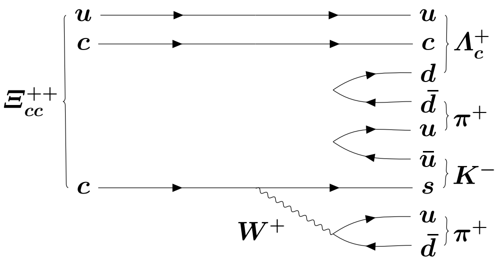
Heavy hadron interactions from Lattice QCD

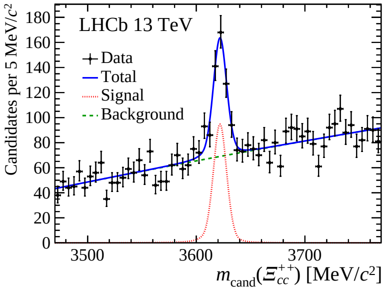
Daniel Mohler

Wien, Sep 14th, 2017

Observation of a doubly-charmed Ξ_{cc}^{++} by LHCb

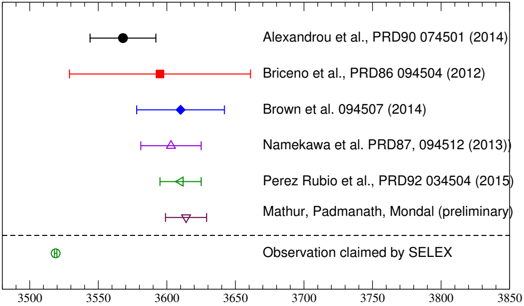
`Roel Aaij et al., LHCb collaboration arXiv:1707.01621`





- Ξ_{cc}^{++} with mass $3621.40 \pm 0.72 \pm 0.27 \pm 0.14$ seen in both 13 TeV and 8 TeV data
- Previous claim of Ξ_{cc} by SELEX wit mass ≈3519 MeV not seen by BaBar, Belle, LHCb
- What about Lattice QCD Predictions?

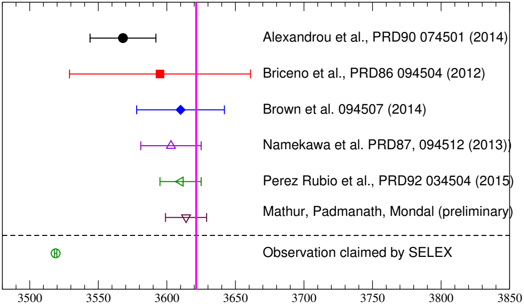
Ξ_{cc} – Recent Lattice QCD predictions



- Full symbols: Good control of systematic uncertainty
  Empty symbols: Continuum extrapolation missing
- All simulations neglect isospin splittings $\Xi_{cc}^{++} - \Xi_{cc}^{+}$
- Publications also contain a number of further predictions and successful postdictions
- History of earlier calculations, most notably

`Mathur, Lewis, Woloshyn, PRD 64 094509 (2001);PRD 66 014502`

Ξ_{cc} – Recent Lattice QCD predictions

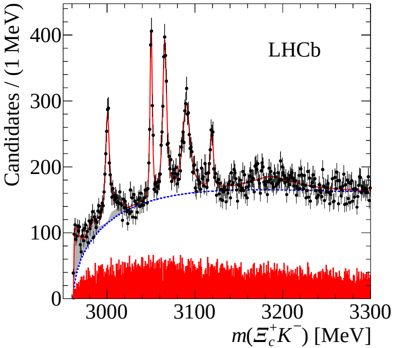


- Full symbols: Good control of systematic uncertainty
  Empty symbols: Continuum extrapolation missing
- All simulations neglect isospin splittings $\Xi_{cc}^{++} - \Xi_{cc}^{+}$
- Publications also contain a number of further predictions and successful postdictions
- History of earlier calculations, most notably

  Mathur, Lewis, Woloshyn, PRD 64 094509 (2001);PRD 66 014502

Observation of 5 narrow Ω_c states

Roel Aaij *et al.*, LHCb collaboration PRL 118 182001 (2017)

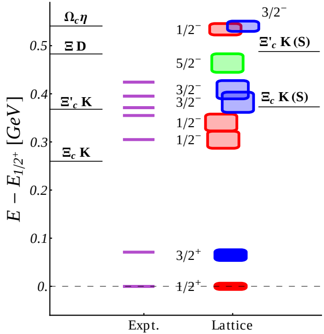


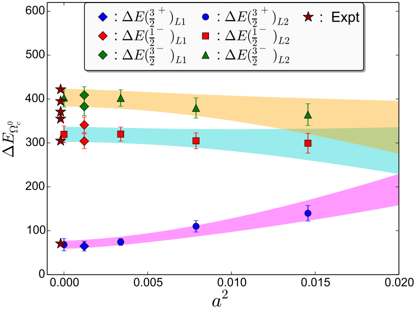
Resonance	Mass [MeV]	Γ [MeV]
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$

- Observation of 5 new Ω_c resonances
- J^P not identified
- All states are narrow $\rightarrow$ can compare to Lattice QCD simulations treating them as stable

What can Lattice QCD say about their spin-parity?

Padmanath, Mathur, PRL 119 042001 (2017)





- Pattern of lattice states agrees well with experiment
- second study with smaller basis can not resolve two states with same J^P; checks systematics
- Scattering thresholds somewhat unphysical

Outline

1. Motivation – Charmed baryons
2. Recent progress in Lattice QCD
3. D, D_s, and B_s
4. Charmonium(-like) states
   - Charmonium-like states: Z_c
   - Charmonium-like states: X(3915)
   - Charmonium-like states: $X(3872)$
5. Exotic doubly-heavy states

Lattice Quantum Chromodynamics: What do we calculate?

Regularization of QCD by a 4-d Euclidean space-time lattice. (Kenneth Wilson 1974)
Provides a calculational method for QCD

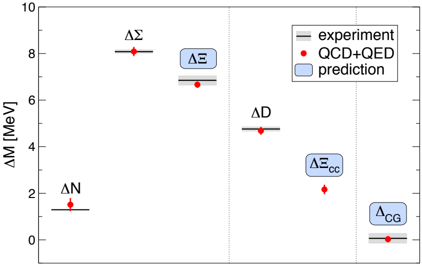
Euclidean correlator of two Hilbert-space operators $\hat{O}_1$ and $\hat{O}_2$.

$$\left\langle \hat{O}_2(t)\hat{O}_1(0)\right\rangle = \sum_n e^{-t\Delta E_n}\langle 0|\hat{O}_2|n\rangle\langle n|\hat{O}_1|0\rangle$$
$$= \frac{1}{Z}\int \mathcal{D}[\psi,\bar{\psi},U]e^{-S_E}O_2[\psi,\bar{\psi},U]O_1[\psi,\bar{\psi},U]$$

- Path integral over the Euclidean action $S_{E,QCD}[\psi,\bar{\psi},U]$; (a sum over quantum fluctuations)
- Can be evaluated with *Markov Chain Monte Carlo* (using methods well established in statistical physics)

Recent progress in Lattice QCD

- Dynamical simulations with 2+1(+1) flavors of sea quarks
- Simulations at physical pion (light-quark) masses
- Isospin splitting and QCD+QED simulations
- Improved heavy quark actions for charm
- Efficient methods for all-to-all propagation (disconnected diagrams)



BMW Collaboration, Borsanyi et al. Science 347 1452 (2015)

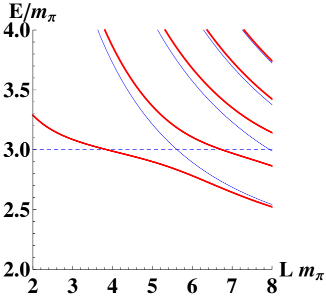
Progress from an old idea: Lüscher's finite-volume method

M. Lüscher Commun. Math. Phys. 105 (1986) 153; Nucl. Phys. B 354 (1991) 531; Nucl. Phys. B 364 (1991) 237.

Basic observation: Finite volume, multi-particle energies are shifted with regard to the free energy levels due to the interaction

$$E = E(p_1) + E(p_2) + \Delta_E$$

- Energy shifts encode scattering amplitude(s)
- Original method: Elastic scattering in the rest-frame in multiple spatial volumes L^3
- Coupled 2-hadron channels well understood
- $2 \leftrightarrow 1$ and $2 \leftrightarrow 2$ transitions well understood (example $\pi\pi \to \pi\gamma^*$)
- significant progress for 3-particle scattering



Reviews by R. A. Briceño arXiv:1411.6944 and M. Hansen arXiv:1511.04737

Fully systematic calculation vs. exploratory study

Important lattice systematics from

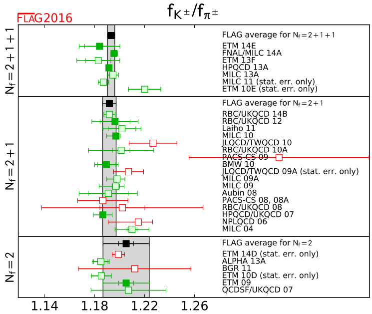
- Taking the *continuum limit*: $a(g,m) \to 0$
- Taking the *infinite volume limit*: $L \to \infty$
- Calculation at (or extrapolation to) the physical pion mass

I cover many *exploratory* results

- Should be compared only qualitatively to experiment
- Provide an outlook on future Lattice QCD results

Example for fully systematic results:

- Flavor physics results listed in the FLAG review
  http://flag.unibe.ch/
  → See talk by U. Wenger



Exotic D_s and B_s candidates

Established s and p-wave D_s and B_s hadrons:

D_s ($J^P = 0^-$) and D_s^* (1^-)
$D_{s0}^*(2317)$ (0^+), $D_{s1}(2460)$ (1^+),
$D_{s1}(2536)$ (1^+), $D_{s2}^*(2573)$ (2^+)

B_s ($J^P = 0^-$) and B_s^* (1^-)

$B_{s1}(5830)$ (1^+), $B_{s2}^*(5840)$ (2^+)

- Corresponding $D_0^*(2400)$ and $D_1(2430)$ are broad resonances
- Peculiarity: $M_{c\bar{s}} \approx M_{c\bar{d}} \quad \rightarrow \quad$ exotic structure? (tetraquark, molecule)

- B_s cousins of the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ not (yet) seen in experiment
- The LHCb experiment at CERN should be able to see these

Exotic D_s and B_s candidates

Established s and p-wave D_s and B_s hadrons:

D_s ($J^P = 0^-$) and D_s^* (1^-)	B_s ($J^P = 0^-$) and B_s^* (1^-)
$D_{s0}^*(2317)$ (0^+), $D_{s1}(2460)$ (1^+),	?
$D_{s1}(2536)$ (1^+), $D_{s2}^*(2573)$ (2^+)	$B_{s1}(5830)$ (1^+), $B_{s2}^*(5840)$ (2^+)

- Corresponding $D_0^*(2400)$ and $D_1(2430)$ are broad resonances
- Peculiarity: $M_{c\bar{s}} \approx M_{c\bar{d}} \quad \rightarrow \quad$ exotic structure? (tetraquark, molecule)

- B_s cousins of the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ not (yet) seen in experiment
- The LHCb experiment at CERN should be able to see these

$D^*_{s0}(2317)$: D-meson – Kaon s-wave scattering

M. Lüscher Commun. Math. Phys. 105 (1986) 153;
Nucl. Phys. B 354 (1991) 531; Nucl. Phys. B 364 (1991) 237.

Charm-light hadrons

$D^*_{s0}(2317)^\pm$

$I(J^P) = 0(0^+)$
J, P need confirmation.

J^P is natural, low mass consistent with 0^+.

Mass $m = 2317.7 \pm 0.6$ MeV
$m_{D^*_{s0}(2317)^\pm} - m_{D_s^\pm} = 349.4 \pm 0.6$ MeV
Full width $\Gamma < 3.8$ MeV, CL = 95%

$$p \cot \delta_0(p) = \frac{2}{\sqrt{\pi}L} Z_{00}\left(1; \left(\frac{L}{2\pi}p\right)^2\right) \approx \frac{1}{a_0} + \frac{1}{2} r_0 p^2$$

Mohler *et al.* PRL 111 222001 (2013)
Lang, DM *et al.* PRD 90 034510 (2014)

Results for ensembles (1) and (2)

$$a_0 = -0.756 \pm 0.025\text{fm} \qquad (1)$$
$$r_0 = -0.056 \pm 0.031\text{fm}$$
$$a_0 = -1.33 \pm 0.20\text{fm} \qquad (2)$$
$$r_0 = 0.27 \pm 0.17\text{fm}$$

$D_{s0}^*(2317)$: D-meson – Kaon s-wave scattering

M. Lüscher Commun. Math. Phys. 105 (1986) 153;
Nucl. Phys. B 354 (1991) 531; Nucl. Phys. B 364 (1991) 237.

Charm-light hadrons

$D_{s0}^*(2317)^\pm$ $I(J^P) = 0(0^+)$
J, P need confirmation.

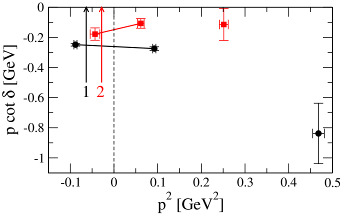
J^P is natural, low mass consistent with 0^+.

Mass $m = 2317.7 \pm 0.6$ MeV
$m_{D_{s0}^*(2317)^\pm} - m_{D_s^\pm} = 349.4 \pm 0.6$ MeV
Full width $\Gamma < 3.8$ MeV, CL = 95%

$$p \cot \delta_0(p) = \frac{2}{\sqrt{\pi}L} Z_{00}\left(1; \left(\frac{L}{2\pi}p\right)^2\right)$$
$$\approx \frac{1}{a_0} + \frac{1}{2} r_0 p^2$$

Mohler *et al.* PRL 111 222001 (2013)
Lang, DM *et al.* PRD 90 034510 (2014)

Results for ensembles (1) and (2)

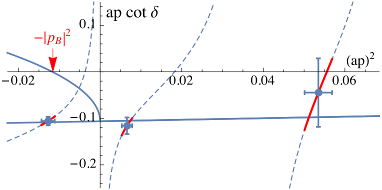


$$a_0 = -0.756 \pm 0.025\text{fm} \qquad (1)$$
$$r_0 = -0.056 \pm 0.031\text{fm}$$
$$a_0 = -1.33 \pm 0.20\text{fm} \qquad (2)$$
$$r_0 = 0.27 \pm 0.17\text{fm}$$

B^*_{s0} and B_{s1}: Results

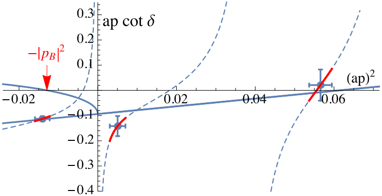
Lang, Mohler, Prelovsek, Woloshyn PLB 750 17 (2015)

B^*_{s0}



$$a_0^{BK} = -0.85(10)\ \mathrm{fm}$$
$$r_0^{BK} = 0.03(15)\ \mathrm{fm}$$
$$M_{B^*_{s0}} = 5.711(13)\ \mathrm{GeV}$$

B_{s1}

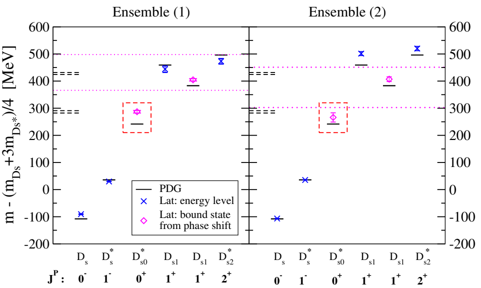


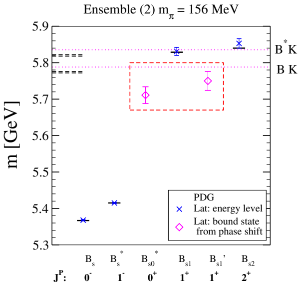
$$a_0^{B^*K} = -0.97(16)\ \mathrm{fm}$$
$$r_0^{B^*K} = 0.28(15)\ \mathrm{fm}$$
$$M_{B_{s1}} = 5.750(17)\ \mathrm{GeV}$$

- Energy from the difference to the $B^{(*)}K$ threshold

D_s and B_s: Spectrum results

Mohler *et al.* PRL 111 222001 (2013)
Lang, Mohler *et al.* PRD 90 034510 (2014)
Lang, Mohler, Prelovsek, Woloshyn PLB 750 17 (2015)

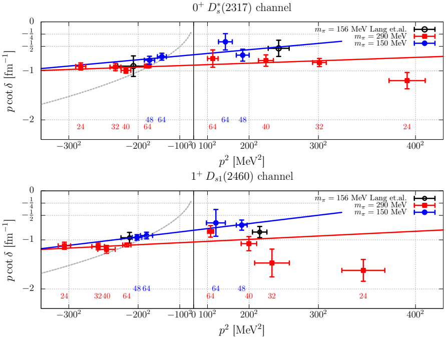




- Discretization uncertainties sizeable for charm
- Many improvements possible for the D_s states
- Full uncertainty estimate only for magenta B_s states
- Prediction of exotic states from Lattice QCD!

Positive parity D_s: More comprehensive results from RQCD

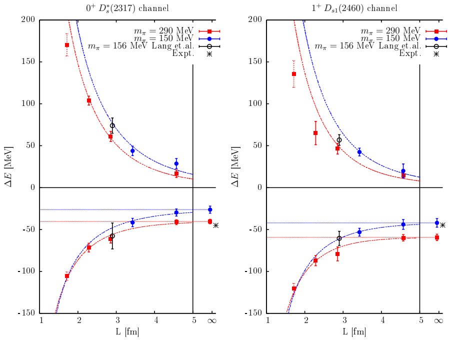
Bali, Collins, Cox, Schäfer, arXiv:1706.01247



- Study with different volumes at pion masses of 150, 290 MeV
- Remaining discretization effects non-negligible
- Results confirm basic behavior seen in previous simulation

Positive parity D_s: More comprehensive results from RQCD

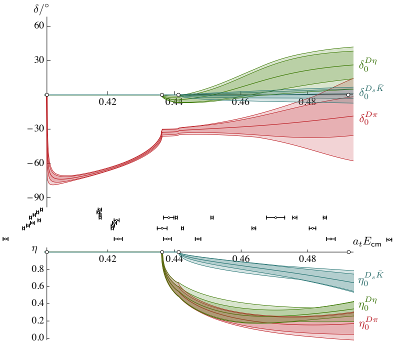
Bali, Collins, Cox, Schäfer, arXiv:1706.01247



- Study with different volumes at pion masses of 150, 290 MeV
- Remaining discretization effects non-negligible
- Results confirm basic behavior seen in previous simulation

Coupled-channel study of $D\pi$, $D\eta$, D_sK scattering

Moir *et al.*, JHEP 1610 011 (2016)



- Lattice data from multiple volumes at $m_\pi = 391$ MeV
- Shallow bound state seen in coupled channel s-wave
- Narrow spin-2 D-wave resonance seen as well
- For older single-channel results see

DM, Prelovsek, Woloshyn PRD 87 034501 (2013)

Search for a Z_c^+ state from Lattice QCD

Prelovsek, Lang, Leskovec, DM, Phys.Rev. D91 014504 (2015)

- Search for a Z_c^+ in the $I^G J^{PC} = 1^+ 1^{+-}$ channel
- Aim at simulating all meson-meson states below ≈ 4.3GeV
- Caveat: Neglects 3-particle states
- Include tetraquark interpolators of type $3_c \times \bar{3}_c$
- Count energy levels and identify them according to their overlaps
- Hope: See an extra level, as would be expected for a (narrow) resonance

More rigorous approach (a la Lüscher) quite challenging

- Coupled channel system with many channels
- Small shifts in finite volume and (largish) discretization effects
- Thresholds should be close to physical
- Suitable ensembles are (probably) not available at the moment.

A look at the spectrum of scattering states

- Expect level close to non-interacting scattering states

$J/\Psi\pi$

$\eta_c\rho$

$J\Psi(1)\pi(-1)$

DD^*

$\Psi_{2S}\pi$

D^*D^*

$\Psi_{3770}\pi$

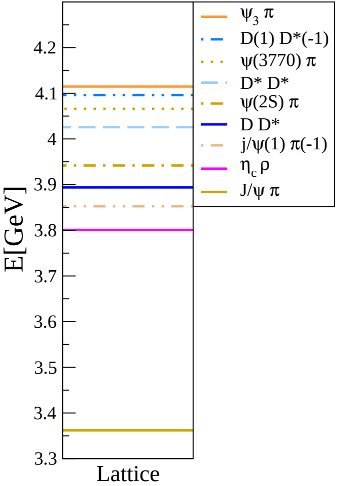
$D(1)D^*(-1)$

$\Psi_3\pi$

$J\Psi(2)\pi(-2)$

$D^*(1)D^*(-1)$

$D(2)D^*(-2)$

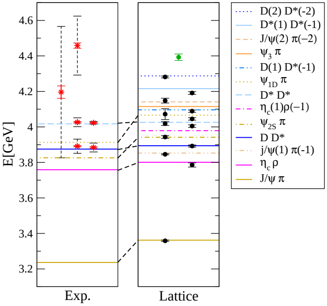


Search for Z_c^+ with $I^G J^{PC} = 1^+1^{+-}$

$X(3900)$ $I^G(J^{PC}) = 1^+(1^{+-})$

Mass $m = 3886.6 \pm 2.4$ MeV (S = 1.6)
Full width $\Gamma = 28.1 \pm 2.6$ MeV

Prelovsek, Lang, Leskovec, DM,
Phys.Rev. D91 014504 (2015)

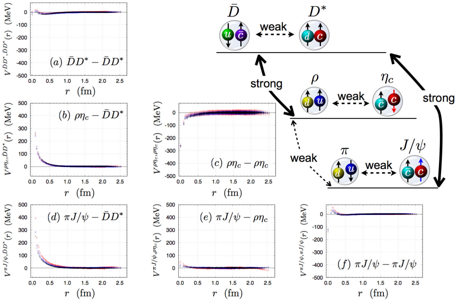


- Simple level counting approach
- We find 13 two meson states as expected
- We find no extra energy level that could point to a Z_c candidate

$Z_c(3900)$ with the HALQCD method I

Ikeda *et al.* PRL 117 242001 (2016); Ikeda arXiv:1706.07300

- Coupled-channel scattering $J/\Psi\pi$, $\eta_c\rho$, $\bar{D}D^*$, $I^G(J^{PC}) = 1^+1^{+-}$
- Uses 2+1 flavor gauge configurations with $a = 0.907(13)$ and $m_\pi = 410, 570, 700$
- HALQCD method Ishii et al. PLB 712, 437 (2012)
  - Calculate a potential as a function of distance r
  - Solve Schrödinger equation with given $V(r)$ and determine scattering phase shifts

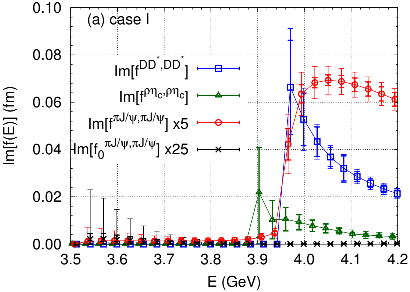


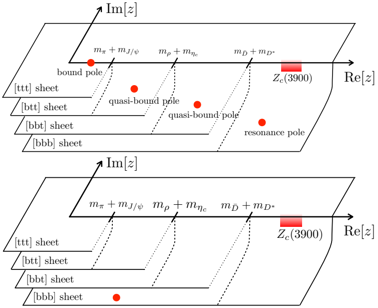
$Z_c(3900)$ with the HALQCD method II

X(3900) $I^G(J^{PC}) = 1^+(1^{+-})$

Mass $m = 3886.6 \pm 2.4$ MeV (S = 1.6)
Full width $\Gamma = 28.1 \pm 2.6$ MeV

Ikeda *et al.* PRL 117 242001 (2016);
Ikeda arXiv:1706.07300





- Pole found far below DD^* threshold for all quark masses
- Authors conclude $Z_c(3900)$ not a usual resonance but a threshold cusp
- Structure comes from strong $\pi J/\Psi - \bar{D}D^*$ coupling
- Analysis at close-to-physical pion mass planned

χ'_{c0} and $X/Y(3915)$

$X(3915)$
was $\chi_{c0}(3915)$

$I^G(J^{PC}) = 0^+(0 \text{ or } 2^{++})$

Mass $m = 3918.4 \pm 1.9$ MeV
Full width $\Gamma = 20 \pm 5$ MeV (S = 1.1)

PDG interpreted $X(3915)$ as a regular charmonium (χ'_{c0})

- Some of the reasons to doubt this assignment:

  Guo, Meissner Phys. Rev. **D**86, 091501 (2012)

  Olsen, PRD 91 057501 (2015)

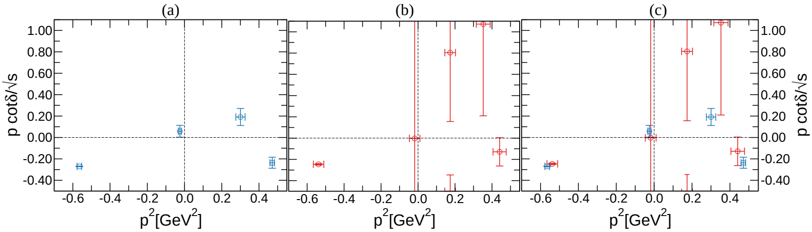
  - No evidence for fall-apart mode $X(3915) \to \bar{D}D$
  - Spin splitting $m_{\chi_{c2}(2P)} - m_{\chi_{c0}(2P)}$ too small
  - Large OZI suppressed $X(3915) \to \omega J/\psi$
  - Width should be significantly larger than $\Gamma_{\chi_{c2}(2P)}$
- Zhou *et al.* (PRL 115 2, 022001 (2015)) argue that what is dubbed X(3915) is the spin 2 state already known and suggests that a broader state is hiding in the experiment data.
- Observation of an alternatice $\chi_{c0}(2P)$ by Belle:

  Chilikin *et al.* PRD 95 112003 (2017)

$$M = 3862^{+26+40}_{-32-13} \qquad \Gamma = 201^{+154+88}_{-067-82}$$

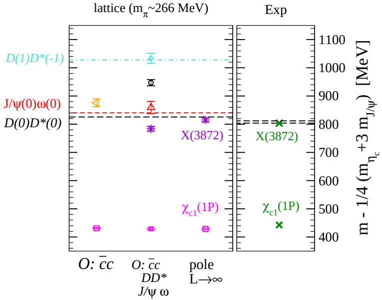
χ'_{c0}: Exploratory lattice calculation

Lang, Leskovec, DM, Prelovsek, JHEP 1509 089 (2015)

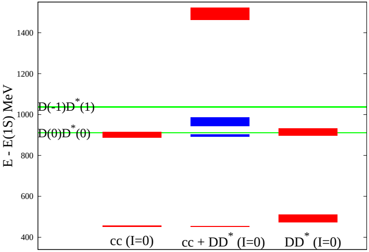


- Assumes only $\bar{D}D$ is relevant
- Lattice data suggests a fairly narrow resonance with $3.9\text{GeV} < M < 4.0\text{GeV}$ and $\Gamma < 100\text{MeV}$
- Future experiment and lattice QCD results needed to clarify the situation

An $X(3872)$ candidate from Lattice QCD



Prelovsek, Leskovec, PRL 111 192001 (2013)

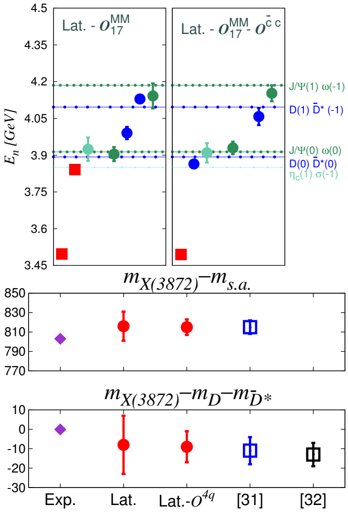


Lee, DeTar, DM, Na, arXiv:1411.1389

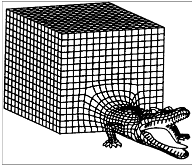
- Neglects charm annihilation and $J/\psi\omega$
- Seen only when $\bar{q}q$ and $\bar{D}^*D$ are used
- The two simulations have vastly different systematics (yet results are similar)

An $X(3872)$ candidate from Lattice QCD II

Padmanath, Lang, Prelovsek, PRD 92 034501 (2015)



- Without $\bar{q}q$ interpolators signal vanishes
- Simulations still unphysical in many ways
- Discretization and finite volume effects sizable!



- Makes interpretation as pure molecule or pure tetraquark unlikely

Recent simulations of charm or beauty tetraquarks

- Searches for charmed tetraquarks
  - Doubly charmed and charmed-strange tetraquarks by HALQCD

    `Ikeda et al. PLB 729 85-90 (2014)`
  - Search for doubly charmed tetraquarks on CLS lattices (preliminary)

    `Guerrieri et al. arXiv:1411.2247`
- HHLL systems with bottom quarks
  - Tetraquark bound states in heavy-light heavy-light systems

    `Brown and Orginos PRD 86 114506 (2012)`
  - Lattice QCD results for a bottom-bottom tetraquark

    `Bicudo and Wagner PRD 87 114511 (2013)`
  - Search for $ud\bar{b}\bar{b}$ $ss\bar{b}\bar{b}$ and $cc\bar{b}\bar{b}$ tetraquarks

    `Bicudo et al., PRD 92 014507 (2015)`
  - *BB* interactions with static bottom quarks

    `Bicudo, Cichy, Peters, Wagner, PRD 93 034501 (2016);`

    `Bicudo, Scheunert, Wagner, PRD 95 034502 (2017)`
  - Deeply bound doubly-heavy tetraquarks with NRQCD b-quarks

    `Francis,Hudspith,Lewis,Maltman, PRL 118 142001 (2017)`

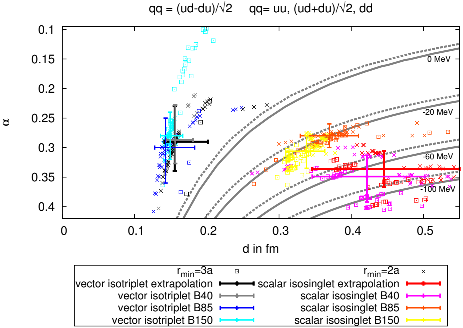
    `Junnarkar, Mathur, Padmanath, presented at Lattice 2017`

BB interactions with static bottom quarks

Bicudo, Cichy, Peters, Wagner, PRD 93 034501 (2016)
Bicudo, Scheunert, Wagner, PRD 95 034502 (2017)

- Potentials of two static antiquarks in the presence of two light quarks
- Search for bound states (rather than resonances)
- Lattices with $a = 0.079$ fm and $m_\pi \approx 650, 480, 340$
- Fit function used for the lattice QCD potentials

$$V(r) = -\frac{\alpha}{r}\exp\left(-\left(\frac{r}{d}\right)^p\right) + V_0$$



Resulting binding energy:

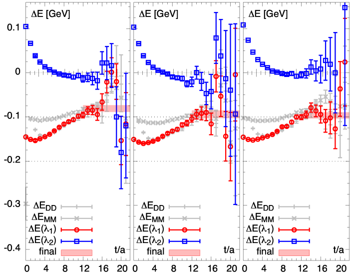
$$E_B = 90^{+43}_{-36}\text{ MeV}$$

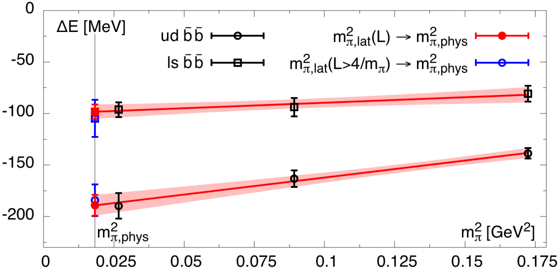
Including heavy $\bar{b}$ spins:

$$E_B = 59^{+30}_{-38}\text{ MeV}$$

Doubly bottom $J^P = 1^+$ tetraquarks with NRQCD b-quarks

Francis, Hudspith, Lewis, Maltman, PRL 118 142001 (2017)

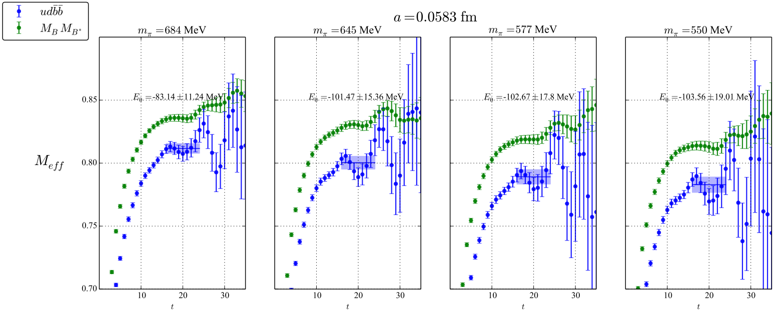




- Study at a single lattice spacing and three pion masses
  $164\text{MeV} \leq M_\pi \leq 415\text{MeV}$
- Authors obtain bound 4-quark states for both $ud\bar{b}\bar{b}$ and $ls\bar{b}\bar{b}$
- Potential issues
  - Binding energies extracted from ratios can be misleading
  - For a bound state, excited state naively expected above threshold
  - Finite volume effects alter the binding energy

$ud\bar{b}\bar{b}$ $J^P = 1^+$ tetraquarks on HISQ lattices

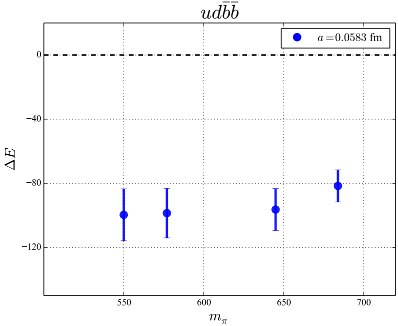
Junnarkar, Padmanath, Mathur, reported at Lattice 2017



- Results from $48^3 \times 144$ HISQ ensemble with $M_{\pi,sea} \approx 310$ MeV
- Four valence pion masses in range 550MeV $\leq M_\pi \leq$ 684MeV
- Same quantum numbers than Francis *et al.* (but notable difference in binding energy)
- Preliminary results confirm existence of a bound state

$ud\bar{b}\bar{b}$ $J^P = 1^+$ tetraquarks on HISQ lattices

Junnarkar, Padmanath, Mathur, reported at Lattice 2017



- Results from $48^3 \times 144$ HISQ ensemble with $M_{\pi,sea} \approx 310$ MeV
- Four valence pion masses in range 550MeV $\leq M_\pi \leq$ 684MeV
- Same quantum numbers than Francis *et al.*
  (but notable difference in binding energy)
- Preliminary results confirm existence of a bound state

Thank you!

Thanks to Parikshit Junnarkar and Nilmani Mathur for sending me unpublished updates

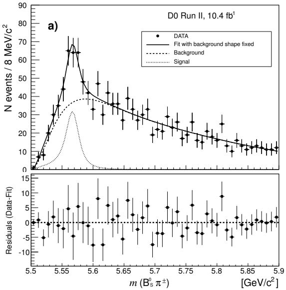
The X(5568)

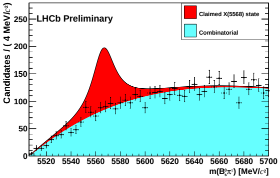
Abazov *et al.* PRL 117, 022003 (2016).

- The D0 collaboration is reporting evidence for a peak in the $B_s\pi^+$ invariant mass not far above threshold
- D0 attributes this to resonance X(5568)

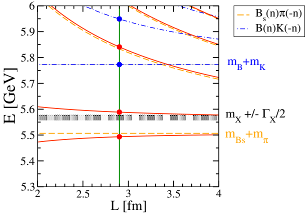
$$m_X = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \text{MeV}$$
$$\Gamma_X = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \text{MeV}$$

- Decay to $B_s\pi^+$ implies exotic flavor structure $\bar{b}s\bar{d}u$
- Most model studies accommodating a X(5568) propose $J^P = 0^+$
- LHCb did not find any peak in the $B_s\pi^+$ invariant mass (with increased statistics)





Expected signatures of the X(5568)

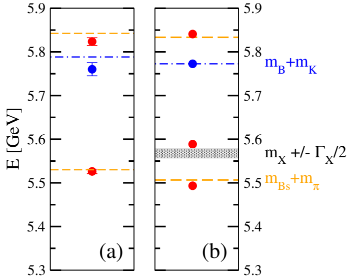


Analytic predictions for energies of eigenstates for an elastic resonance in $B_s\pi$ (with $J^P = 0^+$) as a function of the lattice size L.

- Orange (blue) dashed lines show the $B_s\pi$ (BK) eigenstates when B_s and π (B and K) do not interact
- Red lines show the expectation for lattice energy levels in elastic $B_s\pi$ scattering (decoupled from BK) for a resonance with a mass and width of the X(5568).
- In the scenario of a deeply bound BK state, the simulation would result in an eigenstate with $E \approx m_X$ up to exponentially small corrections in L.

Lattice results and conclusions

Lang, DM, Prelovsek, PRD 94 074509 (2016)

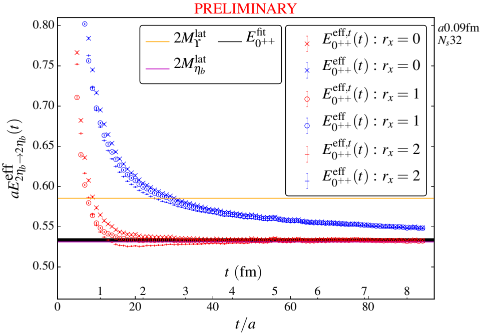


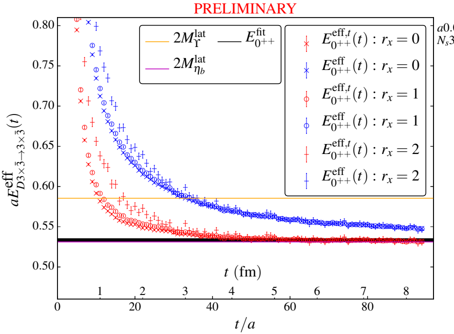
- Exploratory calculation with a single ensemble at $M_\pi = 156$ MeV
- Left pane: eigenenergies of the $\bar{b}s\bar{d}u$ system with $J^P = 0^+$
  Right pane: Analytic prediction based on the $X(5568)$
- Results stable under variations of the fit methodology
- Lattice simulation at close-to-physical quark masses does not yield a second low-lying energy level (expected for the case of the X(5568))
- Results do not support the existence of $X(5568)$ with $J^P = 0^+$.

Search for a deeply bound $bb\bar{b}\bar{b}$ state

C. Hughes, C. Davies, E. Eichten, presented at Lattice 2017

- A number of recent potential model predictions of a very deeply bound $bb\bar{b}\bar{b}$ state
- Lattice study using NRQCD b quarks, 3 different lattice spacings
- Upshot: No deeply bound states but deficiencies in models understood





Search for charmed tetraquarks by HALQCD

Ikeda et al. PLB 729 85-90 (2014)

- Search for bound states or resonances in DD, $\bar{K}D$, DD^* and $\bar{K}D^*$ interactions with flavor structure $cc\bar{u}\bar{d}$ and $cs\bar{u}\bar{d}$
- These contain no quark line diagrams with quark annihilation
- Uses 2+1 flavor gauge configurations with $a = 0.907(13)$ and $m_\pi = 410, 570, 700$
- HALQCD method

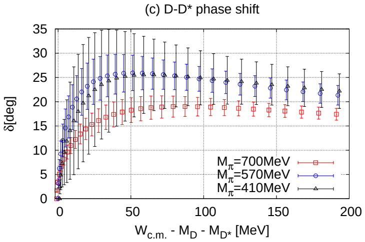
  Ishii et al. PLB 712, 437 (2012)

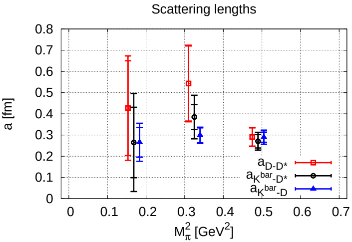
  - Calculate a potential as a function of distance r
  - Solve Schrödinger equation with given $V(r)$ and determine scattering phase shifts
- Uses variant of the Fermilab method (relativistic heavy quark action)

Tetraquarks with the HALQCD method: Results

Ikeda et al. PLB 729 85–90 (2014)

- Repulsive interaction in all $I = 1$ channels considered
- Attractive interaction in all $I = 0$ channels considered





- No bound states or resonances at simulated m_π
- Attraction becomes more prominent at light pion masses
- Authors have some indication that BB^* with $IJ^P = 01^+$ is bound

Lattice simulation

- We use lattices with 2+1 flavors of Wilson-Clover quarks by PACS-CS

$N_L^3 \times N_T$	N_f	a[fm]	L[fm]	#configs	m_π[MeV]	m_K[MeV]
$32^3 \times 64$	2+1	0.0907(13)	2.90	196	156(7)(2)	504(1)(7)

- For a description of the heavy-quark methodology see

`Lang, DM, Prelovsek, Woloshyn PLB 750 17 (2015)`

- Interpolator basis

$$O_{1,2}^{B_s(0)\pi(0)} = \left[\bar{b}\Gamma_{1,2}s\right](\mathbf{p}=0)\left[\bar{d}\Gamma_{1,2}u\right](\mathbf{p}=0)$$

$$O_{1,2}^{B_s(1)\pi(-1)} = \sum_{\mathbf{p}=\pm\mathbf{e_{x,y,z}}\,2\pi/L}\left[\bar{b}\Gamma_{1,2}s\right](\mathbf{p})\left[\bar{d}\Gamma_{1,2}u\right](-\mathbf{p})$$

$$O_{1,2}^{B(0)K(0)} = \left[\bar{b}\Gamma_{1,2}u\right](\mathbf{p}=0)\left[\bar{d}\Gamma_{1,2}s\right](\mathbf{p}=0)$$