



Tel Aviv University



Theory prospects in heavy hadron spectroscopy

Marek Karliner
Tel Aviv University

LHCb workshop, Elba, May 30, 2017



“I know he's a good general,
but is he lucky?”

In hadron spectroscopy
LHCb has consistently
been both very good
and very lucky.

This luck has been
hard-earned.

hadrons w. heavy quarks are *much simpler*:

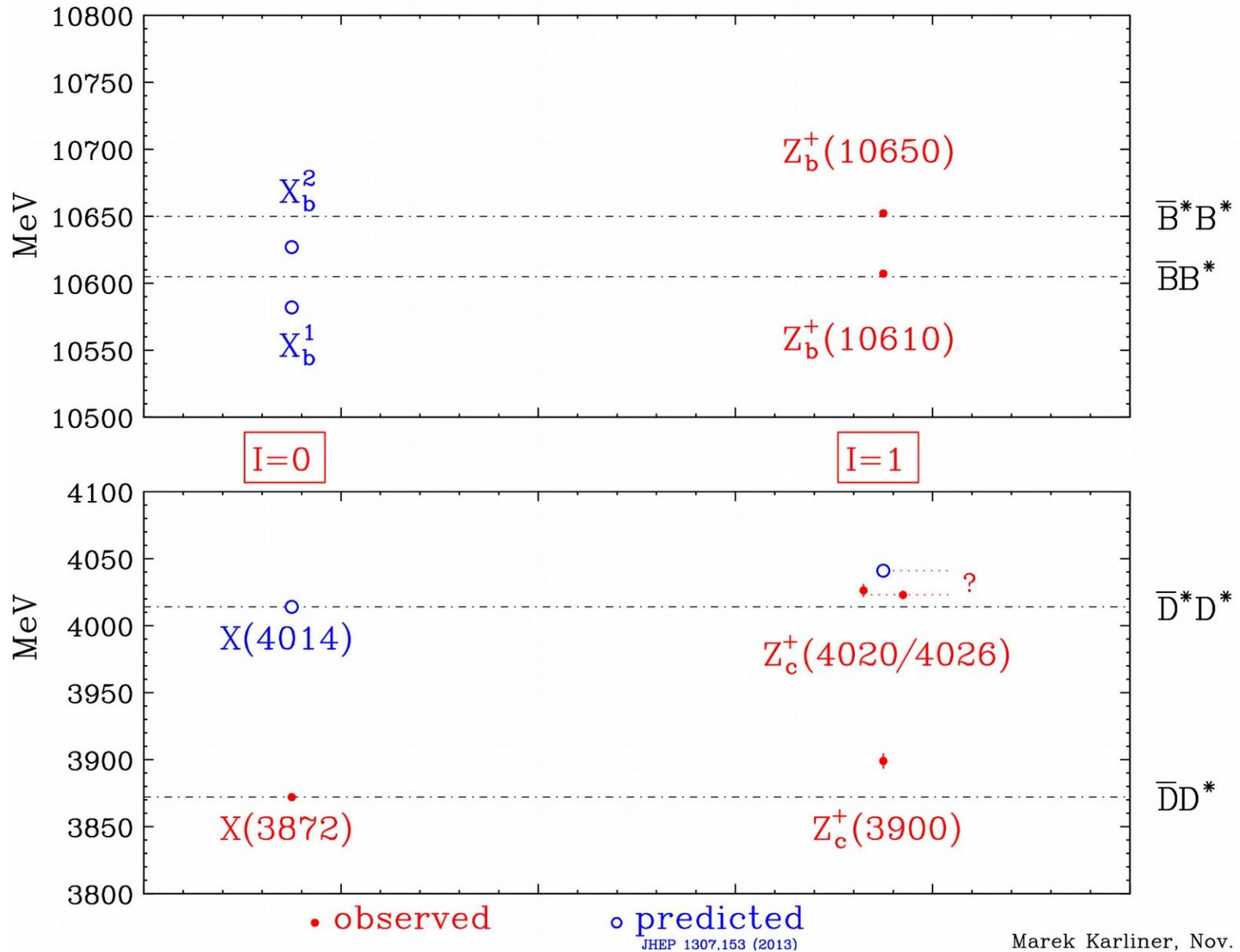
- heavy quarks almost static
- smaller spin-dep. interaction $\propto 1/m_Q$
- key to accurate prediction of b quark baryons

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	$\gamma\pi$	1008	$\bar{B}B^*$	2 ± 2
$Z_b(10650)$	10651	10	$\gamma\pi$	1051	\bar{B}^*B^*	2 ± 2
$Z_c(3900)$	3900	24 – 46	$J/\psi \pi$	663	$\bar{D}D^*$	24
$Z_c(4020)$	4020	8 – 25	$J/\psi \pi$	783	\bar{D}^*D^*	6
×					$\bar{D}D$	
×					$\bar{B}B$	

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

exotic heavy quarkonia vs. two meson thresholds



The Z_Q resonances decay into

$\bar{Q}Q\pi$

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

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

⇒ 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)

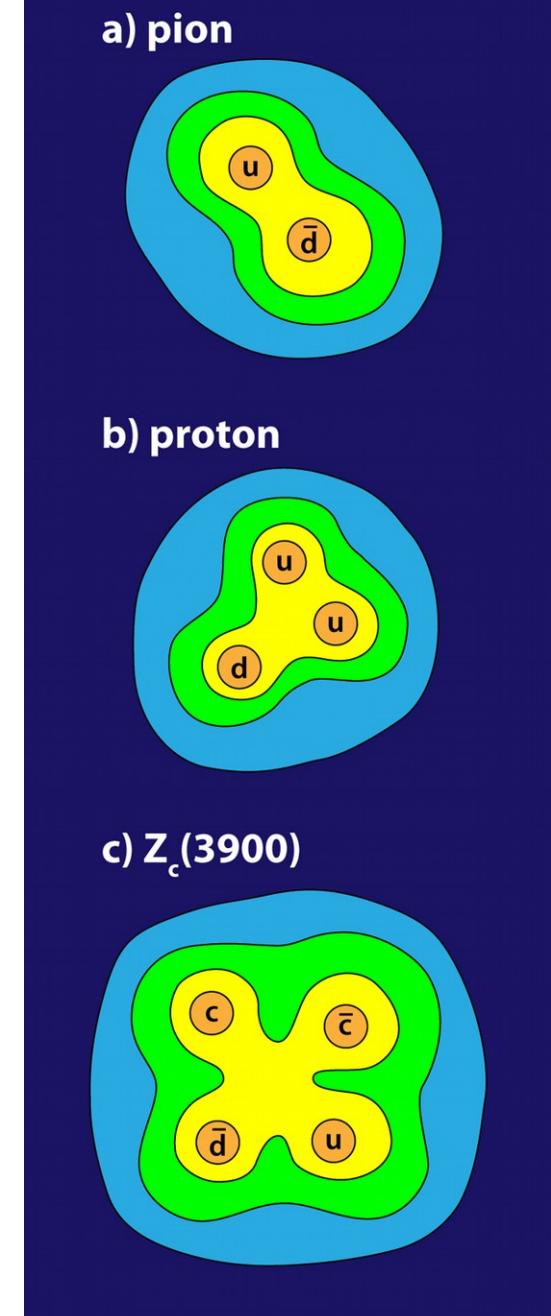
overlap of Z_c wave function with $J/\psi\pi$
much smaller than with $\bar{D}D$

⇒ indicates an extended object

new result from Belle
(analysis by Alexei Garmash):

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

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



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

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

despite -1 MeV vs $400 - 500 \text{ MeV}$ 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)
$\Gamma_1 e^+ e^-$	
$\Gamma_2 \pi^+ \pi^- J/\psi(1S)$	$> 2.6 \%$
$\Gamma_3 \rho^0 J/\psi(1S)$	
$\Gamma_4 \omega J/\psi(1S)$	$> 1.9 \%$
$\Gamma_5 D^0 \bar{D}^0 \pi^0$	$> 32 \%$
$\Gamma_6 \bar{D}^{*0} D^0$	$> 24 \%$

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 π exchange[†]:

explains conspicuous 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 $D \rightarrow D\pi$:
 $J^P = 0^-$, so parity demands $D \rightarrow D\pi$ in P -wave;
but D and π in P -wave give $J = 1$

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

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 ?....

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.
 $\Sigma_c \bar{\Lambda}_c \xrightarrow{\pi} \Lambda_c \bar{\Sigma}_c$.
- (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

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 $\pi^-(s)$
 $b\bar{c}$ 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: $\Theta_{cc} \rightarrow J/\psi p$

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

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

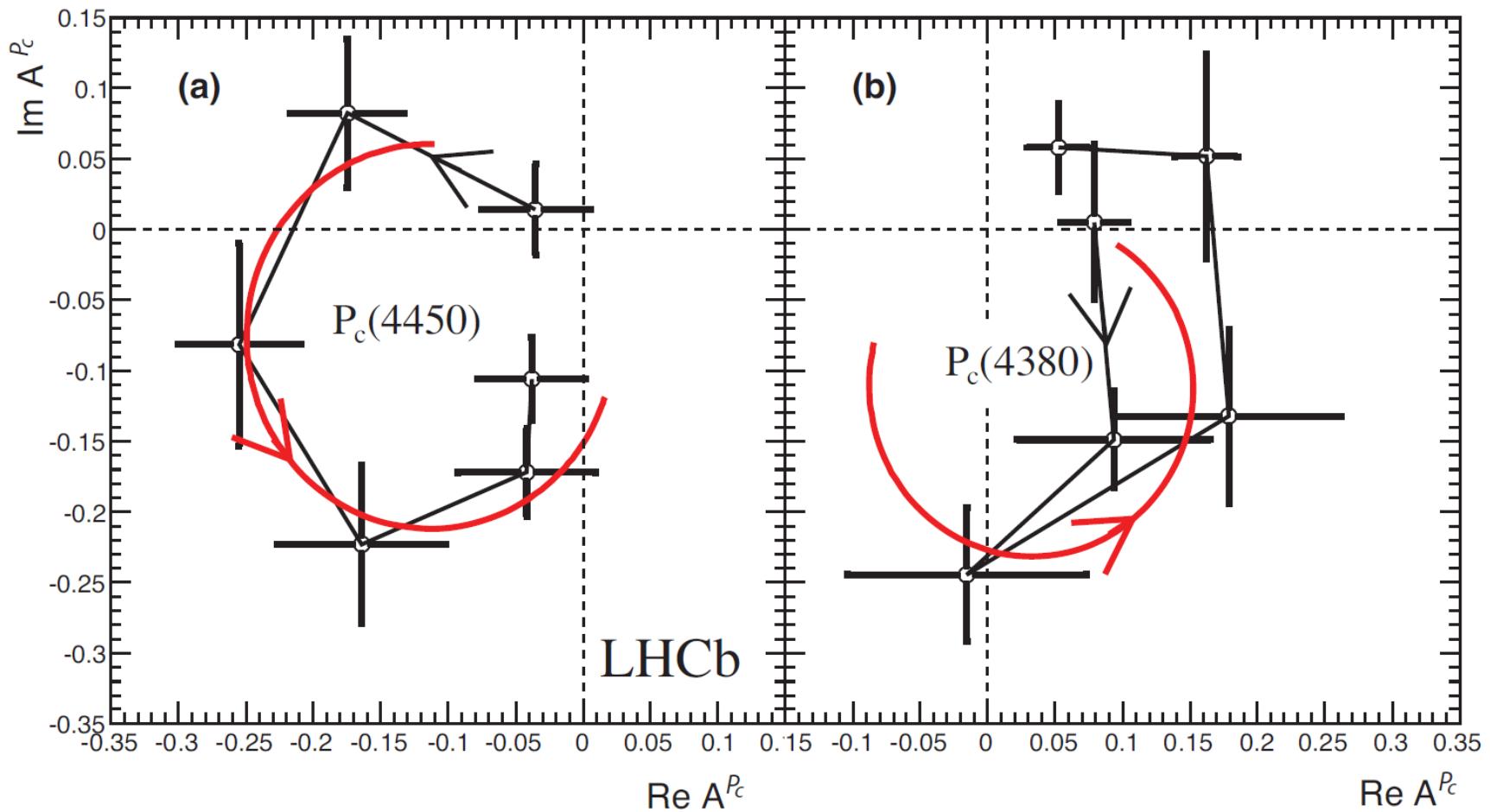
Channel	Minimum isospin	Minimal quark content ^{a,b}	Threshold (MeV) ^c	Example of decay mode
$D\bar{D}^*$	0	$c\bar{c}q\bar{q}$	3875.8	$J/\psi \pi\pi$
$D^*\bar{D}^*$	0	$c\bar{c}q\bar{q}$	4017.2	$J/\psi \pi\pi$
D^*B^*	0	$c\bar{b}q\bar{q}$	7333.8	$B_c^+ \pi\pi$
$\bar{B}B^*$	0	$b\bar{b}q\bar{q}$	10604.6	$\Upsilon(nS)\pi\pi$
\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	$J/\psi p$
$\Sigma_c B^*$	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	$\Upsilon(nS)\rho$
$\Sigma_c\bar{\Lambda}_c$	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	$\Upsilon(nS)\pi\pi$

^aIgnoring annihilation of quarks.

^cBased on isospin-averaged masses.

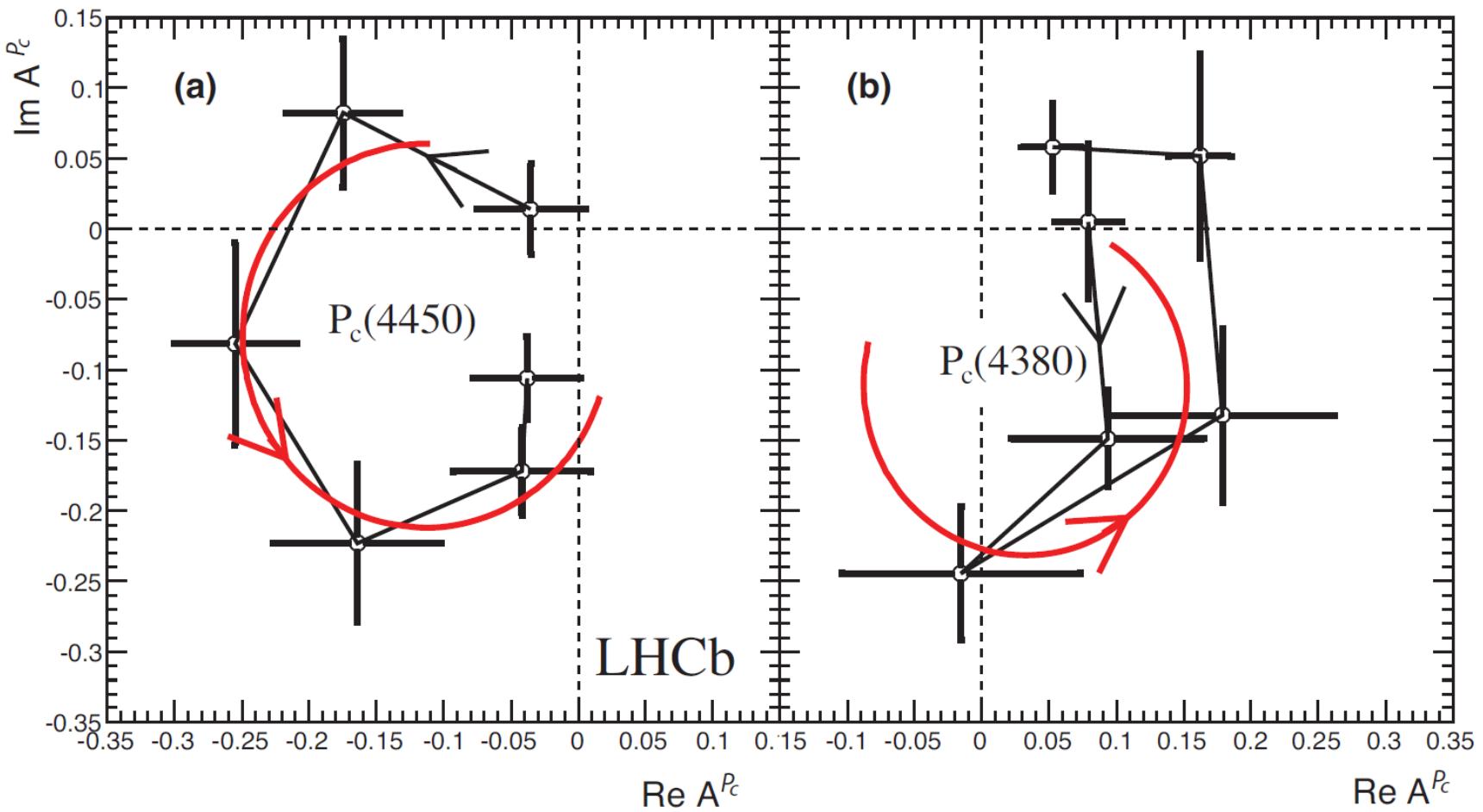
^bPlus other charge states when $I \neq 0$.

^dThresholds differ by 27.6 MeV.



$P_c(4450)$: 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
???



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???

$P_c(4450)$ might be just the first of many “heavy deuterons”

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/ψ

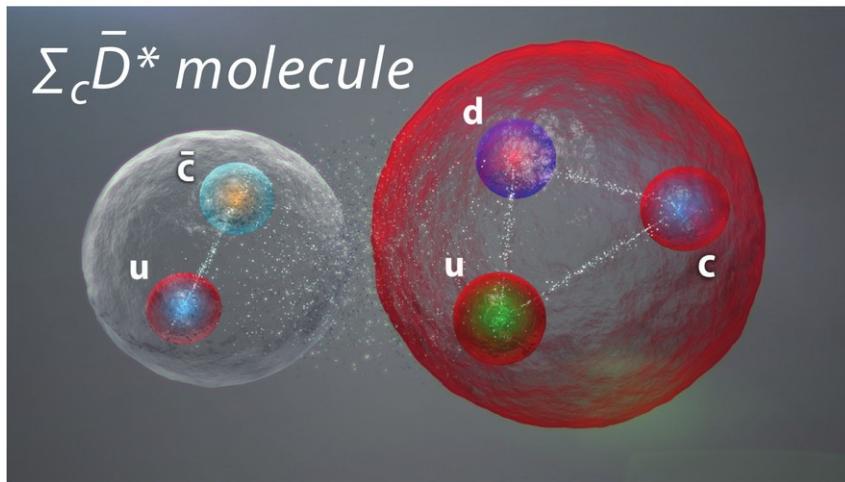
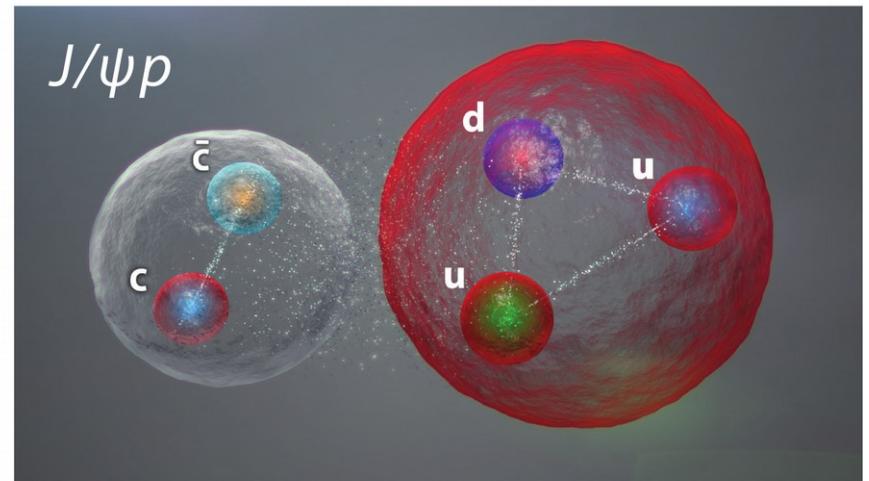
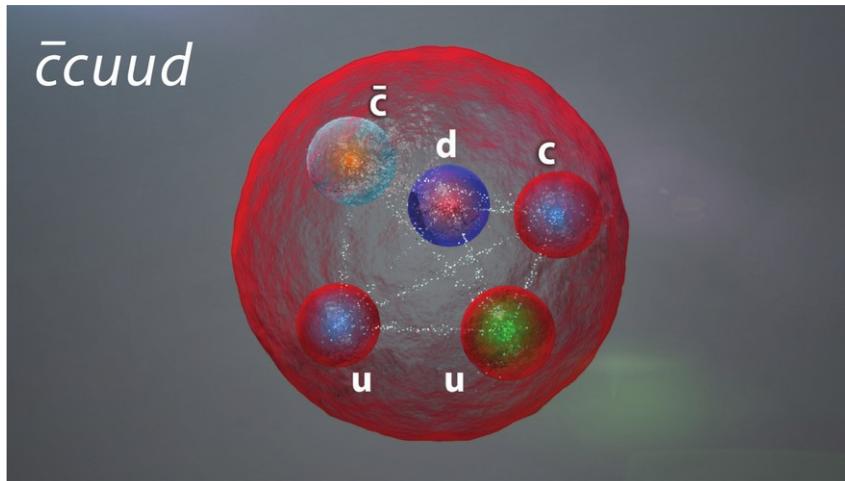
is generically large.

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 $J/\psi p$



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

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”

⇒ need a different production mechanism

Photoproduction of exotic baryon resonances

MK & J. Rosner, arXiv:1508.01496

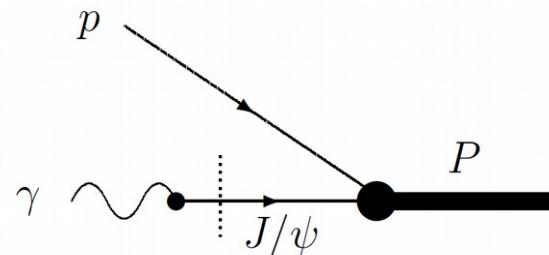
Q. Wang, X. H. Liu and Q. Zhao, arXiv:1508.00339

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

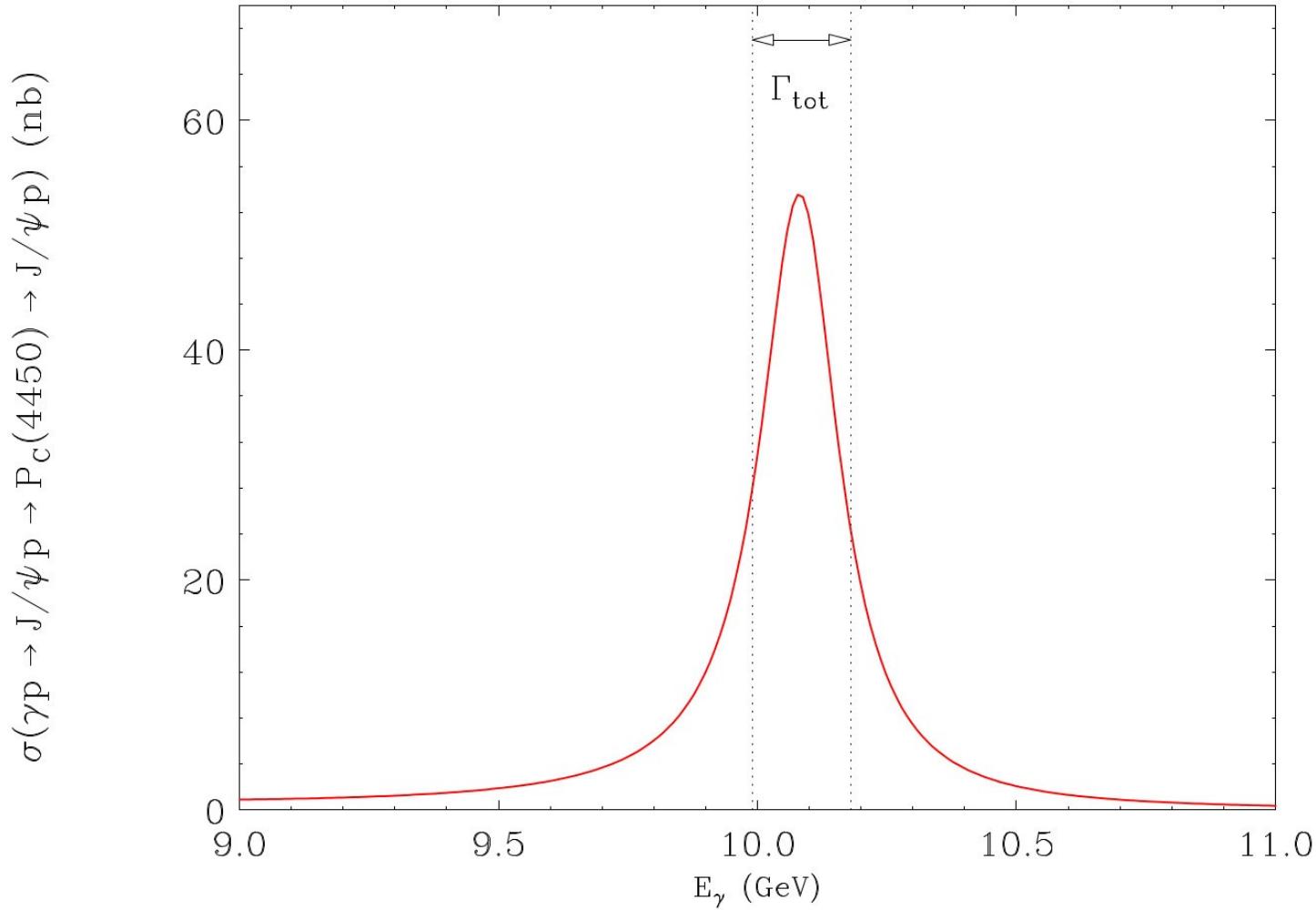
LHCb: new exotic resonances in $J/\psi p$ channel:

⇒ excellent candidates for photoproduction

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



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



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_γ . The vertical dotted lines indicate the width of the $P_c(4450)$ resonance.

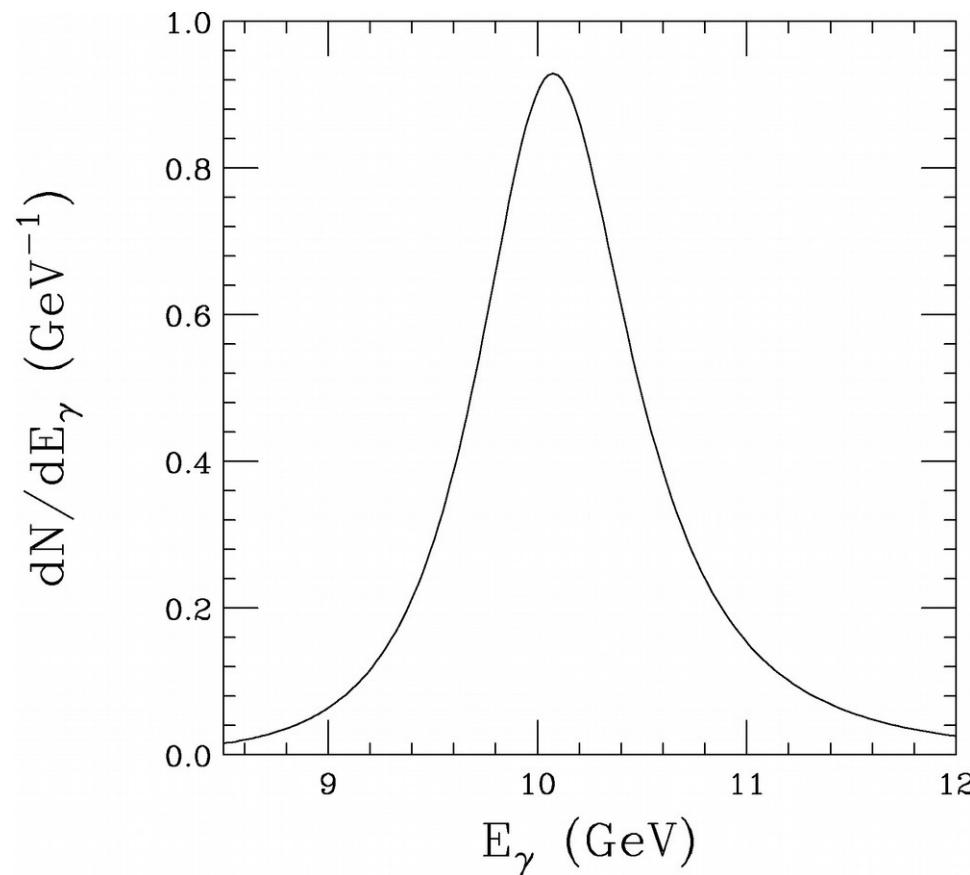
$P_c(4380)$ and $P_c^+(4450) \rightarrow J/\psi p \Rightarrow I_3 = +\frac{1}{2}$

If genuine resonances, $I_3 = -\frac{1}{2}$ partner must exist

$\Rightarrow \gamma d \rightarrow J/\psi n p$

- $\sigma(\gamma n \rightarrow P_c \rightarrow J/\psi n) = \sigma(\gamma p \rightarrow P_c \rightarrow J/\psi p)$
- $M(P_c^0) = M(P_c^+)$
- w/o Fermi motion $\sigma(\gamma d) = 2\sigma(\gamma p)$
- Fermi motion effects significant:
smearing, FF suppression, offshellness
- recoil N momentum $\lesssim 100$ MeV,
so detection problematic

convolution of $\sigma(\gamma N \rightarrow P_c)$ with Fermi motion results in significant broadening of the peak

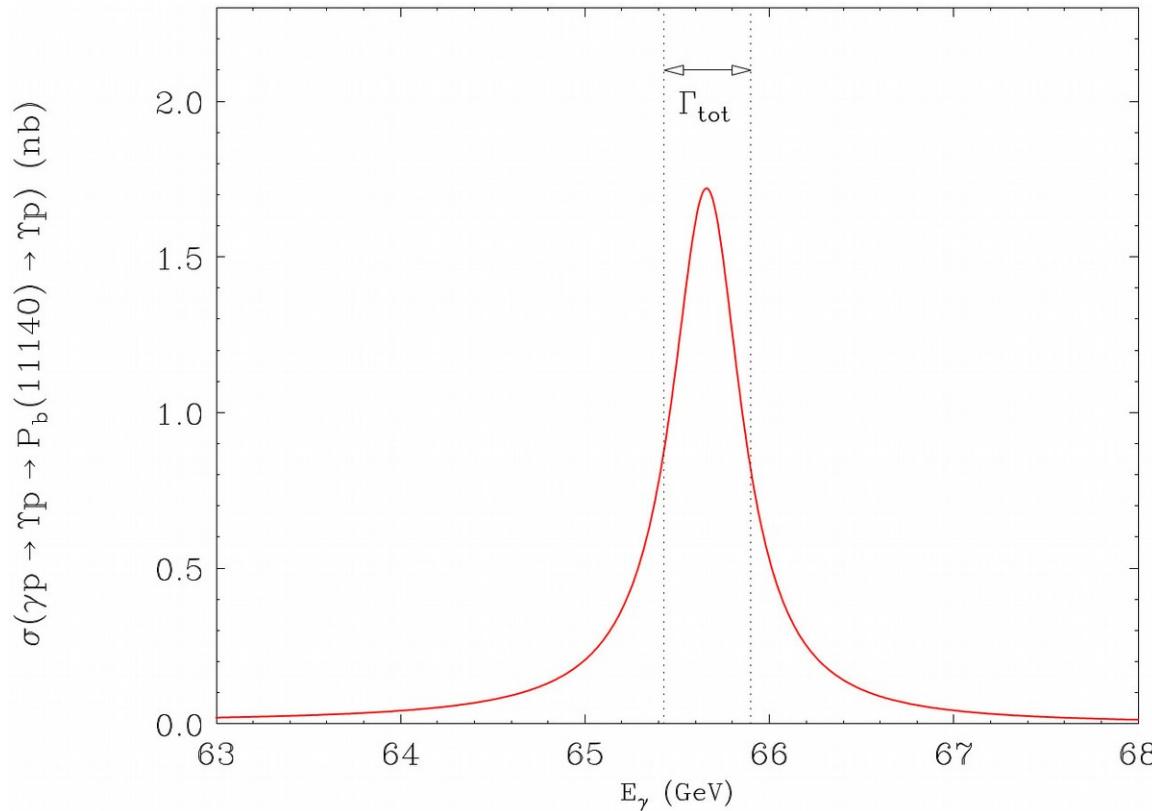


MK and J.L. Rosner,
arXiv:1705.07691 [hep-ph].

Spread in incident photon energy for photoproduction of a narrow $P_c(4450)$ on a deuteron target. The curve is normalized so that its integral over E_γ is 1.

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

$E_\gamma = 65.66$ GeV,
 $\sigma \sim 1$ nb $\gg \sigma_{\text{diffractive}} \sim 50$ pb



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

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

so perhaps LHC can also see continuum production

$$P_c(4450) \rightarrow J/\psi p$$

$$P_b(11140) \rightarrow \gamma p ?$$

bottom analogue of $X(3872)$:

- X_b and $\chi_{b1}(3P)$ 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 $\chi_{1b}(3P)$

⇒ measure $R\gamma\gamma \equiv \frac{\mathcal{B}(\chi_{b1}(3P) \rightarrow \gamma(2S)\gamma)}{\mathcal{B}(\chi_{b1}(3P) \rightarrow \gamma(1S)\gamma)}$

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

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

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

⇒ deuteron-like $J = 1, I = 0$ bound state, “*beutron*”

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.

Exotic resonances due to η exchange

MK and J. Rosner, Nucl. Phys. A **954**, 365 (2016)

- 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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exotic baryons due to η exchange:

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

then analogous baryon-meson resonances should exist

- a heavy baryon and a heavy meson
- at least one w/o light quarks

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

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

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

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

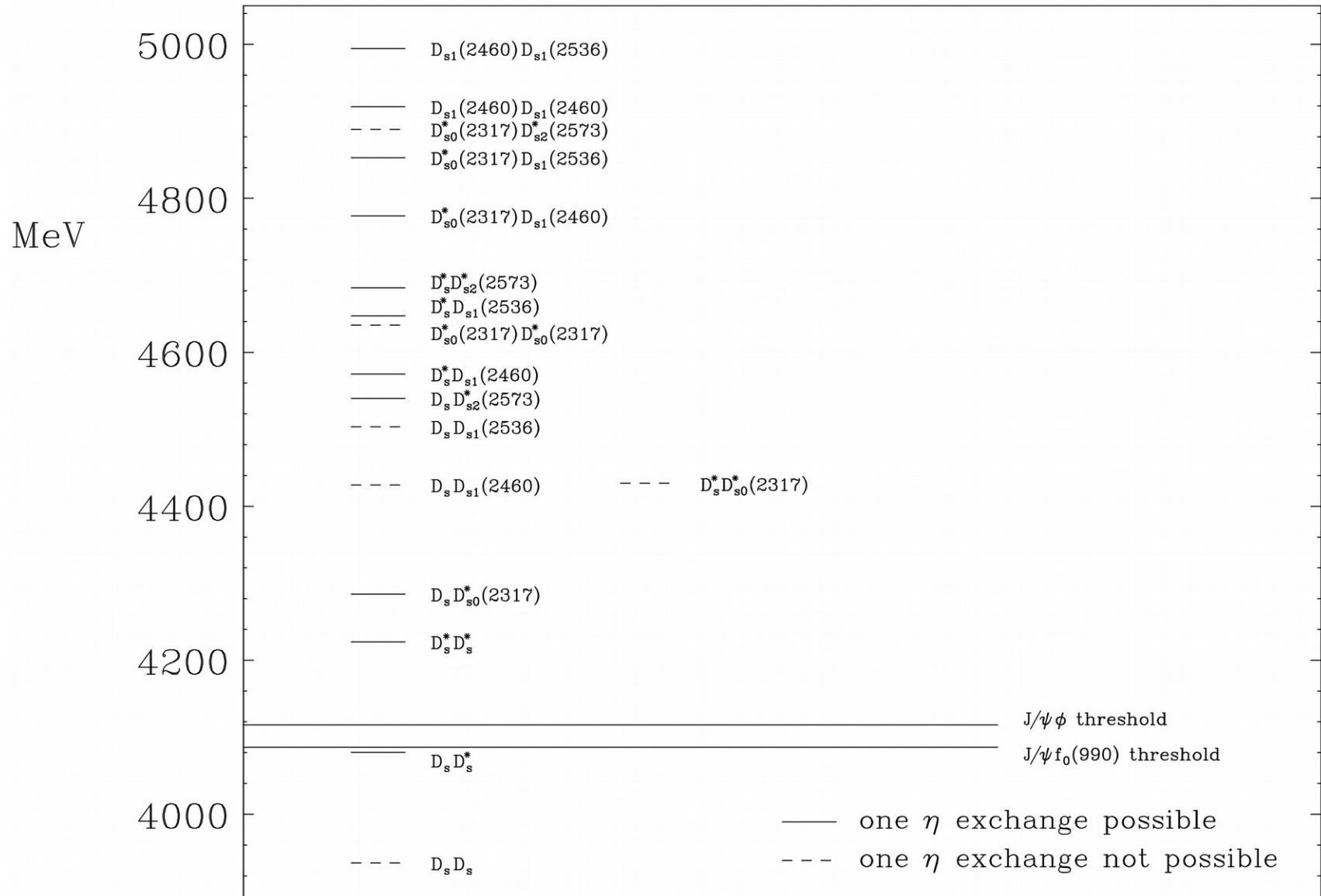
States (J^P)	M (MeV)	$M - M(J/\psi)$ $-M(\phi)$	Binding by η ?	Allowed J^P
$D_s^+(0^-) D_s^-(0^-)$	3936.6	-179.8	No	-
$D_s^+(0^-) D_s^{*-}(1^-)$	4080.4	-36.0	Yes	1^+
$D_s^{*+}(1^-) D_s^{*-}(1^-)$	4224.2	107.8	Yes	$0^+, 2^+ {}^a$
$D_s^+(0^-) D_{s0}^{*-}(2317)(0^+)$	4286.0	169.6	Yes	0^-
$D_s^+(0^-) D_{s1}^-(2460)(1^+)$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

^a $J^P = 1^+$ forbidden by symmetry.

^b Proximity of these two channels may lead to binding. See text.

^c Cannot be produced in $B \rightarrow KX$ because of kinematic mass limit.

Thresholds involving two D_s mesons



doubly heavy baryons QQq :

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

must exist, but have never been seen

fascinating challenge for EXP & TH

LHCb sees thousands of B_c -s

\implies should see bcq, ccq , etc.

QQq baryons are the simplest baryons:

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

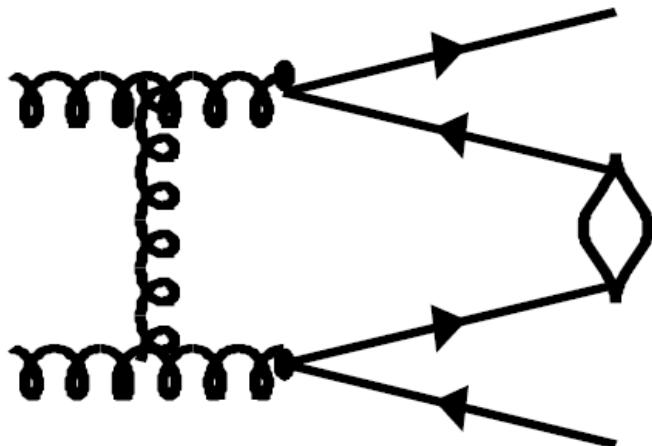
so QQq baryon $\sim \bar{Q}q$ meson

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...

Ξ_{bc} production: same diagram,

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

$$\implies \sigma(pp \rightarrow \Xi_{bc} + X) \stackrel{<}{\sim} \sigma(pp \rightarrow B_c + X)$$

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

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

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

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

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	—	—

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 $c \rightarrow sud\bar{d}$, 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 Ξ_{bb}^0 , but
 $\tau(\Xi_b^0)$ not much different from $\tau(\Xi_b^-)$
so treat Ξ_{bb}^0 and Ξ_{bb}^- generically as Ξ_{bb}

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

rare but spectacular decay mode:

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

rough estimate of Ξ_{cc} production rate

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

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

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

perhaps can generalize to Ξ_{bc} and Ξ_{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 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 $p\bar{p}$

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

Phys. Rev. D 95, 034011 (2017) 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 $Q\bar{Q}$: probability $\sim 0.1\%$

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

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



CERN-EP-2017-037
LHCb-PAPER-2017-002
14 March 2017

Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$

The LHCb collaboration[†]

Abstract

The $\Xi_c^+ K^-$ mass spectrum is studied with a sample of pp collision data corresponding to an integrated luminosity of 3.3 fb^{-1} , collected by the LHCb experiment. The Ξ_c^+ is reconstructed in the decay mode $pK^-\pi^+$. Five new, narrow excited Ω_c^0 states are observed: the $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$. Measurements of their masses and widths are reported.

Submitted to Phys. Rev. Lett.

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[†]Authors are listed at the end of this paper.

$$\Xi_c^+ = csu, \quad K^- = s\bar{u} \\ \Rightarrow css: \text{excited } \Omega_c$$

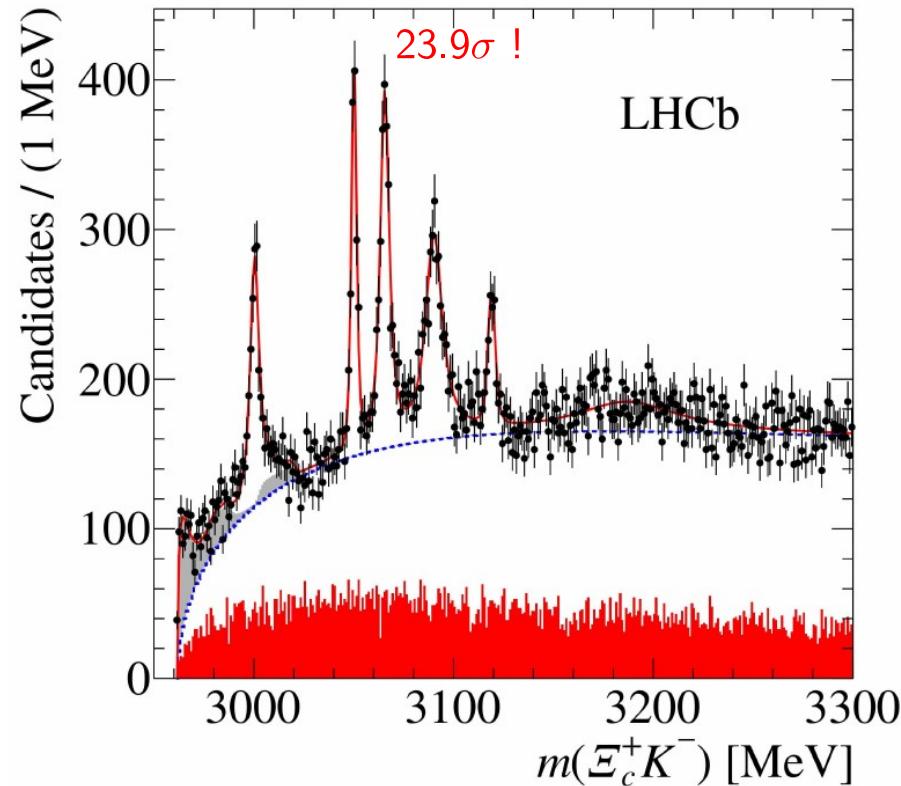


Figure 2: Distribution of the reconstructed invariant mass $m(\Xi_c^+ K^-)$ for all candidates passing the likelihood ratio selection; the solid (red) curve shows the result of the fit, and the dashed (blue) line indicates the fitted background. The shaded (red) histogram shows the corresponding mass spectrum from the Ξ_c^+ sidebands and the shaded (light gray) distributions indicate the feed-down from partially reconstructed $\Omega_c(X)^0$ resonances.

- interpret as bound states
of a c -quark and a P -wave ss -diquark.

⇒ exactly 5 possible combinations of **S** and **L**
splitting due to spin-orbit, spin-spin and tensor
- narrowness:
diquark hard to split and/or D -wave suppression
- predict 5 states:
 $J^P = 1/2^-, 1/2^-, 3/2^-, 3/2^-, 5/2^-$
- assign to 5 observed resonances
(*a priori* $5! = 120$ possibilities)
- Ω_b analogues
- alternative interpretations

historical perspective

- 1974 – spectrum of charmonium: $J/\psi, \psi', \psi''\dots$
- accurately reproduced by nonrel. QM $\bar{c}c$ potential
- “hydrogen atom” of quarkonium: $E = E(n, \ell)$
dependence on radial and orbital quantum numbers
- crucial evidence that quarks are real physical objects
- LHCb Ω_c spectrum enables next step:
highly accurate data on spin-dep. interactions
 - ⇒ spin-orbit, spin-spin and tensor forces
between quarks in baryons
- predictions for other systems, in particular Ω_b

some immediate questions:

- (a) Why five states? Are there more in this css system?
- (b) Why are they so narrow?
- (c) What are their spin-parity assignments?
- (d) Can one understand the mass pattern?
- (e) Are there other similar states with different quark content, in particular very narrow excited Ω_b baryons?

P -wave $c(ss)$ system

$c(ss)$: if ss S -wave $\bar{3}_c$ diquark $\Rightarrow S_{ss} = 1$

combine $S_{ss} = 1$ with $S_c = \frac{1}{2}$ \Rightarrow total $S = \frac{1}{2}$ or $\frac{3}{2}$

take $L = 1$ for c - ss system

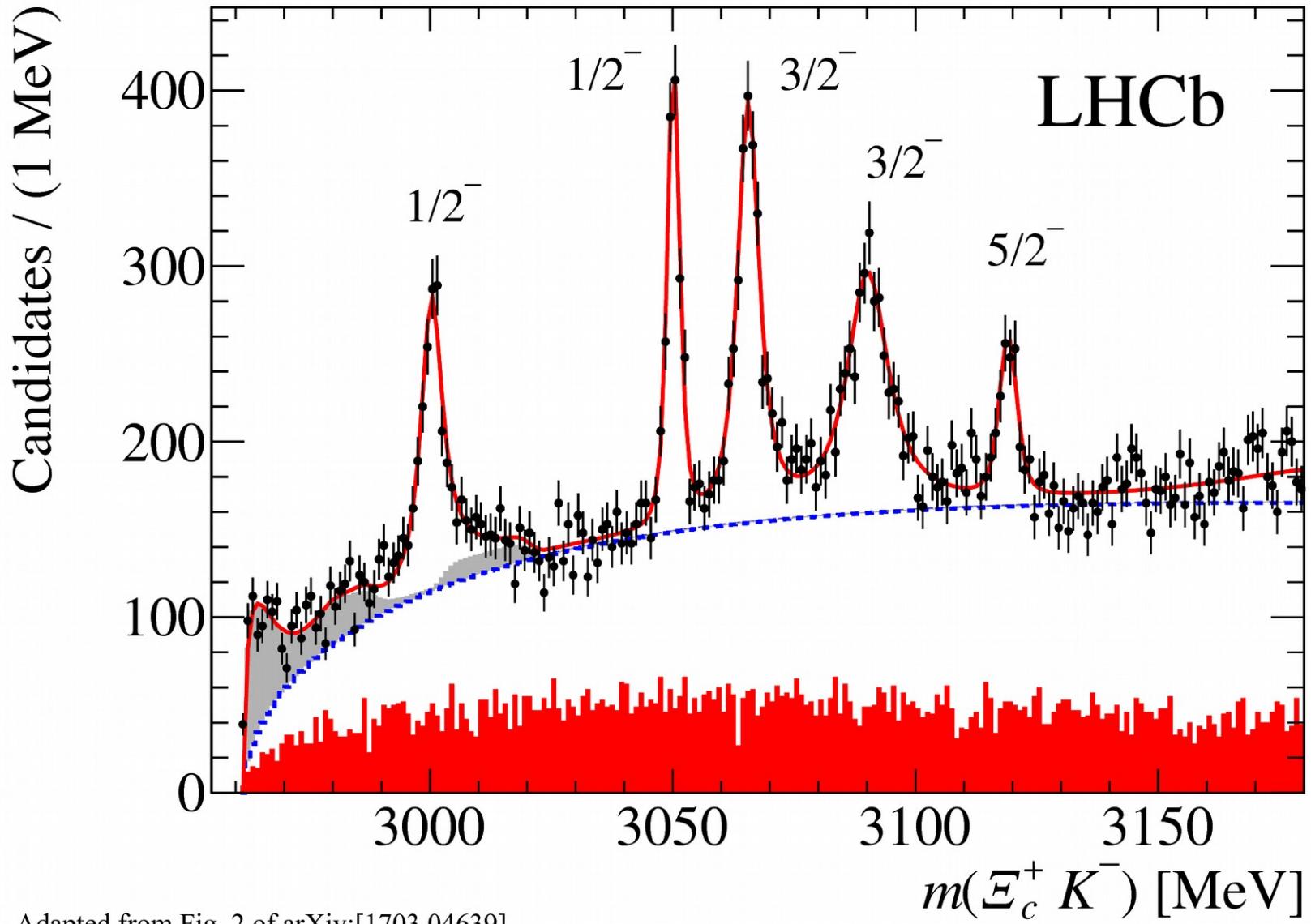
combine $L = 1$ with $S = \frac{1}{2}$ $\Rightarrow J = \frac{1}{2}, \frac{3}{2}$

combine $L = 1$ with $S = \frac{3}{2}$ $\Rightarrow J = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}$ all with negative parity

$\Rightarrow J^P = 1/2^-, 1/2^-, 3/2^-, 3/2^-, 5/2^-$

$J^P = 1/2^-$ decay to $\Xi_c^+ K^-$ in S -wave, D-wave might be narrower
• partially confirmed by preferred J^P
• consistent w. alternate assignment

$J^P = 3/2^-, 5/2^-$ decay to $\Xi_c^+ K^-$ in D -wave



Adapted from Fig. 2 of arXiv:[1703.04639]

Masses and widths of $\Omega_c = css$ candidates reported by LHCb.
The proposed values of spin-parity J^P are ours.
An alternative set of assignments is shown in parentheses.

State	Mass (MeV) ^a	Width (MeV)	Proposed J^P
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1$	$4.5 \pm 0.6 \pm 0.3$	$1/2^- (3/2^-)$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1$	$0.8 \pm 0.2 \pm 0.1$ $< 1.2 \text{ MeV, 95\% CL}$	$1/2^- (3/2^-)$
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3$	$3.5 \pm 0.4 \pm 0.2$	$3/2^- (5/2^-)$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5$	$8.7 \pm 1.0 \pm 0.8$	$3/2^- (1/2^+)$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9$	$1.1 \pm 0.8 \pm 0.4$ $< 2.6 \text{ MeV, 95\% CL}$	$5/2^- (3/2^+)$

^aAdditional common error of $+0.3, -0.5$ MeV from $M(\Xi_c^+)$ uncertainty.

decay of excited Ω_c

strong decay of $c(ss)$ requires ripping ss apart

alternative kinematically forbidden:

$$c(ss) \rightarrow \Xi D^{(*)}: 3180 \text{ MeV} > \Omega_c(3119)$$
$$q(ss) c\bar{q}$$

if reason for narrow width, might also explain
narrowness of some ordinary Ξ s w. substantial ph. space

$$\begin{array}{ccc} \Omega_c & \Xi_c^+ & K^- \\ c-(ss) & (csu) & (s\bar{u}) \end{array}$$

$c \rightarrow u$:

$$\begin{array}{ccc} u-(ss) & (usu) & (s\bar{u}) \\ \Xi^0 & \Sigma^+ & K^- \end{array}$$

decay of excited Ω_c

diquark sturdiness might also explain narrowness
of some ordinary Ξ s w. substantial ph. space

$$\begin{array}{ccc} \Omega_c & \Xi_c^+ & K^- \\ c-(ss) & (csu) & (s\bar{u}) \end{array}$$

$c \rightarrow u$:

$$\begin{array}{ccc} u-(ss) & (usu) & (s\bar{u}) \\ \Xi^0 & \Sigma^+ & K^- \end{array}$$

$\Xi(1690)$, $\Gamma < 30$ MeV (J^P unknown),

$\Xi(1820)$, $\Gamma = 24^{+16}_{-10}$ MeV ($J^P = 3/2^-$),

$\Xi(1950)$, $\Gamma = 60 \pm 20$ MeV (J^P unknown),

$\Xi(2030)$, $\Gamma = 20^{+15}_{-5}$ MeV (J^P unknown).

spin-dependent potential
between a heavy quark Q and the (ss) spin-1 diquark

$$\begin{aligned} V_{SD} = & \quad a_1 \mathbf{L} \cdot \mathbf{S}_{ss} + a_2 \mathbf{L} \cdot \mathbf{S}_Q \quad \text{spin orbit} \\ & + b[-\mathbf{S}_{ss} \cdot \mathbf{S}_Q + 3(\mathbf{S}_{ss} \cdot \mathbf{r})(\mathbf{S}_Q \cdot \mathbf{r})/r^2] \quad \text{tensor force} \\ & + c \mathbf{S}_{ss} \cdot \mathbf{S}_Q , \quad \text{color hyperfine} \end{aligned}$$

\mathbf{L} = angular momentum = 1

\mathbf{S}_{ss} = ss diquark spin = 1

\mathbf{S}_Q = heavy quark spin = 1/2

criteria for parameters

(i) $\mathbf{S}_{ss} \cdot \mathbf{S}_Q$:

c should be small, as it depends on P -wave near the origin.

(ii) $\mathbf{L} \cdot \mathbf{S}_Q$:

a_2 should be close to estimate from Λ_c , $a_2 = 23.9$ MeV

(iii) $\mathbf{L} \cdot \mathbf{S}_{ss}$:

a_1 should be < 40 MeV, from previous $\Sigma_c(cuu)$ analysis

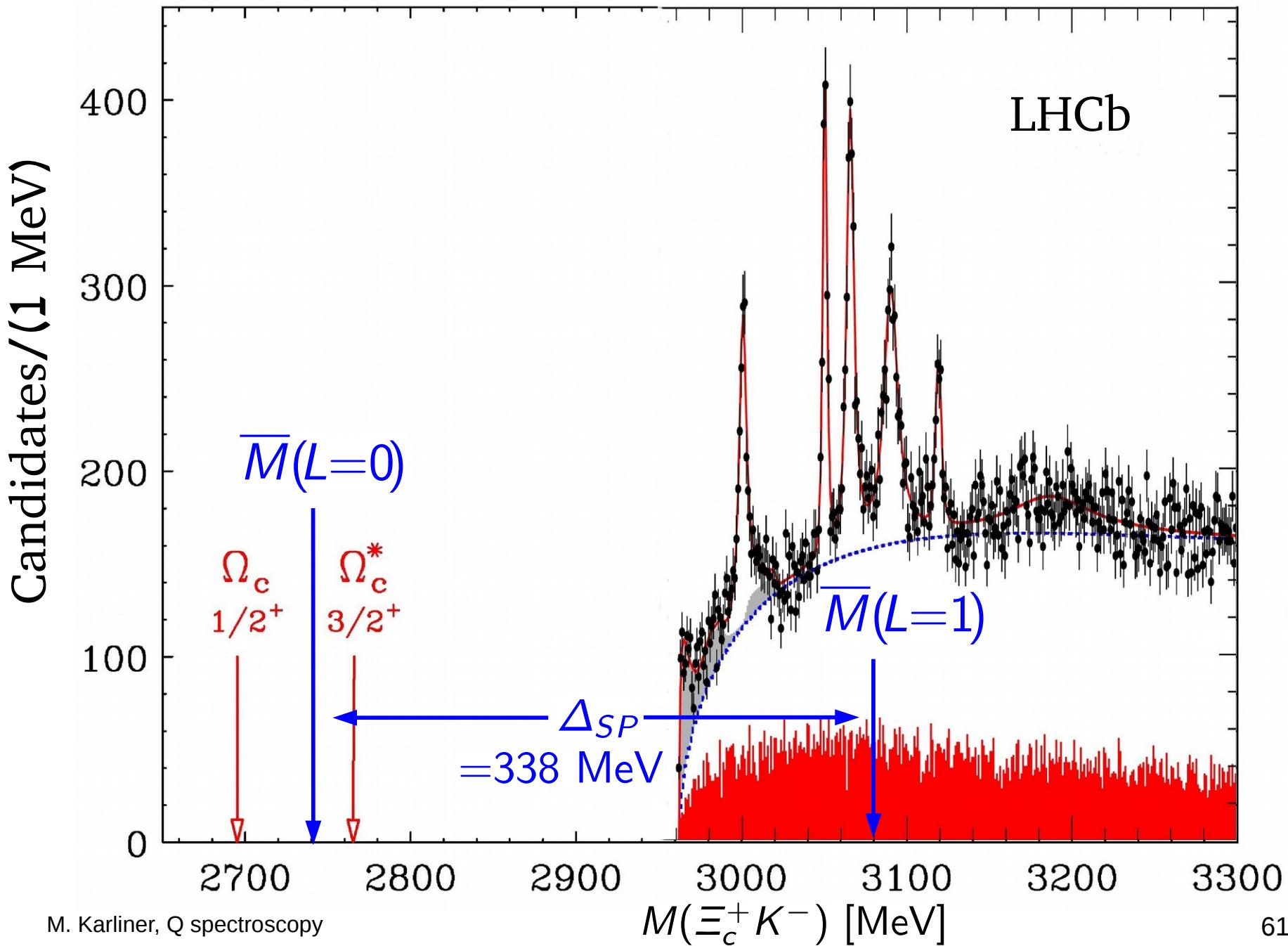
examine all $5! = 120$ *a priori* possible assignments of P -wave states

⇒ assignment in Table favored, with parameters

$$a_1 = 26.95 \text{ MeV}, \quad a_2 = 25.74 \text{ MeV}, \quad b = 13.52 \text{ MeV}, \quad c = 4.07 \text{ MeV}.$$

⇒ the spin-averaged mass:

$$\overline{M} = (1/18) \sum_J (2J+1) M(J) = 3079.94 \text{ MeV}.$$



predictions for $\Omega_b = b(ss)$ states

$$\frac{m_c}{m_b} \sim \frac{1}{3} \Rightarrow \text{expect lin. approx. much better}$$

- set HF parameter $c = 0$.
- $a_1 = 26.95$ MeV as for $c(ss)$, as coeff. of $\mathbf{L} \cdot \mathbf{S}_{(ss)}$.
- $a_2 = 8.72$ MeV, rescaled by m_c/m_b .
- -20 MeV $< b < 20$ MeV.
- $S-P$ splitting: $\Delta E_{PS}(\Omega_b) \sim 300$ MeV.

predictions for $\Omega_b = b(ss)$ states

leading to mass shifts $\Delta M(J, j)$ in MeV:

$$\Delta M(1/2, 0) = -53.9 ,$$

$$\Delta M(1/2, 1) = -31.3 - b ,$$

$$\Delta M(3/2, 1) = -24.8 + \frac{1}{2}b ,$$

$$\Delta M(3/2, 2) = 20.4 + \frac{3}{10}b ,$$

$$\Delta M(5/2, 2) = 31.3 - \frac{1}{5}b .$$

$$\frac{1}{18} \sum_J (2J+1) M(J, j) = \overline{M}(\Omega_b) \approx [6062 + \Delta E_{PS}(\Omega_b)] \text{ MeV} \sim 6362 \text{ MeV}$$

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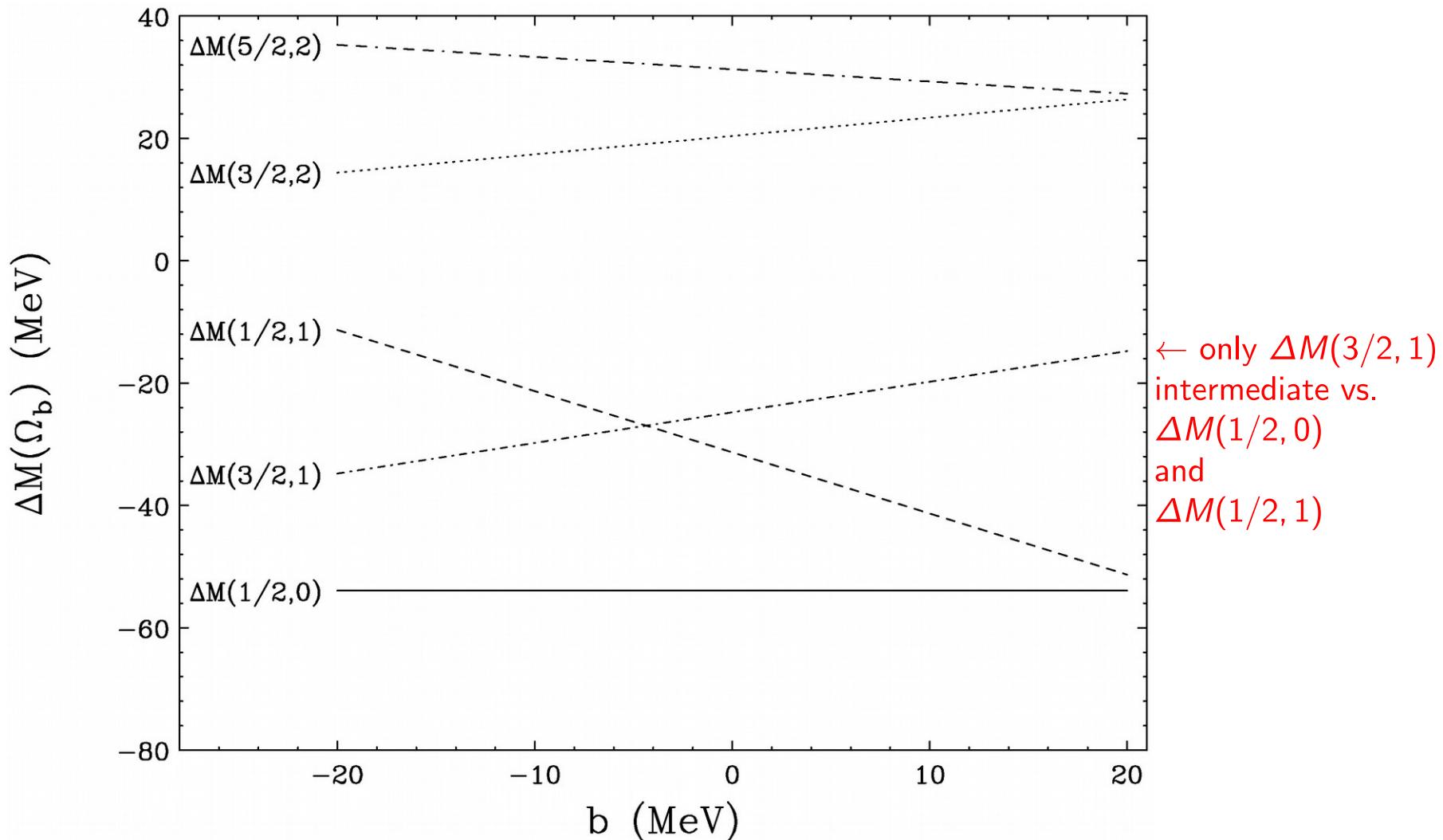
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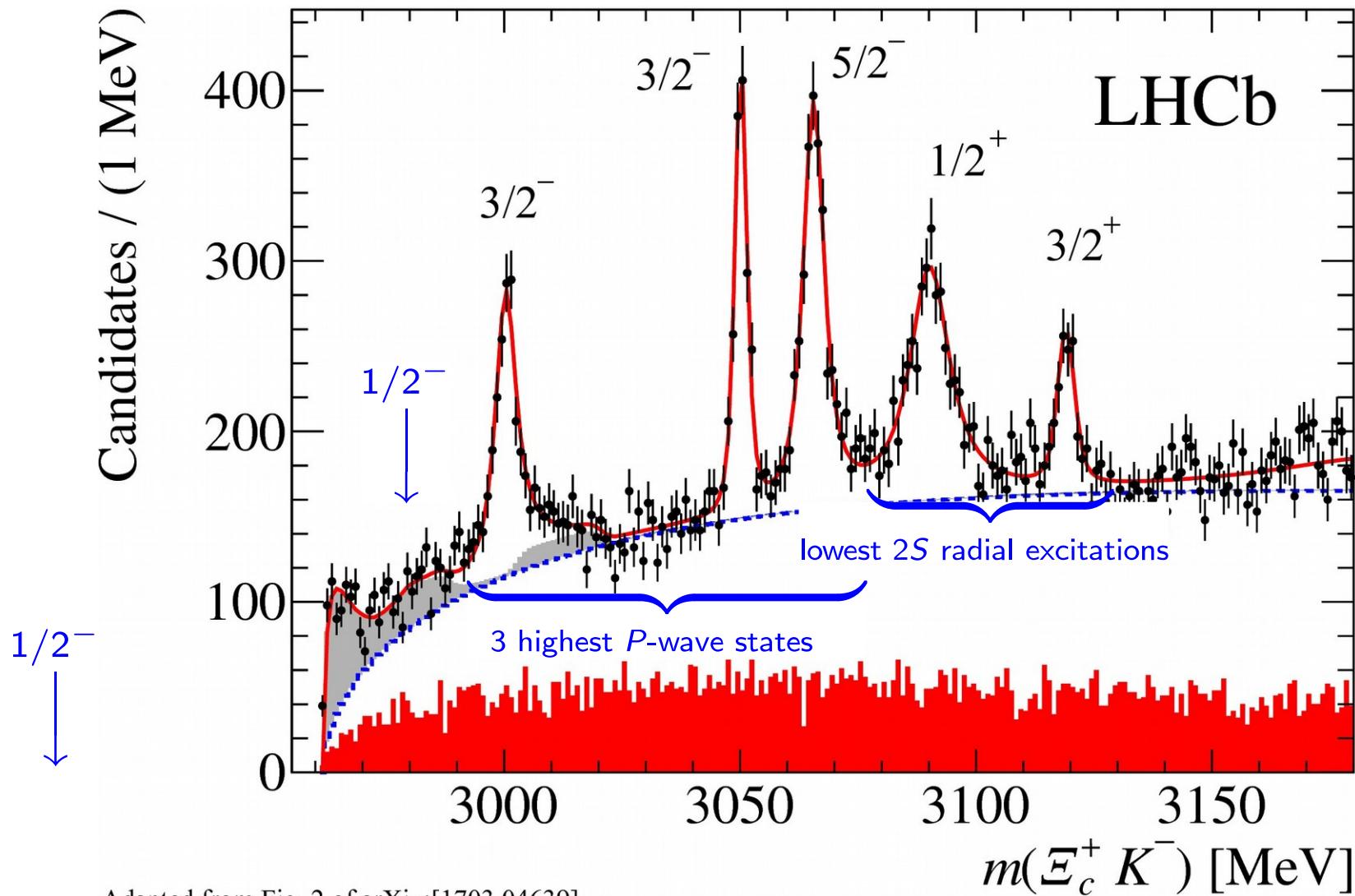
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caveat: $\Xi_b^0 K^-$ threshold at 6286 MeV
so lowest states might be below threshold



Masses of P -wave Ω_b states as functions of tensor force parameter b in scenario with all five peaks observed by LHCb corresponding to P -wave excitations of the (ss) diquark with respect to the charmed quark.

alternate J^P assignment



Upshot on new Ω_c states

- LHCb: 5 new excited Ω_c states: v. narrow & v. high stats
- interpret as 5 states expected in P -wave $c(ss)$ system :
 $J^P = 1/2^-, 1/2^-, 3/2^-, 3/2^-, 5/2^-$
awaits exp. confirmation, spin & parity meas.
- if instead 2 highest states are $2S$, $1/2^+$ and $3/2^+$
then 3 lowest are likely $J^P = 3/2^-, 3/2^-, 5/2^-$
- then expect $1/2^-$ near 2978 MeV $\rightarrow \Xi_c^+ K^-$ in S -wave
and $1/2^-$ near 2904 MeV $\rightarrow \Omega_c$ and/or Ω_c/π^0
- predictions for excited Ω_b -s in $b(ss)$ system

narrow B_{sJ} states

b-quark analogues of the very narrow D_{sJ} states
 $D_{s0}^*(2317)$ and $D_{s1}(2460)$ (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: mainly $D_{s0}^*(2317) \rightarrow D_s^+ \pi^0$

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

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

narrow B_{sJ} states

$J^P = 0^+$: $m(B_{s0}^*) \approx m(B_s) + 345 \text{ MeV} = 5712 \text{ MeV}$

$J^P = 1^+$: $m(B_{s1}) \approx m(B_s^*) + 345 \text{ MeV} = 5760 \text{ MeV}$

both below relevant thresholds:

$$m(B) + m(K) = 5777 \text{ MeV}$$

$$m(B^*) + m(K) = 5822 \text{ MeV}$$

⇒ expect v. narrow widths

dominant decay modes:

$$B_{s0}^* \rightarrow B_s \pi^0, B_s^* \gamma$$

$$B_{s1} \rightarrow B_s^* \pi^0, B_s^{(*)} \gamma$$

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challenging @LHCb:
soft π^0 and γ , so
large combinatorial
background
– Belle II ?

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!
 - *heavy deuterons*: $\Sigma_c D^*$: LHCb $P_c(4450) \Rightarrow$ photoproduction $\Sigma_c B^*$, $\Sigma_b \bar{D}^*$, $\Sigma_b B^*$, $\Sigma_Q \bar{\Lambda}_{Q'}$, $\Sigma_Q^+ \Sigma_Q^-$, ...
 - new isosinglet $\bar{B}B^*$ and \bar{B}^*B^* states below threshold;
hiding as $\chi_{1b}(3P)$?
 - η -mediated: $D_s \bar{D}_s^*$, $\Lambda_c \bar{D}_s^*$, ...
 - doubly & triply heavy baryons QQq , QQQ @ pp & e^+e^-
 - $cc\bar{c}\bar{c}$ @ $6,192 \pm 25$ MeV and $bb\bar{b}\bar{b}$ @ $18,826 \pm 25$ MeV $\Rightarrow 4\ell$
- new excited Ω_c states: spin dep. splittings $\Rightarrow J^P$ prediction, Ω_b analogues
- v. narrow $B_{s0}^* \rightarrow B_s \pi^0$, $B_s \gamma$ and $B_{s1} \rightarrow B_s^* \pi^0$, $B_s^{(*)} \gamma$

exciting new spectroscopy awaiting discovery

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