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The two-pole nature of the $\Lambda(1405)$ from Lattice QCD

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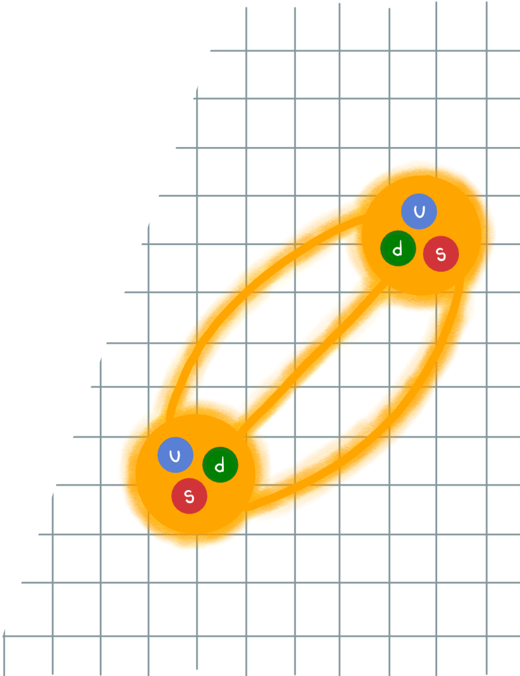

Lattice QCD study of $\pi\Sigma$–$\bar{K}N$ scattering and the $\Lambda(1405)$ resonance

John Bulava,[1] Bárbara Cid-Mora,[2] Andrew D. Hanlon,[3] Ben Hörz,[4] Daniel Mohler,[5,2] Colin Morningstar,[6]
Joseph Moscoso,[7] Amy Nicholson,[7] Fernando Romero-López,[8] Sarah Skinner,[6] and André Walker-Loud[9]
(for the Baryon Scatterir Collaboration)

A lattice QCD computation of the coupled chanr
region is detailed. Results are obtained using a si
$N_f = 2+1$ dynamical quark flavors and $m_\pi \approx 200$
matrices using both single baryon and meson-bary
total momenta and irreducible representations are
scattering K-matrix are utilized to obtain the scat
The amplitudes, continued to the complex energ
threshold and a resonance pole just below the $\bar{K}$

The two-pole nature of the $\Lambda(1405)$ from lattice QCD

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(for the Baryon Scattering (BaSc) Collaboration)

This letter presents the first lattice QCD computation of the coupled channel $\pi\Sigma$–$\bar{K}N$ scattering amplitudes at energies near 1405 MeV. These amplitudes contain the resonance $\Lambda(1405)$ with strangeness $S = -1$ and isospin, spin, and parity quantum numbers $I(J^P) = 0(1/2^-)$. However, whether there is a single resonance or two nearby resonance poles in this region is controversial theoretically and experimentally. Using single-baryon and meson-baryon operators to extract the finite-volume stationary-state energies to obtain the scattering amplitudes at slightly unphysical quark masses corresponding to $m_\pi \approx 200$ MeV and $m_K \approx 487$ MeV, this study finds the amplitudes exhibit a virtual bound state below the $\pi\Sigma$ threshold in addition to the established resonance pole just below the $\bar{K}N$ threshold. Several parametrizations of the two-channel K-matrix are employed to fit the lattice QCD results, all of which support the two-pole picture suggested by $SU(3)$ chiral symmetry and unitarity.

The two-pole nature of the $\Lambda(1405)$ from Lattice QCD *
Lattice QCD study of $\pi\Sigma - \bar{K}N$ scattering and the $\Lambda(1405)$ resonance **

* Letter: 2307.10413 ** Long paper: 2307.13471

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- $\Lambda(1405)$ in a nutshell
- Lattice approach
- The current contribution
  - Correlation functions
  - Finite-volume energy spectra
  - Scattering amplitude analysis
  - Two-poles?
- Summary

The $\Lambda(1405)$ baryon: a brief history

1959
Theoretical Prediction ($\bar{K}p$–$\pi\Sigma$)
Dalitz & Tuan, PRL 2 (1959) 425

1961
Experimental evidence of res., mass spectrum $\pi\Sigma$
Alston et al., PRL 6 (1961) 698

1984–1986
Bag model & Chiral Sym. Meson–Baryon comp. of $\Lambda(1405)$
Veit et al., PLB137 (1984) 415
Jennings, PLB 176 (1986) 229

1990
First time two–poles picture
Fink et al., PRC 41 (1990) 2720

1995–1997
Chiral dynamics approach on coupled–channel
Kaiser et al., NPA 594 (1995) 325
Oset & Ramos, NPA 635 (1997) 99

2003
Lattice: $\Lambda(1405)$ does not fit conventional quark model
Nemoto et al., PRD 68 (2003) 094505

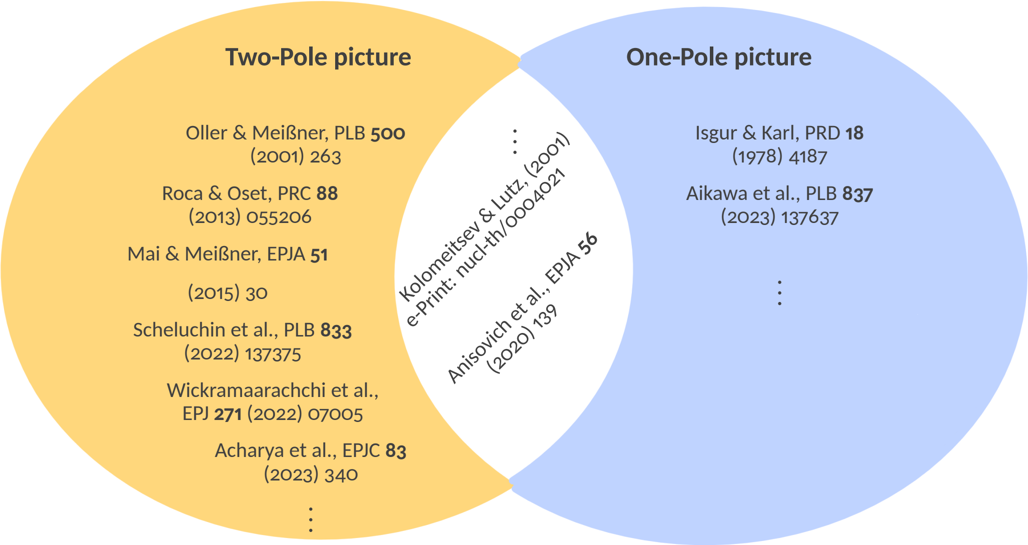
2011
SIDDHARTA at DAΦNE
Det. Scattering length $\bar{K}p$
Bazzi et al., PLB 704 (2011) 113

2013-2014
CLAS Collab at JLAB
Angular depend. study & Spin and Parity
Moriya et al., PRC 87 (2013) 035206
Moriya et al., PRL 112 (2014) 082004

2023
1st Lattice coupled–channel study of the $\Lambda(1405)$
Bulava et al., PRL (submitted)
Bulava et al., PRD (submitted)

Disclaimer: Many other studies contributing to the theoretical development are not listed here.

The $\Lambda(1405)$ baryon: the controversy



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Why is Lattice QCD an important approach to face the controversial $\Lambda(1405)$?

- Allows for predictions once the quark masses and the coupling are fixed.
- Facilitates exploration of the elastic $\pi\Sigma$ scattering amplitude below the $\bar{K}N$ threshold.
- Study of the resulting motion of the poles under variation of the u-, d-, and s-quark masses.

⁕ Implementation of Lüscher's Formalism to study scattering amplitudes.

Recipe for scattering amplitudes

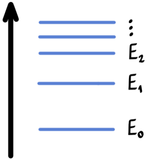
2 Lattice approach

1. Calculate correlation functions for the quantum numbers of interest:

$$\boxed{\Lambda(1405) \to \quad I(J^P) = 0(\tfrac{1}{2}^-) \quad S = -1 \quad \text{[isospin, spin, parity, strangeness]}}$$

2. Extract energy spectrum from lattice data (finite-volume energy spectra).
3. Implement the Lüscher formalism.

   M. Lüscher, NPB **354** (1991) 53, M. Lüscher, NPB **364** (1991) 237; and extensions.



Discrete energy spectra

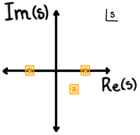
$\rightarrow$ $\det\left[\widetilde{K} + F^{-1}\right] = 0$

Quantization condition

$\rightarrow$ $\widetilde{K}$

Scattering matrix

$\rightarrow$



Pole Positions

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Lattice details

Correlation functions

$a[fm]$	$(L/a)^3 \times (T/a)$	m_π	m_K
$0.0633(4)(6)$	$64^3 \times 128$	≈ 200 MeV	≈ 487 MeV

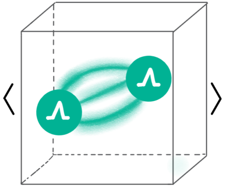
Details of the $\mathbf{D200}$ ensemble generated by the Coordinated Lattice Simulations consortium (CLS). (a : lattice spacing; L, T : lattice extent)

- **Correlation matrices**
  $\longrightarrow$ Stochastic LapH method (sLaph).
  Peardon et al., PRD **80** (2009) 054506
  [Original distillation]
  Morningstar et al., PRD **83** (2011) 114505

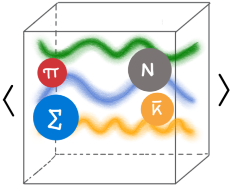
- **Operators**
  $\longrightarrow$ Single and two hadron operators:
  - $\Lambda[\vec{P}]$
  - $\pi[\vec{P}_1]\ \Sigma[\vec{P}_2]$
  - $\bar{K}[\vec{P}_1]\ N[\vec{P}_2]$

Hadrons in the Lattice

Correlation functions



Single hadron operator in the Latice (Λ).

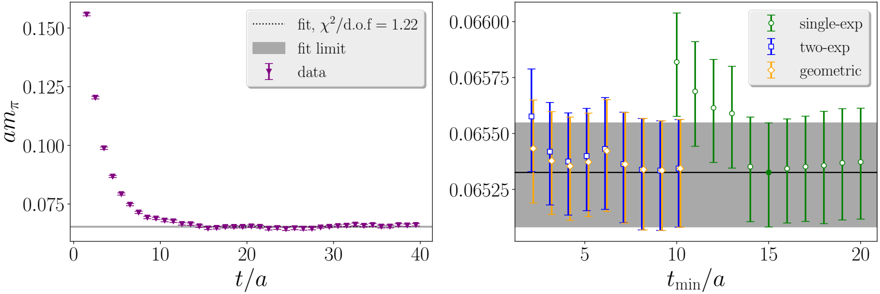


Multihadron operators in the Lattice ($\pi\Sigma$ and $\bar{K}N$).

$$C(t) = \langle \mathcal{O}_1(t)\bar{\mathcal{O}}_2(0)\rangle = \sum_n A_n e^{-tE_n}$$

Single hadrons energy determination

Finite-volume energy spectra

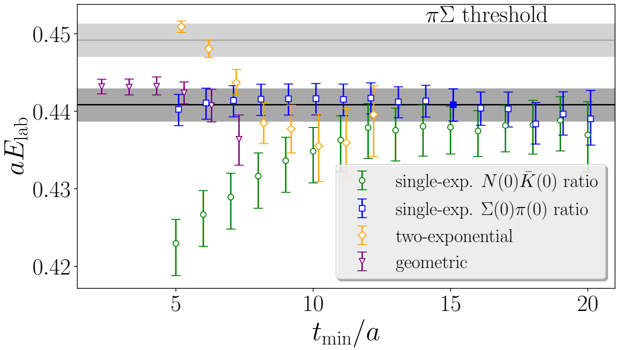


Single hadrons results: π effective mass and variety of fits to Lattice data using different values of t_{min}.

Bulava et al., PRL (2023) [submitted] [arXiv:2307.10413]

Multi-hadron energy spectra determination

Finite-volume energy spectra

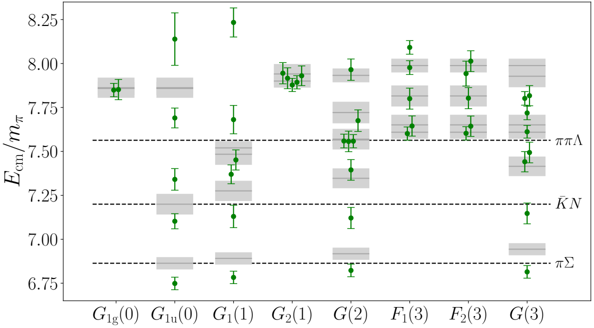


Multihadron results: Variety of fit forms to lattice data vs t_{min} in the energy laboratory frame. (Lowest level of the $G_{1u}(0)$ irrep)

Bulava et al., PRL (2023) [submitted] [arXiv: 2307.13471]

Lüscher Formalism

Scattering amplitude analysis



Finite-volume energy spectra

$$\det\left[\begin{pmatrix} \widetilde{K}_{\pi\Sigma\to\pi\Sigma} & \widetilde{K}_{\pi\Sigma\to\bar{K}N} \\ \widetilde{K}_{\bar{K}N\to\pi\Sigma} & \widetilde{K}_{\bar{K}N\to\bar{K}N} \end{pmatrix} + \begin{pmatrix} F^{-1}_{\pi\Sigma}(E_n,\vec{P},L) & 0 \\ 0 & F^{-1}_{\bar{K}N}(E_n,\vec{P},L) \end{pmatrix}\right] = 0$$

Quantization condition

Scattering amplitude determination

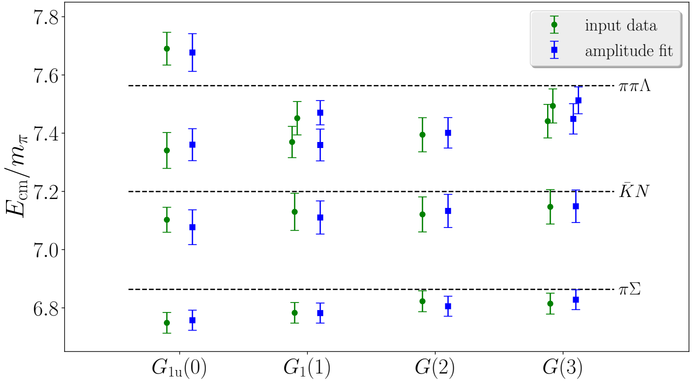
Scattering amplitude analysis

Parametrization of
$\widetilde{K}$-matrix and inverse

$$\frac{E_{\rm cm}}{m_\pi}\widetilde{K}_{ij} = A_{ij} + B_{ij}\Delta_{\pi\Sigma}$$

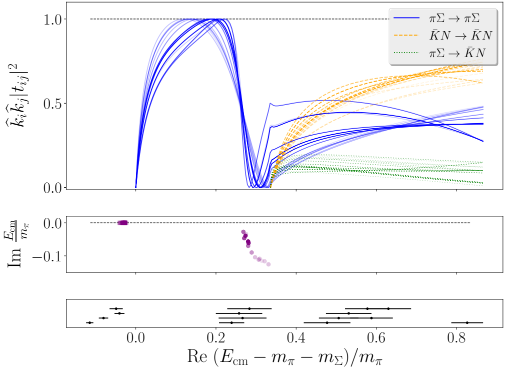
$$\frac{m_\pi}{E_{\rm cm}}\widetilde{K}_{ij}^{-1} = \widetilde{A}_{ij} + \widetilde{B}_{ij}\Delta_{\pi\Sigma}$$

$$\underbrace{\Delta_{\pi\Sigma} = \frac{E_{\rm cm}^2 - (m_\pi + m_\Sigma)^2}{(m_\pi + m_\Sigma)^2}}_{\text{Distance to } \pi\Sigma \text{ threshold}}$$

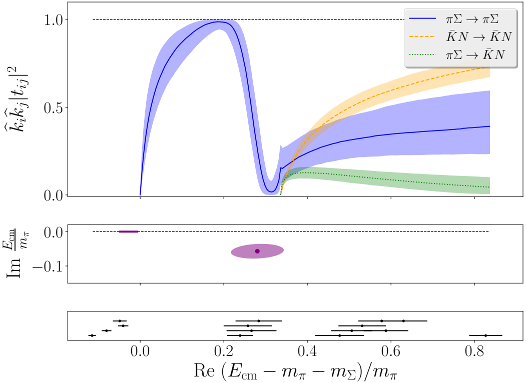


Analytic structure of Scattering amplitude

Scattering amplitude analysis

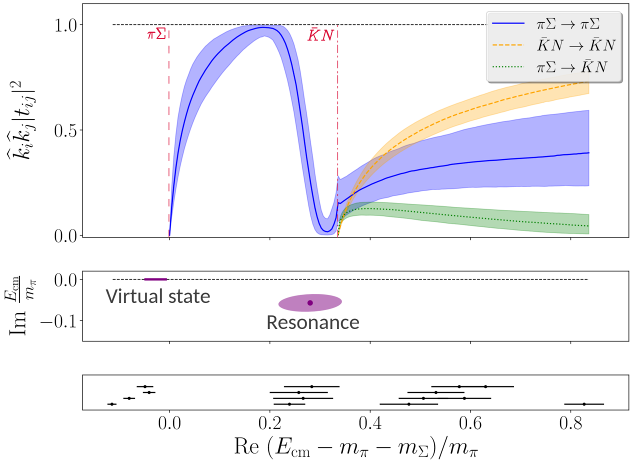


Scattering amplitude results
based on different parametrizations



Preferred parametrization of
the scattering amplitude

Main results: Two-poles!



Virtual bound state

$$E_1 = 1392(9)_{\mathrm{stat}}(2)_{\mathrm{model}}(16)_{\mathrm{a}}\mathrm{MeV}$$

$$\left|\frac{c^{(1)}_{\pi\Sigma}}{c^{(1)}_{\bar{K}N}}\right| = 1.9(4)_{\mathrm{stat}}(6)_{\mathrm{model}}$$

Resonance

$$E_2 = \left[1455(13)_{\mathrm{stat}}(2)_{\mathrm{model}}(17)_{\mathrm{a}} - i11.5(4.4)_{\mathrm{stat}}(4.0)_{\mathrm{model}}(0.1)_{\mathrm{a}}\right]\mathrm{MeV}$$

$$\left|\frac{c^{(2)}_{\pi\Sigma}}{c^{(2}_{\bar{K}N}}\right| = 0.53(9)_{\mathrm{stat}}(10)_{\mathrm{model}}$$

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Two poles were found!

- First Lattice QCD study of coupled-channel $\pi\Sigma - \bar{K}N$ in the $\Lambda(1405)$ region.
- Every parametrization used found two poles in this region.
  - **NOTE:** These parametrizations could accommodate zero, one or two poles.
- Our results show qualitative agreement with phenomenological extractions
  - ⋆ See PDG, section 83

Our results:

Lower Pole: $E_1 = 1392(9)_{\text{stat}}(2)_{\text{model}}(16)_{\text{a}}$ MeV

Higher Pole: $E_2 = [1455(13)_{\text{stat}}(2)_{\text{model}}(17)_{\text{a}} - i11.5(4.4)_{\text{stat}}(4.0)_{\text{model}}(0.1)_{\text{a}}]$ MeV

Reference Results: $\mathcal{R}e\, E_1 = 1325 - 1380$ MeV $\quad \mathcal{R}e\, E_2 = 1421 - 1434$ MeV

- Future work:

- Explore the quark masses dependence of the poles.
- Study lattices with a closer to physical m_π.