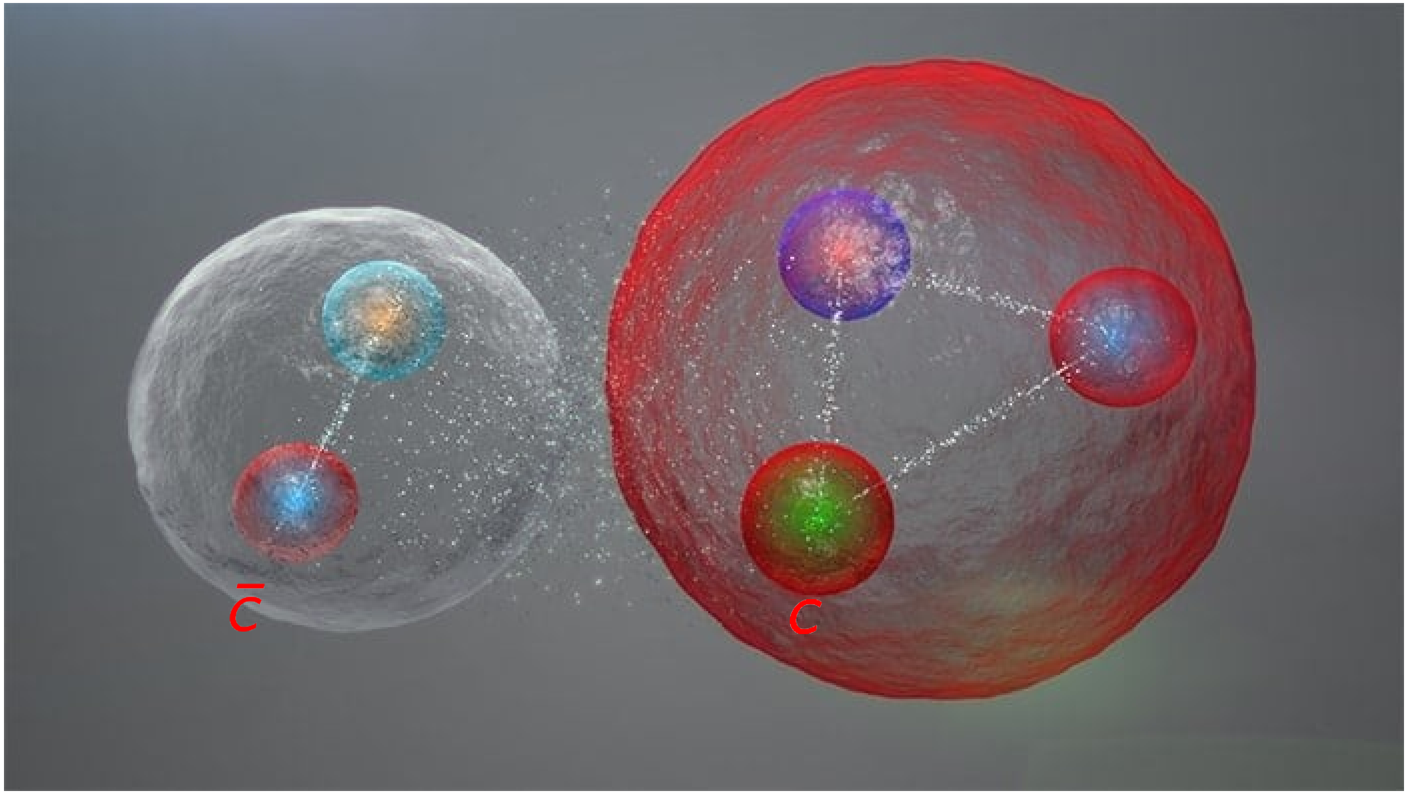


New Strange Pentaquarks

Marek Karliner
Tel Aviv University
Joint work with Jon Rosner

CLUSHIQ22, Sendai, Japan, Oct 31 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"*

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

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

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

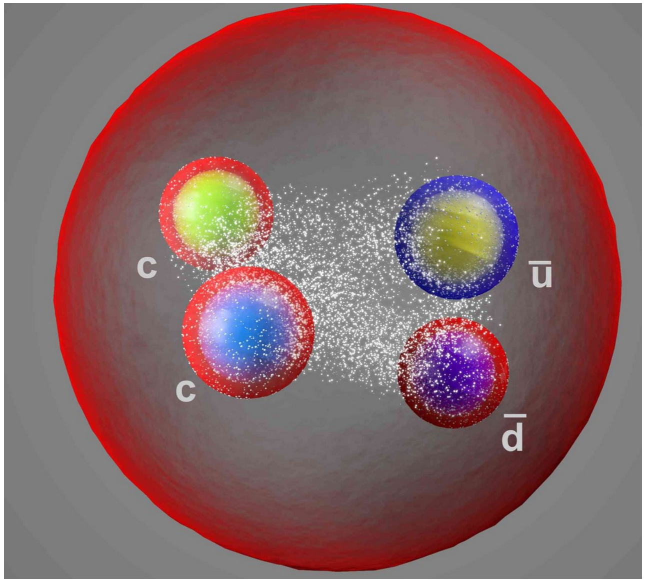
two key questions:

- which additional exotics should we expect?

- how are quarks organized inside them?

Tq dq-dq had. mol.

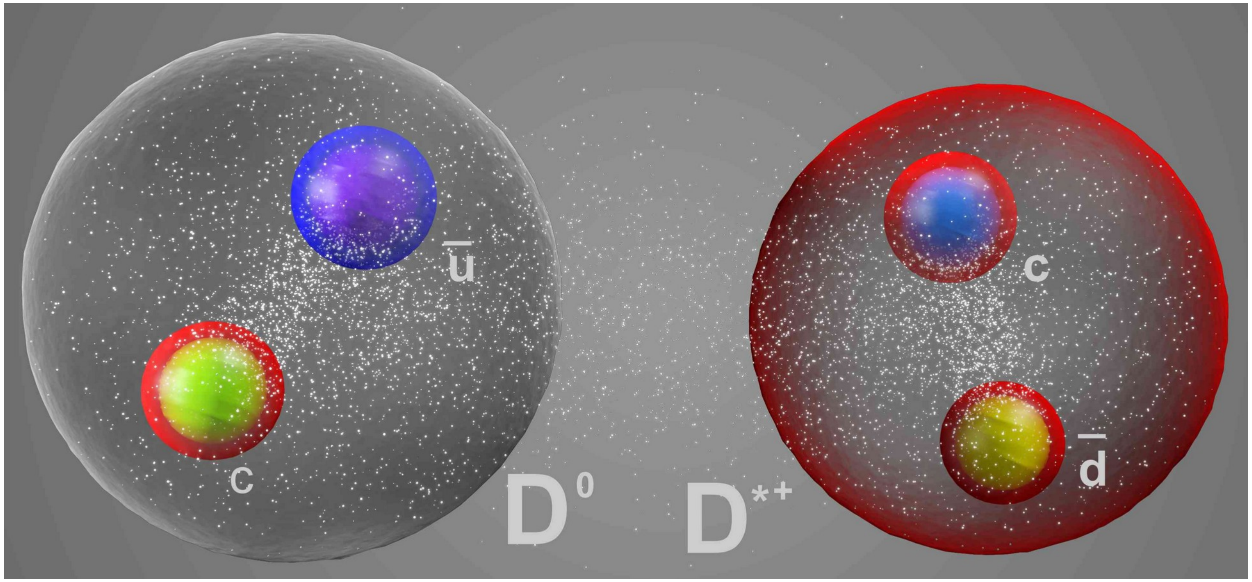
tightly-bound tetraquark



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 $\sqrt{s_{\rm NN}} = 5.02$ 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

Prompt production of $X(3872)$ in Pb-Pb collisions. $\Longrightarrow$ 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

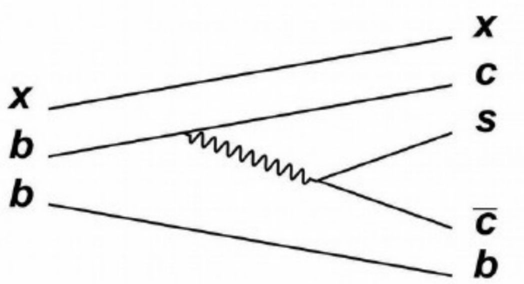
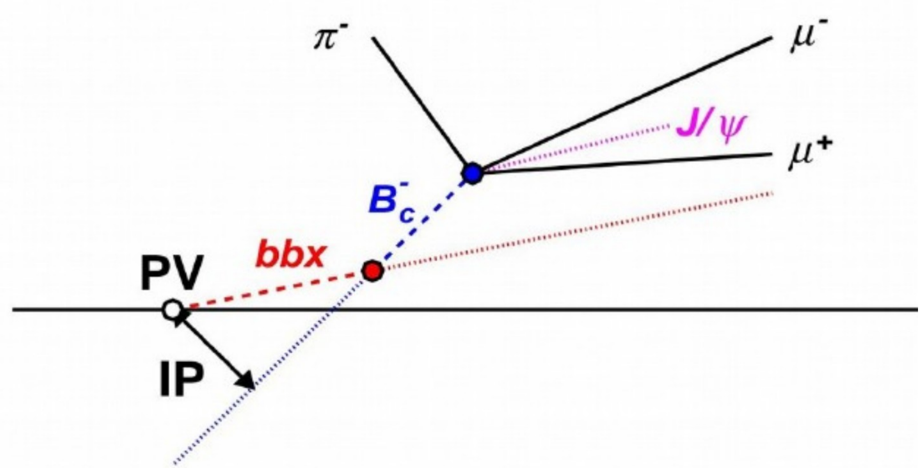


Diagram for production of a B_c^- meson from a double beauty hadron decay.



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

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

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

$\Rightarrow$ displaced B_c @ALICE & RHIC !

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

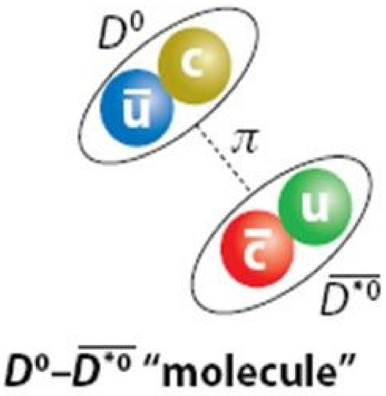
- stable, deeply bound $bbu\bar{d}$ tetraquark
- $J^P = 1^+$, $M(bb\bar{u}\bar{d}) = 10389 \pm 12$ MeV
- 215 MeV below BB^* threshold
- first manifesty exotic stable hadron
- $(bb\bar{u}\bar{d}) \to \bar{B}D\pi^-$, $J/\psi\bar{K}\bar{B}$,
  $J/\psi J/\psi K^-\bar{K}^0$, D^0B^-
- $(bc\bar{u}\bar{d})$: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

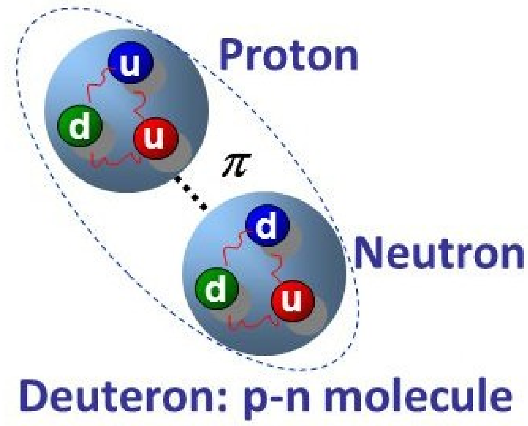
5 narrow exotic states close to meson-meson thresholds

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

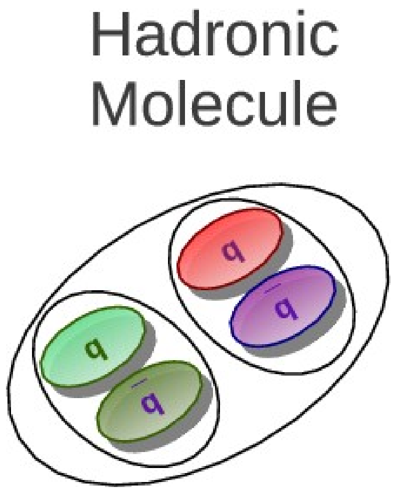
Hadronic molecules: deuteron-like

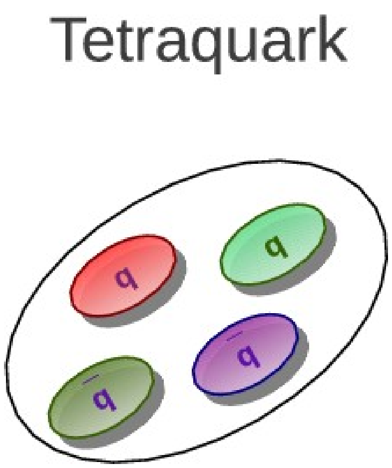




Tetraquarks: same 4 quarks, but tightly bound:

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

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	$J/\psi\,p$
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,†]
[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 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

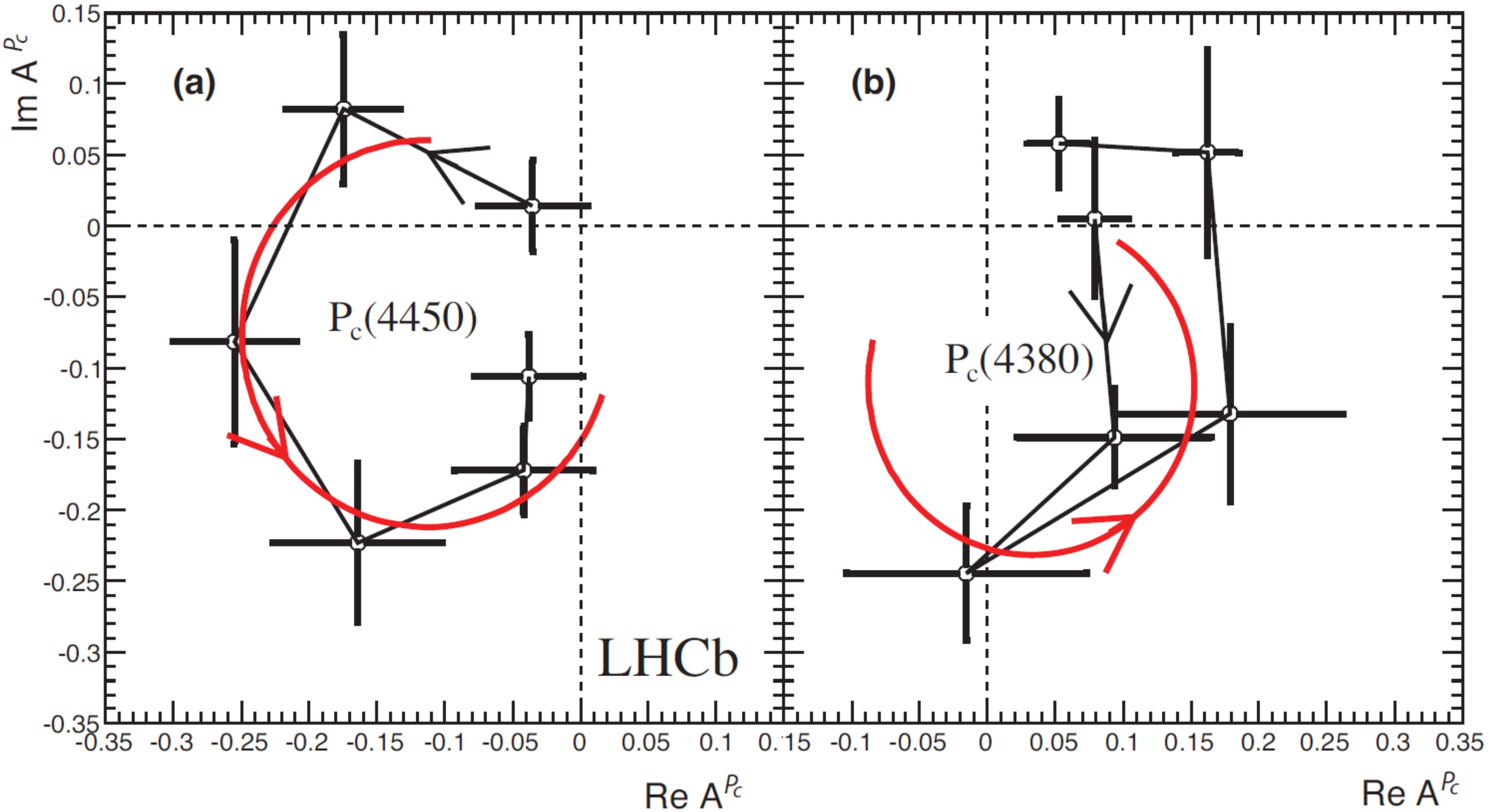
Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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

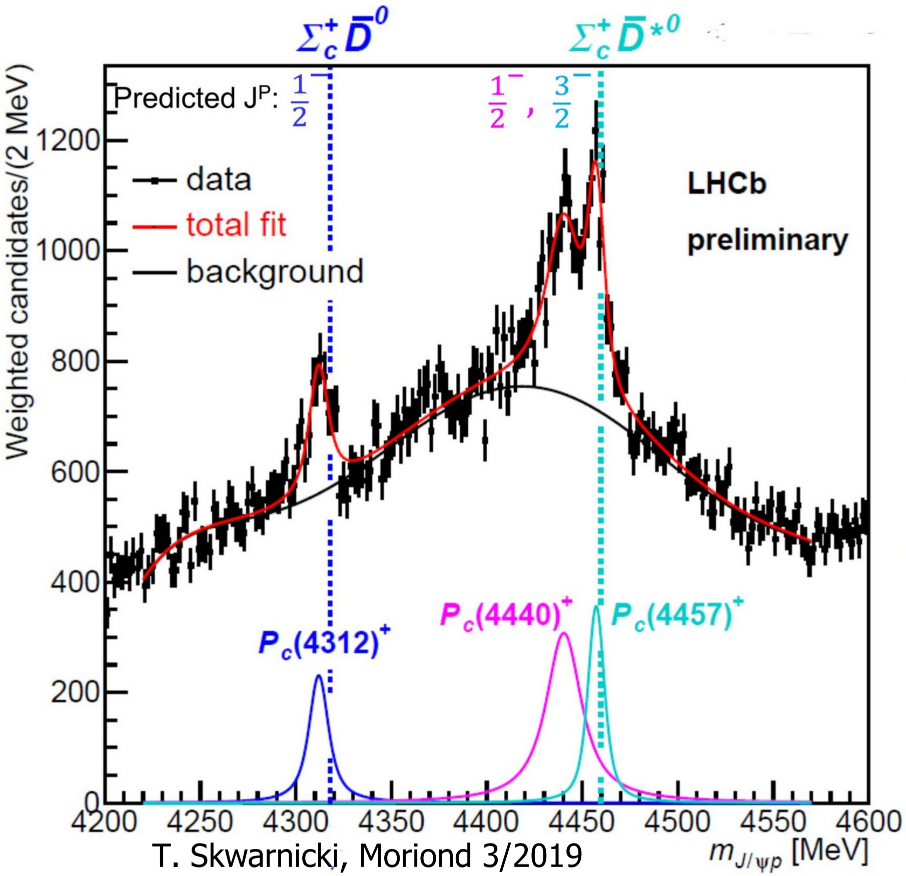


$P_c(4450)$: predicted,
narrow: $\Gamma = 39 \pm 5 \pm 19$,
10 MeV from $\Sigma_c \bar{D}^*$ threshold
perfect Argand plot: a molecule

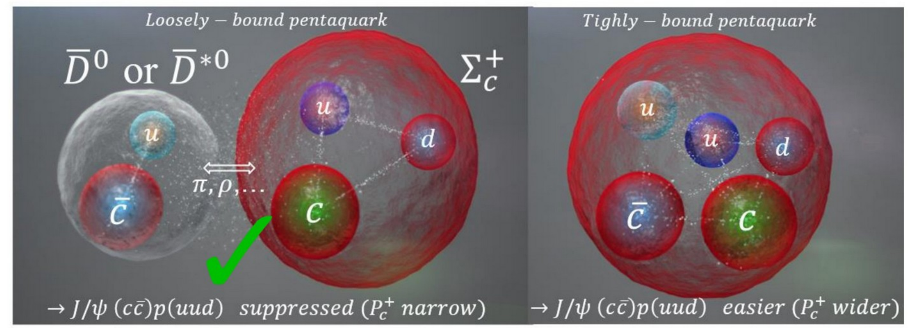
$P_c(4380)$: not predicted,
wide: $\Gamma = 205 \pm 18 \pm 86$ MeV,
Argand plot not resonance-like
???

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

as of 2015



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:

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

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

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...

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

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

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

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

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

$\Xi_c\bar{D}^*$, Ξ_cB^*, $\Xi_b\bar{D}^*$, Ξ_bB^*

like a whole new periodic table

recent news from LHCb

evidence for a new members of the family:

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

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

$\Longrightarrow$ new "molecular" pentaquarks:

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

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.

recent news from LHCb

evidence for a new members of the family:

$J/\psi\,\Lambda$ 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.

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

a very clear peak $> 10\ \sigma$:

$$P^{\Lambda}_{\psi s}(4338): \qquad M = 4338.2 \pm 0.7\ \text{MeV}, \quad \Gamma = 7.0 \pm 1.2\ \text{MeV}$$

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

$$P^{\Lambda}_{\psi s}(4455): \qquad M = 4454.9 \pm 2.7\ \text{MeV}, \quad \Gamma = 7.5 \pm 9.7\ \text{MeV}$$

$$P^{\Lambda}_{\psi s}(4468): \qquad M = 4467.8 \pm 3.7\ \text{MeV}, \quad \Gamma = 5.2 \pm 5.3\ \text{MeV}.$$

Several features of $P^{\Lambda}_{\psi s}(4338)$ strongly suggestive of a $\Xi_c \bar{D}$ hadronic molecule:

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

$M[P^{\Lambda}_{\psi s}(4338)]$ only 0.8 MeV above $\Xi_c^+ D^-$

2.9 MeV above $\Xi_c^0 D^0$

(b) Spin and parity:

$\frac{1}{2}^+$ baryon & 0^- meson

S-wave molecule $\Rightarrow \frac{1}{2}^-$

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

$\Gamma[P^{\Lambda}_{\psi s}(4338)] = \quad 7.0 \pm 1.2$ MeV

vs. Q-value $= 126$ MeV.

More support (with $\ll$ stats) for molecular interpret. from earlier LHCb $P^{\Lambda}_{\psi s}(4459)$ pentaquark data

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

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

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:

$P^{\Lambda}_{\psi s}(4455)$: $M = 4454.9 \pm 2.7$ MeV, $\Gamma = 7.5 \pm 9.7$ MeV

$P^{\Lambda}_{\psi s}(4468)$: $M = 4467.8 \pm 3.7$ MeV, $\Gamma = 5.2 \pm 5.3$ MeV.

highly reminescent of LHCb $P^{N}_{\psi}(4440)^+$ and $P^{N}_{\psi}(4457)^+$

caveat:

analogy between $\Sigma_c\bar{D}^{(*)}$ and $\Xi_c\bar{D}^{(*)}$ h.m. goes only so far, as

$P^{\Lambda}_{\psi s}(4455)$, $P^{\Lambda}_{\psi s}(4468)$ *not* an $SU(3)_F$ rotation $q \to s$ (q=u,d) of

$P^{N}_{\psi}(4440)^+$, $P^{N}_{\psi}(4457)^+$.

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

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

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

$\Delta M \equiv M(\Xi'_c) - M(\Xi_c) \approx 110$ 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 $\Delta M \approx 110$ MeV for each J^P

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

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

New strange pentaquarks

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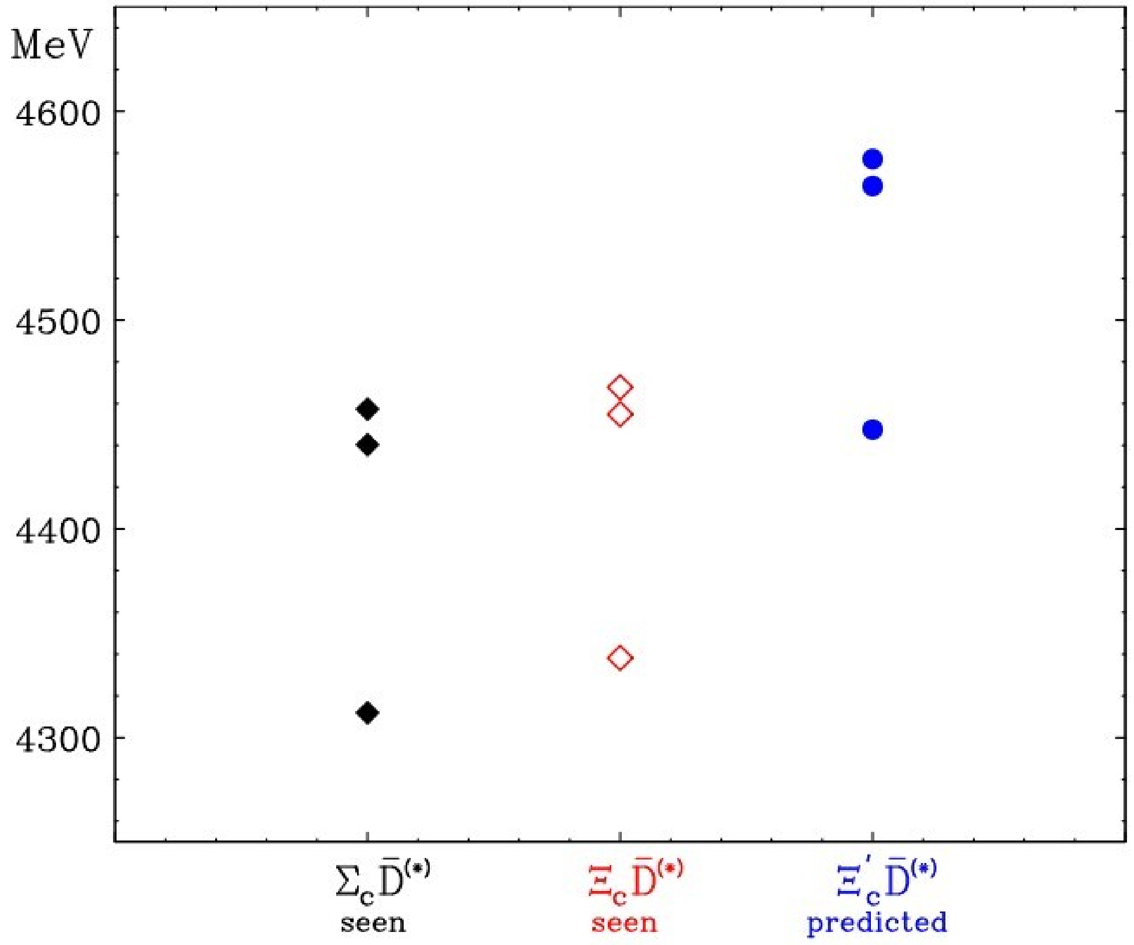
(Received 25 July 2022; accepted 8 August 2022; published 25 August 2022)

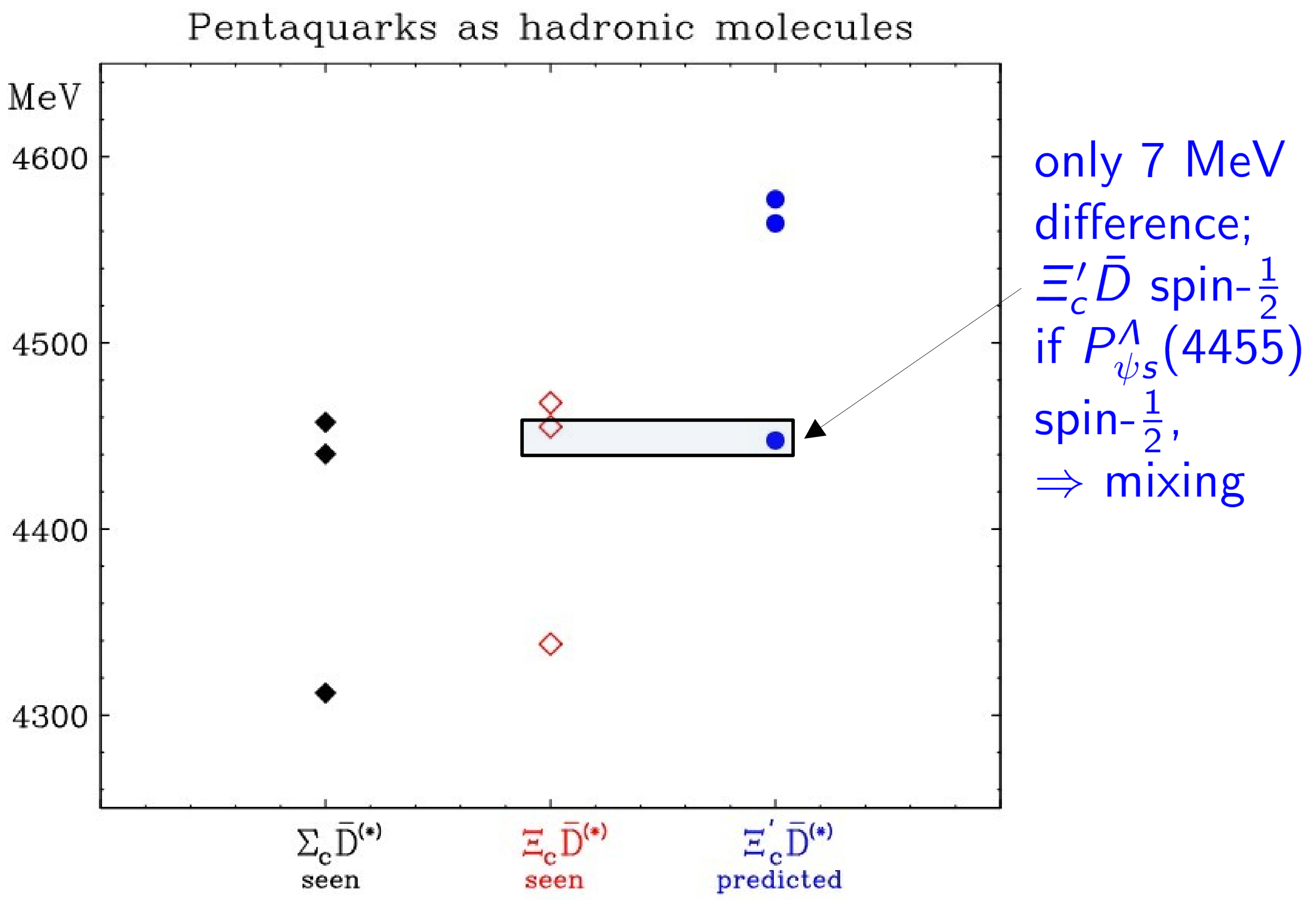
The new strange pentaquarks observed by LHCb are very likely hadronic molecules consisting of $\Xi_c \bar{D}$ and $\Xi_c \bar{D}^*$. We discuss the experimental evidence supporting this conclusion, pointing out the similarities and differences with the $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$ pentaquarks 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



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.

LHCb, 08/2020:

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

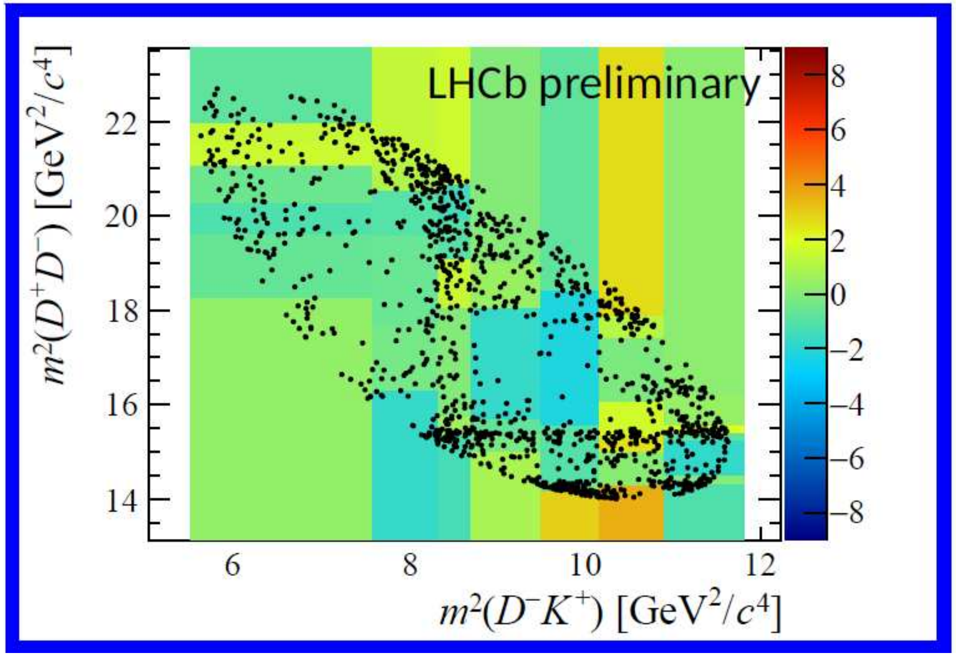
first exotic hadron with open heavy flavor:

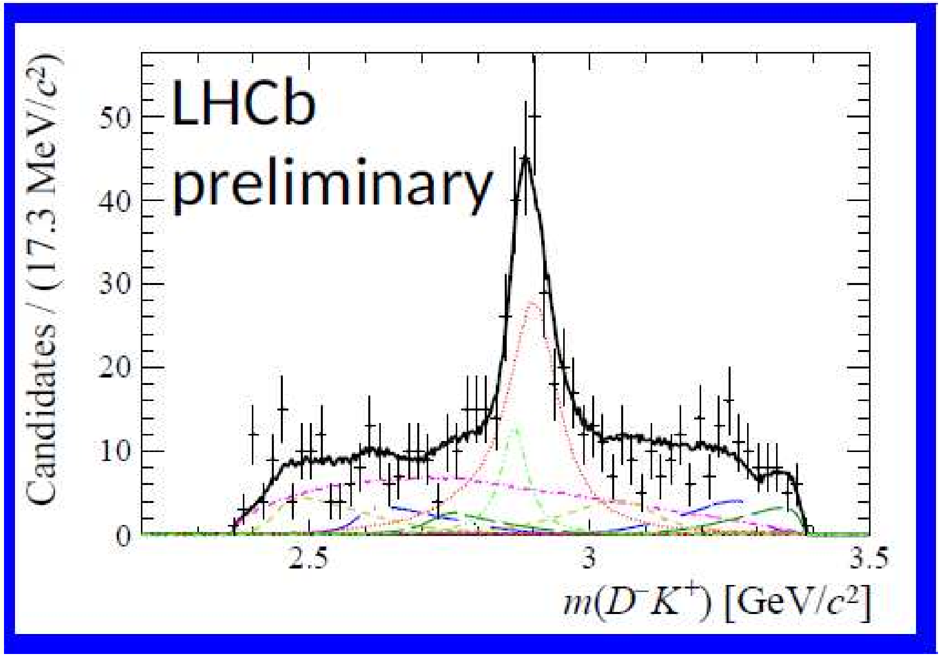
$cs\bar{u}\bar{d}$ tetraquark

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

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

2009.00025 & 2009.00026





MK & JR:arXiv:2008.05993 & PRD, in press

- two BW-s:
  $X_0(2900)$, $J^P = 0^+$ at 2866±7 MeV, $\Gamma_0 =$ 57±13 MeV
  $X_1(2900)$, $J^P = 1^-$ at 2904±7 MeV $\Gamma_1 =$ 110±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

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

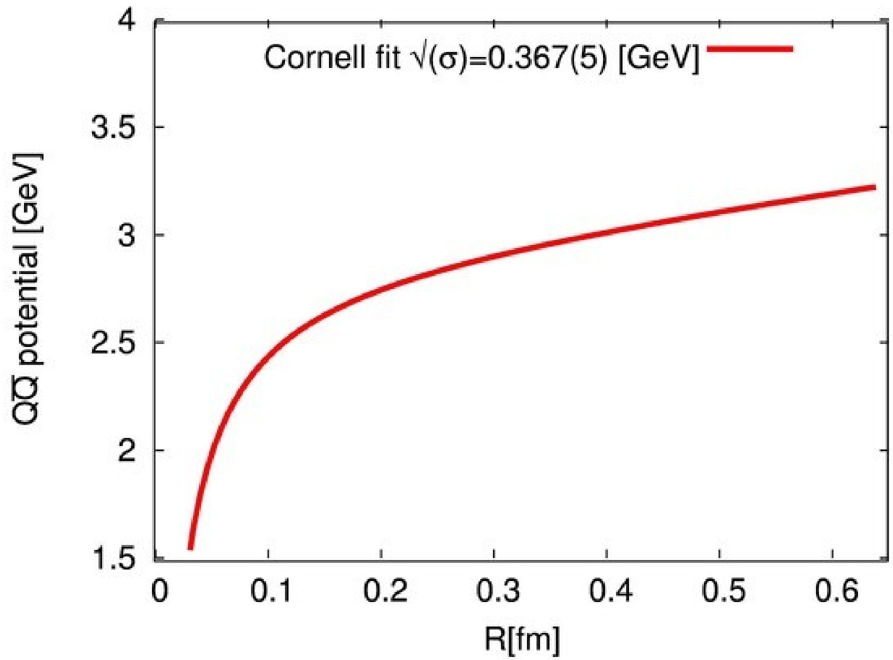
$\Rightarrow R(bb) \sim 0.2$ fm

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

$\Rightarrow B(bb) \approx -280$ 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 $u\bar{d}$, $\quad Z_b \to \Upsilon\pi^+$

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

SUMMARY: NEW STRANGE PENTAQUARKS IN CONTEXT

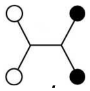
- narrow $cc\bar{u}\bar{d}$ tetraquark discovered by LHCb   what about in heavy ions?
- doubly charmed baryon found exactly where predicted

  $\Xi_{cc}^{++}(ccu) \Rightarrow (bcq), (bbq)$
- stable $bb\bar{u}\bar{d}$ tetraquark: LHCb !
- narrow exotics with $Q\bar{Q}$: "heavy deuterons" / molecules

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

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

3 $\Xi_c\,\bar{D}^{(*)}$ states $\to$ 3 $\Xi_c'\,\bar{D}^{(*)}$ states; $\Delta M \approx 110$ MeV

  $\Sigma_c B^*$, $\Sigma_b\bar{D}^*$, $\Sigma_b B^*$, 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 $2S$, $J/\psi\,\Upsilon$, $\Upsilon\Upsilon$?

exciting new spectroscopy awaiting discovery

Backup transparencies