Tel Aviv University

The Social Life of Heavy Quarks

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IHEP, Nov 13, 2017

Outline

- hadronic molecules, esp. LHCb pentaquark

Implications of Ξ_{cc}^{++} discovery

- stable $bb\bar{u}\bar{d}$ tetraquark,
  215 MeV below $B^-\bar{B}^{0*}$ threshold
- why $QQ\bar{q}\bar{q}$=tetraquarks and $Q\bar{Q}q\bar{q}$=molecules
- quark-level analogue of nuclear fusion,
  $\Lambda_c\Lambda_c \to \Xi_{cc}N, \quad Q = 12$ MeV
  $\Lambda_b\Lambda_b \to \Xi_{bb}N, \quad Q = 138 \pm 12$ MeV
- v. narrow B_{sJ}-s, excited Ω_c quintet (*if time permits*)

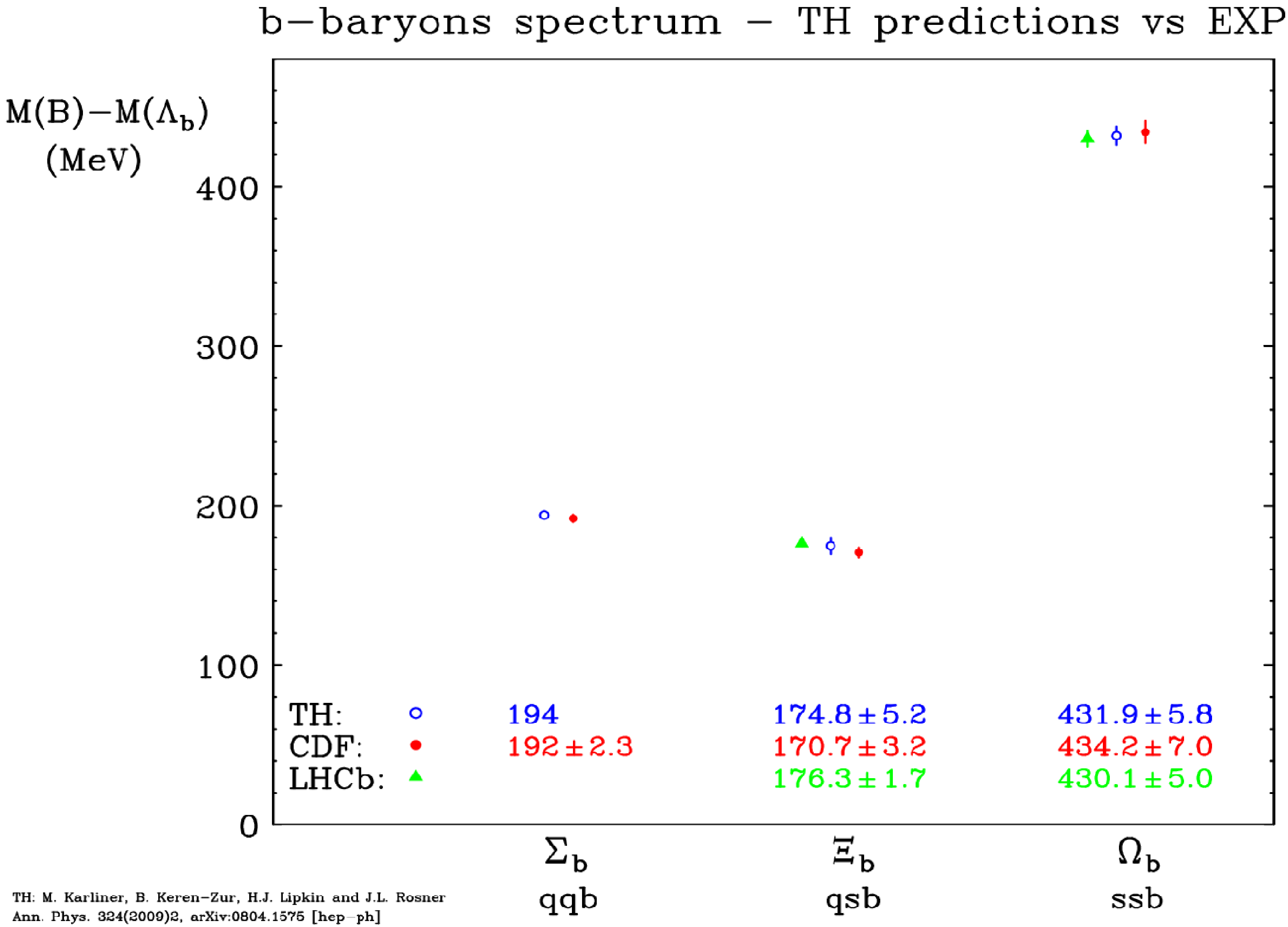
hadrons w. heavy quarks are *much simpler:*

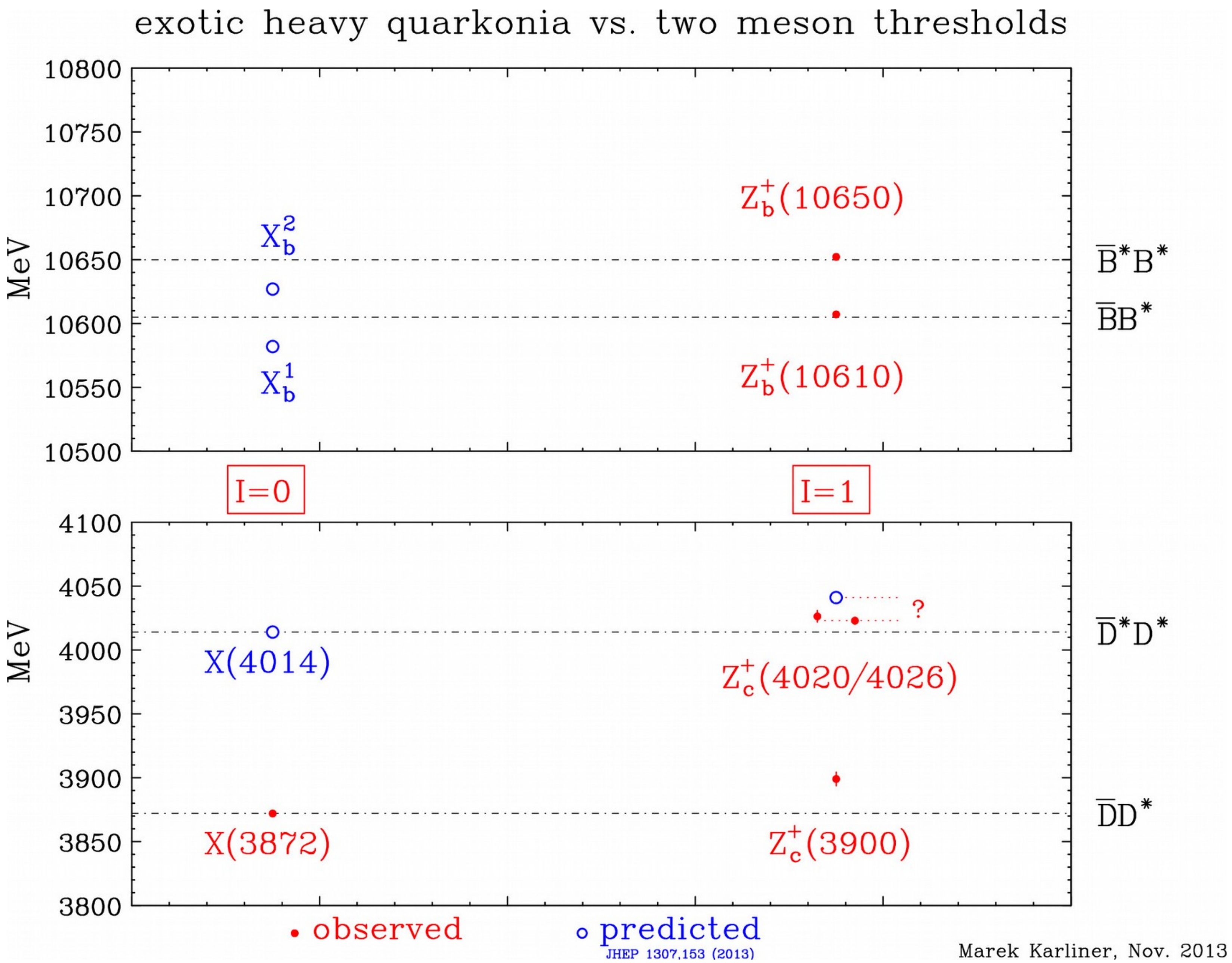
- heavy quarks almost static
- smaller spin-dep. interaction $\propto 1/m_Q$
- key to accurate prediction of b quark baryons

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
$\times$					$\bar{D}D$	
$\times$					$\bar{B}B$	

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


b−baryons spectrum − TH predictions vs EXP
M(B)−M(Λb) (MeV)
400
300
200
100
0
TH: 194 174.8±5.2 431.9±5.8
CDF: 192±2.3 170.7±3.2 434.2±7.0
LHCb: 176.3±1.7 430.1±5.0
Σb qqb
Ξb qsb
Ωb ssb
TH: M. Karliner, B. Keren−Zur, H.J. Lipkin and J.L. Rosner
Ann. Phys. 324(2009)2, arXiv:0804.1575 [hep−ph]


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
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 $\bar{q}q$, $q = u,d$

$\Longrightarrow$ <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

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

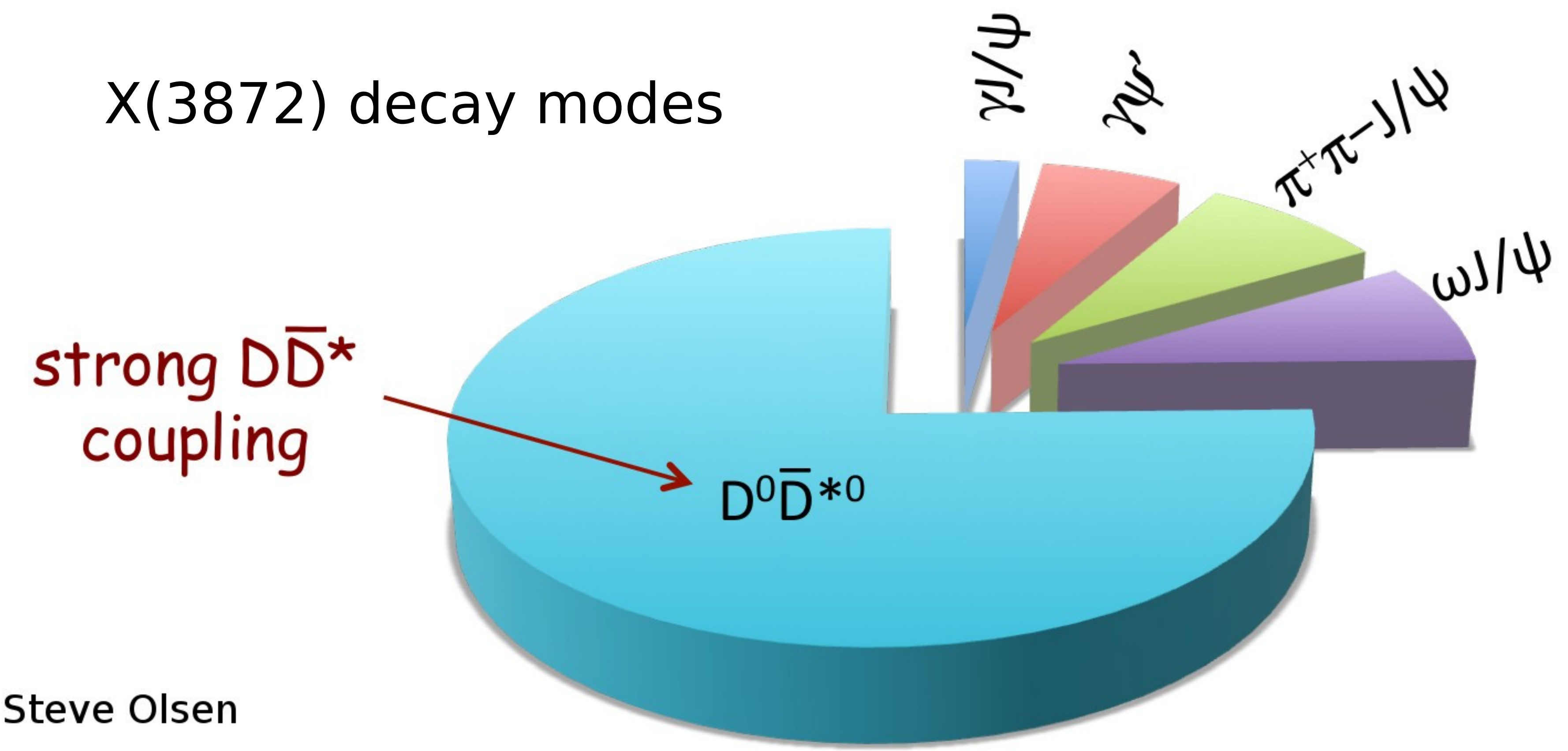
also

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

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

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

$\mathrm{BR}(\bar{D}D^*) \gg \mathrm{BR}(\,J/\psi + X)$



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

crucial test: $X(J^P = 0^{++}) \stackrel{?}{\rightarrow} J/\psi\gamma$ 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^*, $\bar{B}B^*$, $\bar{B}^*B^*$,

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

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

New Exotic Meson and Baryon Resonances from Doubly Heavy Hadronic Molecules

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(Received 13 July 2015; published 14 September 2015)

We predict several new exotic doubly heavy hadronic resonances, inferring from the observed exotic bottomoniumlike and charmoniumlike narrow states $X(3872)$, $Z_b(10610)$, $Z_b(10650)$, $Z_c(3900)$, and $Z_c(4020/4025)$. We interpret the binding mechanism as mostly molecularlike isospin-exchange attraction between two heavy-light mesons in a relative S-wave state. We then generalize it to other systems containing two heavy hadrons which can couple through isospin exchange. The new predicted states include resonances in meson-meson, meson-baryon, baryon-baryon, and baryon-antibaryon channels. These include those giving rise to final states involving a heavy quark $Q = c, b$ and antiquark $\bar{Q}' = \bar{c}, \bar{b}$, namely, $D\bar{D}^*$, $D^*\bar{D}^*$, D^*B^*, $\bar{B}B^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$, Σ_cB^*, $\Sigma_b\bar{D}^*$, Σ_bB^*, $\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, and $\Sigma_b\bar{\Lambda}_c$, as well as corresponding S-wave states giving rise to QQ' or $\bar{Q}\bar{Q}'$.

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

Selected for a Viewpoint in *Physics*

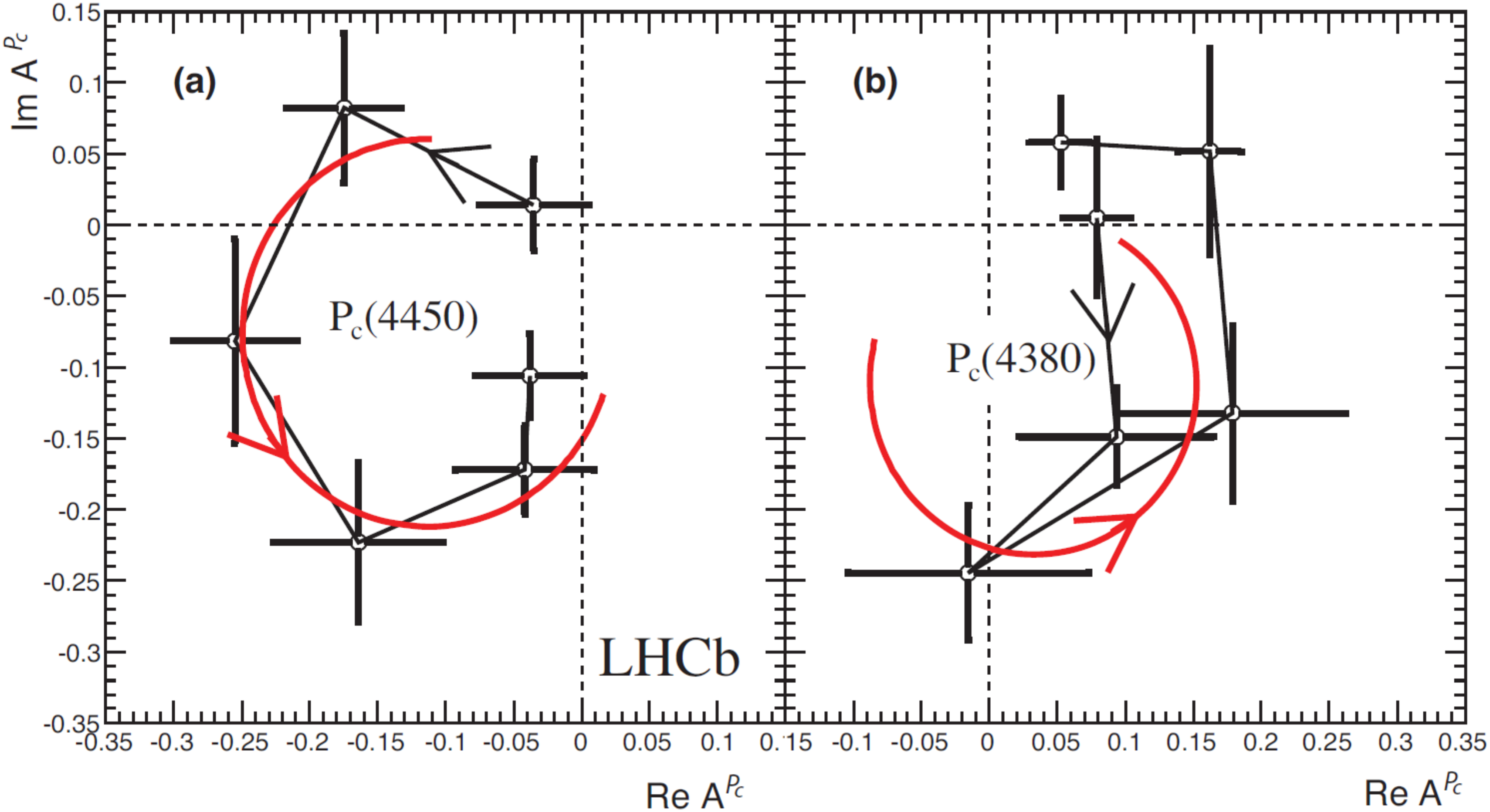
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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

R. Aaij *et al.*[*]
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)

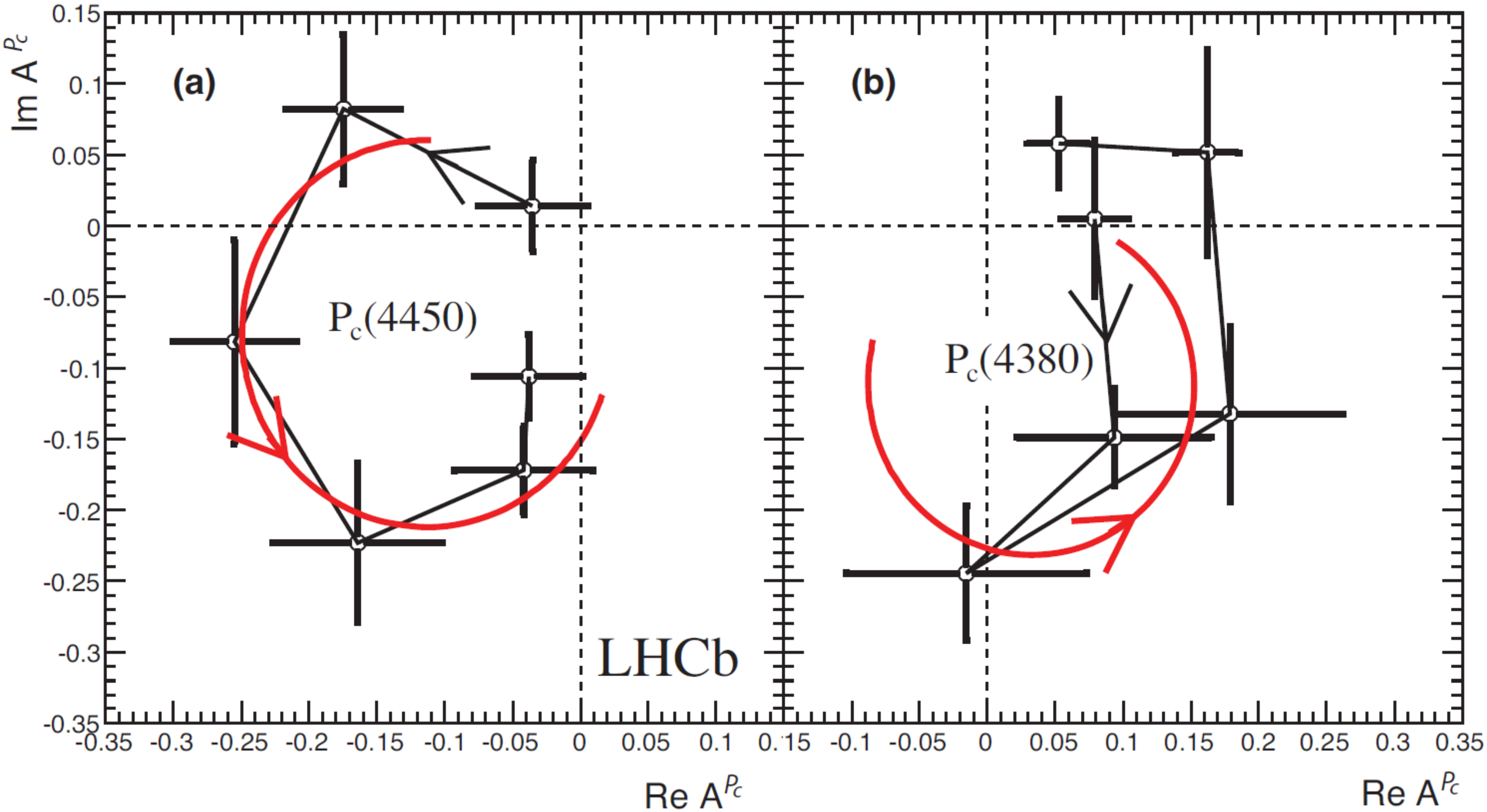
Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions. An amplitude analysis of the three-body final state reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

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



$P_c(4450)$: 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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wide: $\Gamma = 205 \pm 18 \pm 86$ MeV,
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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

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

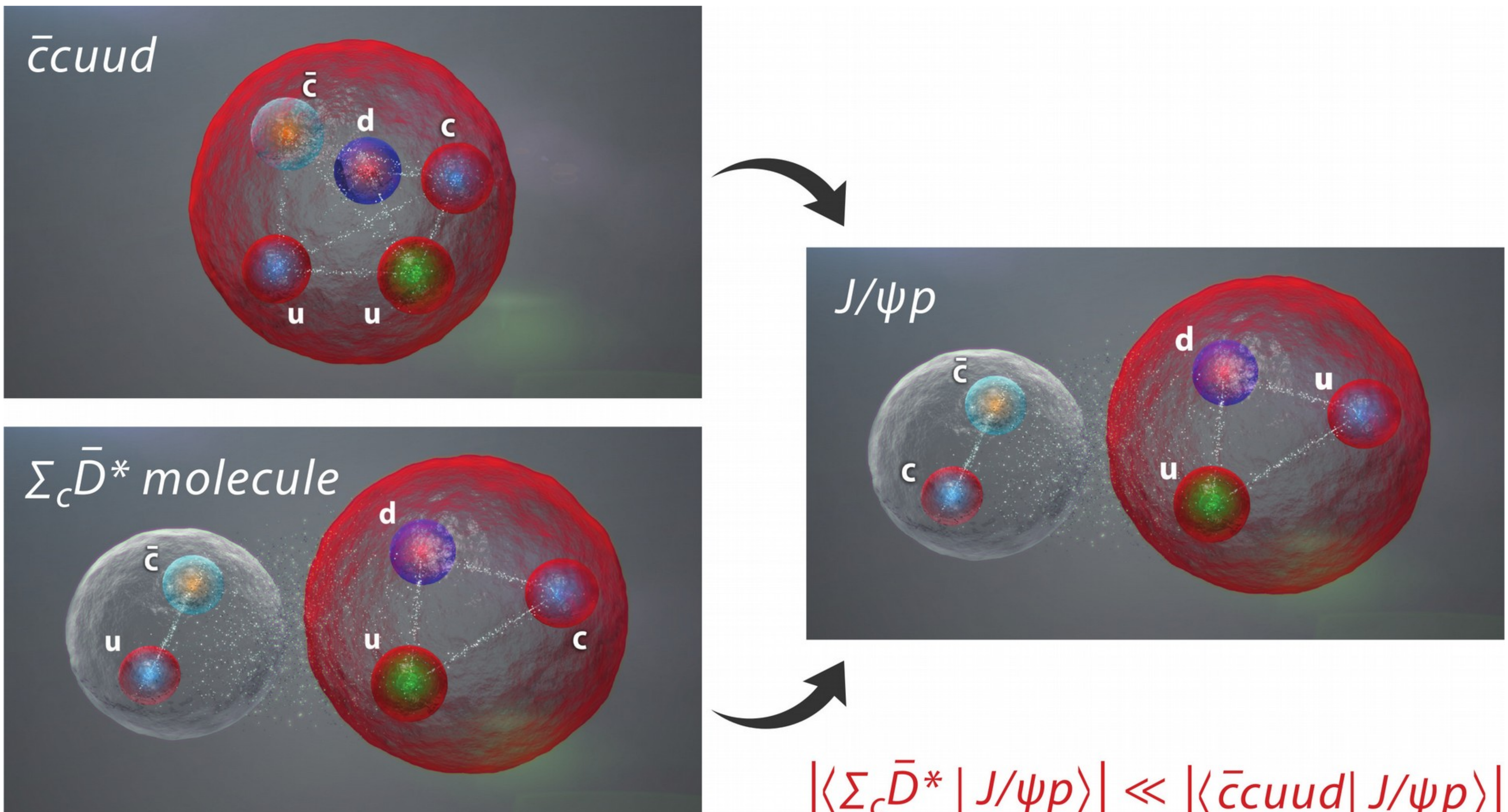
To get $\Gamma = 39$ MeV, the matrix element must be small .

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

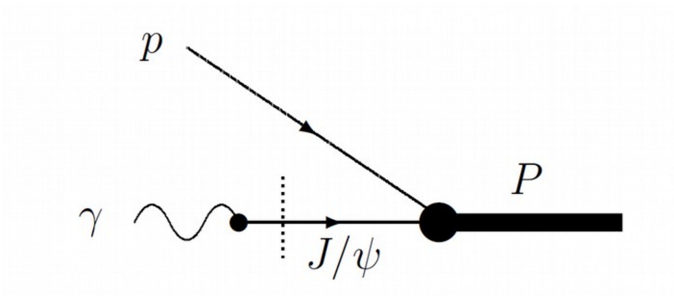
Photoproduction of exotic baryon resonances

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

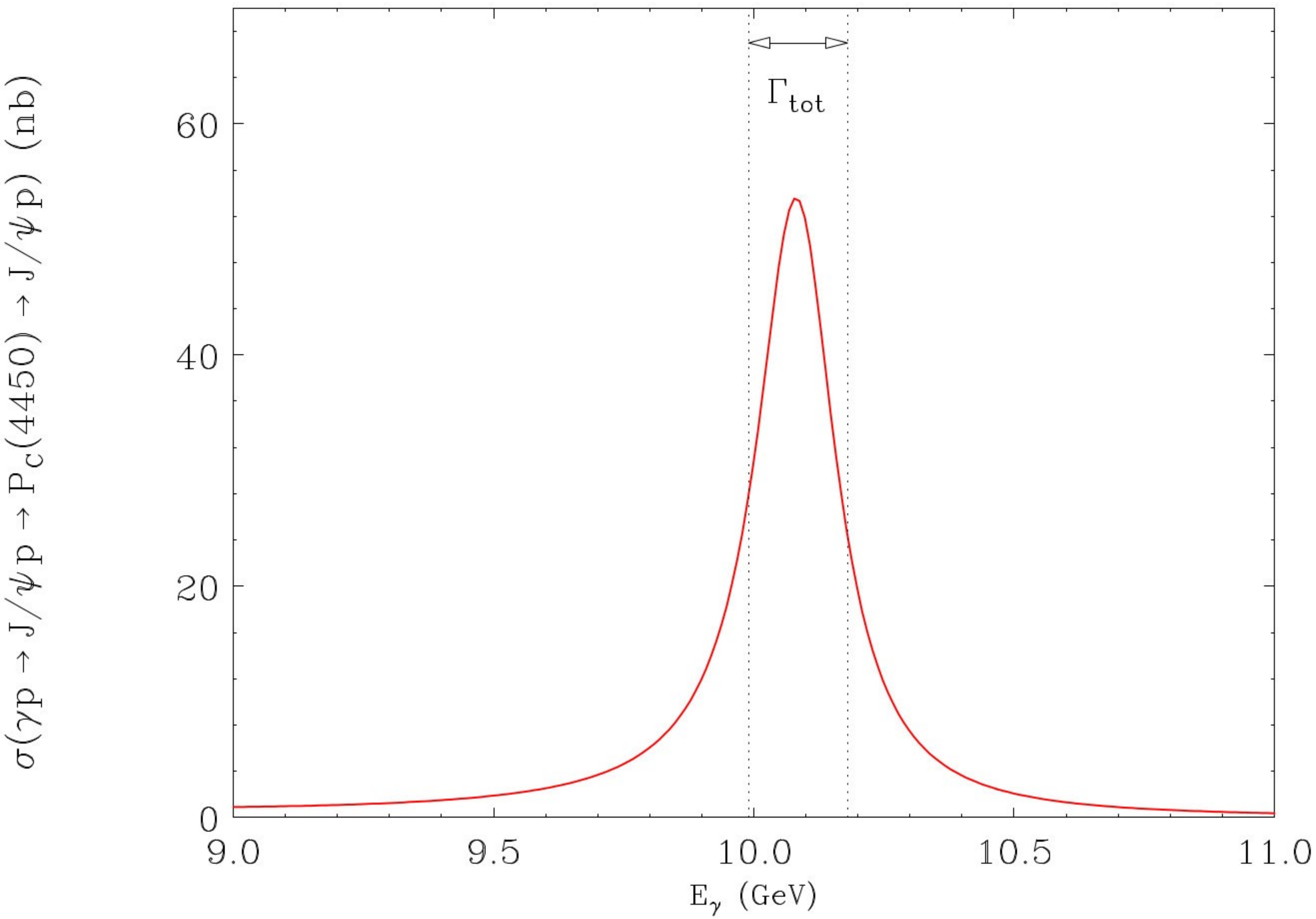
LHCb: new exotic resonances in $J/\psi\, p$ channel:

$\Longrightarrow$ 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



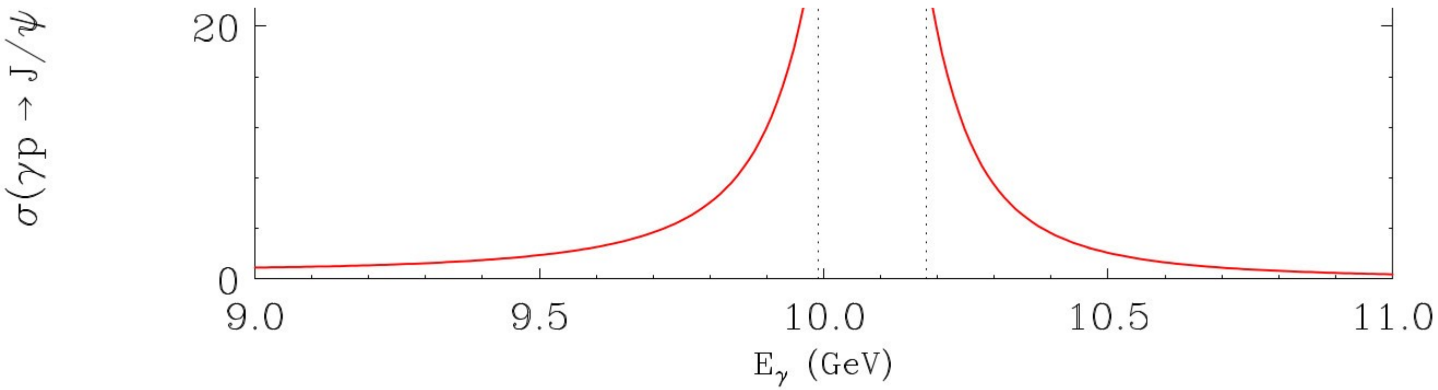
Cross section for resonant photoproduction $\gamma p \to J/\psi\, p \to P_c(4450) \to J/\psi\, p$, assuming $B_{\rm out} = 0.1$, plotted as function of the incident photon energy E_γ.
The vertical dotted lines indicate the width of the $P_c(4450)$ resonance.

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].

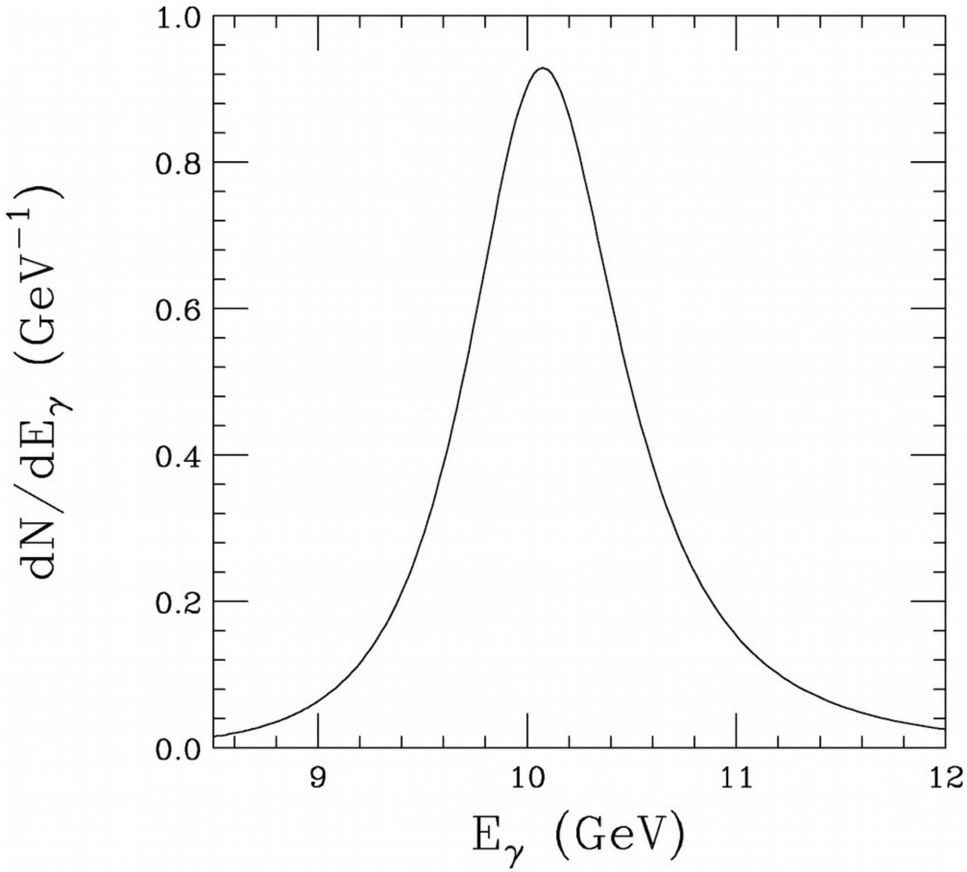
$P_c(4380)$ and $P_c^+(4450) \to J/\psi p \quad \Rightarrow I_3 = +\frac{1}{2}$

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



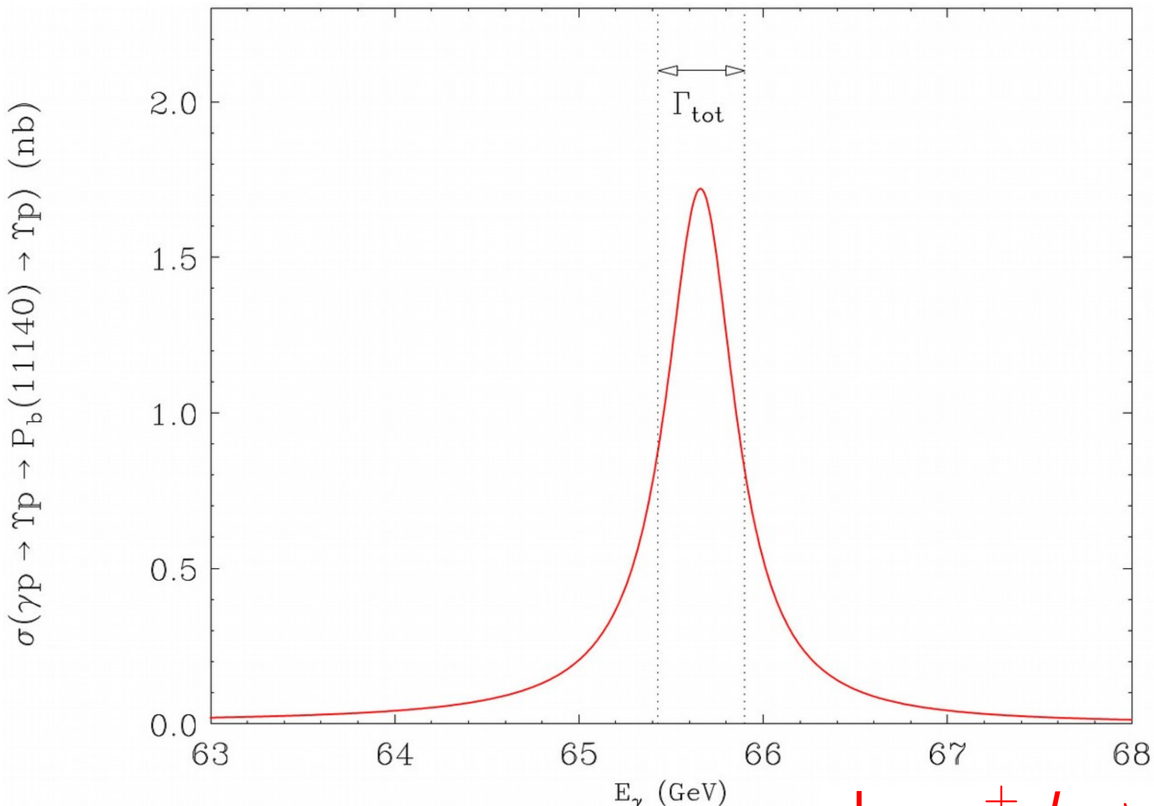
MK and J.L. Rosner, arXiv:1705.07691 [hep-ph].

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



also $\pi^+ d \to P_b(11140)p$

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

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

X(3872) likely produced via its $\chi_{c1}(2P)$ component

LHC not expected to see prompt production

$pp \to P_c(4450) + X$

crucial test of molecular picture

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

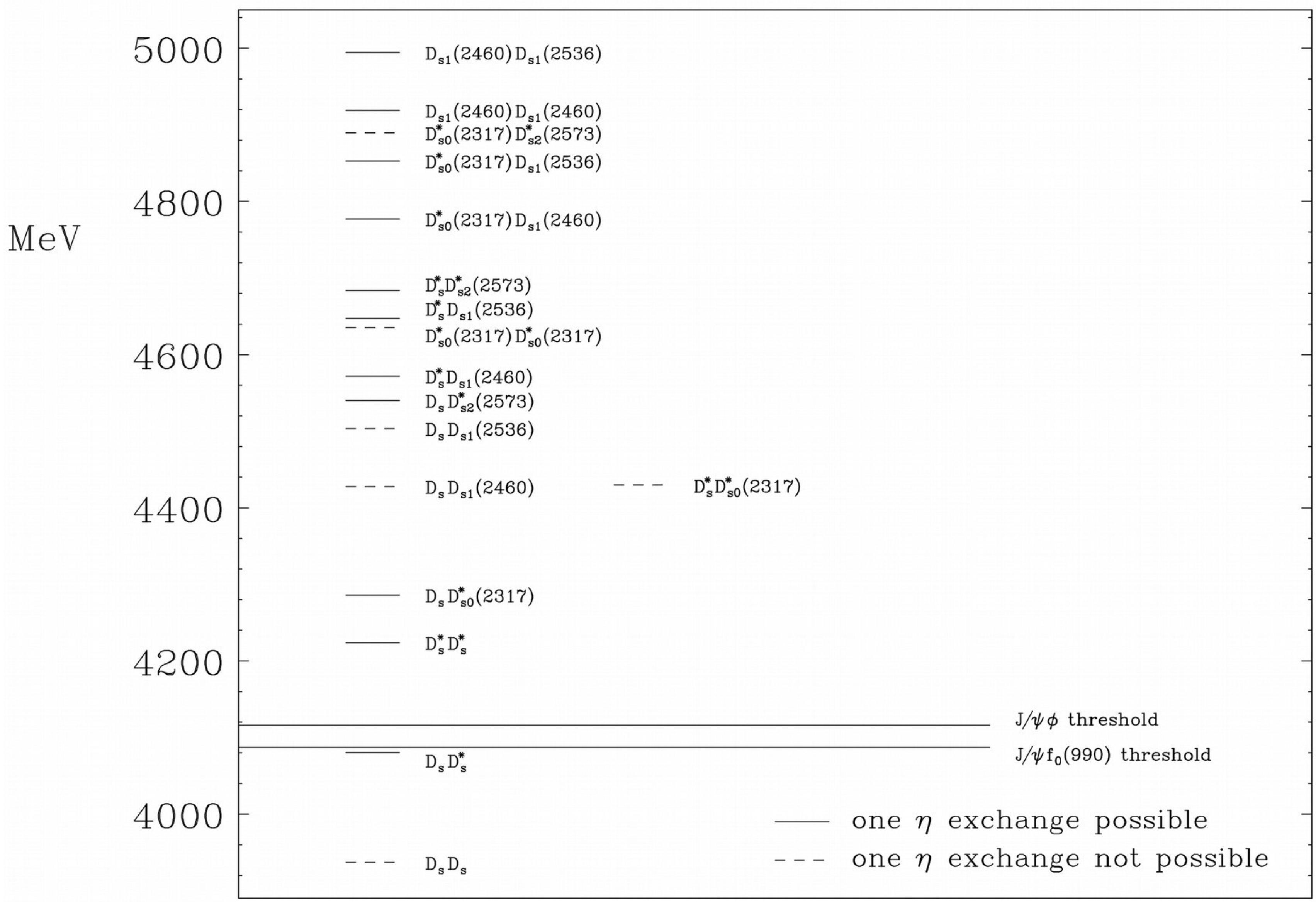
MK and J. Rosner, Nucl. Phys. A **954**, 365 (2016)

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, and now have been seen

fascinating challenge for EXP & TH

LHCb sees thousands of B_c-s
$\Longrightarrow$ should see bcq, ccq, etc.

masses of doubly-heavy baryons:

use same toolbox that predicted

b baryon masses.

PHYSICAL REVIEW D **90,** 094007 (2014)

Baryons with two heavy quarks: Masses, production, decays, and detection

Marek Karliner[*]

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(Received 5 September 2014; published 10 November 2014)

The large number of B_c mesons observed by LHCb suggests a sizable cross section for producing doubly heavy baryons in the same experiment. Motivated by this, we estimate masses of the doubly heavy $J = 1/2$ baryons Ξ_{cc}, Ξ_{bb}, and Ξ_{bc}, and their $J = 3/2$ hyperfine partners, using a method which accurately predicts the masses of ground-state baryons with a single heavy quark. We obtain $M(\Xi_{cc}) = 3627 \pm 12$ MeV, $M(\Xi^*_{cc}) = 3690 \pm 12$ MeV, $M(\Xi_{bb}) = 10162 \pm 12$ MeV, $M(\Xi^*_{bb}) = 10184 \pm 12$ MeV, $M(\Xi_{bc}) = 6914 \pm 13$ MeV, $M(\Xi'_{bc}) = 6933 \pm 12$ MeV, and $M(\Xi^*_{bc}) = 6969 \pm 14$ MeV. As a byproduct, we estimate the hyperfine splitting between B^*_c and B_c mesons to be 68 ± 8 MeV. We discuss P-wave excitations, production mechanisms, decay modes, lifetimes, and prospects for detection of the doubly heavy baryons.

DOI: 10.1103/PhysRevD.90.094007 PACS numbers: 14.20.Lq, 14.20.Mr, 12.40.Yx

doubly heavy baryons: mass predictions

TABLE XVIII. Summary of 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	$\cdots$
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

LHCb: 3621 ± 1

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

preliminary estimate:

H_{QQ} $(QQuudd)$ hexaquarks

below $2\Lambda_Q$

but above $\Xi_{QQ} N$

$\Rightarrow$ unstable

an ugly duckling...

the swan to be presented soon

The same theoretical toolbox

that led to the accurate Ξ_{cc} mass prediction

now predicts

a stable, deeply bound $bb\bar{u}\bar{d}$ tetraquark,

215 MeV below BB^* threshold

The same theoretical toolbox

that led to the accurate Ξ_{cc} mass prediction

now predicts

a stable, deeply bound $bb\bar{u}\bar{d}$ tetraquark,

215 MeV below BB^* threshold

the first manifestly exotic stable hadron

PHYSICAL REVIEW LETTERS

Discovery of the Doubly Charmed Ξ_{cc} Baryon Implies a Stable $bb\bar{u}\bar{d}$ Tetraquark

Marek Karliner[1,*] and Jonathan L. Rosner[2,†]
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[2]*Enrico Fermi Institute and Department of Physics, University of Chicago, 5620 South Ellis Avenue, Chicago, Illinois 60637, USA*
(Received 28 July 2017)

Recently, the LHCb Collaboration discovered the first doubly charmed baryon $\Xi_{cc}^{++} = ccu$ at 3621.40 ± 0.78 MeV, very close to our theoretical prediction. We use the same methods to predict a doubly bottom tetraquark $T(bb\bar{u}\bar{d})$ with $J^P = 1^+$ at $10\,389 \pm 12$ MeV, 215 MeV below the $B^-\bar{B}^{*0}$ threshold and 170 MeV below the threshold for decay to $B^-\bar{B}^0\gamma$. The $T(bb\bar{u}\bar{d})$ is therefore stable under strong and electromagnetic interactions and can only decay weakly, the first exotic hadron with such a property. On the other hand, the mass of $T(cc\bar{u}\bar{d})$ with $J^P = 1^+$ is predicted to be 3882 ± 12 MeV, 7 MeV above the D^0D^{*+} threshold and 148 MeV above the $D^0D^+\gamma$ threshold. $T(bc\bar{u}\bar{d})$ with $J^P = 0^+$ is predicted at 7134 ± 13 MeV, 11 MeV below the $\bar{B}^0D^0$ threshold. Our precision is not sufficient to determine whether $bc\bar{u}\bar{d}$ is actually above or below the threshold. It could manifest itself as a narrow resonance just at threshold.

Calculation of tetraquark $bb\bar{u}\bar{d}$ mass

build on accuracy of the Ξ_{cc} mass prediction

$$V(bb) = \frac{1}{2} V(\bar{b}b)$$

to obtain lowest possible mass, assume:

- $bb\bar{u}\bar{d}$ in S-wave
- $\bar{u}\bar{d}$: $\mathbf{3_c}$ "good" antidiq., $S{=}0$, $I{=}0$

(it's the lightest one)

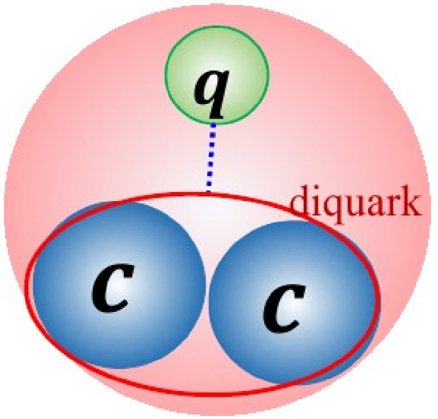
$\Rightarrow$ bb must be $\bar{3}_\mathbf{c}$; Fermi stats: spin 1

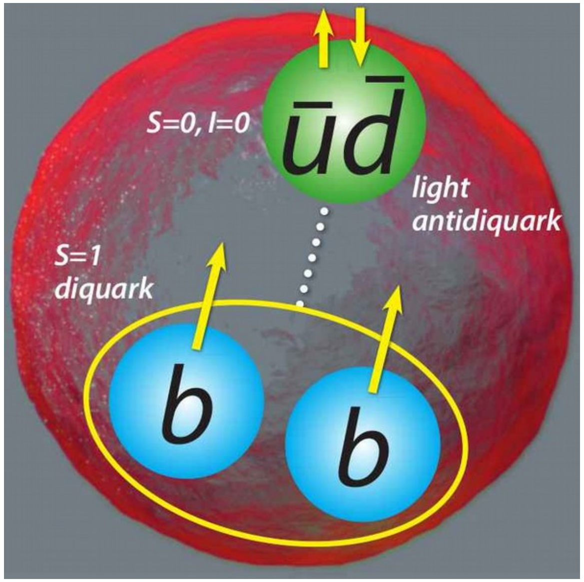
$(bb)_{S=1}\,(\bar{u}\bar{d})_{S=0} \Rightarrow J^P = 1^+$.

$\Rightarrow (bb)\,(\bar{u}\bar{d})$ very similar to bbq baryon:

$q \leftrightarrow (\bar{u}\bar{d})$

bbq baryon





Contributions to mass of $(bb\bar{u}\bar{d})$ Tq with $J^P = 1^+$

Contribution	Value (MeV)
$2m_b^b$	10087.0
$2m_q^b$	726.0
$a_{bb}/(m_b^b)^2$	7.8
$-3a/(m_q^b)^2$	-150.0
bb binding	-281.4
Total	10389.4 ± 12

Contributions to mass of $(cc\bar{u}\bar{d})$ Tq with $J^P = 1^+$

Contribution	Value (MeV)
$2m_c^b$	3421.0
$2m_q^b$	726.0
$a_{cc}/(m_c^b)^2$	14.2
$-3a/(m_q^b)^2$	-150.0
cc binding	-129.0
Total	3882.2 ± 12

7 MeV above $D^0 D^{+*}$ threshold,

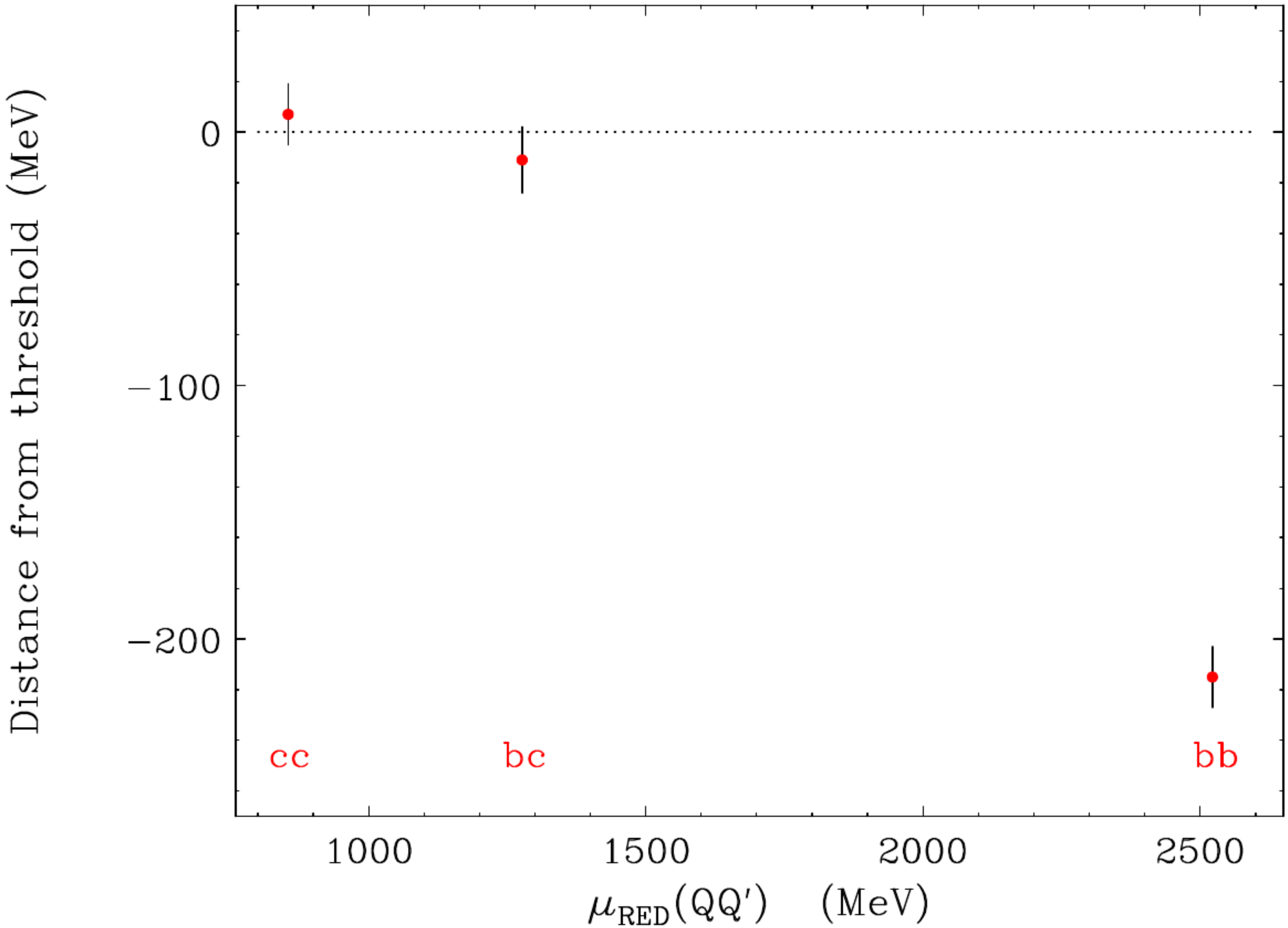
but if use measured $M(X_{cc}^{++}) \Rightarrow$ only 1 MeV above $D^0 D^{+*}$

Contributions to mass of $(bc\bar{u}\bar{d})$ Tq* with $J^P = 0^+$

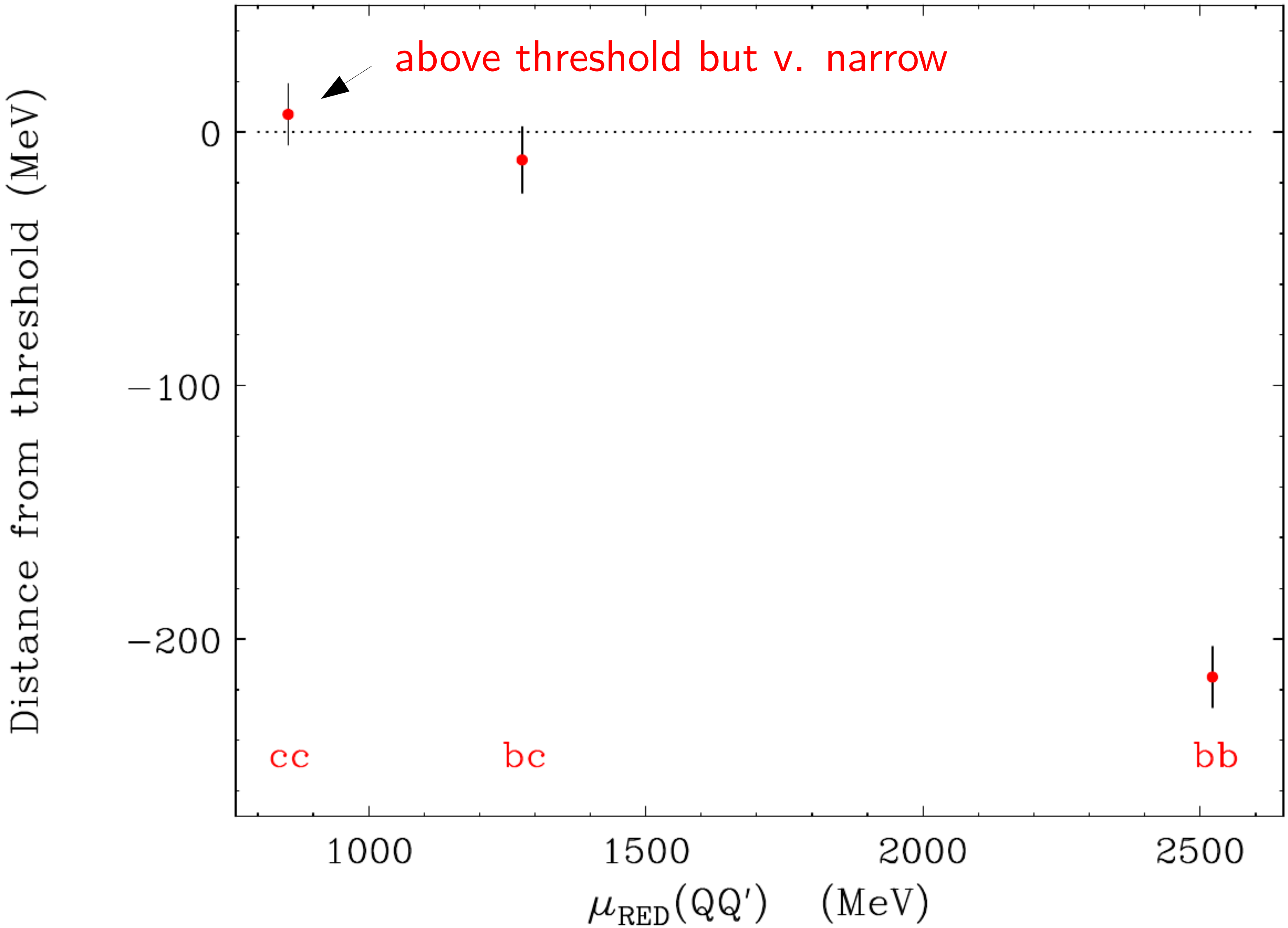
Contribution	Value (MeV)
$m_b^b + m_c^b$	6754.0
$2m_q^b$	726.0
$-3a_{bc}/(m_b^b m_c^b)$	-25.5
$-3a/(m_q^b)^2$	-150.0
bc binding	-170.8
Total	7133.7 ± 13

*lowest-mass *bc* diquark has $S=0$, so $J=0$

Distance of the $QQ'\bar{u}\bar{d}$ Tq masses from the relevant two-meson thresholds (MeV).



Distance of the $QQ'\bar{u}\bar{d}$ Tq masses from the relevant two-meson thresholds (MeV).



Tetraquark production

$$\sigma(pp \to T(bb\bar{u}\bar{d}) + X \lesssim \sigma(pp \to \Xi_{bb} + X)$$

same bottleneck: $\sigma(pp \to \{bb\} + X)$

hadronization:

$$\left.\begin{array}{l} \{bb\} \to \{bb\}q \\ \{bb\} \to \{bb\}\bar{u}\bar{d} \end{array}\right\} \quad \begin{array}{ccc} P(\bar{u}\bar{d}) & \lesssim & P(q) \\ \mathbf{3}_c & & \mathbf{3}_c \end{array}$$

LHCb observed $ccu = \Xi_{cc}^{++}$

$$\sigma(pp \to \Xi_{bb} + X) = (b/c)^2 \cdot \sigma(pp \to \Xi_{cc} + X)$$

$\Rightarrow$ Ξ_{bb} and $T(bb\bar{u}\bar{d})$ accessible,
with much more $\int \mathcal{L} dt$

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$$\sigma(pp \to \Xi_{bb} + X) = (b/c)^2 \cdot \sigma(pp \to \Xi_{cc} + X)$$

$\Rightarrow$ Ξ_{bb} and $T(bb\bar{u}\bar{d})$ accessible, with much more $\int \mathcal{L} dt$

$T(cc\bar{u}\bar{d})$ likely narrow accessible *now*

$bb\bar{u}\bar{d}$ tetraquark production in Z factory

A. Ali

(private communication)

$$Z \to b\bar{b}\, b\bar{b}$$

in high-L Z factory, like CEPC,

$\exists$ huge number of bb pairs.

Might be enough for penalty

due to required proximity in phase space

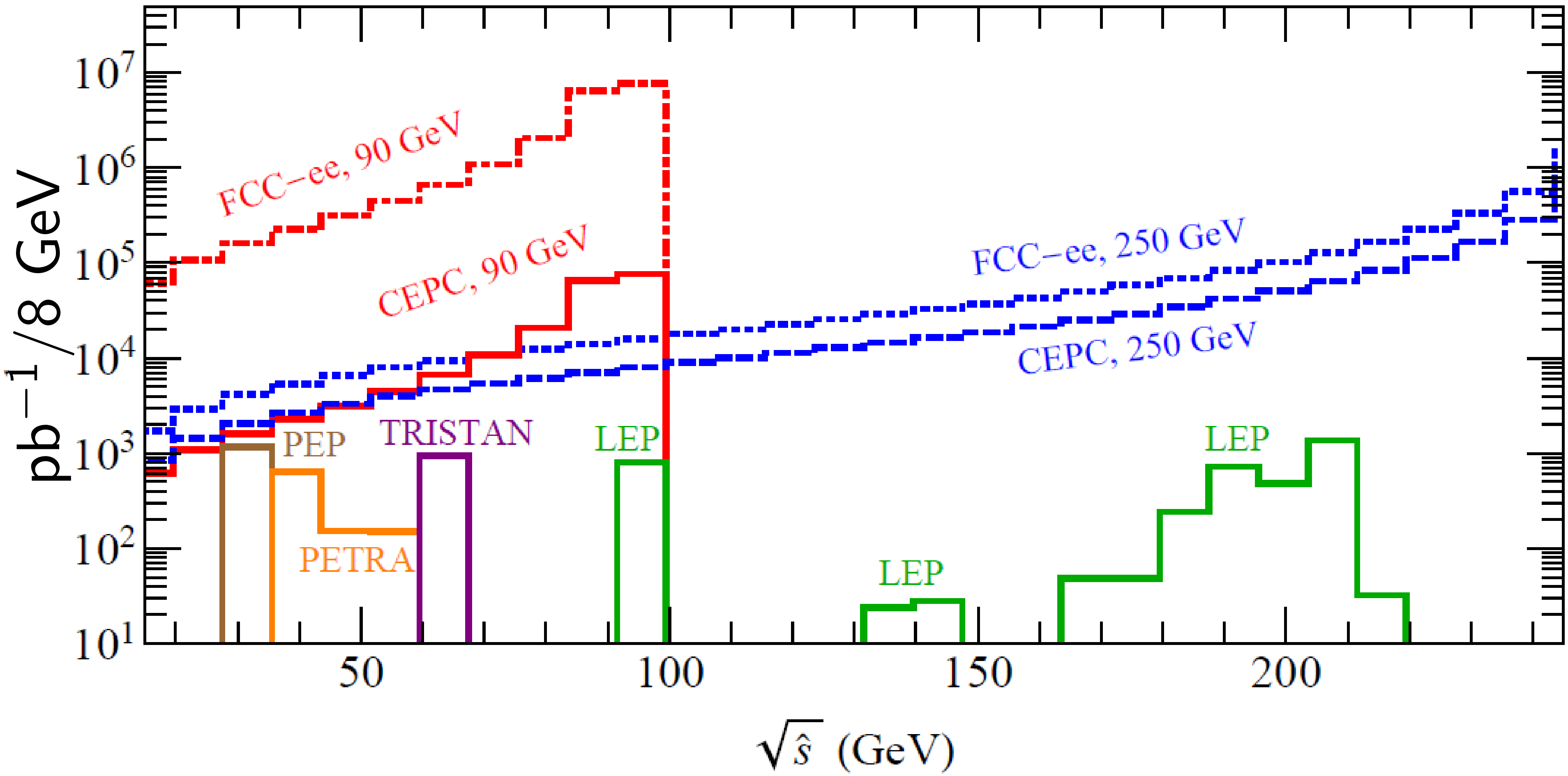
$\Rightarrow$ produce bbq baryons and $bb\bar{u}\bar{d}$ Tq-s

the challenge: reliable estimate of σ

$\Gamma(Z \to B_c + X)$: useful upper bound (MK)

CEPC radiative return

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

crude estimate of $bb\bar{u}\bar{d}$ lifetime

$M_{initial} = M(bb\bar{u}\bar{d}) = 10{,}389.4$ MeV

$M_{final} = M(\bar{B}) + M(D) = 7,144.5$ MeV,

$W^{-*} \to e\bar{\nu}_e,\ \mu\bar{\nu}_\mu,\ \tau\bar{\nu}_\tau$, 3 colors of $\bar{u}d$ and $\bar{c}s$,

a kinematic suppression factor
$F(x) = 1 - 8x + 8x^3 - x^4 + 12x^2 \ln(1/x)$,
$x \equiv \{[M(\bar{B}) + M(D)]/M(bb\bar{u}\bar{d})\}^2$,

$|V_{cb}| = 0.04$, factor of 2 to count each decaying b quark.

$$\Rightarrow \Gamma(bb\bar{u}\bar{d}) = \frac{18\, G_F^2 M(bb\bar{u}\bar{d})^5}{192\pi^3} F(x)|V_{cb}|^2 = 17.9\times 10^{-13} \text{ GeV} ,$$

$$\tau(bb\bar{u}\bar{d}) = 367 \text{ fs.}$$

$bb\bar{u}\bar{d}$ decay channels

(a) "standard process" $bb\bar{u}\bar{d} \to cb\bar{u}\bar{d} + W^{*-}$.

$(bb\bar{u}\bar{d}) \to D^0 \bar{B}^0 \pi^-,\ D^+ B^- \pi^-$

$(bb\bar{u}\bar{d}) \to J/\psi K^- \bar{B}^0,\ \ J/\psi \bar{K}^0 B^-$.

$(bb\bar{u}\bar{d}) \to \Omega_{bc}\, \bar{p},\ \ \Omega_{bc}\, \bar{\Lambda}_c,\ \ \Xi^0_{bc}\, \bar{p},\ \ \Xi^0_{bc}\, \bar{\Lambda}_c$

In addition, a rare process where *both* $b \to c\bar{c}s$,

$(bb\bar{u}\bar{d}) \to J/\psi J/\psi K^- \bar{K}^0$.

striking signature: $2J/\psi$-s from same 2ndary vertex

(b) The W-exchange $b\bar{d} \to c\bar{u}$

e.g. $(bb\bar{u}\bar{d}) \to D^0 B^-$.

$T(bb\bar{u}\bar{d})$ Summary

- stable, deeply bound $bbu\bar{d}$ tetraquark
- $J^P = 1^+$, $M(bb\bar{u}\bar{d}) = 10389 \pm 12$ MeV
- 215 MeV below BB^* threshold
- first manifesty exotic stable hadron
- $(bb\bar{u}\bar{d}) \to \bar{B}D\pi^-$, $J/\psi\bar{K}\bar{B}$,
  $J/\psi J/\psi K^-\bar{K}^0$, D^0B^-
- $(bc\bar{u}\bar{d})$: $J^P = 0^+$, borderline bound
  7134 ± 13 MeV, 11 MeV below $\bar{B}^0D^0$
- $(cc\bar{u}\bar{d})$: $J^P = 1^+$, borderline unbound
  3882 ± 12 MeV, 7 MeV above the D^0D^{*+}

two v. different types of exotics:

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

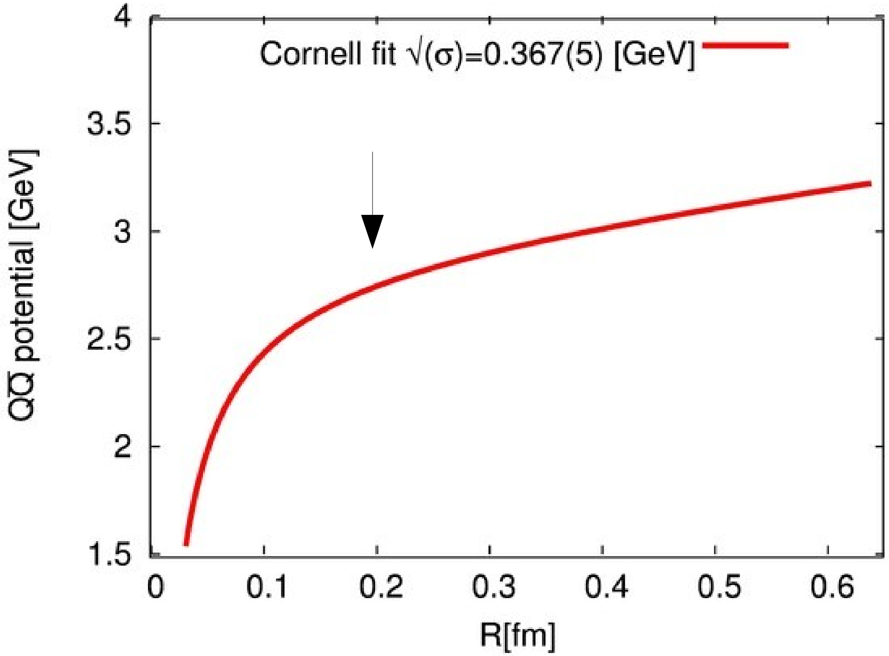
e.g.

$Z_b(10610)$	$T(bb\bar{u}\bar{d})$
$\bar{B}B^*$	tightly-bound
molecule	tetraquark

$T(bb\bar{u}\bar{d})$:
$m_b \approx 5$ GeV
$\Rightarrow R(bb) \sim 0.2$ fm

$$V(r) = -\frac{\alpha_s(r)}{r} + \sigma r$$

$\Rightarrow B(bb) \approx -280$ MeV
tightly bound, but $\bar{3}_c$,
so cannot disangage from $\bar{u}\bar{d}$



$Z_b(10610)$: $b\bar{b}u\bar{d}$

very different!

if $b\bar{b}$ compact $\Rightarrow$ color singlet:
decouple from $u\bar{d}$, $\quad Z_b \to \Upsilon\pi^+$
so only semi-stable config.,
"hadronic molecule:" $\bar{B}B^* \sim 1$ GeV above $\Upsilon\pi$
yet narrow ~ 15 MeV, because $R(\bar{B}B^*)/R(\Upsilon) \gg 1$

$T(bb\bar{u}\bar{d})$:
$m_b \approx 5$ GeV
$\Rightarrow R(bb) \sim 0.2$ fm
$$V(r) = -\frac{\alpha_s(r)}{r} + \sigma r$$
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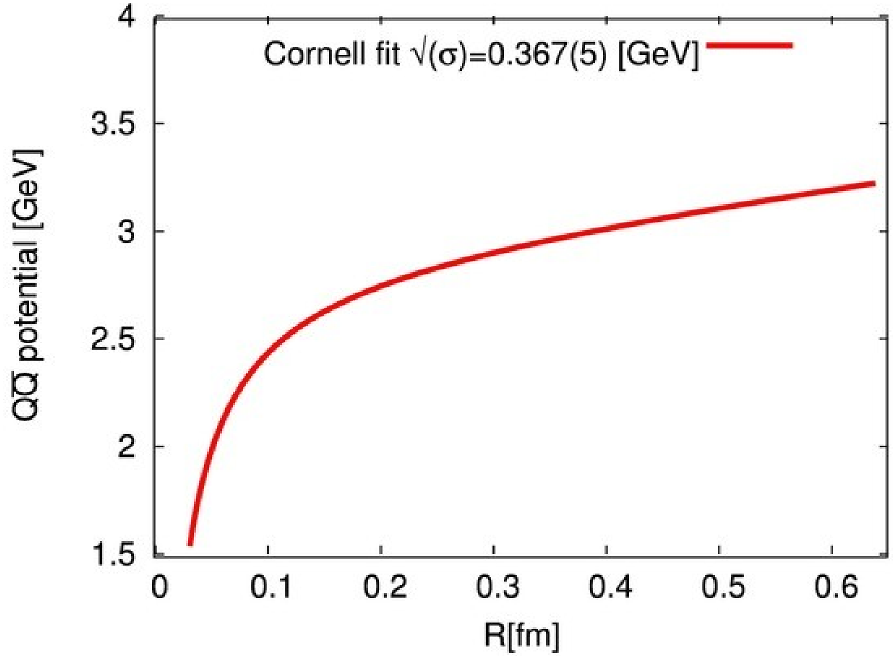

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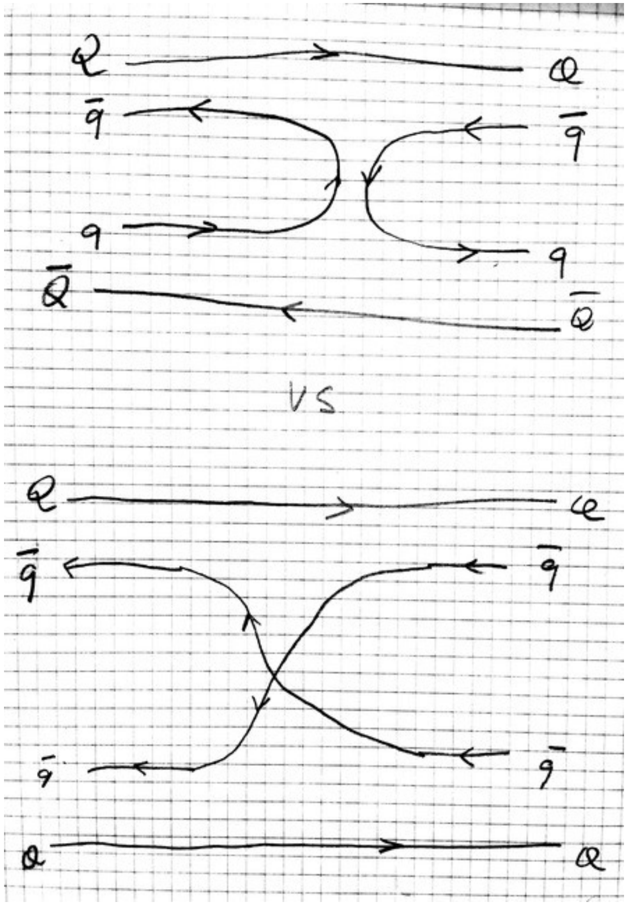
so only semi-stable config.,
"hadronic molecule:" $\bar{B}B^* \sim 1$ GeV above $\Upsilon\pi$
yet narrow ~ 15 MeV, because $R(\bar{B}B^*)/R(\Upsilon) \gg 1$
bottom line: $T(bb\bar{u}\bar{d})$ a tetraquark, $Z_b(b\bar{b}u\bar{d})$ a molecule

molecular binding $\equiv$ meson x-change
$Q\bar{Q}q\bar{q}$ vs. $QQ\bar{q}\bar{q}$

Tornqvist (1994):

molecular binding only in $Q\bar{q}\,\bar{Q}q$ channels.

$Q\bar{q}\,Q\bar{q}$ repulsive or very weakly bound, except maybe B^*B^*.



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

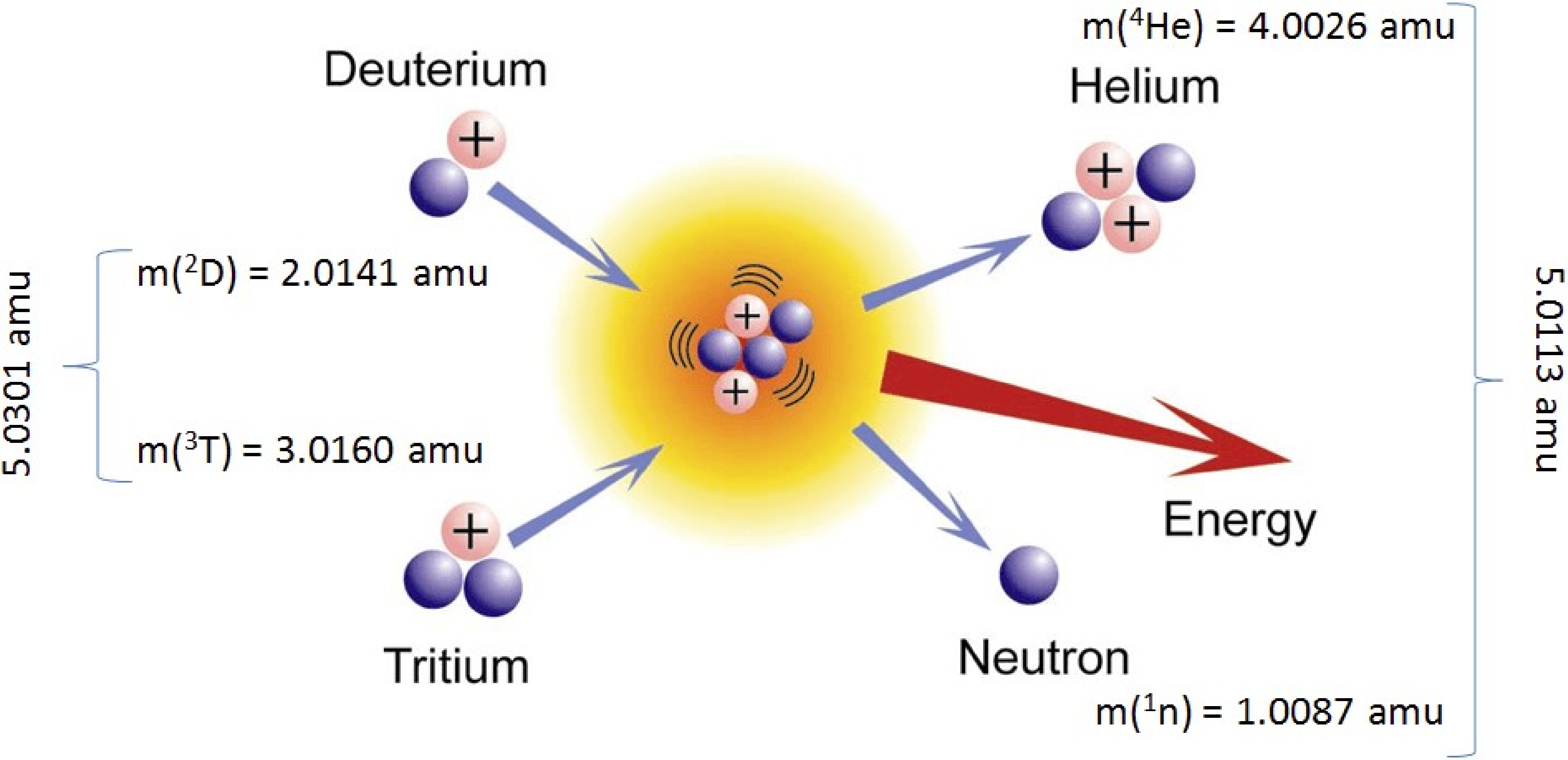
$\Rightarrow$ Inspect neutral 4ℓ final states for possible evidence of $bb\bar{b}\bar{b}$ state; most likely $J^{PC} = 0^{++}$

Quark-level analogue of nuclear fusion with doubly-heavy baryons

Quark-level analogue of nuclear fusion with doubly-heavy baryons

a.k.a. THE SWAN

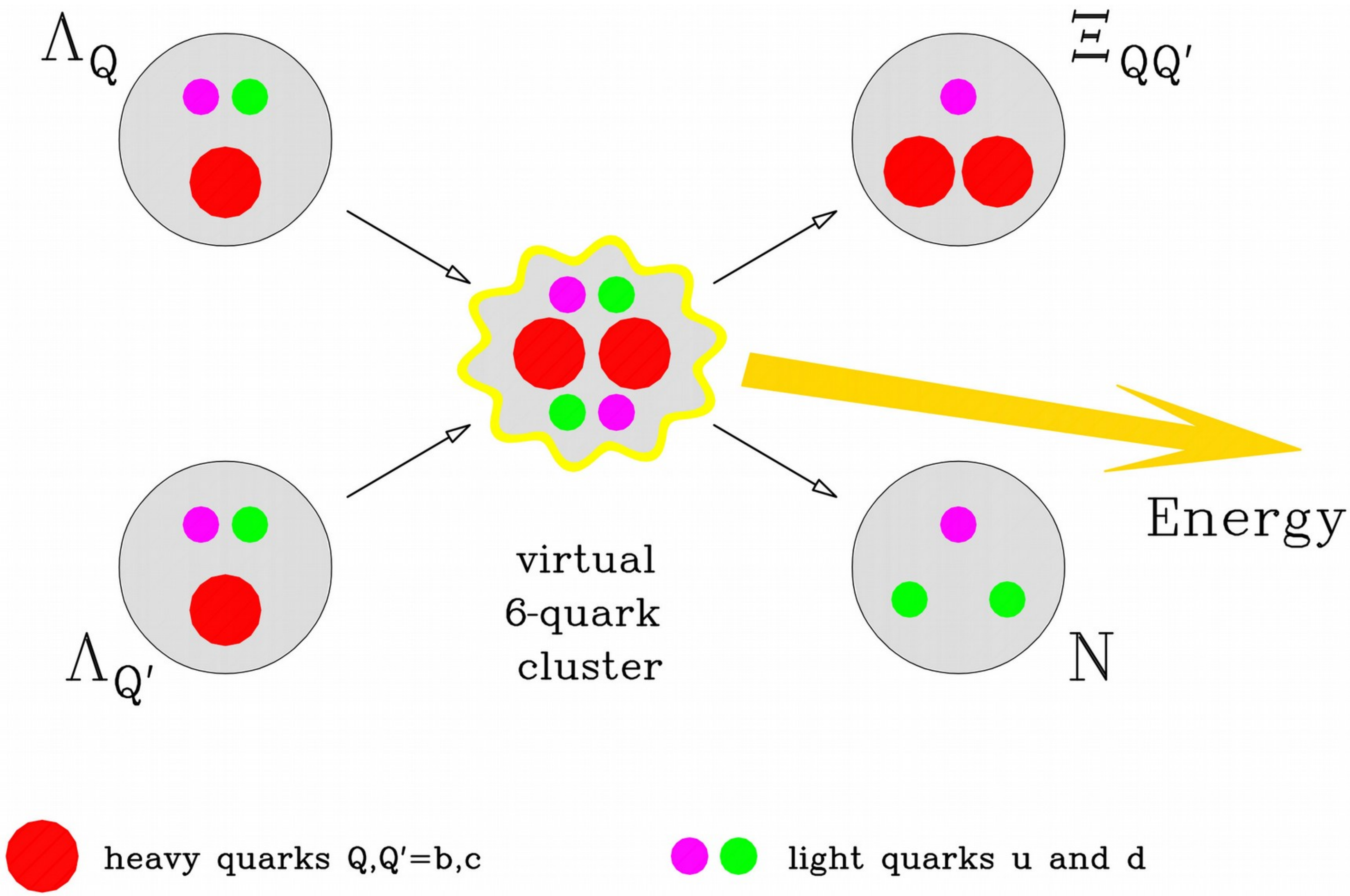
DT fusion: $DT \to {}^4\text{He}\, n$

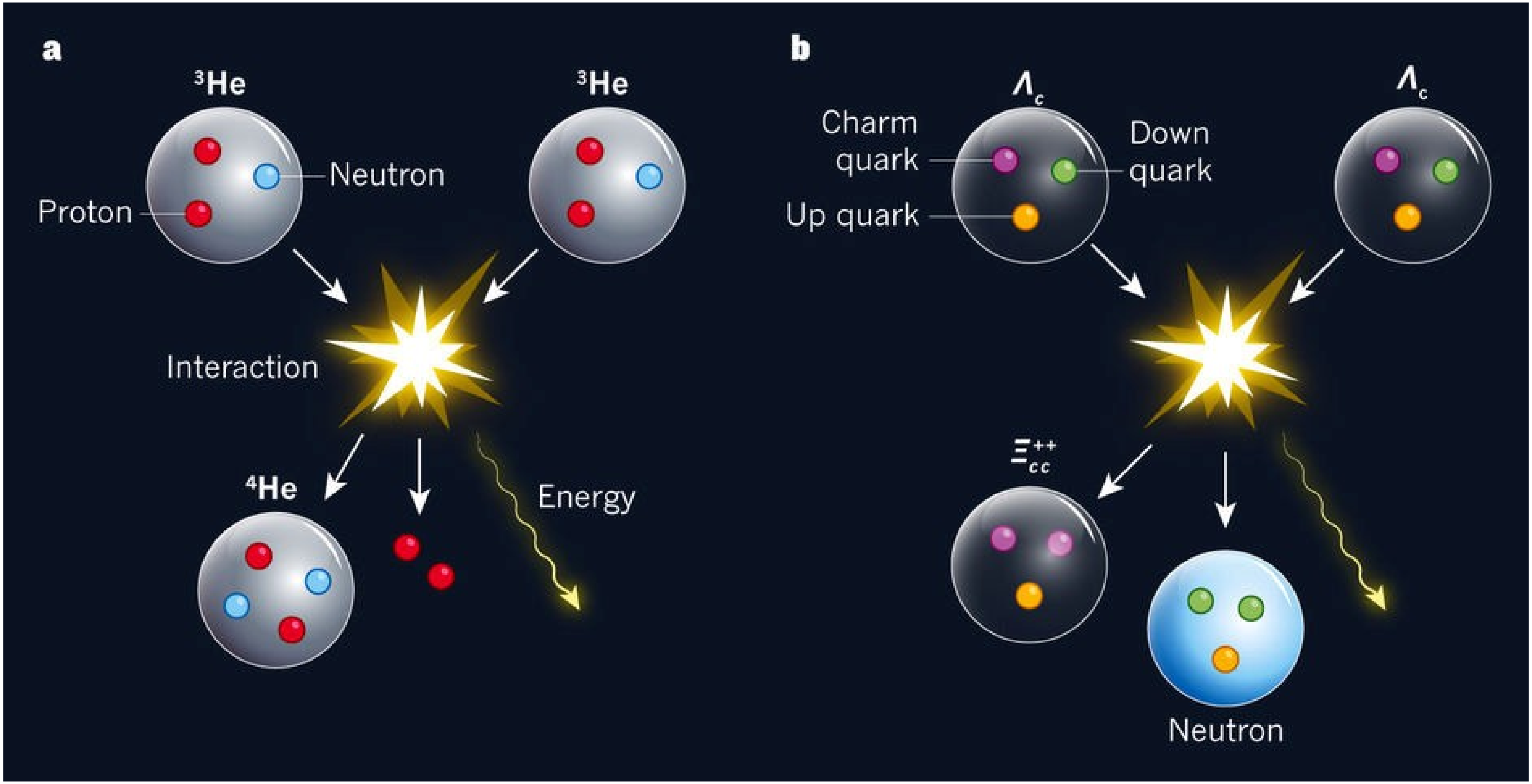


Q = 0.0188 amu x 931.481 MeV/amu = 17.5 MeV

Nuclear fusion reactions w. light nuclei

$$
\begin{array}{lcll}
D\,T & \to & {}^4\mathrm{He}\,n & Q = 17.59\ \mathrm{MeV}, \\
D\,D & \to & {}^3\mathrm{He}\,n & Q = 3.27\ \mathrm{MeV}, \\
D\,D & \to & T\,p & Q = 4.04\ \mathrm{MeV}, \\
T\,T & \to & {}^4\mathrm{He}\,2n & Q = 11.33\ \mathrm{MeV}, \\
D\,{}^3\mathrm{He} & \to & {}^4\mathrm{He}\,p & Q = 18.35\ \mathrm{MeV}, \\
{}^3\mathrm{He}\,{}^3\mathrm{He} & \to & {}^4\mathrm{He}\,2p & Q = 12.86\ \mathrm{MeV}.
\end{array}
$$


Λ_Q
$\Xi_{QQ'}$
virtual
6-quark
cluster
Energy
$\Lambda_{Q'}$
N
heavy quarks Q,Q′=b,c
light quarks u and d


a
^{3}He
^{3}He
Neutron
Proton
Interaction
^{4}He
Energy
b
Λ_c
Λ_c
Charm quark
Down quark
Up quark
Ξ_{cc}^{++}
Neutron

Nature,
Nov 2, 2017

LETTER

doi:10.1038/nature24289

Quark–level analogue of nuclear fusion with doubly heavy baryons

Marek Karliner[1] & Jonathan L. Rosner[2]

The essence of nuclear fusion is that energy can be released by the rearrangement of nucleons between the initial- and final-state nuclei. The recent discovery[1] of the first doubly charmed baryon Ξ_{cc}^{++}, which contains two charm quarks (c) and one up quark (u) and has a mass of about 3,621 megaelectronvolts (MeV) (the mass of the proton is 938 MeV) also revealed a large binding energy of about 130 MeV between the two charm quarks. Here we report that this strong binding enables a quark-rearrangement, exothermic reaction in which two heavy baryons (Λ_c) undergo fusion to produce the doubly charmed baryon Ξ_{cc}^{++} and a neutron n ($\Lambda_c\Lambda_c \to \Xi_{cc}^{++}n$), resulting in an energy release of 12 MeV. This reaction is a quark-level analogue of the deuterium–tritium nuclear fusion reaction (DT $\to$ ^{4}He n). The much larger binding energy (approximately 280 MeV) between two bottom quarks (b) causes the analogous reaction with bottom quarks ($\Lambda_b\Lambda_b \to \Xi_{bb}^0 n$) to have a much larger energy release of about 138 MeV. We suggest some experimental setups in which the highly exothermic nature of the fusion of two heavy-quark baryons might manifest itself. At present, however, the very short lifetimes of the heavy bottom and charm quarks preclude any practical applications of such reactions.

The mass of the doubly charmed baryon Ξ_{cc}^{++} observed in the LHCb experiment[1] 3621.40 ± 0.78 MeV is consistent with several predictions[2], including that of $3{,}627 \pm 12$ MeV (an extensive list of other predictions can be found in refs 1 and 2). The essential insight of ref. 2 is the large binding energy B of the two heavy quarks (the charm c or bottom b quarks) in a baryon, $B(cc) = 129$ MeV and $B(bb) = 281$ MeV. To a very good approximation, this binding energy is half of the quark–antiquark binding energy in their bound states, which are known as quarkonia. This 'half' rule is exact in the one-gluon-exchange limit and has now been validated by the measurement of the Ξ_{cc}^{++} mass. Its successful extension beyond weak coupling implies that the heavy quark potential factorizes into a colour-dependent and a space-dependent part, with the latter being the same for quark–quark and quark–antiquark pairs. The relative factor of 1/2 then results from the colour algebra, just as in the weak-coupling limit.

The large binding energy between heavy quarks has some important implications, such as the existence of a stable $bb\bar{u}\bar{d}$ tetraquark (where $\bar{u}$ and $\bar{d}$ are antiup and antidown quarks, respectively) with spin–parity[3] $J^P = 1^+$ 215 MeV below the $B^-\bar{B}^{*0}$ threshold and 170 MeV below the threshold for decay to $B^-\bar{B}^0\gamma$, where B^- is a spinless meson composed of $b\bar{u}$, $\bar{B}^{*0}$ is a spin-1 meson composed of $b\bar{d}$, $\bar{B}^0$ is a spinless meson composed of $b\bar{d}$ and γ is a photon. Another important consequence is the existence of a quark-level analogue of nuclear fusion. Consider the quark-rearrangement reaction

$$\underbrace{\Lambda_c}_{cud}\underbrace{\Lambda_c}_{cud} \to \underbrace{\Xi_{cc}^{++}}_{ccu}\underbrace{n}_{ddu} \qquad (1)$$

where the quarks are indicated below each baryon. This is a fusion of two singly heavy baryons into a doubly heavy baryon and a nucleon. The masses of all of the particles in reaction (1) are known and the energy release ΔE is 12 MeV, as shown in Table 1.

The exothermic reaction (1) is the quark-level analogue of the well known exothermic nuclear fusion reactions between the lightest nuclei, which contain two or three nucleons[4], with quarks playing the part of the nucleons, hadrons playing the part of the nuclei and the doubly heavy baryon playing the part of ^{4}He:

$$\begin{aligned}
&\mathrm{DT} \to {}^4\mathrm{He}\, n, && \Delta E = 17.59\ \mathrm{MeV}\\
&\mathrm{DD} \to {}^3\mathrm{He}\, n, && \Delta E = 3.27\ \mathrm{MeV}\\
&\mathrm{DD} \to \mathrm{T}\, p, && \Delta E = 4.04\ \mathrm{MeV}\\
&\mathrm{TT} \to {}^4\mathrm{He}\, 2n, && \Delta E = 11.33\ \mathrm{MeV}\\
&\mathrm{D}{}^3\mathrm{He} \to {}^3\mathrm{He}\, p, && \Delta E = 18.35\ \mathrm{MeV}\\
&{}^3\mathrm{He}{}^3\mathrm{He} \to {}^4\mathrm{He}\, 2p, && \Delta E = 12.86\ \mathrm{MeV}
\end{aligned} \qquad (2)$$

where D denotes a deuteron, T represents a triton and p stands for proton. Reaction (1) involves two hadrons with three quarks each, rather than two nuclei with two or three nucleons each, as shown schematically in Fig. 1, which also depicts the analogous reactions $\Lambda_Q\Lambda_{Q'} \to \Xi_{QQ'}N$, where $Q, Q' \in \{b, c\}$. The energy release ΔE of reaction (1) is of a similar order of magnitude to those of reactions (2).

Table 1 lists the ΔE values for four reactions $\Lambda_Q\Lambda_{Q'} \to \Xi_{QQ'}N$, where $Q, Q' \in \{s, c, b\}$. The trend is clear: ΔE increases monotonically with increasing quark mass. The reaction

$$\Lambda\Lambda \to \Xi N \qquad (3)$$

is endothermic with $\Delta E = -23$ MeV. Reaction (1) is exothermic with $\Delta E = +12$ MeV, whereas the reaction

$$\Lambda_b\Lambda_b \to \Xi_{bb}N \qquad (4)$$

is expected to be strongly exothermic with $\Delta E = +138 \pm 12$ MeV. Finally, the reaction

$$\Lambda_b\Lambda_c \to \Xi_{bc}N \qquad (5)$$

is expected to have $\Delta E = +50 \pm 13$ MeV, between the values for the cc and bb reactions (1) and (4). The latter two estimates of ΔE (for reactions (4) and (5)) rely on predictions of the Ξ_{bb} and Ξ_{bc} masses[2].

As already mentioned, the dominant effect that determines ΔE is the binding between two heavy quarks. Because these quarks interact through an effective two-body potential, their binding is determined by their reduced mass, $\mu_{red} = m_Q m_{Q'}/(m_Q + m_{Q'})$, where m_Q and $m_{Q'}$ are the masses of the individual quarks. In Fig. 2, we plot ΔE versus $\mu_{red}(QQ')$. The effective quark masses are as in ref. 2: $m_s = 538$ MeV, $m_c = 1{,}710.5$ MeV and $m_b = 5{,}043.5$ MeV. The straight-line fit $\Delta E = -44.95 + 0.0726\mu_{red}$ (dot-dashed line) describes the data well, which shows that, to a good approximation, ΔE depends linearly on the reduced mass.

[1]School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel. [2]Enrico Fermi Institute and Department of Physics, University of Chicago, 5640 South Ellis Avenue, Chicago, Illinois 60637, USA.

LHCb measured $M(X_{cc}^{++}) = 3621.4 \pm 0.78$ MeV

$\Rightarrow$ Q-value of the reaction:

$$\Lambda_c \; \Lambda_c \quad \rightarrow \quad \Xi_{cc}^{++} \; n, \qquad Q = 12 \text{ MeV}$$

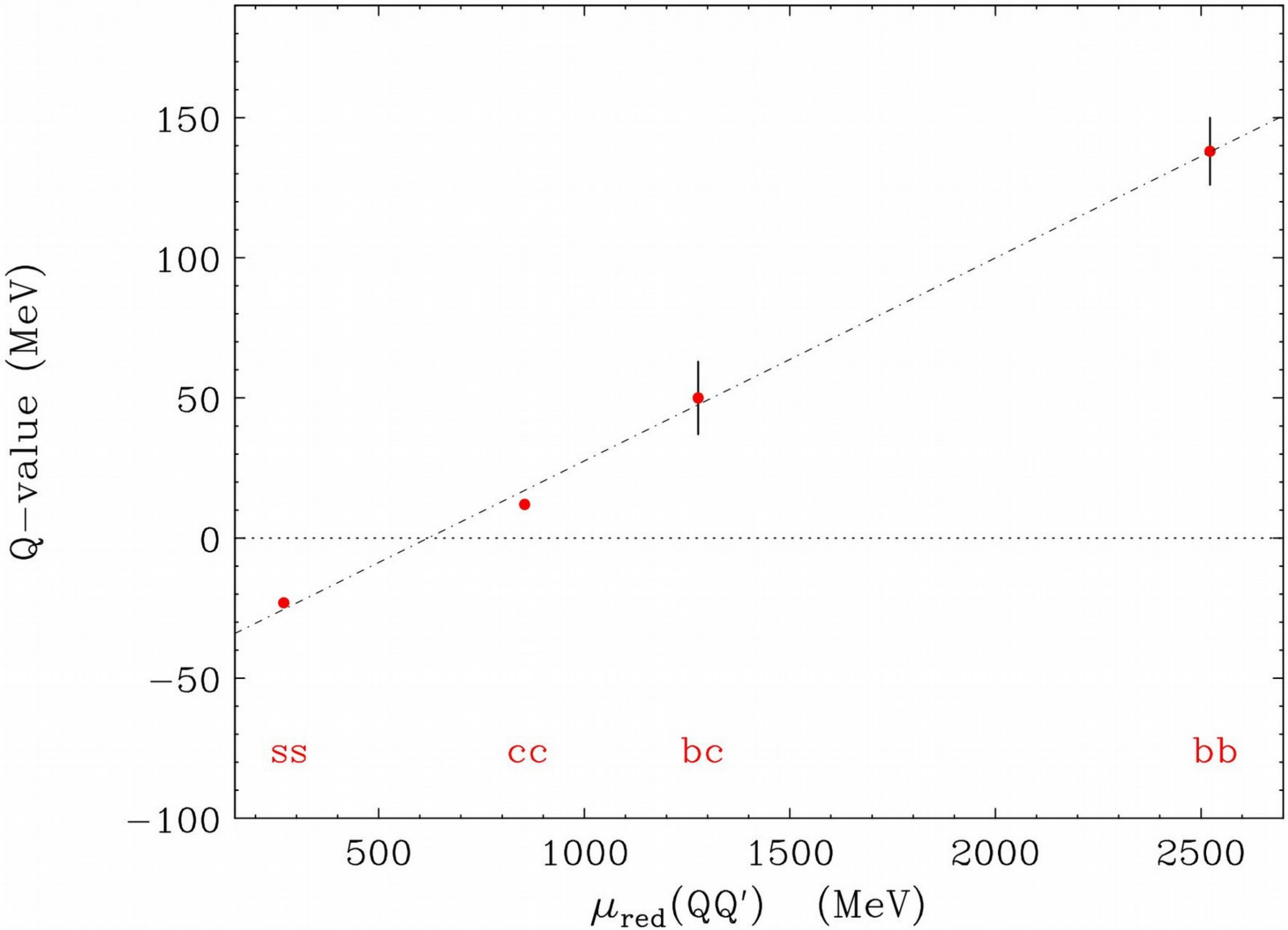
$cud \; cud \qquad\qquad ccu \; ddu$

Table I

Q value in the reaction $\Lambda_Q \Lambda_{\mathcal{Q}'} \to \Xi_{\mathcal{Q}\mathcal{Q}'} N$, $\mathcal{Q}, \mathcal{Q}' = s, c, b$.

Observable (MeV)	$\mathcal{Q}, \mathcal{Q}' = s$	$\mathcal{Q}, \mathcal{Q}' = c$	$\mathcal{Q}, \mathcal{Q}' = b$	$\mathcal{Q} = b, \mathcal{Q}' = c$
$M(\Lambda_{\mathcal{Q}})$	1115.7	2286.5	5619.6	5619.6, 2286.5
$M(\Xi_{\mathcal{Q}\mathcal{Q}'})$	1314.9^a	3621.4 ± 0.78	10162 ± 12^b	6917 ± 13^c
Q-value	-23.1	$+12.0 \pm 0.78$	$+138 \pm 12$	$+50 \pm 13$

^{a}To optimize the Q-value we take here $\Xi^0(ssu)$, $N{=}n$, because $M[\Xi^-(ssd)]$ is 7 MeV larger.
^{b} Ξ_{bb} mass prediction from Ref. [2].
^{c}Average of the two values in Table XI of Ref. [2].



Q-value in the quark-level fusion reactions $\Lambda_Q \Lambda_{Q'} \to \Xi_{\mathcal{Q}\mathcal{Q}'} N$, $\mathcal{Q}, \mathcal{Q}' = s, c, b$, plotted against the reduced masses of the doubly-heavy diquarks $\mu_{red}(\mathcal{Q}\mathcal{Q}')$. The dot-dashed line denotes a linear fit $Q = -44.95 + 0.0726\,\mu_{red}$.

doubly-strange hypernuclei might be produced in

$$K^- \; {}^{16}\mathrm{O} \to K^+ \; {}^{16}_{\Lambda\Lambda}\mathrm{C} \quad \equiv \quad {}^{16}\mathrm{O}(K^-, K^+){}^{16}_{\Lambda\Lambda}\mathrm{C}$$

ongoing exp. at J-PARC.

Suggest bottom analogue:

$$B^- \; {}^{16}\mathrm{O} \to B^+ \; {}^{16}_{\Xi^-_{bb}}\mathrm{C}\,.$$

$E(bb) \approx 280$ MeV $\Rightarrow$ v. high Q-value

main challenge:
$\tau(B^-) = 1.6 \times 10^{-12}$ s,
$\tau(B^-) \cdot c \approx 0.5$ mm

Maybe also charm analogue

$$D^{+}\ {}^{N}\!A \to D^{-}\ \Xi_{cc}^{++}\ {}^{N}\!A'$$

both bottom and charm

in heavy ion collisions ?

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 $\approx m_q^{\rm const.}$

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 $\eta - \pi^0$ 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:

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

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

$\Rightarrow$ 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

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

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

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

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

- Belle II ?

$e^+ e^- \to B^*_{s0} B^*_s$ @$11,127 \pm 10$ MeV

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

$\Rightarrow css$: 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 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.

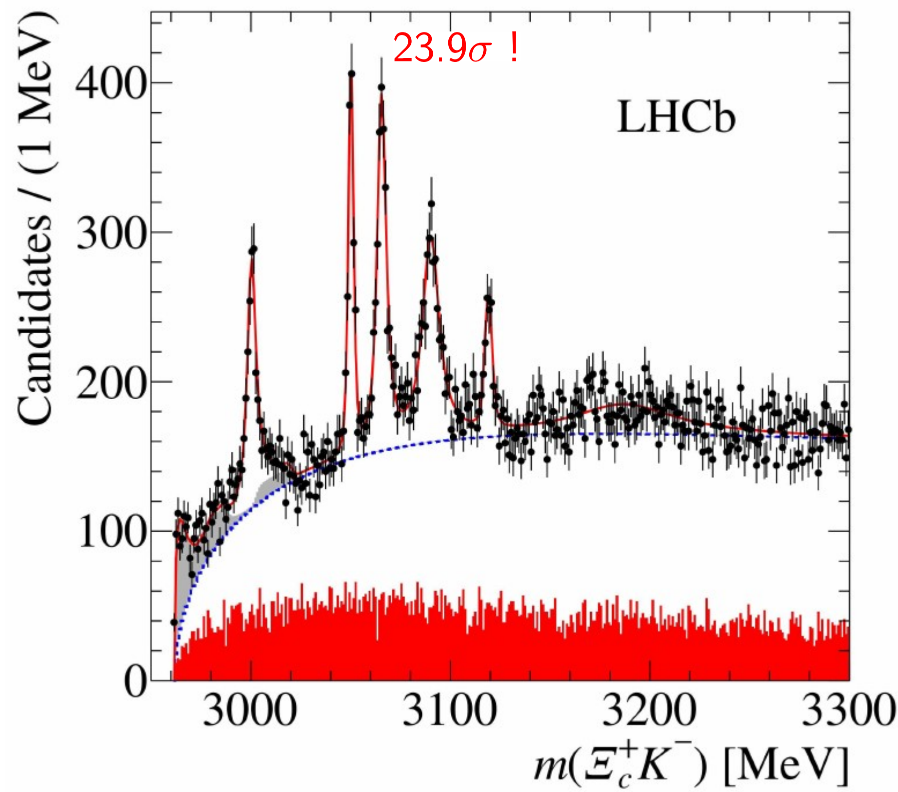


Figure 2: Distribution of the reconstructed invariant mass $m(\Xi_c^+ K^-)$ for all candidates passing the likelihood ratio selection; the solid (red) curve shows the result of the fit, and the dashed (blue) line indicates the fitted background. The shaded (red) histogram shows the corresponding mass 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 $S = \frac{1}{2}$ $\Rightarrow$ $J = \frac{1}{2}, \frac{3}{2}$

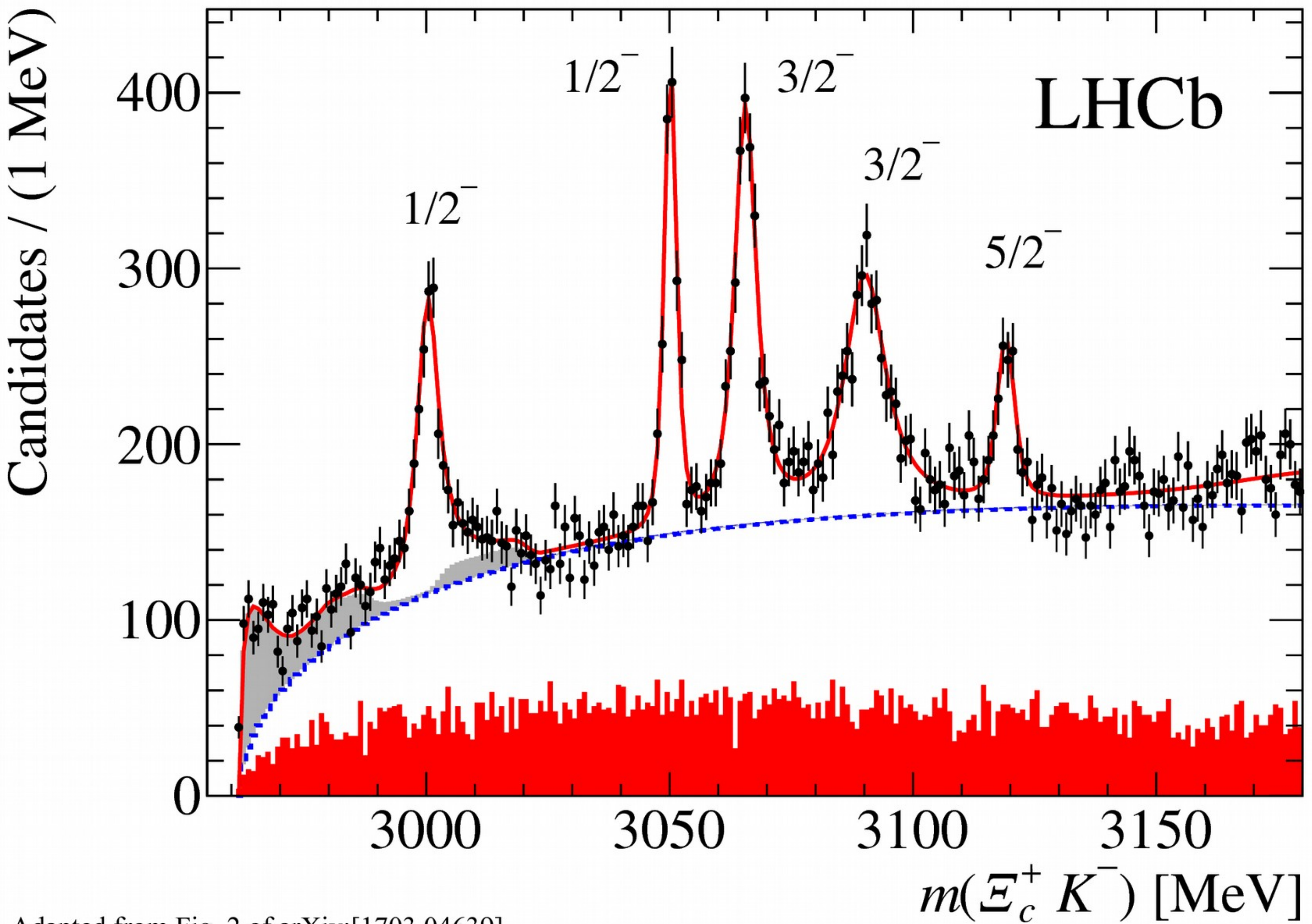
combine $L = 1$ with $S = \frac{3}{2}$ $\Rightarrow$ $J = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}$ — all with negative parity

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

$J^P = 1/2^-$ 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

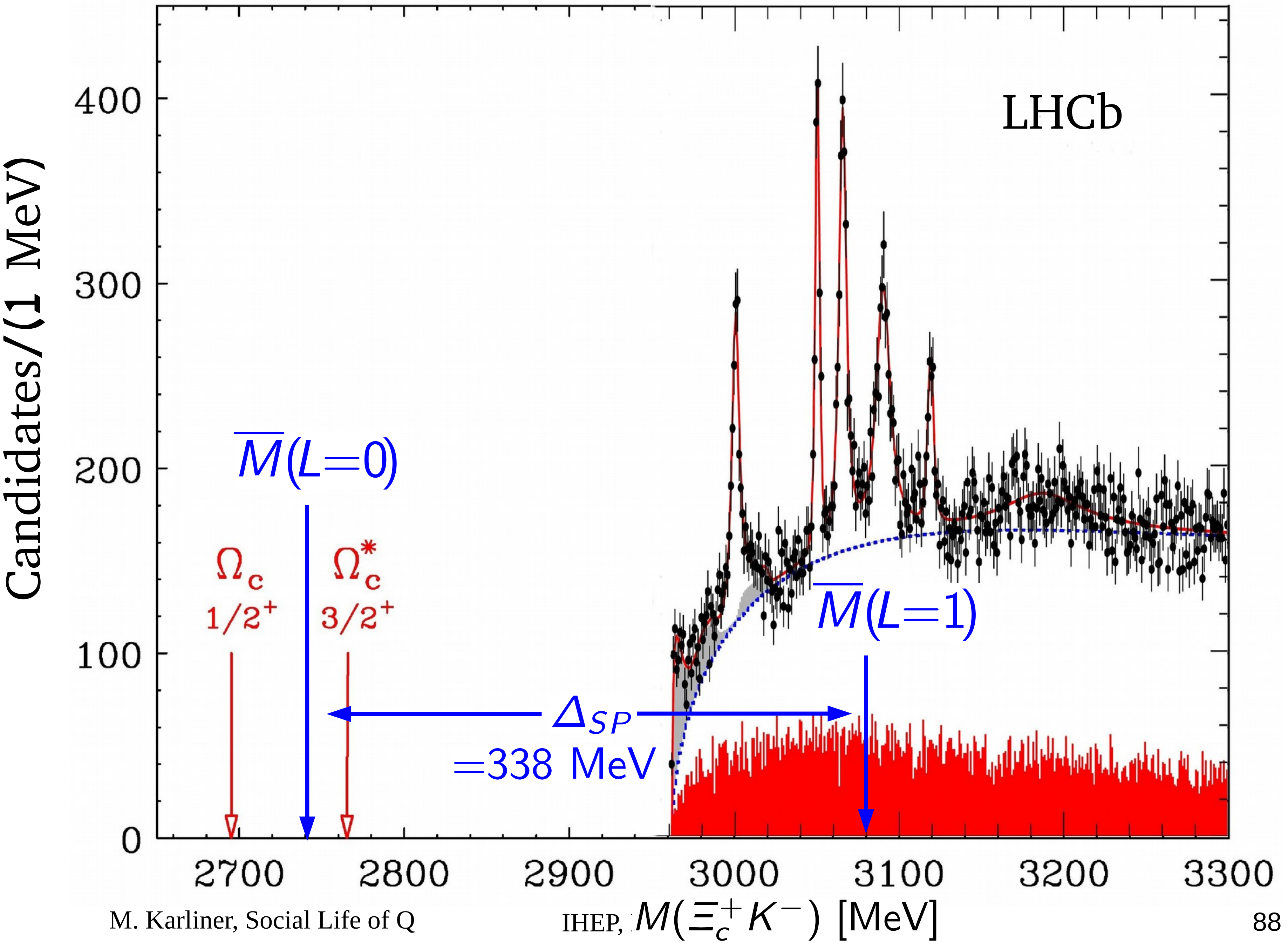
examine all $5! = 120$ *a priori* possible assignments of P-wave states

$\Rightarrow$ 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:

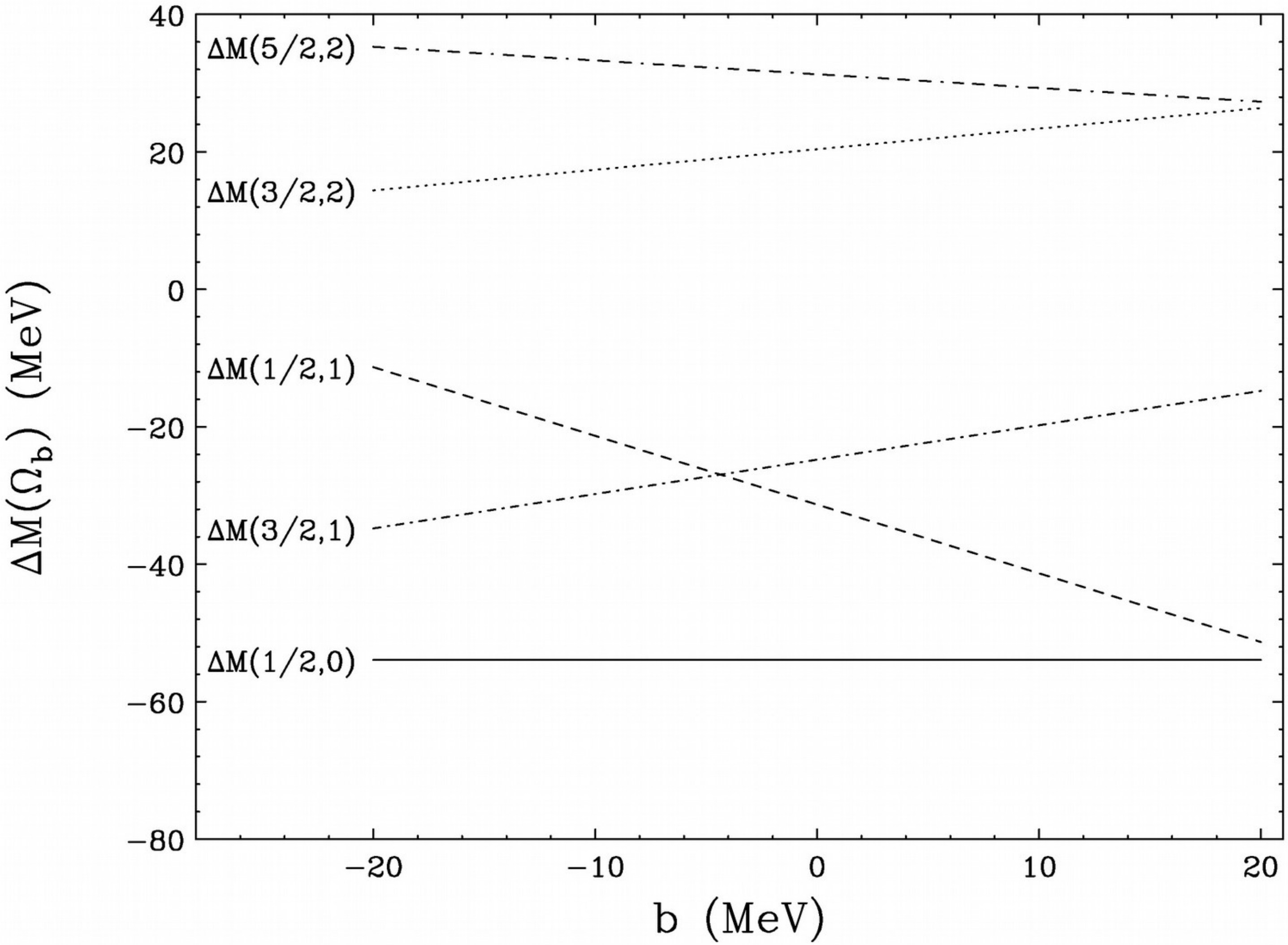
$$\overline{M} = (1/18) \sum_J (2J+1) M(J) = 3079.94 \text{ MeV} \ .$$


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

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

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

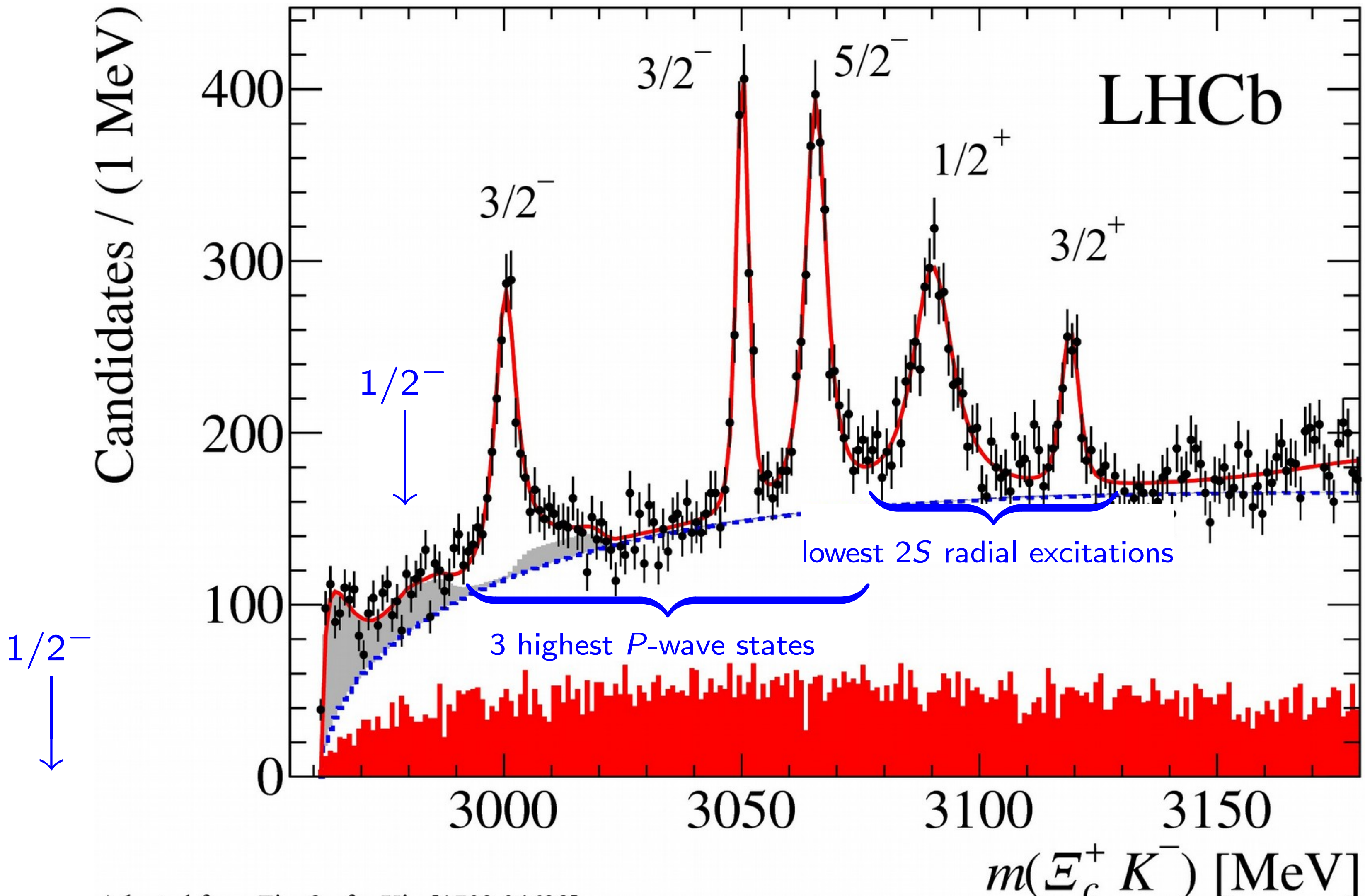
- set HF parameter $c = 0$.
- $a_1 = 26.95$ MeV as for $c(ss)$, as coeff. of $\mathbf{L} \cdot \mathbf{S}_{(ss)}$.
- $a_2 = 8.72$ MeV, rescaled by m_c/m_b.
- -20 MeV $< b < 20$ MeV.
- S-P splitting: $\Delta E_{PS}(\Omega_b) \sim 300$ MeV.



← 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

SUMMARY

- narrow exotics with $Q\bar{Q}$:
  $\bar{D}D^*$, $\bar{D}^*D^*$, $\bar{B}B^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$ molecules

– *heavy deuterons*: $\Sigma_c D^*$: LHCb $P_c(4450) \Rightarrow$ photoproduction
  $\Sigma_c B^*$, $\Sigma_b \bar{D}^*$, $\Sigma_b B^*$, $\Sigma_Q \bar{\Lambda}_{Q'}$, $\Sigma_Q^+ \Sigma_Q^-$, ...

– X_b camouflaged as $\chi_{1b}(3P)$?

– η-mediated: $D_s \bar{D}_s^*$, $\Lambda_c \bar{D}_s^*, \ldots$

- new Ω_c^*-s: spin dep. splittings $\Rightarrow J^P$, Ω_b^*-s
- v. narrow $B_{s0}^* \to B_s \pi^0$, $B_s\gamma$, $B_{s1} \to B_s^* \pi^0$, $B_s^{(*)}\gamma$
- $\Xi_{cc}^{++}(ccu) \Rightarrow (bcq)$, (bbq)
- stable $bb\bar{u}\bar{d}$ tetraquark: LHCb !
- $cc\bar{c}\bar{c}$ @ 6,192±25 MeV, $bb\bar{b}\bar{b}$ @ 18,826±25 MeV $\Rightarrow 4\ell$
- quark-level analogue of nuclear fusion

exciting new spectroscopy awaiting discovery

Supplementary slides

arXiv:1506.06386v1 [hep-ph] 21 Jun 2015

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

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

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]

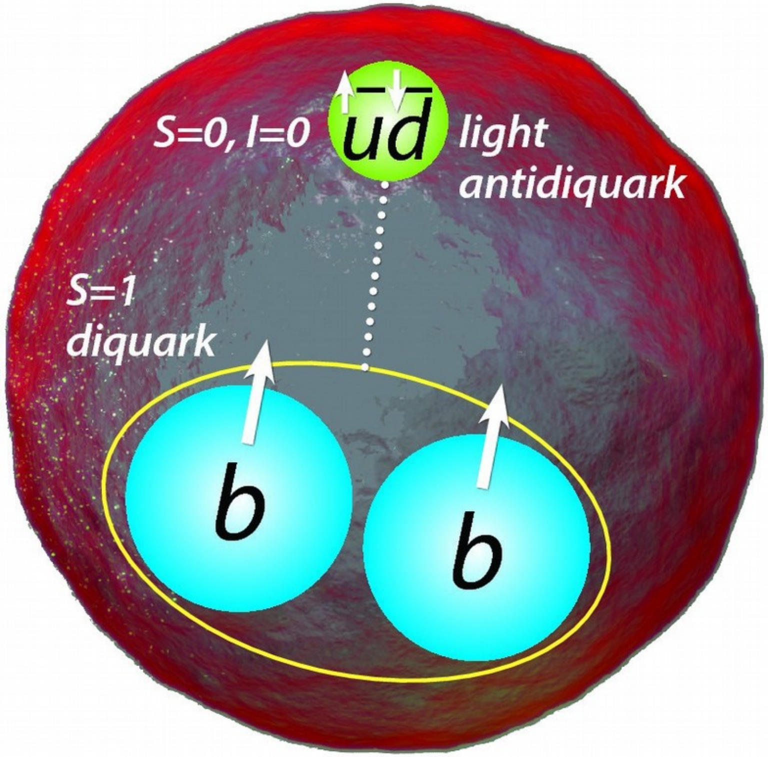
Abstract

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.

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

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


S=0, I=0
$\bar{u}\bar{d}$
light antidiquark
S=1 diquark
b
b