Evidence for a doubly charm tetraquark in DD^* scattering

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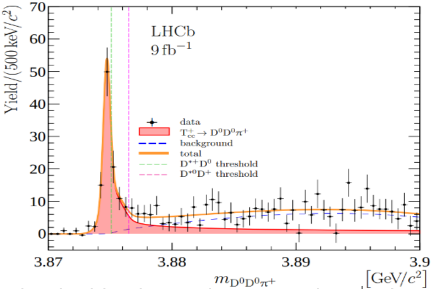
with **S. Prelovsek**. Based on article **PhysRevLett.129.032002**

The motivation, T_{cc}^{+}



LHCb: 2109.01038, 2109.01056

$$\delta m \equiv m_{T_{cc}^{+}} - (m_{D^{*+}} + m_{D^0})$$

$$\delta m_{\rm pole} = -360 \pm 40^{+4}_{-0} \ \text{keV}/c^2 ,$$
$$\Gamma_{\rm pole} = 48 \pm 2^{+0}_{-14} \ \text{keV} .$$

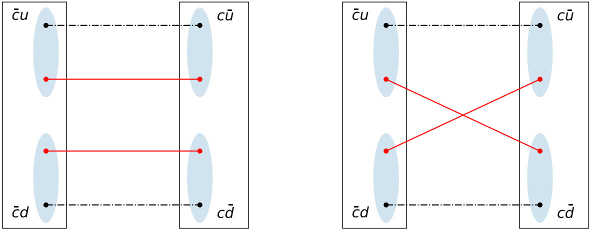
- The doubly charmed tetraquark T_{cc}^{+}, $I = 0$ and favours $J^P = 1^+$. Striking similarities with the longest known heavy exotic, X(3872).
- No features observed in $D^0 D^+ \pi^+$: possibly not $I = 1$.
- Near-threshold state from lattice QCD: Demands pole identification.
- HALQCD procedure: HALQCD 2013. Attraction in $I = 0$, $J^P = 1^+$.
- Two other lattice investigations : HSC 2017, ILGTI 2018. No scattering amplitude determination involved.
- Another recent calculation: CLQCD 2022 Finds attractive interaction, but no claim on poles.

Hadron spectroscopy using lattice QCD

- Compute matrices of two point correlation functions

$$C_{ji}(t) = \langle 0|\bar{O}_j(t) O_i(0)|0\rangle = \sum_n \frac{Z_i^n Z_j^{n*}}{2E_n} e^{-E_n(t)}$$

- For doubly charmed four quark systems near DD^* threshold, we use 'only' O of type $(\bar{q}\Gamma_1 c)_{1_c}(\bar{q}'\Gamma_2 c)_{1_c}$.
- Wick contractions to compute: $[c,\ q,\ q']$



- Lattice QCD ensembles : CLS Consortium

  $m_\pi \sim$ 280 MeV, $m_K \sim$ 467 MeV, $a \sim 0.086$ fm
  Spatial volumes: $L \sim 2$ fm and $L \sim 2.7$ fm
  Charm quark masses ($m_c^?$): $m_D \sim$ 1762 MeV and 1927 MeV

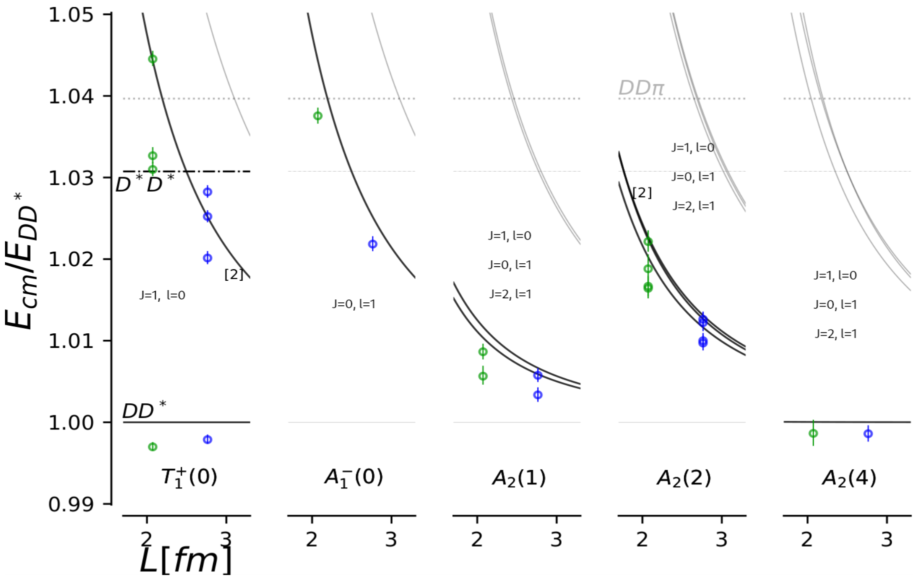
Irreps and interpolators

$\vec{P}$	LG	Λ^P	J^P	l	interpolators: $M_1(\vec{p}_1^{\,2})M_2(\vec{p}_2^{\,2})$
$(0,0,0)$	O_h	T_1^+	1^+	$0,2$	$D(0)D^*(0),\ D(1)D^*(1)\ [2],\ D^*(0)D^*(0)$
$(0,0,0)$	O_h	A_1^-	0^-	1	$D(1)D^*(1)$
$(0,0,1)\frac{2\pi}{L}$	Dic_4	A_2	$0^-,1^+,2^-$	$0,1,2$	$D(0)D^*(1),\ D(1)D^*(0)$
$(1,1,0)\frac{2\pi}{L}$	Dic_2	A_2	$0^-,1^+,2^-,2^+$	$0,1,2$	$D(0)D^*(2),\ D(1)D^*(1)\ [2],\ D(2)D^*(1)$
$(0,0,2)\frac{2\pi}{L}$	Dic_4	A_2	$0^-,1^+,2^-$	$0,1,2$	$D(1)D^*(1)$

- DD^* scattering in s-wave leads to $J^P = 1^+$.
  Our study focus on $T_1^+[0]$, $A_2[1]$, $A_2[2]$, and $A_2[4]$.
- Higher partial wave effects: Consider only up to $l \leq 2$ and $J \leq 2$.
  $l = 1 \rightarrow J^P = 0^-/2^- \Rightarrow A_2[1]$, $A_2[2]$, and $A_2[4]$.
  $l = 2 \rightarrow J^P = 1^+ \Rightarrow A_2[1]$, $A_2[2]$, and $A_2[4]$ and also introduce mixing.
  $l = 2 \rightarrow J^P = 2^+ \Rightarrow A_2[2]$.
- We assume contributions from $l \geq 2$ to be negligible.
  $l = 1 \rightarrow J^P = 0^-$ are constrained also considering $A_1^-[0]$.

+/g refers to positive parity, -/u refers to negative parity.

Finite volume spectrum T_{cc}



What do we learn till now?

- The inelastic threshold D^*D^* is sufficiently high.
  Assume elastic scattering near DD^* threshold.

- At $m_\pi \sim 280$ MeV, lowest three particle threshold $DD\pi$
  is higher up the lowest two particle inelastic threshold.

- Clear signatures for shifts from non-interacting scenario
  in s-wave and p-wave scattering.

- Lowest level with explicit $l = 2$ contribution consistent with
  the non-interacting level.

- Safe to assume no effects from $l \geq 2$.

Scattering amplitude and the parametrization

- For the DD^* system [total spin equals 1], and assuming only $l < 2$, we have a 3×3 diagonal t matrix.

$$(t_l^{(J)})^{-1} = \frac{2(\tilde{K}_l^{(J)})^{-1}}{E_{cm}p^{2l}} - i\frac{2p}{E_{cm}}, \quad (\tilde{K}_l^{(J)})^{-1} = p^{2l+1}\cot\delta_l^{(J)}$$

- Using an effective range expansion near-threshold, we have

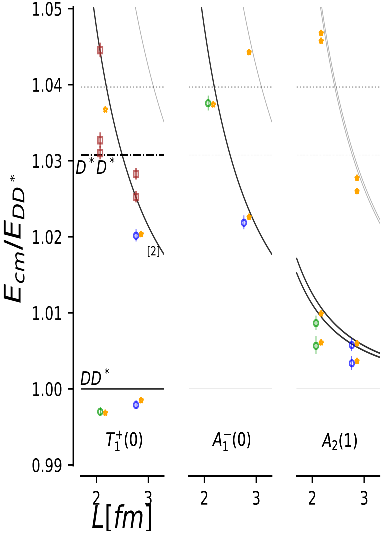
$$\tilde{K}^{-1} = \begin{bmatrix} \frac{1}{a_0^{(1)}} + \frac{r_0^{(1)}p^2}{2} & 0 & 0 \\ 0 & \frac{1}{a_1^{(0)}} + \frac{r_1^{(0)}p^2}{2} & 0 \\ 0 & 0 & \frac{1}{a_1^{(2)}} \end{bmatrix} \begin{matrix} J{=}1 \quad l{=}0 \\ J{=}0 \quad l{=}1 \\ J{=}2 \quad l{=}1 \end{matrix}$$

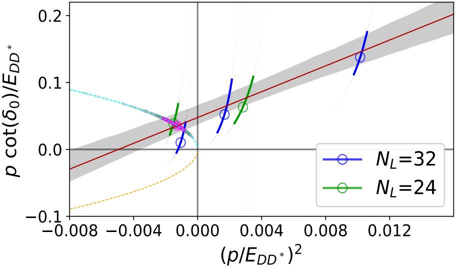
- Constraint on bound states:

$$p^{2l+1}cot(\delta_l) = -1^{\alpha}p^{2l}\sqrt{-p^2}$$

$\alpha = 1(2)$ for a real (virtual) bound state.

DD^* scattering in $I = 0, 1$ @ $m_c^{(h)}$





- Fit quality: $m_\pi \sim 280$ MeV

  $\chi^2/d.o.f. = 3.7/5.$

- Fit parameters:

  $a_0^{(1)} = 1.04(0.29)$ fm & $r_0^{(1)} = 0.96(^{+0.18}_{-0.20})$ fm

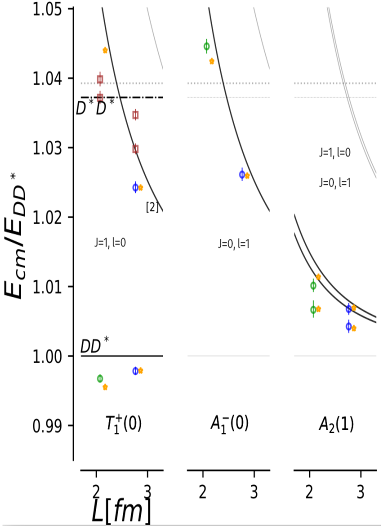
  $a_1^{(0)} = 0.076(^{+0.008}_{-0.009})$ fm^3 & $r_1^{(0)} = 6.9(2.1)$ fm^{-1}

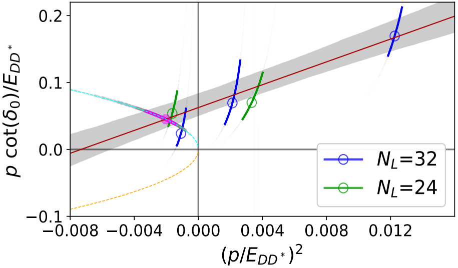
- Binding energy:

  $\delta m_{T_{cc}} = -9.9(^{+3.6}_{-7.2})$ MeV.

+/g refers to positive parity, -/u refers to negative parity.

DD^* scattering in $I = 0, 1$ @ $m_c^{(l)}$

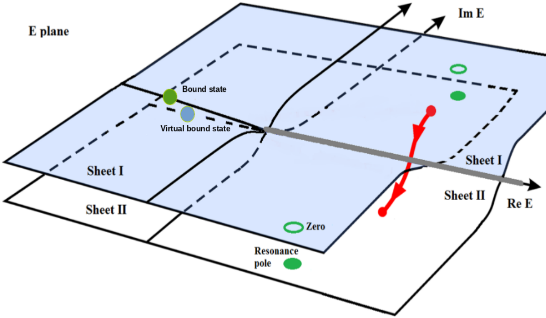




- Fit quality: $\chi^2/d.o.f. = 3.6/5.$ $m_\pi \sim 280$ MeV
- Fit parameters:
  $a_0^{(1)} = 0.86(0.22)$ fm & $r_0^{(1)} = 0.92(^{+0.17}_{-0.19})$ fm
  $a_1^{(0)} = 0.117(^{+0.013}_{-0.014})$ fm^3 & $r_1^{(0)} = 8.6(^{+1.5}_{-1.1})$ fm^{-1}
- Binding energy:
  $\delta m_{T_{cc}} = -15.0(^{+4.6}_{-9.3})$ MeV.

+/g refers to positive parity, -/u refers to negative parity.

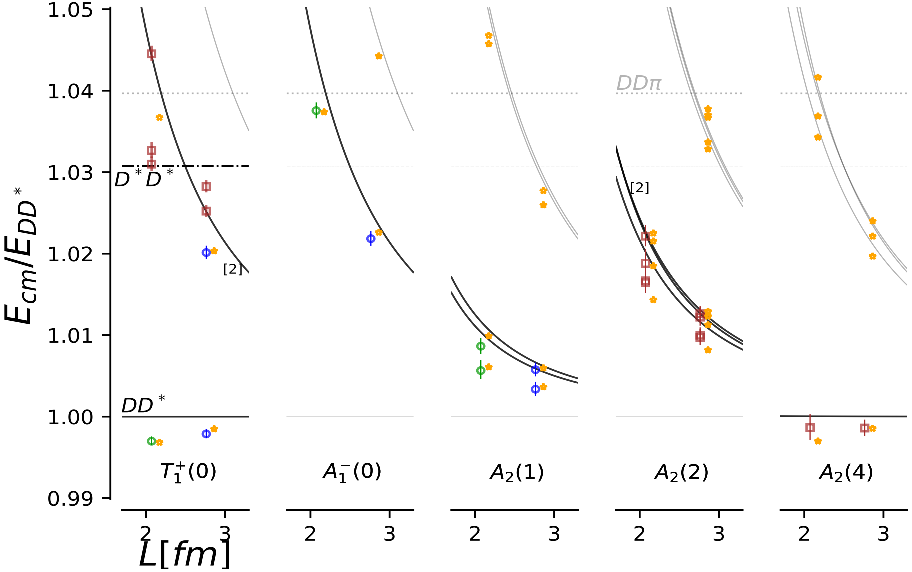
Virtual bound states



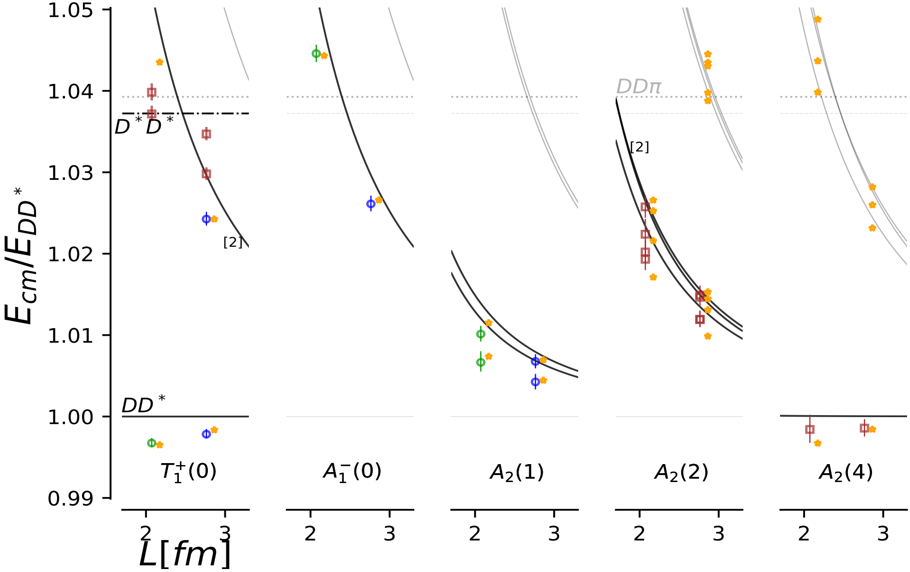
- $T \;\propto\; (pcot\delta_0 - ip)^{-1}$. Bound state is a pole in T with $p = i|p|$. Virtual bound state is a pole in T with $p = -i|p|$.

- An example for virtual bound state: spin-singlet dineutron.

Predicting the finite volume spectrum @ $m_c^{(h)}$



Predicting the finite volume spectrum @ $m_c^{(l)}$



Our observations and inferences

- A shallow virtual bound state pole in s-wave related to T_{cc}.

	m_D [MeV]	$\delta m_{T_{cc}}$ [MeV]	T_{cc}
lat. ($m_\pi \simeq 280$ MeV, $m_c^{(h)}$)	1927(1)	$-9.9^{+3.6}_{-7.2}$	virtual bound st.
lat. ($m_\pi \simeq 280$ MeV, $m_c^{(l)}$)	1762(1)	$-15.0(^{+4.6}_{-9.3})$	virtual bound st.
exp.	1864.85(5)	$-0.36(4)$	bound st.

- Observations in line with the expected light and charm quark mass dependence of a near-threshold pole in simple Quantum Mechanical potentials.

An extended discussion in the next talk by S. Prelovsek

Summary

- First observation of a shallow virtual bound state pole in the DD^* s-wave scattering amplitude related to T_{cc} from lattice QCD.
- The results are qualitatively robust to disretization effects for such a near-threshold pole, where these effects are expected to be small.
- No features observed in p-wave in the energy region constrained by the finite-volume spectrum.
- Quark mass dependence and comparison between lattice result and T_{cc}.

  See next talk, by S. Prelovsek

Thank you