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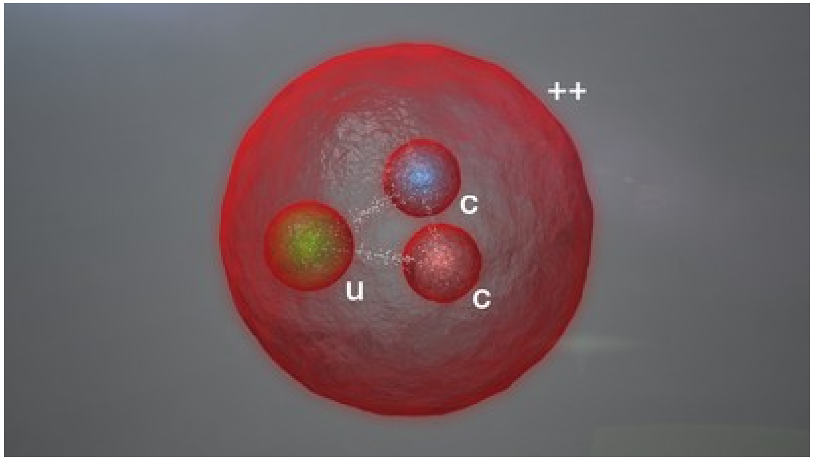

Prediction and discovery of doubly-heavy baryon

Marek Karliner
Tel Aviv University

PRD90 (2014) 9, 094007, with Jon Rosner
and
https://arxiv.org/abs/1707.01621, LHCb

Workshop on heavy hadron spectroscopy, CERN, July 17, 2017

PHYSICAL REVIEW D **90**, 094007 (2014)

Baryons with two heavy quarks: Masses, production, decays, and detection

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The large number of B_c mesons observed by LHCb suggests a sizable cross section for producing doubly heavy baryons in the same experiment. Motivated by this, we estimate masses of the doubly heavy $J = 1/2$ baryons Ξ_{cc}, Ξ_{bb}, and Ξ_{bc}, and their $J = 3/2$ hyperfine partners, using a method which accurately predicts the masses of ground-state baryons with a single heavy quark. We obtain $M(\Xi_{cc}) = 3627 \pm 12$ MeV, $M(\Xi^*_{cc}) = 3690 \pm 12$ MeV, $M(\Xi_{bb}) = 10162 \pm 12$ MeV, $M(\Xi^*_{bb}) = 10184 \pm 12$ MeV, $M(\Xi_{bc}) = 6914 \pm 13$ MeV, $M(\Xi'_{bc}) = 6933 \pm 12$ MeV, and $M(\Xi^*_{bc}) = 6969 \pm 14$ MeV. As a byproduct, we estimate the hyperfine splitting between B^*_c and B_c mesons to be 68 ± 8 MeV. We discuss P-wave excitations, production mechanisms, decay modes, lifetimes, and prospects for detection of the doubly heavy baryons.

DOI: 10.1103/PhysRevD.90.094007 PACS numbers: 14.20.Lq, 14.20.Mr, 12.40.Yx

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arXiv:1707.01621v1 [hep-ex] 6 Jul 2017

Observation of the doubly charmed baryon Ξ_{cc}^{++}

LHCb collaboration†

Abstract

A highly significant structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the Λ_c^+ baryon is reconstructed in the decay mode $pK^-\pi^+$. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon Ξ_{cc}^{++}. The mass, measured relative to that of the Λ_c^+ baryon, is found to be $3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14\,(\Lambda_c^+)\ \text{MeV}/c^2$, where the last uncertainty is due to the limited knowledge of the Λ_c^+ mass. The state is observed in a sample of proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $1.7\,\text{fb}^{-1}$, and confirmed in an additional sample of data collected at 8 TeV.

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Hadrons containing heavy quarks are simpler

than hadrons containing light quarks only,

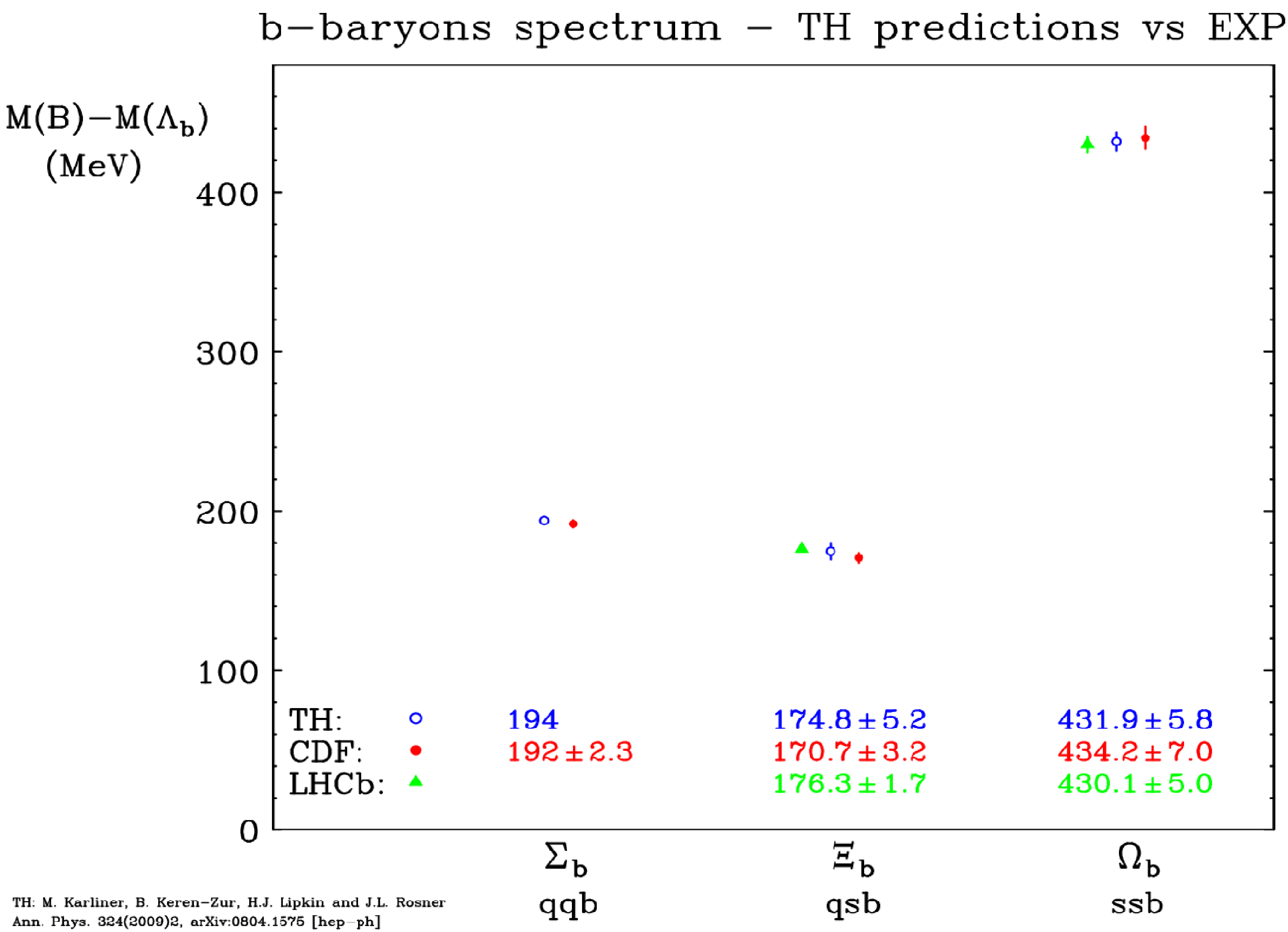
because the heavy quarks are almost static

and have a very small spin-dependent interaction

with other quarks.

This was the key to the accurate prediction of

baryons containing the b quark:



b−baryons spectrum − TH predictions vs EXP
M(B)−M(Λb)
(MeV)
0
100
200
300
400
TH:
CDF:
LHCb:
194
192 ± 2.3
174.8 ± 5.2
170.7 ± 3.2
176.3 ± 1.7
431.9 ± 5.8
434.2 ± 7.0
430.1 ± 5.0
Σb
qqb
Ξb
qsb
Ωb
ssb
TH: M. Karliner, B. Keren−Zur, H.J. Lipkin and J.L. Rosner
Ann. Phys. 324(2009)2, arXiv:0804.1575 [hep−ph]

doubly heavy baryons QQq:

$ccq,\ bcq,\ bbq, \quad q = u, d$

must exist, but have never been seen

fascinating challenge for EXP & TH

MK & J Rosner, PRD90 (2014):

LHCb sees thousands of B_c-s

$\Longrightarrow$ should see bcq, ccq, etc.

doubly heavy baryons QQq:

$ccq,\ bcq,\ bbq, \quad q = u, d$

must exist, but have never been seen until now

fascinating challenge for EXP & TH

MK & J Rosner, PRD90 (2014):

LHCb sees thousands of B_c-s

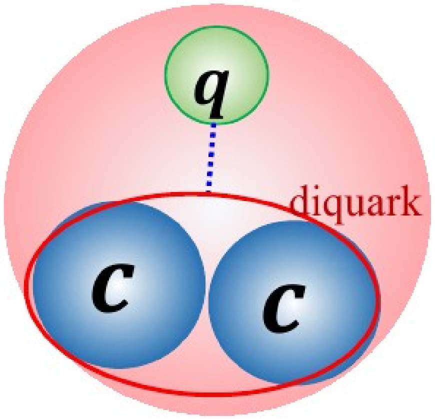
$\Longrightarrow$ should see bcq, ccq, etc.

QQq baryons are the simplest baryons:

when $m_Q \to \infty$, QQ form a static $\overline{3}_c$ diquark

$R_{diquark} \sim 1/(m_Q \alpha_s) \ll 1/\Lambda_{QCD}$

so QQq baryon $\sim$ $\bar{Q}q$ meson

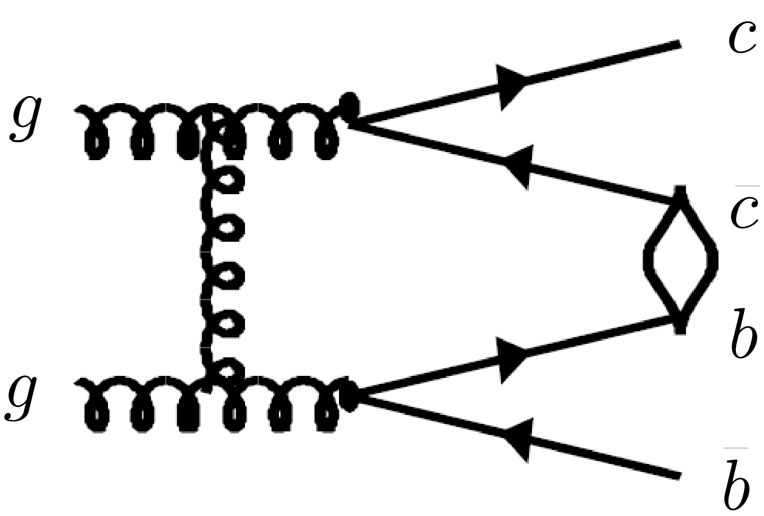


e.g. form factors: $F_{QQq}(q^2) = F_{\bar{Q}q}(q^2$

corrections: $f\left(\frac{\Lambda_{QCD}}{m_Q}\right)$, calculable in QCD

hydrogen atom of baryon physics!

B_c production in LHCb: gg fusion



v. hard to compute reliably from first principles, but...

Ξ_{bc} production: same diagram,

but b needs to pick up c, instead of $\bar{c}$: $\mathbf{3}_c\mathbf{3}_c$ vs. $\bar{\mathbf{3}}_c\mathbf{3}_c$

$$\Longrightarrow \quad \sigma(pp \to \Xi_{bc} + X) \sim \sigma(pp \to B_c + X)$$

LHCb is making a lot of B_c-s. $\sigma(pp \to B_c + X) = 0.4\mu b$

$\Longrightarrow$ LHCb is making a lot of (QQq) baryons !!!

best candidate: $\Xi_{cc}^{++} \equiv (ccu)$

of all QQq-s

- largest x-section, same as (ccd)
- but $\tau(ccu) \gg \tau(ccd)$
  $\Rightarrow$ much easier to detect
- (bcq) might also be accessible

  since $\tau(b) \sim 7\tau(c)$

above to be revisited

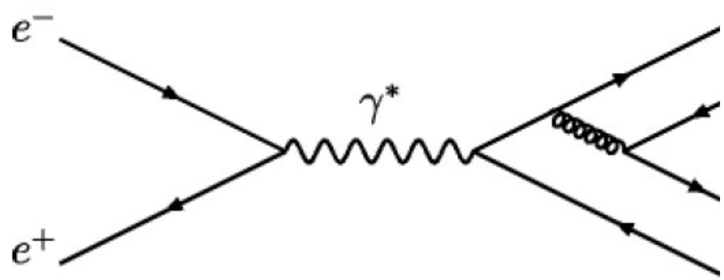
with sufficient E_{CM} may study double heavy flavor production

$e^+e^- \to b\bar{b}c\bar{c} + X$,
$e^+e^- \to b\bar{b}b\bar{b} + X$

$\Rightarrow$ a precondition for producing doubly heavy B_c, B_c^*, and doubly heavy $\Xi_{bc} = bcq$, and $\Xi_{bb} = bbq$, $q = u, d$.

must be able to see the (known) B_c state if one expects to be able to detect Ξ_{bc}

same diagram for B_c and Ξ_{bc}:



estimate $\sigma(e^+e^- \to \gamma B_c^+ B_c^- + X)$

~ 1.7 fb @90 GeV, 0.24 fb @250 GeV

masses of doubly-heavy baryons:

use same toolbox that predicted

b baryon masses.

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

ccq mass calculation

sum of :

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

ccq mass calculation

sum of :

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

$\Big\}$ no exp info ! (applies to V_{cc} in 3^*_c and $V_{HF}(cc)$)

Effective masses

in mesons:

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

in baryons:

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

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

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

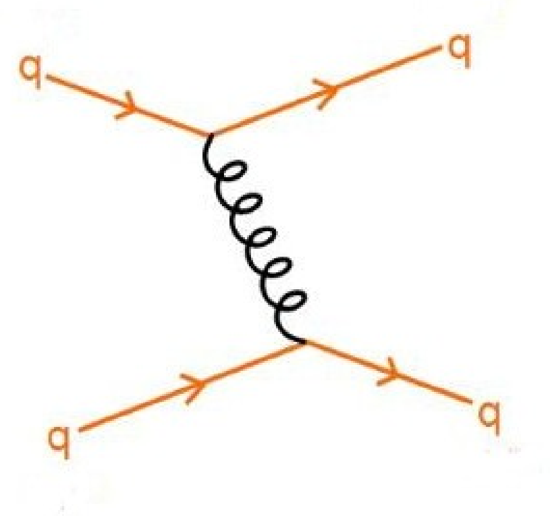
$$V(c\bar{c}) = \bar{M}(c\bar{c}:1S) - 2m_c^m = -258.0 \text{ MeV}.$$

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

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 ± 12 MeV error estimate from ave. error for Qqq baryons

doubly heavy baryons: mass predictions

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

isospin splittings: (ccu)-(ccd), etc.

Experimental mass splittings between octet baryons

Splitting	Symbol	Value (MeV)
$M(p) - M(n)$	N_1	-1.2933
$M(\Sigma^+) - M(\Sigma^-)$	Σ_1	-8.08 ± 0.08
$M(\Sigma^+) - 2M(\Sigma^0) + M(\Sigma^-)$	Σ_2	1.535 ± 0.090
$M(\Xi^0) - M(\Xi^-)$	Ξ_1	-6.85 ± 0.21

sources of isospin splittings:

- $m_u - m_d$
- Coulomb
- color HF
- EM HF

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

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

$$\Xi_{cc,1} \equiv M(\Xi_{cc}^{++}) - M(\Xi_{cc}^{+})$$

$$\Xi_{bb,1} \equiv M(\Xi_{bb}^{0}) - M(\Xi_{bb}^{-})$$

$$\Xi_{bc,1} \equiv M(\Xi_{bc}^{+}) - M(\Xi_{bc}^{0})$$

Contributions to isospin splittings (MeV) using separate constituent-quark masses in mesons and baryons

	N_1	Σ_1	Σ_2	Ξ_1	$\Xi_{cc,1}$	$\Xi_{bb,1}$	$\Xi_{bc,1}$
$m_u - m_d$	–2.48	–4.95	0.00	–2.48	–2.48	–2.48	–2.48
Coulomb	1.02	–1.02	3.05	–2.04	4.07	–2.04	1.02
StrHF	0.67	–0.24	0.00	–0.91	–0.29	–0.10	–0.19
EMHF	–0.51	–1.88	–1.52	–1.37	0.86	–0.15	0.36
Total	–1.293	–8.086	1.535	–6.793	2.167	–4.754	–1.293
					±0.109	±0.058	±0.062

isospin splittings: $M(QQu) - M(QQd)$

$$
\begin{aligned}
M(\Xi_{cc}^{++}) - M(\Xi_{cc}^{+}) &= 1.41 \pm 0.12^{+0.76} \text{ MeV},\\
M(\Xi_{bb}^{0}) - M(\Xi_{bb}^{-}) &= -4.78 \pm 0.06^{+0.03} \text{ MeV},\\
M(\Xi_{bc}^{+}) - M(\Xi_{bc}^{0}) &= -1.69 \pm 0.07^{+0.39} \text{ MeV}.
\end{aligned}
$$

1st errors: uncertainties in input mass splittings,
2nd errors : choice of constituent-quark masses.

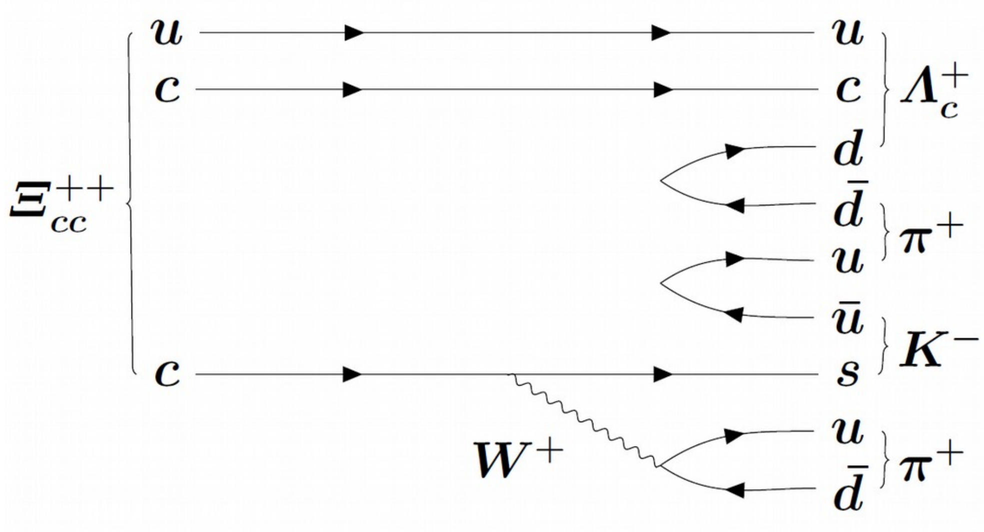
hadronic decay modes of QQq baryons

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

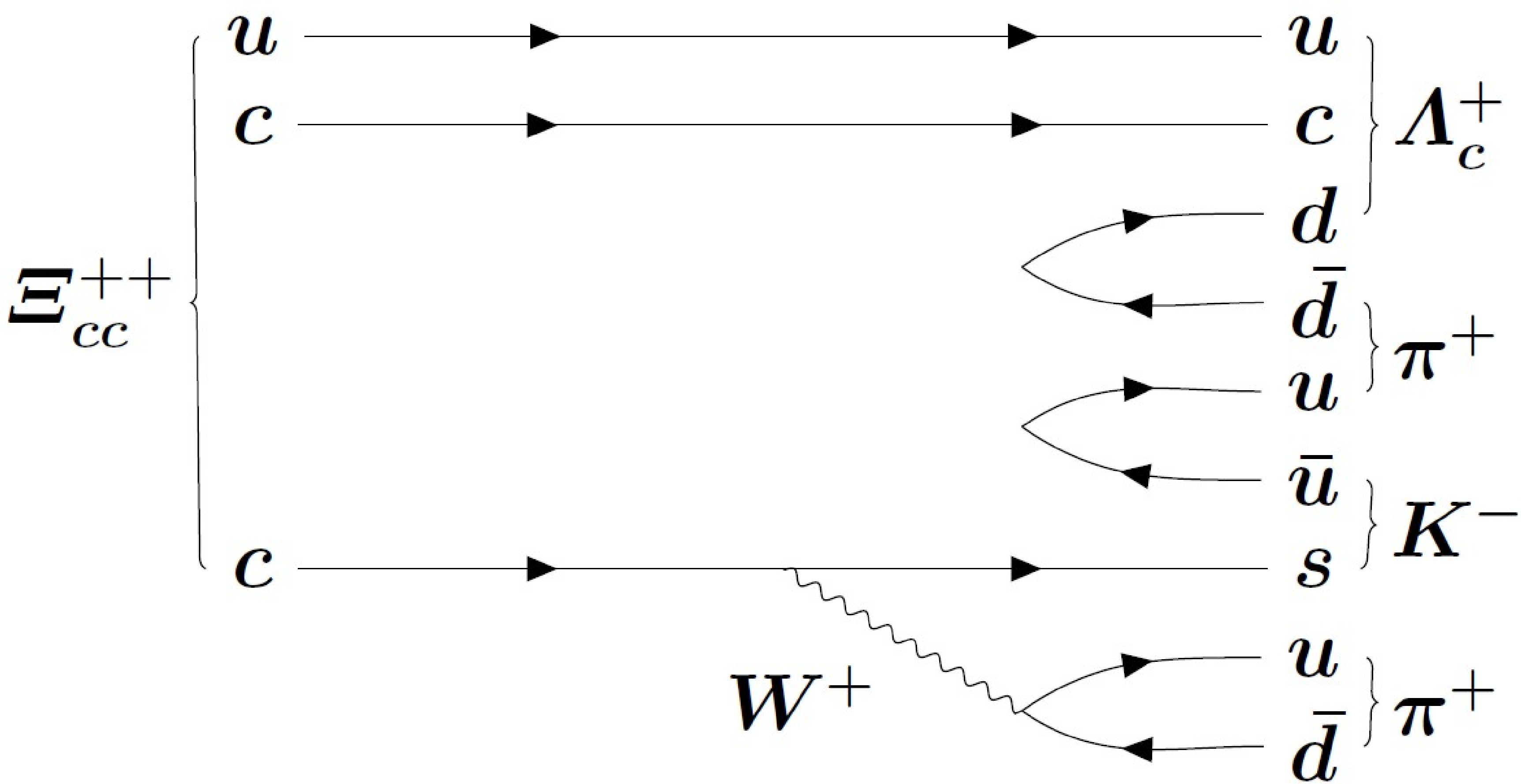
$$\Xi_{cc}^{++} \to (csu)W^+ \to (csu)(\pi^+, \rho^+, a_a^+)$$

e.g.

$$\Xi_{cc}^{++} \to \Lambda_c K^- 2\pi^+$$



$$\Xi_{cc}^{++} \to \Xi^- 3\pi^+ \text{ (missed by CDF trigger)}$$



u
c
c
Ξ_{cc}^{++}
W^+
u
c
d
Λ_c^+
$\bar{d}$
u
π^+
$\bar{u}$
s
K^-
u
$\bar{d}$
π^+

crude estimate of Ξ_{cc}^{++} lifetime:

assume two c quarks decay indep.
$(ccu) \to (csu) + e^+\bar{\nu}_e,\ \ \mu^+\bar{\nu}_\mu,\ \ (u\bar{d}) \times 3$ colors

with kinem. suppression factor,
$F(x) = 1 - 8x + 8x^3 - x^4 + 12x^2 \ln(1/x)$,
$x_{cc} \equiv [M(\Xi_c)/M(\Xi_{cc})]^2 = 0.4634$,

and factor of 2 for each decaying c,

$$\Gamma(\Xi_{cc}^{++}) = \frac{10\ G_F^2 M(\Xi_{cc})^5}{192\pi^3} F(x_{cc}) = 3.56\times 10^{-12}\ \text{GeV}$$

$$\Rightarrow \tau(\Xi_{cc}^{++}) = 185\ \text{fs.}$$

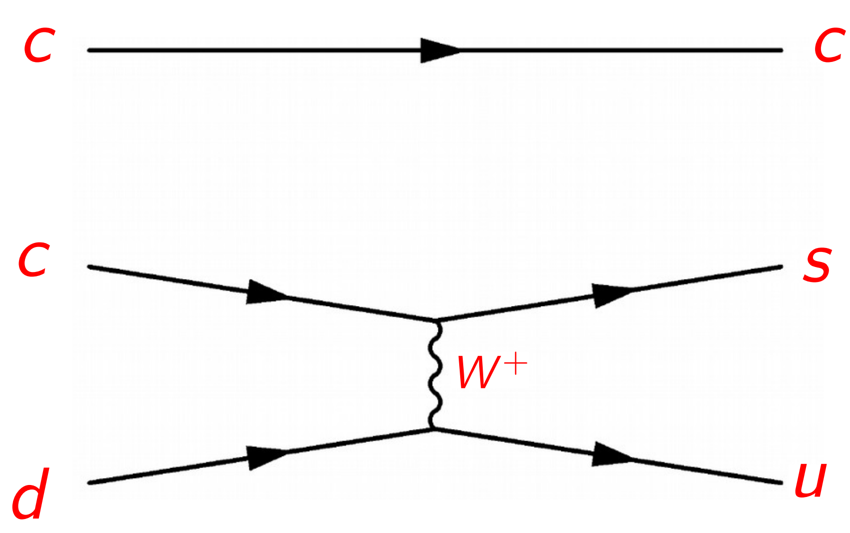
two compensating effects neglected:
(i) $\Xi_{cc} \to \Xi_c$ form factor,
(ii) csu excited states above Ξ_c^+.
assumed $V_{ud} = V_{cs} = 1$
accurate to 10% for Qqq semilep. decays

$\Xi_{cc}^{+} = ccd$:

in addition to $c \to sud$,

have $cd \to su$

$\Rightarrow \tau(\Xi_{cc}^{+}) = 50 \div 100$ fs $\ll \tau(\Xi_{cc}^{++})$



- $\Xi_{bc}^{+} = bcu$

$b \to c d \bar{u},\ c s \bar{c}$ and $c \to s u \bar{d}$

e.g. $\Xi_{bc} \to J/\psi\, \Xi_c$

$\tau(\Xi_{bc}^{+}) \approx 240$ fs

- $\Xi_{bc}^{0} = bcd$

cf. $\tau(\Xi_c^{+}) = (4.42 \pm 0.26) \times 10^{-13}$ s

vs. $\tau(\Xi_c^{0}) = (\,1.12^{+0.13}_{-0.10}\,) \times 10^{-13}$ s

$\Rightarrow \tau(\Xi_{bc}^{0}) = 93$ fs (τ difference due to $cd \to su$)

e.g. $\Xi_{bc}^{0} \to J/\psi\, \Xi^{0},\ \ J/\psi\, \Xi^{-} \pi^{+}$

- $\Xi_{bb}^{+} = bbq$

$bu \to cd$ possible for $\Xi_{bb}^{0} = bbu$,

but cf. $\tau(\Xi_b^0) \approx \tau(\Xi_b^-)$

so treat Ξ_{bb}^{0} and Ξ_{bb}^{-} generically as Ξ_{bb}

$\Rightarrow \tau(\Xi_{bb}) \approx 376$ fs

rare but spectacular decay mode:

$(bbq) \to (\bar{c}cs)(\bar{c}cs)q \to J/\psi\, J/\psi\, \Xi$

doubly heavy baryons predicted lifetimes (fs)

Baryon	This work	[28]	[51]	[71]	[72]
$\Xi_{cc}^{++} = ccu$	185	430±100	460±50	500	~ 200
$\Xi_{cc}^{+} = ccd$	53	120±100	160±50	150	~ 100
$\Xi_{bc}^{+} = bcu$	244	330±80	300±30	200	–
$\Xi_{bc}^{0} = bcd$	93	280±70	270±30	150	–
$\Xi_{bb}^{0} = bbu$	370	–	790±20	–	–
$\Xi_{bb}^{-} = bbd$	370	–	800±20	–	–

[28] K. Anikeev, D. Atwood, F. Azfar, S. Bailey, C. W. Bauer, W. Bell, G. Bodwin, E. Braaten *et al.*, *Workshop on B Physics at Conferences C99-09-23.2 and C00-02-24 (Batavia, IL, Fermilab, 2001)*, arXiv:hep-ph/0201071.

[51] V. V. Kiselev and A. K. Likhoded, Usp. Fiz. Nauk **172**, 497 (2002) [Sov. Phys. Usp. **45**, 455 (2002)].

[71] J. D. Bjorken, Fermilab Report No. FERMILAB-PUB-86-189-T, http://lss.fnal.gov/archive/1986/pub/fermilab-pub-86-189-t.pdf.

[72] M. A. Moinester, Z. Phys. A **355**, 349 (1996).

rough estimate of Ξ_{cc} production rate

assume suppression due to $s \to c$
indep. of spectators, i.e.

Ξ_{cc} suppressed vs. Ξ_c as Ξ_c vs. Ξ :

$$\sigma(pp \to \Xi_{cc} + X) \sim \sigma(pp \to \Xi_c + X) \cdot \frac{\sigma(pp \to \Xi_c + X)}{\sigma(pp \to \Xi + X)}$$

perhaps can generalize to Ξ_{bc} and Ξ_{bb} production rate

$$\sigma(pp \to \Xi_{bc} + X) \sim \sigma(pp \to \Xi_b + X) \cdot \frac{\sigma(pp \to \Xi_c + X)}{\sigma(pp \to \Xi + X)}$$

or

$$\sigma(pp \to \Xi_{bc} + X) \sim \sigma(pp \to \Xi_c + X) \cdot \frac{\sigma(pp \to \Xi_b + X)}{\sigma(pp \to \Xi + X)}$$

and

$$\sigma(pp \to \Xi_{bb} + X) \sim \sigma(pp \to \Xi_b + X) \cdot \frac{\sigma(pp \to \Xi_b + X)}{\sigma(pp \to \Xi + X)}$$

a possible way to check if Ξ_{bc} and B_c

production rates are comparable:

compare analogous prod. rates of Ξ_c and D_s

(or Ξ_b and B_s) in the same setup,

and large enough E_{CM}

be it e^+e^-, $\bar{p}p$ or pp

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2017-156
LHCb-PAPER-2017-018
July 6, 2017

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Submitted to Phys. Rev. Lett.

Summary

- LHCb discovered first QQq baryon $\Xi_{cc}^{++} = (ccu)$
- $M(\Xi_{cc}^{++})$=3621.40$\pm$0.78 MeV vs. the predicted value $M(\Xi_{cc}^{++})$=3627 $\pm$ 12 MeV
- more predictions await testing: lifetimes and masses
- TH goldmine : QQq vs. $\bar{Q}q$ QQ diquark picture ✓
- Outstanding TH challenge: ph model from QCD

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

deuteron-like hadronic molecules

the binding mechanism can in principle

apply to any two heavy hadrons

which couple to isospin

and satisfy certain conditions,

be they mesons or baryons

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: $P_c(4450)$

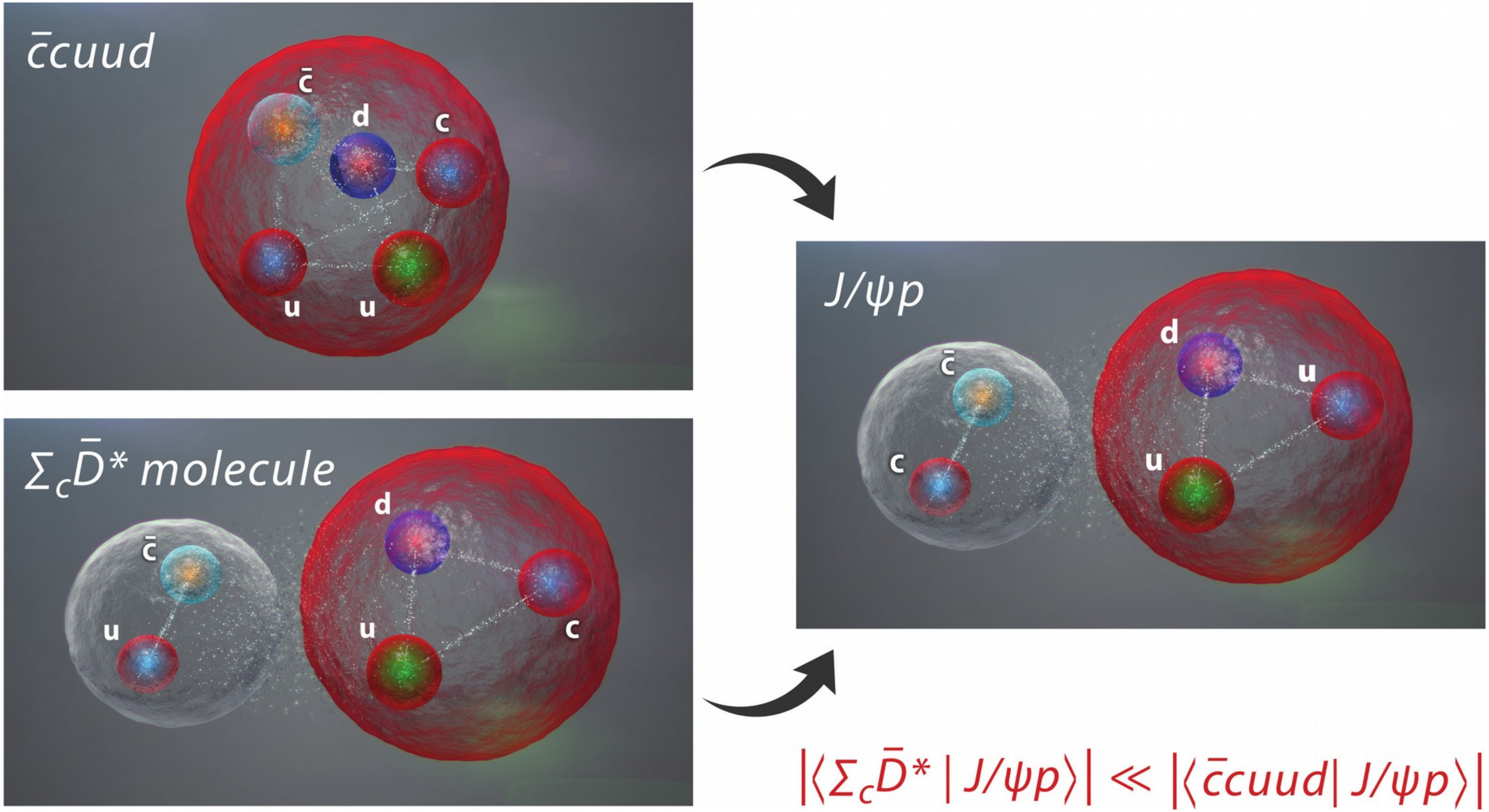
$\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, and $\Sigma_b\bar{\Lambda}_c$.

$c\bar{c}$ 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 $\Sigma_b\Lambda_c$.

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



$QQ\bar{Q}\bar{Q}$ States

Phys. Rev. D **95**, 034011 (2017) MK, J.L. Rosner, S.Nussinov

Toolbox borrowed from QQq baryons

$M_{(cc\bar{c}\bar{c})} = 6{,}192 \pm 25$ MeV, 225 ± 25 MeV above $\eta_c \eta_c$

unlikely to be narrow, nor to have significant non-hadronic decays

$M_{(bb\bar{b}\bar{b})} = 18{,}826 \pm 25$ MeV, 28 ± 25 MeV above $\eta_b \eta_b$

could be narrow & exhibit non-hadronic decays if estim. $> 1\sigma$ high

production of an extra $Q\bar{Q}$: probabillity $\sim 0.1\%$

CMS (arXiv:1610.07095) sees double $\Upsilon(1S)$; production;
38 events, each $\Upsilon \to \mu^+\mu^-$, in 20.7 fb^{-1} at $\sqrt{s} = 8$ TeV

$\Rightarrow$ Inspect neutral 4ℓ final states for possible evidence of $bb\bar{b}\bar{b}$ state; most likely $J^{PC} = 0^{++}$

$\Xi_c^+ = csu, \quad K^- = s\bar{u}$

$\Rightarrow css$: excited Ω_c

arXiv:1703.04639v1 [hep-ex] 14 Mar 2017

CERN-EP-2017-037
LHCb-PAPER-2017-002
14 March 2017

Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+ K^-$

The LHCb collaboration[†]

Abstract

The $\Xi_c^+ K^-$ mass spectrum is studied with a sample of pp collision data corresponding to an integrated luminosity of 3.3 fb^{-1}, collected by the LHCb experiment. The Ξ_c^+ is reconstructed in the decay mode $pK^-\pi^+$. Five new, narrow excited Ω_c^0 states are observed: the $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$. Measurements of their masses and widths are reported.

Submitted to Phys. Rev. Lett.

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[†]Authors are listed at the end of this paper.

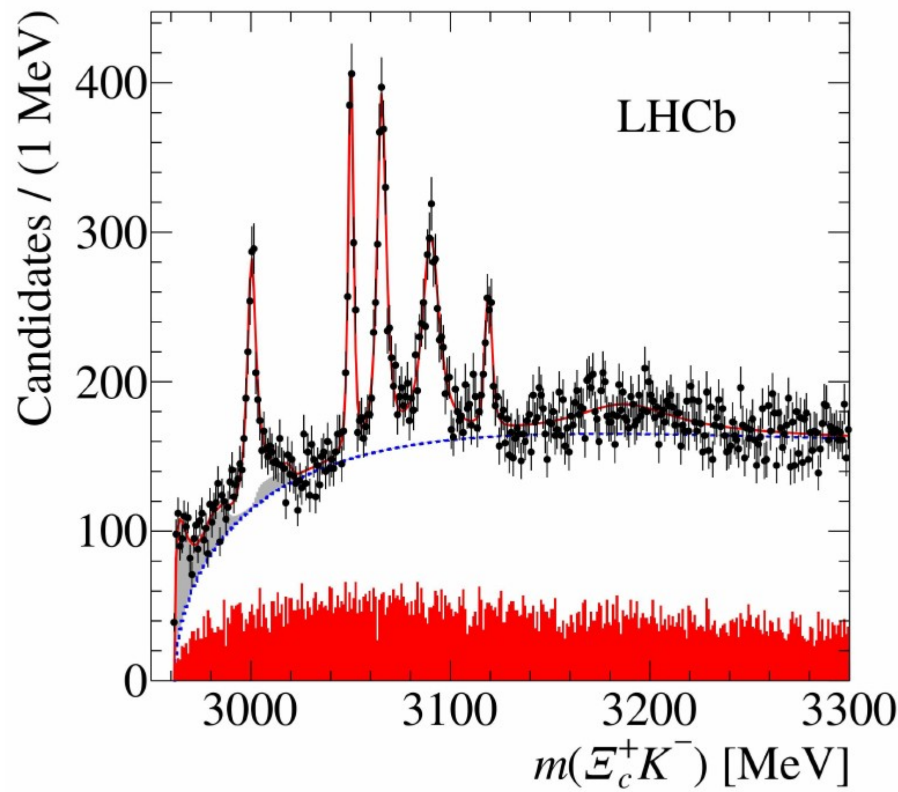


Figure 2: Distribution of the reconstructed invariant mass $m(\Xi_c^+ K^-)$ for all candidates passing the likelihood ratio selection; the solid (red) curve shows the result of the fit, and the dashed (blue) line indicates the fitted background. The shaded (red) histogram shows the corresponding mass spectrum from the Ξ_c^+ sidebands and the shaded (light gray) distributions indicate the feed-down from partially reconstructed $\Omega_c(X)^0$ resonances.

- interpret as bound states
  of a c-quark and a P-wave ss-diquark.

⇒ exactly 5 possible combinations of **S** and **L**
splitting due to spin-orbit, spin-spin and tensor

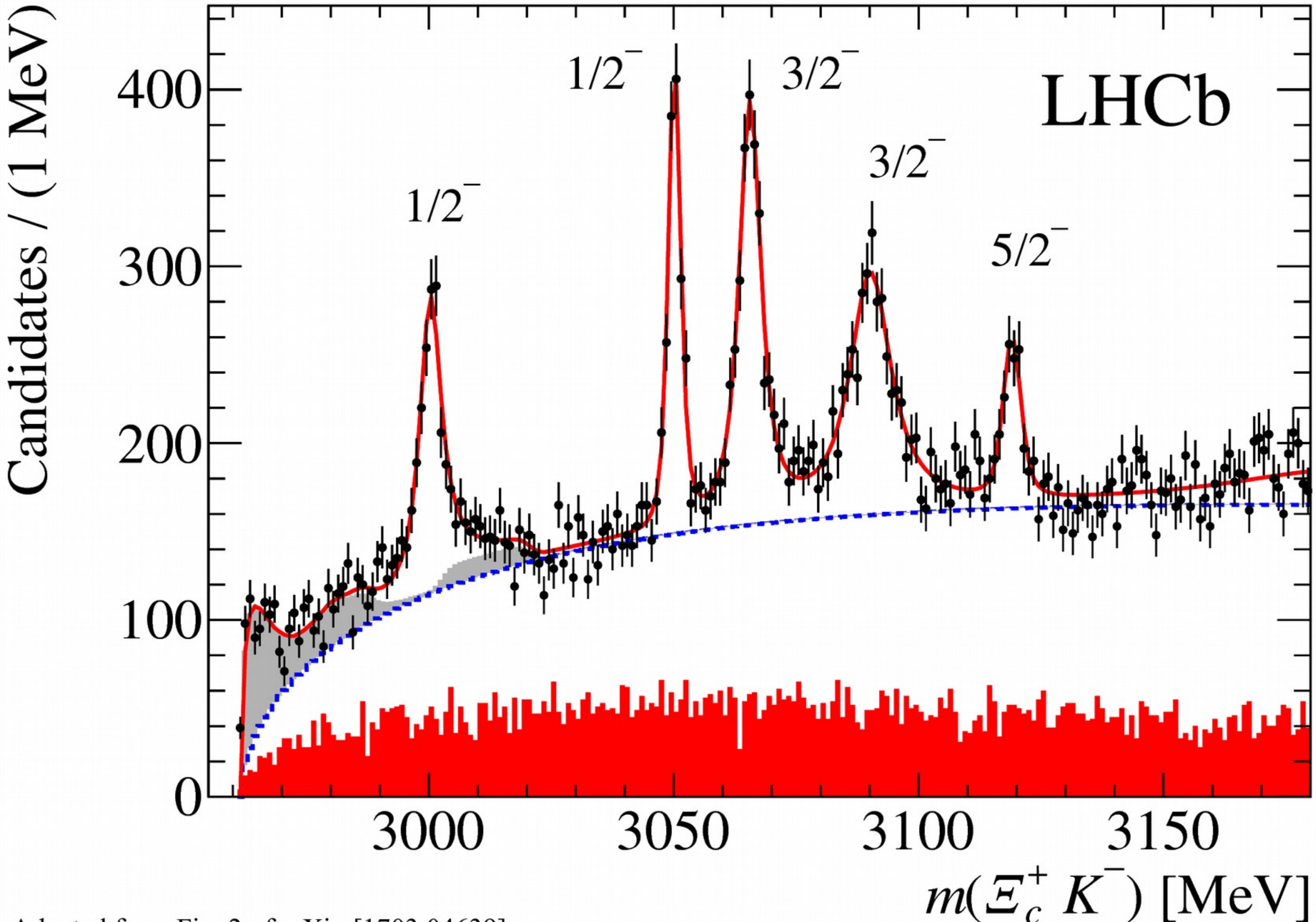
- narrowness:
  diquark hard to split and/or D-wave suppression

- predict 5 states:
  $J^P = 1/2^-, 1/2^-, 3/2^-, 3/2^-, 5/2^-$

- assign to 5 observed resonances
  (*a priori* 5!=120 possibilities)

- Ω_b analogues

- alternative interpretations



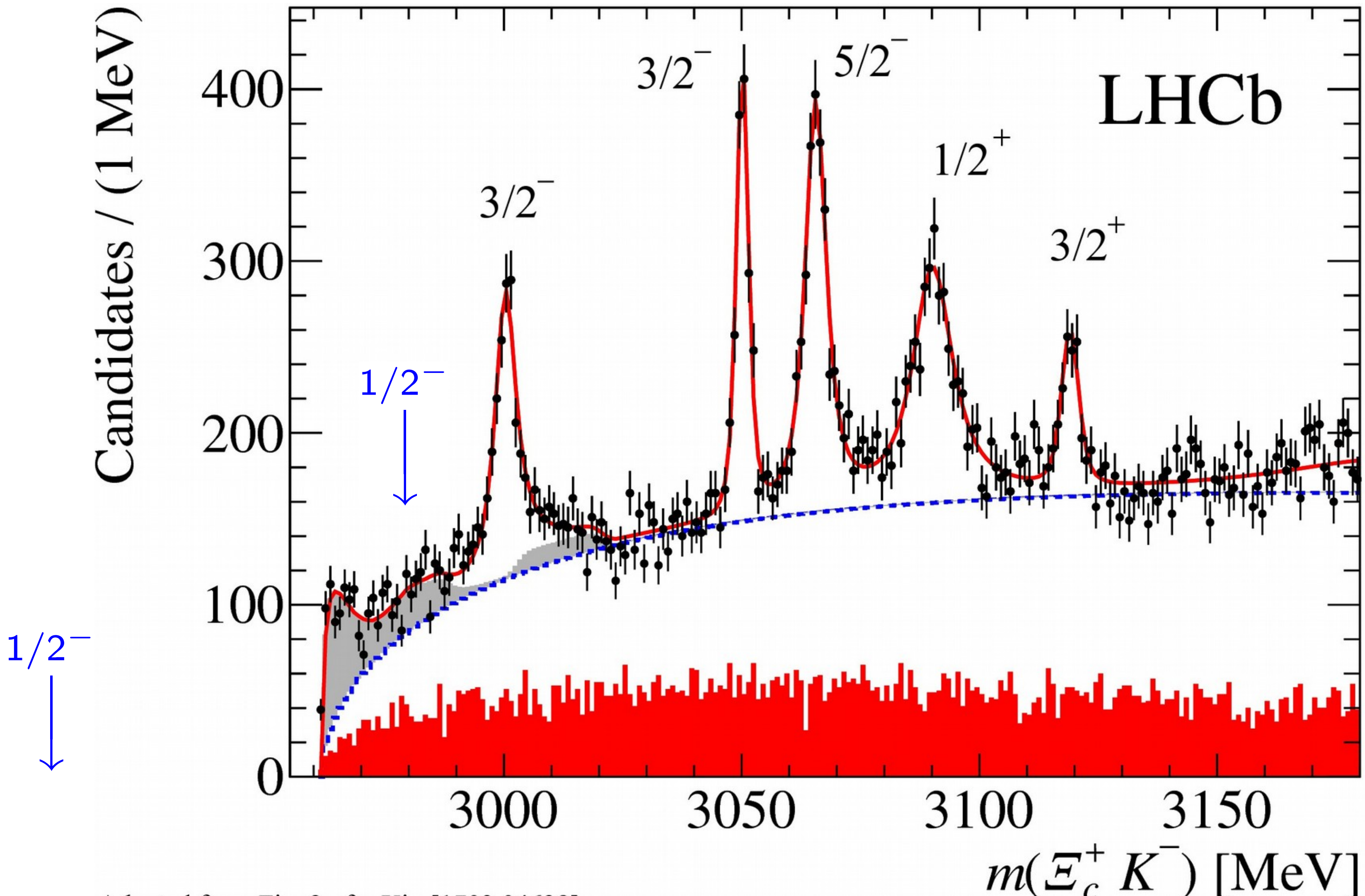
Adapted from Fig. 2 of arXiv:[1703.04639]

spin-dependent potential
between a heavy quark Q and the (ss) spin-1 diquark

$$
\begin{aligned}
V_{SD} &= a_1 \mathbf{L} \cdot \mathbf{S}_{ss} + a_2 \mathbf{L} \cdot \mathbf{S}_Q \\
&+ b[-\mathbf{S}_{ss} \cdot \mathbf{S}_Q + 3(\mathbf{S}_{ss} \cdot \mathbf{r})(\mathbf{S}_Q \cdot \mathbf{r})/r^2] \\
&+ c\mathbf{S}_{ss} \cdot \mathbf{S}_Q \ ,
\end{aligned}
$$

$\mathbf{L}$ = angular momentum = 1
$\mathbf{S}_{ss}$ = ss diquark spin = 1
$\mathbf{S}_Q$ = heavy quark spin = $1/2$

alternate J^P assignment



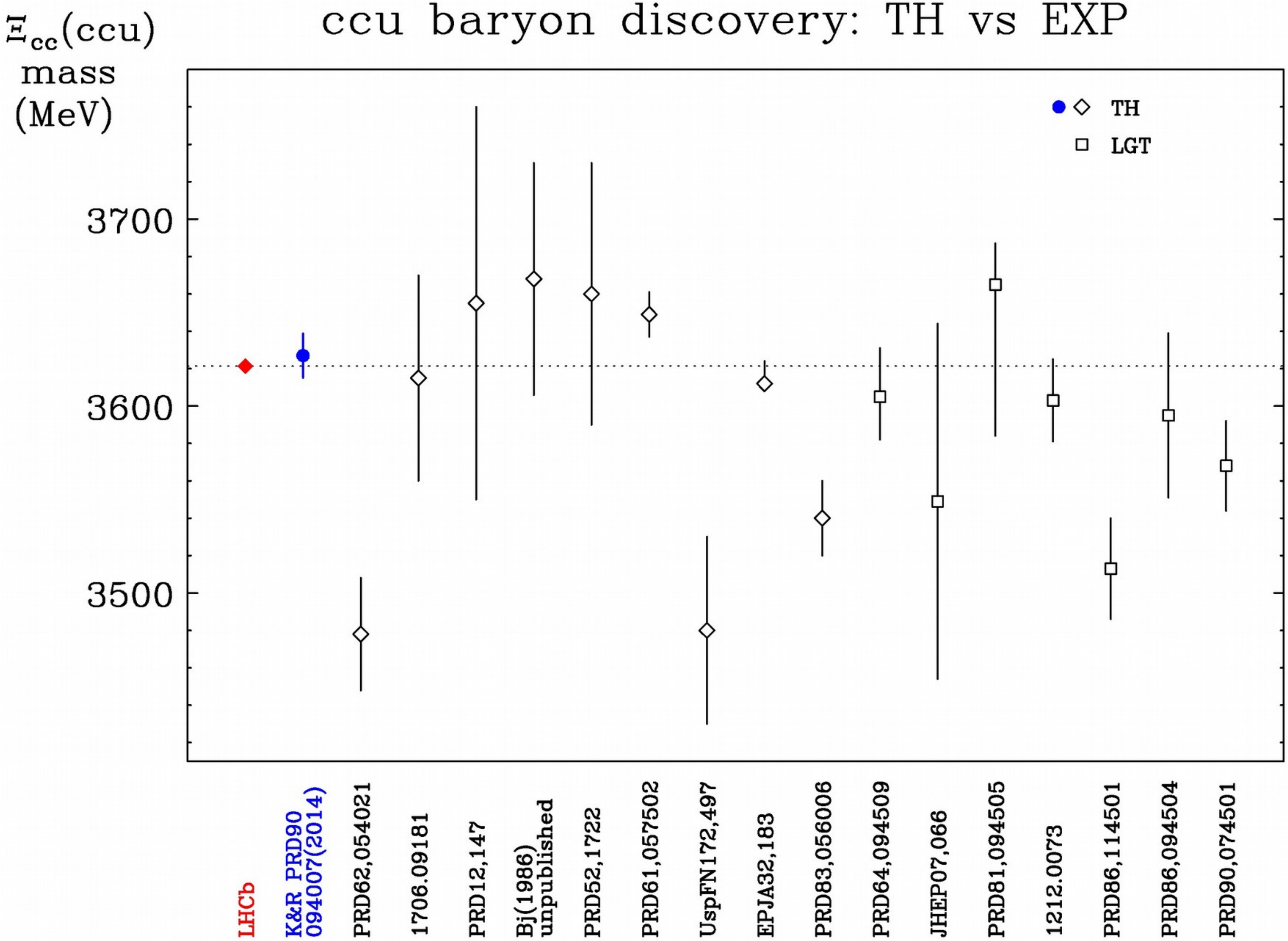
Adapted from Fig. 2 of arXiv:[1703.04639]

Upshot on new Ω_c states

- LHCb: 5 new excited Ω_c states: v. narrow & v. high stats
- interpret as 5 states expected in P-wave $c(ss)$ system :
  $J^P = 1/2^-,\ 1/2^-,\ 3/2^-,\ 3/2^-,\ 5/2^-$
  awaits exp. confirmation, spin & parity meas.
- if instead 2 highest states are $2S$, $1/2^+$ and $3/2^+$
  then 3 lowest are likely $J^P = 3/2^-,\ 3/2^-,\ 5/2^-$
- then expect $1/2^-$ near 2978 MeV $\to \Xi_c^+ K^-$ in S-wave
  and $1/2^-$ near 2904 MeV $\to \Omega_c$ and/or Ω_c/π^0
- predictions for excited Ω_b-s in $b(ss)$ system

Supplementary transparencies

ccu baryon discovery: TH vs EXP



S. Fleck and J.-M. Richard, Prog. Th. Phys. 82(1989)760

Table VIII. Masses of ground-state baryons with double charm, calculated either with a potential model (Eq. (25)) or with the bag model, using the parameter given in Eq. (28).

		Potential	Bag
ccq	Ξ_{cc}	3.613	3.516
	Ξ_{cc}^*	3.741	3.636
ccs	Ω_{cc}	3.703	3.657
	Ω_{cc}^*	3.835	3.805

TABLE I. Quark model description of ground-state baryons containing u, d, s. Here we take $m_u^b = m_d^b \equiv m_q^b = 363$ MeV, $m_s^b = 538$ MeV, and hyperfine interaction term $a/(m_q^b)^2 = 50$ MeV.

State (mass in MeV)	Spin	Expression for mass [24]	Predicted mass (MeV)
$N(939)$	1/2	$3m_q^b - 3a/(m_q^b)^2$	939
$\Delta(1232)$	3/2	$3m_q^b + 3a/(m_q^b)^2$	1239
$\Lambda(1116)$	1/2	$2m_q^b + m_s^b - 3a/(m_q^b)^2$	1114
$\Sigma(1193)$	1/2	$2m_q^b + m_s^b + a/(m_q^b)^2 - 4a/m_q^b m_s^b$	1179
$\Sigma(1385)$	3/2	$2m_q^b + m_s^b + a/(m_q^b)^2 + 2a/m_q^b m_s^b$	1381
$\Xi(1318)$	1/2	$2m_s^b + m_q^b + a/(m_s^b)^2 - 4a/m_q^b m_s^b$	1327
$\Xi(1530)$	3/2	$2m_s^b + m_q^b + a/(m_s^b)^2 + 2a/m_q^b m_s^b$	1529
$\Omega(1672)$	3/2	$3m_s^b + 3a/(m_s^b)^2$	1682

The average magnitude of the errors in this description is about 5 MeV.

TABLE III. Relative attraction or repulsion $\langle T_1 \cdot T_2 \rangle$ of quarks $Q\bar{Q}$ or QQ in various states.

State	Color	$\langle T_1 \cdot T_2 \rangle$
$Q\bar{Q}$	1	–4/3
$Q\bar{Q}$	8	1/6
QQ	3*	–2/3
QQ	6	1/3

TABLE IV. Quark model description of ground-state baryons containing one charmed quark. Here we take $m_u^b = m_d^b \equiv m_q^b = 363$ MeV, $m_s^b = 538$ MeV, $m_c^b = 1710.5$ MeV, and $a/(m_q^b)^2 = 50$ MeV. The spin of the qs pair is taken to be zero in Ξ_c and one in Ξ'_c.

State (M in MeV)	Spin	Expression for mass	Predicted M (MeV)
$\Lambda_c(2286.5)$	1/2	$2m_q^b + m_c^b - 3a/(m_q^b)^2$	Input
$\Sigma_c(2453.4)$	1/2	$2m_q^b + m_c^b + a/(m_q^b)^2 - 4a/(m_q^b m_c^b)$	2444.0
$\Sigma_c^*(2518.1)$	3/2	$2m_q^b + m_c^b + a/(m_q^b)^2 + 2a/(m_q^b m_c^b)$	2507.7
$\Xi_c(2469.3)$	1/2	$B(cs) + m_q^b + m_s^b + m_c^b - 3a/(m_q^b m_s^b)$	2475.3
$\Xi'_c(2575.8)$	1/2	$B(cs) + m_q^b + m_s^b + m_c^b + a/(m_q^b m_s^b) - 2a/(m_q^b m_c^b) - 2a_{cs}/(m_s^b m_c^b)$	2565.4
$\Xi_c^*(2645.9)$	3/2	$B(cs) + m_q^b + m_s^b + m_c^b + a/(m_q^b m_s^b) + a/(m_q^b m_c^b) + a_{cs}/(m_s^b m_c^b)$	2632.6
$\Omega_c(2695.2)$	1/2	$2B(cs) + 2m_s^b + m_c^b + a/(m_s^b)^2 - 4a_{cs}/(m_s^b m_c^b)$	2692.1[a]
$\Omega_c^*(2765.9)$	3/2	$2B(cs) + 2m_s^b + m_c^b + a/(m_s^b)^2 + 2a_{cs}/(m_s^b m_c^b)$	2762.8[a]

[a]Difference between experimental values used to determine $6a_{cs}/(m_s^b m_c^b) = 70.7$ MeV.

The average magnitude of the errors in the predictions of Table IV is about 9 MeV, not much higher than that for the light-quark baryons in Table I.

TABLE VI. Quark model description of ground-state baryons containing one bottom quark. Here we take $m_u^b = m_d^b \equiv m_q^b = 363$ MeV, $m_s^b = 538$ MeV, $m_b^b = 5043.5$ MeV, and $a/(m_q^b)^2 = 50$ MeV. The spin of the qs pair is taken to be zero in Ξ_b and one in Ξ'_b. The parameter a_{bs} is rescaled from a in the same manner as for charmed baryons: $a_{bs} = a_{cs} = (70.7/43.0)a$.

State (M in MeV)	Spin	Expression for mass	Predicted M (MeV)
$\Lambda_b(5619.5)$	1/2	$2m_q^b + m_b^b - 3a/(m_q^b)^2$	Input
$\Sigma_b(5814.3)$	1/2	$2m_q^b + m_b^b + a/(m_q^b)^2 - 4a/(m_q^b m_b^b)$	5805.1
$\Sigma_b^*(5833.8)$	3/2	$2m_q^b + m_b^b + a/(m_q^b)^2 + 2a/(m_q^b m_b^b)$	5826.7
$\Xi_b(5792.7)$	1/2	$B(bs) + m_q^b + m_s^b + m_b^b - 3a/(m_q^b m_s^b)$	5801.5
$\Xi'_b(-)$	1/2	$B(bs) + m_q^b + m_s^b + m_b^b + a/(m_q^b m_s^b) - 2a/(m_q^b m_b^b) - 2a_{bs}/(m_s^b m_b^b)$	5921.3
$\Xi_b^*(5949.7)$	3/2	$B(bs) + m_q^b + m_s^b + m_b^b + a/(m_q^b m_s^b) + a/(m_q^b m_b^b) + a_{bs}/(m_s^b m_b^b)$	5944.1
$\Omega_b(6046.4)$	1/2	$2B(bs) + 2m_s^b + m_b^b + a/(m_s^b)^2 - 4a_{bs}/(m_s^b m_b^b)$	6042.8
$\Omega_b^*(-)$	3/2	$2B(bs) + 2m_s^b + m_b^b + a/(m_s^b)^2 + 2a_{bs}/(m_s^b m_b^b)$	6066.7

The average magnitude of errors in predictions of Table VI is about 8 MeV, a bit below that for charmed baryons in Table IV. We shall use these two errors and those in Table I to extrapolate to the case of two heavy quarks, estimating prediction errors of 12 MeV for $M(\Xi_{cc})$ and $M(\Xi_{bb})$. For $M(\Xi_{bc})$ an additional systematic error is associated with ignorance of the B_c–B_c^* splitting.

TABLE VIII. Comparison of predictions for $M(\Xi_{cc})$. Here KS stands for Kogut-Susskind; LGT stands for lattice gauge theory.

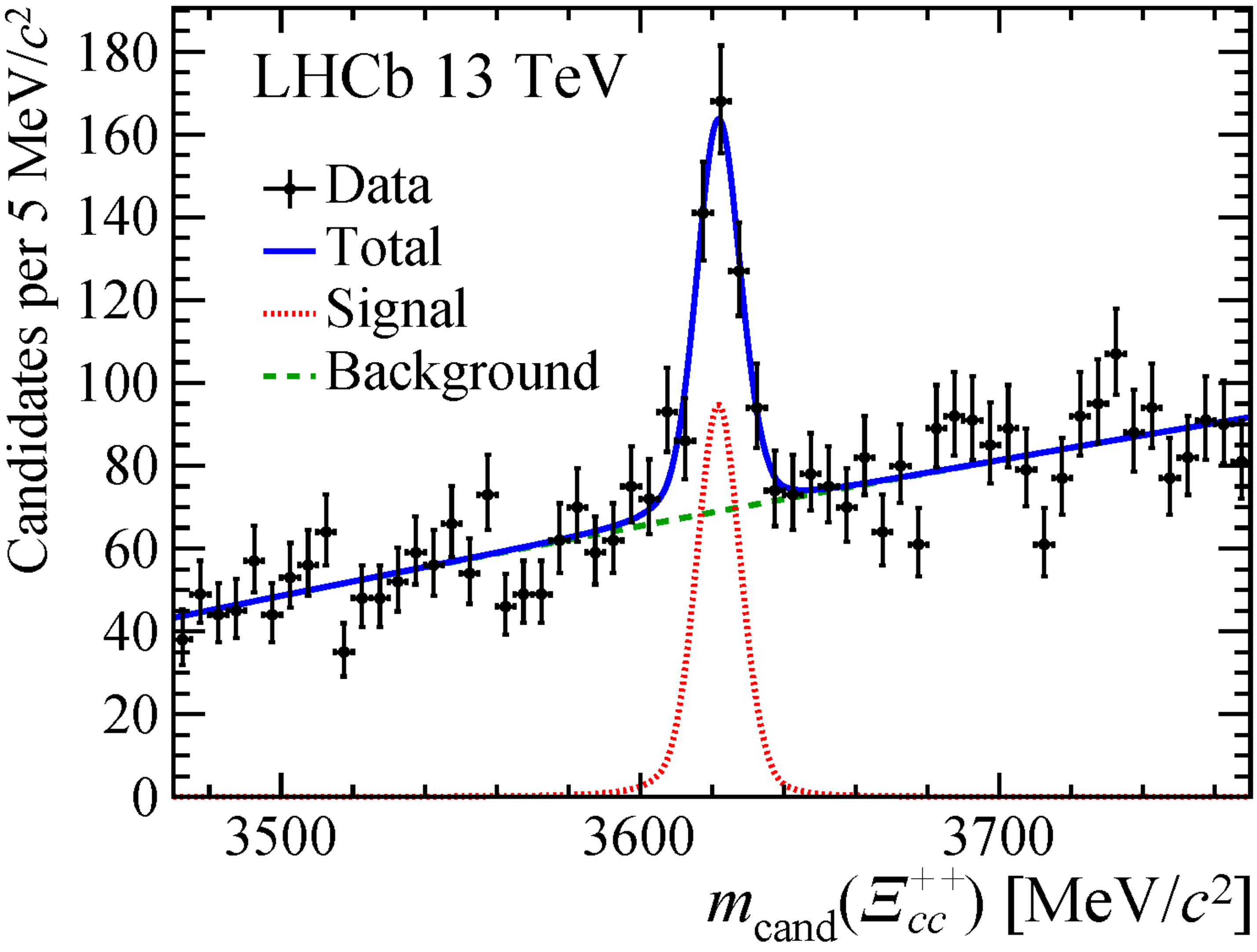
Reference	Value (MeV)	Method
Present work	3627 ± 12	
[23]	3550–3760	QCD-motivated quark model
[25]	3668 ± 62	QCD-motivated quark model
[28]	3651	QCD-motivated quark model
[42]	3613	Potential and bag models
[43]	3630	Potential model
[44]	3610	Heavy-quark effective theory
[45]	3660 ± 70	Feynman-Hellmann + semiempirical formulas
[46]	3676	Mass sum rules
[47]	3660	Relativistic quasipotential quark model
[48]	3607	Three-body Faddeev equations.
[49]	3527	Bootstrap quark model + Faddeev Eqs
[50]	ucc: 3649 ± 12, dcc: 3644 ± 12	Quark model
[51]	3480 ± 50	Potential approach + QCD sum rules
[52]	3690	Nonperturbative string
[53]	3620	Relativistic quark-diquark
[54]	3520	Bag model
[55]	3643	Potential model
[56]	3642	Relativistic quark model + Bethe-Salpeter
[57]	3612^{+17}	Variational
[58]	3678	Quark model
[59]	3540 ± 20	Instantaneous approx + Bethe-Salpeter
[60]	4260 ± 190	QCD sum rules
[61]	$3608(15)\binom{13}{35}$, $3595(12)\binom{21}{22}$	Quenched lattice
[62]	3549(13)(19)(92)	Quenched lattice
[63]	$3665 \pm 17 \pm 14^{+0}_{-78}$	Lattice, domain-wall + KS fermions
[64]	3603(15)(16)	Lattice, $N_f = 2 + 1$
[65]	3513(23)(14)	LGT, twisted mass ferm., $m_\pi = 260$ MeV
[66]	3595(39)(20)(6)	LGT, $N_f = 2 + 1$, $m_\pi = 200$ MeV
[67]	3568(14)(19)(1)	LGT, $N_f = 2 + 1$, $m_\pi = 210$ MeV

TABLE IX. Contributions to the mass of the lightest baryon Ξ_{bb} with two bottom quarks.

Contribution	Value (MeV)
$2m_b^b + m_q^b$	10450.0
bb binding	−281.4
$a_{bb}/(m_b^b)^2$	7.8
$-4a/m_q^b m_b^b$	−14.4
Total	10162 ± 12

TABLE X. Comparison of predictions for $M(\Xi_{bb})$.

Reference	Value (MeV)	Method
Present work	10162 ± 12	
[25]	10294 ± 131	QCD-motivated quark model
[28]	10235	QCD-motivated quark model
[43]	10210	Potential models
[45]	10340 ± 100	Feynman-Hellmann+ semiempirical formulas
[47]	10230	Relativistic quasipotential quark model
[51]	10090 ± 50	Potential approach and QCD sum rules
[52]	10160	Nonperturbative string
[54]	10272	Bag model
[58]	10322	Quark model
[59]	10185 ± 5	Instantaneous approx + Bethe-Salpeter
[60]	9780 ± 70	QCD sum rules
[68]	10045	Coupled channel formalism



in total 313 ± 13 candidates