Theoretical implications of new results

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Joint work with Jon Rosner

Virtual Snowmass RF7, Update on Hadron Spectroscopy, Oct. 25, 2021

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

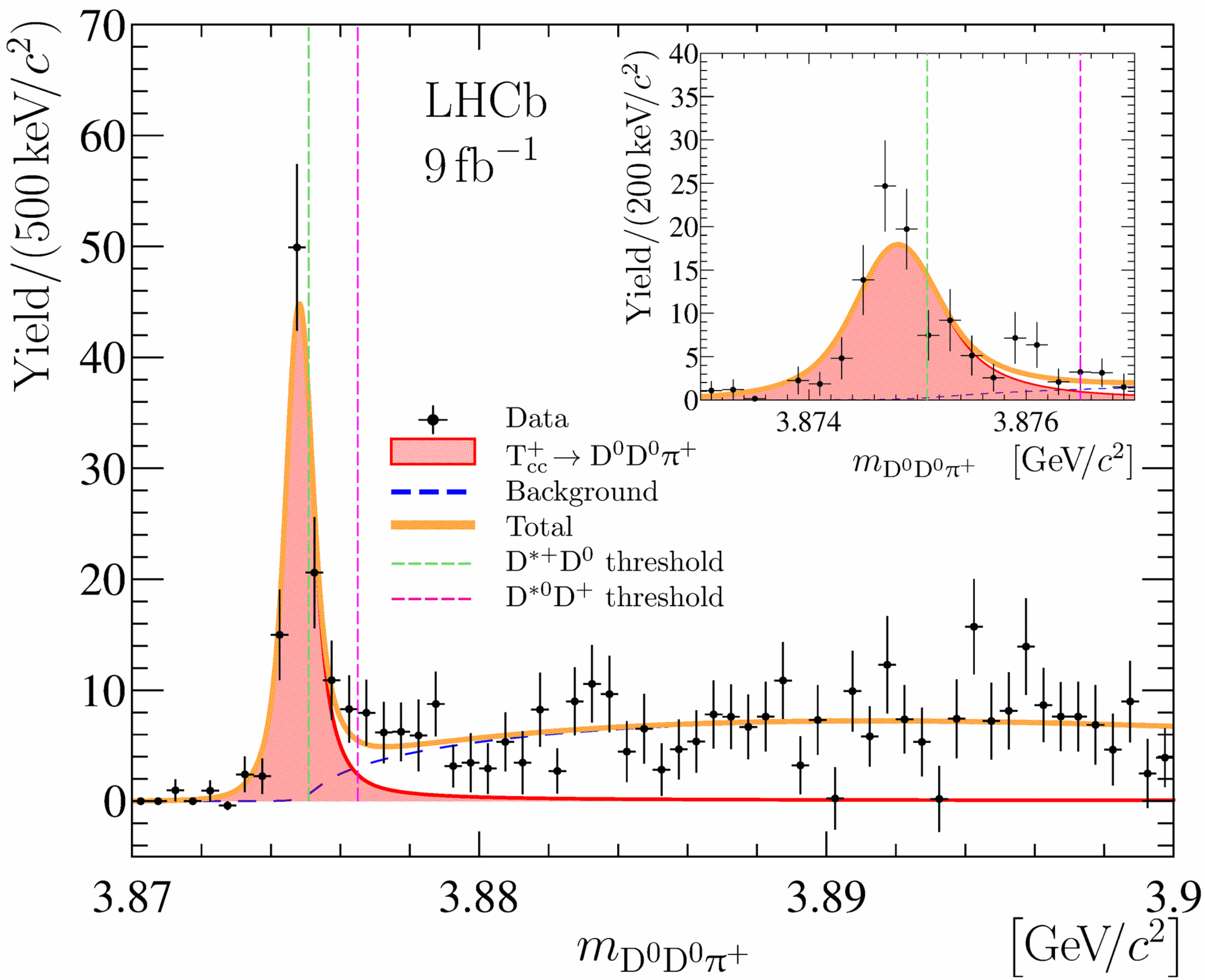
- non $\bar{q}q'$ mesons, e.g. $\bar{Q}Q\bar{q}q$, $QQ\bar{q}\bar{q}$
  $Q = c, b \quad q = u, d, s$
- non $qq'q''$ baryons, e.g. $\bar{Q}Qqq'q''$

two key questions:

- which additional exotics should we expect?
- how are quarks organized inside them?

Tq dq-dq had. mol.

LHCb 2109.01038 & 2109.01056: narrow resonance w. quark content $(cc\bar{u}\bar{d})$



The $D^0D^0\pi^+$ mass distribution. The $D^0D^0\pi^+$ mass distribution where the contribution of the non-D^0 background has been statistically subtracted. The result of the fit described in the text is overlaid.

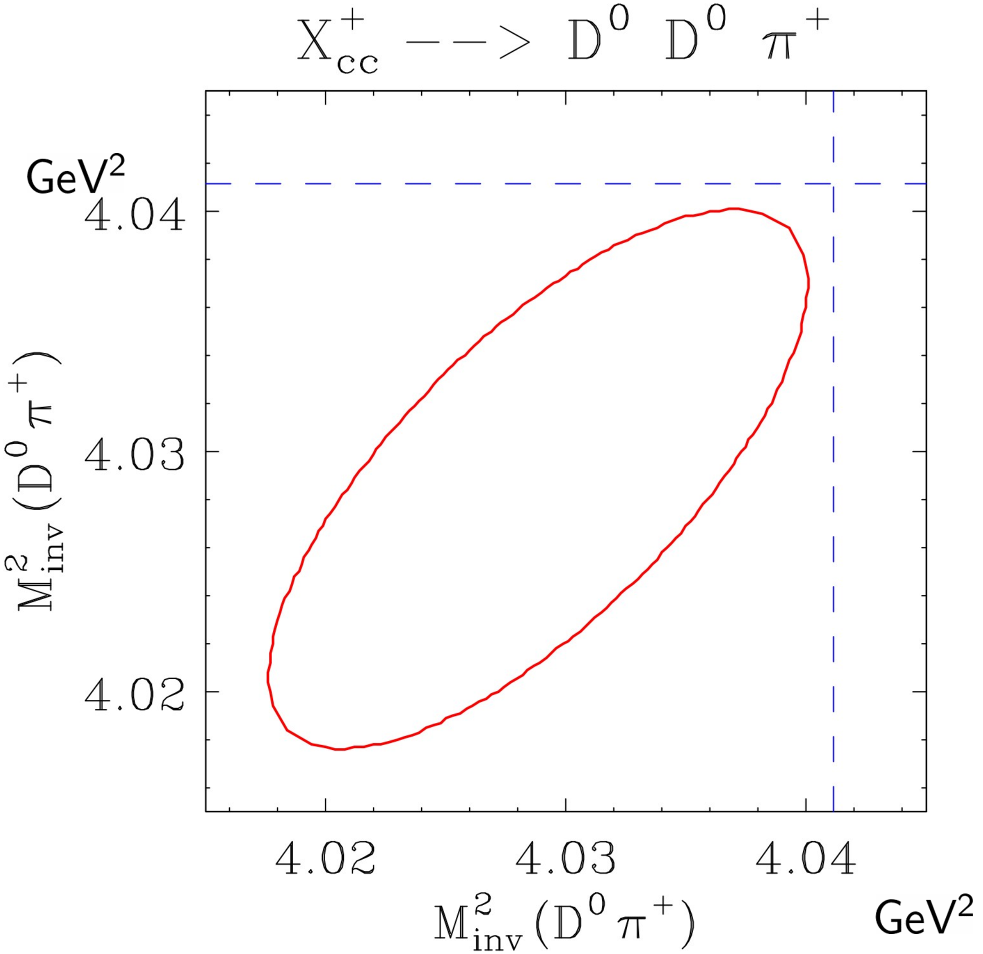
sharp peak in $M_{inv}(D^0 D^0 \pi^+)$:

- a compact $(cc\bar{u}\bar{d})$ Tq?
- *a* $\mathrm{D}^{*+} D^0$ hadronic molecule?
- a kinematic effect?
- a mixture?

wishlist:
amplitude analysis, tracking complex $\mathcal{A}(M_{inv})$

- challenging; needs more data

in the meantime...



overlapping-resonance:

$\Rightarrow$ peak in $M(D^0D^0\pi^+)$ kinematic effect or true Tq ?

propose to study $D^0D^0K^+$ system to help resolve this

- MK & J. Rosner, to appear on arXiv on Tue, Oct 26

$D_{s1}^{*+}(2700)$: lowest-lying $D^0 K^+$ resonant subsystem in $D^0 D^0 K^+$
$M = 2714 \pm 5$ MeV, $\Gamma = 122 \pm 10$ MeV, $J^P = 1^-$; $\equiv D_s(2714)$ analogous to D^{*+}
For $M(D^0 D^0 K^+) = 4588$ MeV $D_s(2714)$ just above threshold

$\Rightarrow$ look for peak in $M(D^0 D^0 K^+)$ near 4588 MeV. analogous to T_{cc} ?

if seen, could indicate tangency condition helps generate 3-body resonance (albeit a broad one, given $D_s(2714)$ width).

possible connection to $T(ccsq)$ at 4106 ± 12 MeV ?

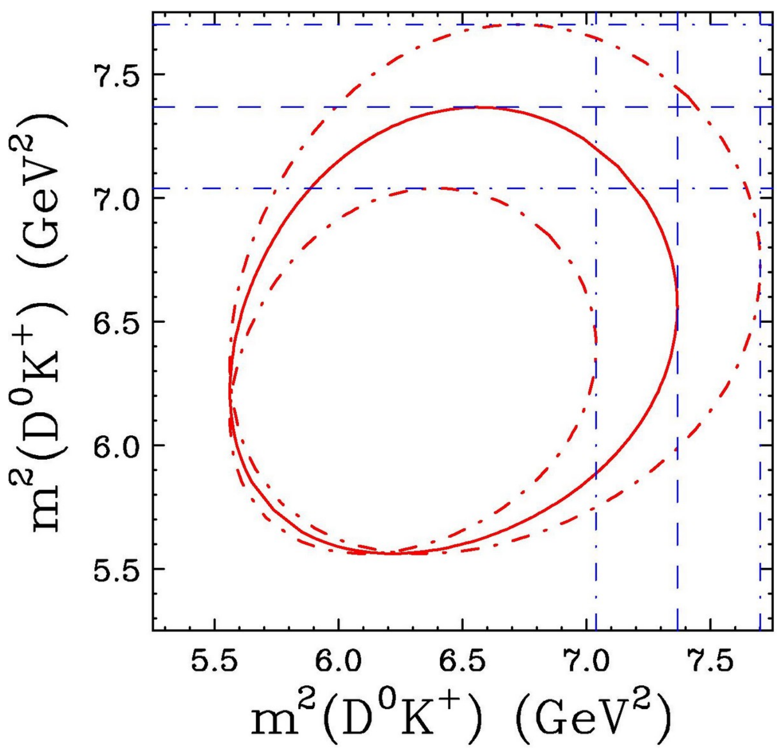


Table 1: Signal yield, N, Breit–Wigner mass relative to $D^{*+}D^0$ mass threshold, δm_{BW}, and width, Γ_{BW}, obtained from the fit to the $D^0D^0\pi^+$ mass spectrum. The uncertainties are statistical only.

Parameter	Value
N	117 ± 16
δm_{BW}	$-273 \pm 61 \quad \text{keV}/c^2$
Γ_{BW}	$410 \pm 165\,\text{keV}$

$$\delta m_{pole} = -360 \pm 40\,^{+4}_{-0}\ \text{keV}/c^2\,, \qquad @\ 4.3\,\sigma$$
$$\Gamma_{pole} = 48 \pm 2\,^{+0}_{-14}\,\text{keV}\,,$$

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

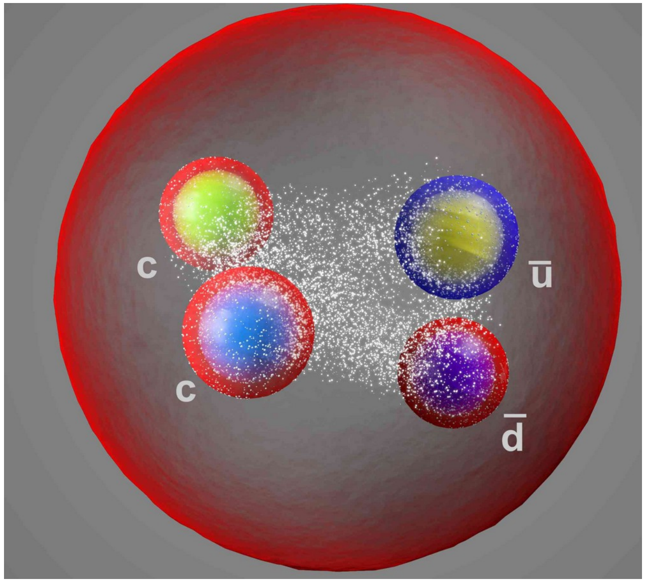
so $T_{cc}^+ \Longleftrightarrow D^{*+}D^0$, with very little $D^{*0}D^+$

$D^*(2010)^\pm$ Decay Modes

$D^*(2010)^-$ modes are charge conjugates of the modes below.

		Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
	Γ_1	$D^0\pi^+$	$(67.7 \pm 0.5)\%$		39
	Γ_2	$D^+\pi^0$	$(30.7 \pm 0.5)\%$		38
EXP?	Γ_3	$D^+\gamma$ M1 transition, destr. interf. between c and dbar (JR)	$(1.6 \pm 0.4)\%$		136

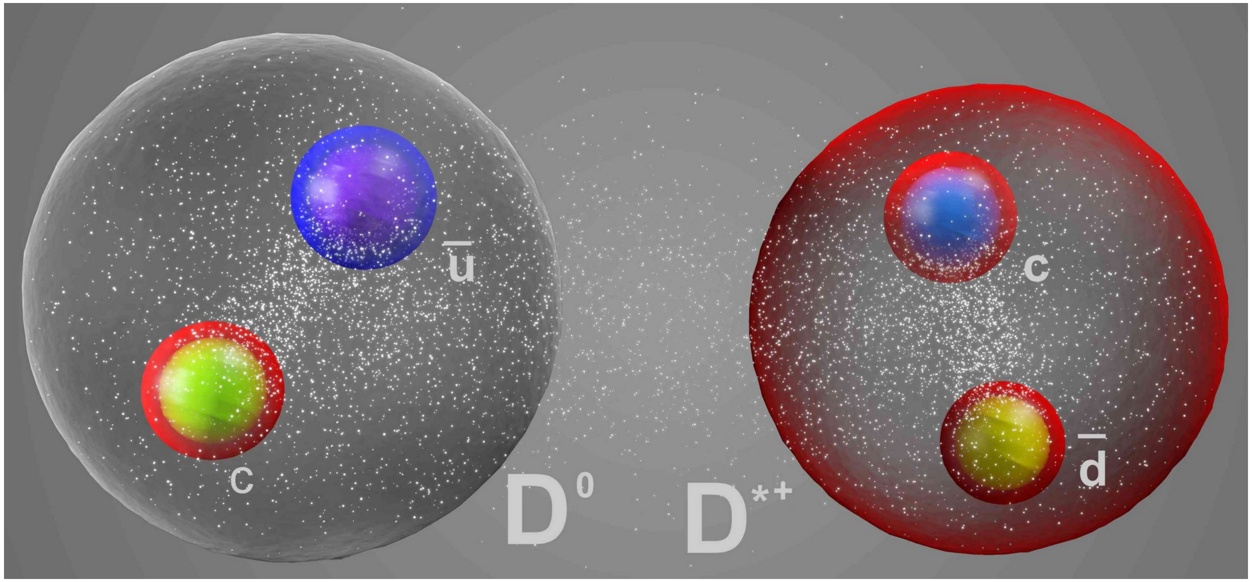
tightly-bound tetraquark



each quark sees the color charges of all other quarks

or

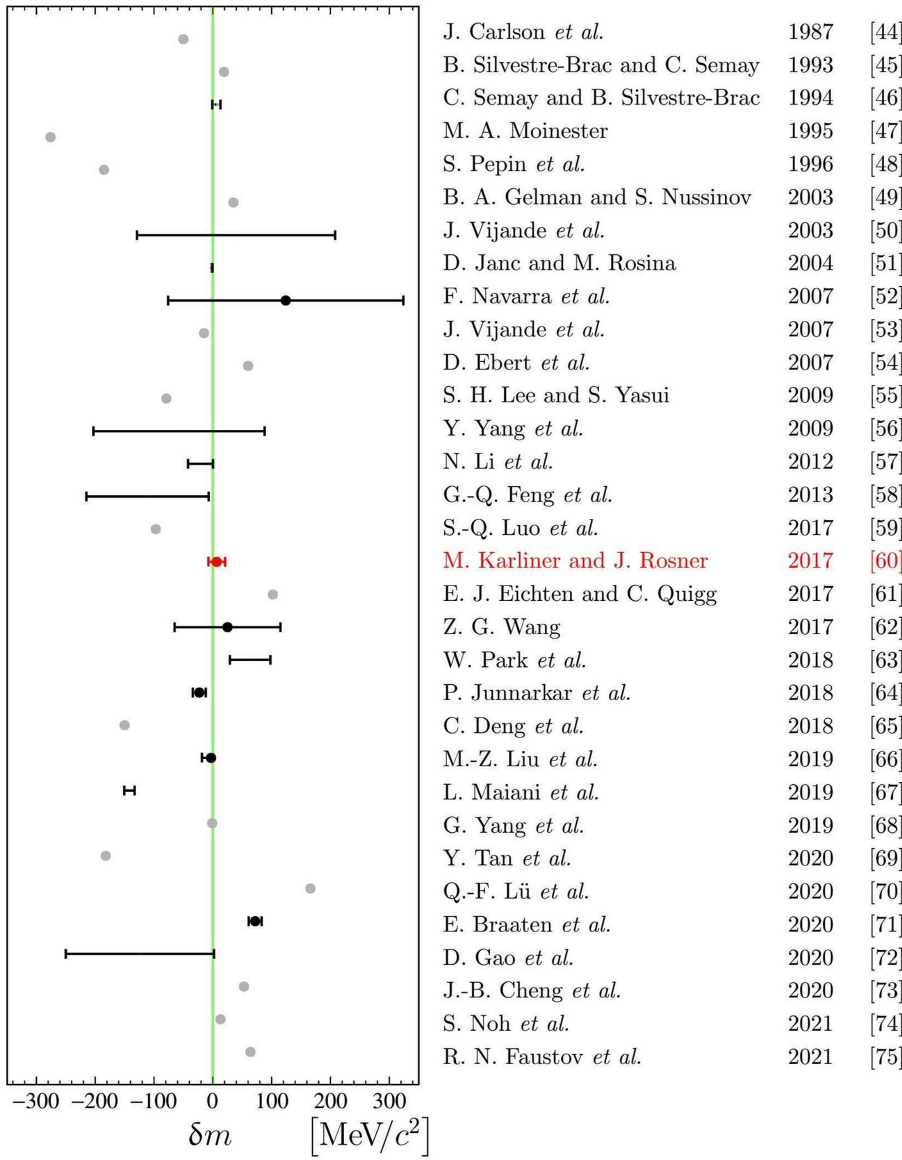
hadronic molecule?



two color singlets interacting by light meson x-change

TH predictions for T_{cc}^{+} mass, $I = 0$, $J^P = 1^+$

$\delta m_{\mathrm{U}} = -359 \pm 40\,^{+9}_{-6}\,\mathrm{keV}/c^2$



Theory predictions for the mass of the ground isoscalar $\mathrm{J^P = 1^+}$ $\mathrm{cc\bar{u}\bar{d}}$ tetraquark $\mathrm{T_{cc}^{+}}$ state [44–75]. Masses are shown relative to the $\mathrm{D^{*+}D^0}$ mass threshold.

Adapted from supplemental material for LHCb-PAPER-2021-032

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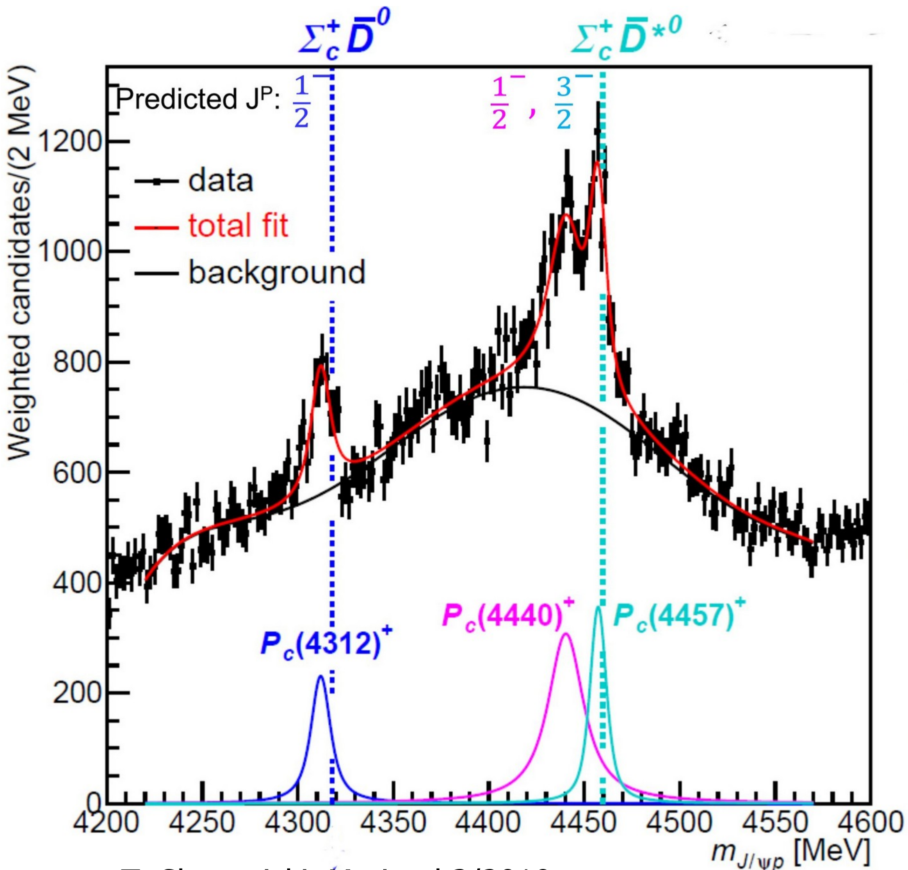
$SU(3)_F$ multiplet structure: different for compact states vs. hadronic molecules

- P_c-s $= (\bar{c}cuud)$ as a clearcut example



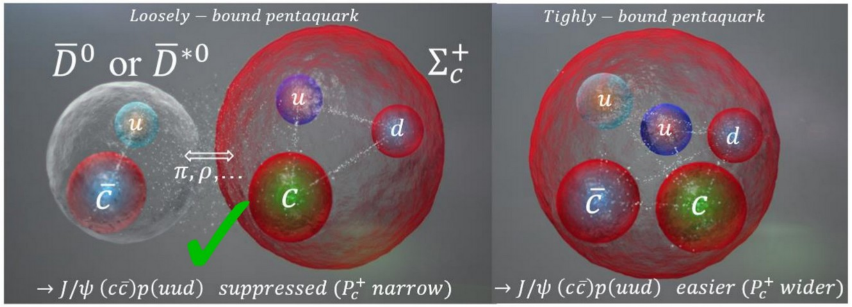
T. Skwarnicki, Moriond 3/2019

observe all 3 S-wave states:

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

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

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!



$SU(3)_F$ multiplet structure: different for compact states vs. hadronic molecules

- P_c-s $= (\bar{c}cuud)$ as a clearcut example

consider $u \to s \Rightarrow$ hypothetical $P_{css} = (\bar{c}cssd)$:

candidate hadronic molecules:
either $(css)(\bar{c}d) \equiv \Omega_c\, D^{*-}$
or $(csd)(\bar{c}s) \equiv \Xi_c^0 D_s^{*-}$

in both cases one hadron doesn't couple to light u, d quarks, so hadronic molecules unlikely

but if P_c-s $= (\bar{c}cuud)$ a compact 5q,
$u \to s$ should still yield narrow resonance
analogous argument for $Z_b = (\bar{b}bu\bar{d})$

- lessons for T_{cc} ?
- what if a mixture of compact Tq and a molecule?

hadrons w. heavy quarks are *much simpler:*

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

- Phenomenological approach
- Identify eff. d.o.f. & their interactions
- Extract model parameters from exp
- Then use them to make predictions

apply the toolbox to

doubly-heavy baryons , e.g. ccu

and

doubly-heavy tetraquarks, e.g. $cc\bar{u}\bar{d}$

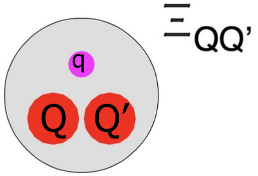
in both heavy cc diquark 3_c^* coupled to a light 3_c

doubly-heavy baryons non-exotic, must exist

$\Rightarrow$ excellent testing ground for the toolbox

MK & JR, PRD 90, 094007(2014)

doubly heavy baryons: mass predictions

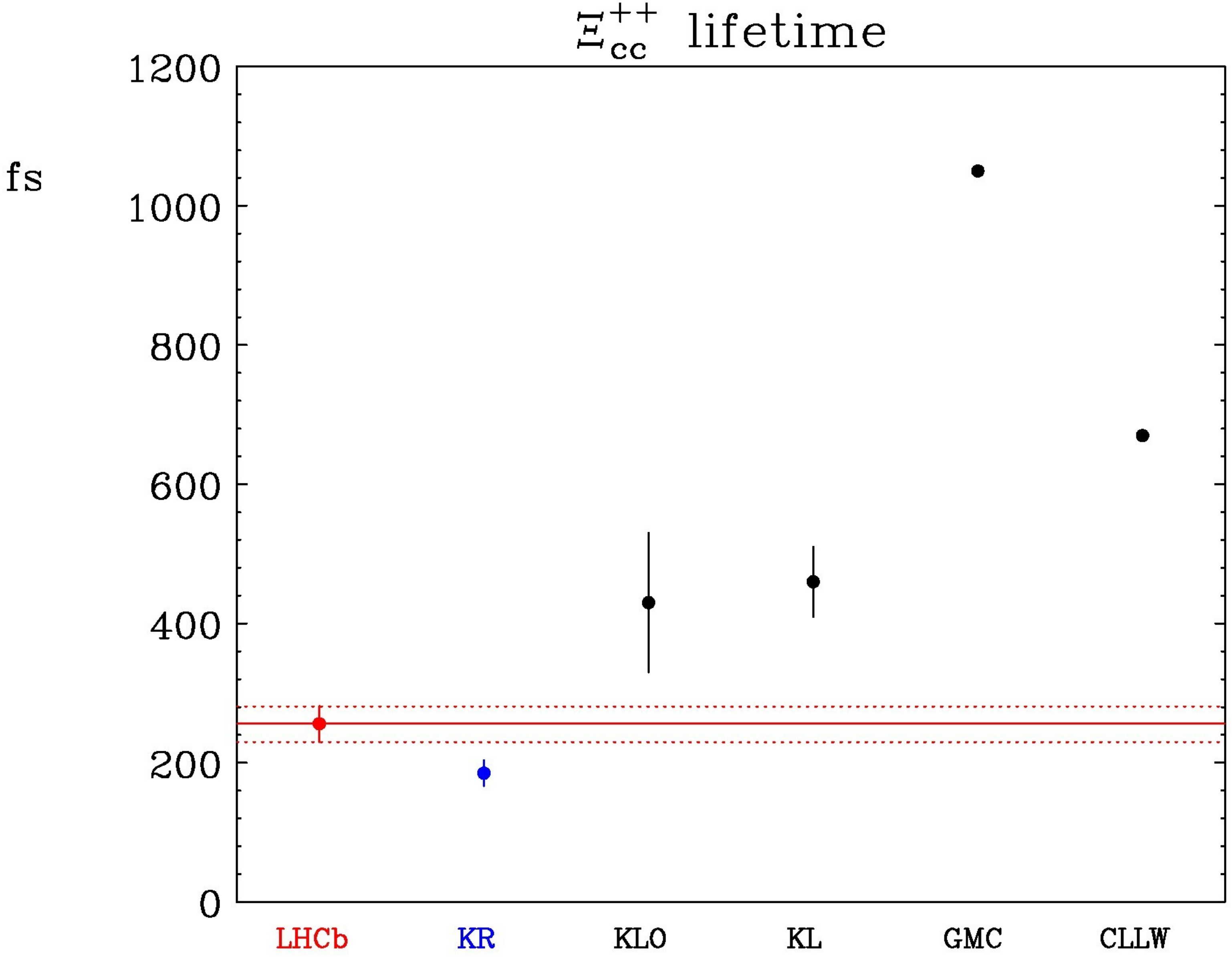


MK & JR, Phys. Rev. D90, 094007 (2014)

TABLE XVIII. Summary of our mass predictions (in MeV) for lowest-lying baryons with two heavy quarks. States without a star have $J = 1/2$; states with a star are their $J = 3/2$ hyperfine partners. The quark q can be either u or d. The square or curved brackets around cq denote coupling to spin 0 or 1.

State	Quark content	$M(J = 1/2)$	$M(J = 3/2)$
$\Xi_{cc}^{(*)}$	ccq	3627 ± 12	3690 ± 12
$\Xi_{bc}^{(*)}$	$b[cq]$	6914 ± 13	6969 ± 14
Ξ'_{bc}	$b(cq)$	6933 ± 12	$\cdots$
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

LHCb: 3621.6 ± 0.4 PRL 119,112001, (2017)



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

ccq mass calculation

sum of :

- $2m_c$
- V_{cc} in 3^*_c
- $V_{HF}(cc)$
- $V_{HF}(cq)$
- m_q

ccq mass calculation

sum of :

- $2m_c$
- V_{cc} in 3^*_c
- $V_{HF}(cc)$

} no exp info !

- $V_{HF}(cq)$
- m_q

Effective masses

in mesons:

$$m_u^m = m_d^m = m_q^m = 310 \text{ MeV}, \; m_c^m = 1663.3 \text{ MeV}$$

in baryons:

$$m_u^b = m_d^b = m_q^b = 363 \text{ MeV}, \; m_c^b = 1710.5 \text{ MeV}$$

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

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

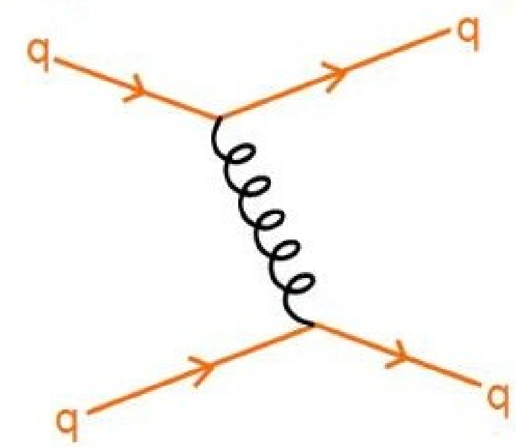
$$V(c\bar{c}) = \bar{M}(c\bar{c}:1S) - 2m_c^m = -258.0 \text{ MeV}.$$

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

in weak coupling follows
from color algebra in $1gx$

here a *dynamical assumption*:

$V(cc)$ and $V(c\bar{c})$ factorize
into color$\times$space



gluon exchange by 2 quarks

$V_{HF}(cc)$ from $V_{HF}(c\bar{c})$:

$$V_{HF}(cc) = \frac{a_{cc}}{m_c^2}$$

$$V_{HF}(c\bar{c}) = M(J/\psi) - M(\eta_c) = 113.2 \text{ MeV} = \frac{4a_{\bar{c}c}}{m_c^2}$$

assume $a_{cc} = \frac{1}{2} a_{c\bar{c}}$,

$$\Rightarrow \quad \frac{a_{cc}}{m_c^2} = 1/2 \cdot \frac{M(J/\psi) - M(\eta_c)}{4} = 14.2 \text{ MeV}$$

Contributions to Ξ_{cc} mass

Contribution	Value (MeV)
$2m_c^b + m_q^b$	3783.9
cc binding	-129.0
$a_{cc}/(m_c^b)^2$	14.2
$-4a/m_q^b m_c^b$	-42.4
Total	3627 ± 12

The $\pm$12 MeV error estimate from ave. error for Qqq baryons can the strong QQ interaction stabilize

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

heavy-quark analogue of the H dibaryon?

$\Rightarrow$ below $2\Lambda_Q$

but above $\Xi_{QQ} N$

$\Rightarrow$ unstable

an ugly duckling...

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.

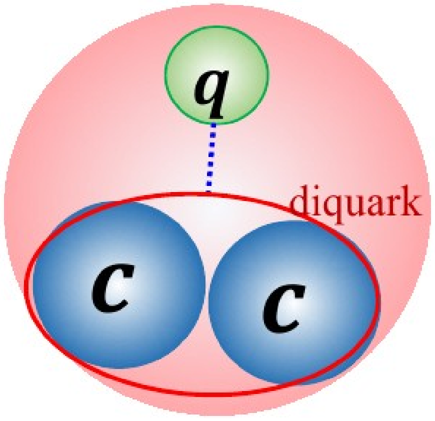
DOI: 10.1103/PhysRevLett.119.202001

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

build on accuracy of the Ξ_{cc} mass prediction

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

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

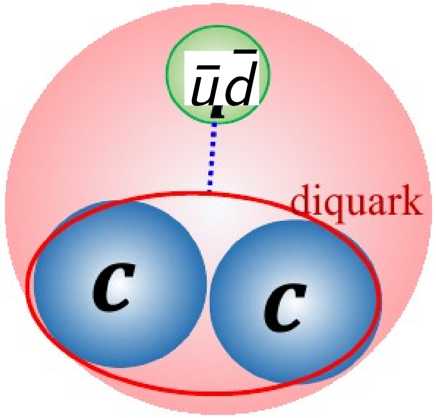
(it's the lightest one)

$\Rightarrow$ 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

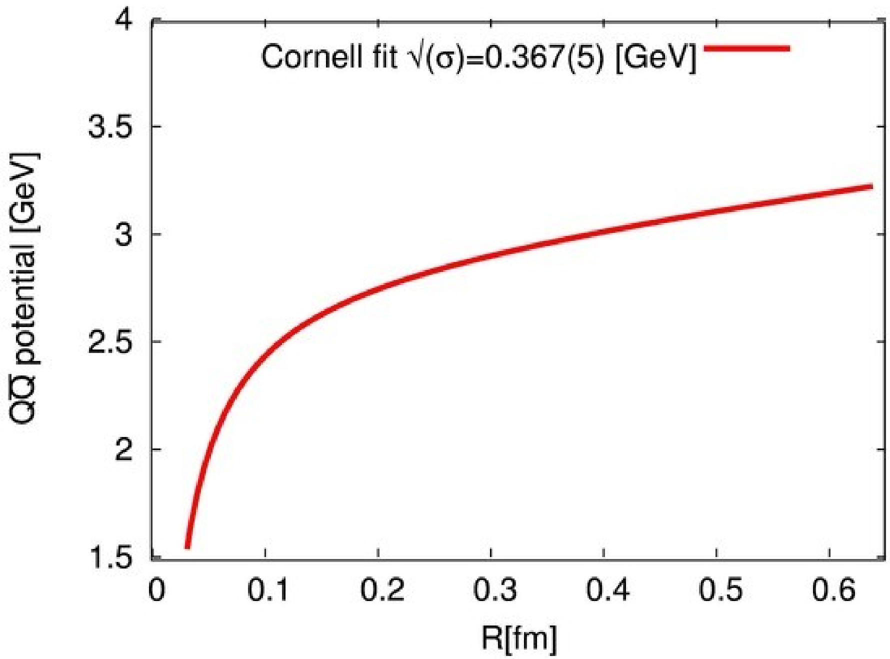
qualitatively $E_{binding} \sim \alpha_s^2 M_Q$

so for $M_Q \to \infty$

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

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



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

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

because in BB^* the two b quarks are far from each other

and the v. large bb binding energy is lost

$\Rightarrow$ T_{bb} is stable against strong decay

Contributions to mass of $(cc\bar{u}\bar{d})$ Tq with $J^P = 1^+$

Contribution	Value (MeV)
$2m_c^b$	3421.0
$2m_q^b$	726.0
$a_{cc}/(m_c^b)^2$	14.2
$-3a/(m_q^b)^2$	-150.0
cc binding	-129.0
Total	3882.2 ± 12

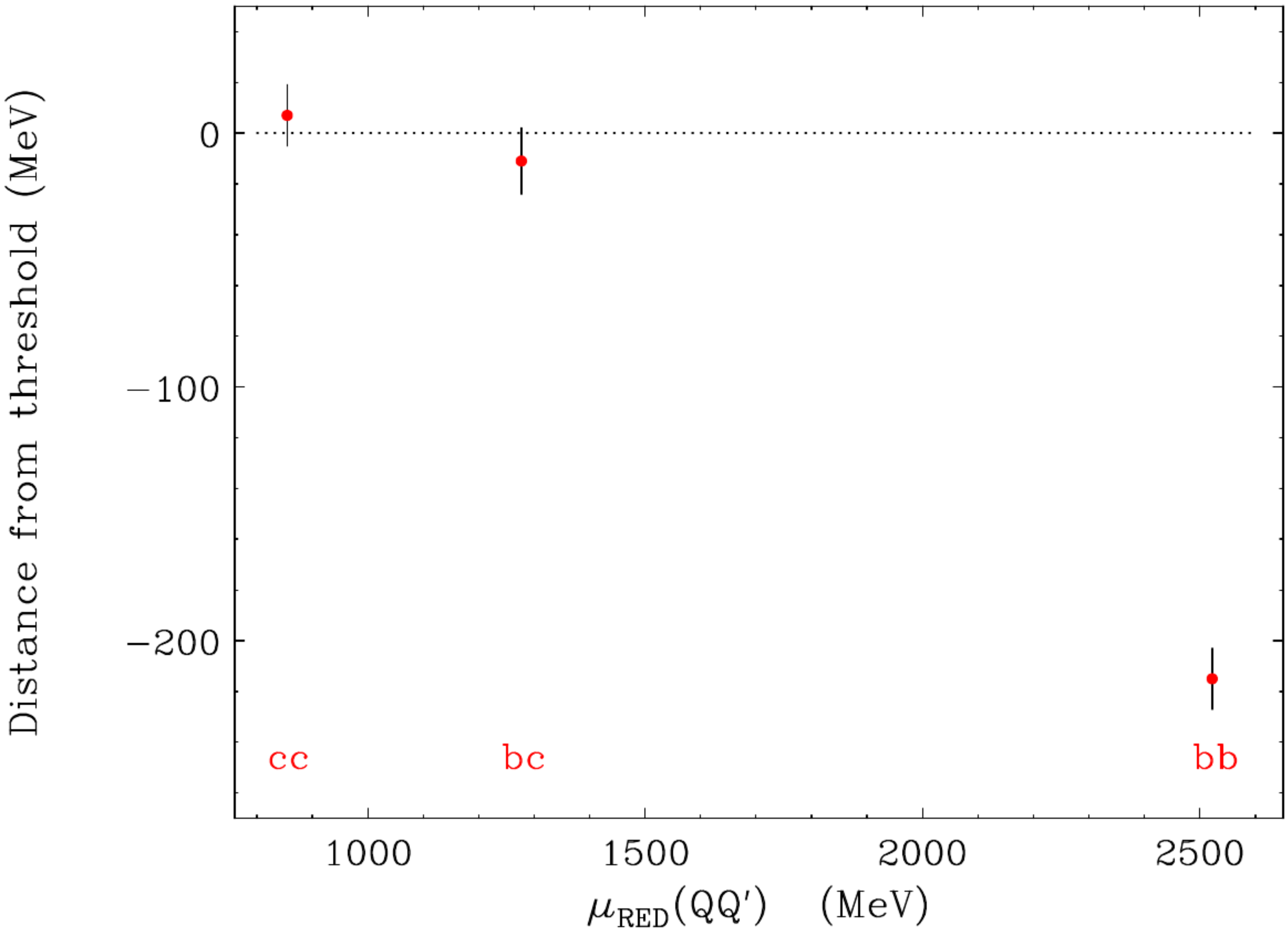
7 MeV above $D^0 D^{+*}$ threshold,
but if use measured $M(X_{cc}^{++}) \Rightarrow$ only 1 MeV above $D^0 D^{+*}$

Contributions to mass of $(bc\bar{u}\bar{d})$ Tq* with $J^P = 0^+$

Contribution	Value (MeV)
$m_b^b + m_c^b$	6754.0
$2m_q^b$	726.0
$-3a_{bc}/(m_b^b m_c^b)$	-25.5
$-3a/(m_q^b)^2$	-150.0
bc binding	-170.8
Total	7133.7 ± 13

*lowest-mass *bc* diquark has $S=0$, so $J=0$

Distance of the $QQ'\bar{u}\bar{d}$ Tq masses from the relevant two-meson thresholds (MeV).



Tetraquark production

$$\sigma(pp \to T(bb\bar{u}\bar{d}) + X \lessapprox \sigma(pp \to \Xi_{bb} + X)$$

same bottleneck: $\sigma(pp \to \{bb\} + X)$

hadronization:

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

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 $\int \mathcal{L}dt$

$T(cc\bar{u}\bar{d})$ near thr. $\to$ v. narrow accessible

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

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

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

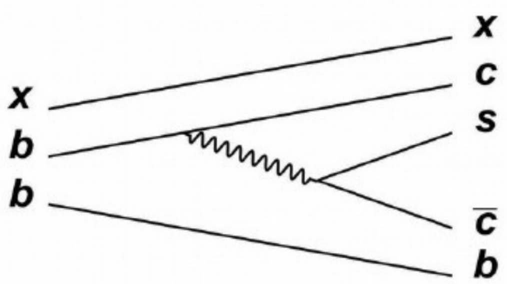
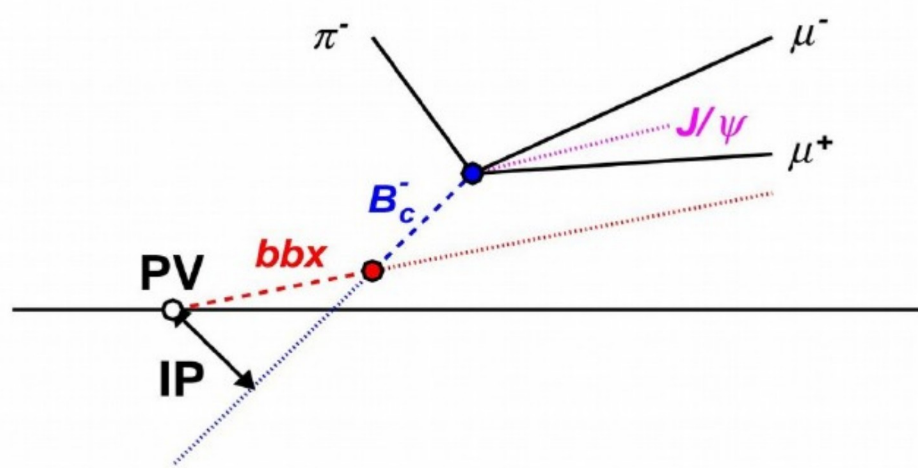


Diagram for production of a B_c^- meson from a double beauty hadron decay.



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

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

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

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

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

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

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

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

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^{*+}

LHCb, 08/2020:

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

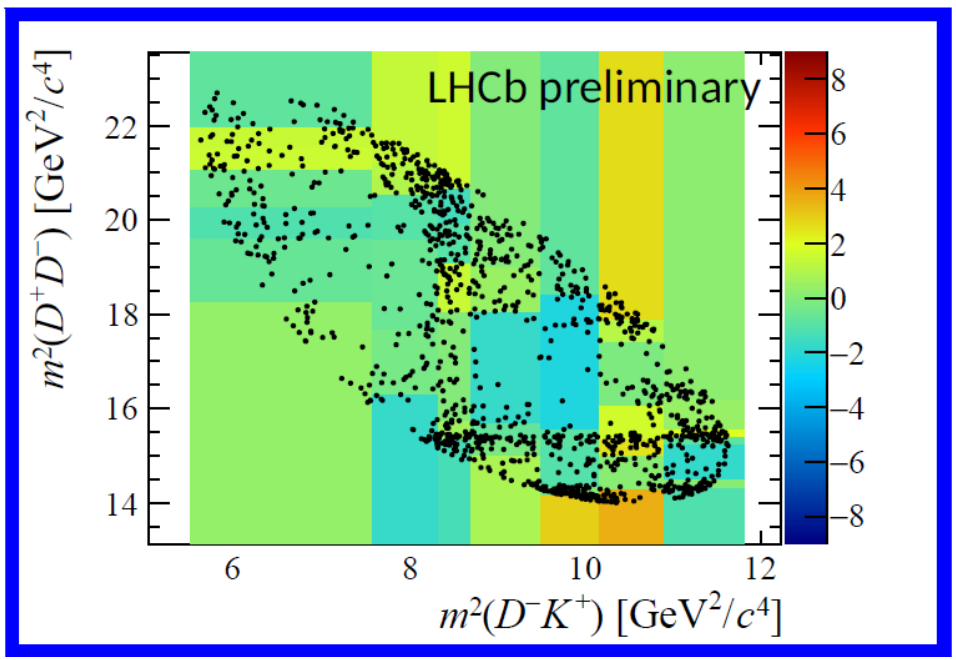
first exotic hadron with open heavy flavor:

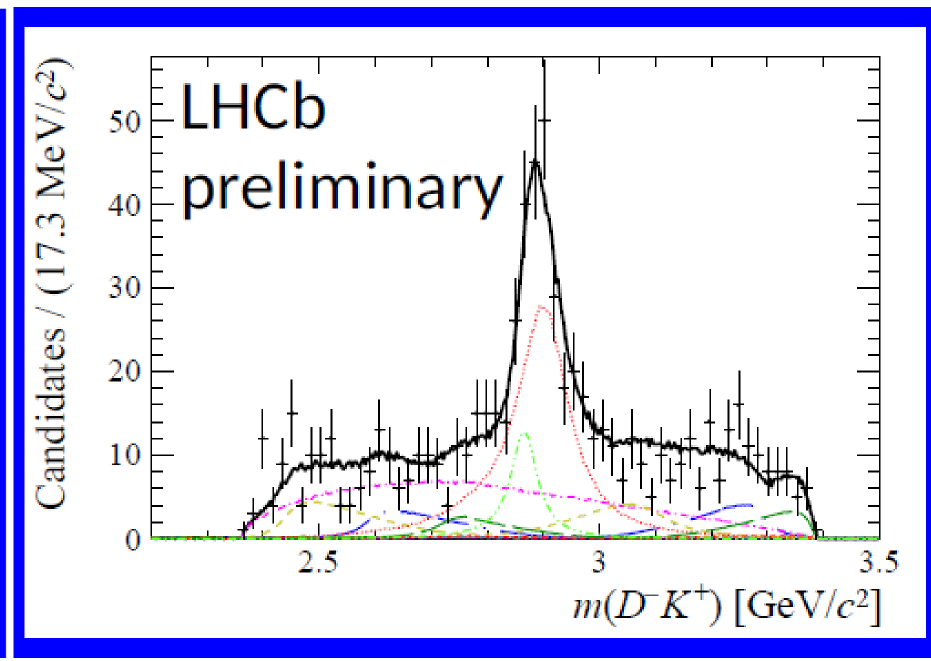
$cs\bar{u}\bar{d}$ tetraquark

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

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

2009.00025 & 2009.00026





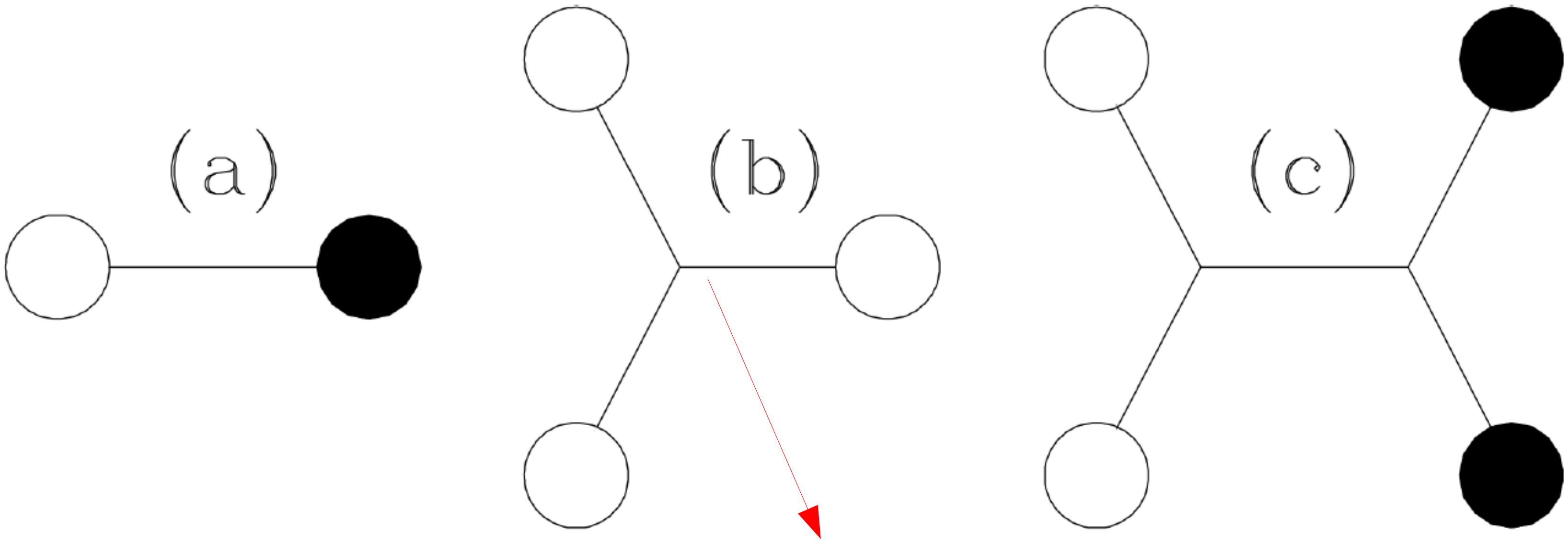
MK & JR:arXiv:2008.05993 & PRD, in press

- two BW-s:
  $X_0(2900)$, $J^P = 0^+$ at 2866±7 MeV, $\Gamma_0 = 57\pm13$ MeV
  $X_1(2900)$, $J^P = 1^-$ at 2904±7 MeV $\Gamma_1 = 110\pm12$ 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



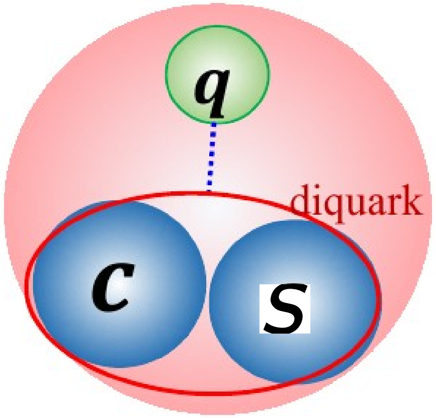
string junction mass: $S = 165.1$ MeV

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.

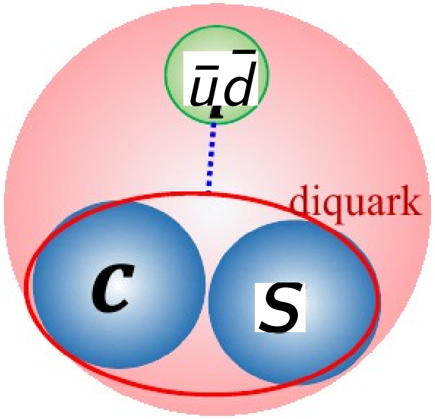
$\Xi_c(csq)$ baryon vs. $cs[\bar{u}\bar{d}]$ tetraquark

- 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:

$m_s = 482.2$ 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^+ 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?

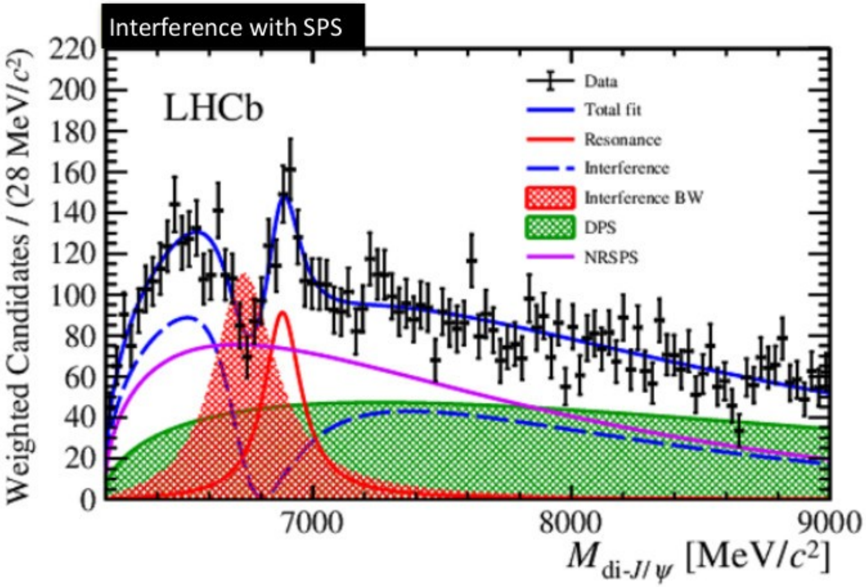
The predictions for masses of the $bb\bar{u}d$, $cc\bar{u}d$, and $bc\bar{u}d$ masses are shifted upward in the string-junction picture by 126, 118, and 122 MeV, respectively. The $bb\bar{u}\bar{d}$ state is still stable with respect to strong and EM interactions, as its mass is predicted to lie 89 MeV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

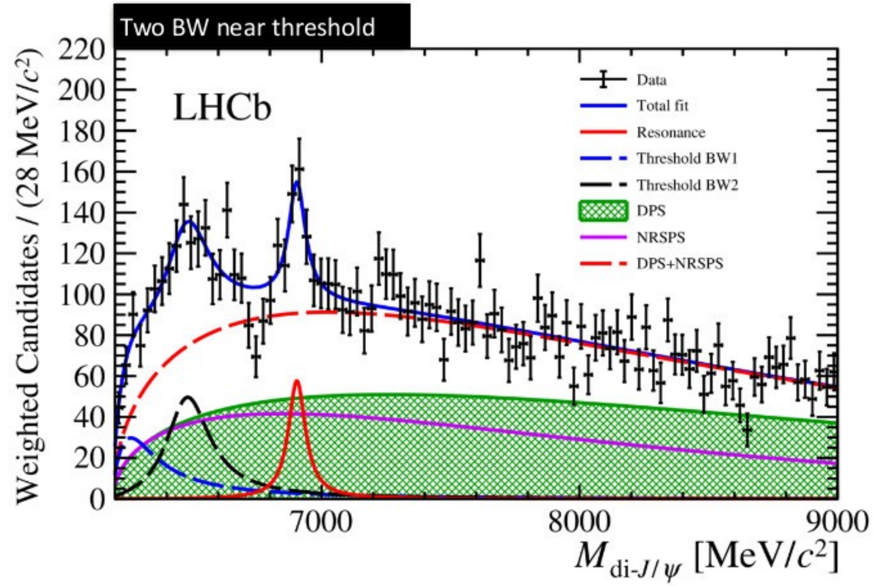
LHCb, June 2020:

- 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

LHCb – talk by Daniel Johnson





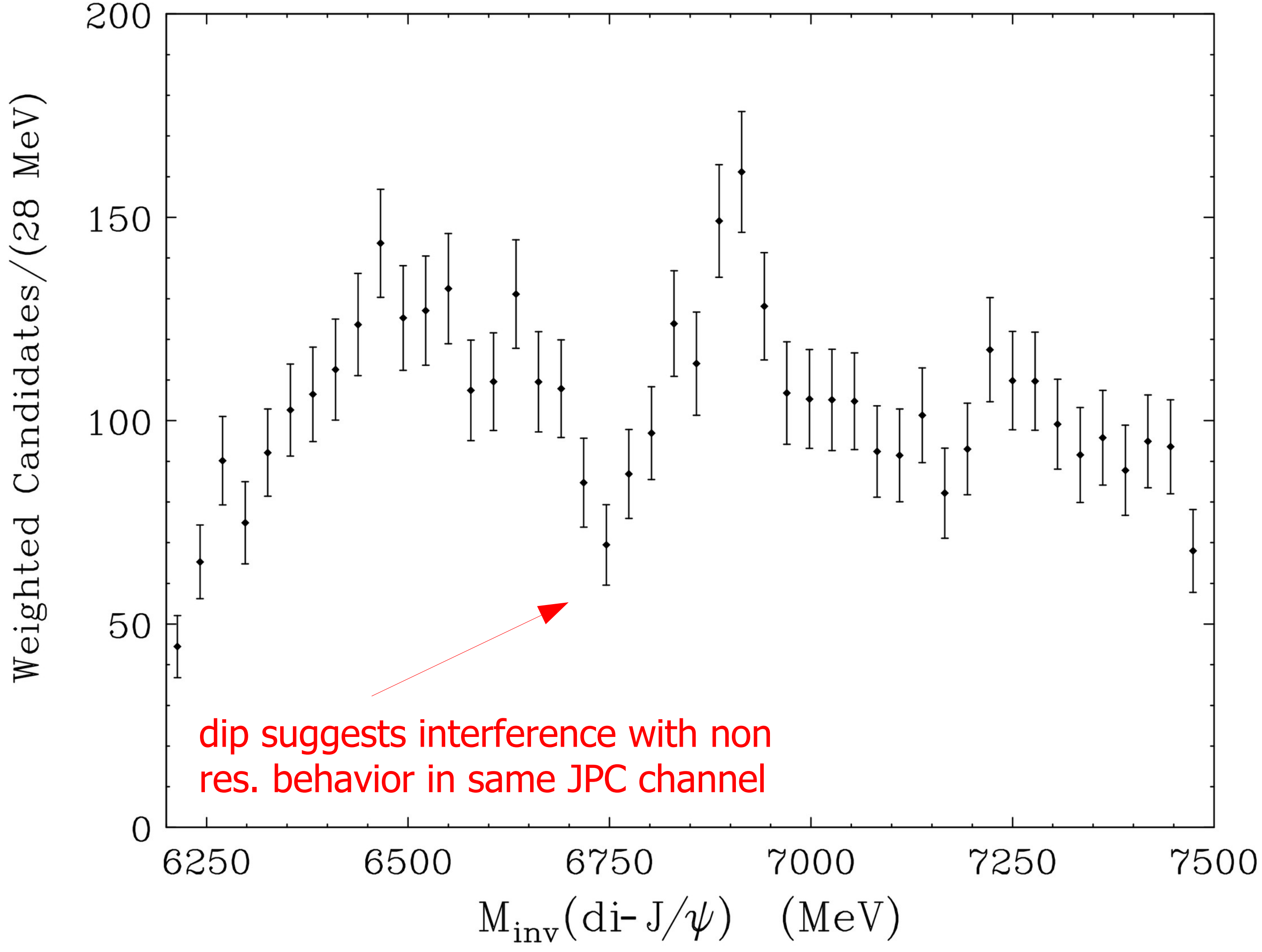
- $T_{c\bar{c}c\bar{c}}$ state at $6.9\ \mathrm{GeV}/c^2$ and either:
  - one more (interfering with NRSPS), or
  - two more, near threshold
- Feed-down may contribute; unlikely for narrow state
- Near-threshold rescattering could be important

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

MK & JR

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:

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

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

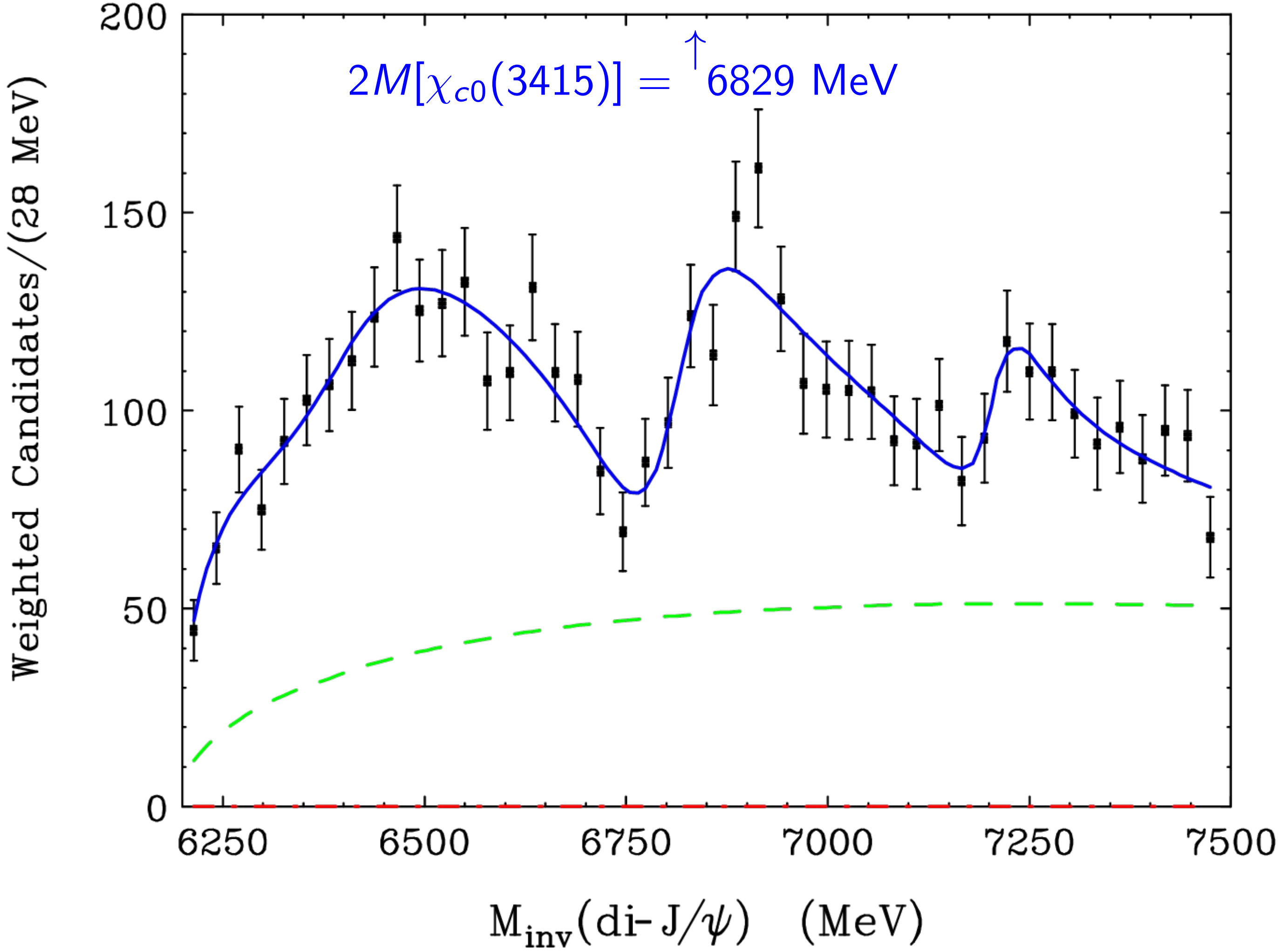


Figure 1: Spectrum of J/ψ pairs reported by the LHCb Experiment [3], together with our best fit to data (blue line), as given in Table I and described in the Appendix. The green dashed line denotes the DPS contribution, subtracted before fitting.

- 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.

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

$\bar{B}B^*$ molecule

tightly-bound tetraquark

why is it so ?

Exotics with $\bar{Q}Q$ vs. QQ: very different

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

but *only* if $\bar{Q}Q$ color singlet

$\Rightarrow$ $\bar{Q}Q$ can immediately hadronize as quarkonium

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

$\Rightarrow$ deuteron-like "hadronic molecules"

vs. QQ *never* a color singlet,

$\Rightarrow$ tightly bound exotics, tetraquarks

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

$m_b \approx 5$ GeV

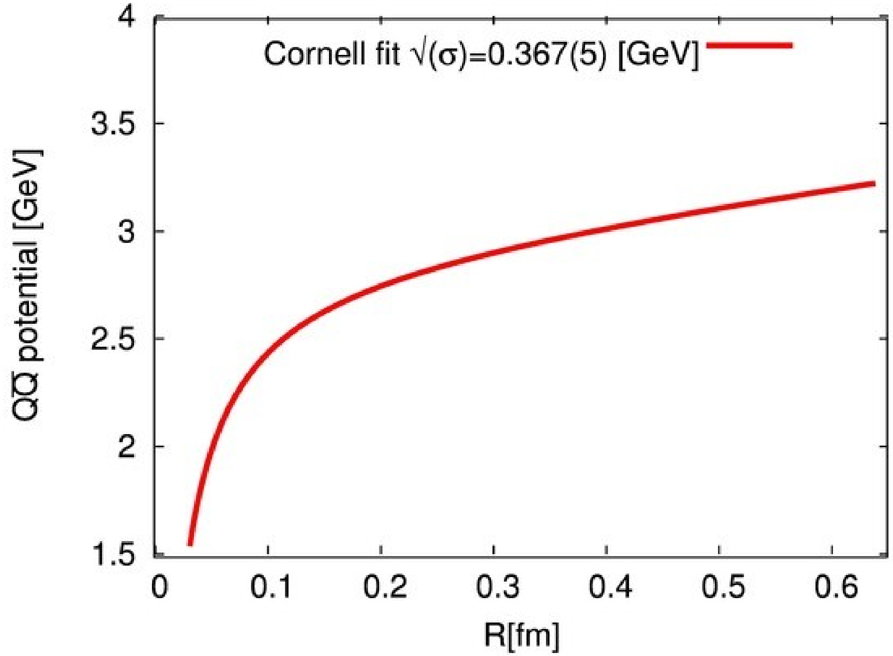
$\Rightarrow R(bb) \sim 0.2$ fm

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

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

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

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



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

if $b\bar{b}$ compact $\Rightarrow$ color singlet:

decouple from $u\bar{d}$, $\quad Z_b \to \Upsilon\pi^+$

so only semi-stable config.,

"hadronic molecule:" $\bar{B}B^* \sim 1$ GeV above $\Upsilon\pi$

yet narrow ~ 15 MeV, because $r(\Upsilon)/r(\bar{B}B^*) \ll 1$

very different!

Upshot:

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

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

SUMMARY

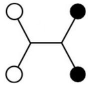
- narrow $cc\bar{u}\bar{d}$ tetraquark discovered by LHCb
- doubly charmed baryon found exactly where predicted

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

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

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

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

  $\Sigma_c B^*,\ \Sigma_b\bar{D}^*,\ \Sigma_b B^*,\ D^*B^*,\ \ldots$
- D^+K^- res. $\Leftrightarrow$ $cs\bar{u}\bar{d}$ Tq w. string junction ; $bs\bar{u}\bar{d} = \bar{B}^0K^-$?
- $J/\psi\, J/\psi$ res. $\Leftrightarrow$ excited $cc\bar{c}\bar{c}$ Tq, probably $2S$, $J/\psi\,\Upsilon,\ \Upsilon\Upsilon$?

exciting new spectroscopy awaiting discovery