Lattice QCD study of doubly heavy bottom tetraquarks

Bhabani Sankar Tripathy[1,2], Nilmani Mathur[3], M. Padmanath[1,2]

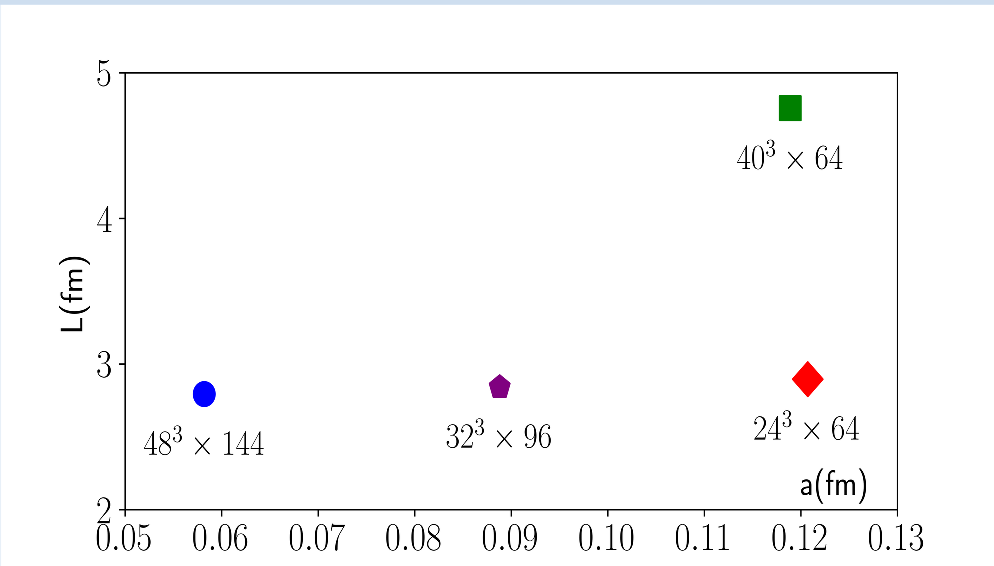
[1] *The Institute of Mathematical Sciences, CIT Campus, Chennai, 600113, India*
[2] *Homi Bhabha National Institute, Training School Complex, Anushaktinagar, Mumbai 400094, India*
[3] *Department of Theoretical Physics, Tata Institute of Fundamental Research, Mumbai 400005, India*
bhabanist@imsc.res.in, (+91)8917329718

Abstract

Baryons and mesons (collectively referred to as hadrons) have been understood as quark-gluon composite states bound by Quantum ChromoDynamics (QCD), the theory of strong interactions. The conventional understanding is that baryons are made of three quarks and mesons are composed of a quark-antiquark pair. QCD also supports the existence of more complex hadrons, made of more than three quarks. Only recently collider experiments such as at LHCb and Belle have reported these unexpected states, referred to as exotic hadrons, that are compelling candidates for such complex hadrons. The discoveries of several such exotic states dubbed as X, Y, Z, and Tcc(3875) in the heavy quark flavor sector have sparked enormous interest in the community. Understanding the binding mechanism of these exotic hadrons can play a crucial role in comprehending the non-perturbative nature of QCD dynamics. In this talk, I will discuss state-of-the-art lattice QCD investigations of two-meson interactions involving at least one bottom meson, relevant for heavy tetraquark channels. The computations were conducted on state-of-the-art MILC ensembles.

Lattice Setup

- We used four lattice QCD ensembles with $N_f = 2{+}1{+}1$ dynamical HISQ fields generated by the MILC collaboration[1].
- Valence quarks up to the strange quark mass were implemented using the overlap fermion action.
- Nonrelativistic QCD Hamiltonian was employed for the bottom quark.
- Bottom quark masses were tuned with 1S spin averaged quarkonia.



$$a\bar{M}^{\bar{b}b}_{kin} = \frac{3}{4}aM_{kin}(V) + \frac{1}{4}aM_{kin}(PS)$$

Extracting Finite Volume Spectrum

In all the systems we have used two types of interpolators

1. Meson-meson $\Phi_{M_{BB^*}}(x) = [\bar{u}(x)\gamma_i b(x)]\,[\bar{d}(x)\gamma_5 b(x)] - [\bar{u}(x)\gamma_5 b(x)]\,[\bar{d}(x)\gamma_i b(x)]$
2. Diquark-antidiquark $\Phi_D(x) = \left[\bar{u}(x)^T C\gamma_5 \bar{d}(x) - \bar{d}(x)^T C\gamma_5 \bar{u}(x)\right] \times (b^T(x) C\gamma_i b(x))$

The finite volume spectrum is determined from Euclidean two-point correlation function $\mathcal{C}_{ij}(t)$, between interpolating operators $\Phi_{i,j}(t)$ with desired quantum numbers:

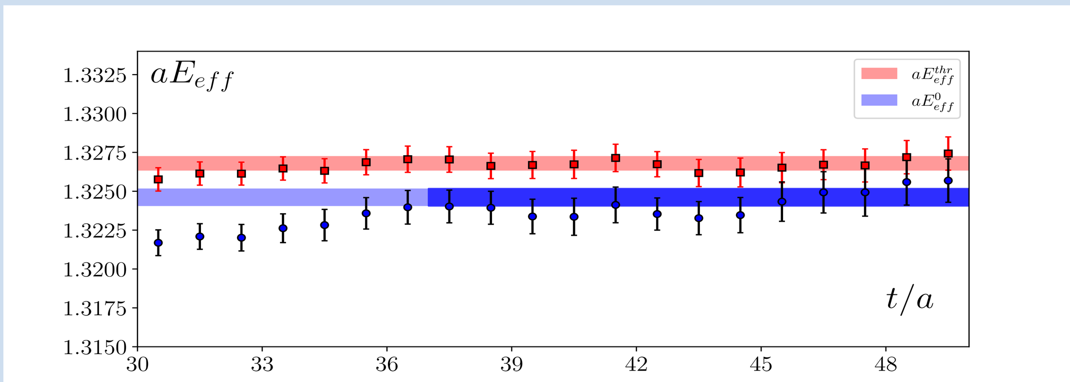
$$\mathcal{C}_{ij}(t) = \langle \Phi_j^\dagger(0)\Phi_i(t)\rangle = \sum_n \langle 0|\Phi_j|n\rangle\langle n|\Phi_i|0\rangle e^{-E_n t}$$

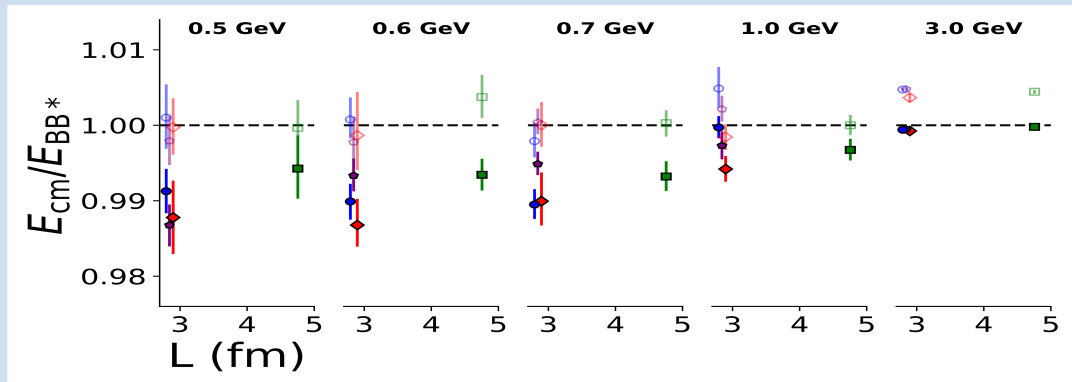
Rest is to solve the GEVP equation:

$$C(t)v^n(t) = \lambda^n(t,t_0)C(t_0)v^n(t)$$

After diagonalization, the eigenvalues of C, denoted as $\lambda^n(t,t_0)$, are obtained. Fitting the leading exponential of $\lambda^n(t,t_0)$ then yields the energy levels E_n.

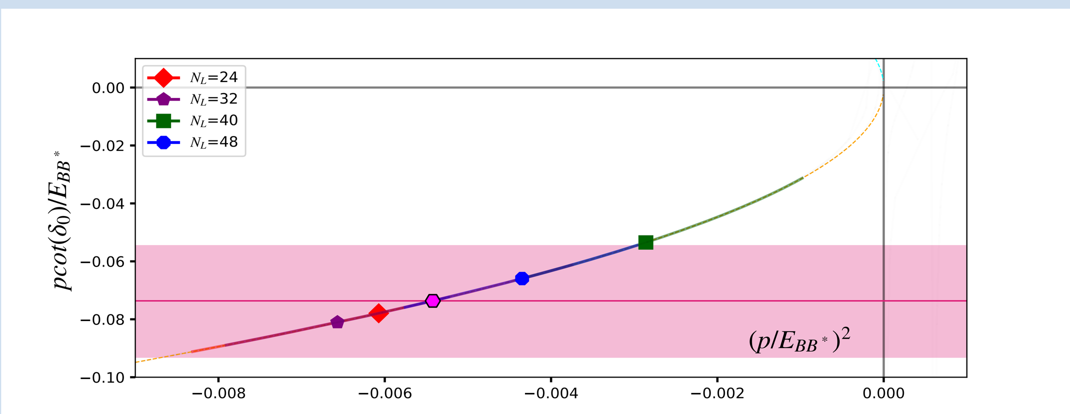
$$\lambda^n(t,t_0) = |A_n|^2 e^{-E_n(t-t_0)}\left[1 + \mathcal{O}\left(e^{-\Delta_n(t-t_0)}\right)\right]$$

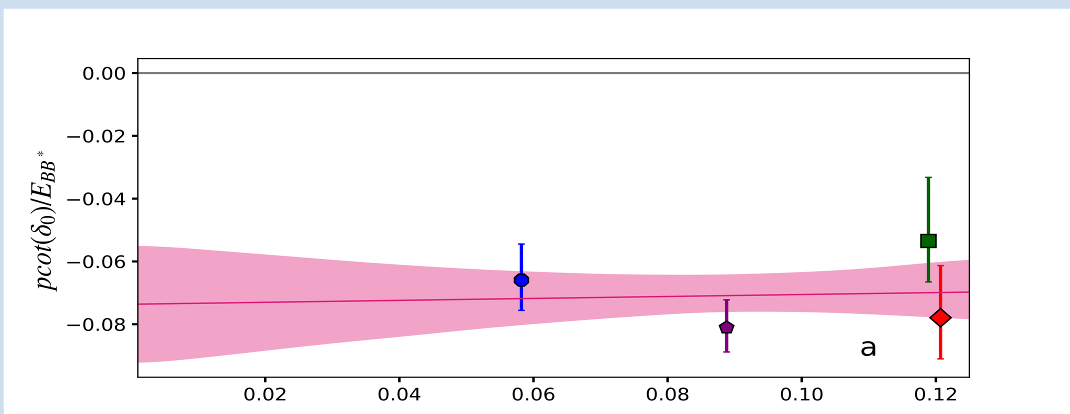




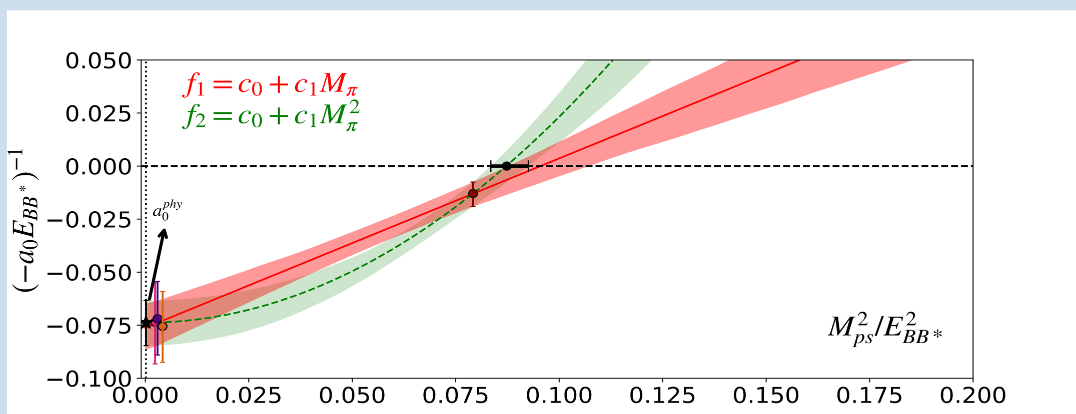
Sacttering Amplitude Analysis and Chiral Extrapolation

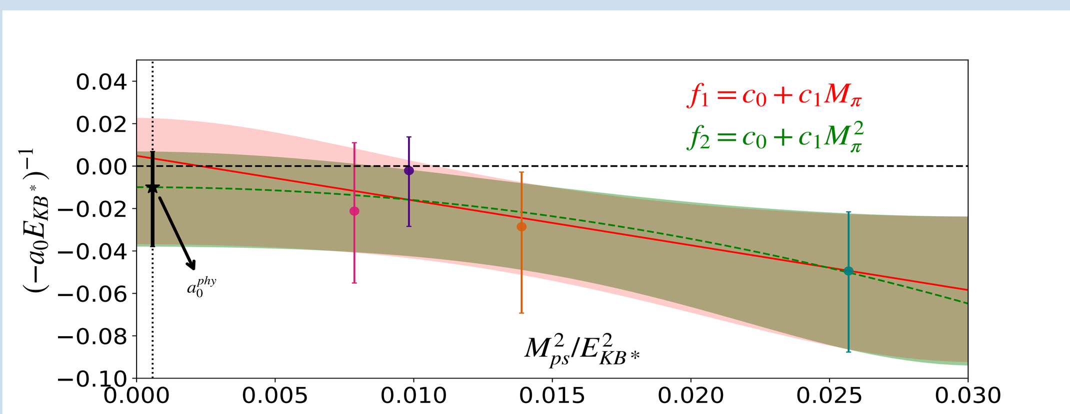
The S-wave scattering amplitude for BB^* is expressed as $T = (p\cot\delta_0 - ip)^{-1}$, where the energy dependence is parameterized using the effective range expansion. Specifically, we consider $p\cot\delta_0 = A_0 + A_1 a$[3], including the lattice spacing dependence through the scattering length term.
To obtain the scattering amplitude in the infinite volume limit, we must first extract $p\cot\delta_0$ in the continuum limit as $a \to 0$, followed by the physical pion mass limit $M_\pi \to M_{\rm phy}$ (or vice versa, as discussed in [2]).

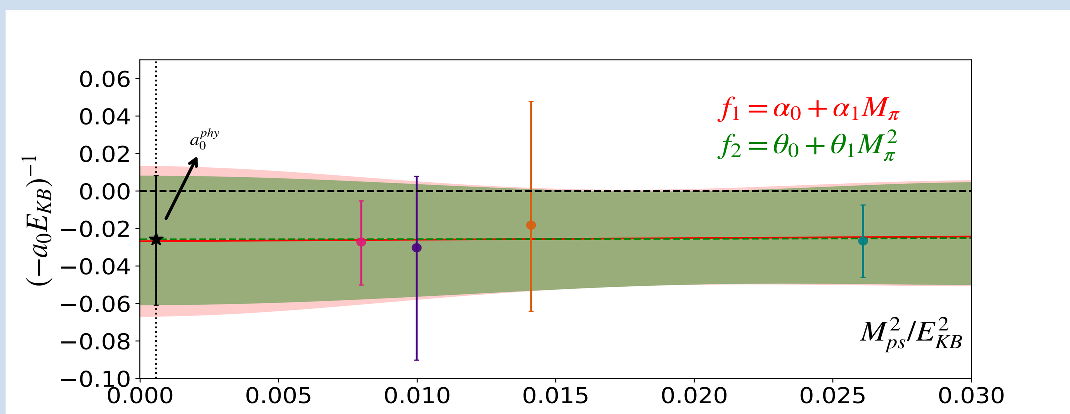




After performing the continuum extrapolation, our next step is to study the pion mass (M_{ps}) dependence. The figure below represents the chiral extrapolation for $bb\bar{u}\bar{d}$. Same repeated for bottom-strange systems.







The three plots represents chiral extrapolation for $bb\bar{u}\bar{d}$ with $J^P = 1^+$, $bs\bar{u}\bar{d}$ with 1^+ and 0^+(from left to right).

Conclusion

We present improved results on the spectroscopy of doubly bottom tetraquarks. In an effort to enhance our previous work [2], we added an additional volume and employed box smearing at the sink. Our findings indicate an attractive interaction (deeply bound state) between the B and B^* mesons, which could form a compact object. The attractive interaction is strong enough to support a real bound state with a binding energy of $-116.145(^{+30.72}_{-36.83})$. A similar analysis was conducted for the bottom-strange tetraquark with spin $S = 0, 1$.

Acknowledgements

This work is supported by the Department of Atomic Energy, GOI, under Project Identification Number RTI 4002. Computations were carried out on the Cray-XC30 of ILGTI, TIFR, and the computing clusters at the DTP, TIFR, Mumbai, and IMSc Chennai. MP gratefully acknowledges support from the Department of Science and Technology, India, SERB Start-up Research Grant No.SRG/2023/001235.

References

1. Bazavov et al. PRD **87** (2013) 054505.
2. Junnarkar et al. PRD **99** (2019) 034507.
3. Padmanath et al. PRL **132** (2024) 201902.