

New Strange Pentaquarks

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Joint work with Jon Rosner

LHCb exotics, CERN, Oct 18 2022

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 pentaquark
- *“like a new layer in the periodic table”*

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

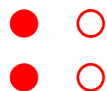
- non $\bar{q}q'$ mesons, e.g. $\bar{Q}Q\bar{q}q$, $QQ\bar{q}\bar{q}$
 $Q = c, b$ $q = u, d, s$
- non $qq'q''$ baryons, e.g. $\bar{Q}Qqq'q''$

two key questions:

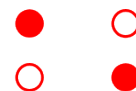
- which additional exotics should we expect?
- how are quarks organized inside them?



Tq



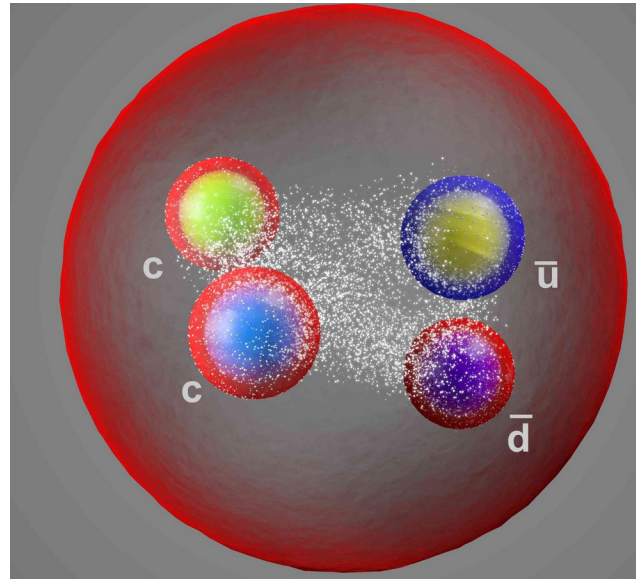
dq-dq



had. mol.

...

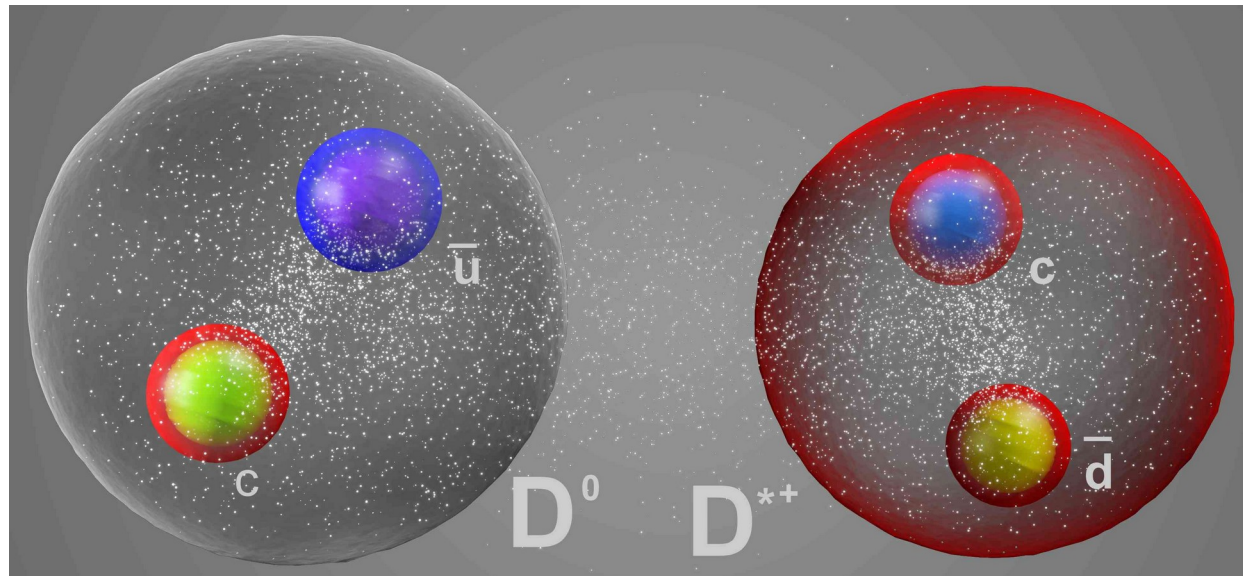
tightly-bound
tetraquark



each quark
sees the color charges
of all other quarks

or

hadronic
molecule?



two color
singlets
interacting
by
light meson
x-change


hadrons w. heavy quarks are *much simpler*:

- heavy quarks almost static
- smaller spin-dep. interaction $\propto 1/m_Q$
- key to accurate predictions:
 b baryons, Ξ_{cc} , T_{cc} , T_{bb} (🙌) ...

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,
deep below $B^0 B^-$ threshold
the first manifestly exotic stable hadron

**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 $\sqrt{s_{NN}} = 5.02$ TeV per nucleon pair, using the decay chain $X(3872) \rightarrow J/\psi\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^-$. 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 $15 < p_T < 50 \text{ GeV}/c$. 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

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

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

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

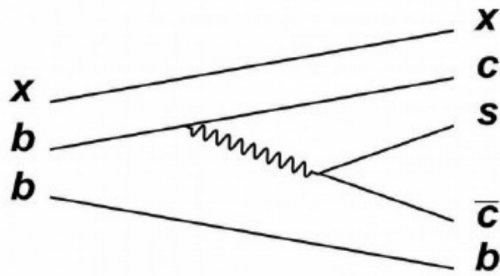
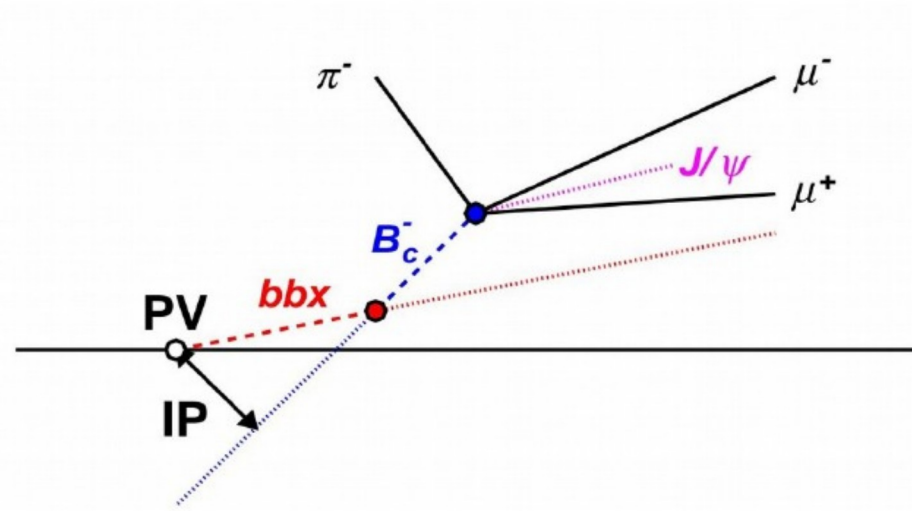


Diagram for production of a B_c^- meson from a double beauty hadron decay.



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

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

incl. $\sigma(bb\bar{x})$:
heavy ions $\gg pp$

\Rightarrow displaced B_c @ALICE & RHIC !

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

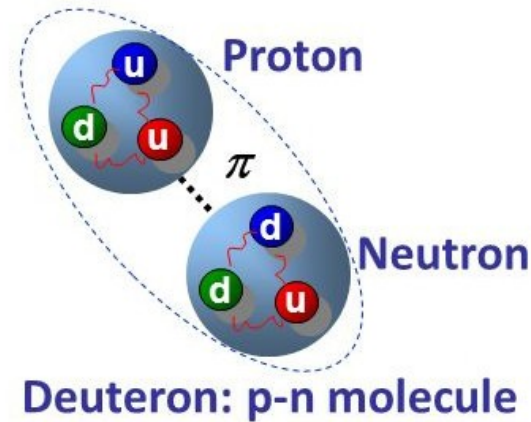
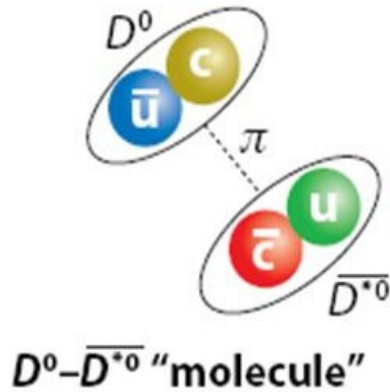
- stable, deeply bound $bb\bar{u}\bar{d}$ tetraquark
- $J^P = 1^+$, $M(bb\bar{u}\bar{d}) = 10389 \pm 12$ MeV
- 215 MeV below BB^* threshold
- first manifestly exotic stable hadron
- $(bb\bar{u}\bar{d}) \rightarrow \bar{B}D\pi^-, J/\psi\bar{K}\bar{B},$
 $J/\psi J/\psi K^- \bar{K}^0, D^0 B^-$
- $(bc\bar{u}\bar{d})$: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

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

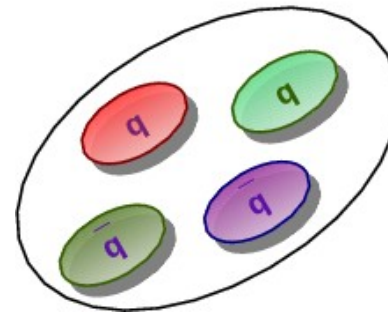
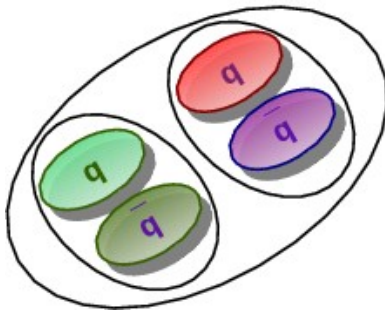


Tetraquarks: same 4 quarks, but tightly bound:

Hadronic Molecule

Tetraquark

two color singlets attract through residual forces



each quark sees color charges of all the other quarks

Belle, PRL 116, 212001 (2016):

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

despite 1000 MeV of phase space
for $\Upsilon(1S)\pi$ vs few MeV for $\bar{B}B^*$!

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

similarly

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

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

4 pieces of experimental evidence in support of molecular interpretation of Z_Q and $X(3872)$:

1. masses near thresholds and J^P of S-wave
2. narrow width despite very large phase space
3. $\text{BR}(\text{fall apart mode}) \gg \text{BR}(\text{quarkonium} + X)$
4. no states which require binding through 3 pseudoscalar coupling

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

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

^aIgnoring annihilation of quarks.

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

^cBased on isospin-averaged masses.

^dThresholds differ by 27.6 MeV.

New Exotic Meson and Baryon Resonances from Doubly Heavy Hadronic Molecules

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

DOI: 10.1103/PhysRevLett.115.122001

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

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

R. Aaij *et al.**

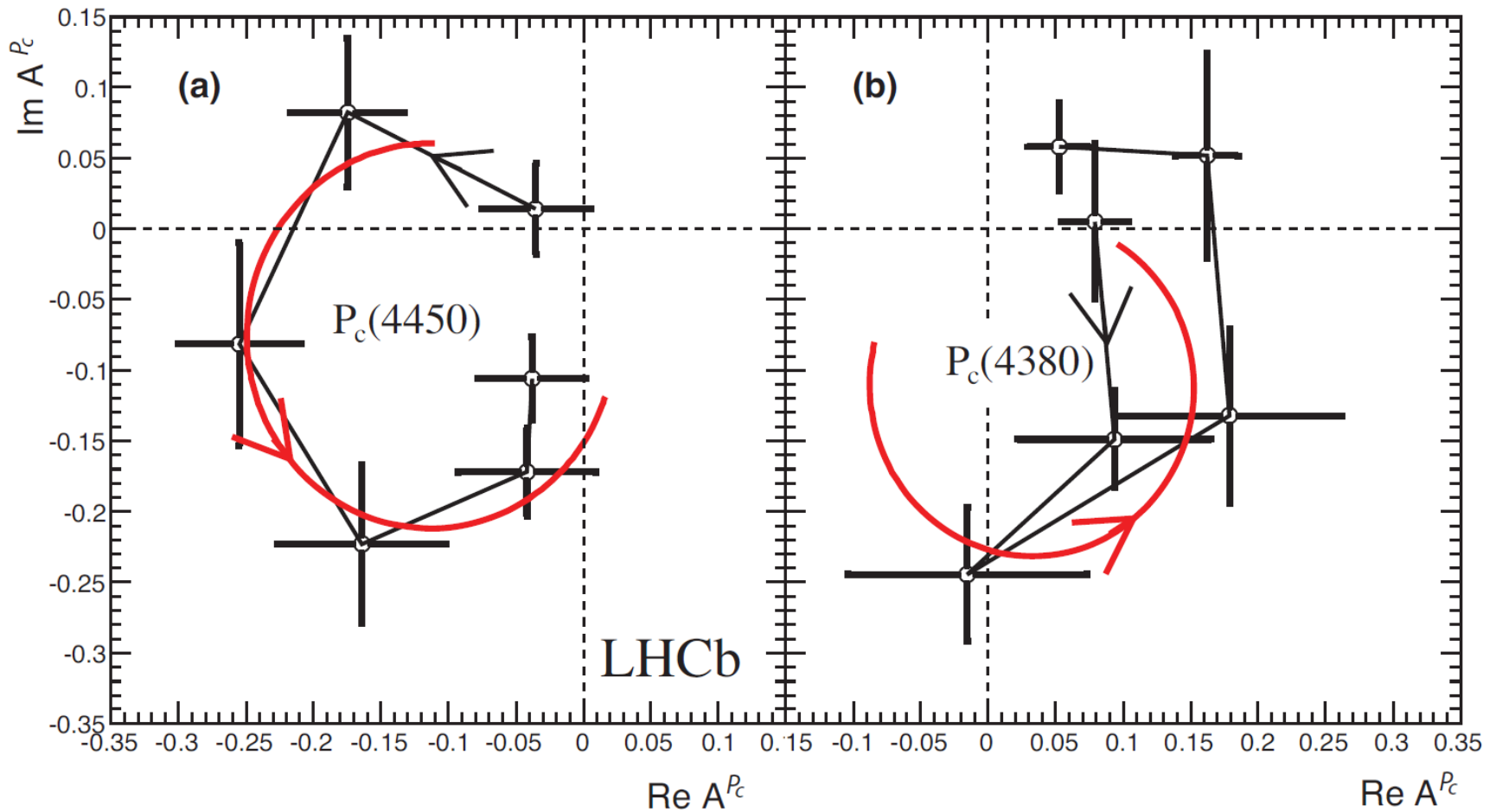
(LHCb Collaboration)

(Received 13 July 2015; published 12 August 2015)

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

DOI: 10.1103/PhysRevLett.115.072001

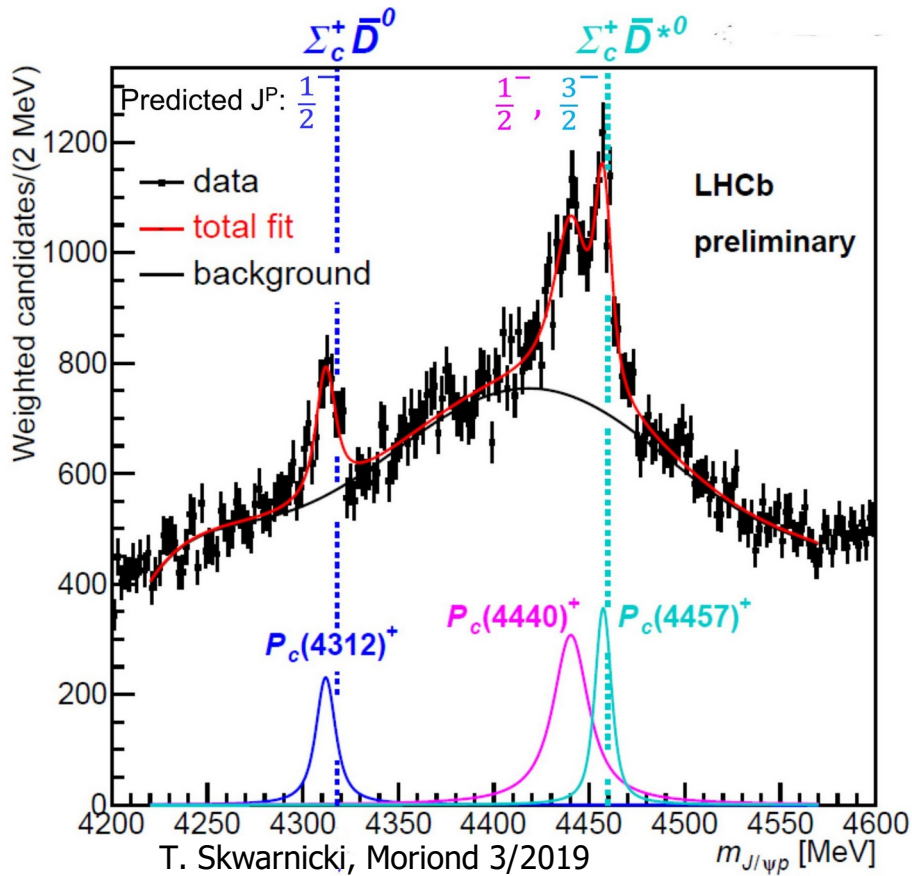
PACS numbers: 14.40.Pq, 13.25.Gv



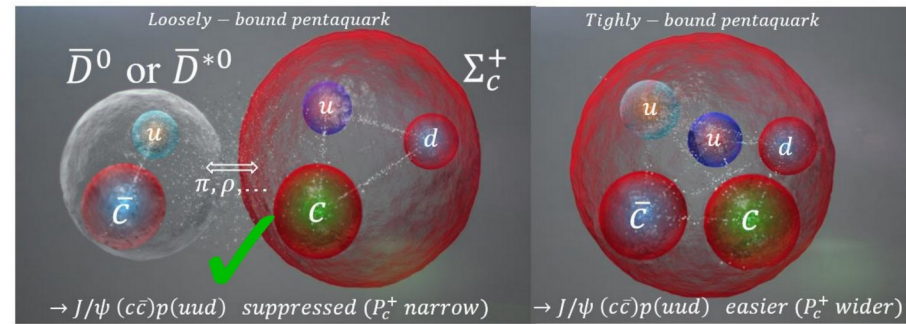
$P_c(4450)$: predicted,
 narrow: $\Gamma = 39 \pm 5 \pm 19$,
 10 MeV from $\Sigma_c \bar{D}^*$ threshold
 perfect Argand plot: a molecule

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

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



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 $Q \rightarrow \infty$ 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 $\Gamma(\Sigma_c^* \rightarrow \Lambda_c \pi) \approx 15 \text{ MeV} \dots$

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

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

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

$J/\psi \Lambda$ resonance \Rightarrow also

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

like a whole new periodic table

recent news from LHCb

evidence for a new members of the family:

$J/\psi \Lambda$ resonances in

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

\implies new “molecular” pentaquarks:

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

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.

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

\implies new “molecular” pentaquarks:

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

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

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

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$(c\bar{c}uds)$ molecular pentaquarks

a very clear peak $> 10 \sigma$:

$$P_{\psi_s}^\Lambda(4338) : \quad M = 4338.2 \pm 0.7 \text{ MeV}, \quad \Gamma = 7.0 \pm 1.2 \text{ MeV}$$

and a structure with two peaks split by 13 MeV, @ 3.1σ

$$P_{\psi_s}^\Lambda(4455) : \quad M = 4454.9 \pm 2.7 \text{ MeV}, \quad \Gamma = 7.5 \pm 9.7 \text{ MeV}$$

$$P_{\psi_s}^\Lambda(4468) : \quad M = 4467.8 \pm 3.7 \text{ MeV}, \quad \Gamma = 5.2 \pm 5.3 \text{ MeV}.$$

Several features of $P_{\psi_s}^\Lambda(4338)$ strongly suggestive of a $\Xi_c \bar{D}$ hadronic molecule:

(a) Vicinity to the relevant baryon-meson threshold(s):

$$M[P_{\psi_s}^\Lambda(4338)] \text{ only } 0.8 \text{ MeV above } \Xi_c^+ D^- \\ 2.9 \text{ MeV above } \Xi_c^0 D^0$$

(b) Spin and parity:

$$\frac{1}{2}^+ \text{ baryon \& } 0^- \text{ meson} \\ S\text{-wave molecule} \Rightarrow \frac{1}{2}^-$$

(c) $\Gamma \lll$ phase space:

$$\Gamma[P_{\psi_s}^\Lambda(4338)] = 7.0 \pm 1.2 \text{ MeV} \\ \text{vs. } Q\text{-value} = 126 \text{ MeV.}$$

More support (with \ll stats) for molecular interpret.

from earlier LHCb $P_{\psi_s}^\Lambda(4459)$ pentaquark data

A peak in $M_{inv}(J/\psi \Lambda)$ in $\Xi_b^- \rightarrow J/\psi \Lambda K^-$,

$$M = 4458.8 \pm 2.9_{-1.1}^{+4.7} \text{ MeV}, \quad \Gamma = 17.3 \pm 6.5_{-5.7}^{+8.0} \text{ MeV}, \quad @3.1 \sigma.$$

M approx. 20 MeV below the $\Xi_c \bar{D}^*$ threshold.

Remarkably, LHCb has equally good fit w. *a two peak structure*, with the two peaks split by 13 MeV:

$$P_{\psi_s}^\Lambda(4455) : \quad M = 4454.9 \pm 2.7 \text{ MeV}, \quad \Gamma = 7.5 \pm 9.7 \text{ MeV}$$

$$P_{\psi_s}^\Lambda(4468) : \quad M = 4467.8 \pm 3.7 \text{ MeV}, \quad \Gamma = 5.2 \pm 5.3 \text{ MeV}.$$

highly reminiscent of LHCb $P_\psi^N(4440)^+$ and $P_\psi^N(4457)^+$

caveat:

analogy between $\Sigma_c \bar{D}^{(*)}$ and $\Xi_c \bar{D}^{(*)}$ h.m. goes only so far, as $P_{\psi_s}^\Lambda(4455)$, $P_{\psi_s}^\Lambda(4468)$ not an $SU(3)_F$ rotation $q \rightarrow s$ ($q=u,d$) of $P_\psi^N(4440)^+$, $P_\psi^N(4457)^+$.

Nor $P_{\psi_s}^\Lambda(4338)$ an $SU(3)_F$ rotation of $P_\psi^N(4312)^+$,

because P_ψ^N are $\Sigma_c \bar{D}^{(*)}$ h.m.

and under $SU(3)_F$ $q \rightarrow s$ ($q = u, d$) $\Sigma_c \rightarrow \Xi'_c$, $\Sigma_c \not\rightarrow \Xi_c$

$\Delta M \equiv M(\Xi'_c) - M(\Xi_c) \approx 110 \text{ MeV} < m_\pi$, so Ξ'_c stable under s.i.

\Rightarrow in addition to the already observed $\Xi_c \bar{D}^{(*)}$ three h.m.

expect three additional v. narrow $\Xi'_c \bar{D}^{()}$ h.m.*

shifted upwards by $\Delta M \approx 110 \text{ MeV}$ for each J^P

$$\Xi_c \bar{D}^{(*)} \text{ molecules} \implies \Xi_c' \bar{D}^{(*)} \text{ molecules}$$

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

New strange pentaquarks

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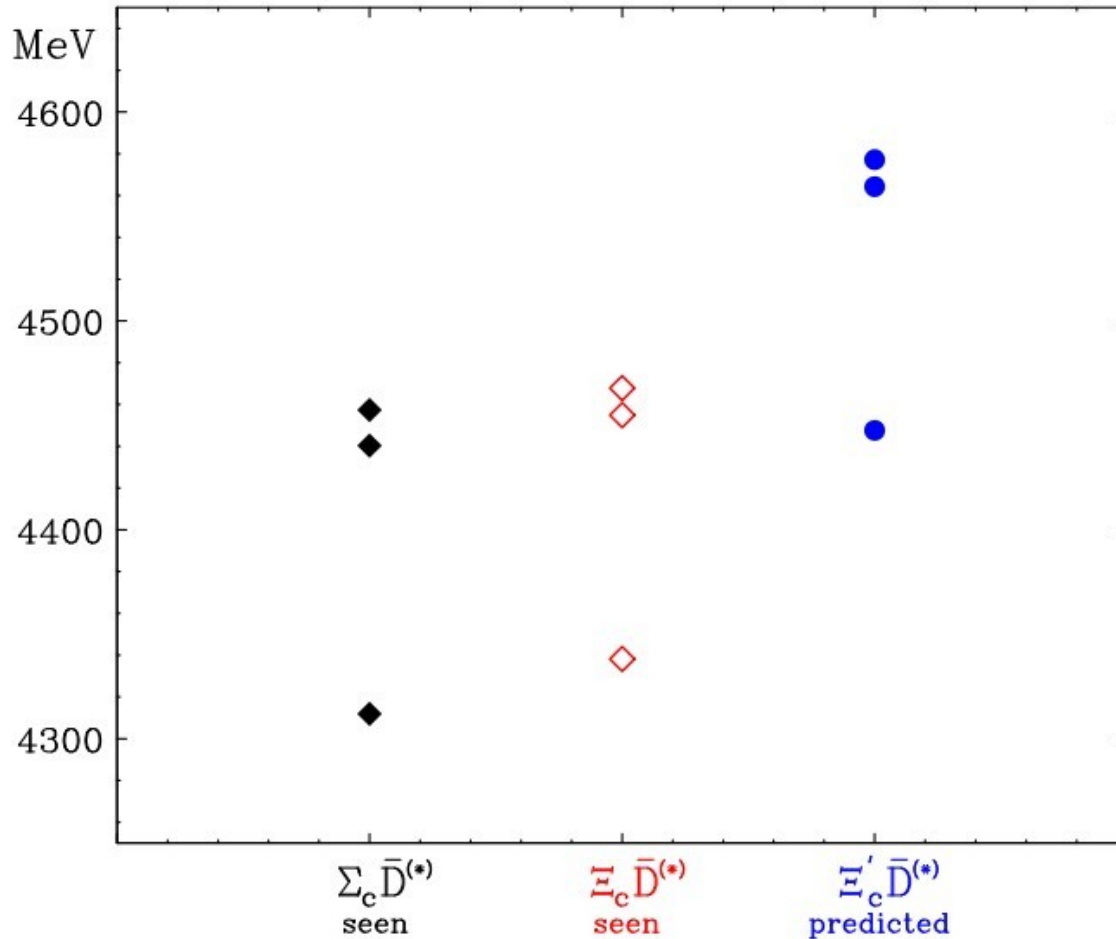
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The new strange pentaquarks observed by LHCb are very likely hadronic molecules consisting of $\Xi_c \bar{D}$ and $\Xi_c \bar{D}^*$. We discuss the experimental evidence supporting this conclusion, pointing out the similarities and differences with 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.**

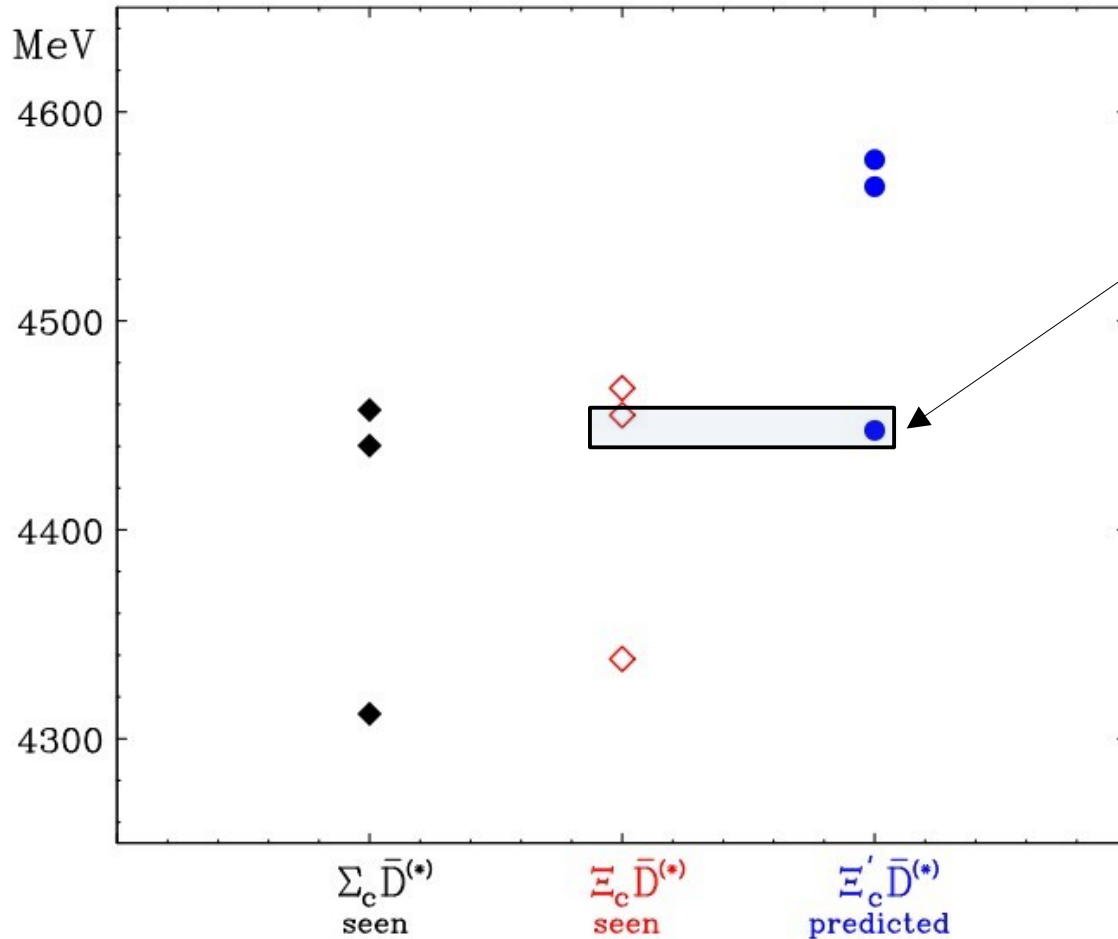
DOI: [10.1103/PhysRevD.106.036024](https://doi.org/10.1103/PhysRevD.106.036024)

Pentaquarks as hadronic molecules



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



only 7 MeV difference;
 $\Xi_c' \bar{D}$ spin- $\frac{1}{2}$
 if $P_{\psi_s}^\Lambda(4455)$
 spin- $\frac{1}{2}$,
 \Rightarrow mixing

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.

LHCb, 08/2020:

narrow $D^+ K^-$ resonance in $B^- \rightarrow D^- D^+ K^-$

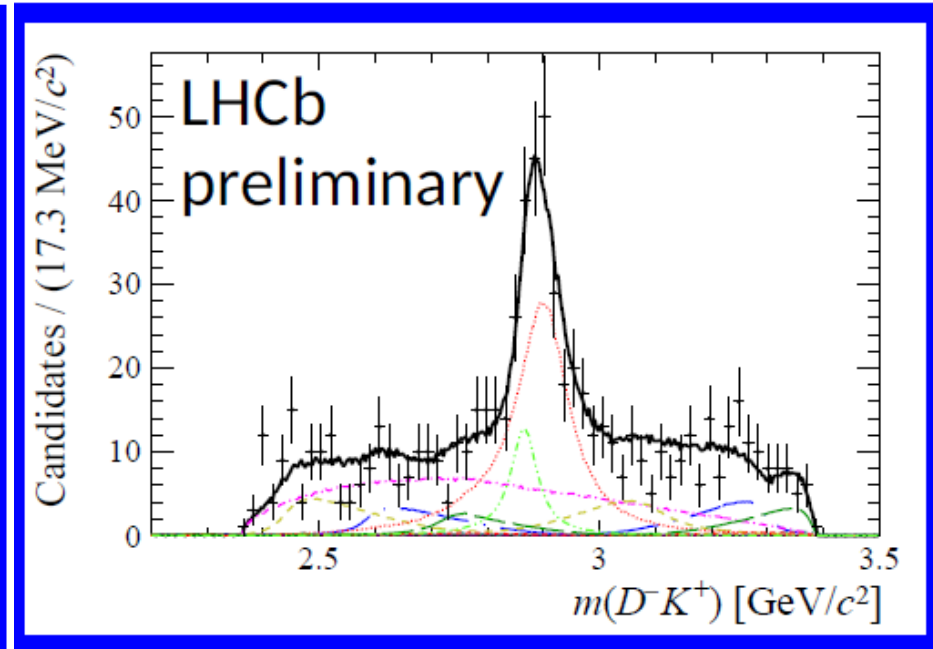
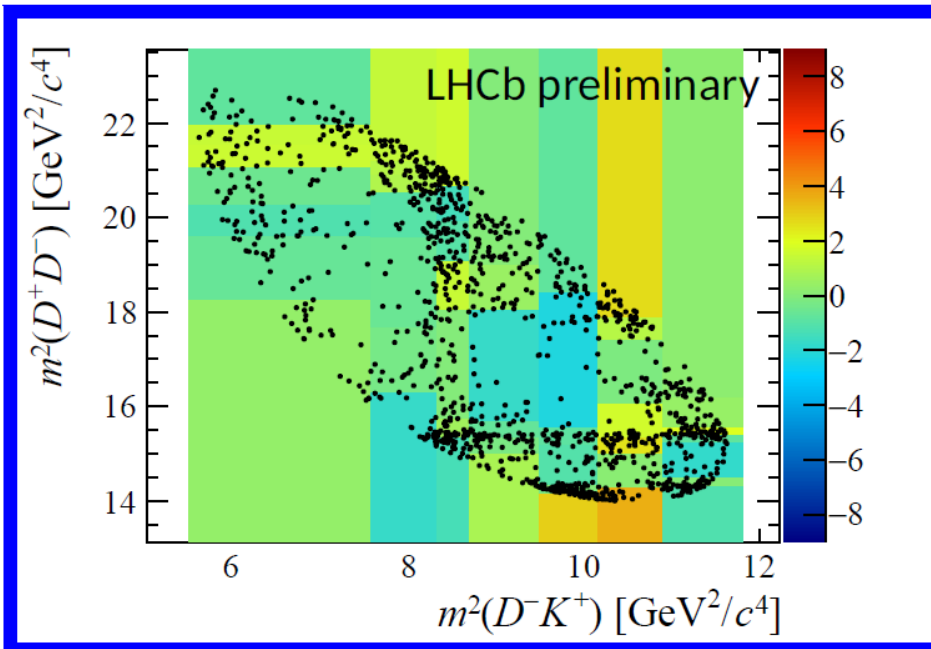
first exotic hadron with open heavy flavor:

$cs\bar{u}\bar{d}$ tetraquark

$cc\bar{u}\bar{d}$: ϵ^+ 2 meson threshold

\Rightarrow expect $cs\bar{u}\bar{d}$ well above $D^+ K^-$ threshold

2009.00025 & 2009.00026



- two BW-s:
 $X_0(2900)$, $J^P = 0^+$ at 2866 ± 7 MeV, $\Gamma_0 = 57 \pm 13$ MeV
 $X_1(2900)$, $J^P = 1^-$ at 2904 ± 7 MeV $\Gamma_1 = 110 \pm 12$ MeV.
- our interpretation:
 $X_0(2900) = cs\bar{u}\bar{d}$ isosinglet compact tetraquark,
mass = 2863 ± 12 MeV, from quark model incl. 2 string junctions
- **the first exotic hadron with open heavy flavor**
- analogous $bs\bar{u}\bar{d}$ Tq predicted at 6213 ± 12 MeV
- $X_1(2900)$: ?
currently $J^P = 1^-$ preferred, but if $J^P = 2^+$,
possibly a D^*K^* molecule, c.f. threshold at 2902 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

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

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

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

$m_b \approx 5 \text{ GeV}$

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

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

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

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

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

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

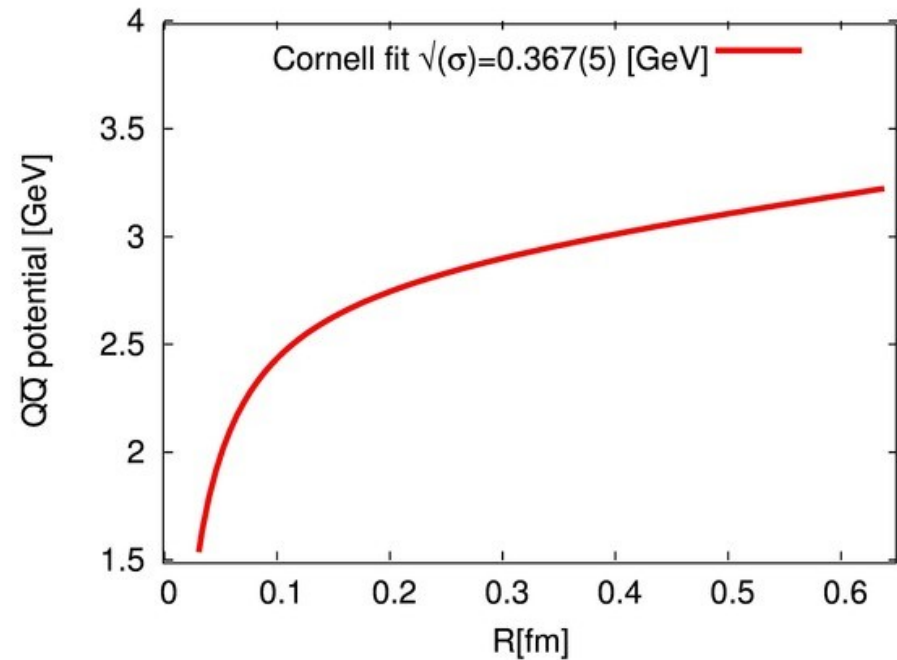
if $b\bar{b}$ compact \Rightarrow color singlet:

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

so only semi-stable config.,

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

yet narrow $\sim 15 \text{ MeV}$, 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

SUMMARY: NEW STRANGE PENTAQUARKS IN CONTEXT

- narrow $cc\bar{u}\bar{d}$ tetraquark discovered by LHCb what about in heavy ions?
- doubly charmed baryon found exactly where predicted

$$\Xi_{cc}^{++}(ccu) \Rightarrow (bcq), (bbq)$$


- stable $bb\bar{u}\bar{d}$ tetraquark: LHCb!
- narrow exotics with $Q\bar{Q}$: “heavy deuterons” / molecules

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

$$\Sigma_c \bar{D}^*(S = \frac{1}{2}, \frac{3}{2}), \Sigma_c \bar{D}(S = \frac{1}{2}); \quad \gamma p \rightarrow J/\psi p ?$$

$$3 \Xi_c \bar{D}^{(*)} \text{ states} \rightarrow 3 \Xi'_c \bar{D}^{(*)} \text{ states}; \quad \Delta M \approx 110 \text{ MeV}$$

$$\Sigma_c B^*, \Sigma_b \bar{D}^*, \Sigma_b B^*, D^* B^*, \dots$$

- $D^+ K^-$ res. $\Leftrightarrow cs\bar{u}\bar{d}$ Tq w. string junction  $bs\bar{u}\bar{d} = \bar{B}^0 K^- ?$
- $J/\psi J/\psi$ res. \Leftrightarrow excited $cc\bar{c}\bar{c}$ Tq, probably $2S$, $J/\psi \gamma$, $\gamma\gamma ?$

exciting new spectroscopy awaiting discovery

Backup transparencies

