Tel Aviv University
特拉维夫大学

Exotics with Heavy Quarks

Marek Karliner, Tel Aviv University
based on joint work with Jon Rosner

CEPC Workshop, PKU, Beijing, July 2 2019

5 narrow exotic states close to meson-meson thresholds

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

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

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 $\chi_{c1}(2P)$

tetraquarks or a “hadronic molecules” ?

The molecule idea has a long history:
Voloshin Okun (1976),
de Rujula, Georgi Glashow (1977)
Tornqvist, Z. Phys. C61,525 (1993)

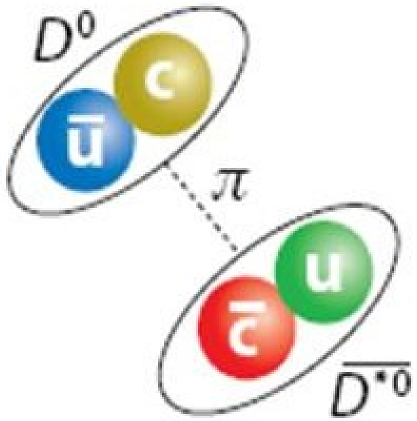
all states close to two-meson thresholds

despite large phase space (hundreds of MeV)
narrow widths in decays into $\bar{Q}Q\,\pi$

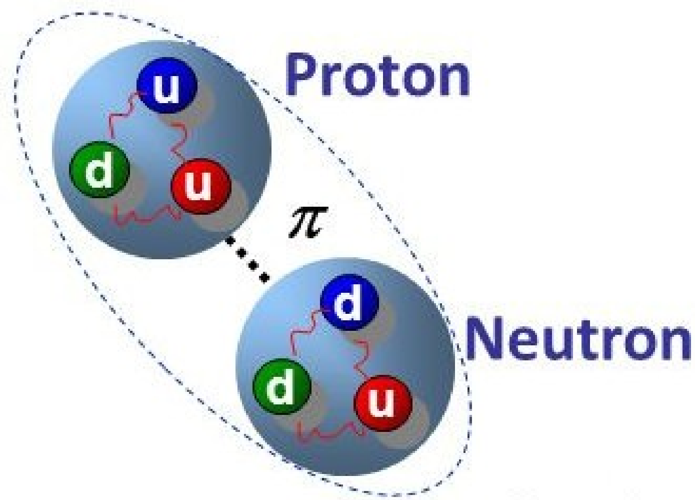
$\Longrightarrow$ very small overlap of wave functions: $|\langle i|f\rangle|^2 \ll 1$

strong hint in favor of molecular interpretation

Hadronic molecules: deuteron-like

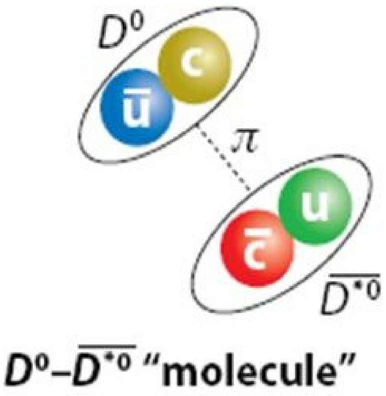


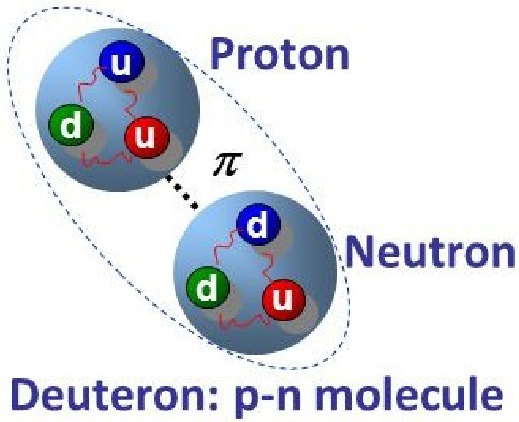
D^0–$\overline{D^{*0}}$ "molecule"



Deuteron: p-n molecule

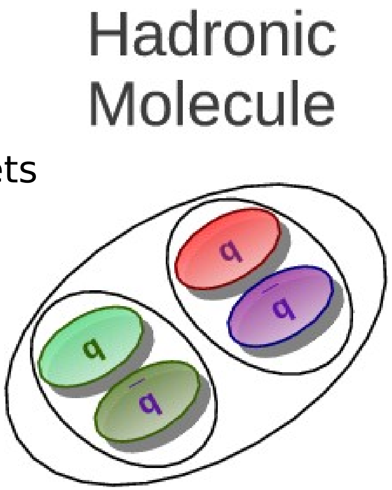
Hadronic molecules: deuteron-like

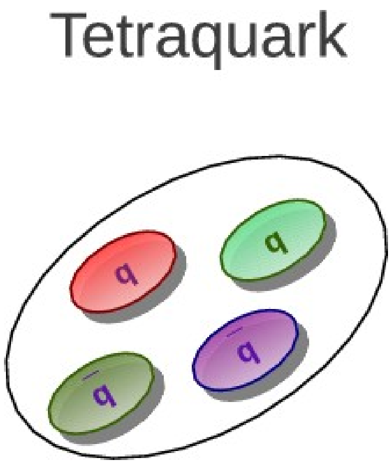




Tetraquarks: same 4 quarks, but tightly bound:

two color singlets
attract through
residual forces





each quark
sees color charges
of all the other quarks

Belle, PRL 116, 212001 (2016):

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

despite 1000 MeV of phase space

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

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

also

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

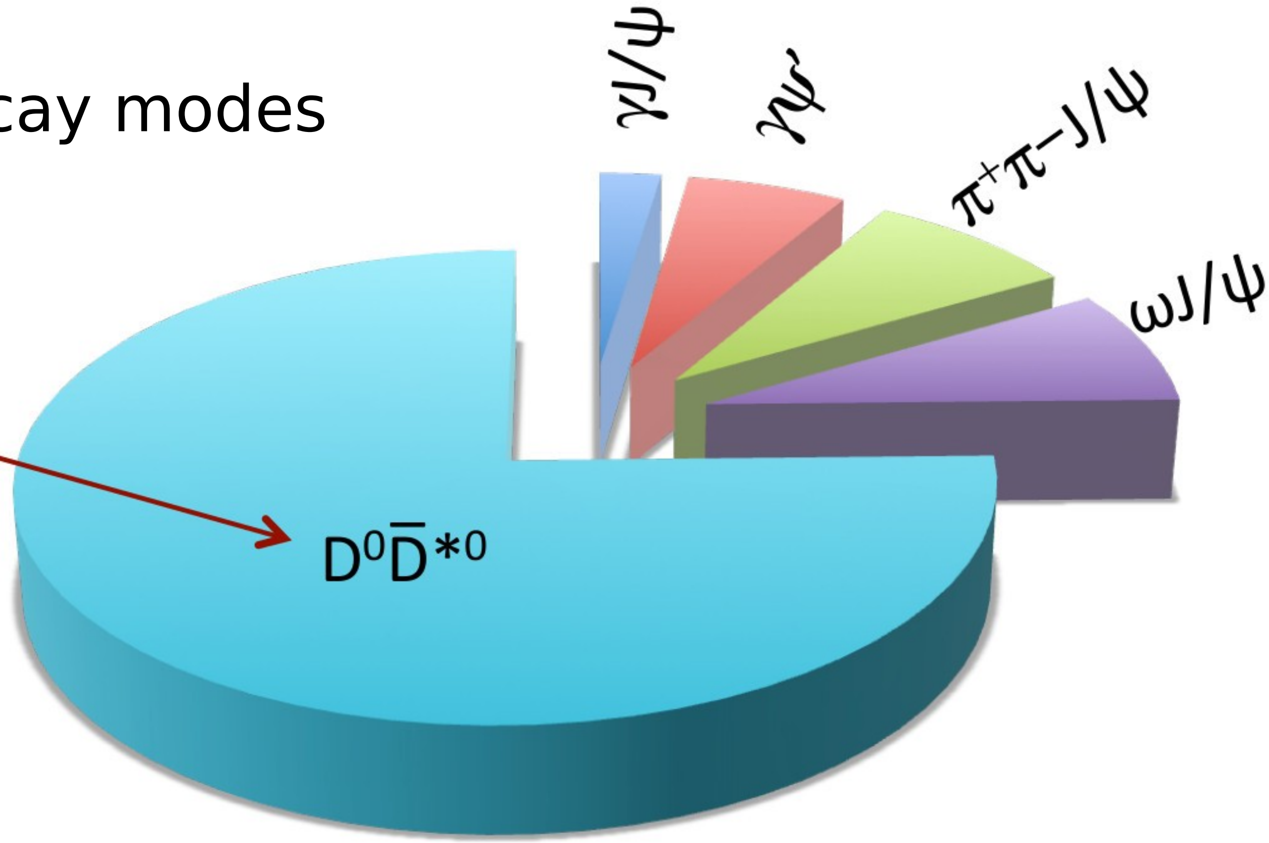
(BESIII/Yu-Ping Guo @EQCD, Jinan 6/2015)

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

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

X(3872) decay modes

strong $D\bar{D}^*$ coupling



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. BR(fall apart mode) $\gg$ BR(quarkonium $+ X$)
4. no states which require binding through 3 pseudoscalar coupling

necessary* conditions for existence of a resonance

(a) <u>both</u> hadrons heavy, as $E_{kin} \sim 1/\mu_{RED}$

(b) both couple to pions;
one of them can have $I = 0$, e.g.
$\Sigma_c \bar{\Lambda}_c \underset{\pi}{\longrightarrow} \Lambda_c \bar{\Sigma}_c$.

(c) $\Gamma(h_1) + \Gamma(h_2) \ll \Gamma(\text{molecule})$

---

* may not be sufficient

the binding mechanism can in principle

apply to any two heavy hadrons

which couple to isospin

and satisfy these conditions,

be they mesons or baryons

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

doubly-heavy hadronic molecules:
most likely candidates with $Q\bar{Q}'$, $Q = c, b$, $\bar{Q}' = \bar{c}, \bar{b}$:

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

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

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

$c\bar{c}$ and $b\bar{b}$ states decay strongly to $\bar{c}c$ or $\bar{b}b$ and π-(s)
$b\bar{c}$ and $c\bar{b}$ states decay strongly to $B_c^\pm$ and π-(s)

QQ' candidates – dibaryons:

$\Sigma_c\Sigma_c$, $\Sigma_c\Lambda_c$, $\Sigma_c\Lambda_b$, $\Sigma_b\Sigma_b$, $\Sigma_b\Lambda_b$, and $\Sigma_b\Lambda_c$.

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like a whole new periodic table

prediction of doubly heavy baryon with hidden charm:

$\Sigma_c \bar{D}^* \equiv \Theta_{\bar{c}c}, \quad m_{\Theta_{\bar{c}c}} \approx 4460$ MeV,

possible decay mode: $\Theta_{cc} \to J/\psi\, p$

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

S-wave $\to J^P = 3/2^-$

small overlap of molecular state with $J/\psi p$

$\Longrightarrow$ narrow width $\lesssim$ few tens of MeV

despite $>$ 400 MeV phase space

$\Theta_{\bar{c}c}$ minimal quark content: $\bar{c}c\, uud$

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

a molecule, not a tightly-bound pentaquark

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

Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	Example of decay mode
$D\bar{D}^*$	0	$c\bar{c}q\bar{q}$	3875.8	$J/\psi\,\pi\pi$
$D^*\bar{D}^*$	0	$c\bar{c}q\bar{q}$	4017.2	$J/\psi\,\pi\pi$
D^*B^*	0	$c\bar{b}q\bar{q}$	7333.8	$B_c^+\pi\pi$
$\bar{B}B^*$	0	$b\bar{b}q\bar{q}$	10604.6	$\Upsilon(nS)\pi\pi$
$\bar{B}^*B^*$	0	$b\bar{b}q\bar{q}$	10650.4	$\Upsilon(nS)\pi\pi$
$\Sigma_c\bar{D}^*$	1/2	$c\bar{c}qqq'$	4462.4	$J/\psi\,p$
Σ_cB^*	1/2	$c\bar{b}qqq'$	7779.5	B_c^+p
$\Sigma_b\bar{D}^*$	1/2	$b\bar{c}qqq'$	7823.0	B_c^-p
Σ_bB^*	1/2	$b\bar{b}qqq'$	11139.6	$\Upsilon(nS)p$
$\Sigma_c\bar{\Lambda}_c$	1	$c\bar{c}qq'\bar{u}\bar{d}$	4740.3	$J/\psi\,\pi$
$\Sigma_c\bar{\Sigma}_c$	0	$c\bar{c}qq'\bar{q}\bar{q}'$	4907.6	$J/\psi\,\pi\pi$
$\Sigma_c\bar{\Lambda}_b$	1	$c\bar{b}qq'\bar{u}\bar{d}$	8073.3[d]	$B_c^+\pi$
$\Sigma_b\bar{\Lambda}_c$	1	$b\bar{c}qq'\bar{u}\bar{d}$	8100.9[d]	$B_c^-\pi$
$\Sigma_b\bar{\Lambda}_b$	1	$b\bar{b}qq'\bar{u}\bar{d}$	11433.9	$\Upsilon(nS)\pi$
$\Sigma_b\bar{\Sigma}_b$	0	$b\bar{b}qq'\bar{q}\bar{q}'$	11628.8	$\Upsilon(nS)\pi\pi$

[a] Ignoring annihilation of quarks.
[b] Plus other charge states when $I \neq 0$.
[c] Based on isospin-averaged masses.
[d] Thresholds differ by 27.6 MeV.

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

New Exotic Meson and Baryon Resonances from Doubly Heavy Hadronic Molecules

Marek Karliner[1,*] and Jonathan L. Rosner[2,†]
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[2]*Enrico Fermi Institute and Department of Physics, University of Chicago, 5620 S. Ellis Avenue, Chicago, Illinois 60637, USA*
(Received 13 July 2015; published 14 September 2015)

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

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

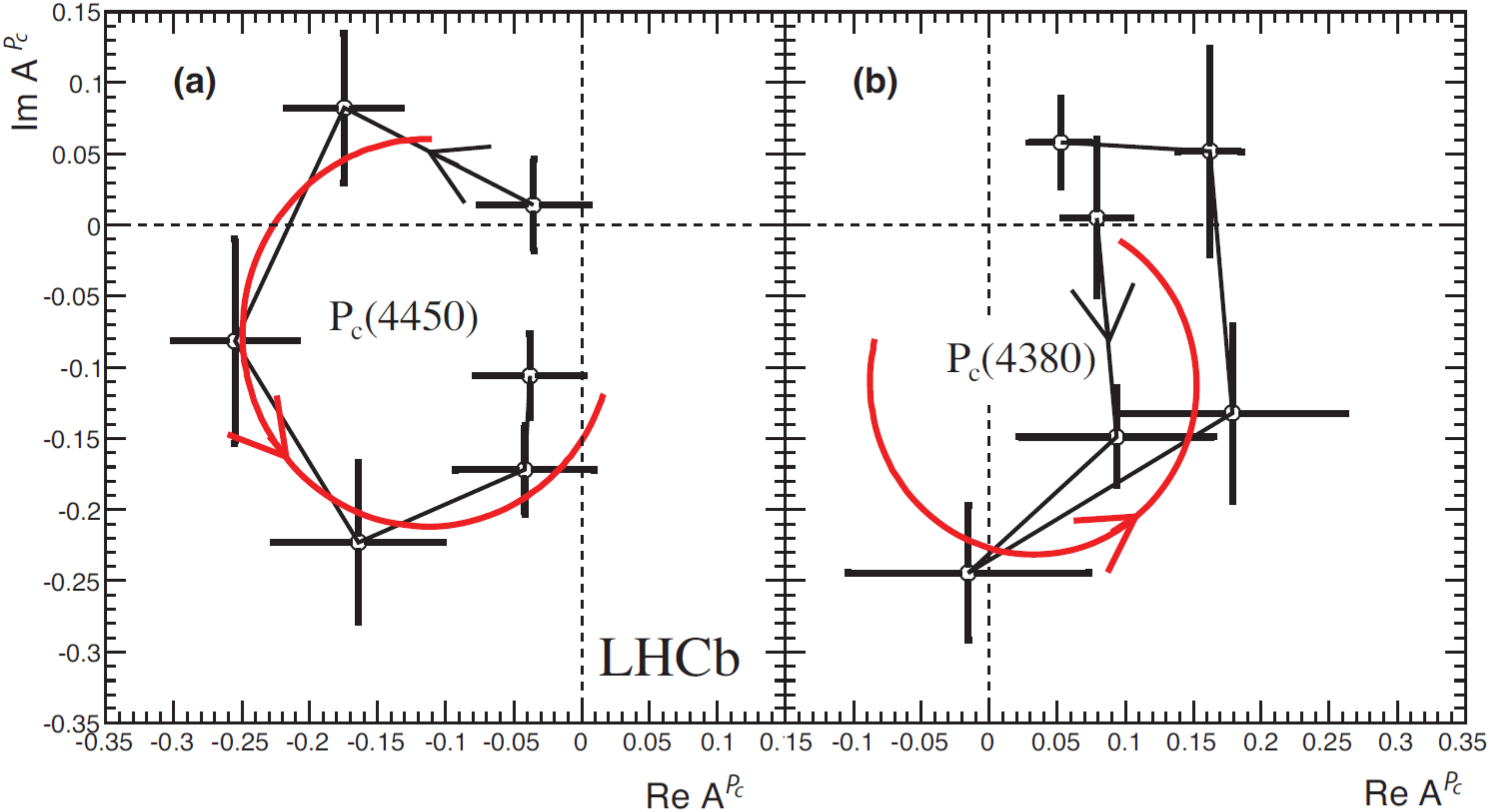
Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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

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

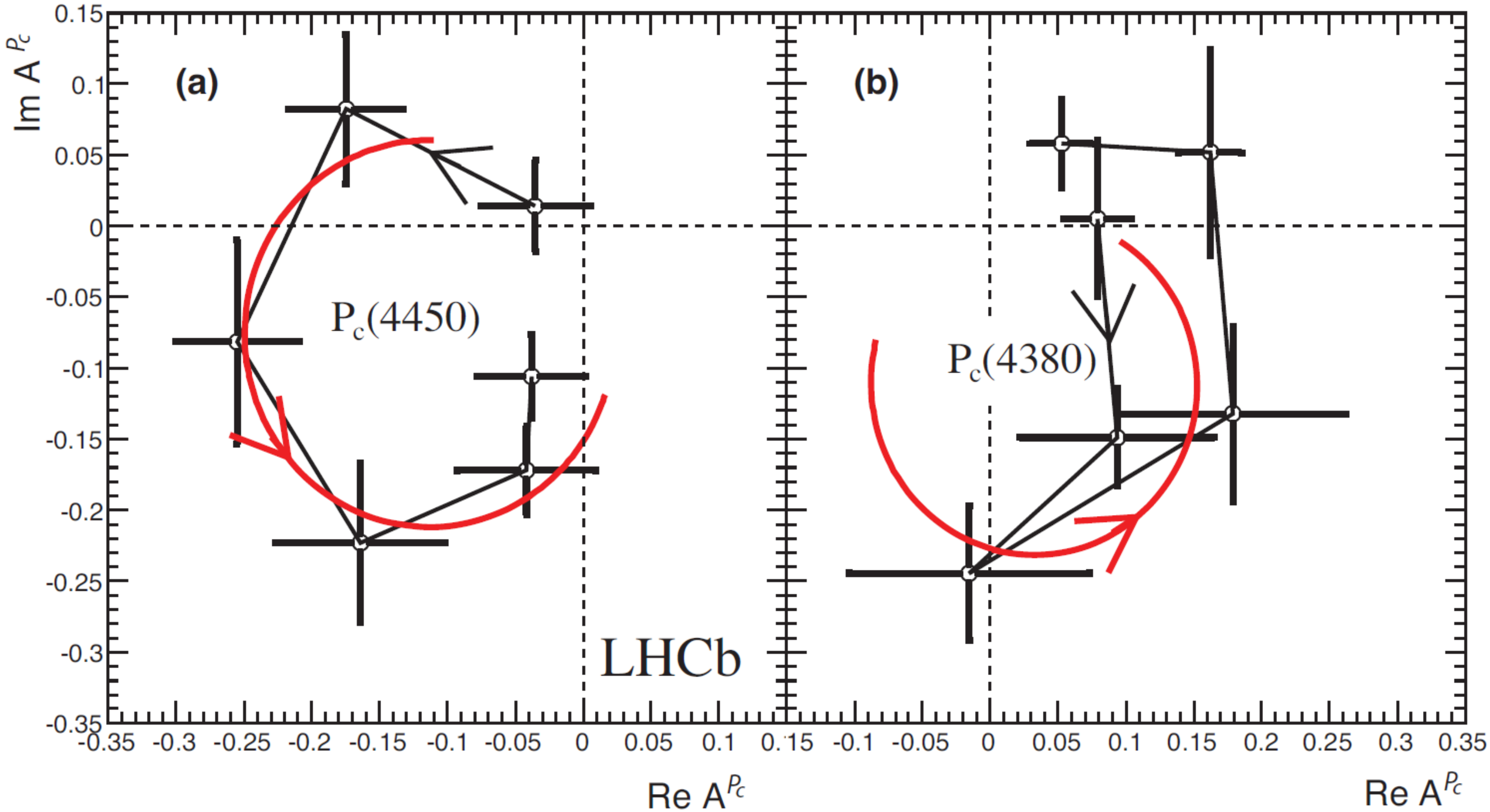
Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions.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

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



$P_c(4450)$: predicted,
narrow: $\Gamma = 39 \pm 5 \pm 19$,
10 MeV from $\Sigma_c \bar{D}^*$ threshold
perfect Argand plot: a molecule

$P_c(4380)$: <u>not</u> predicted,
wide: $\Gamma = 205 \pm 18 \pm 86$ MeV,
Argand plot <u>not</u> resonance-like
???



$P_c(4450)$: predicted,
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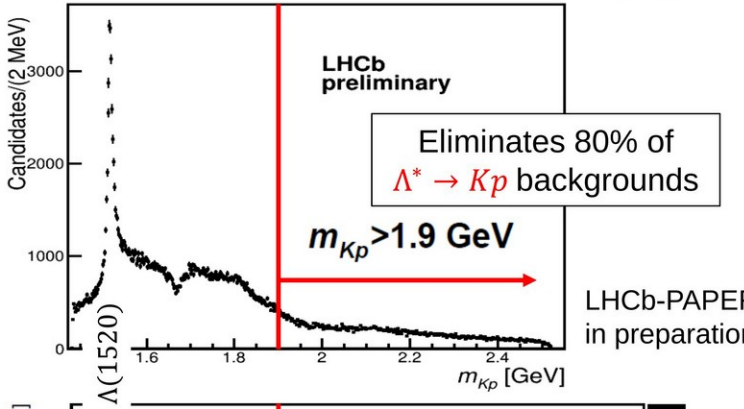
perfect Argand plot: a molecule

$P_c(4380)$: not predicted,
wide: $\Gamma = 205 \pm 18 \pm 86$ MeV,
Argand plot not resonance-like
???

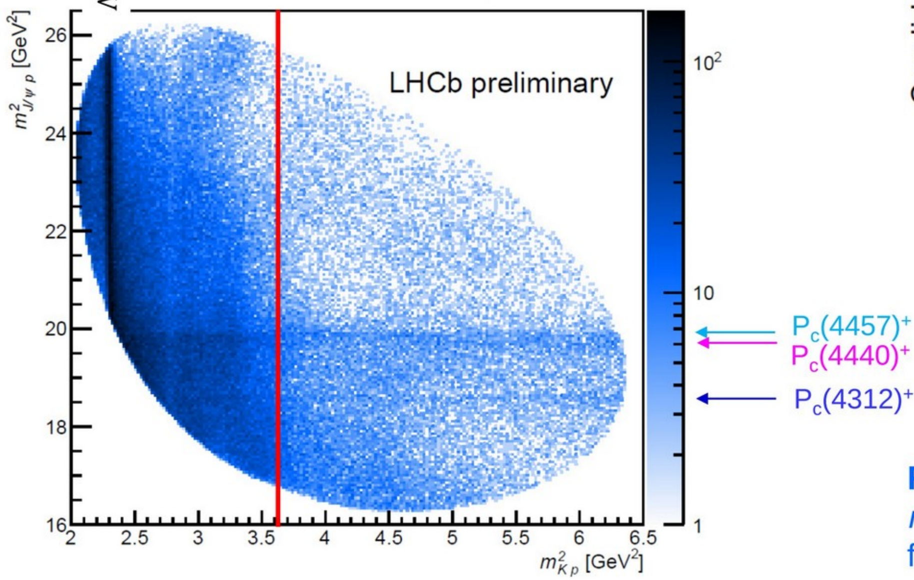
$P_c(4450)$ might be just the first of many “heavy deuterons”

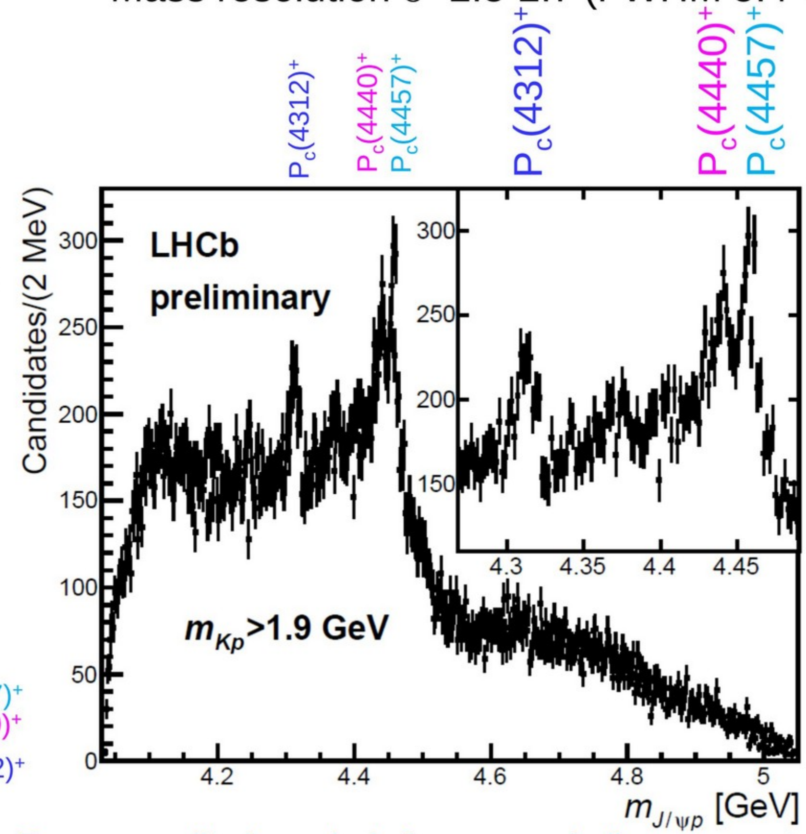
Narrow $P_c^+ \rightarrow J/\psi p$ peaks with Λ^* suppression

Mass resolution σ=2.3-2.7 (FWHM 5.4-6.4) MeV



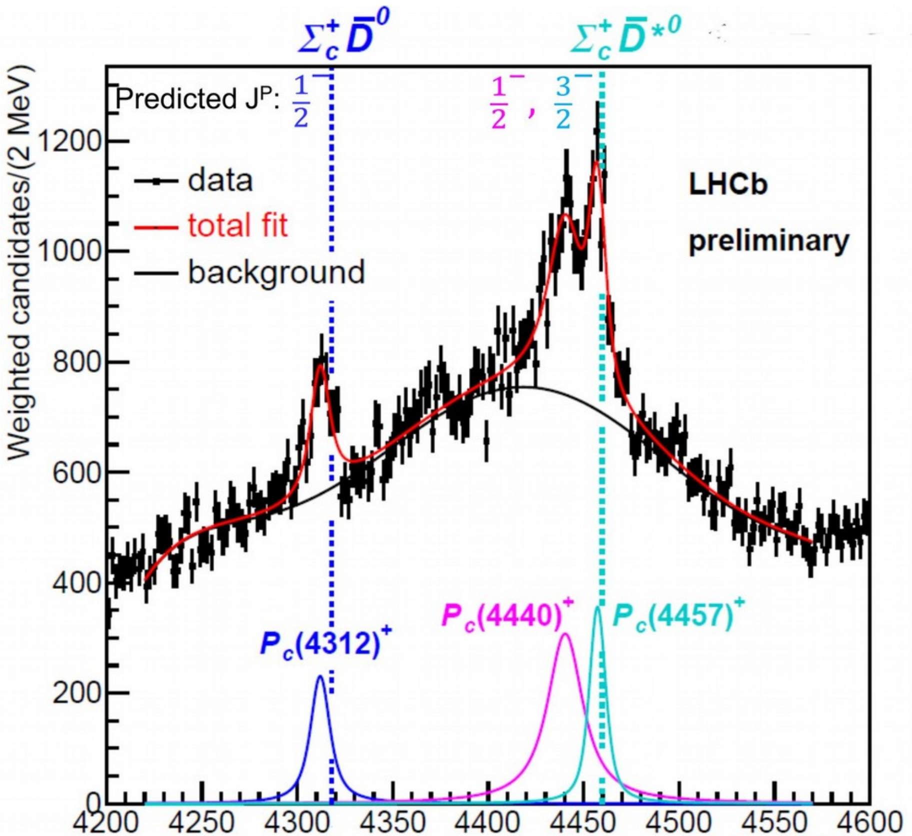
LHCb-PAPER-2019-014
in preparation





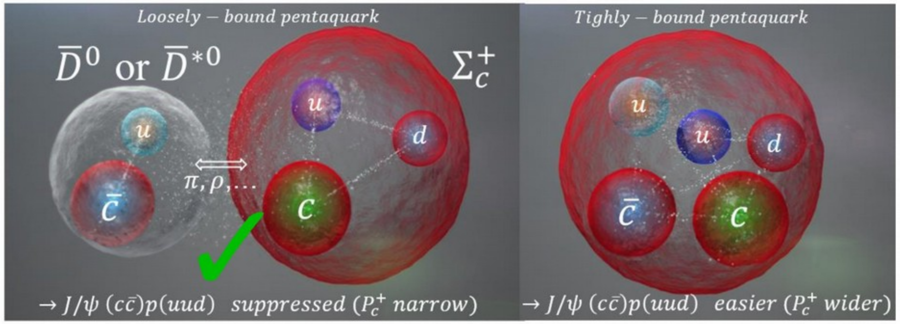
Proper amplitude analysis faces new challenges: must consider $m_{J/\psi p}$ resolution effects, large statistics and sub-percent precision in fit fractions required in the amplitude model – work in progress

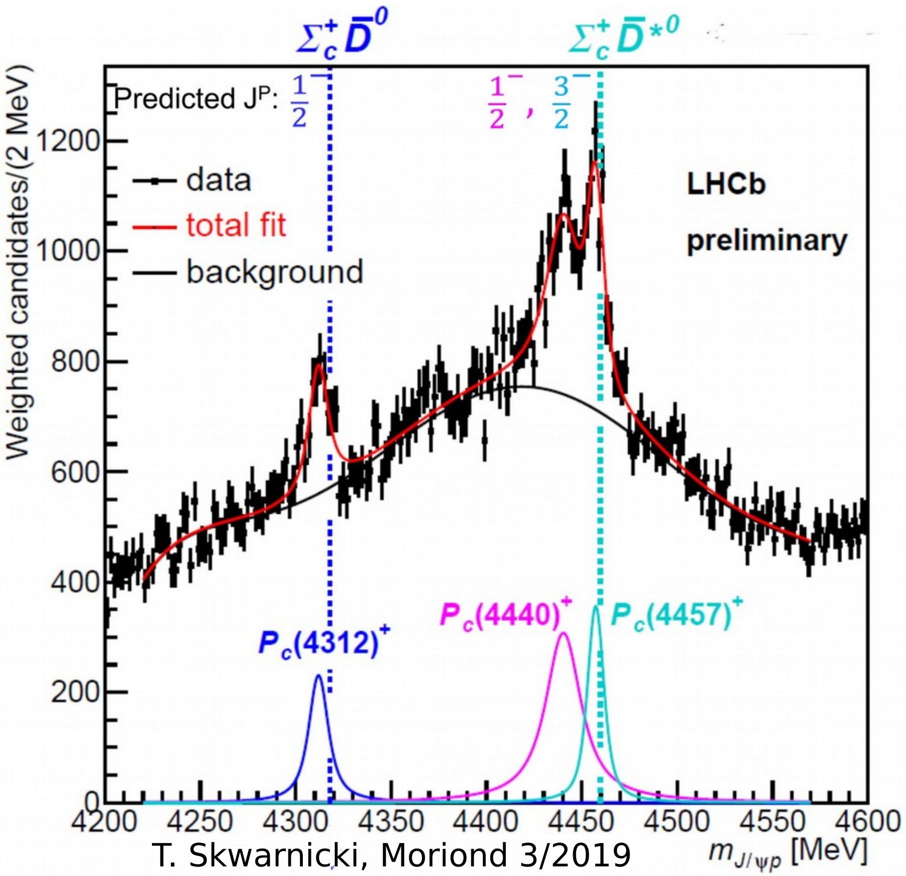
State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$



T. Skwarnicki, Moriond 3/2019

The near-threshold masses and the narrow widths of $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ favor "molecular" pentaquarks with meson-baryon substructure!





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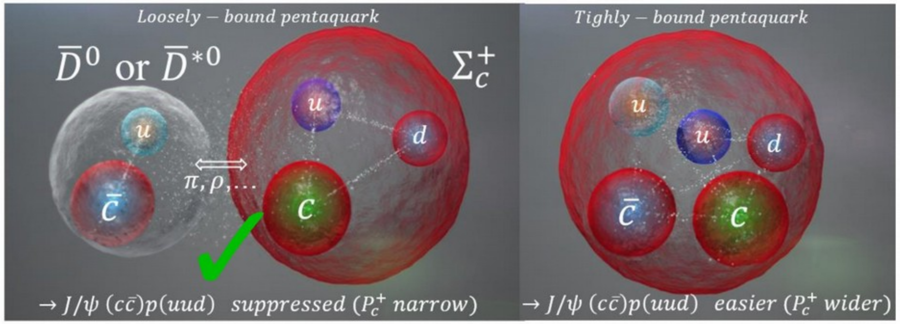


observe all 3 S-wave states:

$\Sigma_c \bar{D}$; $\quad J^P = \frac{1}{2}^-$,

$\Sigma_c \bar{D}^*$; $\; J^P = \frac{1}{2}^-, \; \frac{3}{2}^-$

for $Q \to \infty$ 4 more S-wave states:

$\Sigma_c^* \bar{D}$; $\quad J^P = \frac{3}{2}^-$

$\Sigma_c^* \bar{D}^*$; $\; J^P = \frac{1}{2}^-, \; \frac{3}{2}^-, \; \frac{5}{2}^-$

but $\Gamma(\Sigma_c^* \to \Lambda_c \pi) \approx 15$ MeV...

Open Questions

- LHCb: new narrow states slightly below $\Sigma_c \bar{D}(\bar{D}^*)$ thresholds; highly suggestive of molecules

Several interesting issues:

- Additional 4 $\Sigma_c^* \bar{D}(\bar{D}^*)$ states ?
- Decay into $\Lambda_c \bar{D}$?
- So far no signal in $\gamma p \to J/\psi p$ photoproduction
- If $P_c(4312)$ $\Sigma_c \bar{D}$ molecule, why no $D\bar{D}$ molecule?
- $X(3872) \ll 1$ MeV from $\bar{D}D^*$ threshold
  Z_b-s ~ 2 MeV from $\bar{B}B^*$, $\bar{B}^*B^*$
  deuteron 2.2 MeV below pn
  so why are P_c-s $5 \div 22$ MeV below $\Sigma_c \bar{D}(\bar{D}^*)$?
- $P_c(4440)$ and $P_c(4457)$: likely $\Sigma_c \bar{D}^*$, $S = \frac{1}{2}, \frac{3}{2}$
  17 MeV spin splitting $\gg$ deuteron $(S{=}1)$ vs. pn $S{=}0$
- lattice ?

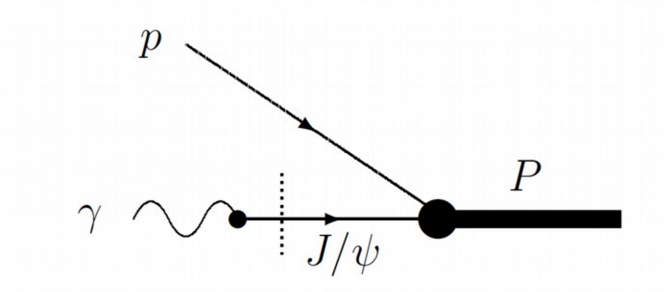
Test via photoproduction

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

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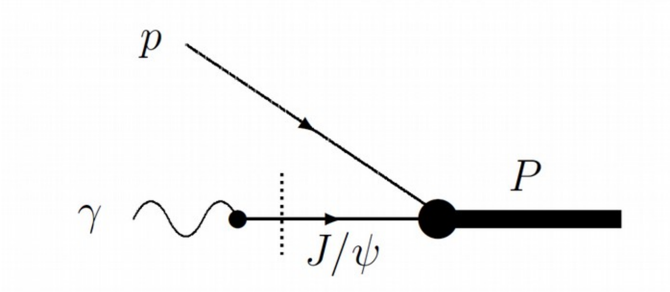
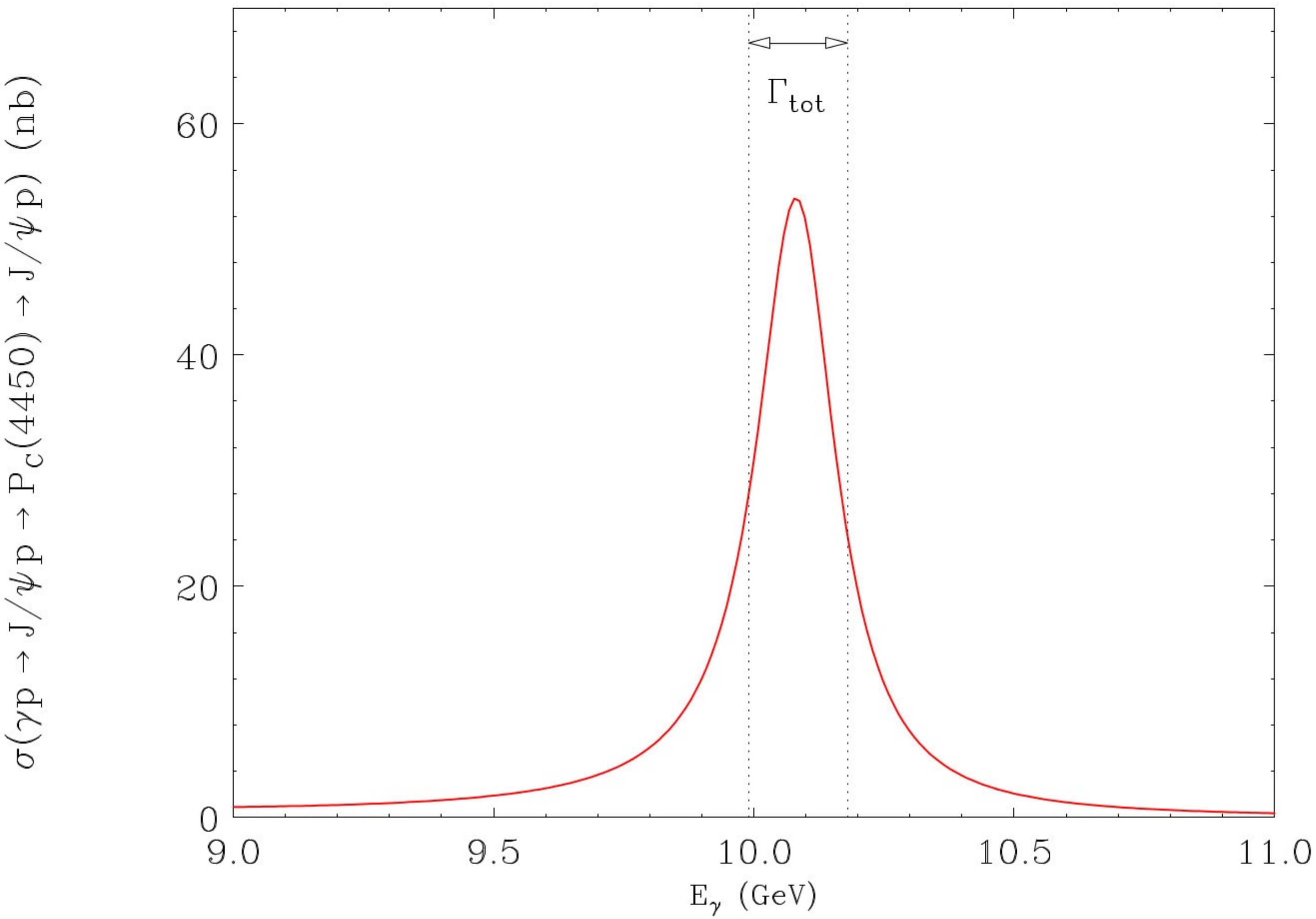


- $E_\gamma = 10$ GeV $\Rightarrow$ CLAS12 & GlueX @JLab & ...

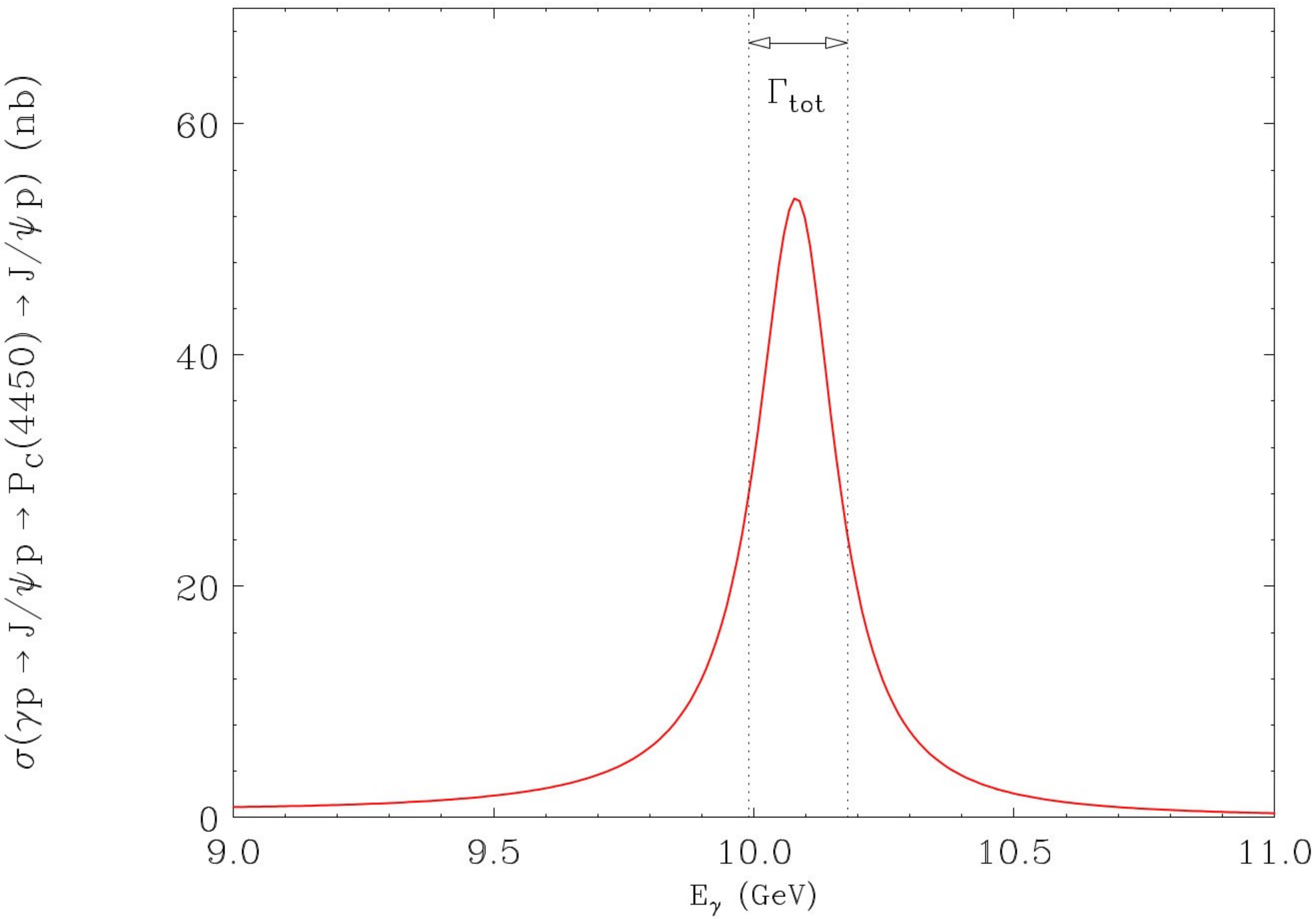
- $\sigma \sim 50$ nb $\gg \sigma_{\text{diffractive}} \sim 1$ nb

Now can also look for $P_c(4312)$ in $\gamma N \to J/\psi N$!
$E_\gamma = 9.44$ GeV



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

Ongoing exps at JLab



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Ongoing exps at Jlab

possible c→ b analogue?

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

Origina

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

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

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

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

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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.

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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 $pK^-\pi^+$. 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 $3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14\,(\Lambda_c^+)\ \text{MeV}/c^2$, 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 $1.7\,\text{fb}^{-1}$, 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	$\cdots$
$\Xi_{bb}^{(*)}$	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	–	–

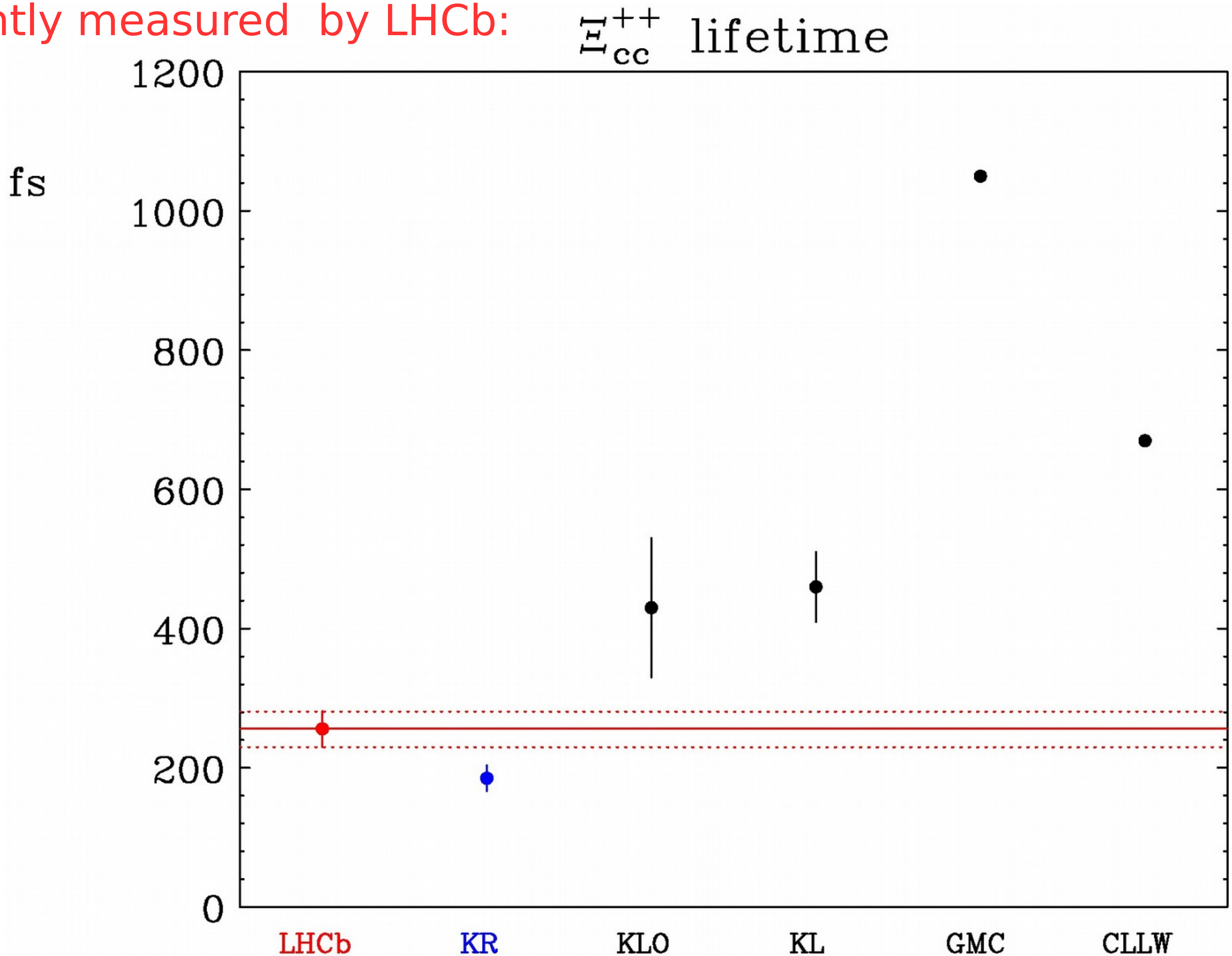
[28] K. Anikeev, D. Atwood, F. Azfar, S. Bailey, C. W. Bauer, W. Bell, G. Bodwin, E. Braaten *et al.*, *Workshop on B Physics at Conferences C99-09-23.2 and C00-02-24 (Batavia, IL, Fermilab, 2001)*, arXiv:hep-ph/0201071.

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

[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).

recently measured by LHCb:



$\tau(\Xi_{cc}^{++}) = 256^{+21}_{-22} \pm 14$ fs masses of doubly-heavy baryons:

use same toolbox that predicted

b baryon masses.

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^*
- $V_{HF}(cc)$
- $V_{HF}(cq)$
- m_q

$\left.\begin{array}{l} V_{cc} \text{ in } 3_c^* \\ V_{HF}(cc) \end{array}\right\}$ no exp info !

Effective masses

in mesons:

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

in baryons:

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

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

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

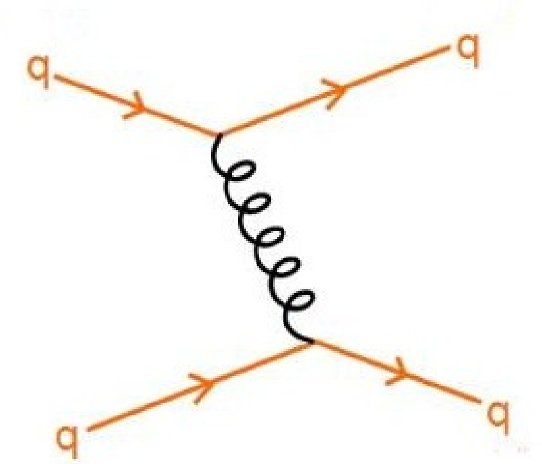
$$V(c\bar{c}) = \bar{M}(c\bar{c}:1S) - 2m_c^m = -258.0 \text{ MeV}.$$

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

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

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

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

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

Editors' Suggestion

PRL **119,** 202001 (2017) PHYSICAL REVIEW LETTERS week ending 17 NOVEMBER 2017

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

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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.

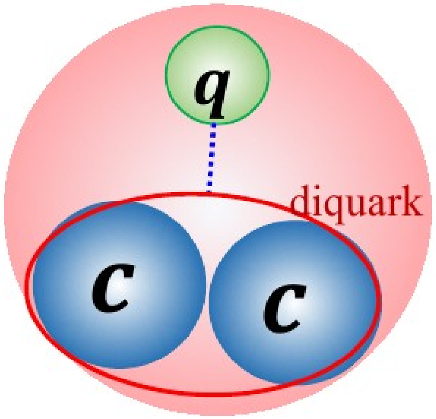
DOI: 10.1103/PhysRevLett.119.202001

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

build on accuracy of the Ξ_{cc} mass prediction

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

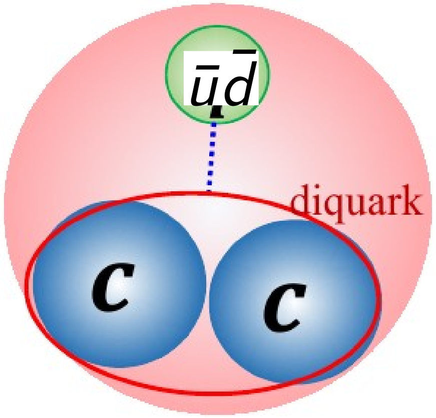
bbq baryon



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:

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

Ξ_{cc} discovery $\Rightarrow$ quantitative validation

qualitatively $E_{binding} \sim \alpha_s^2 M_Q$

so for $M_Q \to \infty$

$QQ\bar{u}\bar{d}$ must be bound

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,

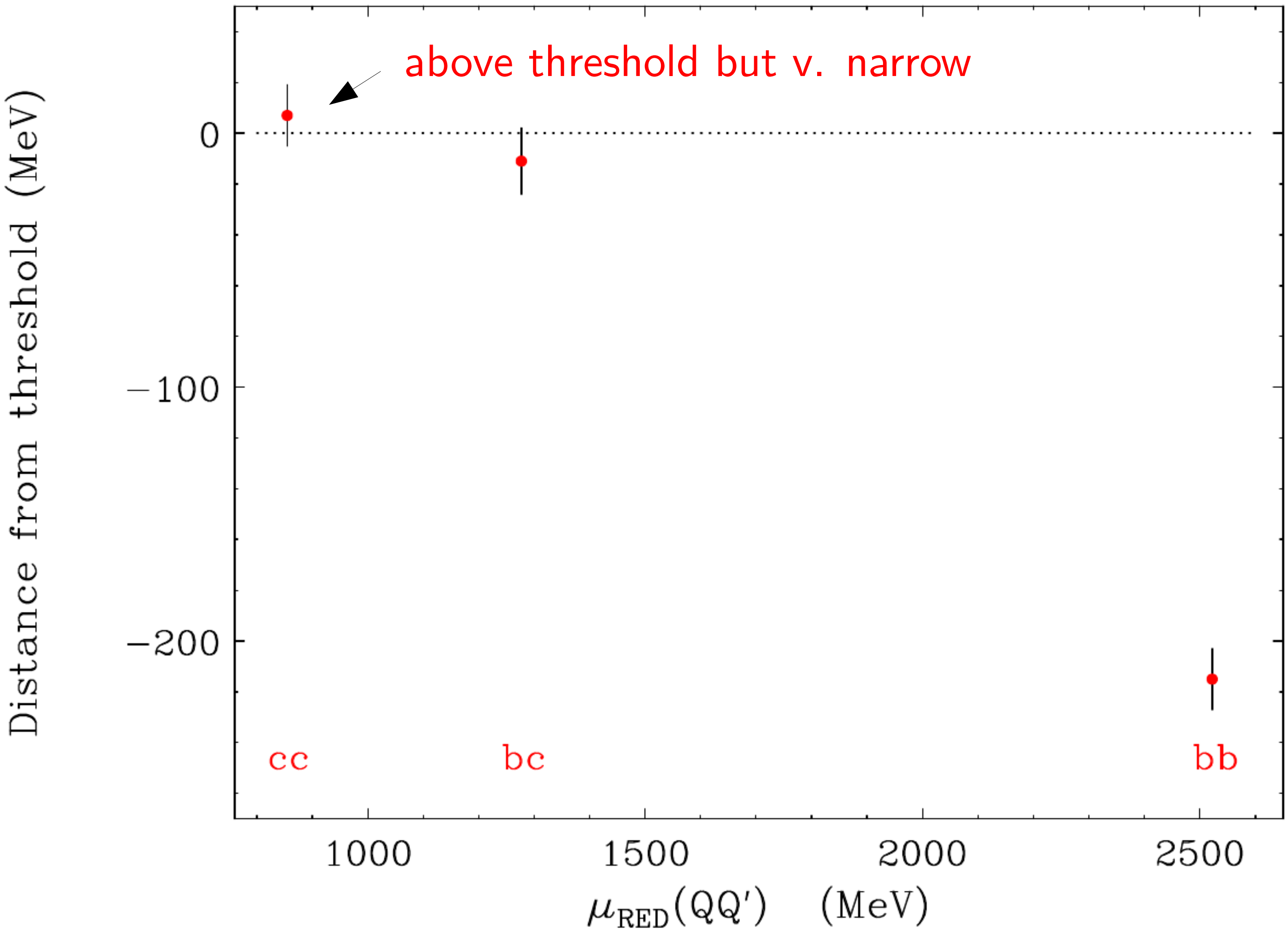
but if use measured $M(X_{cc}^{++}) \Rightarrow$ only 1 MeV above $D^0 D^{+*}$

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

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

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 $\int \mathcal{L} dt$

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 $\int \mathcal{L} dt$

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

Inclusive signature of (bbx): displaced B_c

T. Gershon & A. Poluektov JHEP 1901 (2019) 019

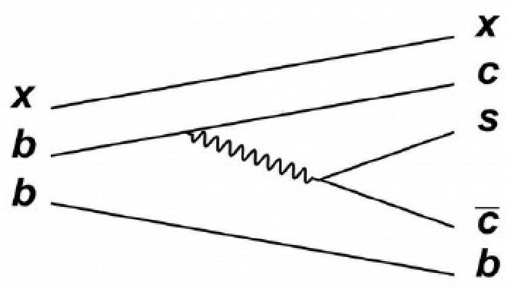
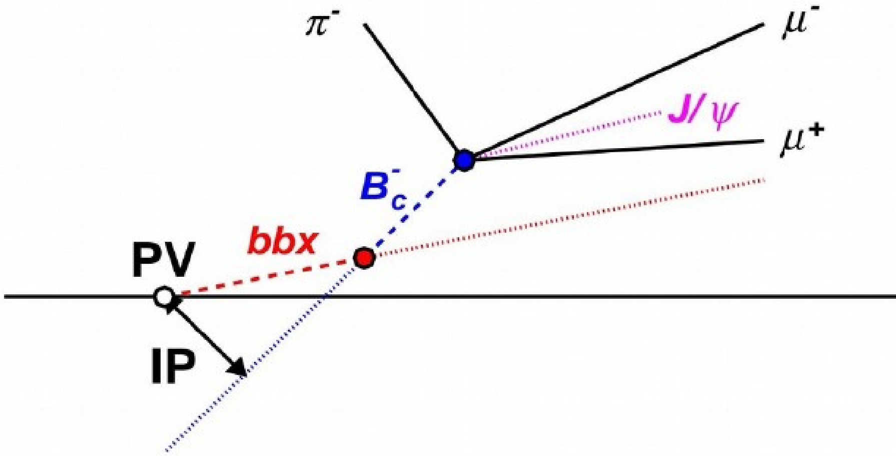


Diagram for production of a B_c^- meson from a double beauty hadron decay.



$\mathcal{O}(1\%)$ of all B_c-s @LHC come from bbx

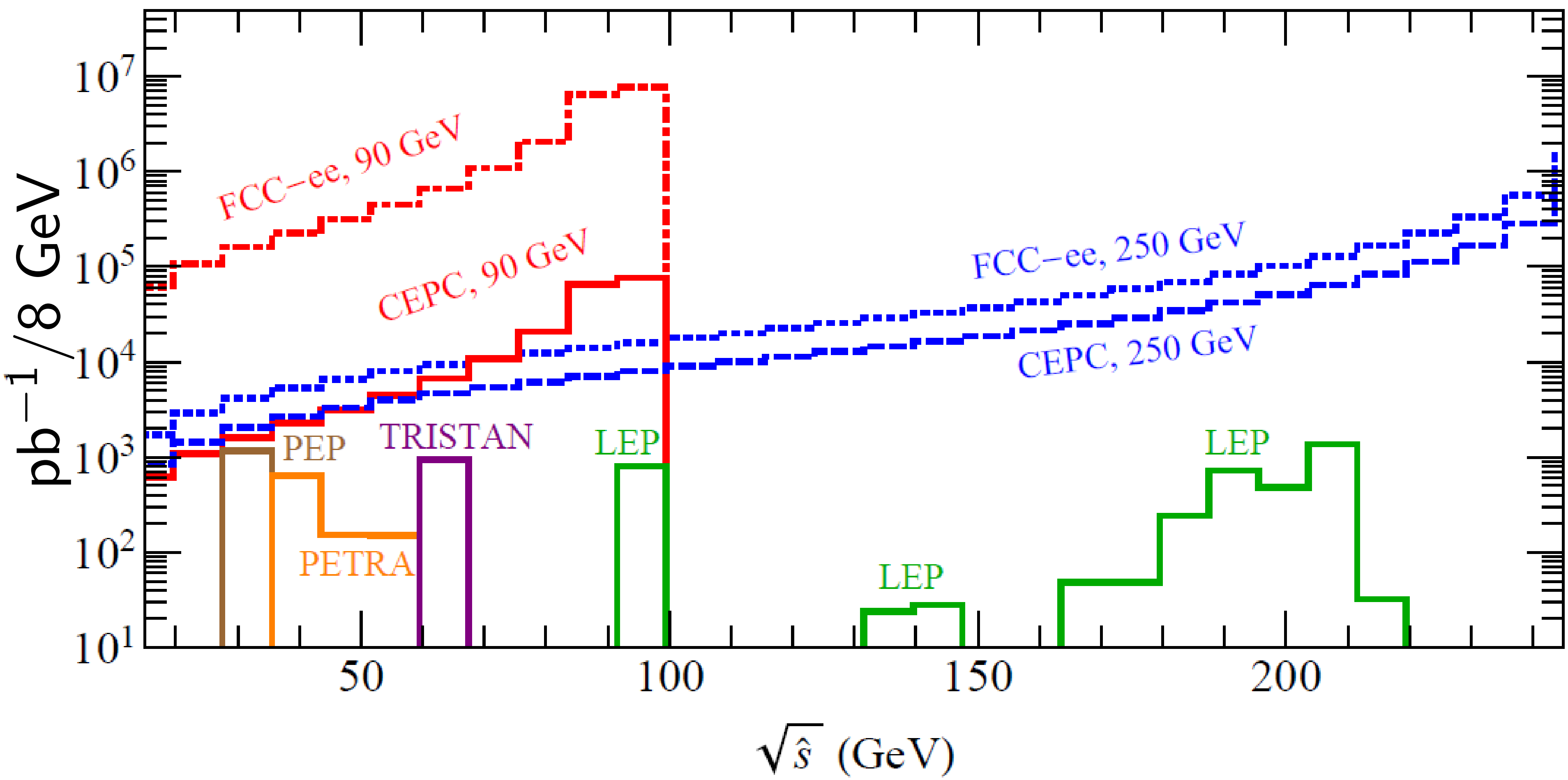
- major enhancement of eff. bbx rate
- bbq or $bb\bar{u}\bar{d}$?

incl. $\sigma(bbx)$:
heavy ions $\gg$ pp

$\Rightarrow$ displaced B_c @ALICE & RHIC !

CEPC radiative return

integrated luminosity



Integrated luminosity from past low energy e^+e^- colliders at their nominal center-of-mass energies compared to the effective luminosity through radiative return from future e^+e^- colliders at $\sqrt{s} = 90$ or 250 GeV

gaps filled in and much more

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

no stable light exotics

unlike $bb\bar{u}\bar{d}$,
stable light exotics *do not* exist,
as $E_{kin} \propto 1/m_q$ too large

e.g. proposed deeply bound
uuddss @ 1860-1880 MeV

recently ruled out by BaBar,
arXiv:1810.04724

a deeply bound compact *uuddss* dibaryon ?

advertised as dark matter candidate

(Glennys Farrar)

- prehistory: $\Lambda\Lambda$ H dibaryon, B=81 MeV (R.L. Jaffe 1976)
  optimization of color-magnetic forces, $SU(3)_F$ symm.
  $SU(3)_F$ breaking $\Longrightarrow$ binding marginal
  1242 citations, but H not seen by exp. nor lattice

- attempt at renaissance as dark matter candidate
  for stability needs $B > 2\,(m_s - m_u) \sim 200$ MeV !
  bounds on DM interaction require r<0.2 fm $=r_p/4.4$
  $\Longrightarrow$ $\Delta p > 1$ GeV for each quark!

$T(bb\bar{u}\bar{d})$ 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
- $(bb\bar{u}\bar{d}) \to \bar{B}D\pi^-$, $J/\psi \bar{K}\bar{B}$,
  $$J/\psi J/\psi K^- \bar{K}^0,\ D^0 B^-$$
- $(bc\bar{u}\bar{d})$: $J^P = 0^+$, 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.	
$Z_b(10610)$	$T(bb\bar{u}\bar{d})$
$\bar{B}B^*$	tightly-bound
molecule	tetraquark

likely a general rule

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

$V(\bar{Q}Q) = 2V(QQ)$, 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"

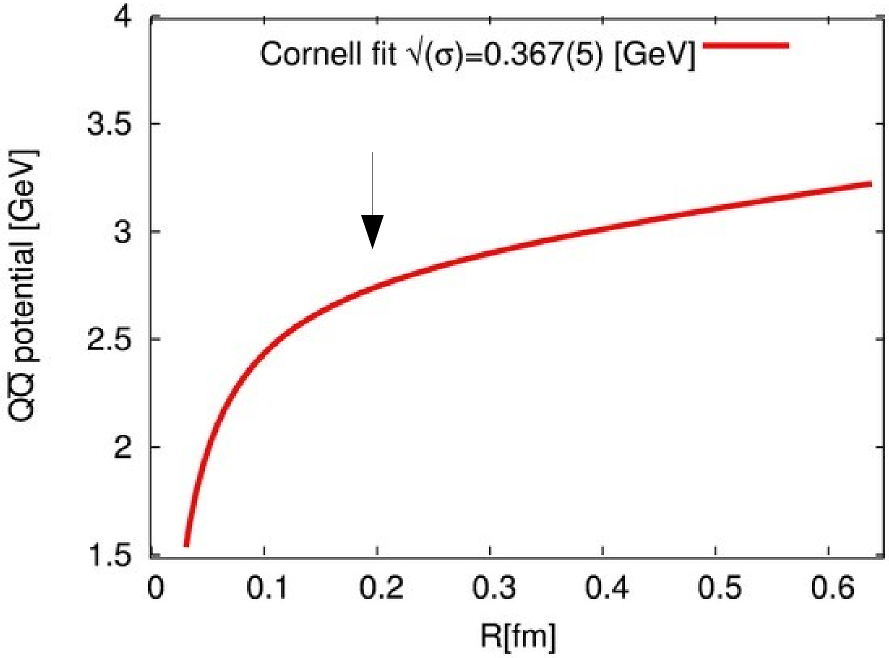
vs. QQ *never* a color singlet,

$\Rightarrow$ tightly bound exotics, tetraquarks

$T(bb\bar{u}\bar{d})$:
$m_b \approx 5$ 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 $R(\bar{B}B^*)/R(\Upsilon) \gg 1$

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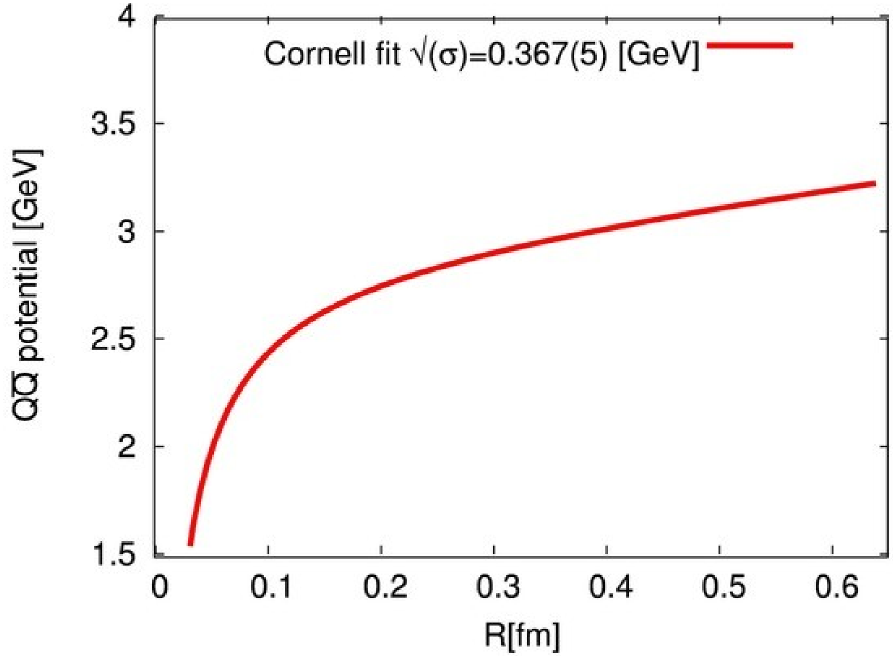

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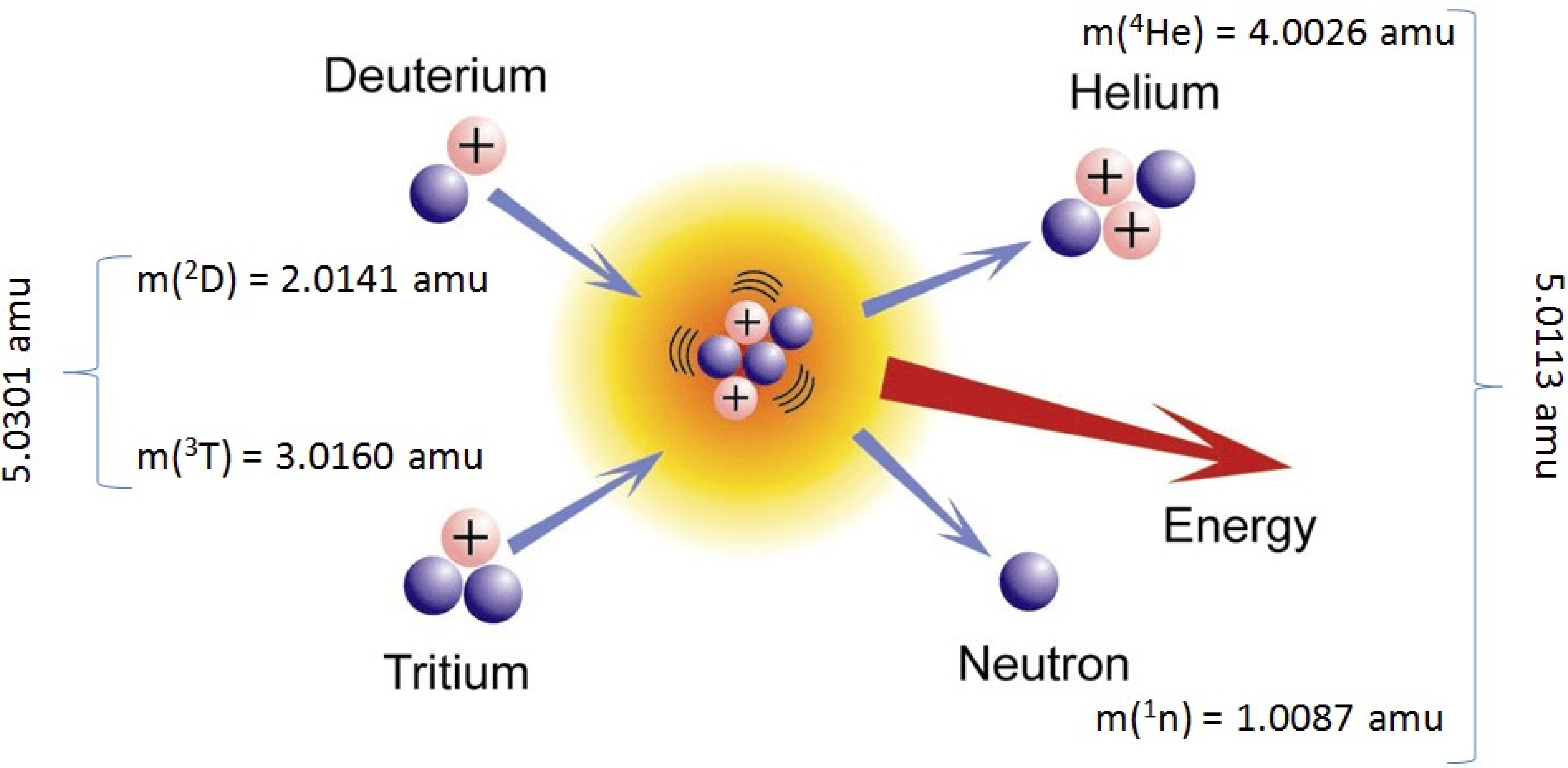
bottom line: $T(bb\bar{u}\bar{d})$ a tetraquark, $Z_b(b\bar{b}u\bar{d})$ a molecule

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

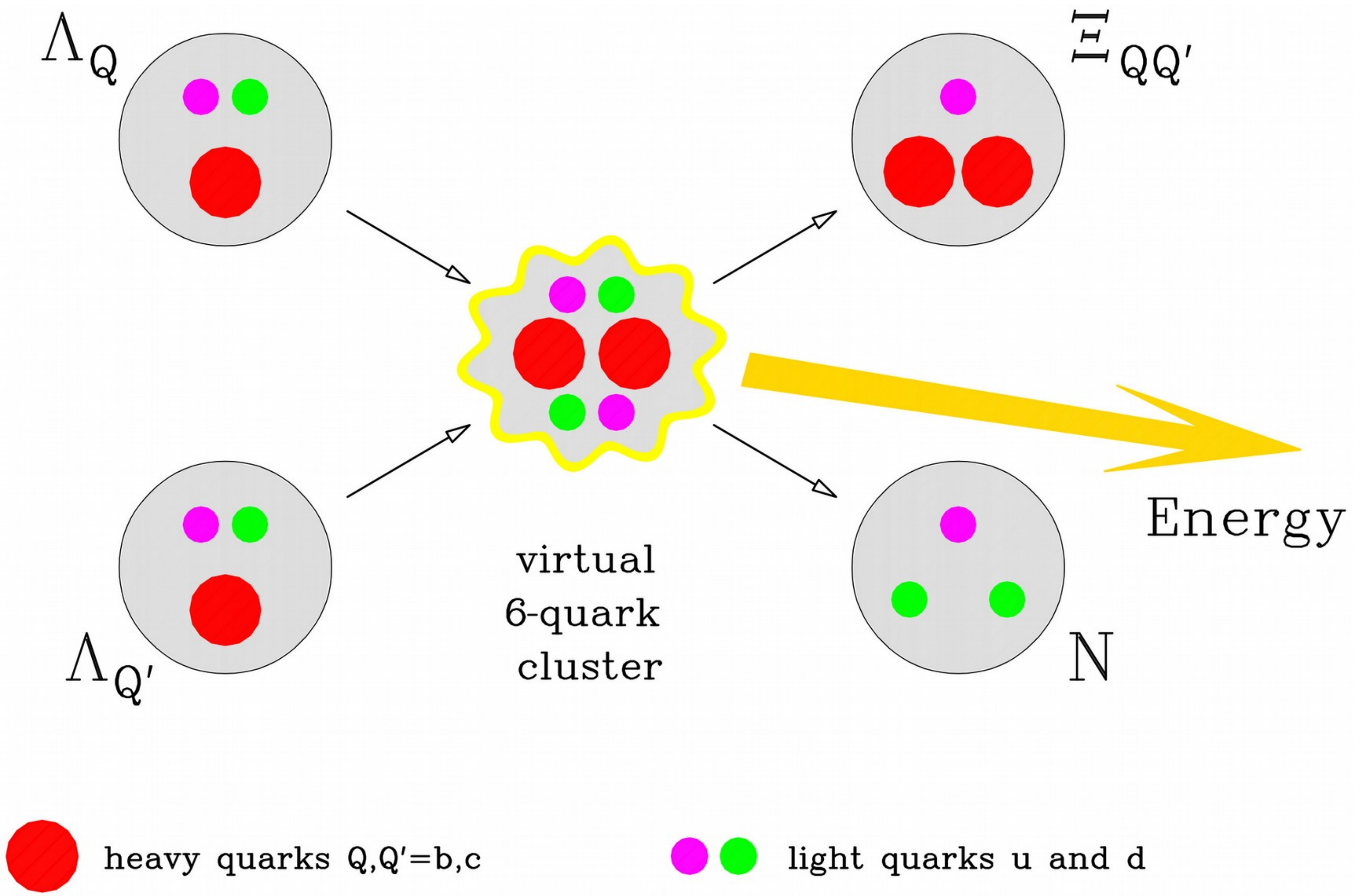
DT fusion: $DT \to {}^4\mathrm{He}\, n$

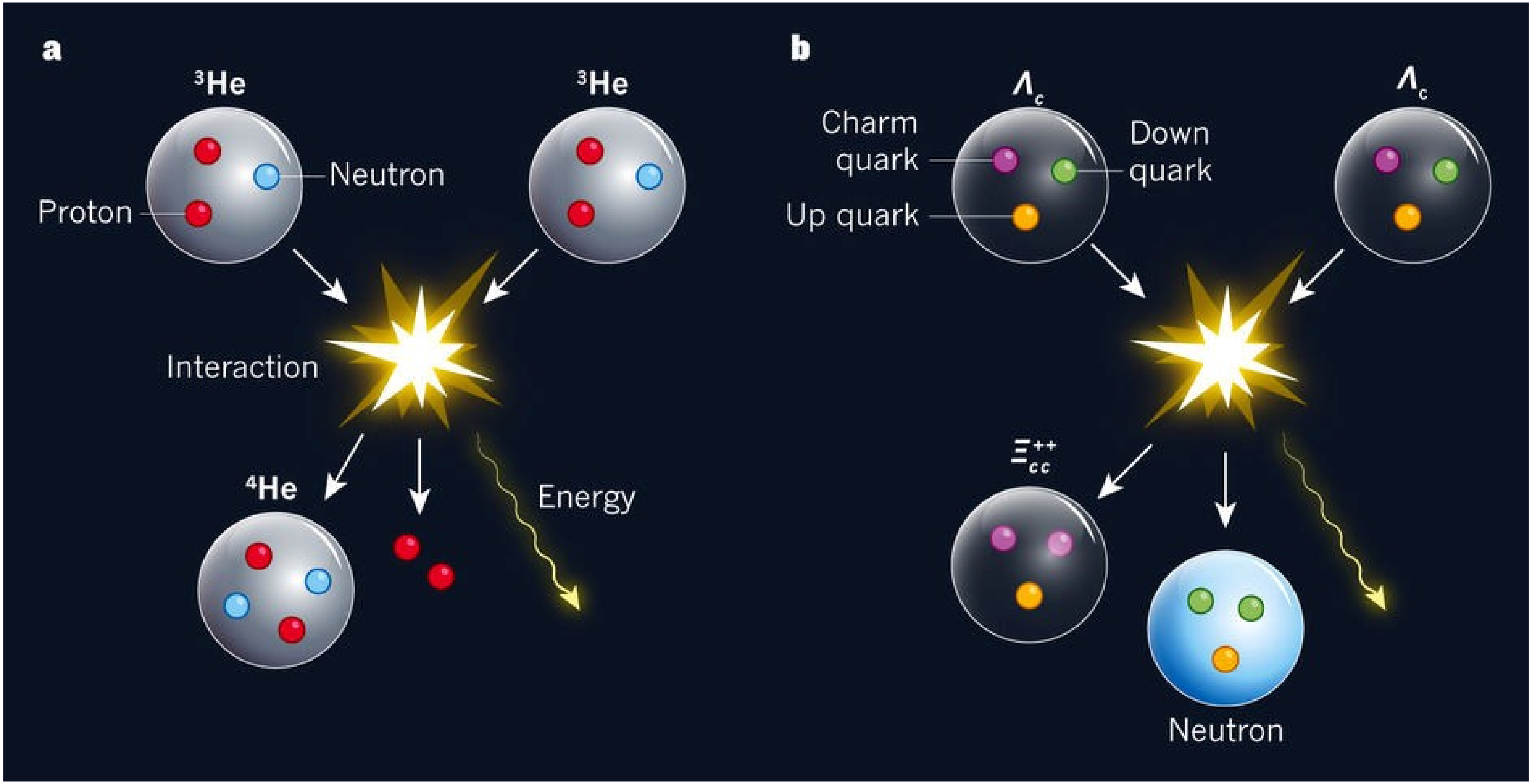


Q = 0.0188 amu x 931.481 MeV/amu = 17.5 MeV

Nuclear fusion reactions w. light nuclei

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


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



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

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

$\Rightarrow$ Q-value of the reaction:

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

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

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   *ccu ddu*

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

$$\Lambda_b\ \Lambda_b \quad \rightarrow \quad \Xi_{bb}^{0}\ n, \qquad Q = 138\ \text{MeV}$$

bud bud   *bbu ddu*

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

$\Rightarrow$ Q-value of the reaction:

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

$cud\ cud \qquad ccu\ ddu$

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

$$\Lambda_b\ \Lambda_b \quad \rightarrow \quad \Xi_{bb}^{0}\ n, \qquad Q = 138 \text{ MeV}$$

$bud\ bud \qquad bbu\ ddu$

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

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LETTER

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Quark–level analogue of nuclear fusion with doubly heavy baryons

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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

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

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:

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

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

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

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

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

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

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

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.

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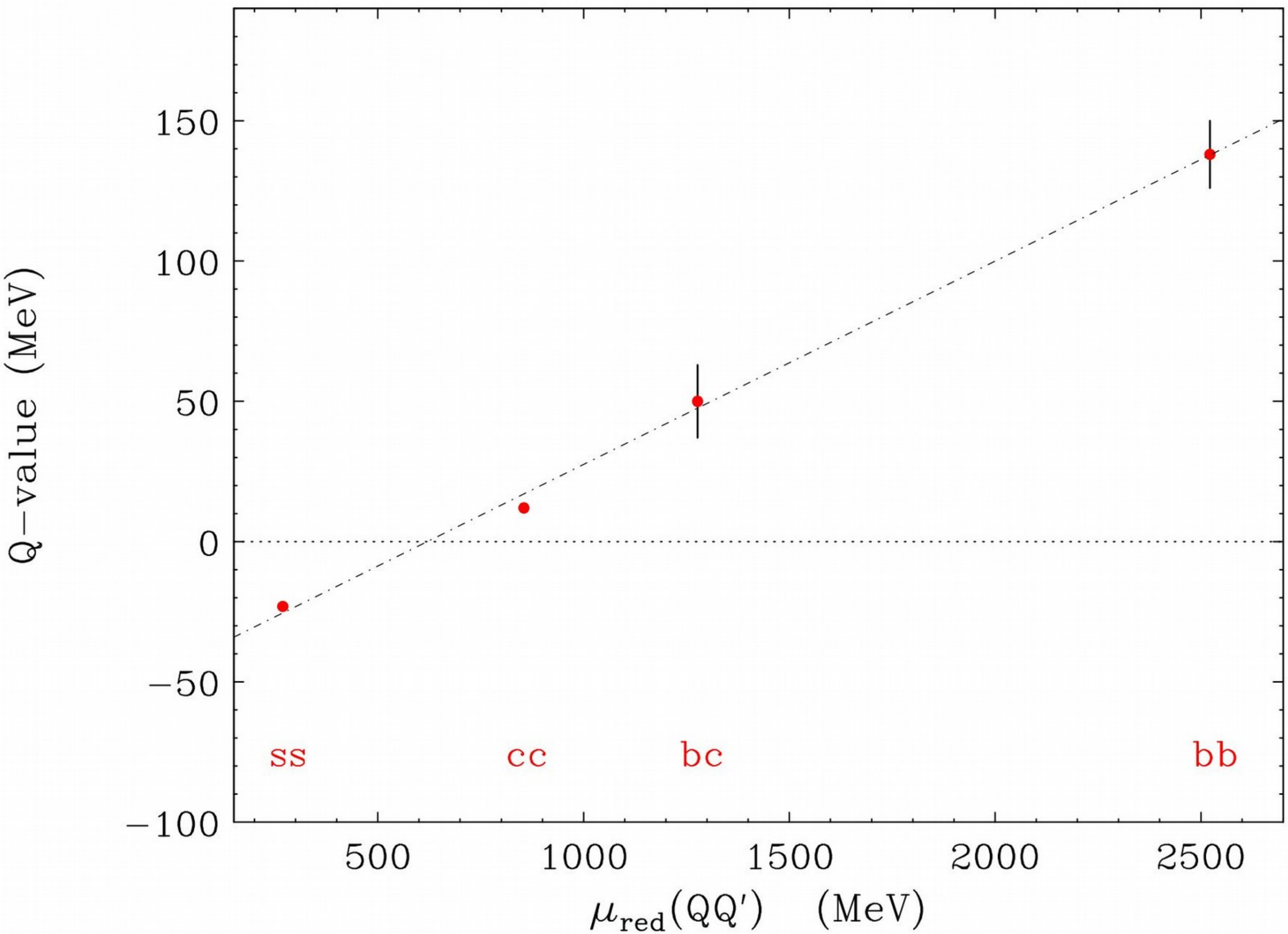
Table I

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

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

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



Q-value in the quark-level fusion reactions $\Lambda_Q \Lambda_{\mathcal{Q}'} \to \Xi_{\mathcal{Q}\mathcal{Q}'} N$, $\mathcal{Q}, \mathcal{Q}' = s, c, b$, 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 @ JPARC,
cf. Tuesday plenary by Hirokazu Tamura

$s \Rightarrow b$ analogue ?

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

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

Maybe also charm analogue

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

both bottom and charm

in heavy ion collisions ?

Possible similar mechanisms in DM sector

QCD-like theories w. confined "dark quarks" $\tilde{q}, \tilde{\mathcal{Q}}$

$m_{\tilde{q}} \lesssim \Lambda_{\widetilde{QCD}}$, m$_{\tilde{\mathcal{Q}}}$ v. large

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

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

$\Rightarrow$ chain reaction involving $\tilde{\mathcal{Q}}$-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±25 MeV, $bb\bar{b}\bar{b}$ @ 18,826±25 MeV $\Rightarrow 4\ell$
- quark-level analogue of nuclear fusion
- possible similar mechanisms in dark matter sector

exciting new spectroscopy awaiting discovery