Axial-vector and scalar bottom-charm tetraquarks from Lattice QCD

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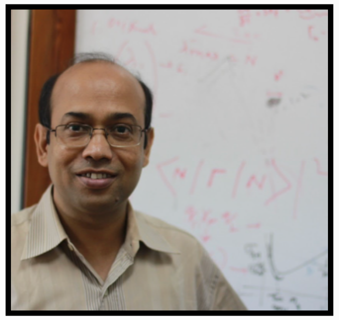
Lattice Conference-2024, Liverpool

In collaboration with



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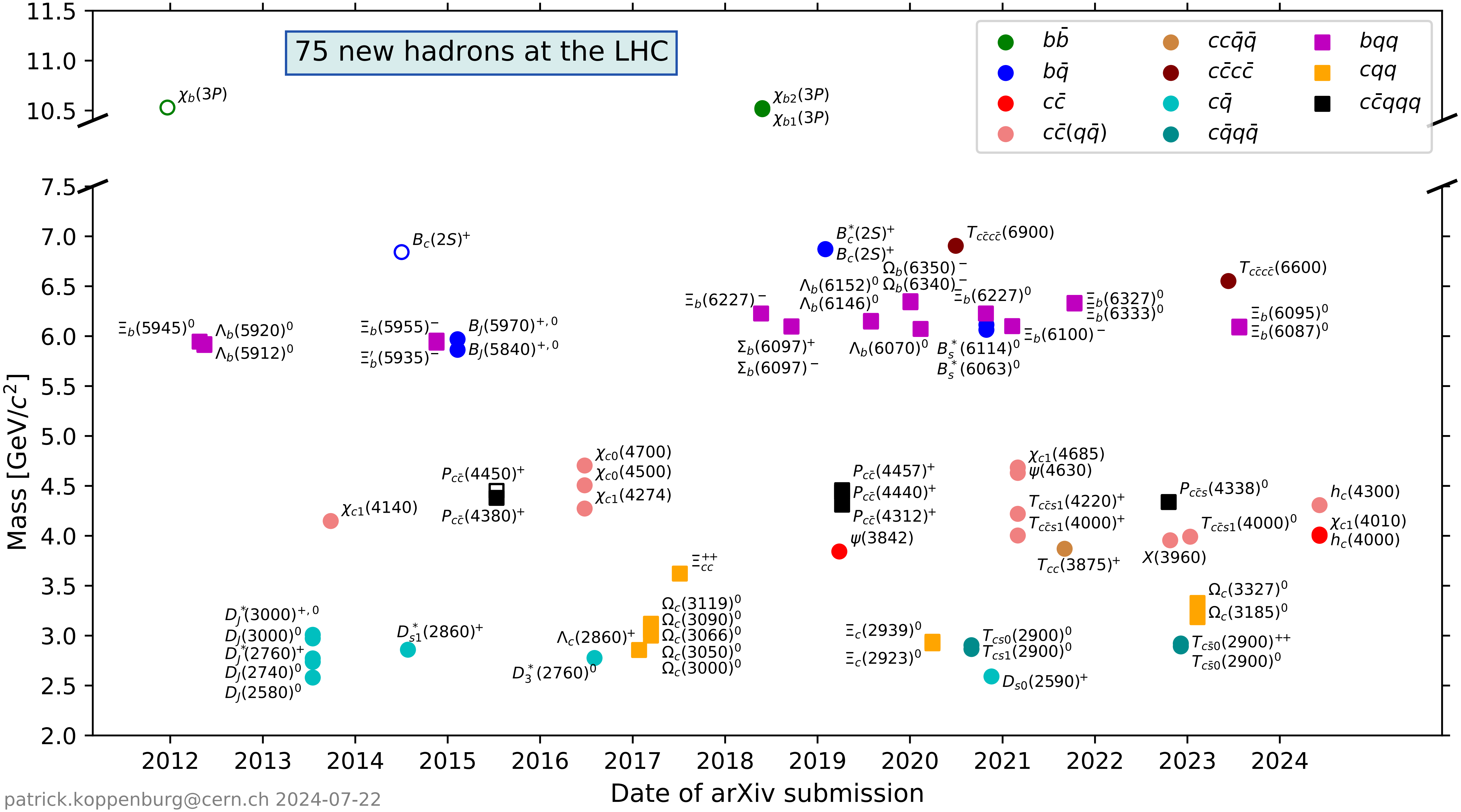
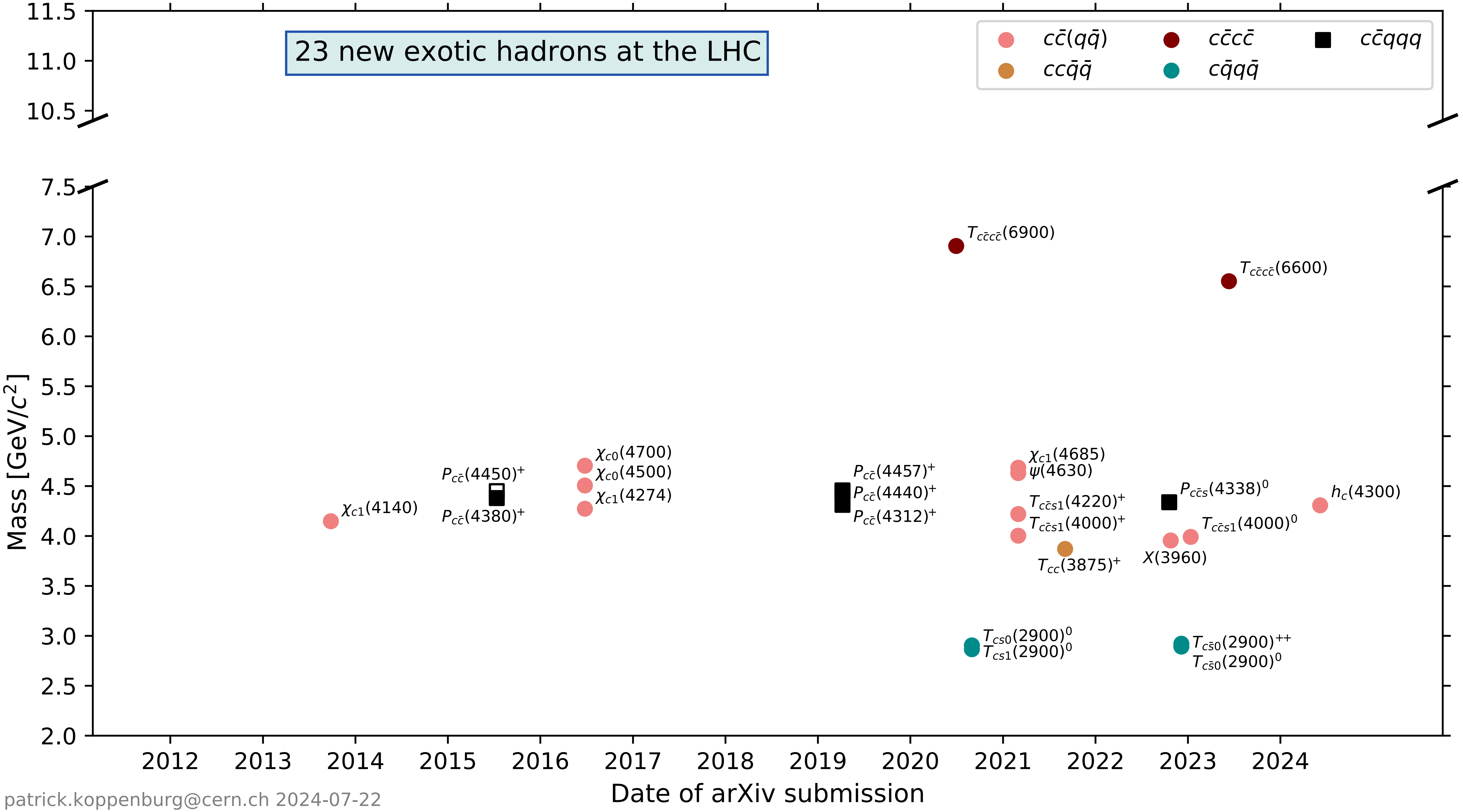
Experimental Status

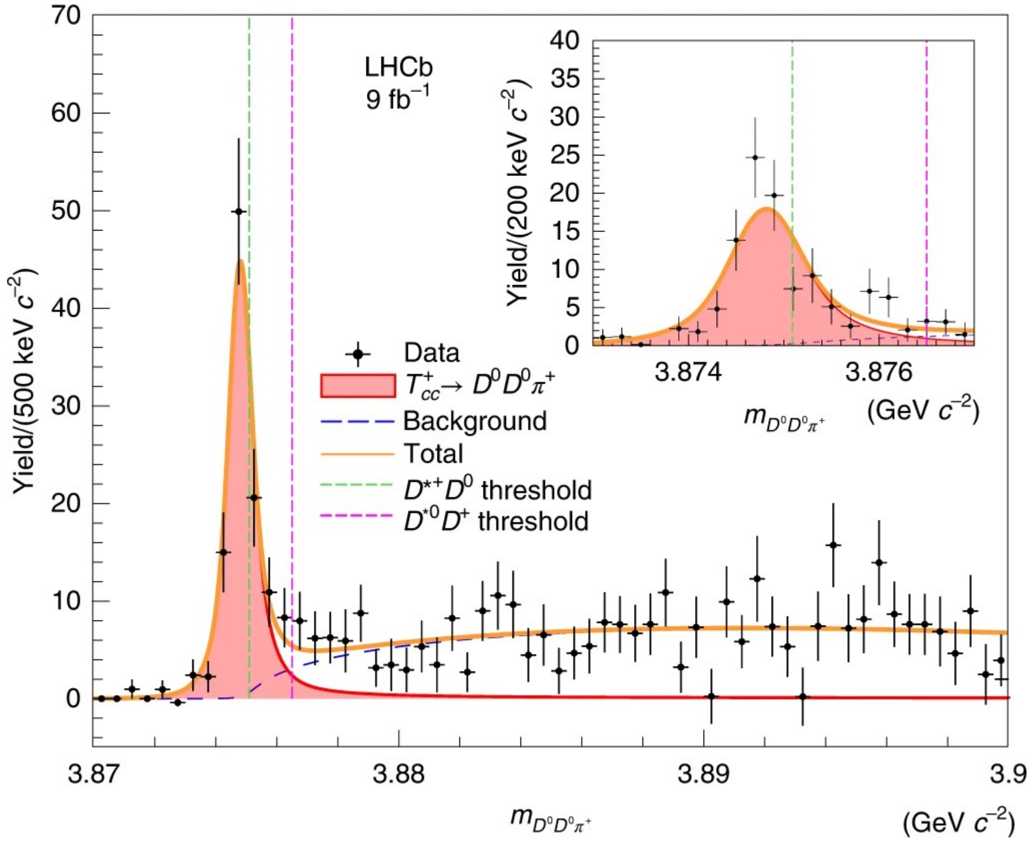


Experimental Status



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

Nat. Phys. **18**, 751–754 (2022)

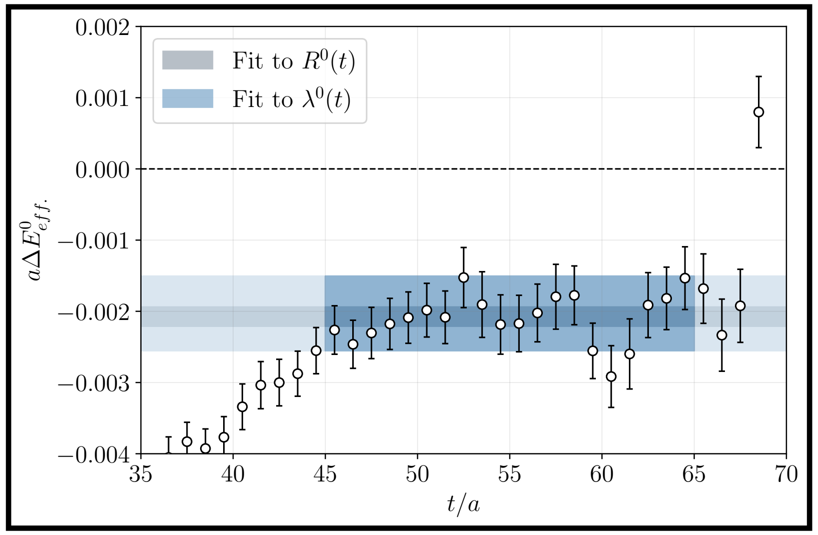


- Doubly-heavy channels are promising places to look for long-lived exotic tetraquarks
- $cc\bar{d}\bar{u}$ observed in 2021 by LHCb

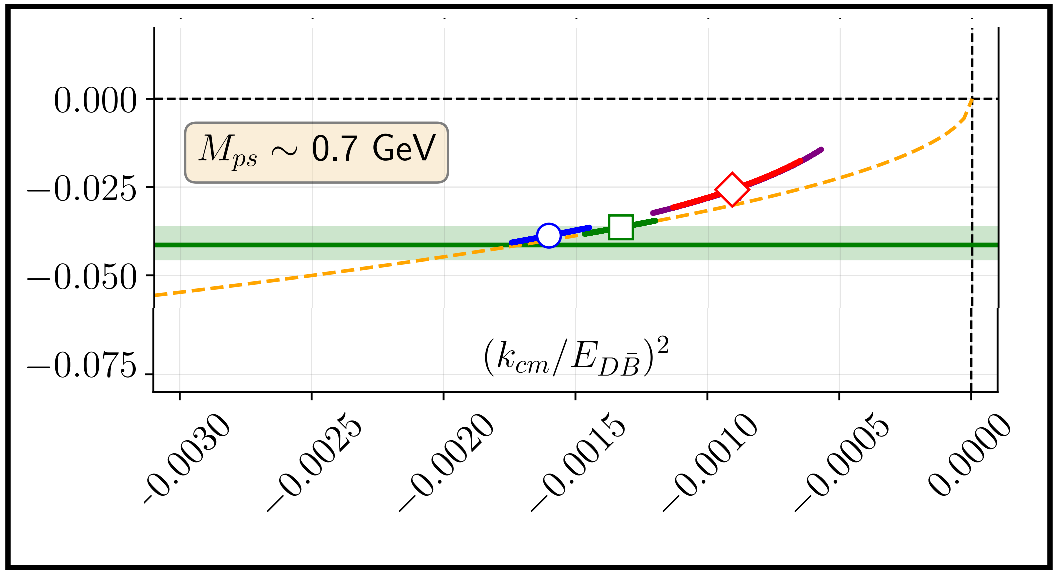
- Where should experiments look to find more such states?
- What does theory tell us?

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

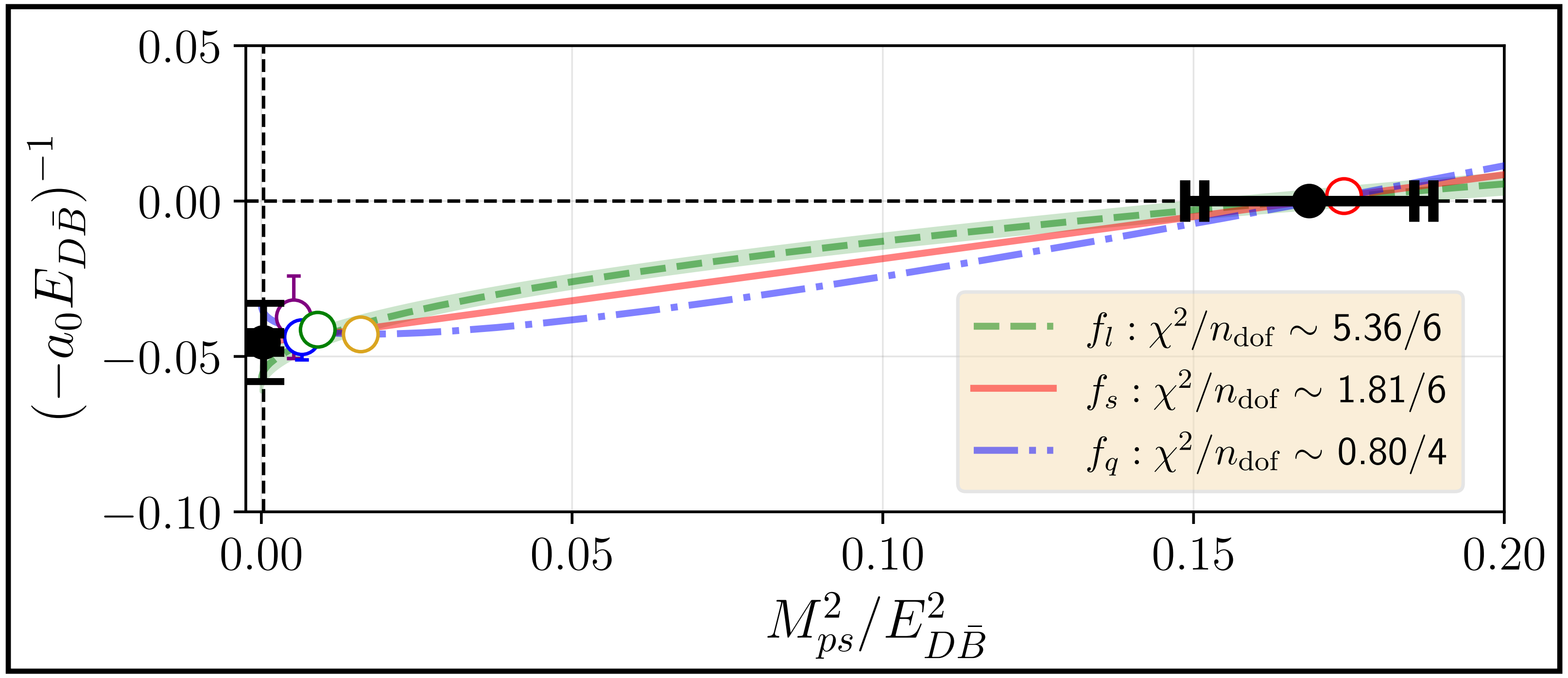
Lattice Methodology



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

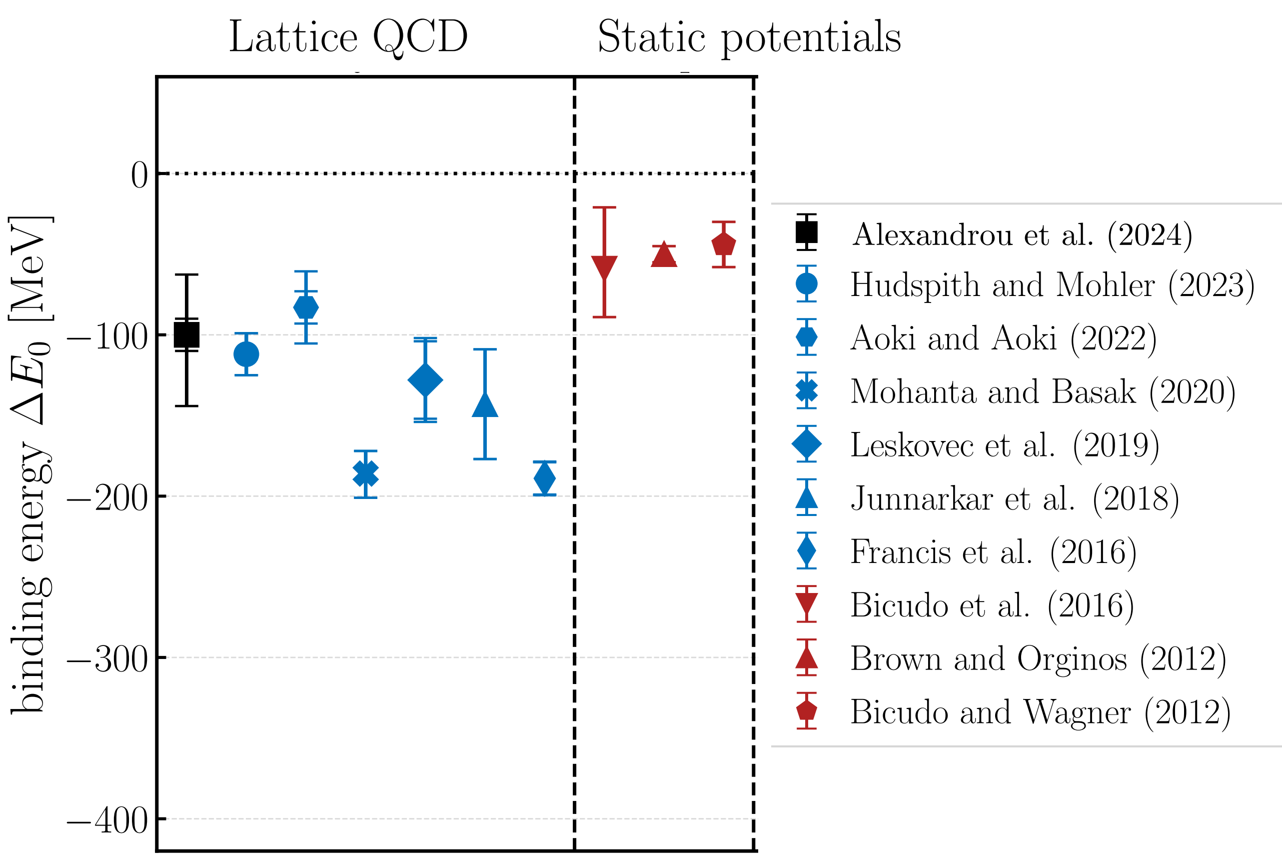


Continuum and chiral extrapolation to get the binding energies

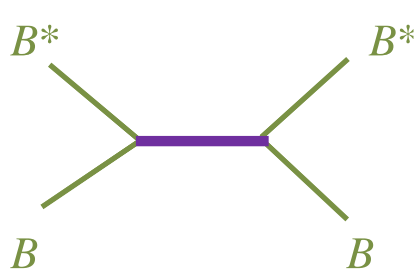
Motivation from T_{bb} and T_{cc}

States well below threshold

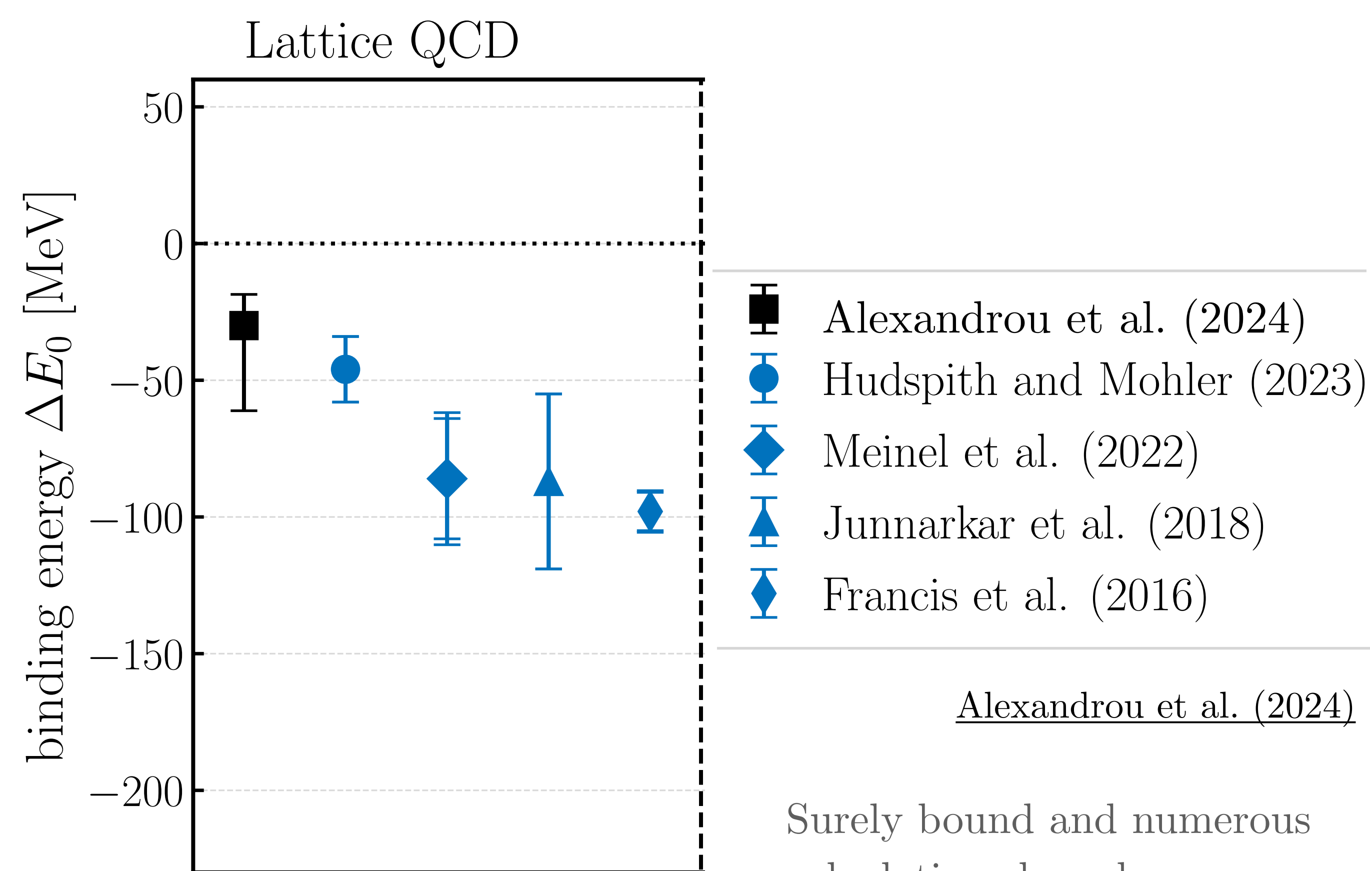
$bb\bar{u}\bar{d}$ $0(1^+)$



Alexandrou et al. (2024)



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



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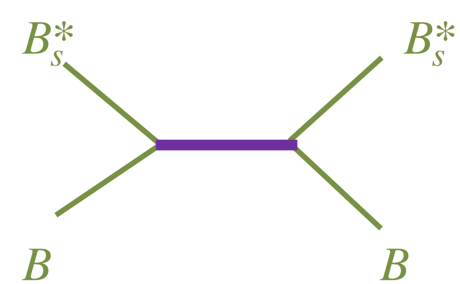


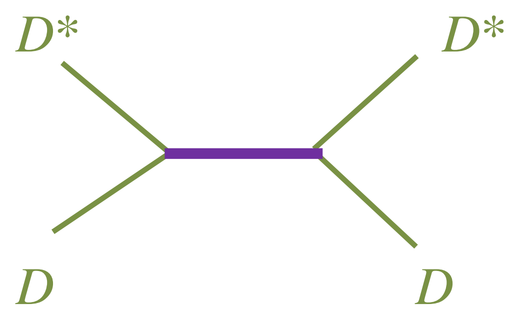
Surely bound and numerous calculations have been performed using LQCD - assuming not substantial finite volume effects **- a reliable claim for deeply bound states with heavy quarks**

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

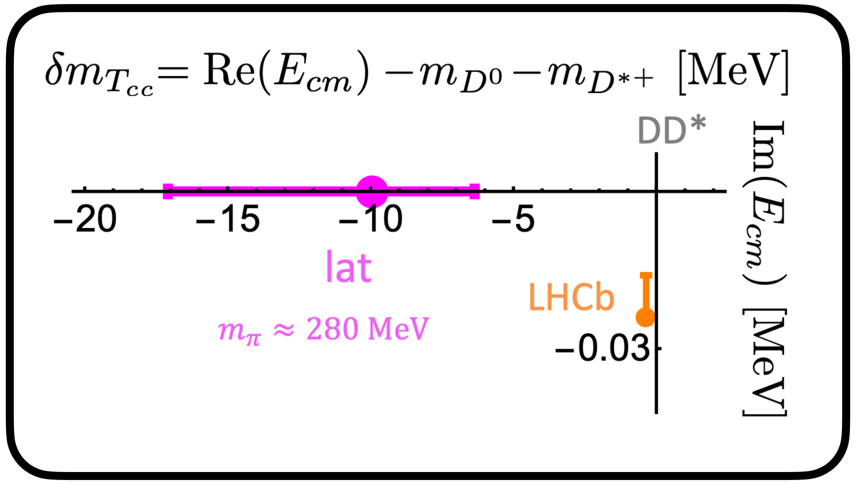
Motivation from T_{bb} and T_{cc}

States near threshold

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



Need to find the poles in the scattering amplitude to extract (virtual) bound poles:

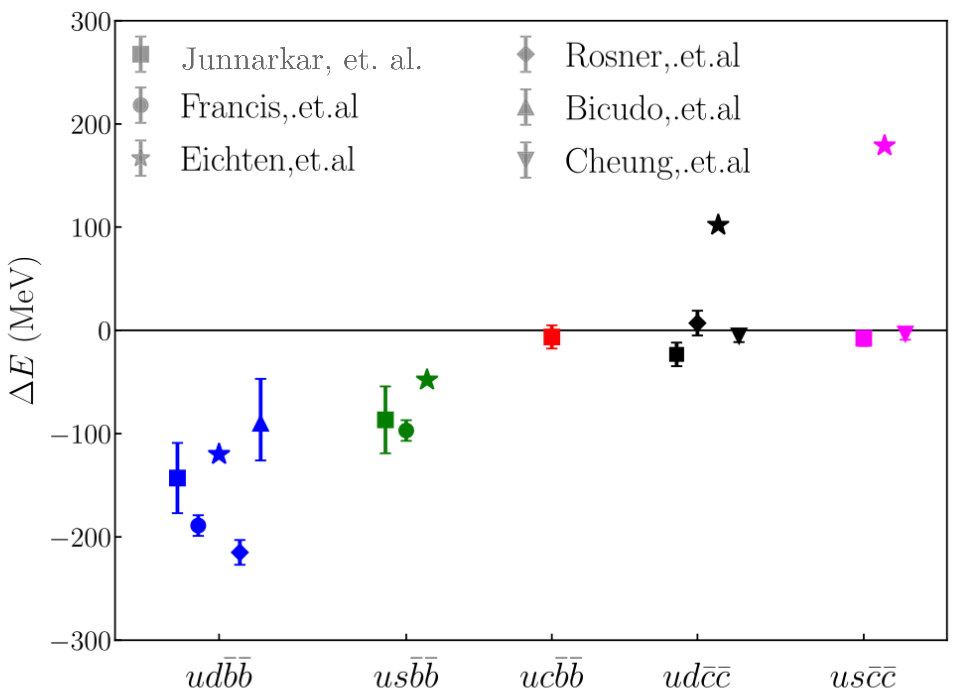


Padmanath et al. PRL. 129 (2022)

Lattice had seen indications of a bound state

- later discovered by LHCb!

Junnarkar et al. (2019)



Other recent lattice studies confirm the presence the bound state

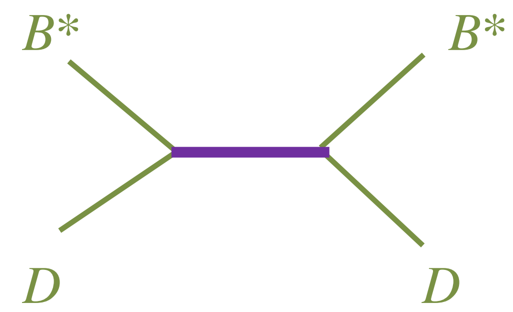
Paper	Results
Padmanath et al. [PRL 129,032002 (2022)]	$-9.9^{+3.6}_{-7.1}$ MeV
Chen et al. [PLB 833,137391 (2022)]	$I = 0, 1$ (attractive,repulsive) no info about the pole
Lyu et al. [PRL 131,161901 (2023)]	$-45\ (^{+41}_{-78})$ keV
Collins et al. [arXiv:2402.14715 (2024)]	quark mass dependence checked
Whyte et al. [arXiv:2405.15741 (2024)]	-62 ± 31 MeV

Exploring tetraquarks with bottom and charm may be accessible to experiments

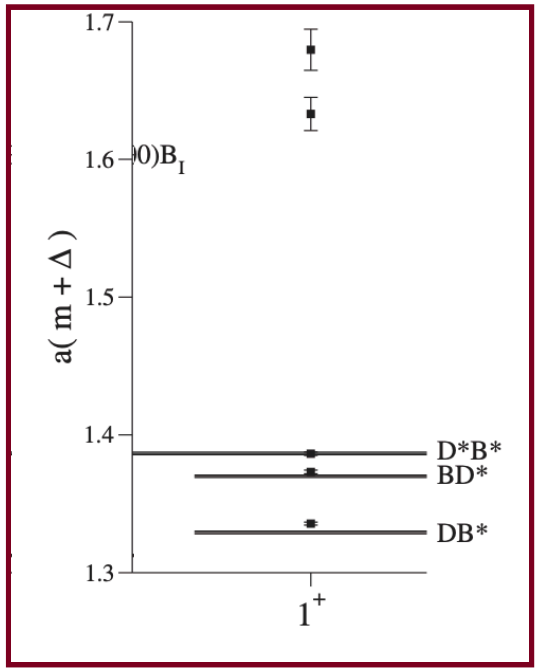
Motivates the study of $bc\bar{u}\bar{d}$

but significant volume effects possible - close to threshold

States near threshold



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



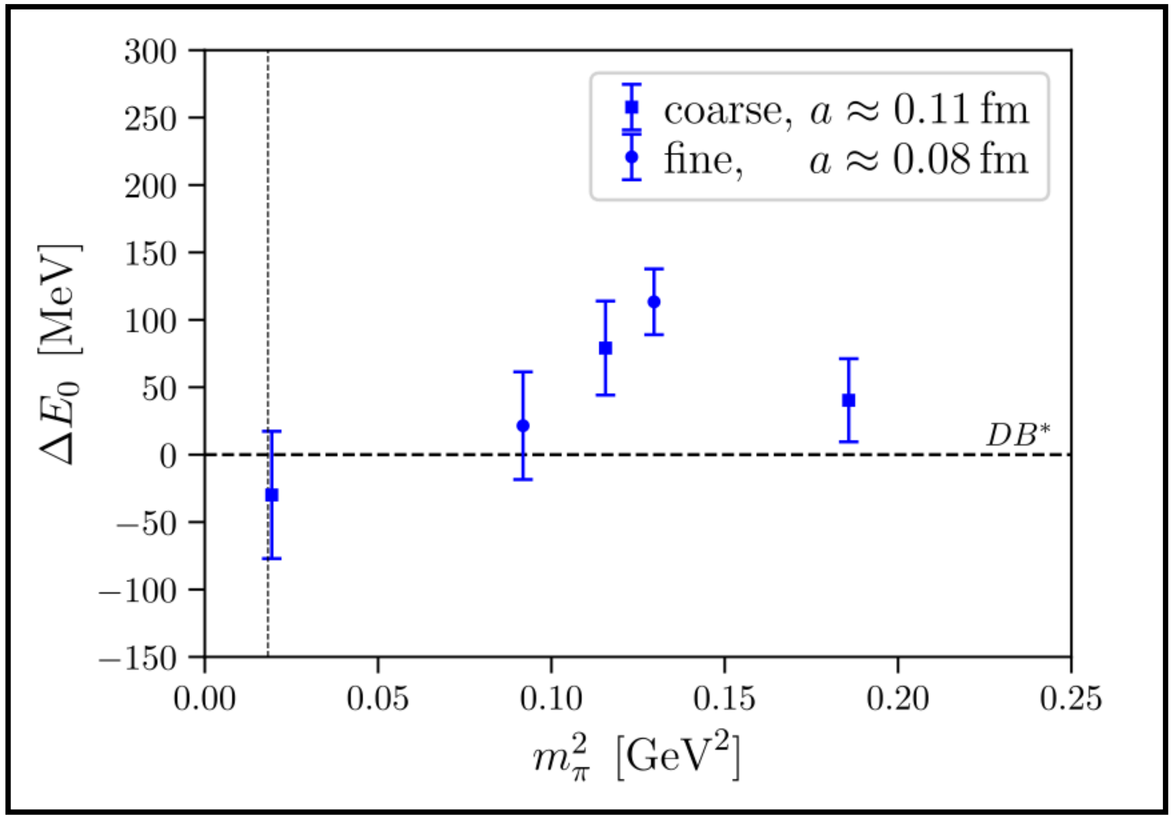
Hudspith et al. Phys. Rev. D 102, 114506

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!

Meinel et al. Phys. Rev. D 106, 034507

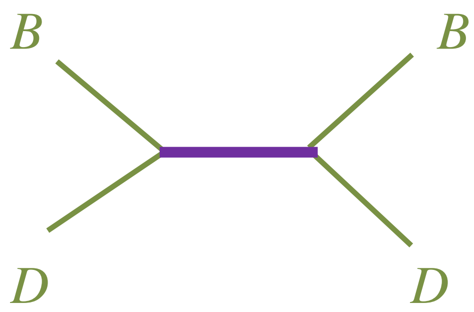
No conclusive evidence of bound states



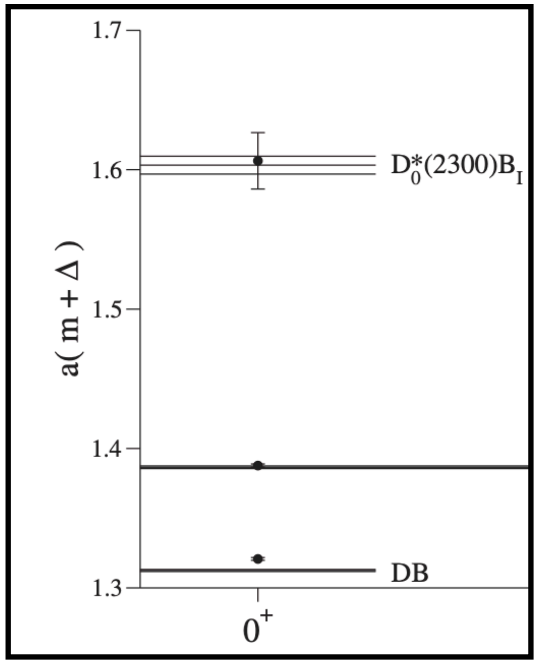
Need more such studies of $bc\bar{u}\bar{d}$

What does LQCD tell us?

States near threshold



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



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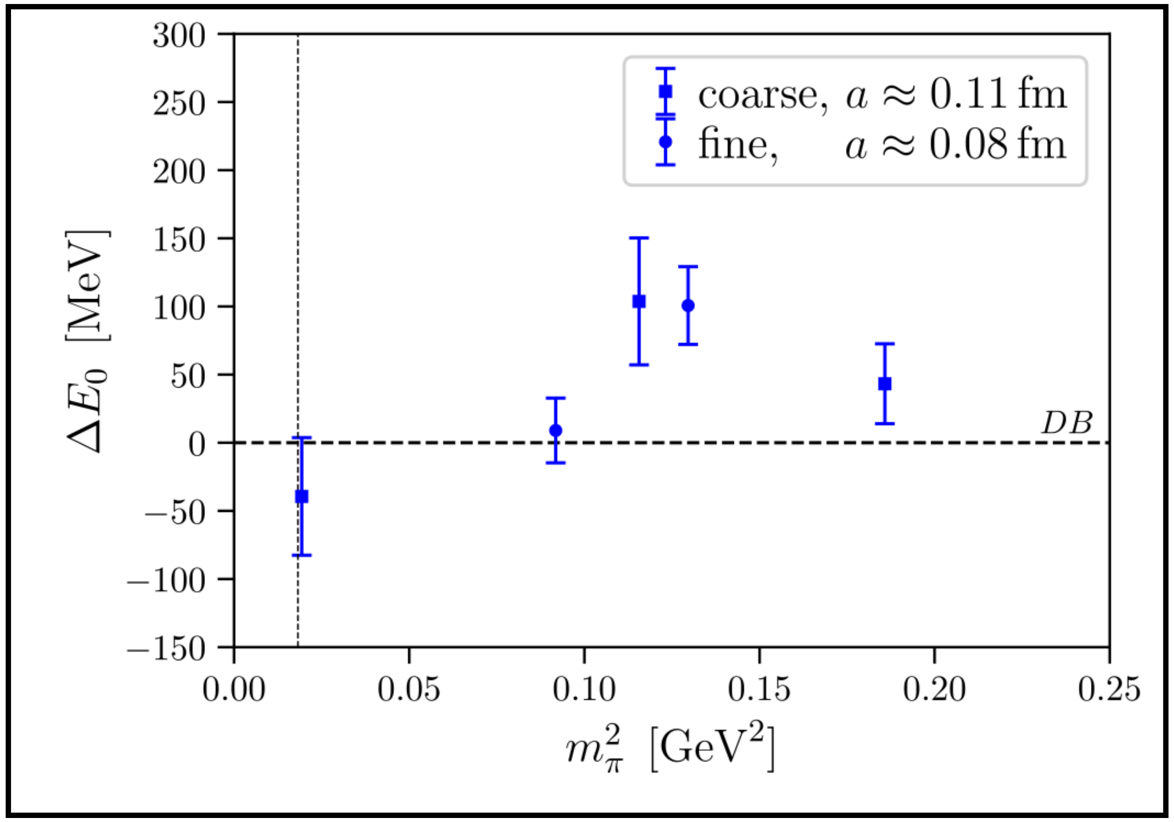
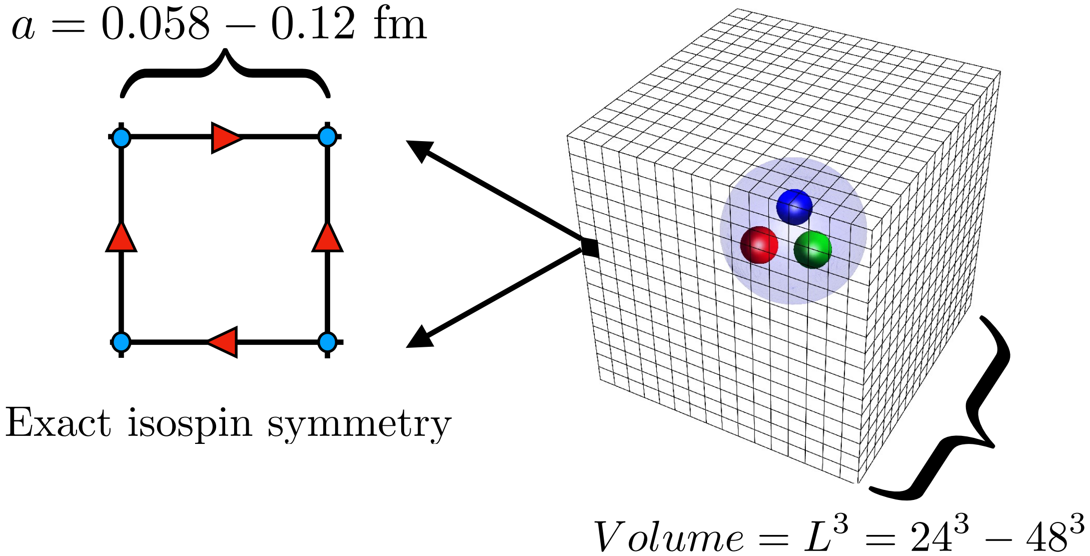


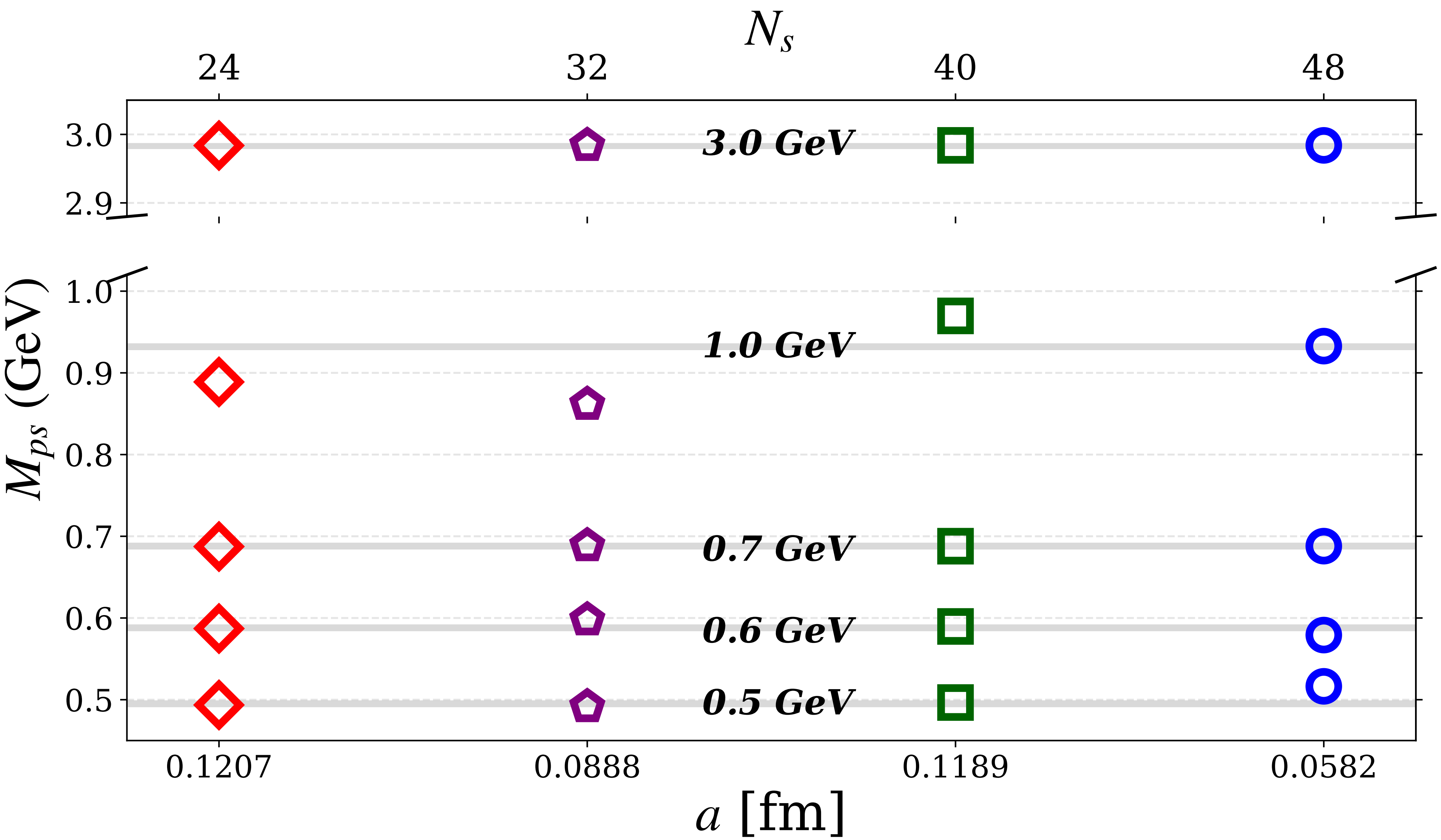
No conclusive evidence of bound states

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,

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

time-evolution

overlaps

at large times they are dominated by the ground state

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

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

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

best linear combination of the basis to interpolate a specific state

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

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

Optimized Operators

Extraction of the energy spectrum

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Adding a complete set of states,

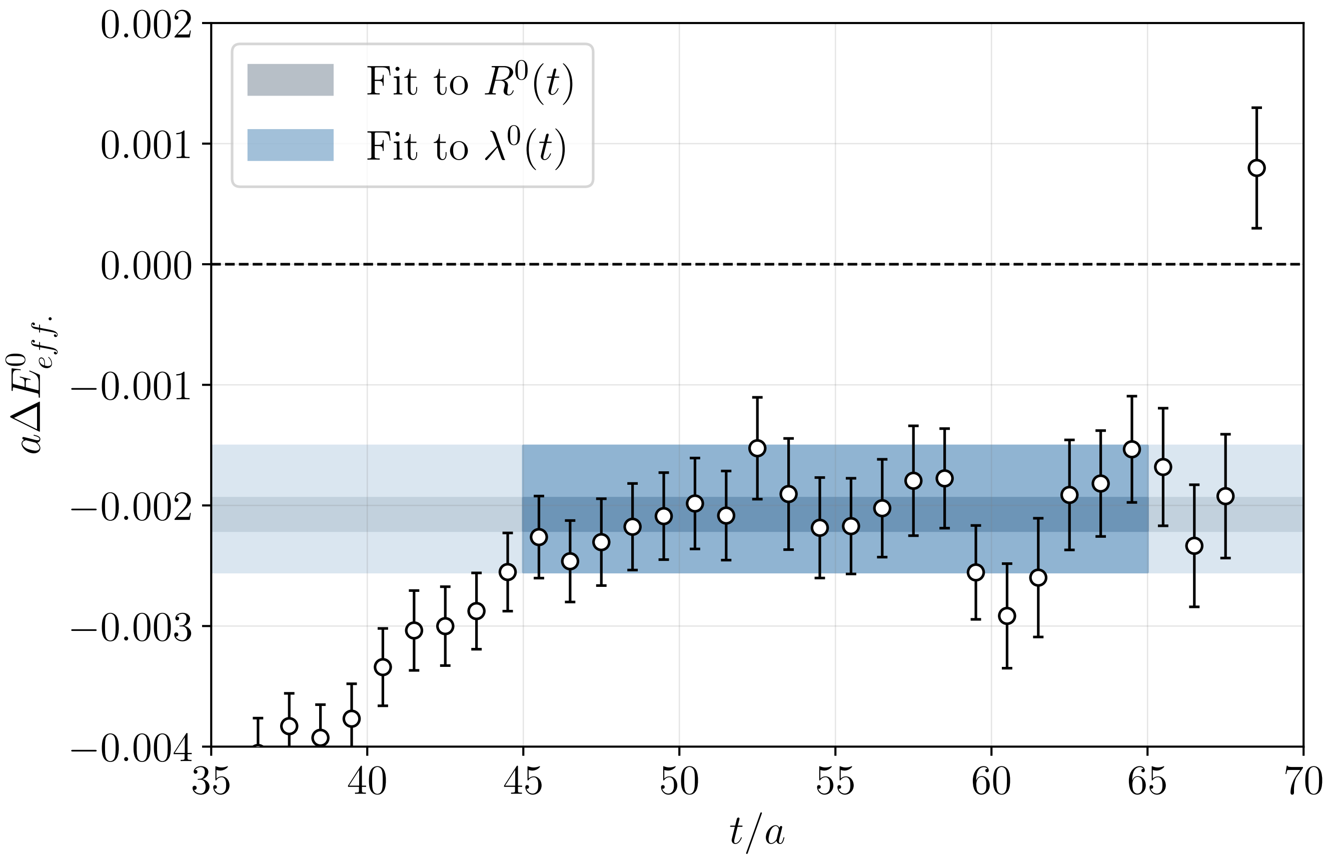
$$C(t) = \sum_n e^{-E_n t} Z_n^f Z_n^i \qquad Z_\alpha^{i\dagger} = \langle 0|\Omega_i^\dagger|\alpha\rangle$$

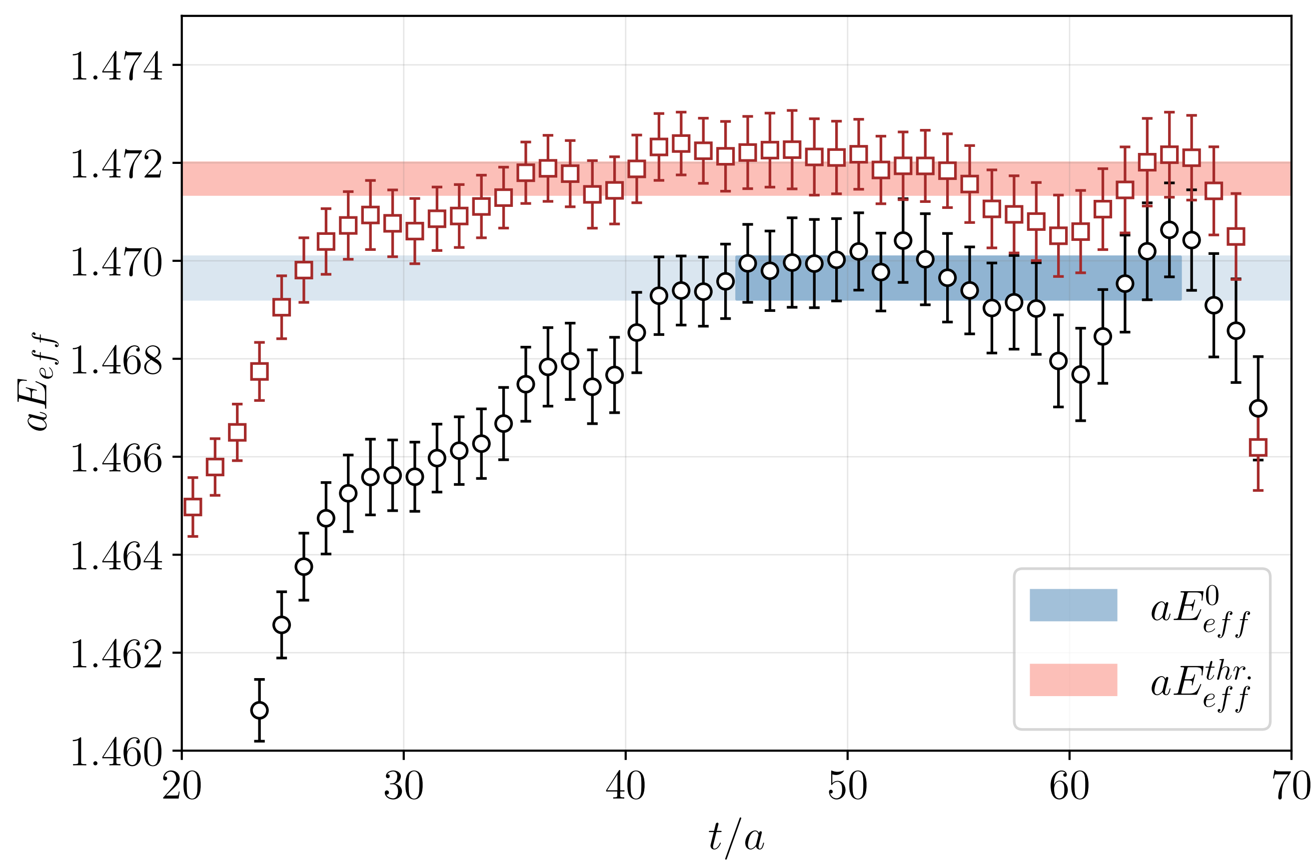
time-evolution

overlaps

at large times they are dominated by the ground state

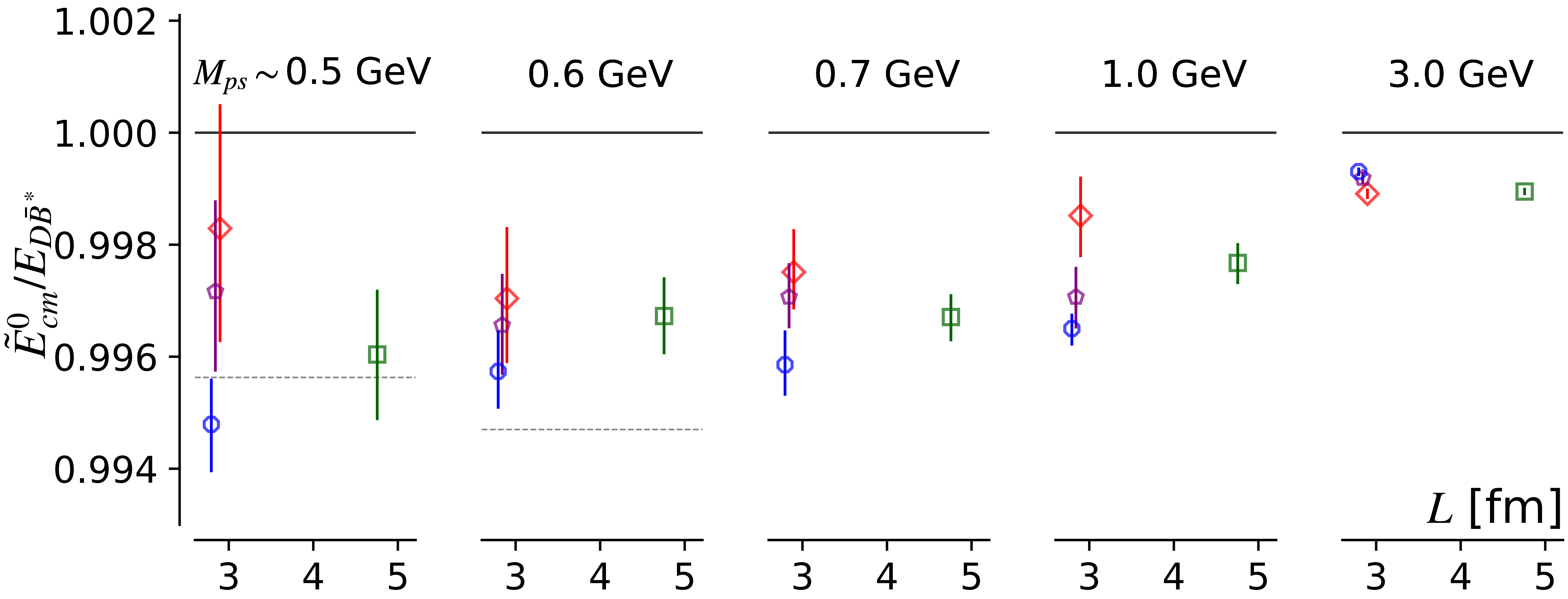
$$m_{eff} = \ln \frac{C(t)}{C(t+1)}$$





Finite Volume Spectra - $\bar{b}\bar{c}ud$ $0(1^+)$

M. Padmanath, AR, Nilmani Mathur [PRL.132.201902]



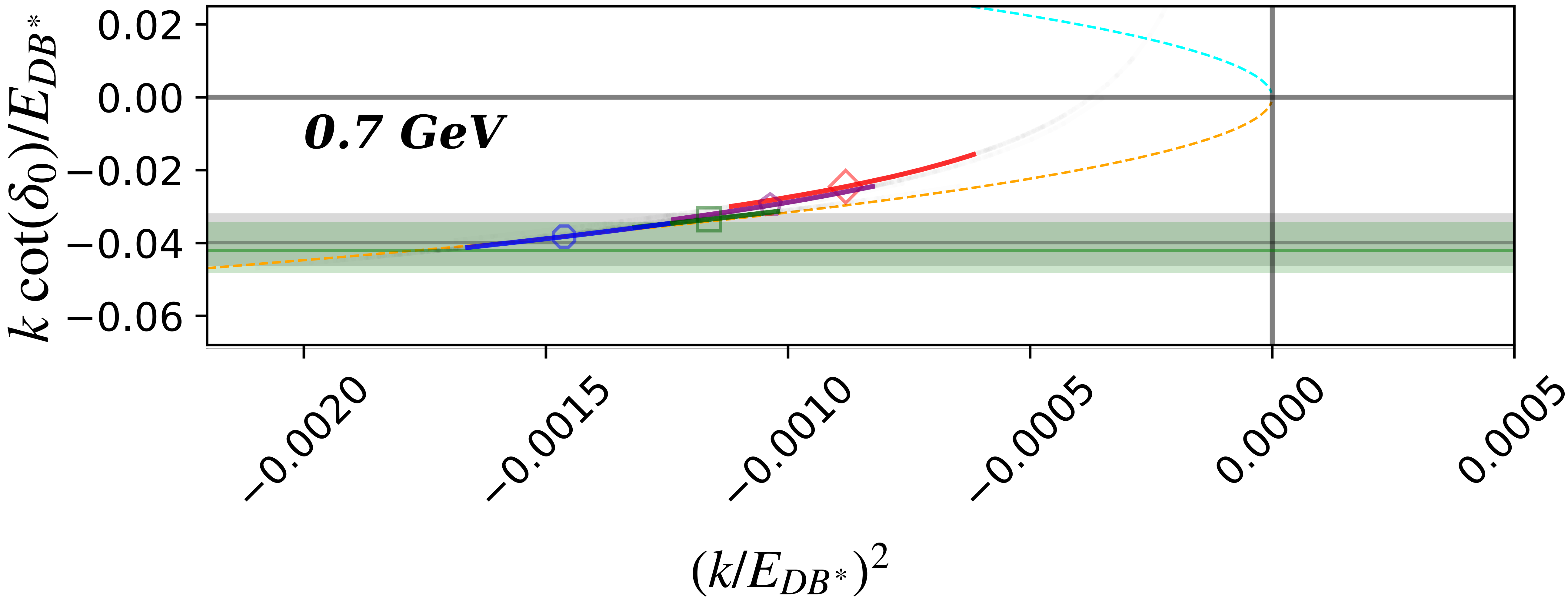
A state **below threshold** is seen consistently for all volumes in the five different pion masses — indicates an attractive interaction

Extract the scattering amplitudes

Extracted infinite volume amplitude with Lüscher- $\bar{b}\bar{c}ud$ $0(1^+)$

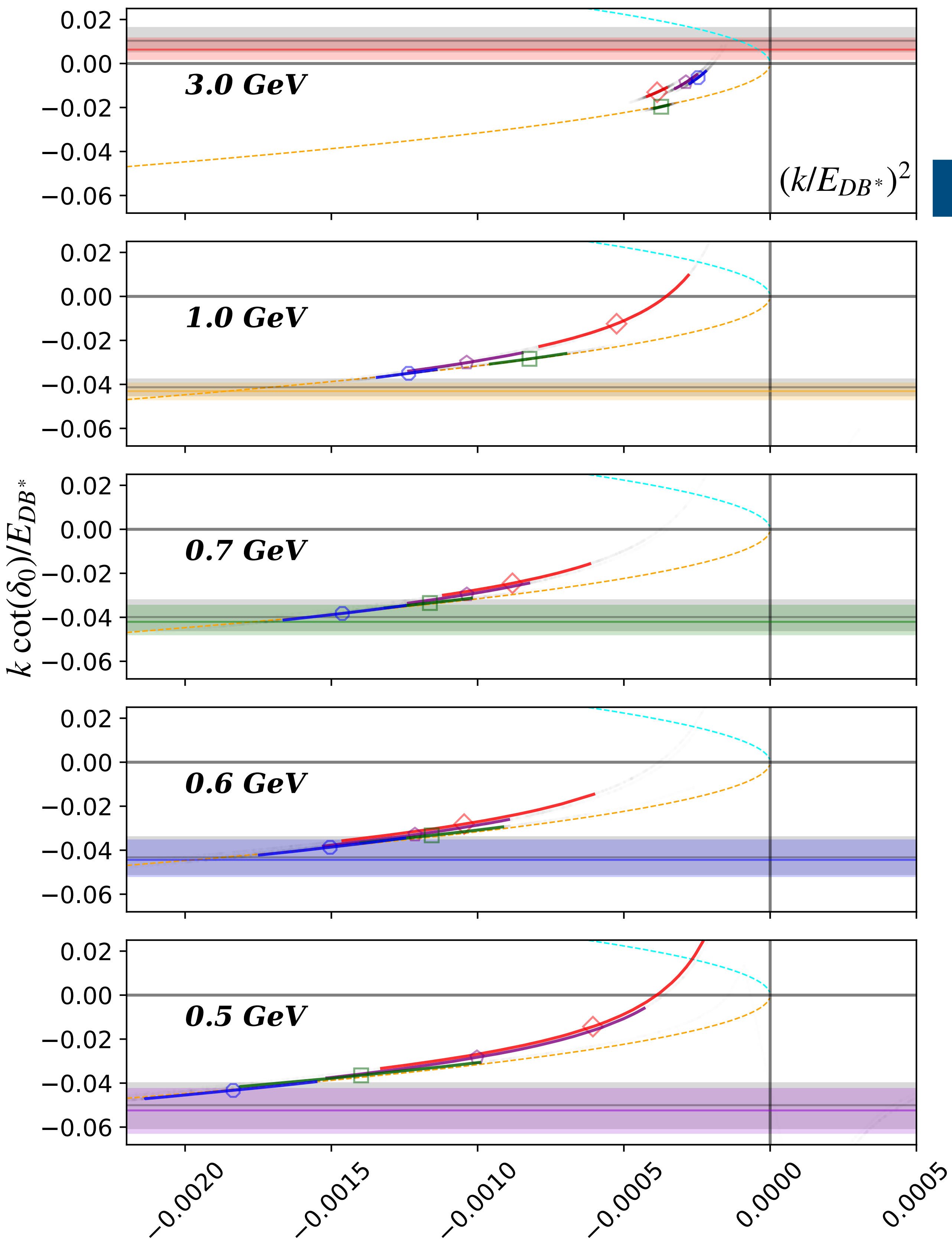
M. Padmanath, AR, Nilmani Mathur [PRL.132.201902]

Amplitude: $k\cot\delta_0 \sim -1/a_0$



- Non-trivial quark mass dependence and lattice spacing dependence is seen.
- Perform a continuum extrapolation and chiral extrapolation to get the physical amplitudes - then find poles in the amplitude to look for bound states or resonances.

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



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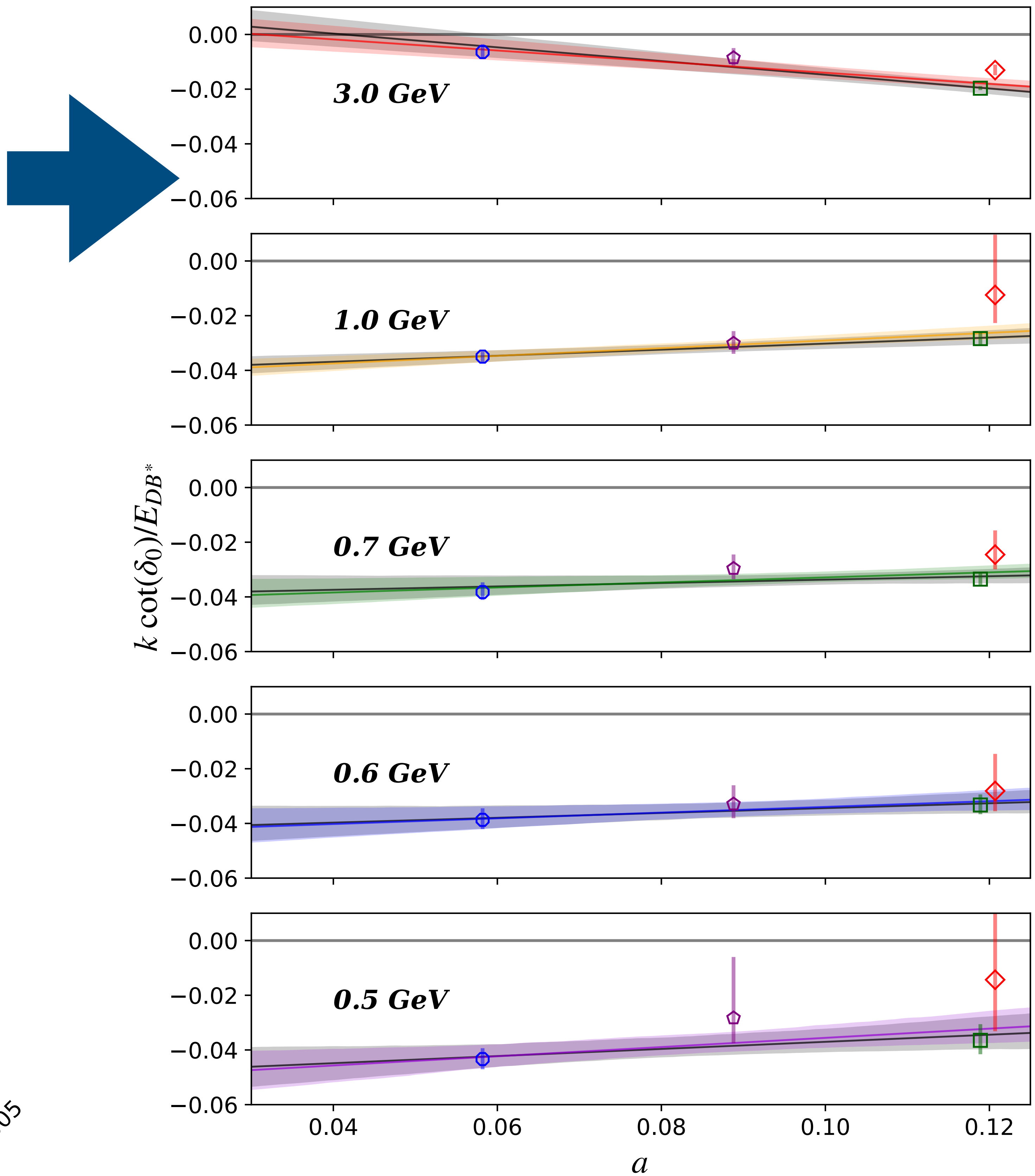

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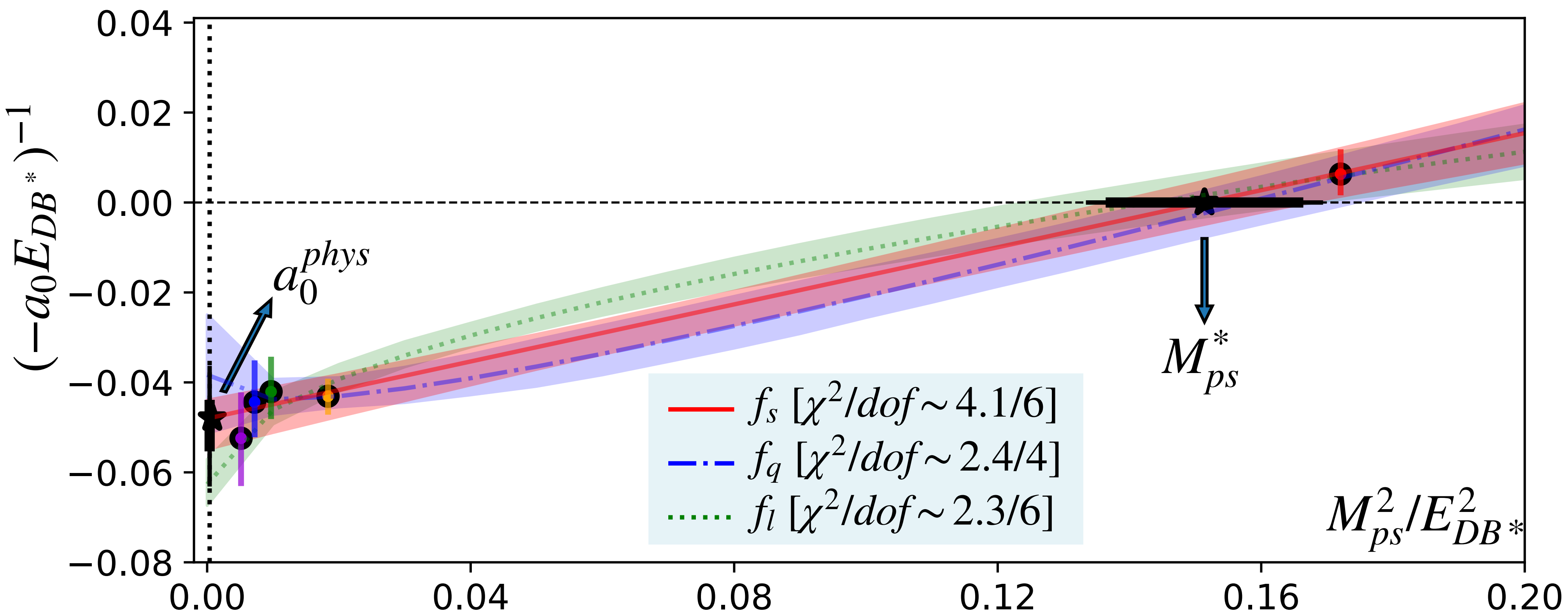


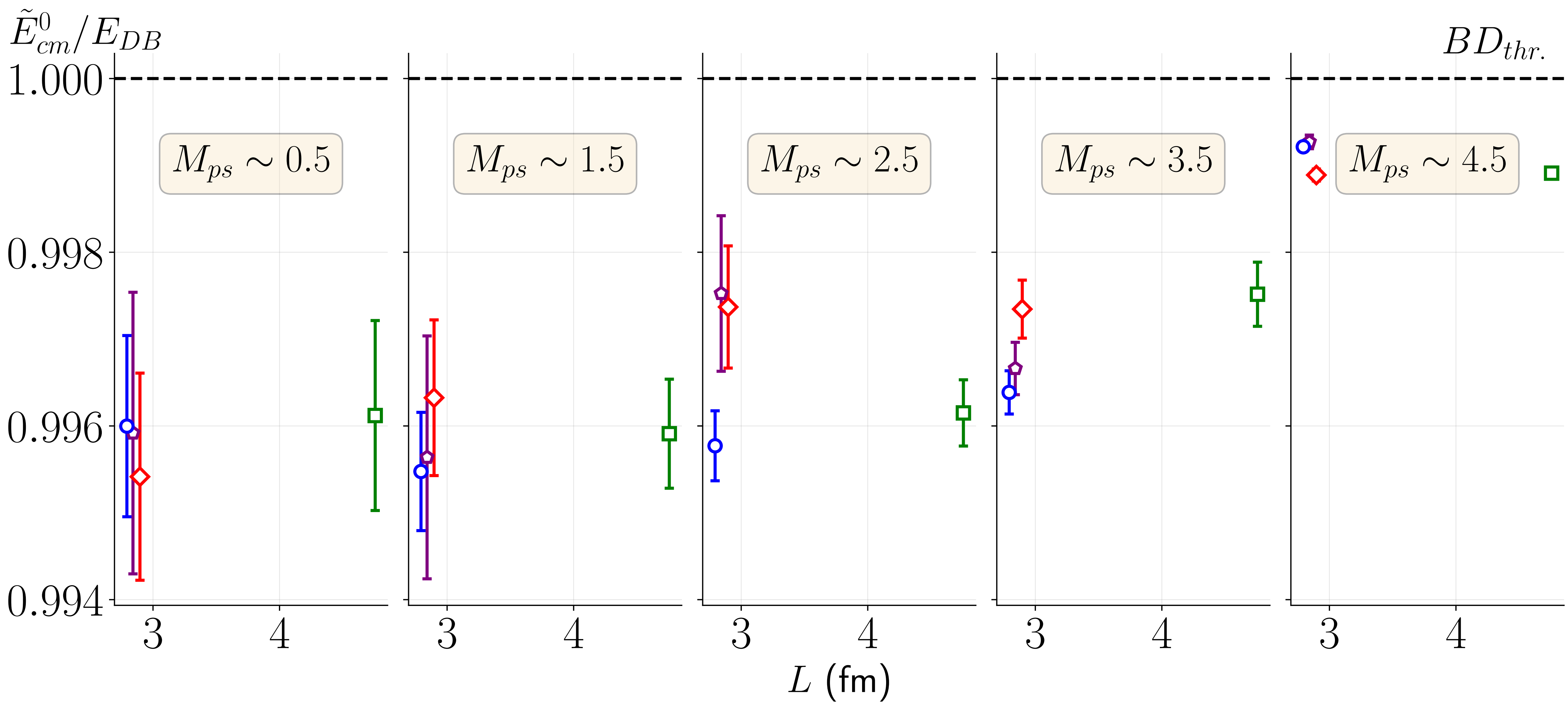
- The binding energy decreases with the increasing light quark mass.
- Indicates the **presence of a real bound state** at physical quark mass.

$a_o = 57(^{+4}_{-5})(17)$ fm

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

Finite Volume Spectra - $\bar{b}\bar{c}ud$ $0(0^+)$

AR, M. Padmanath, Nilmani Mathur [arXiv:2307.14128]



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

Extract the scattering amplitudes

$\bar{b}\bar{c}ud$ $0(0^+)$

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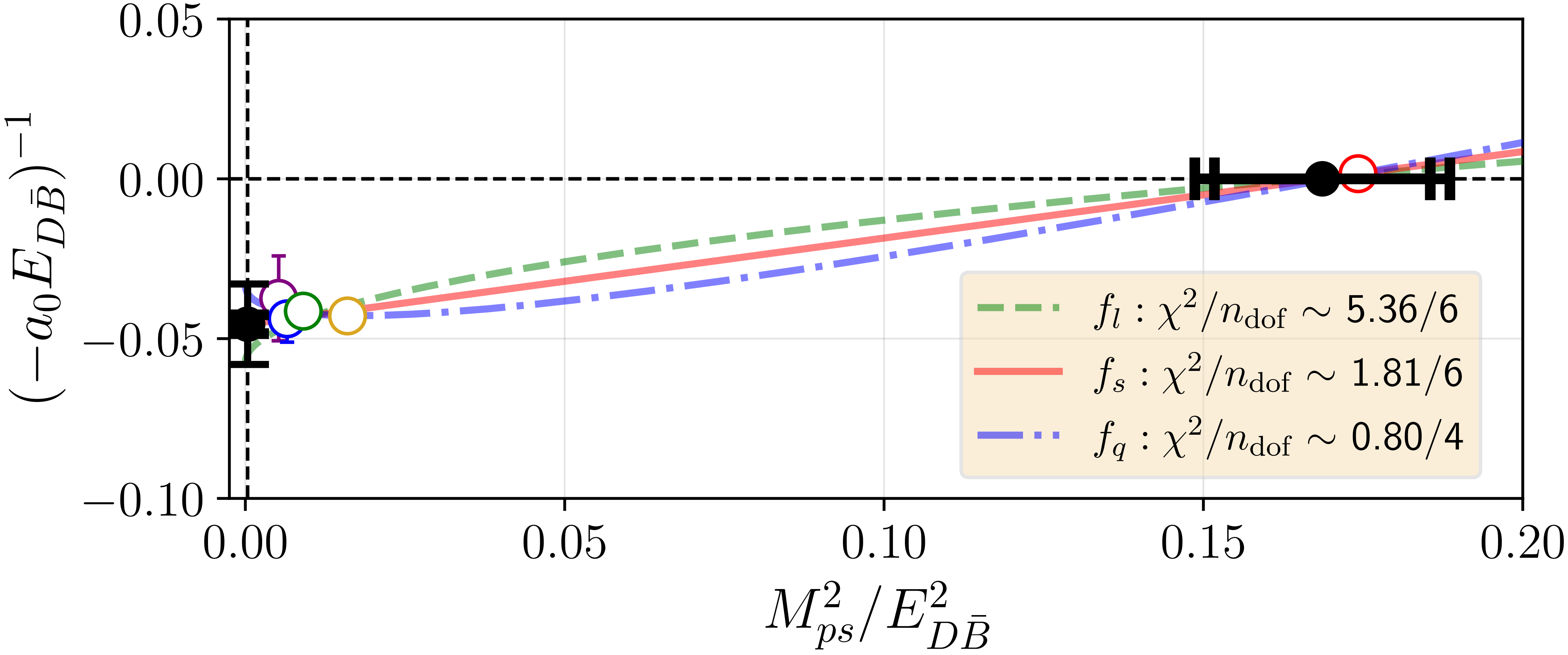


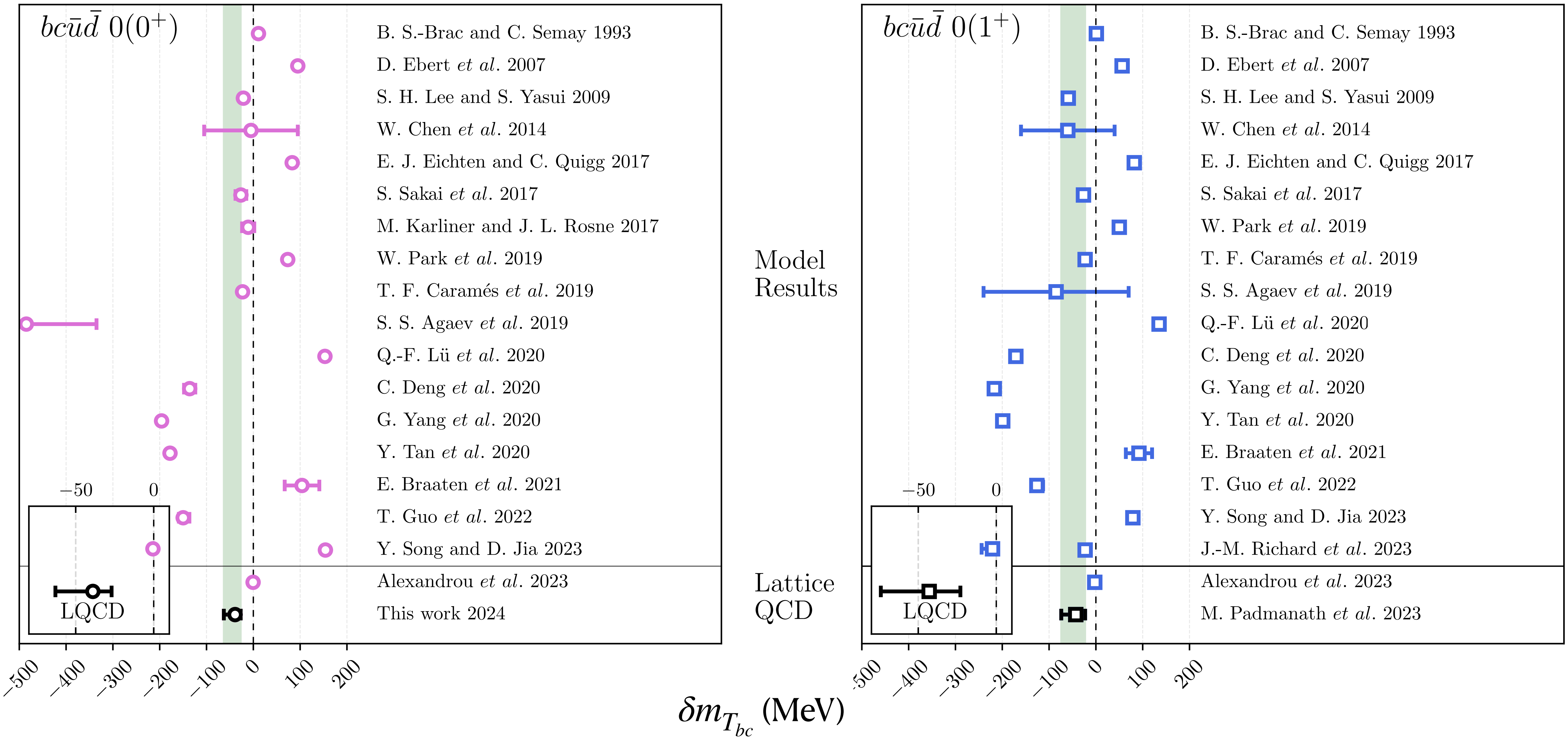
- The binding energy decreases with the increasing light quark mass.
- Indicates the **presence of a real bound state** at physics quark mass.

$a_0 = 0.58(^{+3}_{-4})(18)$ fm

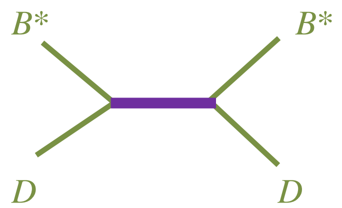
$\delta m_{T_{bc}} = -42(^{+4}_{-6})(^{+24}_{-12})$ MeV

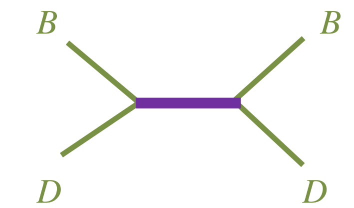
Comparison of T_{bc} binding energy results

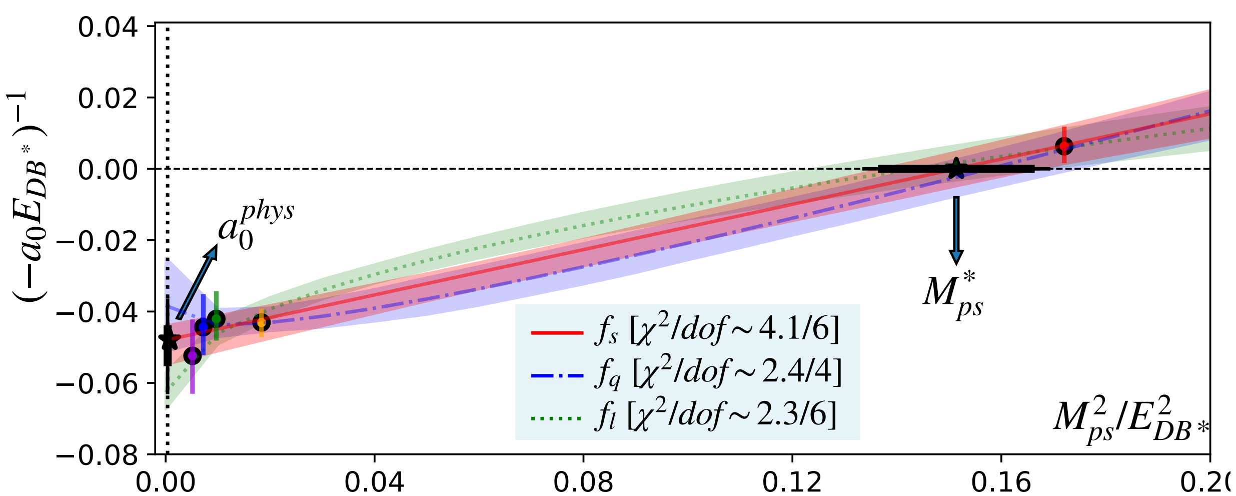
AR, M. Padmanath, Nilmani Mathur [arXiv:2307.14128]

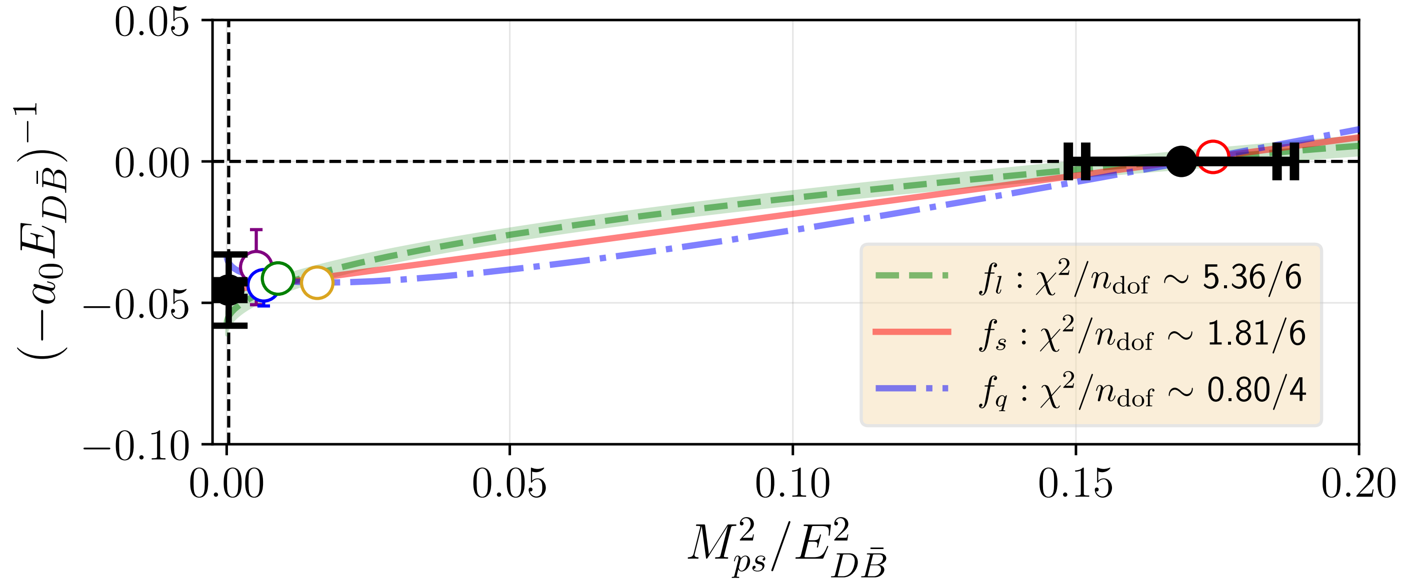


Summary







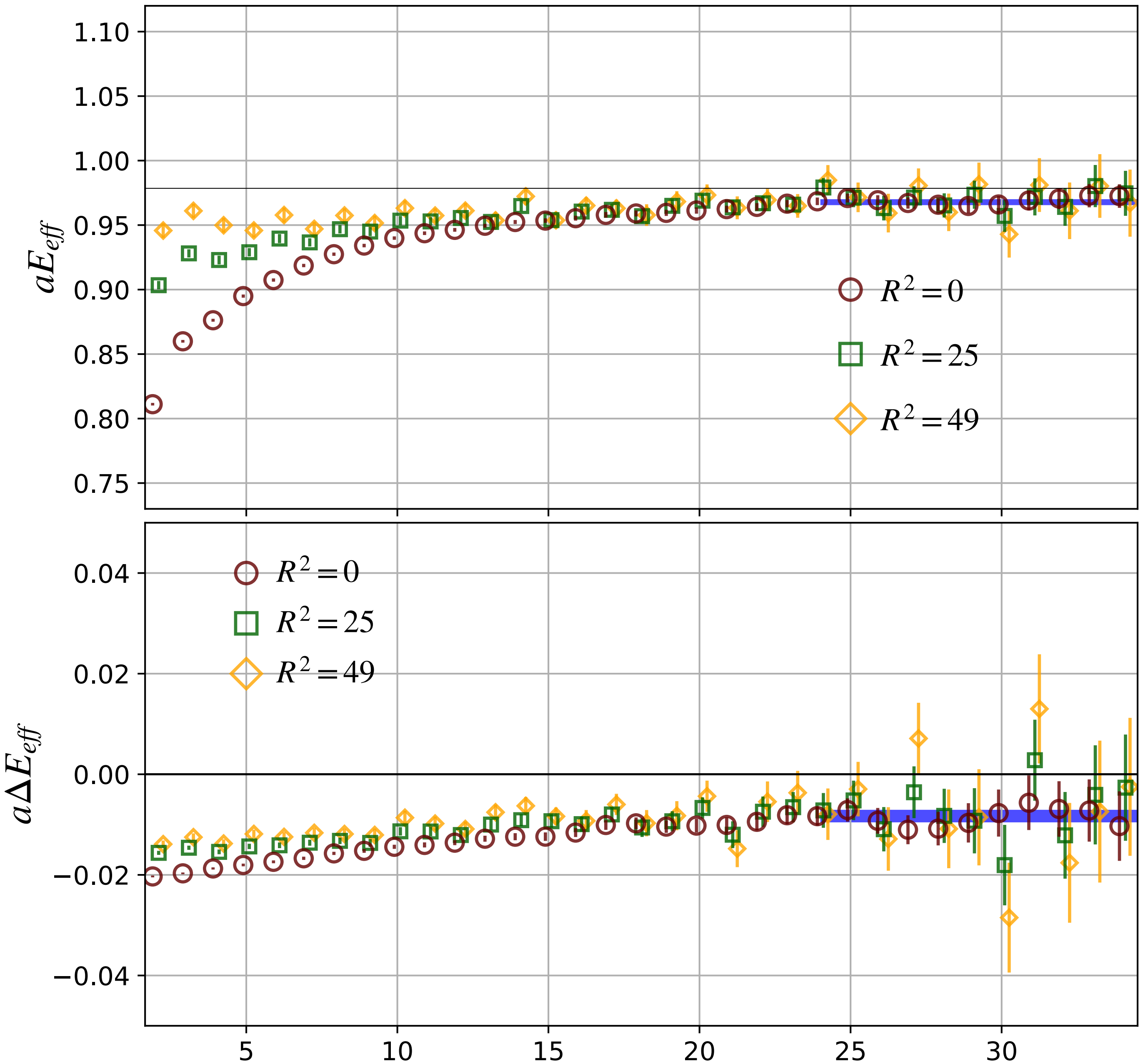


- Lattice QCD can play an important role in understanding these states from QCD and guide such efforts.
- Our preliminary findings suggest the possibility of an attractive interaction between a B^* and D meson (and B and D meson).
- Hope this will motivate experimental searches and complementary LQCD efforts.

BACKUP

Checking the "robustness of the ground state"

1^+



0^+