# Pion mass dependence in $D\pi$ scattering and the $D_0^*(2300)$ resonance from lattice QCD

Hadronic physics and heavy quarks on the lattice 2024

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Based on: arXiv:2404.13479

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Jun 7, 2024

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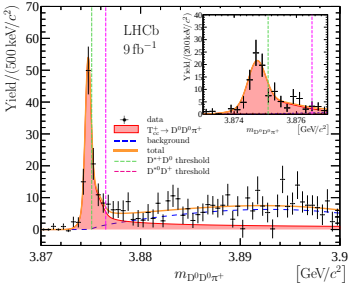
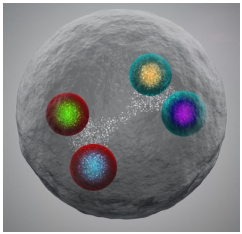
# Introduction

- Most new particles discovered are hadronic resonances in the non-perturbative regime
- LHCb discovered a tetraquark candidate $T_{cc}(3875) \to DD^* \to DD\pi$ in 2022[1]



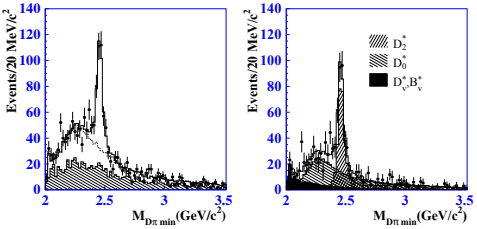
- Previous lattice studies lifted the pion mass and study the two-body $DD^*$ scattering[2] and found the corresponding pole
- The real three-body scattering problem relies on the $D\pi$ scattering amplitudes as an input
- Three-body formalisms: RFT, FVU, and NREFT

[1] LHCb collaboration, NP 18 (2022) 751

[2] Padmanath *et al.*, PRL 129 (2022) 032002; Chen *et al.*, PLB 833 (2022) 137391; Lyu *et al.*, PRL 131 (2023) 161901; Collins *et al.*, PRD 109 (2024) 094509

# Introduction

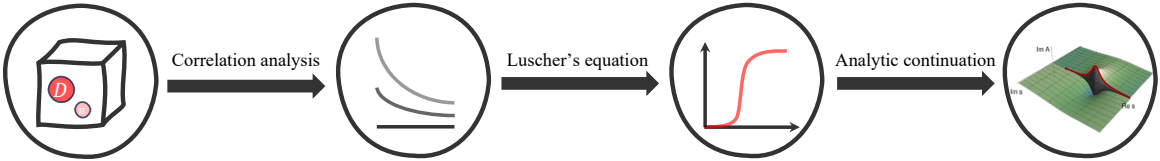
- In the $D\pi$ channel, there is a broad resonance $D_0^*$, found by Belle collboration[3] in 2004




- The mass of $D_0^*(2300)$ is almost identical to $D_{s0}^*(2317)$, which is **not** consistent with the traditional quark model predictions[4]. This can be explained by the strong coupling to $DK$[5]
- UChPT: The possible two-pole structure, and $D_0^*(2100)$ should be the lightest charmed scalar meson[6]

[3] Satpathy *et al.*, PRB 159 (2003) 553.
[4] Du *et al.*, PRD 98 (2018) 094018.
[5] Chen *et al.*, Rep. Prog. Phys. 80 (2017) 076201
[6] Albaladejo *et al.*, PLB 767 (2017) 465.

# Methodology




Previous studies:

- D. Mohler, S. Prelovsek, and R. Woloshyn, PRD 87 (2013) 034501: $D\pi$ $I = \frac{1}{2}$ scattering
- G. Moir, M. Peardon, S. Ryan, C. Thomas, and D. Wilson, JHEP 10 (2016) 011: Coupled $D\pi$, $D\eta$ and $D_s\bar{K}$ scattering
- L. Gayer, N. Lang, S. Ryan, D. Tims, C. Thomas, and D. Wilson, JHEP 07 (2021) 123: $D\pi$ $I = \frac{1}{2}$ scattering
- J. Yeo, C. Thomas, D. Wilson: $D\pi/DK$ scattering at the $SU(3)$ point

We examine the pion-mass dependence and extrapolate to the physical point

# Lattice setup

| configuration | volume | $a$/fm | $m_\pi$/MeV | $N_{\text{cfgs}}$ |
|---|---|---|---|---|
| C48P14 | $48^3 \times 96$ | 0.10530(18) | 135.5(1.6) | 132 |
| F32P21 | $32^3 \times 64$ | 0.07746(18) | 210.9(2.2) | 459 |
| F48P21 | $48^3 \times 96$ | 0.07746(18) | 207.2(1.1) | 222 |
| F32P30 | $32^3 \times 96$ | 0.07746(18) | 303.2(1.3) | 567 |
| F48P30 | $48^3 \times 96$ | 0.07746(18) | 303.4(9) | 201 |
| H48P32 | $48^3 \times 144$ | 0.05187(26) | 317.2(0.9) | 274 |

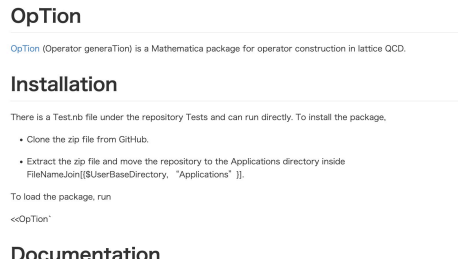
- 4 different pion masses to track the chiral behavior
- 3 lattice spacings to estimate the discretization error
- Two volumes to provide more kinematic points

# Operator construction

- Project the operators into irreps. of the lattice little group[7].

$$O^{[|k|]}_{\Gamma,\mu}(\vec{P}) = \sum_{R\in G} T^{\Gamma}_{\mu,\mu}(R) R O_1(\vec{k}) O_2(\vec{P}-\vec{k}) R^{\dagger},$$

- A Mathematica package **OpTion** (**Op**erator construc**Tion**) is developed to construct general $N$-hadron operators



OpTion

OpTion (Operator generaTion) is a Mathematica package for operator construction in lattice QCD.

Installation

There is a Test.nb file under the repository Tests and can run directly. To install the package,

- Clone the zip file from GitHub.
- Extract the zip file and move the repository to the Applications directory inside FileNameJoin[{$UserBaseDirectory, "Applications" }].

To load the package, run

<<OpTion`

Documentation

**3. Tutorials**

**3.1 One-hadron operator**

The function `OneHadronOperatorAll[Ptot, Rep, RepRow, MaxND]` searches all possible one-hadron operators for the number of covariant derivatives less than `MaxND` and returns the operator lists:

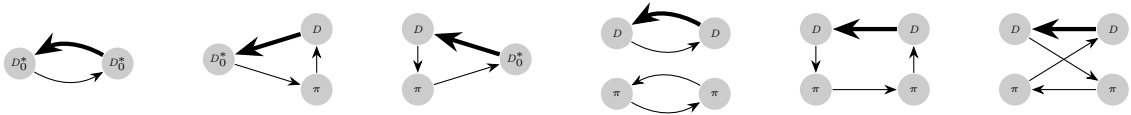
```
(* Particle settings *)
Ptot = {0, 0, 0};
Rep = "T1--";
RepRow = 3;
MaxND = 1;
(* Generate the one--hadron operators *)
Print /@ OneHadronOperatorAll[Ptot, Rep, RepRow, MaxND];
```

- The package has been widely used in CLQCD collaboration
- Available upon request, to be open source on github.com/wittscien/OpTion
- **H. Yan**, in preparation

[7] Prelovsek *et al.*, JHEP 2017 (2017) 1.

# Two-point function

- The Wick contractions contain the following diagrams




- We apply the distillation method[8] to suppress high-lying modes and reduce the cost
- The correlator is

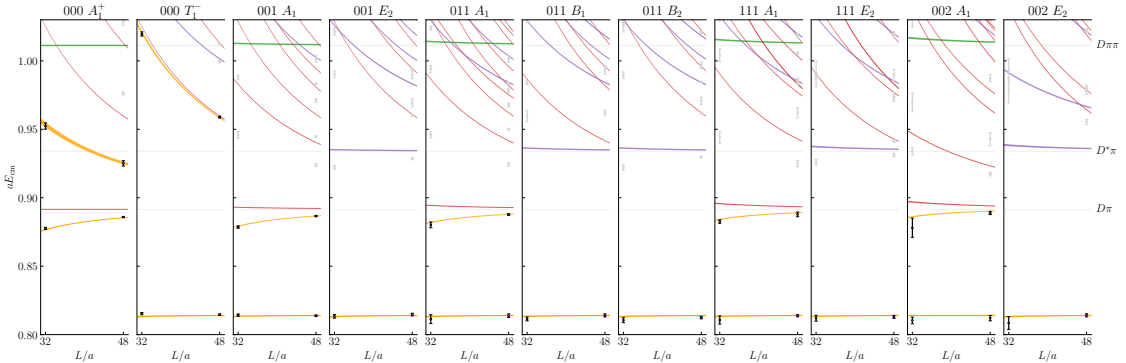
$$\langle OO^\dagger \rangle \sim \sum_n A_n \, \mathrm{e}^{-E_n t} + \text{thermal pollutions},$$

where the thermal pollution is eliminated by generalizing the "weighting and shifting" method[9]

[8] Peardon *et al.*, PRD 80 (2009) 054506.
[9] Dudek *et al.*, PRD 86 (2012) 034031.

# Finite-volume spectra

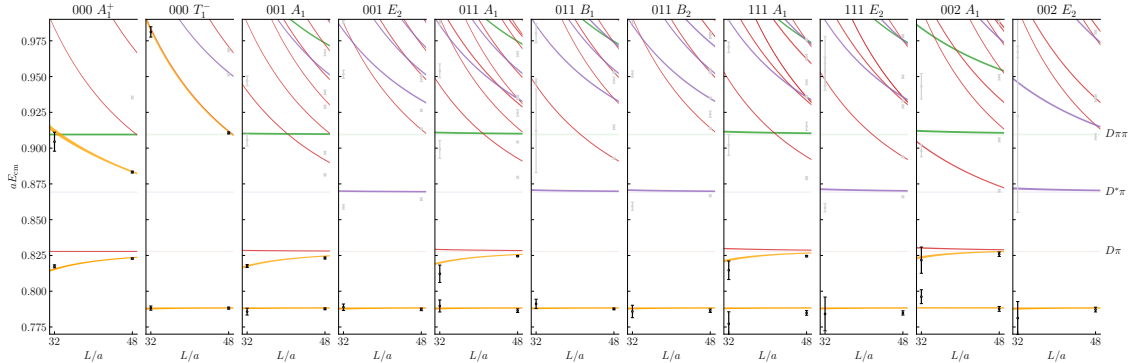
$m_\pi \approx 303$ MeV




- The emergence of $D^*$
- Strong attraction in $S$-wave and small $\delta_1$

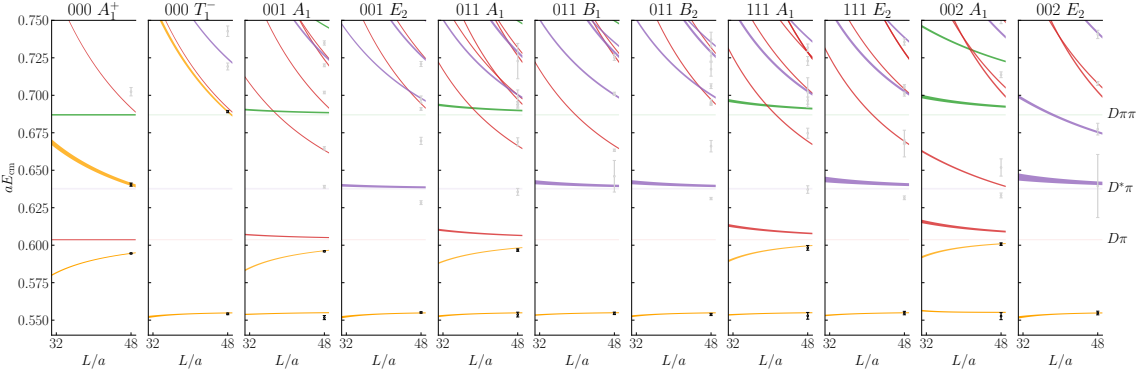
# Finite-volume spectra

$m_\pi \approx 208$ MeV



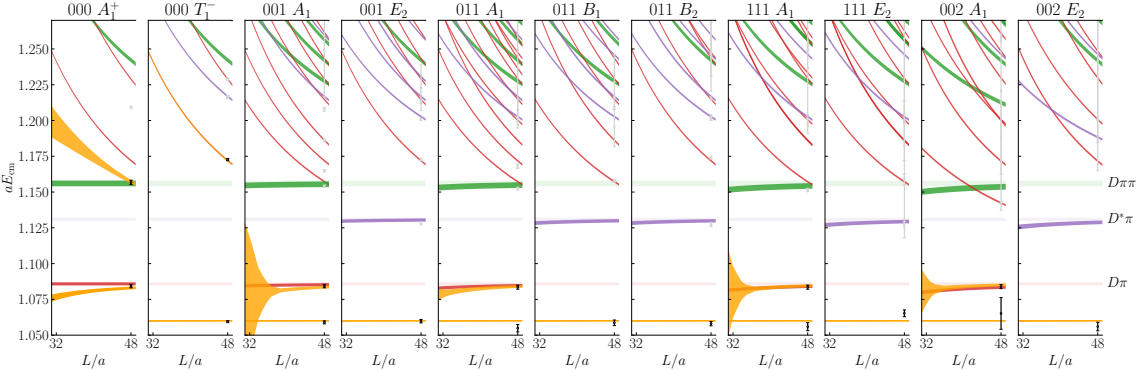
# Finite-volume spectra

$m_\pi \approx 317$ MeV



# Finite-volume spectra

$m_\pi \approx 132$ MeV

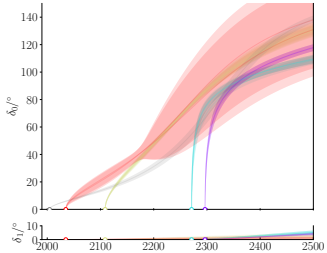


# Phase shifts

- The Lüscher's equation[10]

$$\det[F^{-1}(E, \mathbf{P}; L) + \mathcal{M}(E)] = 0$$

  relates the spectra to the scattering phase shifts in infinite volume (here I cut to $P$-wave)
- Many parametrizations are applied, and little dependency is observed

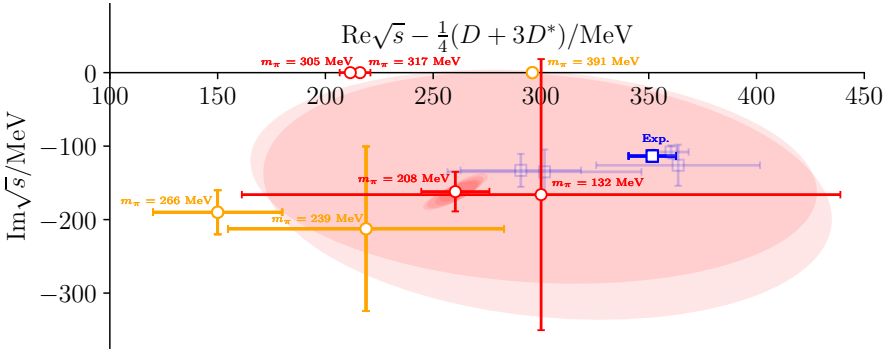



- The $S$-wave phase shift of all $m_\pi$' s rises from $0$ to $180$ degree
- The $P$-wave phase shift is small compared to the $S$-wave in the elastic zone.

[10] Lüscher, NPB 354 (1991) 531.

# The pole positions

- Analytically continuing the energy to the complex plane $\Rightarrow \mathcal{M} \sim \frac{c^2}{s-s_0}$

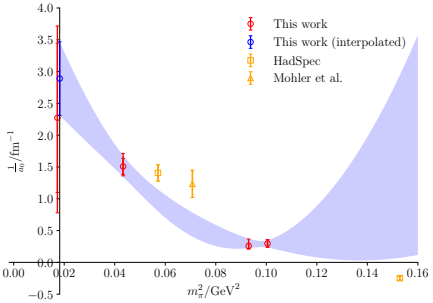


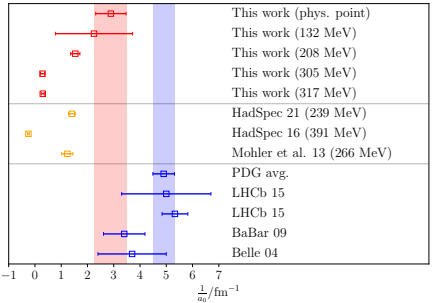

- No two-pole structure
- A surprising behavior of the $m_\pi$ dependence

# Chiral extrapolation/interpolation

- A polynomial form is used to describe the chiral behavior,

$$a_0^{-1}(m_\pi) = c_0 + c_1 m_\pi^2 + c_2 m_\pi^4.$$




- Adding an $a^2$-term gives a measure of the discretization error
- Including $1/a_0$ from previous works gives consistent results with smaller error
- $1/a_0$ at the physical point: not consistent with the PDG value

# Summary

- No two-pole structure is observed
- A large number of operators are constructed. The package is widely used
- The poles in the Riemann sheet at $4$ pion masses are found
- An clear trend for the motion of the $D_0^*(2300)$ pole is identified.

$$\text{bound state} \rightarrow \text{virtual state} \rightarrow \text{resonance}$$

- Coupled $D\pi - D\eta - D_s\bar{K}$ is running

Thank you!