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

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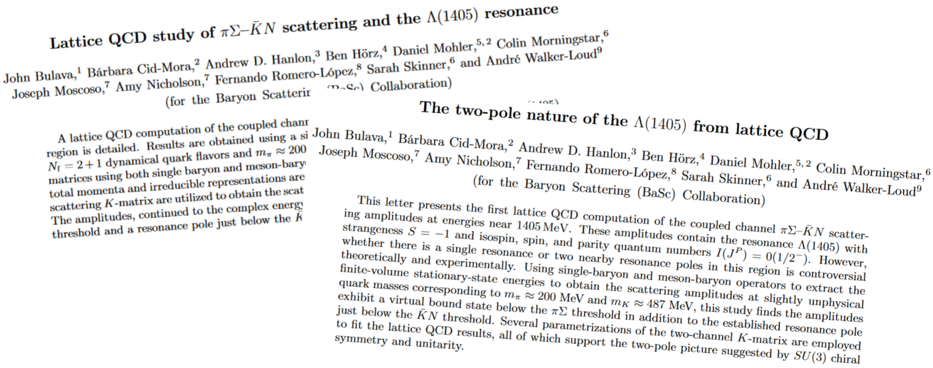

Lattice QCD study of $\pi\Sigma$–$\bar{K}N$ scattering and the $\Lambda(1405)$ resonance

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 Scatterin… Collaboration)

A lattice QCD computation of the coupled chan… 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

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 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 (Accepted by PRL): 2307.10413 ** Long paper (Accepted by PRD): 2307.13471

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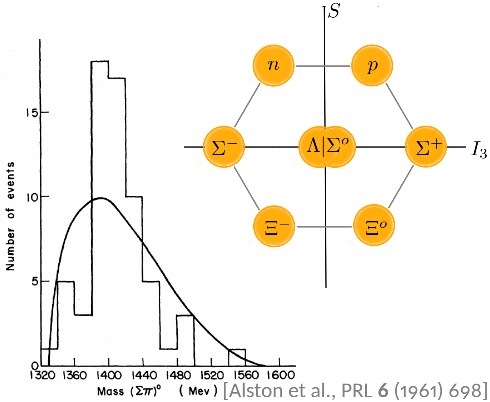
A bit of history

1 About the $\Lambda(1405)$



[Alston et al., PRL **6** (1961) 698]

$$\Lambda(1405) \rightarrow \quad I(J^P) = 0(\tfrac{1}{2}^-) \quad S = -1$$

- Theoretical Prediction $K^- p - \pi\Sigma$
  [Dalitz & Tuan, PRL **2** (1959) 425]
- Experimental evidence of resonance ($\pi\Sigma$ mass spectrum)
  [Alston et al., PRL **6** (1961) 698]
- Meson-Baryon comp. $\Lambda(1405)$ (Chiral sym.)
  [Veit et al., PLB **137** (1984) 415]
  [Jennings, PLB **176** (1986) 229]
- First time two-pole picture
  [Fink et al., PRC **41** (1990) 2720]
- Chiral dynamics: coupled-channel
  [Kaiser et al., NPA **594** (1995) 325]
  [Oset & Ramos, NPA **635** (1997) 99]
- SIDDHARTA at DAΦNE: $K^- p$ Scattering Length det.
  [Bazzi et al., PLB **704** (2011) 113]
- Spin & Parity by CLAS Colllab.
  [Moriya et al., PRC **87** (2013) 035206]
  [Moriya et al., PRL **112** (2014) 082004]

One or two-pole picture?

Λ resonances

[PDG, PTEP **2022** (2022) 083C01]

Hadron	J^P	status
$\Lambda(1116)$	$1/2^+$	$(****)$
$\Lambda(1380)$	$1/2^-$	$(**)$
$\Lambda(1405)$	$1/2^-$	$(****)$
$\vdots$		

Is $\Lambda(1380)$ a second pole of the scattering amplitude in the complex energy plane in the $\Lambda(1405)$ region?

[Isgur & Karl, PRD **18** (1978) 4187]

[Oller & Meißner, PLB **500** (2001) 263]

[Roca & Oset, PRC **88** (2013) 055206]

[Mai & Meißner, EPJA **51** (2015) 30]

[Anisovich et al., EPJA **56** (2020) 139]

[Scheluchin et al., PLB **833** (2022) 137375]

[Wickramaarachchi et al., EPJ **271** (2022) 07005]

[Aikawa et al., PLB **837** (2023) 137637]

[Acharya et al., EPJC **83** (2023) 340]

⋇ [Bulava et al., e-print: 2307.10413 (2023)]

⋇ [Bulava et al., e-print: 2307.13471 (2023)]

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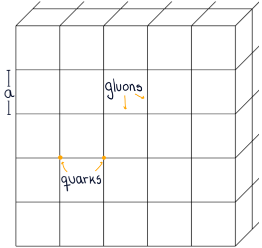
Our approach: Lattice



- Quarks and gluons in a finite size discretized grid
- Observables estimated by sampling gauge configurations
- Correlation functions are computed
- Finite-volume energy spectrum extraction

Importance of lattice QCD to study the $\Lambda(1405)$

→ Predictions once quark masses and couplings fixed

→ Facilitates exploration of the elastic region $\pi\Sigma - \bar{K}N$

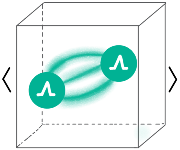
→ Resulting motion of poles under variation of quark masses

Lattice details

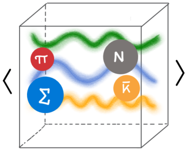
Details of the $D200$ ensemble generated by the Coordinated Lattice Simulations consortium (CLS):
[Bruno et al., JHEP **02** (2015) 043]

$a[fm]$	$(L/a)^3 \times (T/a)$	m_π	m_K	$m_\pi L$
$0.0633(4)(6)$	$64^3 \times 128$	≈ 200 MeV	≈ 487 MeV	$4.181(16)$

- 2000 gauge configurations
- Open temporal boundary conditions



Single hadron operator in the latice (Λ)



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

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

$\Lambda(\mathbf{d}^2)$	Operators
$G_{1g}(0)$	$\Lambda[G_{1g}(0)]_{0,1,3}$
	$\bar{K}[A_2(1)]_1\ N[G_1(1)]_0$
	$\pi[A_2^-(1)]_1\ \Sigma[G_1(1)]_0$

Correlation functions

- **Correlation matrices** $\rightarrow$ Stochastic LapH method (sLaph)

  [Peardon et al., PRD **80** (2009) 054506] (Original distillation)

  [Morningstar et al., PRD **83** (2011) 114505]

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

- **Extraction of energy spectra** $\rightarrow$ Solving the GEVP

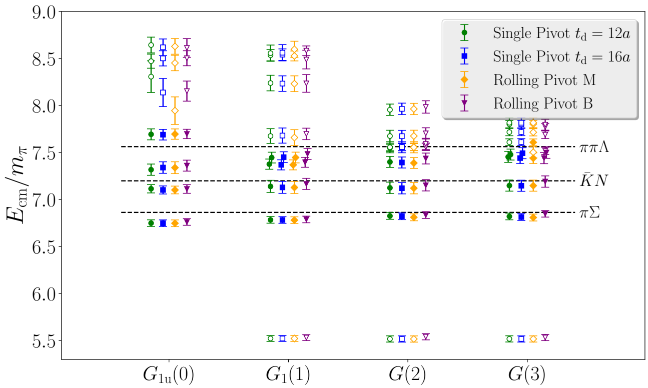
  [Michael & Teasdale, NPB **215** (1983) 433]

  [Blossier et al., JHEP **04** (2009) 094]

$$C(t_\mathrm{d})\vec{v}_n(t_o, t_\mathrm{d}) = \lambda_n(t_o, t_\mathrm{d})\, C(t_o)\, \vec{v}_n(t_o, t_\mathrm{d})$$

Single Pivot & Rolling Pivot

GEVP Results



Center-of-mass finite-volume energy spectra results under variation of implementation of the GEVP method.

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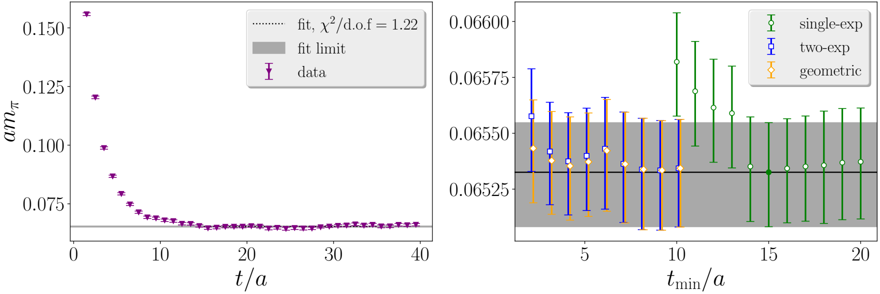
Several fit forms used to extract the finite-volume energy spectra:

$$C(t) = A_n \mathrm{e}^{-tE_n} \text{ (Single exponential)}$$

$$C(t) = A_n \mathrm{e}^{-tE_n} + A_1 \mathrm{e}^{-tD^2} \text{ (Two-exponential)}$$

$$C(t) = \frac{A_n \mathrm{e}^{-tE_n}}{1 - B\mathrm{e}^{-Mt}} \text{ (Geometric)}$$

Single hadrons energy



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

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

Multihadron correlators treatment included

$$R_n(t) = \frac{D_n(t)}{C_A(\mathbf{d}_A^2, t) C_B(\mathbf{d}_B^2, t)} = A_n \mathrm{e}^{-t\Delta E_n} \quad \text{(Ratio of correlators)}$$

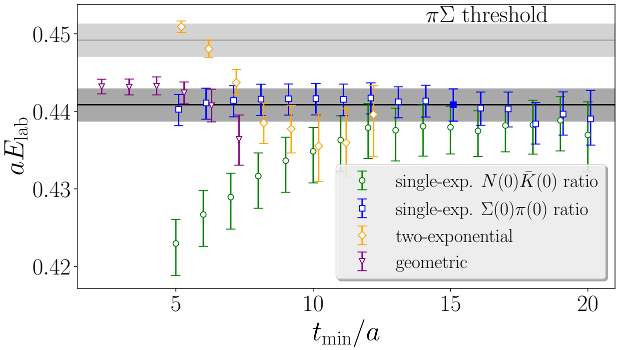
where aE_{lab} is reconstructed

$$aE_n^{\mathrm{lab}} = a\Delta E + aE_n^{\mathrm{non-int}}$$

and

$$E_n^{\mathrm{non-int}} = \sqrt{m_A^2 + \left(\frac{2\pi \mathbf{d}_A^2}{L}\right)^2} + \sqrt{m_B^2 + \left(\frac{2\pi \mathbf{d}_B^2}{L}\right)^2}$$

Multi-hadron 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) [accepted] [arXiv: 2307.13471]

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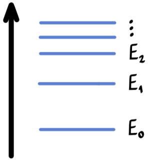
Lüscher formalism

The recipe for scattering amplitudes goes as

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



Discrete energy spectra

→

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

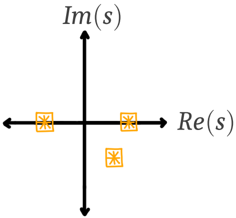
Quantization condition

→

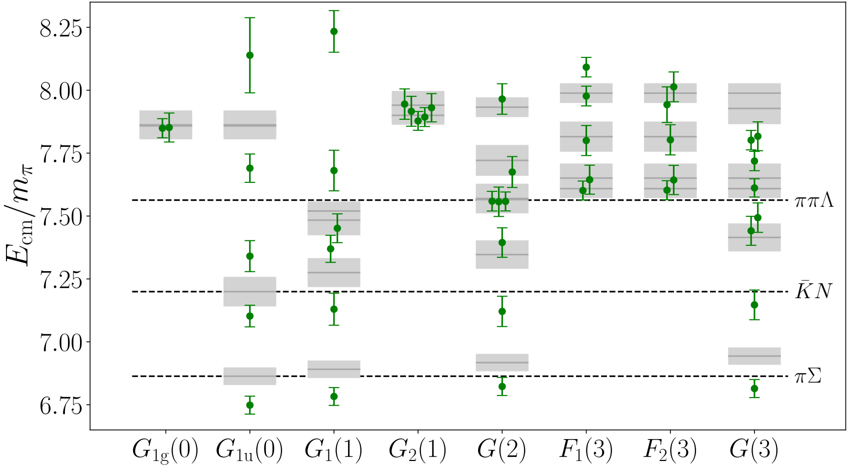
$$\mathcal{M}$$

Scattering matrix

→

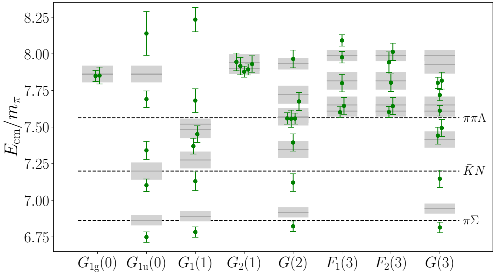


Pole Positions


$E_{\rm cm}/m_\pi$
8.25
8.00
7.75
7.50
7.25
7.00
6.75
$\pi\pi\Lambda$
$\bar{K}N$
$\pi\Sigma$
$G_{1g}(0)$
$G_{1u}(0)$
$G_1(1)$
$G_2(1)$
$G(2)$
$F_1(3)$
$F_2(3)$
$G(3)$

Quantization condition

4 Scattering amplitude analysis



Finite-volume energy spectra

$$\det\left[\widetilde{K}^{-1}(E_{\mathrm{cm}}) - B^{\mathbf{P}}(E_{\mathrm{cm}})\right] = 0$$

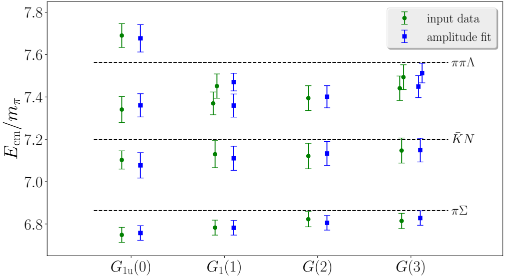
Quantization condition

Scattering amplitude parametrization

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

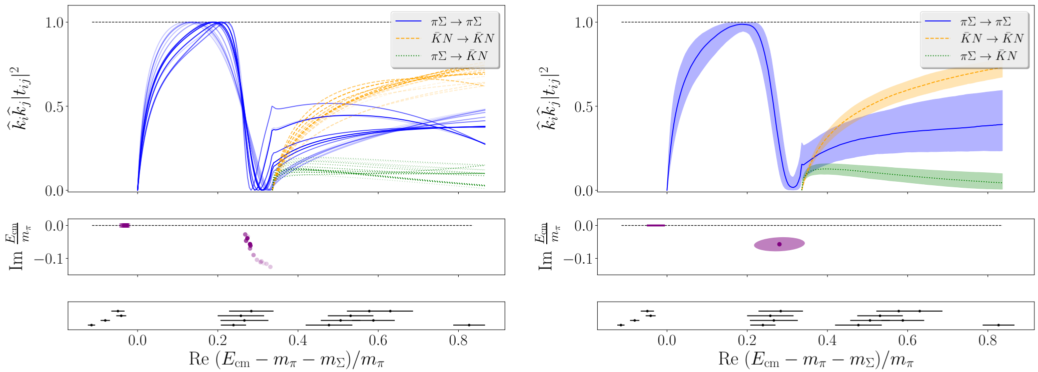
$\widetilde{K}$ – matrix parametrization

$$\begin{cases}\widetilde{K}_{ij}=\frac{m_\pi}{E_{\rm cm}}\left(A_{ij}+B_{ij}\Delta_{\pi\Sigma}\right)\\ \widetilde{K}^{-1}_{ij}=\frac{E_{\rm cm}}{m_\pi}\left(\widetilde{A}_{ij}+\widetilde{B}_{ij}\Delta_{\pi\Sigma}\right)\\ \widetilde{K}=CFC^{-1}\\ \widetilde{K}_{ij}=\widehat{C}_{ij}(2E_{\rm cm}-M_i-M_j)\end{cases}$$



Analytic structure of Scattering amplitude

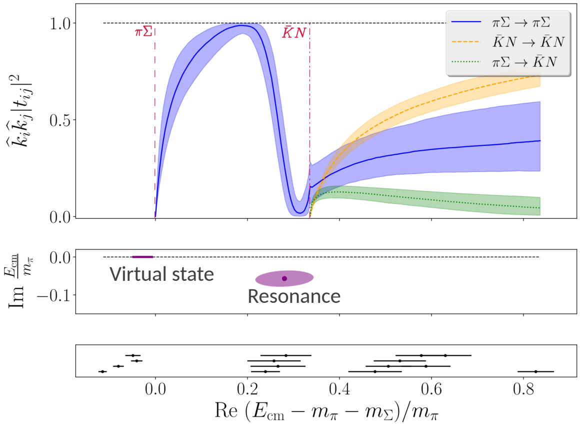
The scattering transition amplitude: $t^{-1} = \widetilde{K}^{-1} - i\hat{k}$



(Left) Scattering amplitude results based on different parametrizations

(Right) Preferred parametrization of the scattering amplitude

Main results: Two-pole structure



Virtual bound state

$$E_1 = 1392(9)_{\text{st}}(2)_{\text{md}}(16)_{\text{a}}\ \text{MeV}$$

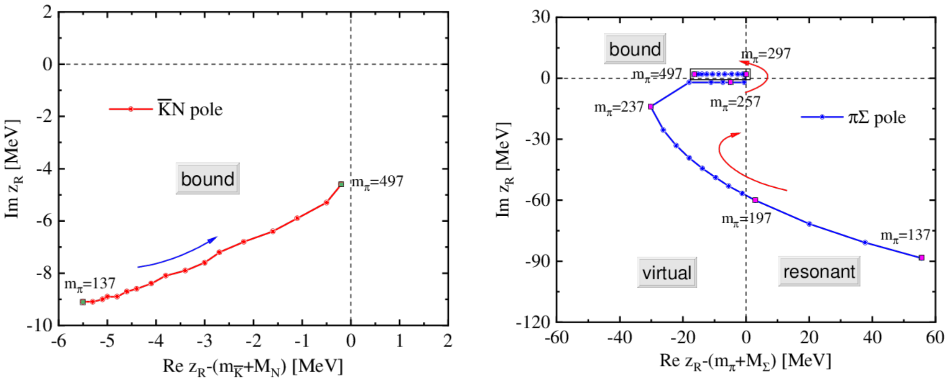
$$\left|\frac{c^{(1)}_{\pi\Sigma}}{c^{(1)}_{\bar{K}N}}\right| = 1.9(4)_{\text{st}}(6)_{\text{md}}$$

Resonance

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

$$\left|\frac{c^{(2)}_{\pi\Sigma}}{c^{(2}_{\bar{K}N}}\right| = 0.53(9)_{\text{st}}(10)_{\text{md}}$$

Example of motion of the poles vs m_π



Trajectories of the two poles of $\Lambda(1405)$ as functions of the pion mass m_π from 137 MeV to 497 MeV. Critical masses are labeled by solid squares, between which the points are equally spaced. ($z_R = m_R - i\Gamma_R/2$) [Xie et al., PRD **108** (2023) 11]

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Summary

- 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]

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; $\mathcal{R}e\,(E_2) = 1421 - 1434$ MeV

- **Future work:**
  - Explore quark masses dependence of the poles
  - Study lattices with a closer to physical m_π

Thanks

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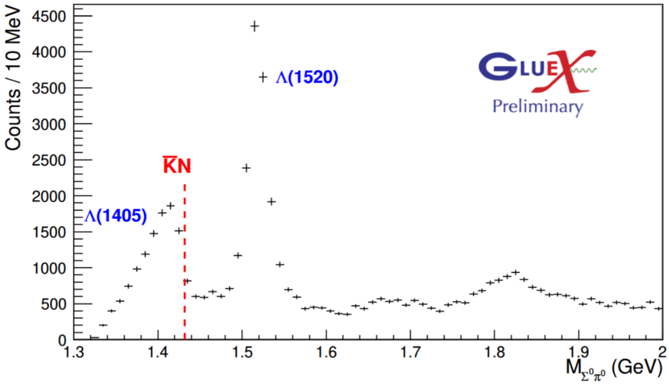
GlueX Preliminary analysis

Back-up



Wickramaarachchi et al., EPJ Web Conf. 271 (2022) 07005, [e-Print: 2209.06230]

Lattice details

Back-up

Ensemble **D200** generated by CLS was used. Its properties are:

- Dynamical mass-degenerate $u-$ and $d-$quarks (heavier than physical), and $s-$quarke (lighter than physical).
- Tree-level improved Lüscher-Weisz gauge action.
- Non-perturbatively $\mathcal{O}(a)$-improved Wilson fermion action.

Effective masses and correlated-χ^2

Back-up

The effective mass is calculated as:

$$m_{eff}(t+1/2) = \ln\left(\frac{C(t)}{C(t+1)}\right)$$

$$\chi^2 = \sum_{t,t'=t_{min}}^{t_{max}} (C(t) - f(t)) \frac{1}{Cov_N(t,t')} (C(t') - f(t'))$$

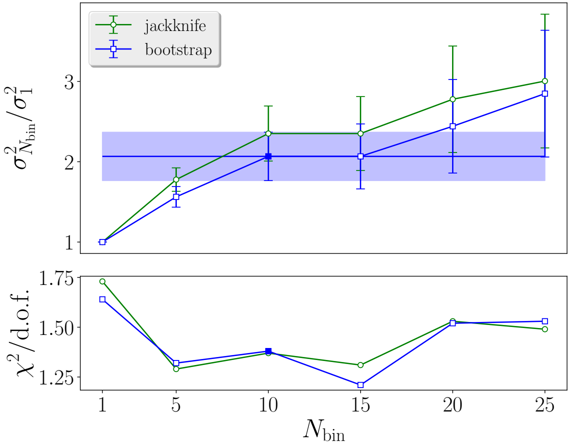
where

$$f(t) = A_i e^{-E_i t}$$

and

$$Cov_N(t,t') = \frac{1}{N-1} \langle (C(t) - \langle C(t) \rangle_N)(C(t') - \langle C(t') \rangle_N) \rangle_N$$

t, t' : lattice time E_i : Energy N : Nr. samples $\langle \dots \rangle_N$: statistical average



(Top) Ratios of variances for fits to m_π versus $N_{\rm bin}$ for jackknife and bootstrap resampling.
(Bottom) Correlated-χ^2 of two-exponential fit to m_π versus $N_{\rm bin}$. In both panels, the final binning choice is illustrated as a blue solid square.

Single Hadron results

Back-up

am_π	$0.06533(25)$	am_K	$0.15602(16)$	am_N	$0.3143(37)$
am_Λ	$0.3634(14)$	am_Σ	$0.3830(19)$	am_Ξ	$0.41543(96)$

Table: Summary of hadron masses in Lattice units.

am_π	~ 200	am_K	~ 487	am_N	~ 980
am_Λ	~ 1120	am_Σ	~ 1194	am_Ξ	~ 1295

Table: Summary of hadron masses in MeV units.

Amplitude Analysis

Back-up

Basically one searches for the zero's of the following equation, using the finite-volume energy spectra as constrain.

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

One fits with respect to the energy shifts of the non-interacting energies:

$$\Delta E_i = E^{latt}_{\rm cm} - E^{free}_{\rm cm}$$

Where one minimize correlated χ^2:

$$\delta_i = \Delta E_{\rm cm,i} - \Delta E^{\rm QC}_{\rm cm,i}$$

And the preferred fit is based on lowest Akaike Information Criterion:

$$\text{AIC} = \chi^2 - 2n_{dof}$$

The following quantity is defined proportional to the scattering transition amplitude and to $\widetilde{K}$ as:

$$t^{-1} = \widetilde{K}^{-1} - i\hat{k}$$

where $\hat{k} = \text{diag}(k_{\pi\Sigma}, k_{\bar{K}N})$, and

$$k^2_{\pi\Sigma} = \frac{1}{E^2_{\text{cm}}}\lambda_K\left(E^2_{\text{cm}}, m^2_\pi, m^2_\Sigma\right)$$
$$k^2_{\bar{K}} = \frac{1}{E^2_{\text{cm}}}\lambda_K\left(E^2_{\text{cm}}, m^2_{\bar{K}}, m^2_N\right)$$

where λ_K is the Källén function. Which is equivalent to searching for the ∞'s of

$$t = \frac{1}{E_{\text{cm}} - E_{\text{pole}}}\begin{pmatrix} c^2_{\pi\Sigma} & c_{\pi\Sigma}c_{\bar{K}N} \\ c_{\pi\Sigma}c_{\bar{K}N} & c^2_{\bar{K}N}\end{pmatrix} + \dots$$

1. An effective range expansion (ERE) of the form

$$\widetilde{K}_{ij} = \frac{m_\pi}{E_{\mathrm{cm}}} \Big(A_{ij} + B_{ij} \Delta_{\pi\Sigma}(E_{\mathrm{cm}}) \Big). \tag{1}$$

2. A variation of the first parametrization without the factor of m_π / E_{cm}:

$$\widetilde{K}_{ij} = \widehat{A}_{ij} + \widehat{B}_{ij} \Delta_{\pi\Sigma}(E_{\mathrm{cm}}). \tag{2}$$

3. An ERE of $\widetilde{K}^{-1}$ of the form

$$\widetilde{K}^{-1}_{ij} = \frac{E_{\mathrm{cm}}}{m_\pi} \left(\widetilde{A}_{ij} + \widetilde{B}_{ij} \Delta_{\pi\Sigma}(E_{\mathrm{cm}}) \right). \tag{3}$$

Amplitude Analysis: Parametrizations

1. A Blatt-Biederharn parametrization:

$$\widetilde{K} = C\,F\,C^{-1}, \tag{4}$$

where

$$C = \begin{pmatrix} \cos\epsilon & \sin\epsilon \\ -\sin\epsilon & \cos\epsilon \end{pmatrix}, \tag{5}$$

$$F = \begin{pmatrix} f_0(E_{\rm cm}) & 0 \\ 0 & f_1(E_{\rm cm}) \end{pmatrix}, \tag{6}$$

and

$$f_i(E_{\rm cm}) = \frac{m_\pi}{E_{\rm cm}} \frac{a_i + b_i \Delta_{\pi\Sigma}(E_{\rm cm})}{1 + c_i \Delta_{\pi\Sigma}(E_{\rm cm})}. \tag{7}$$

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

Back-up

2-pole picture	Different CLAS analysis → Roca & Oset, PRC **88** (2013) 055206 → Mai & Meißner, EPJA **51** (2015) 30 BGOOD analysis → Schluchin et al., PLB **833** (2022) 137375 ALICE at LHC analysis → Acharya et al., EPJC **83** (2023) 340 Preliminary GlueX analysis → Wickramaarachchi et al., EPJ **271** (2022) 07005 Chiral approaches → Oller & Meißner, PLB **500** (2001) 263

1-pole picture	J-PARC analysis → Aikawa et al., PLB **837** (2023) 137637 Simple quark models → Isgur & Karl, PRD **18** (1978) 4187 Combined analysis from different experimental data (does not exclude two-pole picture) → Anisovich et al., EPJA **56** (2020) 139

Nomenclature

Back-up

- EPJ: Eur. Phys. Journal
- EPJA: Eur. Phys. Journal A
- EPJC: Eur. Phys. Journal C
- NPA: Nucl. Phys. **A**
- NPB: Nucl. Phys. **B**
- PLB: Phys. Lett. **B**
- PRC: Phys. Rev. **C**
- PRD: Phys. Rev. **D**
- PRL: Phys. Rev. **L**