A three-body study of the $T_{cc}(3875)$

Fernando Romero-López

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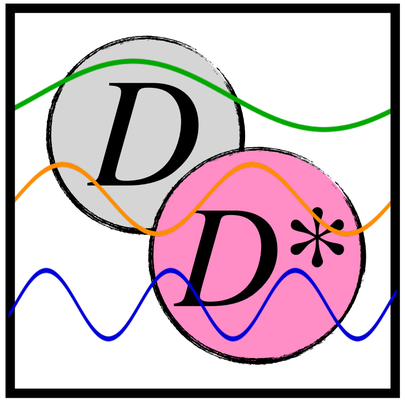
*ECT**
March 4th





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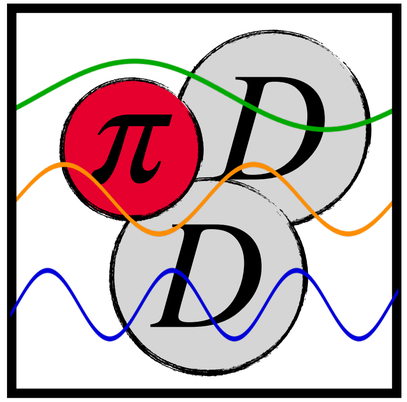


Refs & Acknowledgements

Incorporating $DD\pi$ effects and left-hand cuts in lattice QCD studies of the $T_{cc}(3875)^+$

arXiv:2401.06609

Maxwell T. Hansen[a] , Fernando Romero-López[b] , and Stephen R. Sharpe[c]

Comparison of integral equations used to study T_{cc}^+ for a stable D^*

arXiv:2505.05466

Sebastian M. Dawid[a] , Fernando Romero-López[b] , and Stephen R. Sharpe[a]

Finite- and infinite-volume study of $DD\pi$ scattering

arXiv:2409.17059

Sebastian M. Dawid[a] , Fernando Romero-López[b,c] , and Stephen R. Sharpe[a]

PROCEEDINGS OF SCIENCE

arXiv:2602.17204

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

Herzallah Alharazin,[a] André Baião Raposo,[a,*] John Bulava,[a] Sebastian Dawid,[b1,b2] Jeremy R. Green,[c] Colin Morningstar,[d] Fernando Romero-López,[e] Miguel Salg,[e] Stephen R. Sharpe[f] and Andres Stump[g]

CSCS
Centro Svizzero di Calcolo Scientifico
Swiss National Supercomputing Centre

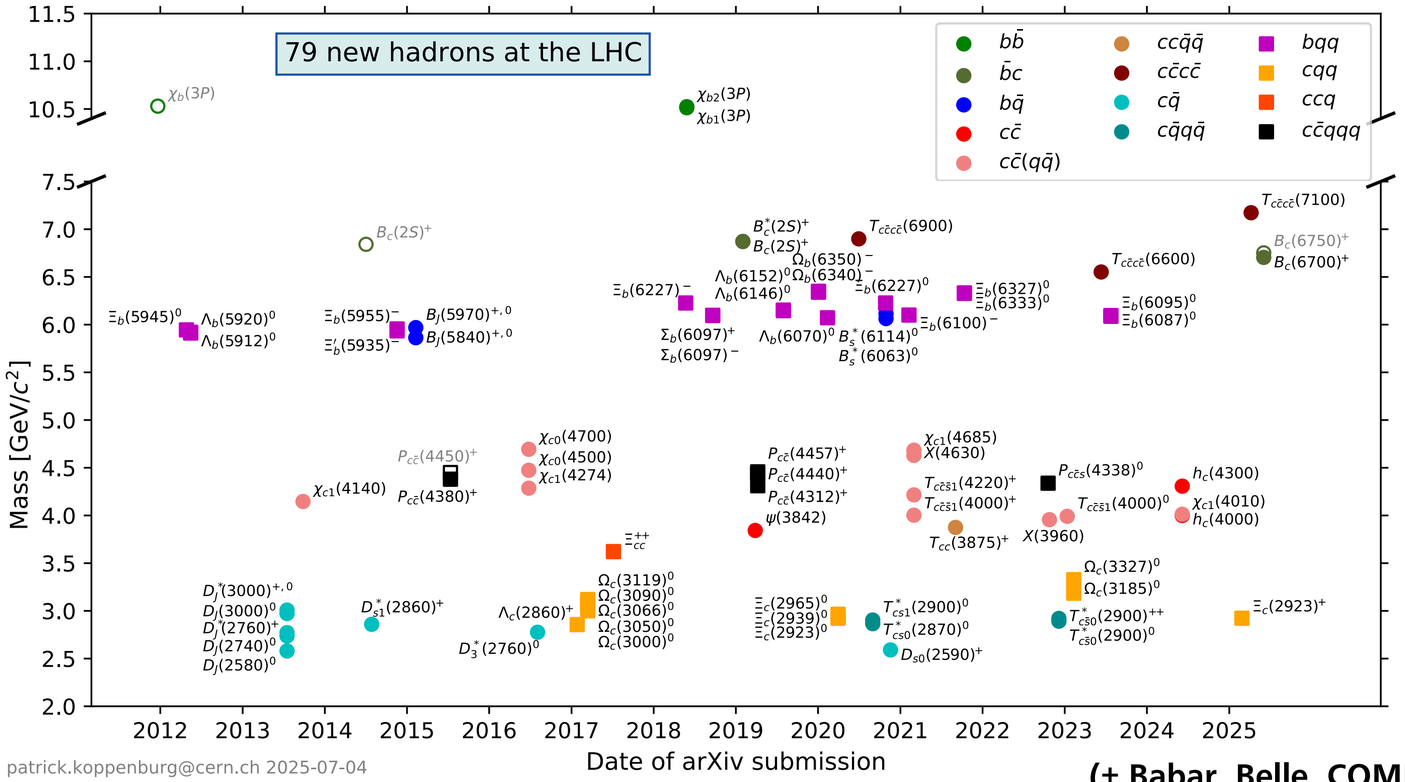
Platform for Advanced Scientific Computing

Schweizerischer Nationalfonds

The Hadron Spectrum

A growing hadron spectrum still requires first principles understanding

[https://www.nikhef.nl/~pkoppenb/particles.html]



(+ Babar, Belle, COMPASS)

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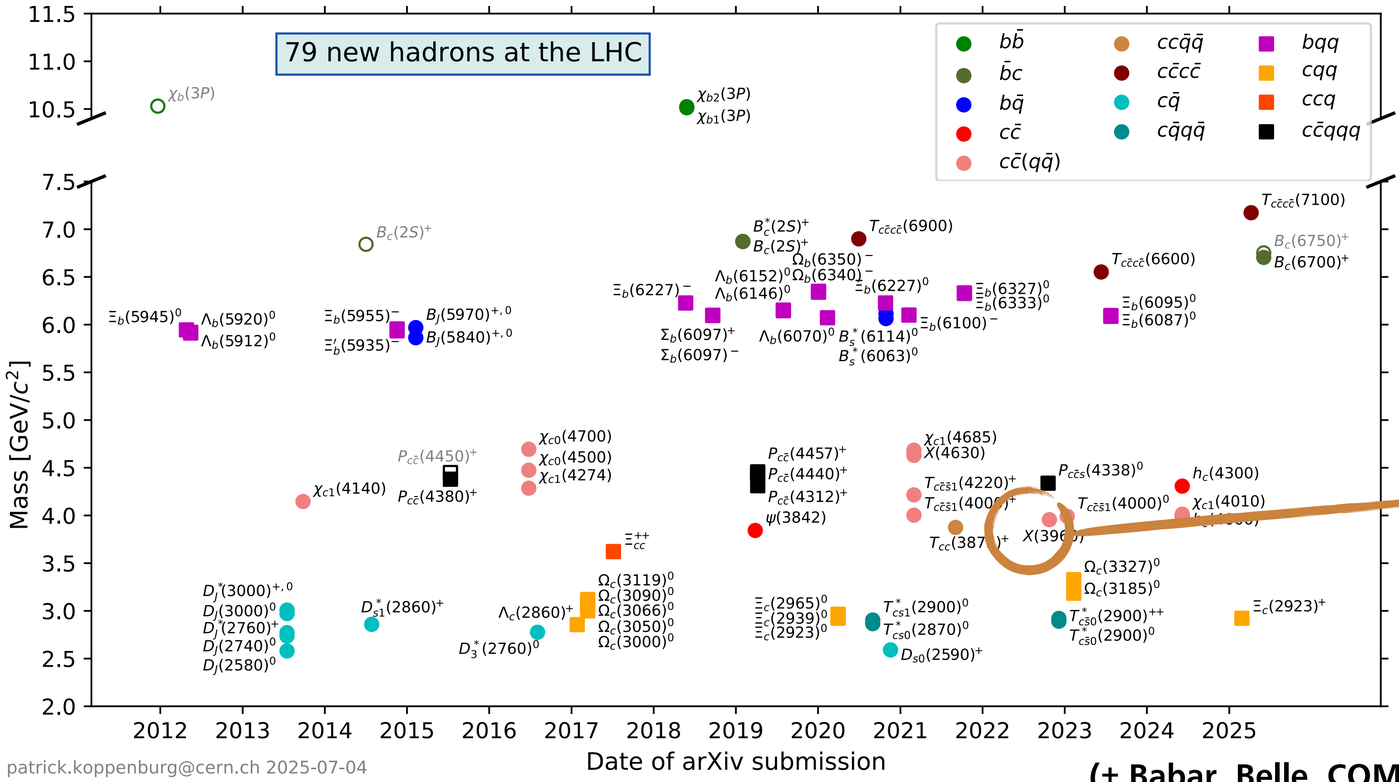
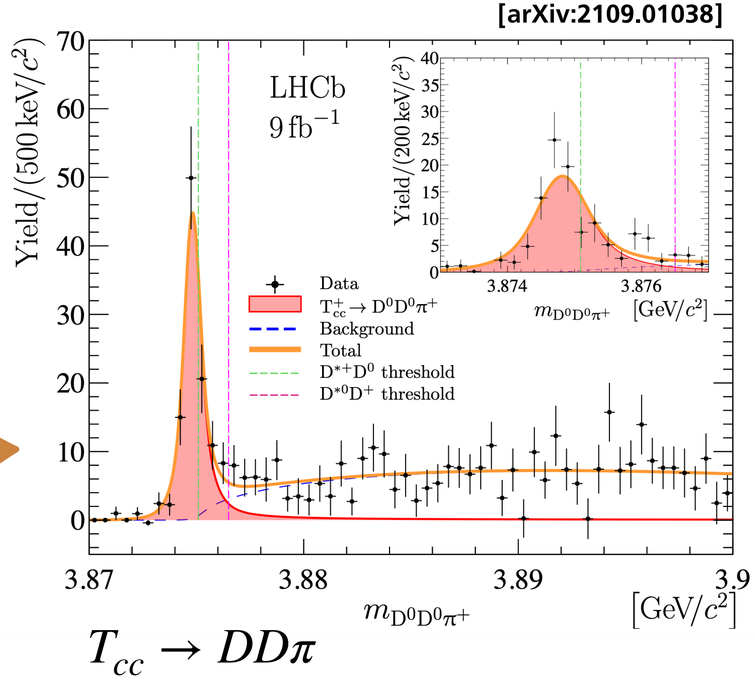


(+ Babar, Belle, COMPASS)

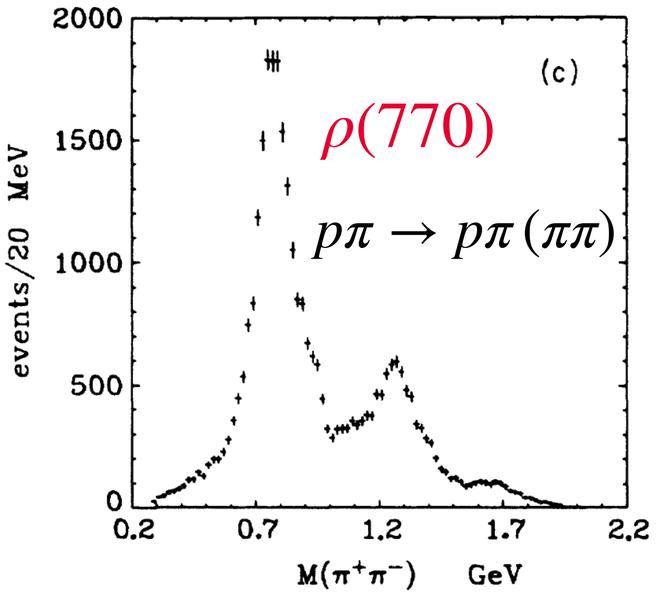
[arXiv:2109.01038]



Finite vs Infinite volume

Experiments

- Asymptotic states
- Direct access to cross section



[Protopopescu et al, PRD7 1973]

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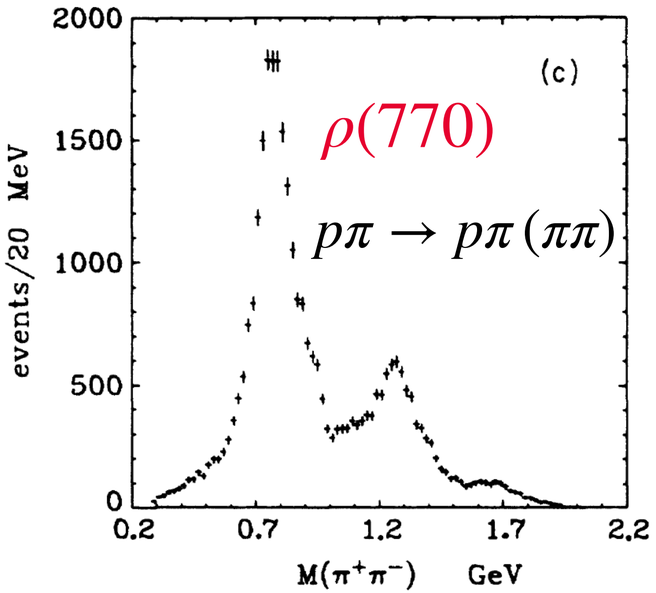
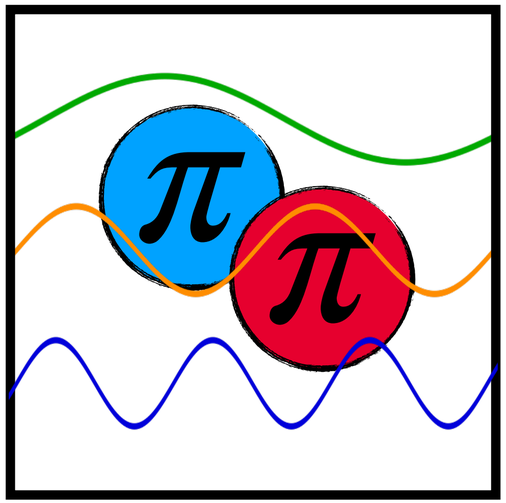


[Protopopescu et al, PRD7 1973]

Lattice QCD

- Euclidean time
- Stationary states in a box



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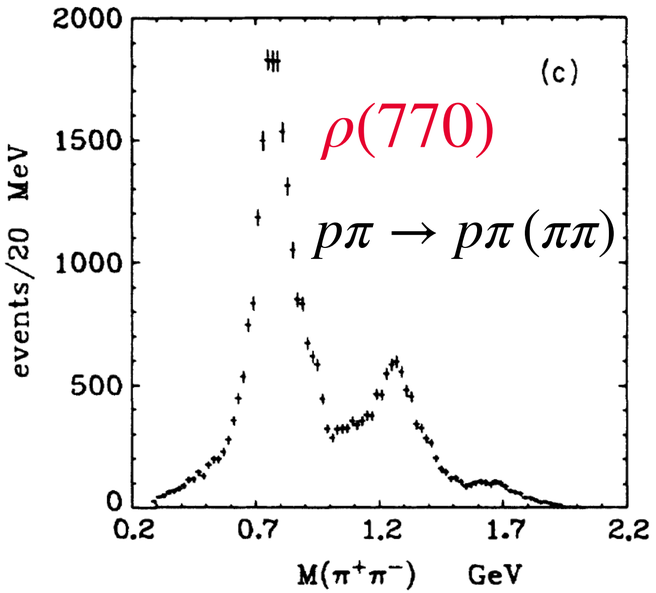

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Finite-volume formalism

[Lüscher, 89']

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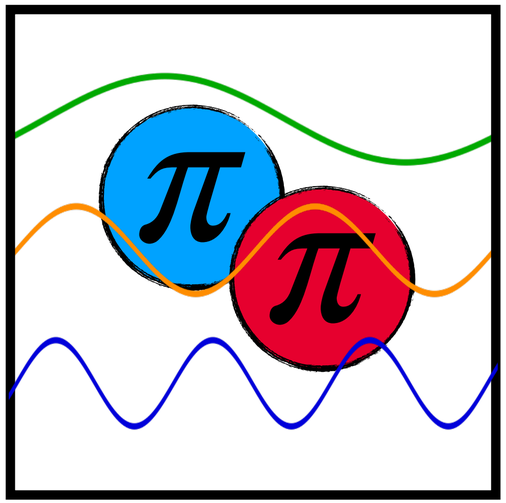

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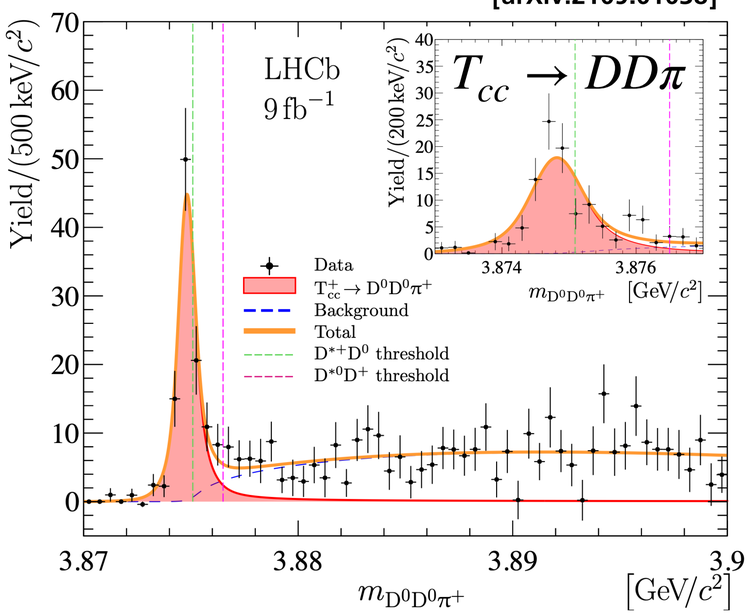

Finite-volume formalism

Need to include 3-body effects!

Lattice QCD

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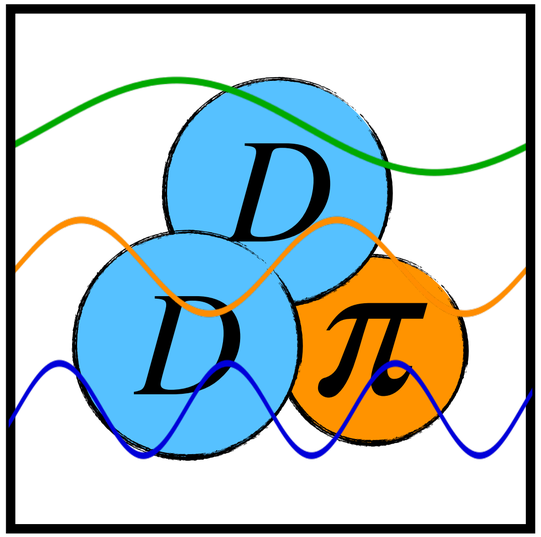


Outline

1) Scattering amplitudes from lattice QCD

2) Three-body strategy for the T_{cc}

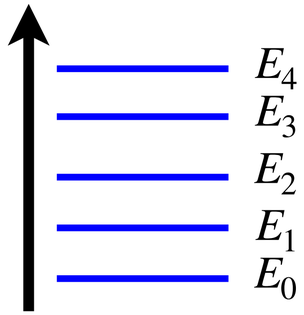
3) Testing the strategy

4) Towards a genuine three-body study of the T_{cc}

Scattering amplitudes from Lattice QCD

The general strategy

Spectrum



From Euclidean

Correlation functions

Quantization condition

$$\det_{\ell m}\left[F^{-1}+\mathcal{K}\right]=0$$

A bridge between:

finite volume ⟶ **infinite volume**

Infinite-volume scattering quantities

K matrix	Phase shift	Amplitude
$\mathcal{K}$	δ_ℓ	$\mathcal{M}$

Resonance poles

$$\mathcal{M}^{-1}(E_{\text{pole}})=0$$

Energy levels from lattice QCD

- The energy levels of the theory are measured from Euclidean correlation functions

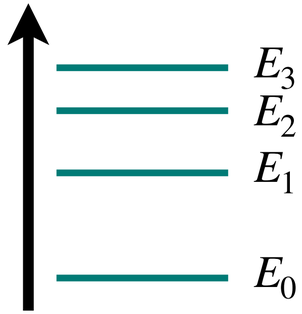
Energy levels from lattice QCD

- The energy levels of the theory are measured from Euclidean correlation functions
- Multiple operators with the same quantum numbers to obtain several energy levels

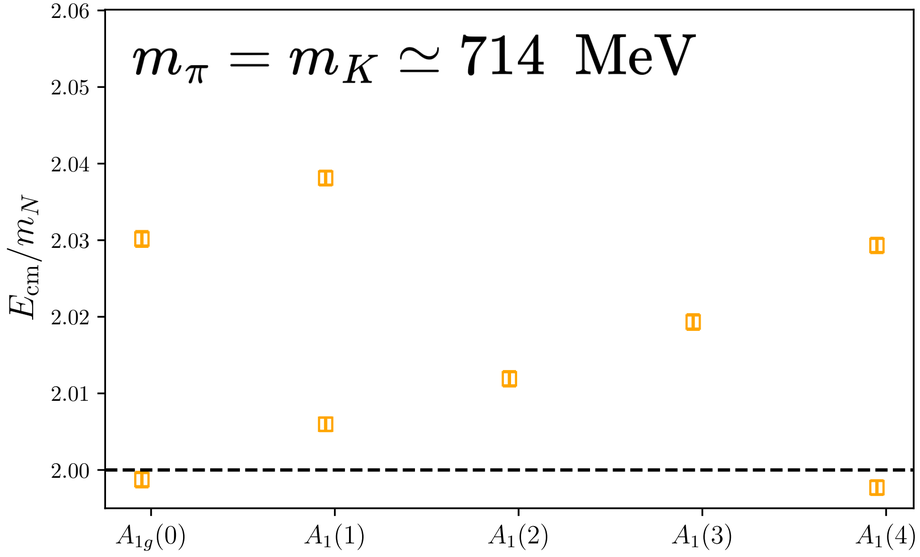
$$C_{ij}(t) = \langle \mathcal{O}_i(t) \mathcal{O}_j^\dagger(0) \rangle$$

$$C_{ij}(t) = \sum_n \langle 0 | \mathcal{O}_i | n \rangle \langle n | \mathcal{O}_j | 0 \rangle^* e^{-E_n t}$$

- (Generalized EigenValue Problem, GEVP)



Finite-volume energies of two neutrons in finite-volume

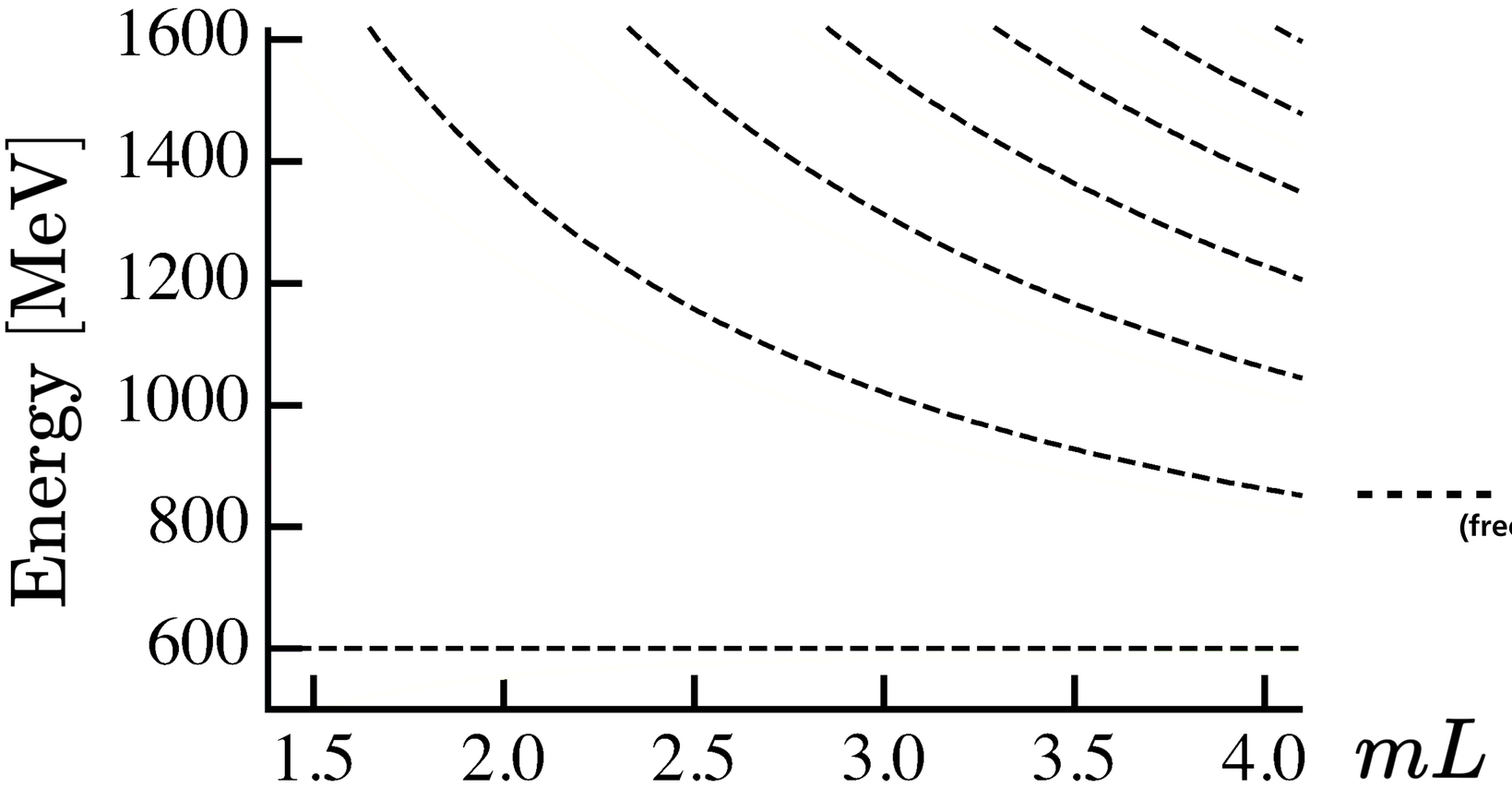


[Baryon Scattering Collaboration (arXiv:2505.0554)]

Key insight

Volume dependence of finite-volume energy states contains scattering information

[Lüscher 89']



Non-interacting case (free theory in finite volume) $\vec{p} = \frac{2\pi}{L}\vec{n}$

[Briceño, Dudek, Young, arXiv:1706.06223]

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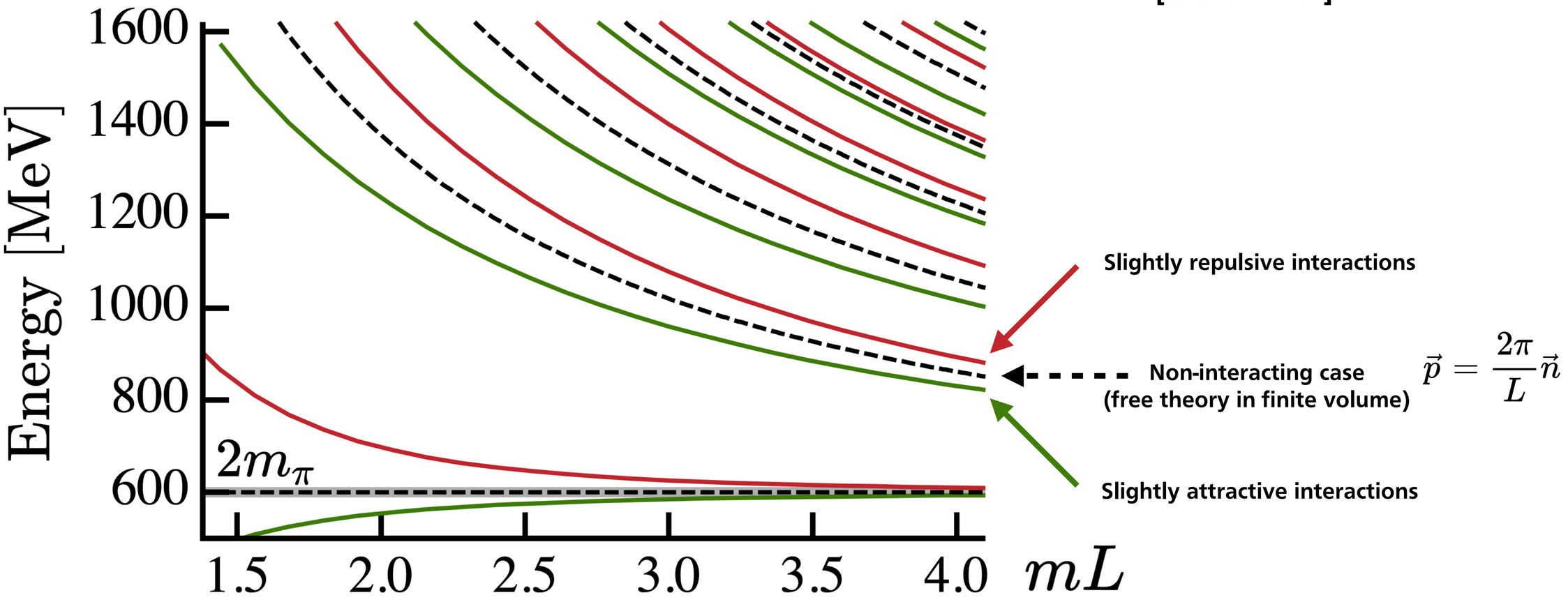

[Briceño, Dudek, Young, arXiv:1706.06223]

Example: two neutrons

Two neutrons in s-wave

$$\mathcal{K}_2^{s-\text{wave}}(E_n) = \frac{-1}{F_{00}(E_n, \vec{P}, L)}$$

$$\mathcal{K}_2^{s-\text{wave}} = \frac{16\pi\sqrt{s}}{q\cot\delta_0}$$

one energy level → a phase shift point

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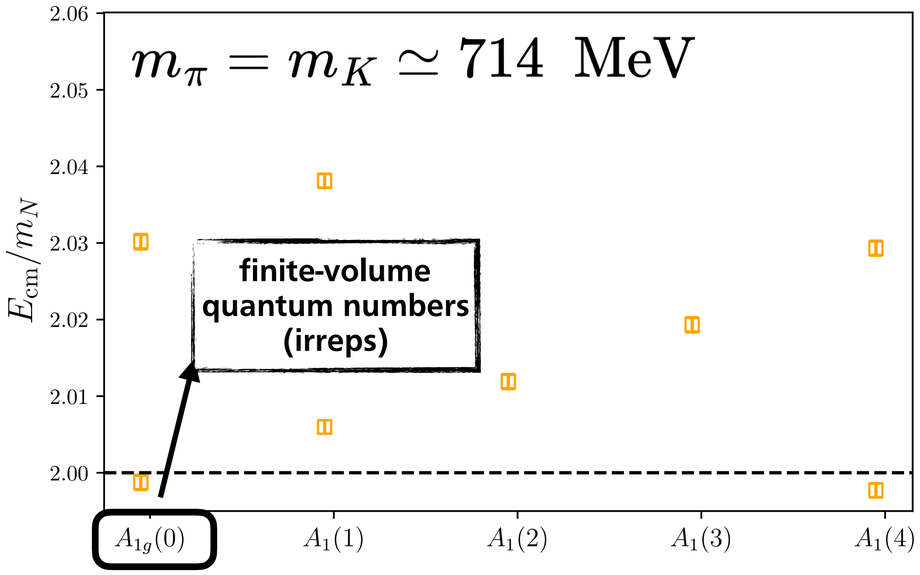

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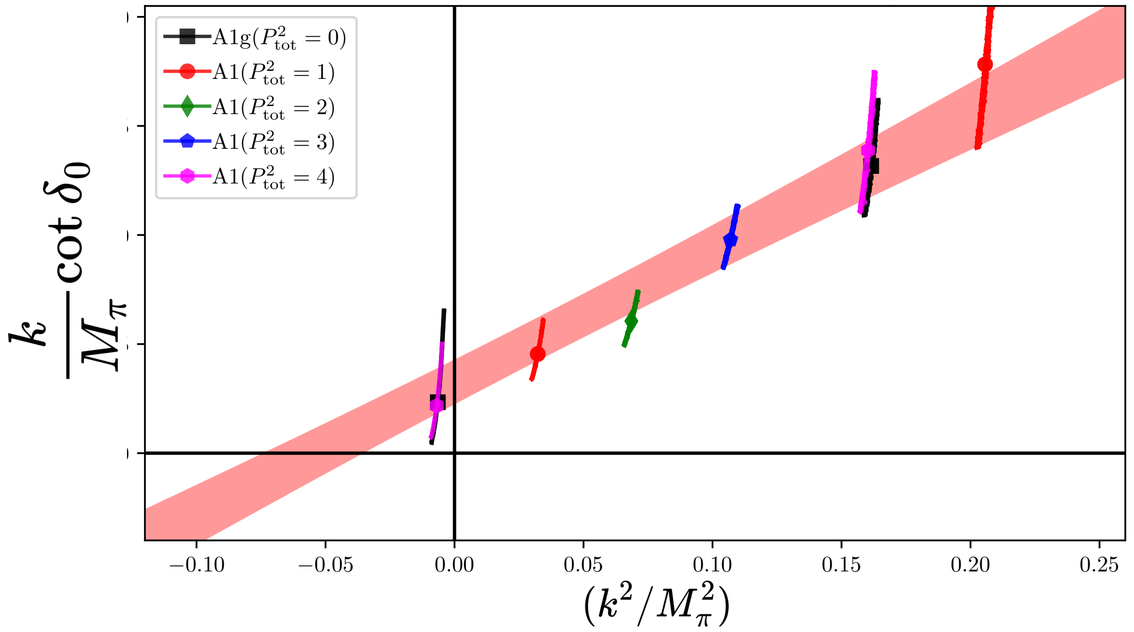
Phase shift of two-neutron scattering



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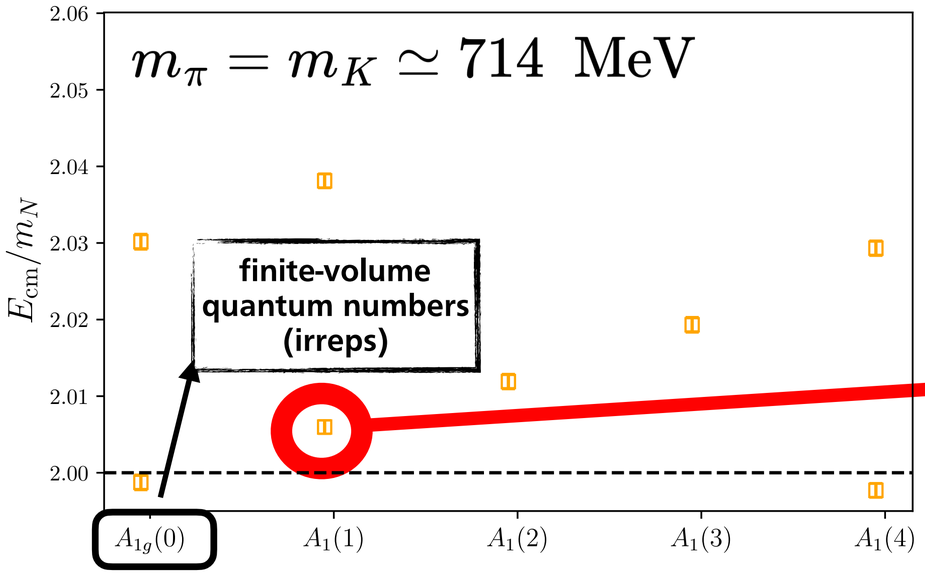

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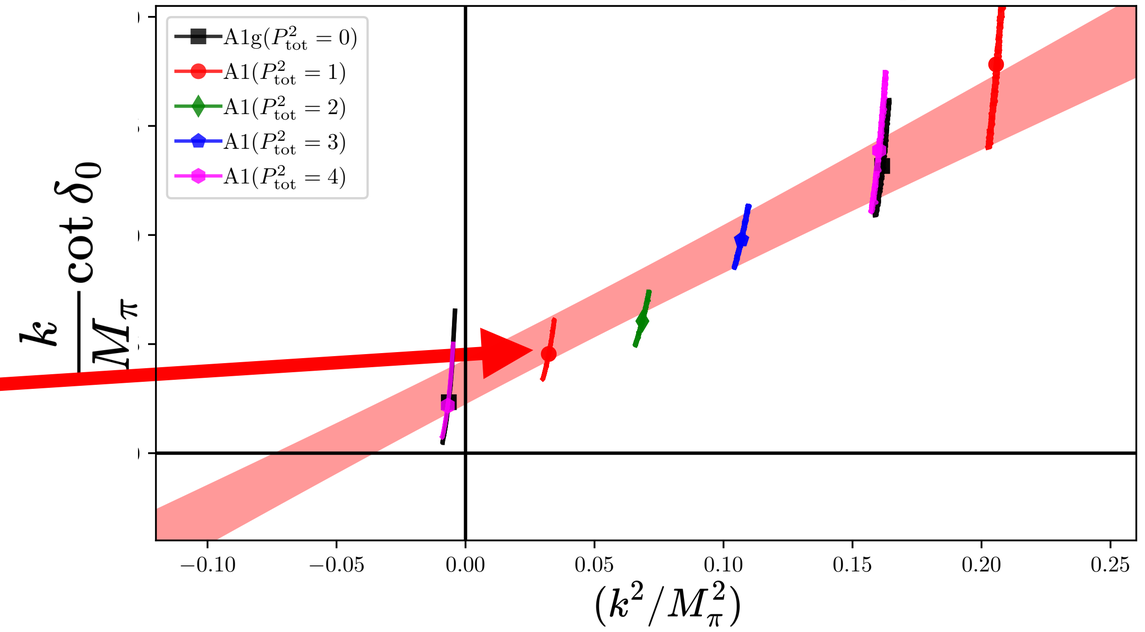

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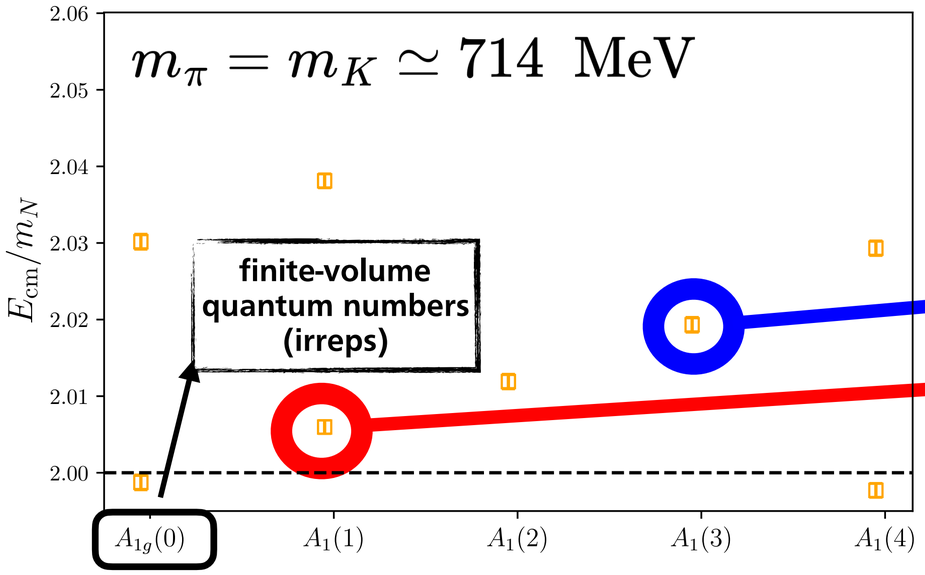

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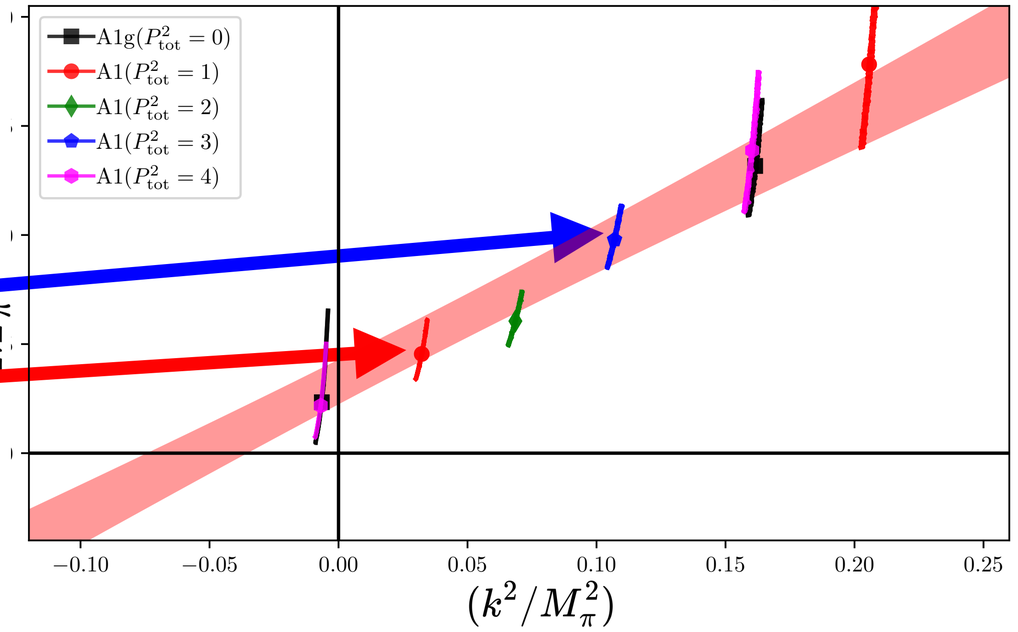

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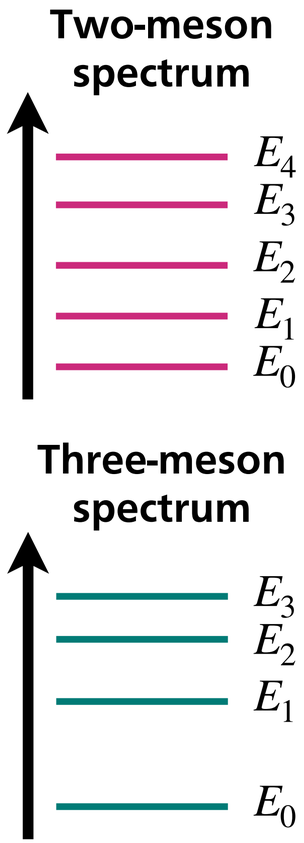
Three-hadron formalism

[Hansen, Sharpe, PRD 2014 & 2015]

See also: [Hammer, Pang, Rusetsky, JHEP 2017], [Mai, Döring, EPJA 2017]



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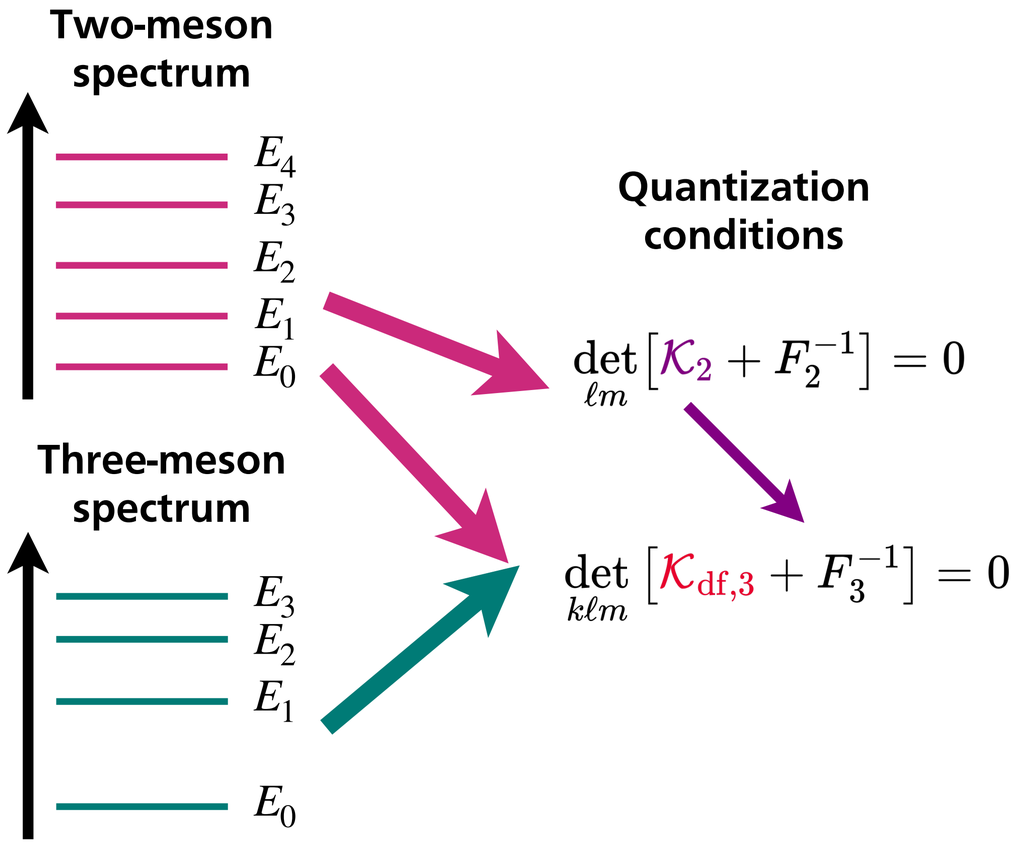

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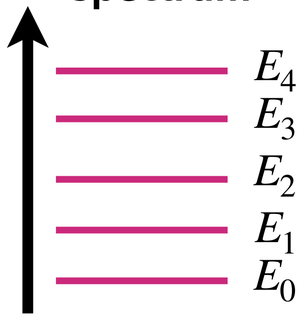
Two-meson spectrum



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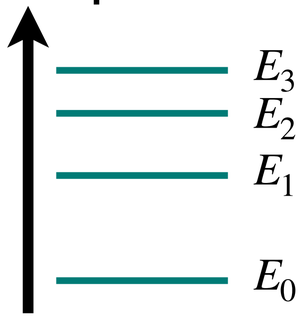

Quantization conditions

$$\det_{\ell m}\left[\mathcal{K}_2 + F_2^{-1}\right] = 0$$

$$\det_{k\ell m}\left[\mathcal{K}_{\mathrm{df},3} + F_3^{-1}\right] = 0$$

Fit

K-matrices

$\mathcal{K}_2$

$\mathcal{K}_{\mathrm{df},3}$

Parametrize:

$$\mathcal{K}_2 = c_0 + c_1 k^2 + \dots$$

$$\mathcal{K}_{\mathrm{df},3} = \mathcal{K}_{\mathrm{df},3}^{\mathrm{iso},0} + \mathcal{K}_{\mathrm{df},3}^{\mathrm{iso},1}\left(\frac{s - 9m^2}{9m^2}\right) + \dots$$

[Blanton, FRL, Sharpe, JHEP 2019]

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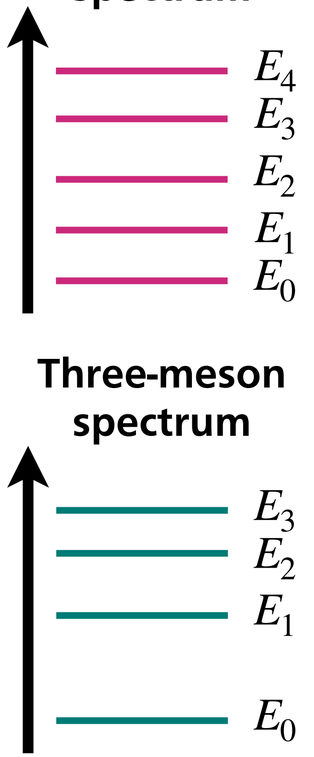
Three-meson spectrum



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$\mathcal{K}_2$

$\mathcal{K}_{\mathrm{df},3}$

Unitarity relations

Integral equations

[Briceño et al., PRD 2018]
[Hansen et al., PRL 2021]
[Jackura et al., PRD 2021]
[Dawid et al., 2303.04394]

Scattering amplitudes

$\mathcal{M}_2$

$\mathcal{M}_3$

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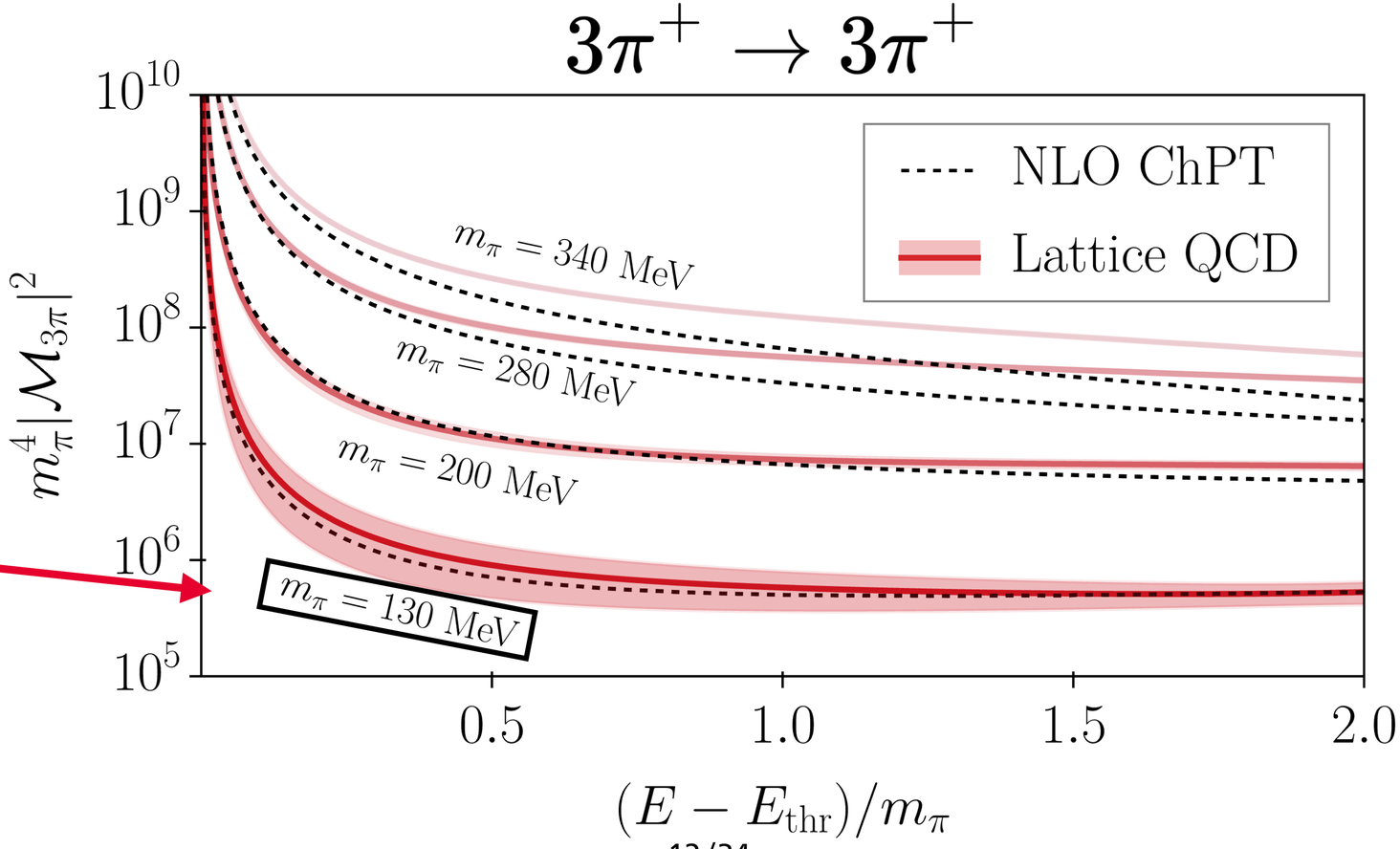
Application to three-pions

Study chiral dependence of the three-meson amplitudes for the first time!

[Dawid, Draper, Hanlon, Hörz, Morningstar, FRL, Sharpe, Skinner, arXiv:2502.17976,2502.13978]

Physical-point three-pion scattering amplitude!



Three-body strategy for the T_{cc}



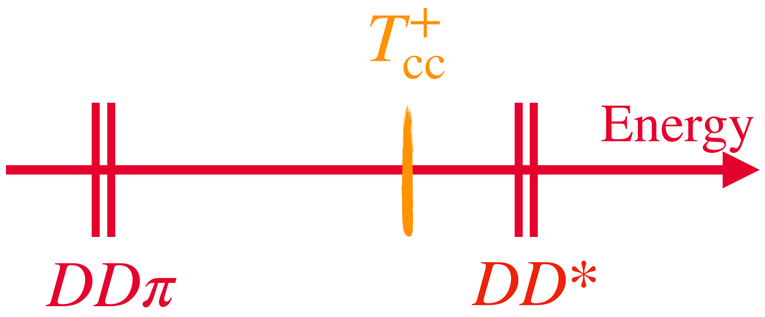
Max Hansen (U. Edinburgh)



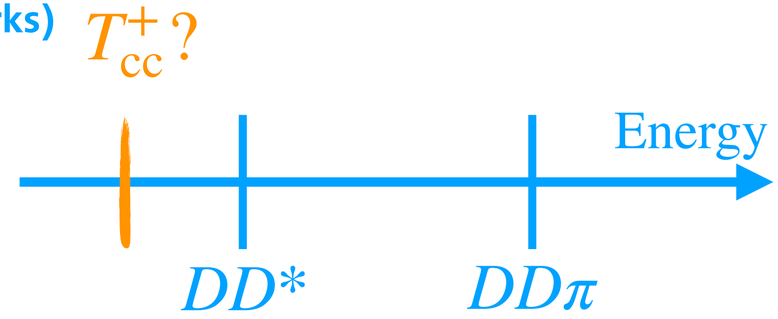
Steve Sharpe (UW)

Doubly-charmed tetraquark

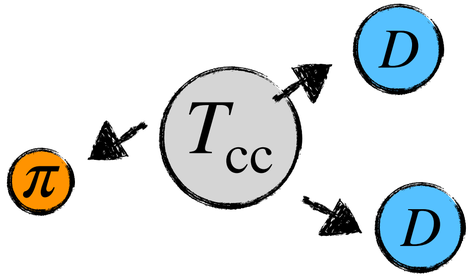
Experiment



N_f=2+1+1 QCD
(heavier quarks)

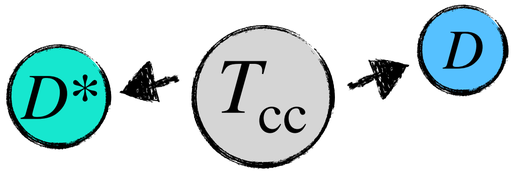


- For physical quark masses is a three-body resonance



need three-body formalism!

- Stable D* at slightly heavier-than-physical quark mases



suitable for the two-body finite-volume formalism?

DD* scattering

- **Several works study the T_{cc} channel in this setup**

  [Chen et al., 2206.06185] [Lyu et al. (HALQCD), 2302.04505]
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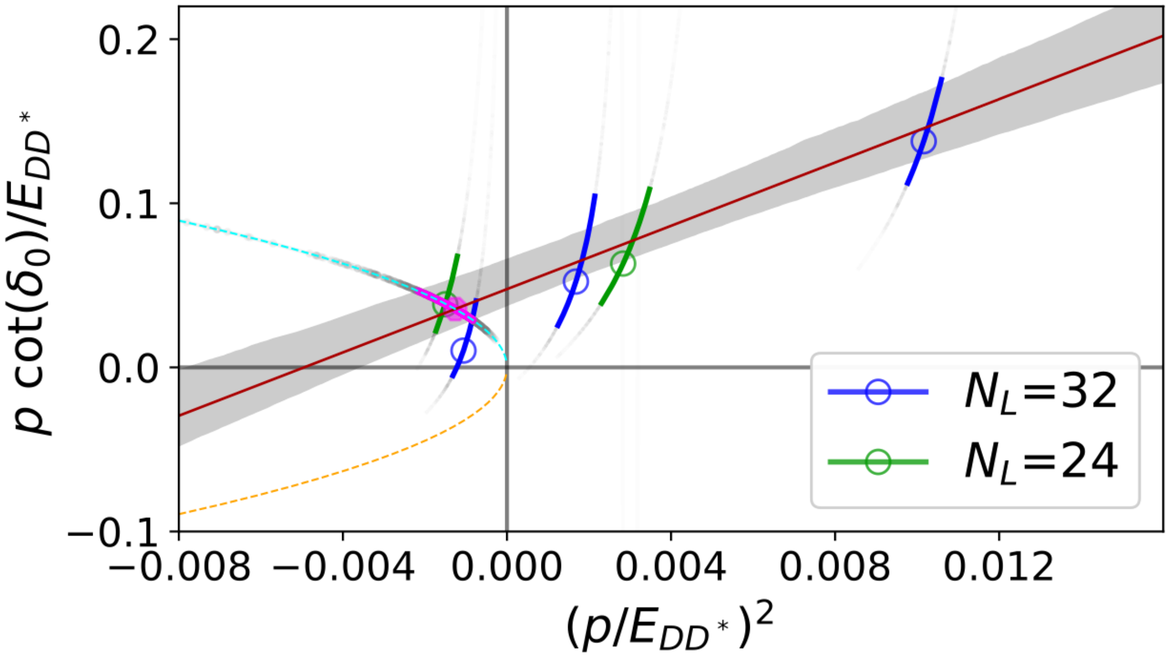
  [Whyte, Thomas, Wilson, 2405.15741]

  - **Signature of virtual bound state?**



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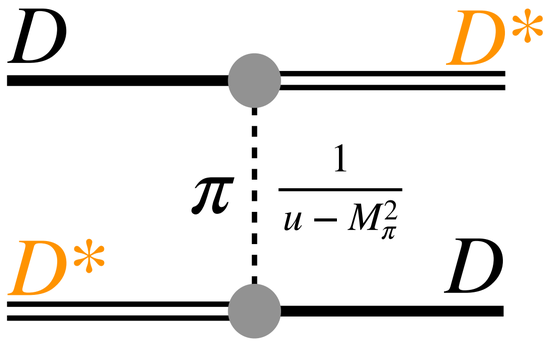
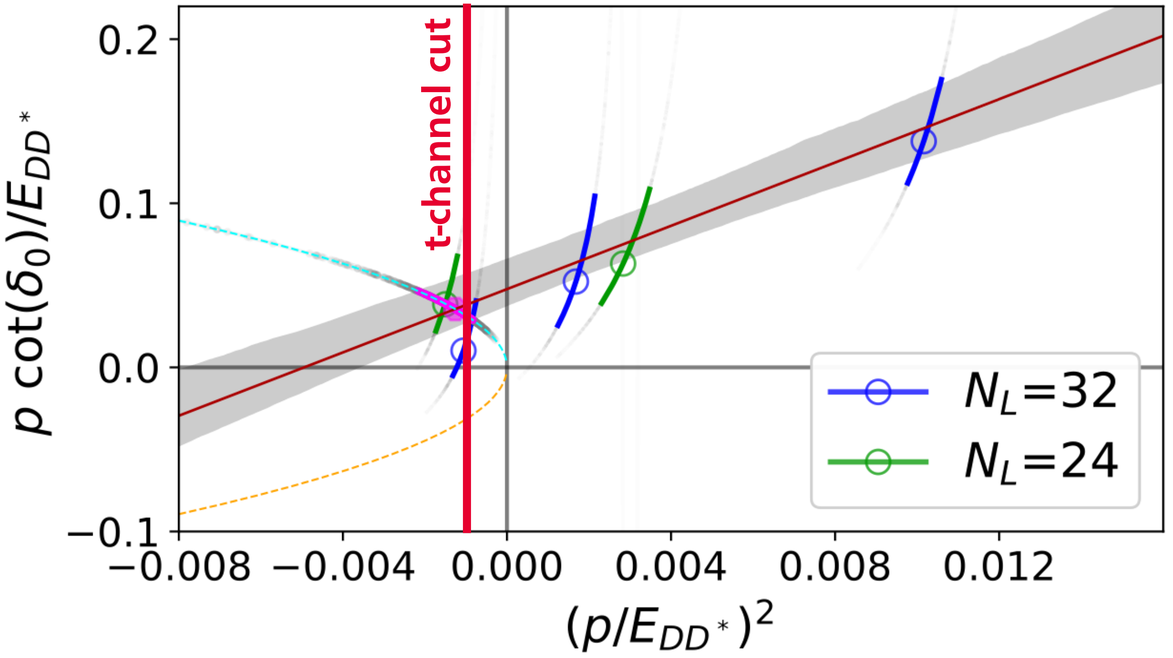
  - But two-particle formalism breaks down
    i.e. complex phase shift

! one-pion exchange creates non-analytic behavior:





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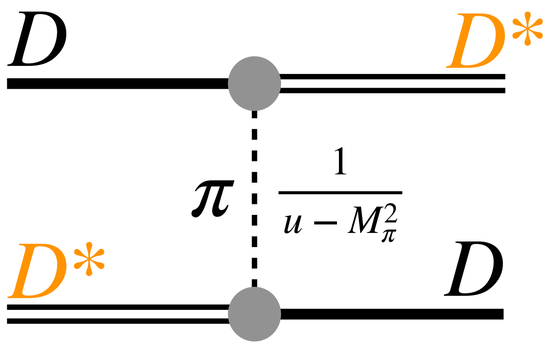
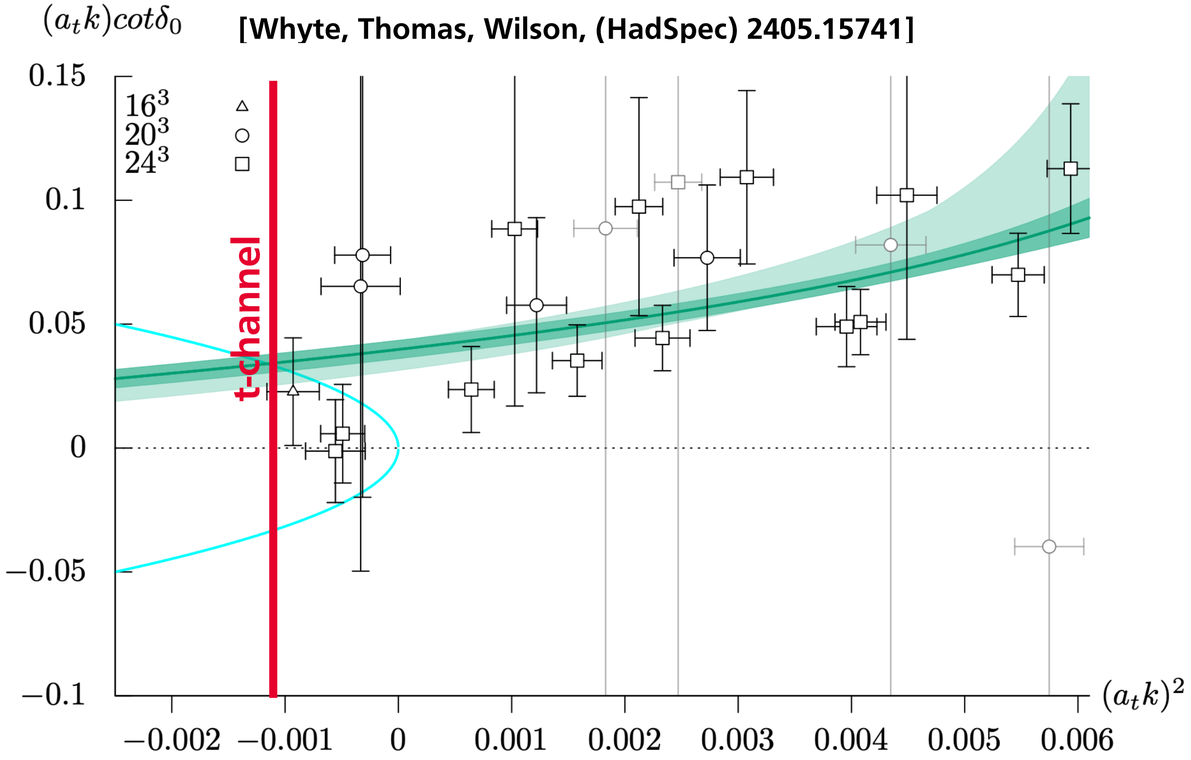


[Whyte, Thomas, Wilson, (HadSpec) 2405.15741]



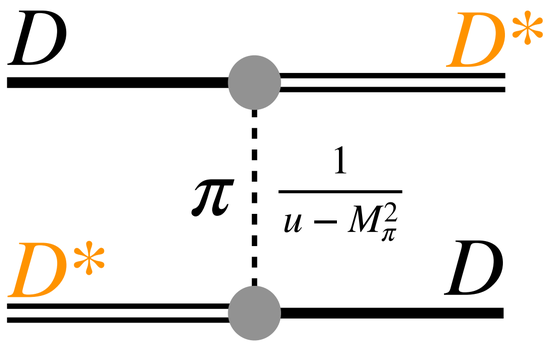
DD* scattering

- **Several works study the T_{cc} channel in this setup**

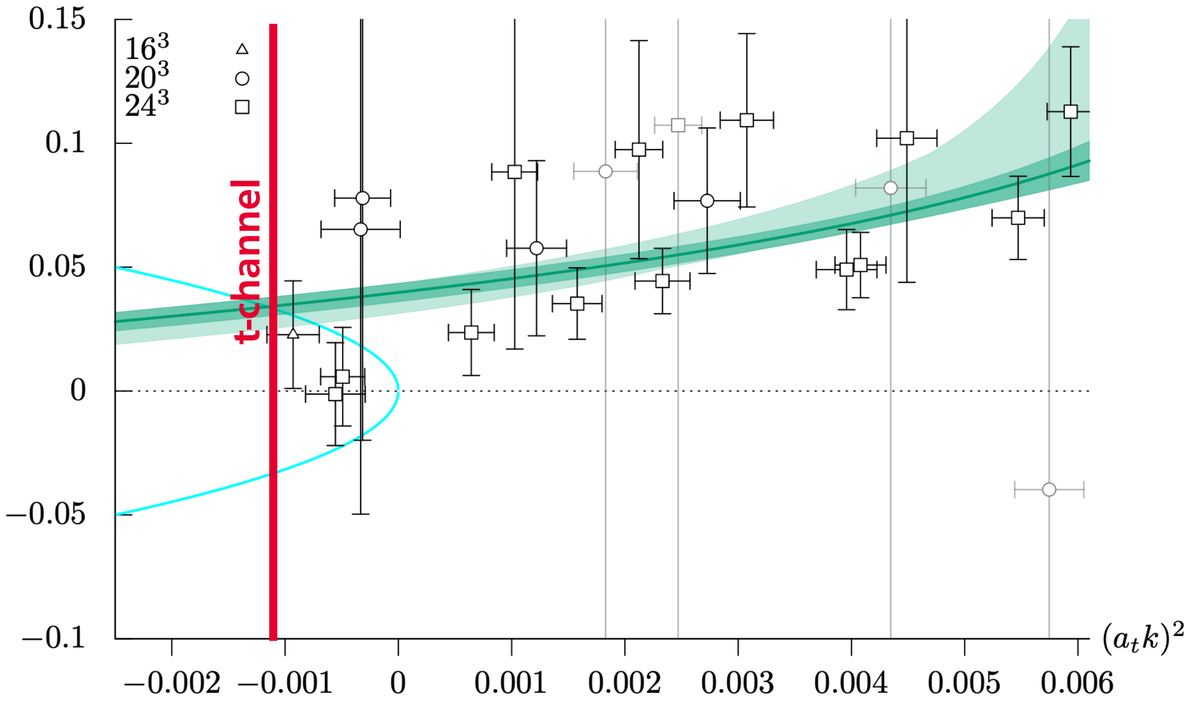
  [Chen et al., 2206.06185] [Lyu et al. (HALQCD), 2302.04505]
  [Padmanath & Prelovsek, 2202.10110] [Collins et al., 2402.14715]
  [Whyte, Thomas, Wilson, 2405.15741]

  - **Signature of virtual bound state?**
  - **But two-particle formalism breaks down**
    i.e. complex phase shift

- **! one-pion exchange creates non-analytic behavior:**



$(a_t k) cot\delta_0$ [Whyte, Thomas, Wilson, (HadSpec) 2405.15741]



Several solution have been proposed and tested

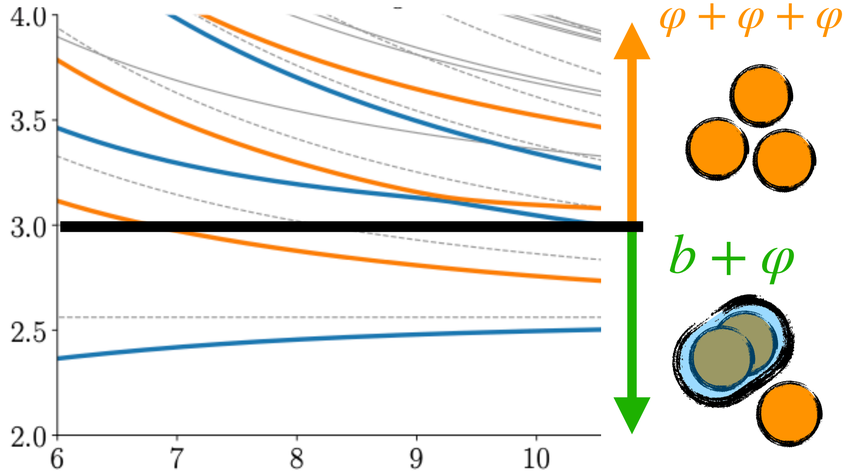
[Du et al (2408.09375), Abolnikov et al. (2407.04649), Bubna et al. (2402.12985),
Meng et al. (2312.01930), Baiao-Raposo, Hansen (2311.18793), Dawid et al (2411.15730)]

A three-body solution

- In the presence of a two-body bound state:
  - Below the three-particle threshold, effective “particle-dimer”

    [FRL et al 2302.04505] [Jackura et al 2010.09820]
    [Dawid, Islam, Briceño, 2303.04394]
    [Briceño, Jackura, Pefkou, FRL 2402.12167]

[FRL, Sharpe, Blanton, Briceño, Hansen 1908.02411]



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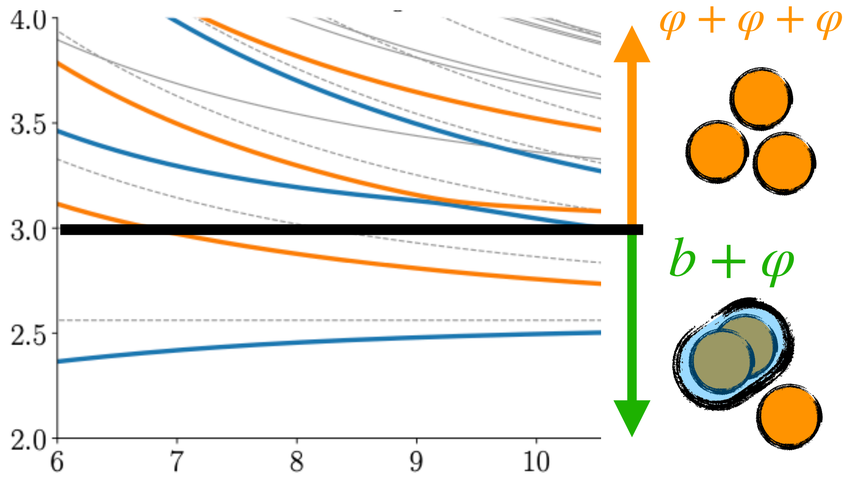
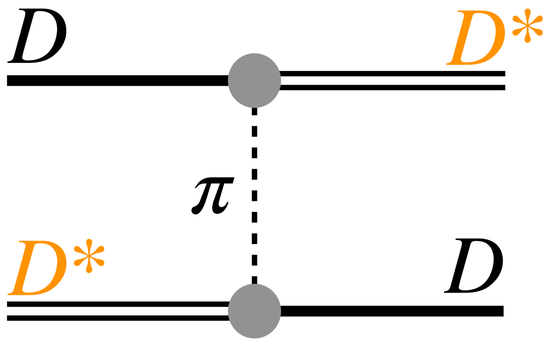
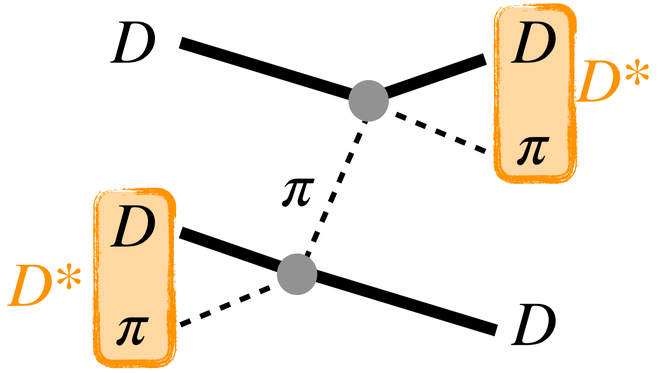


- This solves the left-hand cut problem:
  - Finite-volume effects from one-pion exchange naturally incorporated



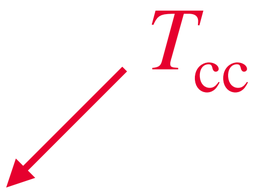
[Hansen, FRL, Sharpe, arXiv:2401.06609]



Three-particle formalism

- The doubly-charmed tetraquark arises in coupled $DD\pi$ scattering

$$D^0 D^0 \pi^+ \quad D^+ D^0 \pi^0 \quad D^+ D^+ \pi^-$$



- Three isospin channels $\mathbf{1/2} \otimes \mathbf{1/2} \otimes \mathbf{1} \longrightarrow \mathbf{2} \oplus \mathbf{1} \oplus \mathbf{1} \oplus \mathbf{0}$

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T_{cc}

- Three isospin channels $\mathbf{1/2} \otimes \mathbf{1/2} \otimes \mathbf{1} \longrightarrow \mathbf{2} \oplus \mathbf{1} \oplus \mathbf{1} \oplus \mathbf{0}$

- Formalism factorizes in three-meson isospin:

$$\prod_{I \in \{0,1,2\}} \det_{i,k,\ell,m} \left[1 + \widehat{\mathcal{K}}_{\mathrm{df},3}^{[I]} \widehat{F}_3^{[I]} \right] = 0$$

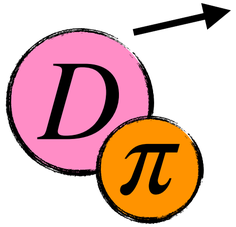
- Isospin 0 equations are formally identical to those for $K^+K^+\pi^+$ systems [Blanton, Sharpe (2105.12094)]
  - Already implemented and tested! [Blanton, FRL, Sharpe (2111.12734)]
  - Need two-meson interactions →

$$\widehat{\mathcal{K}}_{2,L}^{[I=0]} = \mathrm{diag}\left(\overline{\mathcal{K}}_{2,L}^{D\pi,I=1/2}, \frac{1}{2} \overline{\mathcal{K}}_{2,L}^{DD,I=1} \right)$$

T_{cc} pipeline

Two-meson spectrum

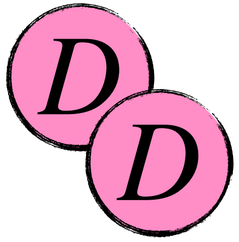
$I_{D\pi} = 1/2$



s and p waves

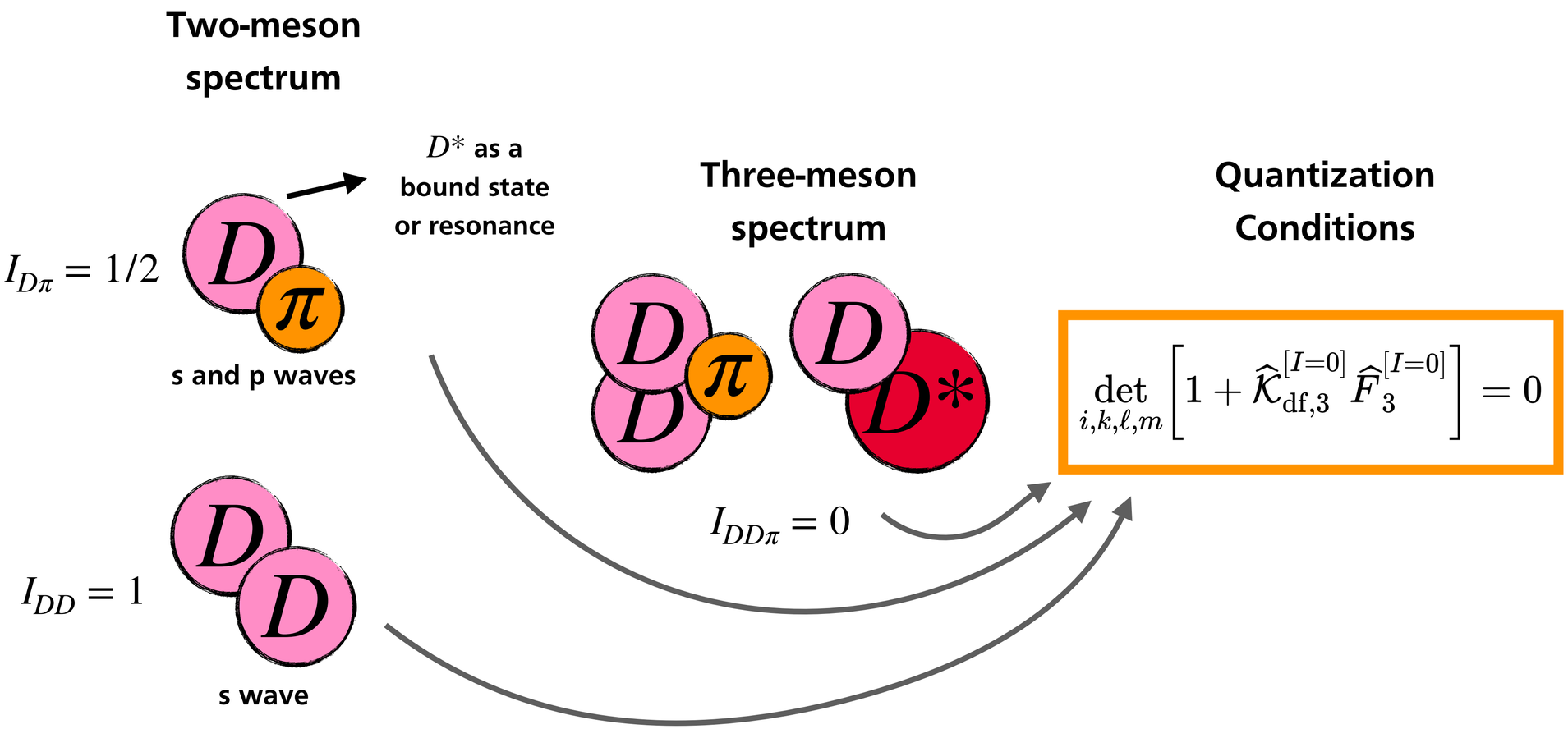
D^* **as a bound state or resonance**

$I_{DD} = 1$



s wave

T_{cc} pipeline



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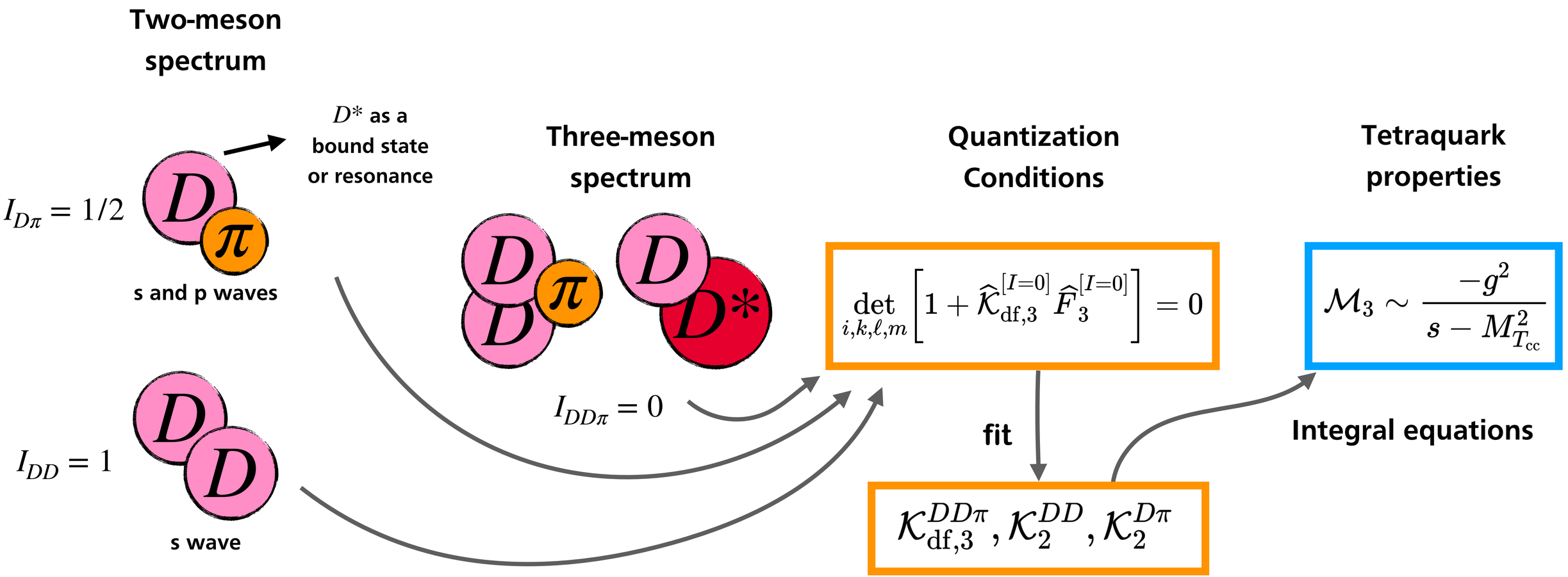

Testing the three-body strategy



Sebastian Dawid (Indiana)



Steve Sharpe (UW)

Three-body strategy

- Applying the three-body formalism requires $DD^*/DD\pi$ energies, as well as DD and $D\pi$ energies
- Published data only provides DD^* energies
  [Padmanath, Prelovsek, 2202.10110] Note: this data has been superseded [Prelovsek et al 2504.03473], but still good for testing!
- For now, fix $D\pi$ and DD interactions from "educated guesses"
  - EFT and lattice results
  - Neglect DD interactions

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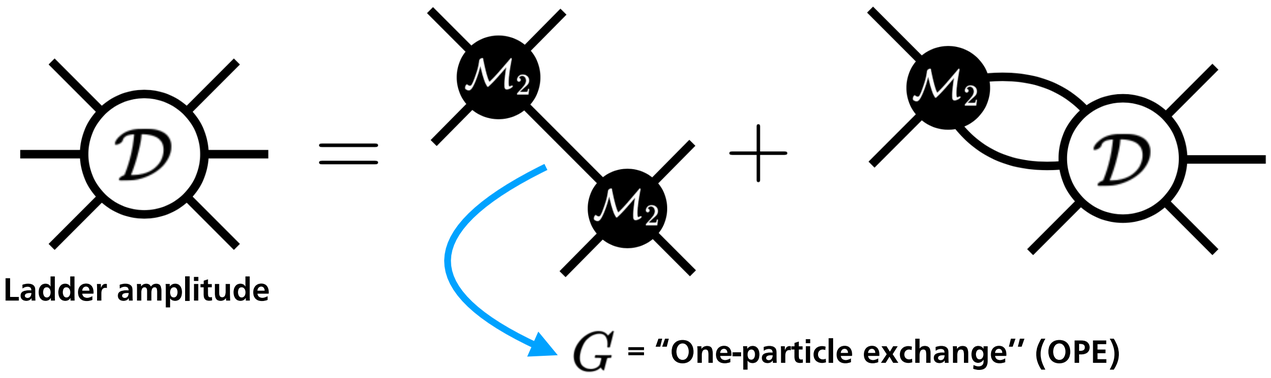
  - EFT and lattice results
  - Neglect DD interactions
- Fix three-body couplings by matching DD^* phase shift to predictions from the three-body formalism

$$\mathcal{K}_2^{D\pi}, \mathcal{K}_2^{DD} \\ \mathcal{K}_3 \xrightarrow{\text{Predict}} k \cot \delta_0^{DD^*} \xrightarrow{\text{Match}} \text{Lattice QCD data}$$

[Padmanath, Prelovsek, 2202.10110]

DDπ integral equations

- We need to solve an integral equation $\mathcal{D} = -\mathcal{M}_2 G \mathcal{M}_2 - \int \mathcal{M}_2 G \mathcal{D}$



Ladder amplitude

G = "One-particle exchange" (OPE)

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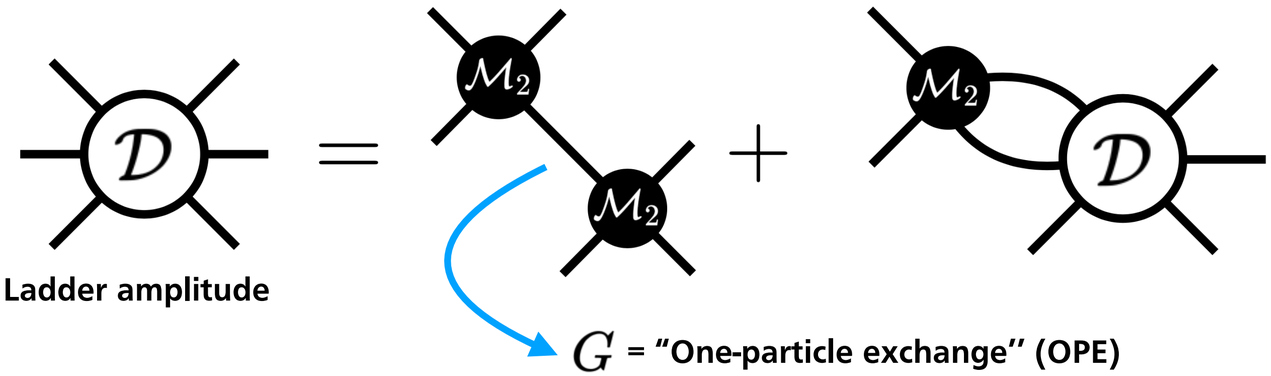

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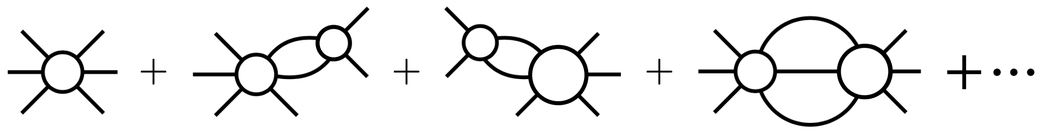
- Three-body forces also included

$$\mathcal{M}_3^{DD\pi} = \mathcal{D} +$$ 

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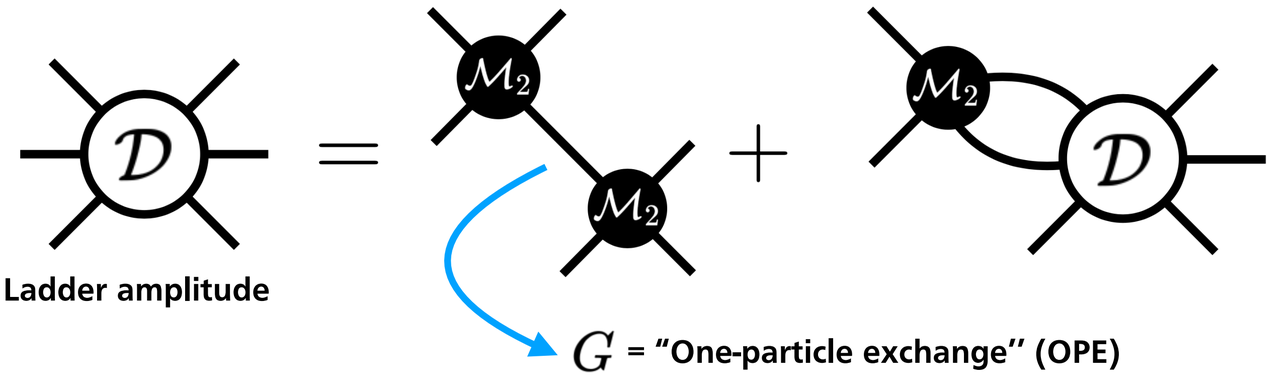

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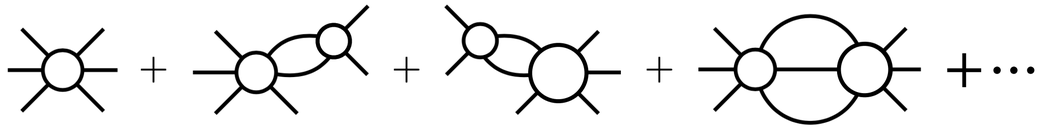
$$\mathcal{M}_3^{DD\pi} = \mathcal{D} + \text{} + \cdots$$

- The DD* amplitude can be obtained using the LSZ reduction formula

$$\mathcal{M}_{DD^*} = \lim_{s_{2p}, s_{2k} \to m_{D^*}^2} \left(s_{2p} - m_{D^*}^2\right) \mathcal{M}_3^{DD\pi}(s, k, p) \left(s_{2k} - m_{D^*}^2\right)$$

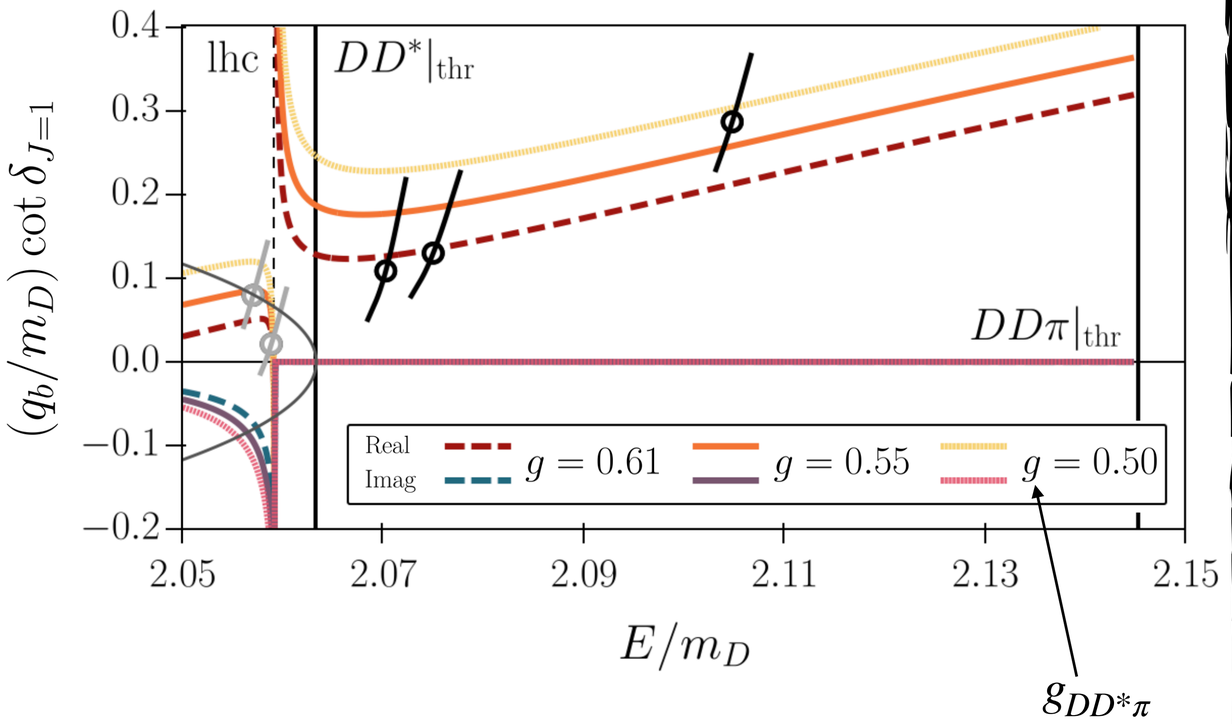
Three-body analysis

[S. Dawid, FRL, S. Sharpe, arXiv:2409.17059]

- Only “free” parameter in the three-body K matrix

$$\mathcal{K}_{\mathrm{df},3} = \mathcal{K}_E(p_\pi - p'_\pi)^2$$

$J^P=1^+$ (T_{cc} channel)



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$$M_{T_{cc}}/M_D = \begin{array}{c|c|c} g = 0.50 & g = 0.55 & g = 0.61 \\ \hline 2.05755 \pm 0.00457\,i & 2.05396 \pm 0.00589\,i & 2.04941 \pm 0.00662\,i \end{array}$$

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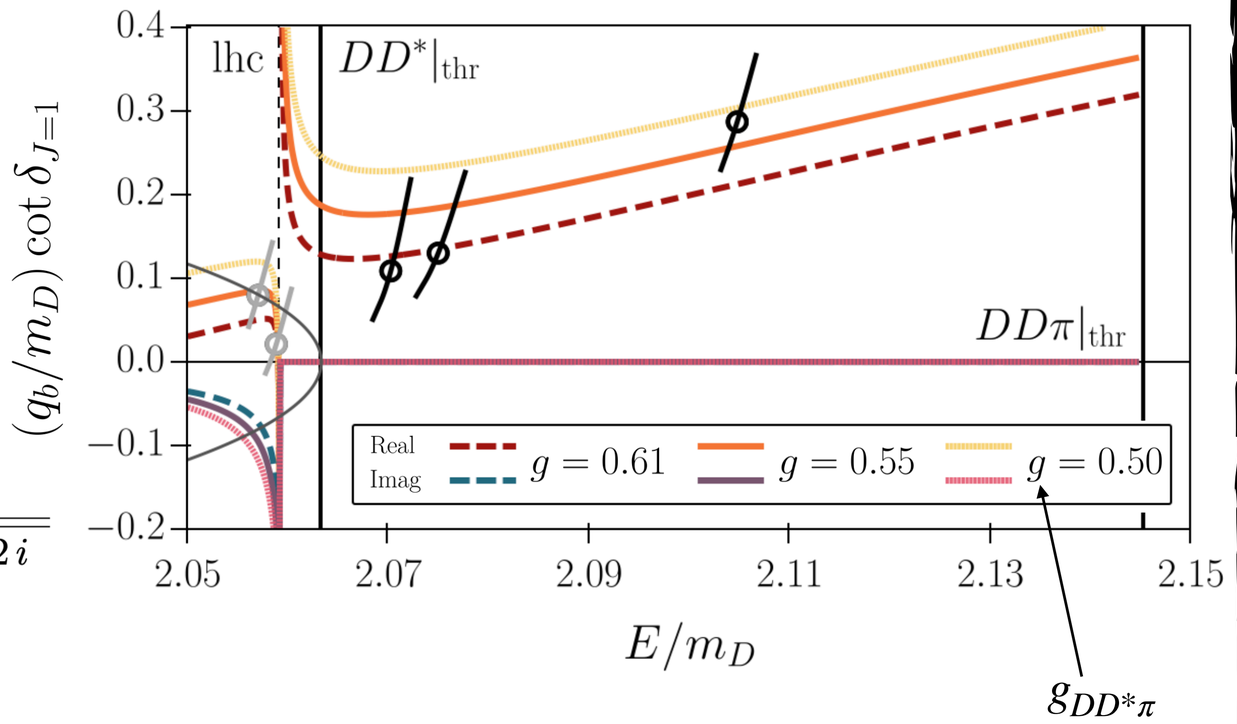

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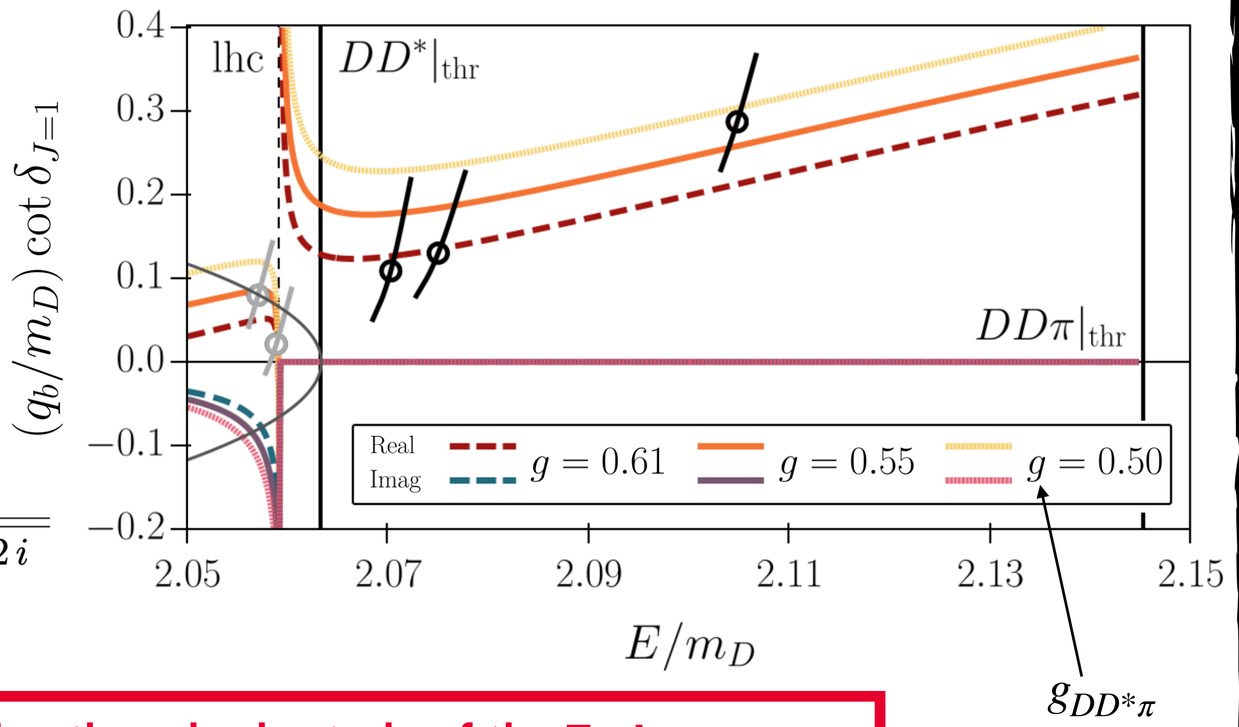


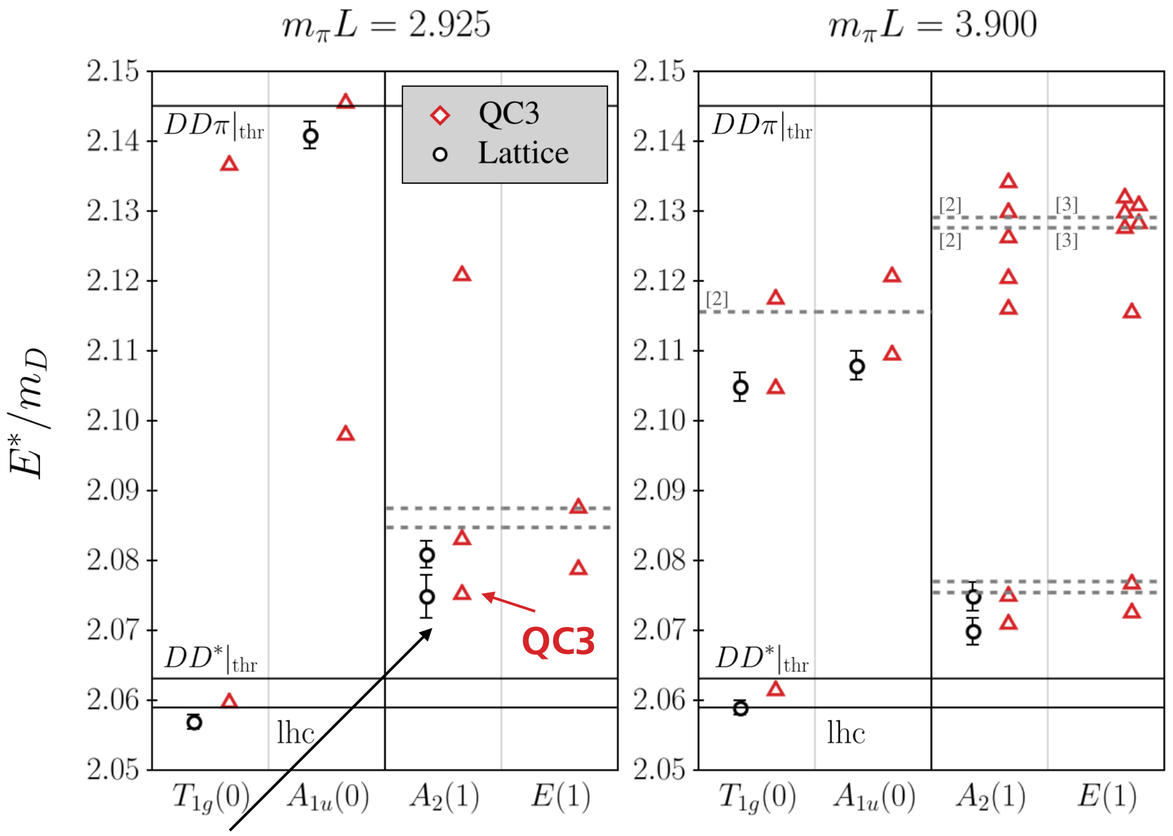
Moving forward, we need a genuine three-body study of the T_{cc} !

- DD and $D\pi$ calculation on the same ensemble
- $DD\pi$ operators in lattice QCD calculations

The finite-volume spectrum

- Expected vs measured finite-volume spectrum
- Qualitatively, many levels agree
  - Several irreps and thus partial waves

[S. Dawid, FRL, S. Sharpe, arXiv:2409.17059]



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[Padmanath, Prelovsek, 2202.10110]

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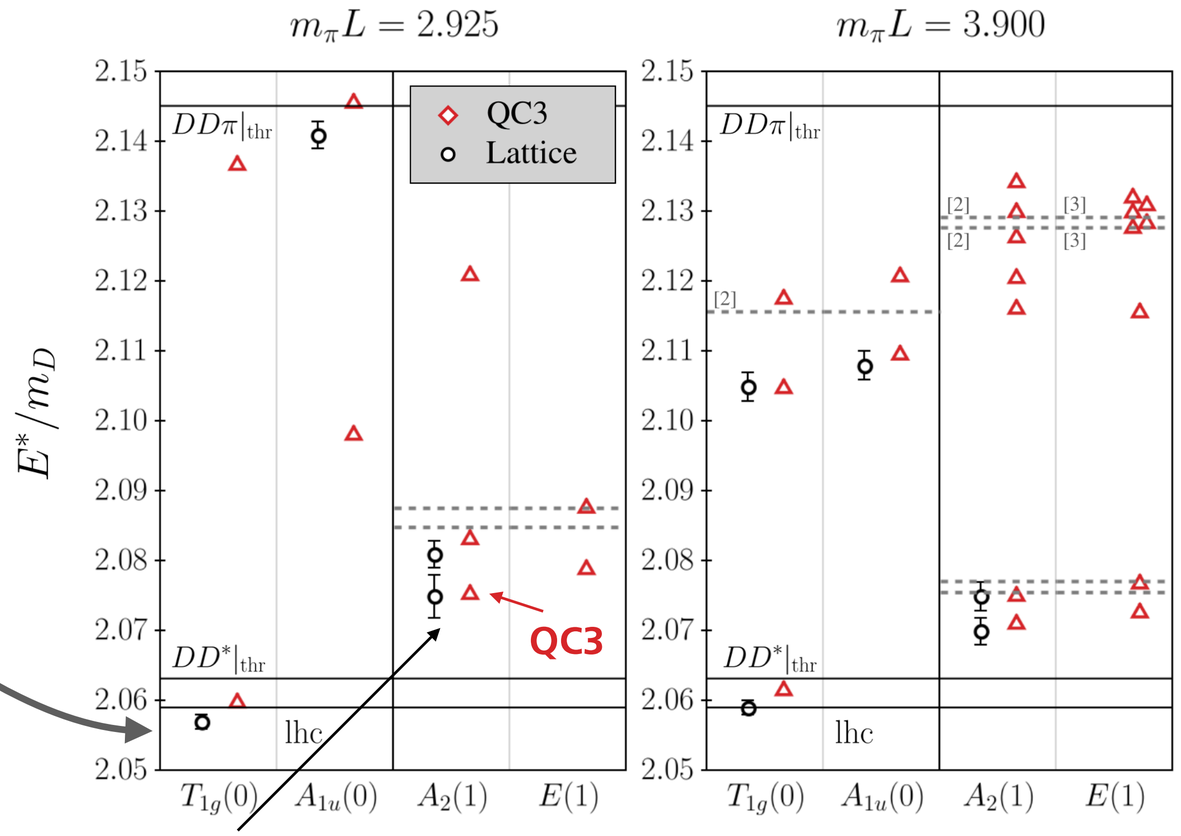

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The finite-volume spectrum

- Expected vs measured finite-volume spectrum
- Qualitatively, many levels agree
  - Several irreps and thus partial waves
- Lowest energy near left-hand cut
- Strong indication for a missed state
  - $A_{1u}(0)$ level is "DDπ - like"

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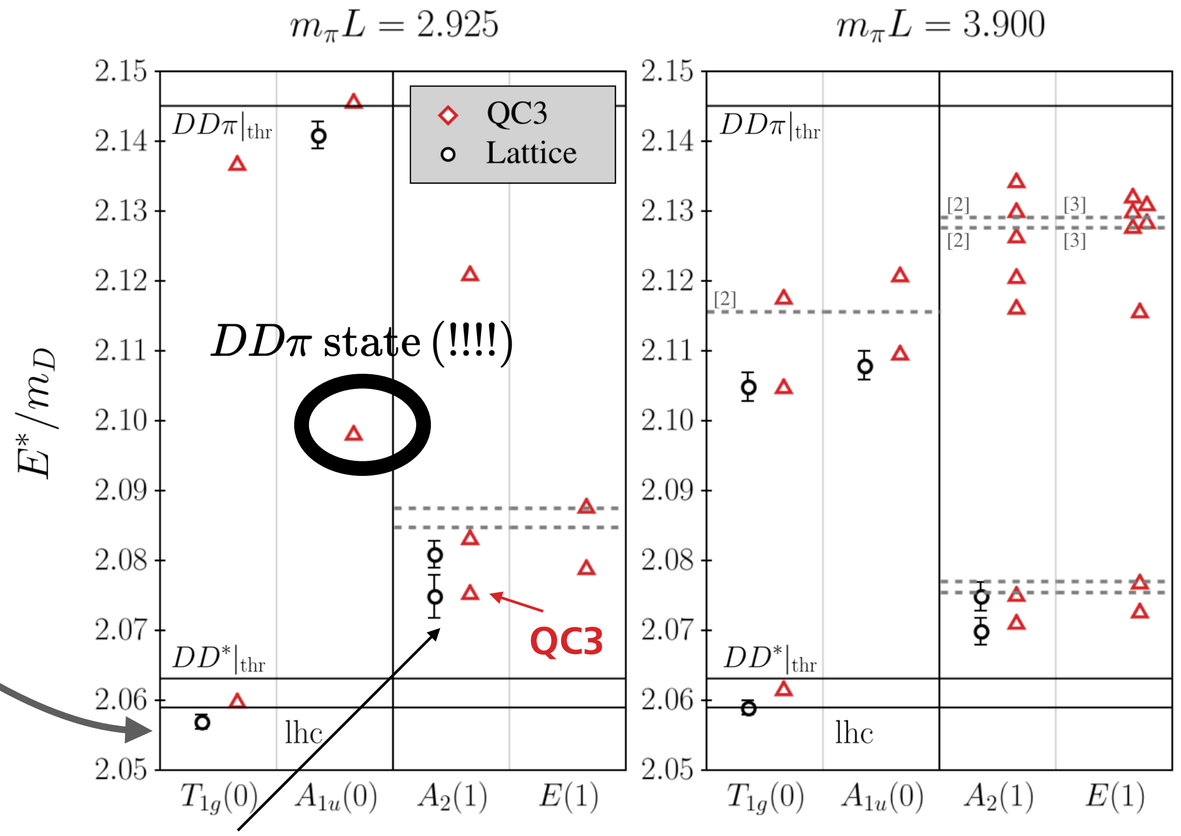

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Comparing approaches

[S. Dawid, FRL, S. Sharpe, arXiv:2505.05466]

- Different approaches have been used to study the Tcc.
  - Three-body relativistic field-theoretic approach (RFT)
    [Hansen, FRL, Sharpe, arXiv:2401.06609]
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  - Chiral EFT / Lippmann-Schwinger (LS)
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- Equivalence by matching the short-range parameters
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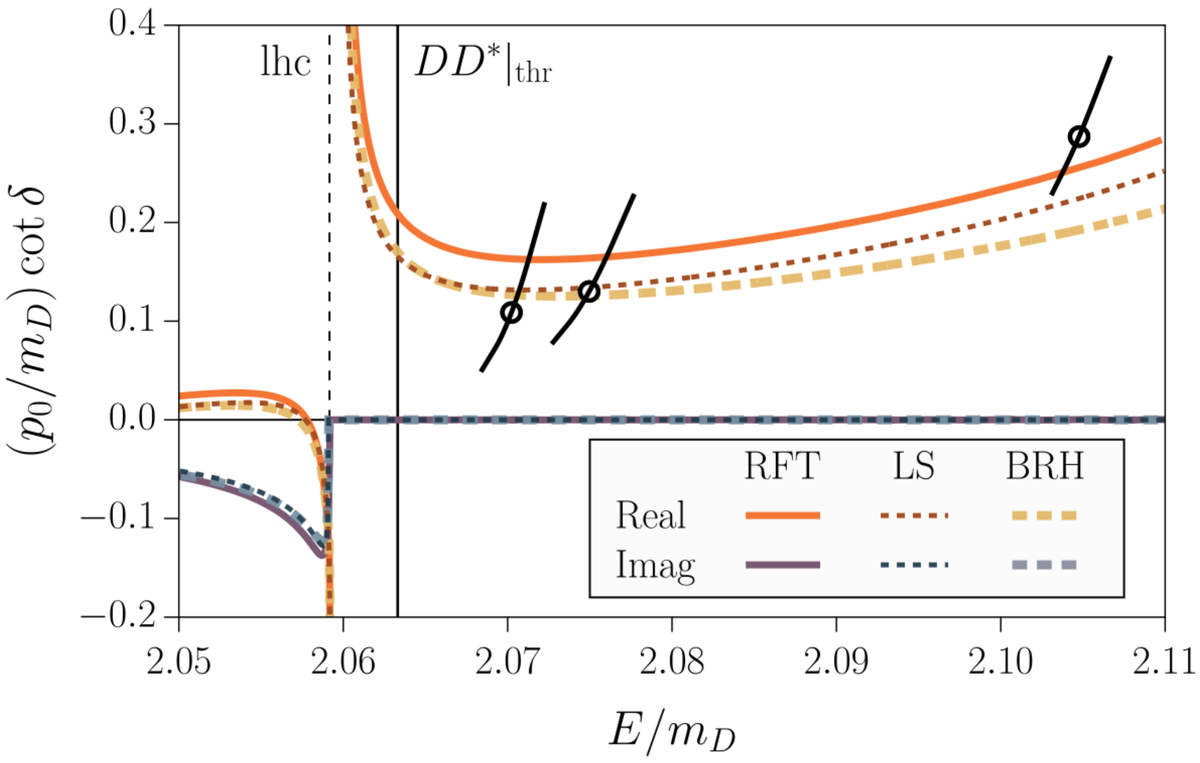

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- They are equivalent for a stable D*
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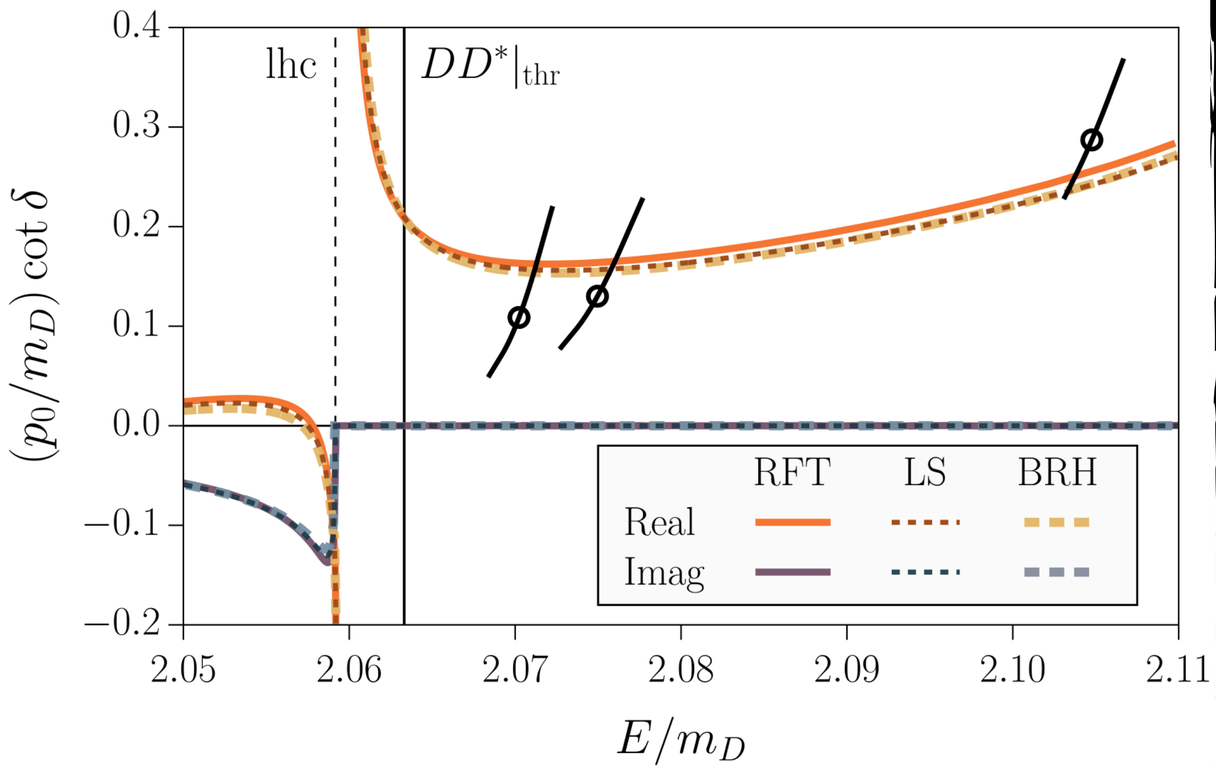
  - Numerical matching agrees very well.



Towards a genuine three-body study






Herzallah Alharazin (Bochum) **Andre Baiao-Raposo (Bochum)** **Miguel Salg (Bern)** **Andres Stump (U. Humboldt)**

+ John Bulava, Sebastian Dawid, Jeremy Green, Colin Morningstar, Steve Sharpe

Doubly-charmed tetraquark

Goal: a genuine three-body study of the Tcc from lattice QCD

- **We use two $N_f = 2 + 1$ ensembles with $m_\pi \approx 280\,\mathrm{MeV}$ and different volume**
- **Charm quark mass tuned so that D mass is average of physical D^0, D^+, D_s^+ masses**
- **We use distillation to compute correlators, QUDA-LAPH is used for perambulators**

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



Preliminary results presented by Andre Baião-Raposo @ Lat25

	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

Operators

- We use a selection of tetraquark, two-meson and three-meson operators

$DD\pi$ / DD^* in $I = 0$: **bilocal/trilocal operators** DD^* , D^*D^* , D_0^*D , $D_0^*D^*$ + $DD\pi$

local tetraquark operators **local** DD^*, D^*D^*,DD_0

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

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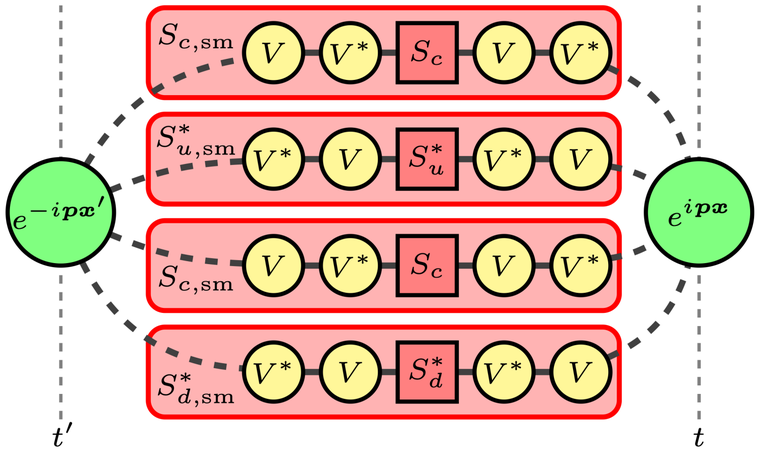
- **Tetraquark operators via "position-space sampling"**

[Stump, Green, arXiv:2510.26459]

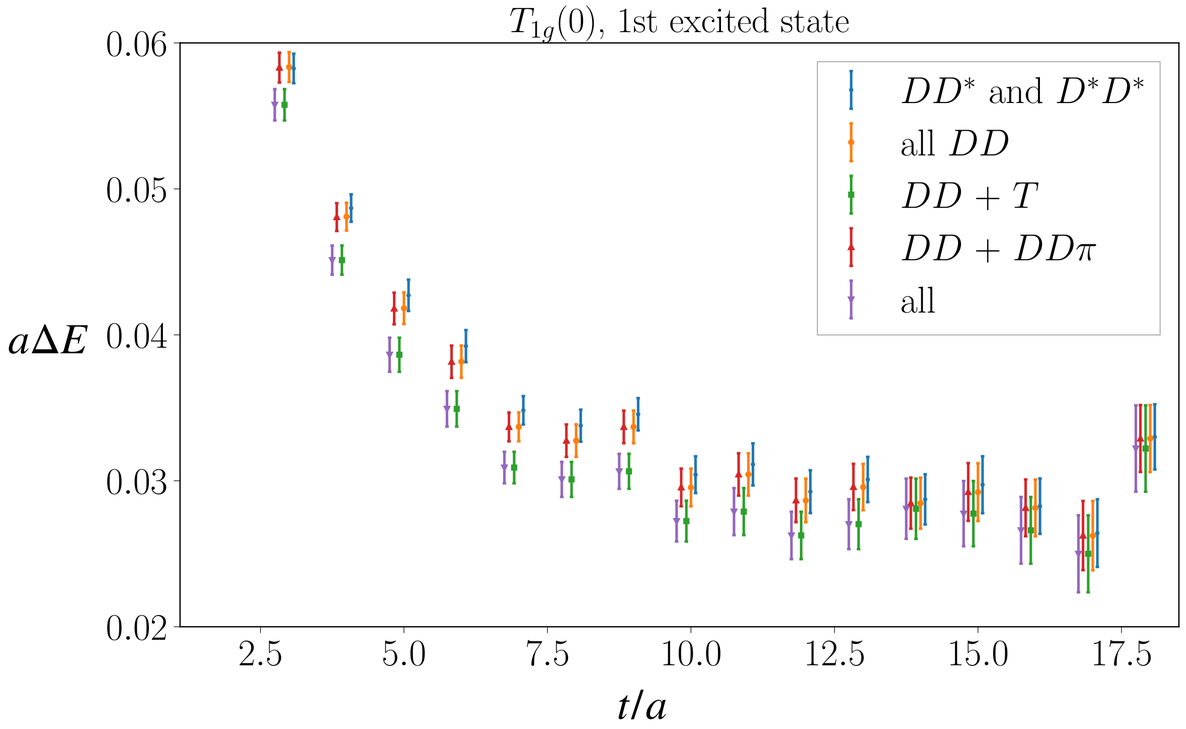


sum over a "sparse grid"



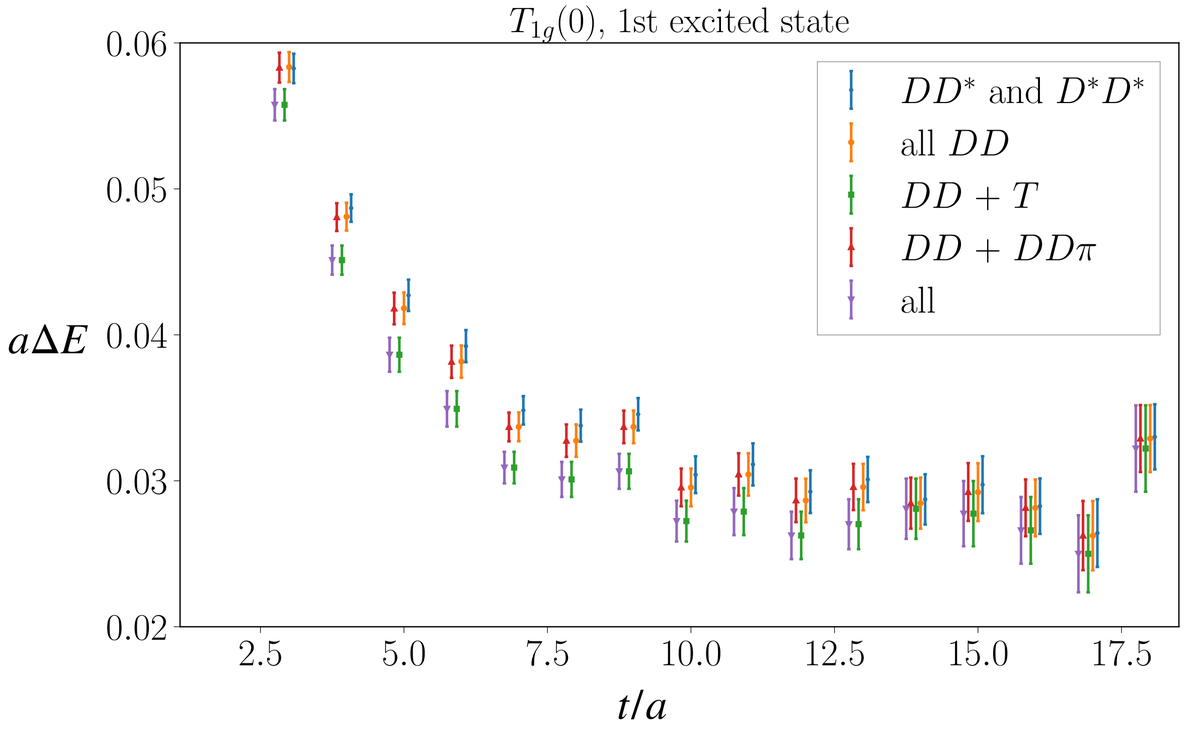
Andres Stump (Humboldt U.)

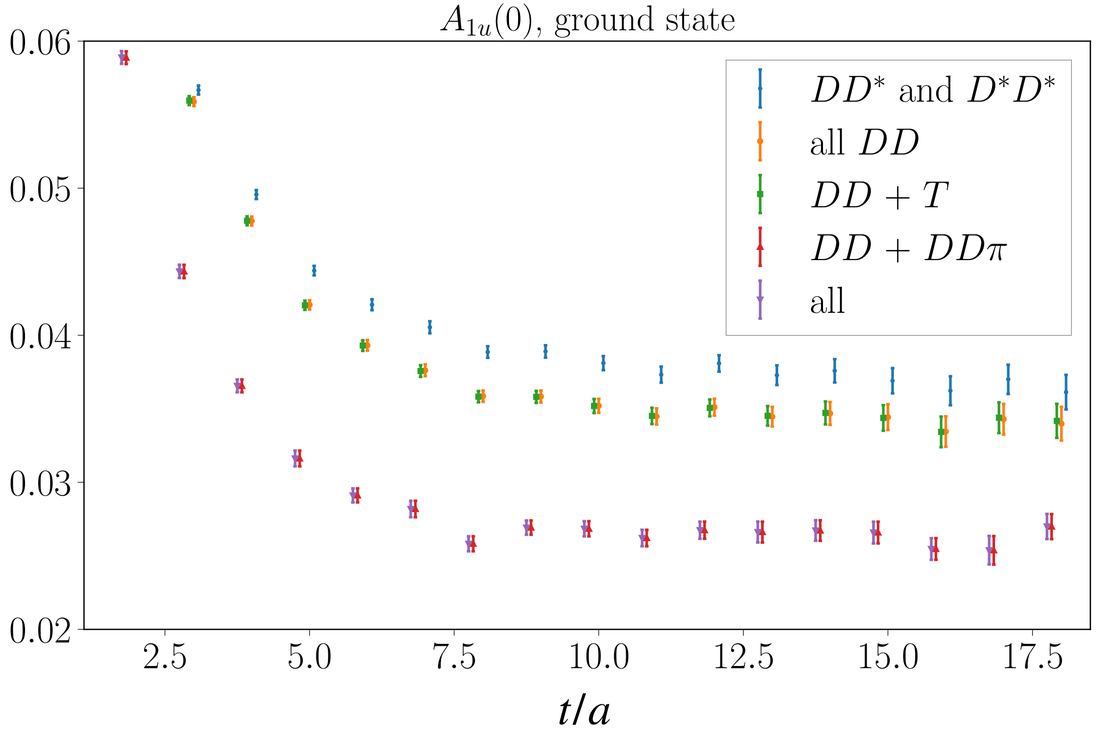
Effect of local/DDπ operators



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

Effect of local/DDπ operators





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

In $A_{1u}(0)$, a $DD\pi$-like state is the lowest —inclusion of $DD\pi$ operators is crucial

I=1 DD subsystem

- 8 levels obtained on X252 in "A_1" irreps
- Finite-volume analysis of s-wave DD scattering with a 3-parameter ERE fit form:

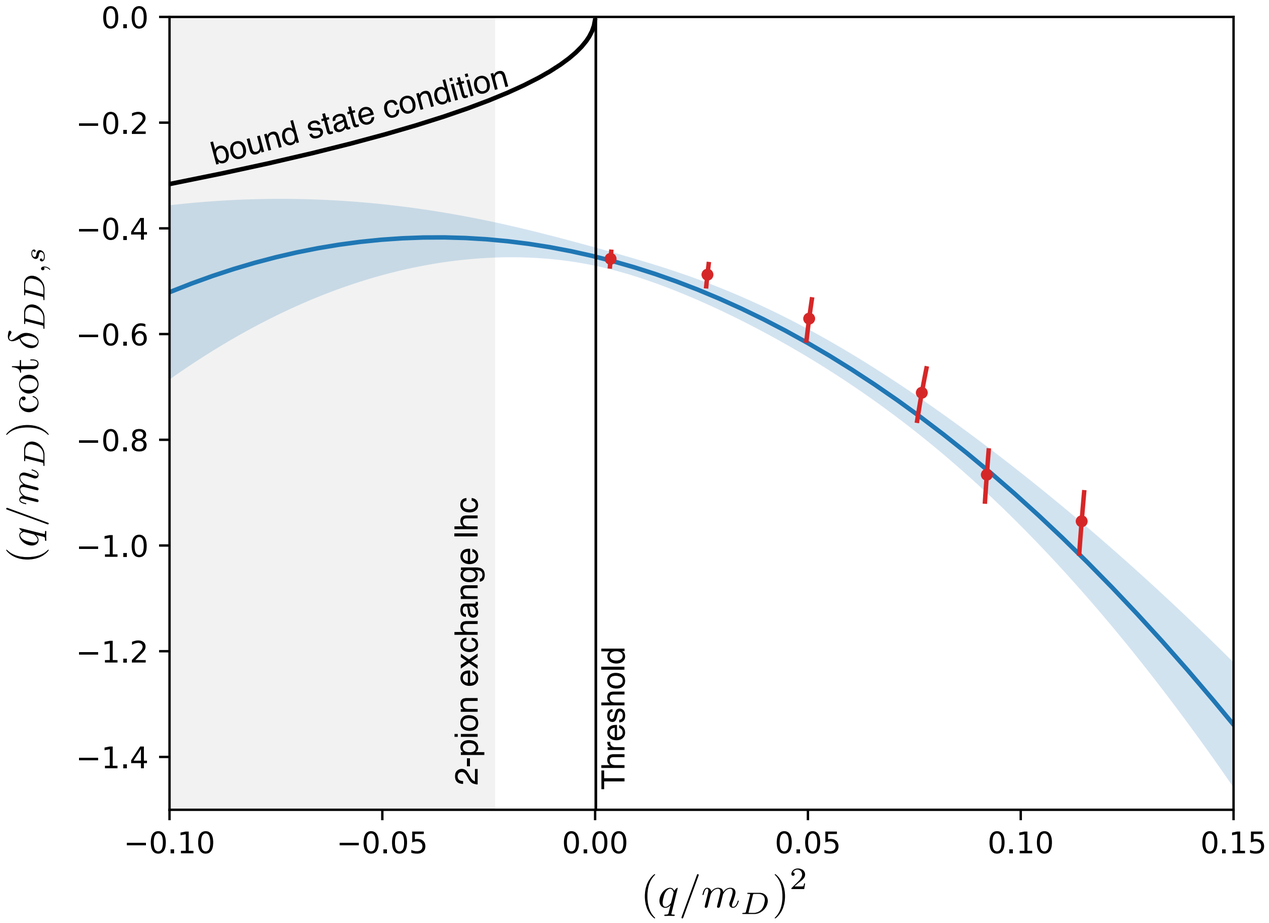
$$\frac{q}{m_D}\cot\delta_{DD,s} = C_1 + C_2\left(\frac{q}{m_D}\right)^2 + C_3\left(\frac{q}{m_D}\right)^4$$

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

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

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

- Weakly interacting system



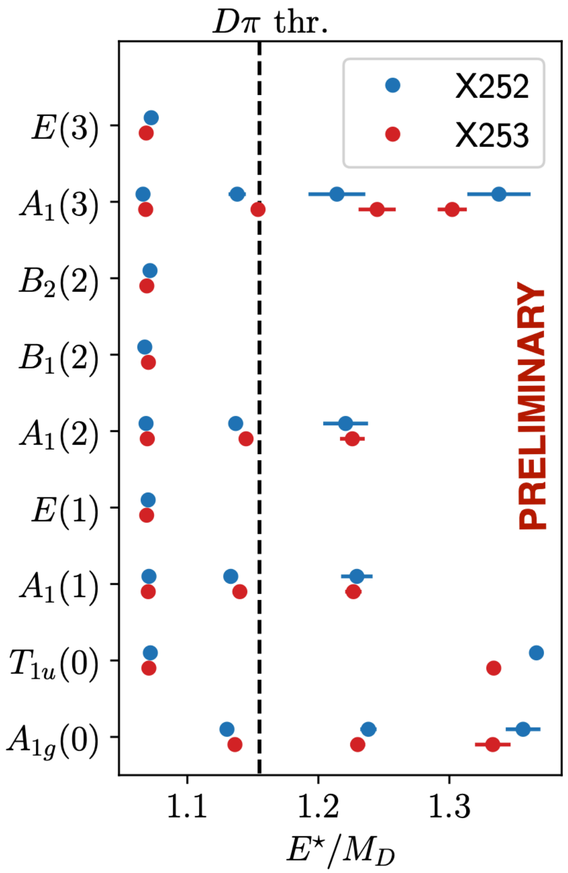
I=1/2 Dπ subsystem

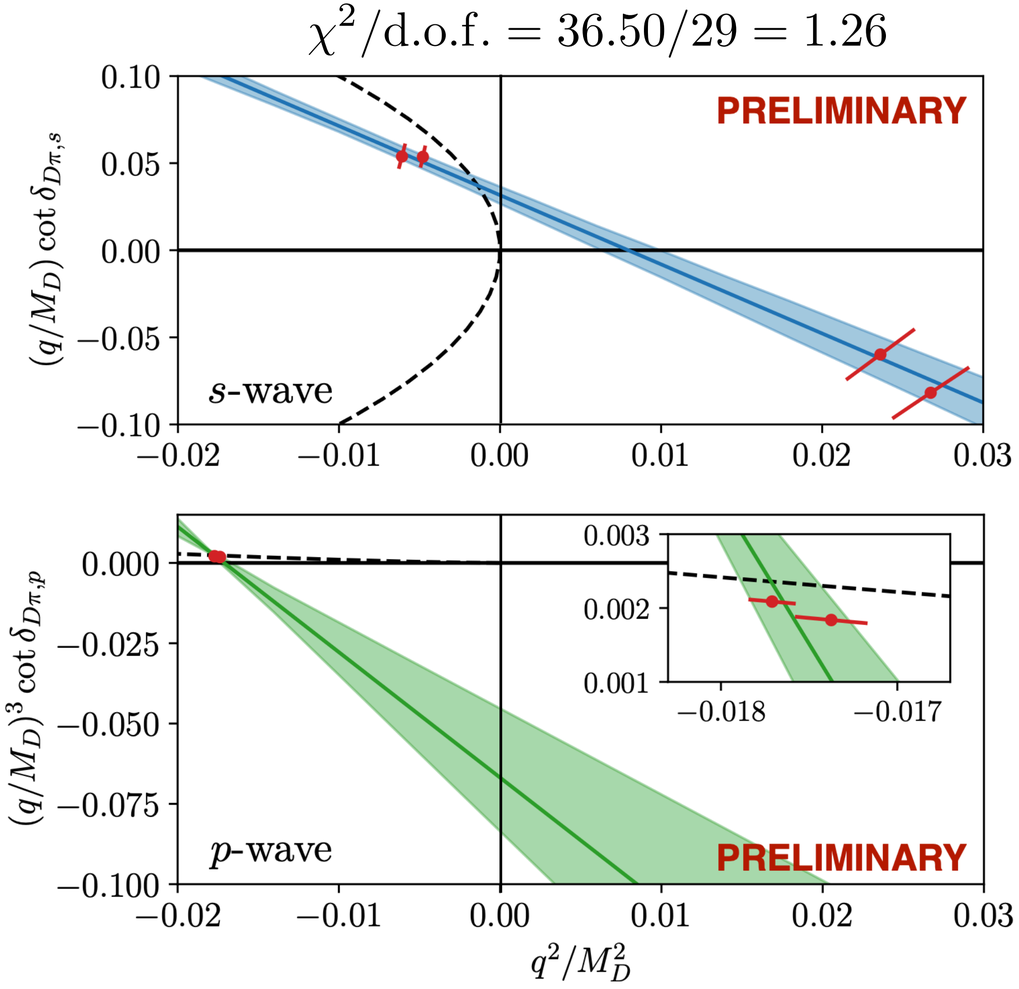
- 36 levels on two ensembles
- ERE in both s and p wave.

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

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

- Caveat:
  - Poor constrain on $g_{DD^*\pi}$
  - Need prior from HQET

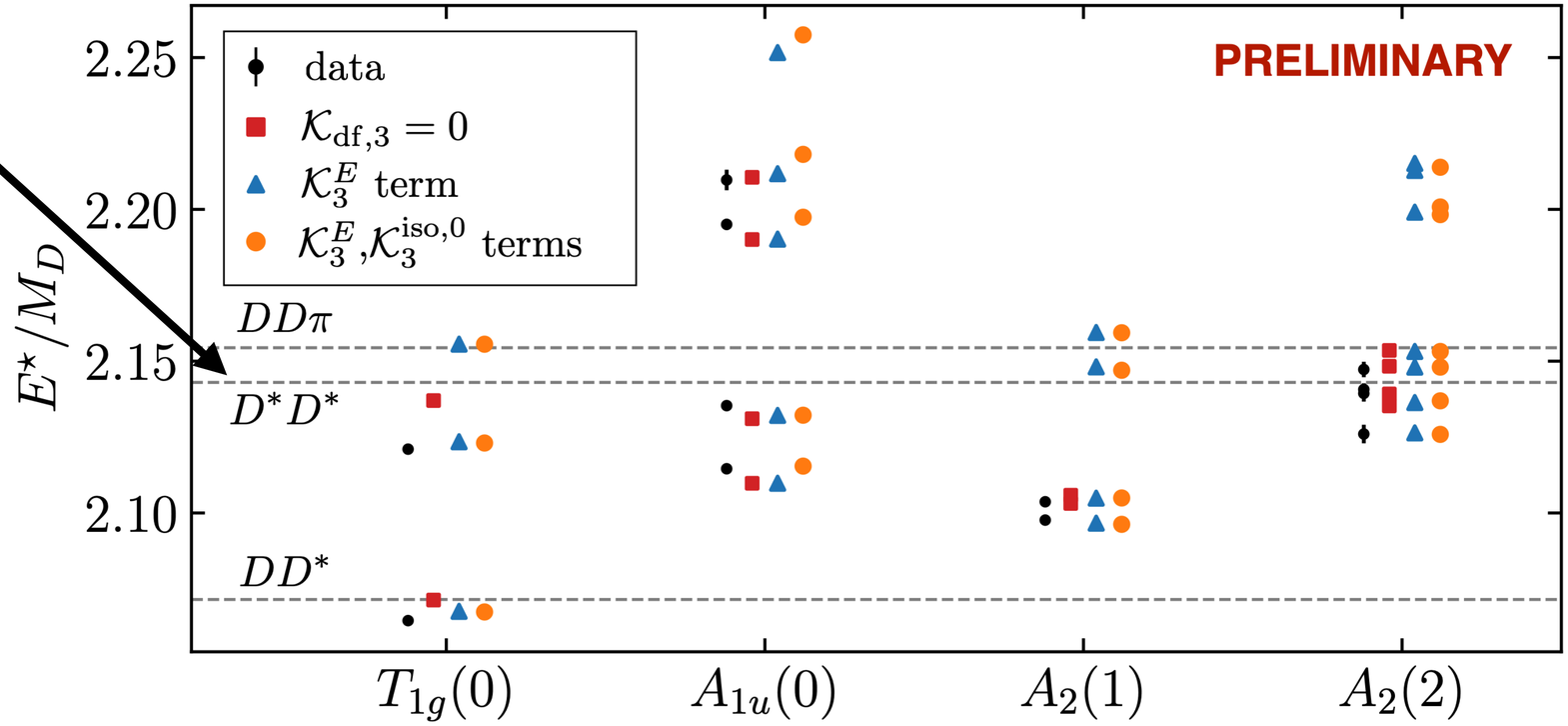




DD* + DDπ spectrum

☑ Preliminary investigation of the three-body spectrum (not yet a fit)

D*D* is the first inelastic threshold



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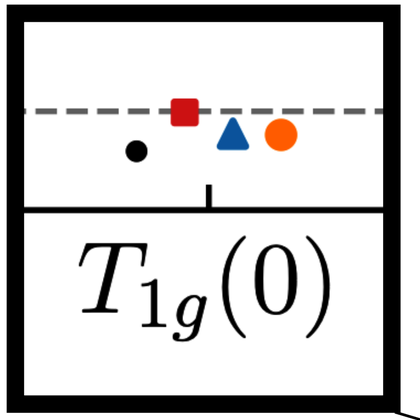
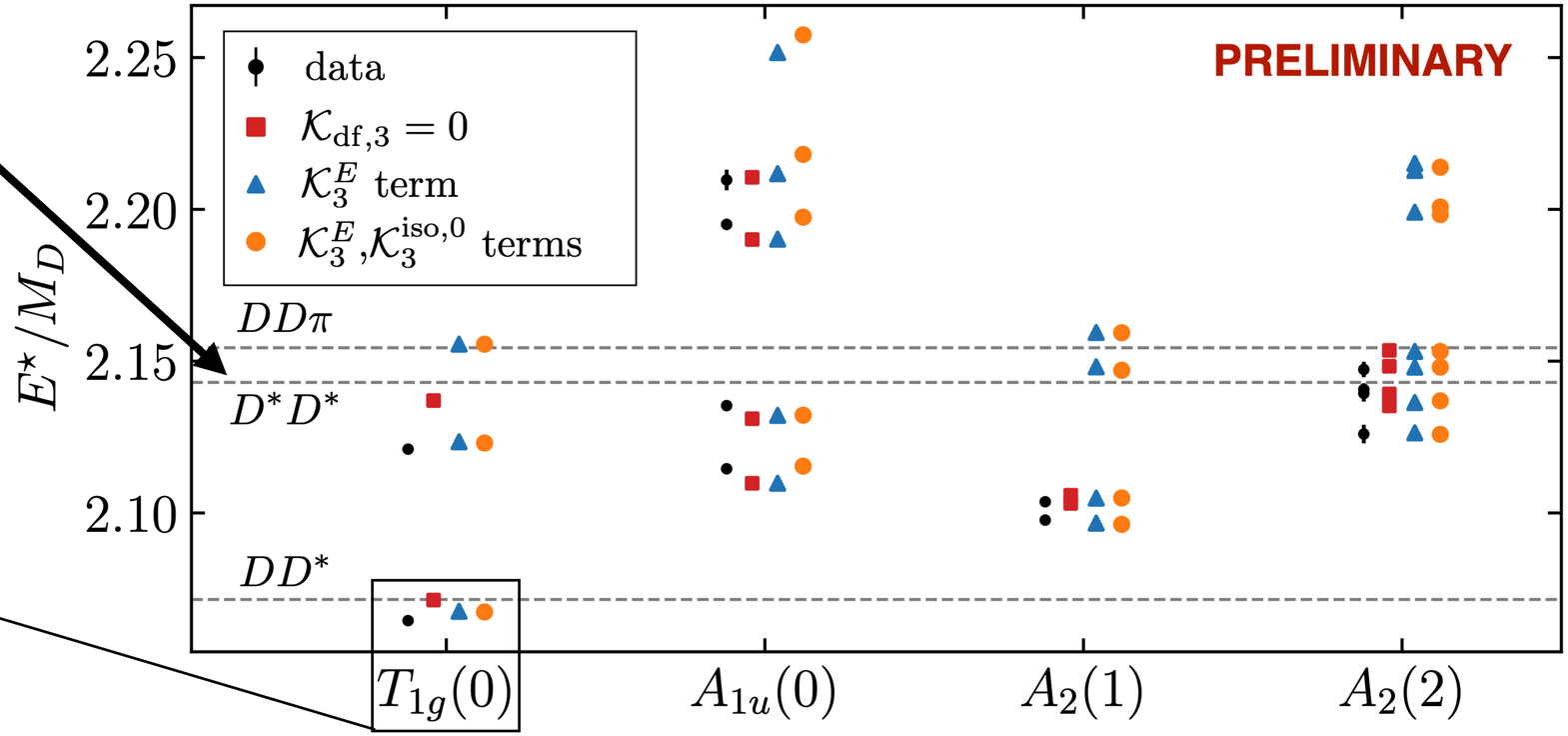


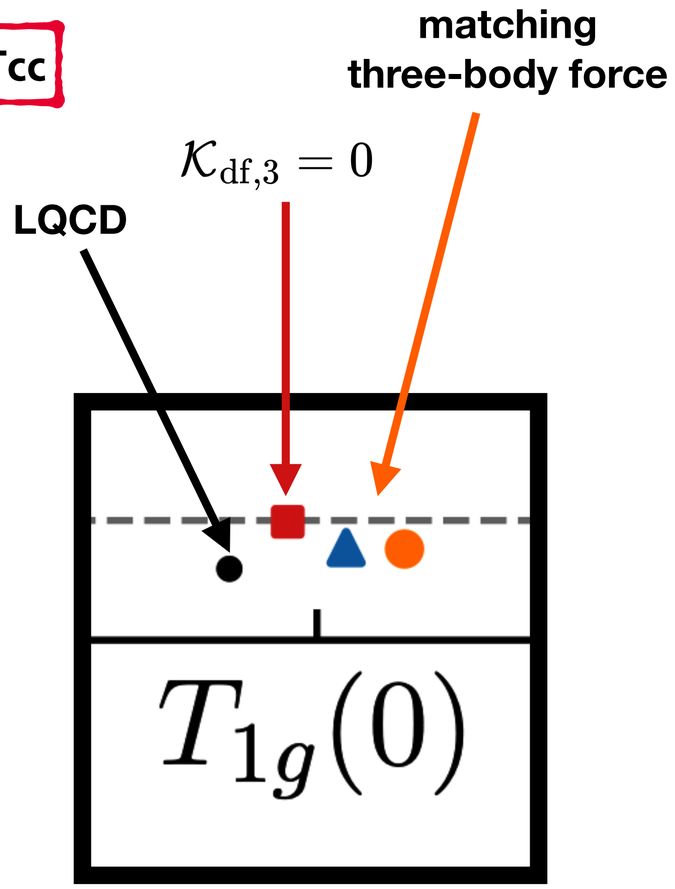
Short-range
three-body force needed



Preliminary conclusions

First (preliminary) genuine three-body study of the Tcc

- ☑ **We studied the two-body subchannels needed for $DD\pi$ scattering**
- ☑ **Reasonable results, but p-wave $D\pi$ scattering in $I = 1/2$ not well constrained from two-particle spectrum**
- ☑ **Qualitative comparisons of $DD^* + DD\pi$ spectrum were done for $\mathcal{K}_{3,\mathrm{df}} = 0$ and nonzero $\mathcal{K}_{3,\mathrm{df}}$**
- ☑ **Reasonable description—needs further exploration**



Summary and Outlook

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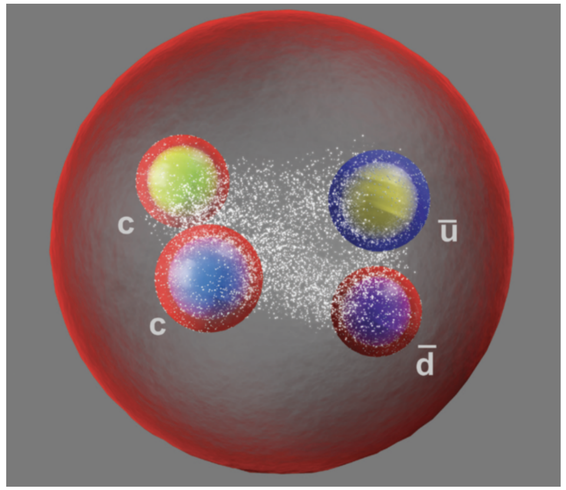
- ☑ Lattice QCD provides a first-principle tool to investigate the hadron spectrum
- ☑ The T_{cc} is a three-body resonance: can be studied with current three-body tools
- ☑ Three-body approach to the T_{cc} allows for its study with stable and unstable D*
- ☑ We laid out and tested the three-body pipeline for the T_{cc}
- ☑ Preliminary three-body study at M_π=280 MeV
- ☐ Outlook: finalize the three-body analysis and move to lighter masses!



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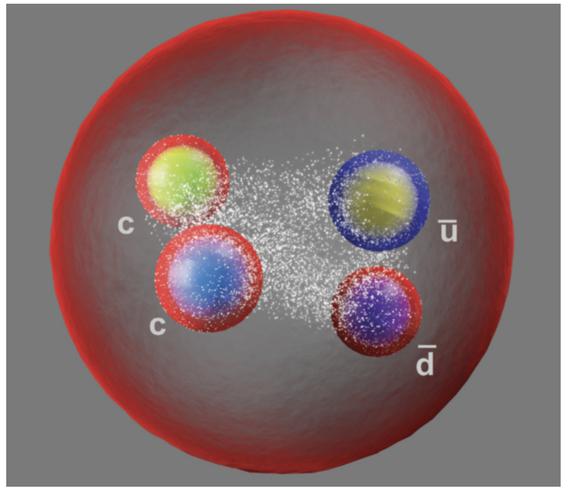

Thanks!