Lattice QCD investigation of a doubly-bottom $\bar{b}\bar{b}ud$ tetraquark with quantum numbers $I(J^P) = 0(1^+)$

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Introduction

- Lattice QCD styudy of a $\bar{b}\bar{b}ud$ tetraquark with quantum numbers $I(J^P) = 0(1^+)$, $\bar{b}$ quarks with NRQCD.
  [L. Leskovec, S. Meinel, M. Pflaumer, M.W., arXiv:1904.04197 [hep-lat]]

- In many aspects similar to
  [A. Francis, R. J. Hudspith, R. Lewis and K. Maltman, Phys. Rev. Lett. **118**, 142001 (2017) [arXiv:1607.05214 [hep-lat]]]
  discussed in the previous talk by A. Francis.

- Time for this talk: 5 minutes.
  $\rightarrow$ Report/focus on differences to arXiv:1607.05214.

- Related work:
  [A. Francis, R. J. Hudspith, R. Lewis and K. Maltman, Phys. Rev. D **99**, 054505 (2019) [arXiv:1810.10550 [hep-lat]]]
  [P. Junnarkar, N. Mathur and M. Padmanath, Phys. Rev. D **99**, 034507 (2019) [arXiv:1810.12285 [hep-lat]]]

Creation operators

- Local creation operators (at the source and at the sink):

$$O_1 = \sum_{\mathbf{x}} \Big(\bar{b}(\mathbf{x})\gamma_5 d(\mathbf{x})\Big)\Big(\bar{b}(\mathbf{x})\gamma_j u(\mathbf{x})\Big) - (d \leftrightarrow u) \quad (BB^* \text{ molecule})$$

$$O_2 = \epsilon_{jkl} \sum_{\mathbf{x}} \Big(\bar{b}(\mathbf{x})\gamma_k d(\mathbf{x})\Big)\Big(\bar{b}(\mathbf{x})\gamma_l u(\mathbf{x})\Big) - (d \leftrightarrow u) \quad (B^*B^* \text{ molecule, new})$$

$$O_3 = \sum_{\mathbf{x}} \Big(\epsilon^{abc}\bar{b}(\mathbf{x})^b \gamma_j \mathcal{C} \bar{b}^{c,T}(\mathbf{x})\Big)\Big(\epsilon^{ade} d^{d,T}(\mathbf{x}) \mathcal{C}\gamma_5 u^e(\mathbf{x})\Big) - (d \leftrightarrow u) \quad (\text{diquark-antidiquark}).$$

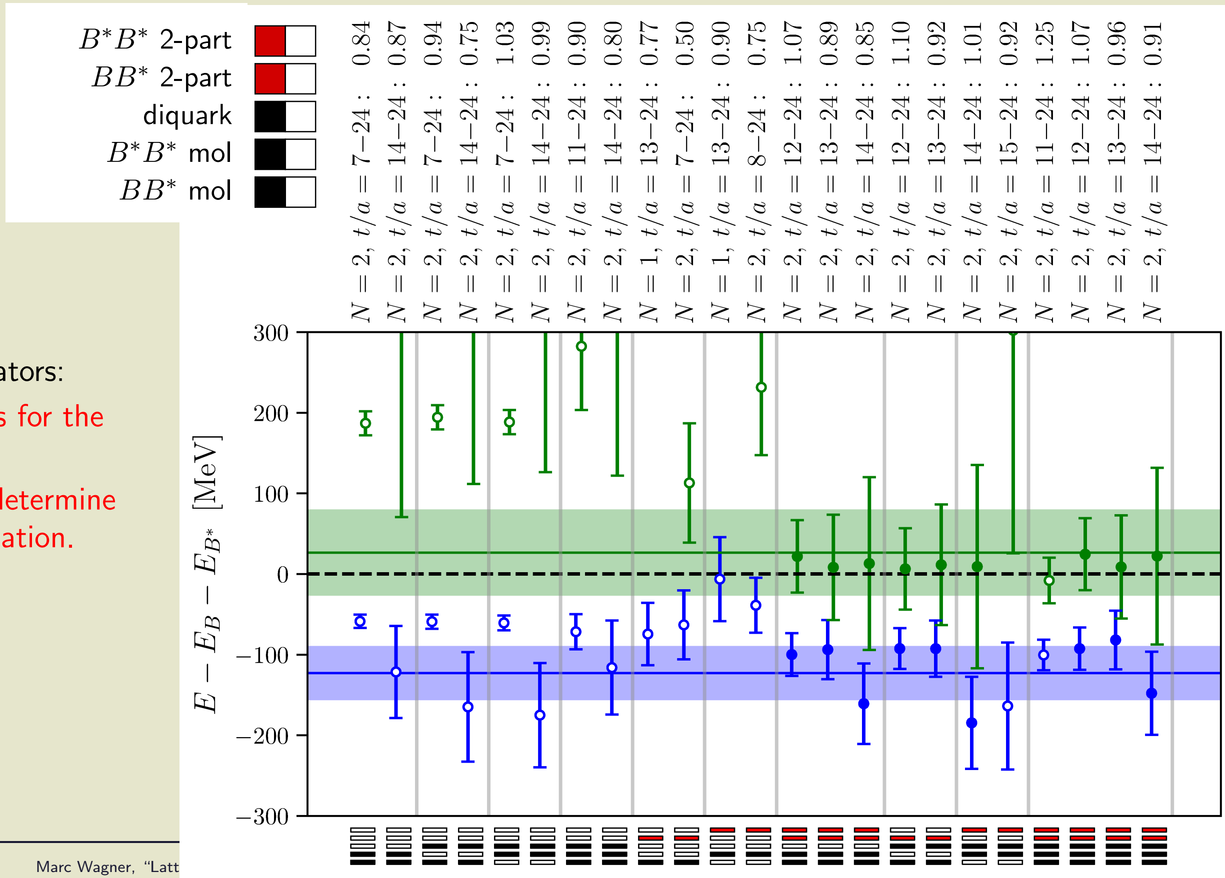
- Non-local creation operators (only at the sink):

$$O_4 = \Big(\sum_{\mathbf{x}} \bar{b}(\mathbf{x})\gamma_5 d(\mathbf{x})\Big)\Big(\sum_{\mathbf{y}} \bar{b}(\mathbf{y})\gamma_j u(\mathbf{y})\Big) - (d \leftrightarrow u) \quad (BB^* \text{ 2-particle state, new})$$

$$O_5 = \epsilon_{jkl}\Big(\sum_{\mathbf{x}} \bar{b}(\mathbf{x})\gamma_k d(\mathbf{x})\Big)\Big(\sum_{\mathbf{y}} \bar{b}(\mathbf{y})\gamma_l u(\mathbf{y})\Big) - (d \leftrightarrow u) \quad (B^*B^* \text{ 2-particle state, new}).$$

  - Allow to resolve the first excitation (a BB^* scattering state), which is close to the ground state (the $\bar{b}\bar{b}ud$ tetraquark).
    $\rightarrow$ Contamination of $\bar{b}\bar{b}ud$ tetraquark mass by BB^* scattering state excluded.
    $\rightarrow$ Infinite volume extrapolation via scattering analysis/Lüscher's method possible.

Resulting energy levels



Non-local operators:

- Smaller errors for the ground state.
- Essential to determine the first excitation.

Infinite volume limit

- Resulting energy levels are energy levels in a finite spatial volume.
- Determine the mass of the $\bar{b}\bar{b}ud$ tetraquark at infinite spatial volume via a scattering analysis (continued to imaginary momenta) and Lüscher's method:
  - Compute the two lowest energy levels in a finite spatial volume (see previous slide).
  - Compute corresponding phase shifts $\delta_0(k_0)$, $\delta_0(k_1)$ using Lüscher's method.
  - Parameterize $\delta_0(k)$ using a 2-parameter ansatz

    $$k \cot(\delta_0(k)) = \frac{1}{a_0} + \frac{r_0}{2} k^2$$

    (effective range expansion; a_0: S wave scattering length; r_0: S wave effective range).
  - The mass of the $\bar{b}\bar{b}ud$ tetraquark at infinite spatial volume corresponds to the pole in the scattering amplitude

    $$T_0(k) = \frac{1}{\cot(\delta_0(k)) - i}.$$

- No difference of finite and infinite spatial volume $\bar{b}\bar{b}ud$ tetraquark mass.
  $\rightarrow$ $\bar{b}\bar{b}ud$ tetraquark survives infinite volume limit.

Summary of $\bar{b}\bar{b}ud$ tetraquark results

- Tension between different lattice QCD computations.
- Possible future direction: use non-local operators both at the source and the sink.
  $\rightarrow$ Requires all-to-all propagators (computationally challenging).