Exotic Hadrons

Marek Karliner
Tel Aviv University
Joint work with Jon Rosner

BiałasFest, Cracow, June 19, 2026

Quarks are never alone.

They always appear in clusters.

We want to know:

- what clusters are allowed?
- how stable are they?

Thus our topic can be rephrased as...

THE SOCIAL LIFE OF QUARKS

Who with whom?

For how long?

a "Passing Fling",

or

"Till Death Us Do Part" ?

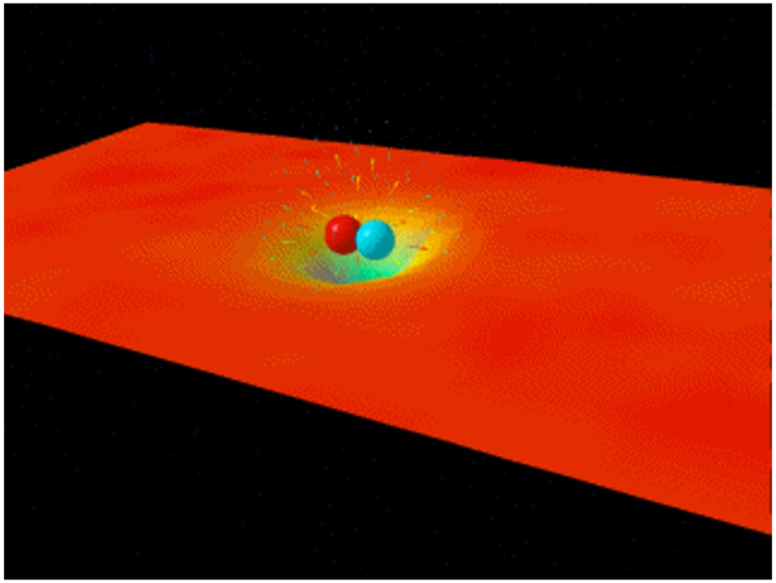
Outline

- 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:

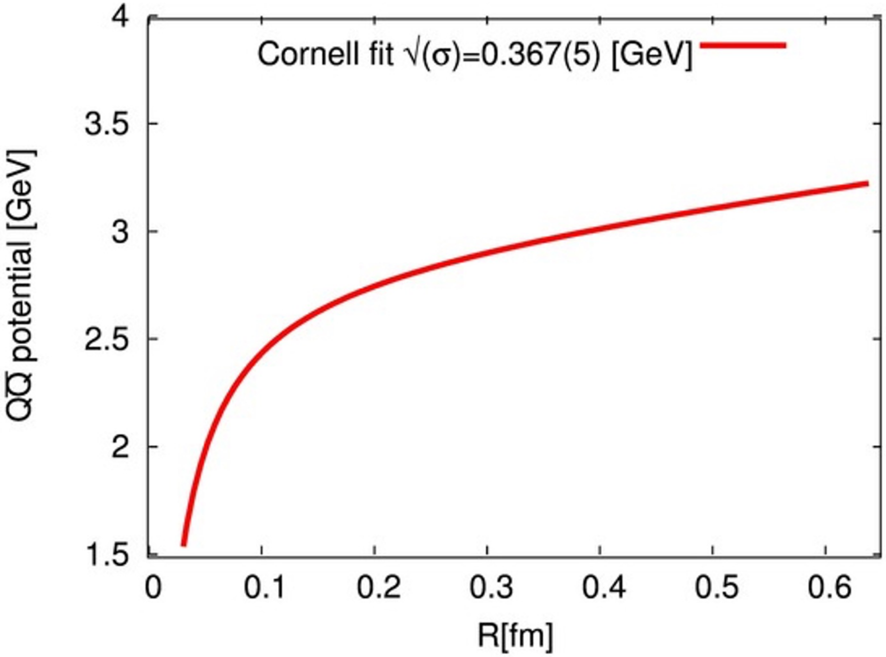
- newly discovered T_{cc}^{+} tetraquark $= (cc\bar{u}\bar{d})$
- stable $bb\bar{u}\bar{d}$ tetraquark
- hadronic molecules, esp. LHCb pentaquark
- *"like a new layer in the periodic table"*

Confinement + Gauss Law → flux tubes

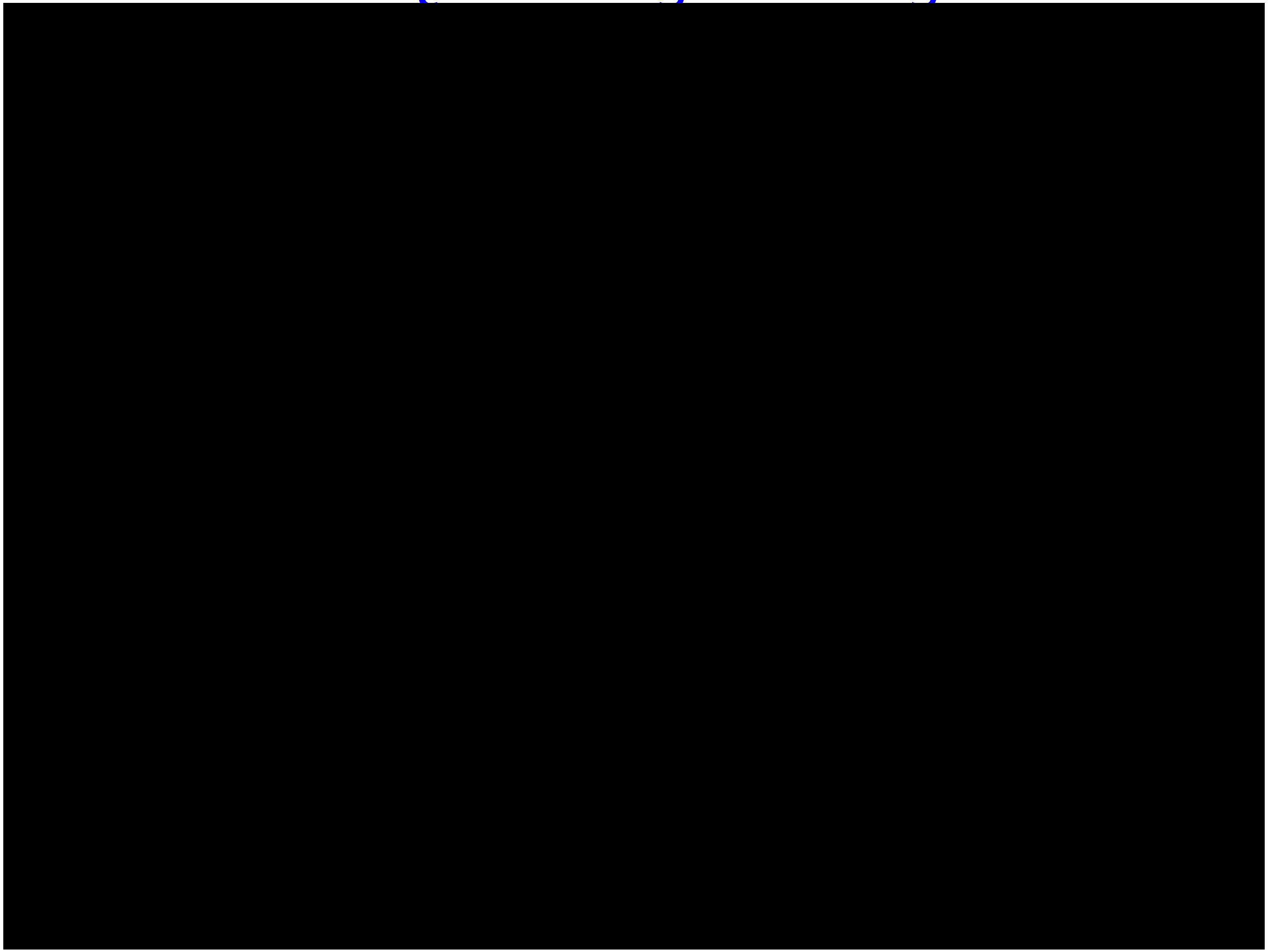


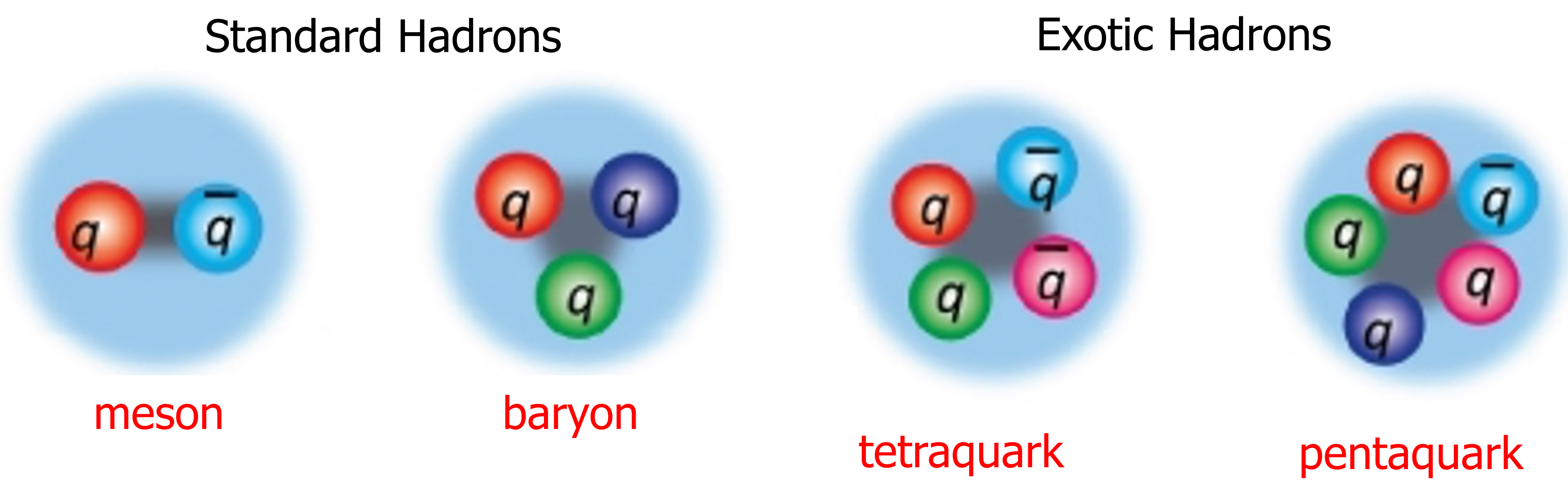
chromoelectric flux tube between a quark and an antiquark in a meson

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



QCD string breaking




Standard Hadrons
Exotic Hadrons
meson
baryon
tetraquark
pentaquark

exotic hadrons – tetra and pentaquarks – discussed right from the start of the quark model

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

. . .

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while

8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING II *)

G. Zweig
CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

. . .

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

> 50 years of searches for exotics made from light (u,d,s) quarks, but no unambiguous exp. evidence

but recently clearcut evidence in heavy-light exotics

∃ robust experimental evidence
for multiquark states, a.k.a.
<u>exotic hadrons</u> 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. $\bar{Q}Qqq'q''$

three key questions:

- which additional exotics should we expect?
- how are quarks organized inside them?
- how long do they survive?

Tq   dq-dq   had. mol.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

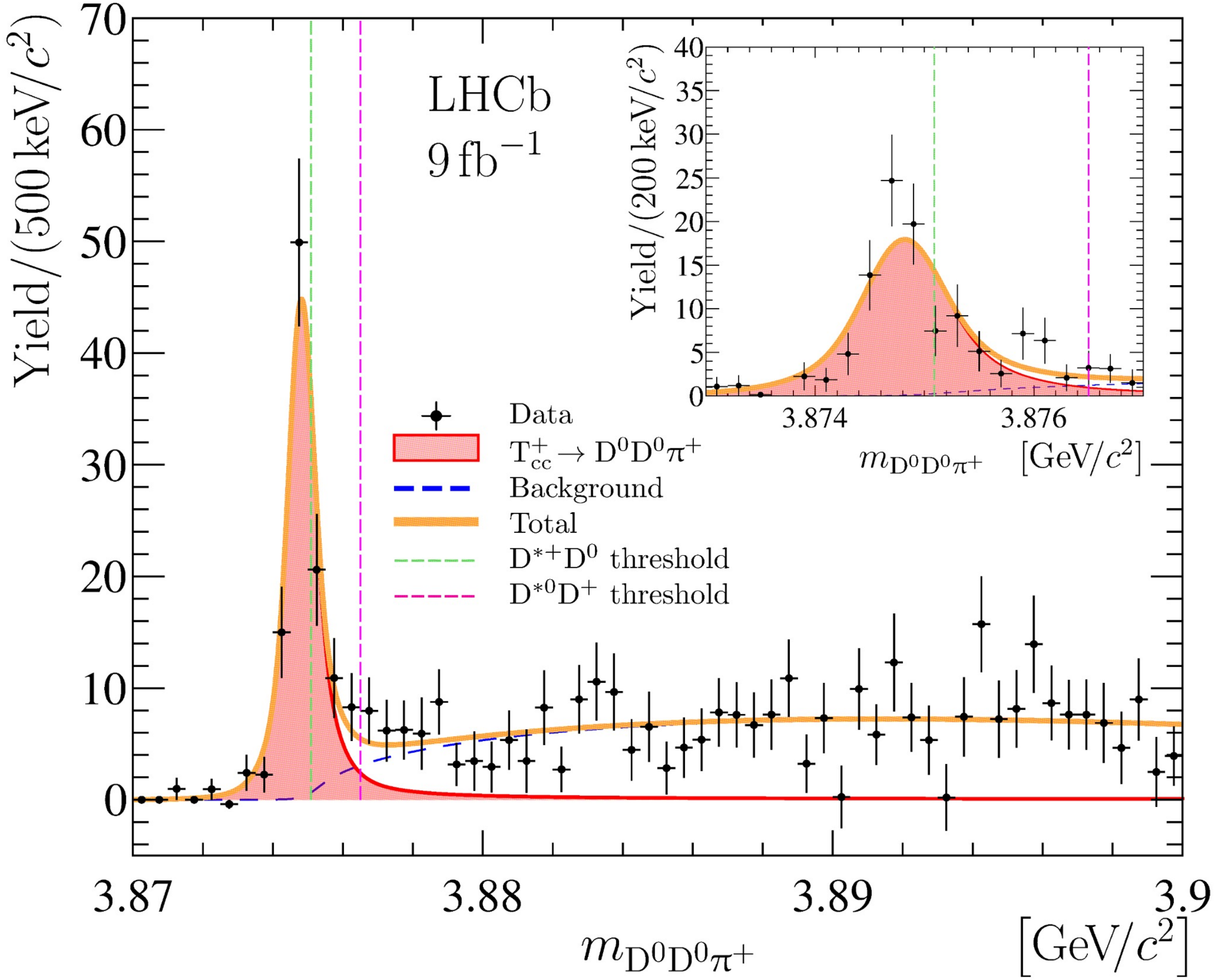
CERN-EP-2021-165
LHCb-PAPER-2021-031
September 2, 2021

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 $\mathrm{D}^{*+}\mathrm{D}^0$ mass threshold, δm_{BW}, and width, Γ_{BW}, obtained from the fit to the $\mathrm{D}^0\mathrm{D}^0\pi^+$ mass spectrum. The uncertainties are statistical only.

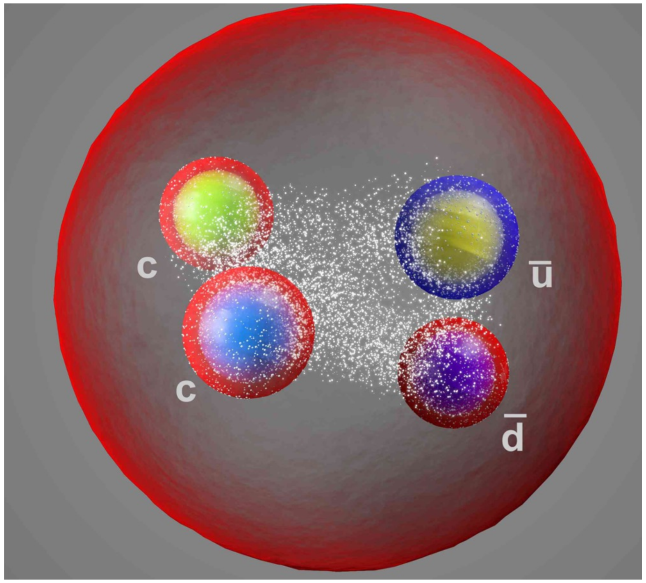
Parameter	Value	
N	117 ± 16	
δm_{BW}	-273 ± 61 keV/c^2	@ 4.3 σ
Γ_{BW}	410 ± 165 keV	

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

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

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

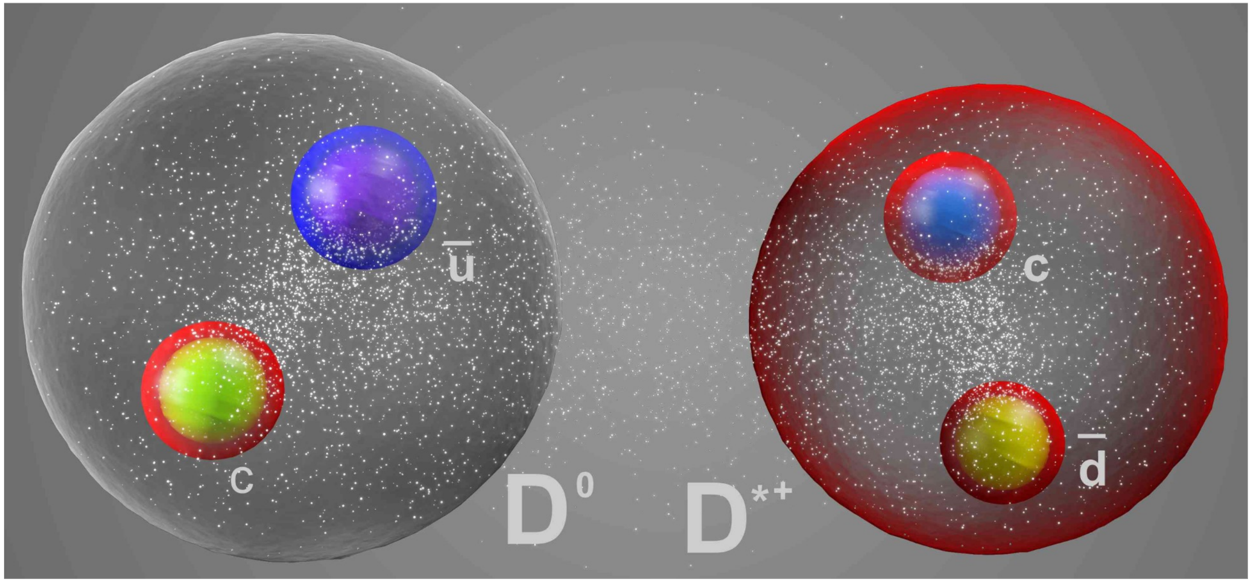
tightly-bound
tetraquark



each quark
sees the color charges
of all other quarks

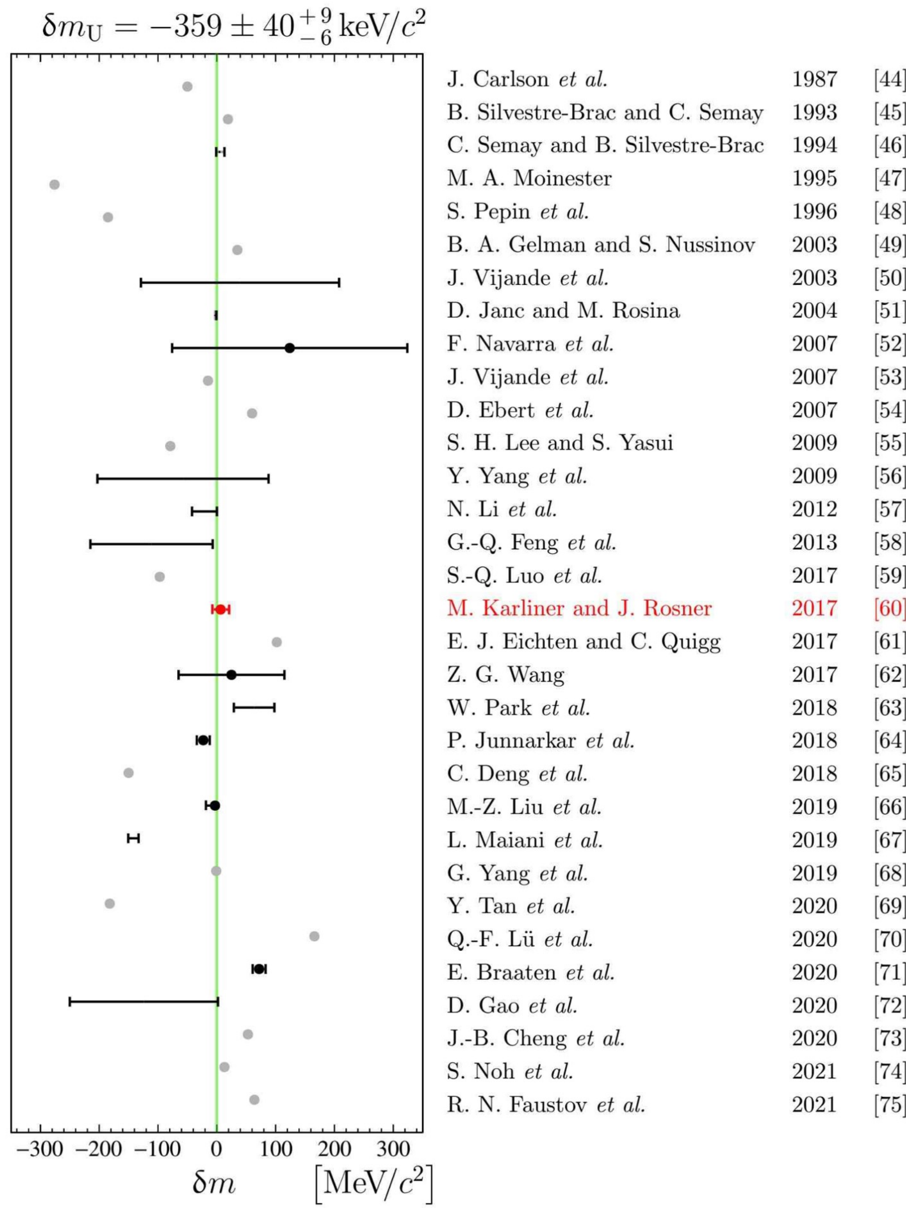
or

hadronic
molecule?



two color
singlets
interacting
by
light meson
x-change

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 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. $cc\bar{u}\bar{d}$

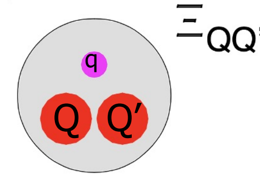
in both heavy cc diquark 3_c^* coupled to a light 3_c

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 (2014)



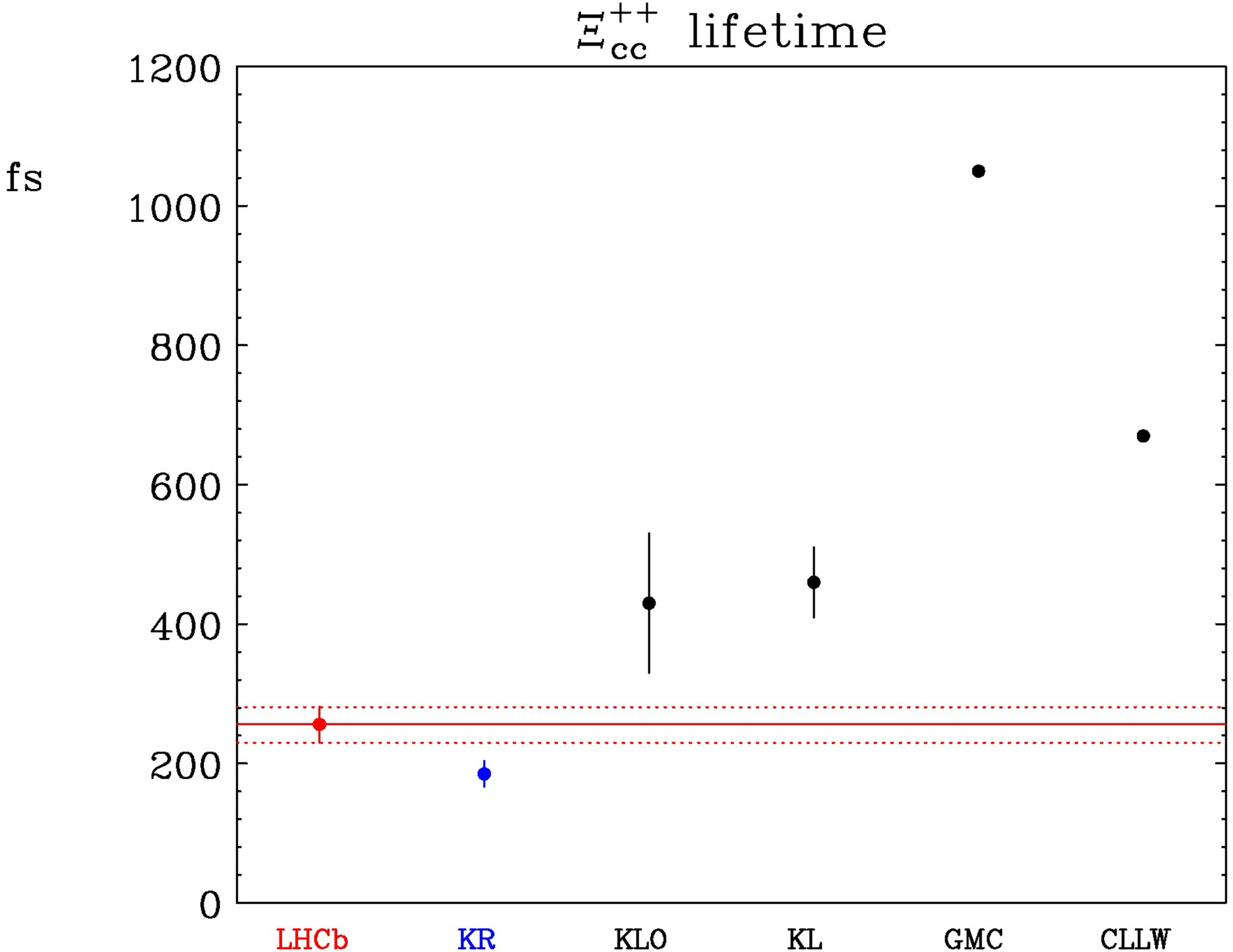
MK & JR, Phys. Rev. D90, 094007 (2014)

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 (2017)

PRL 119,112001, (2017)



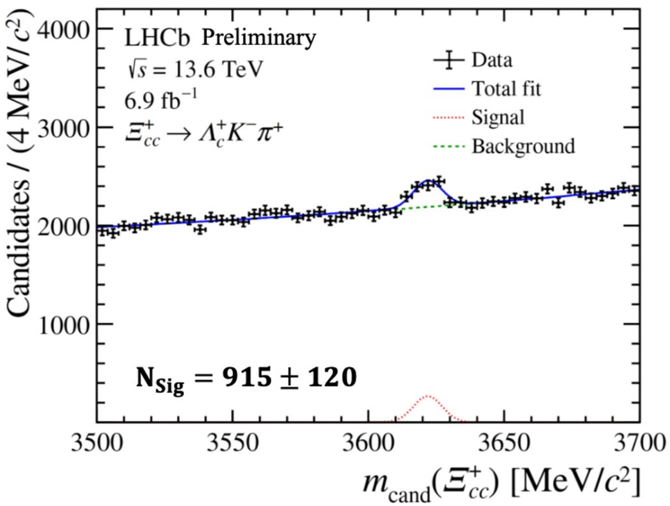
$\tau(\Xi_{cc}^{++}) = 256^{+21}_{-22} \pm 14$ fs

New result from LHCb, announced in March: mass of $(ccd) \equiv \Xi_{cc}^{+}$

[LHCb-PAPER-2026-009, in preparation]

Mass measurement of Ξ_{cc}^{+}

- Precise measurement:
  - Correct the mass bias caused by event selection(backup) and final-state photon radiation.
- Ξ_{cc}^{+} mass with correction: $3619.97 \pm 0.83\,(\mathrm{stat}) \pm 0.26\,(\mathrm{syst})^{+1.90}_{-1.30}\,(\mathrm{lifetime})\ \mathrm{MeV}/c^2$.
- Mass difference: $\Delta M \equiv M(\Xi_{cc}^{+}) - M(\Xi_{cc}^{++}) = -1.77 \pm 0.84\,(\mathrm{stat}) \pm 0.15\,(\mathrm{syst})^{+1.90}_{-1.30}\,(\mathrm{lifetime})\ \mathrm{MeV}/c^2$.
  - Prediction: -0.4 to $-2.3\ \mathrm{MeV}/c^2$.



Systematic uncertainties (in MeV/c^2) on the $M(\Xi_{cc}^{+})$ mass and mass difference ΔM

Source	$M(\Xi_{cc}^{+})$	ΔM
Momentum-scale calibration	0.14	0.03
Energy loss	0.10	0.05
Selection bias correction	0.10	0.10
Mass fit model	0.10	0.10
Λ_c^{+} mass uncertainty	0.14	–
Sum in quadrature	0.26	0.15
Unknown Ξ_{cc}^{+} lifetime	$^{+1.90}_{-1.30}$	$^{+1.90}_{-1.30}$

The bias due to event selection strongly depends on the lifetime.

2017 prediction for $M(ccu) - M(ccd) \equiv$ isospin breaking

PHYSICAL REVIEW D **96,** 033004 (2017)

Isospin splittings in baryons with two heavy quarks

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 26 June 2017; published 25 August 2017)

Isospin splittings in baryons with two heavy quarks and a u or d quark are calculated using simple methods proposed previously by the authors. The results are $M(\Xi_{cc}^{++}) - M(\Xi_{cc}^{+}) = 1.41 \pm 0.12^{+0.76}$ MeV, $M(\Xi_{bb}^{0}) - M(\Xi_{bb}^{-}) = -4.78 \pm 0.06^{+0.03}$ MeV, and $M(\Xi_{bc}^{+}) - M(\Xi_{bc}^{0}) = -1.69 \pm 0.07^{+0.39}$ MeV, where the statistical errors reflect uncertainties in input mass splittings, and the systematic errors are associated with the choice of constituent-quark masses.

TABLE II. Contributions to isospin splittings (MeV) using universal constituent-quark masses in mesons and baryons.

	N_1	Σ_1	Σ_2	Ξ_1	$\Xi_{cc,1}$	$\Xi_{bb,1}$	$\Xi_{bc,1}$
$m_u - m_d$	−2.68	−5.36	0.00	−2.68	−2.68	−2.68	−2.68
Coulomb	0.94	−0.94	2.83	−1.89	3.77	−1.89	0.94
StrHF	0.88	−0.24	0.00	−1.12	−0.33	−0.11	−0.22
EMHF	−0.43	−1.54	−1.30	−1.11	0.64	−0.11	0.27
Total	−1.293	−8.086	1.535	−6.793	1.409	−4.783	−1.687
					±0.116	±0.058	±0.067

$$\Delta M_{\Xi_{cc}} \equiv M(\Xi_{cc}^{++}) - M(\Xi_{cc}^{+})$$

ccu ccd

$$\text{LHCb: } \Delta M_{\Xi_{cc}} = 1.77 \pm 0.84(\text{stat}) \pm 0.15(\text{sys})^{+1.30}_{-1.90}(\text{lifetime}) \text{ MeV}$$

replacing u quark by d quark:

$$m_d - m_u \approx 2.7 \text{ MeV} \longrightarrow m_n(ddu) > m_p(uud)$$

but here $M(ccd \equiv \Xi_{cc}^{+}) < M(ccu \equiv \Xi_{cc}^{++})$???

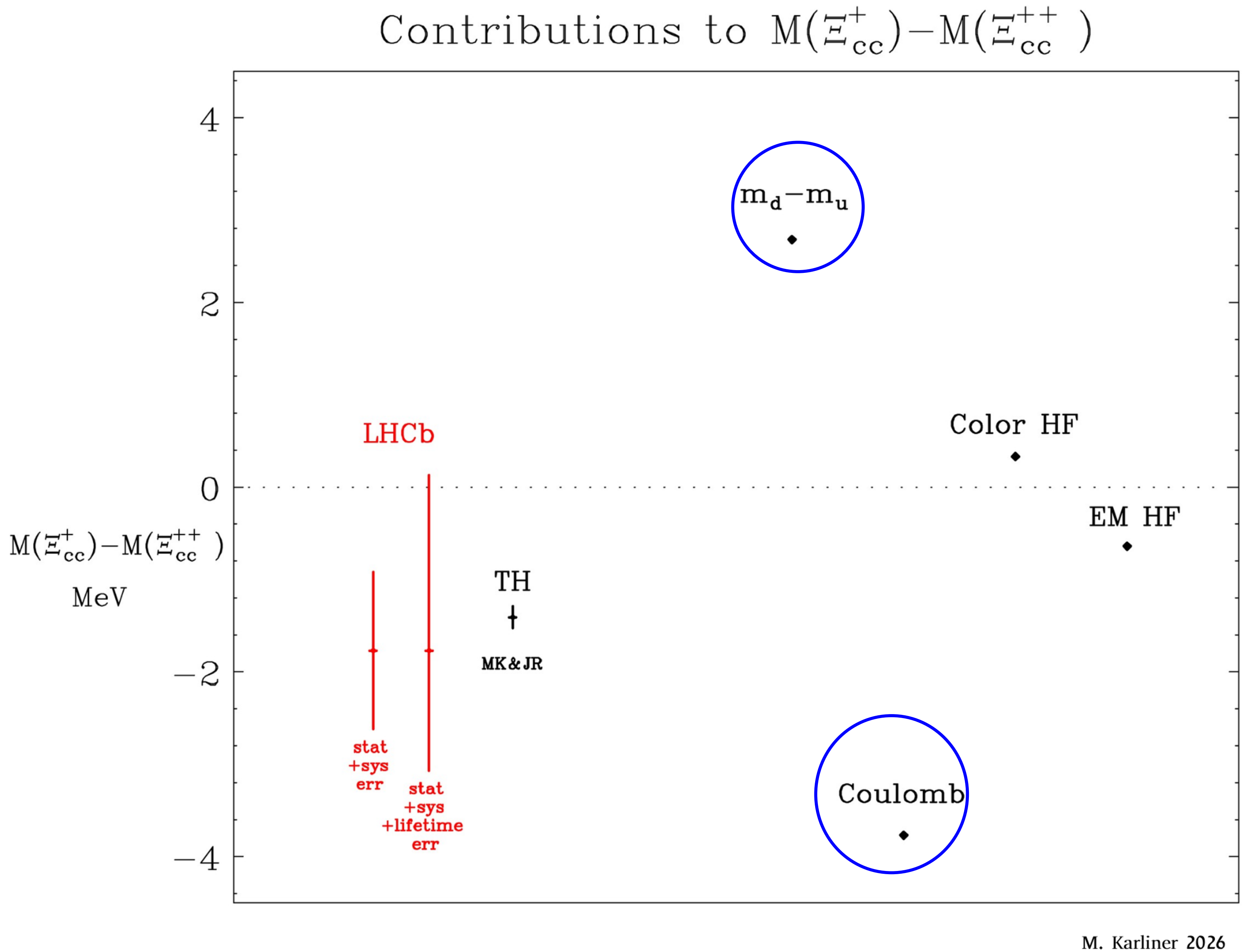
$\Longrightarrow$ new effect: large Coulomb energy w. opposite sign:

$$Q_c = Q_u = +\tfrac{2}{3}; \qquad Q_d = -\tfrac{1}{3}$$

$$\left(+\tfrac{4}{3}\right) \cdot \left(+\tfrac{2}{3}\right) \text{ in } ccu$$

$$\left(+\tfrac{4}{3}\right) \cdot \left(-\tfrac{1}{3}\right) \text{ in } ccd$$

EM energy $\Longleftrightarrow$ mass, via $E = mc^2$


Contributions to $M(\Xi_{cc}^{+})-M(\Xi_{cc}^{++})$
4
2
0
−2
−4
$M(\Xi_{cc}^{+})-M(\Xi_{cc}^{++})$
MeV
m_d-m_u
LHCb
stat
+sys
err
stat
+sys
+lifetime
err
TH
MK&JR
Color HF
EM HF
Coulomb
M. Karliner 2026

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.

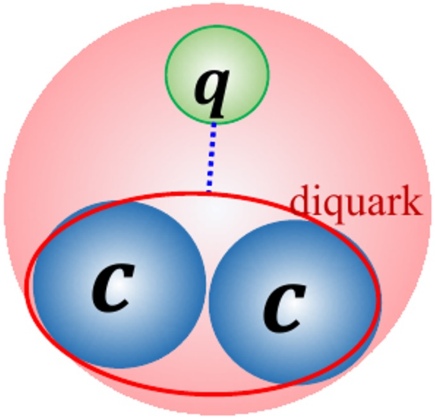
DOI: 10.1103/PhysRevLett.119.202001

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., $S{=}0$, $I{=}0$

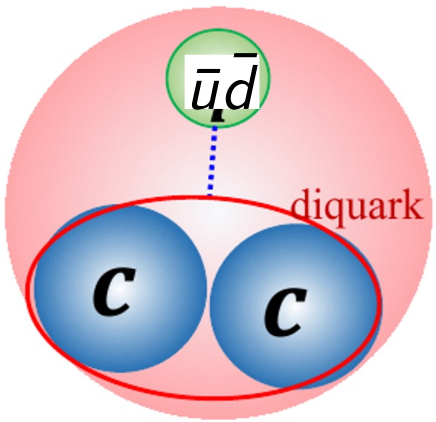
(it's the lightest one)

$\Rightarrow$ 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:

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

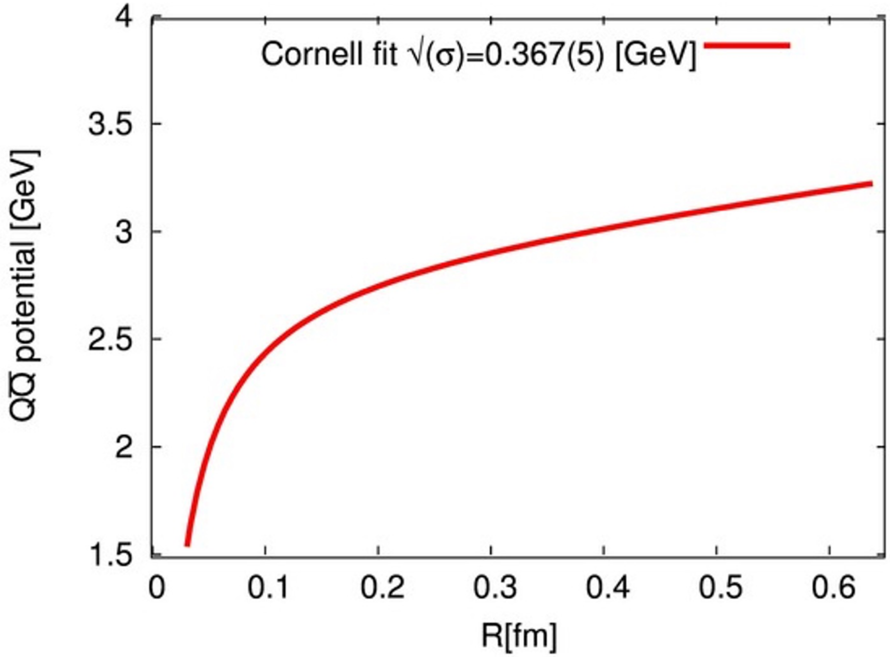


Ξ_{cc} discovery $\Rightarrow$ quantitative validation

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

so for $M_Q \rightarrow \infty$

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



$T(bb\bar{u}\bar{d})$:
$m_b \approx 5$ 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 disengage from $\bar{u}\bar{d}$

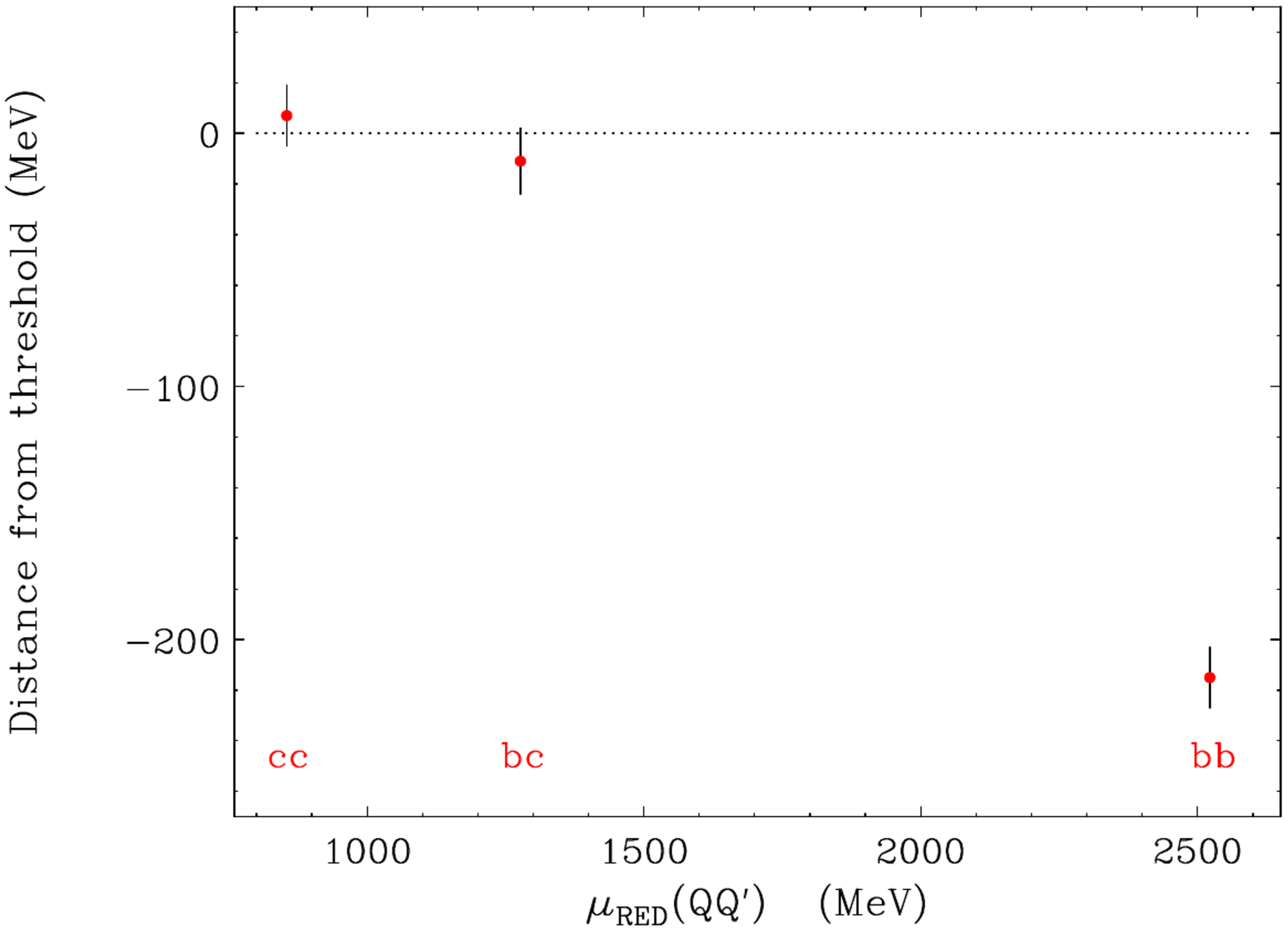
The channel $T_{bb} \to BB^*$ is kinematically closed

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 $ccu = \Xi_{cc}^{++}$

$$\sigma(pp \to \Xi_{bb} + X) \sim \left(\frac{m_c}{m_b}\right)^4 \cdot \sigma(pp \to \Xi_{cc} + X) \quad \text{TINY!}$$

$\Rightarrow$ Ξ_{bb} and $T(bb\bar{u}\bar{d})$ accessible,
but with much more $\int \mathcal{L} dt$

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

Is there a better way?

very likely yes: T_{QQ} production in AA

Ξ_{QQ} & T_{QQ} yields in $AA \gg$ than in pp:

- multiple hard NN collisions vs. single pp
- heavy quark coalescence in QGP
- $T_{QQ} \equiv QQ\bar{u}\bar{d}$ formation: $\bar{u}, \bar{d}$ from QGP

the big challenge: v. large background

proof of concept:

$X(3872)$ 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, but the huge combinatorial background has been a major challenge. Proof of concept: 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}^+ ?

- CMS (2022): first observation of the B_c meson in AA
- new, possibly much more efficient B_c formation mechanism, specific to AA, very different from pp
  $\Longrightarrow (bcu)$ and (bcd) baryons & $(bc\bar{u}\bar{d})$ tetraquark in AA!

PHYSICAL REVIEW LETTERS **128,** 252301 (2022)

Observation of the B_c^+ Meson in Pb-Pb and pp Collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Measurement of its Nuclear Modification Factor

A. Tumasyan *et al.**
(CMS Collaboration)

(Received 7 January 2022; revised 23 February 2022; accepted 9 May 2022; published 21 June 2022)

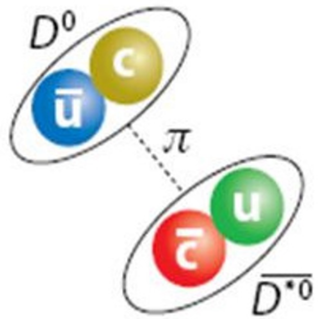
The B_c^+ meson is observed for the first time in heavy ion collisions. Data from the CMS detector are used to study the production of the B_c^+ meson in lead-lead (Pb-Pb) and proton-proton (pp) collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV, via the $B_c^+ \to (J/\psi \to \mu^+\mu^-)\mu^+\nu_\mu$ decay. The B_c^+ nuclear modification factor, derived from the Pb-Pb–to–pp ratio of production cross sections, is measured in two bins of the trimuon transverse momentum and of the Pb-Pb collision centrality. The B_c^+ meson is shown to be less suppressed than quarkonia and most of the open heavy-flavor mesons, suggesting that effects of the hot and dense nuclear matter created in heavy ion collisions contribute to its production. This measurement sets forth a promising new probe of the interplay of suppression and enhancement mechanisms in the production of heavy-flavor mesons in the quark-gluon plasma.

5 narrow exotic states close to meson-meson thresholds

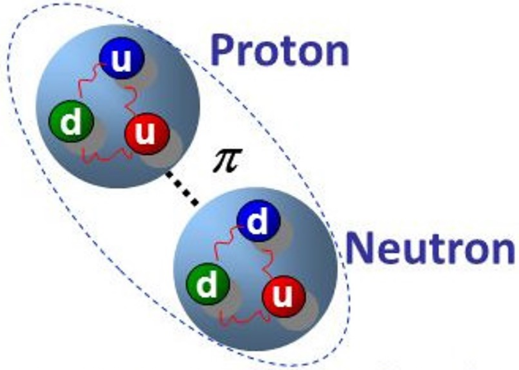
state	mass MeV	width MeV	$\bar{Q}Q$ decay mode	phase space MeV	nearby threshold	ΔE MeV
$X(3872)$	3872	< 1.2	$J/\psi\,\pi^+\pi^-$	495	$\bar{D}D^*$	< 1
$Z_b(10610)$	10608	21	$\Upsilon\pi$	1008	$\bar{B}B^*$	2 ± 2
$Z_b(10650)$	10651	10	$\Upsilon\pi$	1051	$\bar{B}^*B^*$	2 ± 2
$Z_c(3900)$	3900	$24 - 46$	$J/\psi\,\pi$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



D^0–$\overline{D^{*0}}$ "molecule"

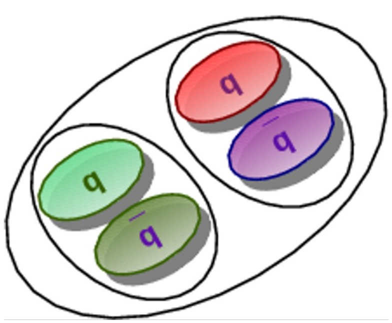


Deuteron: p-n molecule

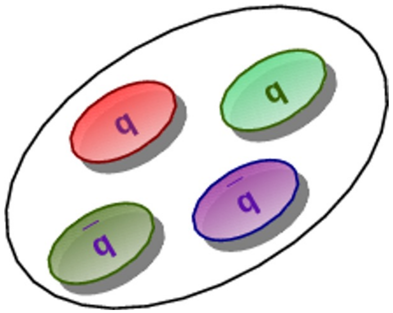
Tetraquarks: same 4 quarks, but tightly bound:

Hadronic Molecule

two color singlets attract through residual forces



Tetraquark



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

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

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

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

QQ' candidates – dibaryons

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

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	$J/\psi\,p$
$\Sigma_c B^*$	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
$\Sigma_b B^*$	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

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

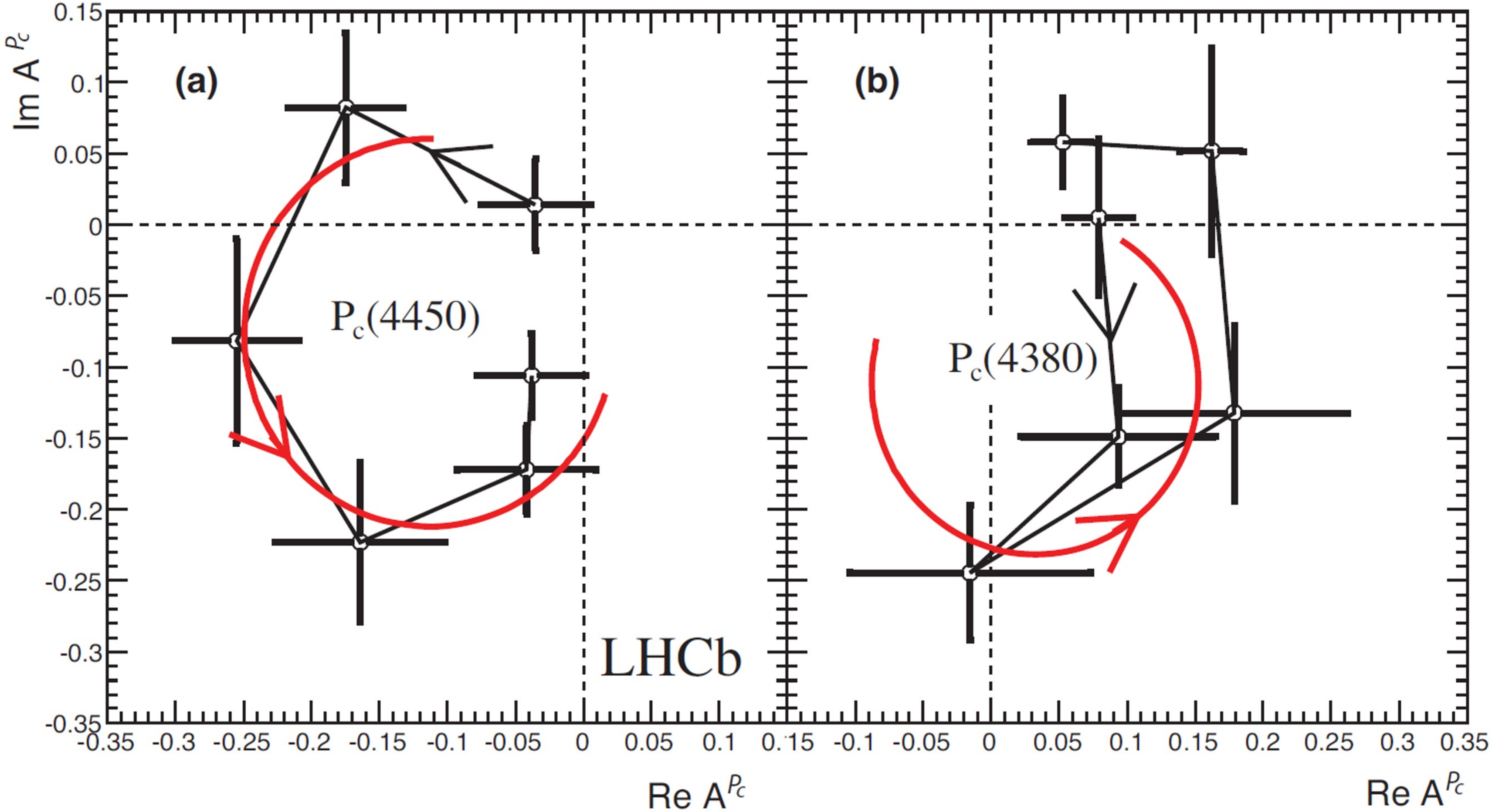
Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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

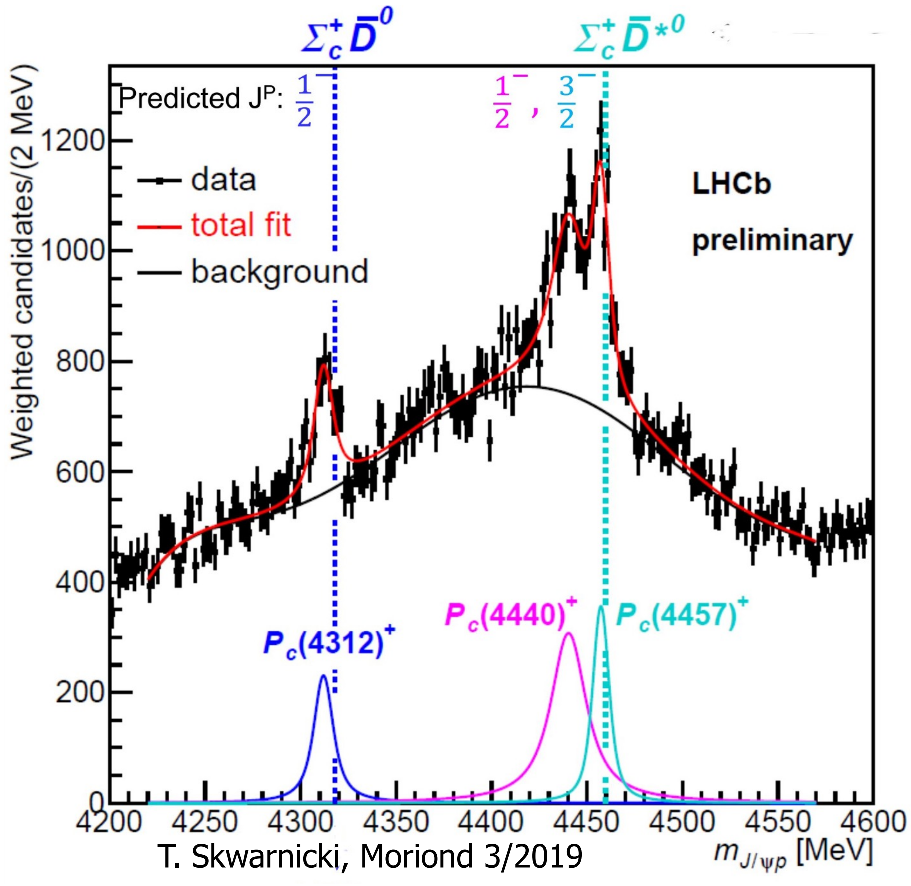


$P_c(4450)$: predicted,
narrow: $\Gamma = 39 \pm 5 \pm 19$,
10 MeV from $\Sigma_c \bar{D}^*$ threshold
perfect Argand plot: a molecule

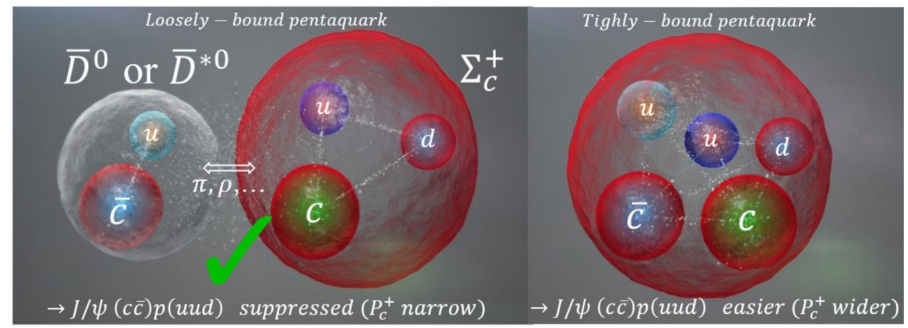
$P_c(4380)$: not predicted,
wide: $\Gamma = 205 \pm 18 \pm 86$ MeV,
Argand plot not resonance-like
???

$P_c(4450)$ 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:

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

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

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...

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

Marek Karliner[1,*] and Jonathan L. Rosner[2,†]

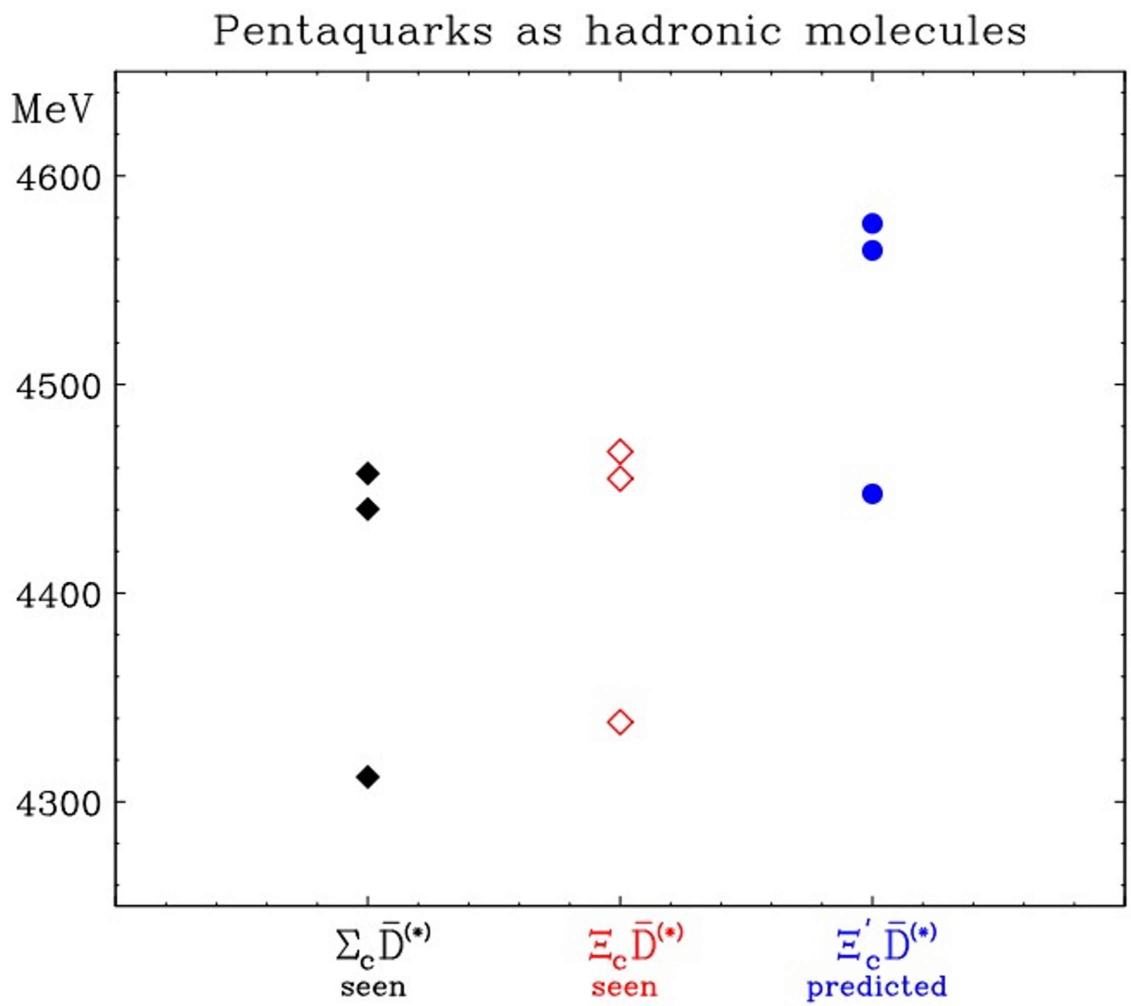
[1]*School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel*

[2]*Enrico Fermi Institute and Department of Physics, University of Chicago, 5620 South Ellis Avenue, Chicago, Illinois 60637, USA*

(Received 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.

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

LHCb, 2020:

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

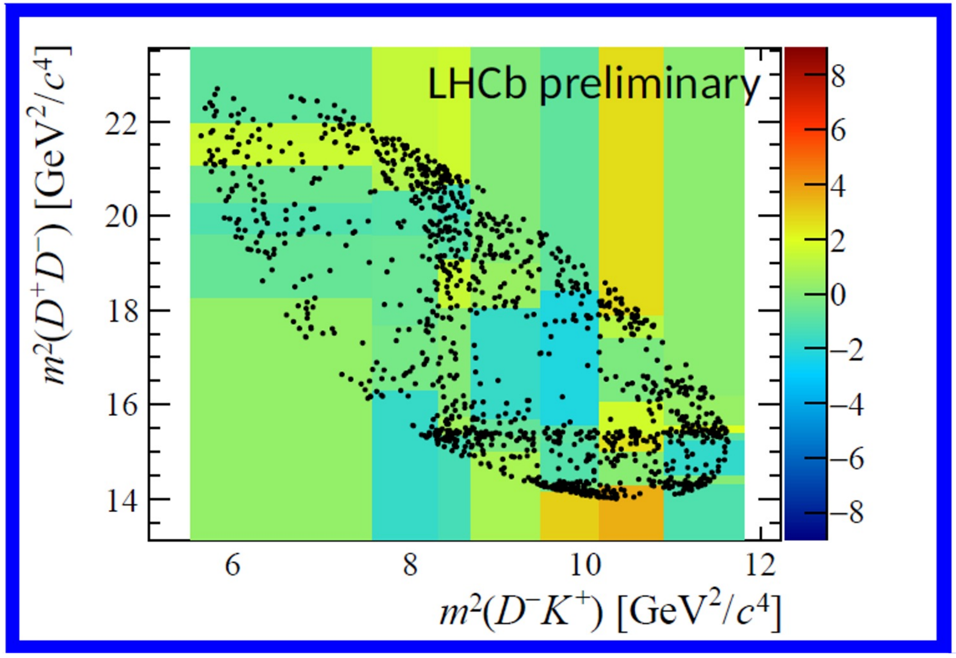
first exotic hadron with open heavy flavor:

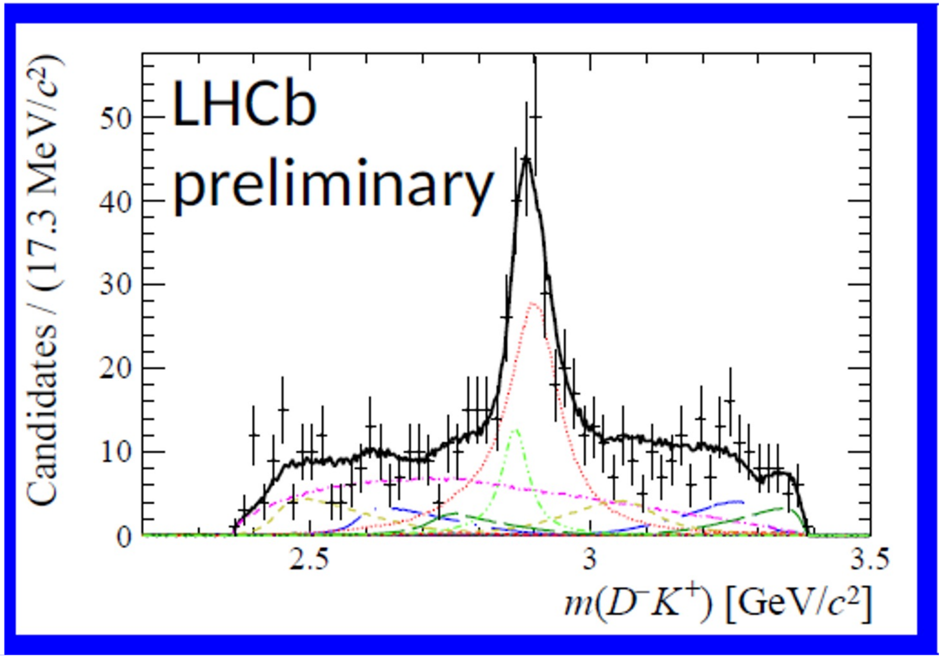
$cs\bar{u}\bar{d}$ tetraquark

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

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

2009.00025 & 2009.00026





- LHCb 2020: narrow res. decaying into two J/ψ -s

  & ATLAS (2022), CMS (2022)

- quark content $cc\bar{c}\bar{c}$
- $M \approx 6.9$ GeV: $X(6900)$
- tetraquark-like
- ~ 700 MeV above $J/\psi\, J/\psi$ threshold

  $\Rightarrow$ probably an excited $cc\bar{c}\bar{c}$ state
- first all-heavy Tq, w. both QQ *and* $\bar{Q}Q$
- CMS 2023 & 2025: 3 narrow states, with $J^{PC} = 2^{++}$

  X(6600), X(6900), X(7100): Nature 648 (2025) 8092, 58

- exciting challenge for EXP and TH

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

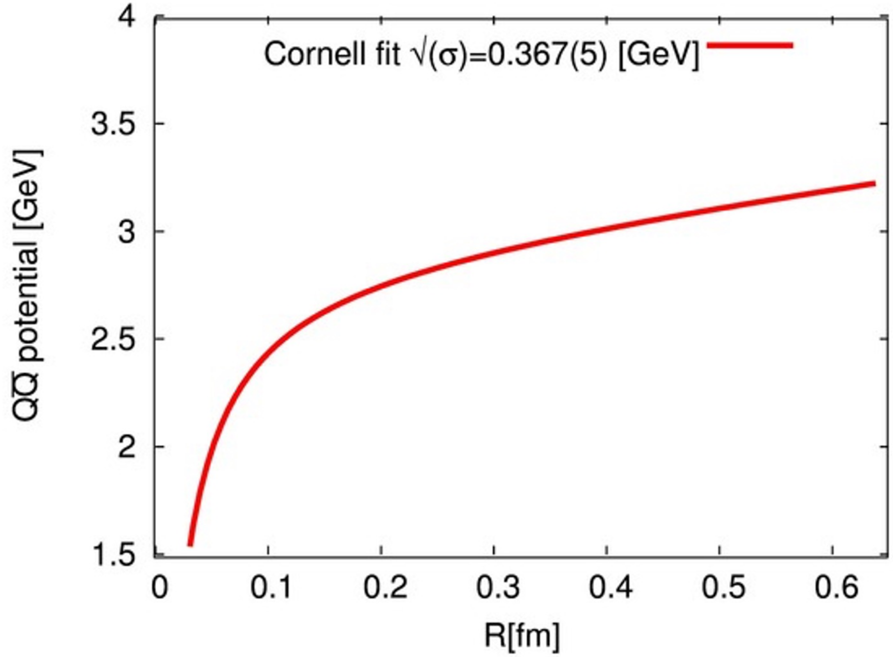
$\Rightarrow R(bb) \sim 0.2$ fm

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

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

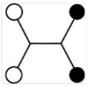
- narrow $cc\bar{u}\bar{d}$ tetraquark discovered by LHCb
- doubly charmed baryon: mass✓, isospin breaking✓

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

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

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

  $\Xi_c\bar{D}^*$: expect $S=\frac{1}{2},\frac{3}{2}$, with $\Delta M \sim 15$ MeV

  $\Sigma_c B^*,\ \Sigma_b\bar{D}^*,\ \Sigma_b B^*,\ D^*B^*,\ \ldots$
- 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 slides

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

} no exp info !

Effective masses

in mesons:
$m_u^m = m_d^m = m_q^m = 310$ MeV, $m_c^m = 1663.3$ MeV

in baryons:
$m_u^b = m_d^b = m_q^b = 363$ MeV, $m_c^b = 1710.5$ MeV

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

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

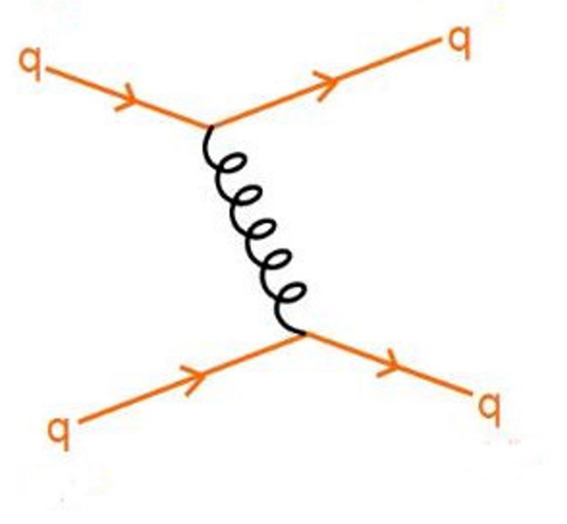
$$V(c\bar{c}) = \bar{M}(c\bar{c}:1S) - 2m_c^m = -258.0 \text{ MeV}.$$

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

in weak coupling follows
from color algebra in 1*g*x

here a *dynamical assumption*:

$V(cc)$ and $V(c\bar{c})$ factorize
into color×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 can the strong QQ interaction stabilize

H_{QQ}: $(QQuudd)$ hexaquarks,

heavy-quark analogue of the H dibaryon?

$\Rightarrow$ below $2\Lambda_Q$

but above $\Xi_{QQ}N$

$\Rightarrow$ unstable

but turned up to be an ugly duckling...

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

- possible mechanism:
- enhanced production of QQq & $QQ\bar{u}\bar{d}$ in AA, from *statistical coalescence*
- unique to quark gluon plasma

PRL **95,** 022301 (2005) PHYSICAL REVIEW LETTERS

Production of Multiply Heavy Flavored Baryons from Quark Gluon Plasma in Relativistic Heavy Ion Collisions

F. Becattini

Università di Firenze and INFN Sezione di Firenze, I-50019 Florence, Italy

(Received 24 March 2005; published 5 July 2005)

It is argued that in heavy ion collisions at the CERN Large Hadron Collider (LHC) there could be a sizable production of baryons containing two or three heavy quarks from statistical coalescence. This production mechanism is peculiar of quark gluon plasma, and the predicted rates, in heavy ion collisions at LHC energies, exceed those from a purely hadronic scenario, particularly for Ξ_{bc} and Ω_{ccc}. Thus, in addition to the interest in the discovery of these new states, enhanced ratios of these baryons over singly heavy flavored hadrons, like B or D, in heavy ion collisions with respect to pp at the same energy, would be a clear indication of kinetic equilibration of heavy quarks in the quark gluon plasma.

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

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

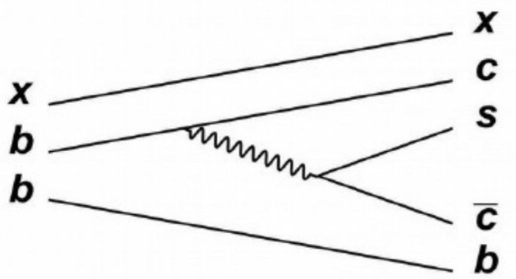
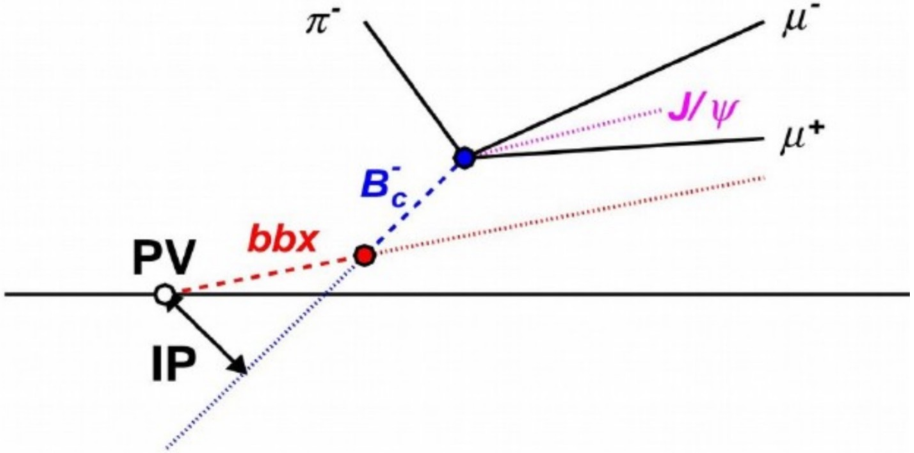


Diagram for production of a B_c^- meson from a double beauty hadron decay.



$\mathcal{O}(1\%)$ 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 $b\bar{d} \to c\bar{u}$

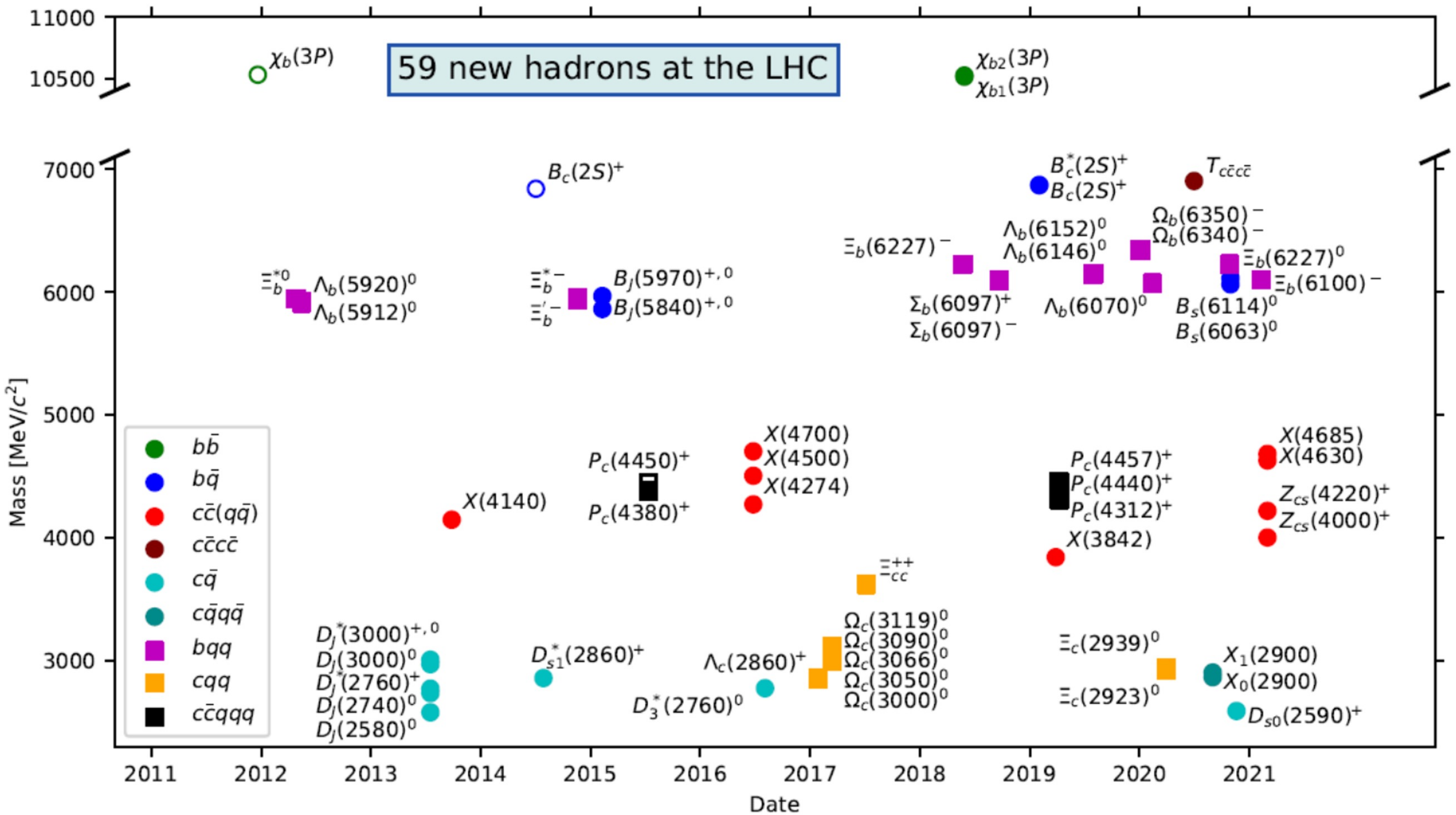
e.g. $(bb\bar{u}\bar{d}) \to D^0 B^-$.

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

- stable, deeply bound $bbu\bar{d}$ 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 $\bar{B}^0 D^0$

  LHCb search in progress
- $(cc\bar{u}\bar{d})$: $J^P = 1^+$, borderline unbound
  3882 ± 12 MeV, 7 MeV above the $D^0 D^{*+}$

  discovered by LHCb just where expected



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)