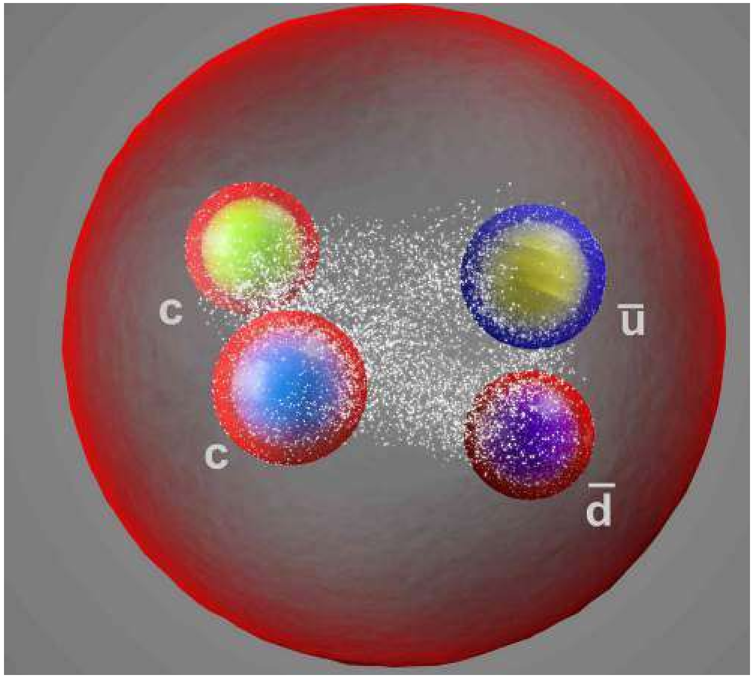


Exotic cousins of the proton: tetraquarks, pentaquarks and hadronic molecules

Marek Karliner
Tel Aviv University
Joint work with Jon Rosner

35-th Recontres de Blois, Oct 23 2024

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:

- newly discovered T_{cc}^{+} tetraquark $= (cc\bar{u}\bar{d})$
- stable $bb\bar{u}\bar{d}$ tetraquark
- hadronic molecules, esp. LHCb pentaquarks 6 by the latest count: 3 nonstrange & 3 strange
- *"like a new layer in the periodic table"*

$\exists$ robust experimental evidence
for multiquark states, a.k.a.
exotic hadrons with heavy Q

- non $\bar{q}q'$ mesons, e.g. $\bar{Q}Q\bar{q}q, \quad QQ\bar{q}\bar{q}$
  $Q = c, b \qquad q = u, d, s$

- non $qq'q''$ baryons, e.g. $\bar{Q}Qqq'q''$

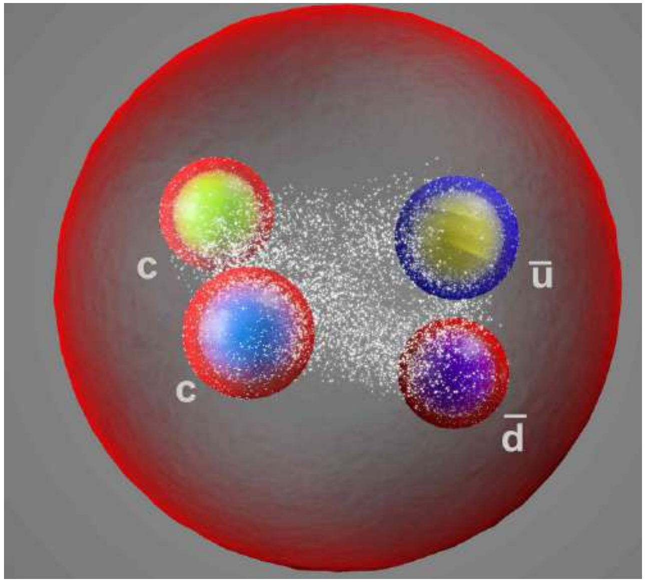
two key questions:

- which additional exotics should we expect?

- how are quarks organized inside them?

Tq   dq-dq   had. mol.

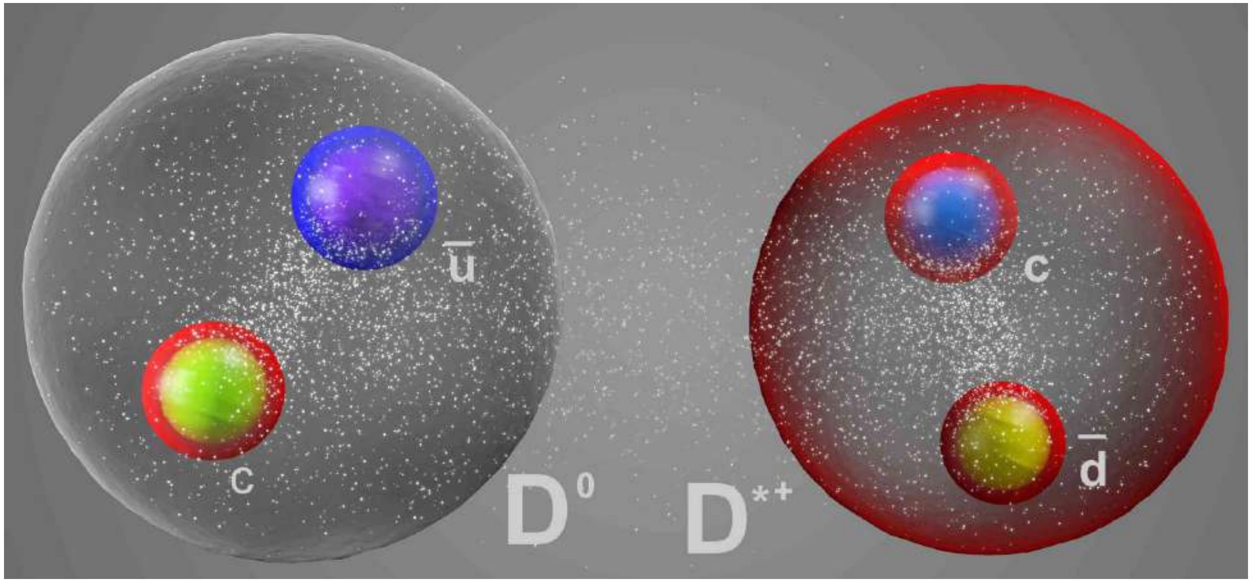
tightly-bound
tetraquark



each quark
sees the color charges
of all other quarks

or

hadronic
molecule?



two color
singlets
interacting
by
light meson
x-change

Phys.Rev.Lett. 131 (2023) 041902
Nature Commun. 13 (2022) 3351
arXiv:2109.01038v1 [hep-ex] 2 Sep 2021

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

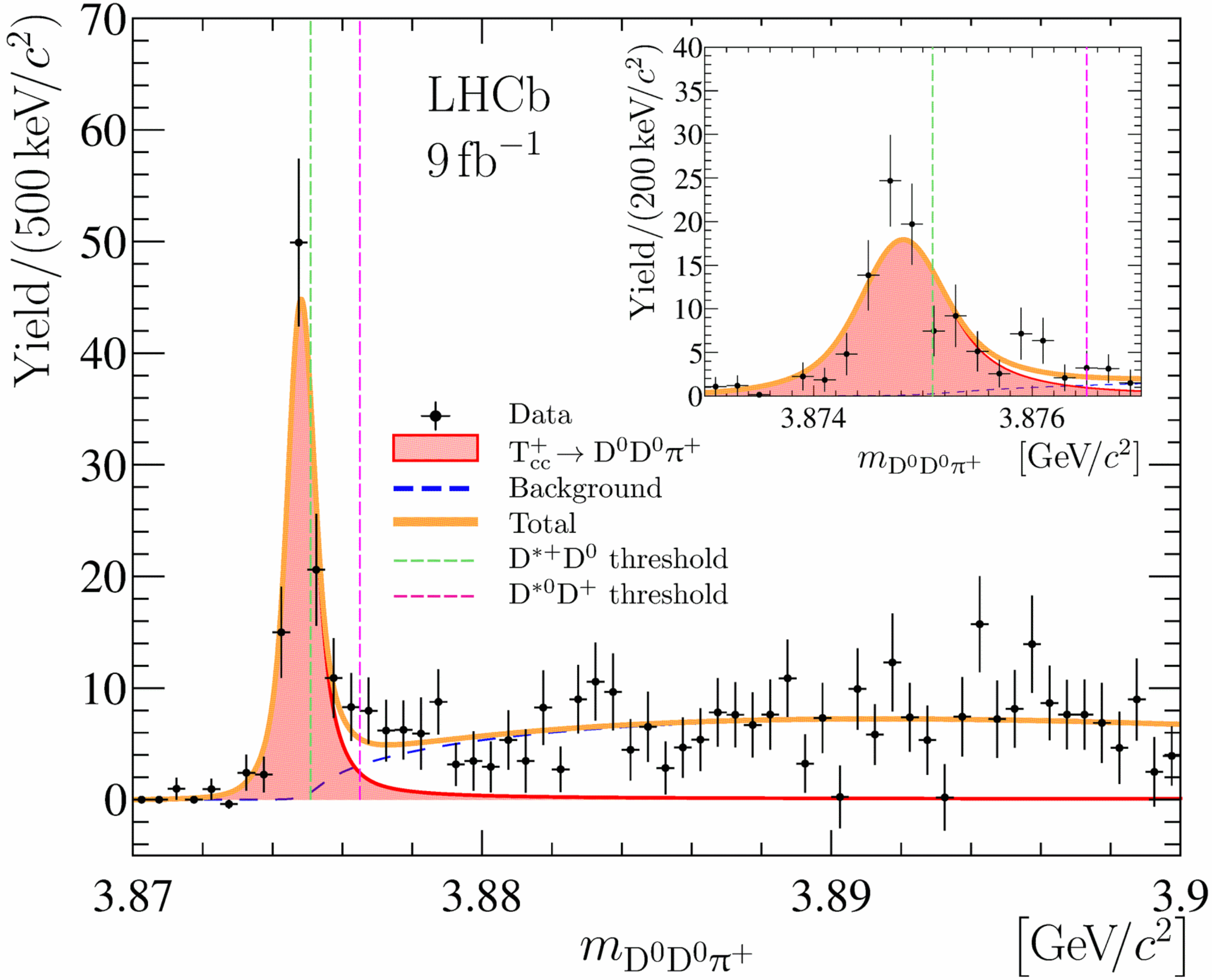
CERN-EP-2021-165
LHCb-PAPER-2021-031
September 2, 2021

Observation of an exotic narrow doubly charmed tetraquark

LHCb collaboration†

Abstract

Conventional hadronic matter consists of baryons and mesons made of three quarks and quark-antiquark pairs, respectively. The observation of a new type of hadronic state, a doubly charmed tetraquark containing two charm quarks, an anti-u and an anti-d quark, is reported using data collected by the LHCb experiment at the Large Hadron Collider. This exotic state with a mass of about 3875 MeV/c^2 manifests itself as a narrow peak in the mass spectrum of $D^0D^0\pi^+$ mesons just below the $D^{*+}D^0$ mass threshold. The near-threshold mass together with a strikingly narrow width reveals the resonance nature of the state.



The $D^0D^0\pi^+$ mass distribution. The $D^0D^0\pi^+$ mass distribution where the contribution of the non-D^0 background has been statistically subtracted. The result of the fit described in the text is overlaid.

Table 1: Signal yield, N, Breit–Wigner mass relative to $D^{*+}D^0$ mass threshold, δm_{BW}, and width, Γ_{BW}, obtained from the fit to the $D^0D^0\pi^+$ mass spectrum. The uncertainties are statistical only.

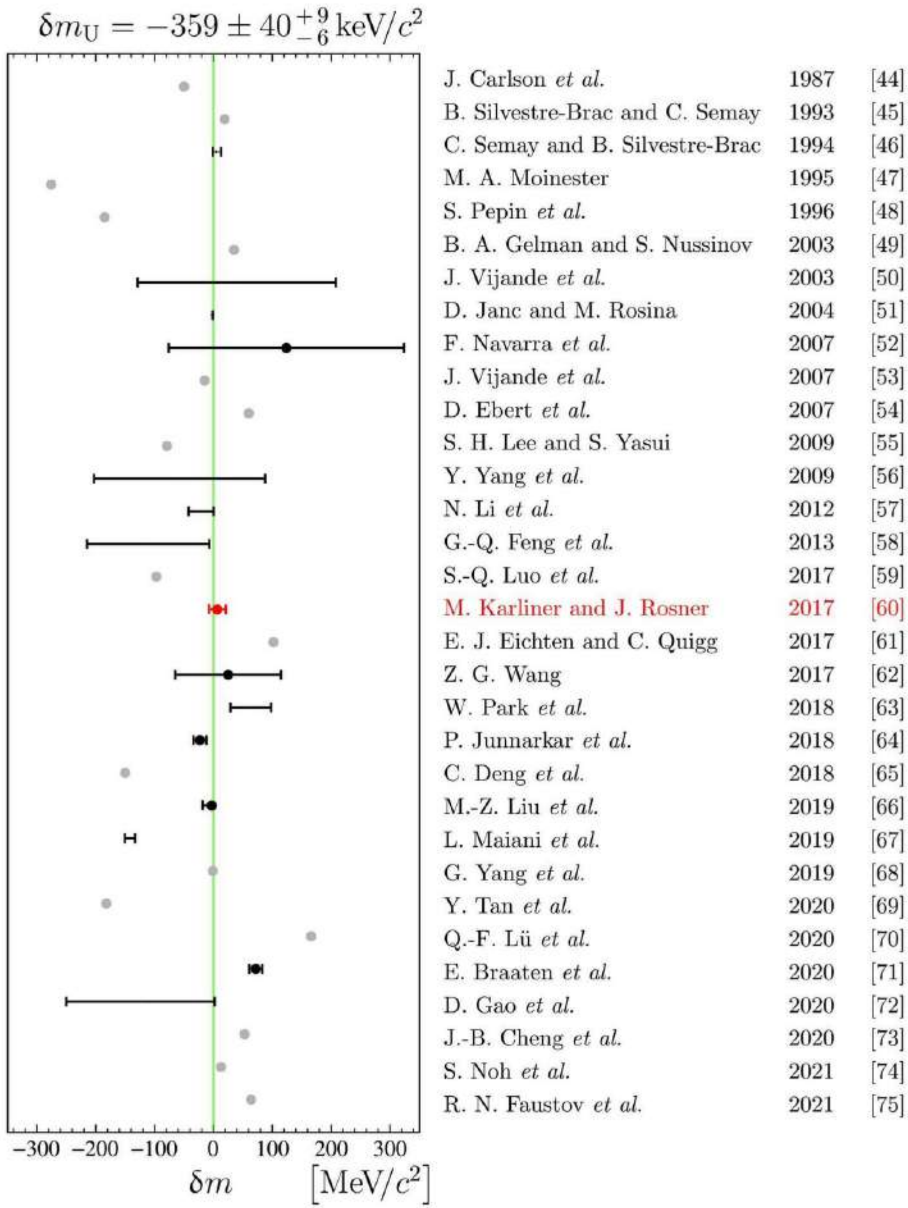
Parameter	Value	
N	117 ± 16	
δm_{BW}	-273 ± 61 keV/c^2	@ 4.3 σ
Γ_{BW}	410 ± 165 keV	

$$\delta m_{pole} = -360 \pm 40^{+4}_{-0} \text{ keV}/c^2 ,$$
$$\Gamma_{pole} = 48 \pm 2^{+0}_{-14} \text{ keV} ,$$

$$[M(D^{*0}) + M(D^+)] - [M(D^{*+}) + M(D^0)] = 1.4 \text{ MeV} \gg \Gamma(T_{cc}^+)$$

so $T_{cc}^+ \Longleftrightarrow D^{*+}D^0$, with very little $D^{*0}D^+$

TH predictions for T_{cc}^{+} mass, $I = 0$, $J^P = 1^+$



Theory predictions for the mass of the ground isoscalar $J^P = 1^+$ $cc\bar{u}\bar{d}$ tetraquark T_{cc}^{+} state [44–75]. Masses are shown relative to the $D^{*+}D^0$ mass threshold.

Adapted from supplemental material for LHCb-PAPER-2021-032

important digression: $X(3872)$ observed by CMS in heavy ion collisions

PHYSICAL REVIEW LETTERS **128,** 032001 (2022)

Evidence for X(3872) in Pb-Pb Collisions and Studies of its Prompt Production at $\sqrt{s_{NN}} = 5.02$ TeV

A. M. Sirunyan *et al.*[*]
CMS Collaboration

(Received 25 February 2021; revised 2 September 2021; accepted 22 December 2021; published 19 January 2022)

The first evidence for X(3872) production in relativistic heavy ion collisions is reported. The X(3872) production is studied in lead-lead (Pb-Pb) collisions at a center-of-mass energy of $\sqrt{s_{\rm NN}} = 5.02$ TeV per nucleon pair, using the decay chain $X(3872) \to J/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$. The data were recorded with the CMS detector in 2018 and correspond to an integrated luminosity of 1.7 nb^{-1}. The measurement is performed in the rapidity and transverse momentum ranges $|y| < 1.6$ and $15 < p_{\rm T} < 50$ GeV/c. The significance of the inclusive X(3872) signal is 4.2 standard deviations. The prompt X(3872) to $\psi 2S$ yield ratio is found to be $\rho^{\text{Pb-Pb}} = 1.08 \pm 0.49(\text{stat}) \pm 0.52(\text{syst})$, to be compared with typical values of 0.1 for pp collisions. This result provides a unique experimental input to theoretical models of the X(3872) production mechanism, and of the nature of this exotic state.

DOI: 10.1103/PhysRevLett.128.032001

The production cross section is much larger, due to multi-parton events, but the huge combinatorial background has been a major challenge. This is a proof that this challenge can be dealt with, at least in some cases,

Prompt production of $X(3872)$ in Pb-Pb collisions. $\Longrightarrow$ what about T_{cc}^+ ?

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

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

apply the toolbox to

doubly-heavy baryons , e.g. ccu

and

doubly-heavy tetraquarks, e.g. $cc\bar{u}\bar{d}$

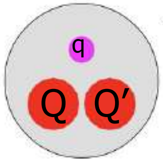
in both heavy cc diquark 3^*_c coupled to a light 3_c

doubly-heavy baryons non-exotic, must exist

$\Rightarrow$ excellent testing ground for the toolbox

MK & JR, PRD 90, 094007(2014)

doubly heavy baryons: mass predictions



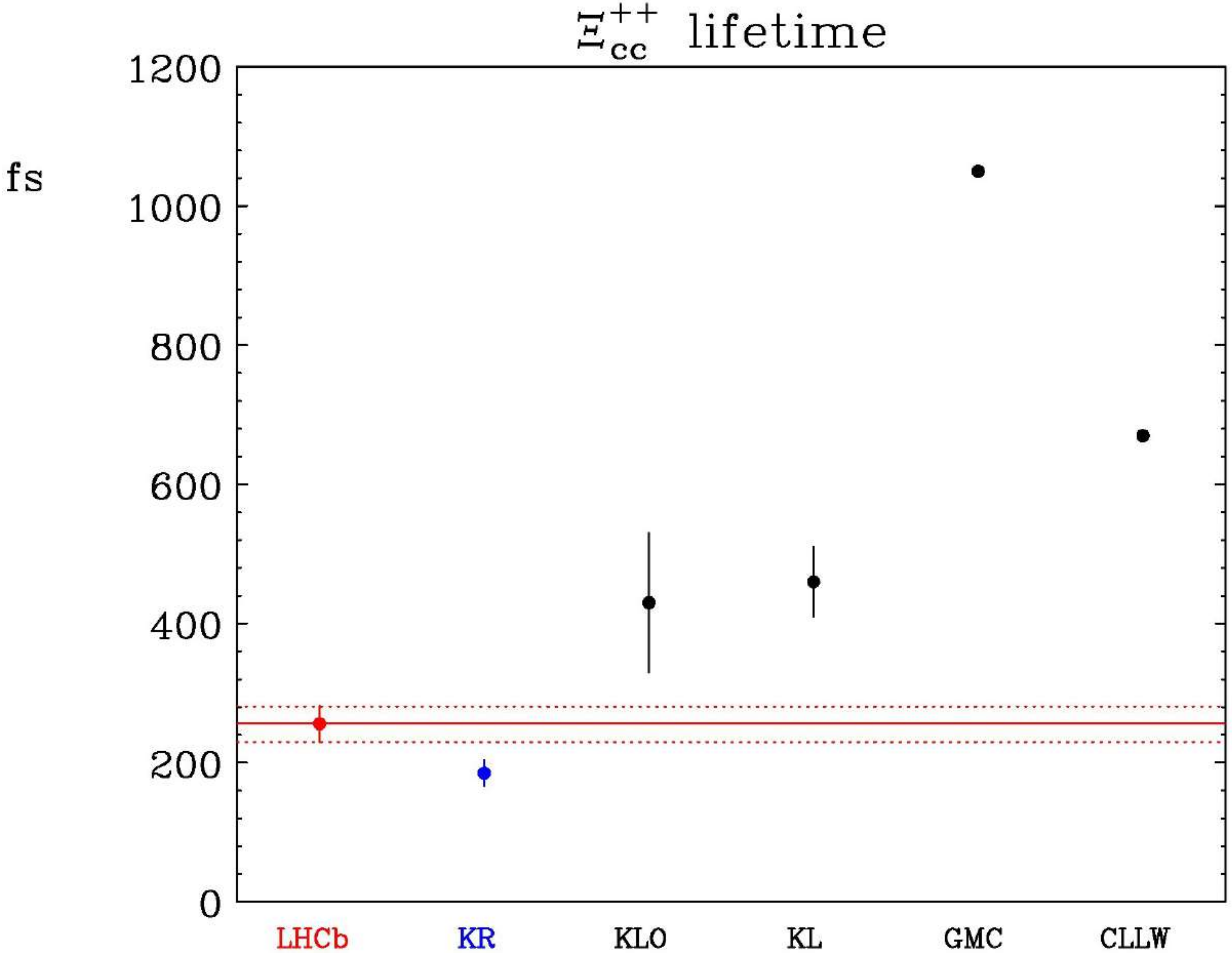
$\Xi_{QQ'}$

MK & JR, Phys. Rev. D90, 094007 (2014)

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: 3621.6 ± 0.4 PRL 119,112001, (2017)



$\tau(\Xi_{cc}^{++}) = 256^{+21}_{-22} \pm 14$ fs

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

$\Big\}$ no exp info !

- $V_{HF}(cq)$
- m_q

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

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

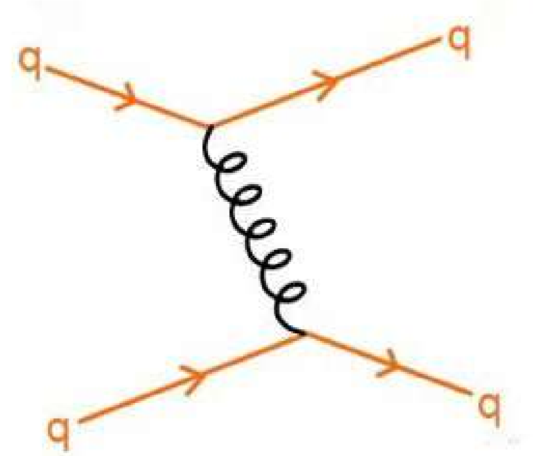
$$V(c\bar{c}) = \bar{M}(c\bar{c}:1S) - 2m_c^m = -258.0 \text{ MeV}.$$

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

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 $\pm$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

Marek Karliner[1,*] and Jonathan L. Rosner[2,†]
[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, 5620 South Ellis Avenue, Chicago, Illinois 60637, USA*
(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 $10\,389 \pm 12$ 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.

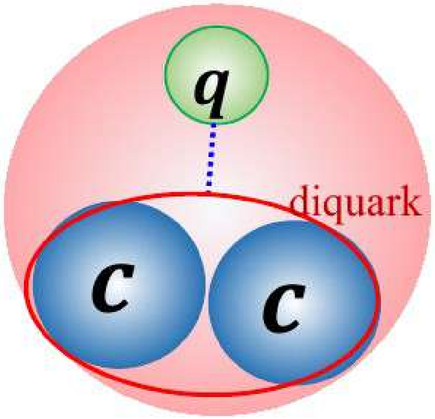
DOI: 10.1103/PhysRevLett.119.202001

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

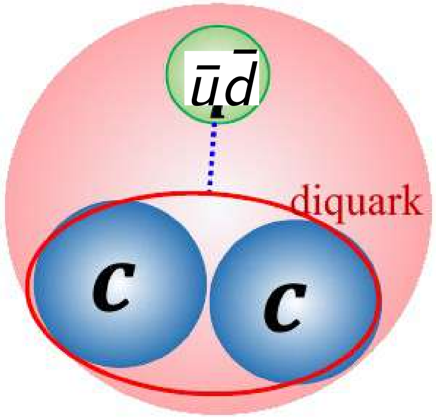


to obtain lowest possible mass, assume:

- $bb\bar{u}\bar{d}$ 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

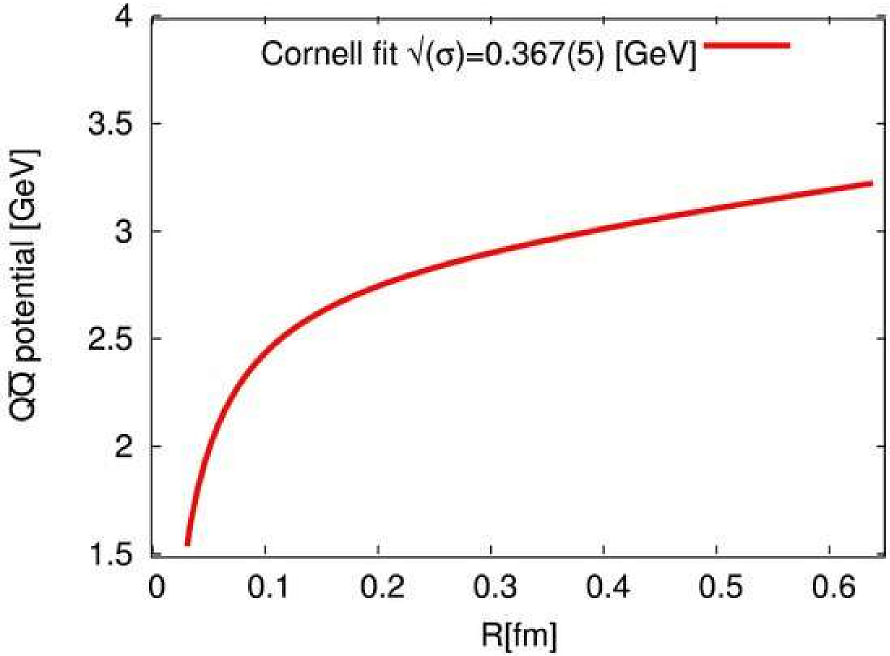
qualitatively $E_{binding} \sim \alpha_s^2 M_Q$

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



$T(bb\bar{u}\bar{d})$:
$m_b \approx 5$ GeV
$\Rightarrow R(bb) \sim 0.2$ fm
$V(r) = -\dfrac{\alpha_s(r)}{r} + \sigma r$
$\Rightarrow B(bb) \approx -280$ MeV
tightly bound, but $\bar{3}_c$,
so cannot disangage from $\bar{u}\bar{d}$

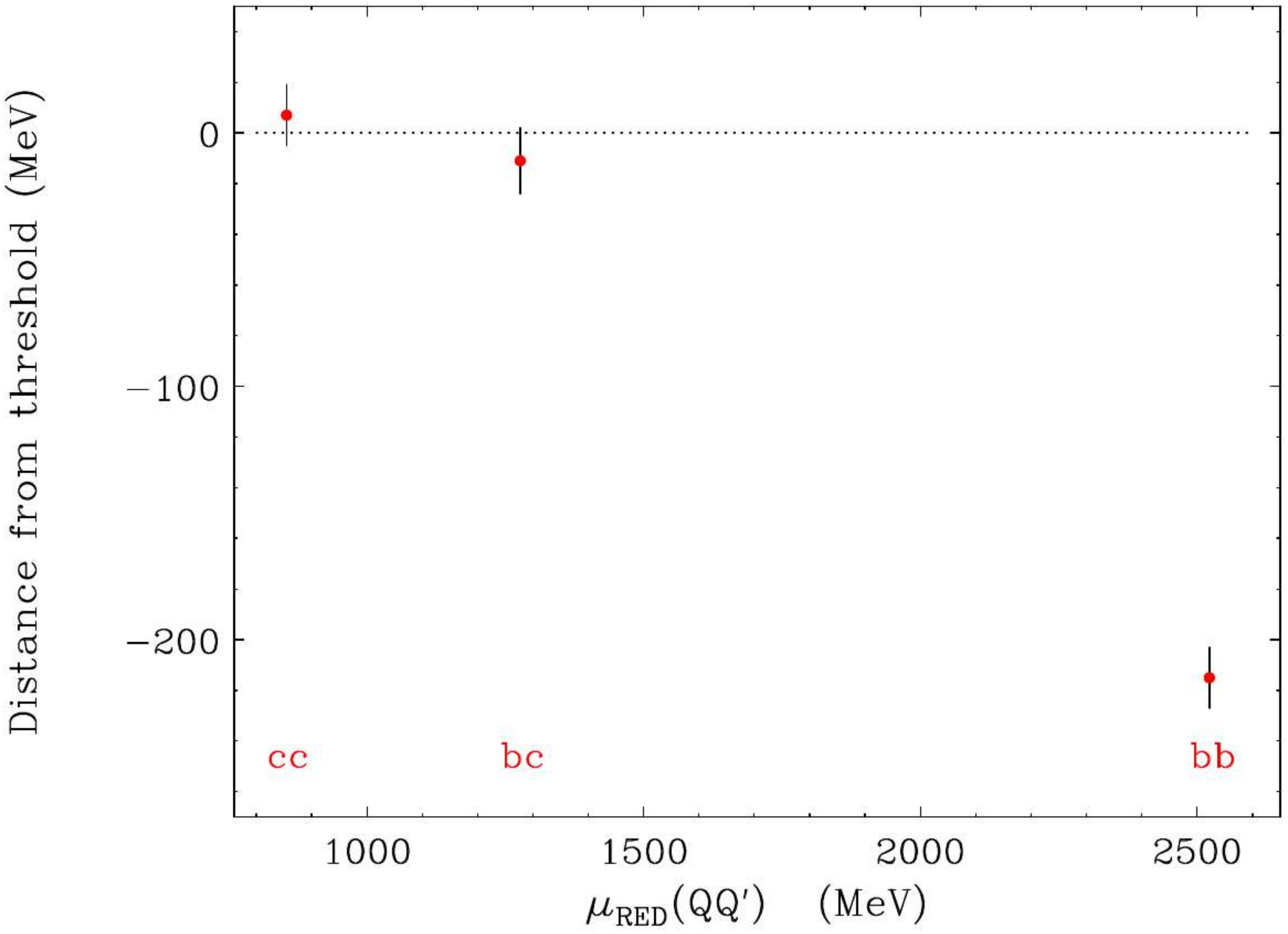
The channel $T_{bb} \to BB^*$ is kinematically closed

because in BB^* the two b quarks are far from each other

and the v. large bb binding energy is lost

$\Rightarrow$ T_{bb} is stable against strong decay

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 $\int \mathcal{L} dt$

$T(cc\bar{u}\bar{d})$
near thr. $\to$ v. narrow
accessible
<u>*now*</u>: $D^0 D^{*+}, etc.$

Inclusive signature of either bbq or $bb\bar{q}\bar{q}$: displaced B_c

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

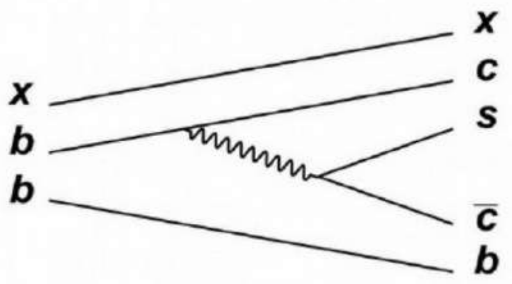
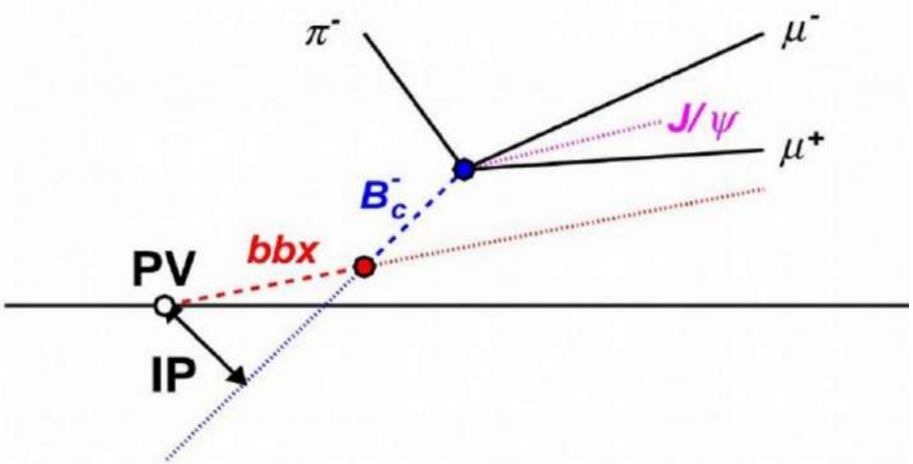


Diagram for production of a B_c^- meson from a double beauty hadron decay.



$\mathcal{O}(1\%)$ 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 !

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

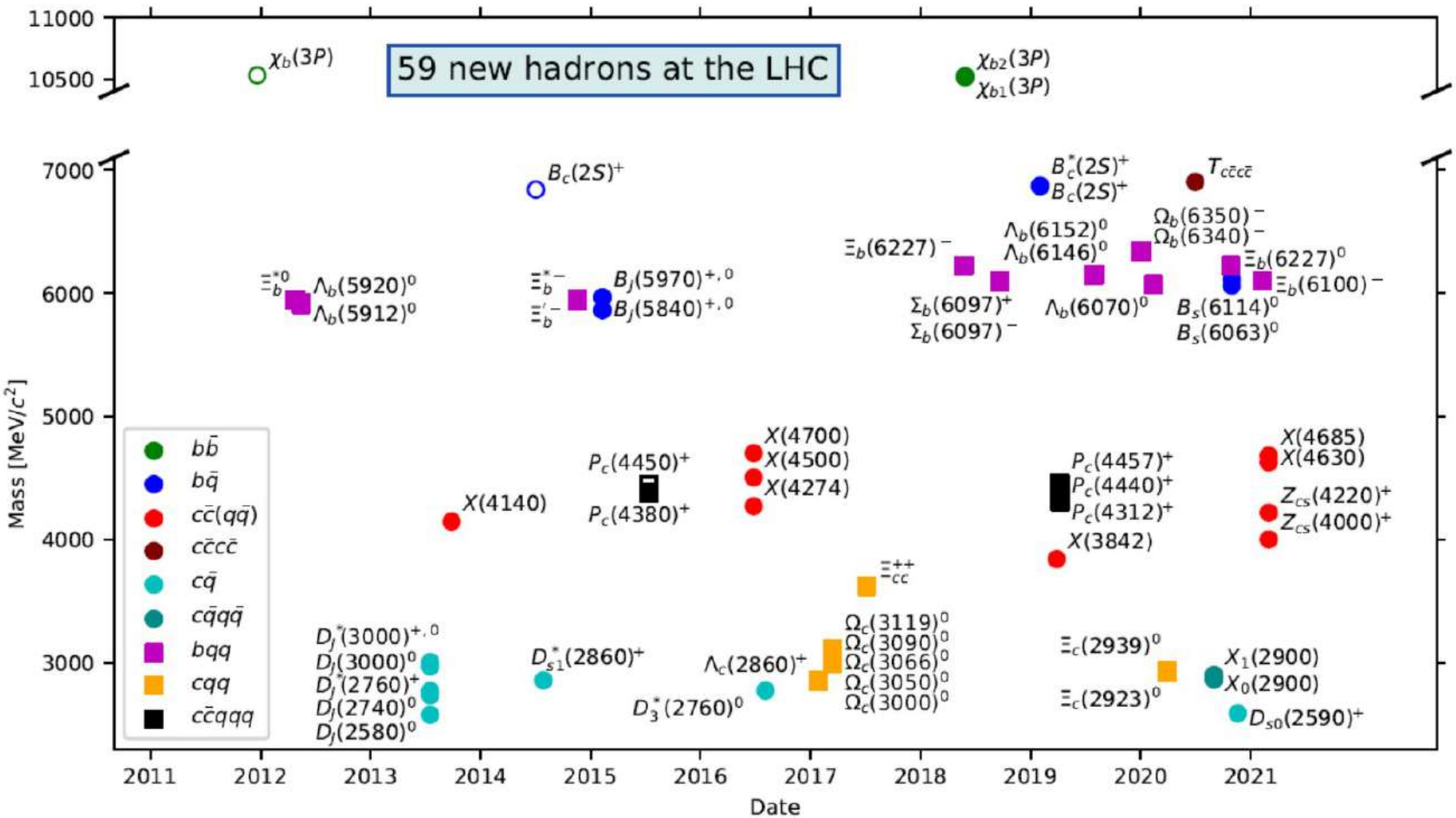
e.g. $(bb\bar{u}\bar{d}) \to D^0 B^-$.

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

- stable, deeply bound $bb\bar{u}\bar{d}$ tetraquark
- $J^P = 1^+$, $M(bb\bar{u}\bar{d}) = 10389 \pm 12$ MeV
- 215 MeV below BB^* threshold
- first manifesty exotic stable hadron
- $(bb\bar{u}\bar{d}) \to \bar{B}D\pi^-$, $J/\psi\bar{K}\bar{B}$,
  $J/\psi J/\psi K^- \bar{K}^0$, $D^0 B^-$

$bb\bar{u}\bar{d}$ cousins

- $(bc\bar{u}\bar{d})$: $J^P = 0^+$, borderline bound
  7134 ± 13 MeV, 11 MeV below $\bar{B}^0 D^0$
- $(cc\bar{u}\bar{d})$: $J^P = 1^+$, observed: 3875 MeV,
  just $\mathcal{O}(300)$ keV below $D^0 D^{*+}$, $\Gamma \ll 1$ MeV



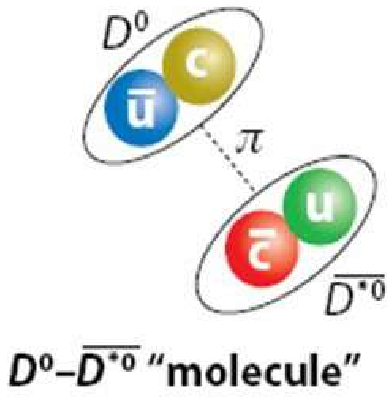
The full list of new hadrons found at the LHC, organised by year of discovery (horizontal axis) and particle mass (vertical axis). The colours and shapes denote the quark content of these states. (Image: LHCb/CERN)

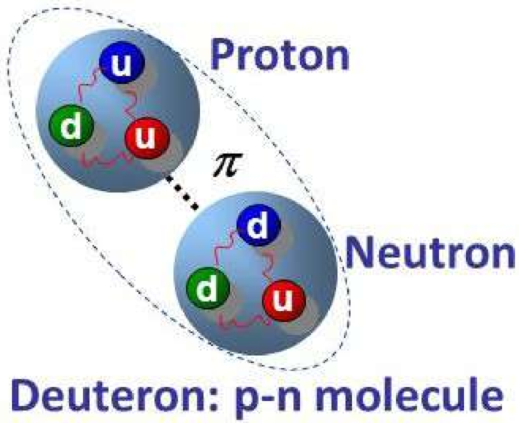
5 narrow exotic states close to meson-meson thresholds

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

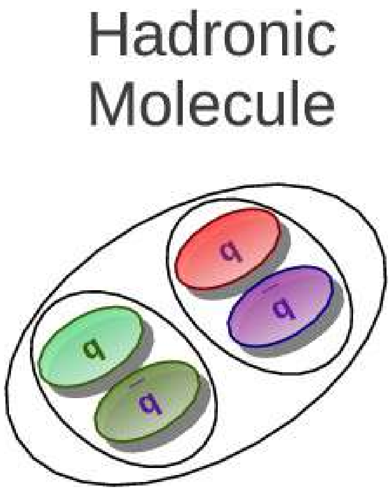
Hadronic molecules: deuteron-like

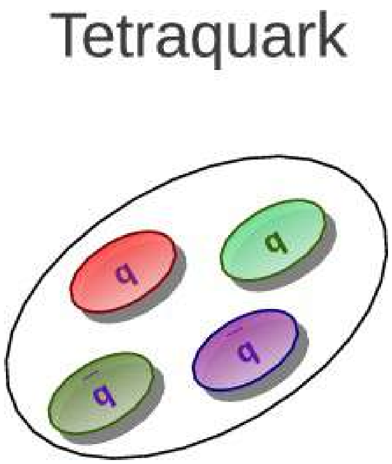




Tetraquarks: same 4 quarks, but tightly bound:

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_b wave function with $\Upsilon\pi$
dramatically smaller than with $\bar{B}B^*$

similiarly

$$\frac{\Gamma(X(3872) \to \bar{D}D^*)}{\Gamma(X(3872) \to J/\psi\pi^+\pi^-)} = 9.1^{+3.4}_{-2.0}$$

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

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

the binding mechanism can in principle

apply to any two heavy hadrons

which couple to isospin

and are heavy enough,

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 $\Sigma_b\Lambda_c$.

like a whole new periodic table

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	$c\bar{c}qq'$	4462.4	$J/\psi\,p$
Σ_cB^*	1/2	$c\bar{b}qq'$	7779.5	B_c^+p
$\Sigma_b\bar{D}^*$	1/2	$b\bar{c}qq'$	7823.0	B_c^-p
Σ_bB^*	1/2	$b\bar{b}qq'$	11139.6	$\Upsilon(nS)p$
$\Sigma_c\bar{\Lambda}_c$	1	$c\bar{c}qq'\bar{u}\bar{d}$	4740.3	$J/\psi\,\pi$
$\Sigma_c\bar{\Sigma}_c$	0	$c\bar{c}qq'\bar{q}\bar{q}'$	4907.6	$J/\psi\,\pi\pi$
$\Sigma_c\bar{\Lambda}_b$	1	$c\bar{b}qq'\bar{u}\bar{d}$	8073.3[d]	$B_c^+\pi$
$\Sigma_b\bar{\Lambda}_c$	1	$b\bar{c}qq'\bar{u}\bar{d}$	8100.9[d]	$B_c^-\pi$
$\Sigma_b\bar{\Lambda}_b$	1	$b\bar{b}qq'\bar{u}\bar{d}$	11433.9	$\Upsilon(nS)\pi$
$\Sigma_b\bar{\Sigma}_b$	0	$b\bar{b}qq'\bar{q}\bar{q}'$	11628.8	$\Upsilon(nS)\pi\pi$

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

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

New Exotic Meson and Baryon Resonances from Doubly Heavy Hadronic Molecules

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(Received 13 July 2015; published 14 September 2015)

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

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

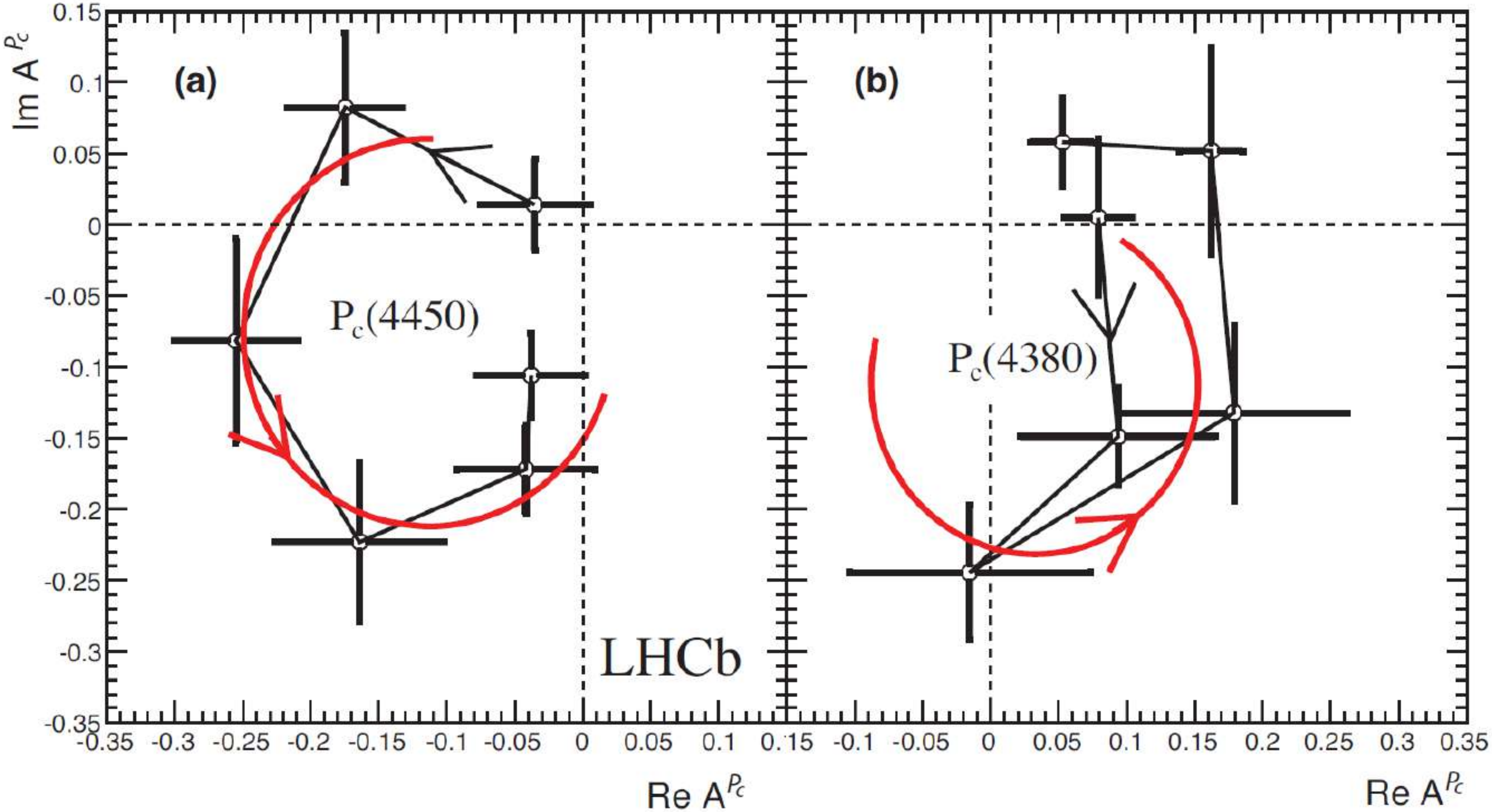
Selected for a Viewpoint in *Physics*
PRL 115, 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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

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

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

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

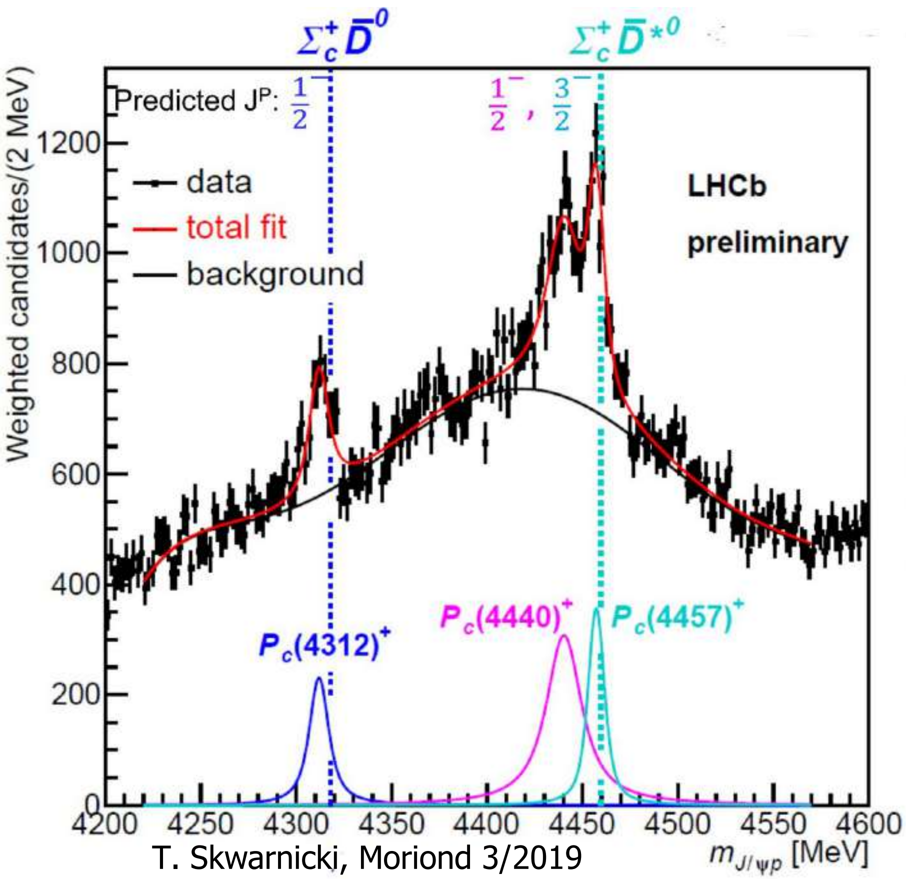


$P_c(4450)$: predicted,
narrow: $\Gamma = 39 \pm 5 \pm 19$,
10 MeV from $\Sigma_c \bar{D}^*$ threshold
perfect Argand plot: a molecule

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

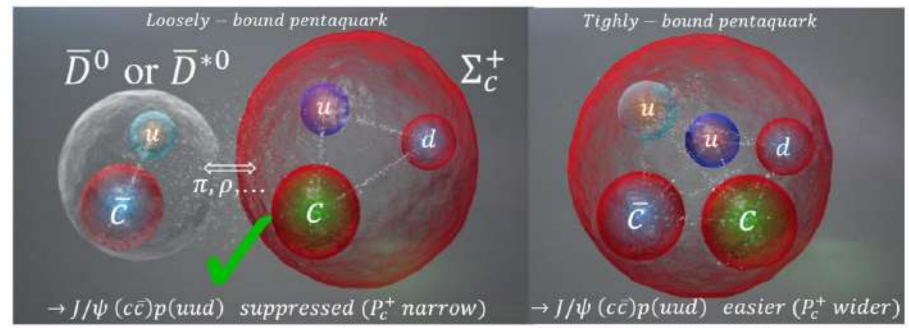
$P_c(4450)$ might be just the first of many "heavy deuterons"

as of 2015



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!



observe all 3 S-wave states:

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

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

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

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

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

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

why is it so ?

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 as quarkonium

$\Rightarrow$ 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

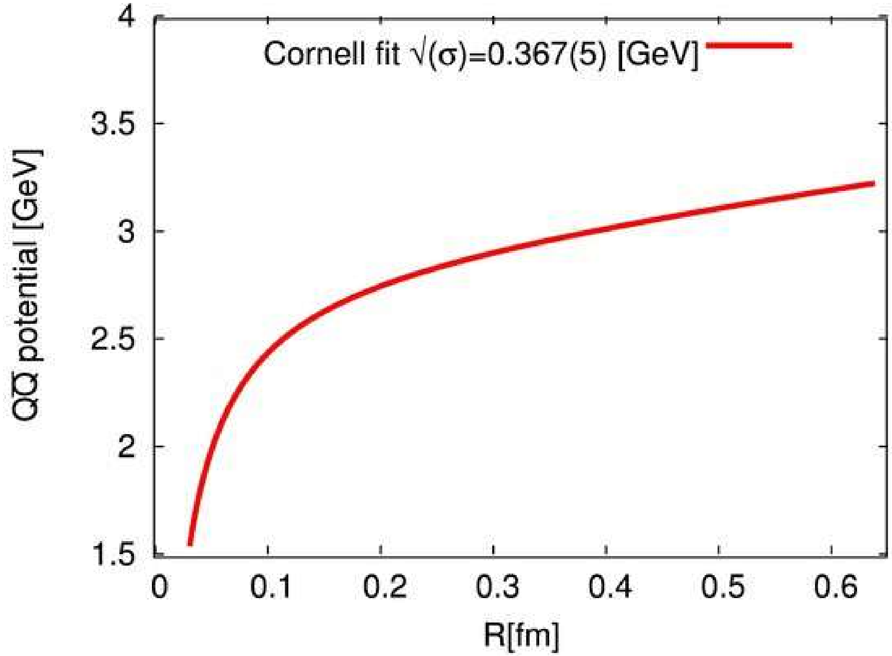
$\Rightarrow R(bb) \sim 0.2$ fm

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

$\Rightarrow B(bb) \approx -280$ MeV

tightly bound, but $\bar{3}_c$,

so cannot disangage from $\bar{u}\bar{d}$



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

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 $r(\Upsilon)/r(\bar{B}B^*) \ll 1$

very different!

Upshot:

$bb\bar{u}\bar{d}$: tightly bound tetraquark

$b\bar{b}q\bar{q}$: a molecule

recent news from LHCb: new strange Pq-s

$J/\psi\,\Lambda$ resonances in

$$B^- \to J/\psi\,\Lambda\bar{p}, \quad \Xi_b^- \to J/\psi\,\Lambda K^-$$

$\Longrightarrow$ new "molecular" pentaquarks:

$$(c\bar{c}sud) \approx \Xi_c^0(csd)\bar{D}^{*0}(\bar{c}u) \to J/\psi\,\Lambda$$

vs. $(c\bar{c}uud) \approx \Sigma_c^+(cud)\bar{D}^{*0}(\bar{c}u) \to J/\psi\,p$

LHCb arXiv:2012.10380, Sci. Bull. **66**, 1278-1287 (2021)

LHC seminar *"Particle Zoo 2.0: New tetra- and pentaquarks at LHCb"*, July 5, 2022, `https://indico.cern.ch/event/1176505/` and LHCb-PAPER-2022-031, in preparation.

$\Xi_c \bar{D}^{(*)}$ molecules $\Longrightarrow$ $\Xi'_c \bar{D}^{(*)}$ molecules

PHYSICAL REVIEW D **106,** 036024 (2022)

New strange pentaquarks

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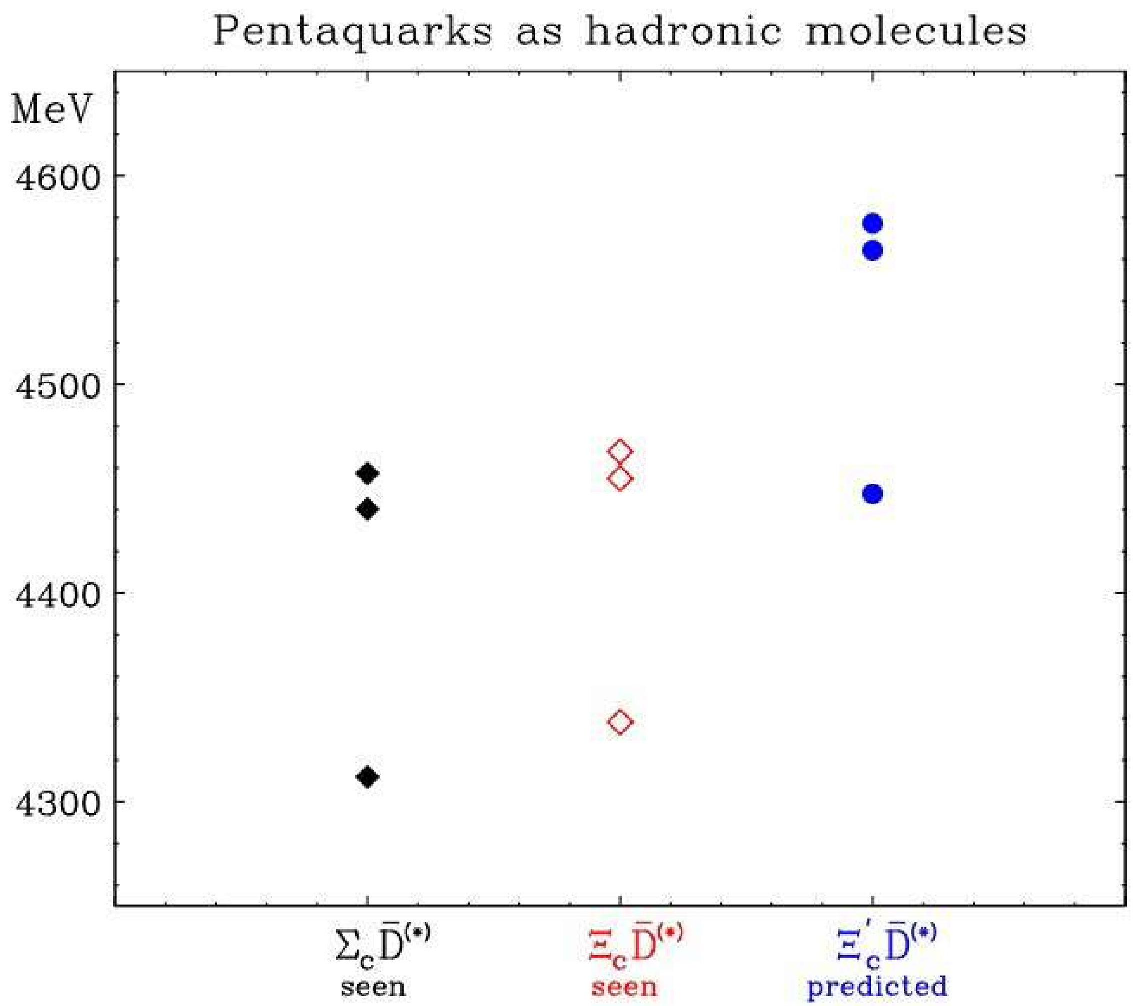
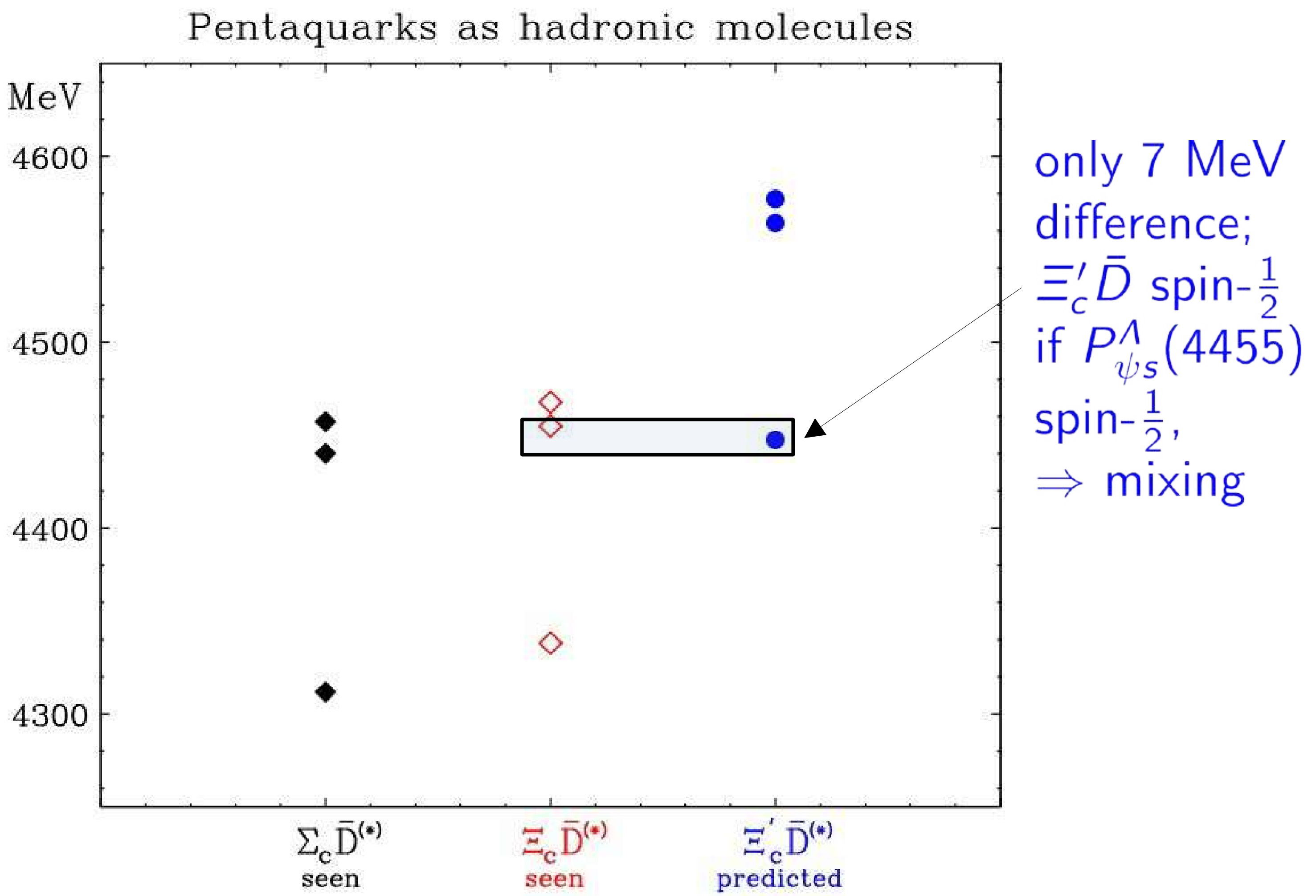
(Received 25 July 2022; accepted 8 August 2022; published 25 August 2022)

The new strange pentaquarks observed by LHCb are very likely hadronic molecules consisting of $\Xi_c\bar{D}$ and $\Xi_c\bar{D}^*$. We discuss the experimental evidence supporting this conclusion, pointing out the similarities and differences with the $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ pentaquarks in the nonstrange sector. The latter clearly are hadronic molecules consisting of $\Sigma_c\bar{D}$ and $\Sigma_c\bar{D}^*$. Following this line of thought, we predict three additional strange pentaquarks consisting of $\Xi'_c\bar{D}$ and $\Xi'_c\bar{D}^*$. The masses of these states are expected to be shifted upward by $M(\Xi'_c) - M(\Xi_c) \approx 110$ MeV with respect to the corresponding known strange pentaquarks.

DOI: 10.1103/PhysRevD.106.036024



Pentaquarks as hadronic molecules. $\Sigma_c \bar{D}^{(*)}$ states are denoted by black diamonds, $\Xi_c \bar{D}^{(*)}$ states by open red diamonds and $\Xi_c' \bar{D}^{(*)}$ states by blue circles.



Pentaquarks as hadronic molecules. $\Sigma_c\bar{D}^{(*)}$ states are denoted by black diamonds, $\Xi_c\bar{D}^{(*)}$ states by open red diamonds and $\Xi_c'\bar{D}^{(*)}$ states by blue circles.

Sci.Bull. 65 (2020) 23, 1983
arXiv:2006.16957
Liupan An, $\exists$ here at FTCF2024

LHCb, June 2020:

- a narrow resonance decaying into two J/ψ -s
- quark content $cc\bar{c}\bar{c}$, confirmed by CMS
- $M \approx 6.9$ GeV: $X(6900)$
- tetraquark-like
- $\sim$ 700 MeV above $J/\psi\, J/\psi$ threshold

  $\Rightarrow$ probably a $2S$ excited $cc\bar{c}\bar{c}$ state
- first exotic containing both QQ *and* $\bar{Q}Q$
- $\Longrightarrow$ bottom analogue: $\Upsilon\Upsilon$ at $\gtrsim$ 19.4 GeV ?
- stimulating challenge for EXP and TH

Interpretation of structure in di$-J/\psi$ spectrum

MK & JR PRD 102 (2020) 11

- structure in LHCb di$-J/\psi$ spectrum around 6.9 and 7.2 GeV
- interpreted in terms of $J^{PC} = 0^{++}$ (cc)-$(\bar{c}\bar{c})$ Tq resonances
- Tq masses from recently confirmed string-junction picture
- main peak around 6.9 GeV likely dominated by the $0^{++}(2S)$, radial exc. of (cc)-$(\bar{c}\bar{c})$ Tq, predicted at 6.871 ± 0.025 GeV
- dip around 6.75 GeV: opening of S-wave di-χ_{c0} channel
- dip around 7.2 GeV: opening of di-$\eta_c(2S)$ & $\Xi_{cc}\bar{\Xi}_{cc}$ channels?
- low-mass structure appears to require broad resonance consistent with predicted $0^{++}(1S)$ at 6191.5 ± 25MeV.
- Implications for $bb\bar{b}\bar{b}$ tetraquarks

recent venture into exotics with light quarks only

arXiv:2406.05920v1 [hep-ph] 9 Jun 2024

Possible mixing of a diquark-antidiquark with a $p\bar{p}$ hadronic molecule

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ABSTRACT

We discuss the possibility that the two nearby resonances observed by BESIII partially below the $p\bar{p}$ threshold might be due to mixing between two metastable states with the same $J^{PC} = 0^{-+}$ quantum numbers, but rather different internal structure. One is a $p\bar{p}$ hadronic molecule and the other a bound state of a light-quark diquark and an antidiquark, both with spin 1 and isospin 0, a composite color antitriplet and triplet, respectively. The doubling of resonances, one of which may be interpreted as a hadronic molecule, while the other arises from $q\bar{q}$ annihilation in a state with vacuum quantum numbers may be a more general feature than the specific case considered here.

mixing of diquark-antidiquark with a $p\bar{p}$ H.M. ?

- BESIII: two close resonances in $J/\psi \to \gamma\, 3(\pi^+\pi^-)$
  $X(1840)$: $M = 1842.2 \pm 4.2^{+7.1}_{-2.6}$ MeV, $\Gamma = 83 \pm 14 \pm 11$ MeV, $J^{PC}{=}0^{-+}$
  $X(1880)$: $M = 1882.1 \pm 1.7 \pm 0.7$ MeV, $\Gamma = 30.7 \pm 5.5 \pm 2.4$ MeV, $J^{PC}{=}0^{-+}$
  width includes ∼10 MeV below $p\bar{p}$ threshold   if $p\bar{p}$

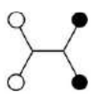
- postulate: 2nd state a P-wave narrow diquark-antidquark state, both $S = 1$

- $p\bar{p} \Longleftrightarrow \{qq\}_{S=1}$-$\{\bar{q}\bar{q}\}_{S=1}$ via $q\bar{q}$ annihilation in $^3P_0$ flavor singlet vacuum q. numbers

- $M\,(\{qq\}_{S=1}$-$\{\bar{q}\bar{q}\}_{S=1}) = 1886$ MeV, (quark model estimate)

- possible analogues:
  - $f_0(980)$: $K\bar{K}$ molecule and mixture of $(u\bar{u} + d\bar{d})/\sqrt{2}$ and $s\bar{s}$ in $^3P_0$
  - $D_{s0}(2317)$: $c\bar{s}$ in $^3P_0$; expect DK^+ molecule near 2359 MeV threshold
  - $\chi_{c1}(3872)$: $\bar{D}D^*$ with admixture of $c\bar{c}$ in $^3P_1$

SUMMARY

- narrow $cc\bar{u}\bar{d}$ tetraquark discovered by LHCb
- doubly charmed baryon found exactly where predicted
  $\Xi_{cc}^{++}(ccu) \Rightarrow (bcq), (bbq)$
- stable $bb\bar{u}\bar{d}$ (?also $bc\bar{u}\bar{d}$) tetraquark: LHCb !
- narrow exotics with $Q\bar{Q}$: "heavy deuterons"/hadronic molecules
  $\bar{D}D^*$, $\bar{D}^*D^*$, $\bar{B}B^*$, $\bar{B}^*B^*$,
  $\Sigma_c\bar{D}^*(S=\frac{1}{2},\frac{3}{2})$, $\Sigma_c\bar{D}(S=\frac{1}{2})$; $\gamma p \to J/\psi\, p$?
  $\Xi_c\bar{D}^{(*)}$ seen, expect 3 additional $\Xi_c'\bar{D}^{(*)}$ states
  $\Sigma_c B^*$, $\Sigma_b\bar{D}^*$, $\Sigma_b B^*$, D^*B^*, . . .
- D^+K^- res. $\Leftrightarrow$ $cs\bar{u}\bar{d}$ Tq w. string junction  ; $bs\bar{u}\bar{d} = \bar{B}^0K^-$?
- $J/\psi\, J/\psi$ res. $\Leftrightarrow$ excited $cc\bar{c}\bar{c}$ Tq, probably $2S$, $J/\psi\,\Upsilon$, $\Upsilon\Upsilon$?
- light quark sector: possible mixture of $p\bar{p}$ and $\{qq\}_{S=1}$-$\{\bar{q}\bar{q}\}_{S=1}$, etc.

both kinds of exotic hadrons exist in Nature

exciting new spectroscopy awaiting discovery