EXOTIC HADRONS - SEMIEMPIRICAL APPROACH

J. Rosner (Univ. of Chicago) – LHCb Workshop - CERN - Oct. 18, 2018

1964: M. Gell-Mann and G. Zweig proposed that the known mesons were $q\bar{q}$ and baryons qqq, with quarks known at the time u ("up"), d ("down"), and s ("strange") having charges (2/3,–1/3,–1/3). Mesons and baryons would then have integral charges.

Mesons such as $qq\bar{q}\bar{q}$ and baryons such as $qqqq\bar{q}$ would also have integral charges. Why weren't they seen?

They *have* now been seen, as "molecules" of heavy-quark hadrons or as deeply bound states involving heavy quarks (charm and bottom).

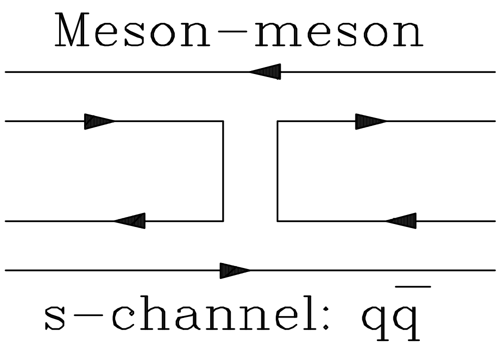
Charm-anticharm and bottom-antibottom molecules; "pentaquark" as a charmed meson – baryon molecule; $\Xi_{cc}^{++} = ccu$ as the first doubly charmed baryon; ccs mass; stable $bb\bar{u}\bar{d}$ tetraquark; quark fusion.

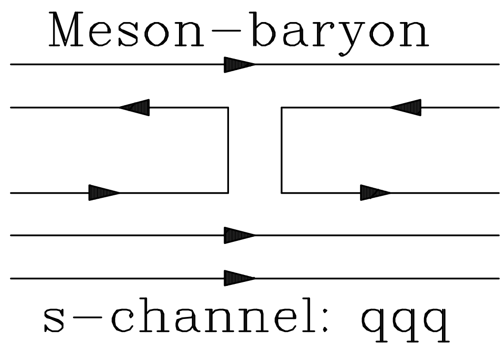
Thanks to Marek Karliner, Michael Gronau, and Shmuel Nussinov for enjoyable collaborations. References at end; review by M. Karliner, T. Skwarnicki, JLR, arXiv:1711.10626.

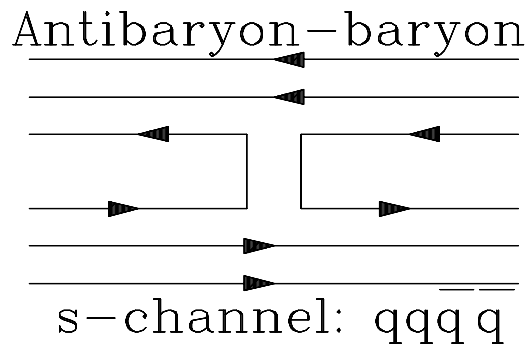
Today: $\Xi_{cc}^{++} = ccu$, $\Omega_c = ccs$ mass; stable $bb\bar{u}\bar{d}$ tetraquark.

EARLY HINT OF EXOTICS

Processes "dual" (JLR, 1968) to t-channel $q\bar{q}$ exchange:





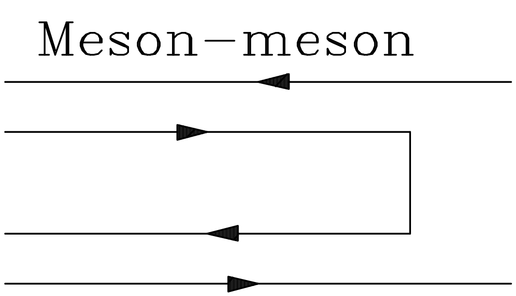


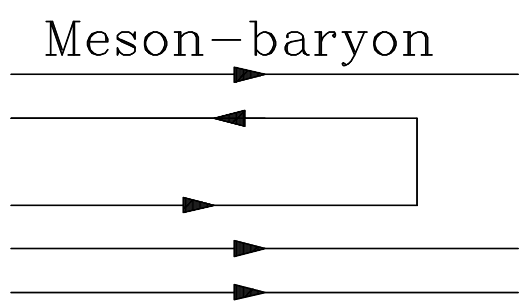
s-channel resonances $\Leftrightarrow$ t-channel Regge trajectories

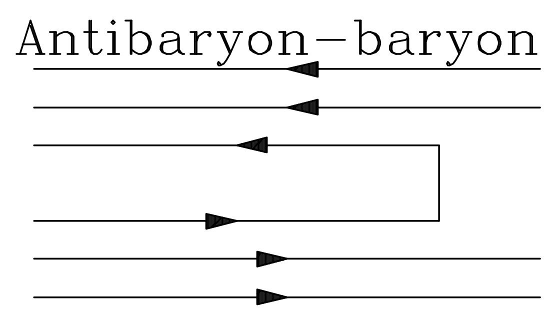
In antiproton-proton scattering, $q\bar{q}$ dual to $qq\bar{q}\bar{q}$

Predicts "exotic" $qq\bar{q}\bar{q}$ mesons, but where?

Do resonances form via $q\bar{q}$ annihilation? (JLR, 1972):







$p^* \leq 350$ MeV$/c$ $\qquad$ $p*^{\leq} 250$ MeV$/c$ $\qquad$ $p^* \leq 200$ MeV$/c$?

HEAVY QUARKS STABILIZE EXOTICS

Compton wavelengths are shorter; deeper QCD binding

Molecular states (predicted in 1976) make their appearance

Heavier quarks: less kinetic energy; favorable to binding

Two or more heavy quarks have an affinity for one another

First heavy exotic: $X(3872)$, $\to J/\psi\pi\pi,\ J/\psi 3\pi$

Appears to be an S-wave bound state of $D^0\overline{D}^{*0} + c.c.$ mixed with a charmonium $\chi_{c1}(2P)$ state

Mass within 0.2 MeV of $D^0\overline{D}^{*0}$ threshold; bound?

Similar behavior with b quarks: $Z_b(10610)$ near $B\overline{B}^*$ threshold, $Z_b(10650)$ near $B^*\overline{B}^*$ threshold

$P_c = c\bar{c}uud$ candidates at (4380,4450) MeV: $\Sigma_c\overline{D^*}$ molecules or tightly bound pentaquarks?

BARYONS WITH > 1 HEAVY QUARK

So far: $Q\bar{Q}q\bar{q}'$ or $Q\bar{Q}qqq'$ ($Q =$ heavy, $q, q' =$ light). Can we predict masses of (simpler) $QQ'q$ systems?

SELEX at Fermilab (2002-5) claimed $\Xi_{cc}^{++}(3520) = ccu$ and $\Xi_{cc}^{+}(3460) = ccd$; not confirmed by others

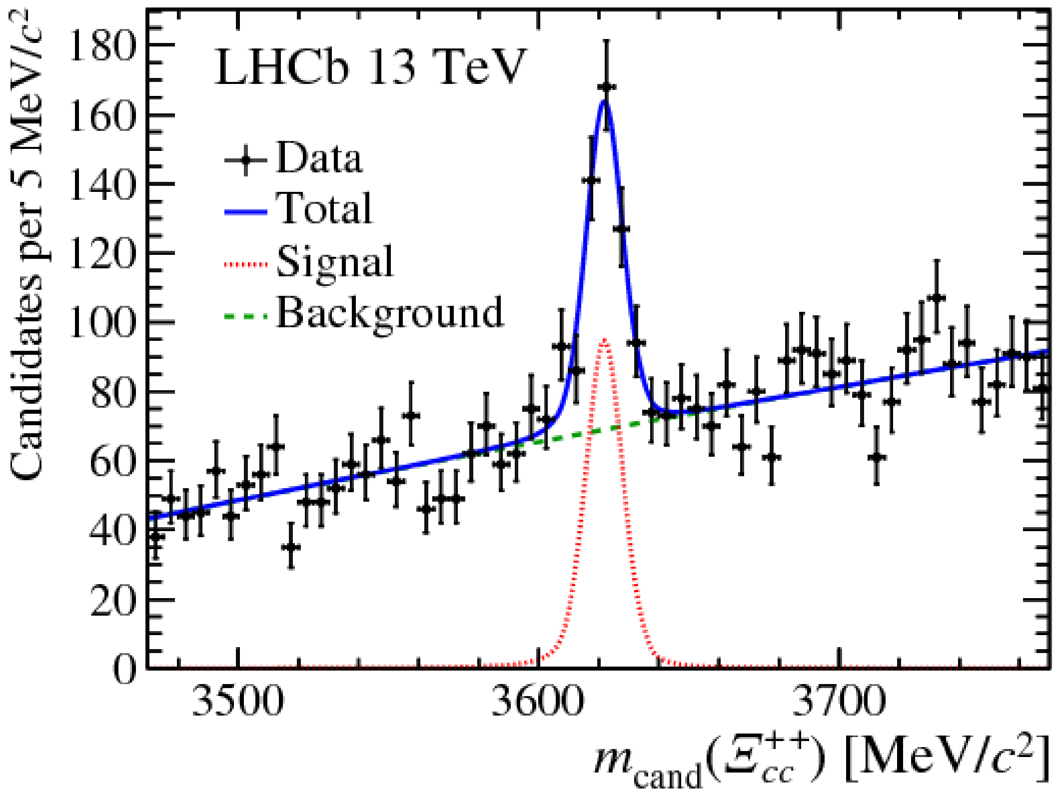
M. Karliner + JLR (PR D **90**): Constituent-quark masses, hyperfine splittings, estimates of QQ' binding ($q = u, d$):

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	–
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

LHCb PRL **119**, 112001: $M(\Xi_{cc}^{++}) = 3621.40 \pm 0.78$ MeV

Other estimates (> 30): spread of at least 100 MeV

$\Lambda_c K^- \pi^+ \pi^+$ SPECTRUM



Similar peak seen in 8 TeV data; no $\Lambda_c K^- \pi^+$ peak

We predicted $\tau(\Xi_{cc}^{++,+}) = (\mathbf{185},53)$ fs; $\Lambda_c K^- \pi^+$ peak disfavored by LHCb lifetime cut $\tau > 150$ fs

LHCb (PRL **121**, 052001): $\tau(\Xi_{cc}^{++}) = 256^{+24}_{-22} \pm 14$ fs

INPUTS

Describe ground-state baryons containing u, d, s taking $m_u^b = m_d^b \equiv m_q^b = 363$ 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	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

Describe mesons with quark masses $m_{u,d,s}^m \sim 55$ MeV less

$M(\Lambda_{c,b}) - M(\Lambda) \Rightarrow m_{c,b}^b = (1710.5, 5043.5)$ MeV

CHARMED & BOTTOM BARYONS

Above choices of mass sufficient to describe nonstrange baryons with one c or b quark

When taking account of deeper cs or bs binding in baryons with one or two strange quarks and one charm or bottom fit all baryons with one c or b

Charmed baryons			Bottom baryons		
State (M in MeV)	Spin	Predicted M (MeV)	State (M in MeV)	Spin	Predicted M (MeV)
$\Lambda_c(2286.5)$	1/2	Input	$\Lambda_b(5619.5)$	1/2	Input
$\Sigma_c(2453.4)$	1/2	2444.0	$\Sigma_b(5814.3)$	1/2	5805.1
$\Sigma_c^*(2518.1)$	3/2	2507.7	$\Sigma_b^*(5833.8)$	3/2	5826.7
$\Xi_c(2469.3)$	1/2	2475.3	$\Xi_b(5792.7)$	1/2	5801.5
$\Xi_c'(2575.8)$	1/2	2565.4	$\Xi_b'(-)$	1/2	5921.3
$\Xi_c^*(2645.9)$	3/2	2628.6	$\Xi_b^*(5949.7)$	3/2	5944.1
$\Omega_c(2695.2)$	1/2	2692.1	$\Omega_b(6046.4)$	1/2	6042.8
$\Omega_c^*(2765.9)$	3/2	2762.8	$\Omega_b^*(-)$	3/2	6066.7

HEAVY QUARK PAIR BINDING

Quark pair more deeply bound when neither is u or d

$B(c\bar{s}) = [3M(D_s^*) + M(D_s)]/4 - m_s^m - m_c^m = -69.9$ MeV

Assume $B(cs)/B(c\bar{s}) = 1/2$ as for single-gluon exchange

Then $B(cs) = -35$ MeV; also find $B(bs) = -41.8$ MeV

Rescale hyperfine interactions when neither quark is u or d; take a cue from $M(D_s^*) - M(D_s) \simeq M(D^*) - M(D)$

Now we are ready to deal with cc, cb, bb

Charm-anticharm binding: $B(c\bar{c}) = [3M(J/\psi) + M(\eta_c)]/4 - 2m_c^m = -258$ MeV, so $B(cc) = -129$ MeV

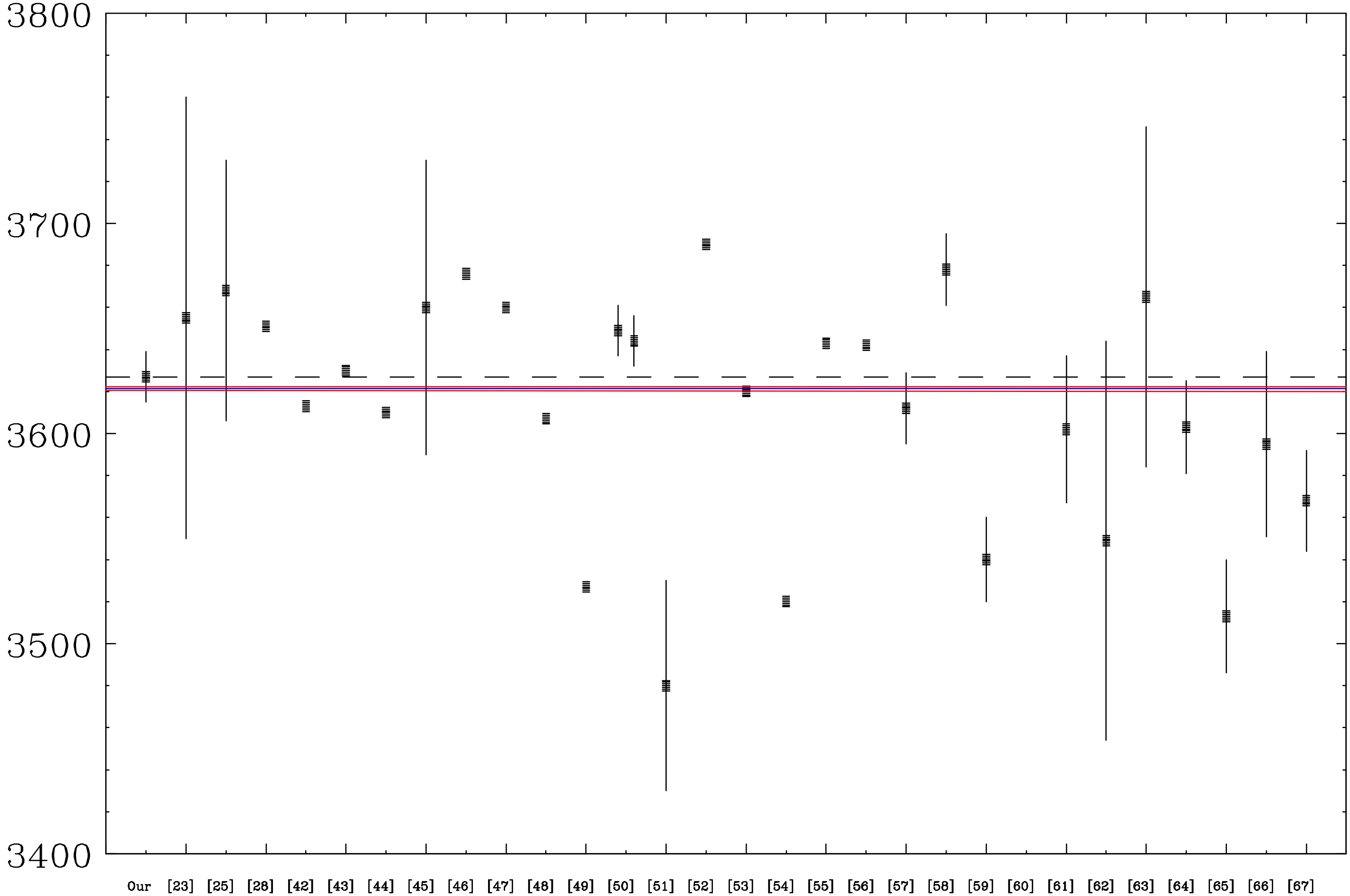
Similar calculations give $B(bb) = -281.4$ MeV and $B(bc) = -167.8 \pm 3.0$ MeV (uncertainty in B_c^* mass)

CONTRIBUTIONS

Contribution	Value (MeV)	Contribution	Value (MeV)
$2m_c^b + m_q^b$	3783.9	$2m_b^b + m_q^b$	10450.0
cc binding	-129.0	bb binding	-281.4
$a_{cc}/(m_c^b)^2$	14.2	$a_{bb}/(m_b^b)^2$	7.8
$-4a/m_q^b m_c^b$	-42.4	$-4a/m_q^b m_b^b$	-14.4
$M(\Xi_{cc})$	3627±12	$M(\Xi_{bb})$	10162±12

Contribution	Value (MeV)	Contribution	Value (MeV)
$m_b^b + m_c^b + m_q^b$	7117.0	$m_b^b + m_c^b + m_q^b$	7117.0
bc binding	-170.8	bc binding	-170.8
$-3a/(m_c^b m_q^b)$	-31.8	$a/(m_c^b m_q^b)$	10.6
–	–	$-2a/(m_b^b m_q^b)$	-24.2
–	–	$-2a_{bc}/(m_b^b m_c^b)$	
$M(\Xi_{bc})$	6914± 13	$M(\Xi'_{bc})$	6933± 12

PREDICTIONS FOR Ξ_{cc}



Our prediction is on the left; others: PR D **90**, 094007

PREDICTIONS FOR $\Omega_{cc} = ccs$

Strange quark is about 175 MeV heavier than nonstrange but more deeply bound to cc diquark than nonstrange

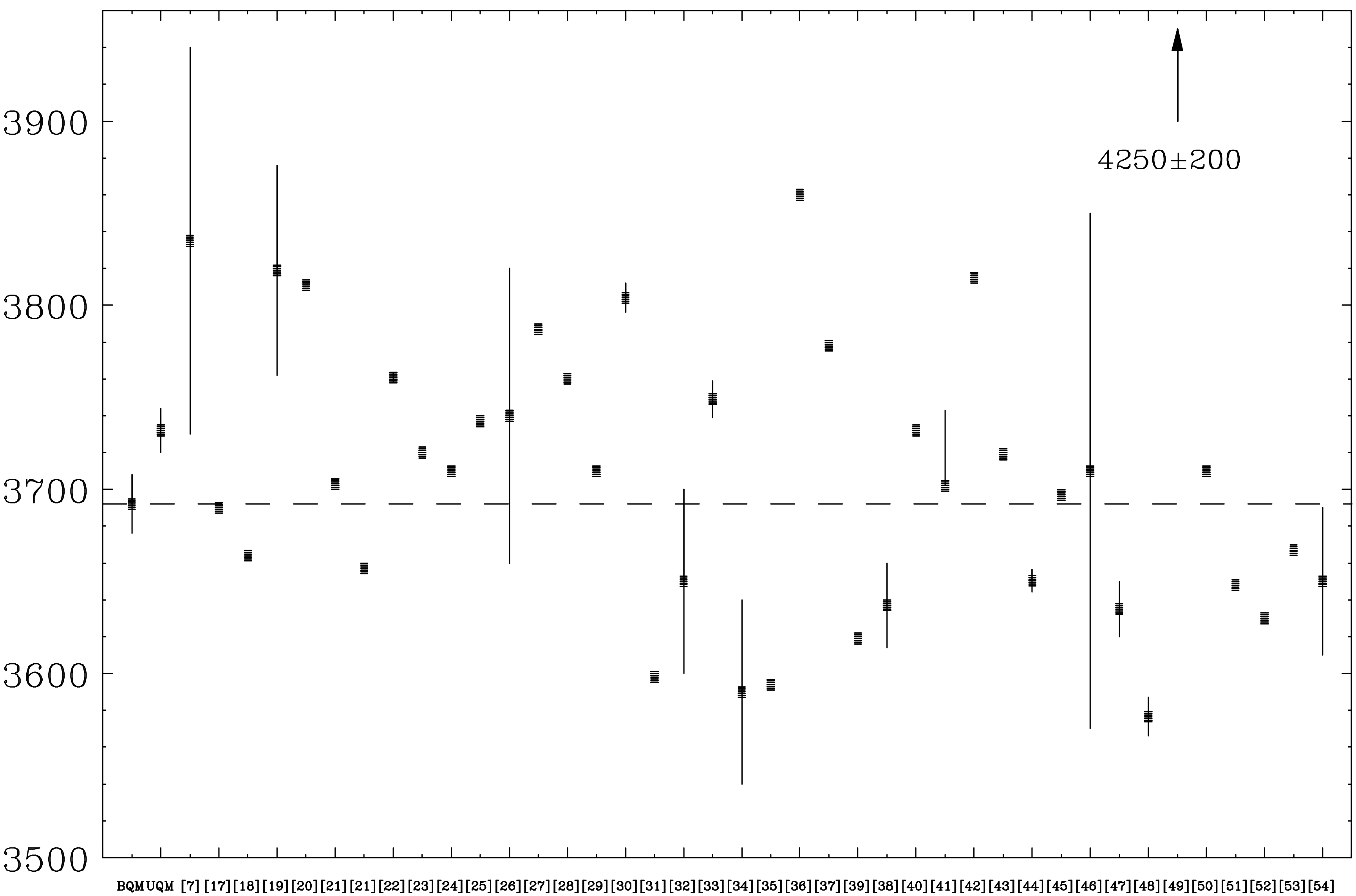
$\Xi_{cc} = ccq$			$\Omega_{cc} = ccs$		
Contribution	Value (MeV)		Contribution	Value (MeV)	
$2m_c^b + m_q^b$		3789.0	$2m_c^b + m_s^b$		3959.0
cc binding		-129.0	cc binding		-129.0
$a_{cc}/(m_c^b)^2$		14.2	$a_{cc}/(m_c^b)^2$		14.2
$-4a/m_q^b m_c^b$		-42.4	$-4a'/m_s^b m_c^b$		-42.4
Total	3626.8	± 12	Subtotal	3801.8	± 12

Additional binding of s to cc: -109.4 ± 10.5 MeV, giving $M(\Omega_{cc}) = 3692 \pm 16$ MeV, $M(\Omega^*_{cc}) = 3756 \pm 16$ MeV

Superscripts on quark masses: value in a baryon

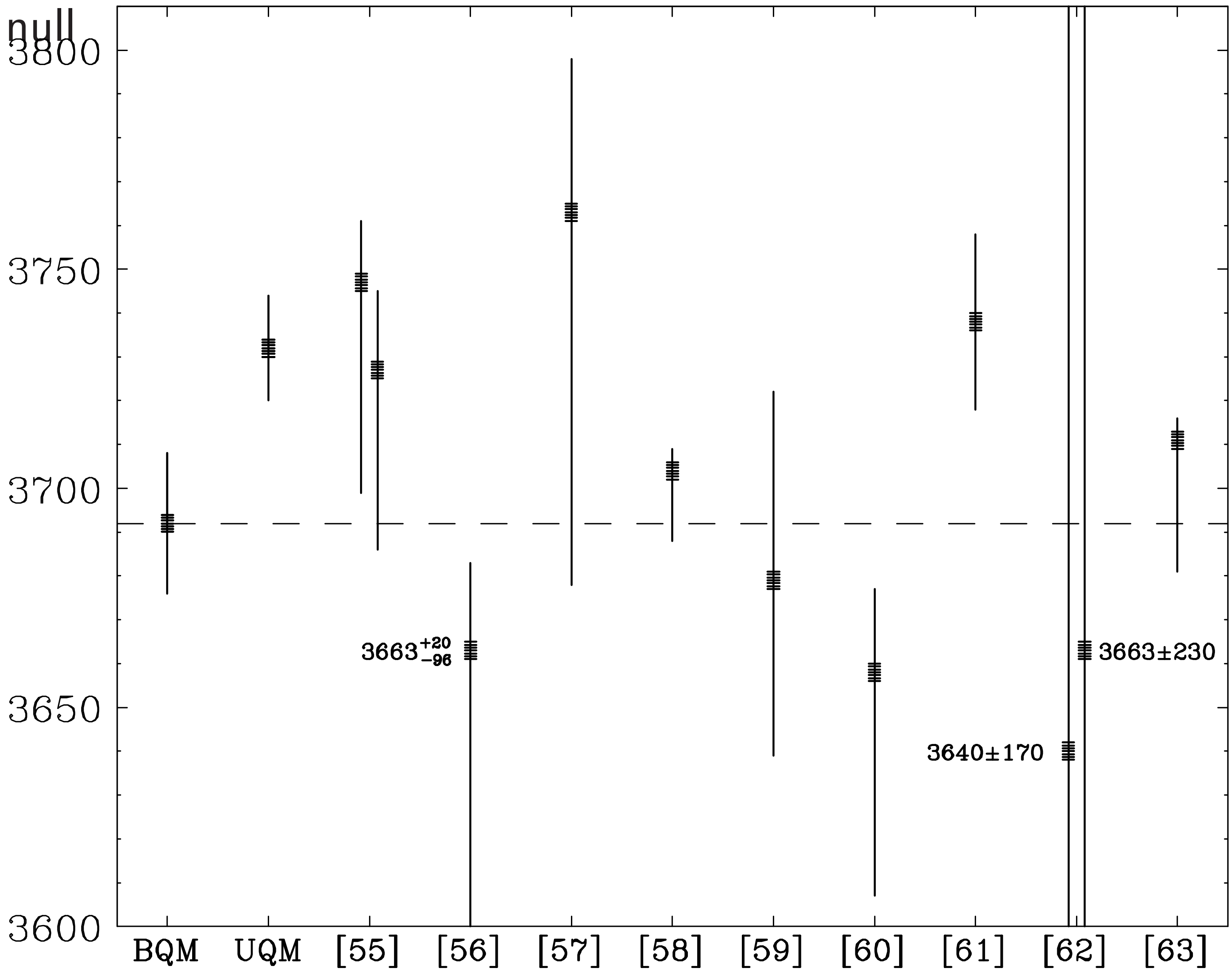
Universal quark masses and 165 MeV "string junction" term for baryons: predict $M(\Omega_{cc}) \sim 40$ MeV higher

COMPARISONS (NON-LATTICE)



Our prediction is on the left; others: PR D **97**, 094006

COMPARISONS (LATTICE)



Our prediction is on the left; others: PR D **97**, 094006

DECAYS AND LIFETIMES

$\Xi_{cc}^{++} = ccu$: A c quark decays to $W^{*+}s \to (\pi^+, \rho^+, a_1^+)s$

Remnant csu can decay to $W^{*+}s$ and ssu remnant which then can be Ξ^0 (hard to detect) or decay to (e.g.) $\Xi^-\pi^+$

Or remnant csu fragments $\to (\Lambda_c K^-\pi^+,\ \Xi_c^0\pi^+, \ldots)$

$\Xi_{cc}^{+} = ccd$: Subprocess $c(cd) \to c(su)$ shortens lifetime

$\Xi_{bc}^{+} = bcu$: $\Gamma(W^{*-}(\Xi_{cc}, \Xi_b)) = (6.9, 20.1) \times 10^{-13}$ GeV

Some predicted lifetimes, in fs:

Baryon	This work	Anikeev	Kiselev	bj2	Moinester	Expt.
$\Xi_{cc}^{++} = ccu$	185	430±100	460±50	500	~ 200	256± 27
$\Xi_{cc}^{+} = ccd$	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	–	–	–

PRODUCTION

Production of two heavy quarks: need also two antiquarks

Production of $\Xi_{cc} = ccu$ related to that of $B_c = \bar{b}c$

Somewhat smaller because have to pick up a light quark

PR D **90**, 2014: $\sigma(\Xi_{cc}, \Xi_{bc})/\sigma(B_c + B_c^*) \simeq 10 - 50\%$

Result: estimate $\Sigma(pp \to \Xi_{cc} + X) \leq 40$ nb at 7 TeV

A. V. Berezhnoy +, arXiv:1809.10058:
$\sigma(\Xi_{bc})/\sigma(B_c) \leq 1/3$; $\sigma(\Xi_{bc}) \sim 10 - 25$ nb at 13 TeV

A useful ratio to be measured in e^+e^-:

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

STABLE $bb\bar{u}\bar{d}$ TETRAQUARK

We looked at $QQ'\bar{u}\bar{d}$ systems ($Q = c$ or b) (PRL **119**)

We found $cc\bar{u}\bar{d}$ unbound; it could decay to DD^* or $DD\gamma$

Lowest-lying $bc\bar{u}\bar{d}$ state was near $BD\gamma$ threshold and we could not tell for sure whether it was bound or unbound

Predicted $M(bb\bar{u}\bar{d}) = 10,389 \pm 12$ MeV, 215 MeV below B^-B^{*0} threshold and 170 MeV below $B^-B^0\gamma$ threshold

Regard bb as a color-3^* diquark (transforming under QCD as an antiquark); fermi statistics require its spin to be 1

Lightest $\bar{q}\bar{q}'$ state ($q, q' = u, d$) is a color-3 $\bar{u}\bar{d}$ state with isospin zero; fermi statistics require its spin to be zero

Mass prediction then relies on accounting for constituent-quark masses, hyperfine interactions, and binding effects

TETRAQUARKS $QQ'\bar{u}\bar{d}$

Contributions (MeV) to mass of lightest tetraquark:

$cc\bar{u}\bar{d}$, $J^P = 1^+$		$bc\bar{u}\bar{d}$, $J^P = 0^+$		$bb\bar{u}\bar{d}$, $J^P = 1^+$	
Contribution	Value	Contribution	Value	Contribution	Value
$2m^b_c$	3421.0	$m_b + m_c$	6754.0	$2m^b_b$	10087.0
$2m^b_q$	726.0	$2m^b_q$	726.0	$2m^b_q$	726.0
cc hyperfine	14.2	bc hyperfine	-25.5	bb hyperfine	7.8
$-3a/(m^b_q)^2$	-150.0	$-3a/(m^b_q)^2$	-150.0	$-3a/(m^b_q)^2$	-150.0
cc binding	-129.0	bc binding	-170.8	bb binding	-281.4
Total	3882±12	Total	7134±13	Total	10389 ± 12

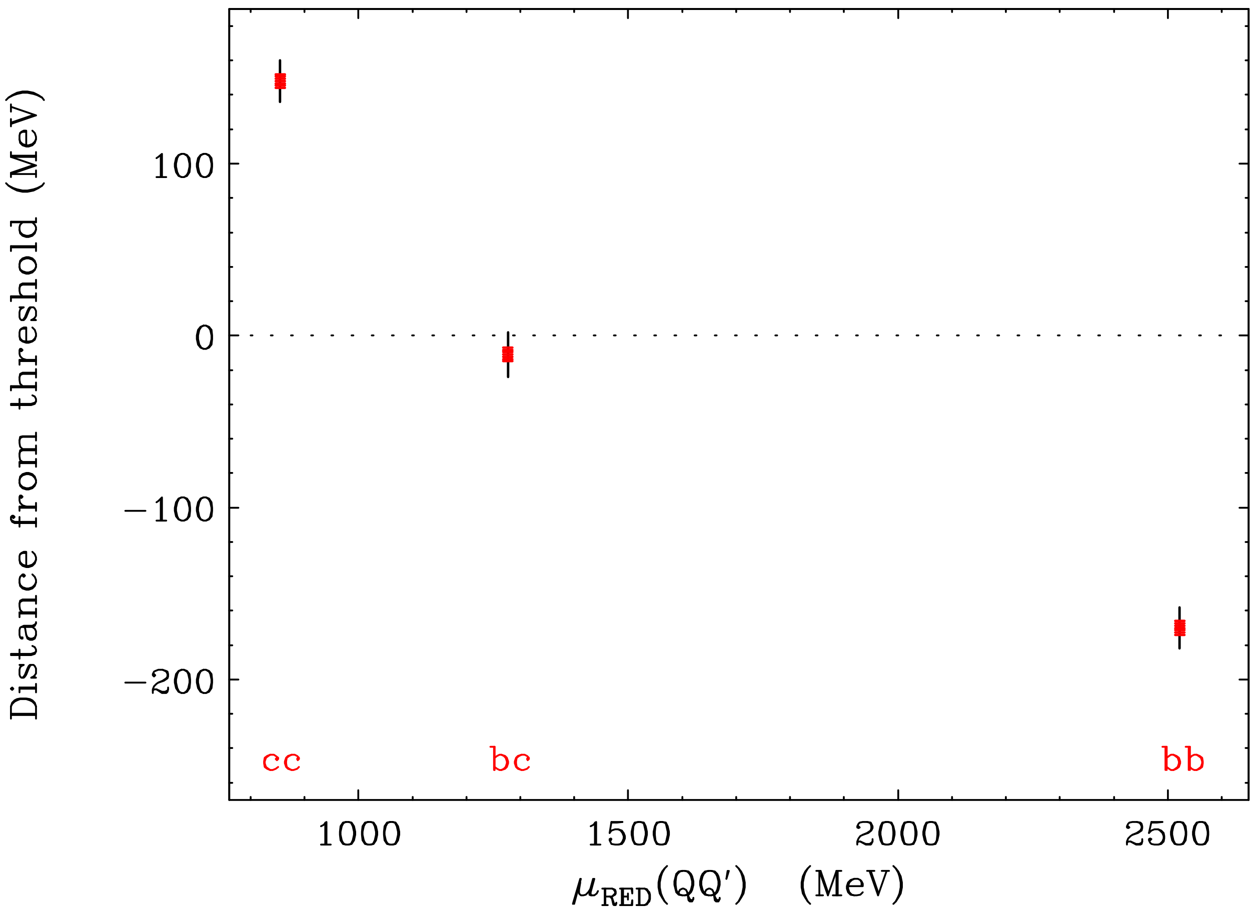
Spin zero allowed for the $bc\bar{u}\bar{d}$ state, taking advantage of the attractive bc hyperfine interaction

Since $M(cc\bar{u}\bar{d}) > M(D^0) + M(D^+) = 3734$ MeV, it can decay to $D^0D^+\gamma$ (decay to D^0D^+ is forbidden)

$M(bc\bar{u}\bar{d}) < M(D^0) + \bar{M}(B^0) = 7144$ MeV?

Estimated lifetime of $bb\bar{u}\bar{d}$ state: 367 fs

COMPARISON OF TQ MASSES



Distance in MeV of the $cc\bar{u}\bar{d}$, $bc\bar{u}\bar{d}$ and $bb\bar{u}\bar{d}$ tetraquark masses from corresponding thresholds $D^0D^+\gamma$, $\bar{B}^0D^0$, and $\bar{B}^0B^-\gamma$, plotted against reduced masses of the doubly-heavy diquarks $\mu(QQ')$, Q,Q'=c, b.

PROSPECTS

Exotic mesons and baryons (beyond $q\bar{q}$ and qqq) *do* exist; molecular configurations are at least part of the story

Heavy quarks have a lower kinetic energy and help to stabilize exotic configurations containing them

Techniques for mass estimation (constituent-quark masses, hyperfine interactions, binding effects) relatively straightforward and starting to be tested for $QQ'q$ baryons

Frontier: $Q_1Q_2\bar{Q}_3\bar{Q}_4$; any $cc\bar{c}\bar{c}$ lighter than $2M(\eta_c)$? Any $bb\bar{b}\bar{b}$ lighter than $2M(\eta_b)$?

Can quark-level analogue of nuclear fusion be put to use?

Still to be known: What does it cost to produce one or more extra heavy quarks via strong interactions? When do two heavy quarks end up in the same hadron?

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M. Karliner and JLR, arXiv:1808.07869 (P-wave excitation energies)

P-WAVE EXCITATIONS

What is the splitting between S and P wave levels?

M. Karliner and JLR, arXiv:1808.07869, to be published in PR D

Shortcut avoids solving relativistic wave equation

Quarks have effective masses and pair binding energies

Effective quark masses, MeV

Quark	In a meson	In a baryon
u	$m_u^m = 310$	$m_u^b = 363$
d	$m_d^m = 310$	$m_d^b = 363$
s	$m_s^m = 483$	$m_s^b = 538$
c	$m_c^m = 1663.3$	$m_c^b = 1710.5$
b	$m_b^m = 5003.8$	$m_b^b = 5043.5$

Binding terms $B(q_1q_2)$, MeV

Pair q_1q_2	$B(q_1q_2)$	$B(q_1\bar{q}_2)$
cs	35.0	70.0
bs	41.8	83.6
cc	129	258
bc	170.8	341.5
bb	281.4	562.8

Know S–P splitting of Λ, Λ_c, Λ_b, Ξ_c, and Ω_c baryons (treat as 2-body systems); D_s, $c\bar{c}$, and $b\bar{b}$ mesons

Plot differences $\Delta E_R \equiv \Delta E_{P-S} - \sum B$ vs. reduced mass μ_{12}

RESIDUAL ENERGY DIFFERENCES ΔE_R

System	q_1	q_2	m_1	m_2	μ_{12}	ΔE_{P-S}	$\sum B$	ΔE_R
Λ	$[ud]$	s	576.0	538	278.2	365.7	0	365.7
Λ_c	$[ud]$	c	576.0	1710.5	430.9	329.7	0	329.7
Λ_b	$[ud]$	b	576.0	5043.5	517.0	297.8	0	297.8
Ξ_c	$[qs]$	c	799.8	1710.5	545.0	340.3	35.0	305.3
Ω_c	(ss)	c	1098.8	1710.5	669.0	337.6	70.0	267.6
D_s	c	s	1663.3	483	374.3	436.0	70.0	366.0
$c\bar{c}$	c	c	1663.3	1663.3	831.6	456.8	258.0	198.8
$b\bar{b}$	b	b	5003.8	5003.8	2501.9	454.8	563	–108.2

$[ud]$ is a spin-zero isospin-zero color-3^* diquark

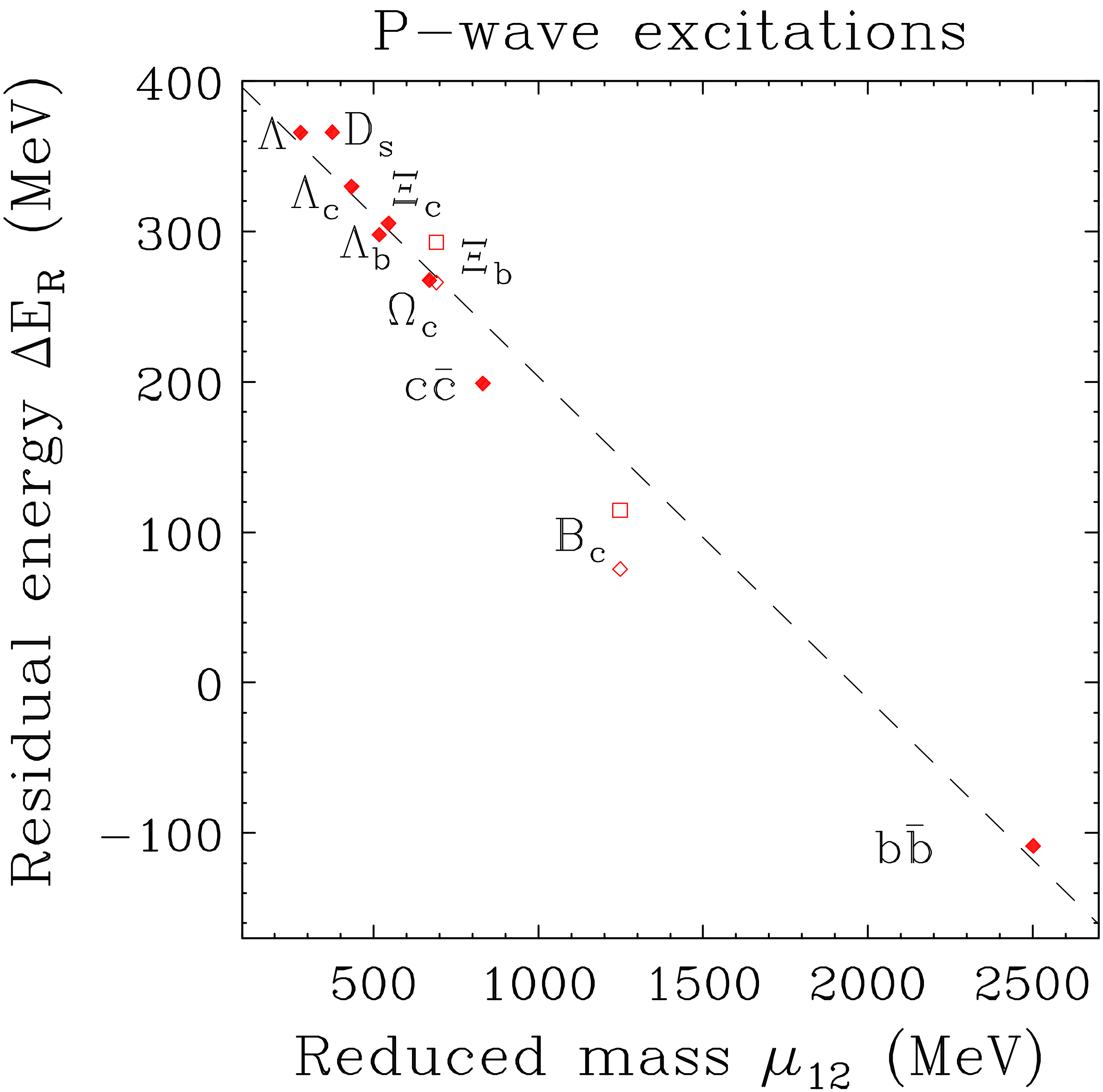
$[qs]$ is a spin-zero isospin-1/2 color-3^* diquark $(q = u, d)$

(ss) is a spin-1 isospin-zero color 3^* diquark

Effective masses and hyperfine interactions $\Rightarrow m_1$ values

Approximate relation $\Delta E_R \simeq (417.37 - 0.2141\,\mu_{12})$ MeV

ΔE_R VS. REDUCED MASS



Dashes: lin. fit

D, B: Not all P waves known

Filled diamonds: data used in fit

Hollow symbols: Theor. preds.

arXiv:1808.07869: consequences for $\Sigma_{c,b}, \Omega_c, \Xi_b$ baryons, D, D_s, B, B_c mesons