Isoscalar axial-vector bottom-charm tetraquarks from QCD

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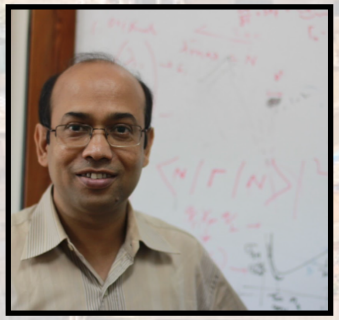
HADRON 2023

In collaboration with



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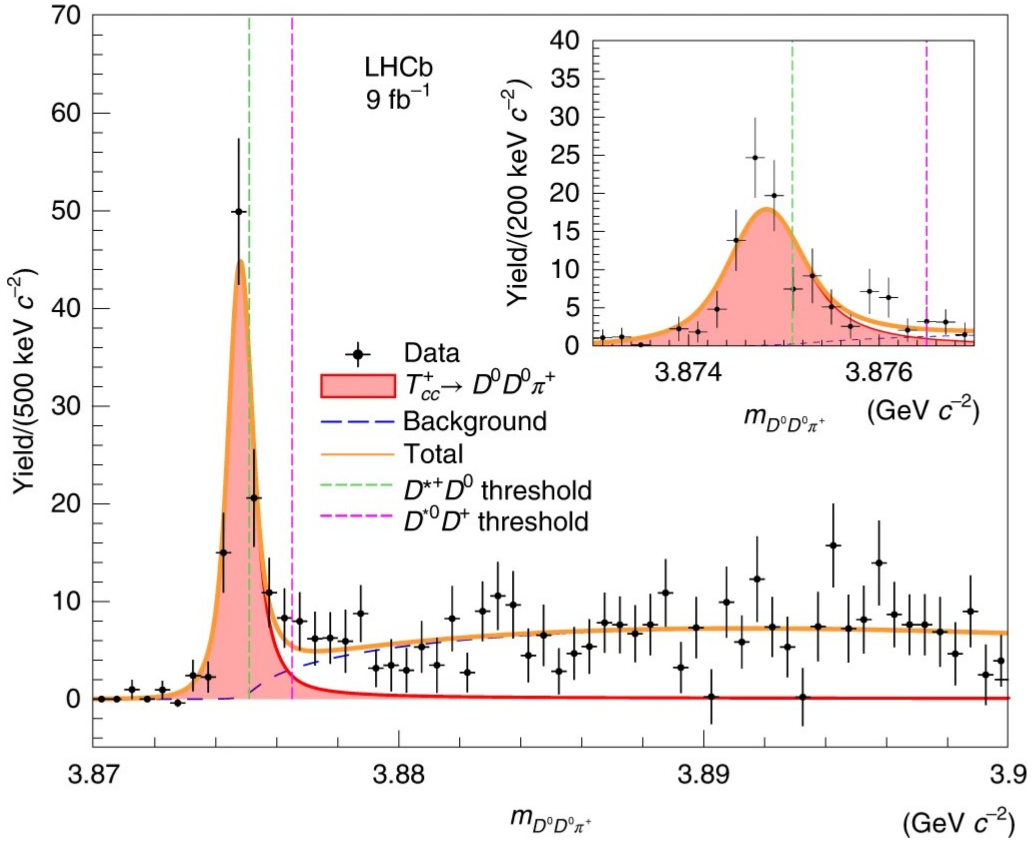
Discovery of T_{cc}^{+} and the prospects for other $QQ'qq'$ states

Nat. Phys. **18**, 751–754 (2022)



- Doubly-heavy tetraquarks are promising candidates for long-lived exotic tetraquarks
- $cc\bar{d}\bar{u}$ observed in 2021 by LHCb

- Where should experiments look to find more such states?
- What does theory tell us?

Other possible $QQ'qq'$ states: $bb\bar{u}\bar{d}$ and $bc\bar{u}\bar{d}$

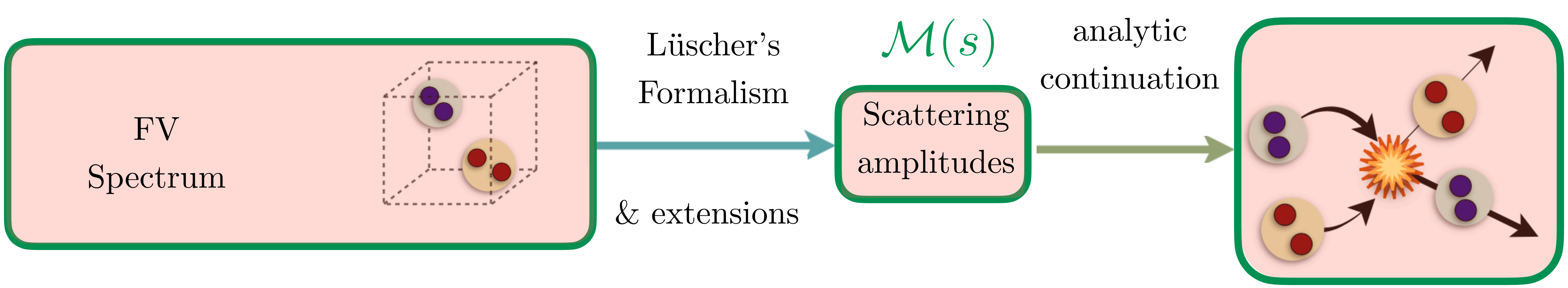
See June 5 plenary by E. Spadaro Norella

Lattice QCD

- Currently the only known non-perturbative technique to study QCD systematically using high performance computing
- Uses Monte-Carlo importance sampling to perform the integral in Euclidean space

$$\int DA_\mu D\psi D\overline{\psi} f(\psi, \overline{\psi}, A_\mu) e^{-S_{\mathrm{Euc.}}}$$

- Calculations done at a finite lattice spacing and finite volume.



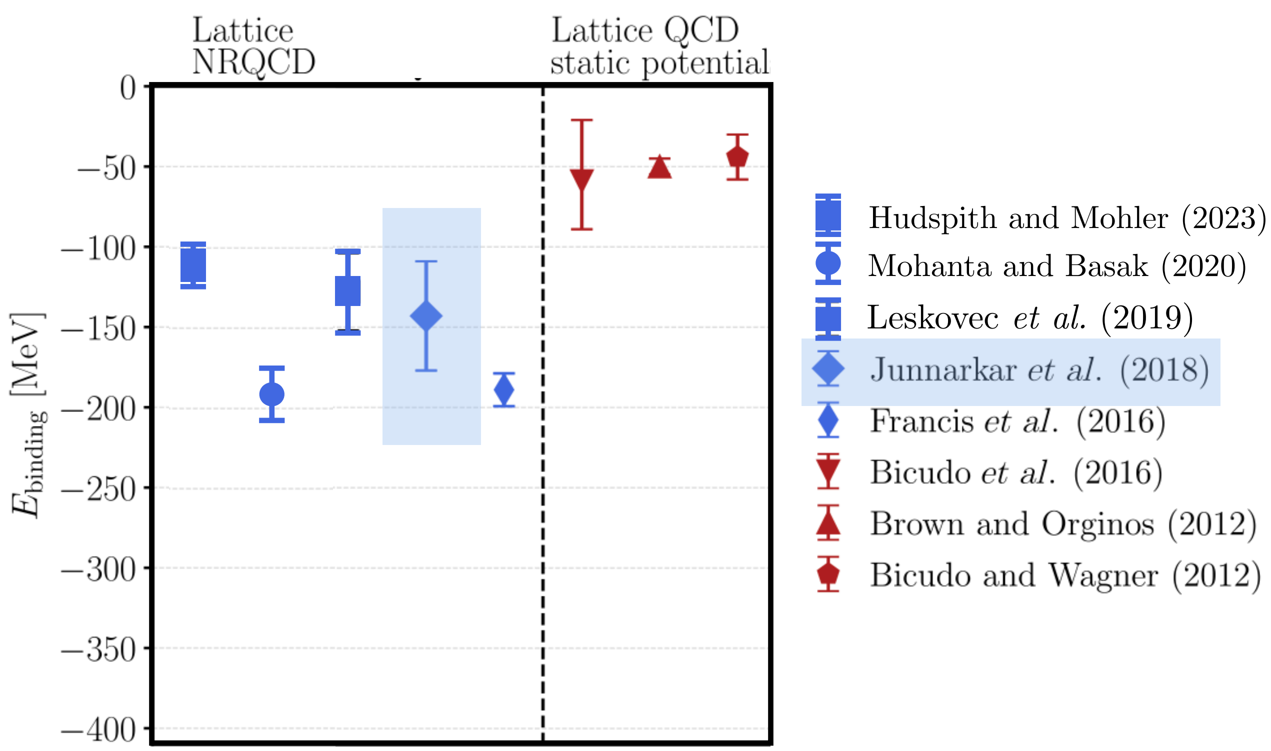
The time dependence of two point correlation functions gives discrete energy levels that depend on the volume of the lattice

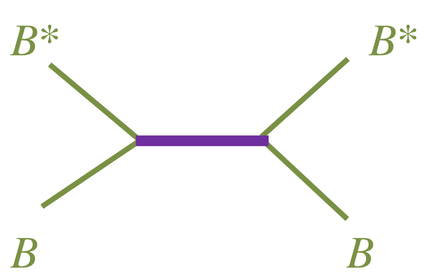
Map the discrete energy levels to the scattering amplitudes that can be compared with experiments

What does LQCD tell us?

States well below threshold

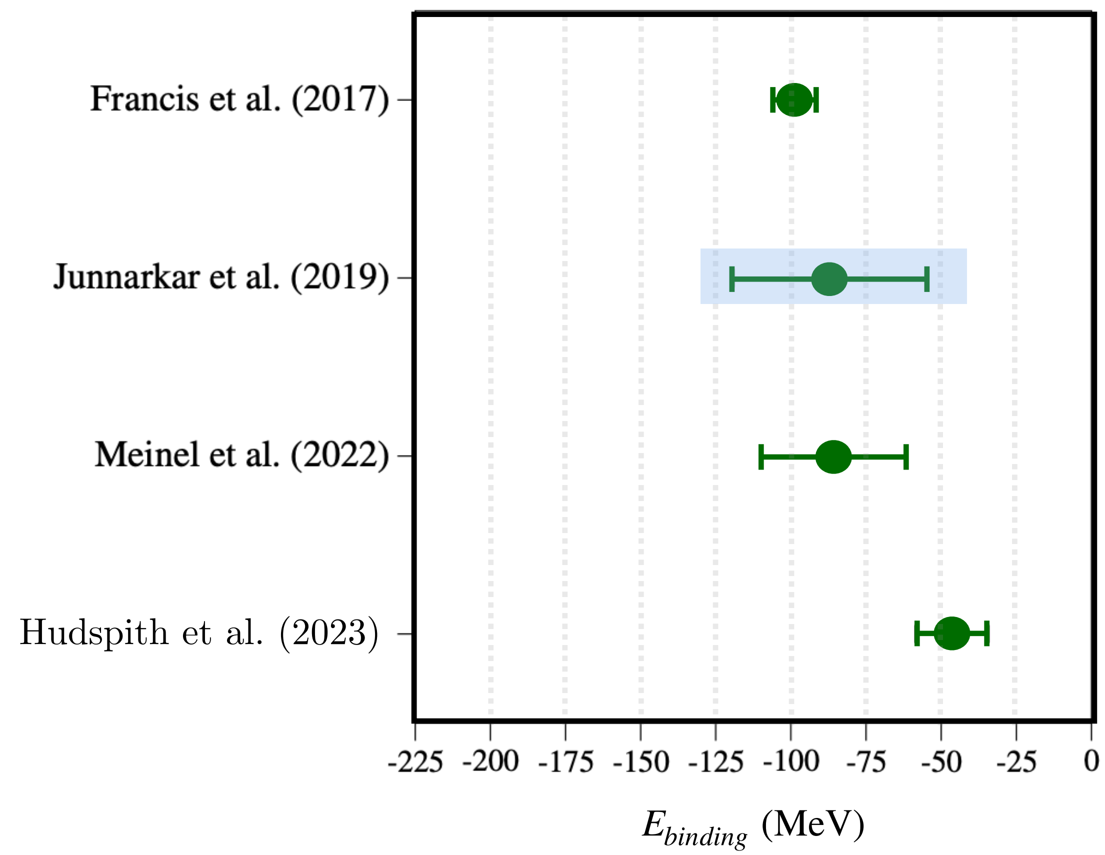
$bb\bar{u}\bar{d}$ $0(1^+)$

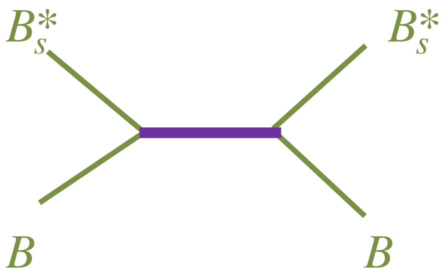




Surely bound and numerous calculations have been performed using LQCD - assuming not substantial finite volume effects **- a reliable claim for deeply bound states with heavy quarks**

$bb\bar{u}\bar{s}$ $0(1^+)$





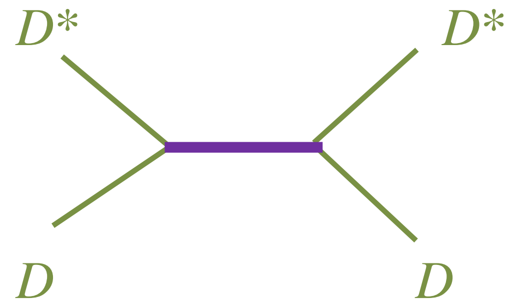
These states may be discovered in future, but the energies might be too high for current experiments to reliably explore

What does LQCD tell us?

States near threshold

See June 7 plenary by S Prelovsek

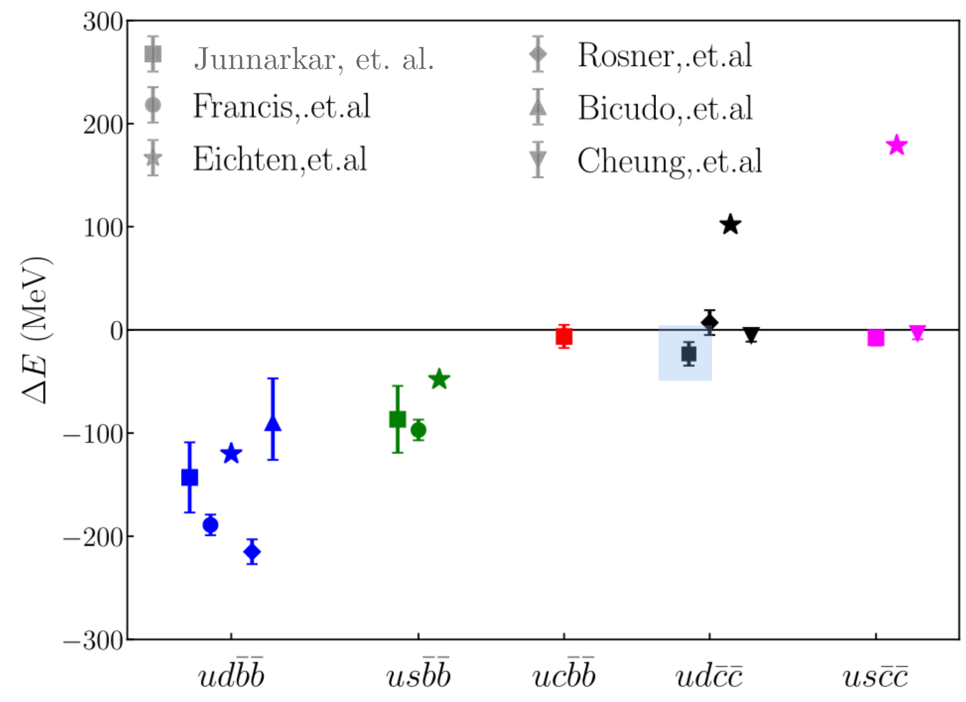
$cc\bar{u}\bar{d}$ 0(1$^+$)



Lattice had seen indications of a bound state

- later discovered by LHCb!

Junnarkar et al. (2019)

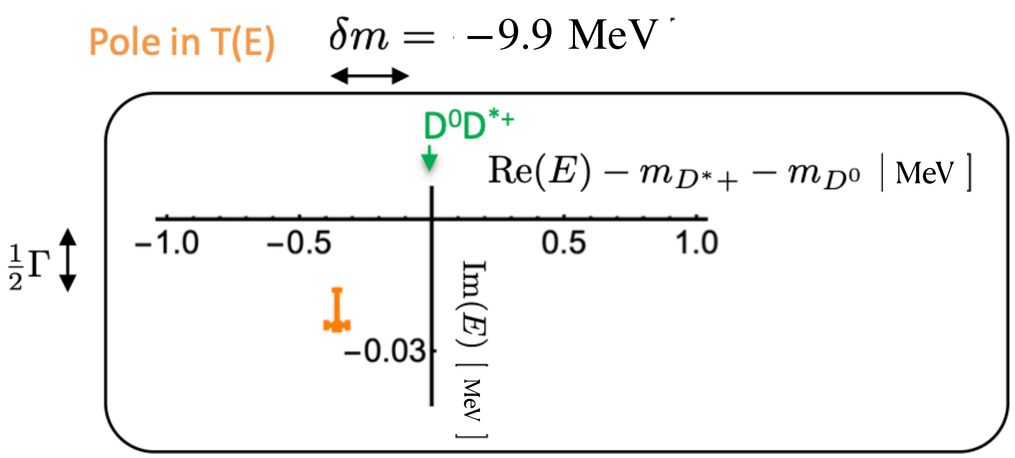


Exploring tetraquarks with bottom and charm may be accessible to experiments

Motivates the study of $bc\bar{u}\bar{d}$

but significant finite volume effects possible close to threshold

Need to find the poles in the scattering amplitude to extract (virtual) bound poles: *Padmanath et al. Phys.Rev.Lett.* 129 (2022



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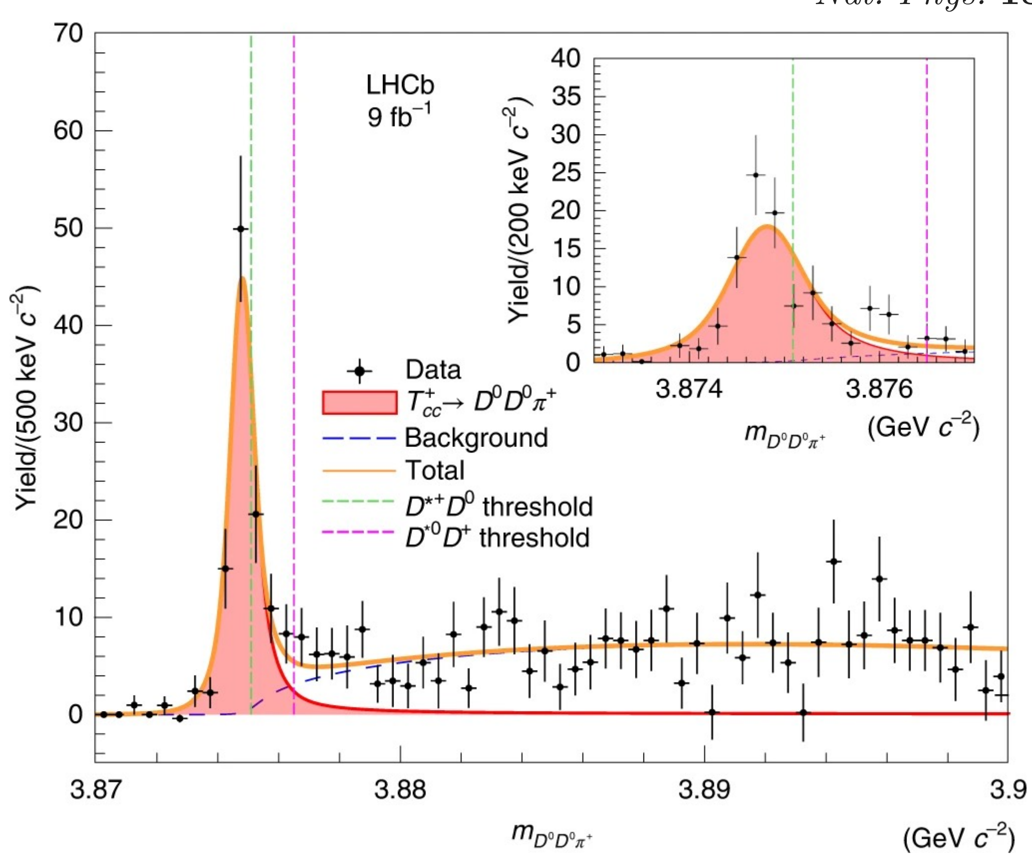
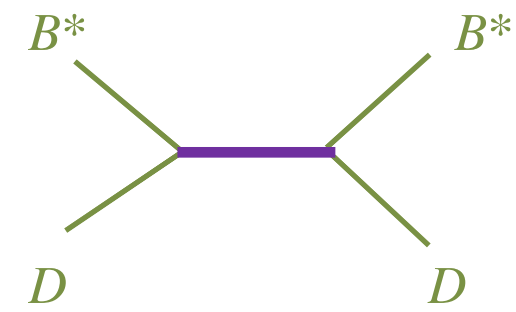


Other recent lattice studies confirm the presence the bound state:

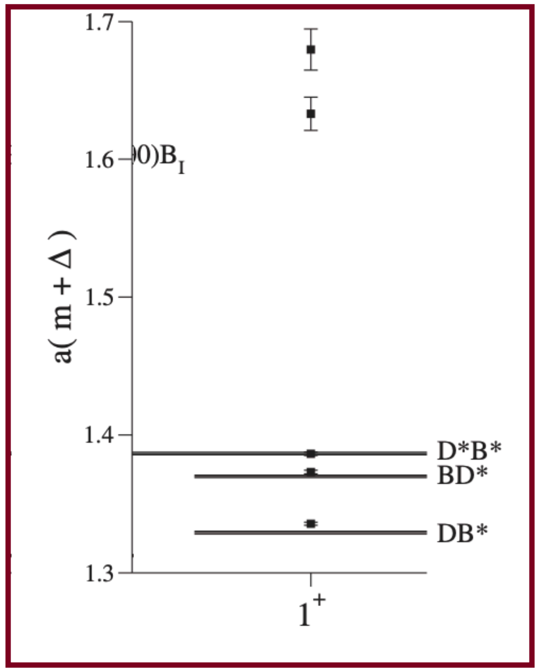
Lyu et al. arXiv.2302.04505
Chen et al. j.physletb.2022.137391

What does LQCD tell us?

States near threshold



$bc\bar{u}\bar{d}$ $0(1^+)$

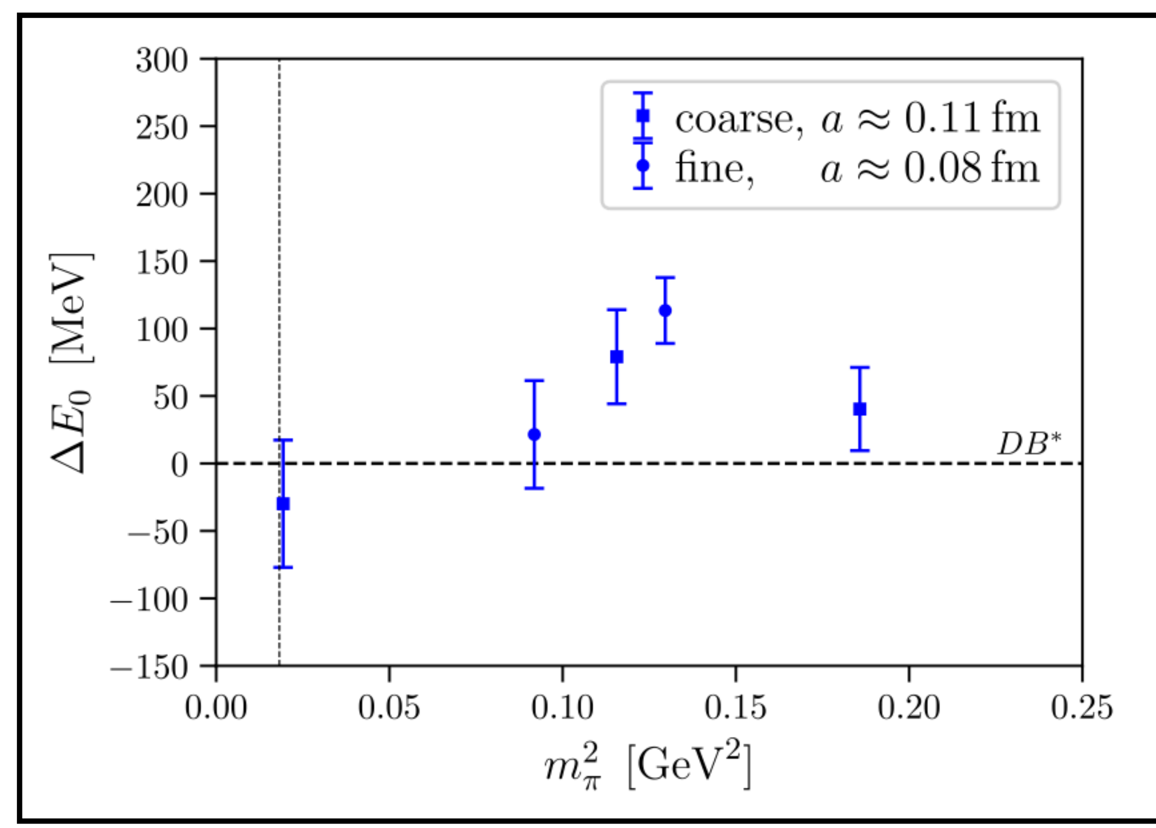


Hudspith et al. Phys. Rev. D **102**, 114506

Infinite volume scattering amplitude was not extracted

Tetraquarks with charm and bottom can be currently accessible to experiments - theoretical predictions can help in such searches!

Mienel et al. Phys. Rev. D **106**, 034507

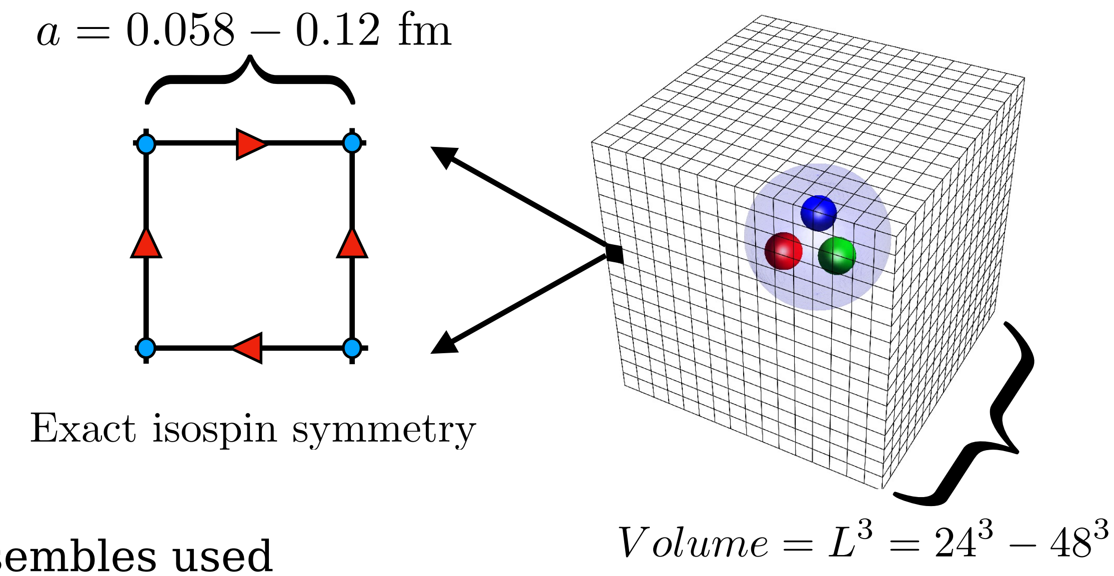


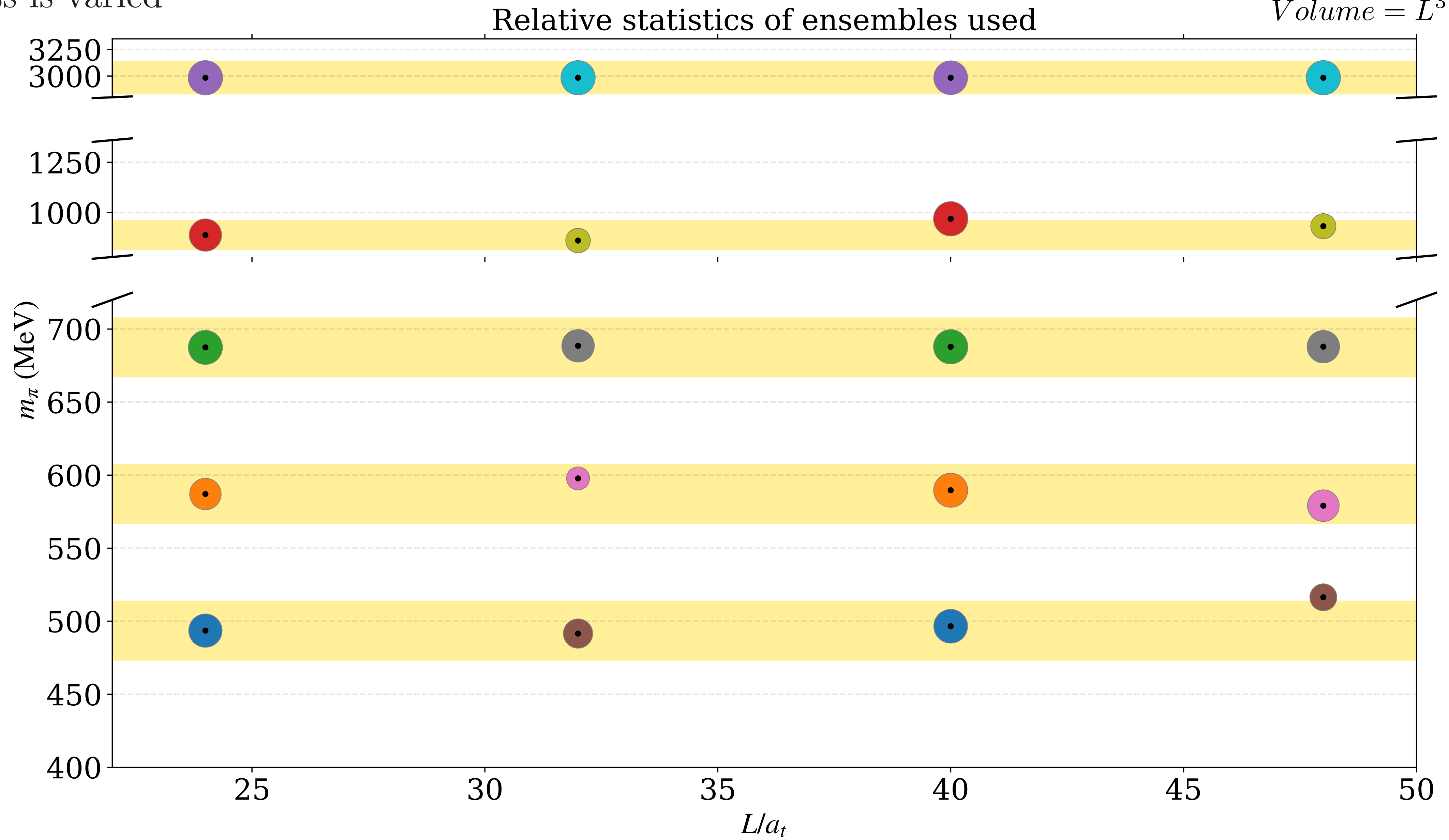
Conclusive evidence of bound state not reached

Need more such studies of $bc\bar{u}\bar{d}$

Lattice details

- MILC ensembles NF=2+1+1 HISQ action.
- valence quarks were implemented using an overlap action (u, d, s, c).
- the evolution of the bottom quark was studied within a non-relativistic QCD framework.
- b, c, s at the physical point and light quark mass is varied





Extraction of the energy spectrum

The time dependence of Euclidean two point correlation function gives the energy,

$$C(t) = \langle 0|\Omega_f(t)\Omega_i^\dagger(0)|0\rangle$$

Adding a complete set of states,

$$C(t) = \sum_n \underbrace{e^{-E_n t}}_{\text{time-evolution}} \underbrace{Z_n^f Z_n^i}_{\text{overlaps}} \qquad Z_\alpha^{i\dagger} = \langle 0|\Omega_i^\dagger|\alpha\rangle$$

at large times they are dominated by the ground state

Meson-meson type		Antidiquark-diquark type	
1	$(\bar{b}\gamma_5 q_1)(\bar{c}\gamma_i q_2)$	4	$([\bar{b}C\gamma_i\bar{c}][q_1 C\gamma_5 q_2])$
2	$(\bar{b}\gamma_i q_1)(\bar{c}\gamma_5 q_2)$	5	$([\bar{b}C\gamma_5\bar{c}][q_1 C\gamma_i q_2])$
3	$\epsilon_{ijk}(\bar{b}\gamma_j q_1)(\bar{c}\gamma_k q_2)$	6	$\epsilon_{ijk}([\bar{b}C\gamma_j\bar{c}][q_1 C\gamma_k q_2])$

$$\begin{bmatrix} C(t)_{00} & C(t)_{01} & \cdots \\ \vdots & \ddots & \\ C(t)_{N0} & & C(t)_{NN} \end{bmatrix} v_a = \lambda_a(t,t_0) \begin{bmatrix} C(t_0)_{00} & C(t_0)_{01} & \cdots \\ \vdots & \ddots & \\ C(t_0)_{N0} & & C(t_0)_{NN} \end{bmatrix} v_a$$

$$\lambda_\alpha(t,t_0) \sim e^{-E_\alpha(t-t_0)}$$

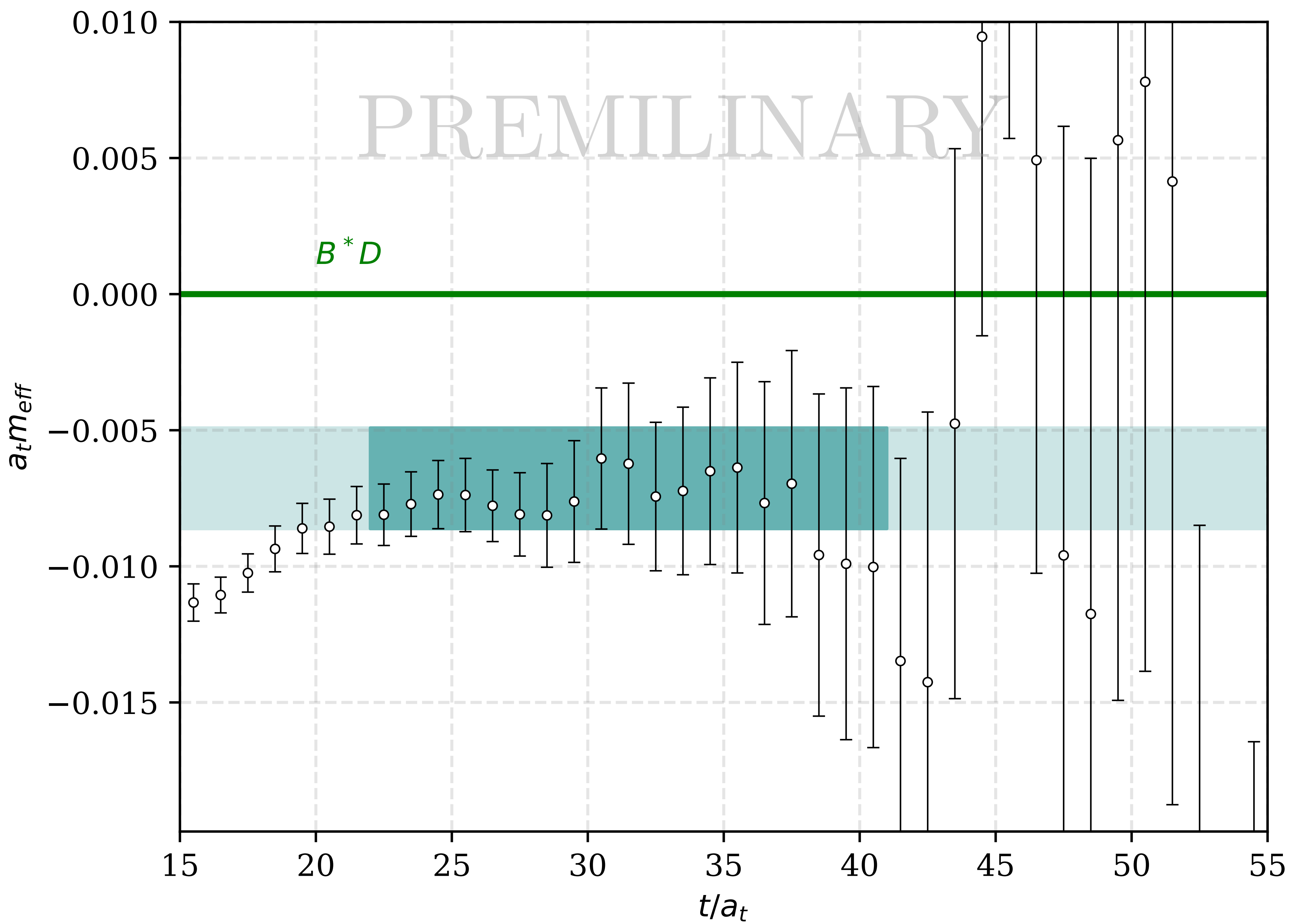
best linear combination of the basis to interpolate a specific state

$$\mapsto \Omega_{K\pi}^\alpha = \sum_i v_\alpha^i \mathcal{O}_i$$

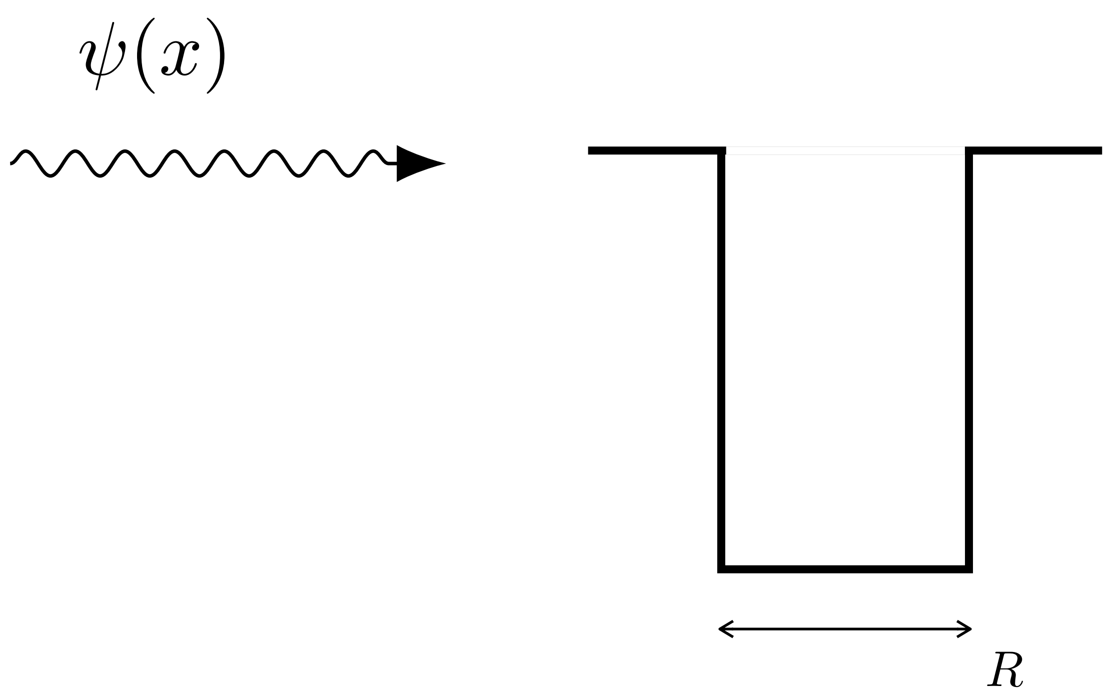
Optimized Operators

Extraction of the energy spectrum

$$a\delta m_{eff} = \ln \frac{C(t)}{C(t+1)} - \ln \frac{C_{thr.}(t)}{C_{thr.}(t+1)}$$



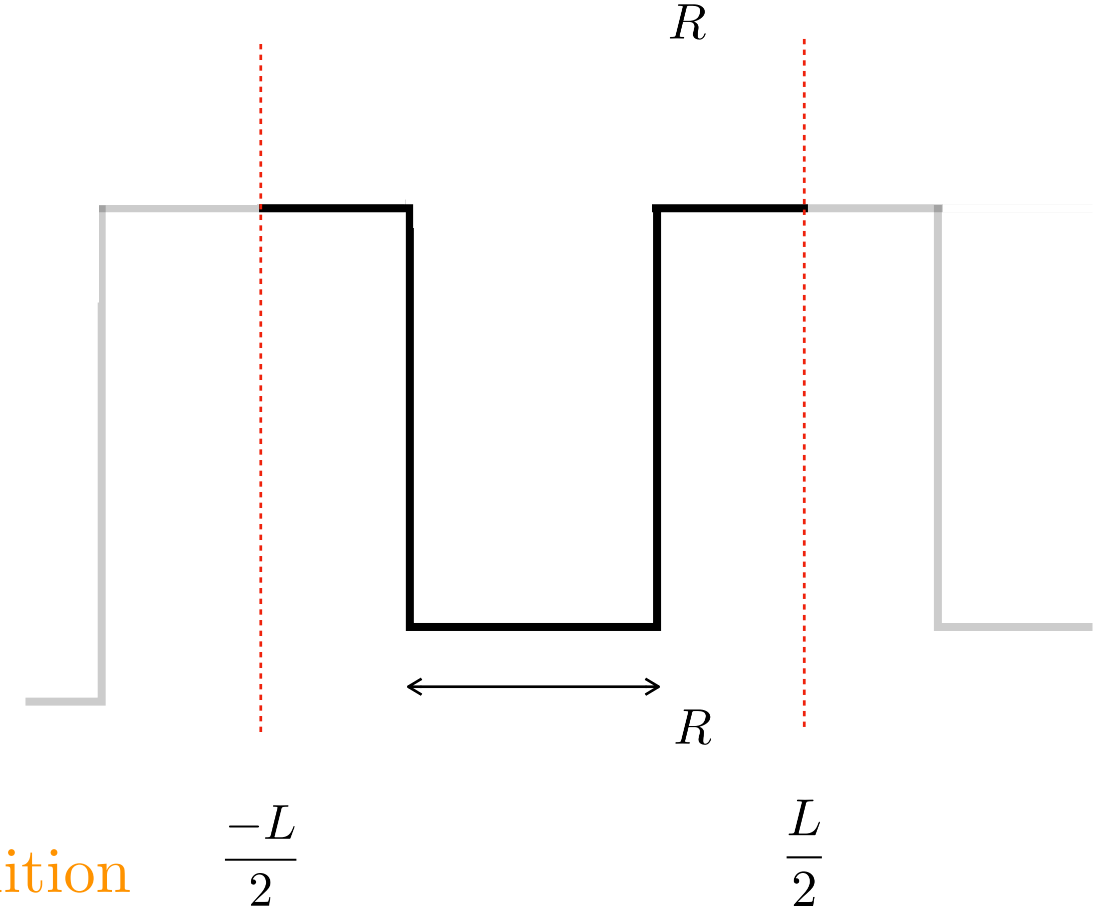
Finite volume "scattering"



Two particles in an infinite volume interacting through a finite potential

$$\psi(|x| > R) \sim \cos(k|x| + \delta(k))$$

phase shift



in finite volume with periodic boundary conditions

Constrains for the wave-function at the boundary

$$\psi(L/2) = \psi(-L/2)$$

$$\psi'(L/2) = \psi'(-L/2)$$

$$k = \frac{2n\pi}{L} - \frac{2\delta(k)}{L}$$

phase shift

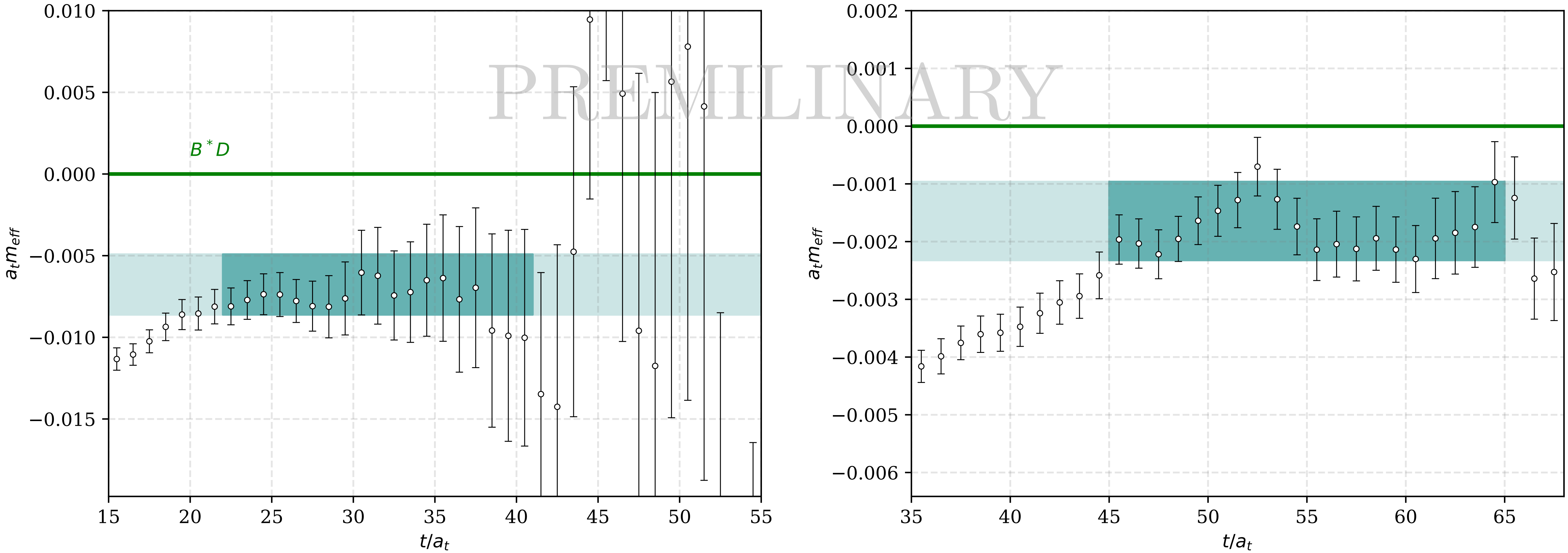
discrete momenta

Lüscher's condition

$$\det\left[F^{-1} + \mathcal{M}\right] = 0$$

$\bar{b}\bar{c}ud$ $0(1^+)$ tetraquarks from LQCD

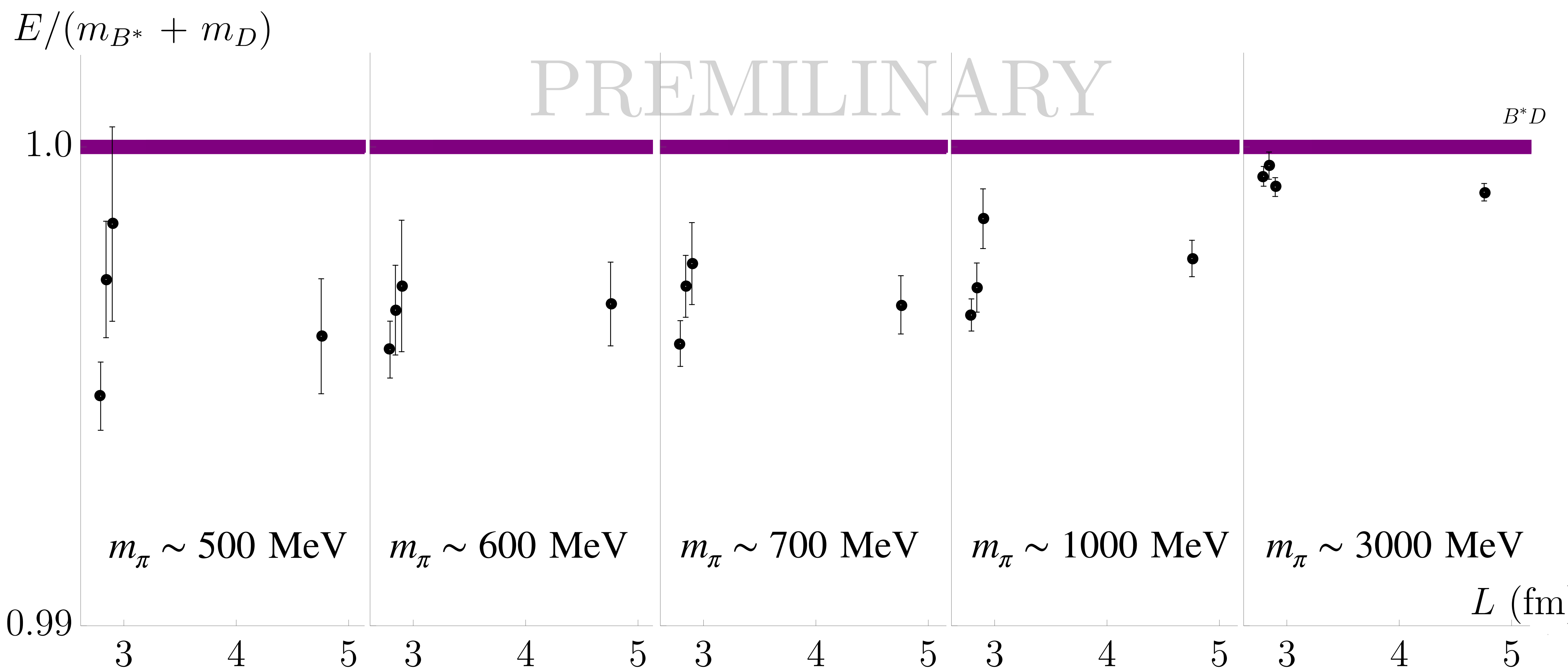
Example of the finite volume spectra extracted in this calculation for the finest lattice we use where the discretization effects are minimal



<u>Preliminary Finding:</u>

A finite volume state below threshold is seen (indicates an attractive interaction) - have to do a finite volume analysis to examine the scattering amplitude that can be compared with experiments

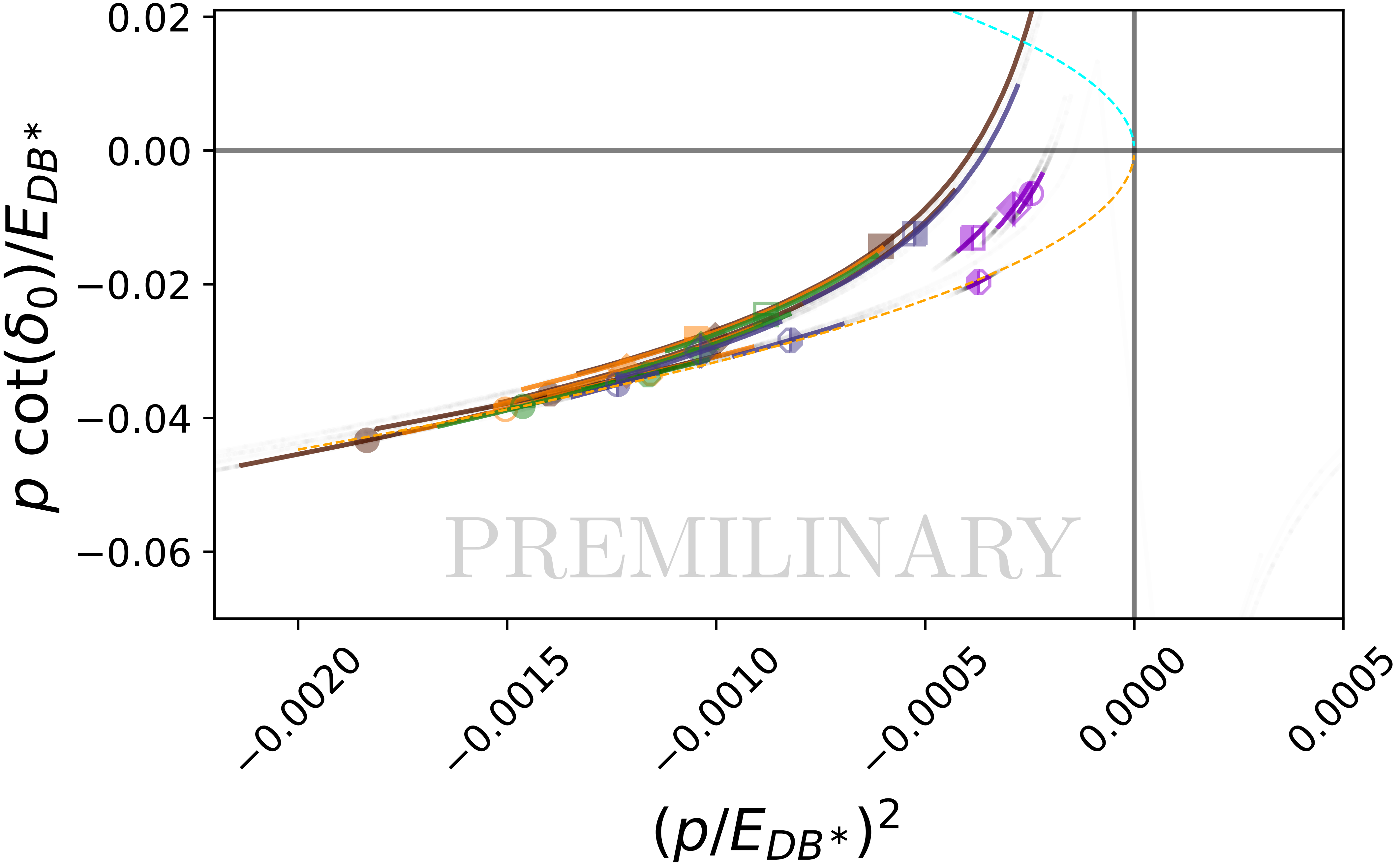
Finite Volume Spectra



A state **below threshold** is seen consistently for all volumes in the five different pion masses — indicates an attractive interaction

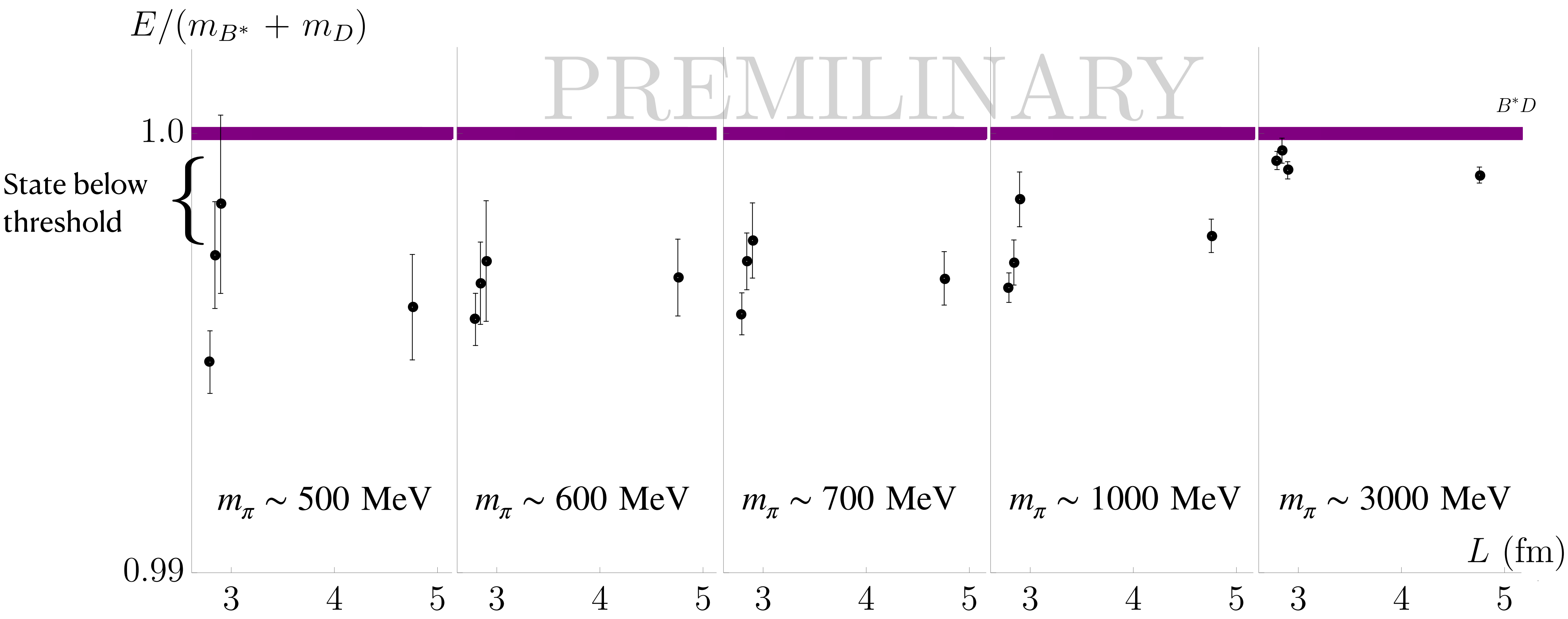
Extract the scattering amplitudes

Extracted phase shift



- Non-trivial quark mass dependence and lattice spacing dependence is see that needs to investigated further.
- Currently extracting the scattering amplitudes to find poles.

Summary



- Doubly-heavy tetraquarks are promising candidates for long lived exotic states in QCD.
- Lattice QCD can play an important role in these searches by predicting their masses.
- The T_{CC}^+ which was discovered in 2021 - is a good example of such searches.
- Our preliminary findings suggest the possibility of an attractive interaction between a $B*$ and D meson.
- Hope this will motivate experimental searches in the future!