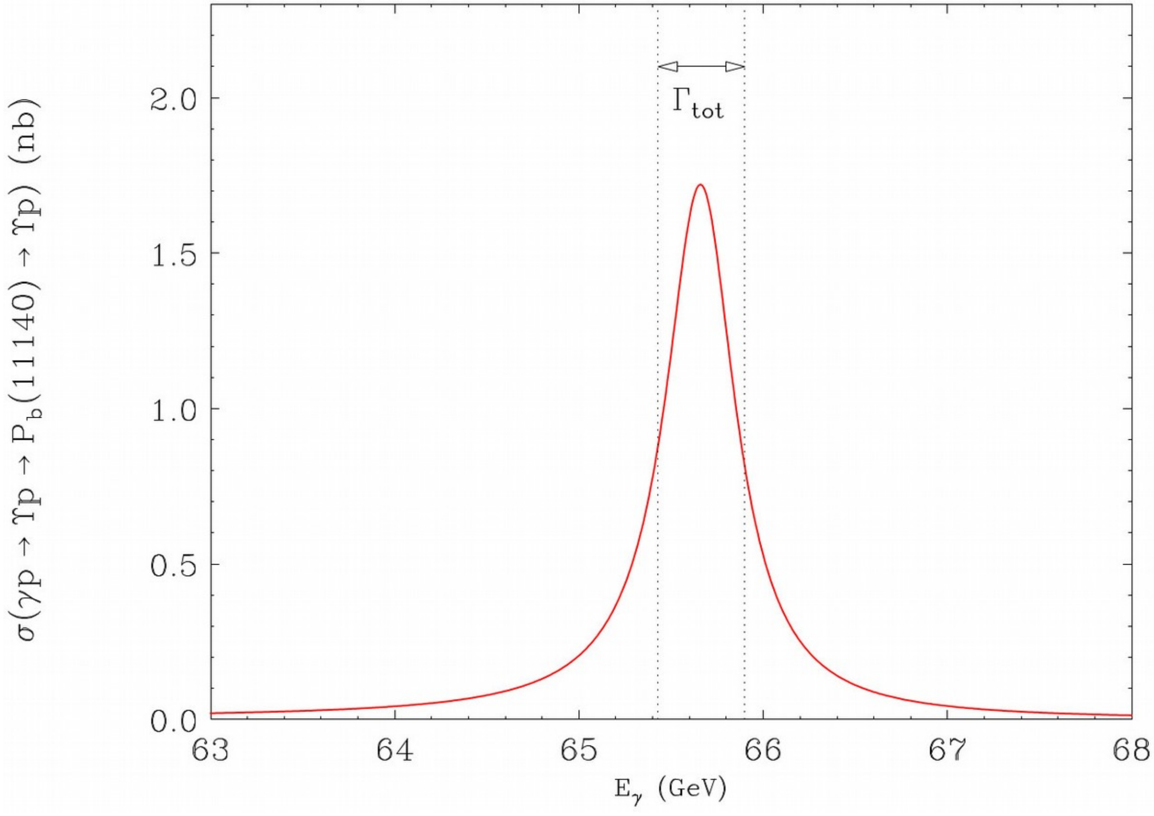
b) mostly forward scattering data

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



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

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

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

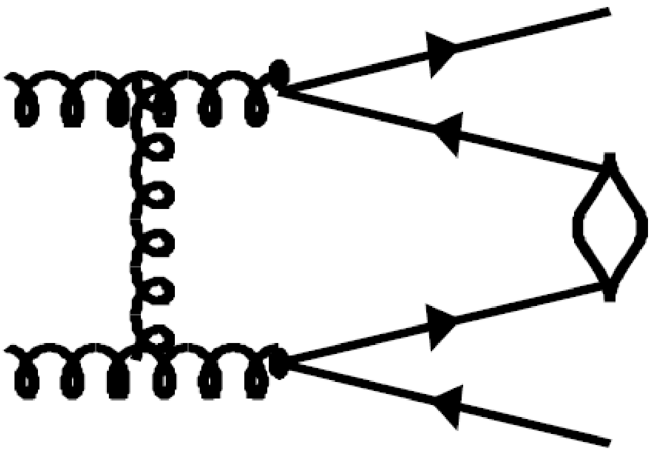
so QQq baryon $\sim \bar{Q}q$ meson

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 $\bar{c}$: $\mathbf{3}_c\mathbf{3}_c$ vs. $\bar{\mathbf{3}}_c\mathbf{3}_c$

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

LHCb is making a lot of B_c-s

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

Ξ_{cc} is the lightest doubly-heavy baryon

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

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

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

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

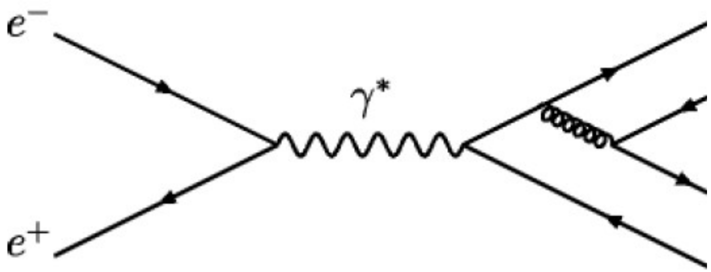
verified by detailed lifetime calculation with sufficient E_{CM} may study double heavy flavor production

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

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

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

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

lifetime: each c quark can decay independently

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

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

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

In addition to $c \to s u \bar{d}$, 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
$\tau(\Xi_b^0)$ 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:

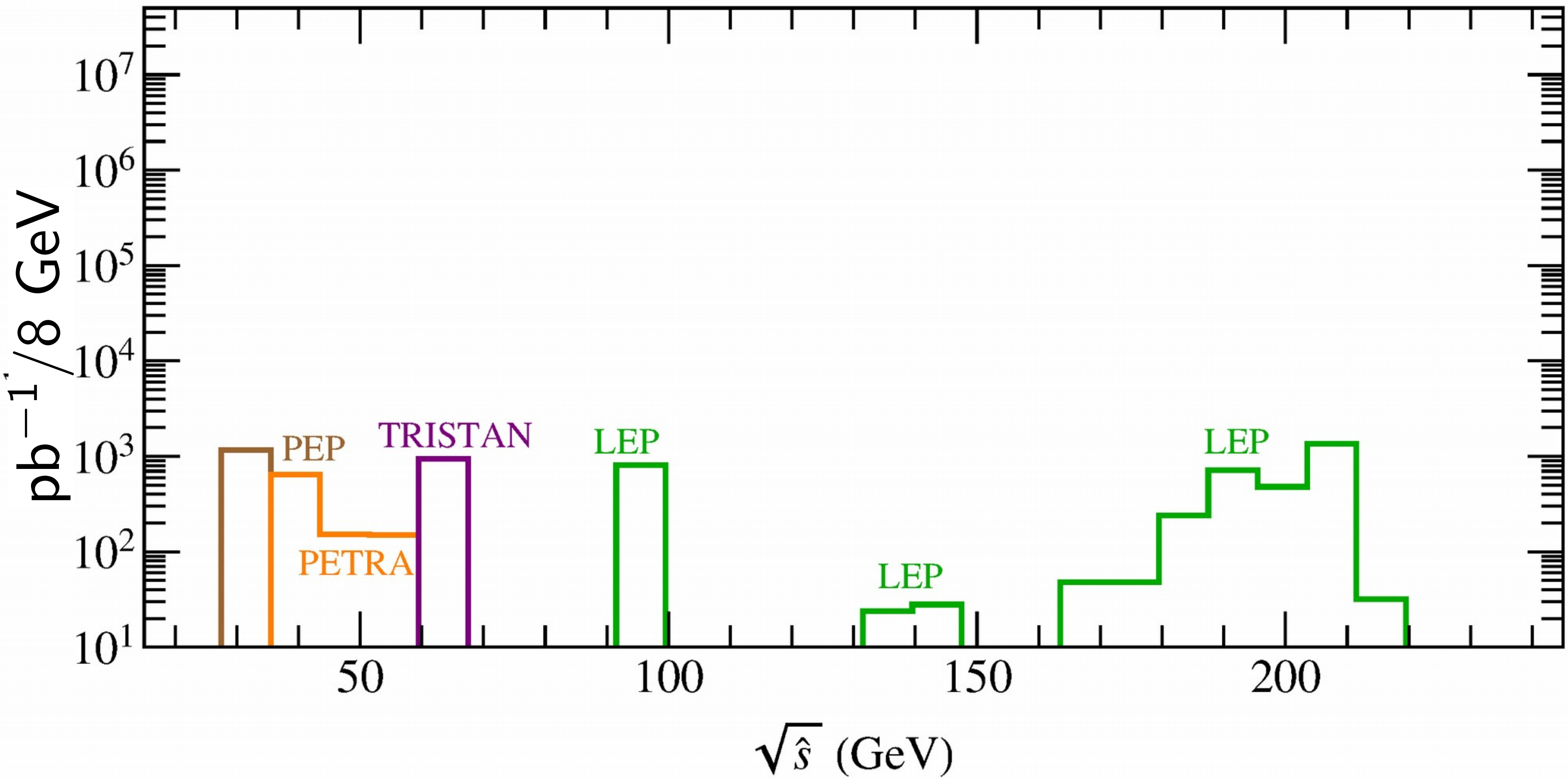
compare analogous prod. rates of Ξ_c and D_s

(or Ξ_b and B_s) in the same setup,

and large enough E_{CM}

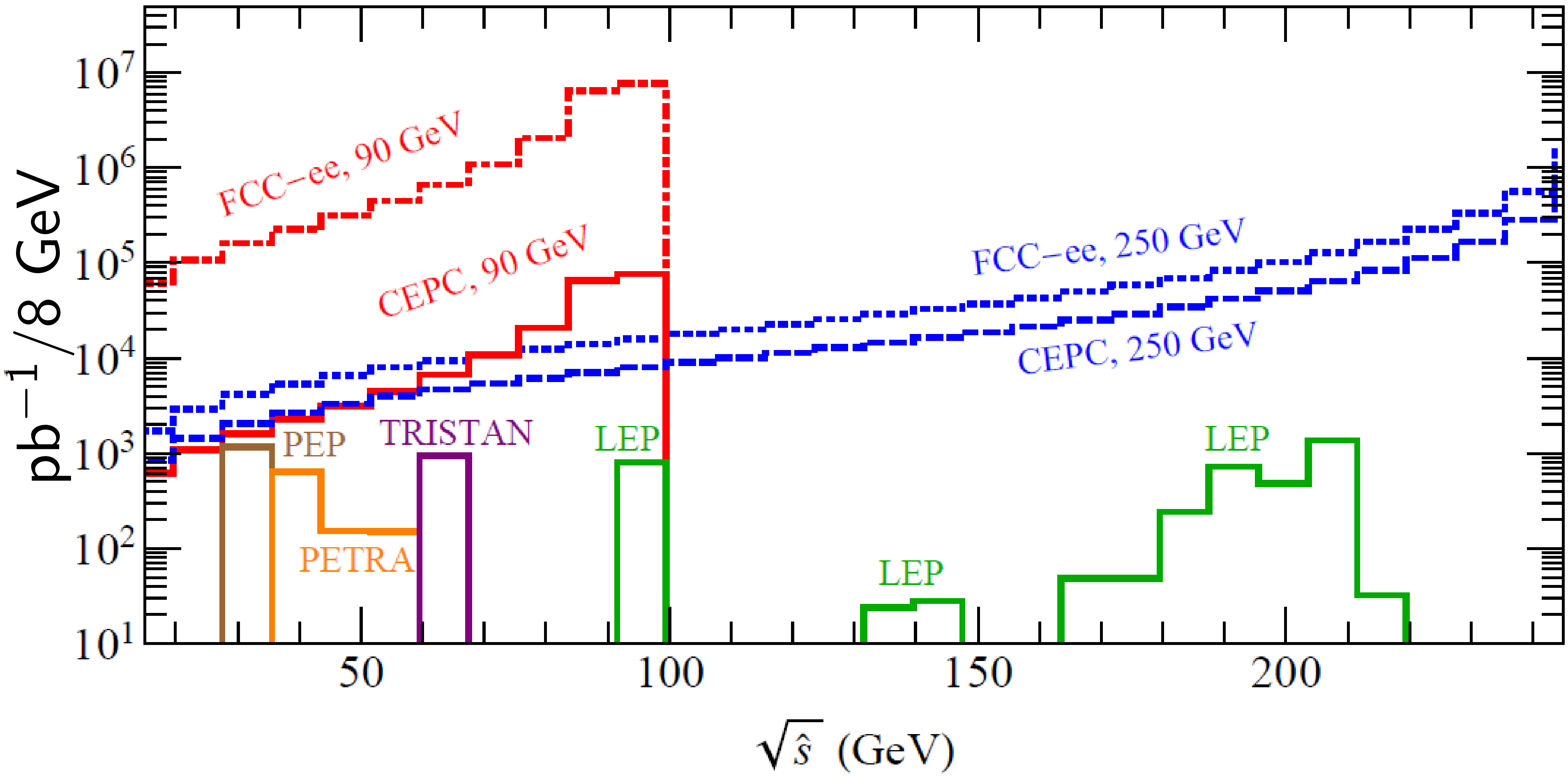
be it e^+e^-, $\bar{p}p$ or pp

integrated luminosity



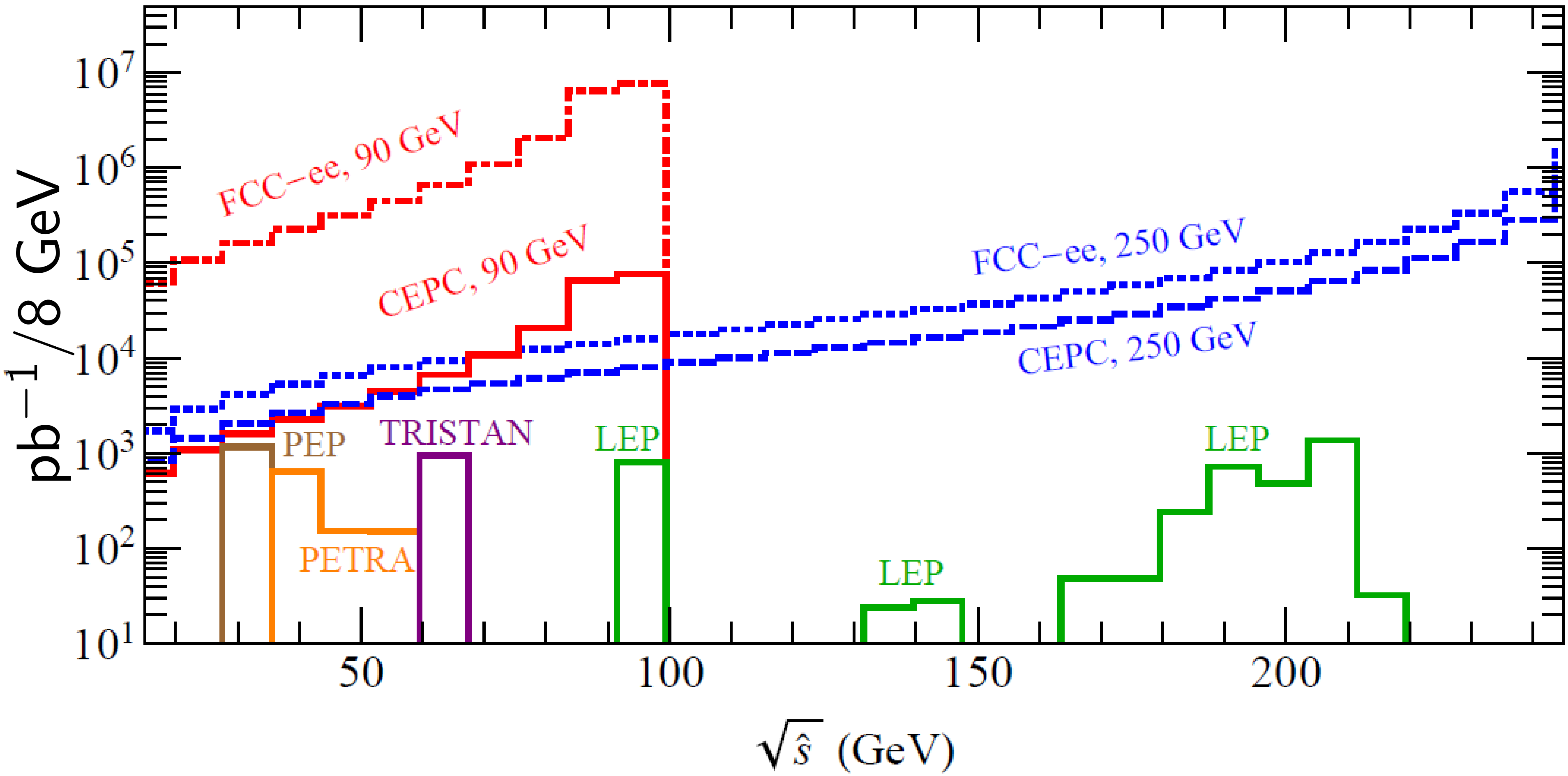
gaps left by PEP, PETRA, TRISTAN and LEP

integrated luminosity



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

integrated luminosity



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

gaps filled in and much more

new rich heavy flavor QCD spectroscopy

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

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

(c) doubly heavy QQq baryons

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

SUMMARY

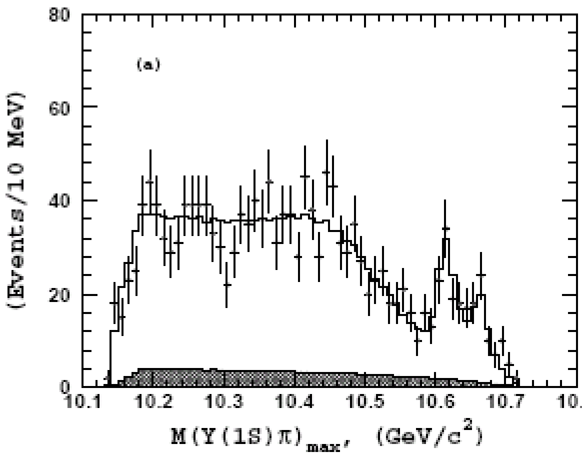
- the new narrow exotic resonances are loosely bound states of $\bar{D}D^*$, $\bar{D}^*D^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$

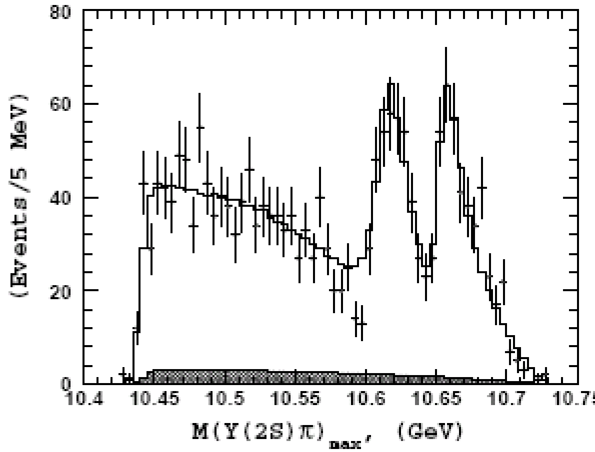
  predictions:

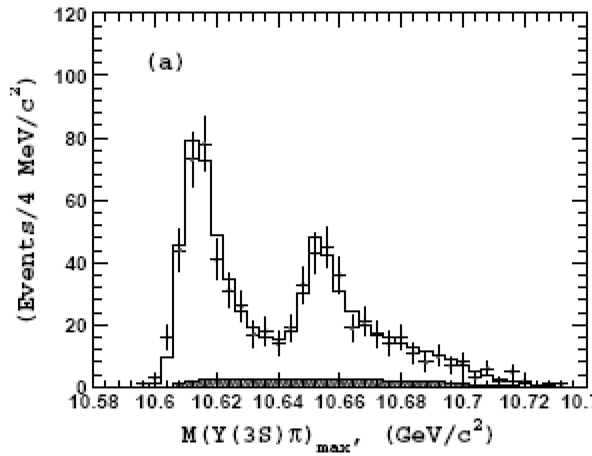
  - $\bar{D}^*D^*$ in $I=0$ and $I=1$ channels; $I=1$ seen!
  - new isosinglet $\bar{B}B^*$ and $\bar{B}^*B^*$ states below threshold; $\chi_1 b(3P)$?
  - *heavy deuterons*: $\Sigma_c D^*$: LHCb $P_c(4450) \Longrightarrow$ photoproduction $\Sigma_c B^*$, $\Sigma_b\bar{D}^*$, $\Sigma_b B^*$, $\Sigma_Q\bar{\Lambda}_{Q'}$, $\Sigma_Q^+\Sigma_Q^-, \ldots$
  - doubly & triply heavy baryons QQq, QQQ @pp & e^+e^-

- exciting new spectroscopy

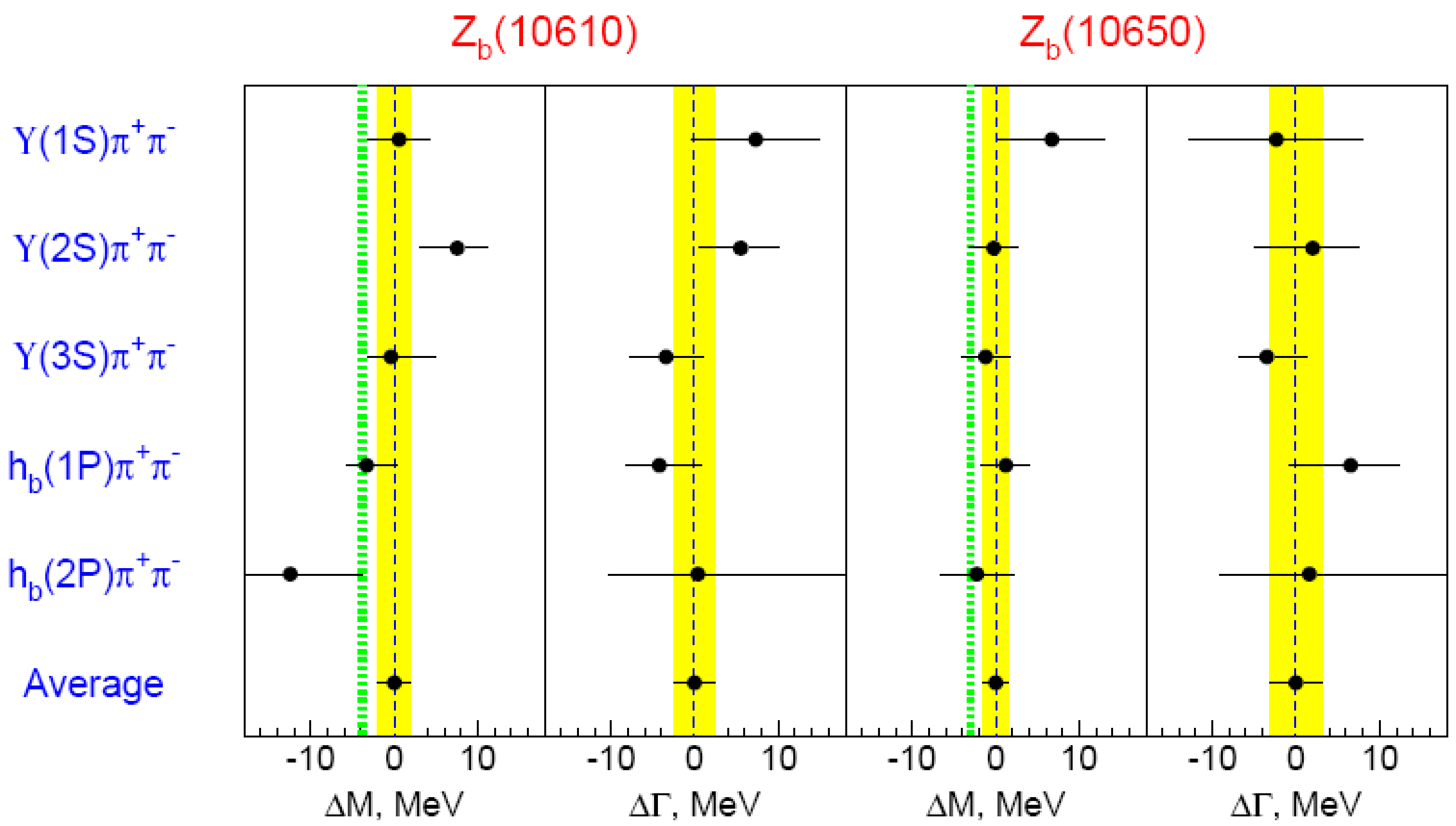
Supplementary transparencies







$\Upsilon(3S)\pi^+$ $\Upsilon(2S)\pi^+$ $\Upsilon(1S)\pi^+$



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

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

Full Amplitude Analysis with Full Statistics

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

$J^P = 1^+$ for both Z_b is favored over 1^-, 2^- and 2^+ at more than 6σ

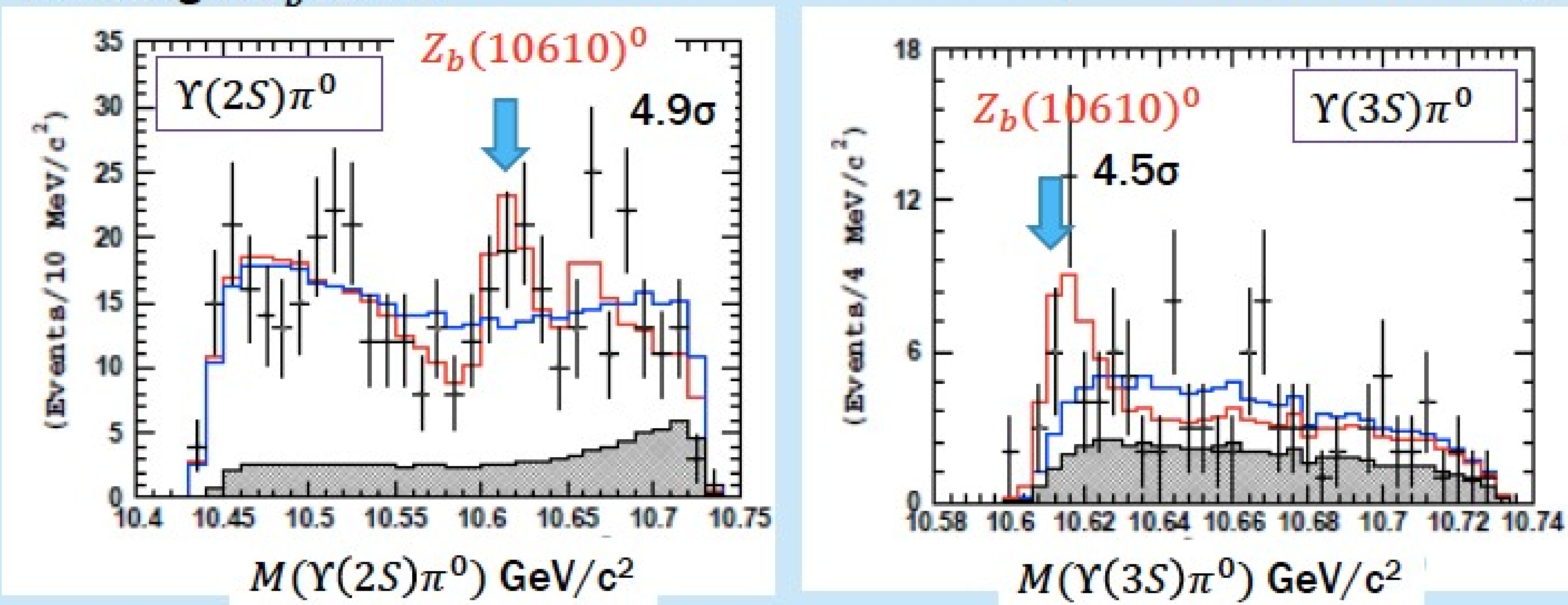
A. Garmash et al., Phys. Rev. D 91 (2015) 072003

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

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

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

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



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

arXiv:1207.4345

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

one caveat:

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

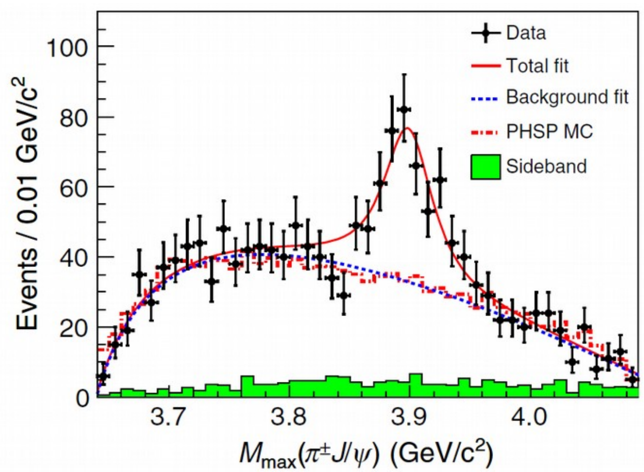
in March 2013 BES in Beijing,
followed by Belle in KEK provided
the answer for the question if charm is heavy enough:

BESIII Collaboration

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

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

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



PRL **110,** 252002 (2013)

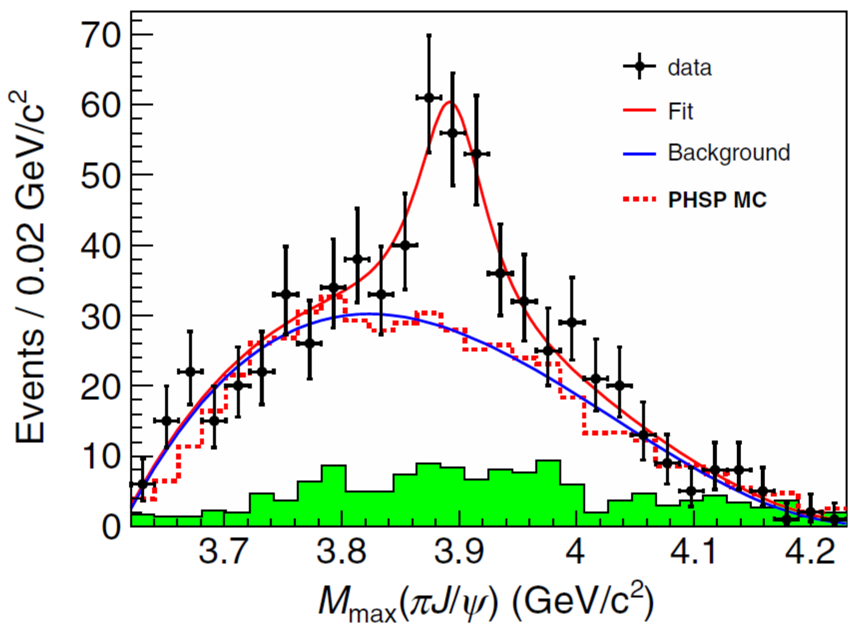
Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending 21 JUNE 2013

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

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



Heavy Quark Nuclear Physics!

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

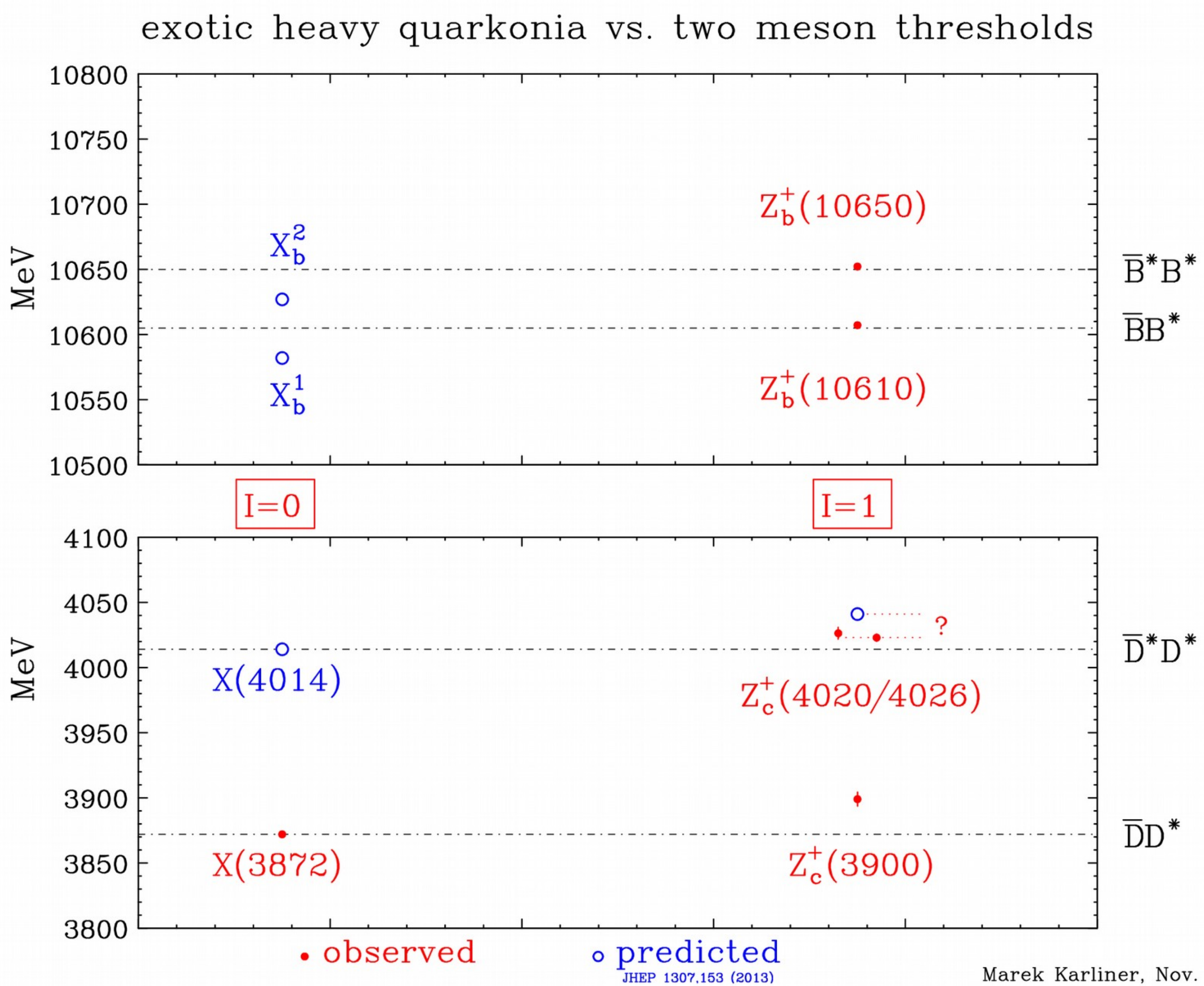
- $I=0$ narrow resonance very close to $\bar{D}^*D^*$ threshold
- $I=1$ narrow resonance a bit above $\bar{D}^*D^*$ threshold

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

same phenomena in charmonium

and bottomonium systems.

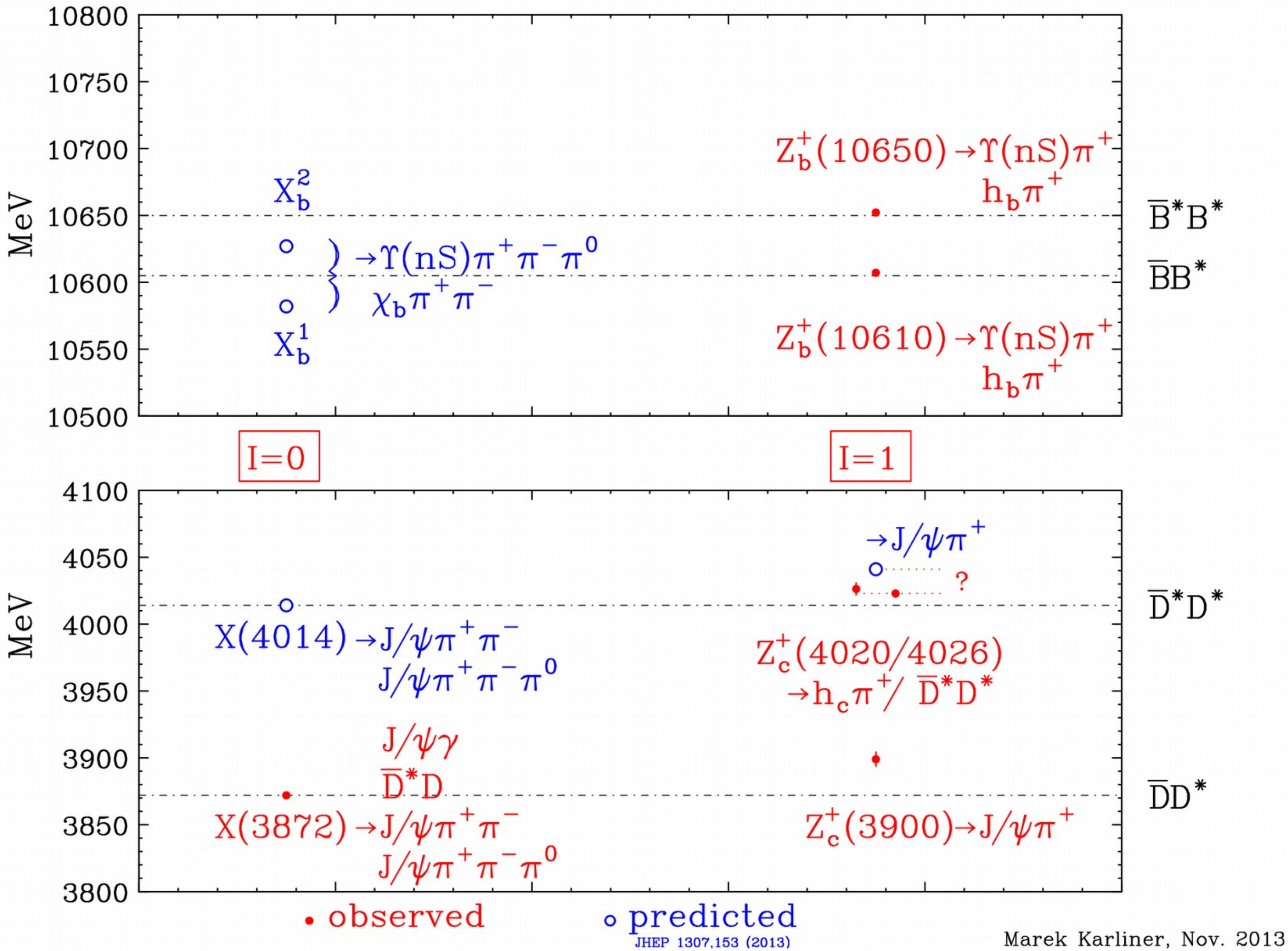
need a unified picture:



Marek Karliner, Nov. 2013

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

exotic heavy quarkonia vs. two meson thresholds



Caveat about mass predictions:

$m(D^*) - [m(D) + m(\pi)] \approx 0^{\pm}$,

depending on D^* and π charges;

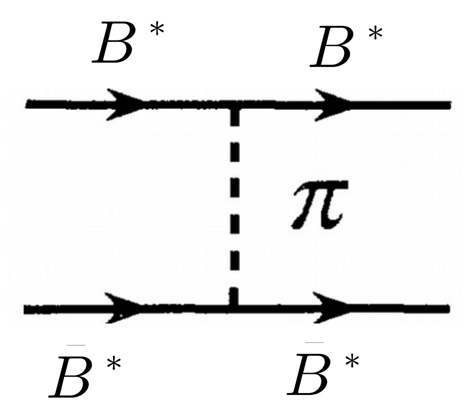
affects $D^* \to D\pi$ (strong decay)

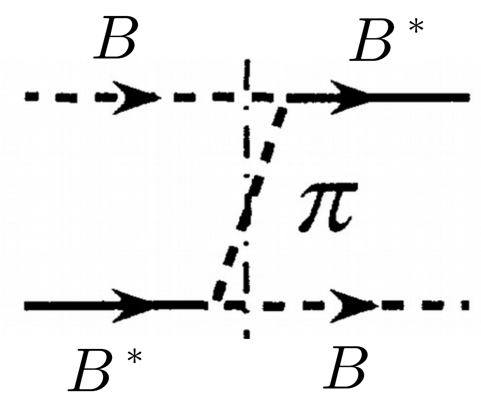
vs.

$B^* \to B\gamma$ (EM decay)

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

might be slightly different from $\bar{B}B^*$ and $\bar{B}^*B^*$





Likely observable at LHC and Tevatron:

$\sim$ nb x-section for $Z_b(10610)$, $Z_b(10650)$ and X_b

for $Z_c(3900)$, $Z_c(4020)$ 20-30$\times$ larger

Guo, Meiner Wang, arXiv:1308.0193

Guo, Meiner, Wang & Yang, arXiv:1402.6236

large enough to be observed

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