



Tel Aviv University

Heavy Exotics Spectroscopy

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Beauty 2018, Elba, May 7

Social life of heavy quarks:

“Who with whom,

For how long ?

A “one-night stand”,

“avventura di una notte”

Or “Till Death Us Do Part” ?

“finché morte non ci separi”

Outline

- quarks are fundamental building blocks of protons, neutrons and all hadrons
- all quarks are equal, but heavy quarks are more equal than others

new combinations with heavy quarks, incl. exotics:

- hadronic molecules, esp. LHCb pentaquark
- prediction and discovery of doubly-charmed baryon
- stable $bb\bar{u}\bar{d}$ tetraquark
- quark-level analogue of nuclear fusion
- possible similar mechanisms in dark matter sector

The big questions about exotic hadrons:

- do they exist ?
- if yes, which ones ?
- what is their internal structure ?
- how best to look for them ?

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

Exotics with $\bar{Q}Q$ vs. QQ : very different

$$V(\bar{Q}Q) = 2V(QQ), \text{ hundreds of MeV}$$

but *only* if $\bar{Q}Q$ color singlet

$\Rightarrow \bar{Q}Q$ can immediately hadronize

$\Rightarrow$ exotics: $\bar{Q}$ in one hadron and Q in the other

$\Rightarrow$ deuteron-like "hadronic molecules"

vs. QQ *never* a color singlet,

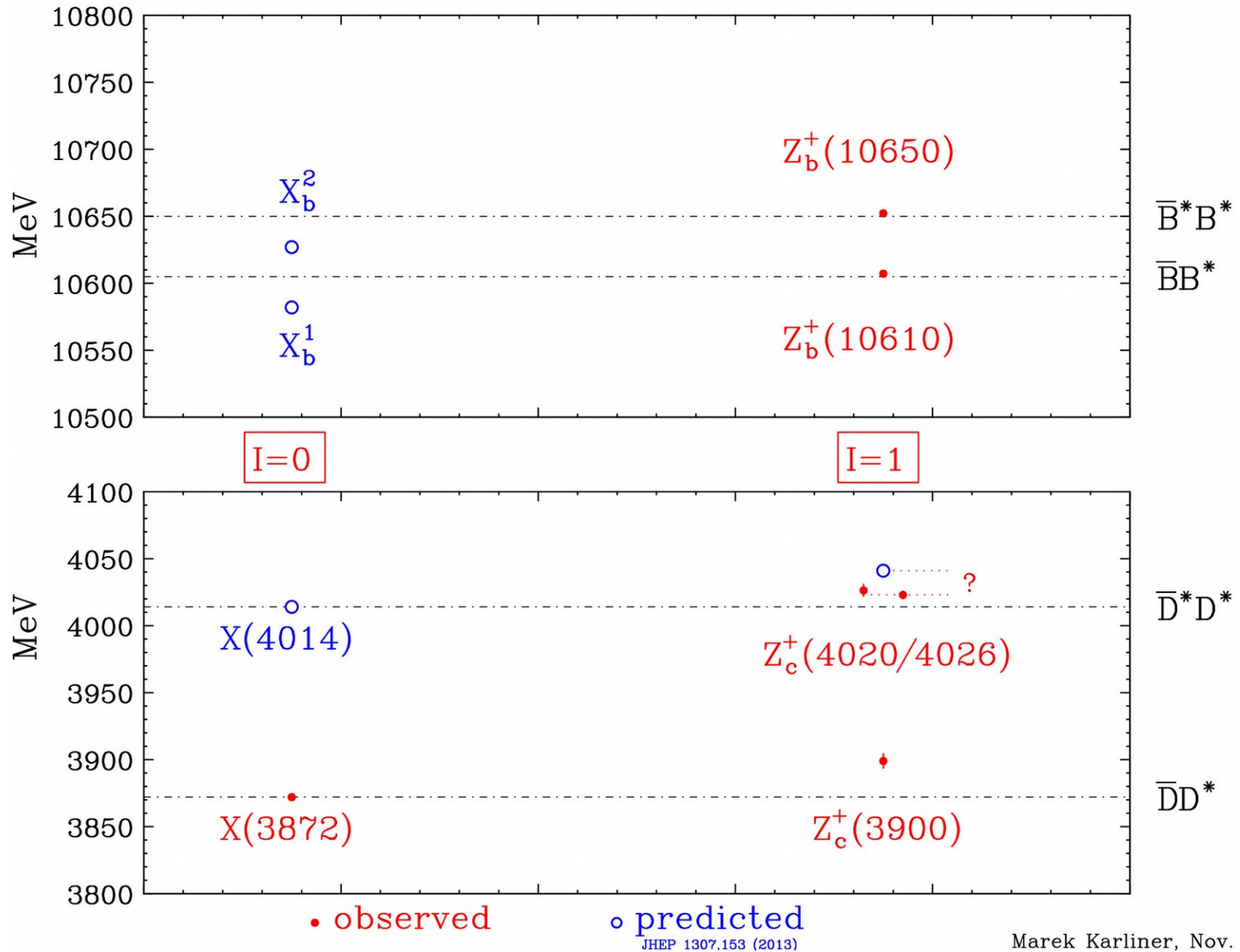
$\Rightarrow$ tightly bound exotics, tetraquarks

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

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

exotic heavy quarkonia vs. two meson thresholds



Marek Karliner, Nov. 2013

The Z_Q resonances decay into

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

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

$\implies$ 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

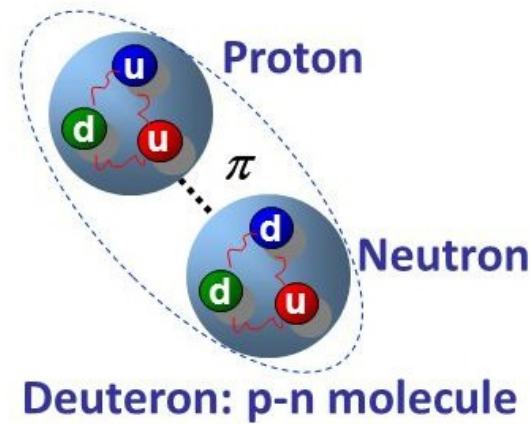
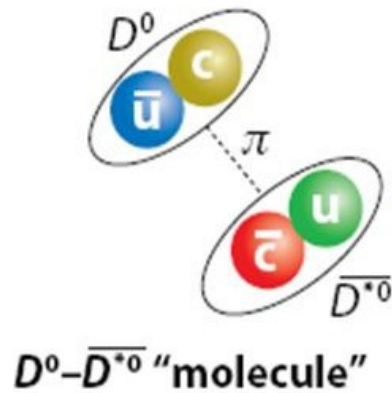
despite large phase space (hundreds of MeV)

narrow widths in decays into $\bar{Q}Q\pi$

$\Rightarrow$ very small overlap of wave functions: $|\langle i|f\rangle|^2 \ll 1$

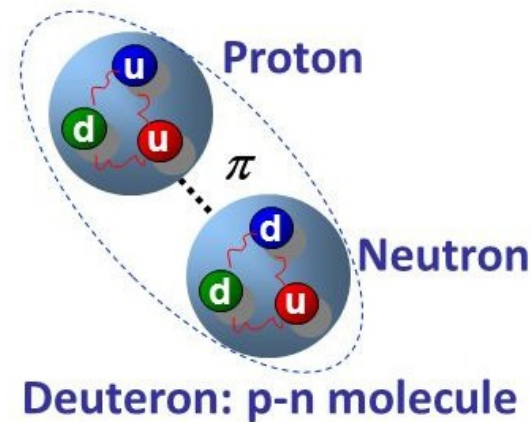
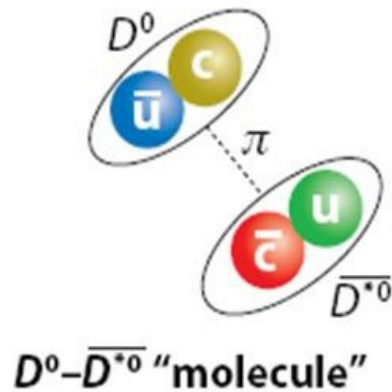
strong hint in favor of molecular interpretation

Hadronic molecules: deuteron-like



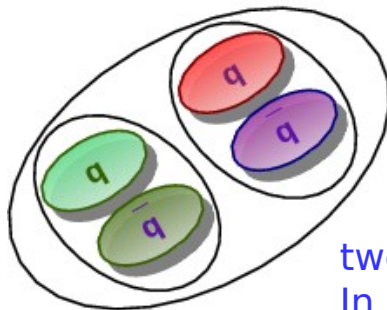
cf. two couples on a joint trip,
but separate bedrooms

Hadronic molecules: deuteron-like



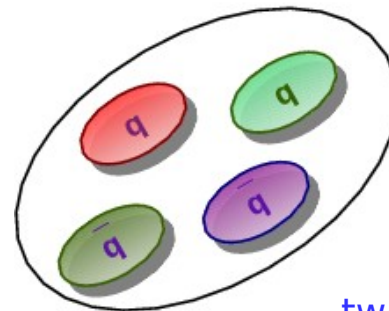
Tetraquarks: same 4 quarks, but tightly bound:

Hadronic
Molecule



two couples
In separate bedrooms

Tetraquark



two couples
In same bedroom...

Belle, PRL 116, 212001 (2016):

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

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

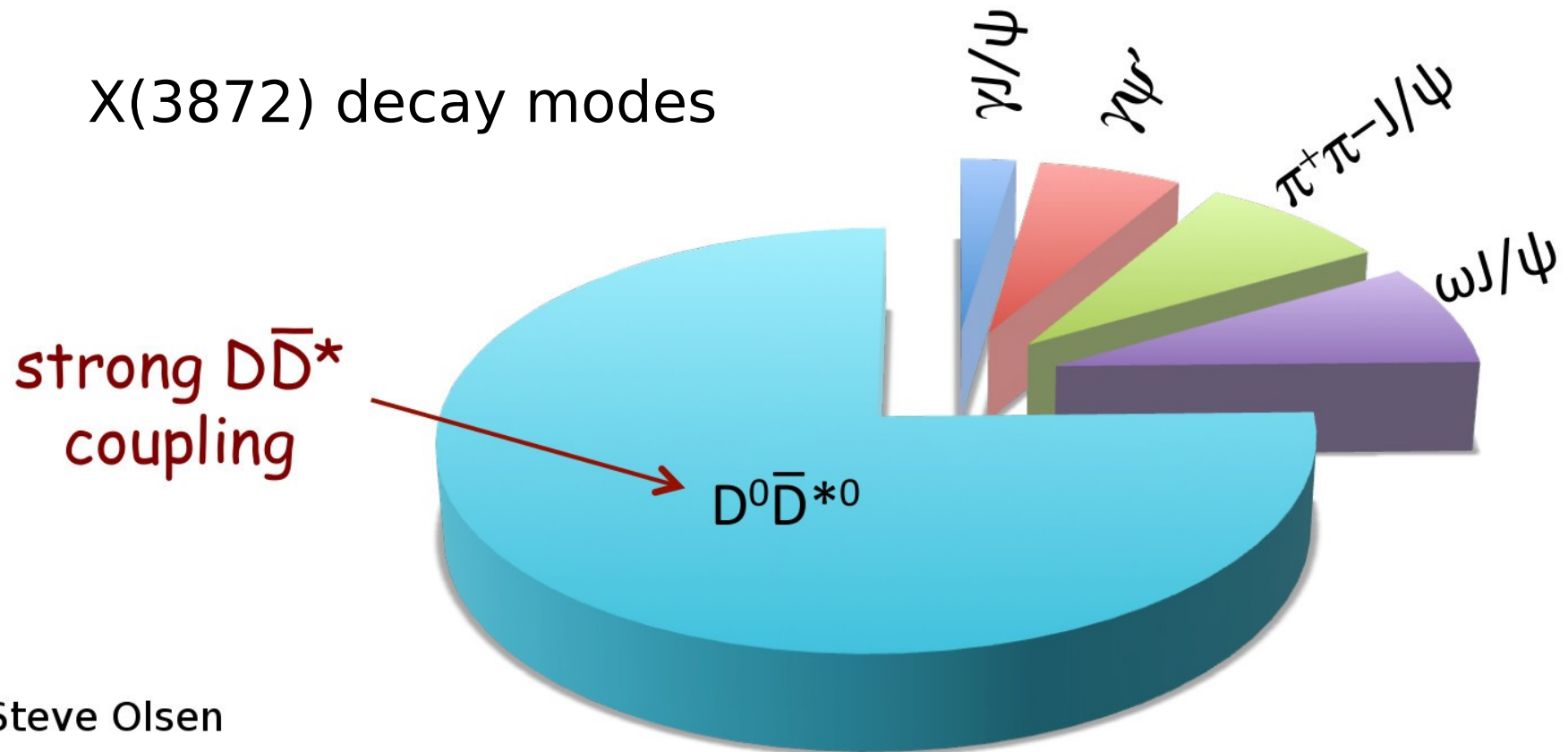
$$\frac{\Gamma(Z_c(3885) \rightarrow \bar{D}D^*)}{\Gamma(Z_c(3885) \rightarrow J/\psi\pi)} = 6.2 \pm 1.1 \pm 2.7$$

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

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

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

$X(3872)$ decay modes



Steve Olsen

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

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 $Q\bar{Q}'$, $Q = c, b$, $\bar{Q}' = \bar{c}, \bar{b}$:

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

$$\Sigma_c\bar{D}^*, \Sigma_cB^*, \Sigma_b\bar{D}^*, \Sigma_bB^*, \text{ the lightest of new kind}$$

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

$c\bar{c}$ 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:

$$\Sigma_c\Sigma_c, \Sigma_c\Lambda_c, \Sigma_c\Lambda_b, \Sigma_b\Sigma_b, \Sigma_b\Lambda_b, \text{ and } \Sigma_b\Lambda_c.$$

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	$\Upsilon(nS)p$
$\Sigma_c\bar{\Lambda}_c$	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	$\Upsilon(nS)\pi\pi$

^aIgnoring annihilation of quarks.

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

^cBased on isospin-averaged masses.

^dThresholds differ by 27.6 MeV.

New Exotic Meson and Baryon Resonances from Doubly Heavy Hadronic Molecules

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

DOI: 10.1103/PhysRevLett.115.122001

PACS numbers: 14.20.Pt, 12.39.Hg, 12.39.Jh, 14.40.Rt

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

R. Aaij *et al.**

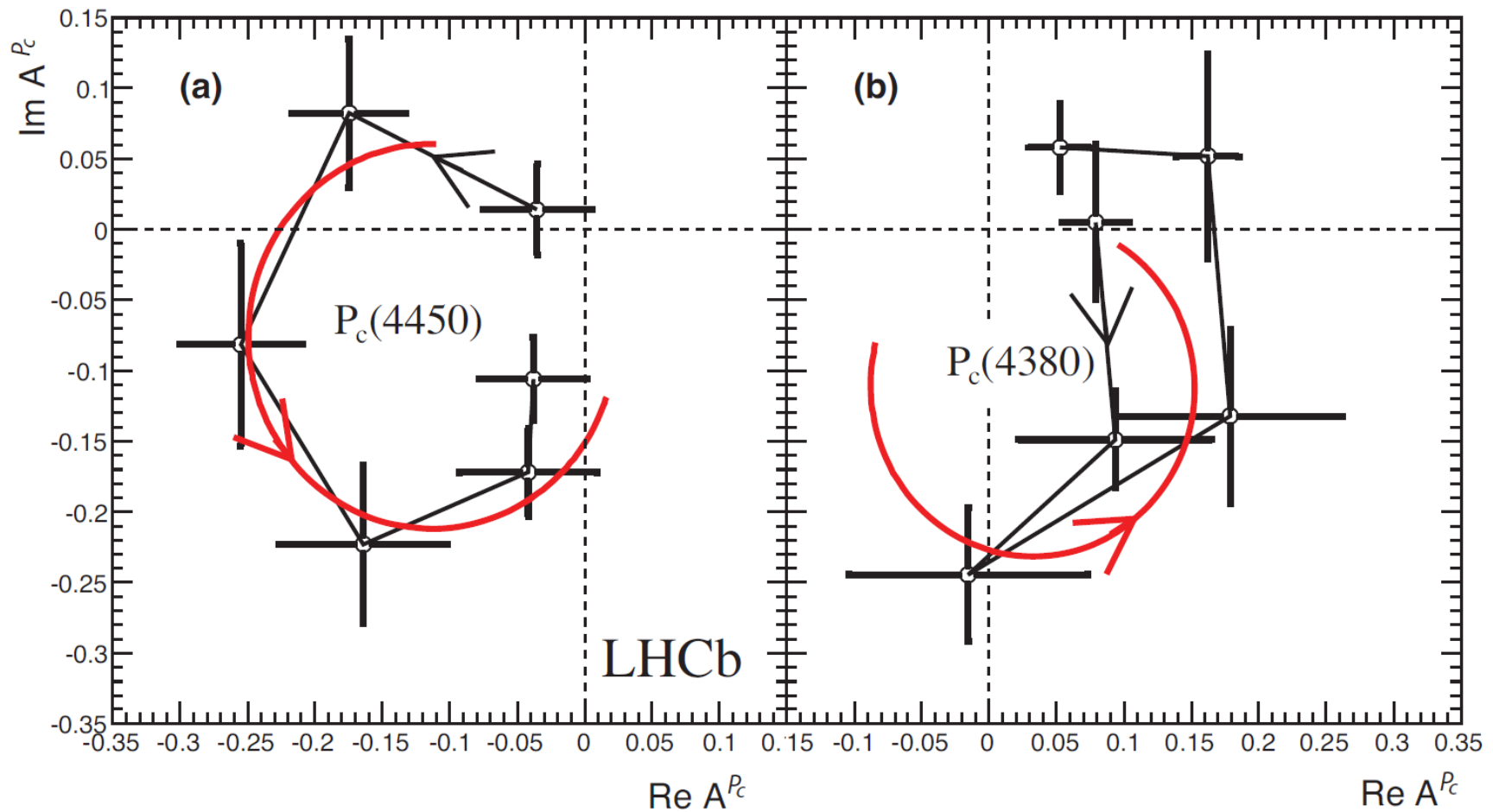
(LHCb Collaboration)

(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 $\Lambda_b^0 \rightarrow J/\psi K^- p$ 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 $4380 \pm 8 \pm 29 \text{ MeV}$ and a width of $205 \pm 18 \pm 86 \text{ MeV}$, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$ and a width of $39 \pm 5 \pm 19 \text{ MeV}$. The preferred J^P assignments are of opposite parity, with one state having spin $3/2$ and the other $5/2$.

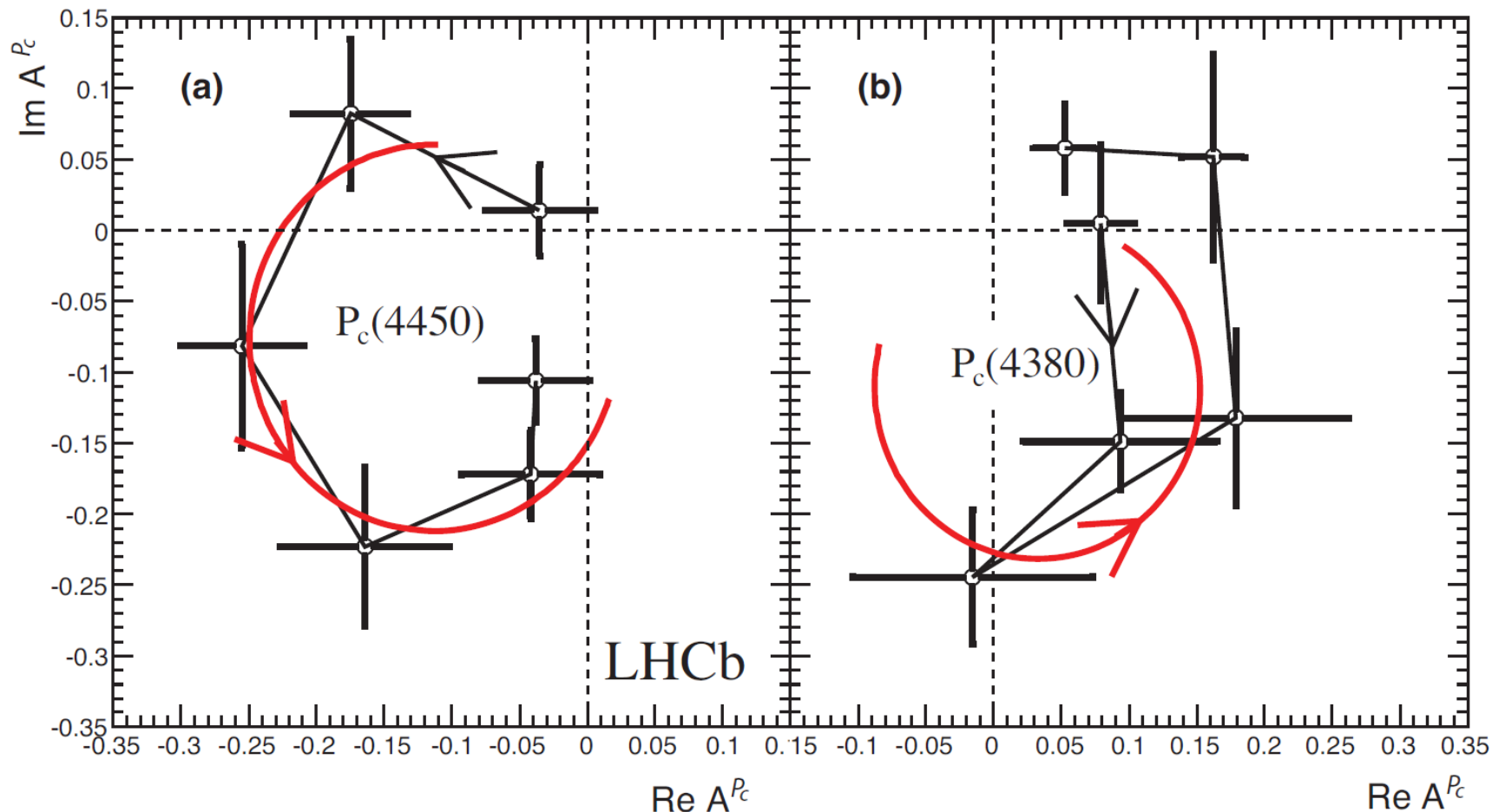
DOI: 10.1103/PhysRevLett.115.072001

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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 Argand plot not resonance-like
 ???

$P_c(4450)$ 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

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

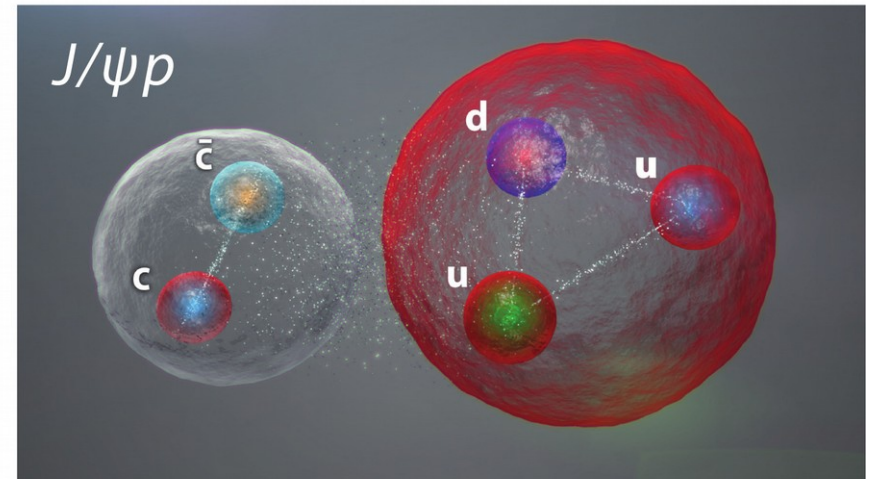
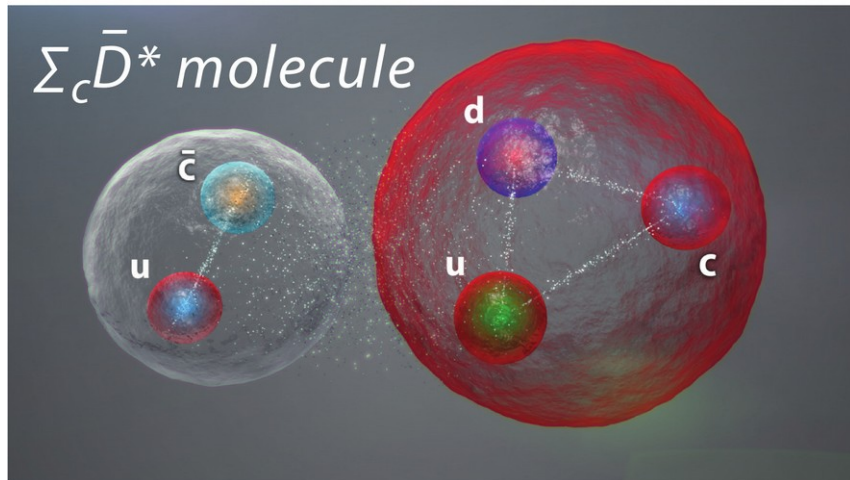
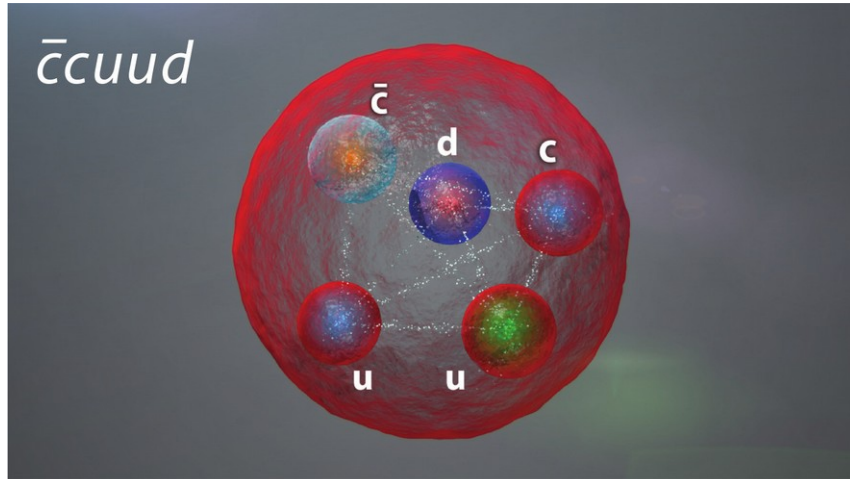
To get $\Gamma = 39$ MeV, the matrix element must be small .

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”

$\implies$ need a different production mechanism

Photoproduction of exotic baryon resonances

MK & J. Rosner, arXiv:1508.01496

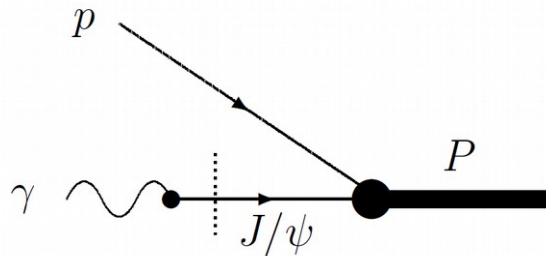
Q. Wang, X. H. Liu and Q. Zhao, arXiv:1508.00339

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

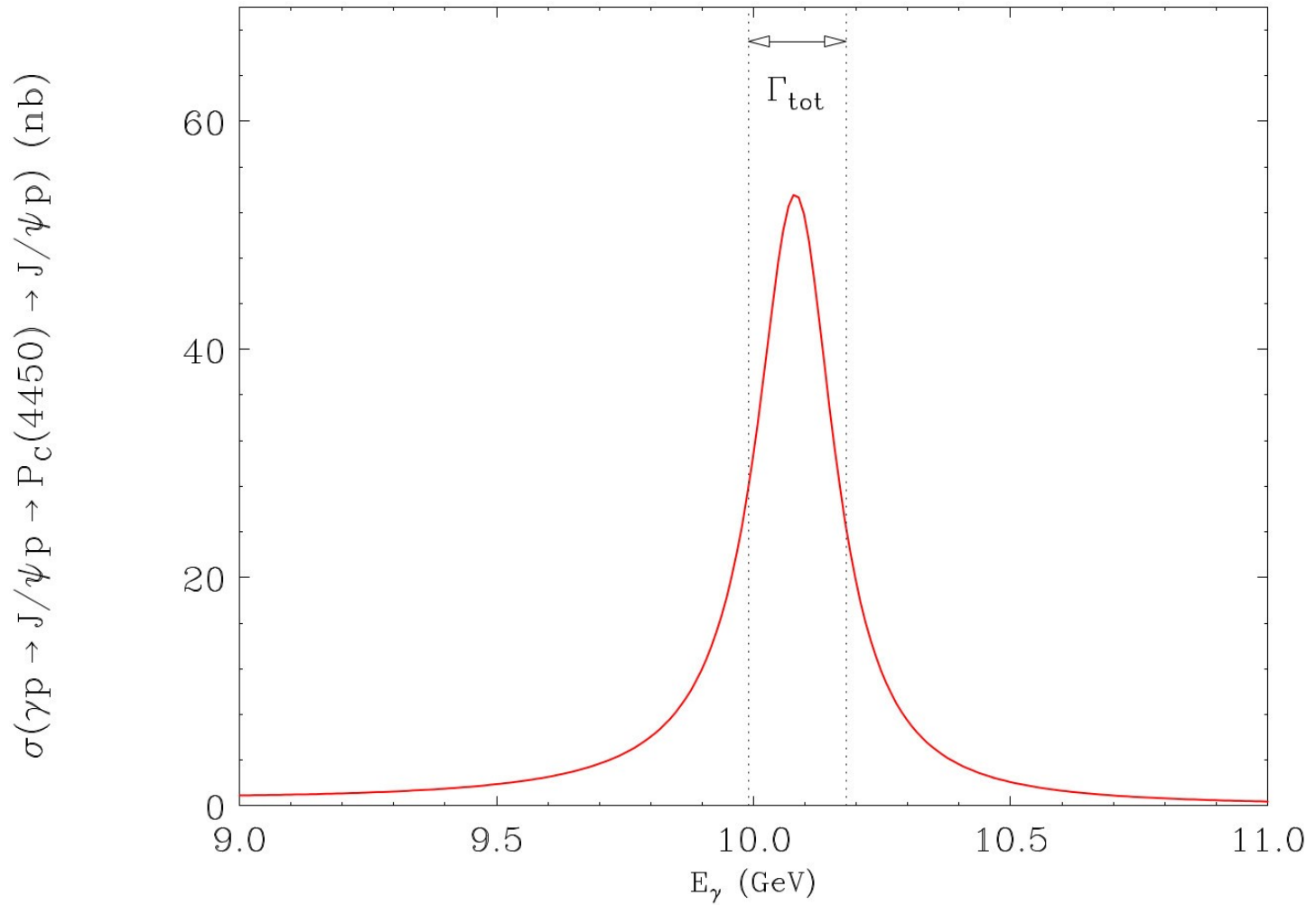
LHCb: new exotic resonances in $J/\psi p$ channel:

$\Rightarrow$ natural candidates for photoproduction

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



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



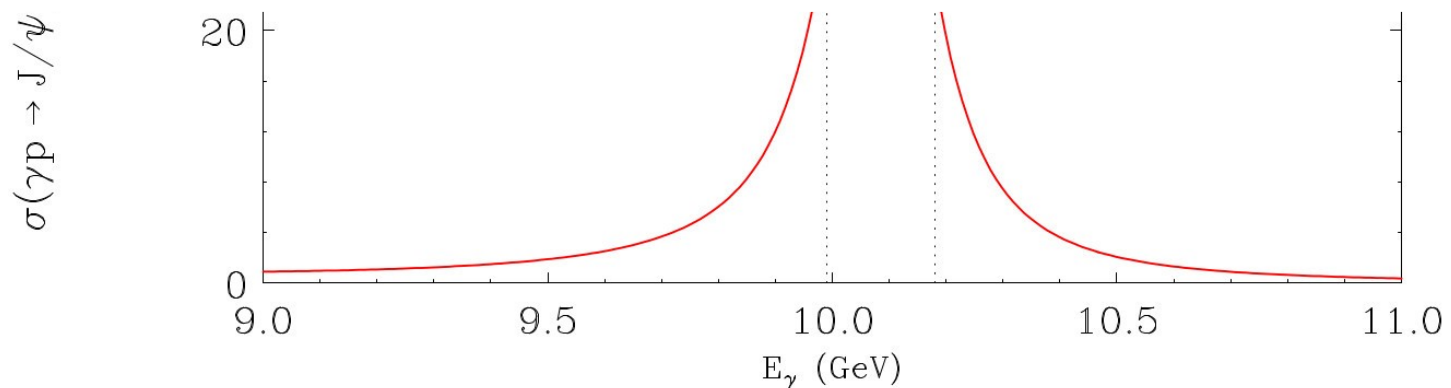
Cross section for resonant photoproduction $\gamma p \rightarrow J/\psi p \rightarrow P_c(4450) \rightarrow J/\psi p$, assuming $B_{\text{out}} = 0.1$, plotted as function of the incident photon energy E_γ . The vertical dotted lines indicate the width of the $P_c(4450)$ resonance.

Caveat:

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

$$BR(\text{quarkonium mode}) \ll BR(\text{“fall apart” mode})$$

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



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.

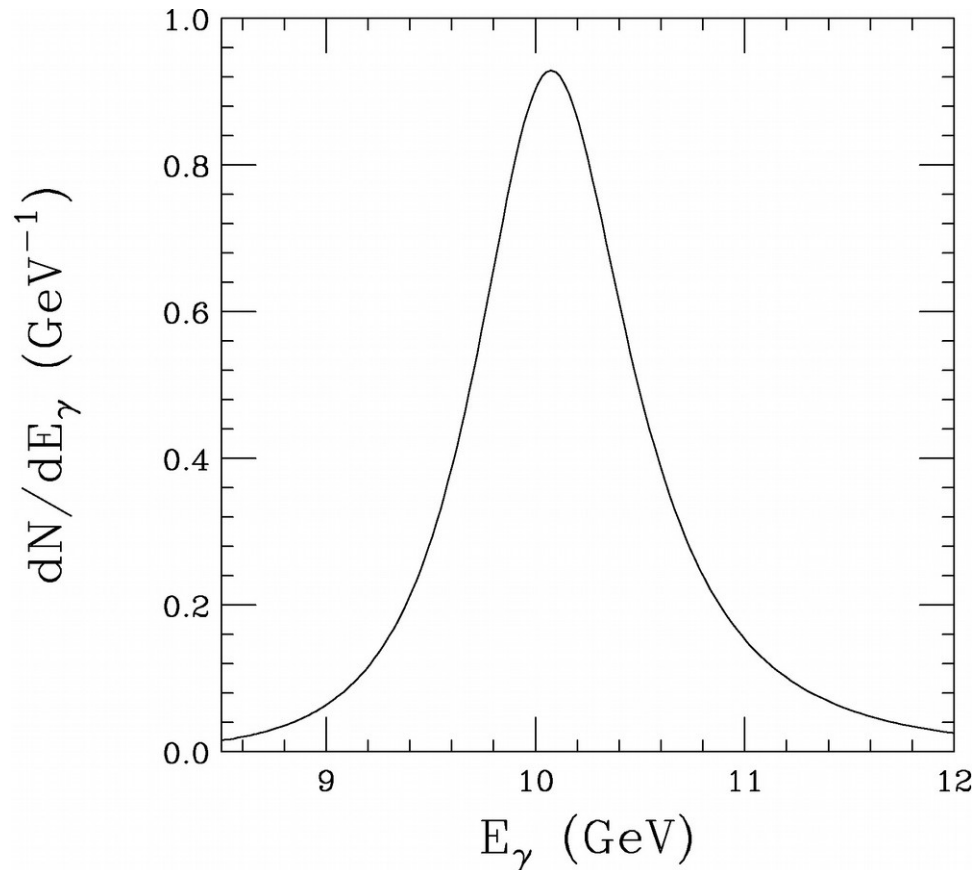
$$P_c(4380) \text{ and } P_c^+(4450) \rightarrow J/\psi p \Rightarrow I_3 = +\frac{1}{2}$$

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



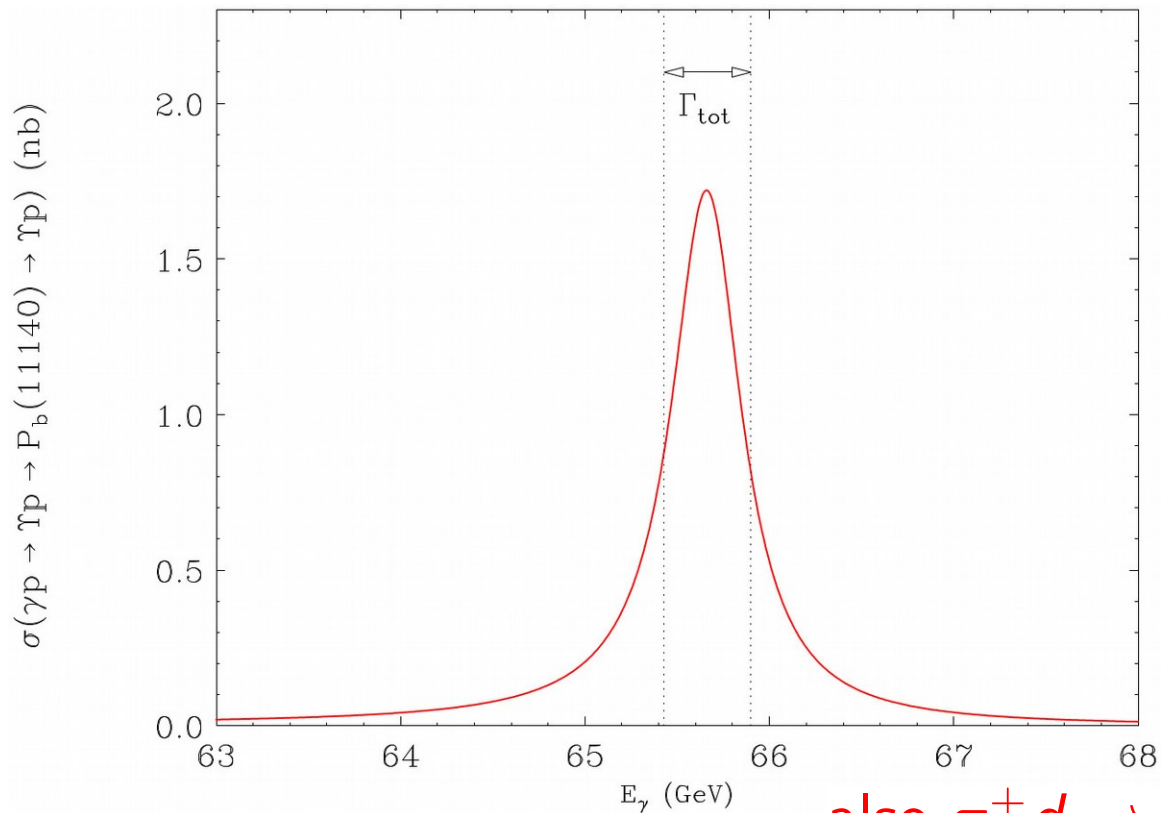
MK and J.L. Rosner,
arXiv:1705.07691 [hep-ph].

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

$$E_\gamma = 65.66 \text{ GeV},$$

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



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

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

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

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

LHC not expected to see prompt production

$$pp \rightarrow P_c(4450) + X$$

crucial test of molecular picture

bottom analogue of $X(3872)$:

- X_b and $\chi_{b1}(3P)$ have the same quantum numbers
 - their masses are close
- $\Rightarrow$ mixing is inevitable

$\Rightarrow$ X_b might have been seen already,
by ATLAS, D0 and LHCb,
camouflaging as $\chi_{1b}(3P)$

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

$\Sigma_b^+ \Sigma_b^-$ 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 $\rightarrow J/\psi \phi$
in $B \rightarrow XK \rightarrow J/\psi \phi K$

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

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

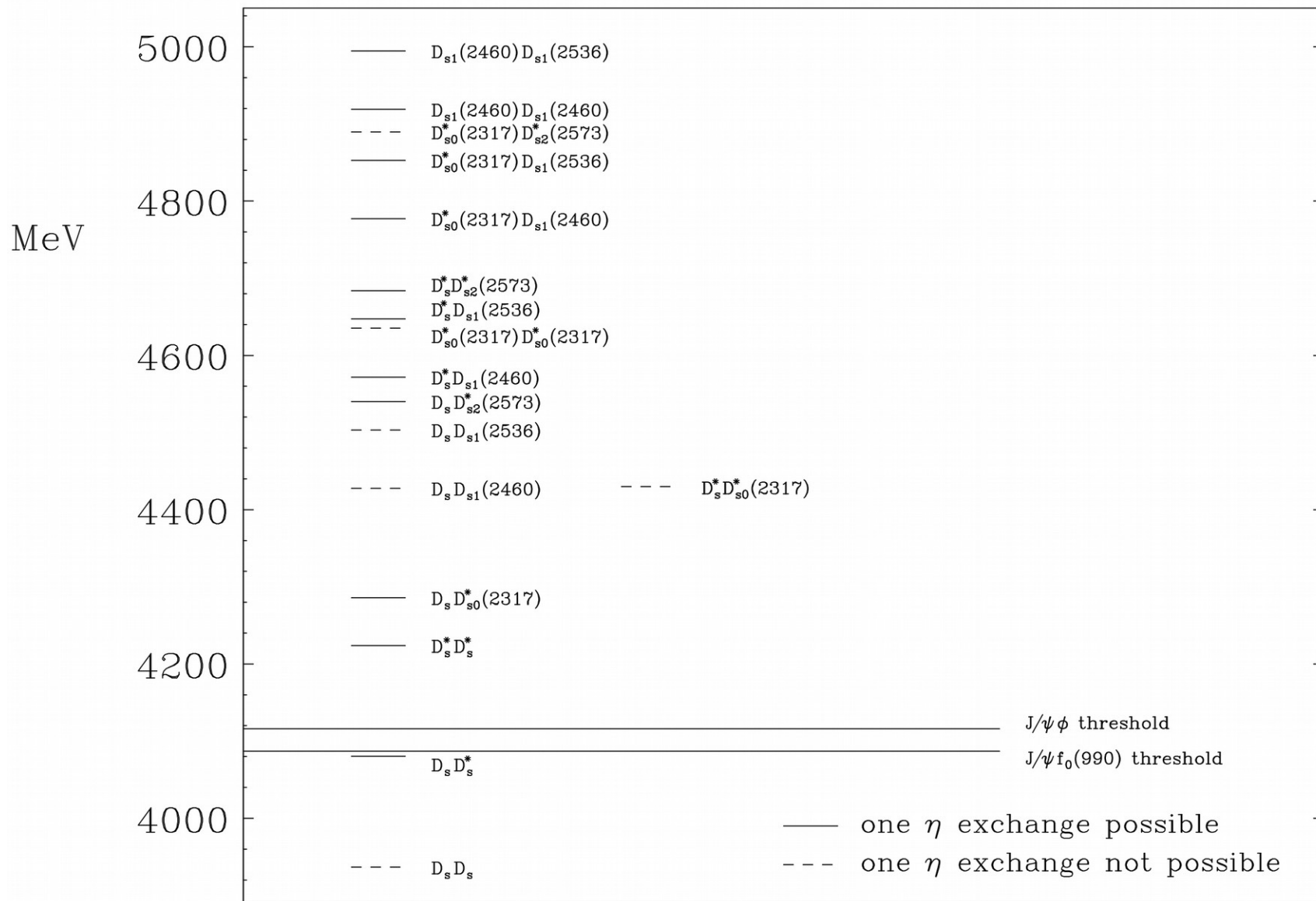
States (J^P)	M (MeV)	$M - M(J/\psi)$ $-M(\phi)$	Binding by η ?	Allowed J^P
$D_s^+(0^-) D_s^-(0^-)$	3936.6	-179.8	No	—
$D_s^+(0^-) D_s^{*-}(1^-)$	4080.4	-36.0	Yes	1^+
$D_s^{*+}(1^-) D_s^{*-}(1^-)$	4224.2	107.8	Yes	$0^+, 2^+{}^a$
$D_s^+(0^-) D_{s0}^{*-}(2317)(0^+)$	4286.0	169.6	Yes	0^-
$D_s^+(0^-) D_{s1}^-(2460)(1^+)$	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 $B \rightarrow KX$ because of kinematic mass limit.

Thresholds involving two D_s mesons



doubly heavy baryons QQq :

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

must exist, and now have been seen

fascinating challenge for EXP & TH

Original argument:

LHCb sees thousands of B_c -s

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

masses of doubly-heavy baryons:
use same toolbox that predicted
b baryon masses.

- Phenomenological approach
- Identify eff. d.o.f. & their interactions
- Extract model parameters from exp
- Then use them to make predictions

ccq mass calculation

sum of :

- $2m_c$
- V_{cc} in 3_c^*
- $V_{HF}(cc)$
- $V_{HF}(cq)$
- m_q

ccq mass calculation

sum of :

- $2m_c$
 - V_{cc} in 3_c^*
 - $V_{HF}(cc)$
- } no exp info !
- $V_{HF}(cq)$
 - m_q

Effective masses

in mesons:

$$m_u^m = m_d^m = m_q^m = 310 \text{ MeV}, \quad m_c^m = 1663.3 \text{ MeV}$$

in baryons:

$$m_u^b = m_d^b = m_q^b = 363 \text{ MeV}, \quad m_c^b = 1710.5 \text{ MeV}$$

$V(cc)$ from $V(c\bar{c})$:

$$\bar{M}(c\bar{c} : 1S) \equiv [3M(J/\psi) + M(\eta_c)]/4 = 3068.6 \text{ MeV}$$

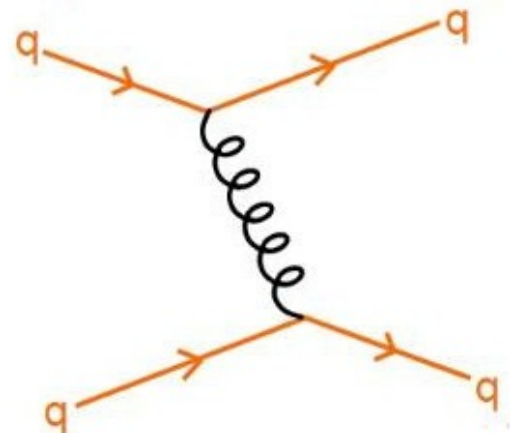
$$V(c\bar{c}) = \bar{M}(c\bar{c} : 1S) - 2m_c^m = -258.0 \text{ MeV}.$$

$$V(cc) = \frac{1}{2} V(c\bar{c}) = -129.0 \text{ MeV}.$$

in weak coupling follows
from color algebra in 1gx

here a dynamical assumption:

$V(cc)$ and $V(c\bar{c})$ factorize
into color $\times$ space



gluon exchange by 2 quarks

$V_{HF}(cc)$ from $V_{HF}(c\bar{c})$:

$$V_{HF}(cc) = \frac{a_{cc}}{m_c^2}$$

$$V_{HF}(c\bar{c}) = M(J/\psi) - M(\eta_c) = 113.2 \text{ MeV} = \frac{4a_{\bar{c}c}}{m_c^2}$$

assume $a_{cc} = \frac{1}{2}a_{c\bar{c}}$,

$$\Rightarrow \frac{a_{cc}}{m_c^2} = 1/2 \cdot \frac{M(J/\psi) - M(\eta_c)}{4} = 14.2 \text{ MeV}$$

Contributions to Ξ_{cc} mass

Contribution	Value (MeV)
$2m_c^b + m_q^b$	3783.9
cc binding	−129.0
$a_{cc}/(m_c^b)^2$	14.2
$−4a/m_q^b m_c^b$	−42.4
Total	3627 ± 12

The ± 12 MeV error estimate from
ave. error for Qqq baryons

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

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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](https://doi.org/10.1103/PhysRevD.90.094007)

PACS numbers: 14.20.Lq, 14.20.Mr, 12.40.Yx

3627+-12 MeV

Observation of the doubly charmed baryon Ξ_{cc}^{++}

LHCb collaboration[†]

Abstract

A highly significant structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the Λ_c^+ baryon is reconstructed in the decay mode $p K^- \pi^+$. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon Ξ_{cc}^{++} . The mass, measured relative to that of the Λ_c^+ baryon, is found to be 3621.40 ± 0.72 (stat) ± 0.27 (syst) ± 0.14 (Λ_c^+) MeV/ c^2 , where the last uncertainty is due to the limited knowledge of the Λ_c^+ mass. The state is observed in a sample of proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 1.7 fb^{-1} , and confirmed in an additional sample of data collected at 8 TeV.

3621+-1 MeV

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	$\dots$
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

LHCb: 3621 ± 1

doubly heavy baryons predicted lifetimes (fs)

Baryon	This work	[28]	[51]	[71]	[72]
$\Xi_{cc}^{++} = ccu$	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	—	—

[28] K. Anikeev, D. Atwood, F. Azfar, S. Bailey, C. W. Bauer, W. Bell, G. Bodwin, E. Braaten *et al.*, *Workshop on B Physics at Conferences C99-09-23.2 and C00-02-24 (Batavia, IL, Fermilab, 2001)*, arXiv:hep-ph/0201071.

[71] J. D. Bjorken, Fermilab Report No. FERMILAB-PUB-86-189-T, <http://lss.fnal.gov/archive/1986/pub/fermilab-pub-86-189-t.pdf>.

[72] M. A. Moinester, *Z. Phys. A* **355**, 349 (1996).

[51] V. V. Kiselev and A. K. Likhoded, *Usp. Fiz. Nauk* **172**, 497 (2002) [*Sov. Phys. Usp.* **45**, 455 (2002)].

Predicted isospin splittings (MeV) in QQq baryons.

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

MK & J. Rosner, PRD 96, 033004 (2017), arXiv:1706.06961

can the strong QQ interaction stabilize
 H_{QQ} : $(QQqudd)$ hexaquarks,
heavy-quark analogue of the H dibaryon?
 $\Rightarrow$ below $2\Lambda_Q$
but above $\Xi_{QQ}N$
 $\Rightarrow$ unstable
an ugly duckling...

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

The ugly duckling that became a swan!



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

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(Received 28 July 2017; published 15 November 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 10389 ± 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.

DOI: [10.1103/PhysRevLett.119.202001](https://doi.org/10.1103/PhysRevLett.119.202001)

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)

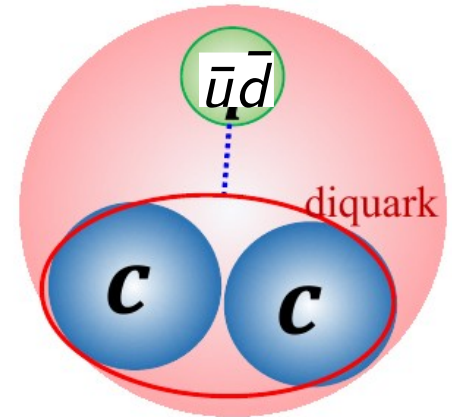
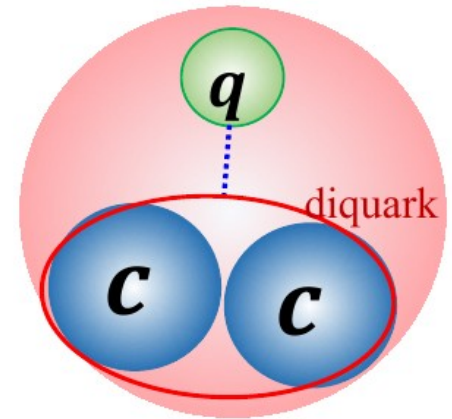
$\Rightarrow bb$ must be $\bar{\mathbf{3}}_c$; Fermi stats: spin 1

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

$\Rightarrow (bb)(\bar{u}\bar{d})$ 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,

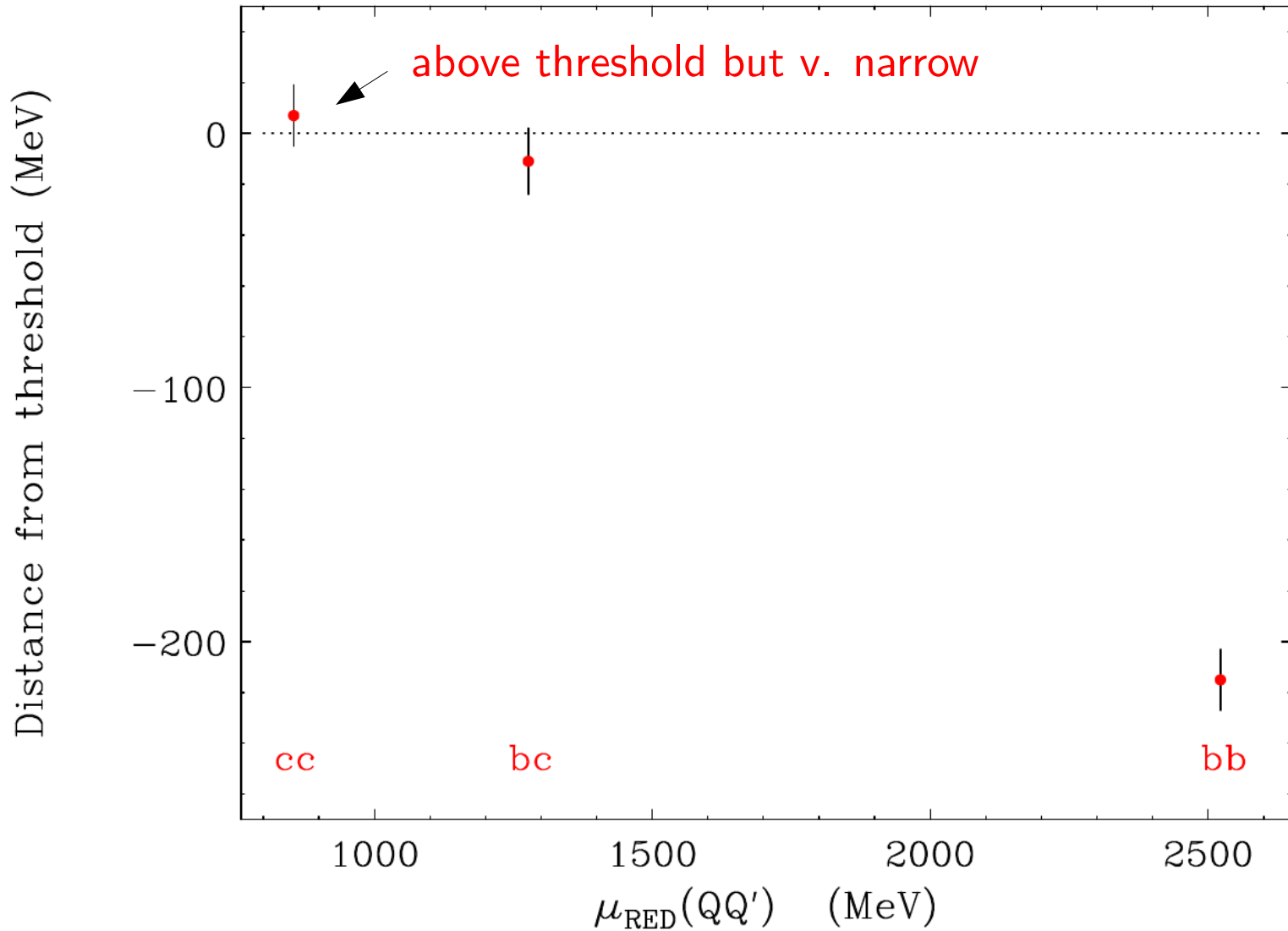
but if use measured $M(X_{cc}^{++}) \Rightarrow$ only 1 MeV above $D^0 D^{+*}$

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).



Tetraquark production

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

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

hadronization:

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

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

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

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

Tetraquark production

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

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

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

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

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

now

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

A. Ali

(private communication)

$$Z \rightarrow b\bar{b} b\bar{b}$$

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

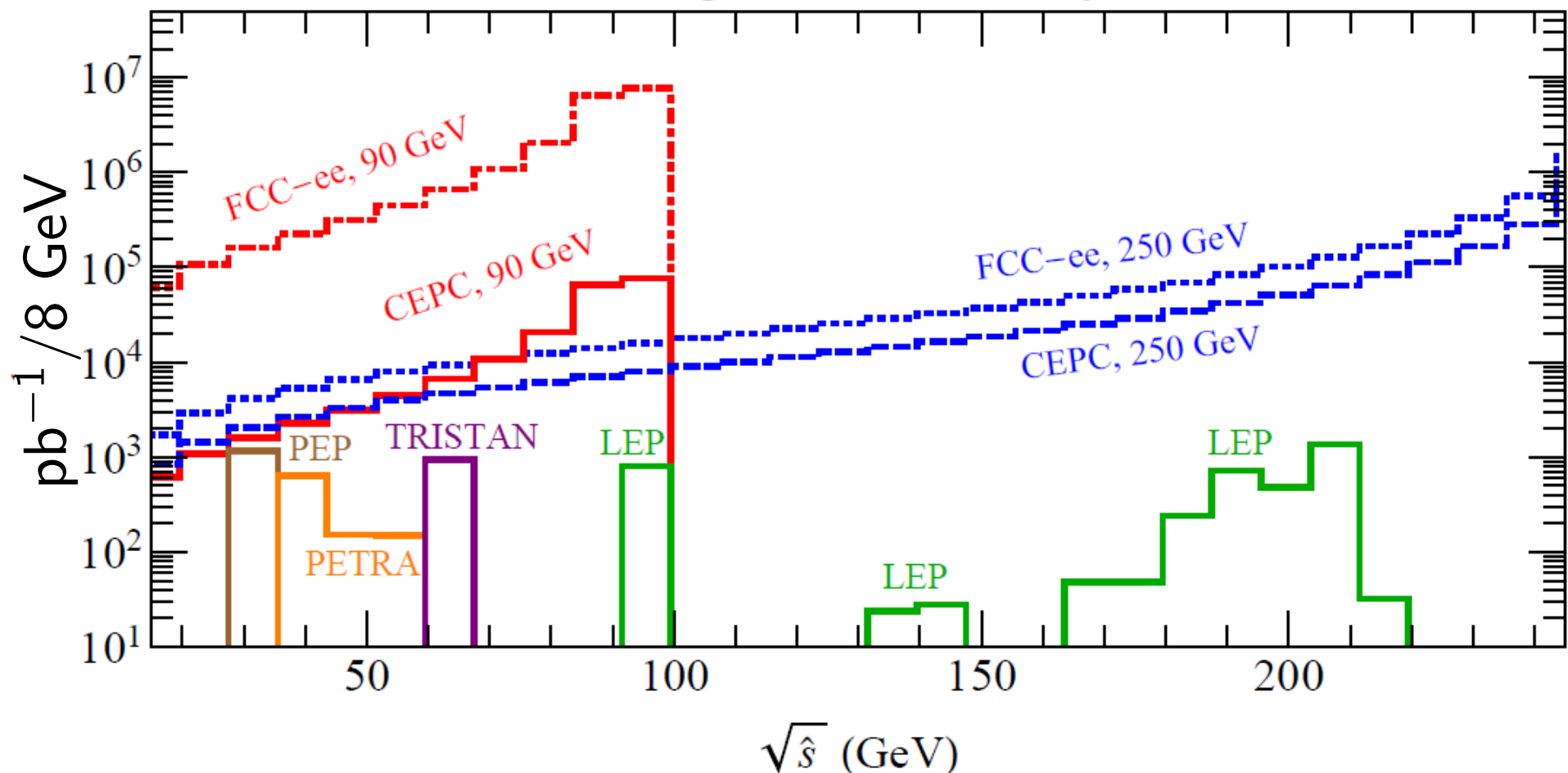
$\Rightarrow$ produce bbq baryons and $bb\bar{u}\bar{d}$ Tq-s

the challenge: reliable estimate of σ

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

$$\mathcal{B}(Z \rightarrow T_{[\bar{u}\bar{d}]}^{\{bb\}} + \bar{b}\bar{b}) = (1.4_{-0.5}^{+1.1}) \times 10^{-6},$$

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

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

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

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

a kinematic suppression factor

$$F(x) = 1 - 8x + 8x^3 - x^4 + 12x^2 \ln(1/x),$$

$$x \equiv \{[M(\bar{B}) + M(D)]/M(bb\bar{u}\bar{d})\}^2,$$

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

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

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

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

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

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

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

$$(bb\bar{u}\bar{d}) \rightarrow \Omega_{bc} \bar{p}, \Omega_{bc} \bar{\Lambda}_c, \Xi_{bc}^0 \bar{p}, \Xi_{bc}^0 \bar{\Lambda}_c$$

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

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

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

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

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

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

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

two v. different types of exotics:

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

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

e.g.

$$Z_b(10610)$$

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

molecule

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

tightly-bound
tetraquark

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

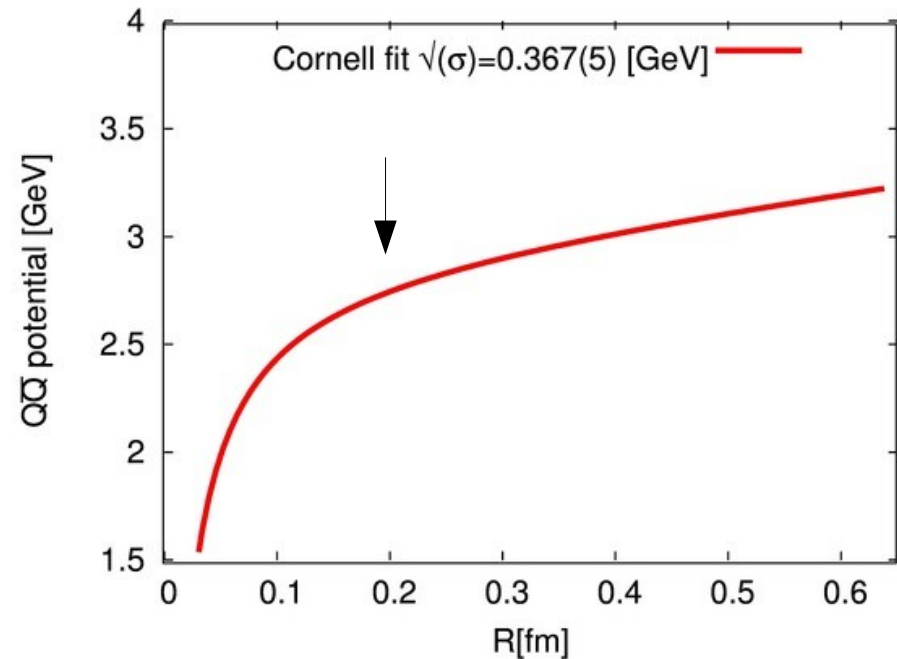
$$m_b \approx 5 \text{ GeV}$$

$$\Rightarrow R(bb) \sim 0.2 \text{ fm}$$

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

$$\Rightarrow B(bb) \approx -280 \text{ MeV}$$

tightly bound, but $\bar{3}_c$,
so cannot disengage from $\bar{u}\bar{d}$



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

if $b\bar{b}$ compact $\Rightarrow$ color singlet:

decouple from $u\bar{d}$, $Z_b \rightarrow \gamma\pi^+$

so only semi-stable config.,

“hadronic molecule:” $\bar{B}B^* \sim 1 \text{ GeV}$ above $\gamma\pi$

yet narrow $\sim 15 \text{ MeV}$, because $R(\bar{B}B^*)/R(\gamma) \gg 1$

very different!

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

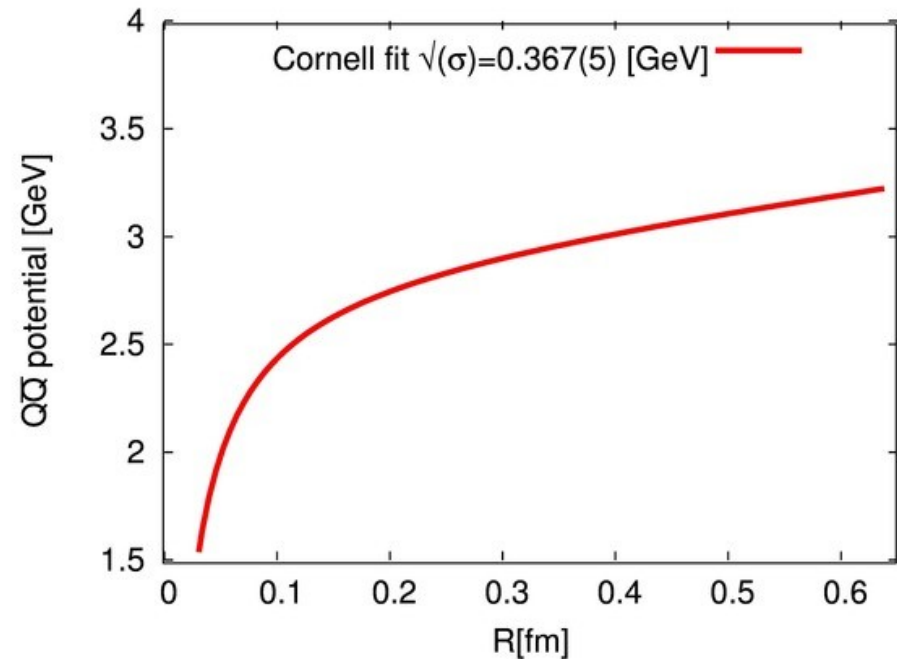
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bottom line: $T(bb\bar{u}\bar{d})$ a tetraquark, $Z_b(b\bar{b}u\bar{d})$ a molecule

very different!

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

Phys. Rev. D **95**, 034011 (2017) MK, J.L. Rosner, S.Nussinov

Toolbox borrowed from QQq baryons

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

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

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

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

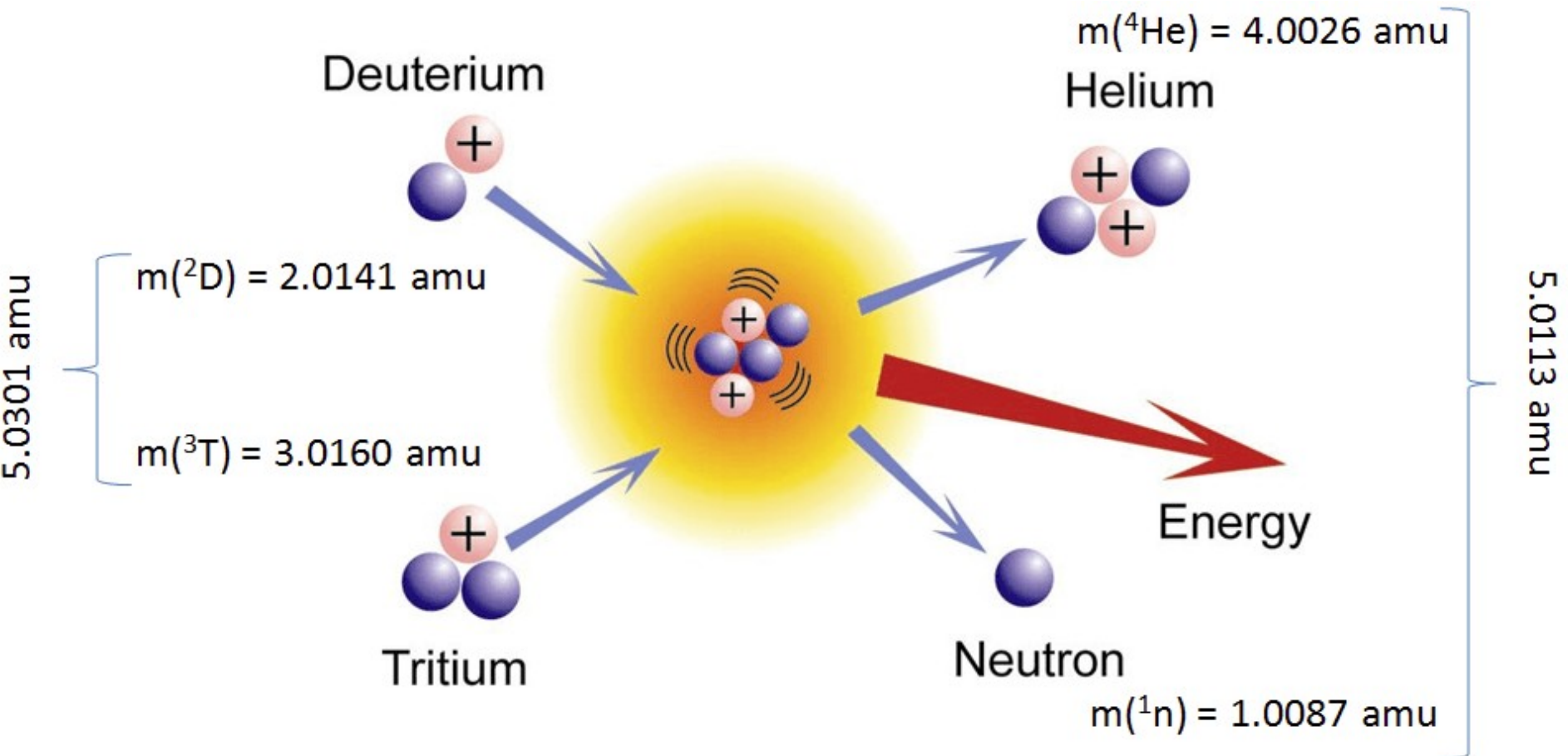
production of an extra $Q\bar{Q}$: probability $\sim 0.1\%$

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

$\Rightarrow$ 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

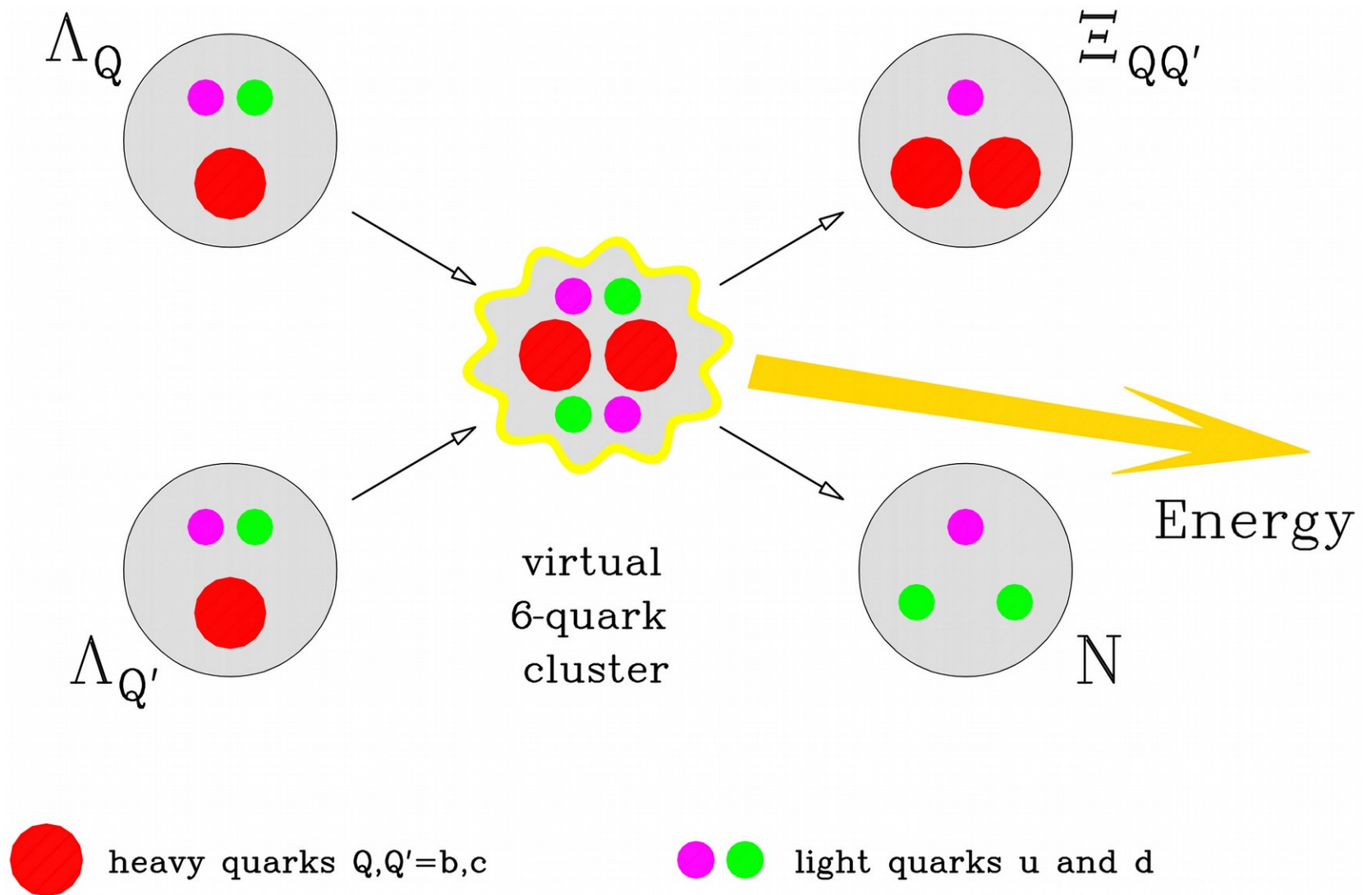
DT fusion: $DT \rightarrow {}^4\text{He} n$

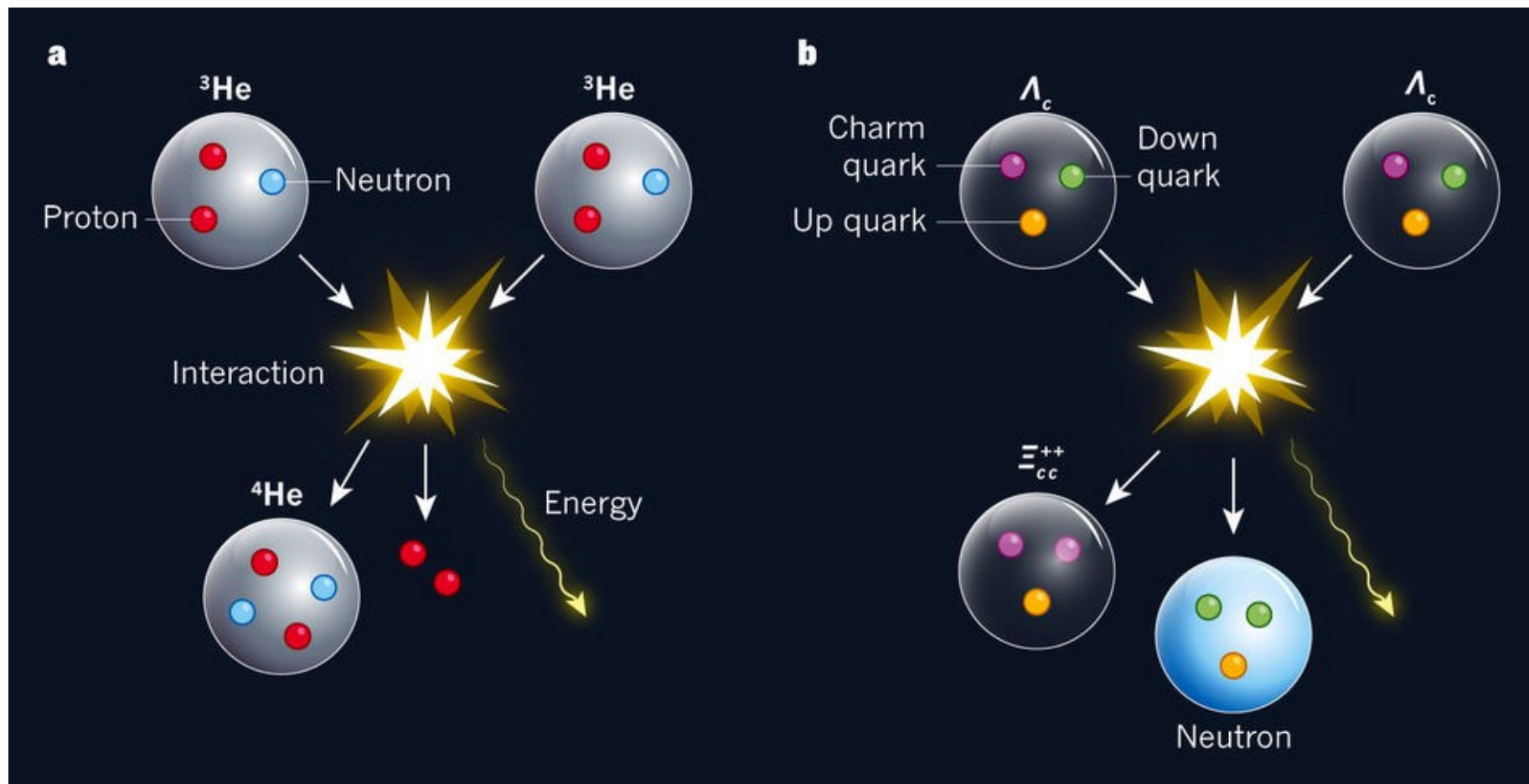


$$Q = 0.0188 \text{ amu} \times 931.481 \text{ MeV/amu} = 17.5 \text{ MeV}$$

Nuclear fusion reactions w. light nuclei

$D T$	$\rightarrow$	${}^4\text{He } n$	$Q = 17.59 \text{ MeV},$
$D D$	$\rightarrow$	${}^3\text{He } n$	$Q = 3.27 \text{ MeV},$
$D D$	$\rightarrow$	$T p$	$Q = 4.04 \text{ MeV},$
$T T$	$\rightarrow$	${}^4\text{He } 2n$	$Q = 11.33 \text{ MeV},$
$D {}^3\text{He}$	$\rightarrow$	${}^4\text{He } p$	$Q = 18.35 \text{ MeV},$
${}^3\text{He } {}^3\text{He}$	$\rightarrow$	${}^4\text{He } 2p$	$Q = 12.86 \text{ MeV}.$





Nature,
Nov 2, 2017

Quark-level analogue of nuclear fusion with doubly heavy baryons

Marek Karliner¹ & Jonathan L. Rosner²

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 discovery¹ 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 (A_c) undergo fusion to produce the doubly charmed baryon Ξ_{cc}^{++} and a neutron n ($A_c A_c \rightarrow \Xi_{cc}^{++} n$), resulting in an energy release of 12 MeV. This reaction is a quark-level analogue of the deuterium-tritium nuclear fusion reaction ($DT \rightarrow {}^4\text{He } n$). The much larger binding energy (approximately 280 MeV) between two bottom quarks (b) causes the analogous reaction with bottom quarks ($A_b A_b \rightarrow \Xi_{bb}^0 n$) 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 experiment¹ 3621.40 ± 0.78 MeV is consistent with several predictions², 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.

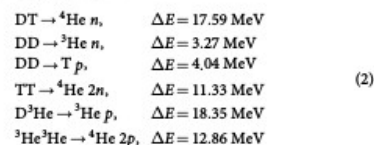
The large binding energy between heavy quarks has some important implications, such as the existence of a stable $bb\bar{u}\bar{d}$ tetraquark (where $\bar{u}$ and $\bar{d}$ are antiup and antidown quarks, respectively) with spin-parity³ $J^P = 1^+ 215$ MeV below the $B^- B^0$ threshold and 170 MeV below the threshold for decay to $B^- B^0 \gamma$, where B^- is a spinless meson composed of $b\bar{u}$, B^0 is a spin-1 meson composed of $b\bar{d}$, 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



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 nucleons⁴, with quarks playing the part of the nucleons, hadrons playing the part of the nuclei and the doubly heavy baryon playing the part of ${}^4\text{He}$:



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 $A_Q A_{Q'} \rightarrow \Xi_{QQ'} N$, 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 $A_Q A_{Q'} \rightarrow \Xi_{QQ'} N$, where $Q, Q' \in \{s, c, b\}$. The trend is clear: ΔE increases monotonically with increasing quark mass. The reaction



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



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



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} masses².

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, $\mu_{\text{red}} = m_Q m_{Q'} / (m_Q + m_{Q'})$, where m_Q and $m_{Q'}$ are the masses of the individual quarks. In Fig. 2, we plot ΔE versus $\mu_{\text{red}}(QQ')$. 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 $\Delta E = -44.95 + 0.0726\mu_{\text{red}}$ (dot-dashed line) describes the data well, which shows that, to a good approximation, ΔE depends linearly on the reduced mass.

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

$\Rightarrow$ Q -value of the reaction:

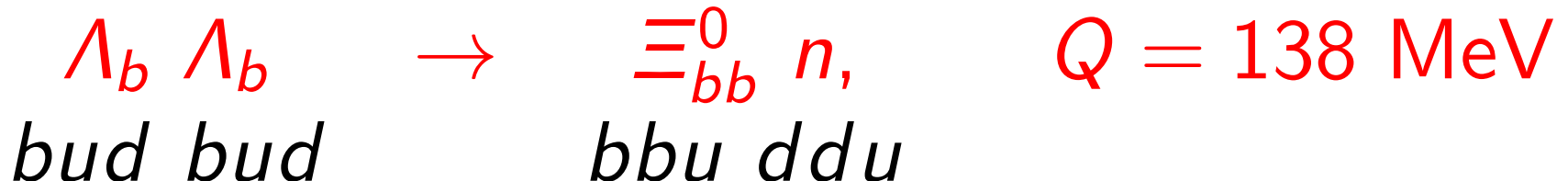


LHCb measured $M(X_{cc}^{++}) = 3621.4 \pm 0.78 \text{ MeV}$

$\Rightarrow$ Q -value of the reaction:



robust estimate of Ξ_{bb}^0 mass, so expect

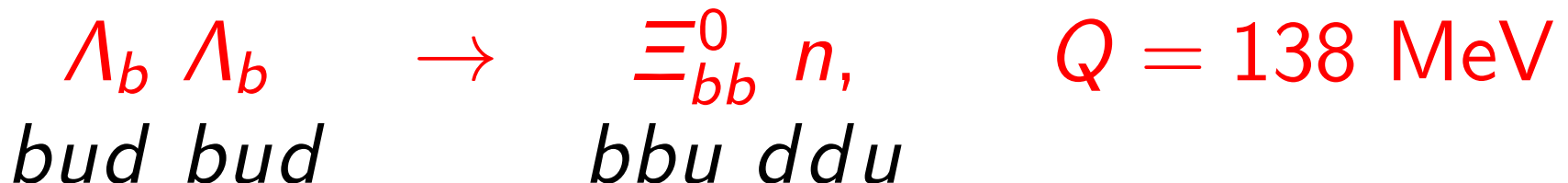


LHCb measured $M(X_{cc}^{++}) = 3621.4 \pm 0.78 \text{ MeV}$

$\Rightarrow$ Q -value of the reaction:



robust estimate of Ξ_{bb}^0 mass, so expect



But no chain reaction, as $\tau(Q) \sim 10^{-13} \text{ sec}$

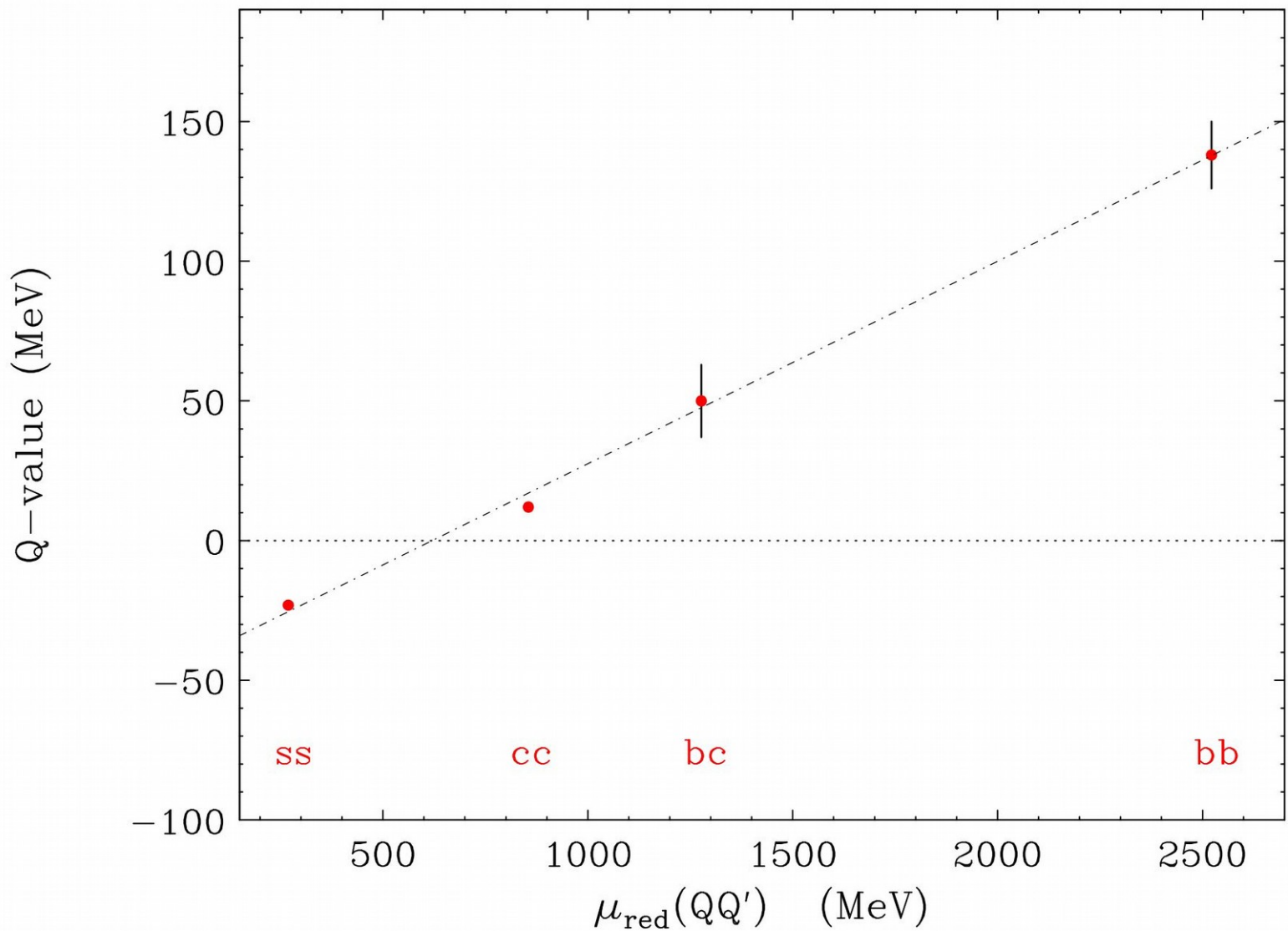
Table I
 Q value in the reaction $\Lambda_Q \Lambda_{Q'} \rightarrow \Xi_{QQ'} N$, $Q, Q' = s, c, b$.

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

^aTo optimize the Q -value we take here $\Xi^0(ssu)$, $N=n$, because $M[\Xi^-(ssd)]$ is 7 MeV larger.

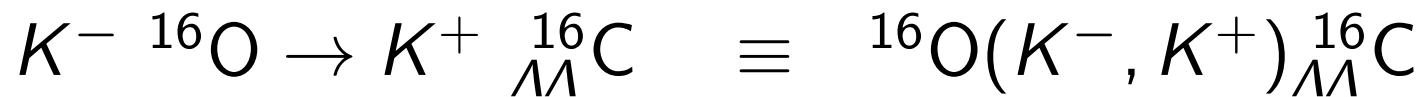
^b Ξ_{bb} mass prediction from Ref. [2].

^cAverage of the two values in Table XI of Ref. [2].



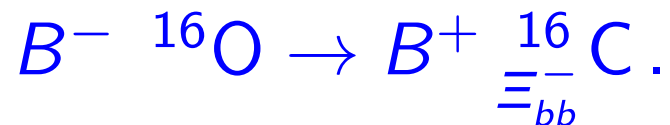
Q -value in the quark-level fusion reactions $\Lambda_Q \Lambda_{Q'} \rightarrow \Xi_{QQ'} N$, $Q, Q' = s, c, b$, plotted against the reduced masses of the doubly-heavy diquarks $\mu_{\text{red}}(QQ')$. The dot-dashed line denotes a linear fit $Q = -44.95 + 0.0726 \mu_{\text{red}}$.

doubly-strange hypernuclei might be produced in



ongoing exp. at J-PARC.

Suggest bottom analogue:



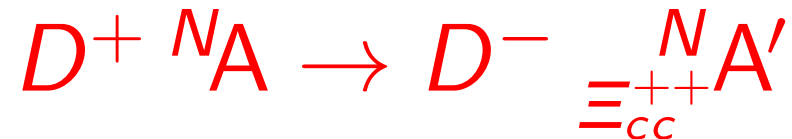
$E(bb) \approx 280 \text{ MeV} \Rightarrow$ v. high Q -value

main challenge:

$$\tau(B^-) = 1.6 \times 10^{-12} \text{ s},$$

$$\tau(B^-) \cdot c \approx 0.5 \text{ mm}$$

Maybe also charm analogue



both bottom and charm
in heavy ion collisions ?

Possible similar mechanisms in DM sector

QCD-like theories w. confined “dark quarks” $\tilde{q}, \tilde{Q}$
 $m_{\tilde{q}} \lesssim \Lambda_{\widetilde{QCD}}$, $m_{\tilde{Q}}$ v. large

in many scenarios $\tilde{Q}$ stable, unlike Q in SM

⇒ *stable* tightly-bound $\tilde{Q}\tilde{Q}\tilde{q}$

⇒ chain reaction involving $\tilde{Q}$ -level fusion

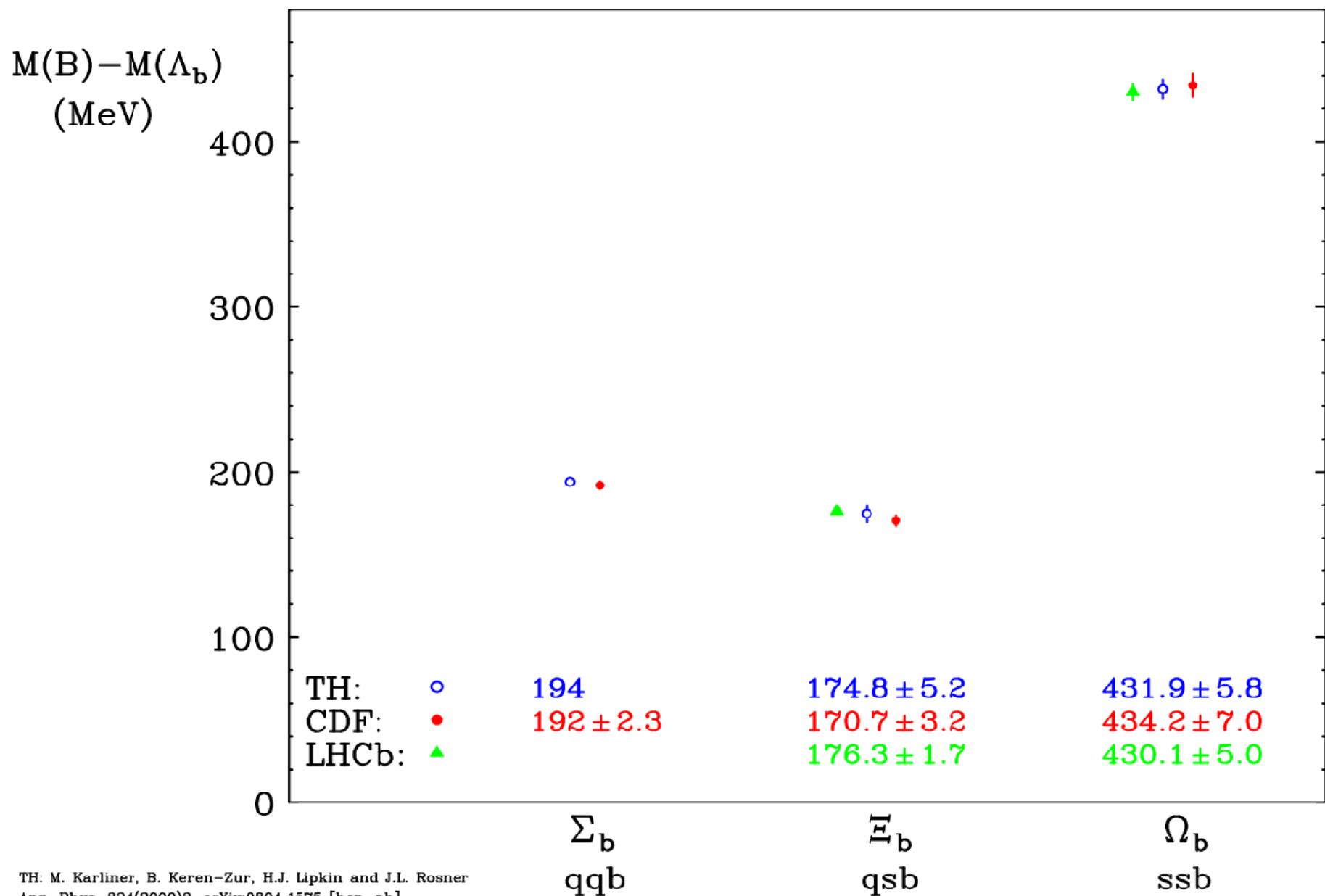
SUMMARY

- 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
 $\Sigma_c B^*$, $\Sigma_b \bar{D}^*$, $\Sigma_b B^*$
- doubly charmed baryon found exactly where predicted
 $\Xi_{cc}^{++}(ccu) \Rightarrow (bcq), (bbq)$
- *stable $bb\bar{u}\bar{d}$ tetraquark*: LHCb !
- $cc\bar{c}\bar{c}$ @ $6,192 \pm 25$ MeV, $bb\bar{b}\bar{b}$ @ $18,826 \pm 25$ MeV $\Rightarrow 4\ell$
- *quark-level analogue of nuclear fusion*
- possible similar mechanisms in dark matter sector

exciting new spectroscopy awaiting discovery

Supplementary slides

b-baryons spectrum – TH predictions vs EXP



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

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 ?....



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

Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays

The LHCb collaboration¹

Abstract

Observations of exotic structures in the $J/\psi p$ channel, that we refer to as pentaquark-charmonium states, in $\Lambda_b^0 \rightarrow J/\psi K^- p$ 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 $4380 \pm 8 \pm 29 \text{ MeV}$ and a width of $205 \pm 18 \pm 86 \text{ MeV}$, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$ and a width of $39 \pm 5 \pm 19 \text{ MeV}$. The preferred J^P assignments are of opposite parity, with one state having spin $3/2$ and the other $5/2$.

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narrow resonance at
 $4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$

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

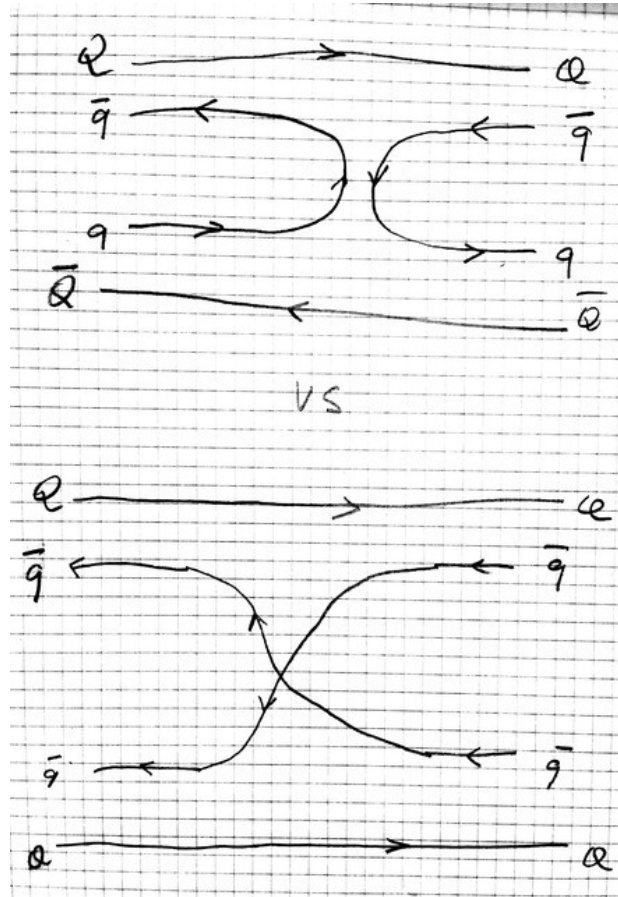
molecular binding $\equiv$ meson x-change $Q\bar{Q}q\bar{q}$ vs. $QQ\bar{q}\bar{q}$

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^* .



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 χ SB

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:

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

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

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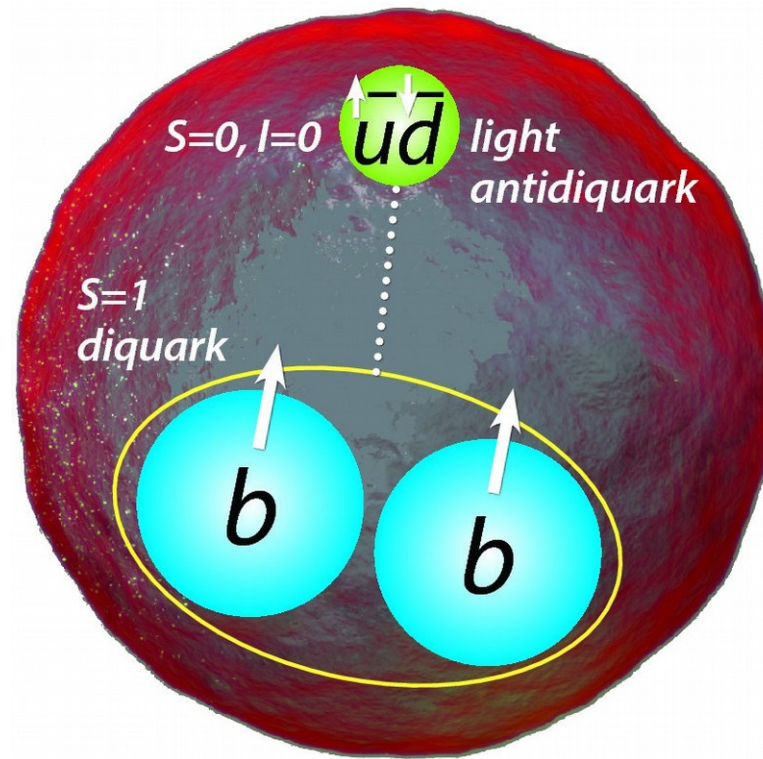
$$B_{s1} \rightarrow B_s^* \pi^0, B_s^{(*)} \gamma$$

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

• Belle II ?

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

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



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

exciting new spectroscopy awaiting discovery



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.

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

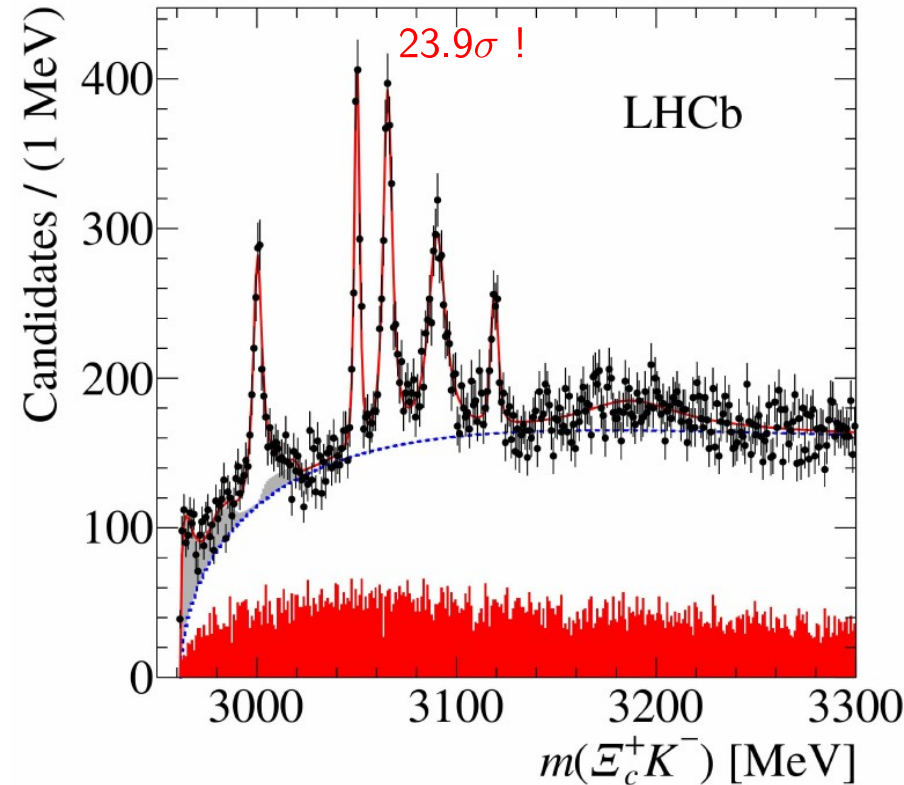


Figure 2: Distribution of the reconstructed invariant mass $m(\Xi_c^+ K^-)$ for all candidates passing the likelihood ratio selection; the solid (red) curve shows the result of the fit, and the dashed (blue) line indicates the fitted background. The shaded (red) histogram shows the corresponding mass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

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

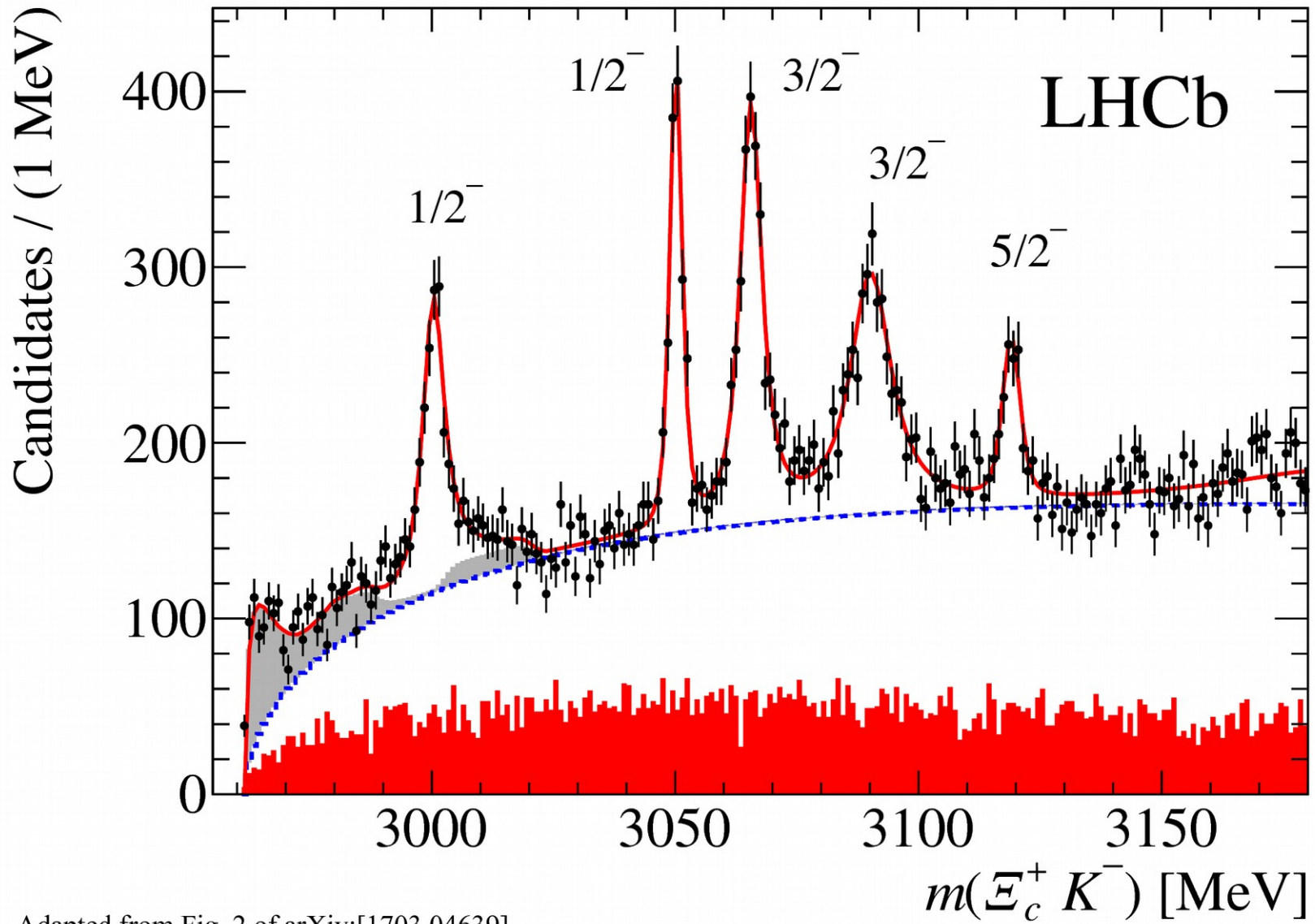
combine $L = 1$ with $S = \frac{1}{2} \Rightarrow J = \frac{1}{2}, \frac{3}{2}$

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

^aAdditional common error of $+0.3, -0.5 \text{ MeV}$ 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

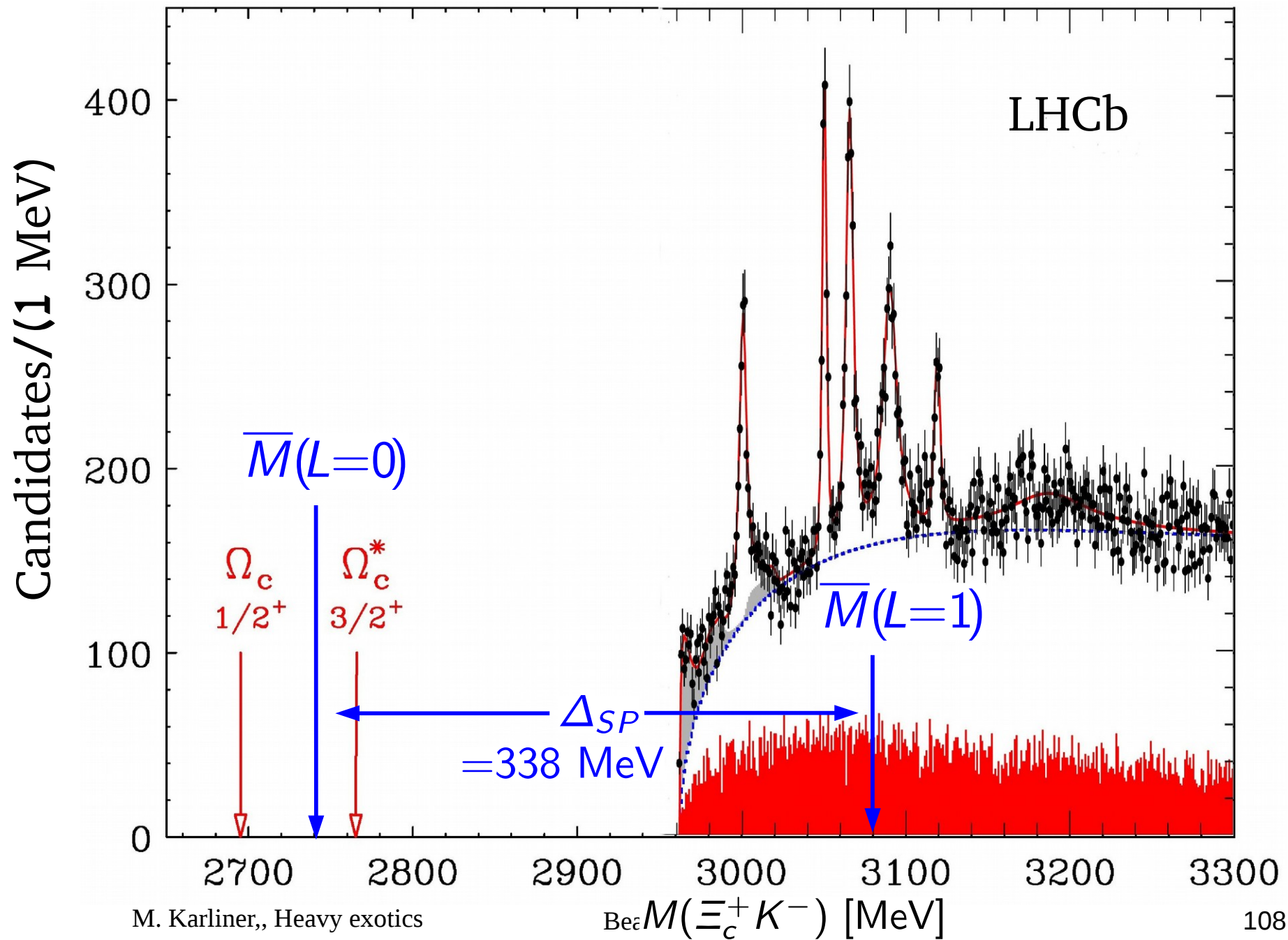
examine all $5! = 120$ *a priori* possible assignments of P -wave states

$\Rightarrow$ assignment in Table favored, with parameters

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

$\Rightarrow$ the spin-averaged mass:

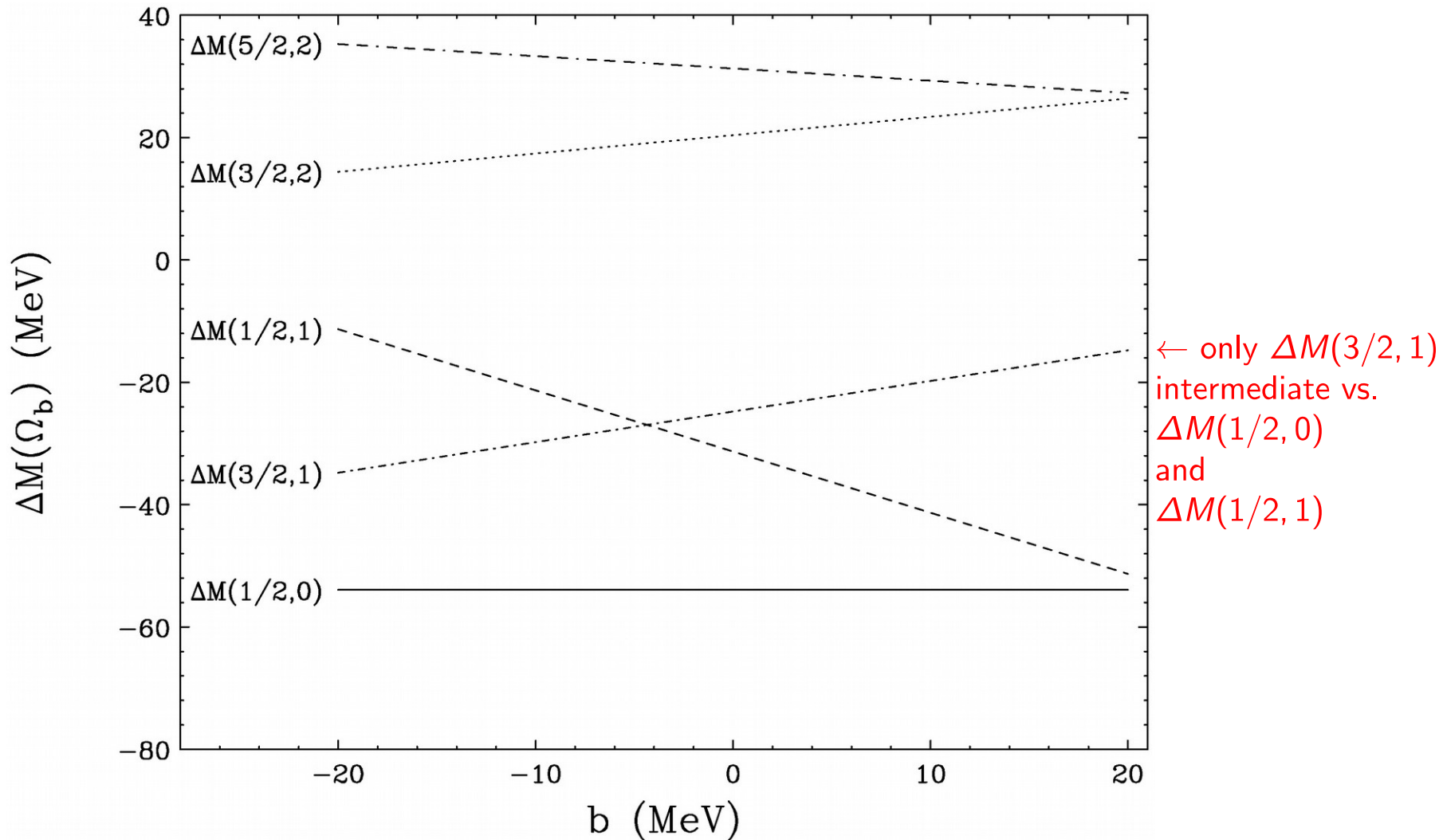
$$\overline{M} = (1/18) \sum_J (2J + 1) M(J) = 3079.94 \text{ MeV} .$$



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

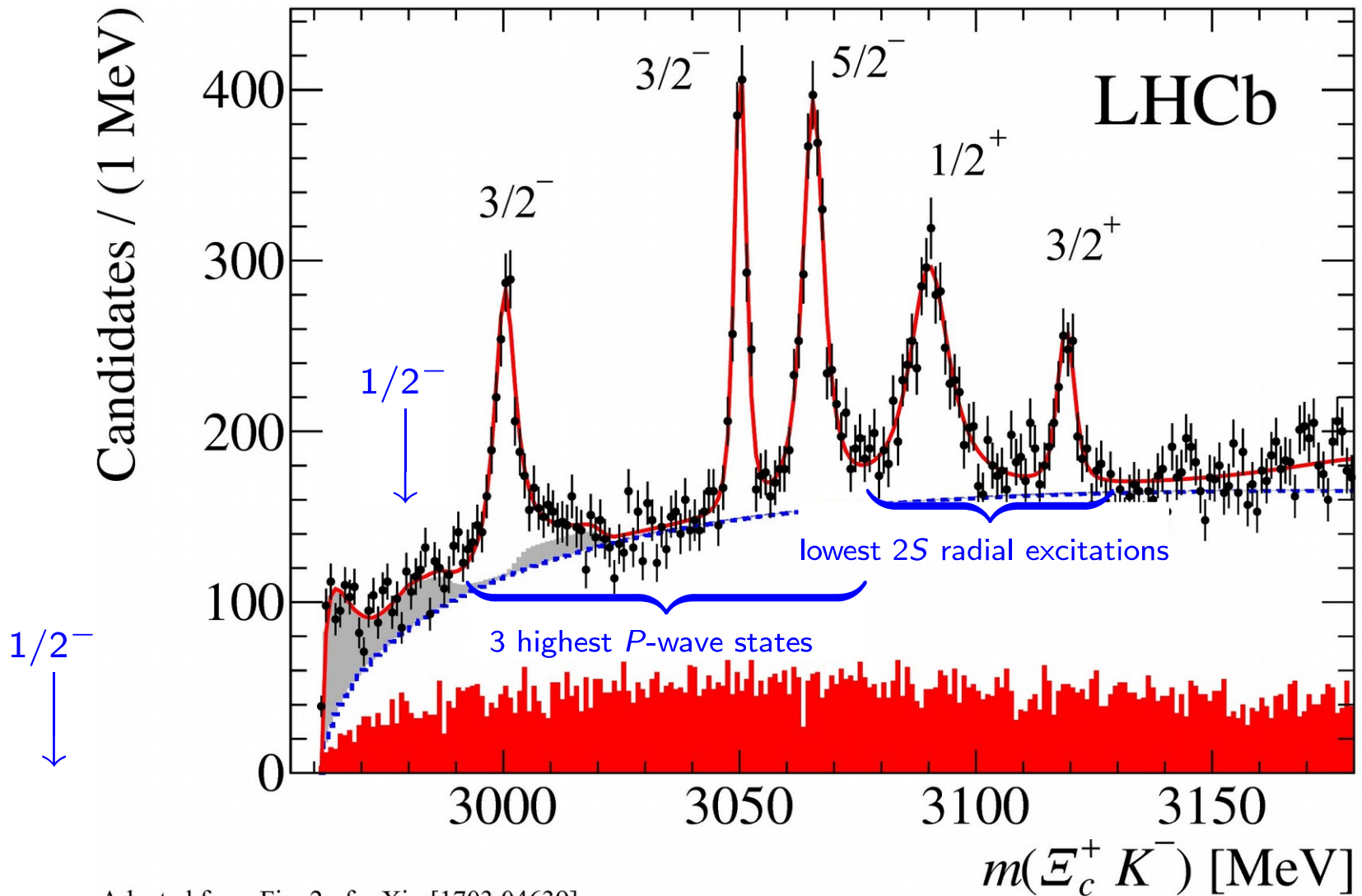
$$\frac{m_c}{m_b} \sim \frac{1}{3} \Rightarrow \text{expect lin. approx. much better}$$

- 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 .
- $-20 \text{ MeV} < b < 20 \text{ MeV}$.
- S - P splitting: $\Delta E_{PS}(\Omega_b) \sim 300 \text{ MeV}$.



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 $\rightarrow \Xi_c^+ K^-$ 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

