Heavy Tetraquarks and Pentaquarks

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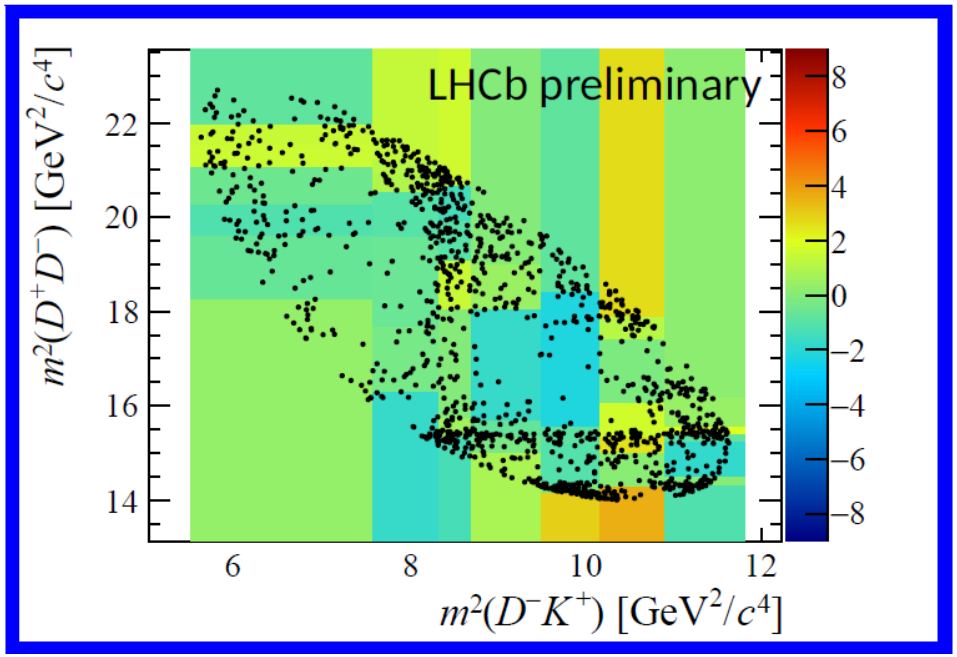
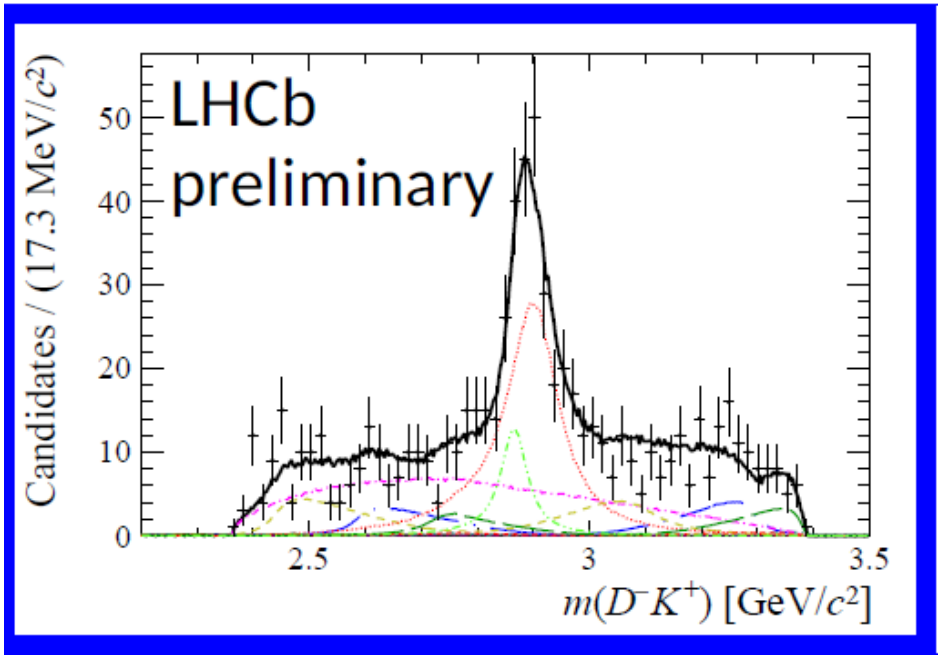
hadrons w. heavy quarks are *much simpler:*

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

Very 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

2009.00025 & 2009.00026





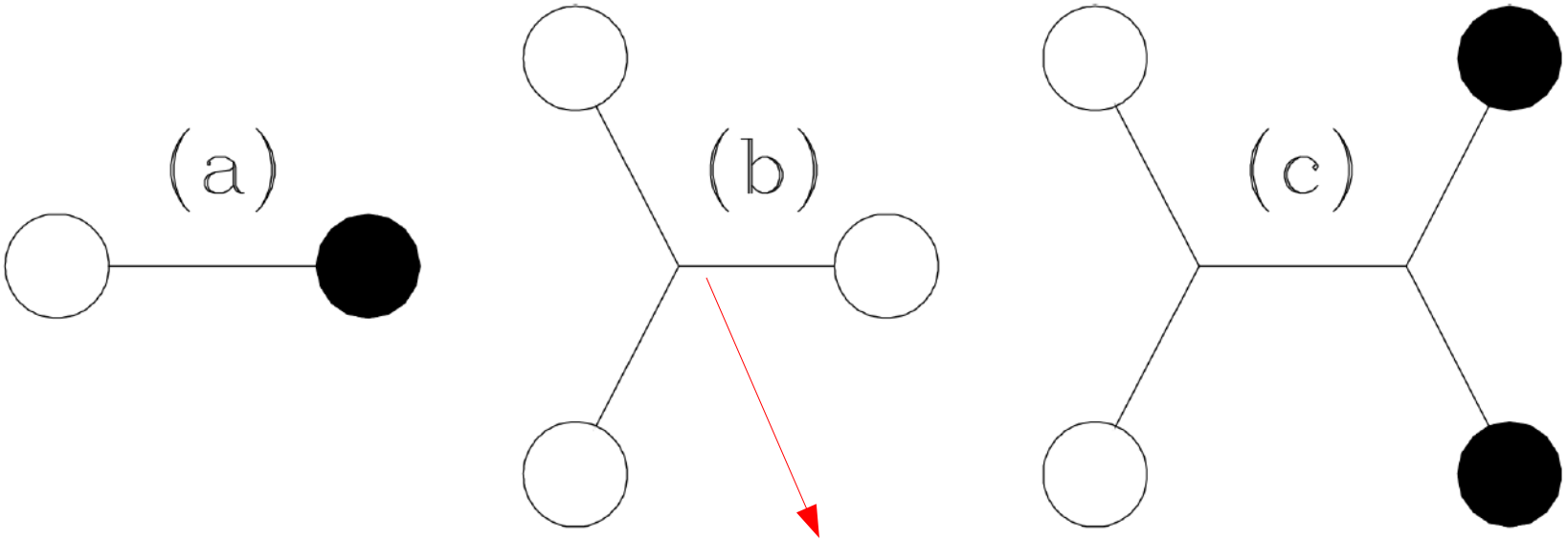
MK & JR: arXiv:2008.05993

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

meson
no string junction

baryon
one string junction

tetraquark
two string junctions



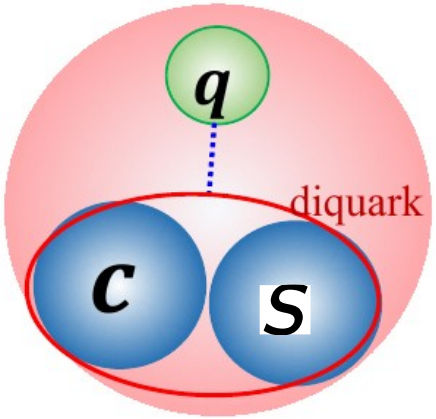
string junction mass: $S = 165.1$ MeV

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.

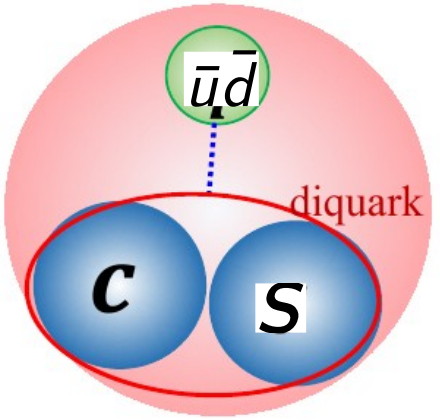
$\Xi_c(csq)$ baryon vs. $cs[\bar{u}\bar{d}]$ tetraquark

- 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:

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

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^+ Tq($[cs][\bar{u}\bar{d}]$) has a hyperfine partner
- 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$(cc\bar{u}\bar{d}) \rightarrow D^0 D^{*+}$

  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

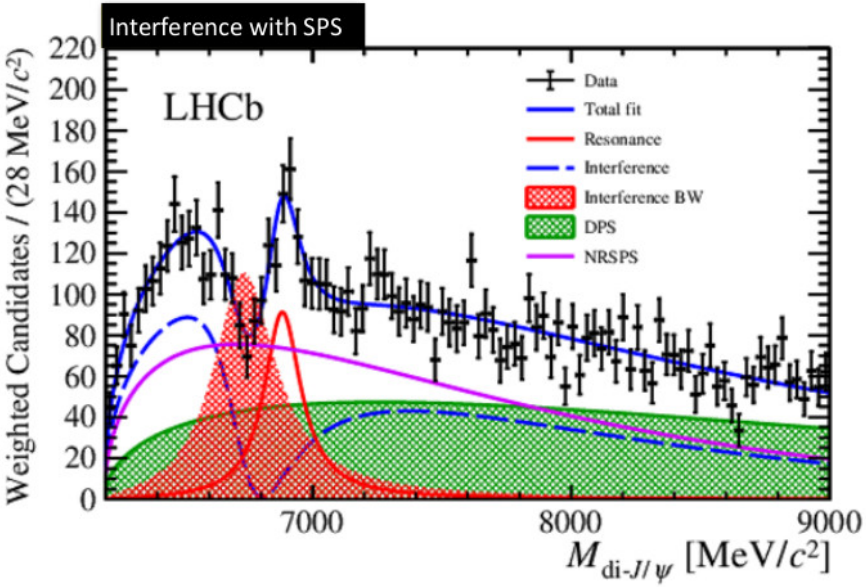
recent news from LHCb, June 2020:

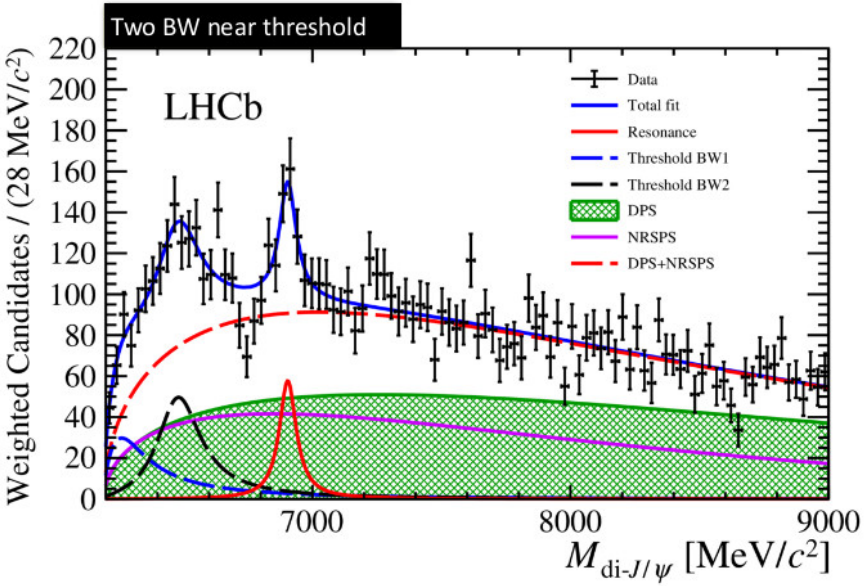
- a narrow resonance decaying into two -s
- quark content $cc\bar{c}\bar{c}$
- $M \approx 6.9$ GeV: $X(6900)$
- tetraquark-like
- ~ 700 MeV above threshold
  $\Rightarrow$ probably an excited $cc\bar{c}\bar{c}$ state
- first exotic containing both QQ *and* $\bar{Q}Q$
- exciting challenge for EXP and TH

Interpretation

arXiv:2006.16957

LHCb – talk by Daniel Johnson





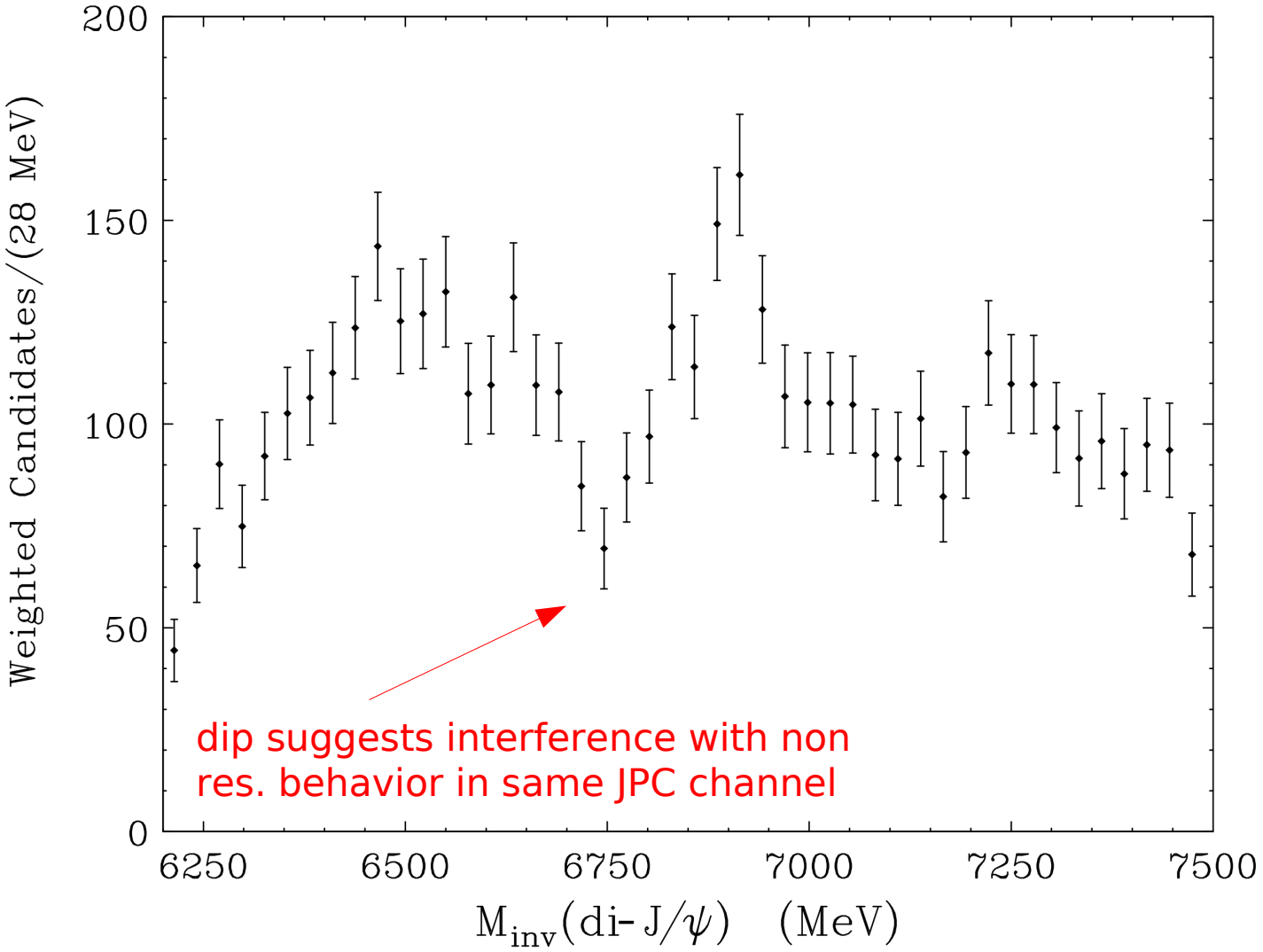
- $T_{c\bar{c}c\bar{c}}$ state at $6.9\ \text{GeV}/c^2$ and either:
  - one more (interfering with NRSPS), or
  - two more, near threshold
- Feed-down may contribute; unlikely for narrow state
- Near-threshold rescattering could be important

MK & JR arXiv:2009.04429v2 [hep-ph] 15 Sep 2020

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

- 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


200
150
100
50
0
Weighted Candidates/(28 MeV)
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 $M_{\rm inv}({\rm di}{-}J/\psi\,) \approx 6.75$ 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: 9 params + 2 params for bkgr $\longrightarrow$ 11 params

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

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

added coherently to the sum of three Breit-Wigner resonances each of the form

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

where M_i and Γ_i are the mass and width of the ith resonance. We set $\eta_1 \equiv 1$ and absorb normalization of resonance 1 into the constant C_1. The parameters $\eta_{(2,3)}$, being less than 1, indicate that the branching fractions to di$-J/\psi$ of resonances 2 and 3 are less than that of resonance 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

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

The numerical data $N \pm dN$ are those in Fig. 3(a) of Ref. [3], restricted to the range $6200 \le M_{\rm inv} \le 7488$ 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.

By comparing Tables I and III, one sees that certain parameters are not well determined by the χ^2 criterion. These must thus be regarded as only representative values.

Table I: Parameters in best fit to data (see Appendix for definitions) with $\chi^2 = 31.072$ for 35 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. Dimensionless parameters η_i ($\eta_1 \equiv 1$) describe relative normalizations of i-th Breit-Wigner shapes.

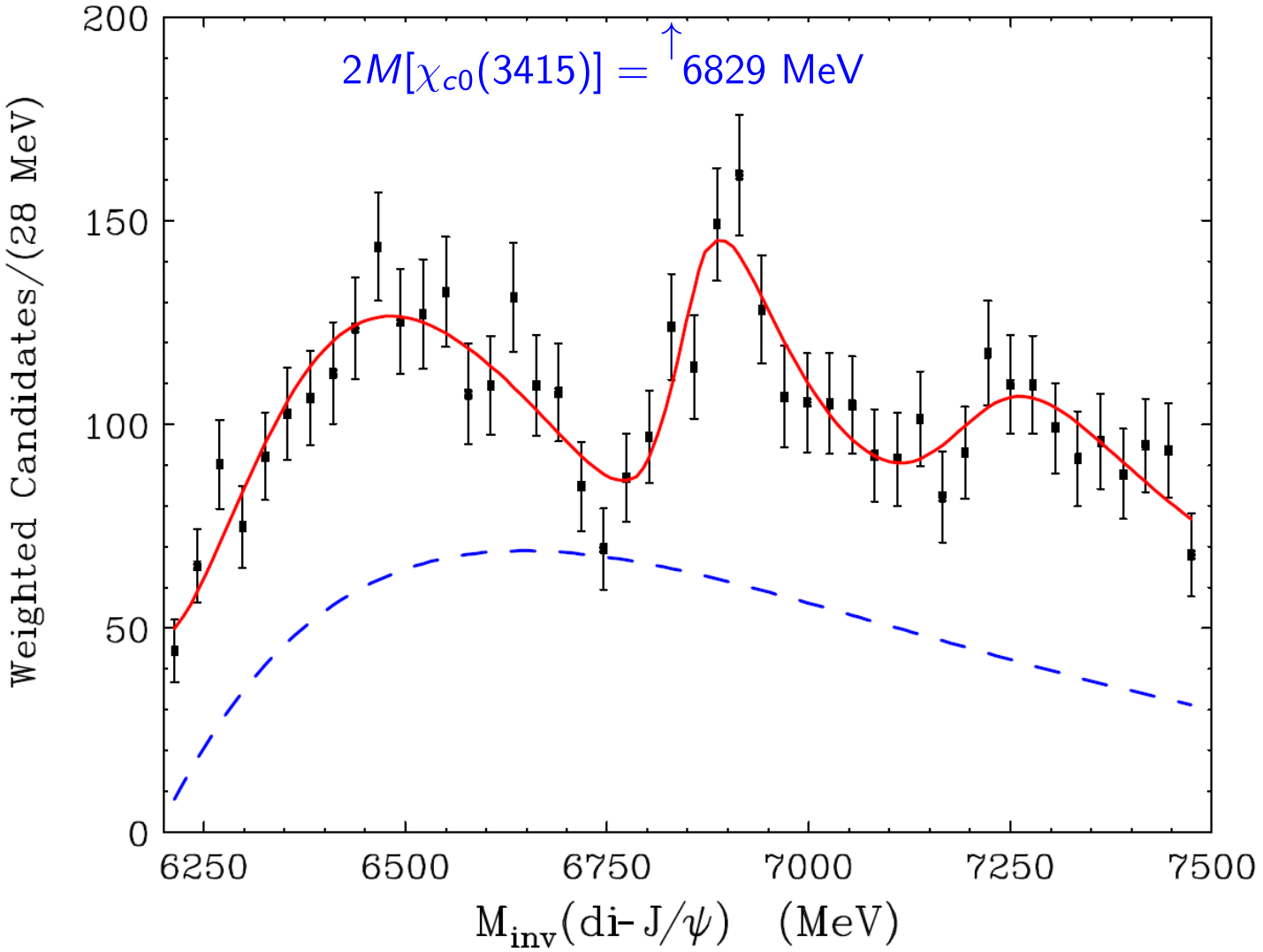
Peak i	i=1	i=2	i=3
M_i	6279.5	6851.5	7201.0
Γ_i	564.9	152.6	305.5
C_i	7.296	13.94	1.145
η_i	1.000[a]	0.536	0.376

[a] Input

Table III: Parameters in best fit to data with $M_1 = 6191.5 \pm 25$ MeV, giving $\chi^2 = 31.712$ for 35 degrees of freedom (d.o.f.) Notation as in Table I.

Peak i	i=1	i=2	i=3
M_i	6212.5[a]	6850.7	7201.1
Γ_i	625.0	140.5	258.4
C_i	6.48	13.98	1.138
η_i	1.000[b]	0.573	0.397

[a] Constraint $M_1 = 6191.5 \pm 25$ MeV [b] Input



Spectrum of J/ψ pairs reported by the LHCb Experiment [3], together with our best fit to data (red line), as given in Table I and described in the Appendix. The blue dashed line denotes the square of the background amplitude, Eq. (3) in the Appendix.

- 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

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

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

Summary

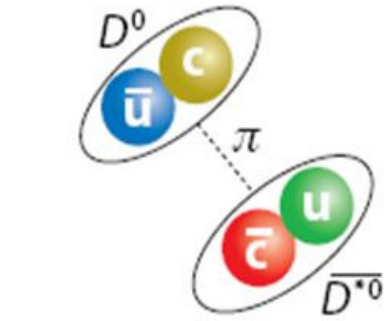
- narrow D^+K^- LHCb 0^+ resonance at 2866 ± 7 MeV:
  likely compact isosinglet $cs\bar{u}\bar{d}$ tetraquark
  mass predicted at 2863 ± 12 MeV
  from quark model + 2 string junctions
- wider D^+K^- LHCb 1^- resonance at 2904 ± 7 MeV:
  tantalizingly close to D^*K^* threshold at 2902 MeV
  but inconsistent 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

5 narrow exotic states close to meson-meson thresholds

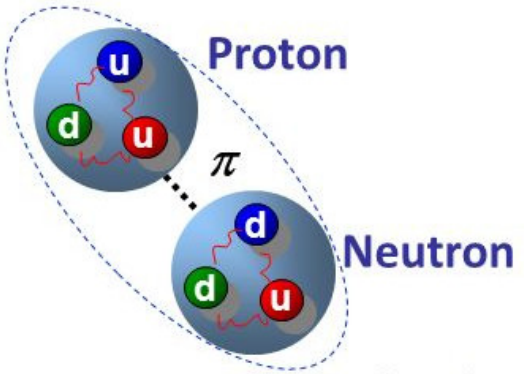
state	mass MeV	width MeV	$\bar{Q}Q$ decay mode	phase space MeV	nearby threshold	ΔE MeV
$X(3872)$	3872	< 1.2	$J/\psi\,\pi^+\pi^-$	495	$\bar{D}D^*$	< 1
$Z_b(10610)$	10608	21	$\Upsilon\pi$	1008	$\bar{B}B^*$	2 ± 2
$Z_b(10650)$	10651	10	$\Upsilon\pi$	1051	$\bar{B}^*B^*$	2 ± 2
$Z_c(3900)$	3900	$24 - 46$	$J/\psi\,\pi$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

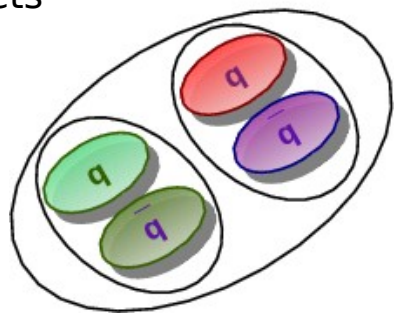


Deuteron: p-n molecule

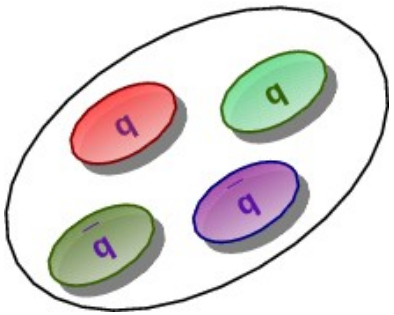
Tetraquarks: same 4 quarks, but tightly bound:

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

[a] Ignoring annihilation of quarks.
[b] Plus other charge states when $I \neq 0$.
[c] Based on isospin-averaged masses.
[d] Thresholds differ by 27.6 MeV.

New Exotic Meson and Baryon Resonances from Doubly Heavy Hadronic Molecules

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

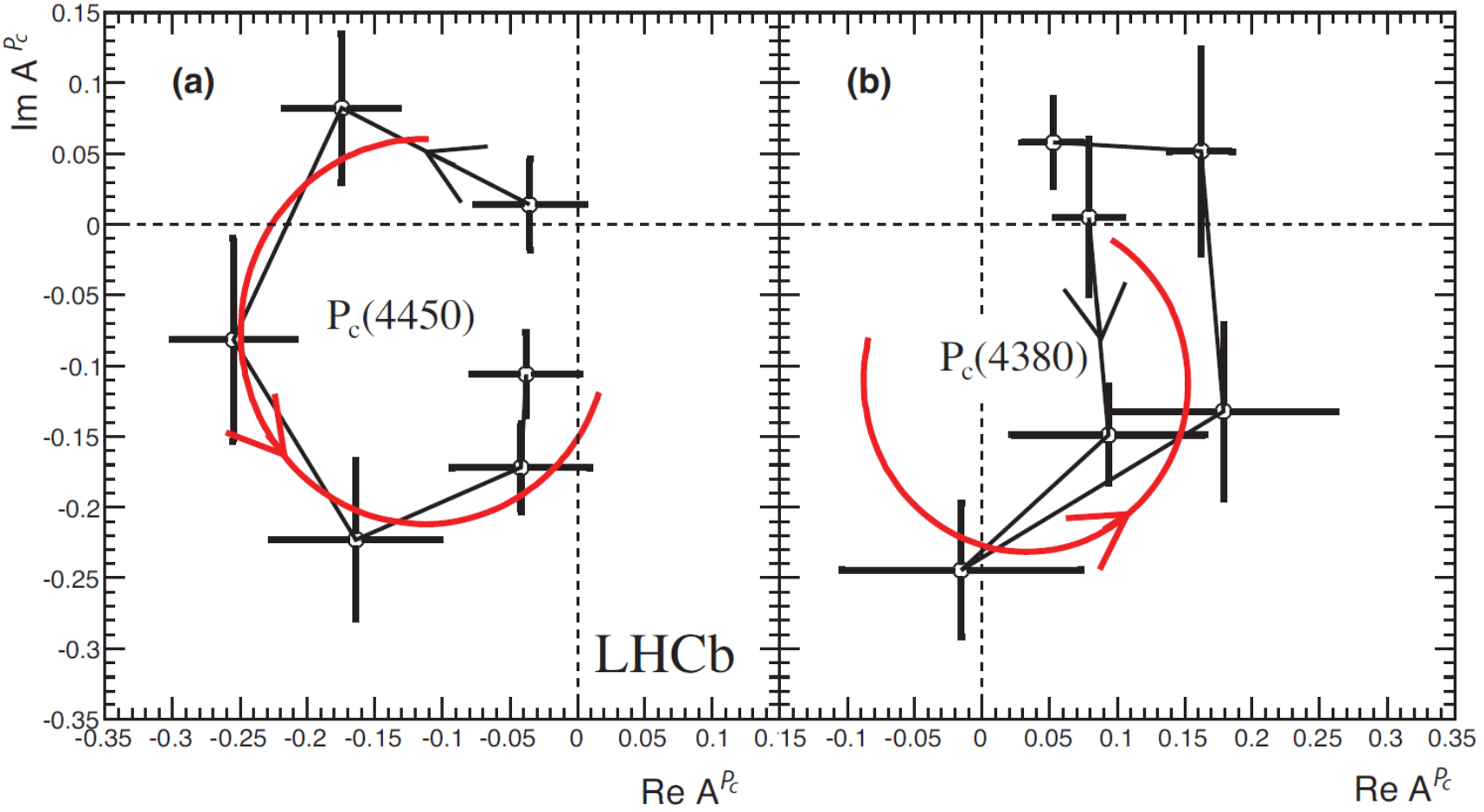
DOI: 10.1103/PhysRevLett.115.122001 PACS numbers: 14.20.Pt, 12.39.Hg, 12.39.Jh, 14.40.Rt

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

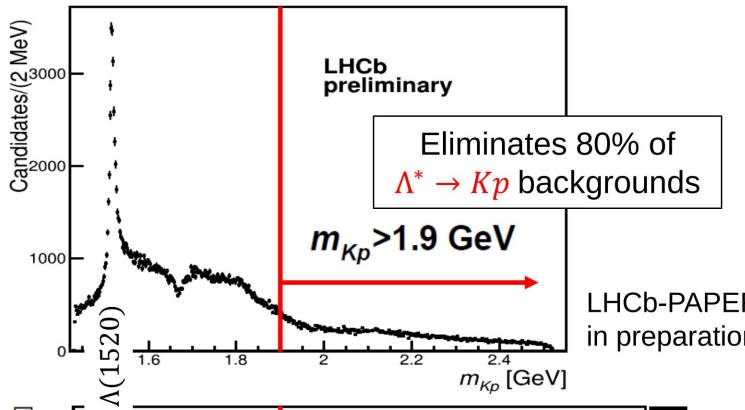
$P_c(4380)$: not predicted,
wide: $\Gamma = 205 \pm 18 \pm 86$ MeV,
Argand plot not resonance-like
???

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

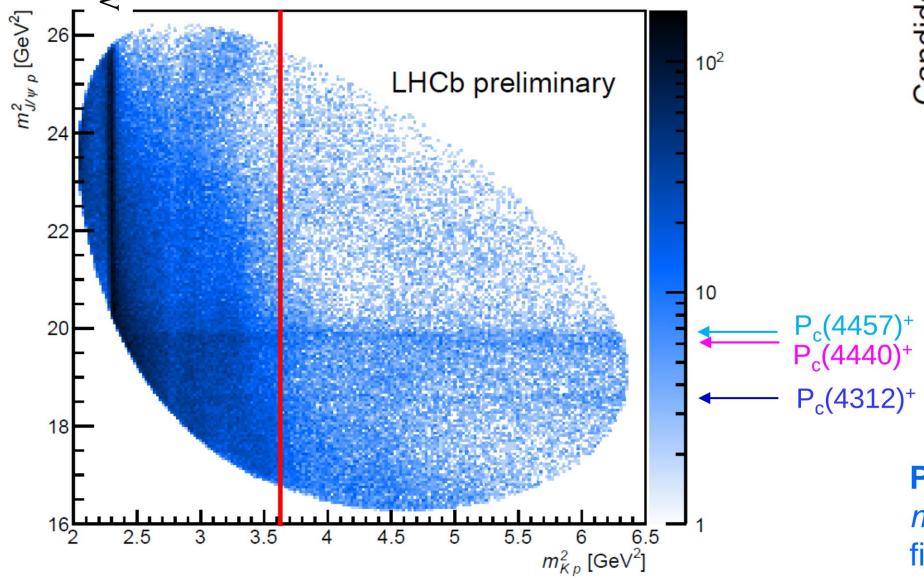
as of 2015

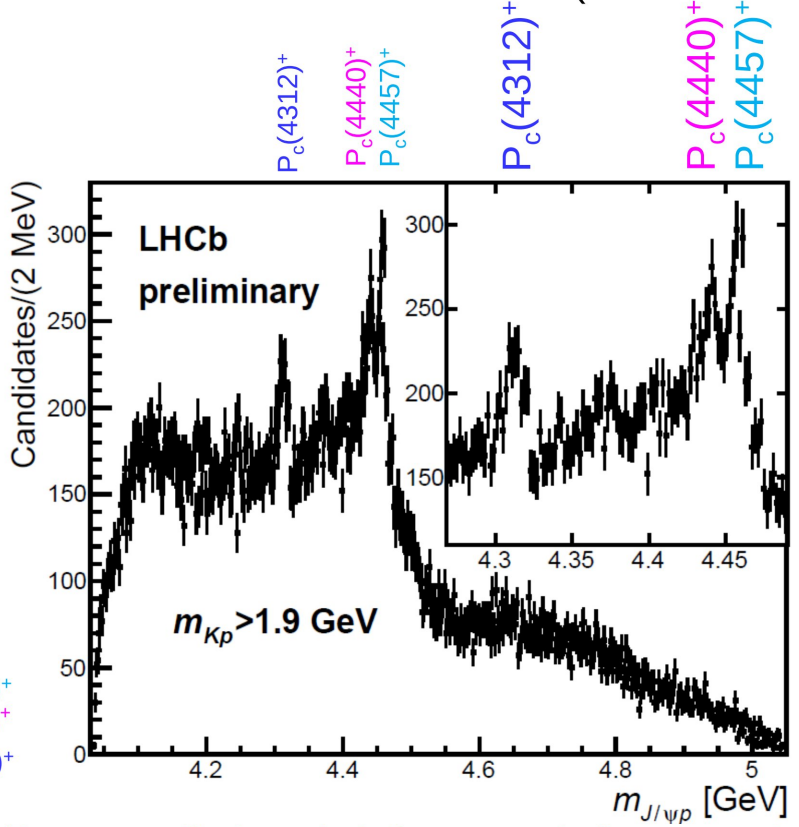
Narrow $P_c^+ \to J/\psi p$ peaks with Λ^* suppression

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



LHCb-PAPER-2019-014
in preparation



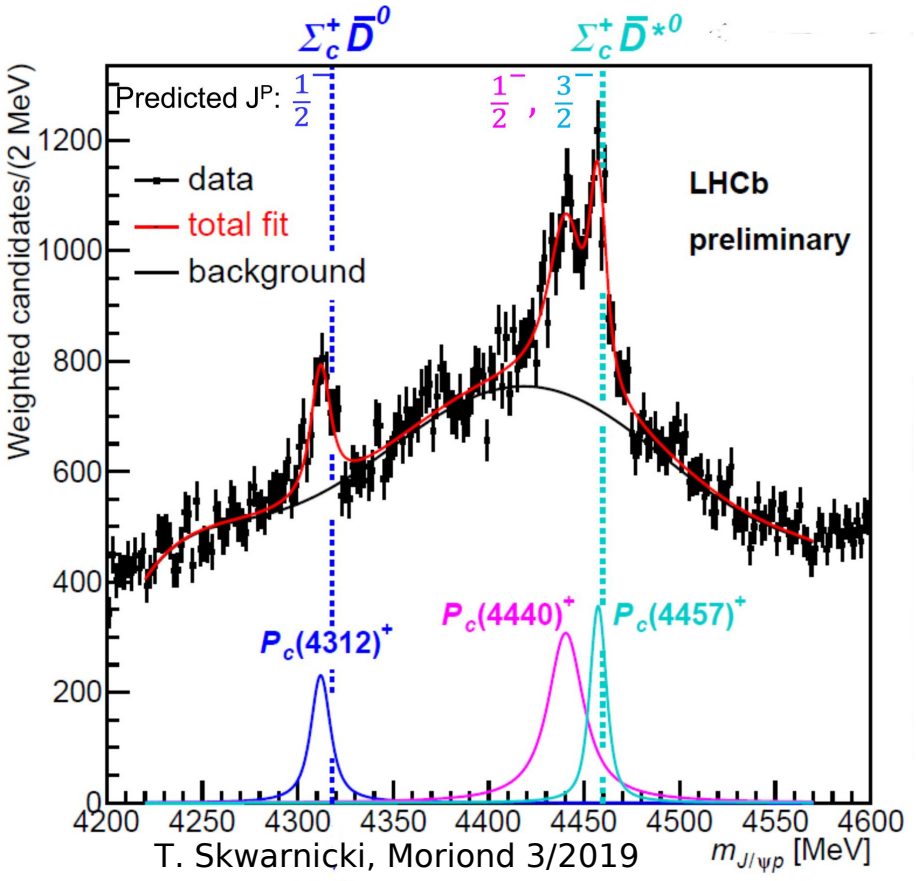


Proper amplitude analysis faces new challenges: must consider $m_{J/\psi p}$ resolution effects, large statistics and sub-percent precision in fit fractions required in the amplitude model – work in progress

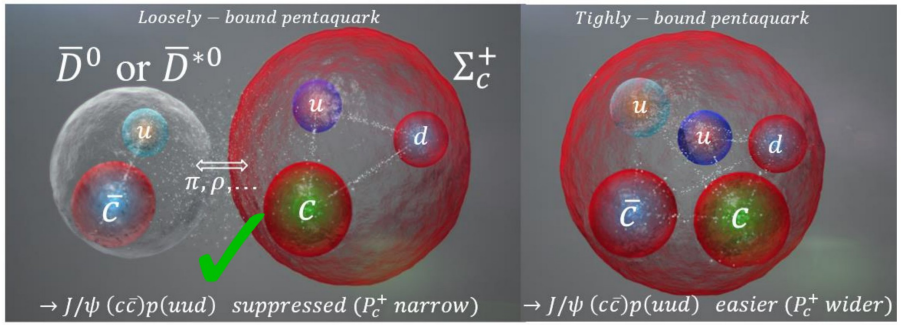
State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3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

M.

as of 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:

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

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

for $Q \to \infty$ 4 more S-wave states:

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

$\Sigma_c^*\bar{D}^*$; $J^P = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$

but $\Gamma(\Sigma_c^* \to \Lambda_c\pi) \approx 15$ MeV...

M. Karliner, Heavy 4q and 5q

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 $D\bar{D}$?

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

$\Longrightarrow 2^* \left(m(D^*) - m(D)\right) = 282$ 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: $I = \frac{1}{2}$

$\Longrightarrow \Sigma_c$ has stronger coupling to light hadrons

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

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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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.

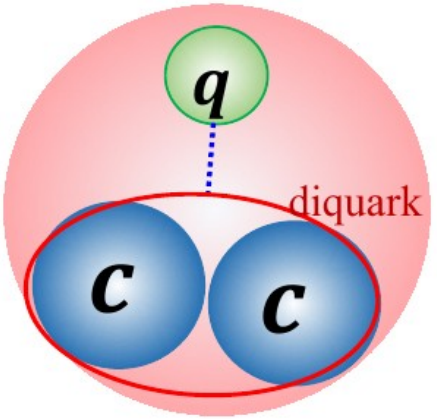
DOI: 10.1103/PhysRevLett.119.202001

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

build on accuracy of the Ξ_{cc} mass prediction

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

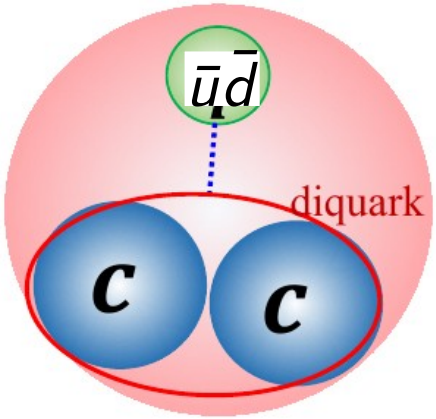
bbq baryon



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:

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

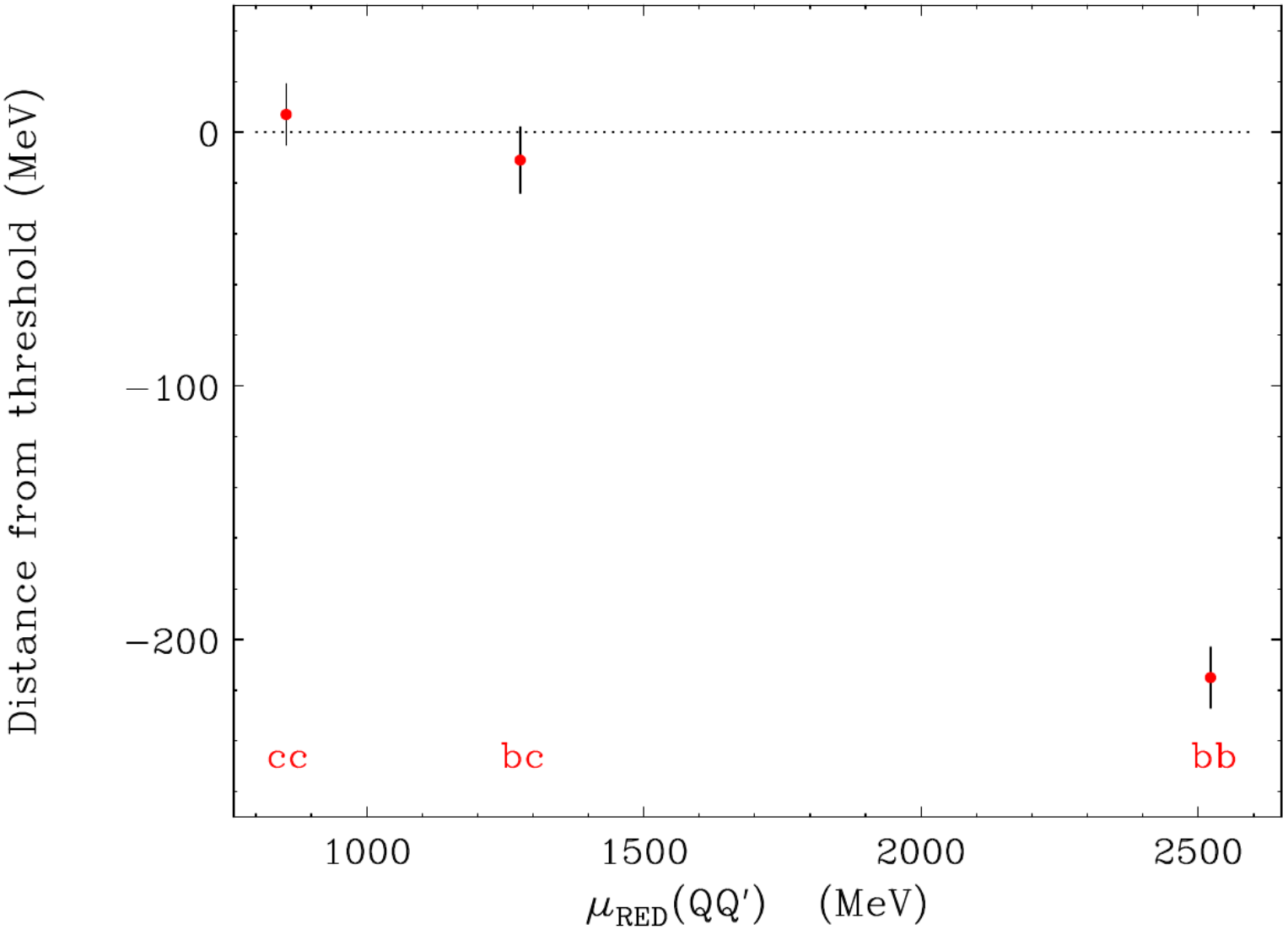
Ξ_{cc} discovery $\Rightarrow$ quantitative validation

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

so for $M_Q \to \infty$

$QQ\bar{u}\bar{d}$ 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:

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

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 *now*: $D^+ D^{*0}$, *etc.*

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

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

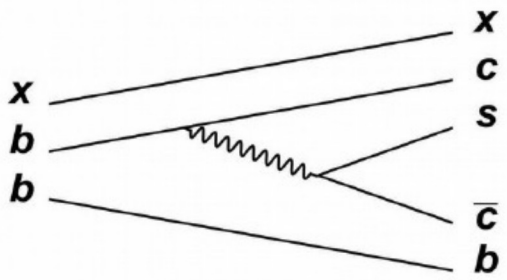
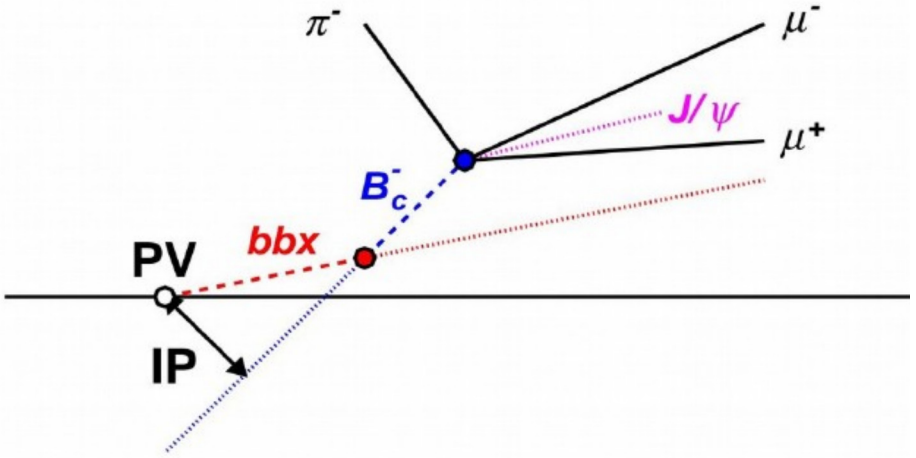


Diagram for production of a B_c^- meson from a double beauty hadron decay.



$\mathcal{O}(1\%)$ 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.

$$\Rightarrow \Gamma(bb\bar{u}\bar{d}) = \frac{18\, G_F^2 M(bb\bar{u}\bar{d})^5}{192\pi^3} F(x)|V_{cb}|^2 = 17.9\times10^{-13} \text{ GeV} ,$$

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

$bb\bar{u}\bar{d}$ 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^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^{*+}

two v. different types of exotics:

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

e.g.

$Z_b(10610)$ $\qquad$ $T(bb\bar{u}\bar{d})$

$\bar{B}B^*$ $\qquad$ tightly-bound

molecule $\qquad$ 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

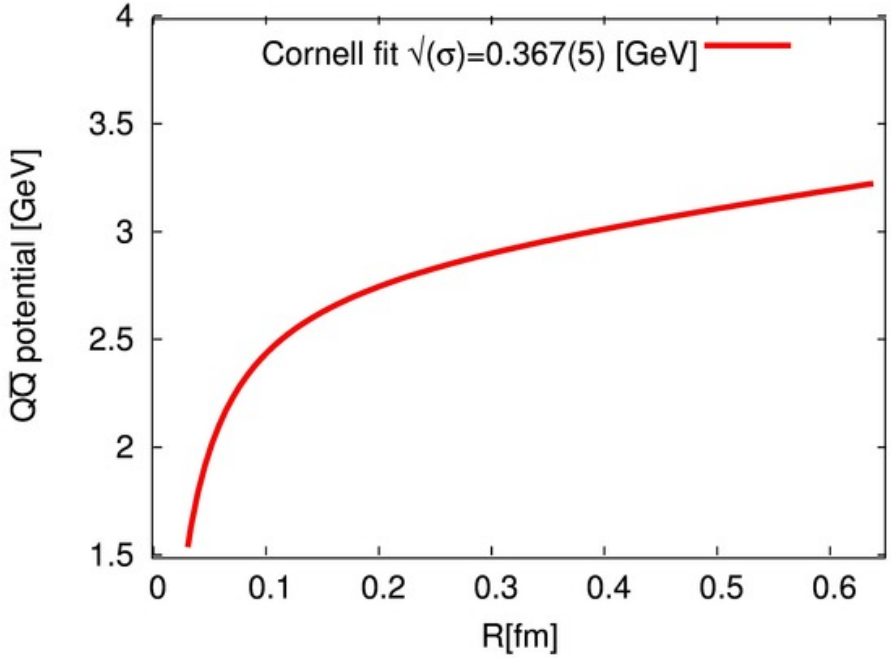
$\Rightarrow R(bb) \sim 0.2$ fm

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

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

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

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



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

very different!

Upshot:

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

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

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

SUMMARY

- narrow exotics with $Q\bar{Q}$:
  $\bar{D}D^*$, $\bar{D}^*D^*$, $\bar{B}B^*$, $\bar{B}^*B^*$, $\Sigma_c\bar{D}^*$, ... molecules

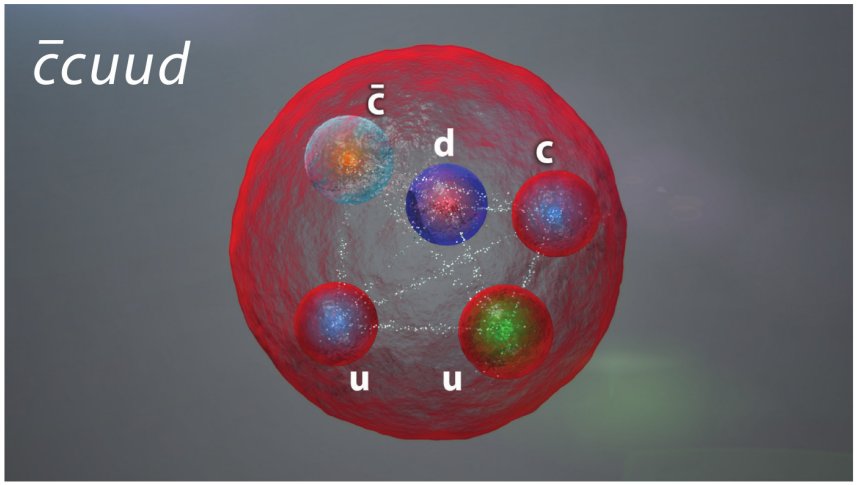
– *heavy deuterons*: $\Sigma_c D^{(*)}$: LHCb found 3 molecular P_c states
  $\Sigma_c B^*$, $\Sigma_b\bar{D}^*$, $\Sigma_b B^*$?...

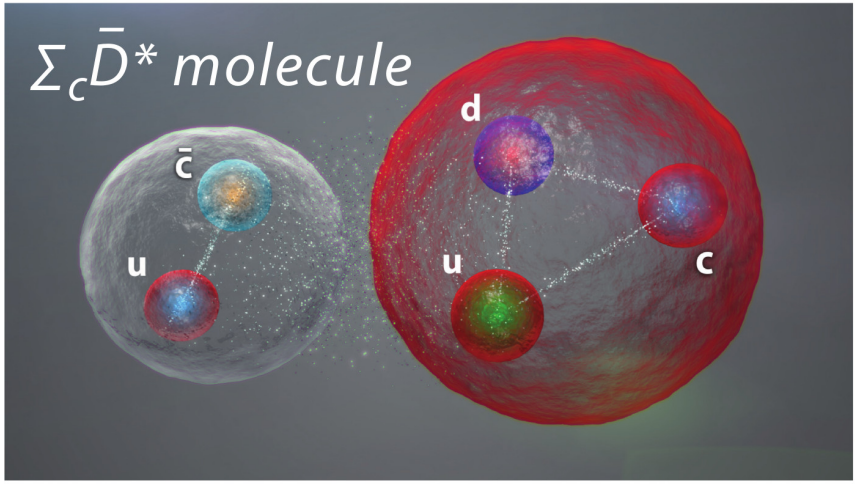
- doubly charmed baryon found exactly where predicted
  $\Xi_{cc}^{++}(ccu) \Rightarrow (bcq), (bbq)$
- stable $bb\bar{u}\bar{d}$ tetraquark: LHCb !
- narrow $cc\bar{u}\bar{d}$ tetraquark: accessible at LHCb already now?
- LHCb: strong candidate for g.s. $(cs)(\bar{u}\bar{d})$ Tq, $I = 0$, $J^{PC} = 0^{++}$
- LHCb: strong candidate for exc. $(cc)(\bar{c}\bar{c})$ Tq, $0^{++}(2S)$

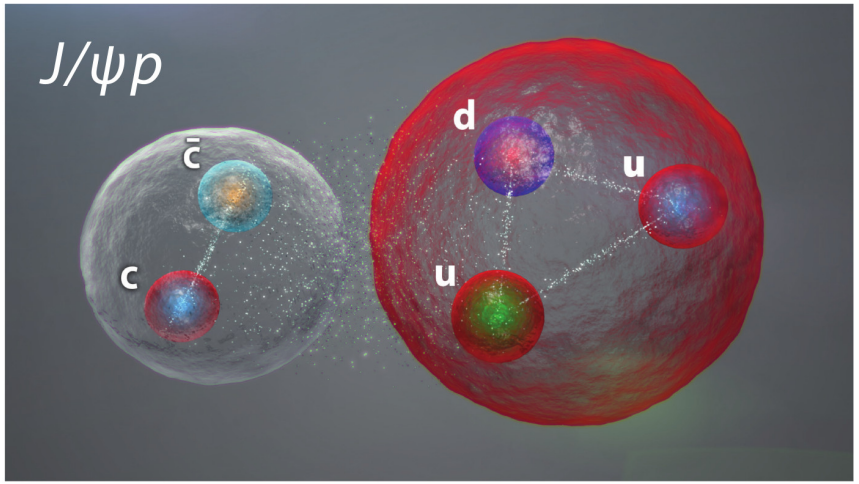
exciting new spectroscopy awaiting discovery!

Backup transparencies

Decay of a tightly bound pentaquark vs. hadronic molecule to $J/\psi p$







$$\left|\langle \Sigma_c\bar{D}^* \,|\, J/\psi p\rangle\right| \ll \left|\langle \bar{c}cuud|\, J/\psi p\rangle\right|$$

$P_c \to \Lambda_c \bar{D}(\bar{D}^*)$?

$m(\Lambda_c) + m(\bar{D}^0) = 4150$ MeV

$m(\Lambda_c) + m(\bar{D}^{0*}) = 4293$ MeV

P_c at 4312, 4440, 4457 MeV, same quark content

spin & parity constraints:

$\Longrightarrow (\Sigma_c \bar{D}^*, S{=}\frac{3}{2}) \to \Lambda_c \bar{D}^*$

$(\Sigma_c \bar{D}^*, S{=}\frac{1}{2}) \to \Lambda_c \bar{D},\ \Lambda_c \bar{D}^*$

$(\Sigma_c \bar{D}, S{=}\frac{1}{2}) \to \Lambda_c \bar{D},\ \Lambda_c \bar{D}^*$

no c & $\bar{c}$ rearrangement

$\Longrightarrow$ likely $|\langle P_c | \Lambda_c \bar{D}(\bar{D}^*)\rangle|^2 > |\langle P_c | J/\psi p\rangle|^2$

so why $\Lambda_c \bar{D}(\bar{D}^*)$ decay not seen ?

why $P_c \to \Lambda_c \bar{D}^0$ not seen?

Most likely an experimental issue: product of several small BR-s, large # of charged tracks & background rejection. Compare

$P_c \to J/\psi p$

$\mathrm{BR}(J/\psi \to \mu^+\mu^-) = 6\%$

so finally $P_c \to \mu^+\mu^- p$, 3 charged prongs

$P_c \to \Lambda_c \bar{D}^0$

$\mathrm{BR}(\Lambda_c \to K^- p \pi^+) = 6.28\%$,

$\mathrm{BR}(\bar{D}^0 \to K^+\pi^-) = 4\%$

$\mathrm{BR}(\ldots)\times\mathrm{BR}(\ldots) = 0.25\%$, 5 charged prongs

why $P_c \to \Lambda_c \bar{D}^{*0}$ not seen?

on top of $\Lambda_c \bar{D}^0$ issues,

need to observe π^0 from $\bar{D}^{*0} \to \bar{D}^0 \pi^0, \quad \pi^0 \to 2\gamma$,

or γ from $\bar{D}^{*0} \to \bar{D}^0 \gamma$,

LHCb has very low efficiency for such soft photons

upshot: $P_c \to \Lambda_c \bar{D}^0 (\bar{D}^{*0})$ should be seen with $\gg$ data

$\mathrm{BR}(P_c \to \Lambda_c \bar{D}(\bar{D}^*)) > \mathrm{BR}(P_c \to J/\psi p)$

suggests relatively small coupling in $\gamma p \to P_c \to J/\psi p$

$P_c \to \eta_c\, p$?

- extra decay channel influences BR($P_c \to J/\psi p$)
- only P_c states with $S = \frac{1}{2}$
- detection difficult
- $\Sigma_c^{+\downarrow}\, \bar{D}^{*0\uparrow\uparrow}$, $S{=}\frac{1}{2}$: $(c^{\uparrow} u^{\downarrow} d^{\downarrow})\,(\bar{c}^{\uparrow} u^{\uparrow}) \Longrightarrow J/\psi^{\uparrow\uparrow}$ preferred
- $\Sigma_c \bar{D}$: no preference for $J/\psi^{\uparrow\uparrow}$ over $\eta_c^{\uparrow\downarrow}$

$P_c(4312) \sim \Sigma_c \bar{D}$ molecule.
So why no $D\bar{D}$ molecule?

Parity & ang. mom. conservation $\Rightarrow$ no $DD\pi$ vertex

no $\Rightarrow$ one-π exchange in $D\bar{D}$, $B\bar{B}$

explains why $D\bar{D}$, $B\bar{B}$ not seen

But one π exchange does contribute to

$D\bar{D}^* \sim X(3872), Z_c(3900)$, $D^*\bar{D}^* \sim Z_c(4020)$

and $B\bar{B}^* \sim Z_b(10610)$, $B^*\bar{B}^* \sim Z_b(10650)$

so what binds $\Sigma_c \bar{D}$ but not $D\bar{D}$?

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