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The Social Life of Qeavy Quarks

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Quarkonium 2017, PKU, Nov 6

Outline

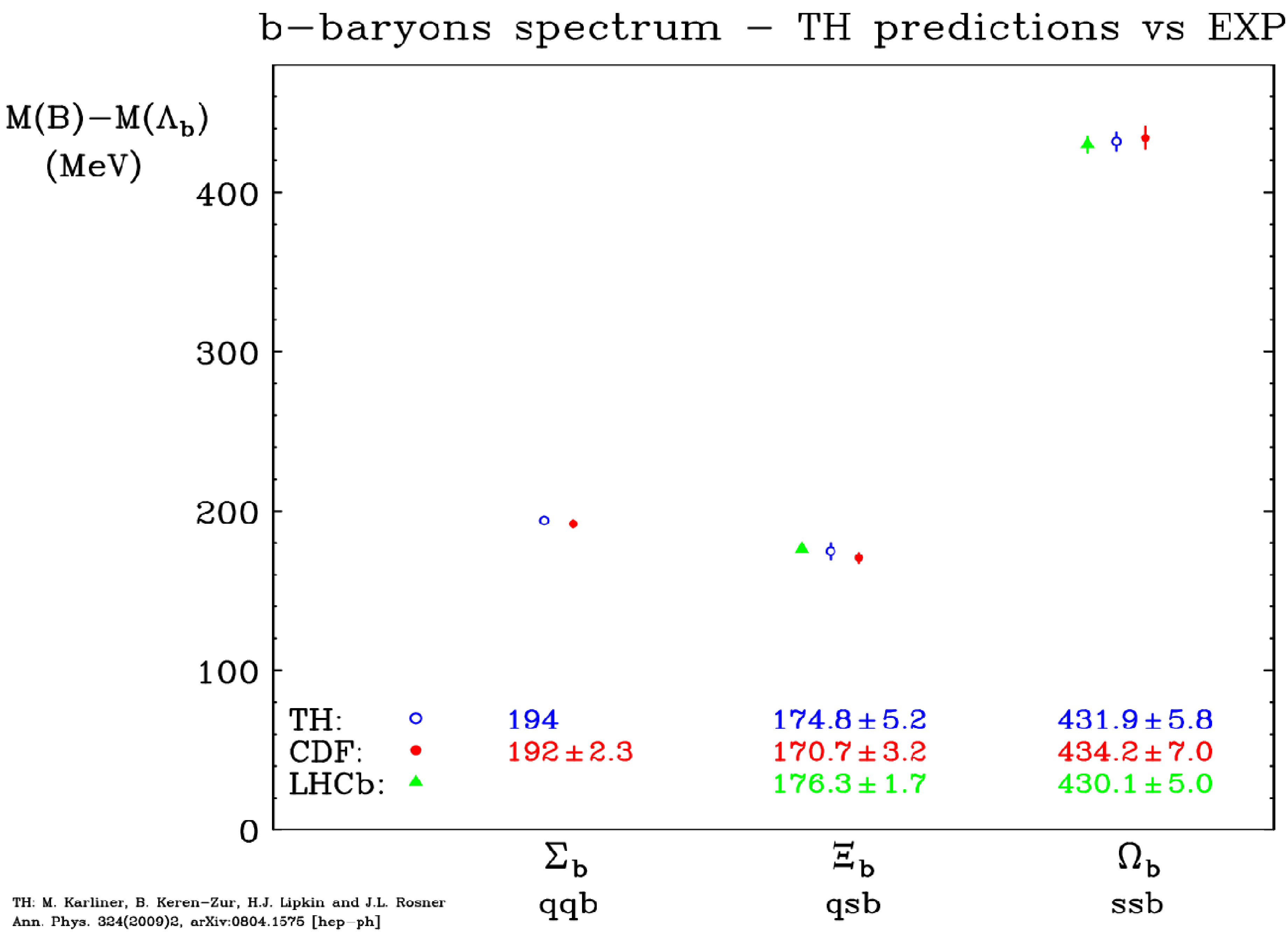
- hadronic molecules, esp. LHCb pentaquark
- excited Ω_c quintet

Implications of Ξ_{cc}^{++} discovery

- stable $bb\bar{u}\bar{d}$ tetraquark,
  215 MeV below $B^-\bar{B}^{0*}$ threshold
- 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
- why $QQ\bar{q}\bar{q}$=tetraquarks and $Q\bar{Q}q\bar{q}$=molecules

hadrons w. heavy quarks are *much simpler:*

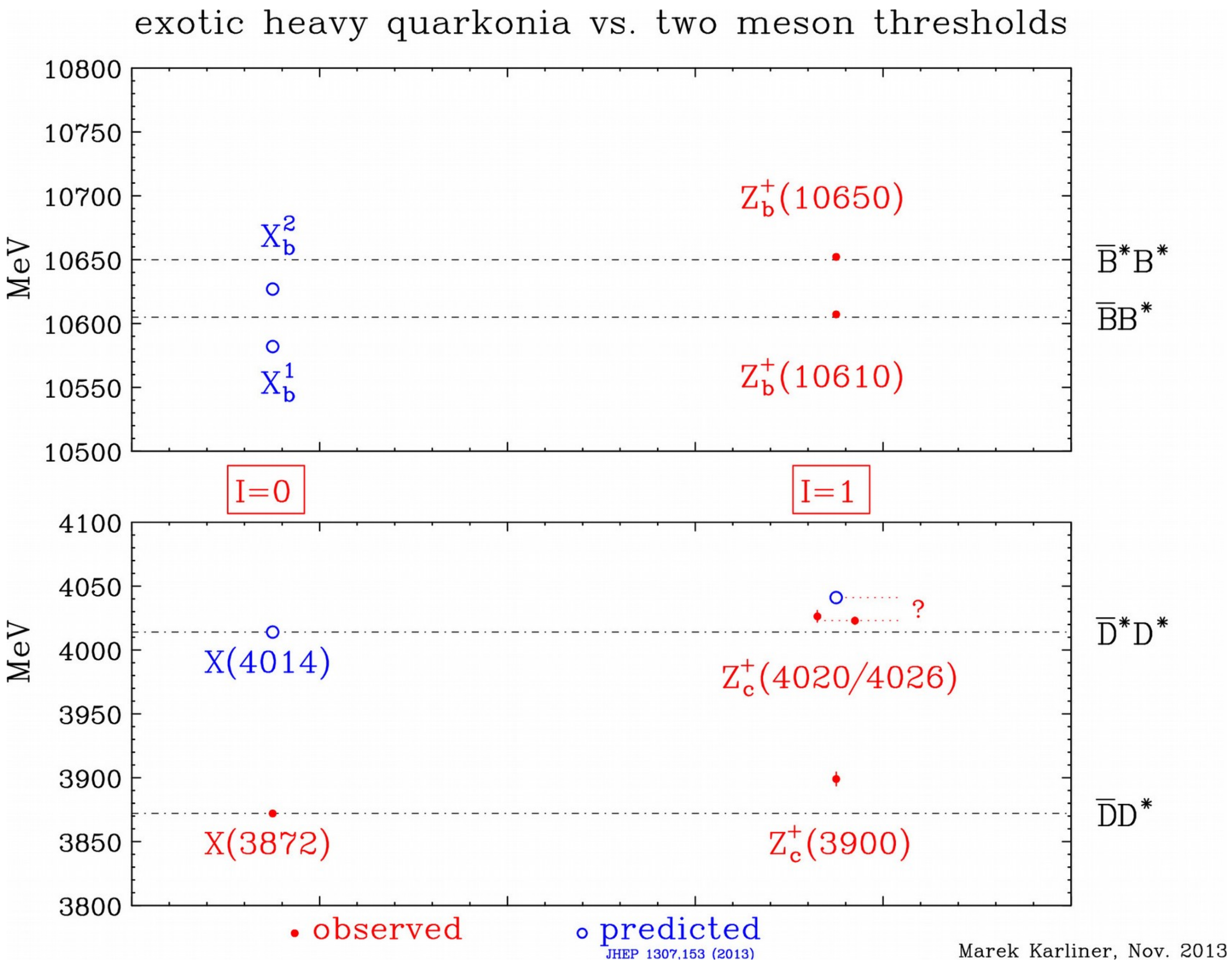
- heavy quarks almost static
- smaller spin-dep. interaction $\propto 1/m_Q$
- key to accurate prediction of b quark baryons


b−baryons spectrum − TH predictions vs EXP
M(B)−M(Λb)
(MeV)
0
100
200
300
400
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]

5 narrow exotic states close to meson-meson thresholds

state	mass MeV	width MeV	$\bar{Q}Q$ decay mode	phase space MeV	nearby threshold	ΔE MeV
$X(3872)$	3872	< 1.2	$J/\psi\,\pi^+\pi^-$	495	$\bar{D}D^*$	< 1
$Z_b(10610)$	10608	21	$\Upsilon\pi$	1008	$\bar{B}B^*$	2 ± 2
$Z_b(10650)$	10651	10	$\Upsilon\pi$	1051	$\bar{B}^*B^*$	2 ± 2
$Z_c(3900)$	3900	$24 - 46$	$J/\psi\,\pi$	663	$\bar{D}D^*$	24
$Z_c(4020)$	4020	$8 - 25$	$J/\psi\,\pi$	783	$\bar{D}^*D^*$	6
×					$\bar{D}D$	
×					$\bar{B}B$	

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


exotic heavy quarkonia vs. two meson thresholds
10800
10750
10700
10650
10600
10550
10500
MeV
X_b^2
X_b^1
$Z_b^+(10650)$
$Z_b^+(10610)$
$\bar{B}^*B^*$
$\bar{B}B^*$
I=0
I=1
4100
4050
4000
3950
3900
3850
3800
MeV
X(4014)
X(3872)
?
$Z_c^+(4020/4026)$
$Z_c^+(3900)$
$\bar{D}^*D^*$
$\bar{D}D^*$
• observed
○ predicted
JHEP 1307,153 (2013)
Marek Karliner, Nov. 2013

The Z_Q resonances decay into

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

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

$\Longrightarrow$ manifestly exotic

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

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

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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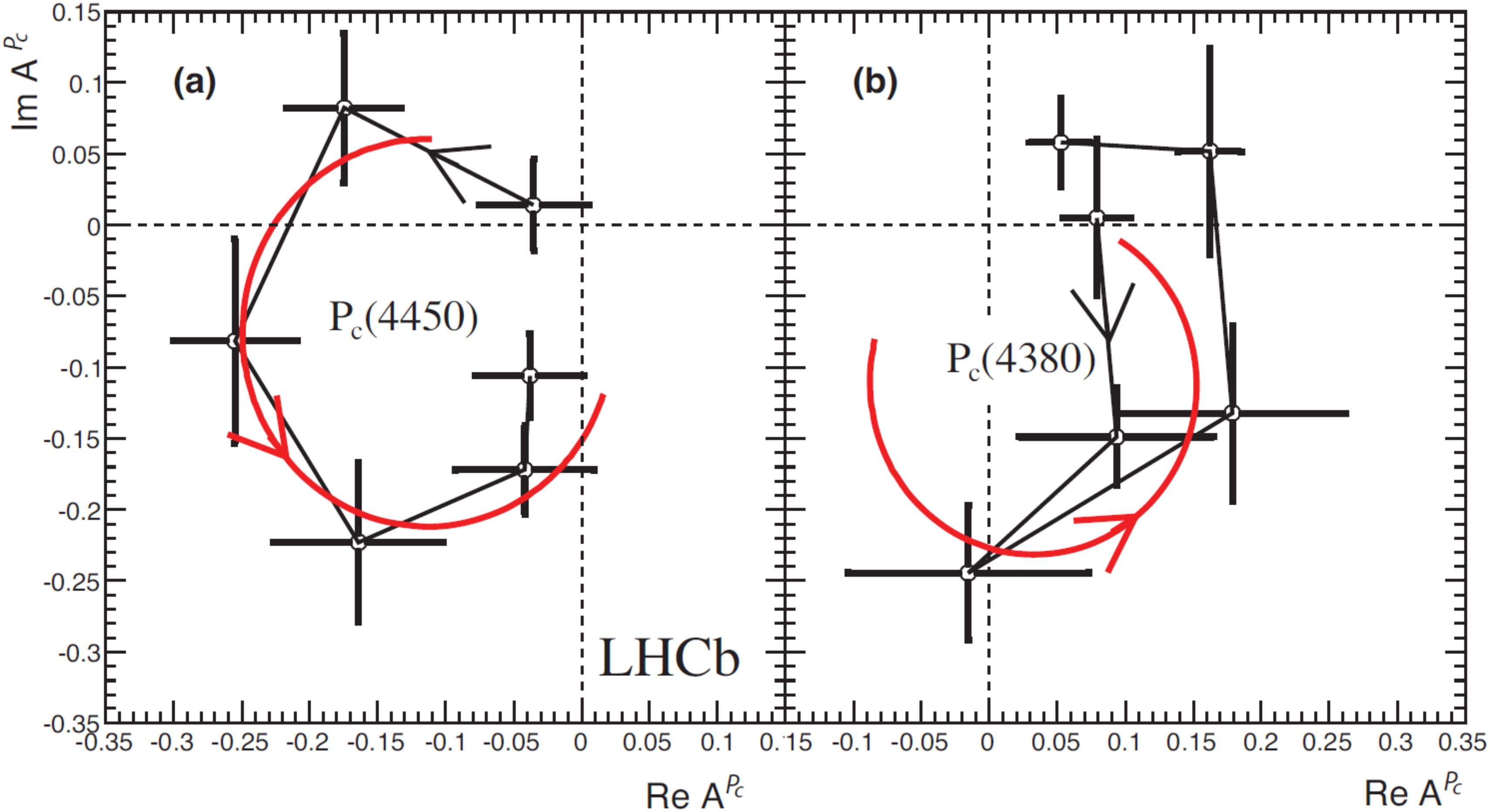
$\Theta_{\bar{c}c}$ minimal quark content: $\bar{c}c\, uud \equiv P_c(4450)$

a molecule, not a tightly-bound pentaquark

Thresholds for $Q\bar{Q}'$ molecular states

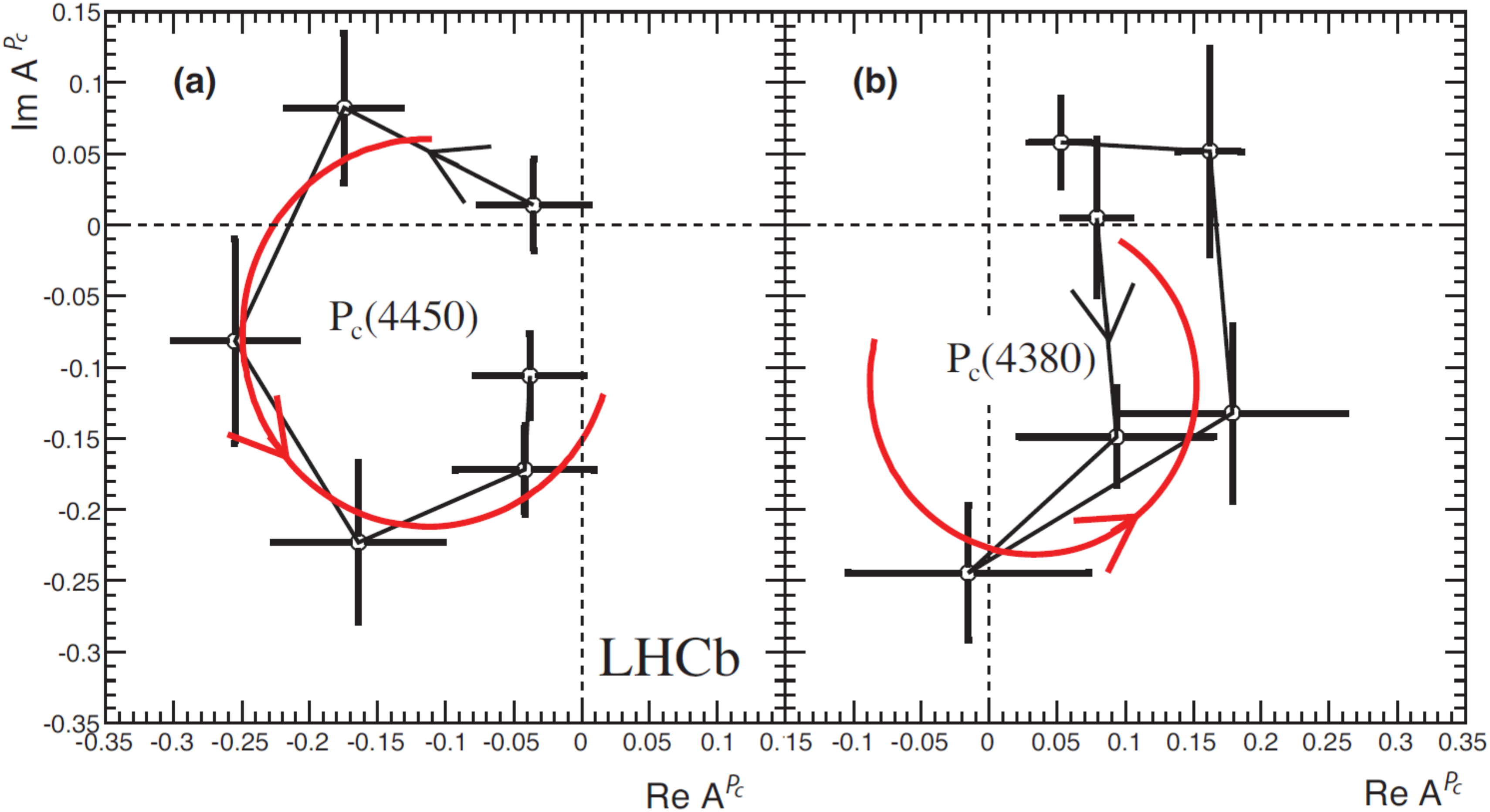
Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	Example of decay mode
$D\bar{D}^*$	0	$c\bar{c}q\bar{q}$	3875.8	$J/\psi\,\pi\pi$
$D^*\bar{D}^*$	0	$c\bar{c}q\bar{q}$	4017.2	$J/\psi\,\pi\pi$
D^*B^*	0	$c\bar{b}q\bar{q}$	7333.8	$B_c^+\pi\pi$
$\bar{B}B^*$	0	$b\bar{b}q\bar{q}$	10604.6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



$P_c(4450)$: 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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???

$\mathbf{P_c(4450)}$ 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

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

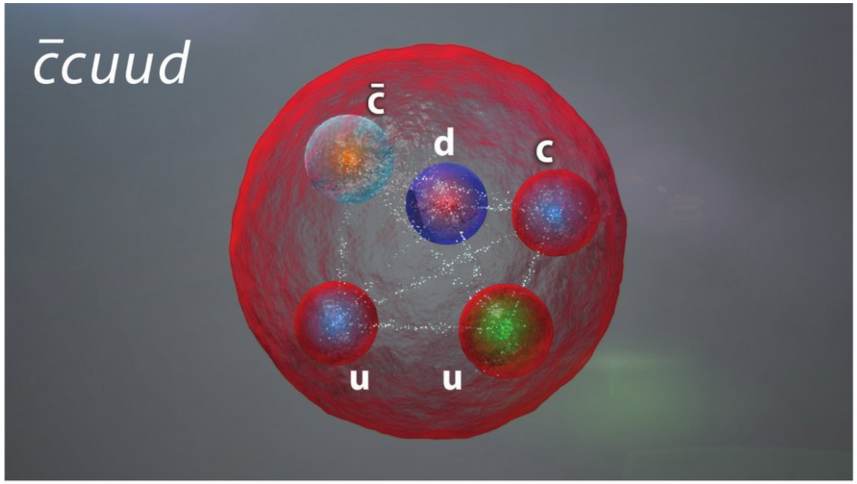
To get $\Gamma = 39$ MeV, the matrix element must be small .

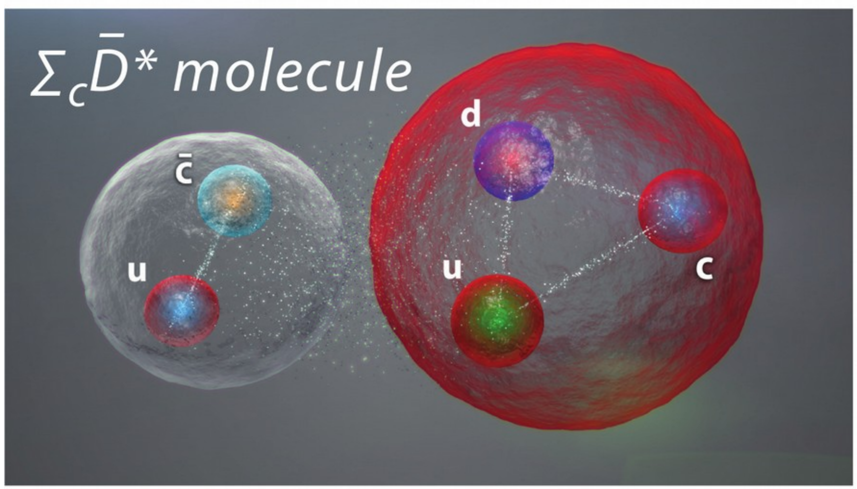
But in a pentaquark c and $\bar{c}$ are close to each other within the same confinement volume, so overlap with J/ψ is generically large.

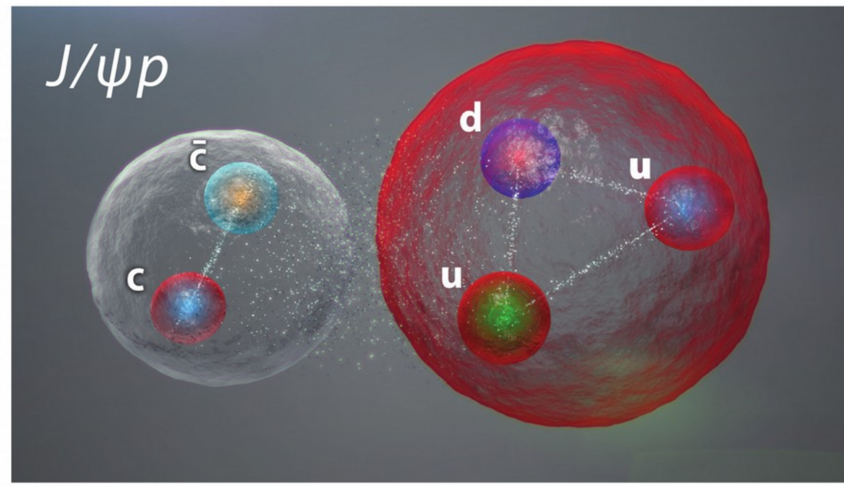
In a molecule narrow width is automatic:

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 $J/\psi p$







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

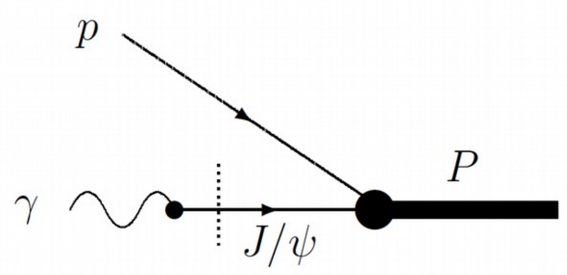
Photoproduction of exotic baryon resonances

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

$X(3872) \to J/\psi\,\pi^+\pi^-$ 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

$\Sigma_b^+\Sigma_b^-$ 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.

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

$\Rightarrow css$: 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.

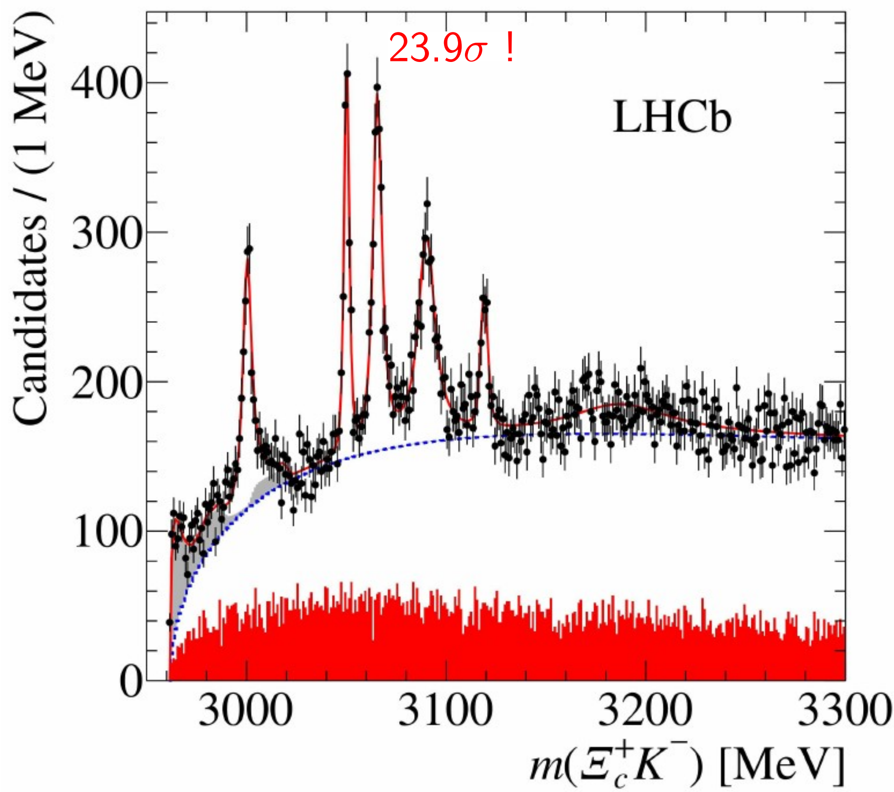
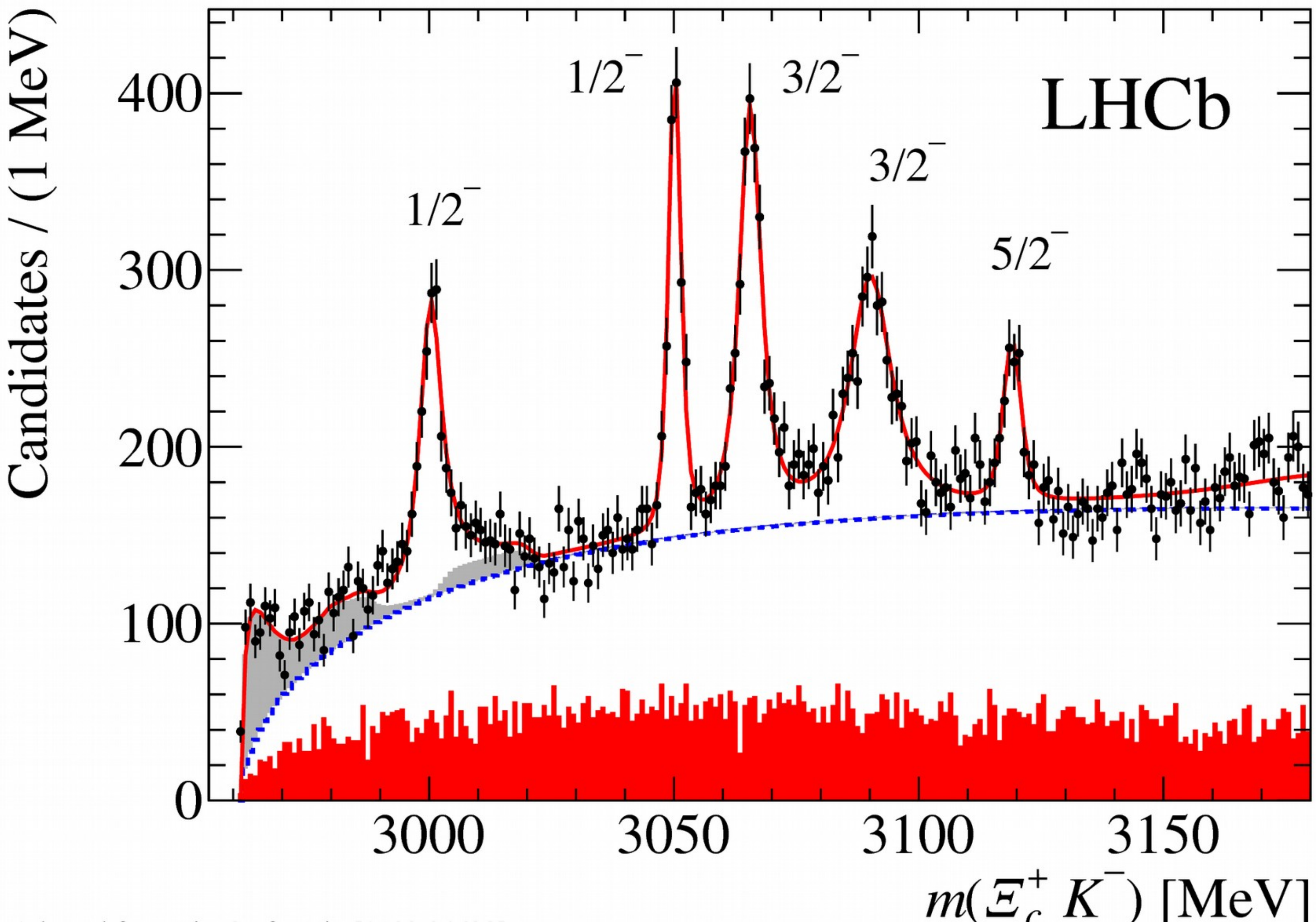


Figure 2: Distribution of the reconstructed invariant mass $m(\Xi_c^+ K^-)$ for all candidates passing the likelihood ratio selection; the solid (red) curve shows the result of the fit, and the dashed (blue) line indicates the fitted background. The shaded (red) histogram shows the corresponding mass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

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



Adapted from Fig. 2 of arXiv:[1703.04639]

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

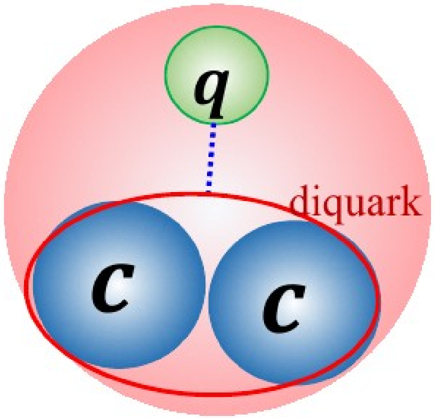
fascinating challenge for EXP & TH

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

QQq baryons are the simplest baryons:

when $m_Q \to \infty$, QQ form a static $\overline{3}_c$ diquark

$R_{diquark} \sim 1/(m_Q \alpha_s) \ll 1/\Lambda_{QCD}$



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

e.g. form factors: $F_{QQq}(q^2) = F_{\bar{Q}q}(q^2)$

corrections: $f\left(\frac{\Lambda_{QCD}}{m_Q}\right)$, calculable in QCD

hydrogen atom of baryon physics!

masses of doubly-heavy baryons:

use same toolbox that predicted

b baryon masses.

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

preliminary estimate:

H_{QQ} $(QQuudd)$ hexaquarks

below $2\Lambda_Q$

but above $\Xi_{QQ} N$

$\Rightarrow$ unstable

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

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

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the first manifestly exotic stable hadron

Discovery of doubly-charmed Ξ_{cc} baryon implies a stable $bb\bar{u}\bar{d}$ tetraquark

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Raymond and Beverly Sackler Faculty of Exact Sciences
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ABSTRACT

Recently LHCb 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 $Tq(bb\bar{u}\bar{d})$ with $J^P{=}1^+$ at 10,389 ± 12 MeV, 215 MeV below the BB^* threshold. $Tq(bb\bar{u}\bar{d})$ is therefore stable under strong and EM interactions and can only decay weakly, the first exotic hadron with such a property. On the other hand, the mass of $Tq(cc\bar{u}\bar{d})$ with $J^P{=}1^+$ is predicted to be 3882 ± 12 MeV, 7 MeV above the $D^0 D^{*+}$ threshold. $Tq(bc\bar{u}\bar{d})$ with $J^P{=}0^+$ is predicted at 7134 ± 13 MeV, 11 MeV below the $\bar{B}^0 D^0$ threshold. Our precision is not sufficient to determine whether $cc\bar{u}\bar{d}$ and $bc\bar{u}\bar{d}$ are actually above or below the threshold. They could manifest themselves as narrow resonances just at threshold.

PHYSICAL REVIEW LETTERS

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)

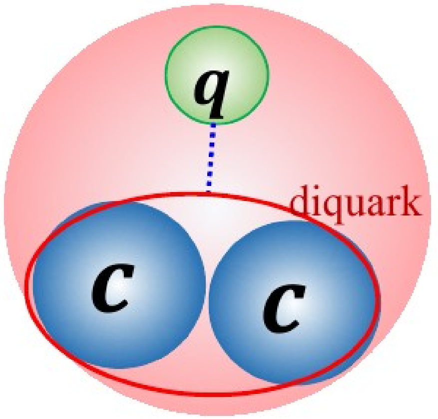
Recently, the LHCb Collaboration discovered the first doubly charmed baryon $\Xi_{cc}^{++} = ccu$ at 3621.40 ± 0.78 MeV, very close to our theoretical prediction. We use the same methods to predict a doubly bottom tetraquark $T(bb\bar{u}\bar{d})$ with $J^P = 1^+$ at $10\,389 \pm 12$ MeV, 215 MeV below 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

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

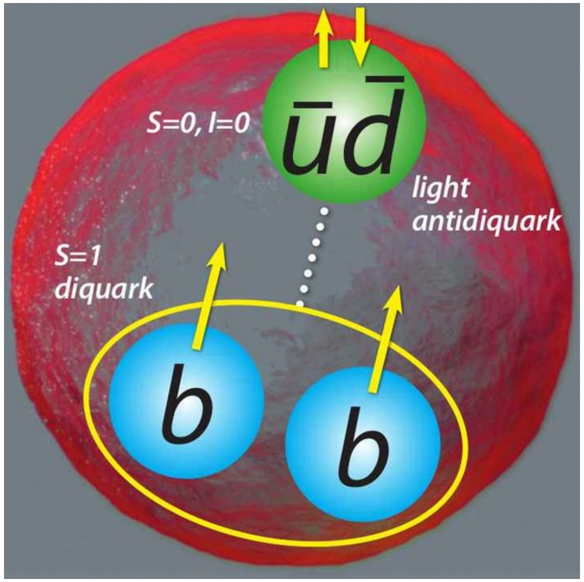
bbq baryon



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:

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

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

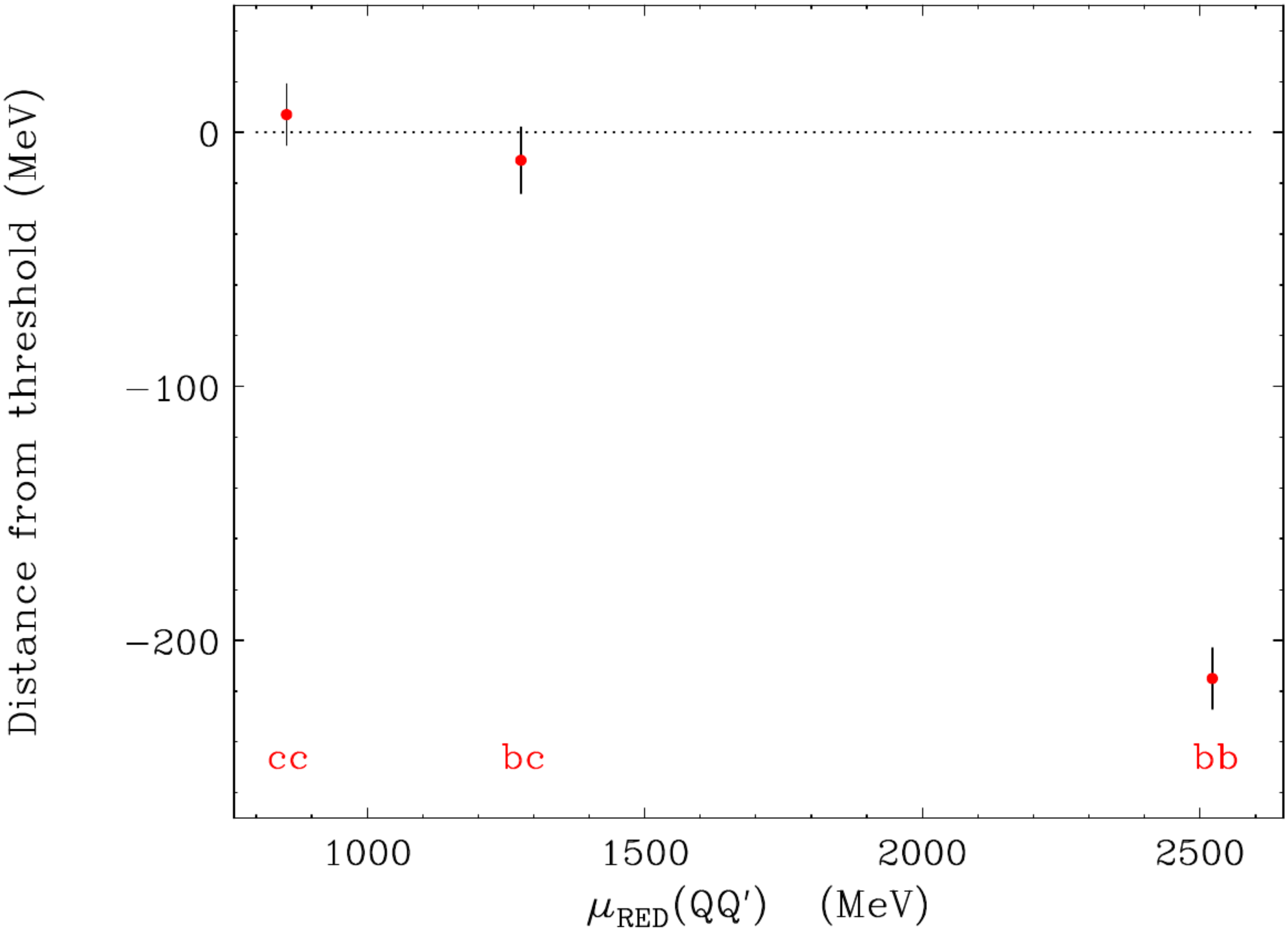
7 MeV above $D^0 D^{+*}$ threshold,
but if use measured $M(X_{cc}^{++}) \Rightarrow$ only 1 MeV above $D^0 D^{+*}$

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).



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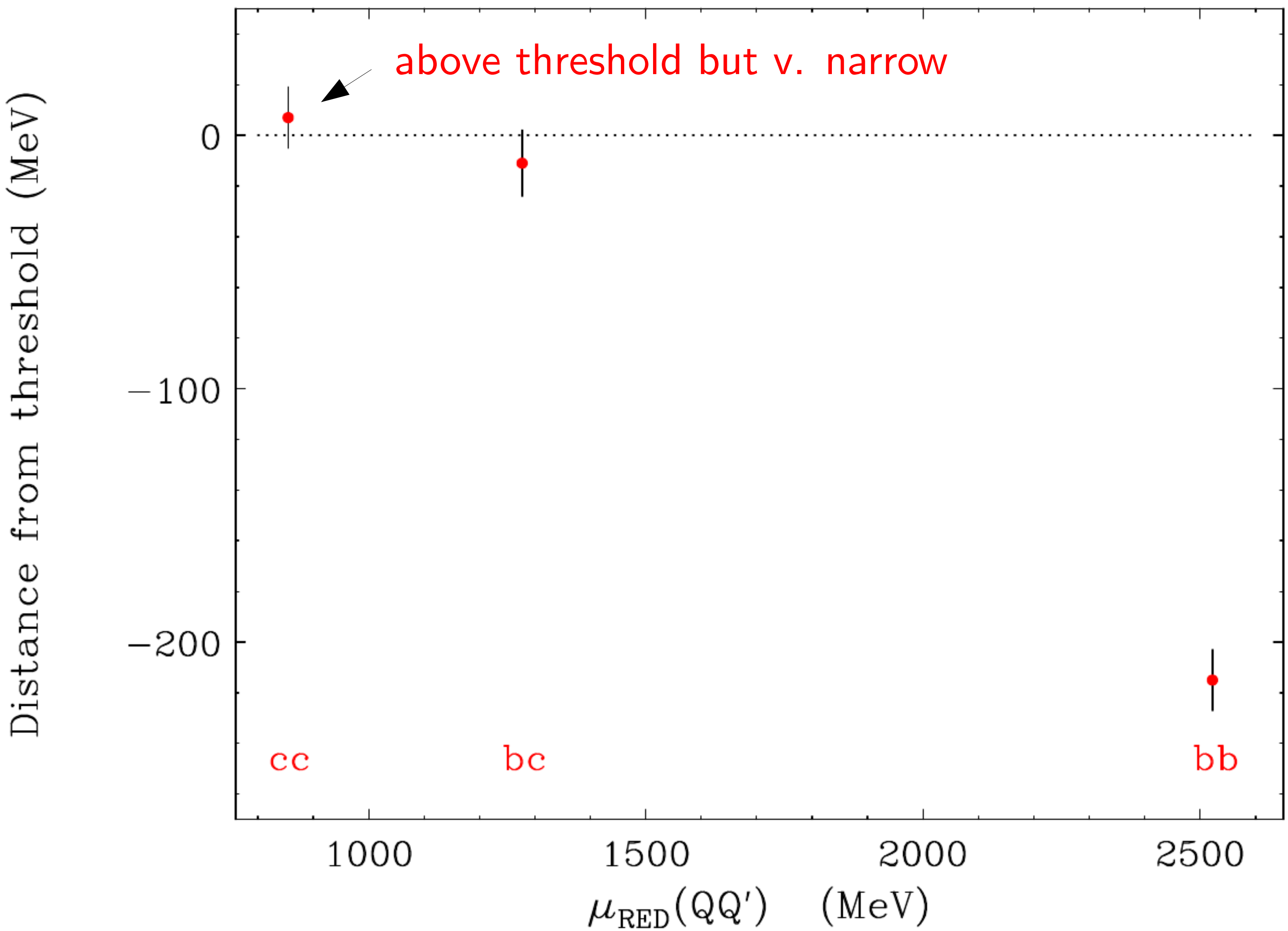

Tetraquark production

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

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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$\Rightarrow$ 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 <u>*now*</u>

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" $bb\bar{u}\bar{d} \to cb\bar{u}\bar{d} + W^{*-}$.

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

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

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

$T(bb\bar{u}\bar{d})$ 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^{*+}

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

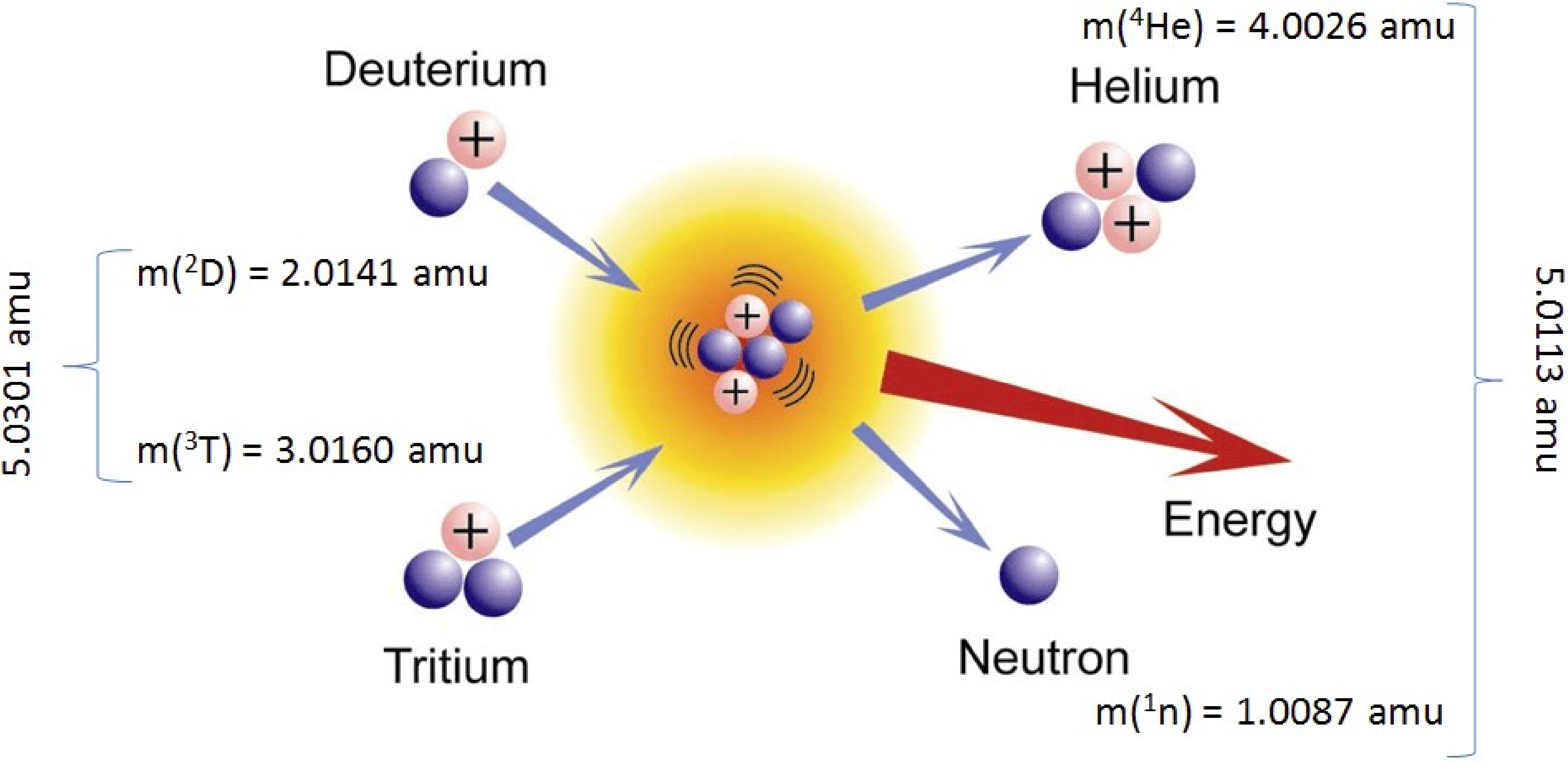
production of an extra $Q\bar{Q}$: probabillity $\sim 0.1\%$

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

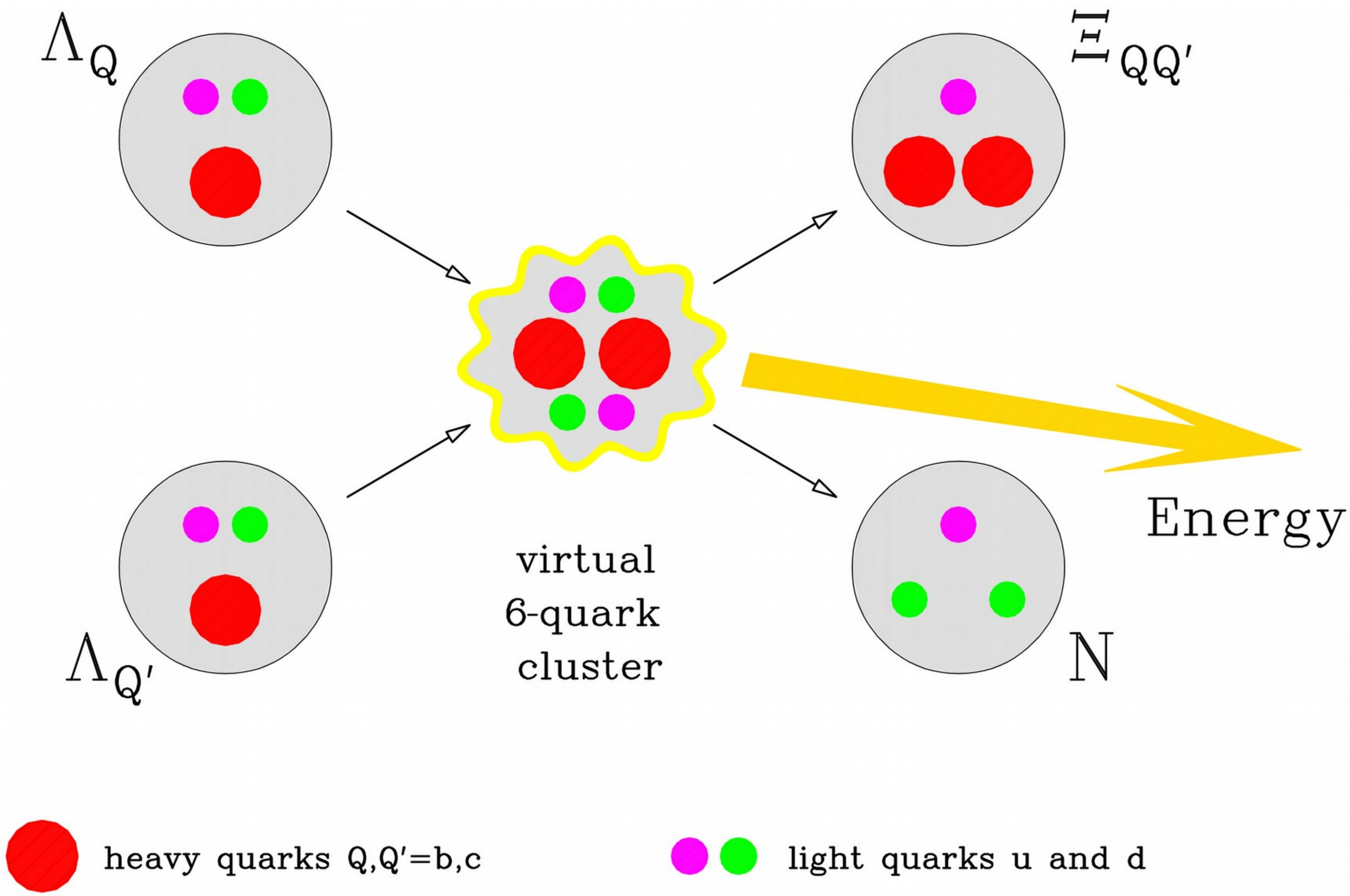
DT fusion: $DT \to {}^4\text{He}\, n$

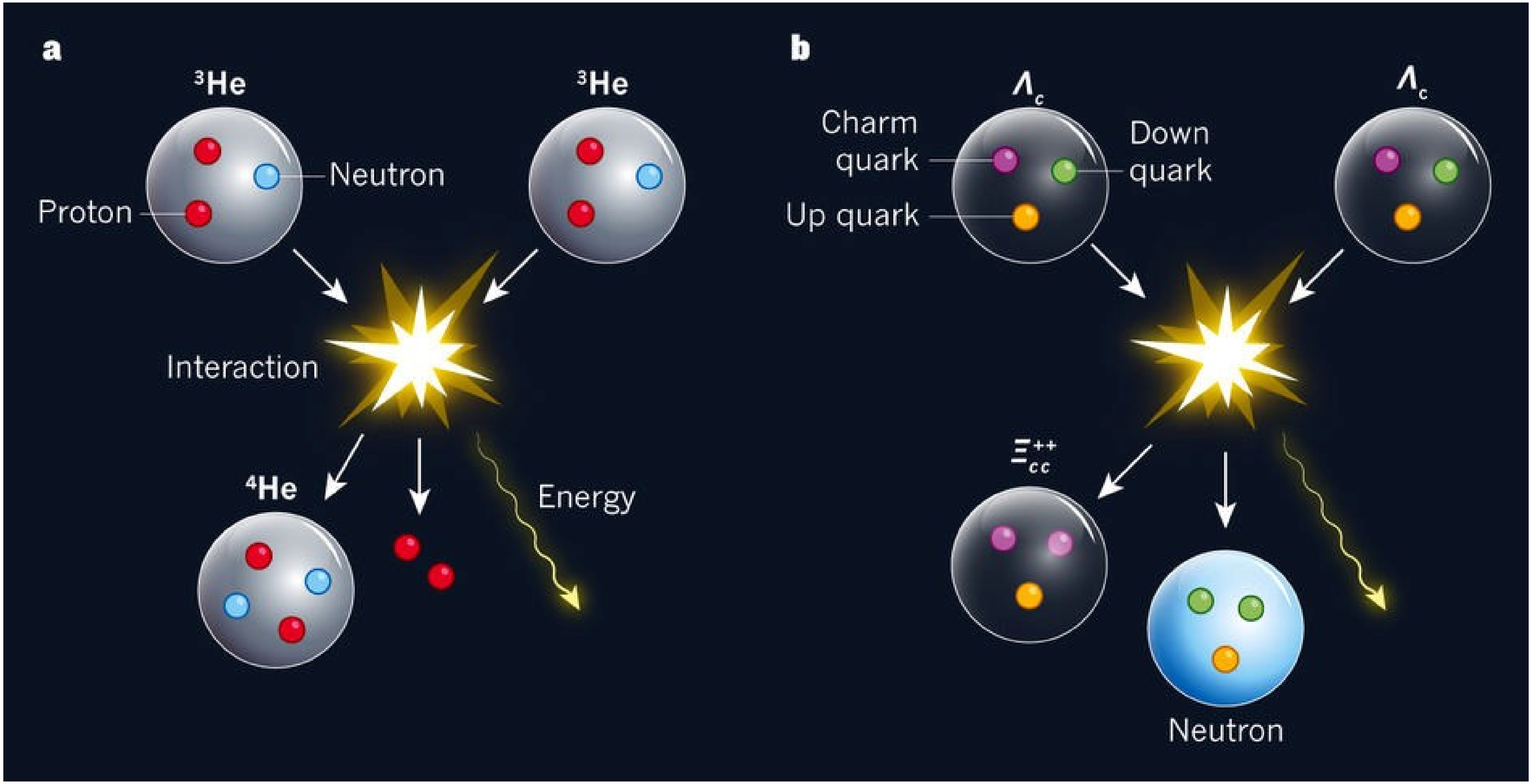


Q = 0.0188 amu x 931.481 MeV/amu = 17.5 MeV

Nuclear fusion reactions w. light nuclei

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


Λ_Q
$\Xi_{QQ'}$
Energy
$\Lambda_{Q'}$
virtual
6-quark
cluster
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:

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

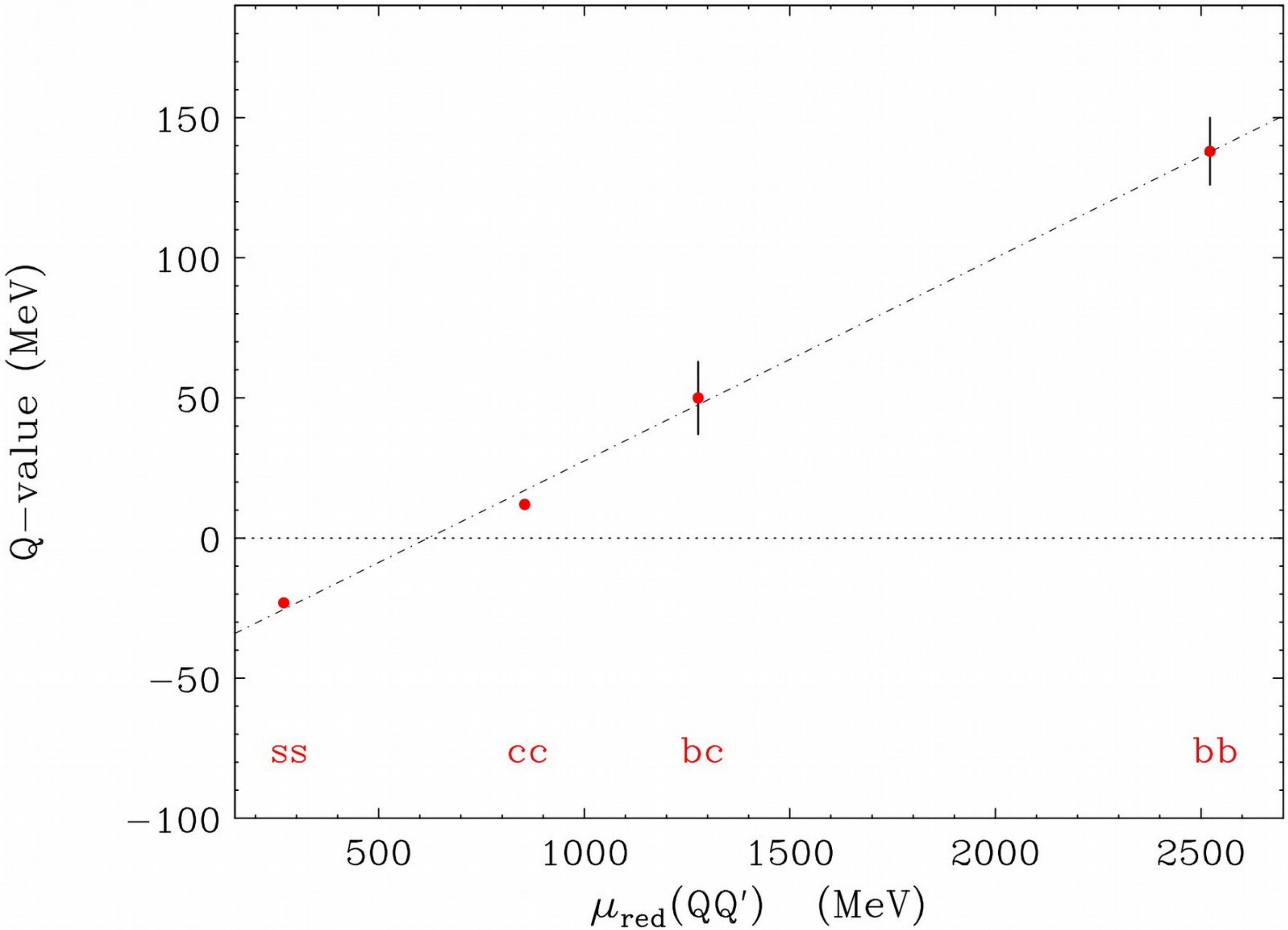
$cud \; cud \qquad\qquad ccu \; ddu$

Table I

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

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 $\Lambda_Q \Lambda_{\mathcal{Q}'} \to \Xi_{\mathcal{Q}\mathcal{Q}'} N$, $\mathcal{Q}, \mathcal{Q}' = s, c, b$, 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

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

ongoing exp. at J-PARC.

Suggest bottom analogue:

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

$E(bb) \approx 280$ 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

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

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

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

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

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

narrow B_{sJ} states

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

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

both below relevant thresholds:

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

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

$\Rightarrow$ expect v. narrow widths

dominant decay modes:

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

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

narrow B_{sJ} states

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

two v. different types of exotics:

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

e.g.

$Z_b(10610)$ $T(bb\bar{u}\bar{d})$

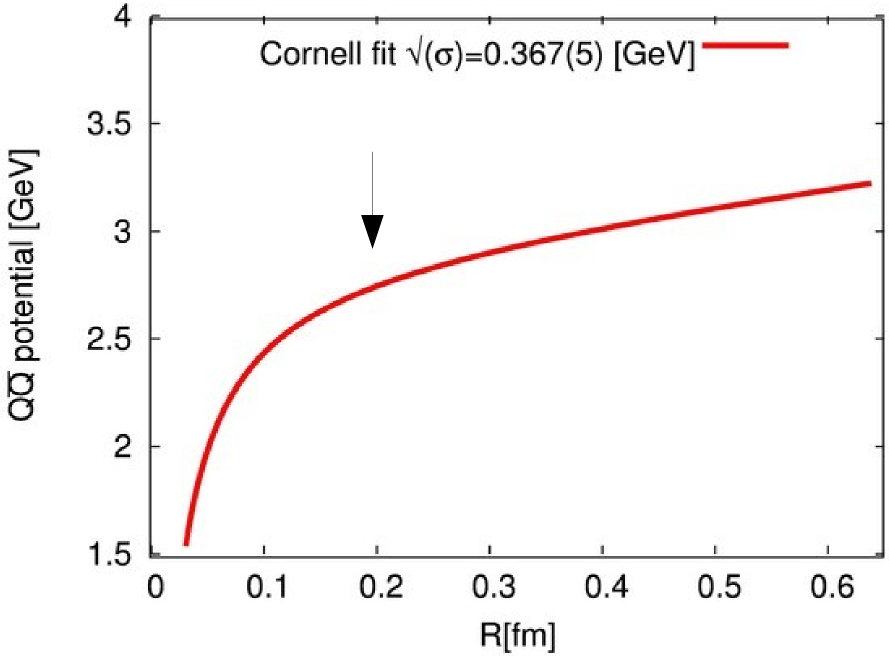
$\bar{B}B^*$ molecule

tightly-bound 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 $u\bar{d}$, $Z_b \to \Upsilon\pi^+$
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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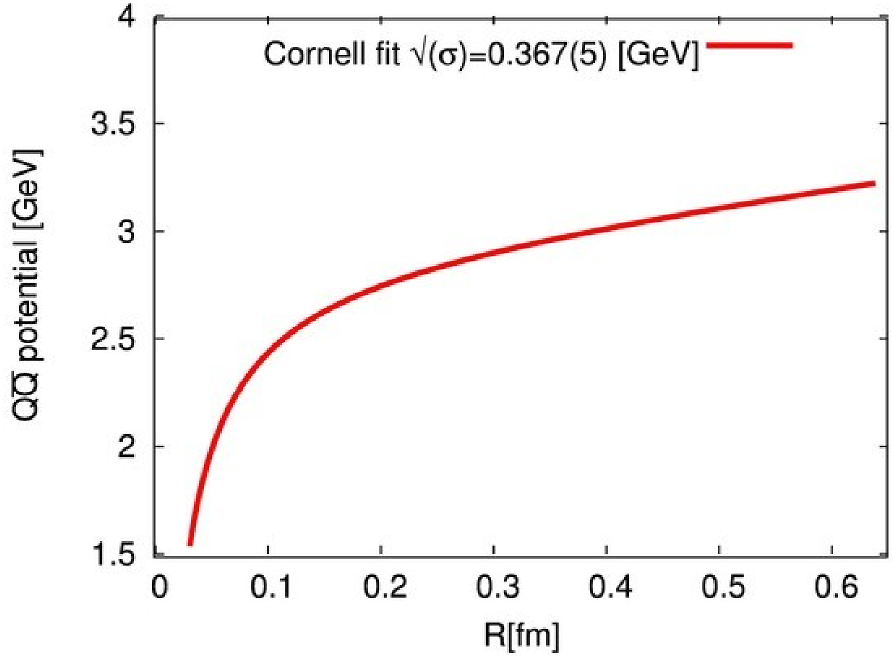

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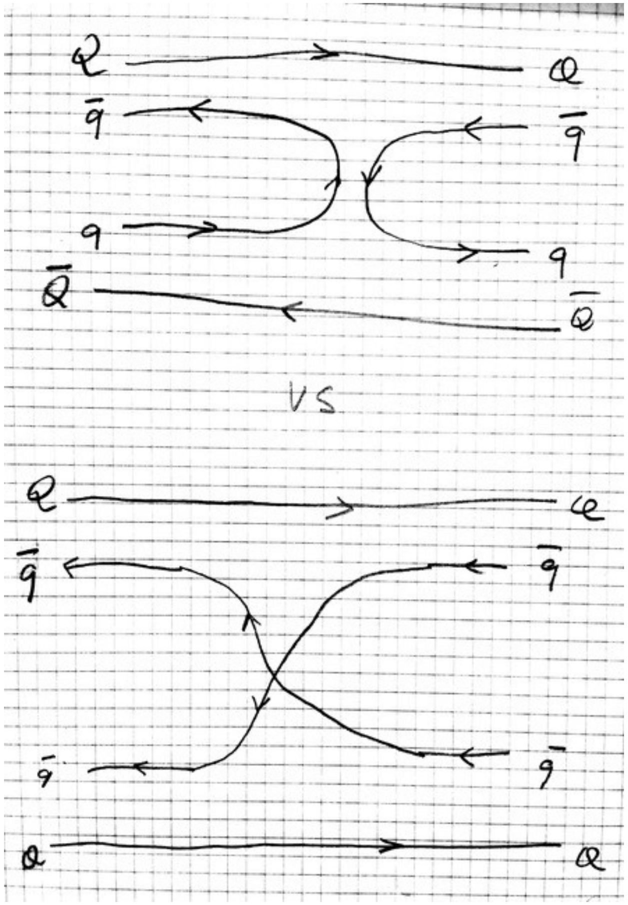
"hadronic molecule:" $\bar{B}B^* \sim 1$ GeV above $\Upsilon\pi$
yet narrow ~ 15 MeV, because $R(\bar{B}B^*)/R(\Upsilon) \gg 1$
bottom line: $T(bb\bar{u}\bar{d})$ a tetraquark, $Z_b(b\bar{b}u\bar{d})$ a molecule

molecular binding ≡ 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^*.



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
  $\Sigma_c B^*$, $\Sigma_b\bar{D}^*$, $\Sigma_b B^*$, $\Sigma_Q\bar{\Lambda}_{Q'}$, $\Sigma_Q^+\Sigma_Q^-$, ...

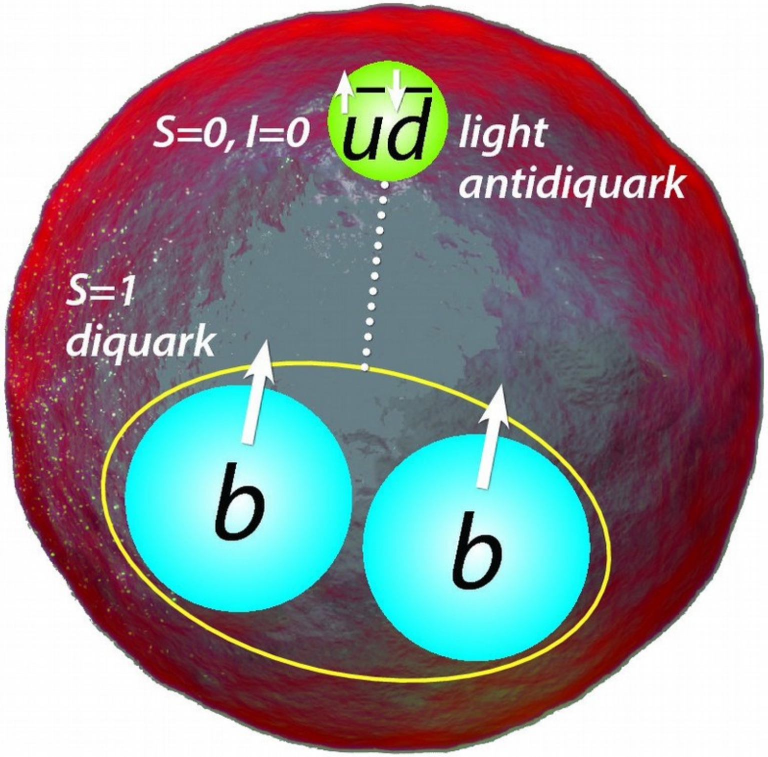
– X_b camouflaged as $\chi_{1b}(3P)$?

– 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 $B_{s0}^* \to B_s\pi^0$, $B_s\gamma$, $B_{s1} \to B_s^*\pi^0$, $B_s^{(*)}\gamma$
- $\Xi_{cc}^{++}(ccu) \Rightarrow (bcq)$, (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



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