Lattice QCD rules out some predictions for deeply-bound light-heavy tetraquarks

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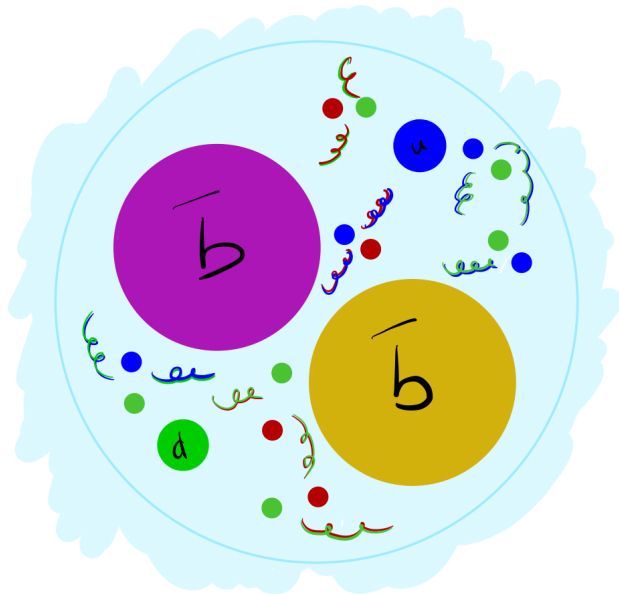

May 19 2021

Long wait for tetraquarks

SCHEMATIC MODEL OF BARYONS AND MESONS

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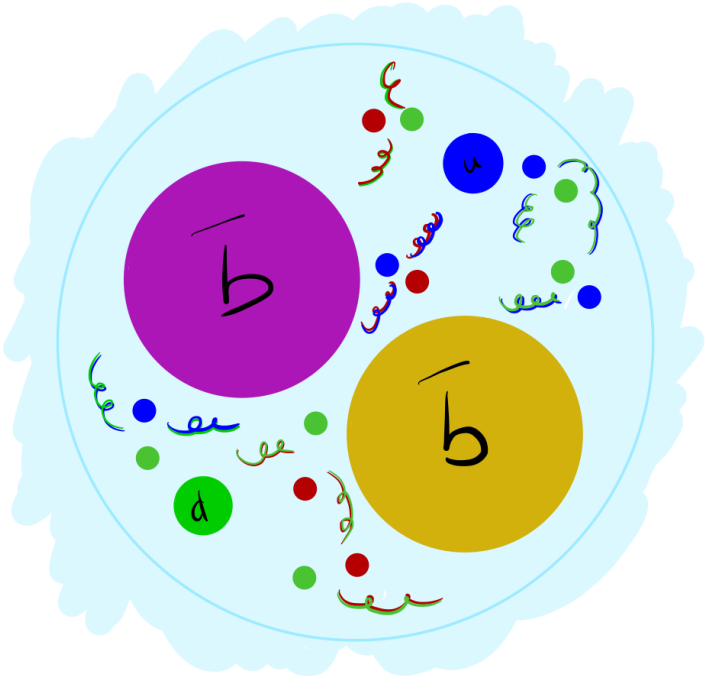
The existence of tetraquarks and pentaquarks has long been suspected!

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

Diquarks

- ★ Idea: diquarks, qq or $\bar{q}\bar{q}$ pairs
- ★ Not colourless, so not physical.
- ★ But combining two colours is equivalent to the anti-colour of the remaining colour, e.g., $r + b = \bar{g}$



- ★ We are interested in:
  - light diquarks in a colour $\bar{3}_c$, flavour $\bar{3}_f$ and spin 0 configuration
    - "good light diquark"
  - heavy diquarks in a colour 3_c configuration

The term "good diquark" is of Jaffe's invention, for a nice review: [hep-ph/0409065]

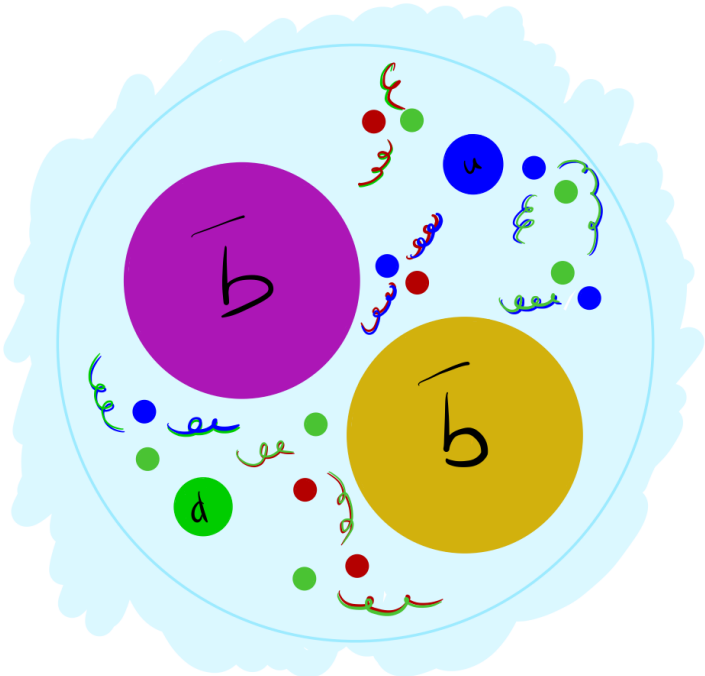
Tetraquarks

We are interested in states with "good light diquarks". Depending on the anti-diquark content and its configuration, we have access to $J^P = 1^+$ or $J^P = 0^+$ states.

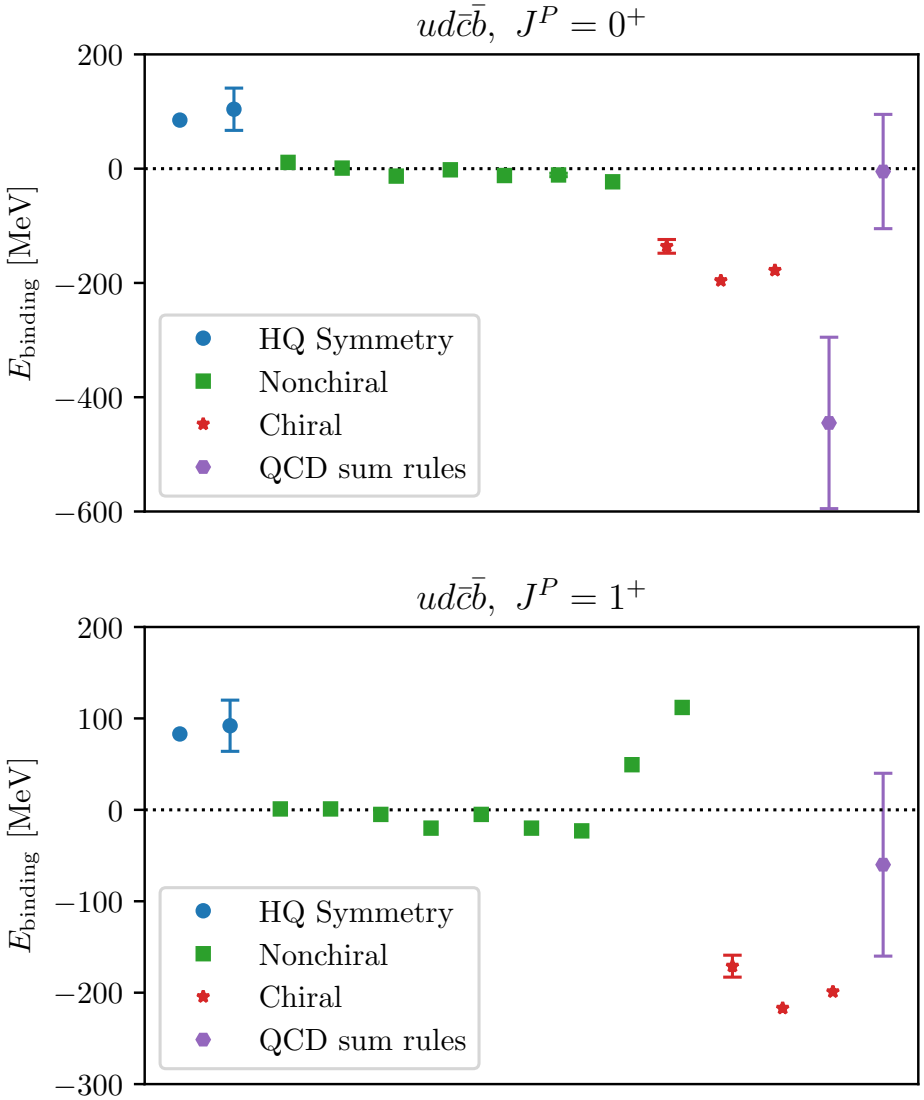
Expectations:

- ★ deeper binding with lighter light diquarks
- ★ deeper binding with heavier heavy diquarks

But there are many states to explore and contradictory claims from models. Predictions of binding and ruling out states both useful for experimentalists.



Example of model predictions



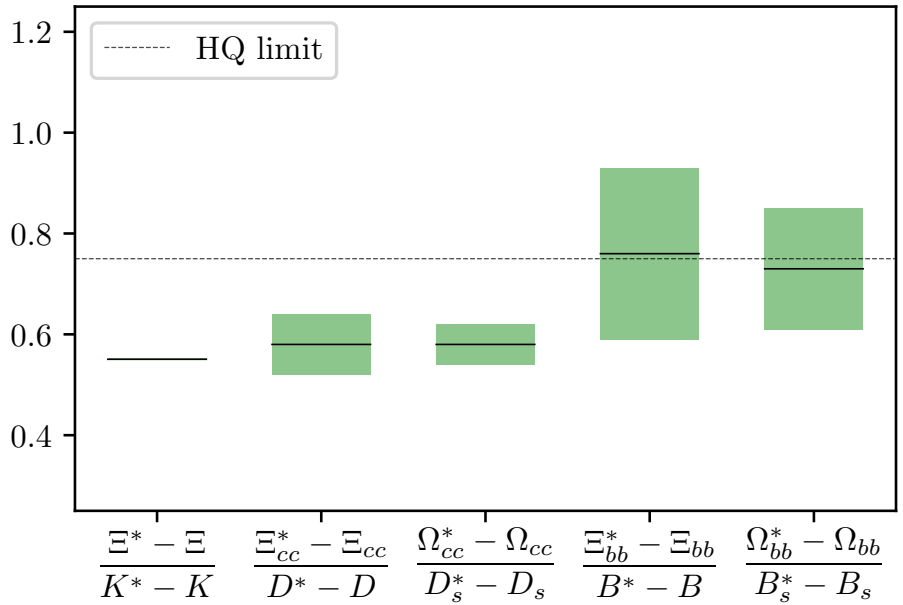
Examples of various $ud\bar{c}\bar{b}$ masses relative to the lowest two-meson threshold in the $I = 0,\ J^P = 0^+$ and $I = 0\ J^P = 1^+$ channels.

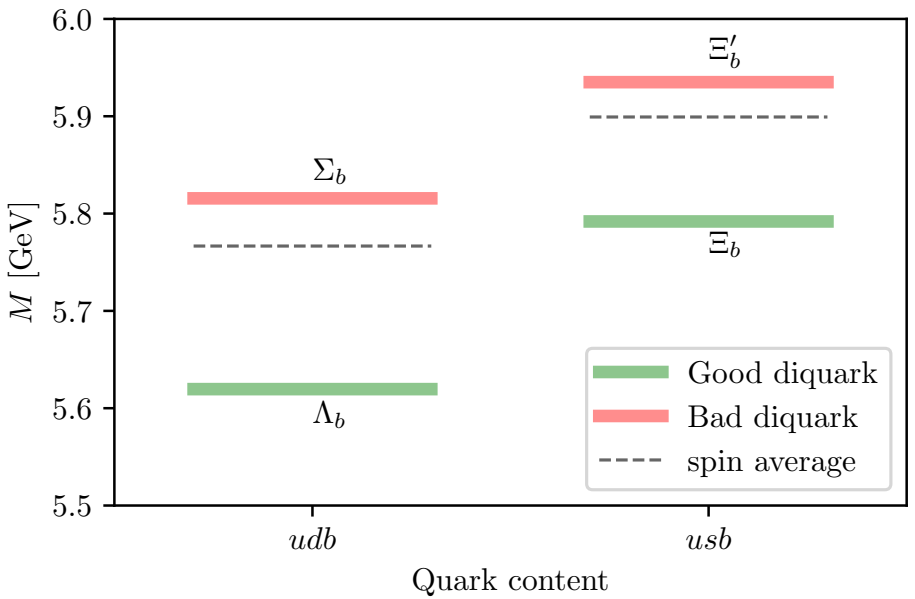
We discuss model results more completely for all channels in R.J. Hudspith, BC, A. Francis, R. Lewis and K. Maltman Phys. Rev. D 102, 114506 (2020), [2006.14294].

Information from baryons and mesons

- ★ Ordinary baryon and meson spectra can provide constraints for models
- ★ $\bar{Q}\bar{Q}$ serves as nearly static colour source, like a single Q in a baryon

Numbers from PDG & [1409.0497]





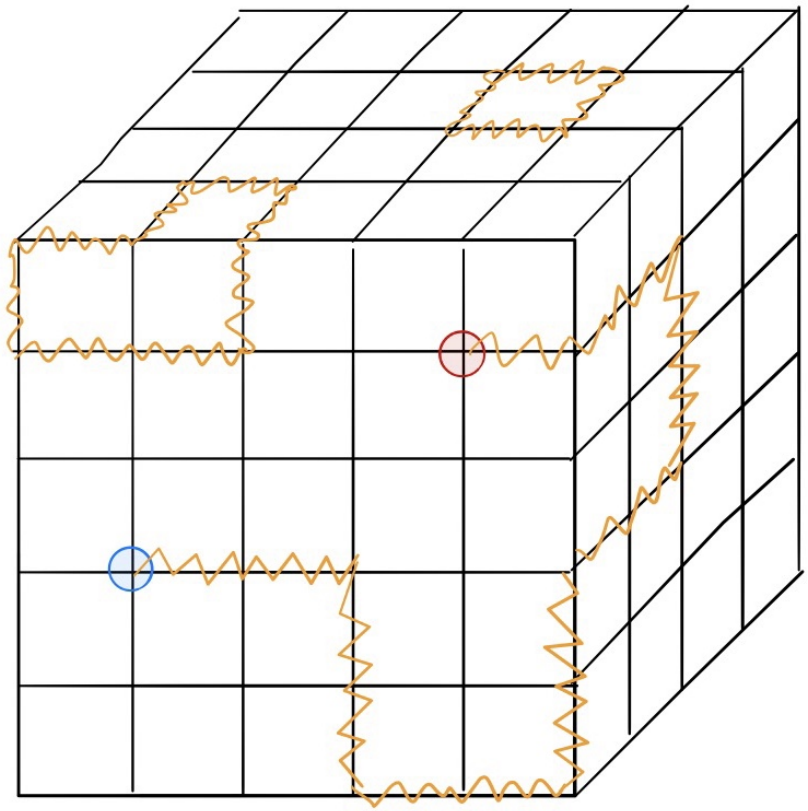
- ★ Baryon spectrum suggests "good" light diquarks result in strong attraction.
- ★ Lighter quark mass $\rightarrow$ stronger attraction

Some lattice details

Lattice details

R. J. Hudspith, BC, A. Francis, R. Lewis, K. Maltman [2006.14294]

- ★ $n_f = 2 + 1$
- ★ $L^3 \times T = 48^3 \times 64$
- ★ $a^{-1} = 2.194(10)$ GeV
- ★ $m_\pi \approx 192$ MeV
  - ▶ $m_\pi L \approx 4.2$
- ★ Box-sink construction improves projection onto ground state.



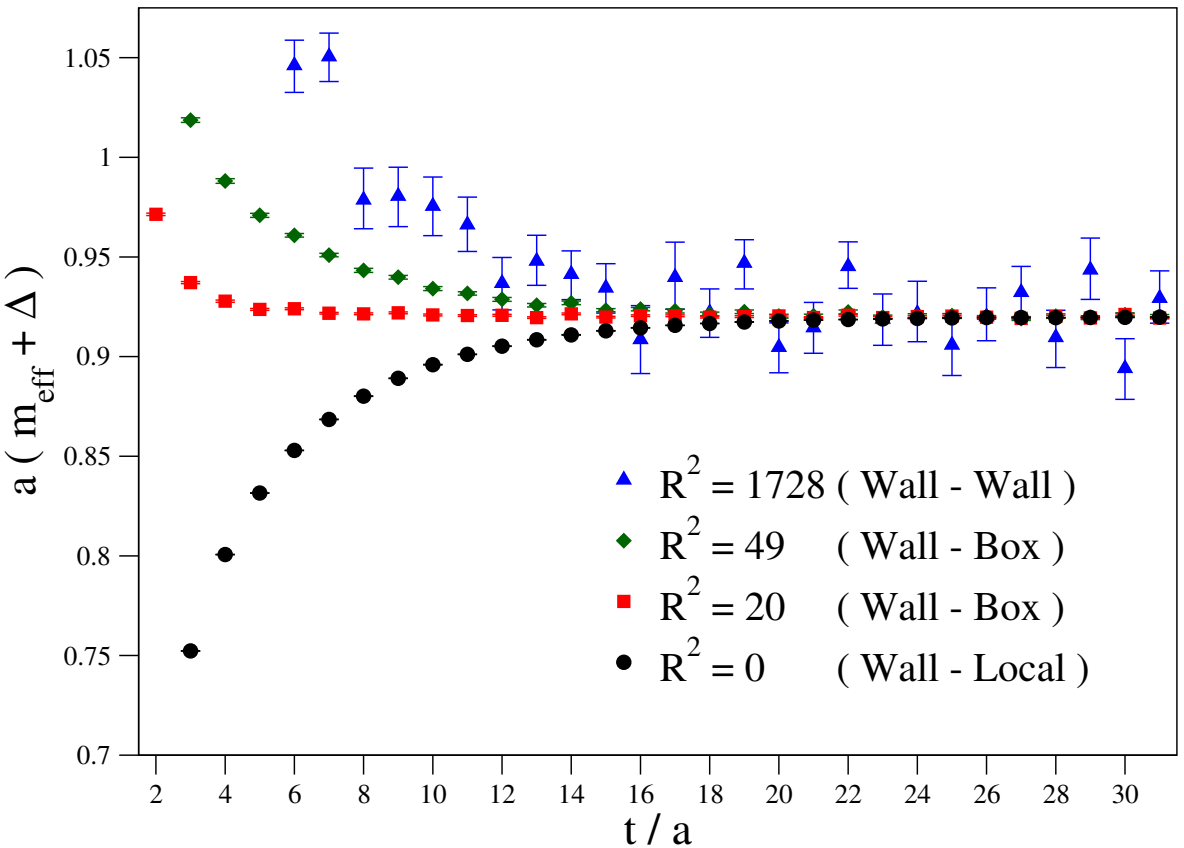
Note: Upcoming update on doubly-bottom tetraquarks uses multiple pion masses and lattice sizes.

Recent update: Box-Sinks

R. J. Hudspith, BC, A. Francis, R. Lewis, K. Maltman [2006.14294]

Improvement: box-sinks for better overlap with ground states.

$$S^B(x,t) = \frac{1}{N}\sum_{r^2 \leq R^2} S(x+r,t)$$



Tetraquarks on the Lattice

Various lattice tetraquark studies

- ★ Recent years has seen progress in lattice QCD calculations of tetraquarks with $J^P = 1^+$
  - Static $\bar{b}\bar{b}b$ potentials:
    - P. Bicudo & M. Wagner [1209.6274]
    - Z. S. Brown & K. Orginos [1210.1953]
    - P. Bicudo, J. Scheunert & M. Wagner [1612.02758]
  - NRQCD $\bar{b}\bar{b}b$:
    - A. Francis, R. J. Hudspith, R. Lewis, K. Maltman [1607.05214]
    - P. Junnarkar, N. Mathur & M. Padmanath [1810.12285]
    - L. Leskovec, S. Meinel, M. Pflaumer & M. Wagner [1904.04197]
  - RHQ & NRQCD $\bar{c}\bar{b}$,$\bar{s}\bar{b}$,$s\bar{c}$:
    - R. J. Hudspith, BC, A. Francis, R. Lewis, K. Maltman [2006.14294]
  - NRQCD $bb\bar{b}\bar{b}$:
    - C. Hughes, E. Eichten, C. T. H. Davies [1710.03236]

Fitting our tetraquarks

Construct correlators, $C_{\mathcal{O}_1\mathcal{O}_2}(t) = \sum_n \frac{\langle 0|\mathcal{O}_1|n\rangle\langle n|\mathcal{O}_2|0\rangle}{2E_n} e^{-E_n t}$ from:

$$D(\Gamma_1,\Gamma_2) = (\psi_a^T C\Gamma_1\phi_b)(\bar{\theta}_a C\Gamma_2\bar{\omega}_b^T),$$
$$E(\Gamma_1,\Gamma_2) = (\psi_a^T C\Gamma_1\phi_b)(\bar{\theta}_a C\Gamma_2\bar{\omega}_b^T - \bar{\theta}_b C\Gamma_2\bar{\omega}_a^T),$$
$$M(\Gamma_1,\Gamma_2) = (\bar{\theta}\Gamma_1\psi)(\bar{\omega}\Gamma_2\phi), \qquad N(\Gamma_1,\Gamma_2) = (\bar{\theta}\Gamma_1\phi)(\bar{\omega}\Gamma_2\psi),$$
$$O(\Gamma_1,\Gamma_2) = (\bar{\omega}\Gamma_1\psi)(\bar{\theta}\Gamma_2\phi), \qquad P(\Gamma_1,\Gamma_2) = (\bar{\omega}\Gamma_1\phi)(\bar{\theta}\Gamma_2\psi).$$

We want to solve a GEVP to get energy levels:

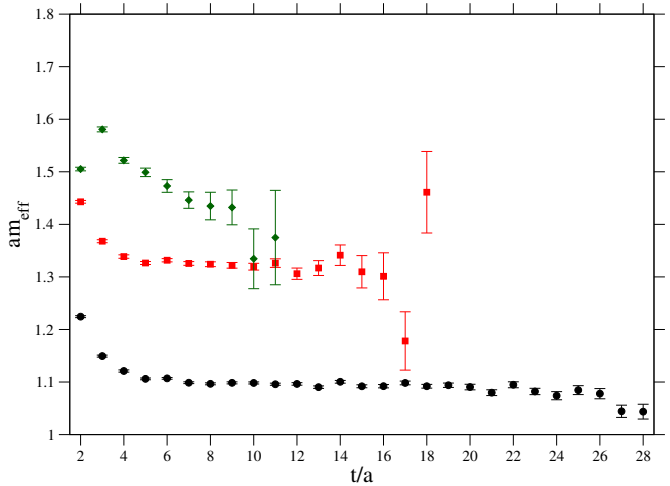
$$C_i(t) = \sum_{j,k} V_{ij}(\tau)^\dagger C_{jk}(t) V_{ki}(\tau)$$

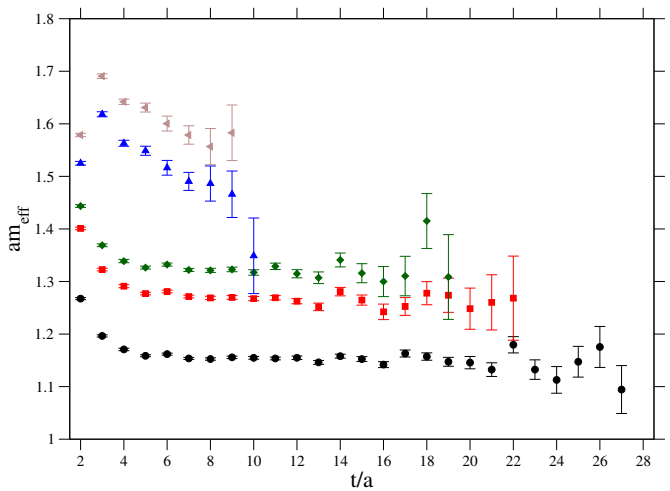
where V is made from columns of the eigenvector solution to:

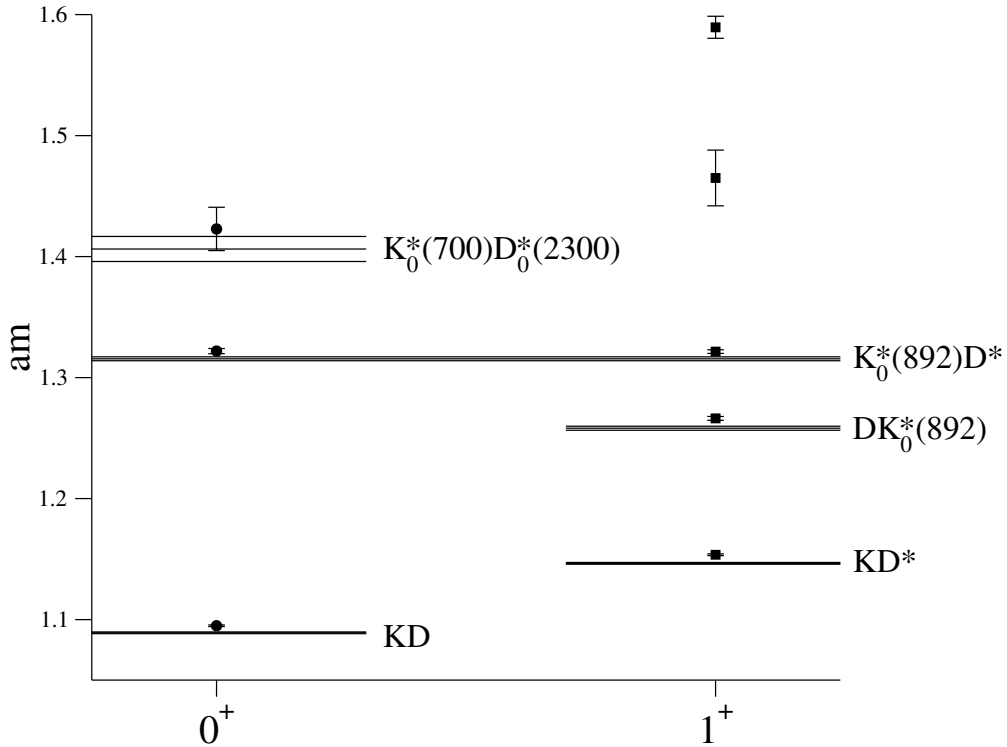
$$C_{ij}(t)v_j(t) = \lambda_i C_{ij}(t+t_0)v_j(t)\ .$$

$ud\bar{s}\bar{c}$ tetraquarks

R. J. Hudspith, BC, A. Francis, R. Lewis, K. Maltman [2006.14294]







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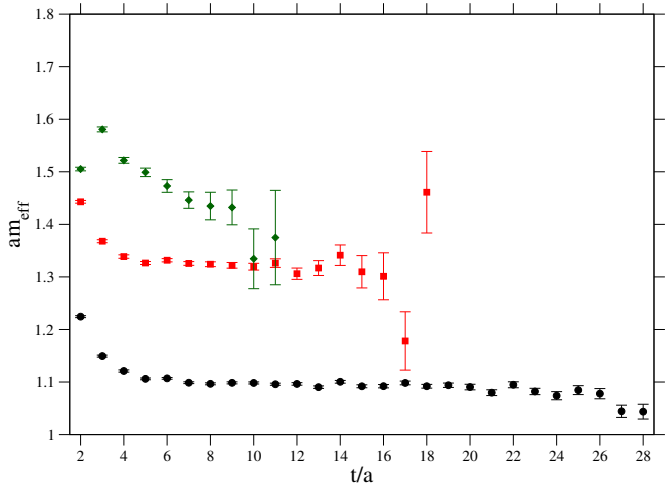

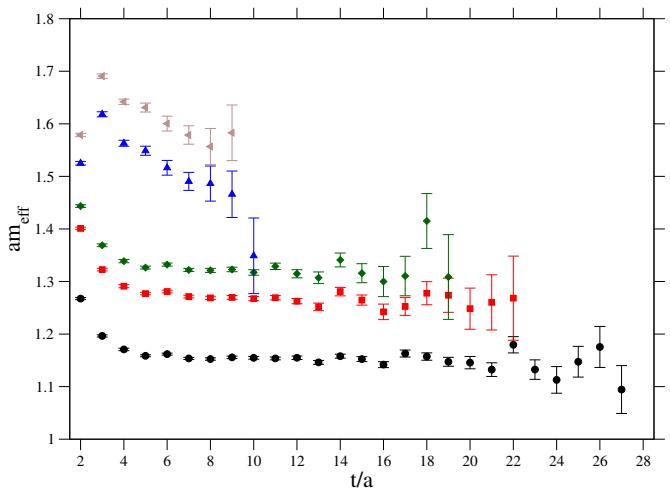

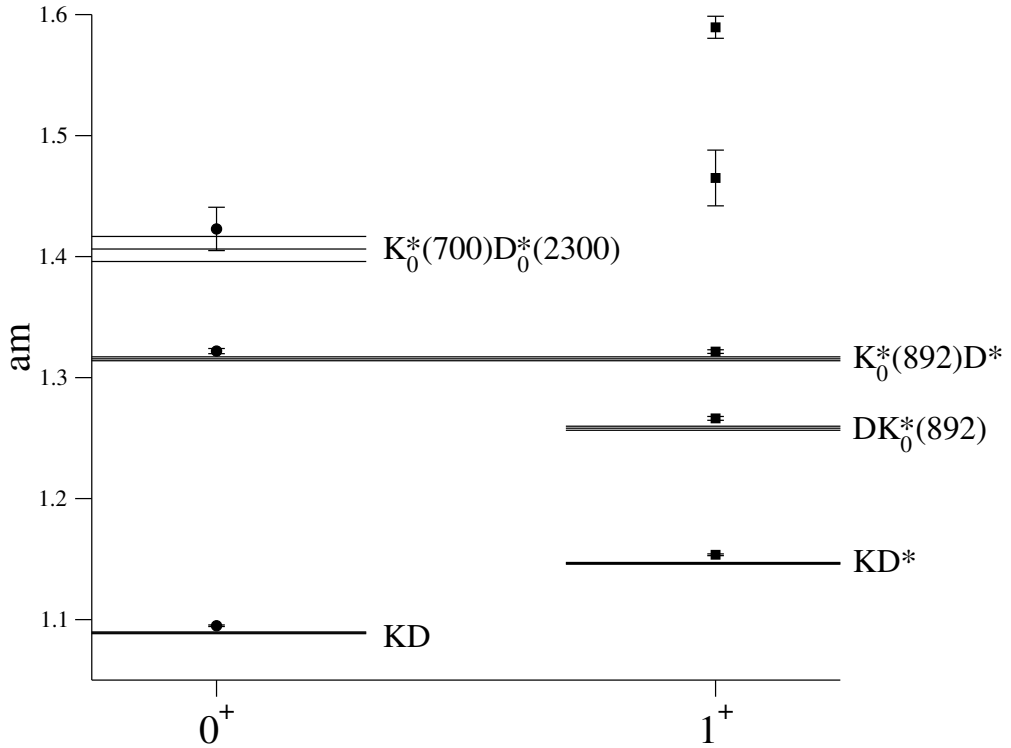

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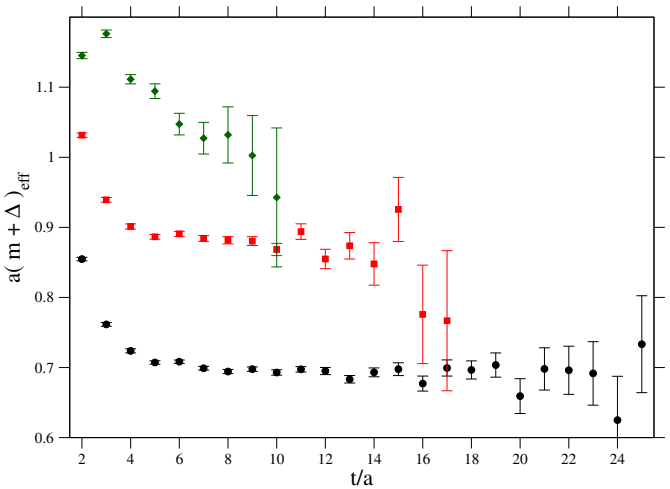

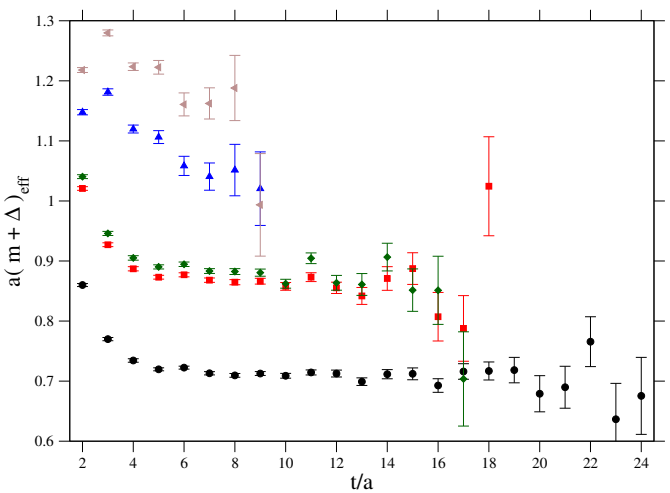

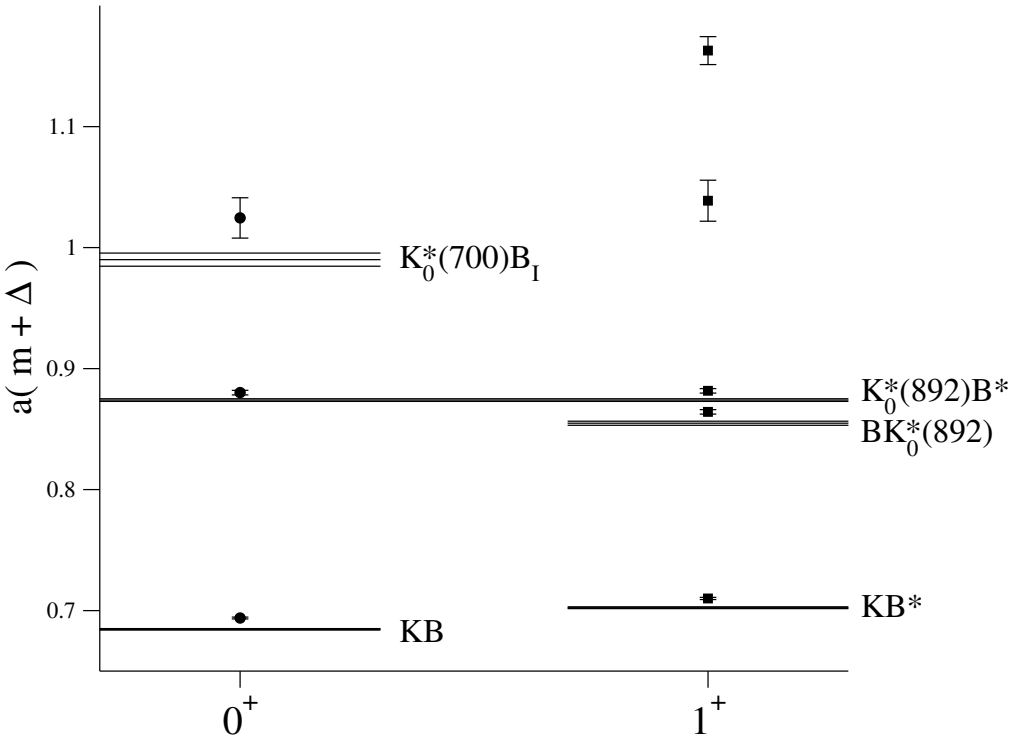

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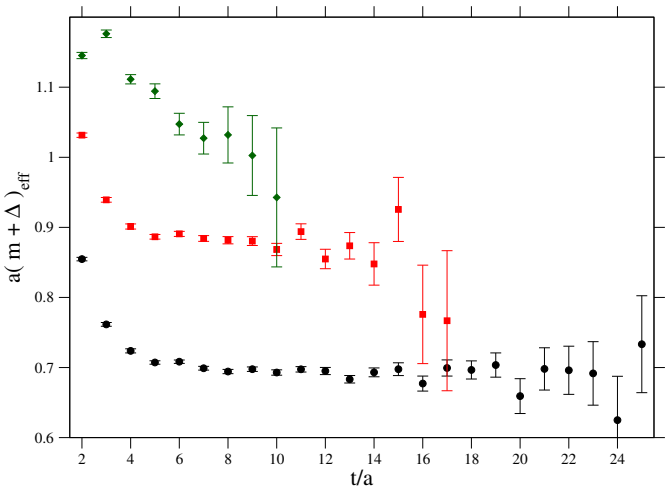

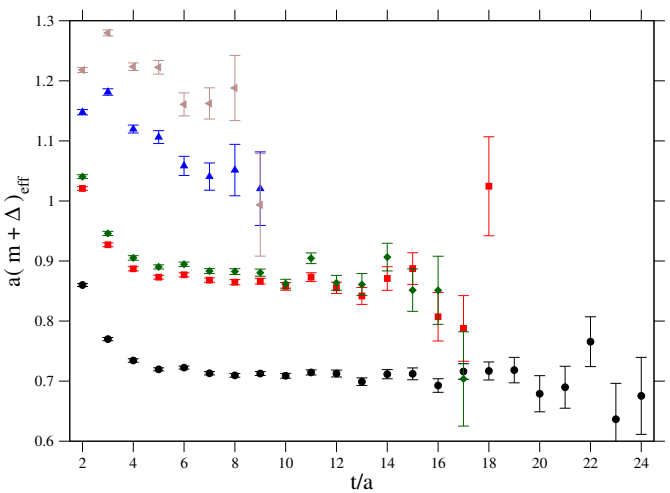

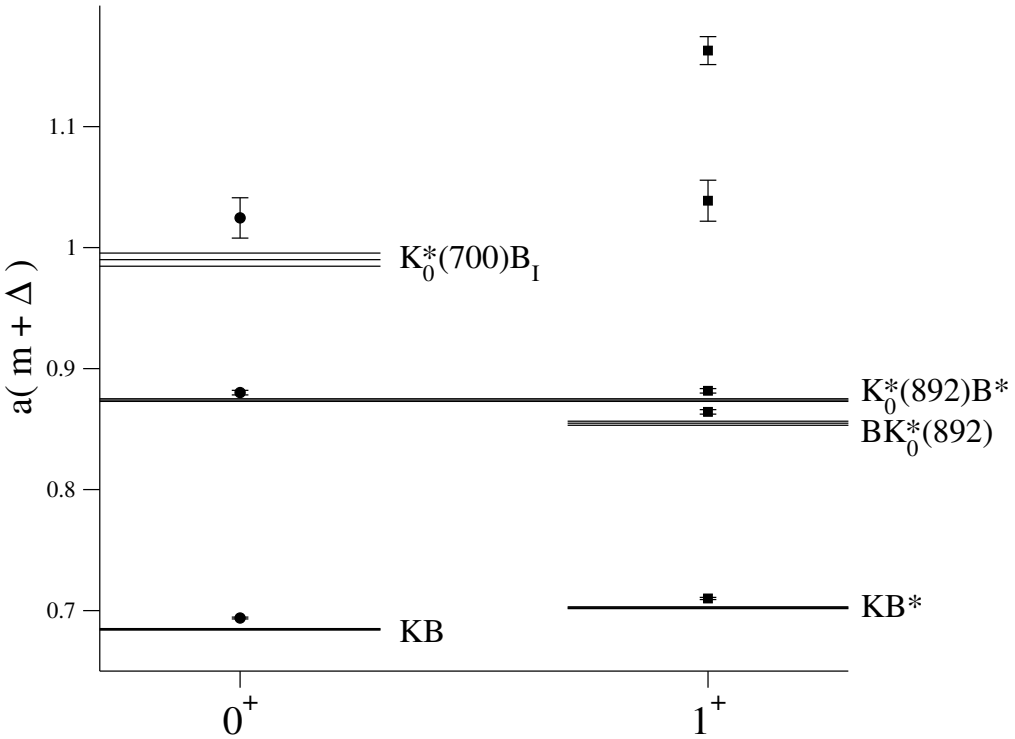

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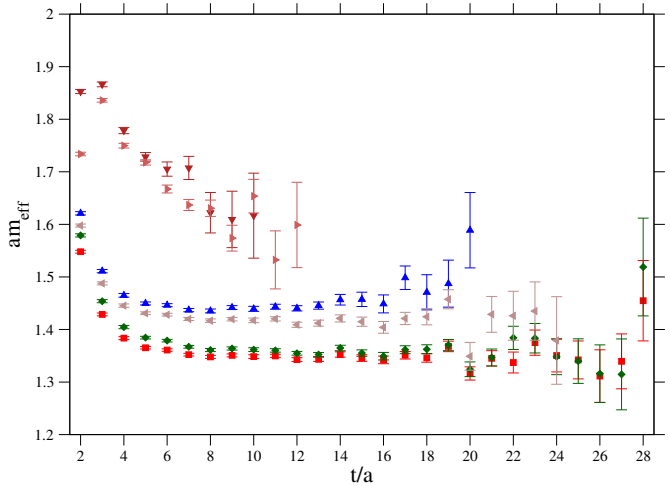

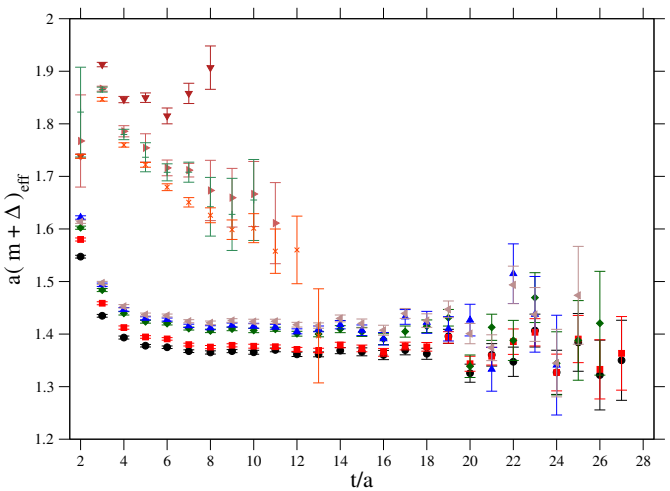

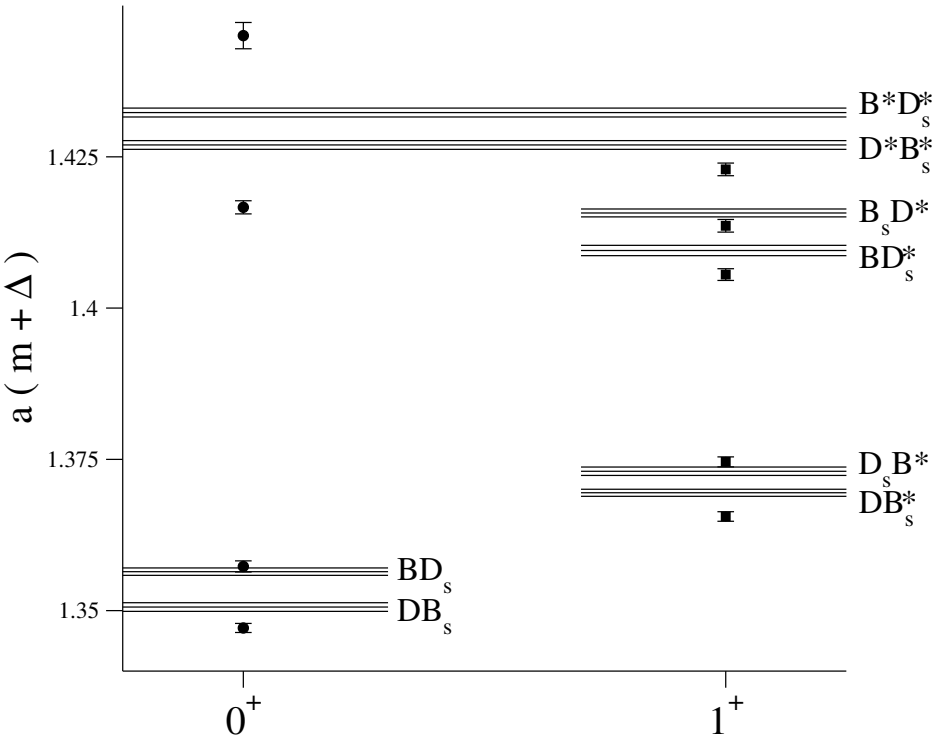

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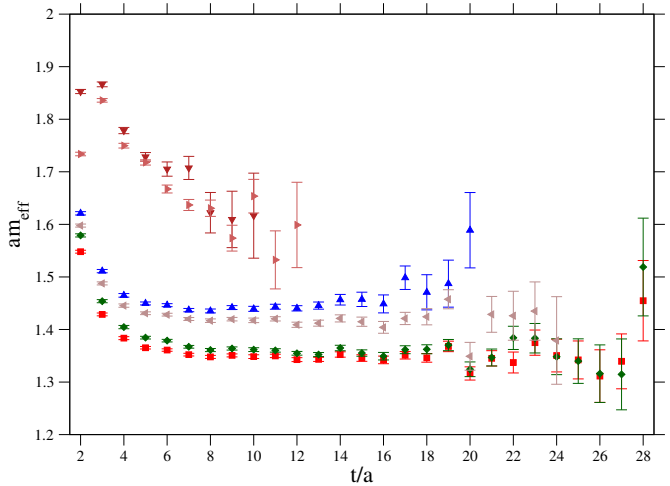

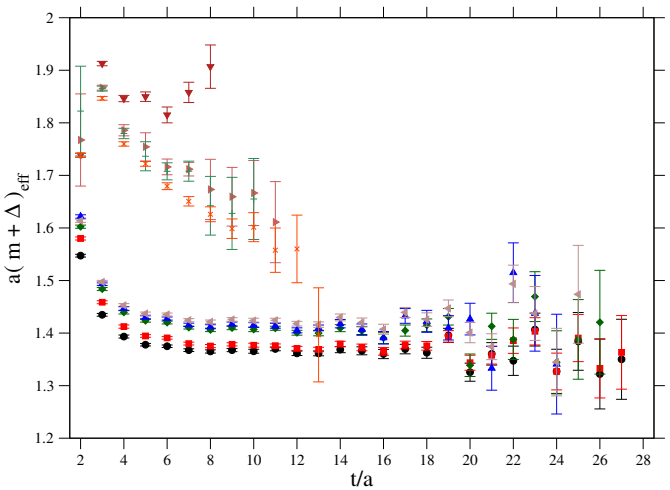

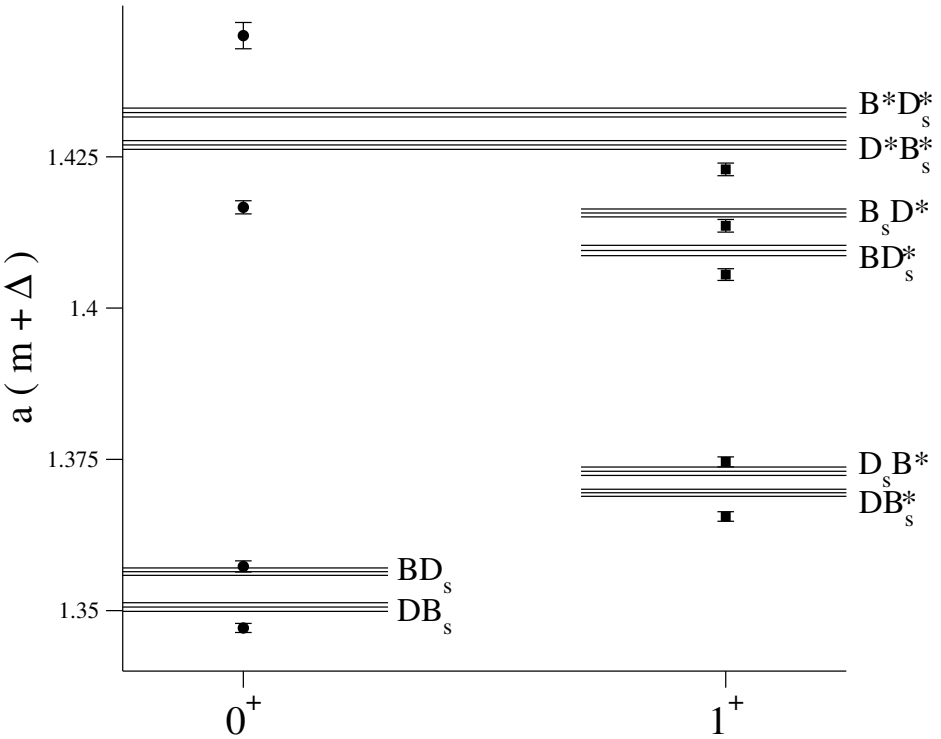

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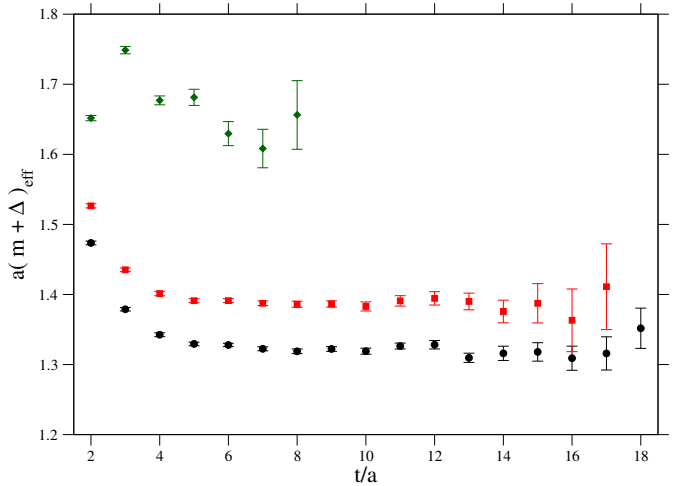

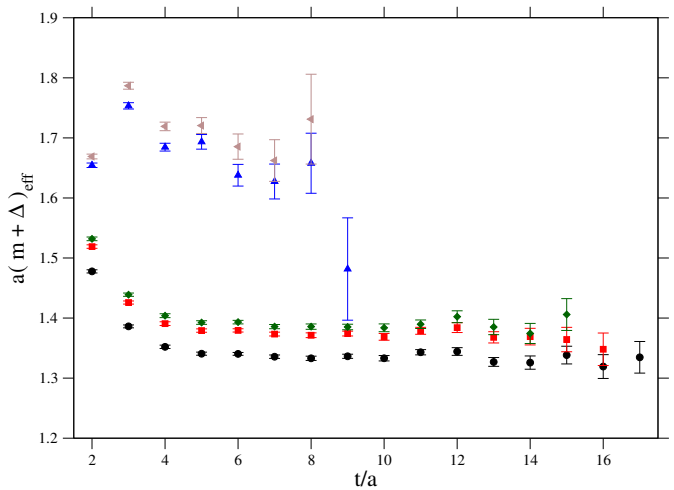

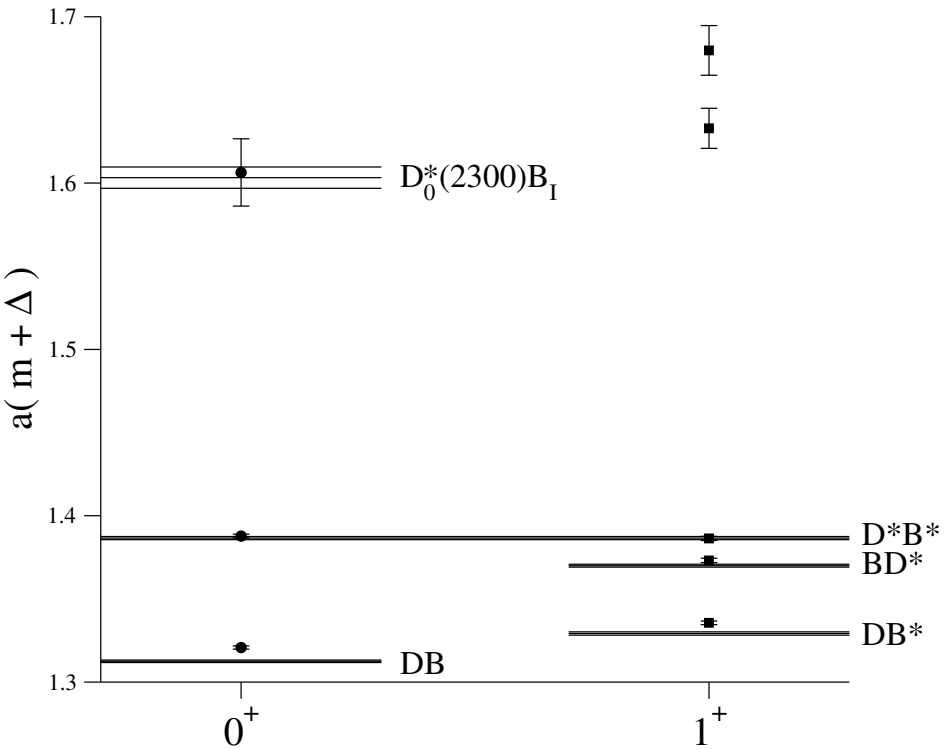

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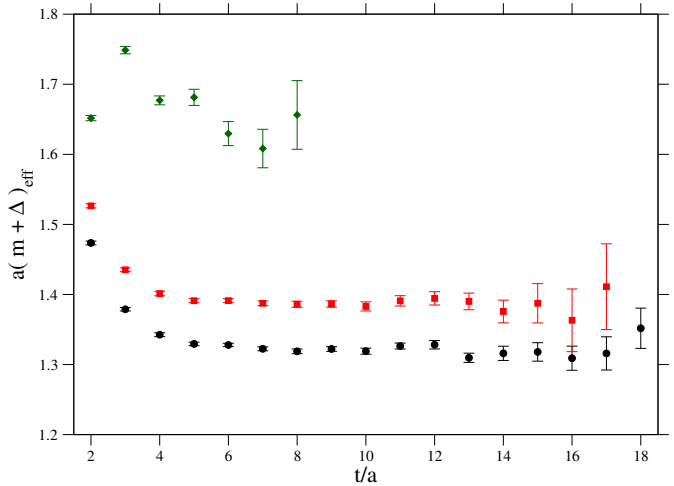

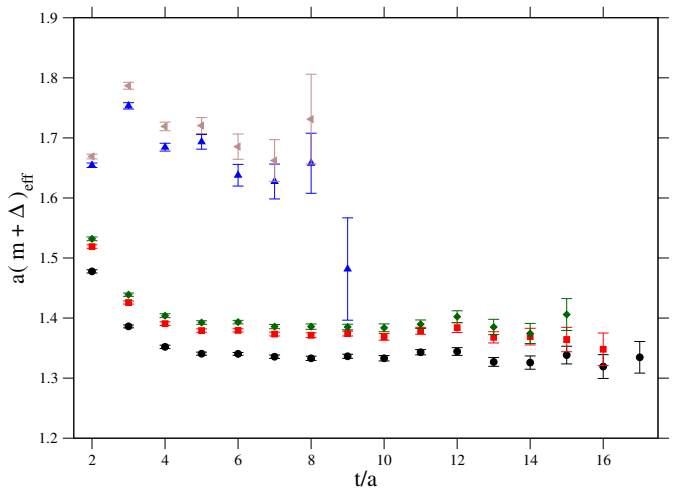

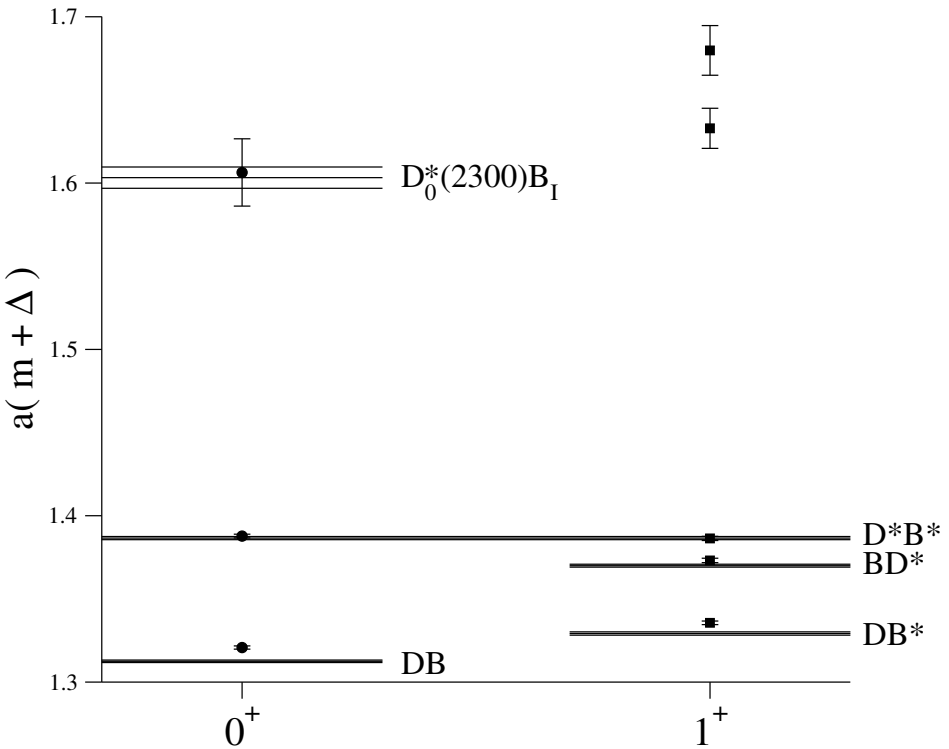

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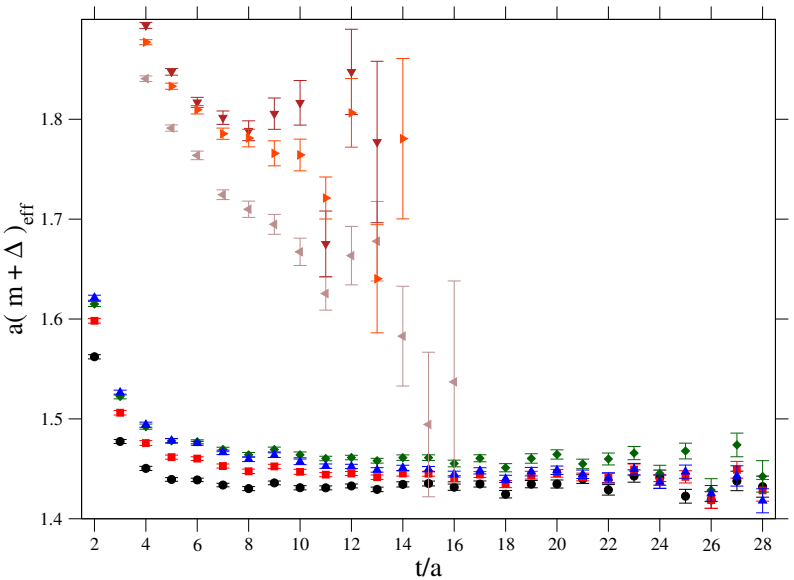

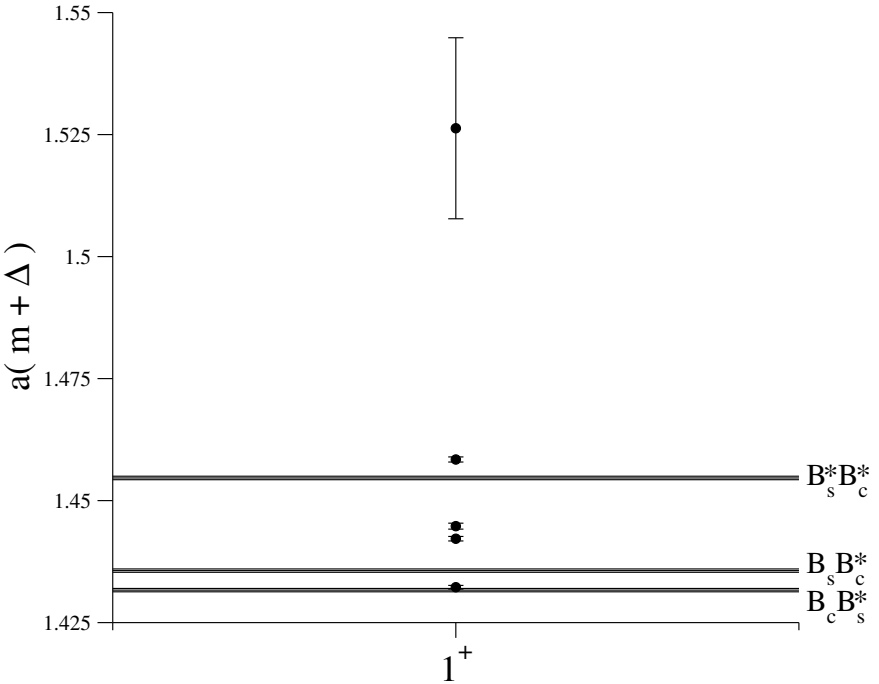

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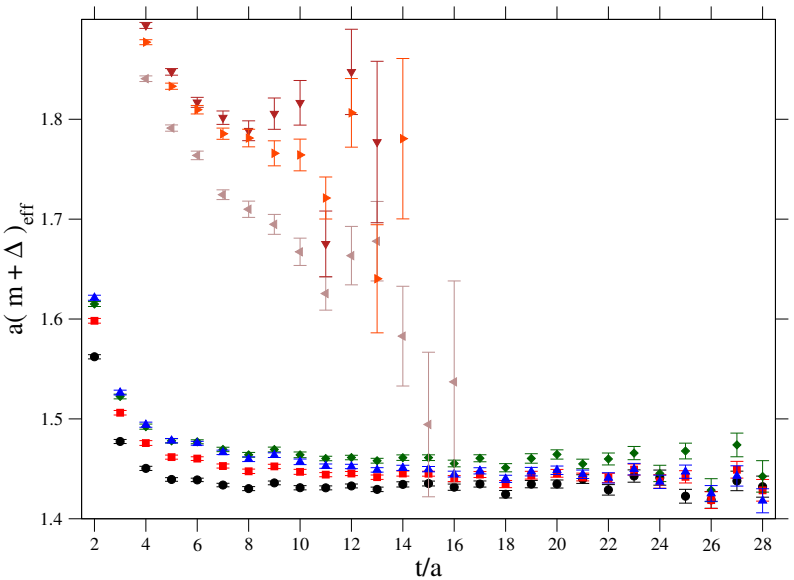

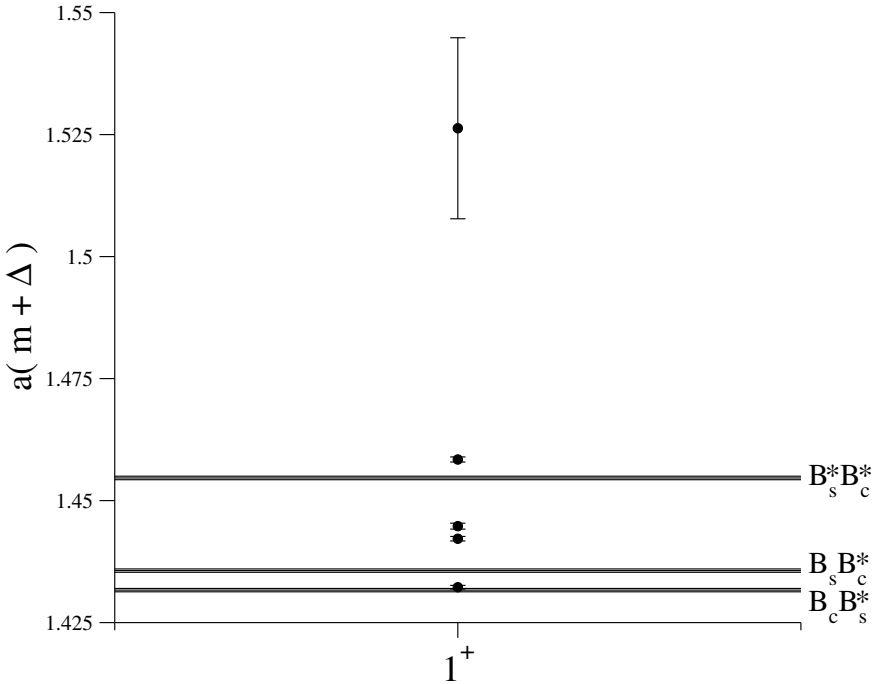

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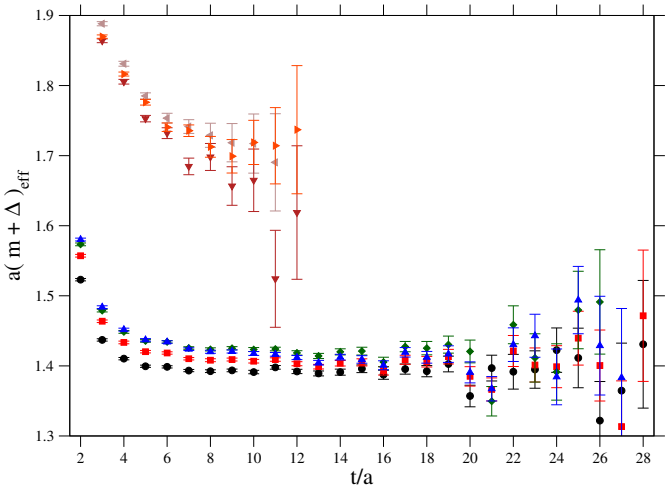

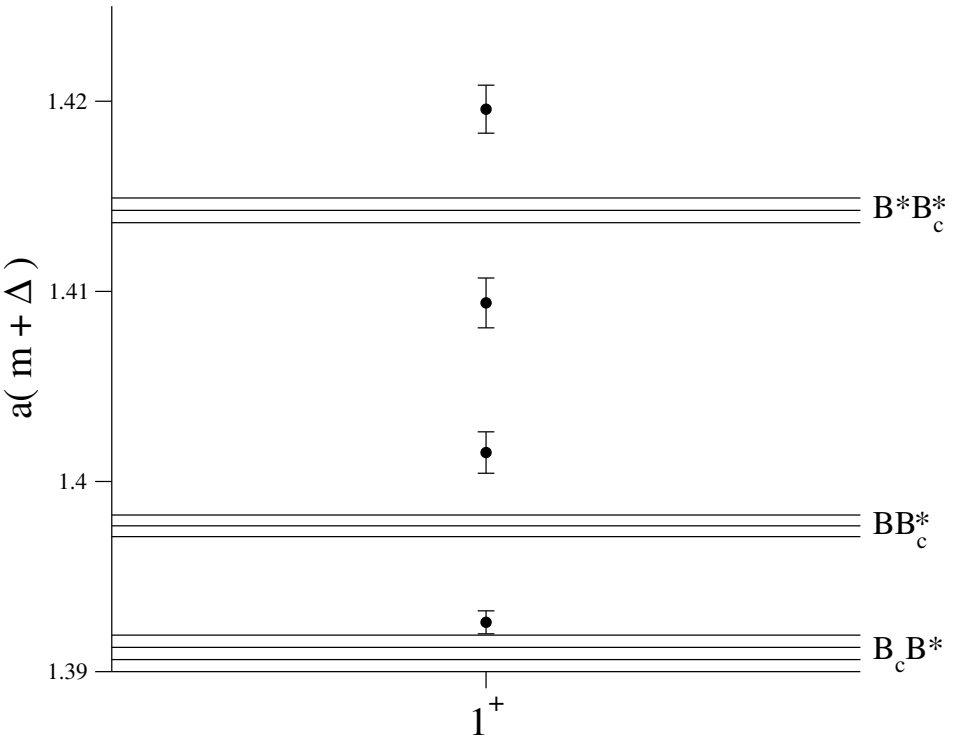

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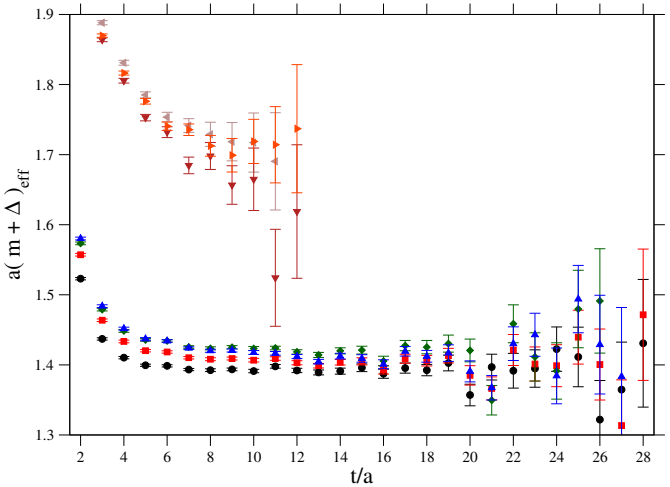

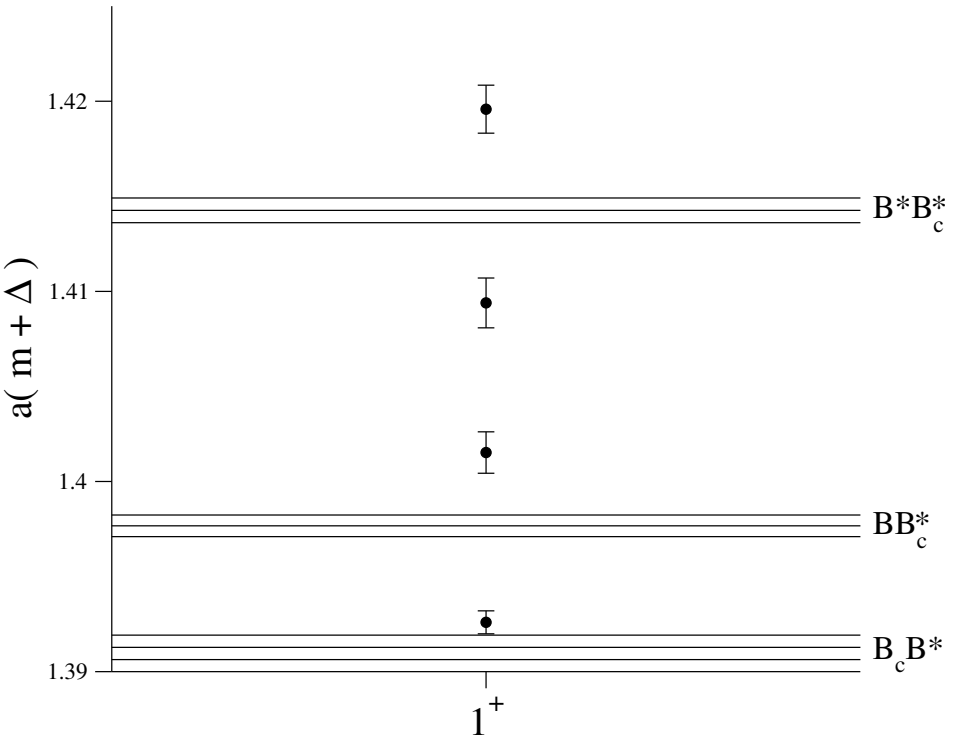

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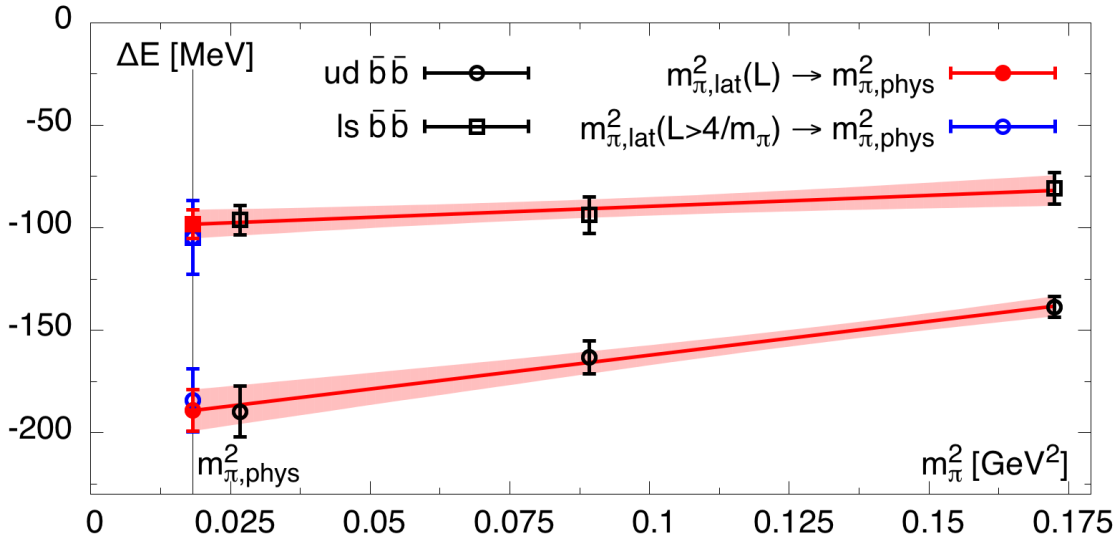
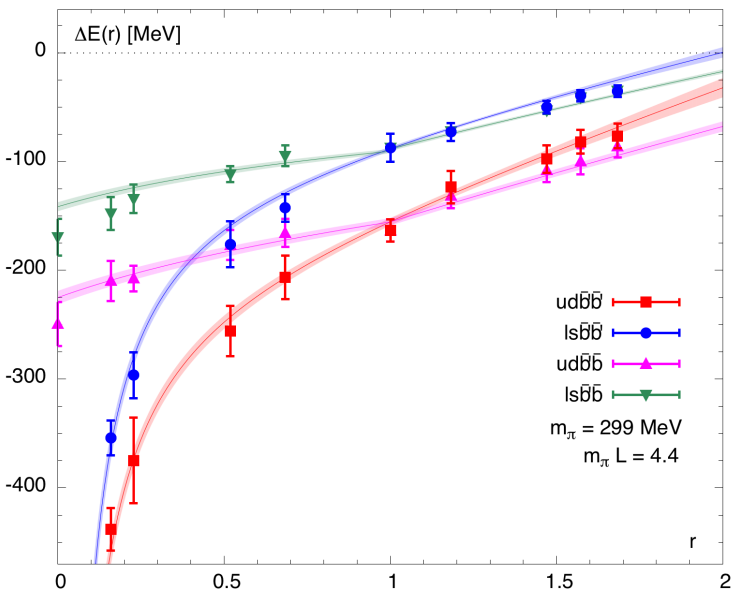
Doubly-bottom tetraquarks

(Update to Francis et al. results due in coming months.)

Francis *et al.* [1607.05214]

- ★ $ud\bar{b}\bar{b}$ clearly bound
- ★ Multiple lattice groups also find evidence of binding



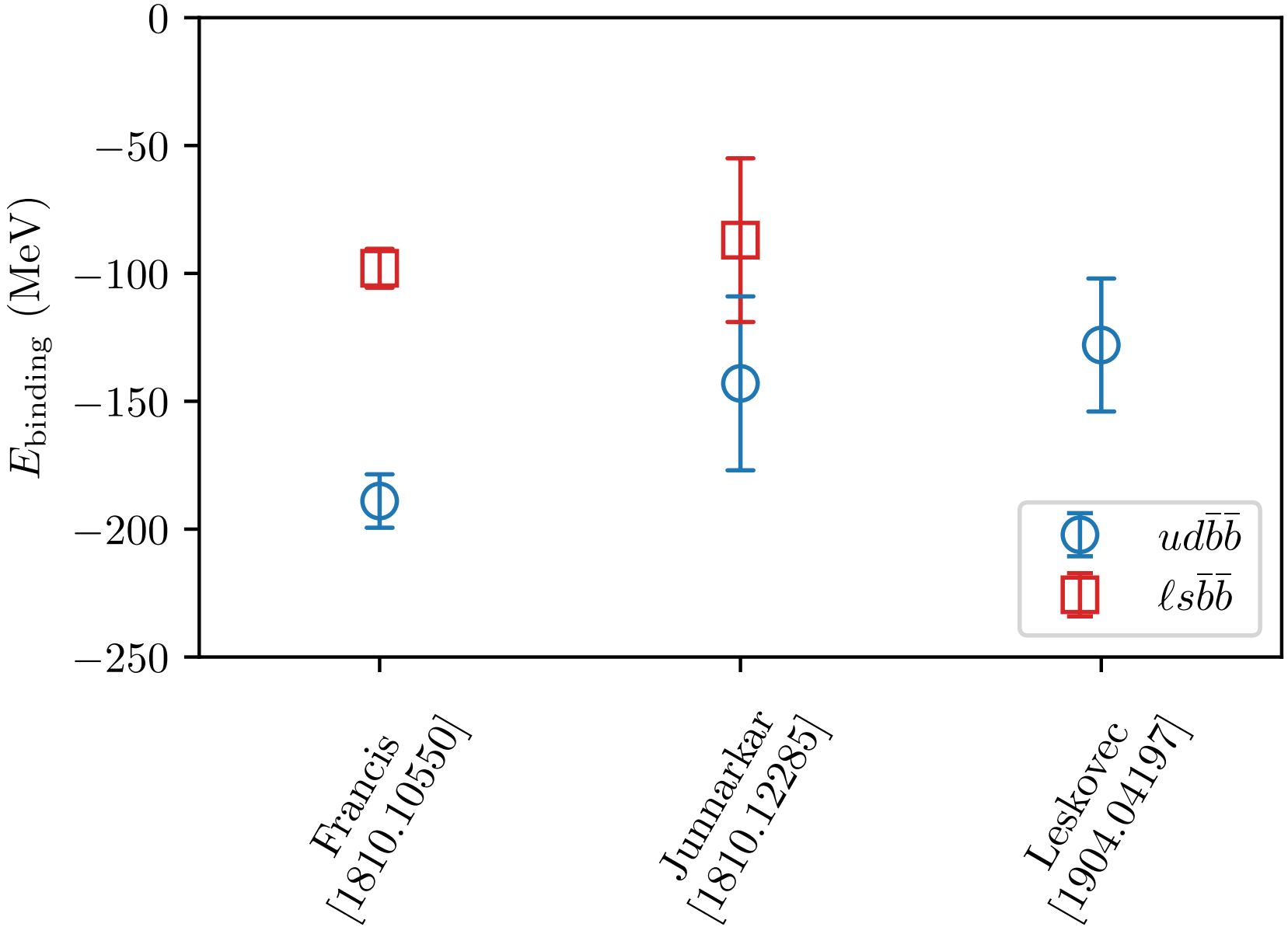


- ★ Binding increases with increasing heavy quark mass

Francis *et al.* [1810.10550]

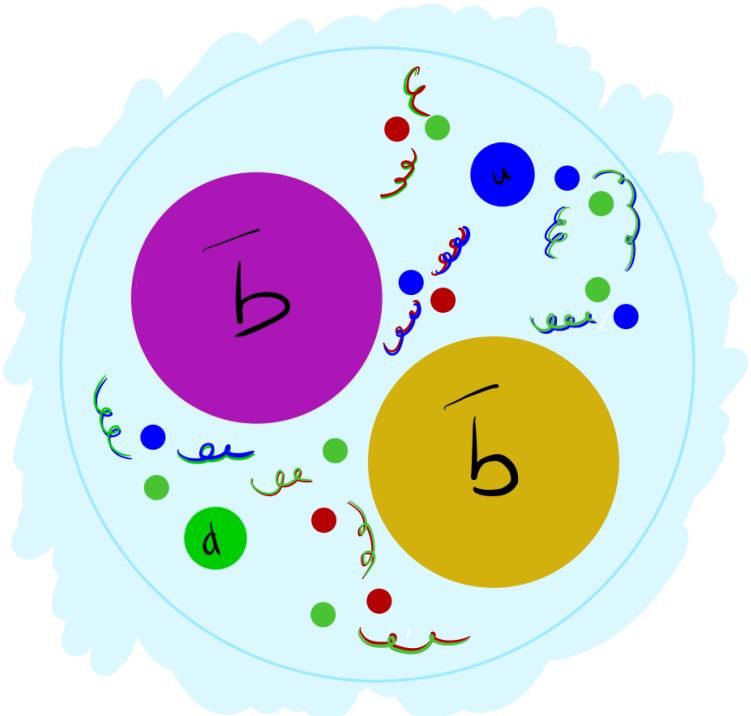
Binding energy comparisons

(Update to Francis et al. results due in coming months.)



Summary

- ★ $ud\bar{b}\bar{b}$ state studied by various groups: agreement bound $\mathcal{O}(100)$ MeV
- ★ Experimental search worthwhile for $ud\bar{b}\bar{b}$
- ★ Evidence also: $\ell s\bar{b}\bar{b}$
- ★ No evidence of deeply-bound tetraquarks in any of other channel explored.
- ★ On this basis, we can rule out models claiming deep binding in such channels.



Thank you!

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