Search for isoscalar axialvector $bc\bar{u}\bar{d}$ tetraquark bound states

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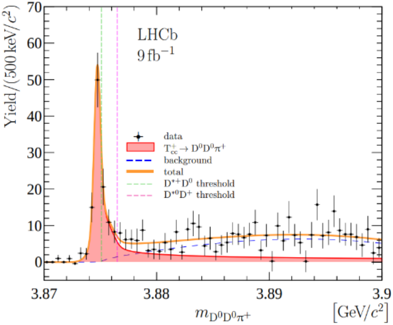
:ONLINE:

with **A. Radhakrishnan** and **N. Mathur**.

Based on article **arXiv:2307.14128**

Motivation from experiments, T_{cc}^+



LHCb: 2109.01038, 2109.01056

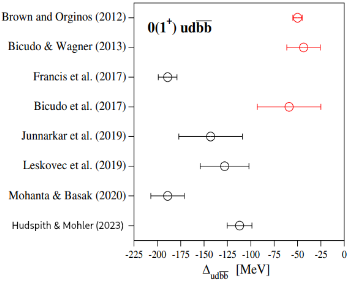
$$\delta m \equiv m_{T_{cc}^+} - (m_{D^{*+}} + m_{D^0})$$

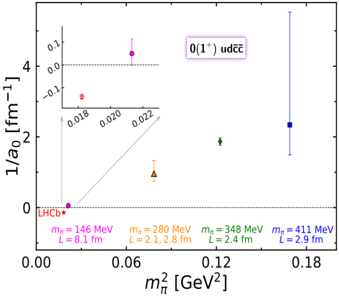
$$\delta m_{\text{pole}} = -360 \pm 40 {}^{+4}_{-0} \text{ keV}/c^2\,,$$
$$\Gamma_{\text{pole}} = 48 \pm 2 {}^{+0}_{-14} \text{ keV}\,.$$

- The doubly charmed tetraquark T_{cc}^+, $I = 0$ and favours $J^P = 1^+$. Nature Phys., Nature Comm. 2022
  Striking similarities with the longest known heavy exotic, X(3872).
- No features observed in $D^0D^+\pi^+$: possibly not $I = 1$.
- Many more exotic tetraquark candidates discovered recently, T_{cs}, $T_{c\bar{s}}$, $X(6900)$.
  T_{bc} likely most important in next 5-10 years. Polyakov, Hadron 2023
- Doubly heavy tetraquarks: theory proposals date back to 1980s.

c.f. Ader&Richard PRD25(1982)2370

Motivation from lattice, T_{bb} and T_{cc}





- Isoscalar axialvector channel $I(J^P) = 0(1^+)$.
- Deeper binding in doubly bottom tetraquarks $\mathcal{O}(100MeV)$. Fig: Hudspith&Mohler PRD 2023
- Shallow bound state in doubly charm tetraquarks $\mathcal{O}(100keV)$. Fig: HALQCD 2023 [Aoki Mon 1410]

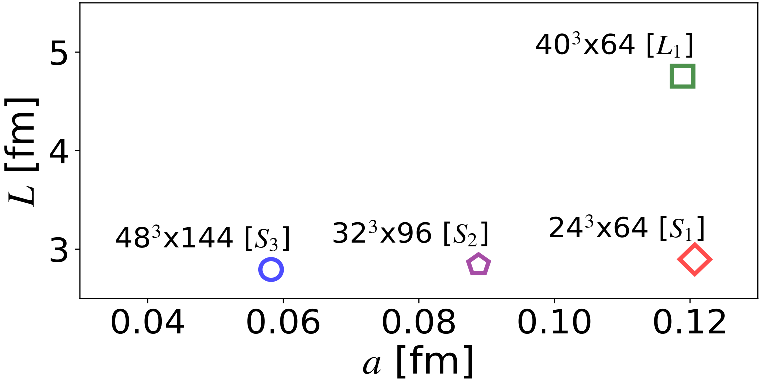
On cut off effects for lattice estimates of T_{cc}, see [Jeremy Mon 1330]

Relevance of diquark-antidiquark operators for T_{cc}, see [Emmanuel Mon 1350]

- No conclusive results in the bottom-charm tetraquark sector.

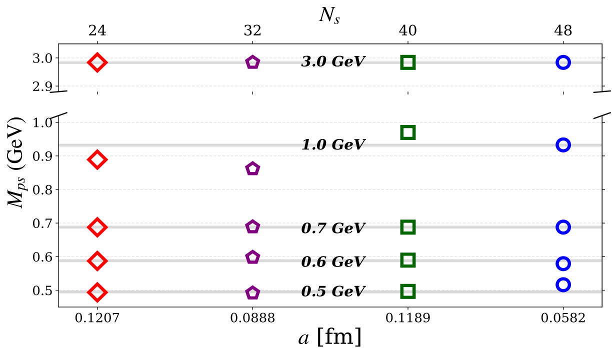
Meinel *et al* PRD 2022, Hudspith *et al* PRD 2020

Lattice setup



- MILC dynamical ensembles with $N_f = 2 + 1 + 1$ HISQ fields.
- Valence quark fields with masses ranging from light to charm: overlap action
- Bottom quark evolution using a NRQCD Hamiltonian.
  tuned using kinetic mass of 1S bottomonium spin averaged $\overline{M}^{\bar{b}b}$ Mathur *et al* Lattice 2016

Valence light quark masses studied



- One quark mass at the charm point ($M_{ps} \sim 3.0$ GeV). Basak *et al* Lattice 2014
  tuned using kinetic mass of 1S charmonium spin averaged $\overline{M}^{\bar{c}c}$
- Another at the strange point ($M_{ps} \sim 0.7$ GeV). Chakraborty *et al* PRD 2015
  tuned using the fictituous pseudoscalar $\bar{s}s$
- Three other quark masses approximately corresponding to pseudoscalar masses,
  $M_{ps} \sim 0.5,\ 0.6,\ \mathit{and}\ 1.0$ GeV.

Correlation functions and Interpolators

- Focus on the T_{1g} finite volume irrep in the rest frame.

- Two point correlations computed as

$$\mathcal{C}_{ij}(t) = \sum_{\mathbf{x}} \left\langle \mathcal{O}_i(\mathbf{x}, t)\mathcal{O}_j^\dagger(0) \right\rangle = \sum_n \frac{Z_i^n Z_j^{n\dagger}}{2E^n} e^{-E^n t},$$

with wall smearing for quark fields at source.

- Focus only on the ground state energy splitting. Relevant low lying two meson thresholds

$$\begin{aligned} DB^* \ [included]: \quad & E_{et}^{phys} \sim 7.190 GeV \\ BD^* \ [included]: \quad & E_{it1}^{phys} \sim 7.290 GeV \\ D^*B^* \ [excluded]: \quad & E_{it2}^{phys} \sim 7.334 GeV \end{aligned}$$

- Local 2 two-meson-like interpolators and one diquark-antidiquark-like interpolator

$$\begin{aligned} \mathcal{O}_1(x) &= [\bar{u}\gamma_i b][\bar{d}\gamma_5 c](x) - [\bar{d}\gamma_i b][\bar{u}\gamma_5 c](x), \\ \mathcal{O}_2(x) &= [\bar{u}\gamma_5 b][\bar{d}\gamma_i c](x) - [\bar{d}\gamma_5 b][\bar{u}\gamma_i c](x), \\ \mathcal{O}_3(x) &= [(\bar{u}^T \Gamma_5 \bar{d} - \bar{d}^T \Gamma_5 \bar{u})(b \Gamma_i c)](x). \end{aligned}$$

Spectrum extraction

- $\mathcal{C}_{ij}(t)$ are solved for the generalized eigenvalue problem [GEVP]

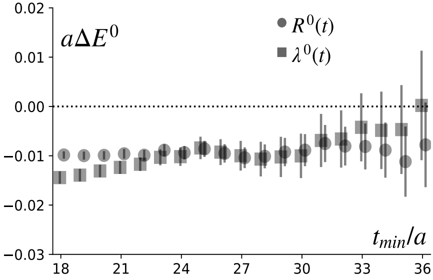
$$\mathcal{C}(t)v^n(t) = \lambda^n(t)\mathcal{C}(t_0)v^n(t)$$

- Fits to the eigenvalue correlators $[\lambda^n]$ and the ratio of eigenvalue correlators with a non-interacting correlator $[R^n(t) = \frac{\lambda^n(t)}{\mathcal{C}_{m_1}(t)\mathcal{C}_{m_2}(t)}]$. MP *et al* Lattice 2021

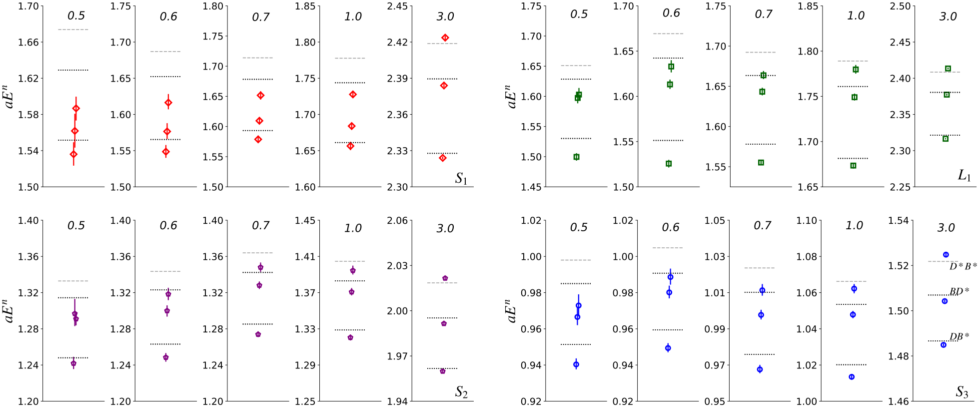
- Fits to the ground state in the finest ensembl with $M_{ps} \sim 0.7$ GeV in terms of energy splittings from $M_{B^*} + M_D$.

$$\Delta E^0 = E^0 - M_{B^*} - M_D$$

- t_{min} dependence of energy estimates from fits to $R^0(t)$ and $\lambda^0(t)$ →

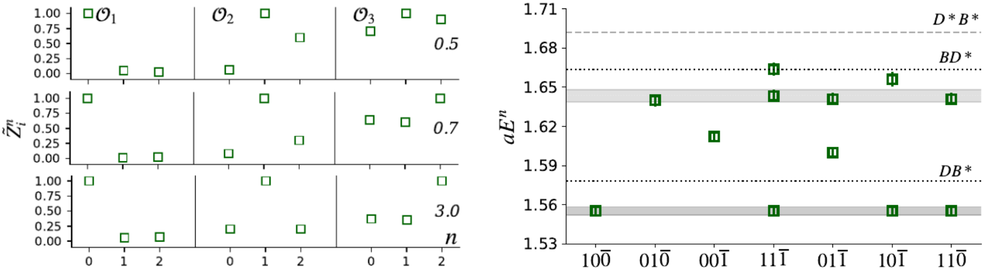


Finite volume spectrum



- Similar excited state pattern for all ensembles, for any given pseudoscalar mass.
- Statistically significant negative energy shifts:
  attractive interaction between the mesons involved.
- Not yet accounted for the additive energy corrections inherent to NRQCD.

Operator state overlaps and operator basis dependence

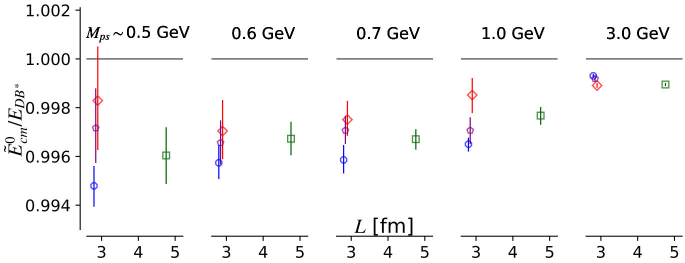


- Ground state very well determined by the DB^*-like operator $\mathcal{O}_1$.
- Excited states shows dominant two-meson and diquark-antidiquark Fock components. Decreasing diquark-antidiquark Fock component with increasing $m_{u/d}$. Consistent with phenomenological expectations.

Junnarkar&Mathur&MP PRD 2018, Hudspith *et al* PRD 2020

- Consistent negative energy shift for ground state from full basis. Similar negative energy shift observed for first excited state in the full basis.
- Example shown for the case: $M_{ps} \sim 0.7$ GeV in the large volume ensemble.

The reconstructed ground state spectrum

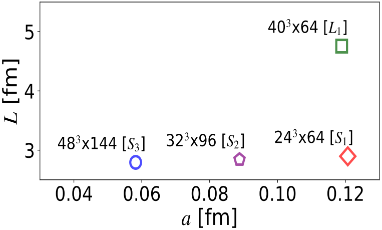


- Energy spectrum determined based on fits to $R^0(t)$.
  Automatic accounting for NRQCD additive correction.

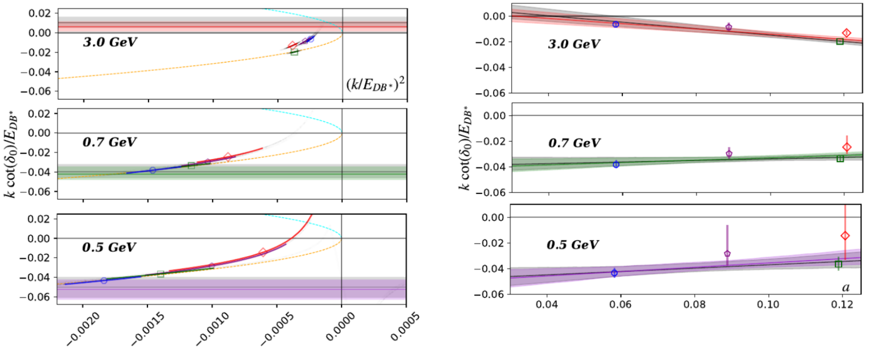
- Energy reconstructed using $\tilde{E}^0 = \Delta E^0 + \overline{M}^{lat}_{B^*} + M^{lat}_D$
  where $\overline{M}^{lat}_{B^*} = M^{lat}_{B^*} - 0.5\overline{M}^{\bar{b}b,\ lat} + 0.5\overline{M}^{\bar{b}b,\ phys}$

- Consistent negative energy shifts.
  Decreasing magnitude with increasing $m_{u/d}$ or M_{ps}

- Non-trivial lattice spacing dependence.

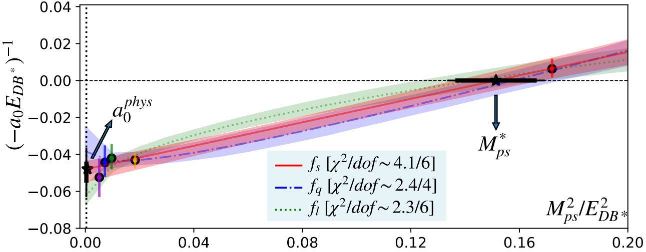


Finite volume analysis and continuum extrapolation



- Elastic DB^* scattering: finite volume analysis *à la* Lüscher. Briceño PRD 2014
  Only ground states used and only scattering length in an ERE. $[k cot\delta_0 \sim -1/a_0]$
- A linear lattice spacing dependence assumed for the fitted amplitude.
- Determined DB^* scattering length in the continuum limit for all M_{ps}.
  Results indicate attractive interaction between D and B^* mesons at all M_{ps}.

M_{ps} dependence of DB^* scattering length



✿ Light quark mass ($m_{u/d}$ or M_{ps}) dependence.

$$f_l(M_{ps}) = \alpha_c + \alpha_l M_{ps}, \quad f_s(M_{ps}) = \beta_c + \beta_s M^2_{ps}, \quad \text{and} \quad f_q(M_{ps}) = \theta_c + \theta_l M_{ps} + \theta_s M^2_{ps}.$$

indicates a real bound state at physical pion mass.

✿ DB^* scattering length and binding energy in the continuum limit

$$a_0^{phys} = 0.57(^{+4}_{-5})(17) \text{ fm} \quad \text{and} \quad \delta m_{T_{bc}} = -43(^{+6}_{-7})(^{+14}_{-24}) \text{ MeV}$$

✿ The critical M_{ps} at which T_{bc} becomes unbound

$$M^*_{ps} = 2.73(21)(14) \text{ GeV}$$

Summary

- Simulate DB^*-BD^* scattering on the lattice and determine DB^* scattering length.
- Transparent evidence for negative energy shifts and hence attractive interaction between D and B^* mesons.
- Scattering length from rigorous finite volume analysis *à la* Lüscher and continuum extrapolation.
- Studied light quark mass ($m_{u/d}$ or M_{ps}) dependence from M_{ps} ~0.5 to ~ 3.0 GeV.
- Real bound state with binding energy

$$\delta m_{T_{bc}} = -43(^{+6}_{-7})(^{+14}_{-24}) \text{ MeV}$$

- The critical M_{ps} at which T_{bc} becomes unbound

$$M^*_{ps} = 2.73(21)(14) \text{ GeV}$$

- We ignored effects from higher partial wave mixing and left hand cuts in our analysis.

c.f. talks on Thu. 1330 to 1430

Thank you