New Heavy Exotics

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Joint work with Jon Rosner

60 Jubilee — Cracow School of Theoretical Physics — Nov 20, 2020

∃ 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 $\bar{q}q'q''$ 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.

hadrons w. heavy quarks are *much simpler:*

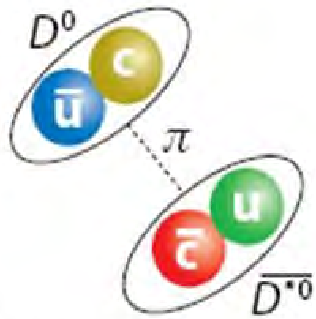
- heavy quarks almost static
- smaller spin-dep. interaction $\propto 1/m_Q$
- key to accurate prediction of b quark baryons

5 narrow exotic states close to meson-meson thresholds

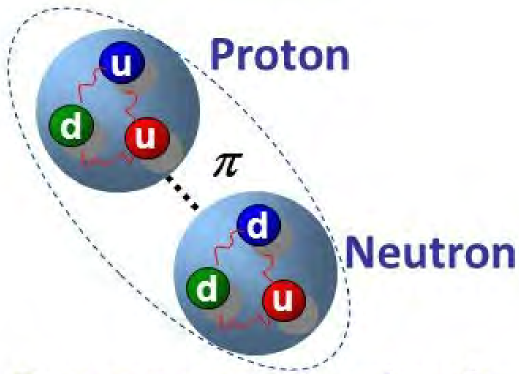
state	mass MeV	width MeV	$\bar{Q}Q$ decay mode	phase space MeV	nearby threshold	ΔE MeV
$X(3872)$	3872	< 1.2	$J/\psi\,\pi^+\pi^-$	495	$\bar{D}D^*$	< 1
$Z_b(10610)$	10608	21	$\Upsilon\pi$	1008	$\bar{B}B^*$	2 ± 2
$Z_b(10650)$	10651	10	$\Upsilon\pi$	1051	$\bar{B}^*B^*$	2 ± 2
$Z_c(3900)$	3900	$24 - 46$	$J/\psi\,\pi$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

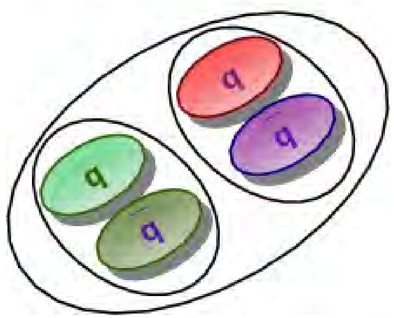


Deuteron: p-n molecule

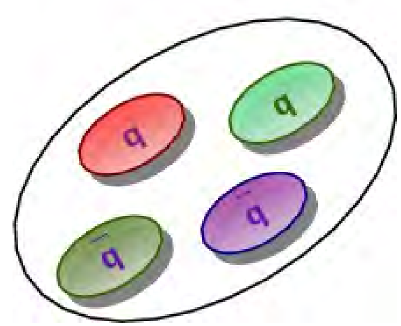
Tetraquarks: same 4 quarks, but tightly bound:

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

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

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

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

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

New Exotic Meson and Baryon Resonances from Doubly Heavy Hadronic Molecules

Marek Karliner[1,*] and Jonathan L. Rosner[2,†]
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[2] *Enrico Fermi Institute and Department of Physics, University of Chicago, 5620 S. Ellis Avenue, Chicago, Illinois 60637, USA*

(Received 13 July 2015; published 14 September 2015)

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

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

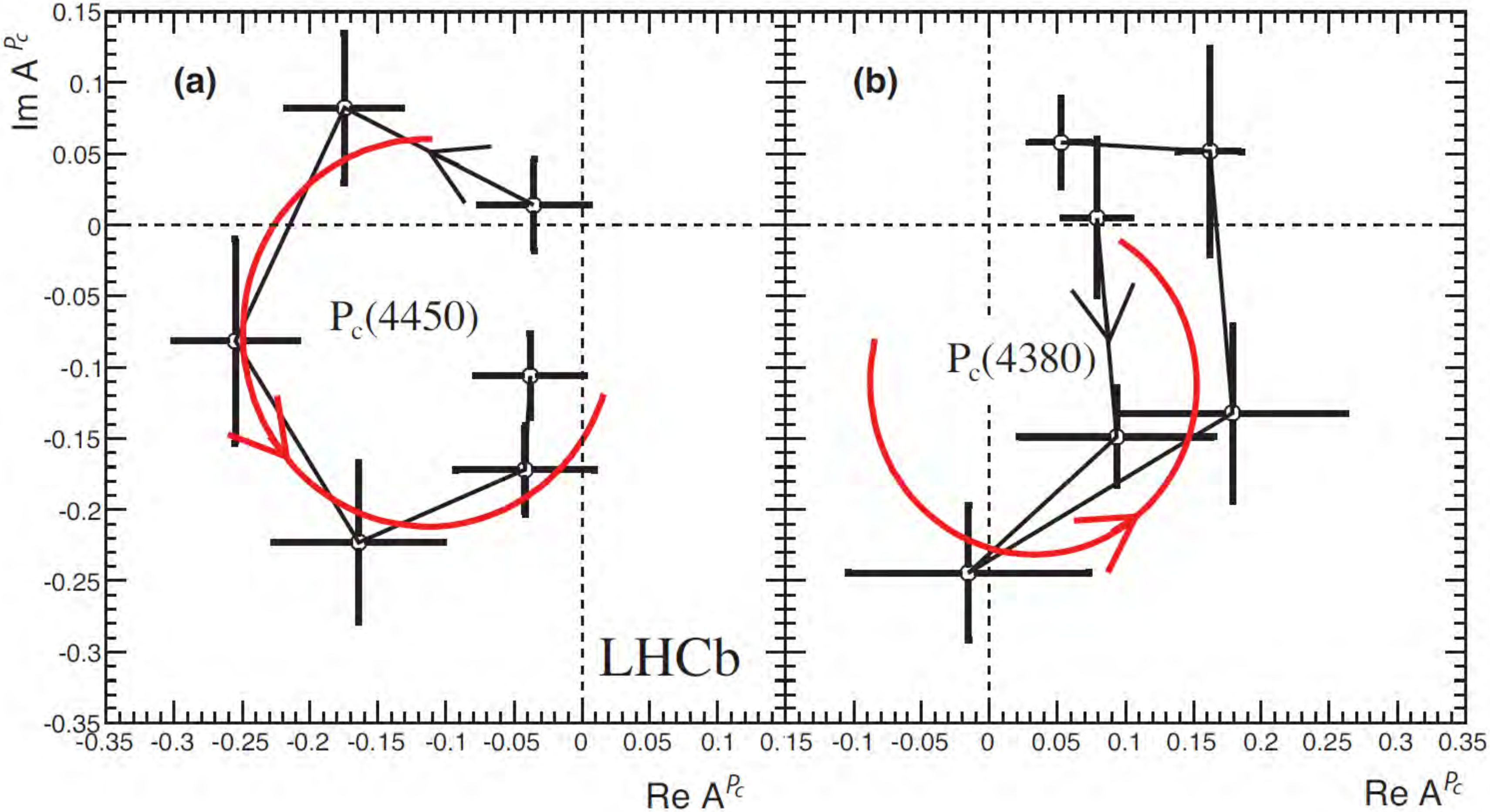
Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

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

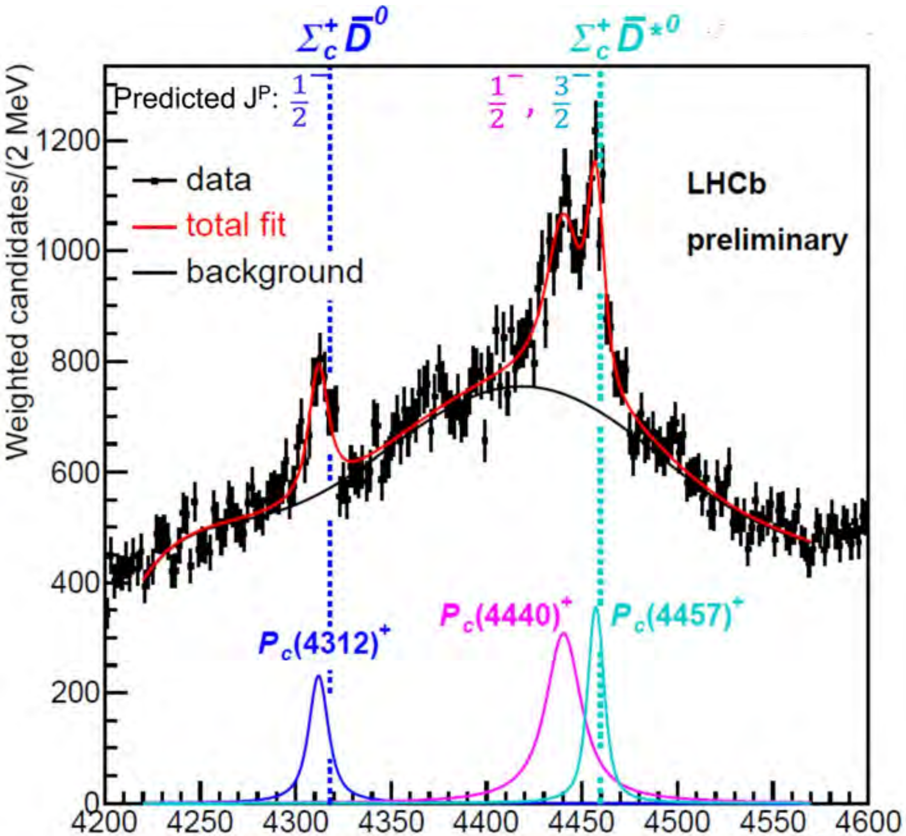


$P_c(4450)$: predicted,
narrow: $\Gamma = 39 \pm 5 \pm 19$,
10 MeV from $\Sigma_c \bar{D}^*$ threshold
perfect Argand plot: a molecule

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

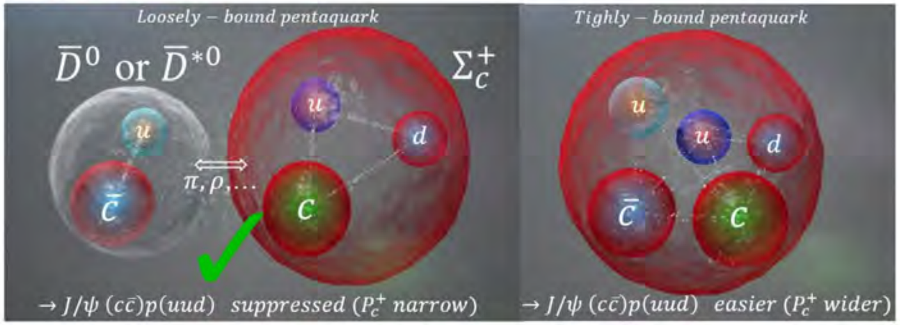
$P_c(4450)$ might be just the first of many "heavy deuterons"

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:

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

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

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...

Very recent news from LHCb

evidence for a new member of the family:

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

$$\Xi_b^- \to J/\psi\,\Lambda\,K^-$$

$\Longrightarrow$ new "molecular" pentaquark:

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

talk by Mengzhen Wang at LHCb workshop, Oct. 29

& LHCb-PAPER-2020-039, in preparation

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

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not an $SU(3)_F$ rotation, as $\Xi_c^0 \sim \Lambda_c$, $[sd]_{S=0}$, not $\sim \Sigma_c$, $(uu)_{S=1}$

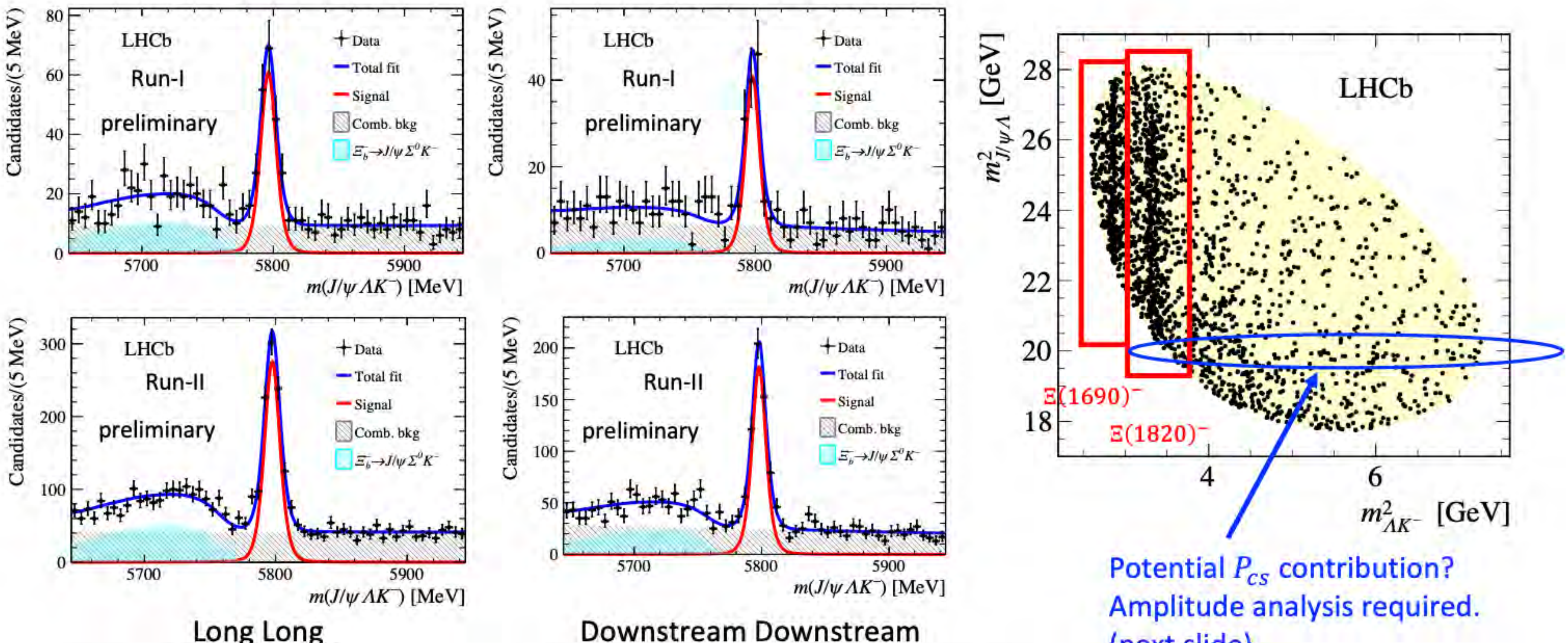
talk by Mengzhen Wang at LHCb workshop, Oct. 29

& LHCb-PAPER-2020-039, in preparation

The $\Xi_b^- \to J/\psi K^- \Lambda$ data sample

PRC93(2016)065203

- Used to search for predicted $[udsc\bar{c}]$ pentaquark P_{cs}
- Run-I + Run-II data: ~1750 signals, purity ~80%



Potential P_{cs} contribution?
Amplitude analysis required.
(next slide)

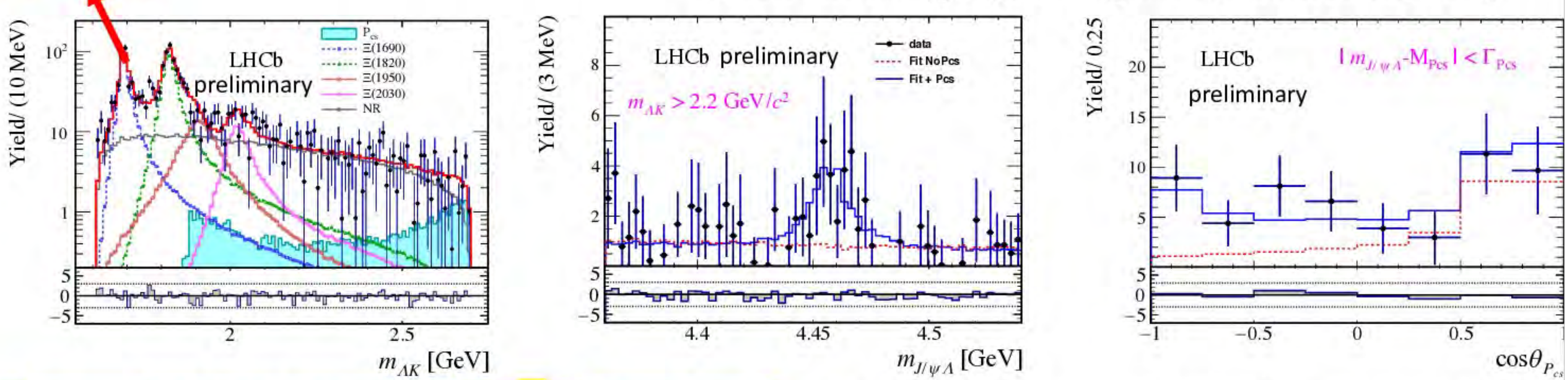
10/29/20 Implications workshop 2020

Full 6D amplitude analysis

- Adding a P_{cs} improves $-2\ln L$ by 43 units, $\sim 4.3\sigma$ significance
  - **3.1σ significance** when syst. uncertainty considered

Two Ξ^{*-} states

Zooms in to P_{cs} signal region for better visibility



P_{cs} mass 19MeV below the $\Xi_c^0\overline{D}^{*0}$ threshold. Statistic not enough for J^P determination.

State	M_0 [MeV]	Γ[MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$

Consistent with PDG, with improved precision

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

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

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

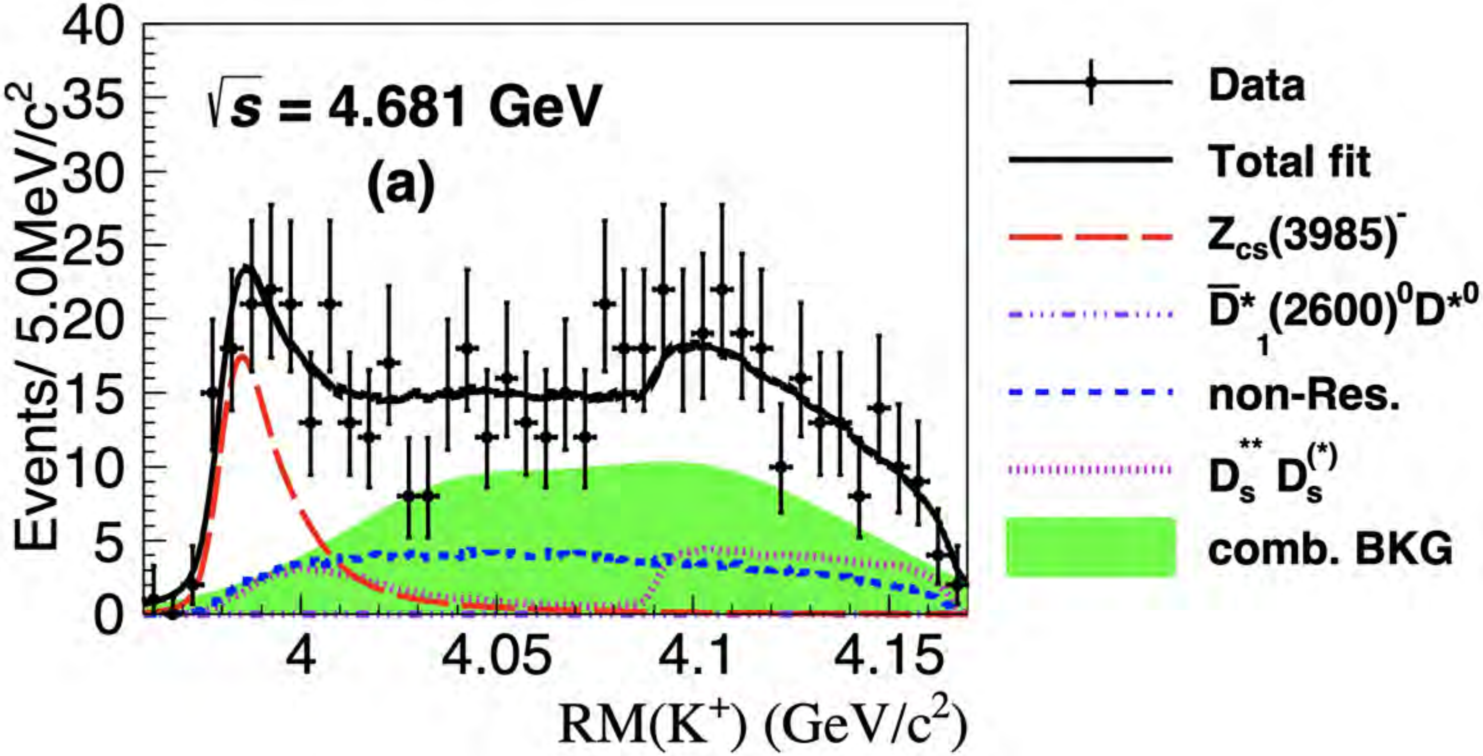
$\Xi_c\bar{D}^*$, $\Xi_c B^*$, $\Xi_b\bar{D}^*$, $\Xi_b B^*$

like a whole new periodic table

very new

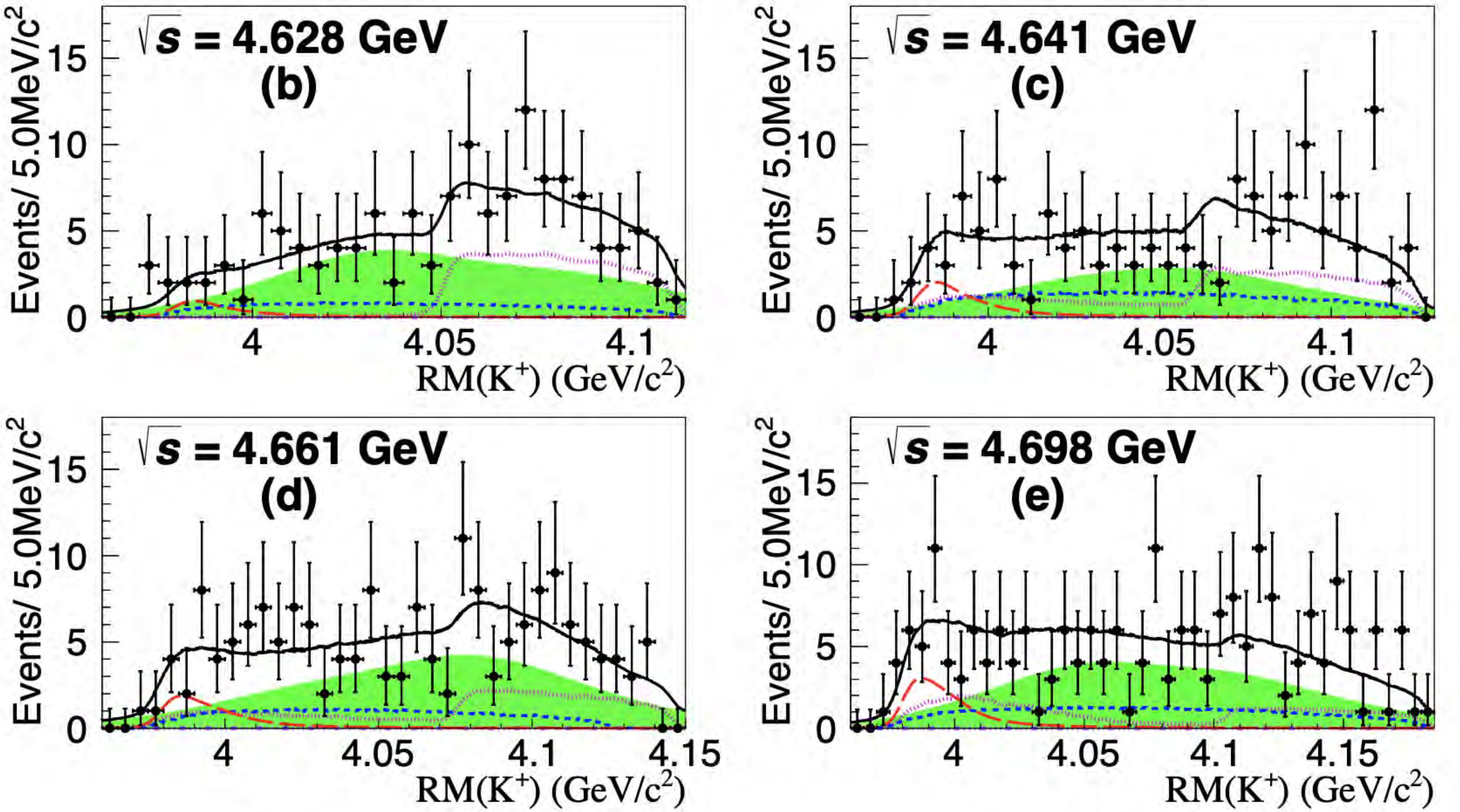
BESIII: 5.3 σ near-threshold structure in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

2011.07855
16 Nov 2020



Simultaneous unbinned maximum likelihood fit to the K^+ recoil-mass spectra in data at $\sqrt{s}$= 4.681 GeV.

significant s dependence: signal strongest at $\sqrt{s} = 4.681$ GeV. ???



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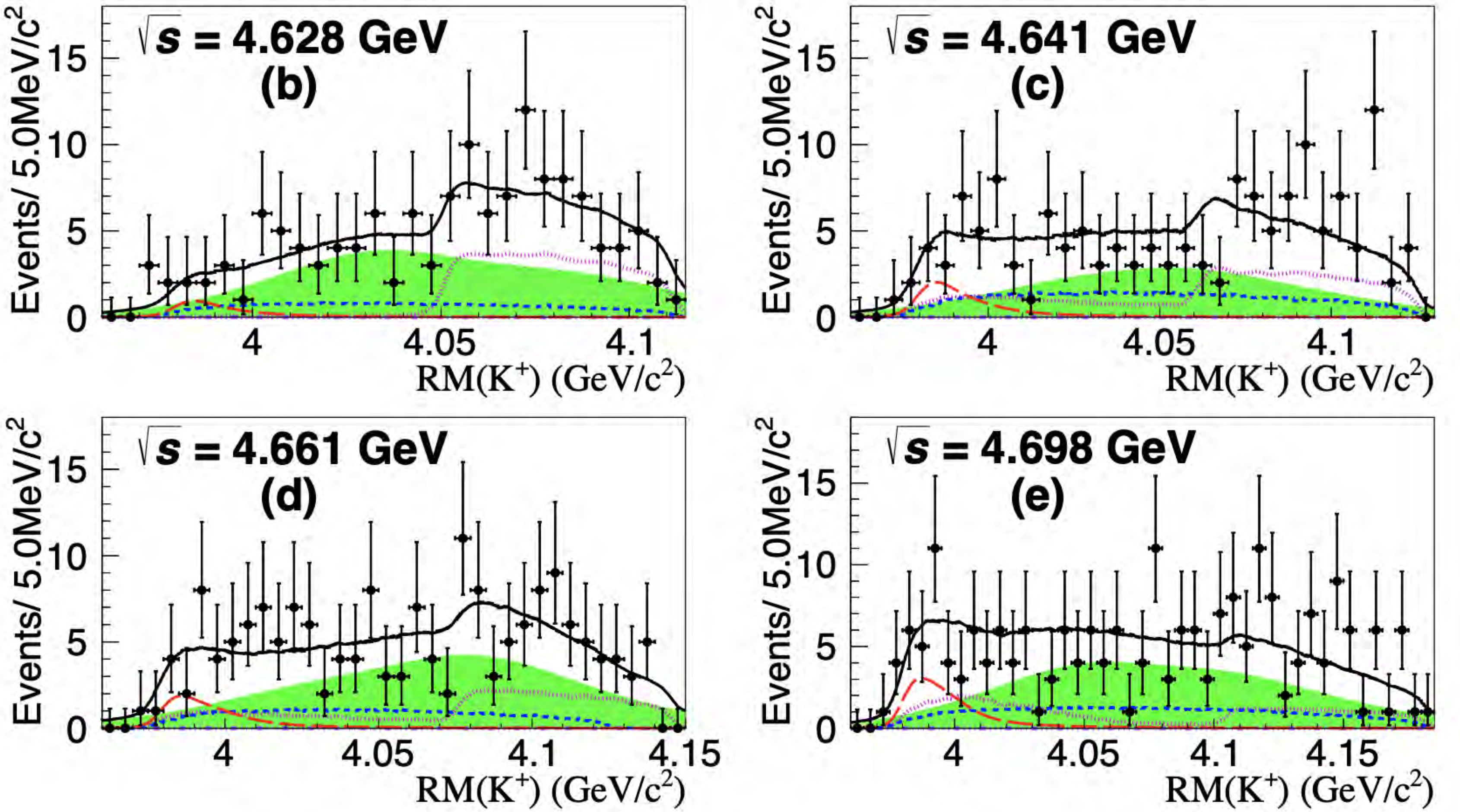


? $e^+e^- \to D_s^{*-} D_{s2}^*(2573)^+ \to D_s^{*-}(D^0 K^+)$

$D_s^{*-} D_{s2}^*(2573)^+$ thresh. $= 4.681$ GeV

but BESIII did not see $D_s^{*-} D_{s2}^*(2573)^+$ at 4.681 GeV

$(D_s^- D^{*0} + D_s^{*-} D^0) = (c\bar{c}s\bar{u}) \equiv Z_{cs}(3985) \rightarrow J/\psi\, K^-$?

$M = 3982.5^{+1.8}_{-2.6} \pm 2.1$ MeV, $\Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0$ MeV

vs. thresholds: $D_s^- D^{*0} + 7$ MeV, $D_s^{*-} D^0 + 5$ MeV

vicinity of thresholds $\overset{?}{\Longrightarrow}$ molecule, then $J^P = 1^+$

but what binding mechanism, as no π exchange ???

cf.

$(D^- D^{*0} + D^{*-} D^0) = (c\bar{c}d\bar{u}) \equiv Z_c(3900) \rightarrow J/\psi\, \pi^-$

cf. LHCb Dalitz plot in $B_s \to J/\psi\, K^+ K^-$

JHEP 1708 (2017) 037, arXiv:1704.08217

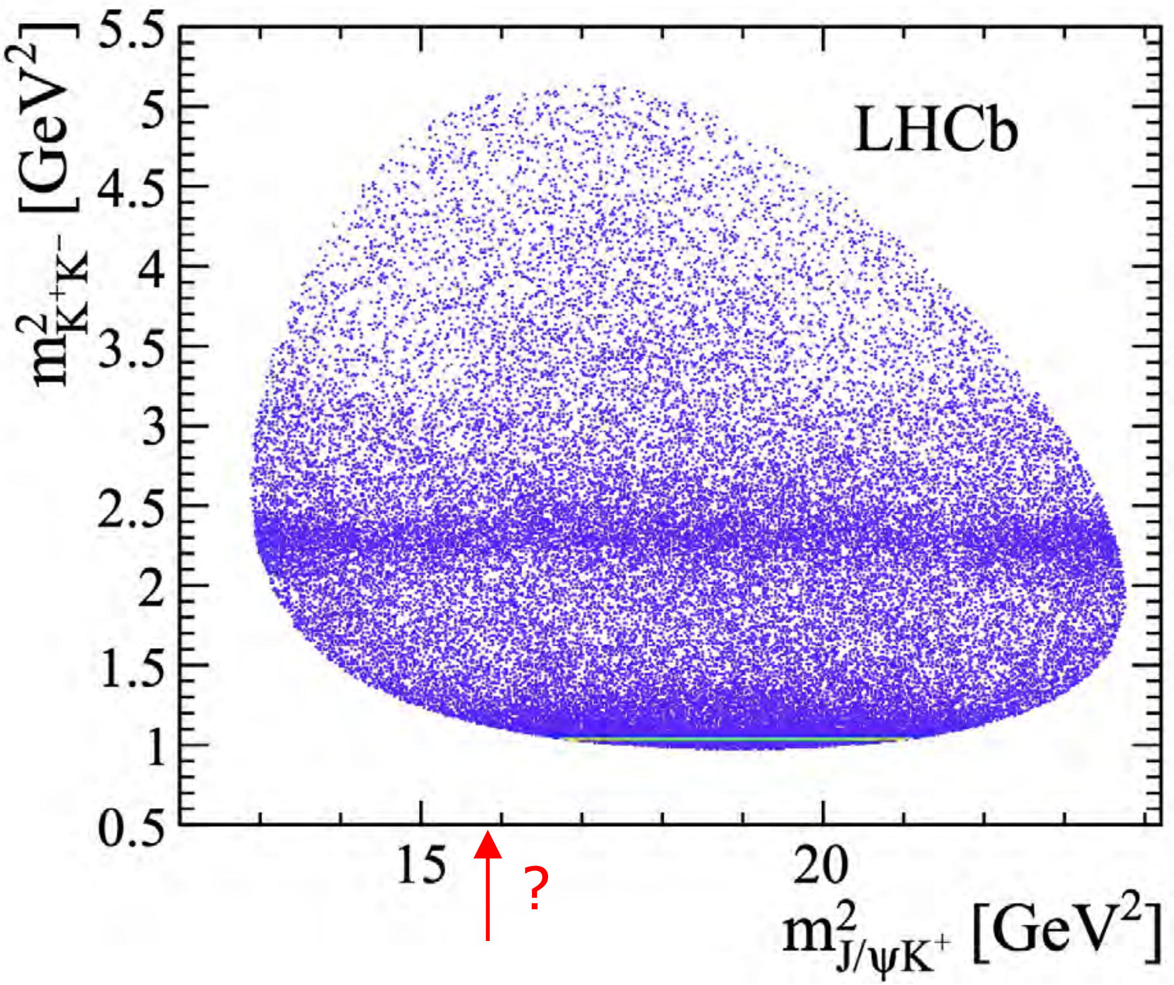
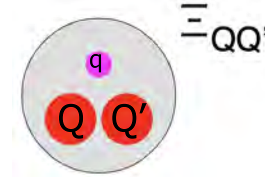


Figure 3: Invariant mass squared of K^+K^- versus $J/\psi\, K^+$ for $B^0_s \to J/\psi\, K^+ K^-$ candidates within ± 15 MeV of the B^0_s mass peak. The high intensity $\phi(1020)$ resonance band is shown with a line (light green).

doubly heavy baryons: mass predictions



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 ± 1 PRL 119,112001, (2017) The same theoretical toolbox

that led to the accurate Ξ_{cc} mass prediction

now predicts

a stable, deeply bound $bb\bar{u}\bar{d}$ tetraquark,

215 MeV below BB^* threshold

the first manifestly exotic stable hadron

Editors' Suggestion

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

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

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(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.

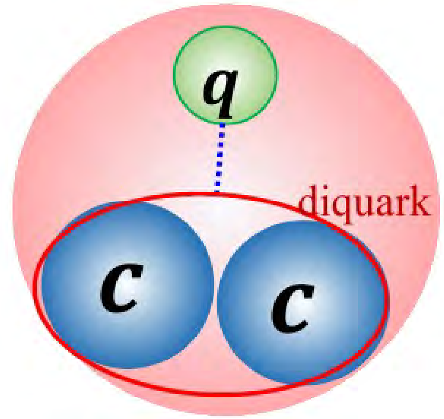
DOI: 10.1103/PhysRevLett.119.202001

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

build on accuracy of the Ξ_{cc} mass prediction

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

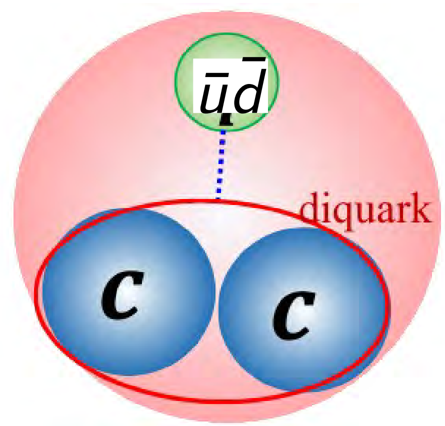
bbq baryon



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:

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

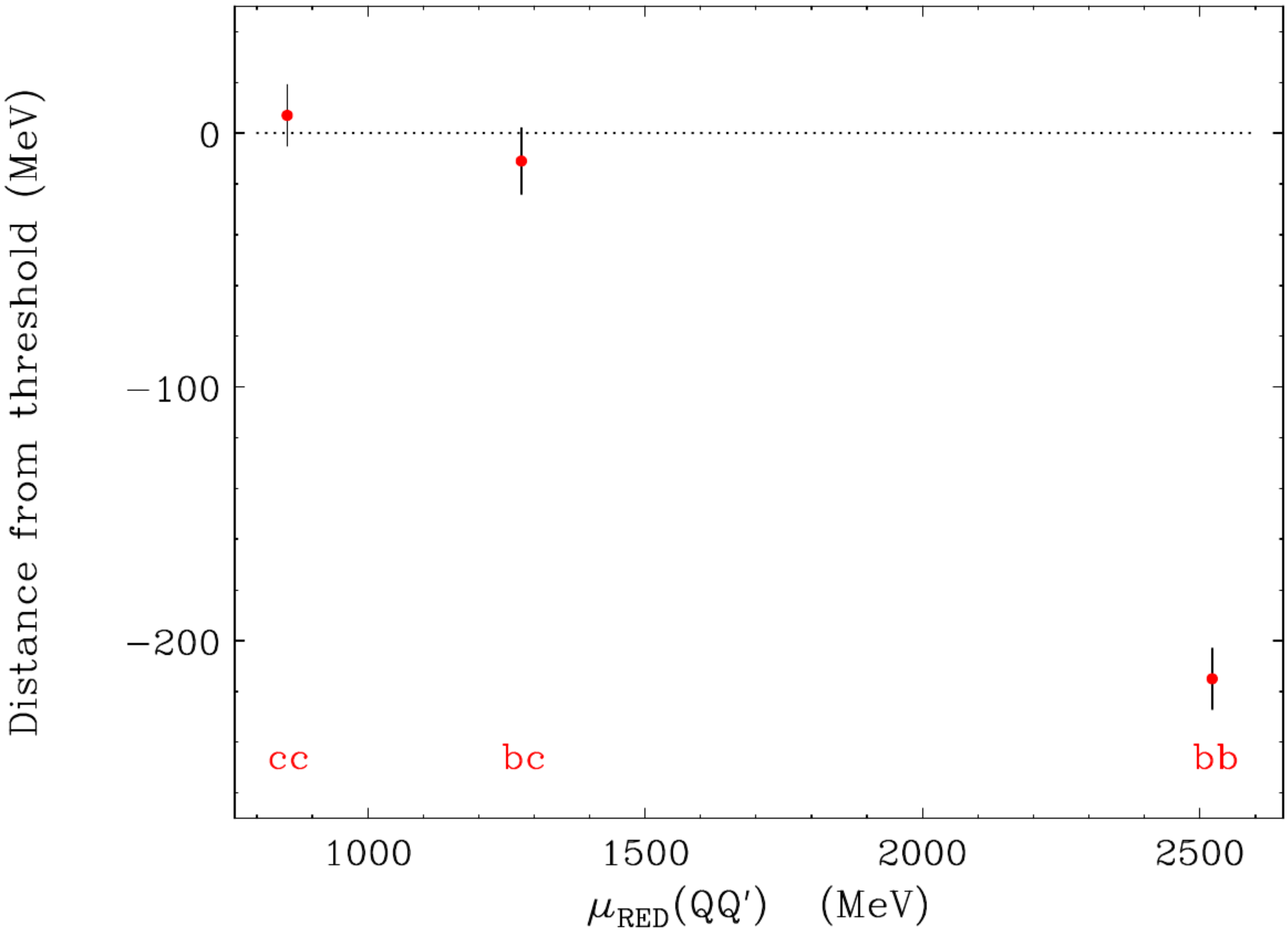
Ξ_{cc} discovery $\Rightarrow$ quantitative validation

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

so for $M_Q \rightarrow \infty$

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

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:

$$\left.\begin{array}{l} \{bb\} \to \{bb\}q \\ \{bb\} \to \{bb\}\bar{u}\bar{d} \end{array}\right\} \quad \begin{array}{cc} P(\bar{u}\bar{d}) \lesssim & P(q) \\ \mathbf{3}_c & \mathbf{3}_c \end{array}$$

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

$$\sigma(pp \to \Xi_{bb} + X) = (b/c)^2 \cdot \sigma(pp \to \Xi_{cc} + X)$$

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

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

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.

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

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

recent news from LHCb, 08/2020:

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

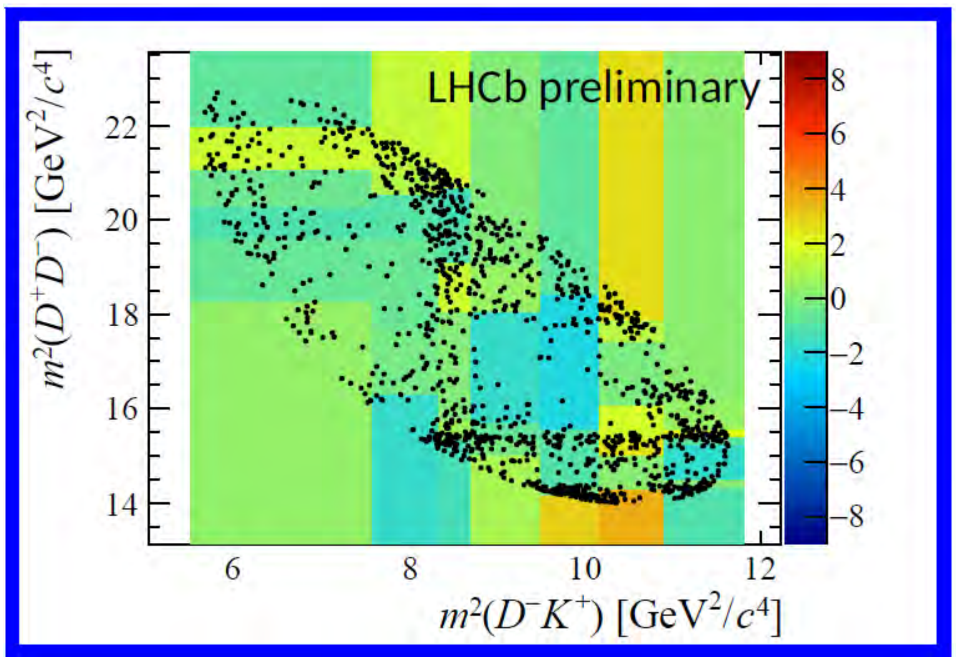
first exotic hadron with open heavy flavor:

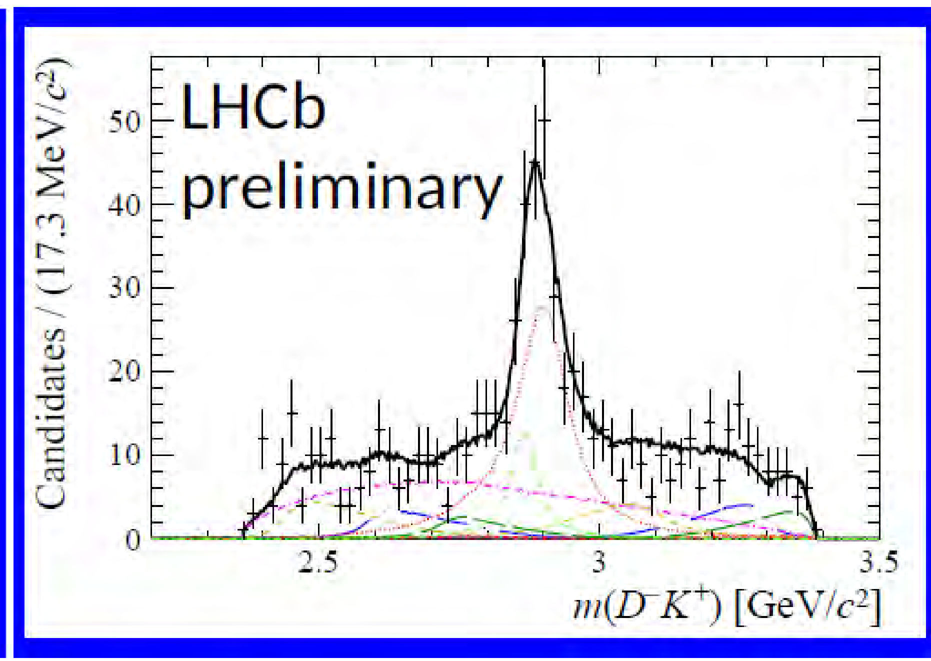
$cs\bar{u}\bar{d}$ tetraquark

$cc\bar{u}\bar{d}$: 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 $\Gamma_1 = 110 \pm 12$ 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**

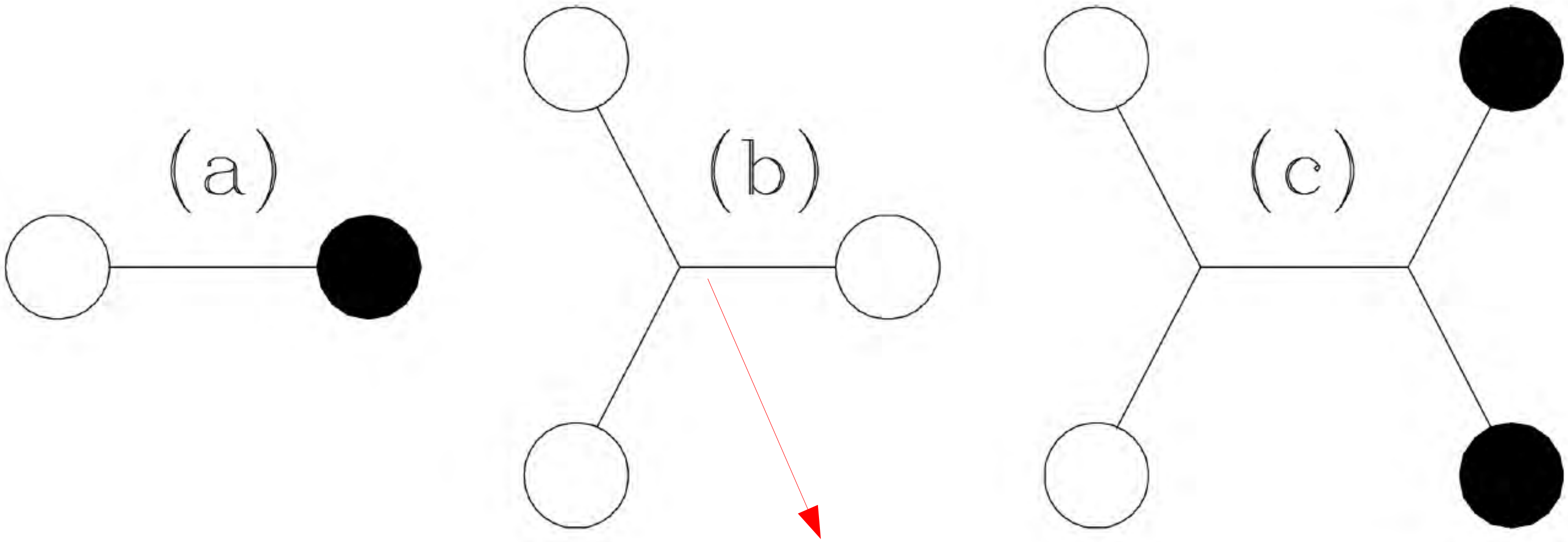
- analogous $bs\bar{u}\bar{d}$ Tq predicted at 6213±12 MeV

- $X_1(2900)$: ?
  currently $J^P = 1^-$ preferred, but if $J^P = 2^+$,
  possibly a D^*K^* molecule, c.f. threshold at 2902 MeV

meson
no string junction

baryon
one string junction

tetraquark
two string junctions



string junction mass: $S = 165.1$ MeV

FIG. 1: QCD strings connecting quarks (open circles) and antiquarks (filled circles). (a) Quark-antiquark meson with one string and no junctions; (b) Three-quark baryon with three strings and one junction; (c) Baryonium (tetraquark) with five strings and two junctions.

- bottom analogue:

  $M[Tq(bs\bar{u}\bar{d})] = 6213 \pm 12$ MeV

  cf. $B^* K^*$ threshold at 6216 MeV
- 440 MeV above BK threshold
- should be seen in

  $T(bs\bar{u}\bar{d}) \to \bar{B}^0 K^-$

  and

  $T(bs\bar{u}\bar{d}) \to B^- \bar{K}^0$.
- 1-st mode is preferable, as no s vs. $\bar{s}$ $\bar{K}^0$ ambiguity.
- observe in LHCb & other LHC experiments?

The predictions for masses of the $bb\bar{u}d$, $cc\bar{u}d$, and $bc\bar{u}d$ masses are shifted upward in the string-junction picture by 126, 118, and 122 MeV, respectively. The $bb\bar{u}\bar{d}$ state is still stable with respect to strong and EM interactions, as its mass is predicted to lie 89 MeV below threshold for strong decay and 44 MeV below that for radiative decay, while the $cc\bar{u}\bar{d}$ and $bc\bar{u}\bar{d}$ masses lie well above strong decay thresholds.

- $\Xi_{cc}^{++} = (ccu)$ observed by LHCb
- expect similar x-section for Tq$(cc\bar{u}\bar{d})$
- see Tq$(cc\bar{u}\bar{d})$ with current $\int\mathcal{L}dt$?
- Tq$(cc\bar{u}\bar{d}) \rightarrow D^0 D^{*+}$

  and

  Tq$(cc\bar{u}\bar{d}) \rightarrow D^+ D^{*0}$
- measured mass will then tell us if string-junction picture applies to this state as well

recent news from LHCb, June 2020:

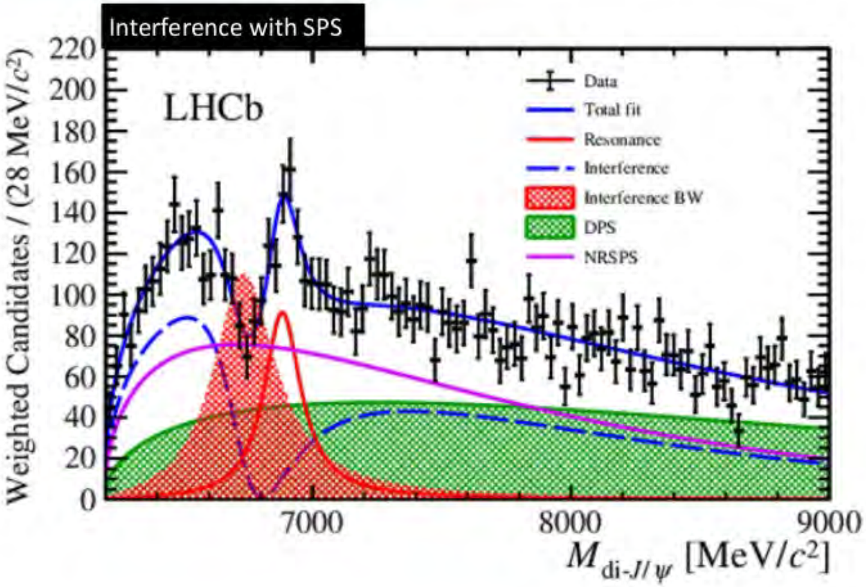
- a narrow resonance decaying into two J/ψ-s
- quark content $cc\bar{c}\bar{c}$
- $M \approx 6.9$ GeV: $X(6900)$
- tetraquark-like
- ~ 700 MeV above $J/\psi\, J/\psi$ threshold

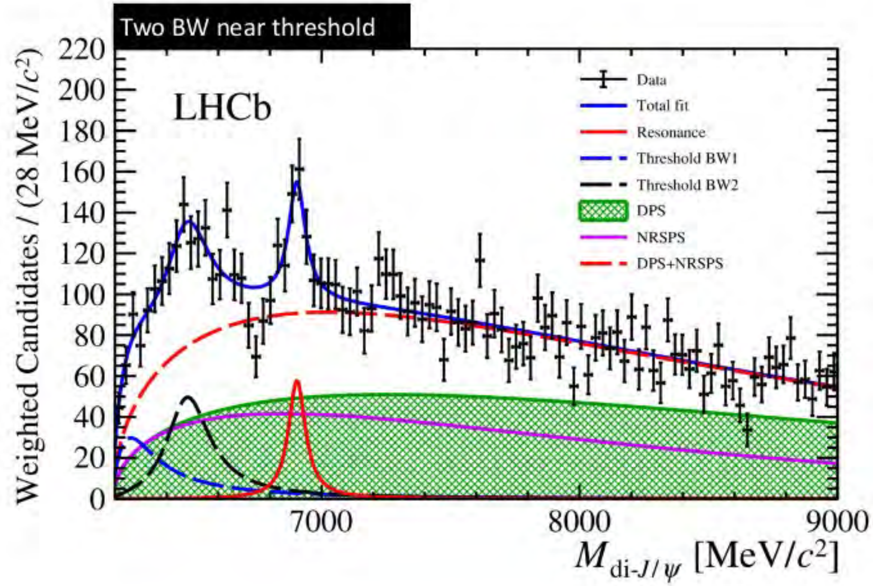
  $\Rightarrow$ probably an excited $cc\bar{c}\bar{c}$ state
- first exotic containing both QQ *and* $\bar{Q}Q$
- exciting challenge for EXP and TH

Interpretation

arXiv:2006.16957

LHCb – talk by Daniel Johnson





- $T_{c\bar{c}c\bar{c}}$ state at $6.9\ \mathrm{GeV}/c^2$ and either:
  - one more (interfering with NRSPS), or
  - two more, near threshold
- Feed-down may contribute; unlikely for narrow state
- Near-threshold rescattering could be important

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

- 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

Fit with coherent sum of 3 BW-s + background

M_i, Γ_i, W_i, C_1, $\eta_{2,3}$, ϕ_i: 12 params + 3 params for bkgr $\longrightarrow$ 15 params

We assume the di$-J/\psi$ spectrum is due to a smooth background with proper threshold behavior:

$$B(M_{\rm inv}) = -C_2 q \exp[(2M(J/\psi) - M_{\rm inv})({\rm GeV})C_3] \ , \quad q \equiv (M_{\rm inv}^2/4 - [M(J/\psi)]^2)^{1/2} \ , \qquad (3)$$

of which an amplitude fraction α is added coherently to the sum of three Breit-Wigner resonances each of the form

$$\begin{aligned} A_i &= N_i/D_i \ , \quad N_i = C_1 e^{i\phi_i} \eta_i M_{\rm inv} \Gamma_i \ , \\ D_i &= M_i^2 - M_{\rm inv}^2 - i M_{\rm inv} \Gamma_i \ , \quad (i = 1, 2, 3) \ , \end{aligned} \qquad (4)$$

where M_i and Γ_i are the mass and width of the ith resonance. The best fit is obtained for $\alpha = 1$, consistent with the assumption in Model II of Ref. [3]. We set $\eta_1 \equiv 1$ and absorb normalization of resonance 1 into the constant C_1. The constants C_2 and C_3 parametrize background normalization and shape, respectively. The observed number of events per 28 MeV bin is then

$$N(M_{\rm inv}) = |T(M_{\rm inv})|^2 \ , \quad T \equiv B + \sum_1^3 A_i \ . \qquad (5)$$

The numerical data $N \pm dN$ are those in Fig. 3(a) of Ref. [3], restricted to the range $6200 \leq M_{\rm inv} \leq 7488$ MeV (our choice of upper bound; the data are quoted up to 8000 MeV). We minimize $\chi^2 \equiv \sum_j \{[N_j({\rm fit}) - N_j({\rm data})]/dN_j\}^2$, the sum over 46 28-MeV-wide bins centered on from 6214 to 7474 MeV.

Some parameters are not well determined by the χ^2 criterion, and must be regarded as only representative values. To illustrate this, we present in Table V the best fits for $\alpha = 0.7156$ (a local χ^2 minimum with $\chi^2 = 25.86787$ for 32 d.o.f.) and $\alpha = 0$ (giving the largest global χ^2 minimum, $\chi^2 = 26.19538$, for any fixed value of α between 0 and 1.

Table I: Parameters in best fit to data (see Appendix for definitions) with $\chi^2 = 25.855$ for 31 degrees of freedom (d.o.f.). Masses M_i and widths Γ_i are in MeV. Constants C_i describe signal normalization, background normalization, and background shape, respectively. Parameters η_i ($\eta_1 \equiv 1$) and ϕ_i (in degrees) describe normalizations and phases of i-th Breit-Wigner amplitudes.

Peak i	i=1	i=2	i=3
M_i	6377.1	6808.6	7208.1
Γ_i	277.3	138.0	82.96
C_i	5.057	25.74	1.184
η_i	1.000[a]	1.445	0.7754
ϕ_i	−26.62	−34.78	−4.995
α	1.000	Coherence factor	

[a]input

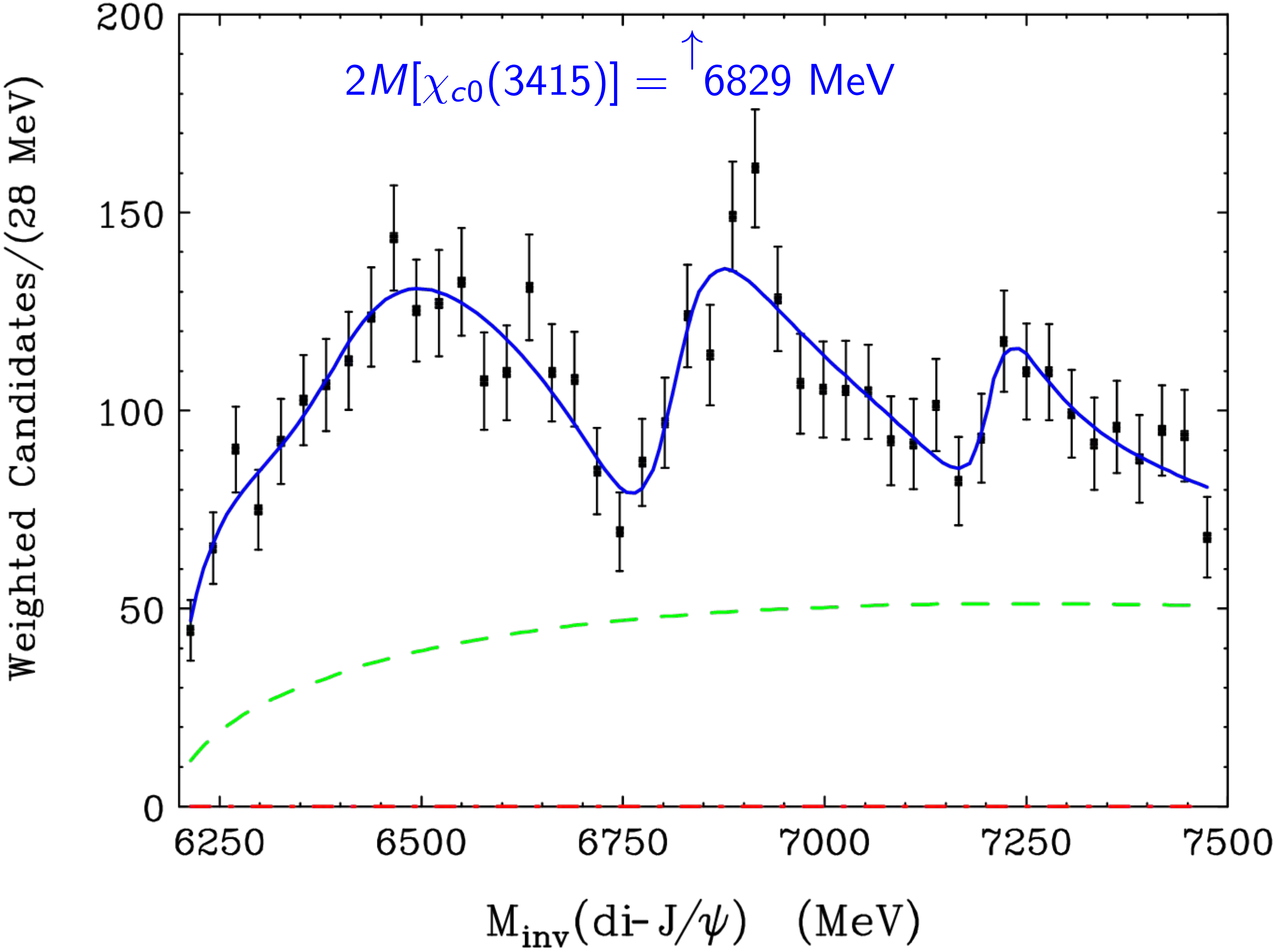


Figure 1: Spectrum of J/ψ pairs reported by the LHCb Experiment [3], together with our best fit to data (blue line), as given in Table I and described in the Appendix. The green dashed line denotes the DPS contribution, subtracted before fitting.

tetraquark interpretation of peak near 6.9 GeV

- GS of $T(cc\bar{c}\bar{c})$ from string junction picture:
  $(cc)_{3_c^*}(\bar{c}\bar{c})_{3_c}$: two spin-1 diquarks coupled in S-wave to
  $0^{++}(1S)$, $M = 6191.5 \pm 25$ MeV
  just below $2J/\psi$ at 6194 MeV and above $2\eta_c$ at 5968 MeV
- $2^{++}(1S)$ at 6429 ± 25 MeV
- $0^{++}(2S)$ at 6871 ± 25 MeV
- $2^{++}(2S)$ at 6967 ± 25 MeV
- peak around 7200 in the right place for $3S$ of $(cc)_{3_c^*}(\bar{c}\bar{c})_{3_c}$
- $\Xi_{cc}\bar{\Xi}_{cc}$ threshold at 7242 MeV: very natural – lightest state created when $(cc)_{3_c^*}(\bar{c}\bar{c})_{3_c}$ string breaks via $\bar{q}q$ production

$(cc)_{3_c^*}(\bar{c}\bar{c})_{3_c}$

Table IV: Predicted masses of lowest-lying bound states of a color-antitriplet spin-1 cc diquark and a color-triplet spin-1 $\bar{c}\bar{c}$ antidiquark. The $\chi_{c0}\chi_{c0}$ threshold is 6829 MeV.

	$M(1S)$ (MeV)	$M(2S)$ (MeV)
$J^{PC} = 0^{++}$	6192	6871
$J^{PC} = 2^{++}$	6429	6967

$(bb)_{3_b^*}(\bar{b}\bar{b})_{3_c}$

Table V: Predicted masses of lowest-lying bound states of a color-antitriplet spin-1 bb diquark and a color-triplet spin-1 $\bar{b}\bar{b}$ antidiquark. The $\chi_{b0}\chi_{b0}$ threshold is 19719 MeV.

$\Upsilon(1S)\Upsilon(1S)$ threshold is 18920 MeV

$\Xi_{bb}\bar{\Xi}_{bb}$ threshold is at 20324 MeV

	$M(1S)$ (MeV)	$M(2S)$ (MeV)
$J^{PC} = 0^{++}$	18826	19434
$J^{PC} = 2^{++}$	18956	19481

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

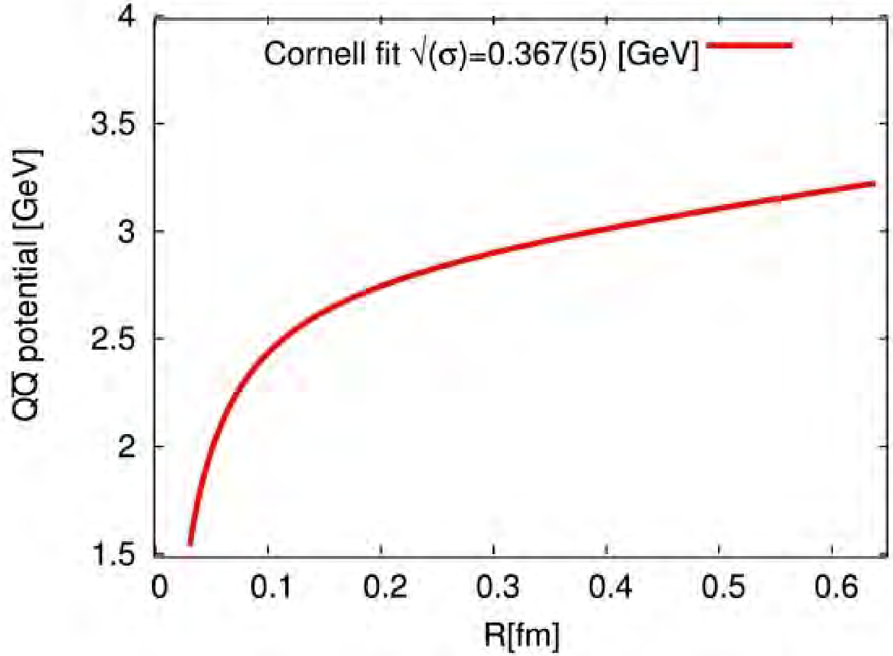
$\Rightarrow R(bb) \sim 0.2$ fm

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

$\Rightarrow B(bb) \approx -280$ 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 $r(\Upsilon)/r(\bar{B}B^*) \ll 1$

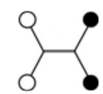
very different!

Upshot:

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

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

SUMMARY

- narrow exotics with $Q\bar{Q}$: "heavy deuterons" / molecules
  $\bar{D}D^*$, $\bar{D}^*D^*$, $\bar{B}B^*$, $\bar{B}^*B^*$,
  $\Sigma_c D^*(S=\frac{1}{2},\frac{3}{2})$, $\Sigma_c \bar{D}(S=\frac{1}{2})$; $\gamma p \to J/\psi\, p$?
  very new: $\Xi_c \bar{D}^*$; expect $S=\frac{1}{2},\frac{3}{2}$, $\Delta m \sim \mathcal{O}(15)$ MeV
  $\Sigma_c B^*$, $\Sigma_b \bar{D}^*$, $\Sigma_b B^*$, $D^* B^*$, ...
- doubly charmed baryon found exactly where predicted
  $\Xi_{cc}^{++}(ccu) \Rightarrow (bcq)$, (bbq)
- stable $bb\bar{u}\bar{d}$ tetraquark: LHCb !
- narrow $cc\bar{u}\bar{d}$ tetraquark: accessible at LHCb already now?
- 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 $2S$, $J/\psi\, \Upsilon$, $\Upsilon\Upsilon$?

exciting new spectroscopy awaiting discovery