New Heavy Exotics

Marek Karliner
Tel Aviv University
Joint work with Jon Rosner

Future charm-tau factory workshop, Nov 16, 2020

∃ 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 $\bar{q}q'q''$ baryons, e.g. $\bar{Q}Qqq'q''$

two key questions:

- which additional exotics should we expect?

- how are quarks organized inside them?

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^*, $\bar{B}B^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$, $\Sigma_c B^*$, $\Sigma_b\bar{D}^*$, $\Sigma_b B^*$, $\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, 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*

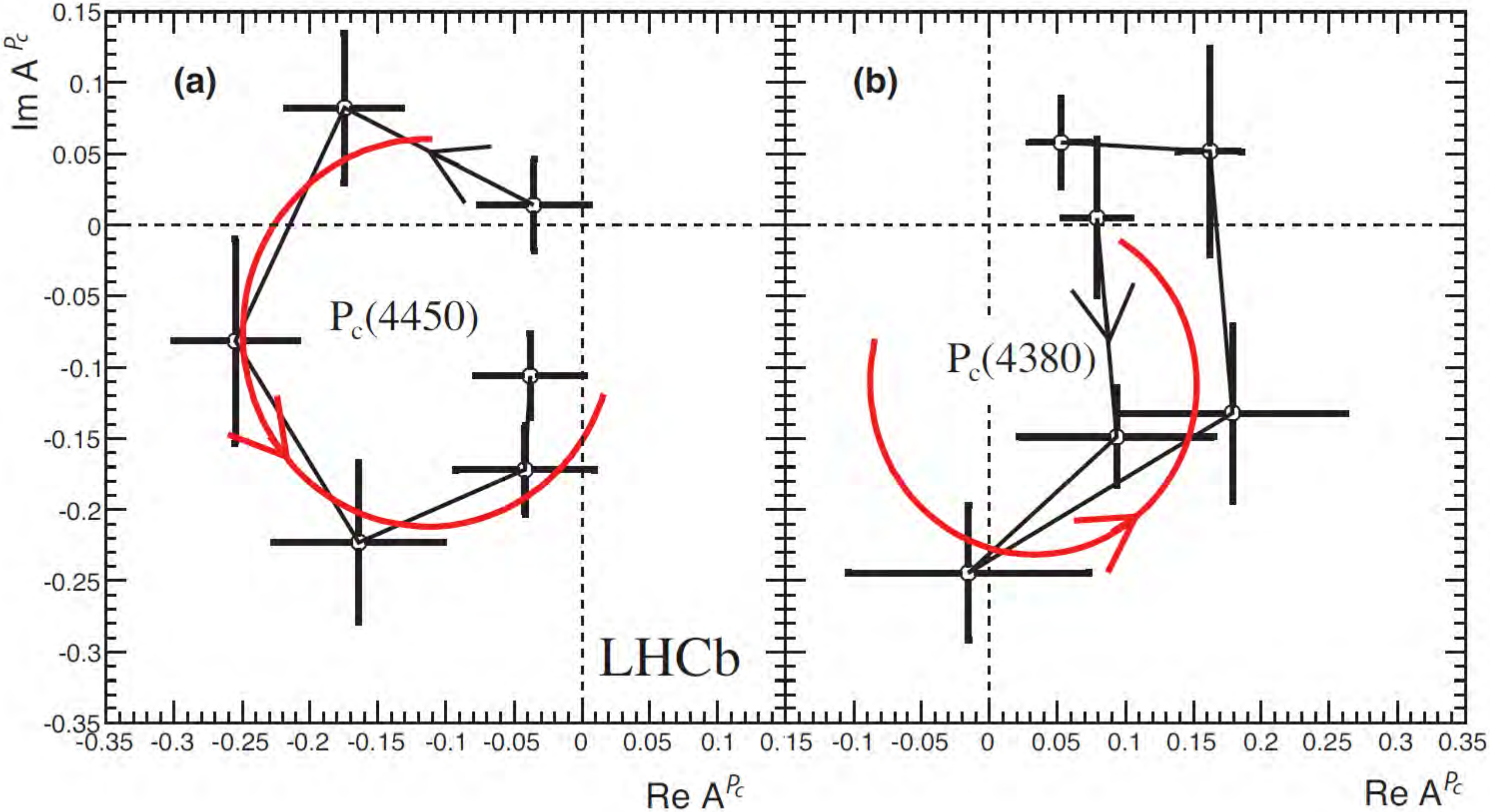
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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

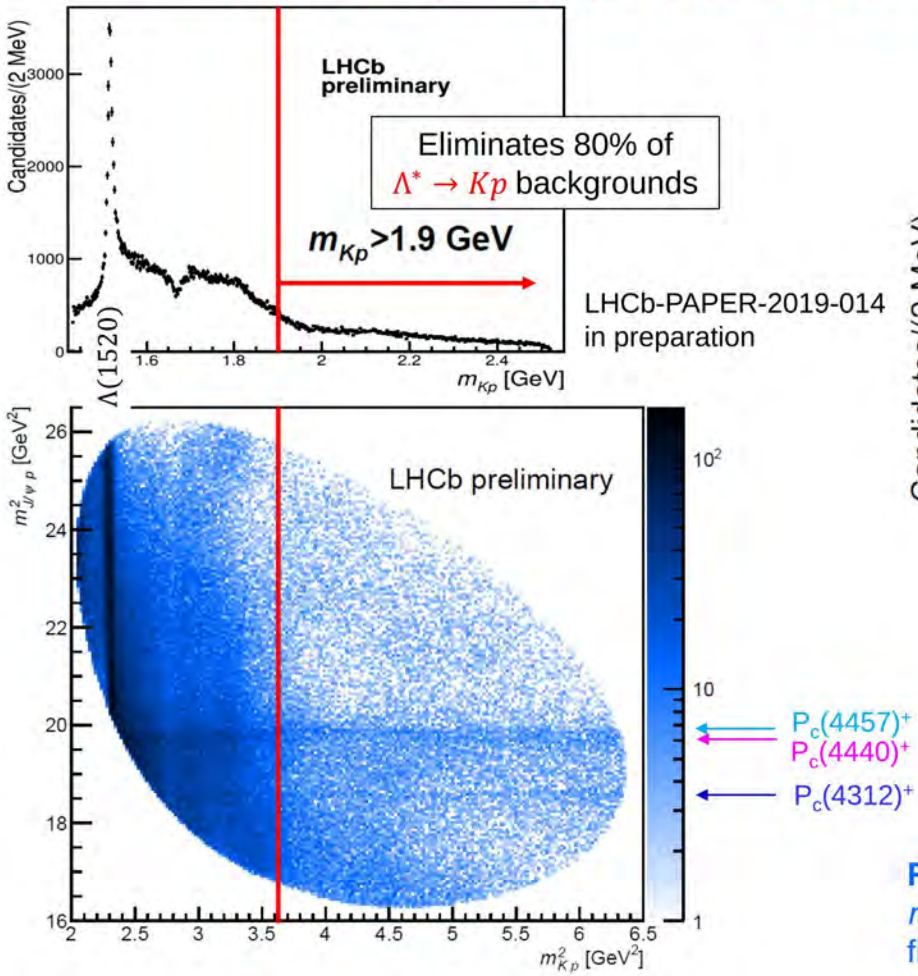
$P_c(4380)$: not predicted,
wide: $\Gamma = 205 \pm 18 \pm 86$ MeV,
Argand plot not resonance-like
???

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

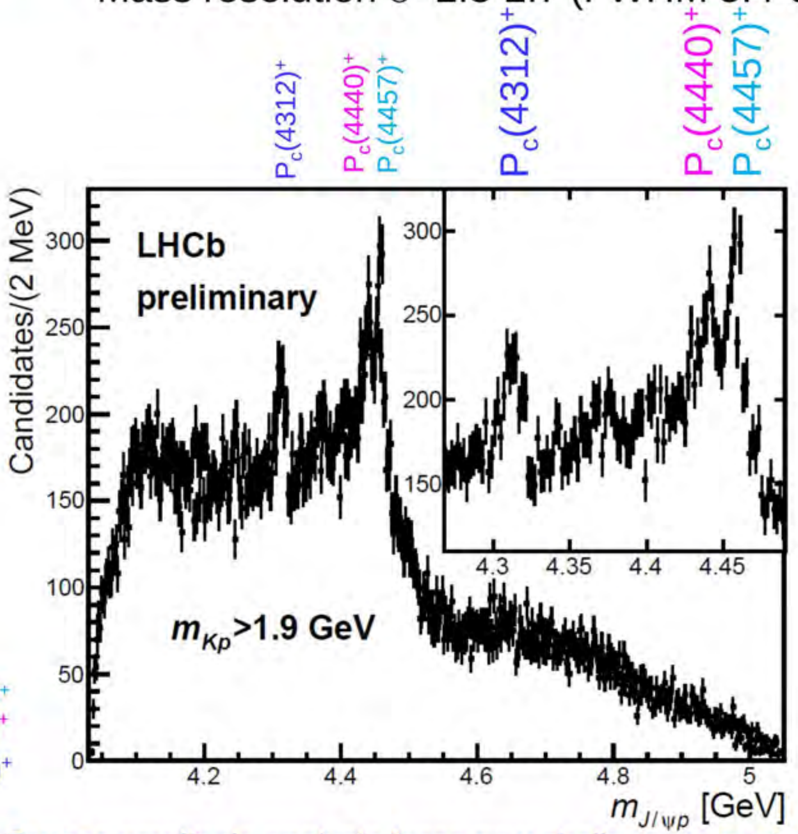
as of 2015

Narrow $P_c^+ \to J/\psi p$ peaks with Λ^* suppression

Mass resolution σ=2.3-2.7 (FWHM 5.4-6.4) MeV



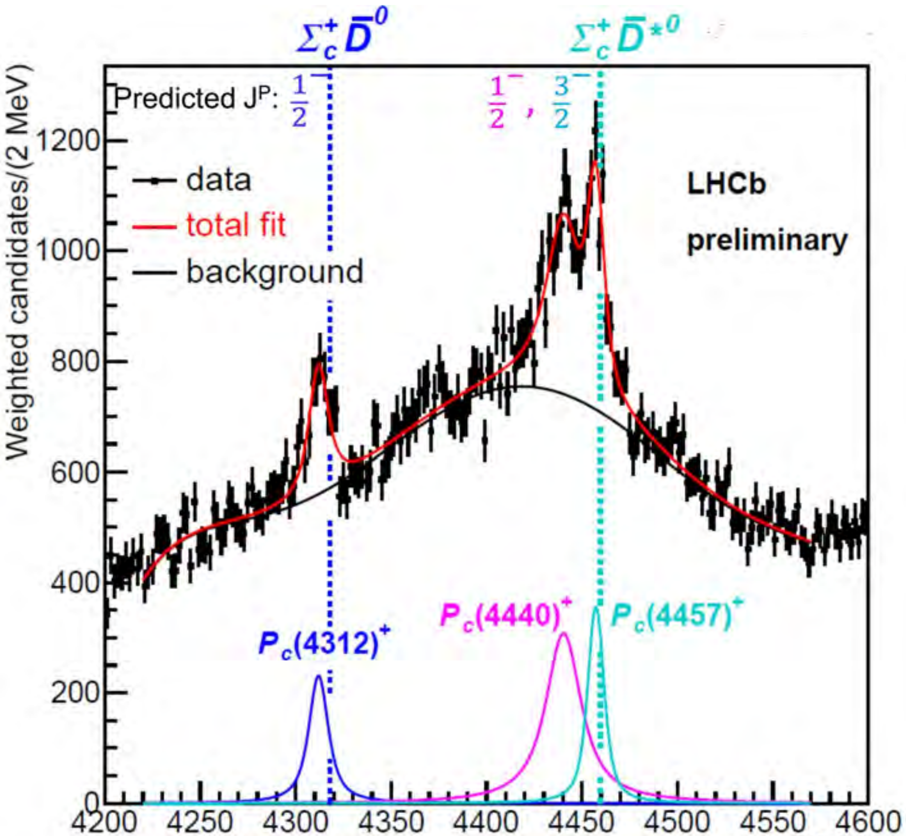
LHCb-PAPER-2019-014
in preparation



Proper amplitude analysis faces new challenges: must consider $m_{J/\psi p}$ resolution effects, large statistics and sub-percent precision in fit fractions required in the amplitude model – work in progress

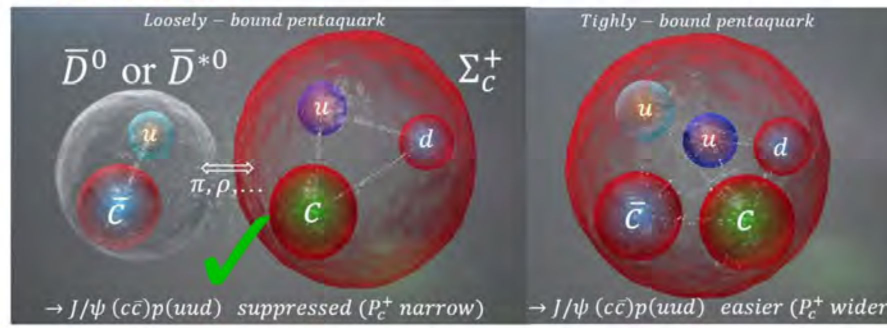
State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

as of 2019



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

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:

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

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

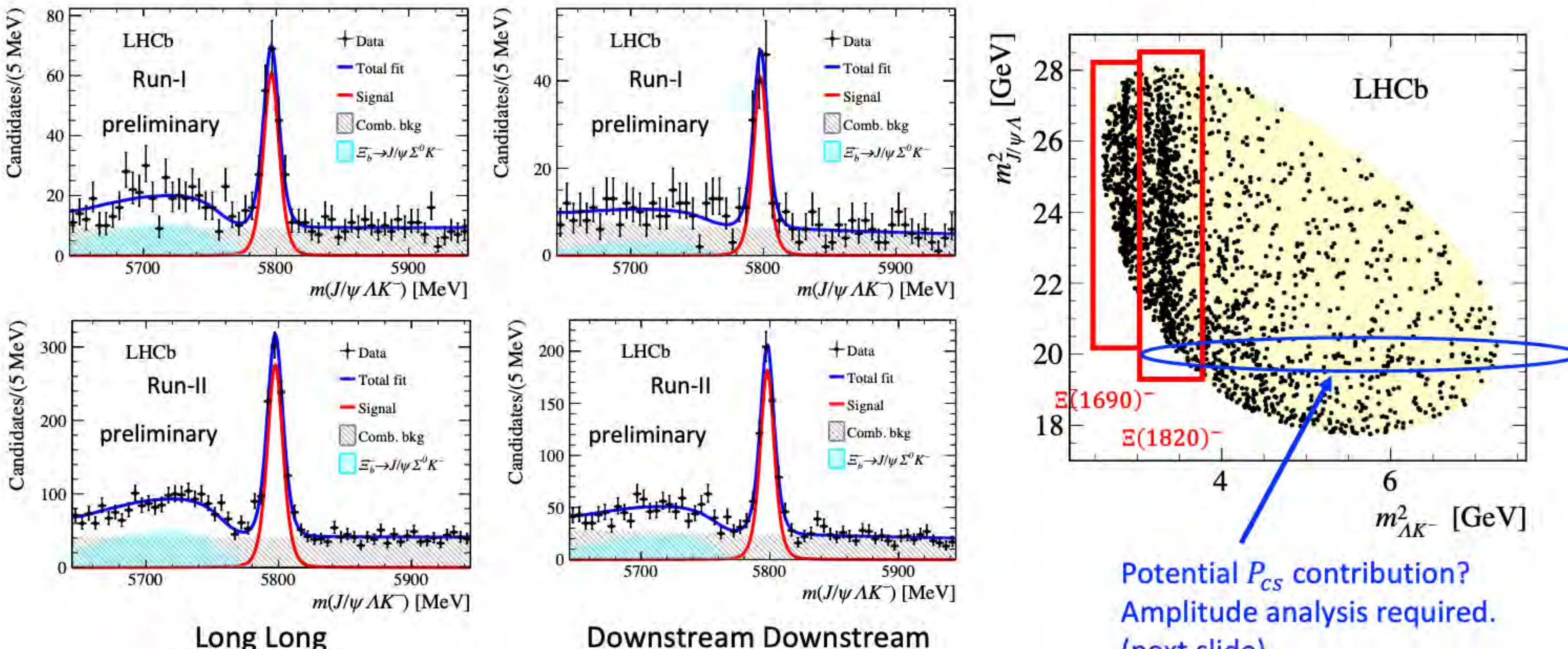
talk by Mengzhen Wang at LHCb workshop, Oct. 29

& 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)

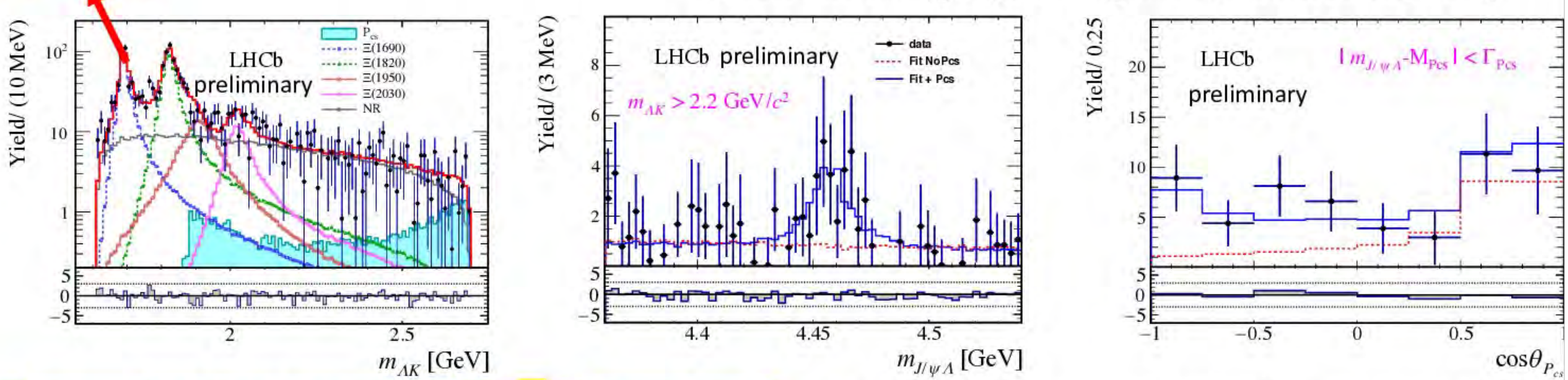
10/29/20 Implications workshop 2020

Full 6D amplitude analysis

- Adding a P_{cs} improves $-2\ln L$ by 43 units, ~4.3σ 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 $\Xi_c^0\bar{D}^{*0}$ 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 $Q\bar{Q}'$, $Q = c, b$, $\bar{Q}' = \bar{c}, \bar{b}$:

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

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

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

like a whole new periodic table

Open Questions

- LHCb: new narrow states slightly below $\Sigma_c \bar{D}(\bar{D}^*)$ thresholds; highly suggestive of molecules

Several interesting issues:

- Additional 4 $\Sigma_c^* \bar{D}(\bar{D}^*)$ states ?
- Decay into $\Lambda_c \bar{D}$?
- So far no signal in $\gamma p \to J/\psi p$ photoproduction
- If $P_c(4312)$ $\Sigma_c \bar{D}$ molecule, why no $D\bar{D}$ molecule?
- $X(3872) \ll 1$ MeV from $\bar{D}D^*$ threshold
  Z_b-s ~ 2 MeV from $\bar{B}B^*$, $\bar{B}^*B^*$
  deuteron 2.2 MeV below pn
  so why are P_c-s $5 \div 22$ MeV below $\Sigma_c \bar{D}(\bar{D}^*)$?
- $P_c(4440)$ and $P_c(4457)$: likely $\Sigma_c \bar{D}^*$, $S = \frac{1}{2}, \frac{3}{2}$
  17 MeV spin splitting $\gg$ deuteron (S=1) vs. pn S=0
- lattice ?

What binds $\Sigma_c \bar{D}$ but not $D\bar{D}$?

- 2π exchange in $D\bar{D}$: $D \to D^* \to D$, $\bar{D} \to \bar{D}^* \to \bar{D}$

$\Longrightarrow 2^*\,(m(D^*) - m(D)) =$ 282 MeV energy denominator

in $\Sigma_c D$, $\Sigma_c \to \Lambda_c$: -167 MeV, $\bar{D} \to \bar{D}^*$: $+141$ MeV

$\Sigma_c \bar{D} \to \Lambda_c \bar{D}^*$: -25 MeV energy denominator

- Σ_c: $I = 1$ vs. D: $I = \frac{1}{2}$

$\Longrightarrow$ Σ_c has stronger coupling to light hadrons

- $M_{\rm reduced}(\Sigma_c \bar{D})$=1060 MeV $>$ $M_{\rm reduced}(D\bar{D})$=932 MeV

$\Longrightarrow$ repulsive kinetic energy 12% smaller

not clear if this is the whole story

alternative: *"$D\bar{D}$ does exist, but hard to see"* (Voloshin)

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 $D^0 D^{*+}$ threshold and 148 MeV above the $D^0 D^+ \gamma$ threshold. $T(bc\bar{u}\bar{d})$ with $J^P = 0^+$ is predicted at 7134 ± 13 MeV, 11 MeV below the $\bar{B}^0 D^0$ 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

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

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

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

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

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

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

$T(bb\bar{u}\bar{d})$ 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^{*+}

recent news from LHCb, 08/2020:

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

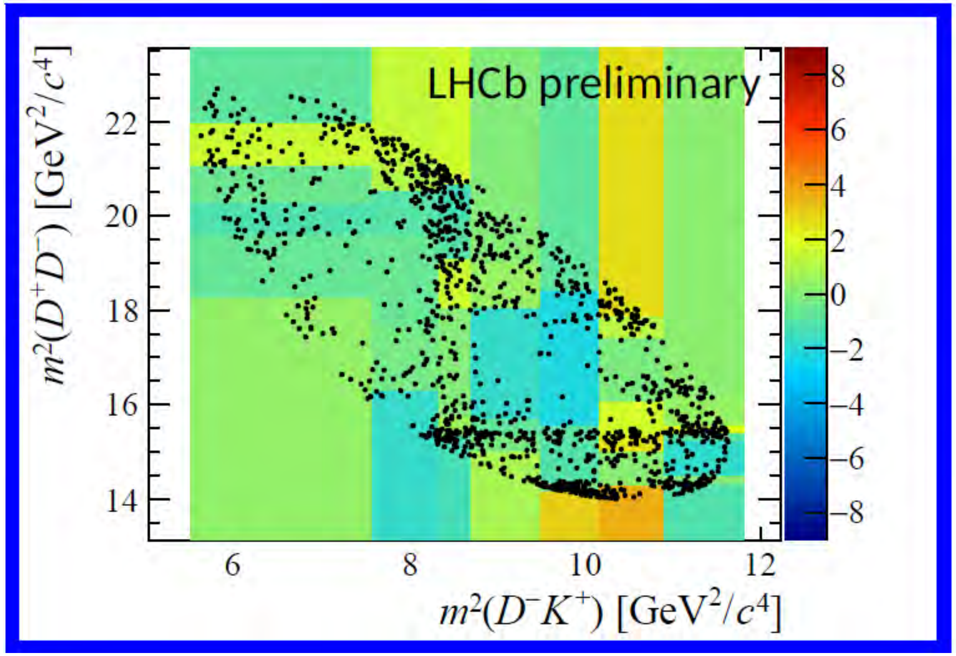
first exotic hadron with open heavy flavor:

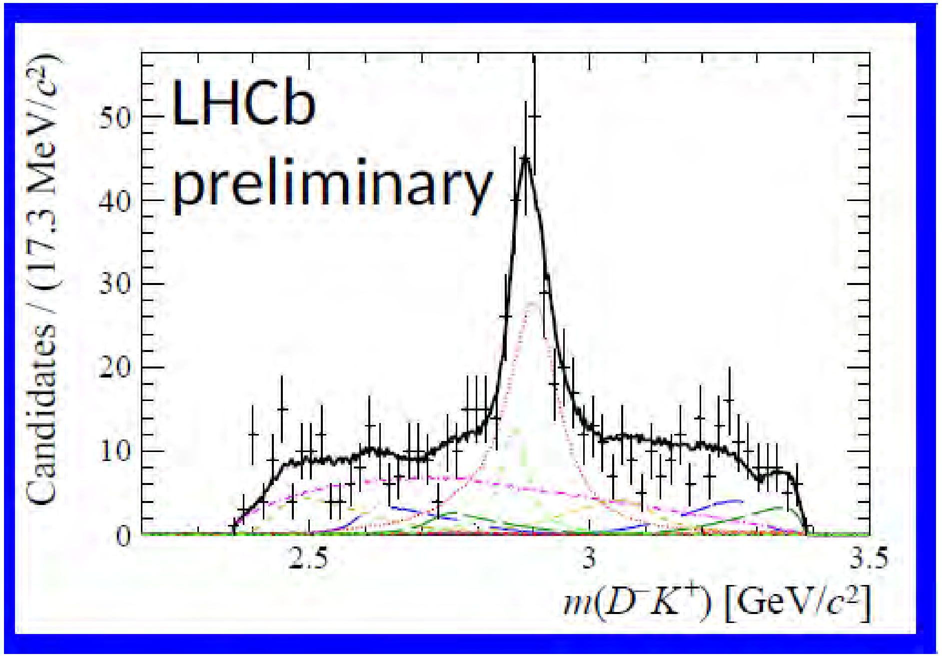
$cs\bar{u}\bar{d}$ tetraquark

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

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

2009.00025 & 2009.00026





- two BW-s:
  $X_0(2900)$, $J^P = 0^+$ at 2866$\pm$7 MeV, $\Gamma_0 =$ 57$\pm$13 MeV
  $X_1(2900)$, $J^P = 1^-$ at 2904$\pm$7 MeV $\Gamma_1 =$ 110$\pm$12 MeV.
- our interpretation:
  $X_0(2900) = cs\bar{u}\bar{d}$ isosinglet compact tetraquark,
  mass = 2863$\pm$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$\pm$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

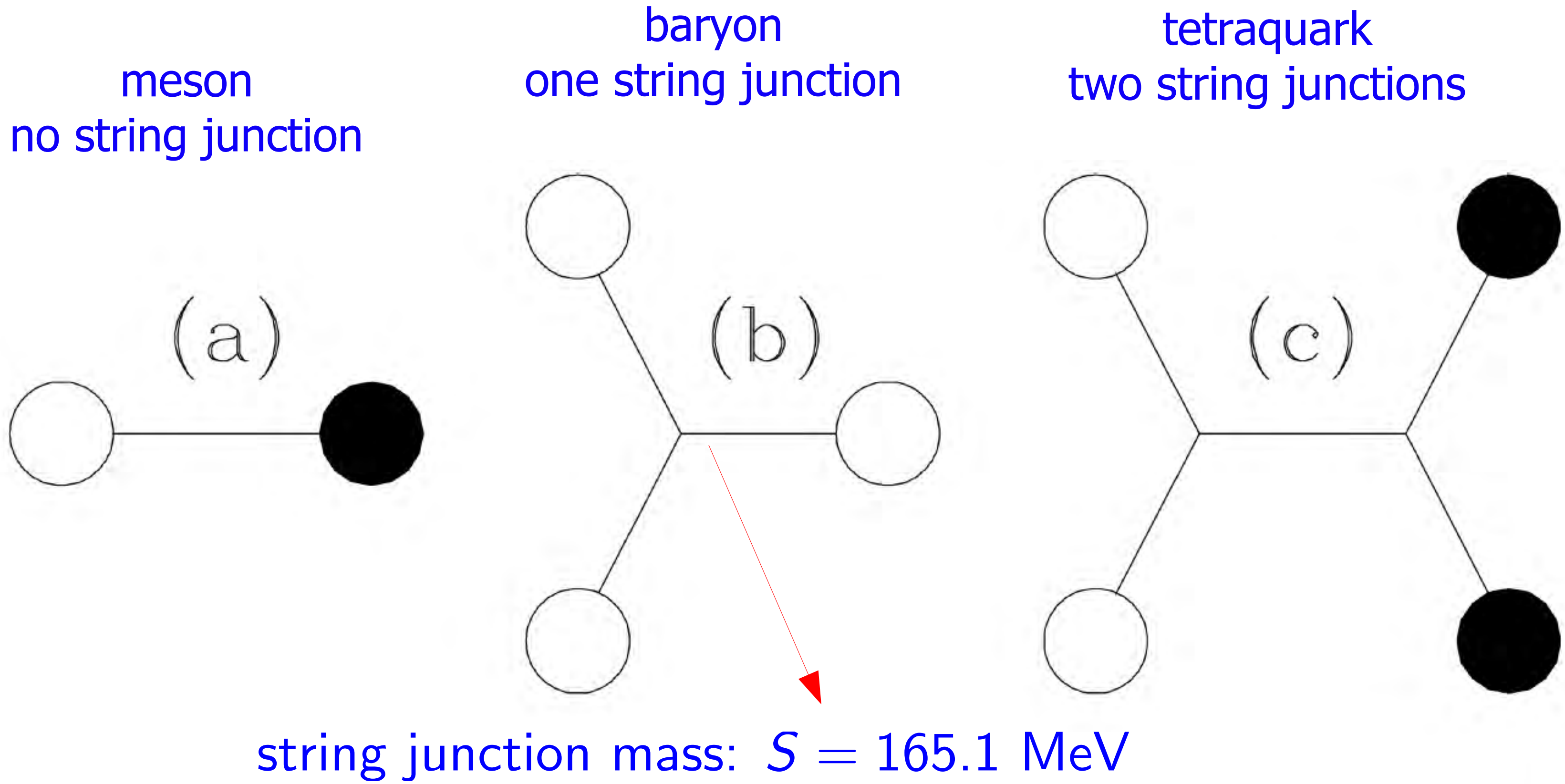
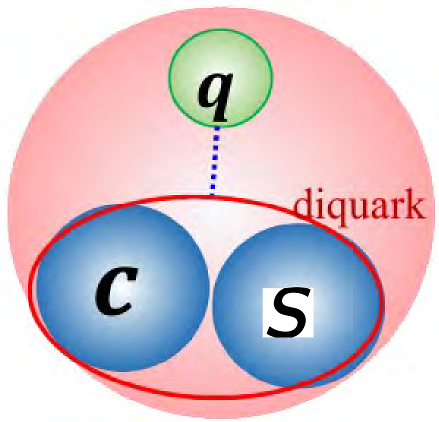


FIG. 1: QCD strings connecting quarks (open circles) and antiquarks (filled circles). (a) Quark-antiquark meson with one string and no junctions; (b) Three-quark baryon with three strings and one junction; (c) Baryonium (tetraquark) with five strings and two junctions.

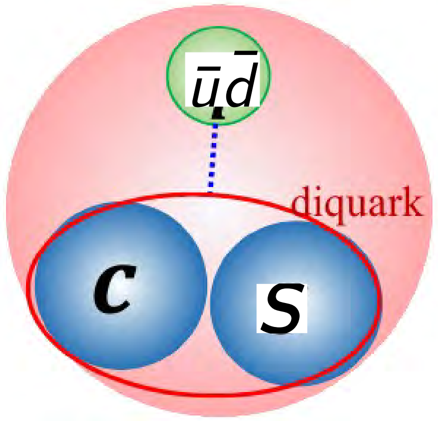
$\Xi_c(csq)$ baryon vs. $cs[\bar{u}\bar{d}]$ tetraquark

- cs color antitriplet diquark in both
- 3^*_c $[cs]$ $S=0$ interacts with 3_c: q or $[\bar{u}\bar{d}]$
- $\bar{u}\bar{d}$: $S=0$, $I=0$ "good" diquark $[\bar{u}\bar{d}]$ much lighter that $S=1$, $I=1$ $(\bar{u}\bar{d})$, due to strong spin-dep. interaction between light quarks, c.f. $\Sigma_b(b(ud)) - \Lambda_b(b[ud]) \approx 194$ MeV
- $J^P = 0^+$
- all parameters from ordinary hadrons

Ξ_c



$Tq(cs[\bar{u}\bar{d}])$



$T(cs\bar{u}\bar{d})$ mass in the string-junction picture:

cs: spin-0 diquark $[cs] \Rightarrow \Delta E_{HF}(cs)$: attractive color HF

$B(cs)$: binding energy in 3^*_c

$$M[T(cs\bar{u}\bar{d})] = m_c + m_s + m_{[ud]} + 2S + B(cs) + \Delta E_{HF}(cs) \ ,$$

use $M(\Lambda_c) = m_c + m_{[ud]} + S = 2286.5$ MeV, and

values from fits to ordinary hadronic spectra:

$m_s = 482.2$ MeV, $\quad B(cs) = -35.0$ MeV, $\quad \Delta E_{HF}(cs) = -35.4$ MeV

so

$$M[T(cs\bar{u}\bar{d})] = \Lambda_c + m_s + S + B(cs) + \Delta E_{HF}(cs) =$$
$$= 2863.4 \pm 12 \text{ MeV}$$

- The 0^+ $\mathrm{Tq}([cs][\bar{u}\bar{d}])$ has a hyperfine partner
- $\mathrm{Tq}((cs)[\bar{u}\bar{d}])$ with $J^P = 1^+$ and mass 2916.5 ± 12 MeV.
- 1^+: unnatural parity $\Rightarrow$ cannot decay to DK
- cannot account for the $X_1(2900)$ state
- one possibility:

  $DK \to D^* K^*$ rescattering w. threshold at 2.9 GeV

- 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$(cc\bar{u}\bar{d}) \to D^0 D^{*+}$

  and

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

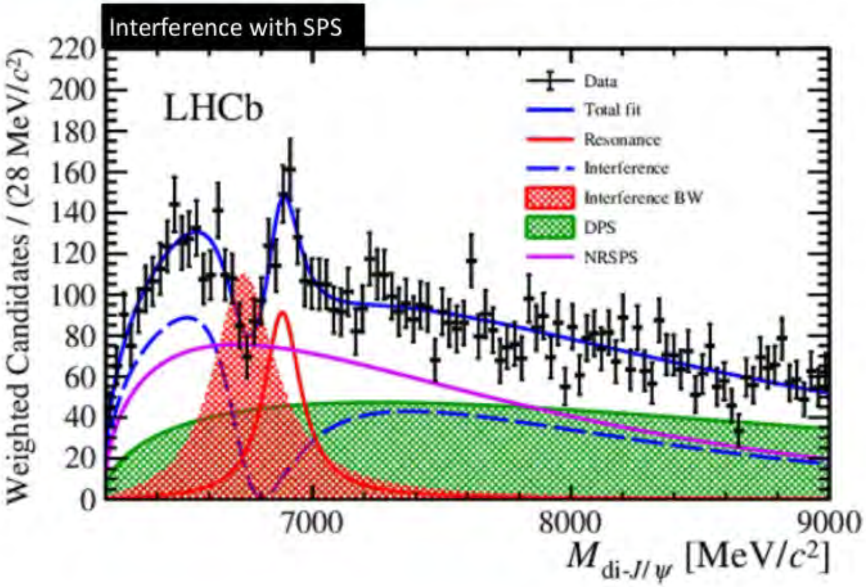
recent news from LHCb, June 2020:

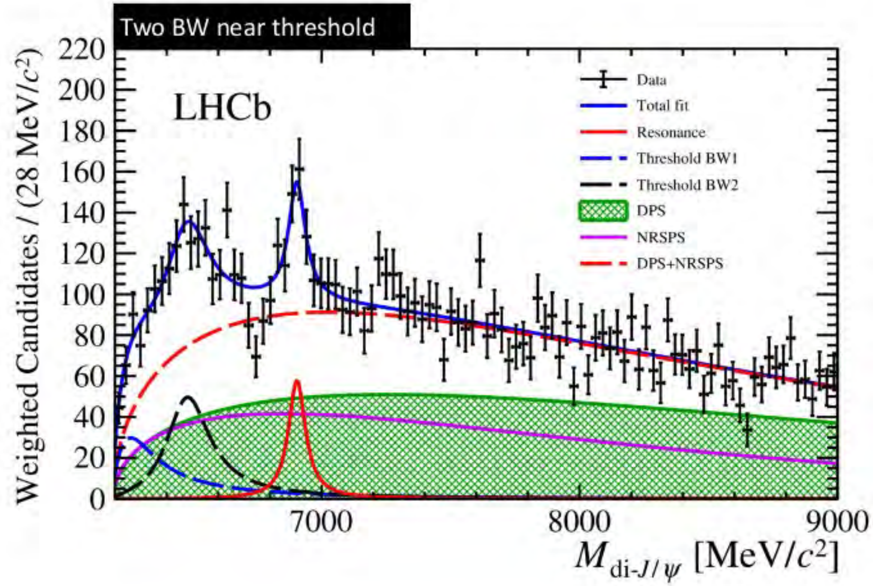
- a narrow resonance decaying into two J/ψ-s
- quark content $cc\bar{c}\bar{c}$
- $M \approx 6.9$ GeV: $\quad X(6900)$
- tetraquark-like
- ~ 700 MeV above $J/\psi\, J/\psi$ threshold

  $\Rightarrow$ 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

LHCb – talk by Daniel Johnson



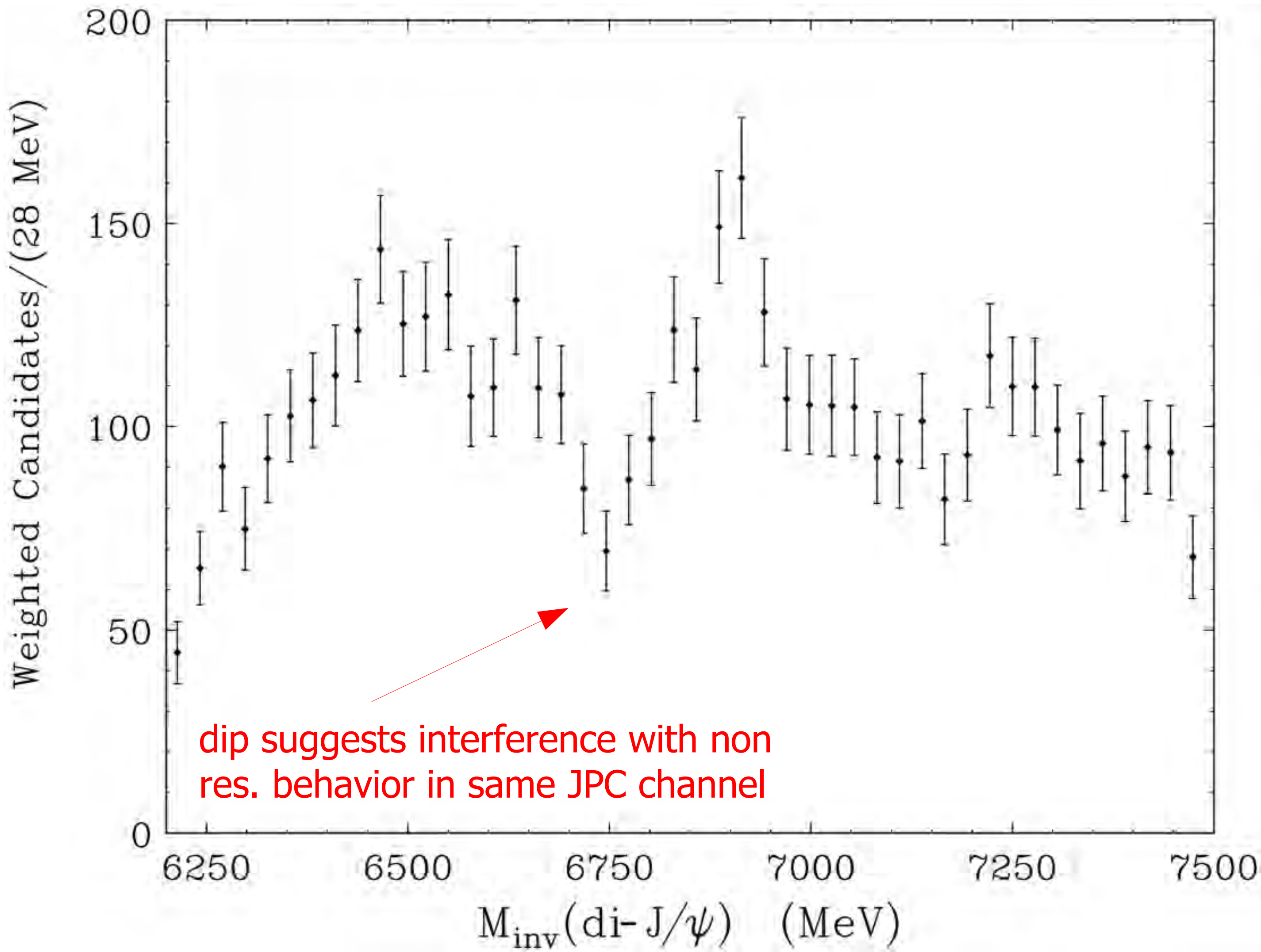


- $T_{c\bar{c}c\bar{c}}$ state at $6.9\ \mathrm{GeV}/c^2$ and either:
  - one more (interfering with NRSPS), or
  - two more, near threshold
- Feed-down may contribute; unlikely for narrow state
- Near-threshold rescattering could be important

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

LHCb data


Weighted Candidates/(28 MeV)
200
150
100
50
0
6250
6500
6750
7000
7250
7500
M_inv(di-J/ψ) (MeV)
dip suggests interference with non
res. behavior in same JPC channel

- dip at $M_{\rm inv}(\text{di}-J/\psi) \approx 6.75$ GeV suggests interference w. nonresonant behavior in a channel with the same J^{PC}.
- difficult to regard from a molecular standpoint, but compatible with a compact $cc\bar{c}\bar{c}$
- dip position $\sim 2M[\chi_{c0}(3415)]$.
- if di$-J/\psi$ resonance mostly $J^{PC} = 0^{++}$, can produce $2\chi_{c0}(3415)$-s in S-wave as soon as above threshold
- unitarity then can induce a *dip* in the production channel – several examples of such behavior provided in the paper

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:

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

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

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

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

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

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

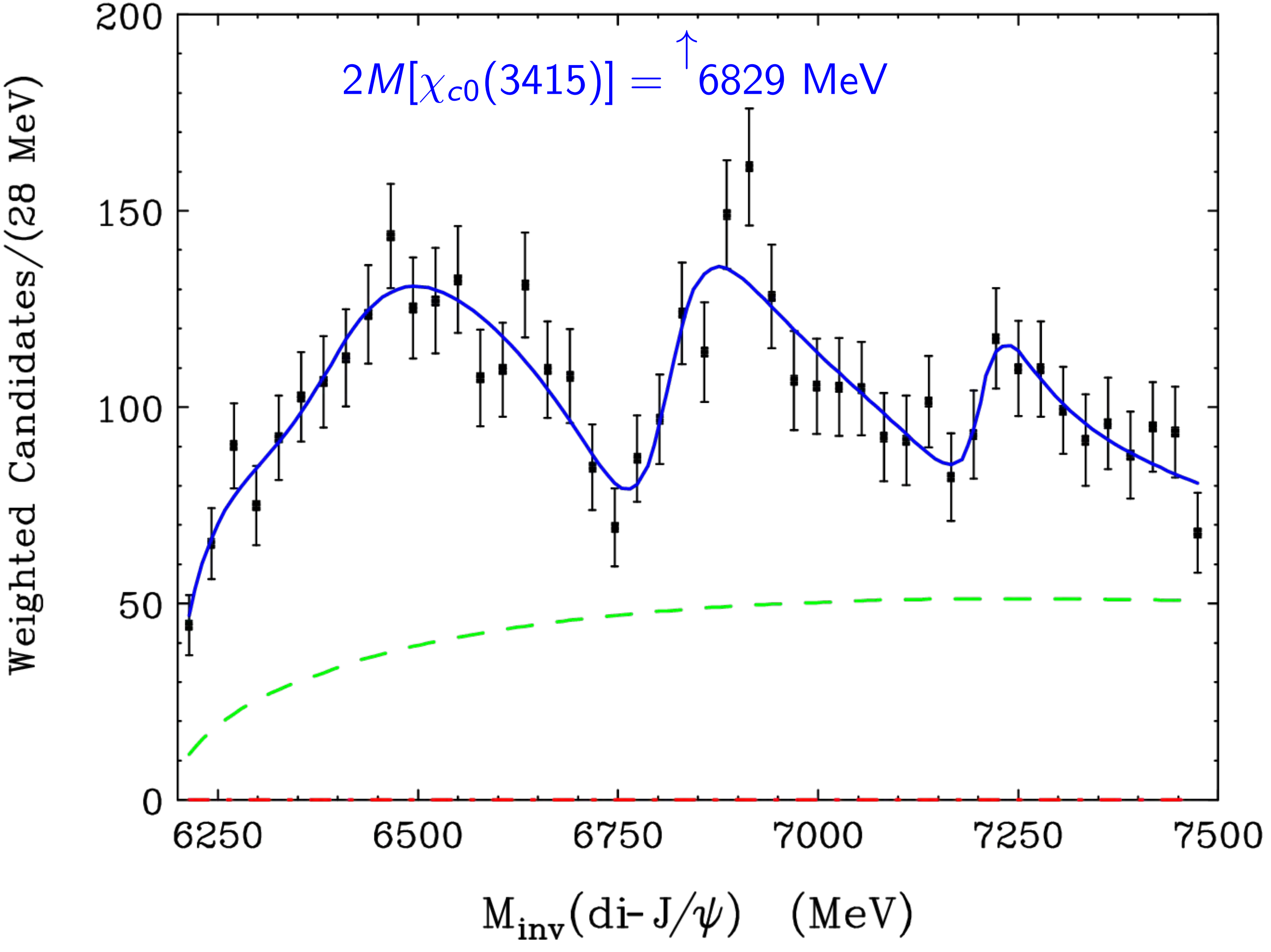


Figure 1: Spectrum of J/ψ pairs reported by the LHCb Experiment [3], together with our best fit to data (blue line), as given in Table I and described in the Appendix. The green dashed line denotes the DPS contribution, subtracted before fitting.

- detection of 2 χ_{c0}-s challenging because of small BR-s of χ_{c0} to observable final states
- with sufficient mass resolution, could combine modes with all charged tracks to get an eff. BR $\gtrsim 5\%$
- $\Gamma(\chi_{c0}) = 10.8 \pm 0.6$ MeV, while exp. mass resolution in other LHCb analyses is somewhat greater, and thus dominates the sensitivity to a signal
- an explicit simulation would be helpful

Branching fractions of $\chi_{c0}(3415)$ exceeding a percent.

Mode	Percent
$2(\pi^+\pi^-)$	2.34 ± 0.18
$\pi^+\pi^-\pi^0\pi^0$	3.3 ± 0.4
$\pi^+\pi^-K^+K^-$	1.81 ± 0.14
$K^+\pi^-\bar{K}^0\pi^0$ + c.c.	2.49 ± 0.33
$3(\pi^+\pi^-)$	1.20 ± 0.18
$\gamma J/\psi$	1.40 ± 0.05

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

$cs\bar{u}\bar{d}$ & $cc\bar{c}\bar{c}$ summary

- narrow D^+K^- LHCb 0^+ resonance at 2866 ± 7 MeV:
  likely compact isosinglet $cs\bar{u}\bar{d}$ tetraquark
  mass predicted at 2863 ± 12 MeV
  from quark model + 2 string junctions
- wider D^+K^- LHCb 1^- resonance at 2904 ± 7 MeV:
  tantalizingly close to D^*K^* threshold at 2902 MeV
  but inconsistent J^P ?
- 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
  + opening of thresholds; dip around 6.75 GeV: S-wave di-χ_{c0}
- main peak around 6.9 GeV likely dominated by $0^{++}(2S)$,
  radial exc. of (cc)-$(\bar{c}\bar{c})$ Tq, predicted at 6.871 ± 0.025 GeV

two v. different types of exotics:

$Q\bar{Q}q\bar{q}$	$QQ\bar{q}\bar{q}$

e.g.

$Z_b(10610)$	$T(bb\bar{u}\bar{d})$
$\bar{B}B^*$	tightly-bound
molecule	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

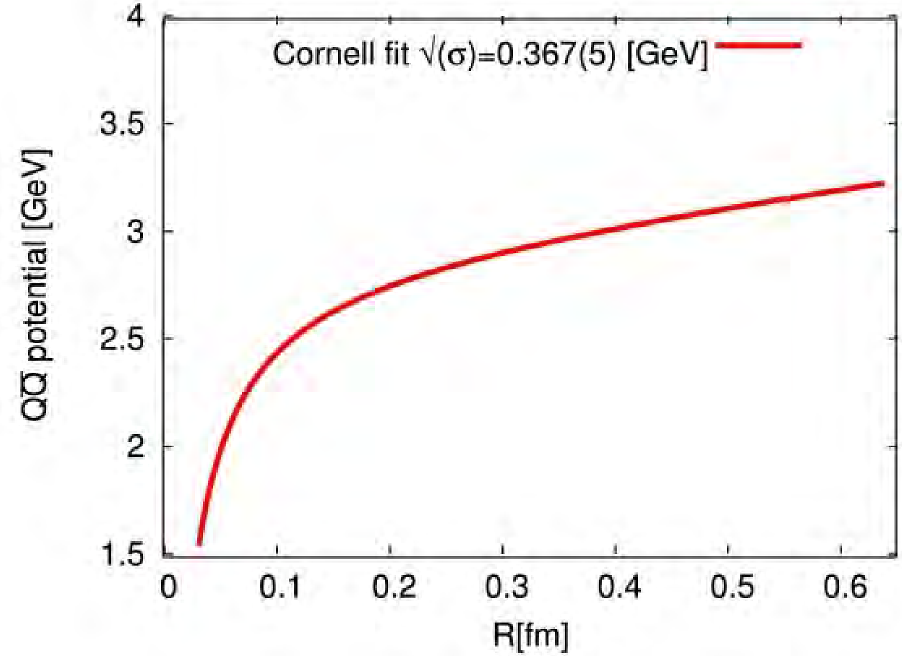
$\Rightarrow$ exotics: $\bar{Q}$ in one hadron and Q in the other

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

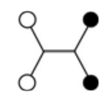
very different!

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  ; $bs\bar{u}\bar{d} = \bar{B}^0K^-$?
- $J/\psi\, J/\psi$ res. $\Leftrightarrow$ excited $cc\bar{c}\bar{c}$ Tq, probably $2S$, $J/\psi\,\Upsilon$, $\Upsilon\Upsilon$?

exciting new spectroscopy awaiting discovery

two general comments about charm-tau factory program

- $J/\psi\, K^{\pm}$ resonances:
  $Z_c(3900)$ analogue?
  $Z_c(3900)^+ = (c\bar{c}u\bar{d})$; $d \to s$: $(c\bar{c}u\bar{s}) \sim D_s \bar{D}^*$
  no natural molecular binding,
  so if discovered, would indicate
  Tq or a novel mechanism

- $\Lambda_c \to \ell^+ \nu_\ell \, \Lambda(1520)$:
  interesting to measure, to elucidate the form factor;
  charm-tau factory has an edge over LHCb here