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Recent issues
in
heavy quark spectroscopy

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PHI2PSI, Mainz,June 28, 2017

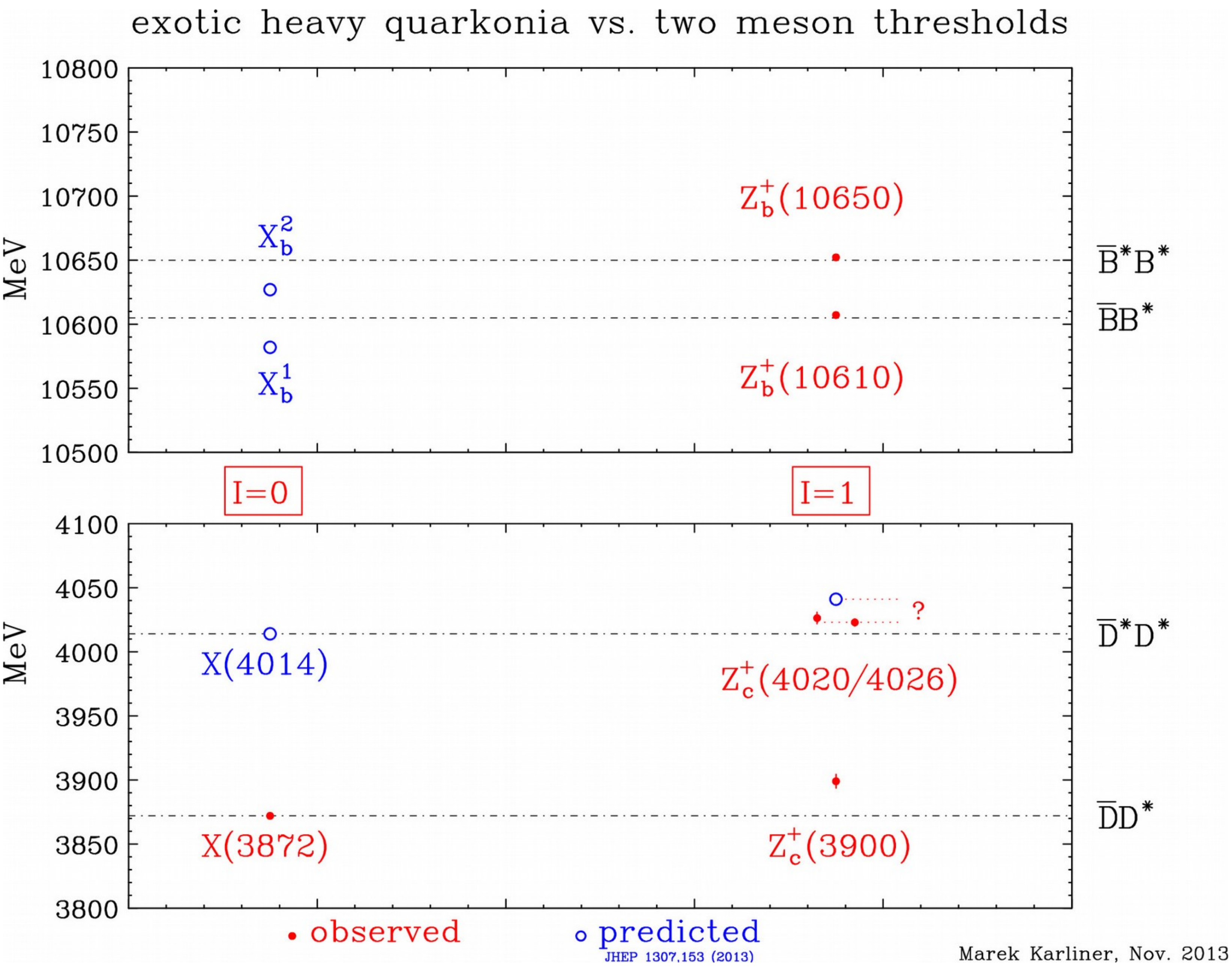
hadrons w. heavy quarks are *much simpler:*

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

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


exotic heavy quarkonia vs. two meson thresholds
MeV
10800
10750
10700
10650
10600
10550
10500
X_b^2
X_b^1
$Z_b^+(10650)$
$Z_b^+(10610)$
$\overline{B}^*B^*$
$\overline{B}B^*$
I=0
I=1
MeV
4100
4050
4000
3950
3900
3850
3800
X(4014)
X(3872)
?
$Z_c^+(4020/4026)$
$Z_c^+(3900)$
$\overline{D}^*D^*$
$\overline{D}D^*$
● 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 $\bar{q}q, \quad q = u,d$

$\Longrightarrow$ 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

Belle, PRL 116, 212001 (2016):

$$\frac{\Gamma(Z_b(10610) \to \bar{B}B)}{\Gamma(Z_b(10610) \to \Upsilon(1S)\pi)} \approx \frac{86\%}{0.54\%} = \mathcal{O}(100)$$

despite 1000 MeV of phase space

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

overlap of Z_c wave function with $J/\psi\pi$
much smaller than with $\bar{D}D$ $\Rightarrow$ indicates an extended object

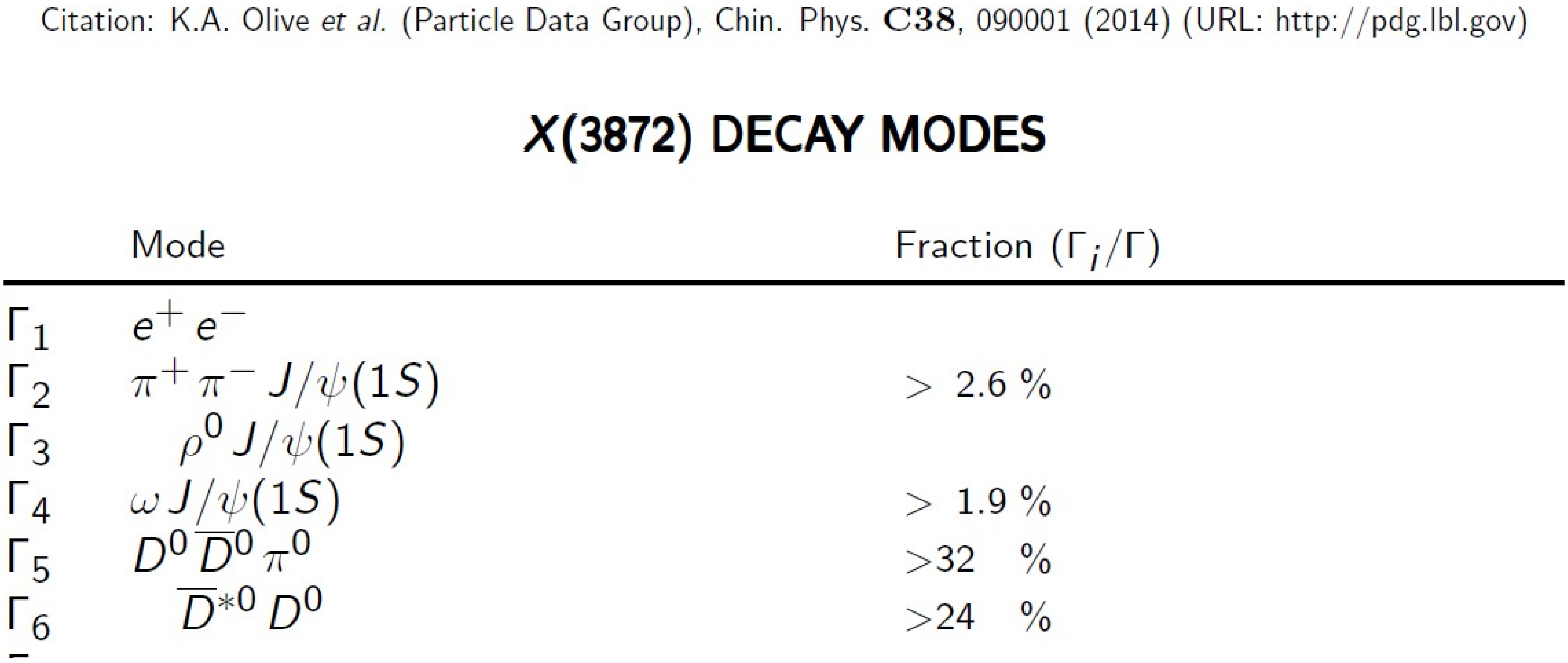
also

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

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

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

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

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

crucial test: $X(J^P = 0^{++}) \overset{?}{\rightarrow} J/\psi\gamma$ near $\bar{D}D$

$\bar{D}D^*$ $(I = 0)$ 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 $I = 0$, 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

M. Karliner and J. L. Rosner,
Phys. Rev. Lett. **115**, no. 12, 122001 (2015)

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

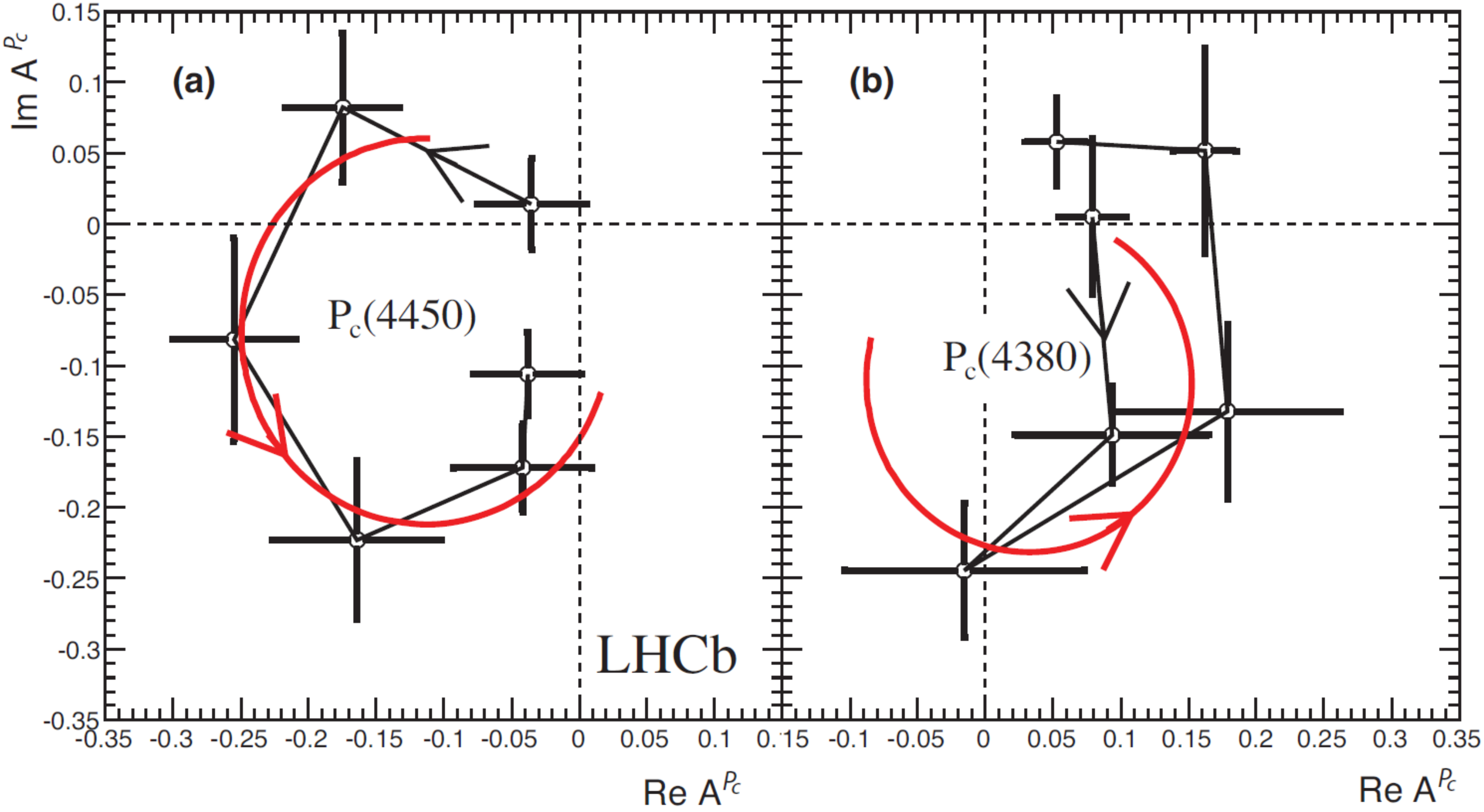
Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	Example of decay mode
$D\bar{D}^*$	0	$c\bar{c}q\bar{q}$	3875.8	$J/\psi\,\pi\pi$
$D^*\bar{D}^*$	0	$c\bar{c}q\bar{q}$	4017.2	$J/\psi\,\pi\pi$
D^*B^*	0	$c\bar{b}q\bar{q}$	7333.8	$B_c^+\pi\pi$
$\bar{B}B^*$	0	$b\bar{b}q\bar{q}$	10604.6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

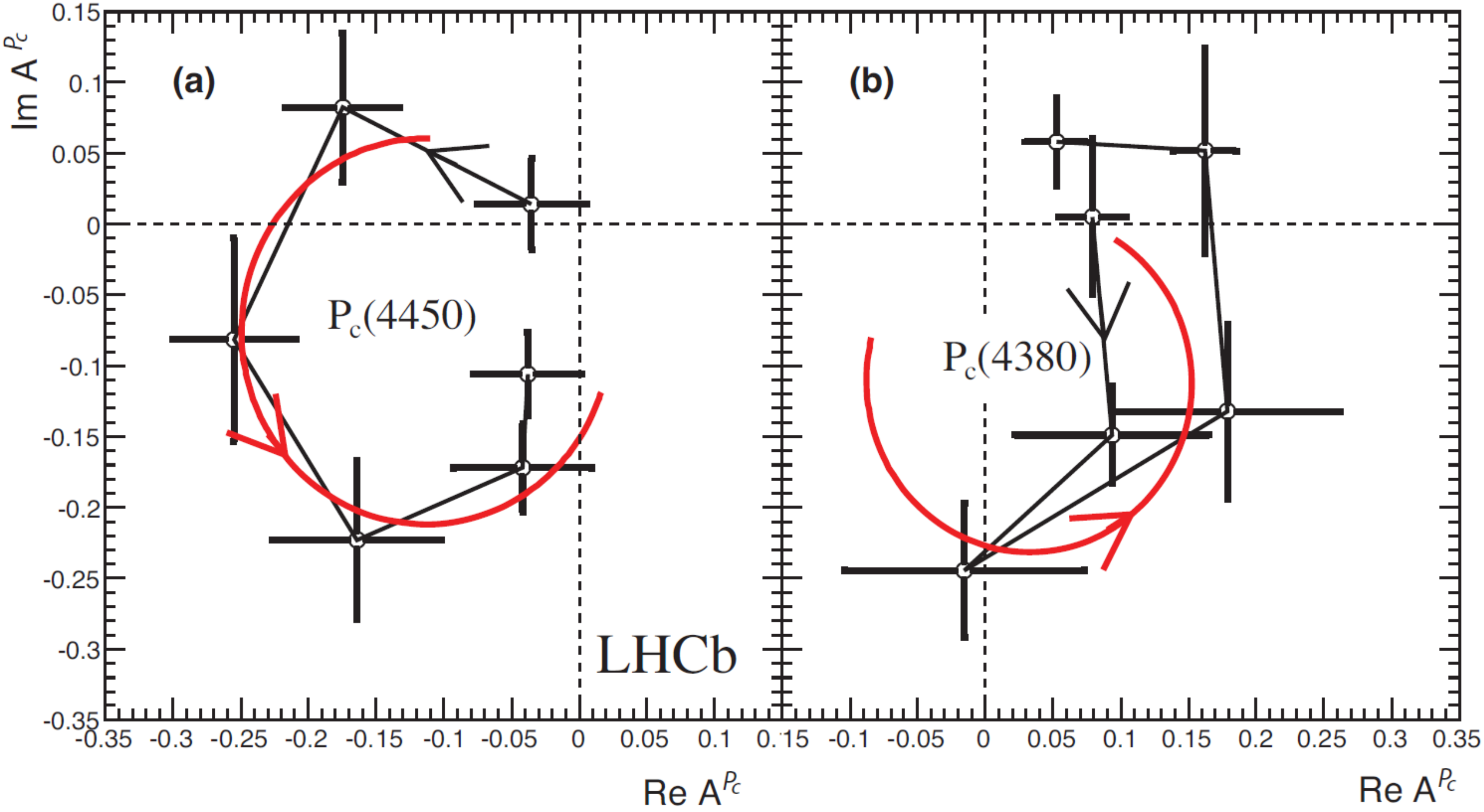
[c] Based on isospin-averaged masses.

[d] Thresholds differ by 27.6 MeV.



$P_c(4450)$: 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

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

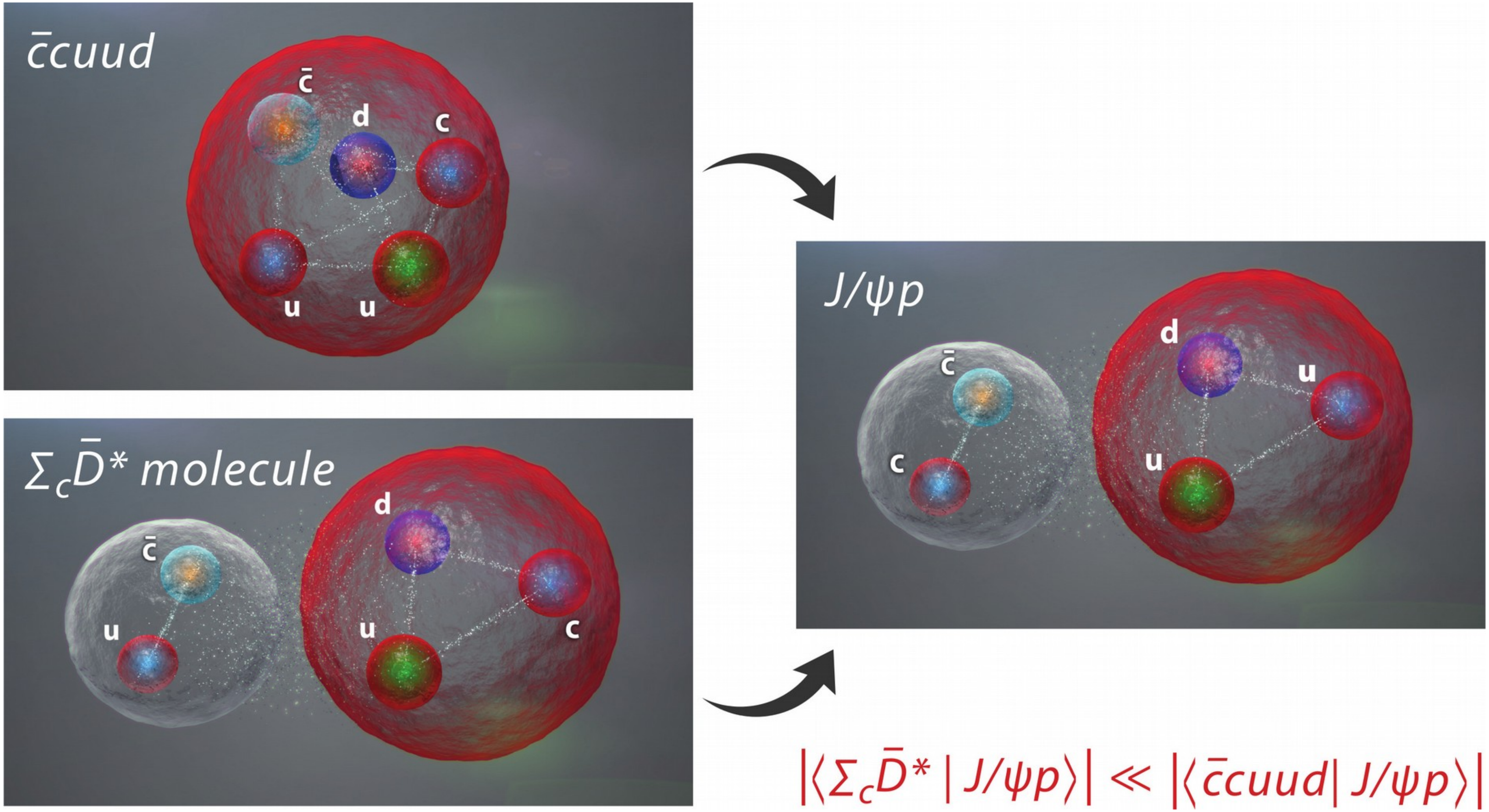
To get $\Gamma = 39$ MeV, the matrix element must be small .

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 $J/\psi p$



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

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

$P_c(4450)$ 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

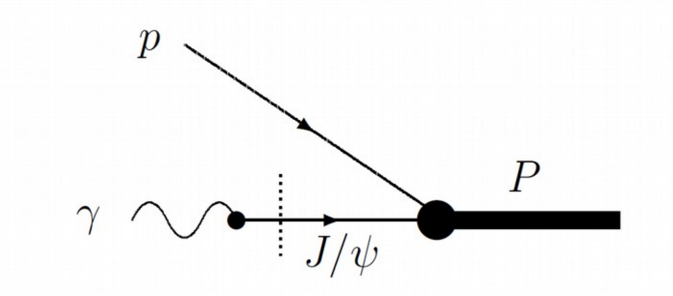
Photoproduction of exotic baryon resonances

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

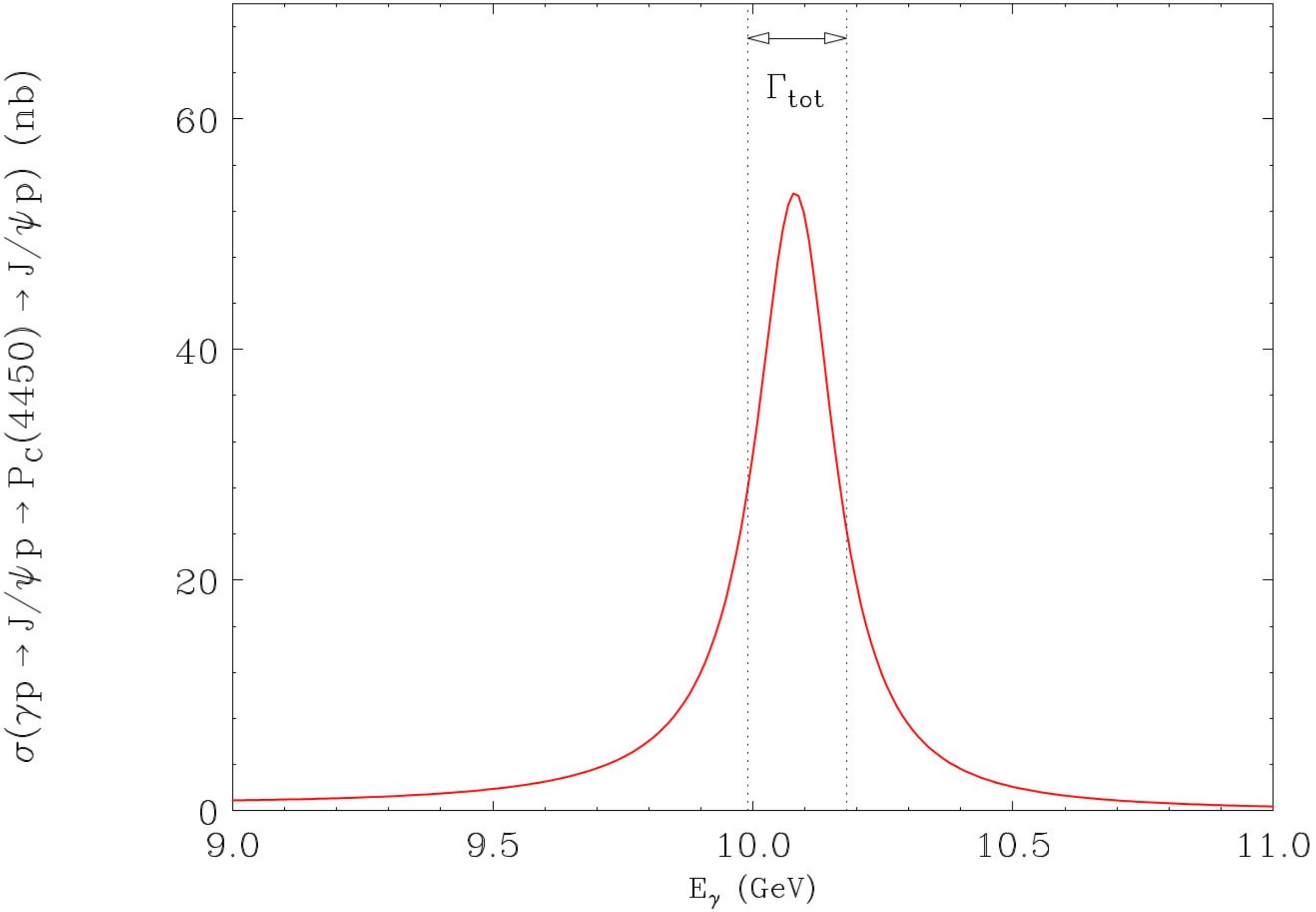
LHCb: new exotic resonances in $J/\psi\, p$ channel:

$\Longrightarrow$ natural 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



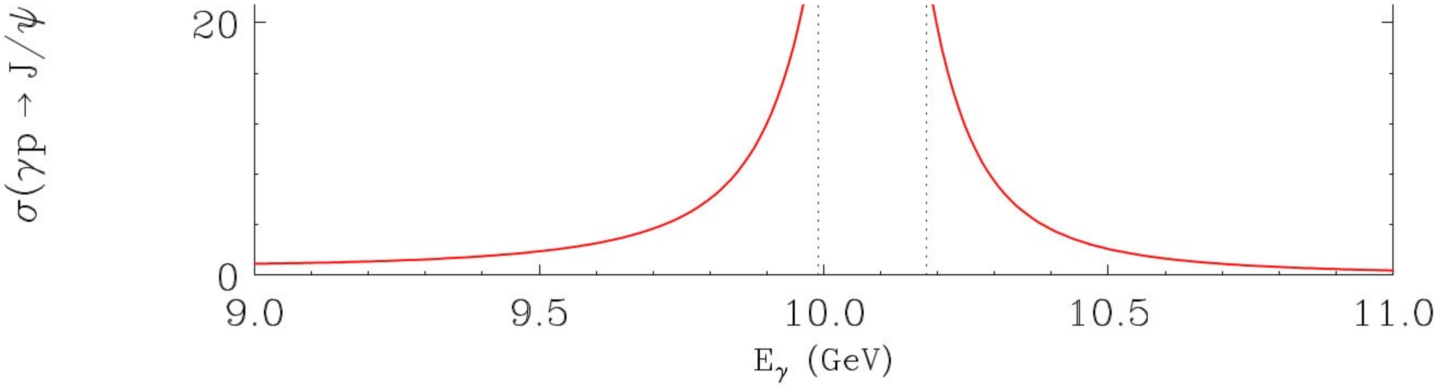
Cross section for resonant photoproduction $\gamma p \to J/\psi\, p \to P_c(4450) \to J/\psi\, p$, assuming $B_{\mathrm{out}} = 0.1$, plotted as function of the incident photon energy E_γ. The vertical dotted lines indicate the width of the $P_c(4450)$ resonance.

Caveat:

$BR(P_c(4450) \to J/\psi p) \ll BR(P_c(4450) \to \Sigma_c \bar{D}^*)$

BR(quarkonium mode) $\ll$ BR("fall apart" mode)

with significantly more data LHCb might be able to look for $P_c \to \Sigma_c^{++} D^{-*}$



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

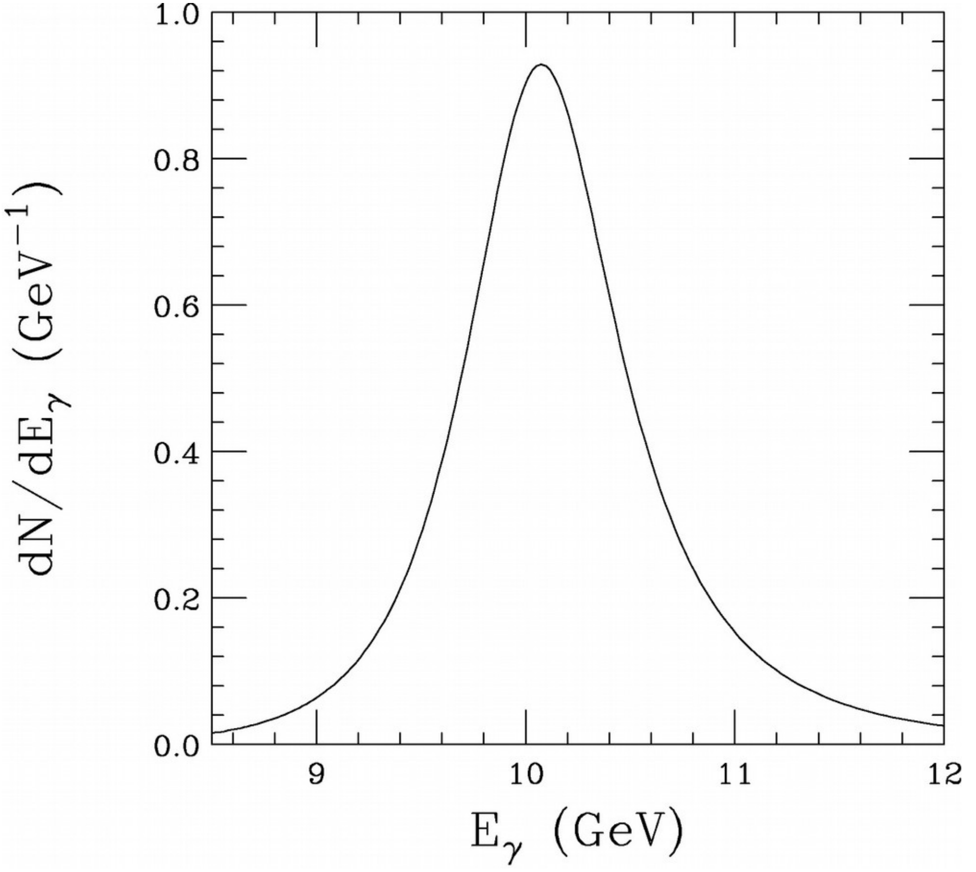
$P_c(4380)$ and $P_c^+(4450) \to J/\psi p \quad \Rightarrow I_3 = +\frac{1}{2}$

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

$\Rightarrow \gamma d \to J/\psi\, n\, p$

- $\sigma(\gamma n \to P_c \to J/\psi n) = \sigma(\gamma p \to P_c \to J\psi p)$
- $M(P_c^0) = M(P_c^+)$
- 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 $\sigma(\gamma N \to P_c)$ with Fermi motion results in significant broadening of the peak



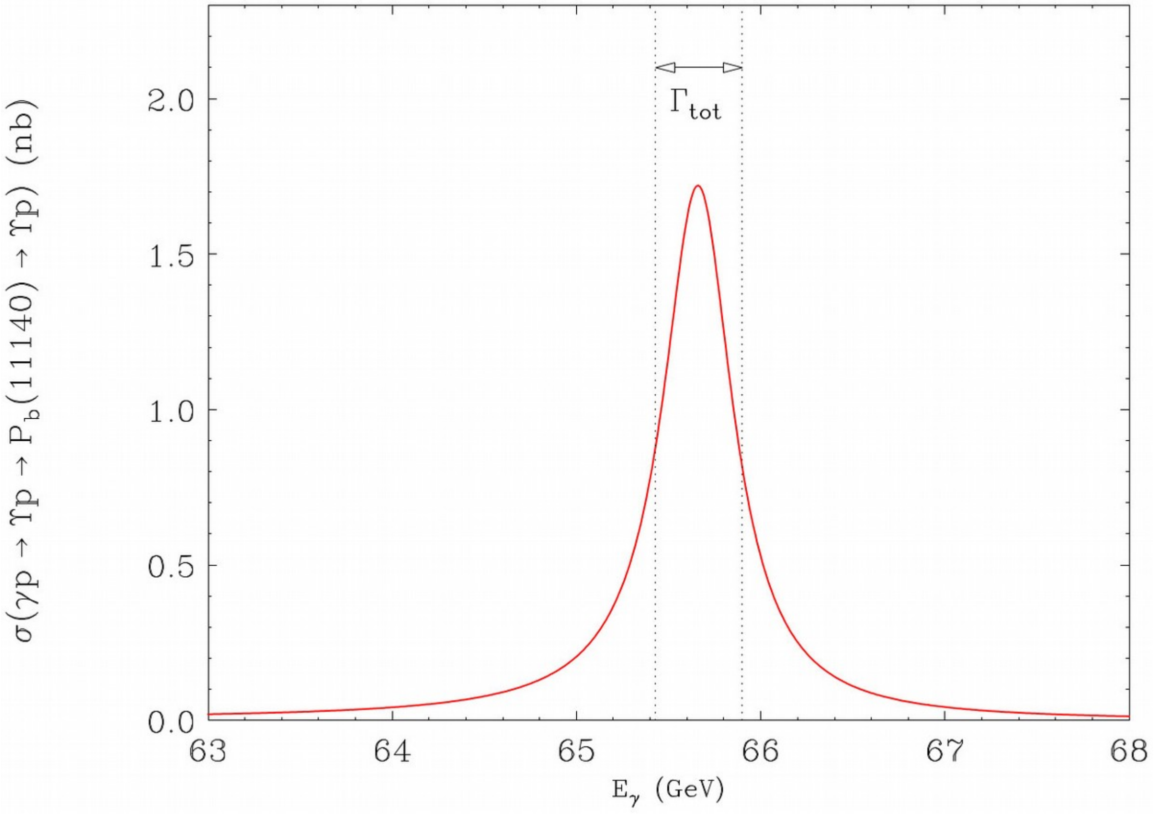
MK and J.L. Rosner,
arXiv:1705.07691 [hep-ph].

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



$X(3872) \to J/\psi\,\pi^+\pi^-$ 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 <u>continuum</u> production

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

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

MK and J. L. Rosner,
Phys. Rev. D **91**, no. 1, 014014 (2015)

bottom analogue of $X(3872)$:

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

$\Rightarrow$ measure $R_{\Upsilon\gamma} \equiv \dfrac{\mathcal{B}(\chi_{b1}(3P) \to \Upsilon(2S)\gamma)}{\mathcal{B}(\chi_{b1}(3P) \to \Upsilon(1S)\gamma)}$

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

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

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

Exotic resonances due to η exchange

- 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 $\to J/\psi\,\phi$

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

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

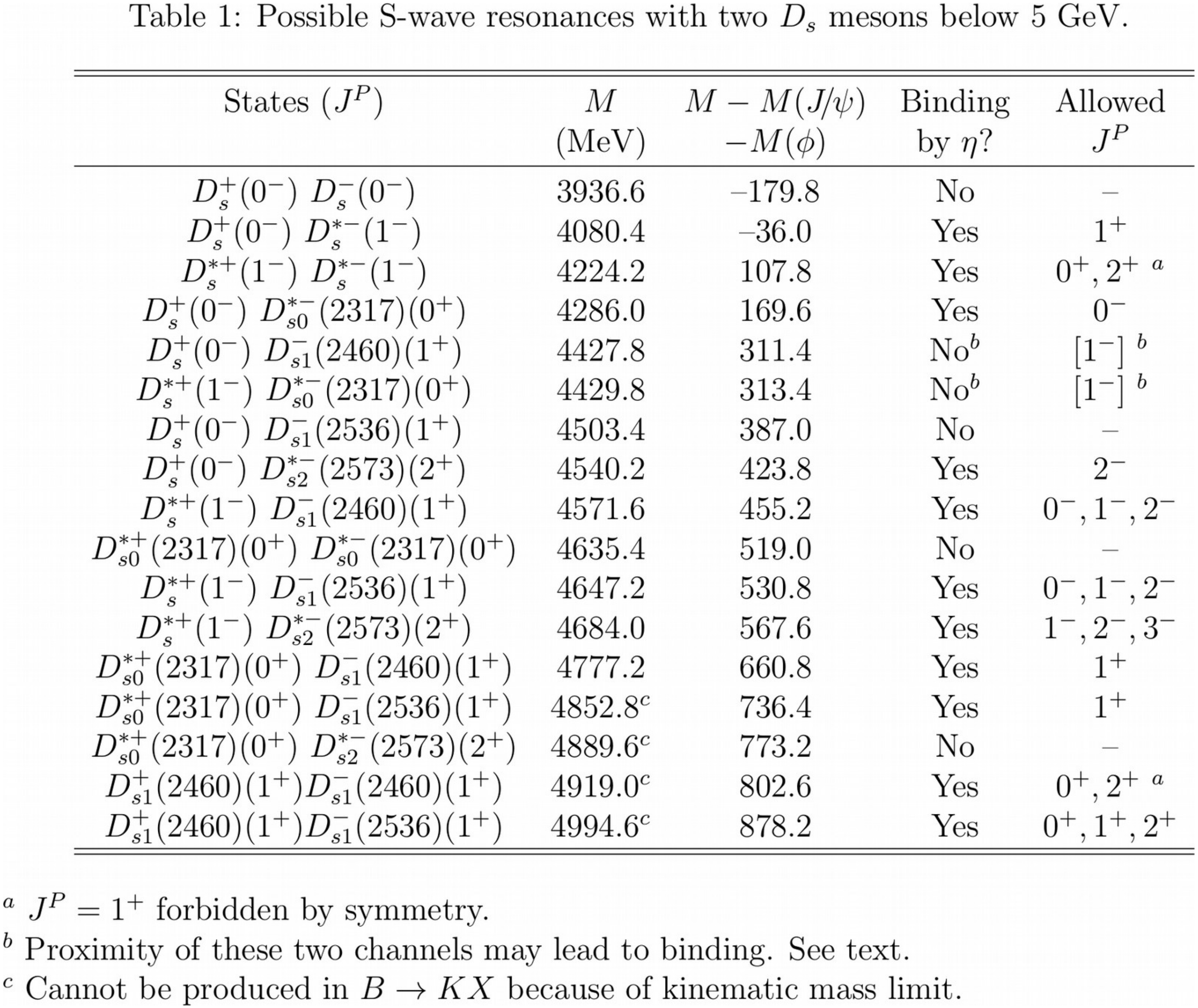


Table 1: Possible S-wave resonances with two D_s mesons below 5 GeV.

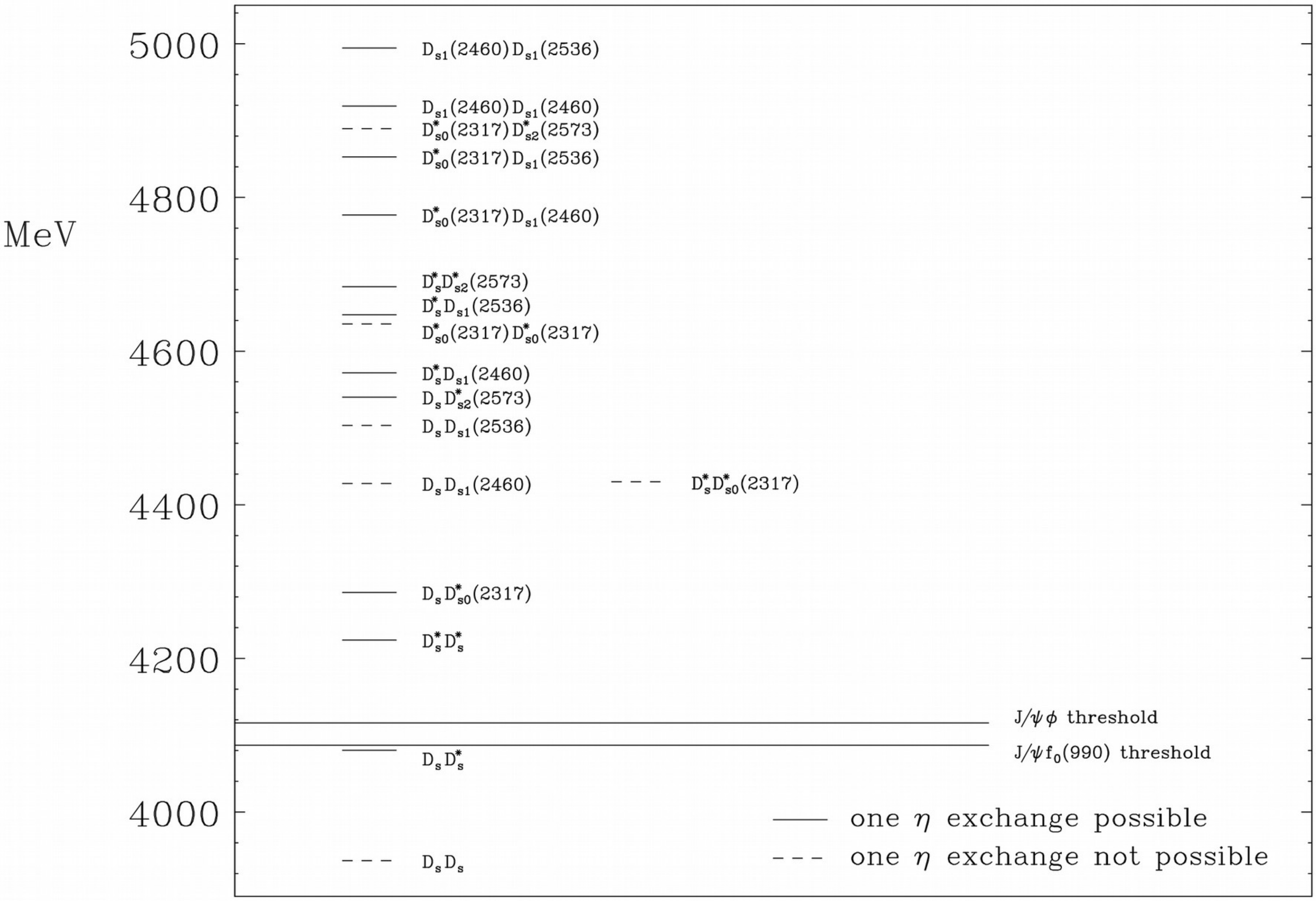
States (J^P)	M (MeV)	$M - M(J/\psi)$ $-M(\phi)$	Binding by η?	Allowed J^P
$D_s^+(0^-)\ D_s^-(0^-)$	3936.6	–179.8	No	–
$D_s^+(0^-)\ D_s^{*-}(1^-)$	4080.4	–36.0	Yes	1^+
$D_s^{*+}(1^-)\ D_s^{*-}(1^-)$	4224.2	107.8	Yes	$0^+, 2^+$ [a]
$D_s^+(0^-)\ D_{s0}^{*-}(2317)(0^+)$	4286.0	169.6	Yes	0^-
$D_s^+(0^-)\ D_{s1}^-(2460)(1^+)$	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



MK and J.L. Rosner,
Phys. Rev. D **90**, no. 9, 094007 (2014)

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

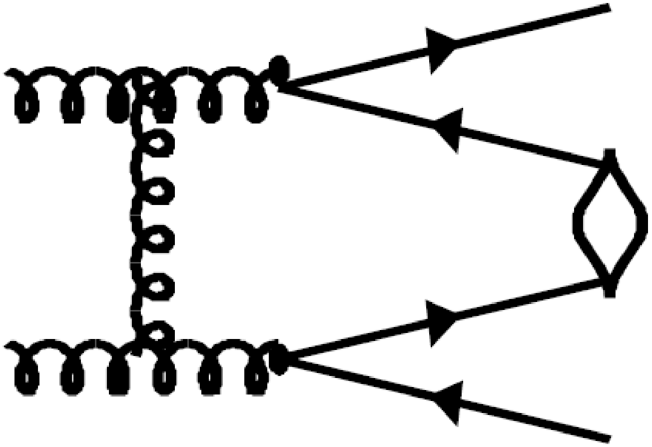
so QQq baryon $\sim \bar{Q}q$ meson

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

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

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 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
$\Xi_{bc}^{\prime}$	$b(cq)$	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	–	–

Predicted isospin splittings (MeV) in QQq baryons.

$M(ccu) - M(ccd)$	$M(bbu) - M(bbd)$	$M(bcu) - M(bcd)$
$1.41 \pm 0.12^{+0.76}$	$-4.78 \pm 0.06^{+0.03}$	$-1.69 \pm 0.07^{+0.39}$

arXiv:1706.06961

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

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

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

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

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

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

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

$$\tau(\Xi_c^{+}) = (4.42 \pm 0.26) \times 10^{\ 13}\ \mathrm{s}$$
$$\tau(\Xi_c^{0}) = (1.12^{+0.13)}_{\ 0.10}) \times 10^{\ 13}\ \mathrm{s}$$

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}

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

rare but spectacular decay mode:

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

rough estimate of Ξ_{cc} production rate

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

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

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

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

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

or

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

and

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

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

production rates are comparable:

compare analogous prod. rates of Ξ_c and D_s

(or Ξ_b and B_s) in the same setup,

and large enough E_{CM}

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

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

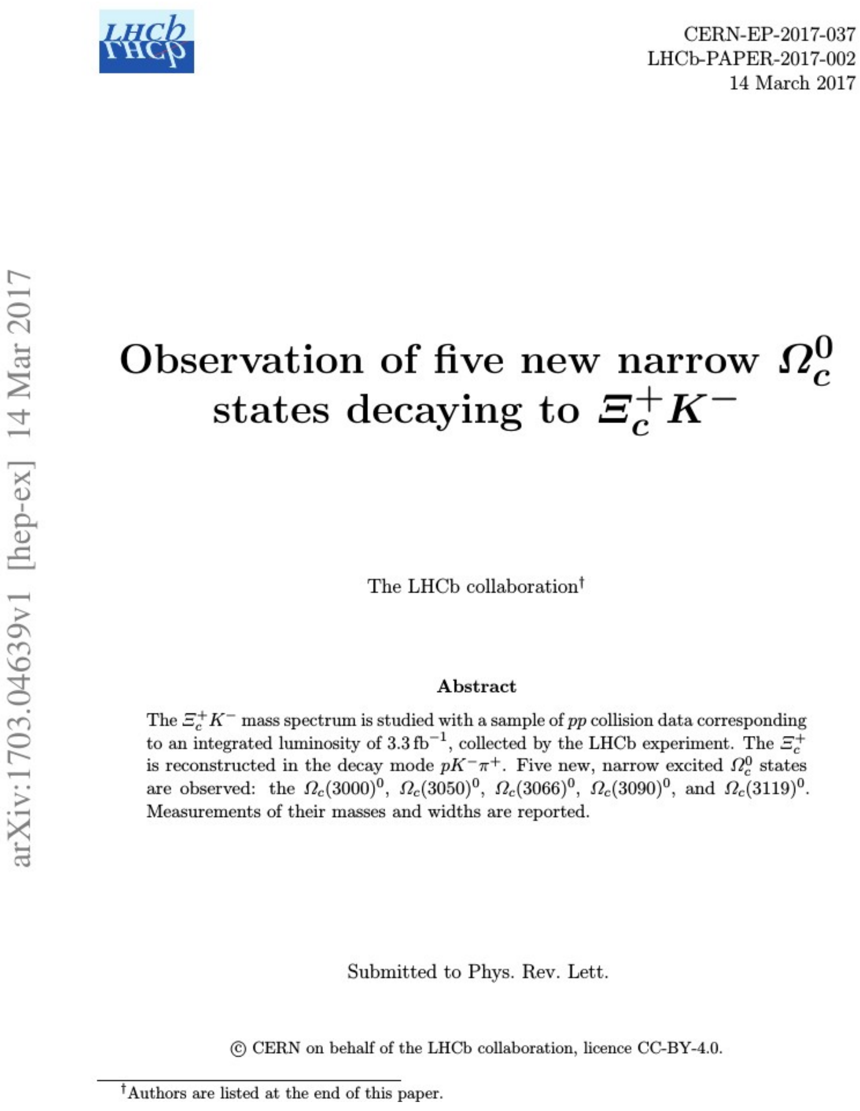
production of an extra $Q\bar{Q}$: probabillity $\sim 0.1\%$

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 $J^{PC} = 0^{++}$

$\Xi_c^+ = csu, \quad K^- = s\bar{u}$

$\Rightarrow css$: excited Ω_c



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

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

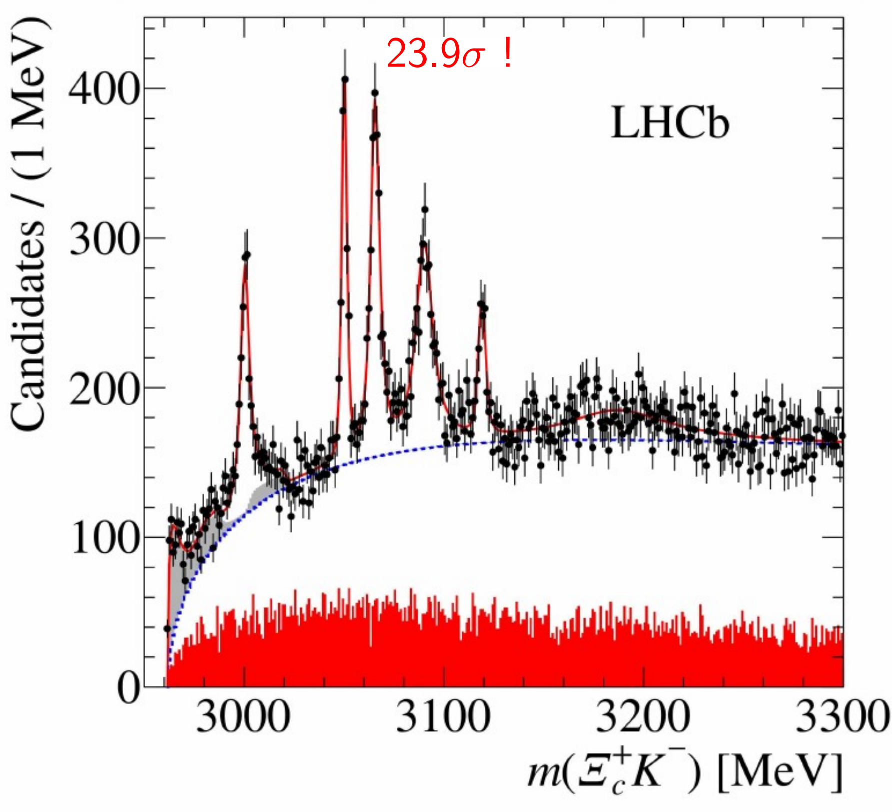
The LHCb collaboration[†]

Abstract

The $\Xi_c^+ K^-$ mass spectrum is studied with a sample of pp collision data corresponding to an integrated luminosity of $3.3\,\mathrm{fb}^{-1}$, 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.

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



23.9σ !

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.

MK and J.L. Rosner,
arXiv:1703.07774 [hep-ph], PRD, in print

- 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

some immediate questions:

(a) Why five states? Are there more ?

(b) Why are they so narrow?

(c) What are their spin-parity assignments?

(d) Can one understand the mass pattern?

(e) Other similar states ?
e.g. 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 $S = \frac{3}{2}$ $\Rightarrow$ $J = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}$

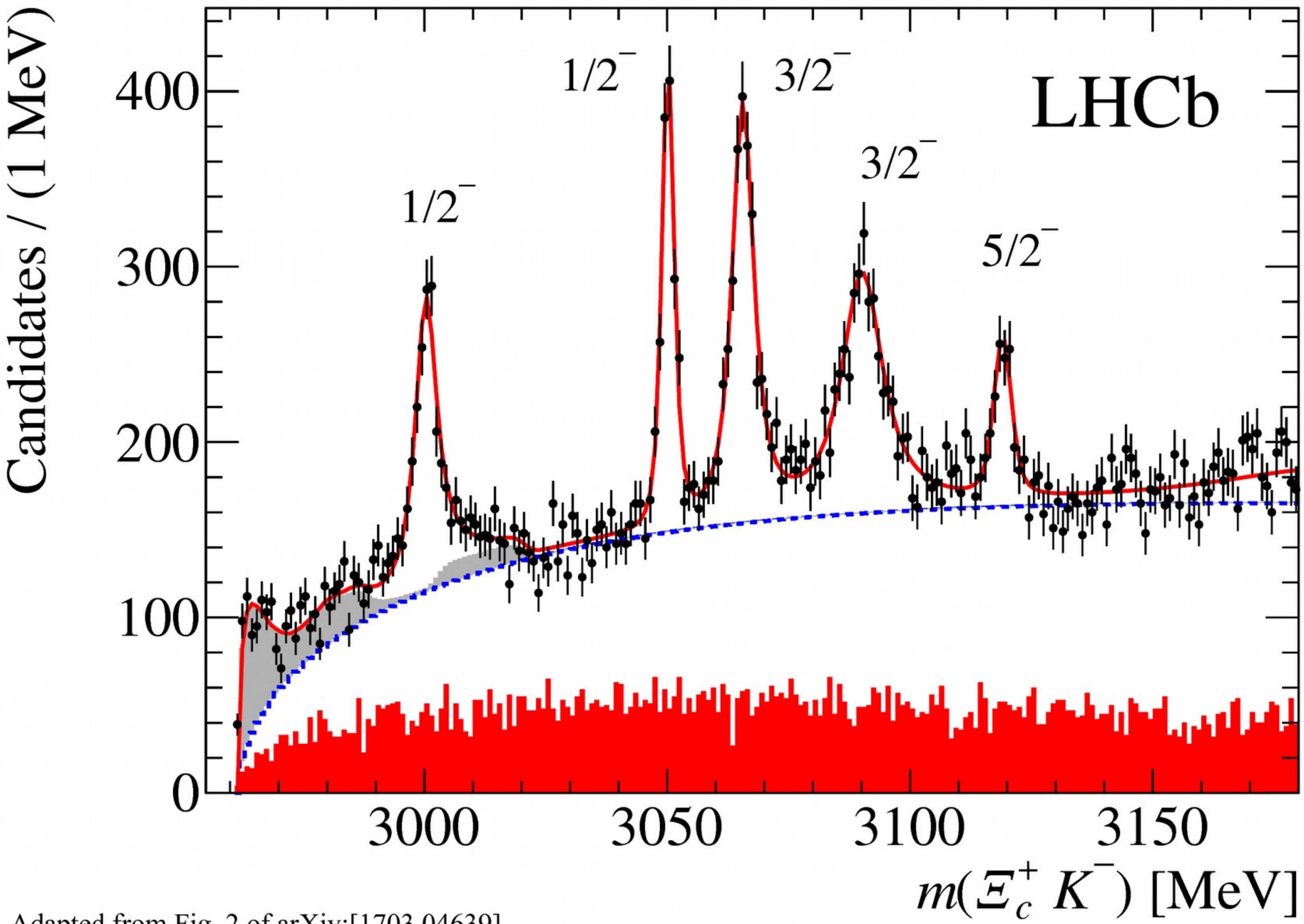
all with negative parity

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

$J^P = 1/2^-$ decay to $\Xi_c^+ K^-$ in S-wave,

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

D-wave might be narrower
- partially confirmed by preferred J^P
- consistent w. alternate assignment



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

[a] Additional common error of +0.3,–0.5 MeV from $M(\Xi_c^+)$ uncertainty.

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

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

$\mathbf{L}$ = 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

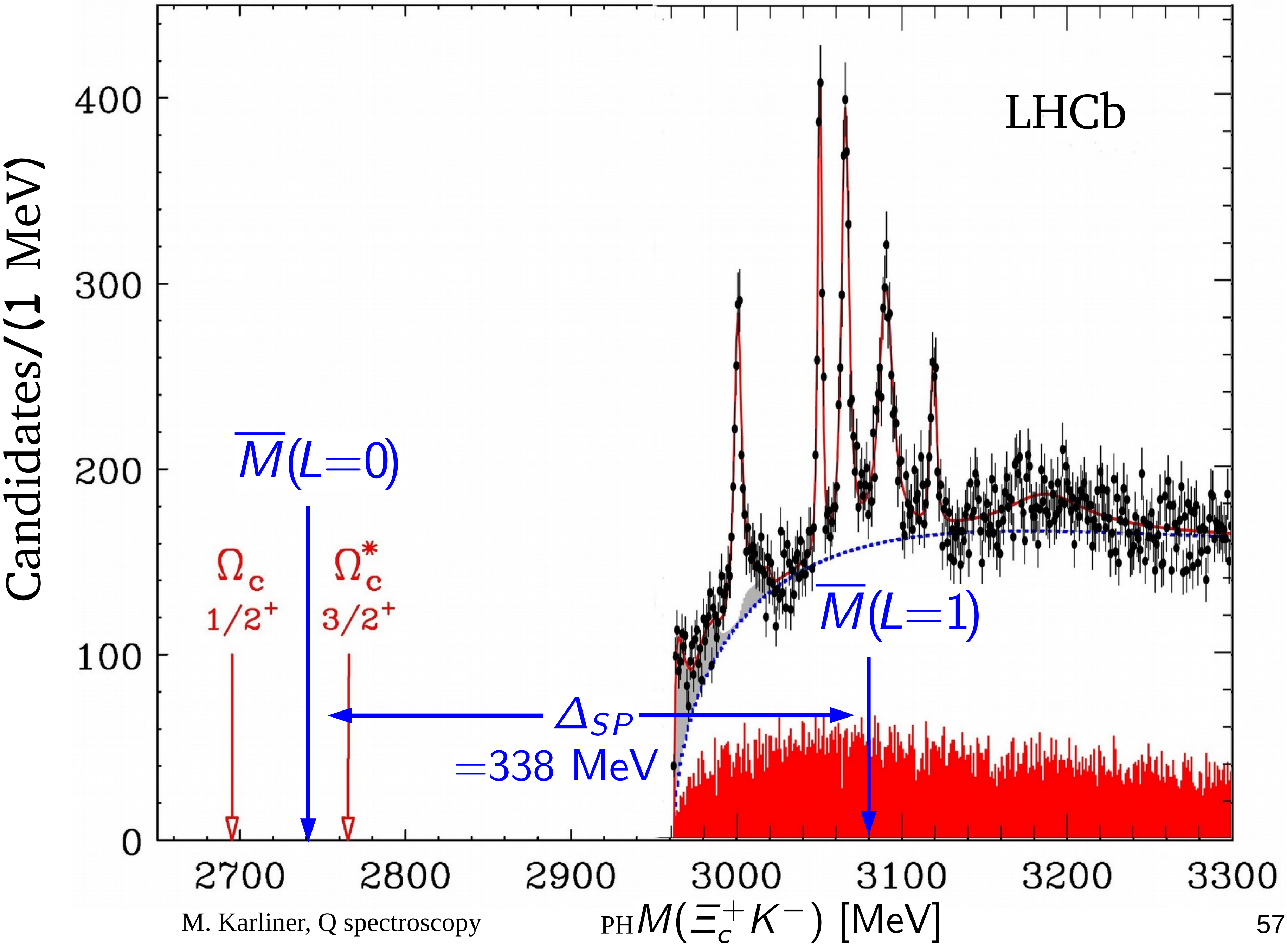
examine all $5! = 120$ *a priori* possible assignments of P-wave states

$\Rightarrow$ assignment in Table favored, with parameters

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

$\Rightarrow$ the spin-averaged mass:

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


LHCb
Candidates/(1 MeV)
400
300
200
100
0
2700
2800
2900
3000
3100
3200
3300
PH $M(\Xi_c^+ K^-)$ [MeV]
$\overline{M}(L{=}0)$
$\overline{M}(L{=}1)$
Ω_c
$1/2^+$
Ω_c^*
$3/2^+$
Δ_{SP}
$=338$ MeV

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

$\dfrac{m_c}{m_b} \sim \dfrac{1}{3} \Rightarrow$ 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.
- $-20 \text{ MeV} < b < 20 \text{ MeV}$.
- 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:

$$
\begin{aligned}
\Delta M(1/2,0) &= -53.9\ , \\
\Delta M(1/2,1) &= -31.3 - \ b\ , \\
\Delta M(3/2,1) &= -24.8 + \tfrac{1}{2} b\ , \\
\Delta M(3/2,2) &= \ \ 20.4 + \tfrac{3}{10} b\ , \\
\Delta M(5/2,2) &= \ \ 31.3 - \tfrac{1}{5} b\ .
\end{aligned}
$$

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

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

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

$$
\begin{aligned}
\Delta M(1/2,0) &= -53.9 \,, \\
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\Delta M(3/2,2) &= \ \ 20.4 + \tfrac{3}{10} b \,, \\
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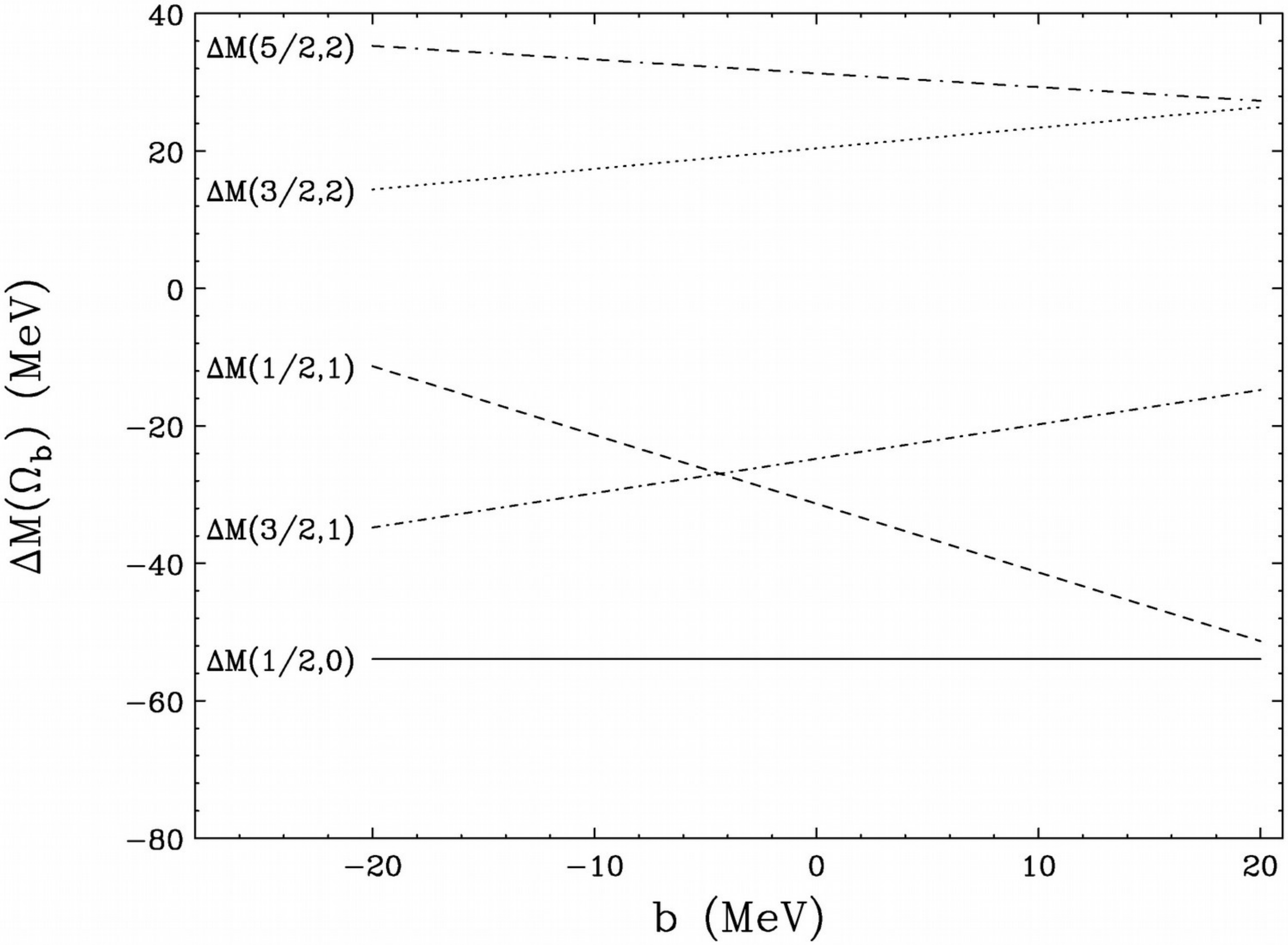
\end{aligned}
$$

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

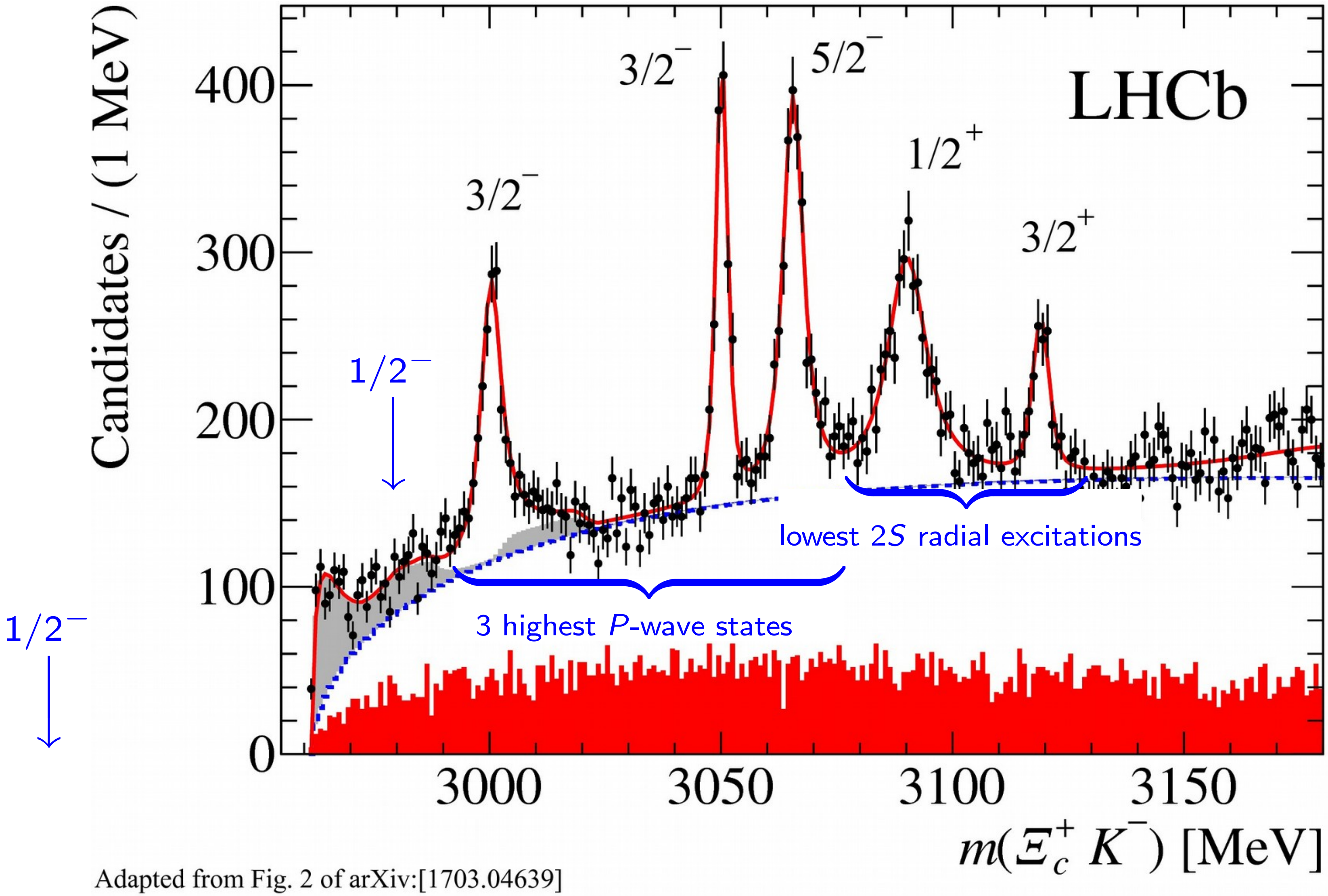
caveat: $\Xi_b^0 K^-$ threshold at 6286 MeV
so lowest states might be below threshold



← only $\Delta M(3/2,1)$ intermediate vs. $\Delta M(1/2,0)$ and $\Delta M(1/2,1)$

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



Adapted from Fig. 2 of arXiv:[1703.04639]

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 $\to \Xi_c^+ K^-$ in S-wave
  and $1/2^-$ near 2904 MeV $\to \Omega_c$ and/or Ω_c/π^0
- predictions for excited Ω_b-s in $b(ss)$ system

MK, M. Low, J.L. Rosner and L.T. Wang,
Phys. Rev. D **92**, 035010 (2015)

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:

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

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

decay: mainly $D^*_{s0}(2317) \to D_s^+ \pi^0$
through v. small isospin-violating η–π^0 mixing

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

narrow B_{sJ} states

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

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

both below relevant thresholds:

$m(B) + m(K) = 5777$ MeV

$m(B^*) + m(K) = 5822$ MeV

$\Rightarrow$ expect v. narrow widths

dominant decay modes:

$B^*_{s0} \to B_s \pi^0,\ B^*_s \gamma$

$B_{s1} \to B^*_s \pi^0,\ B^{(*)}_s \gamma$

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:

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

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

$\Rightarrow$ expect v. narrow widths

dominant decay modes:

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

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

challenging @LHCb: soft π^0 and γ, so large combinatorial background

- Belle II ?

$e^+e^- \to B_{s0}^* B_s^*$

$@11,127 \pm 10\text{ MeV}$

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 $P_c(4450)$ $\Longrightarrow$ 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±25 MeV and $bb\bar{b}\bar{b}$ @ 18,826±25 MeV $\Rightarrow 4\ell$

- new excited Ω_c states: spin dep. splittings $\Rightarrow$ J^P prediction, Ω_b analogues
- v. narrow $B_{s0}^* \to B_s\pi^0$, $B_s\gamma$ and $B_{s1} \to B_s^*\pi^0$, $B_s^{(*)}\gamma$

exciting new spectroscopy awaiting discovery