Three-particle study of the $T_{cc}(3875)^+$ from Lattice QCD

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in collaboration with

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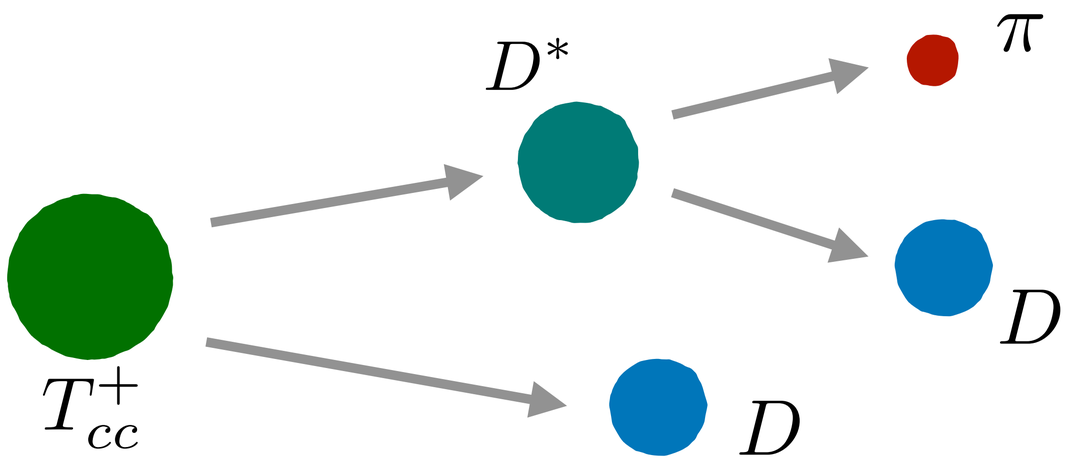
The $T_{cc}(3875)^+$ via scattering

- The $T_{cc}(3875)^+$ is $I = 0$ and $J^P = 1^+$ state with minimal quark content $cc\bar{u}\bar{d}$
- In nature, primarily decays to 3-hadron final state via a 2-hadron intermediate state

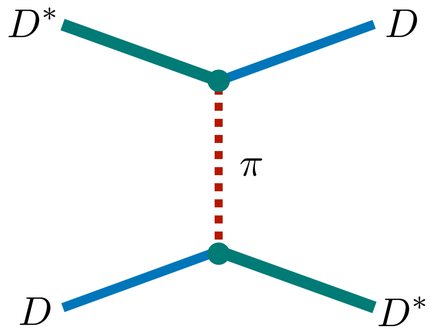
$$T_{cc}^+ \to D^0 D^{*+} \to D^0 D^+ \pi^0, D^0 D^0 \pi^+$$

- Working at slightly heavier-than-physical pion mass, D^* becomes stable
- In this setting, T_{cc}^+ can be studied via $I = 0$ DD^* scattering on the lattice — *see talks in the Monday spectroscopy session*



Why a three-body approach?

- **Three-body $DD\pi$ effects** play increasingly important role as we go towards physical pion mass
- For DD^* scattering, the two-body **Lüscher formalism fails on the left-hand cut** (lhc) arising due to u-channel single-π exchanges between D and D^*



→ the **3-particle RFT formalism** takes into account DD^* and $DD\pi$ intermediate states and bypasses the lhc issue by avoiding on-shell placement and partial-wave projection of the problematic π exchange

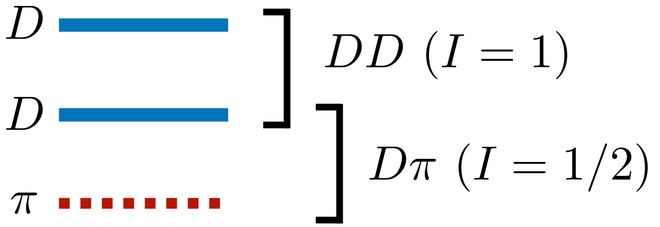
The $T_{cc}(3875)^+$ through a 3-body approach

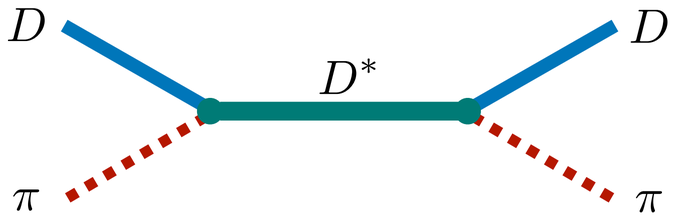
3-particle finite-volume formalism for $DD\pi$ systems for general isospin was laid out in *[Hansen, Romero-López, Sharpe 2024]* and initially explored in *[Dawid, Romero-López, Sharpe 2025]*

To investigate the T_{cc}^+ , we focus on $I = 0$:

- two 2-particle sub-channels to consider:
  $DD\,(I = 0)$, $D\pi\,(I = 1/2)$

- the D^* is taken into account as a p**-wave pole in the** $D\pi$ **subchannel amplitude** (a bound state for stable D^*)





The $T_{cc}(3875)^+$ through a 3-body approach

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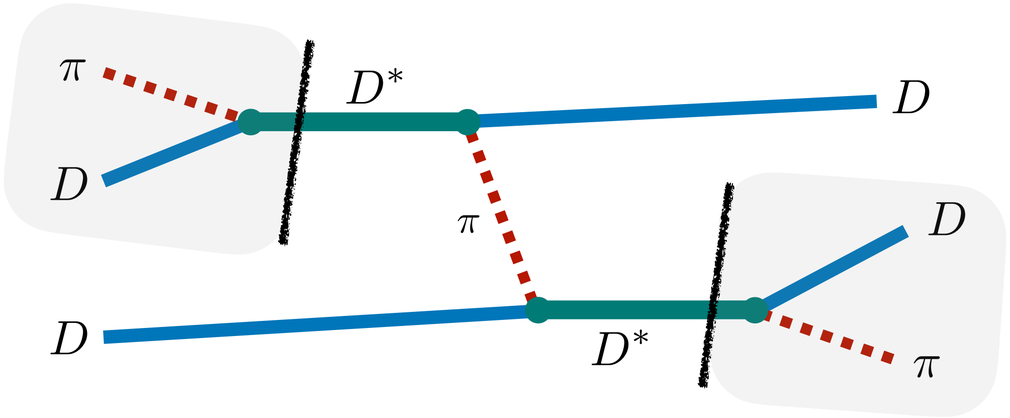
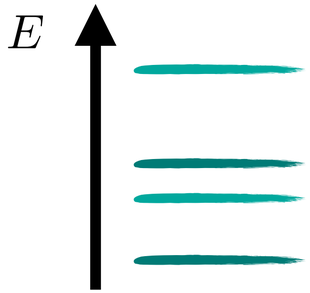
DD^* amplitude accessed by **LSZ-reducing** $DD\pi$ **amplitude and analytically continuing it** below $DD\pi$ threshold, e.g.:



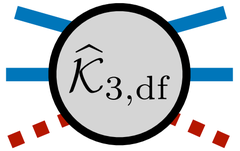
The 3-particle formalism pipeline



finite-volume
$DD^*/DD\pi$ spectrum

$$\det_{i\boldsymbol{k}\ell m}\left[\widehat{\mathcal{K}}_{3,\mathrm{df}}+\widehat{F}_3^{-1}\right]=0$$

3-particle quantization condition (QC3)



constraining 3-body K-matrix

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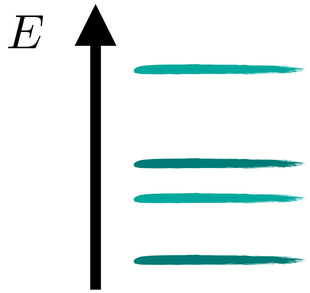

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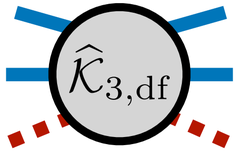

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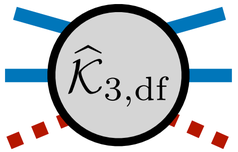
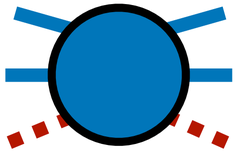
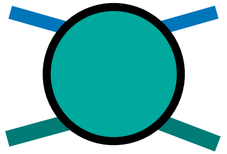


integral equations



$DD\pi$ amplitude

LSZ reduction



DD^* amplitude

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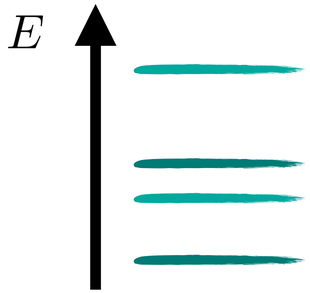

finite-volume $DD^*/DD\pi$ spectrum

$$\det_{i\boldsymbol{k}\ell m}\left[\widehat{\mathcal{K}}_{3,\mathrm{df}}+\widehat{F}_3^{-1}\right]=0$$

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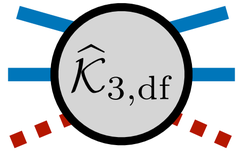


constraining 3-body K-matrix

$$\widehat{F}_3=\frac{\widehat{F}}{3}-\widehat{F}\frac{1}{1+\widehat{\mathcal{M}}_{2,L}\widehat{G}}\widehat{\mathcal{M}}_{2,L}\widehat{F}$$

$$\widehat{\mathcal{M}}_{2,L}=\frac{1}{\widehat{\mathcal{K}}_{2,L}^{-1}+\widehat{F}}\qquad\widehat{\mathcal{K}}_{2,L}=\begin{pmatrix}\mathcal{K}_{2,L}^{D\pi} & 0\\ 0 & \frac{1}{2}\mathcal{K}_{2,L}^{DD}\end{pmatrix}$$

$DD\pi$ QC3 involves matrices in enlarged index space:

i – spectator flavor

$\boldsymbol{k}$ – spectator 3-momentum

ℓm – 2-particle subsystem AM

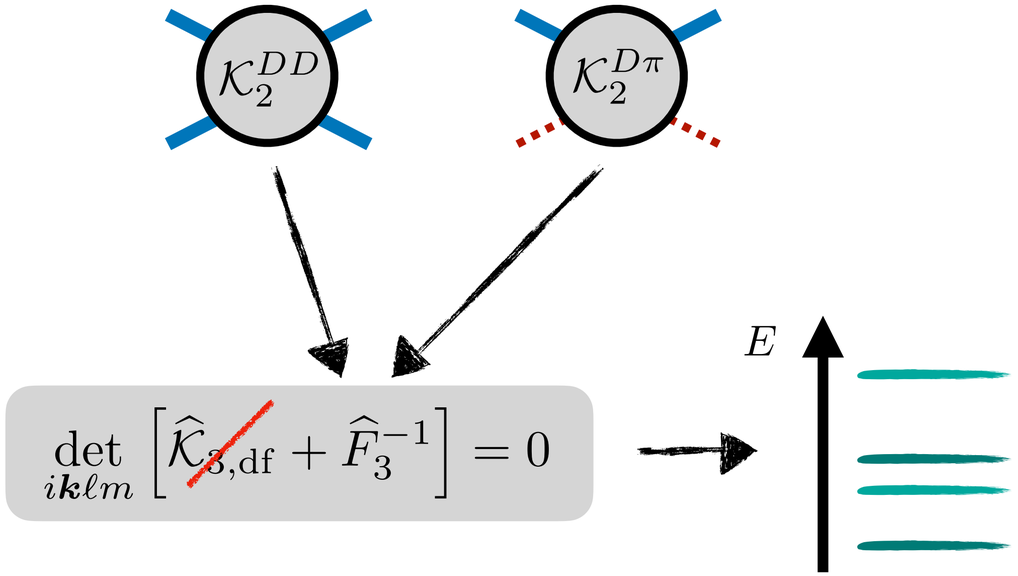
$DD\ (I=1)$

$D\pi\ (I=1/2)$

information about infinite-volume scattering in 2-particle subchannels is needed as input for QC3

Outline of preliminary analysis

- Plan for preliminary analysis as follows:
  - Obtain finite-volume spectra for the 2-particle subsystems
  - 2-body Lüscher formalism used on each subsystem to get K-matrices
  - Parameters fed into QC3, initially using $\mathscr{K}_{3,\mathrm{df}} = 0$ to get a predicted 3-particle spectrum
  - Qualitative comparison of predicted spectrum and data



Lattice setup

- For initial analysis, we have primarily used the X252 CLS ensemble for $DD\pi$ /DD^* and both two-particle subsystems
- X253 is, for now, used only to further constrain the $D\pi$ subsystem, but extension of DD and $DD^* + DD\pi$ to this ensemble ongoing
- $N_f = 2 + 1$ ensembles with same pion mass $m_\pi \approx 280\,\mathrm{MeV}$ and lattice spacing, but different volume
- c valence quark mass tuned so that D mass is average of physical D^0, D^+, D_s^+meson masses
- We use distillation to compute correlators, QUDA-LAPH is used for perambulators

  https://github.com/cosmon-collaboration/quda_laph

	L/a	T/a	$m_\pi L$	$m_\pi[\mathrm{MeV}]$	$a[\mathrm{fm}]$	N_{LapH}
X252	36	128	3.4	280	0.064	48
X253	40	128	3.7	280	0.064	64

Operator bases

- For the two particle subsystems, the following types of operator were used
  - DD in $I = 1$: DD , DD^* , D^*D^* , $D_0^*D_0^*$ (where D_0^* is a scalar, cf. $D_0^*(2300)$ resonance)
  - $D\pi$ in $I = 1/2$: $D\pi$, D^* , $D^*\pi$, D_0^* *David Thoma's poster on $I = 1/2$ $D\pi$ scattering in CLS ensembles*
- For the main system…

$DD\pi$ / DD^* in $I = 0$:

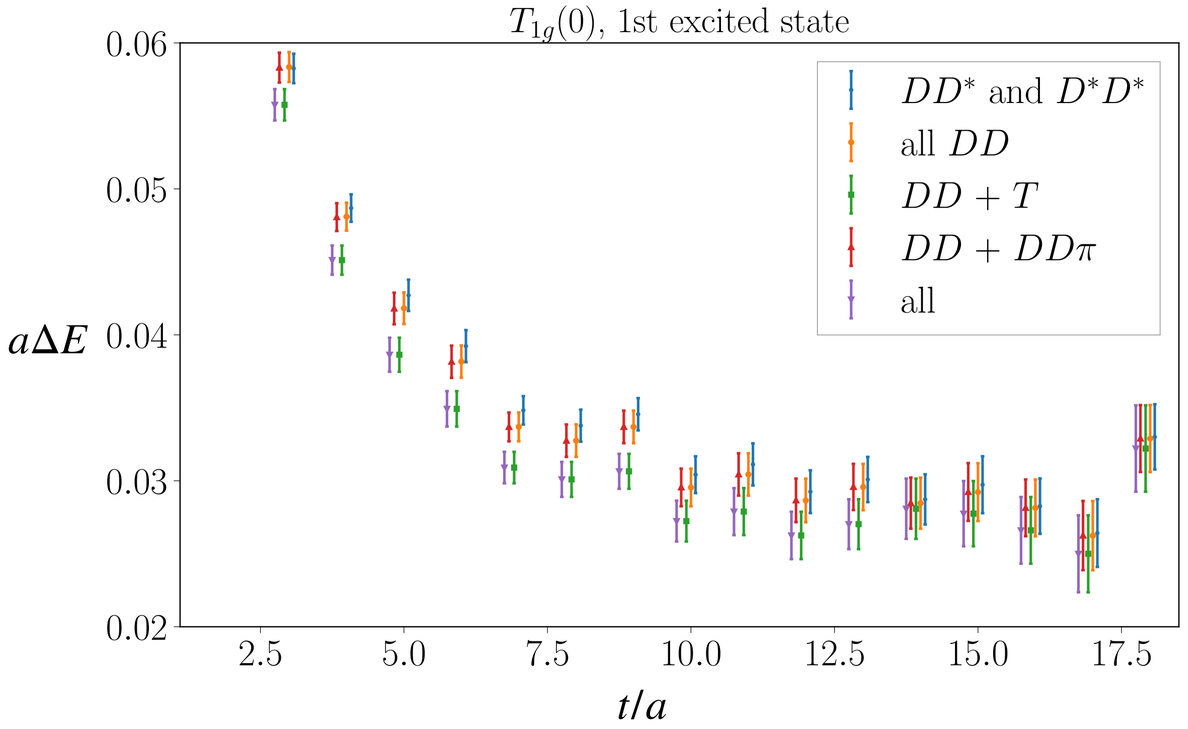
bilocal/trilocal operators DD^* , $DD\pi$, D^*D^* , D_0^*D , $D_0^*D^*$

local tetraquark operators local DD^*, D^*D^*

e.g. $T^i_{DD^*}(t, \boldsymbol{x}) = \left(\bar{u}\gamma^i c\, \bar{d}\gamma^5 c - \bar{d}\gamma^i c\, \bar{u}\gamma^5 c\right)(t, \boldsymbol{x})$

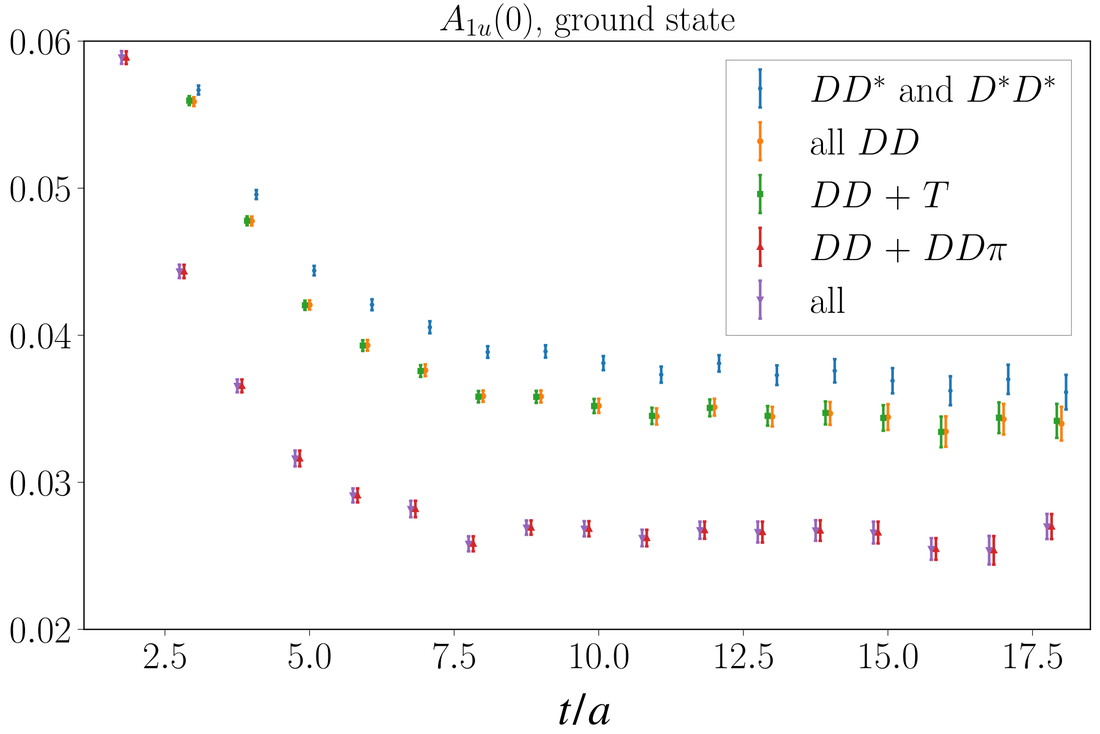
- We build correlator matrices using these bases and solve the associated GEVPs
- Combination of single-exponential ratio fits and single-exponential fits directly to principal correlators are used to extract energies

Importance of tetraquark and $DD\pi$ operators



Significant impact on the energies due to inclusion of tetraquark operators in irreps where T_{cc}^+ appears

talks by A. Stump and M. Padmanath



In $A_{1u}(0)$, a $DD\pi$ state appears below lowest DD^* state – inclusion of $DD\pi$ operators crucial to resolve the true ground state

Results for DD in $I = 1$

- 8 levels obtained on X252 in the $A_{1g}(0)$, $A_1(1)$, $A_1(2)$, $A_1(3)$ irreps
- Lüscher analysis of s-wave DD K-matrix performed using a 3-parameter ERE fit form:

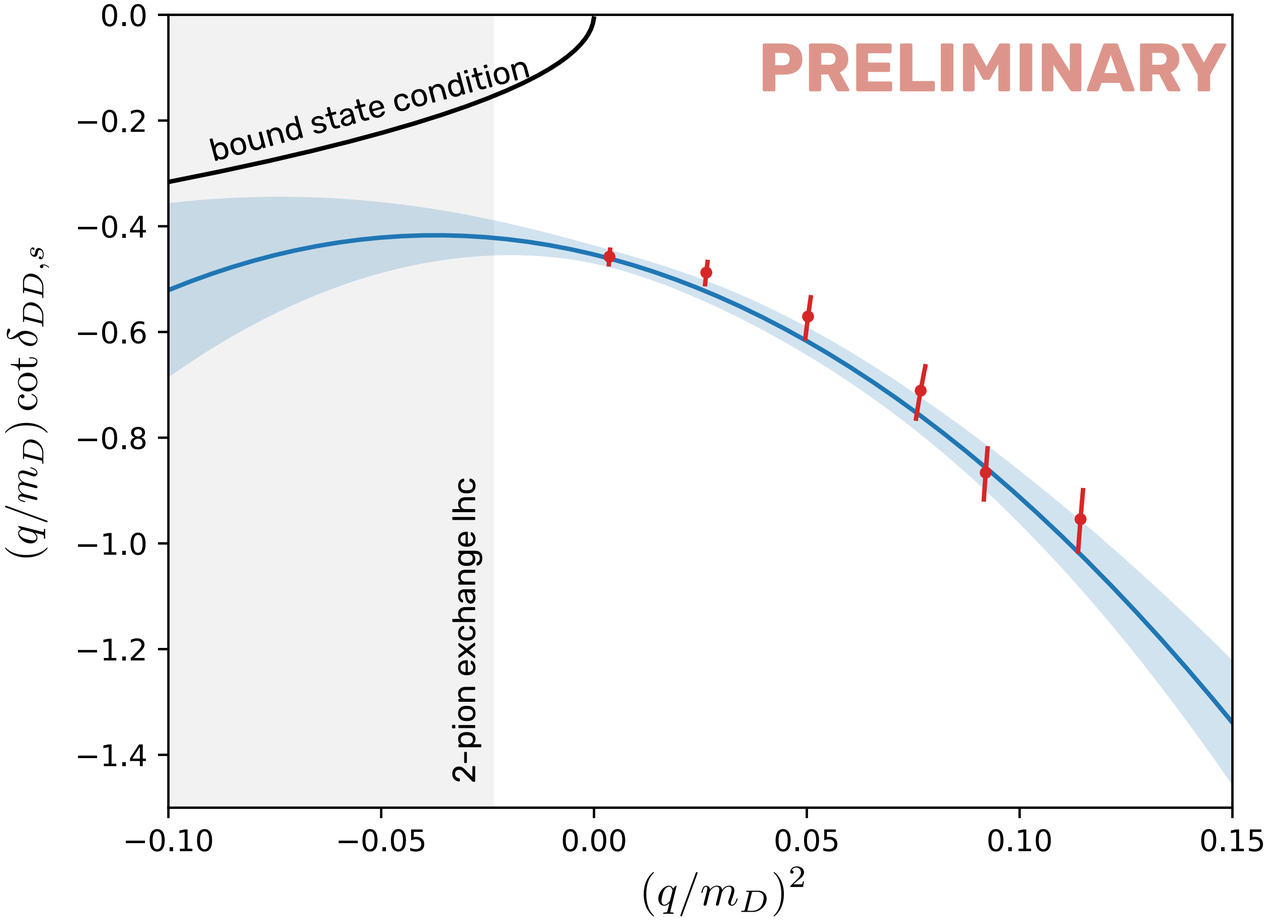
$$\frac{q}{m_D}\cot\delta_{DD,s} = C_1 + C_2\left(\frac{q}{m_D}\right)^2 + C_3\left(\frac{q}{m_D}\right)^4$$

$$C_1 = -0.454(14)\,, \quad C_2 = -1.96(77)\,, \quad C_3 = -26.3(8.5)$$

$$\chi^2/\text{d.o.f.} = 5.83/5 = 1.17$$

$$(a_{0,s}m_D = 2.21(7)\,, \quad r_{0,s}m_D = -3.91(1.54))$$

- as expected, weakly interacting system



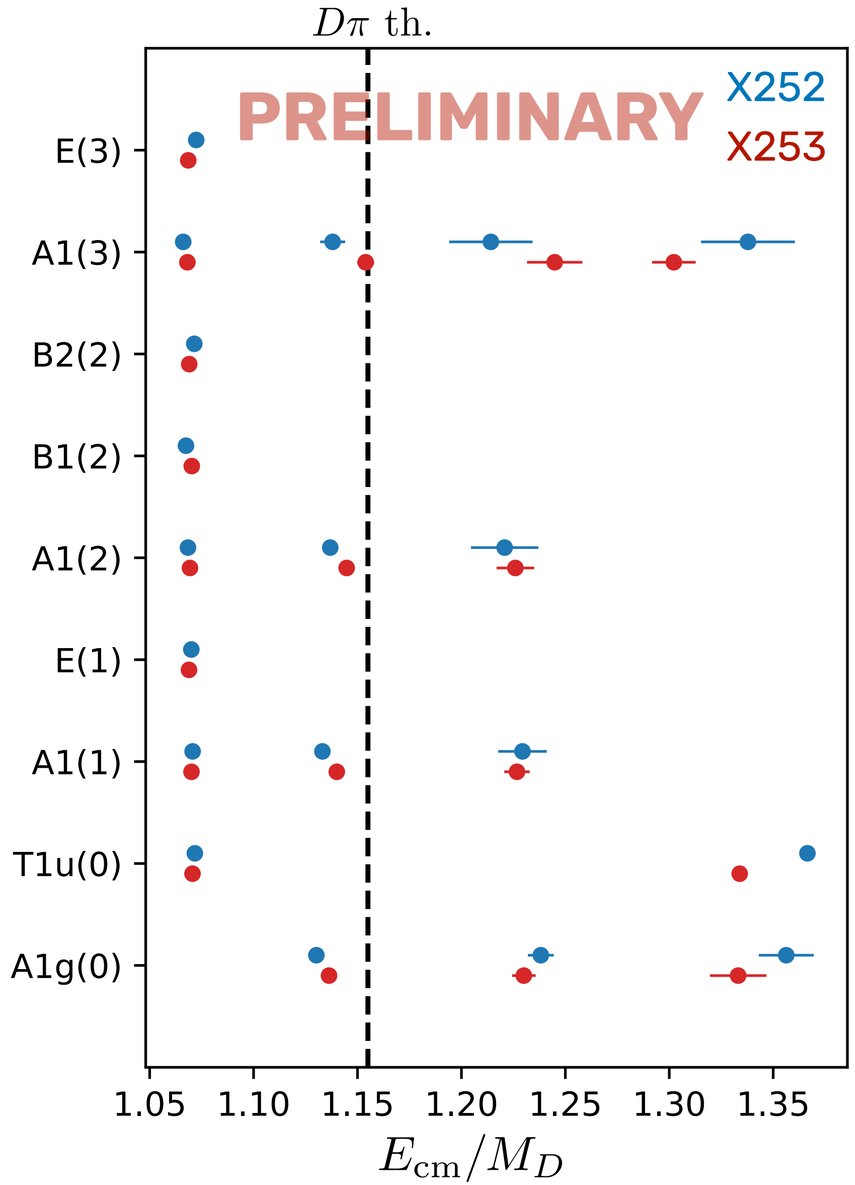
Results for $D\pi$ in $I = 1/2$

- Total of 38 levels extracted on X252 and X253 (19 in each)
- Lüscher analysis performed using 2-parameter ERE models for s- and p -waves (other models were also investigated)

$$q \cot \delta_{D\pi,s} = \frac{1}{2} r_{0,s} \left(q^2 - q_{0,s}^2\right)$$

$$q^3 \cot \delta_{D\pi,p} = \frac{1}{2} r_{0,p} \left(q^2 - q_{0,p}^2\right)$$

- For p-wave, we use instead the $D^*D\pi$ HQET coupling g and D^* mass M_{D^*} as fit parameters (which uniquely determine $r_{0,p}$ and $q_{0,p}^2$)
- g is quite poorly constrained by data — we introduce a Bayesian prior $g = 0.55(10)$ (experimental value ~ 0.57 and lattice-determined values ranging $\sim 0.50 - 0.65$, see *[Dawid, Romero-López, Sharpe 25]*)



Results for $D\pi$ in $I = 1/2$

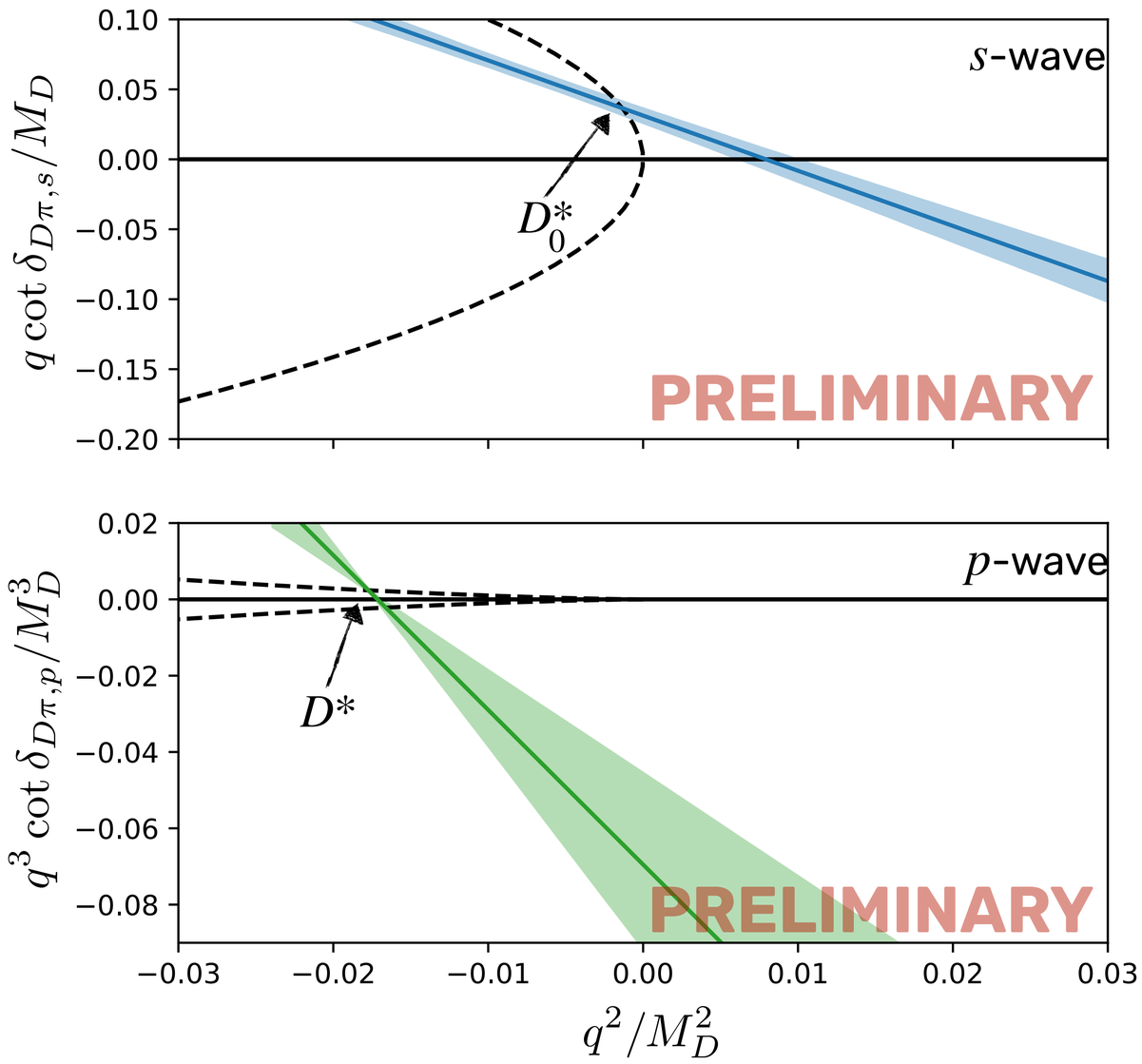
- Best fit parameters obtained to a fit of 32 levels

$$q^2_{0,s}/M_D^2 = 0.00801(182)\,,\ r_{0,s}M_D = -7.91(80)$$

$$M_{D^*}/M_D = 1.07041(63)\,,\ gM_D = 0.542(96)$$

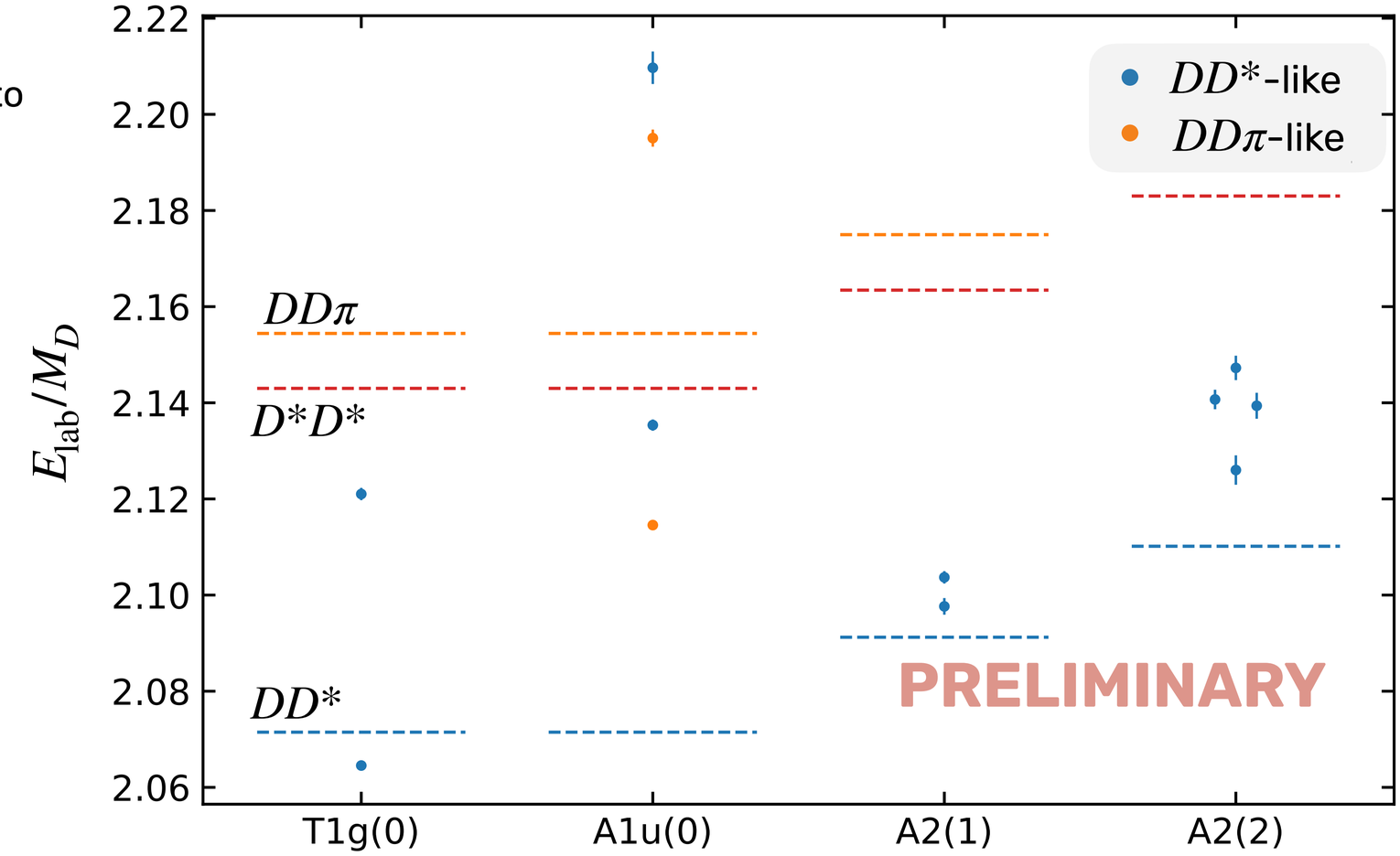
$$\chi^2/\text{d.o.f.} = 36.50/29 = 1.26$$

- Bayesian prior stabilizes the fit slightly, but coupling and its error barely change from prior values…
  - Alternative determinations are being considered e.g. through three-point functions



$DD^* + DD\pi$ spectrum on X252

In this initial analysis, we use 12 $DD^*/DD\pi$ levels on X252, going up to the lowest D^*D^* or $DD\eta$ state

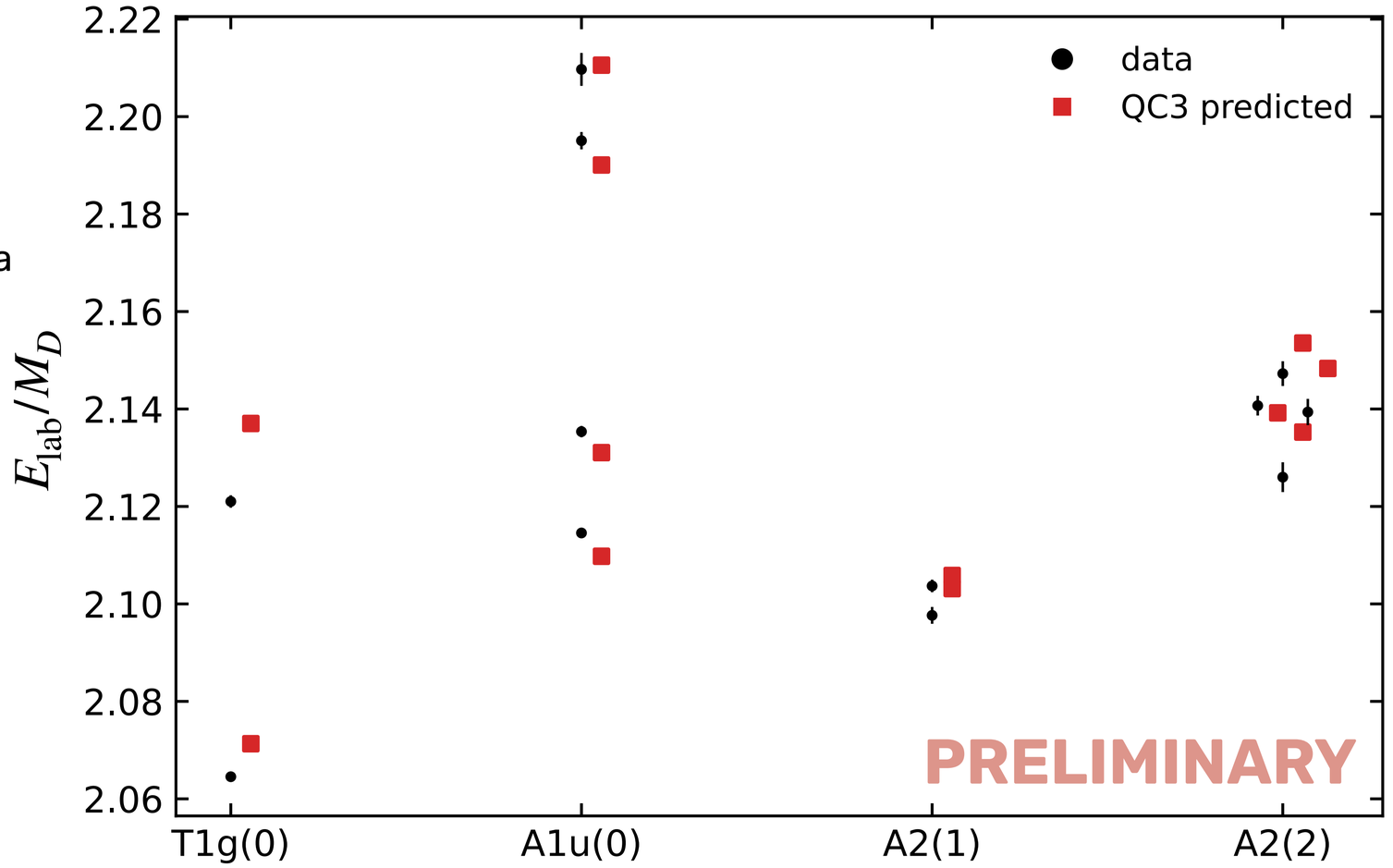


A first non-fit of the data...

- Use the 2-body subsystem parameters we determined and setting $\mathscr{K}_{3,\mathrm{df}} = 0$ and solve the QC3
- This gives a poor description of the data

$$\chi^2 = 247.28$$

- as expected, we need $\mathscr{K}_{3,\mathrm{df}} \neq 0$ to adequately describe the spectrum



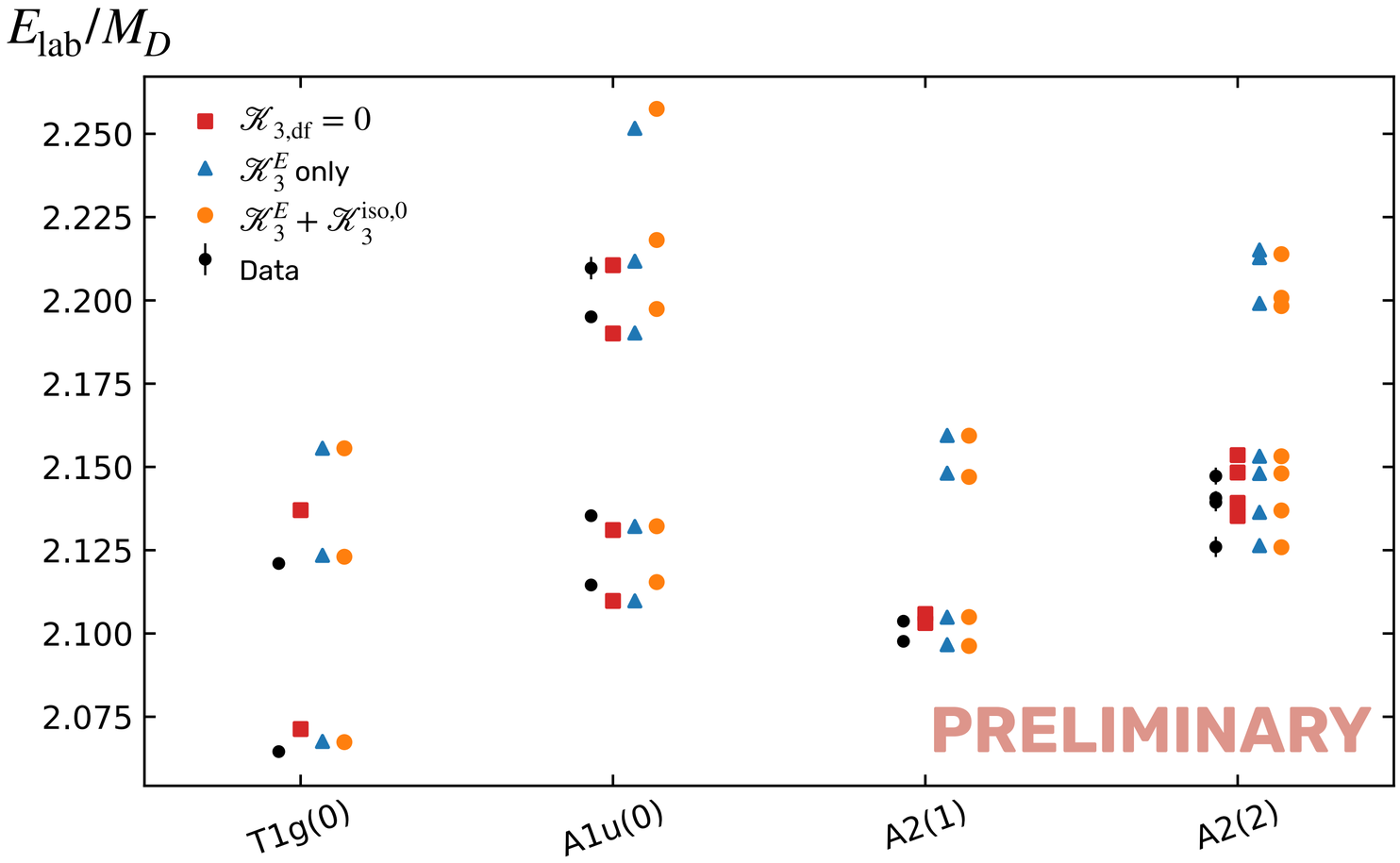
A few preliminary fits...

- We can improve the situation by performing fits using a K-matrix parametrization

$$\mathcal{K}_{3,\mathrm{df}}(\{\boldsymbol{p}\},\{\boldsymbol{k}\}) = \mathcal{K}_3^{\mathrm{iso},0} + \mathcal{K}_3^{E}\frac{(k_\pi - p_\pi)^2}{M^2}$$

$$M = 2M_D + M_\pi$$

- Using $\mathscr{K}_3^E$ term only brings χ^2 down to ~ 100, and including $\mathscr{K}_3^{\mathrm{iso},0}$ contributions lowers it to ~ 65, with 10 degrees of freedom
- Better, and spectrum looks reasonable, but 2-particle parameters are set, not fit



Next steps and outlook

- Clear next step is to perform simultaneous fits to DD, $D\pi$, $DD\pi + DD^*$ data to help further constrain interactions in 2-particle subsystems
- Adding more ensembles to the analysis
- Parallel investigation of alternative methods to obtain the $D^*D\pi$ coupling underway
- Once we have a better handle on 2-body parameters and 3-body K-matrix, the machinery to compute DD^* amplitudes is in place from previous work *[Dawid, Romero López, Sharpe 2025]* to perform an immediate analysis of the T_{cc}^+

Thank you for your attention!