Lattice investigation of charmed and bottom hadrons

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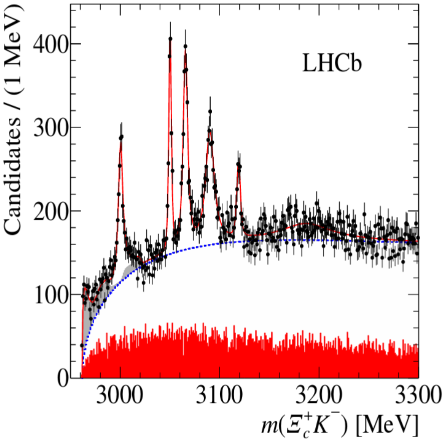
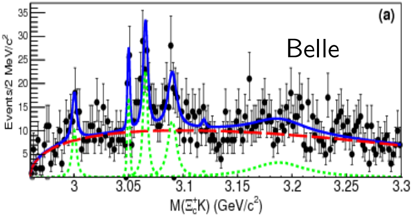
Collaborators: Nilmani Mathur, HSC and ILGTI.
Based on PRL 119(2017), 042001; PRL 121(2018), 202002;
PRD 99(2019), 031501; PRD 99 (2019), 034507.

LHCb discovery of excited Ω_c^0 baryons: 2017



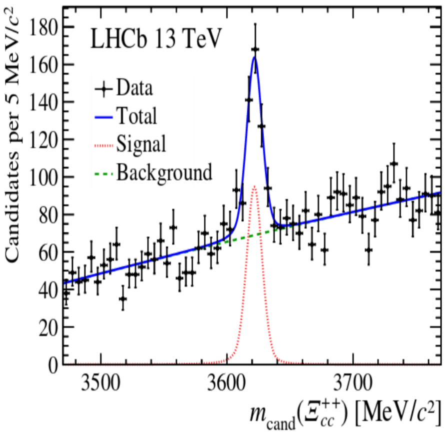
Resonance	Energy	Width	Q.no.
Ω_c^0	2695(2)	-	$1/2^+$
$\Omega_c^0(2770)$	2766(2)	-	$3/2^+$
$\Omega_c^0(3000)$	3000(1)	4.5(1)	?
$\Omega_c^0(3050)$	3050(1)	1(-)	?
$\Omega_c^0(3066)$	3066(1)	3.5(-)	?
$\Omega_c^0(3090)$	3090(1)	8.7(1)	?
$\Omega_c^0(3119)$	3119(1)	1(1)	?



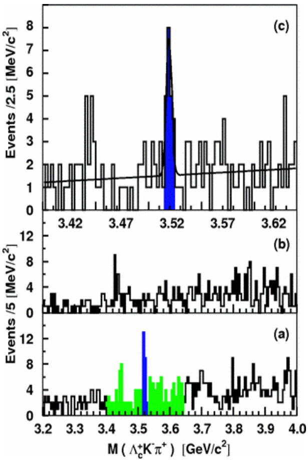
Aaij *et al.* (LHCb) 1703.04639

Confirmation by Belle : Yelton *et al.* (Belle) 1711.07927

A year of heavy baryons (2017) : Ξ_{cc}



Aaij *et al.* (LHCb) 1707.01621



Mattson *et al.* (SELEX) hep-ex/0208014

Other papers from LHCb on properties of Ξ_{cc} : 1905.02421; 1807.01919; 1806.02744

Doubly heavy tetraquarks : possibly stable system

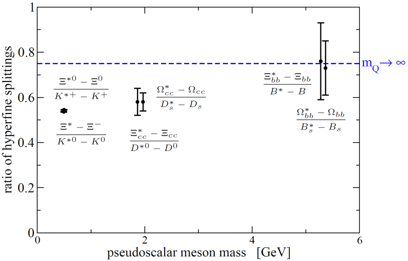
PRL **119,** 202001 (2017) PHYSICAL REVIEW LETTERS week ending 17 NOVEMBER 2017

Discovery of the Doubly Charmed Ξ_{cc} Baryon Implies a Stable $bb\bar{u}\bar{d}$ Tetraquark

Marek Karliner[1,*] and Jonathan L. Rosner[2,†]
[1]*School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel*
[2]*Enrico Fermi Institute and Department of Physics, University of Chicago, 5620 South Ellis Avenue, Chicago, Illinois 60637, USA*
(Received 28 July 2017; published 15 November 2017)

Heavy Quark Symmetry implies for a sufficiently heavy "heavy" quark, the doubly heavy tetraquarks should be stable to strong decays.

Carlson *et al.* PRD**37** 744 (1988); Eichten and Quigg 1707.09575



For a heavy-light meson-like system of doubly charm baryons

$$\frac{M(\Xi^*_{QQ}) - M(\Xi_{QQ})}{M(V_Q) - M(PS_Q)} \to \frac{3}{4}$$

Brambilla *et al* hep-ph/0506065

Data : Brown *et al* 1409.0497

Figure : Lewis CHARM-2018

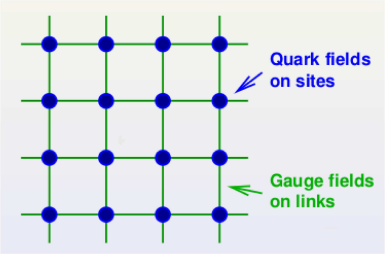
Heavy hadrons

- Clean signature for many observables, even though rarity in events.
- A large number of discoveries in heavy hadron sector over the past decade.
  - usual quarkonium mesons like $h_c(1P)$, $h_b(1P)$, $h_b(2P)$, $\psi(1^3D_2)$.
  - heavy baryons like Ξ_{cc} and highly excited states of Ω_c (LHCb).
  - new beauty baryons like $\Sigma_b^{\pm}(6097)$, $\Lambda_b(6146)$ and $\Lambda_b(6152)$ by LHCb.
  - tetraquarks (LHCb, Belle) and pentaquarks (LHCb).
  - many other states with less theoretical understanding (XYZ).
- Charmed-bottom hadrons : largely unexplored unlike others.
  Discovered : $B_c(1S, 0^-)$ at 6275(1) MeV
  $B_c(2S, 0^-)$ at 6842(6) MeV (ATLAS)
  $B_c(2S, 0^-)$ at 6872(6) MeV and $B_c(2S, 1^-)$ (LHCb) at 6841(6) MeV*

Lattice QCD : theoretical prospects

LQCD : A non-perturbative, gauge invariant regulator for the QCD path integrals.

- Quarks lives on sites
- Gauge fields lives on links
- Lattice spacing : UV cut off
- Lattice size : IR cut off



Discretization $\Rightarrow$ Finite number of degrees of freedom
$\Rightarrow$ Infinite dimensional path integrals $\rightarrow$ finite dimensional integrals.

Employ Monte Carlo importance sampling methods on Euclidean metric for numerical studies.

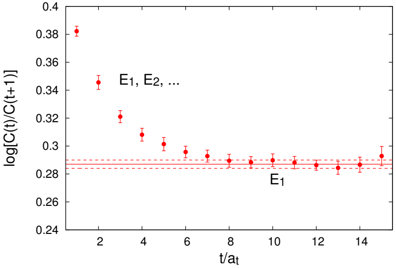
QCD spectrum from Lattice QCD

- Aim : to extract the physical states of QCD.
- Euclidean two point current-current correlation functions

$$C_{ji}(t_f - t_i) = \langle 0|\Phi_j(t_f)\bar{\Phi}_i(t_i)|0\rangle = \sum_n \frac{Z_i^{n*} Z_j^n}{2m_n} e^{-m_n(t_f - t_i)}$$

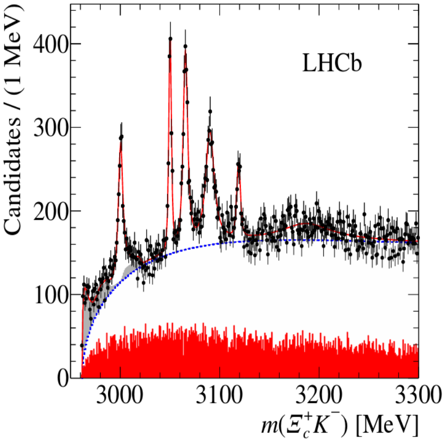
where $\Phi_j(t_f)$ and $\bar{\Phi}_i(t_i)$ are the desired interpolating operators and $Z_j^n = \langle 0|\Phi_j|n\rangle$.

- Effective mass defined as $\log[\frac{C(t)}{C(t+1)}]$



- The ground states : from the exponential fall off at large times. Non-linear fitting techniques.

LHCb discovery of excited Ω_c^0 baryons: 2017



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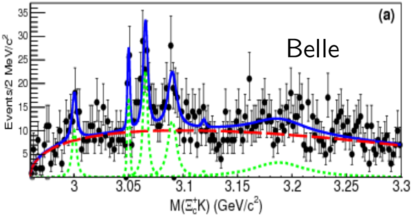


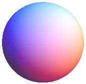
Aaij *et al.* (LHCb) 1703.04639

Confirmation by Belle : Yelton *et al.* (Belle) 1711.07927

Excited baryon spectroscopy

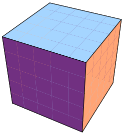
- Aim : Extraction of highly excited states.
  Local operators → low lying states.
  Extended operators → Radial and orbital excitations.
- Continuum operators with well defined quantum nos.
  Reduce/subduce into the irreps of the reduced symmetry.

$O(3)$



$O_i^{J^{PC},M}$

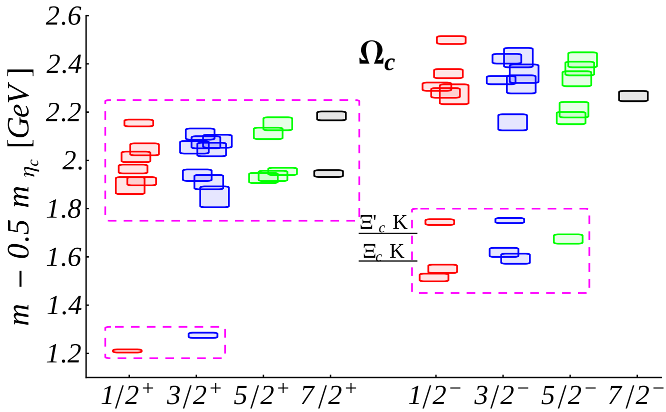
O_h



$O_{i,\Lambda^{PC}}^{[J^{PC}]}$

- Variational analysis of correlation matrices, C_{ji}.
- Rigorous spin identification procedure using operator state overlaps, Z.

Results : Ω_c spectrum (L1)

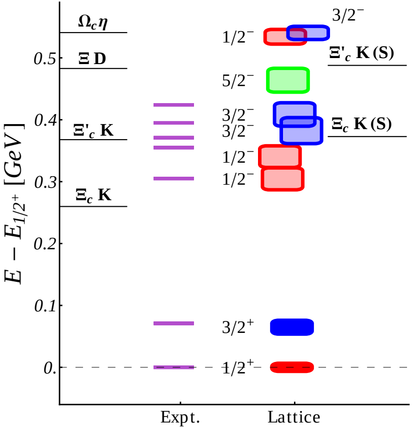


MP & Mathur 1704.00259, Charm 2013 (1311.4806), Charm 2015 (1508.07168).

Magenta ellipses : States with strong non-relativistic content.

The low lying spectrum same as non-relativistic expectations.

Experiment vs. lattice predictions (L1)



Energy	Expt.	Lattice
$\Delta E_{\Omega_c^0(3119)}$	422(1)	464(20)
$\Delta E_{\Omega_c^0(3090)}$	395(1)	409(19)
$\Delta E_{\Omega_c^0(3066)}$	371(1)	383(21)
$\Delta E_{\Omega_c^0(3050)}$	355(1)	341(18)
$\Delta E_{\Omega_c^0(3000)}$	305(1)	304(17)
$\Delta E_{\Omega_c^0(2770)}$	70.7(1)	65(11)
$E_{\Omega_c^0} - \frac{1}{2} E_{\eta_c}$	1203(2)	1209(7)

Here $\Delta E = E - E_{\Omega_c^0}$.
The new states correspond to the excited p-wave excitations.

Spin 1/2, 3/2, 5/2
Ω_{ccc} : HSC 1307.7022
Ξ_{cc} and Ω_{cc} : HSC 1502.01845

On anisotropic $N_f = 2 + 1$ lattices
$L \sim 1.9\ fm$, $a_t m_c = 0.114$
and $m_\pi = 391\ MeV$

Edwards *et al.* 0803.3960

MP & Mathur 1704.00259, Charm 2013, Charm 2015.

Heavy quarks on the lattice

Fermion action: $\bar{\psi}(\gamma.\mathbf{D} + \mathbf{m})\psi$

Only dimensionless quantities defined on the lattice

Lattice fermion action: $\bar{\psi}(\mathbf{x})(\gamma.\mathbf{D_L} + \mathbf{am})\psi(\mathbf{x})$

Discretization $\rightarrow \mathbf{D_L}$; clover, staggered, overlap, domain-wall, etc.

Discretization errors on observables $\mathcal{O}(\mathbf{am})$.

Charm quarks: $m_c \sim 1.275$ GeV

$$am_c = 0.5 \quad \Rightarrow \quad a \sim 0.075 \text{ fm}$$

$$am_c = 0.3 \quad \Rightarrow \quad a \sim 0.046 \text{ fm}$$

Bottom quarks: $m_b \sim 4.66$ GeV

$$am_b = 0.5 \quad \Rightarrow \quad a \sim 0.021 \text{ fm}$$

$$am_b = 0.3 \quad \Rightarrow \quad a \sim 0.013 \text{ fm}$$

Another lattice calculation: L2

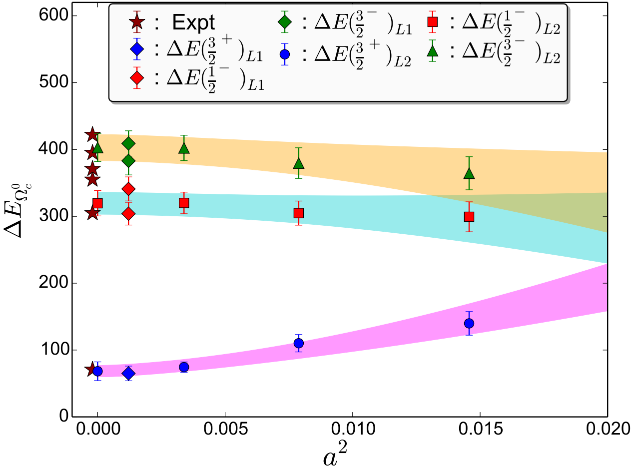
- State-of-the-art ensembles : N_f =2+1+1 HISQ (MILC)
  a =0.1207(11), 0.0888(8) and 0.0582(5) fm.
  MILC Collaboration 1212.4768
- Chiral fermion action for quark masses from light to charm.
  Exact chiral symmetry at finite lattice spacing. No $\mathcal{O}(am)$ errors.
- Heavy quark mass tuning Dowdall *et al.* 1110.6887
  $\Delta E_{hfs}^{1S,\bar{c}c} = 115(2)(3)$ MeV ($Lattice$) & $\Delta E_{hfs}^{1S,\bar{c}c} = 114$ MeV ($Expt$).
- We work with energy splittings

$$\Delta M_H = [M_H^L - n_c \overline{1S}_c/2]a^{-1}.$$

- Continuum extrapolation fit forms $Q^f = A + a^2 B$, $L^f = A + a^2 log(a) B$.
- We extract the mass of hadrons from

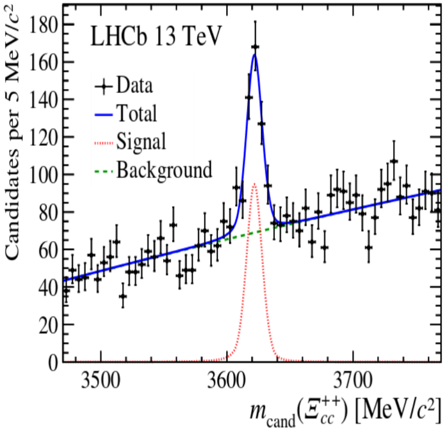
$$M_H^c = \Delta M_H^c + n_c(\overline{1S}_c)_{phys}/2.$$

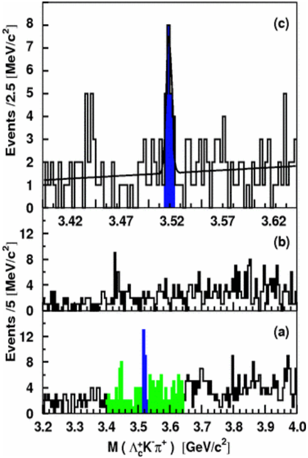
Comparison between two lattice determinations



MP & Mathur (HSC) 1704.00259

A year of heavy baryons (2017) : Ξ_{cc}





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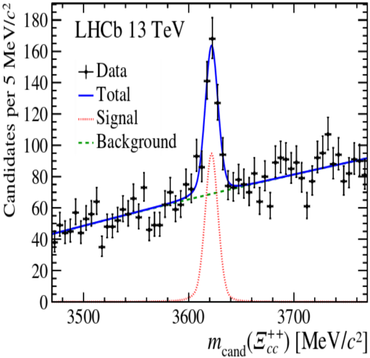
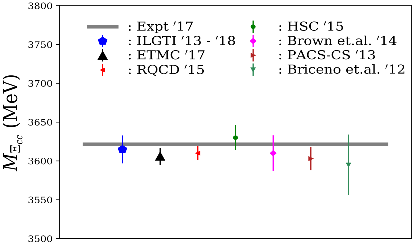
Mattson *et al.* (SELEX) hep-ex/0208014

Others papers from LHCb on properties of Ξ_{cc} : 1905.02421; 1807.01919; 1806.02744

Ξ_{cc} from lattice QCD





Aaij *et al.* (LHCb) 1707.01621

Alexandrou *et al.* (ETMC) 1704.02647

Briceño *et al.* 1207.3536

Namekawa *et al.* (PACS) 1301.4743

MP *et al.* (HSC) 1502.01845 (L1)

Brown *et al.* 1409.0497

Pérez-Rubio *et al.* (RQCD) 1503.08440

ILGTI 1807.00174, 1312.3050 (L2)

Ξ_{cc} isospin splitting (LQCD), 2.16(11)(17) MeV : BMW 1406.4088

SELEX measurement (3519 MeV) : Mattson *et al.* hep-ex/0208014

Doubly charmed baryons from lattice QCD

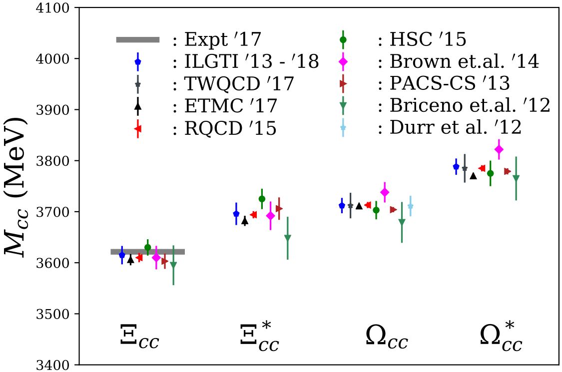


Figure from arXiv:1905.09651 [hep-lat]

Ω_{cc}: probably the next doubly charm baryon to be observed in LHCb.

Ξ^*_{cc}: radiative decay might be predominant over strong decays.
So might be difficult for LHCb to discover.

Singly charmed baryons from lattice QCD

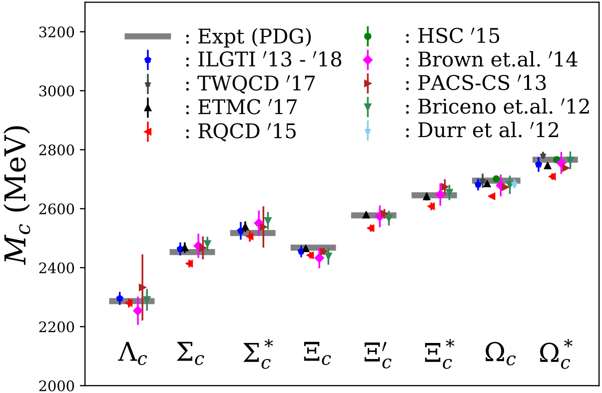


Figure from arXiv:1905.09651 [hep-lat]

Charmed-bottom hadrons from lattice QCD: L2

- State-of-the-art ensembles : N_f =2+1+1 HISQ (MILC)
  $24^3 \times 64$, $32^3 \times 96$ and $48^3 \times 144$
  a =0.1207(11), 0.0888(8) and 0.0582(5) *fm*.
  MILC Collaboration 1212.4768
- Chiral fermion action for quark masses from light to charm.
  Exact chiral symmetry at finite lattice spacing. No $\mathcal{O}(am)$ errors.
- Bottom quarks realized using NRQCD formulation.
  Includes terms in the Hamiltonian through $\mathcal{O}(\alpha\nu_b^4)$.
  HPQCD Collaboration 1110.6887, Hammant *et al* 1303.3234.
- Heavy quark mass tuning Dowdall *et al.* 1110.6887
  $\Delta E_{hfs}^{1S,\bar{c}c} = 115(2)(3)$ MeV and $\Delta E_{hfs}^{1S,\bar{b}b} = 63(3)(5)$ MeV Lattice
  $\Delta E_{hfs}^{1S,\bar{c}c} = 114$ MeV and $\Delta E_{hfs}^{1S,\bar{b}b} = 62(1)$ MeV Expt.

Charmed-bottom hadrons from lattice QCD: L2

- We work with energy splittings and dimensionless ratios

$$\Delta M_H = [M_H^L - n_b\overline{1S}_b/2 - n_c\overline{1S}_c/2]a^{-1} \qquad \text{and}$$
$$R_H = \frac{M_H^L - n_b\overline{1S}_b/2}{M_{B_c(0^-)}^L - n_b\overline{1S}_b/2}.$$

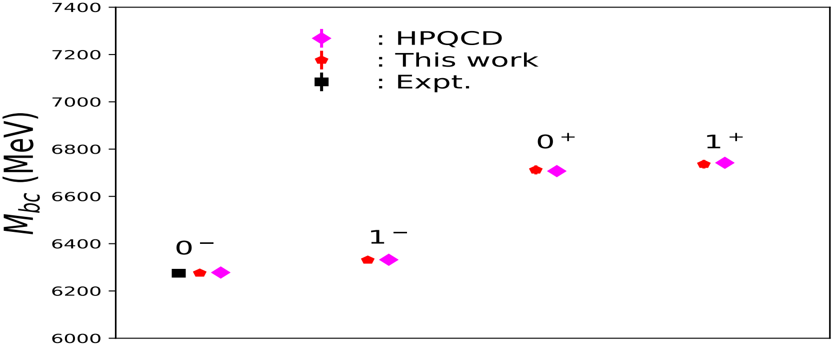
- Chiral extrapolation (Ξ_{bc}) using $A + m_\pi^2 B$ and other fancy chiral extrapolation forms as in Brown *et al* 1409.0497.
- Continuum extrapolation fit forms $Q^f = A + a^2B$, $C^f = A + a^3B$, $L^f = A + a^2 log(a)B$.
- We extract the mass of hadrons from

$$M_H^c = \Delta M_H^c + n_b(\overline{1S}_b)_{phys}/2 + n_c(\overline{1S}_c)_{phys}/2 \qquad \text{and}$$
$$M_H^c = R_H^c \times (M_{B_c(0^-)} - n_b\overline{1S}_b/2)_{phys} + n_b(\overline{1S}_b)_{phys}/2.$$

B_c meson results (L2)

Hadrons	Lattice	HPQCD	Wurtz *et al*	Experiment
$B_c(0^-)$	6276(3)(6)	6278(9)	-	6274.9(8)
$B_c^*(1^-)$	6331(4)(6)	6332(9)	6332.5(3)	?
$B_c(0^+)$	6712(18)(7)	6707(17)	6711(2)	?
$B_c(1^+)$	6736(17)(7)	6742(16)	6752(2)	?

Mathur, MP, Mondal 1806.04151; Dowdall *et al.* (HPQCD) 1207.5149; Wurtz *et al.* 1505.04410



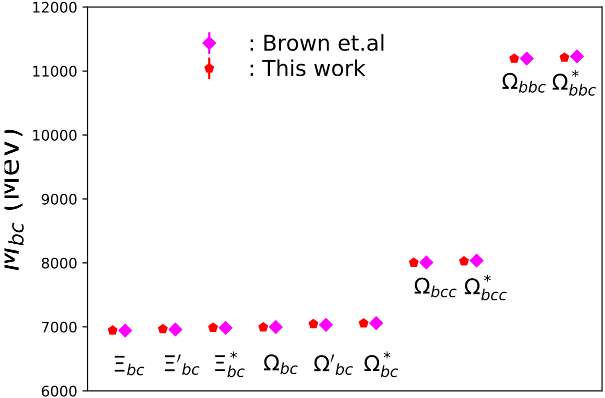
bc baryons: L2 Vs other lattice results

Hadrons	Lattice	Brown *et al*	Experiment
$\Xi_{cb}(cbu)(1/2^+)$	6945(22)(14)	6943(33)(28)	?
$\Xi'_{cb}(cbu)(1/2^+)$	6966(23)(14)	6959(36)(28)	?
$\Xi^*_{cb}(cbu)(3/2^+)$	6989(24)(14)	6985(36)(28)	?
$\Omega_{cb}(cbs)(1/2^+)$	6994(15)(13)	6998(27)(20)	?
$\Omega'_{cb}(cbs)(1/2^+)$	7045(16)(13)	7032(28)(20)	?
$\Omega^*_{cb}(cbs)(3/2^+)$	7056(17)(13)	7059(28)(21)	?
$\Omega_{ccb}(1/2^+)$	8005(6)(11)	8007(9)(20)	?
$\Omega^*_{ccb}(3/2^+)$	8026(7)(11)	8037(9)(20)	?
$\Omega_{cbb}(1/2^+)$	11194(5)(12)	11195(8)(20)	?
$\Omega^*_{cbb}(3/2^+)$	11211(6)(12)	11229(8)(20)	?

Brown *et al* 1409.0497

Mathur, MP, Mondal 1806.04151

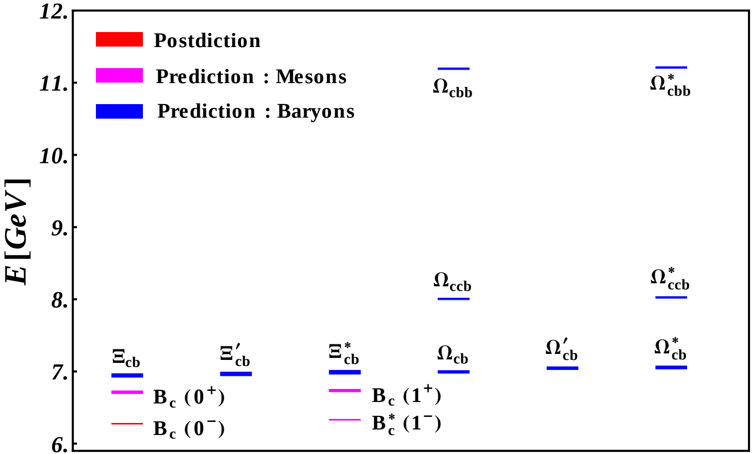
bc baryons: L2 Vs other lattice results



Brown *et al* 1409.0497

Mathur, MP, Mondal 1806.04151

Summary in predictions for *bc* hadrons (L2)



Mathur, MP, Mondal 1806.04151

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[2]*Enrico Fermi Institute and Department of Physics, University of Chicago, 5620 South Ellis Avenue, Chicago, Illinois 60637, USA*
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Heavy Quark Symmetry implies for a sufficiently heavy "heavy" quark, the doubly heavy tetraquarks should be stable to strong decays.

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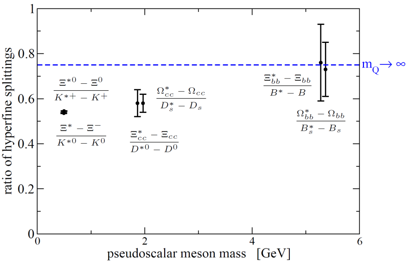


For a heavy-light meson-like system of doubly charm baryons

$$\frac{M(\Xi^*_{QQ}) - M(\Xi_{QQ})}{M(V_Q) - M(PS_Q)} \to \frac{3}{4}$$

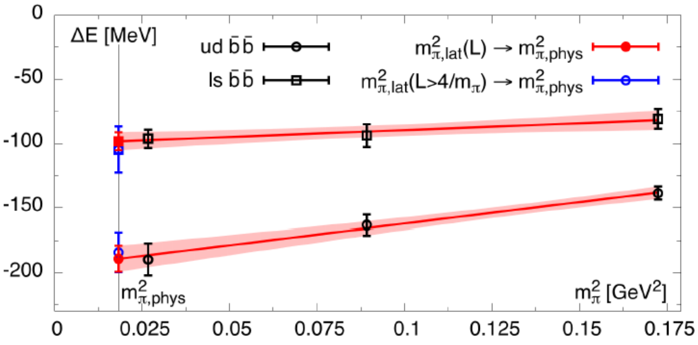
Brambilla *et al* hep-ph/0506065

Data : Brown *et al* 1409.0497

Figure : Lewis CHARM-2018

$\bar{b}\bar{b}ud$ and $\bar{b}\bar{b}ls$ tetraquarks on lattice

Francis *et al.* 1607.05214

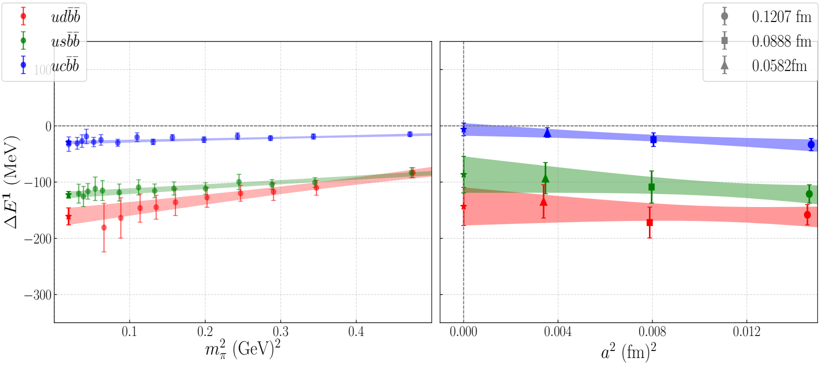


Study of pseudovector doubly bottom tetraquarks on $N_f = 2 + 1$ PACS-CS lattices
Correlation matrices out of tetraquark as well as meson-meson interpolators
Binding energies : $\Delta E_{\bar{b}\bar{b}ud} = 189(10)$ MeV and $\Delta E_{\bar{b}\bar{b}us} = 98(7)$ MeV

Other existing lattice calculations :

Bicudo *et al.* 1510.03441, Leskovec *et al.* 1904.04197

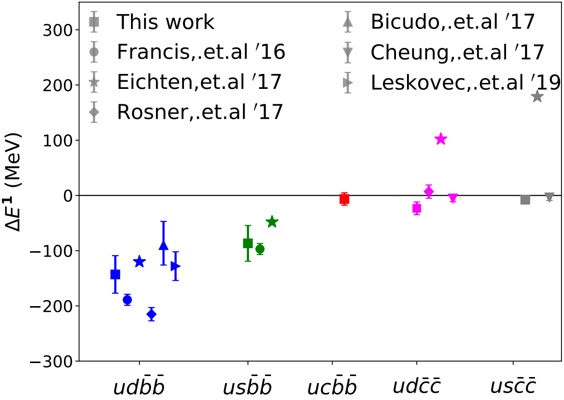
Doubly heavy tetraquarks from L2



Junnarkar, Mathur & MP (ILGTI) 1810.12285

- Extensive study of quark mass dependence on binding energies of doubly heavy tetraquarks.
- Correlation matrices out of tetraquark as well as meson-meson interpolators.
- Binding energies from difference in the lowest non-interacting levels.

Summary doubly heavy tetraquarks ($J^P = 1^+$)



1810.12285 (ILGTI, This work), 1607.05214 (Francis),
1707.09575 (Eichten and Quigg) 1707.07666 (Karliner and Rosner),
1510.03441 (Bicudo), 1709.01417 (HSC, Cheung), 1904.04197 (Leskovec).

Summary

- Discussed exploratory investigation of excited Ω_c baryon spectrum. Highlighted predictions for the quantum numbers of LHCb discovered excited Ω_c baryons.
- Summarized lattice QCD predictions for singly and doubly charm baryons. Compared lattice results with experimental values.
- Presented precision lattice QCD predictions/postdictions for masses of charmed-bottom hadron ground states. Predictions compared with other existing lattice estimates and postdictions compared with the respective experimental values and other lattice results.
- Beyond conventional hadrons : Promising platforms to study.
  Doubly heavy tetra-quarks: possibly deeply bound states.
  Discussed our study on m_q dependence of these binding energies.
  Ongoing investigations for $bc\bar{u}\bar{d}$ tetraquarks.

Thank you...

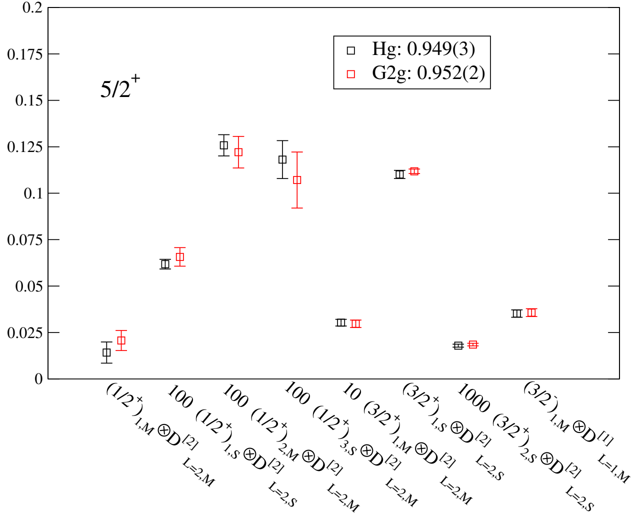
Spin identification : $J > \frac{3}{2}$ (L1)

- For example, a continuum operator $O = [ccc \otimes (\frac{3}{2}^+)^1_S \otimes D^{[2]}_{L=2,S}]^{J=\frac{5}{2}}$.
  Projects on to $\frac{5}{2}^+$.
- In the continuum, $\langle 0|O|\frac{5}{2}^+\rangle = Z$.
- On lattice, O gets subduced over two lattice irreps H_g and G_{2g}.
- Then

$$\langle 0|O_{H_g}|\frac{5}{2}^+\rangle = Z_1\alpha \qquad \& \qquad \langle 0|O_{G_{2g}}|\frac{5}{2}^+\rangle = Z_2\beta$$

  where α and β are the Clebsch-Gordan coefficients.
- If "close" to the continuum, then $Z \sim Z_1 \sim Z_2$.

Overlap factors (Z) across multiple irreps : $5/2^+$ (L1)



Errors in predictions for *bc* hadrons (L2)

- Wall sources to reduce statistical errors. All well below percent level.
- Discretization errors : Largest found to be in Ξ_{bc}, ~ 6 MeV.
- Scale setting : Independently calibrate the lattice using Ω baryon.
  This work : $a =$0.1192(14), 0.0877(10) and 0.0582(5) *fm*.
  MILC(r_1) : $a =$0.1207(11), 0.0888(8) and 0.0582(5) *fm*.
  Largest errors to be ~ 6 MeV.
- Chiral extrapolation : Robust with different extrapolation forms.
- Uncertainties in NRQCD : missing higher order terms, $\mathcal{O}(\alpha^2\nu^4)$ and $\mathcal{O}(\alpha\nu^6)$.
  ~ 4 MeV for mesons
  ~ 5, 5 and 6 MeV for *bcq*, *bcc* and *bbc* baryons respectively.
- Other sources : Quark mass mis-tuning, unphysical sea quark mass effects, electromagnetism, isospin breaking effects and absence of dynamical bottom quarks collectively to be within few MeV.

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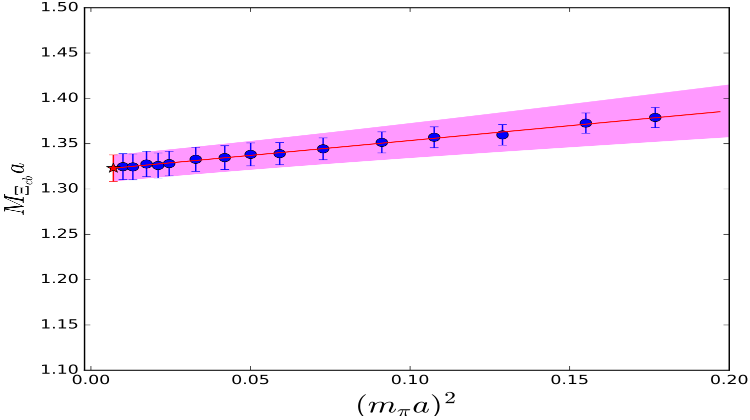
Ξ_{bc} baryon chiral extrapolation (L2)



On the coarse lattice. Chiral extrapolation form $A + m_\pi^2 B$.

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