Recent results on charm spectroscopy from the lattice

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Panda LV Collaboration meeting, Vienna, Dec 2nd 2015.

Outline

- Motivation and general considerations.
- Lower lying meson (D, D_s, $c\bar{c}$) and baryon (cqq, ccq) spectra.
  - Aim for precision results.
- Higher states: near threshold and resonances.
  - First step: excited state spectra with $q\bar{q}$, qqq operators.
  - Proper treatment: including multiparticle channels.
- Summary

Motivation

- Postdiction of states well established experimentally.
  - Demonstration of lattice techniques.
  - (Precision) tests show systematics are under control, supports determinations of other quantities, m_c, m_b, f_D, f_{D_s}.
- Postdiction of states less established experimentally.
  - Help with spin and parity assignments.
  - Whether a bound state/resonance exists.
- Prediction of new states (better test of lattice methods).
  - Expected from quark model.
  - Non-standard, $q\bar{q}q\bar{q}$, hybrids.
- Investigating internal structure of non-standard candidates.
- Testing theoretical descriptions: validity range of HQET/NRQCD.

Lattice considerations

General:

- QED effects neglected (not for much longer).
- Identification of quantum numbers: construct lattice operations respecting lattice cubic symmetry. Example bosons:
  - $A_1 \to J = 0, 4, \ldots,\ T_1 \to J = 1, 3, 4, \ldots$
  - $E \to J = 2, 4,\ T_2 \to J = 2, 3, 4,\ A_2 \to J = 3, \ldots$
- Stability under strong decay (lattice simulation).

Input: $\mathcal{L}_{QCD} = -\frac{1}{16\pi\alpha_L} FF + \bar{q}_f(\not{D} + m_f)q_f$

$$m_N^{\text{latt}} = m_N^{\text{phys}} \longrightarrow a, \qquad m_\pi^{\text{latt}}/m_N^{\text{latt}} = m_\pi^{\text{phys}}/m_N^{\text{phys}} \longrightarrow m_u \approx m_d, \cdots$$

Output: hadron masses, matrix elements, decay constants, etc...

Extra- & interpolations:

1. $a \to 0$: $\mathcal{O}(a^2)$ or $\mathcal{O}(\alpha_s a)$, depending on the lattice action (systematically improvable).
2. $L = Na \to \infty$: FSE suppressed with $\exp(-cLm_\pi)$: harmless but computationally expensive since $V \propto L^4$. High excitations?
3. $m_q^{\text{latt}} \to m_q^{\text{phys}}$: chiral perturbation theory (χPT) helps for $q = ud$ but m_{ud}^{latt} must be sufficiently small to start with.

Landscape of lattice simulations

m_u, m_s

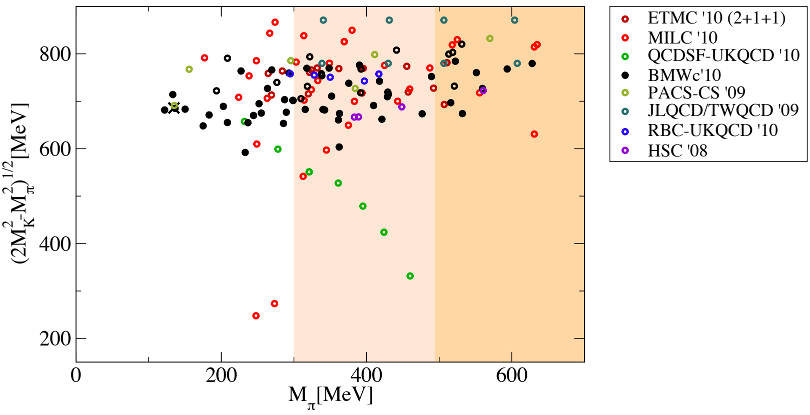


Figure taken from C Hoelbling, arXiv:1410.3403

Landscape of lattice simulations

Volume.

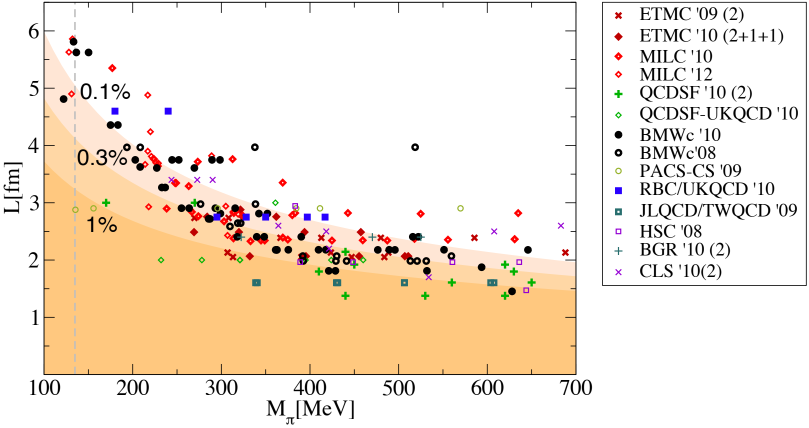


Figure taken from C Hoelbling, arXiv:1410.3403

Landscape of lattice simulations

Lattice spacing.

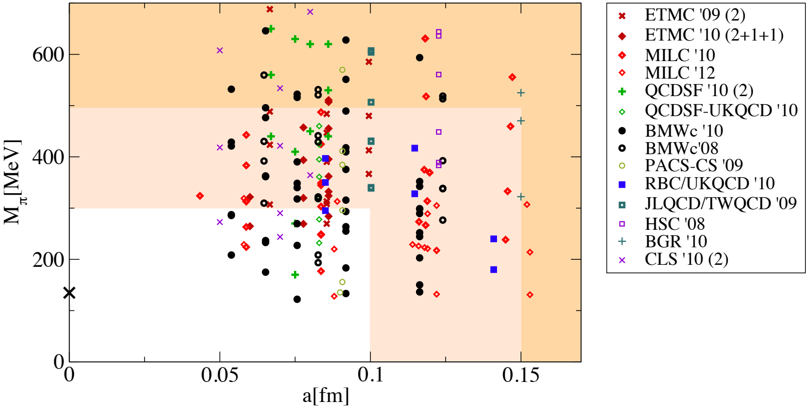
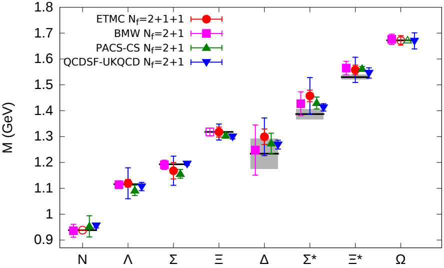
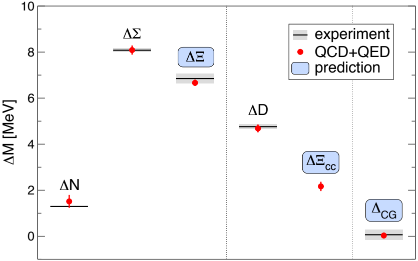


Figure taken from C Hoelbling, arXiv:1410.3403

Lower lying light hadron spectrum





Left summary plot from ETMC [arXiv:1406.4310]

ETMC $N_f = 2 + 1 + 1$ [arXiv:1406.4310]
BMW-c $N_f = 2 + 1$ [arXiv:0906.3599]
PACS-CS $N_f = 2 + 1$ [arXiv:0807.1661]
QCDSF=UKQCD $N_f = 2 + 1$ [arXiv:1102.5300]

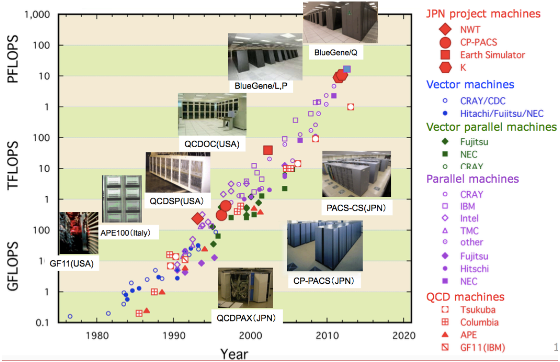
Right BMW-c [arXiv:1406.4088], $N_f = 1 + 1 + 1 + 1$, QCD+QED
Coleman-Glashow relation: $\Delta_{CG} = \Delta N - \Delta\Sigma + \Delta\Xi = 0.00(11)(06)$

Hardware improvements and algorithmic developments

Adjusting $L \propto 1/m_\pi$, $\text{cost} \propto \frac{1}{a^{\geq 6}\, m_\pi^{7.5}}$

Huge progress in Hybrid Monte Carlo, solver, source design.

In addition to hardware advances.

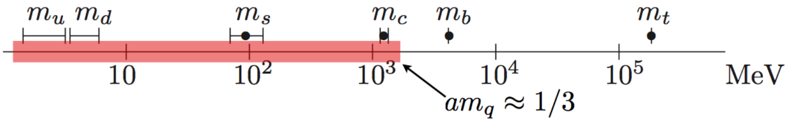


[Akira Ukawa, Conceptual advances in lattice gauge theory, CERN, 31st July 2014]

Also: APEMille, APENext, QPACE (Regenburg+Wuppertal, SFB-TRR 55).

Charm quark on the lattice

Past lattice simulations $a \geq 0.05$ fm or $a^{-1} \approx 4$ GeV:



Picture C. Pena, Lattice 2015 plenary talk, Kobe, Japan

Effective field theories:

- HQET
- NRQCD
- Relativistic heavy quark actions
- ...

Relativistic actions:

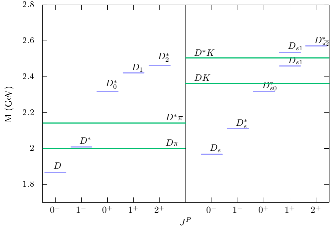
- staggered (HISQ), $O((am_c)^2)$
- Wilson (Clover), $O(\alpha am_c)$, $O((am_c)^2)$
- Twisted mass, $O((am_c)^2)$
- ...

Charm systems sit between non-relativistic and relativistic regimes and are not so amenable to heavy quark effective field theory methods.

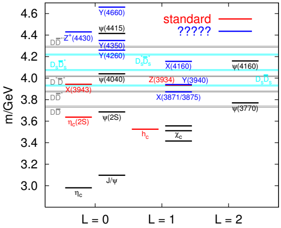
Lattice actions: systematically improvable.

(Incomplete) charmed meson and baryon expt. spectra

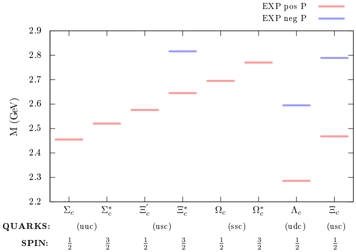
D D_s



charmonium

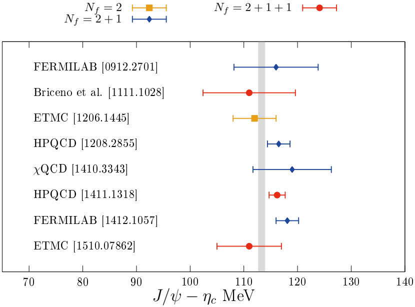


Singly charmed baryons



Hyperfine splittings: charmonium

Sensitive to many systematics: discretisation effects, quark mass tuning, ...



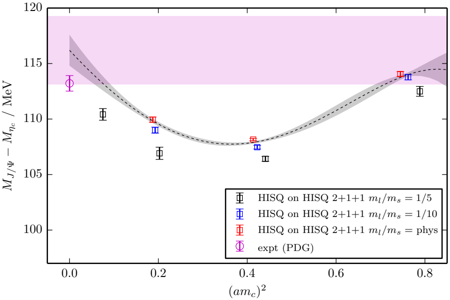
NB: ETMC 2015: $J/\psi = 3096(6)$ GeV, $\eta_c = 2985(6)$ GeV $\rightarrow \Delta M = 111(6)$ MeV.

Fermilab: MILC $N_f = 2+1$, $a = 0.09 - 0.15$ fm, update $a = 0.045 - 0.15$ fm.
Briceno et al.: MILC $N_f = 2+1+1$, $a = 0.09, 0.12$ fm, Fermilab charm.
HPQCD: MILC $N_f = 2+1$, $a = 0.044 - 0.12$ fm, update MILC $N_f = 2+1+1$, $a = 0.06 - 0.15$ fm.
χQCD: RBC/UKQCD $N_f = 2+1$, $a = 0.086, 0.11$ fm, Overlap.
ETMC: $N_f = 2$, $a = 0.05 - 0.10$ fm update, $N_f = 2+1+1$, $a = 0.062 - 0.089$ fm, twisted mass.

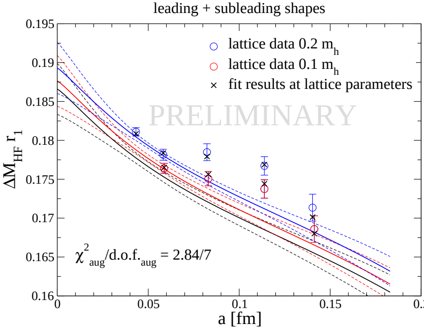
Hyperfine splittings: charmonium

Continuum and chiral extrapolations:

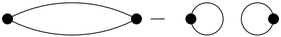
HPQCD [arXiv:1411.1318]



Fermilab [arXiv:1412.1057]



Precision in some cases close to estimates of omitting disconnected diagrams:

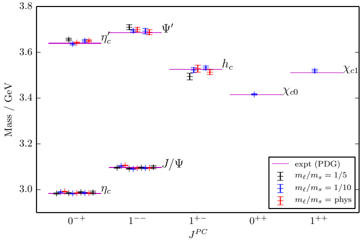


Levkova et al. [arXiv:1012.1837]: 1-4 MeV decrease in $J/\psi - \eta_c$.

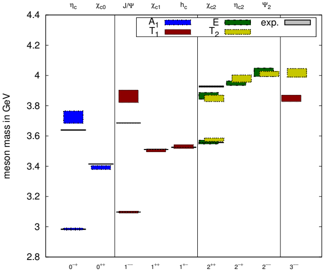
Ehmann et al. [1110.2381] η_c mixing with light flavour singlets: $\Delta M\eta_c = 11(24)$ MeV.

Lower lying charmonium spectrum

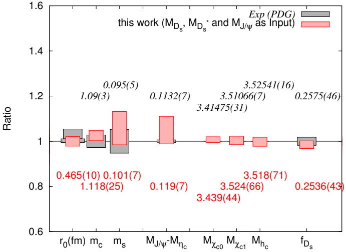
HPQCD [arXiv:1411.1318]



ETMC [arXiv:1510.07862]

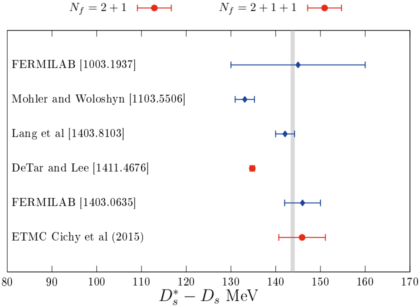


χQCD [arXiv:1410.3343]



Hyperfine splittings: D_s

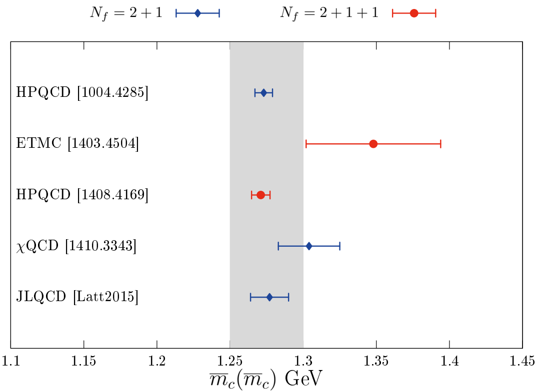
Sensitive to many systematics: discretisation effects, quark mass tuning, ...



NB: ETMC $D_s^* = 2.1107(52)$ GeV, $D_s = 1.9648(36)$ GeV $\rightarrow \Delta M = 145.9(5.2)$ MeV.

Fermilab: MILC $N_f = 2+1$, $a = 0.09 - 0.15$ fm, update $a = 0.045 - 0.15$ fm.
DeTar and Lee: MILC $N_f = 2+1+1$, $a = 0.15$ fm, Fermilab charm.
ETMC: $N_f = 2+1+1$, $a = 0.062 - 0.089$ fm, twisted mass.
Lang at al: PACS-CS $N_f = 2+1$, $a = 0.091$ fm, Fermilab charm.
Mohler and Woloshyn: PACS-CS $N_f = 2+1$, $a = 0.091$ fm, Fermilab charm.

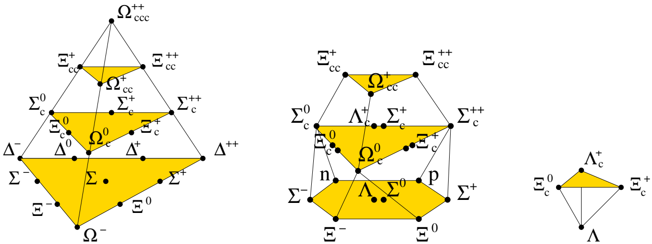
Charm quark mass



HPQCD+JLQCD: compute ratios of moments of current-current correlators + use continuum perturbative expansion.

ETMC+χQCD: $m_c^{\mathrm{RI}}(\mu) = Z_m^{\mathrm{RI}}(\mu, 1/a)\, m_{c0}$,
$Z_m^{\mathrm{RI}}(\mu, 1/a)$ determined non-perturbatively in RI/MOM scheme + cont. pert. theory to convert to $\overline{MS}$.

Charmed baryons

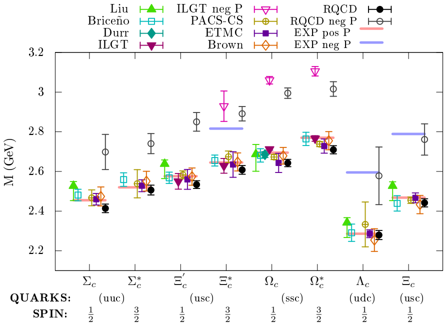


$SU(4)$ representations : $\quad 4 \otimes 4 \otimes 4 \quad = \quad 20_S \ \oplus 20_M \oplus 20_M \ \oplus \overline{4}_A$

Ground states: 20_S has $J = \frac{3}{2}^+$, 20_M has $J = \frac{1}{2}^+$ and $\overline{4}_A$ has $J = \frac{1}{2}^-$ (non-rel. limit).

Spectrum singly charmed baryons

Perez-Rubio [1503.08440]



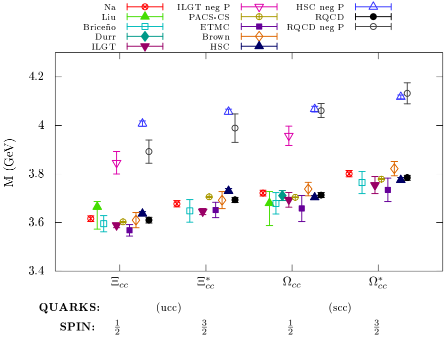
$N_f = 2+1$: Liu et al. clover/DW [0909.3294], PACS-CS NP-clover/NP-clover [1301.4743], Brown et al. FNAL-clover/Domain Wall [1409.0497].

$N_f = 2+1+1$: Briceno et al. clover/HISQ [1207.3536], ILGTI overlap/HISQ [1312.3050], ETMC Twisted Mass/Twisted Mass [1406.4310].

Also HSC [1410.8791], QCDSF [1311.5010], Na et al. [0812.1235]

Spectrum doubly charmed baryons

Perez-Rubio [1503.08440]



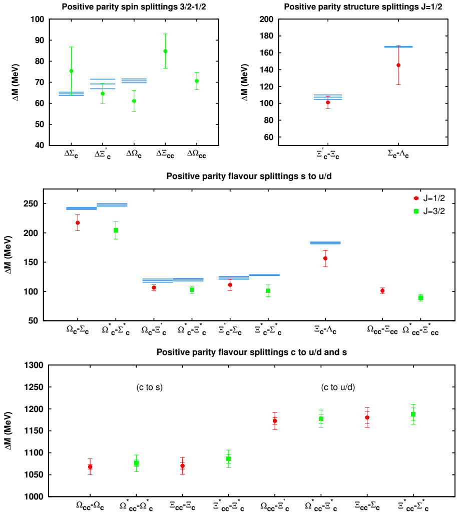
Including also $N_f = 2$: Dürr et al. Brilloin/NP-clover [1208.6270]

Lattice results are consistent and approx. 80 MeV above SELEX result for $\Xi_{cc} = 3518.7(1.7)$ [hep-ex/0406033].

Borsanyi et al. [1406.4088] QCD+QED: $\Xi_{cc}^{++} - \Xi_{cc}^{+} = 2.16(11)(17)$ MeV.

Spin and flavour splittings

P.Perez-Rubio[arXiv:1503.08440]



In HQET/pNRQCD picture:

$$\Delta M_{\Xi_{cc}} = \Xi^*_{cc} - \Xi_{cc} = \frac{3}{4}(D^* - D)$$

85(9) c.f. 95(8) MeV

$$\Delta M_{\Omega_{cc}} = \Omega^*_{cc} - \Omega_{cc} = \frac{3}{4}(D^*_s - D_s)$$

71(4) c.f. 92(2) MeV

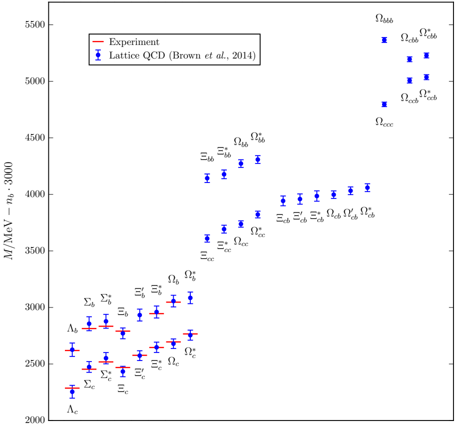
Similarly for singly charmed baryons.

Brown et al. [1409.0497]

$$\Delta M_{\Xi_{cc}}/(\Delta M_{D^0}[Expt]) \sim$$
$$\Delta M_{\Omega_{cc}}/(\Delta M_{D_s}[Expt]) = 0.58(6)$$
$$\Delta M_{\Xi_{bb}}/(\Delta M_{B^0}[Expt]) \sim$$
$$\Delta M_{\Omega_{bb}}/(\Delta M_{B_s}[Expt]) = 0.76(17)$$

Charmed-bottomed baryons

Brown et al. [1409.0497], RBC/UKQCD $N_f = 2 + 1$ domain wall sea + valence. Relativistic heavy quark action for charm, NRQCD for bottom.

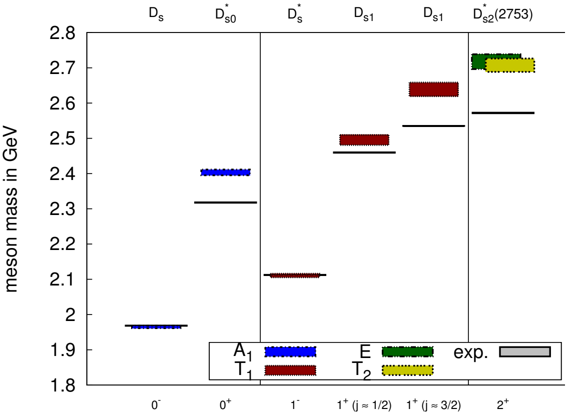


Higher states

More challenging - signal/noise worse, isolating each level, identifying J^{PC}, ...
both more difficult + correct treatment as resonances/including nearby thresholds.

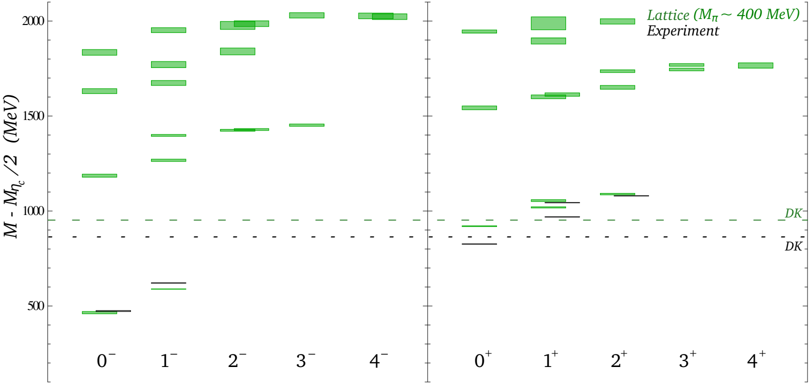
First step use (large) basis of $q\bar{q}$ operators: example D_s spectrum

ETMC [arXiv:1510.07862]



Higher states with $q\bar{q}$

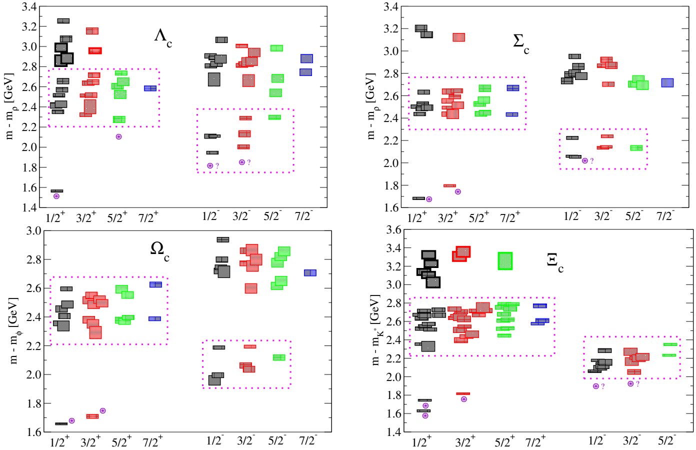
HSC exploratory calculation of D_s spectrum [1301.7670]: $N_f = 2 + 1$, anisotropic lattices, $a_t^{-1} = 0.035$ fm, $a_s = 0.12$ fm, tree-level clover quark action, $L = 1.9$ fm and 2.9 fm (shown).



D/D_s: Mohler and Woloshyn [1103.5506], De Tar and Lee [1411.4676], Hadron Spectrum Collaboration [1301.7670],...

Excited singly charmed baryons

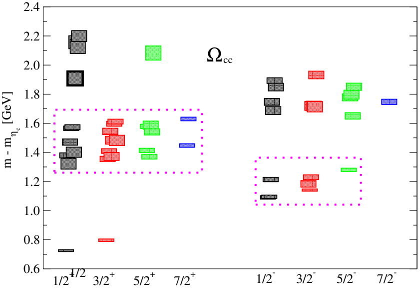
HSC [1508.07168], exploratory calculation

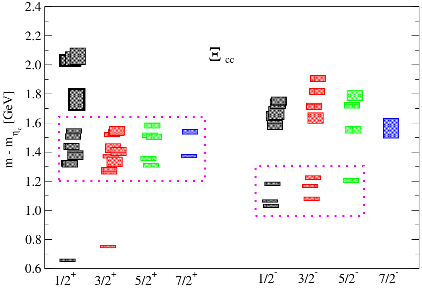


Pattern of levels agree with expectations of models with $SU(6) \otimes O(3)$ symmetry.

Excited doubly charmed baryons

HSC [1502.01845], exploratory calculation





Near threshold states and resonances

To treat near threshold states and resonances properly on the lattice one needs to include the multiparticle channels.

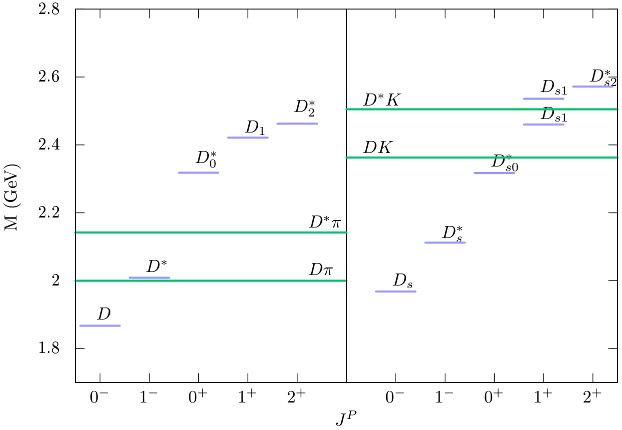
Recent studies, open charm:

- $D_{s0}^*(2317)$ $[\bar{D}K]$ $J^P = 0^+$, $D_{s1}(2460)$ $[\bar{D}^*K]$ $J^P = 1^+$ Lang et al. [1403.8103]
- $D_0^*(2400)$ $[\bar{D}\pi]$ $J^P = 0^+$, $D_1(2430)$ $[\bar{D}^*\pi]$ $J^P = 1^+$, Mohler et al. [1208.4059]

Hidden charm:

- $\psi(3770)$ $J^{PC} = 1^{--}$, $\chi_{c0}(2P)$ $J^{PC} = 0^{++}$ $[\bar{D}D]$ Lang et al. [1503.05363].
- $X(3872)$ $I = 0$ $[D\bar{D}^*, J/\psi\omega]$ $J^{PC} = 1^{++}$, Prelovsek et al. [1307.5172], DeTar et al. [1411.1389], update detailed in [1508.07322]
- $X(3872)$ $I = 1$ $[D\bar{D}^*, J/\psi\rho, (\bar{c}\bar{d})(cu)]$ $J^{PC} = 1^{++}$ Padmanath et al. [1503.03257], no candidate found.
- $Y(4140)$ $[J/\psi\phi, D_s\bar{D}_s^*, (\bar{c}\bar{s})(cs)]$ $J^{PC} = 1^{++}$ channel by Padmanath et al. [1503.03257], s and p wave scattering Ozaki et al. [1211.5512]. No candidate found.
- $Z_c(3900)^+$ $[J/\psi\pi, D\bar{D}^*, \eta_c\rho, \ldots]$ $I^G(J^P) = 1^+(1^+)$, Prelovsek et al. [1405.7623], Lee et al. [1411.1389]. No candidate found.

$D_{s0}^*(2317)$, $J^P = 0^+$



$D_{s0}^*(2317)$, $J^P = 0^+$, $D_{s1}(2460)$, $J^P = 1^+$, narrow states just below (S-wave) DK and D^*K thresholds.

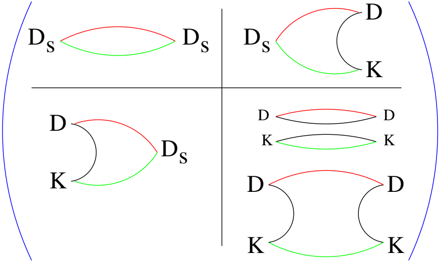
Before discovery model expectations suggested broad states above threshold.

$D_{s0}^*(2317)$, $J^P = 0^+$

Lattice calculation of "bound" states close to threshold

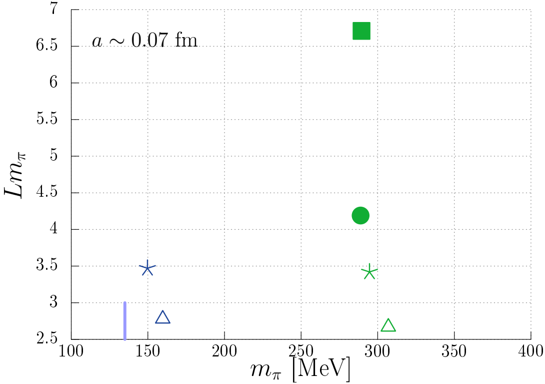
- Physical DK threshold: close to physical light quark mass, study the volume dependence.
- DK in S-wave, consider $D(0)K(0)$ ($D(p)K(-p)$ omitted).
- Two particle channels enter the spectrum, energies shifted from non-interacting values due to finite volume.

Diagonalise



Lattice details

RQCD+QCDSF: $N_f = 2$ non-perturbatively improved clover.



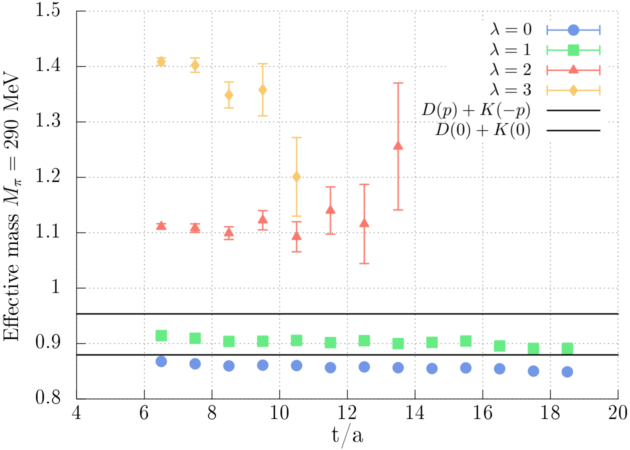
Operators: $c\bar{s}$, $c\gamma_4\bar{s}$, 3 smearings, $c\gamma_5\bar{\ell}(0)\ell\gamma_5\bar{s}(0)$, 1 smearing.

Use stochastic estimation: one-end trick + sequential propagators following CP-PACS [0708.3705] ($\rho \to \pi\pi$). Statistics: 800-2000 configurations.

Eigenvalues, $M_\pi = 290$ MeV, $L = 40$

Eigenvalues of correlator matrix: $\lambda_n \sim e^{m_n t} + \dots$

Antonio Cox (Regensburg)



Comparison with $c\bar{s}$

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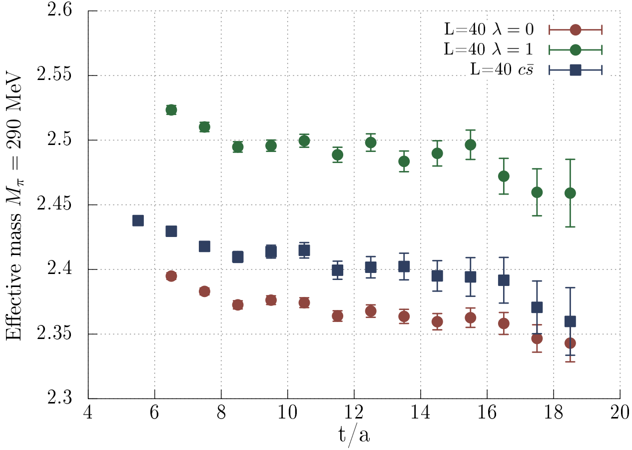
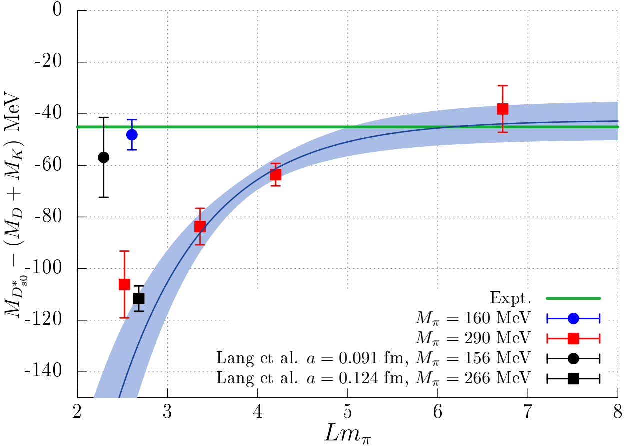


Splitting with threshold

A. Cox (Regensburg): PRELIMINARY



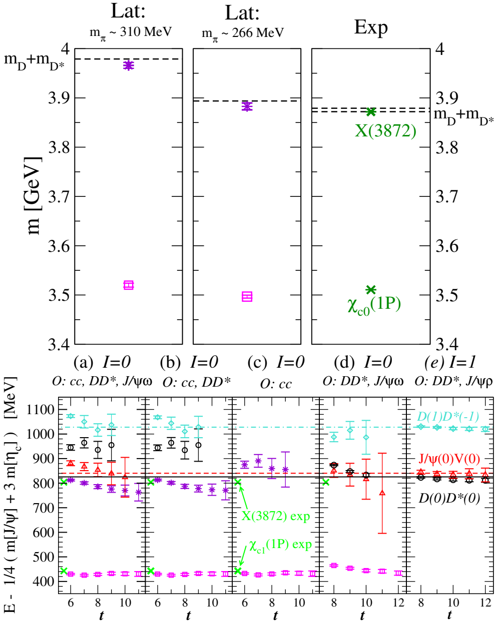
Comparison with Lang et al. [1403.8103].

$X(3872)$, $I = 0$, $J^{PC} = 1^{++}$

Within 1 MeV of $D^0\overline{D}^{0*}$ threshold, also close to $J/\psi\omega$.

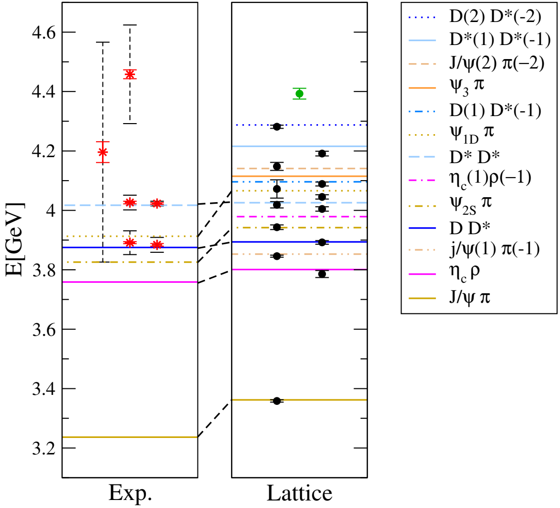
Prelovsek et al. [1307.5172], DeTar et al. [1411.1389]

Prelovsek et al. [1307.5172]



$Z_c(3900)^+$, $I^G(J^P) = 1^+(1^+)$

Prelovsek et al. [1405.7623]



Basis of 22 operators: no candidate for a Z_c^+ found below 4.2 GeV.

Summary

- Charmed meson and baryon spectra are very actively being studied within the lattice community.
- Precision studies as a test of systematics: e.g. charmonium hyperfine splittings,
  - At the level where annihilation effects, mixing of η_c with light flavour singlets etc. need to be taken into account.

  Lower lying charmonium spectrum reproduced.
- General agreement of lattice results of charmed baryons with experimental results.
- Move to calculate the wider spectrum, to contribute to the understanding of the wealth of near threshold states and resonances that have been discovered, in particular for hidden charm.
  - Necessary techniques being developed for dealing with large numbers of states.
  - First studies including two-particle channels.
- Prospects are good for further improvement in lattice results.