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Two-pole structures in QCD

a universal phenomenon governed by chiral dynamics

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Jia-Ming Xie, Jun-Xu Lu，LSG*, Bing-Song Zou, PRD108(2023)L111502

Zejian Zhuang, R. Molina∗, Jun-Xu Lu, and LSG, 2405.07686

Ying-Bo He, Xiao-Hai Liu*, LSG*, Feng-Kun Guo*, Ju-Jun Xie*, 2407.13486

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- ☞ $\Lambda(1405)$: **first exotic hadron and two-pole structures**
- ☞ **Two-pole structures: flavor symmetry/group theory**
- ☞ **Two-pole structures: chiral dynamics at work**
- ☞ **Test the flavor content of the two poles**
- ☞ **Summary and outlook**

$\Lambda(1405)$: why is it special

In the constituent quark model, $\Lambda(1405)$ is the first P-wave orbital excitation of the ground-state baryon $\Lambda(1115)$

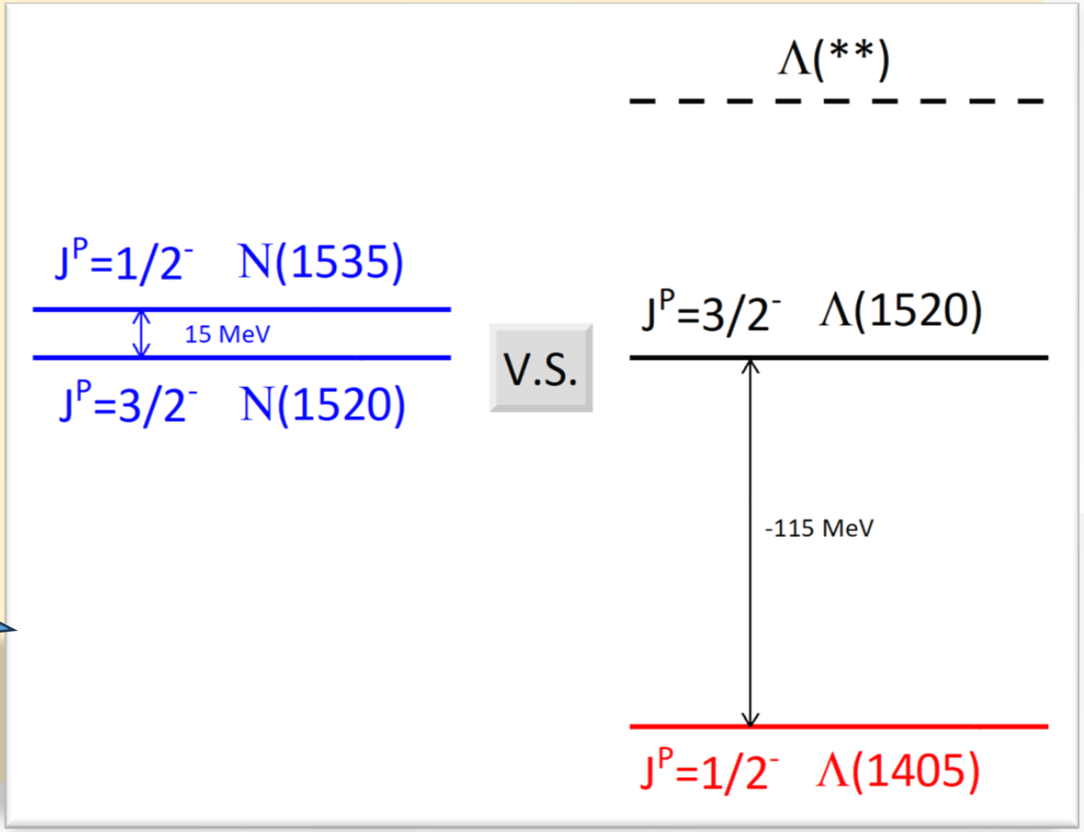
PDG

$I(J^P) = 0(1/2^-), S = -1$

$M = 1405.1^{+1.3}_{-1.0}$ MeV, $\Gamma = 50.5 \pm 2.0$ MeV

Two puzzles

Low mass vs. N*(1535)
large spin splitting vs. $\Lambda(1520)$



$\Lambda(1405)$: predicted before discovery as $\bar{K}N$ b state

Possible Resonant State in Pion-Hyperon Scattering

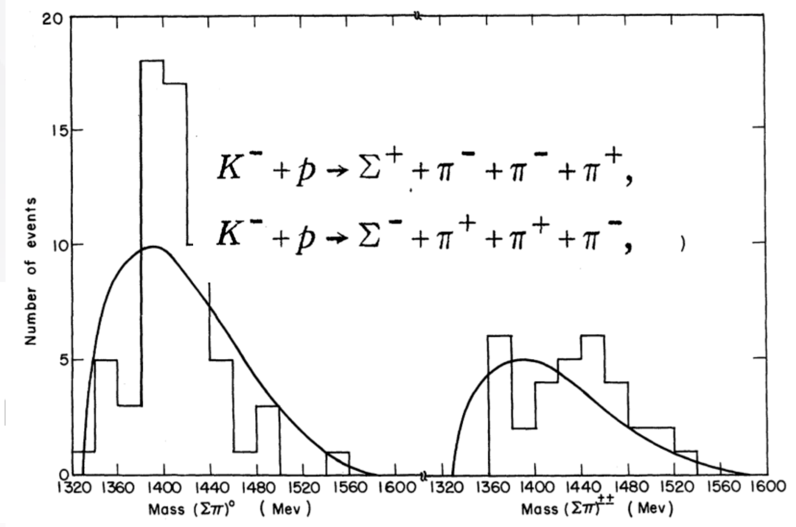
R. H. Dalitz and S. F. Tuan
Phys. Rev. Lett. **2**, 425 – Published 15 May 1959

Predicted in 1959

Study of Resonances of the $\Sigma - \pi$ System

Margaret H. Alston, Luis W. Alvarez, Philippe Eberhard, Myron L. Good, William Graziano, Harold
Stanley G. Wojcicki
Phys. Rev. Lett. **6**, 698 – Published 15 June 1961

Discovered in 1961

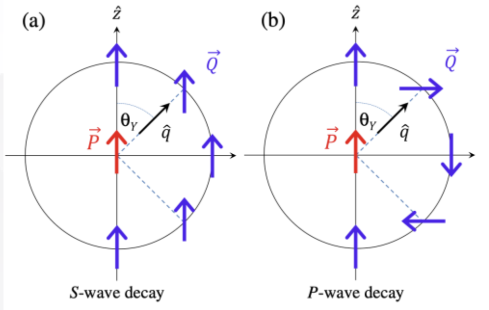


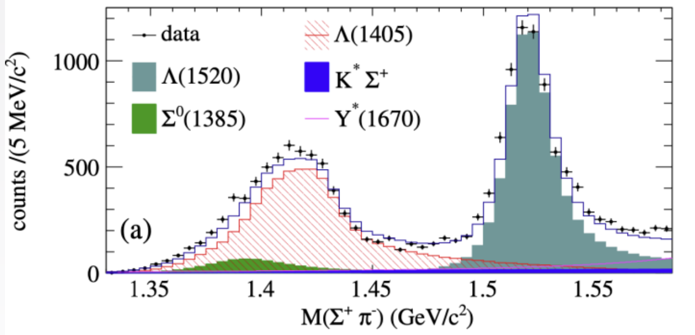
Spin and parity measurement of the $\Lambda(1405)$ baryon

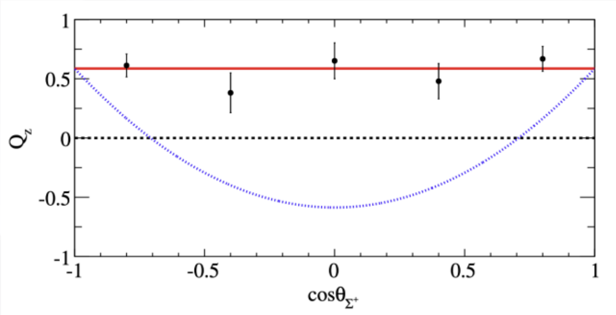
$\gamma + p \to K^+ + \Lambda(1405)$

K. Moriya *et al.* (CLAS Collaboration)
Phys. Rev. Lett. **112**, 082004 – Published 28 February 2014

Spin & Parity measured 2014

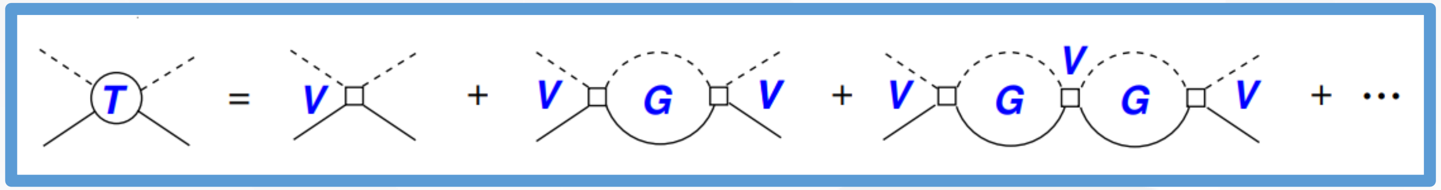






$\Lambda(1405)$ as a dynamically generated state

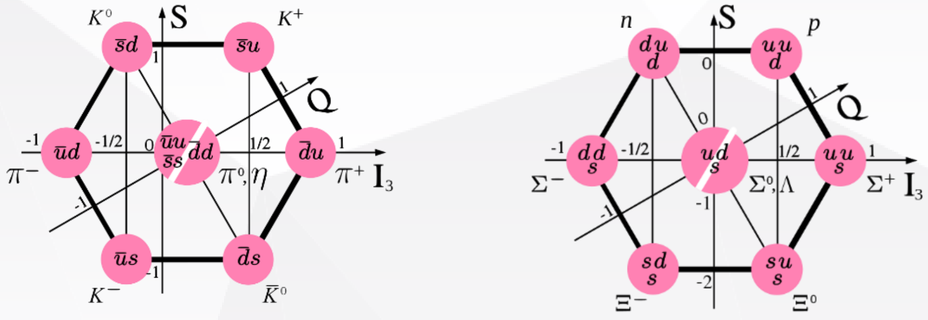
- Modern picture for $\Lambda(1405)$: a $\bar{K}N$ bound state **dynamically generated by coupled-channel chiral dynamics** implemented in the so-called chiral unitary approaches



Bethe-Salpeter Equation

- Weinberg-Tomozawa potential

$$\boxed{V_{ij} = -\frac{C_{ij}}{4f^2}(E_i + E_j)}$$

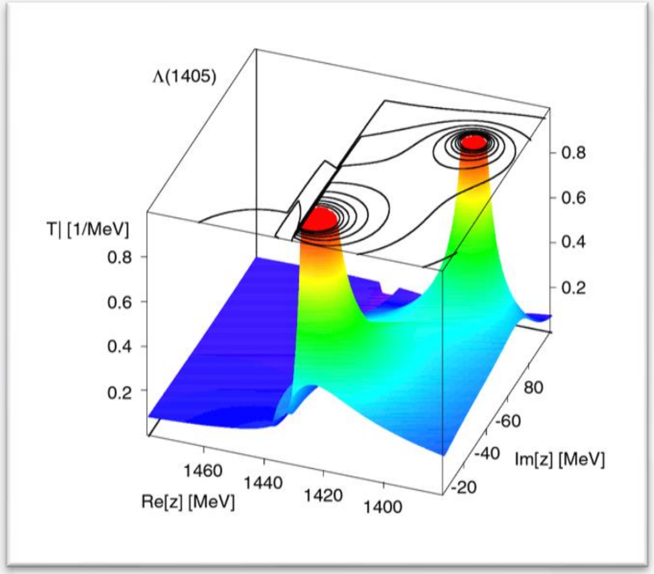


- LO&NLO, Kaiser, Siegel, Weise, NPA594, 325(1995), **748** citations
- LO, Oset and Ramos, NPA635, 99(1998), **874** citations
- NLO, Oller and Meissner, PLB500, 263(2001), **928** citations

as of 2024.08.23

Unexpected two-pole structure!

- **Two poles:** $W_H = 1424.3 - 17.1i$, $W_L = 1389.1 - 64.1$



	$\Lambda(1405)$	
z_R (MeV)	$1390 - 66i$	$1426 - 16i$
$\lvert g_i \rvert(\pi\Sigma)$	2.9	1.5
$\lvert g_i \rvert(\bar{K}N)$	2.1	2.7
$\lvert g_i \rvert(\eta\Lambda)$	0.77	1.4
$\lvert g_i \rvert(K\Xi)$	0.61	0.35

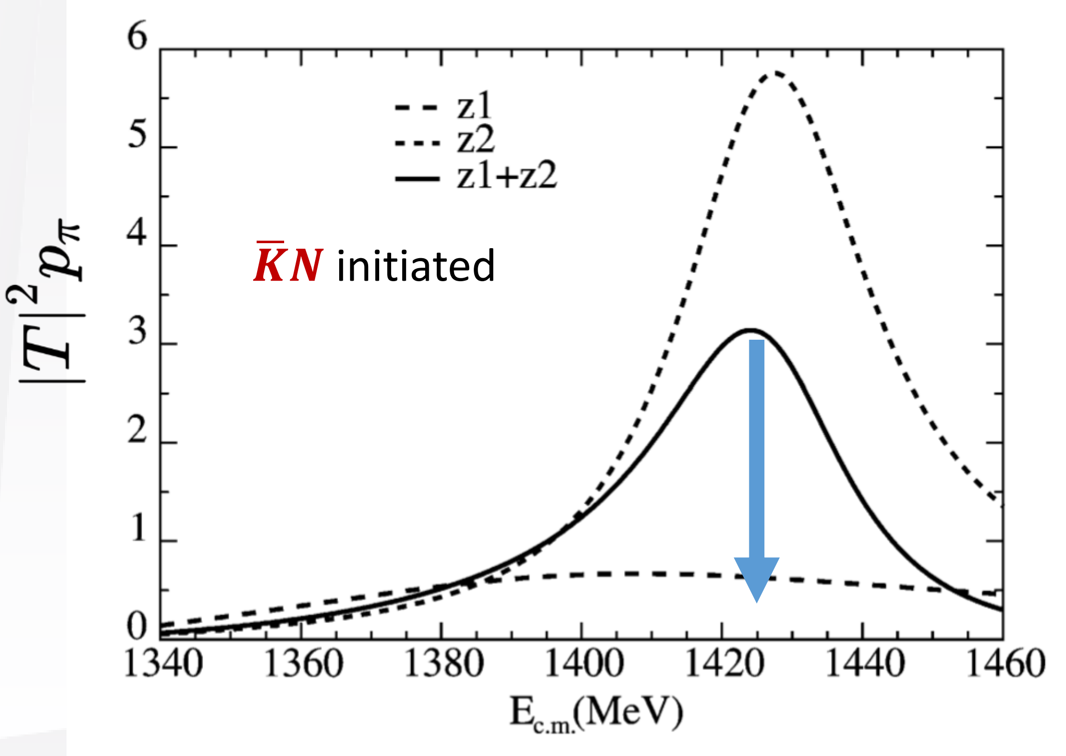
Isopin 0, four coupled channels: $\boldsymbol{\pi\Sigma(1330)}$, $\boldsymbol{\bar{K}N(1433)}$, $\eta\Lambda(1662)$, $K\Xi(1813)$ (renormalization scale $\mu = 630$ MeV, with four different $a_i(\mu)$)

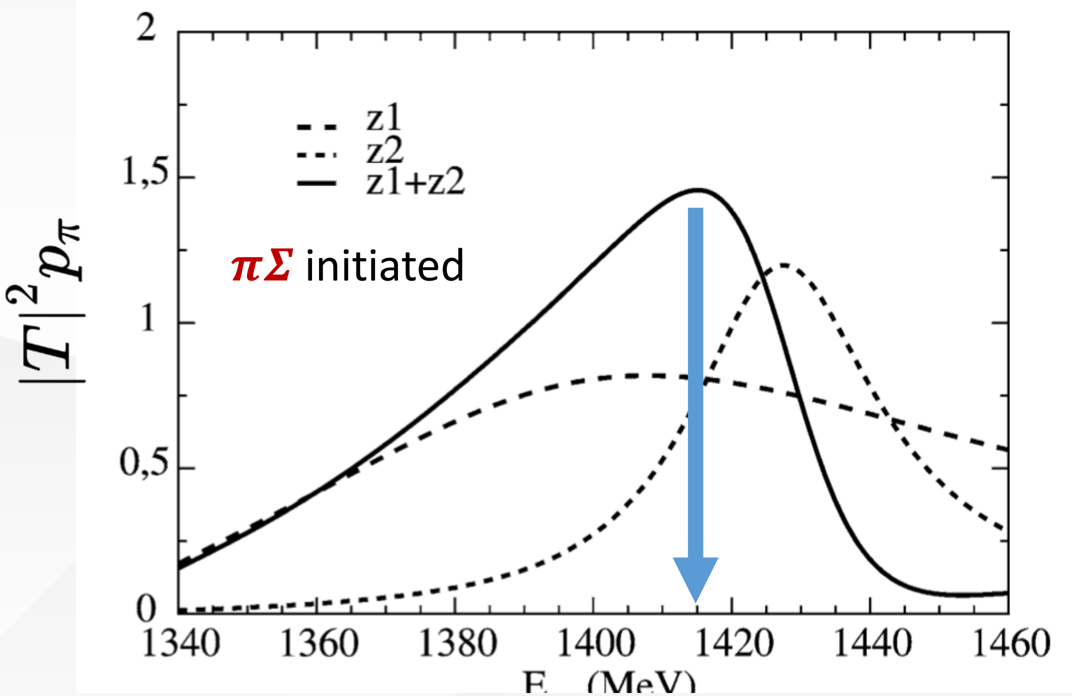
Oller and Meissner, PLB500, 263(2001)
Jido, Oller, Oset, Ramos, and Meissner, NPA725, 181 (2003)
Hyodo and Jido, PPNP67, 55 (2012)

$\Lambda(1405)$-dynamical generated two-pole structure!

$$g^{R_1}_{\bar{K}N}\frac{1}{W-M_{R_1}+i\Gamma_{R_1}/2}g^{R_1}_{\pi\Sigma}+g^{R_2}_{\bar{K}N}\frac{1}{W-M_{R_2}+i\Gamma_{R_2}/2}g^{R_2}_{\pi\Sigma},$$

$$g^{R_1}_{\pi\Sigma}\frac{1}{W-M_{R_1}+i\Gamma_{R_1}/2}g^{R_1}_{\pi\Sigma}+g^{R_2}_{\pi\Sigma}\frac{1}{W-M_{R_2}+i\Gamma_{R_2}/2}g^{R_2}_{\pi\Sigma}$$





Oller and Meissner, PLB500(2001)263
Jido, Oller, Oset, Ramos, and Meissner, NPA725, 181 (2003)
Hyodo and Jido, PPNP67, 55 (2012)

Evidence for the two-pole structure of the $\Lambda(1405)$ state

PRL **95,** 052301 (2005) PHYSICAL REVIEW LETTERS week ending 29 JULY 2005

Evidence for the Two-Pole Structure of the $\Lambda(1405)$ Resonance

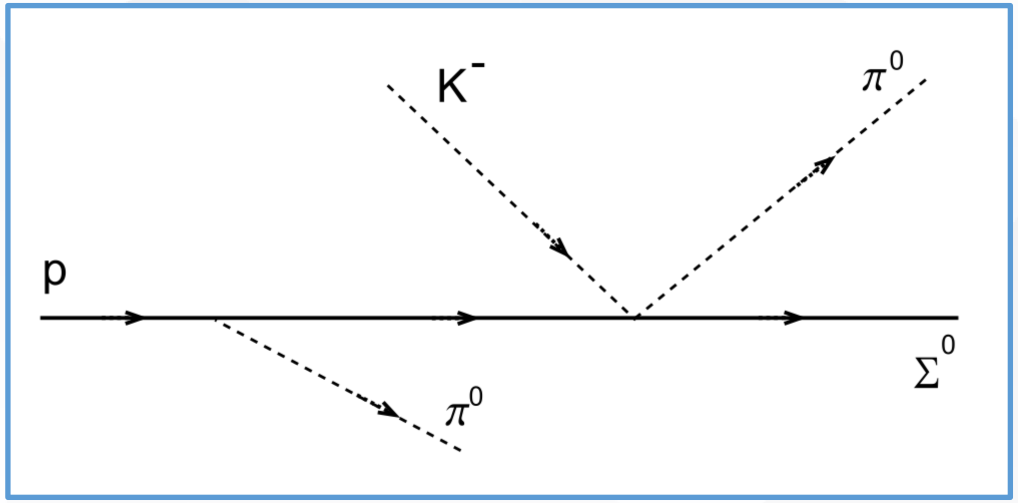
V. K. Magas,[1] E. Oset,[1] and A. Ramos[2]

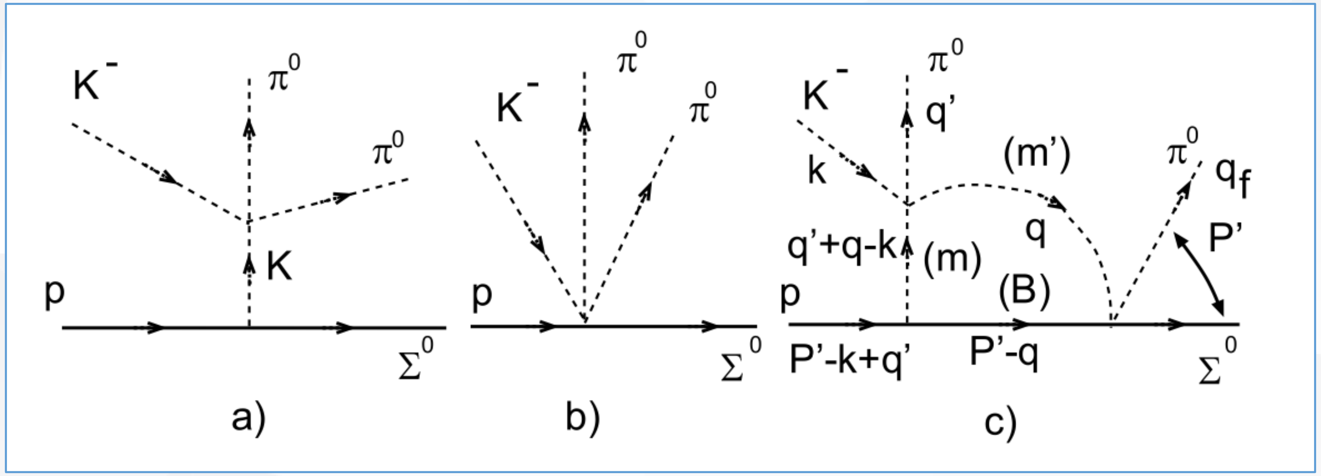
[1]*Departamento de Física Teórica and IFIC, Centro Mixto, Institutos de Investigación de Paterna–Universidad de Valencia-CSIC, Apartado correos 22085, 46071, Valencia, Spain*

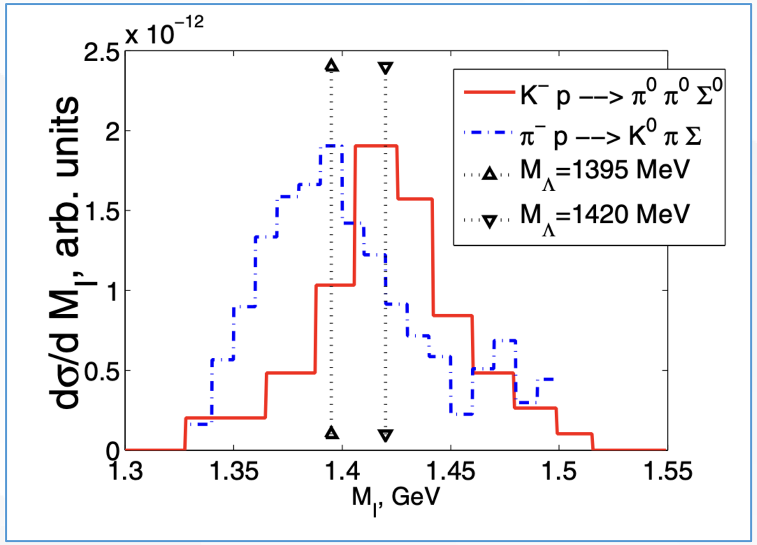
[2]*Departament d'Estructura i Constituents de la Matéria, Universitat de Barcelona, Diagonal 647, 08028 Barcelona, Spain*

(Received 7 March 2005; published 28 July 2005)

The $K^- p \to \pi^0 \pi^0 \Sigma^0$ reaction is studied within a chiral unitary model. The distribution of $\pi^0 \Sigma^0$ states forming the $\Lambda(1405)$ shows, in agreement with a recent experiment, a peak at 1420 MeV and a relatively narrow width of $\Gamma = 38$ MeV. The mechanism for the reaction is largely dominated by the emission of a π^0 prior to the $K^- p$ interaction leading to the $\Lambda(1405)$. This ensures the coupling of the $\Lambda(1405)$ to the $K^- p$ channel, thus maximizing the contribution of the second state found in chiral unitary theories, which is narrow and of higher energy than the nominal $\Lambda(1405)$. This is unlike the $\pi^- p \to K^0 \pi \Sigma$ reaction, which gives more weight to the pole at lower energy and with a larger width. The data of these two experiments, together with the present theoretical analysis, provide firm evidence of the two-pole structure of the $\Lambda(1405)$.

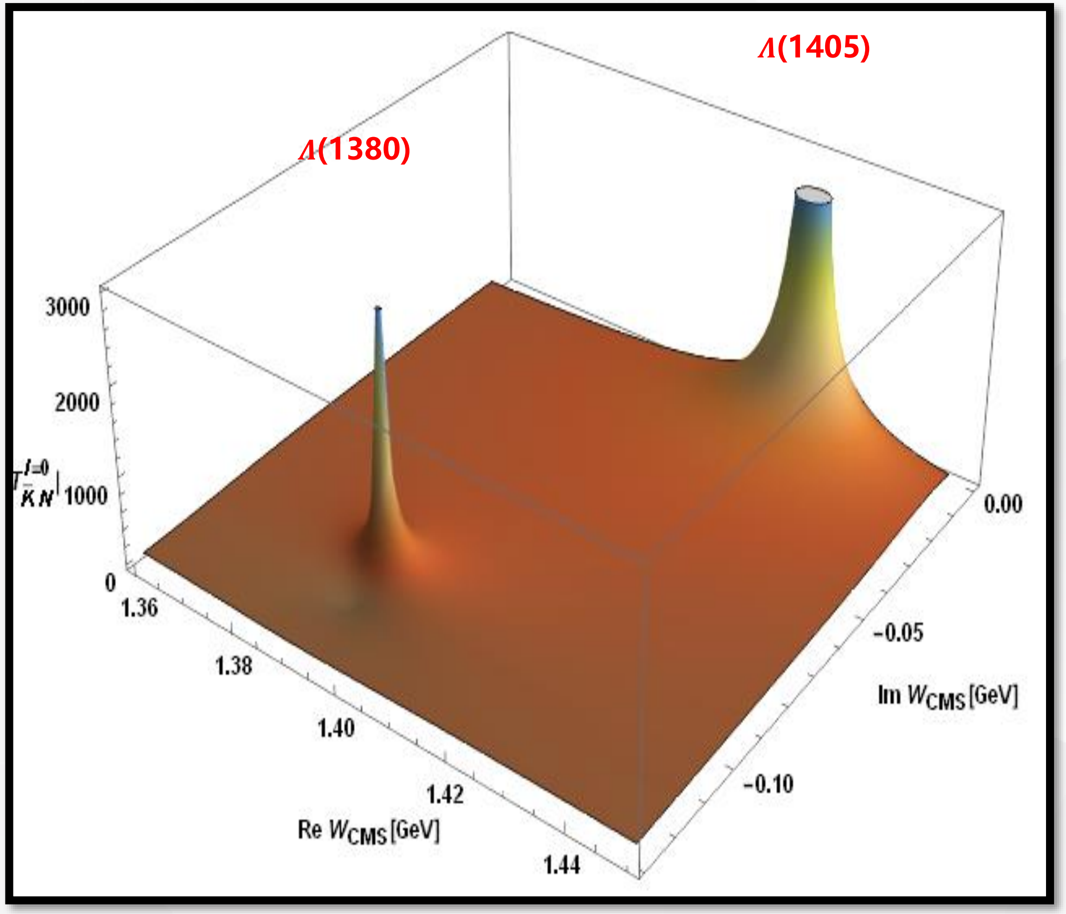


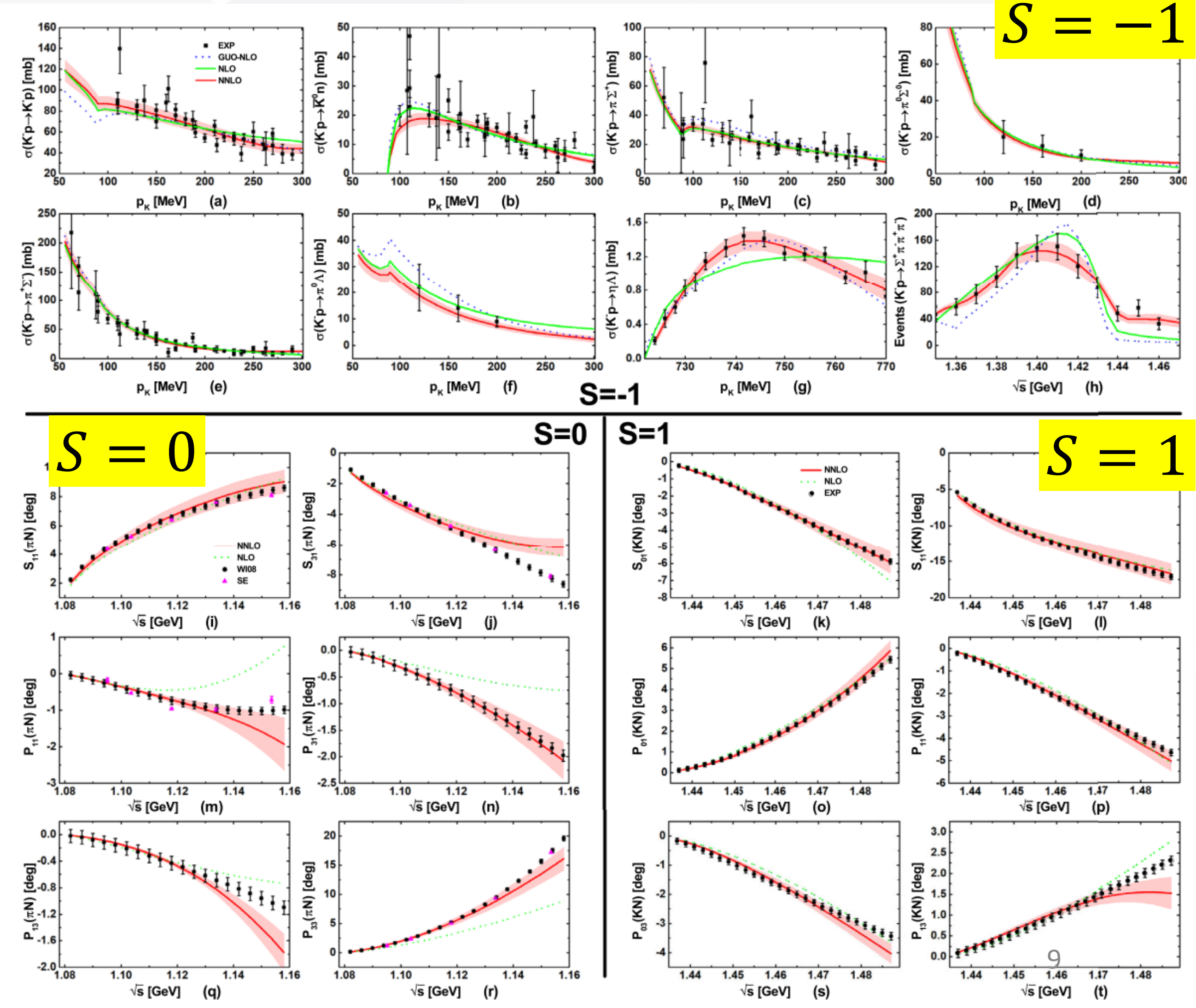




The two-pole structure persists at N2LO

Meson-baryon scattering up to N2LO, Jun-Xu Lu, LSG*, M. Doering and M. Mai, PRL130, 071902(2023)





Already in the review of particle physics

Lambda Baryons ($S = -1, I = 0$)					
Lambda $1/2^+$	PDF	pdgLive	Lambda(1890) $3/2^+$	PDF	pdgLive
Lambda(1380) $1/2^-$	PDF	pdgLive	Lambda(2000)	PDF	pdgLive
Lambda(1405) $1/2^-$	PDF	pdgLive	Lambda(2050) $3/2^-$	PDF	pdgLive
Lambda(1520) $3/2^-$	PDF	pdgLive	Lambda(2070) $3/2^+$	PDF	pdgLive
Lambda(1600) $1/2^+$	PDF	pdgLive	Lambda(2080) $5/2^-$	PDF	pdgLive
Lambda(1670) $1/2^-$	PDF	pdgLive	Lambda(2085) $7/2^+$	PDF	pdgLive
Lambda(1690) $3/2^-$	PDF	pdgLive	Lambda(2100) $7/2^-$	PDF	pdgLive
Lambda(1710) $1/2^+$	PDF	pdgLive	Lambda(2110) $5/2^+$	PDF	pdgLive
Lambda(1800) $1/2^-$	PDF	pdgLive	Lambda(2325) $3/2^-$	PDF	pdgLive
Lambda(1810) $1/2^+$	PDF	pdgLive	Lambda(2350) $9/2^+$	PDF	pdgLive
Lambda(1820) $5/2^+$	PDF	pdgLive	Lambda(2585)	PDF	pdgLive
Lambda(1830) $5/2^-$	PDF	pdgLive			

Latest lattice QCD study

$$\det[\widetilde{K}^{-1}(E_{\text{cm}}) - B^{\boldsymbol{P}}(E_{\text{cm}})] = 0$$

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

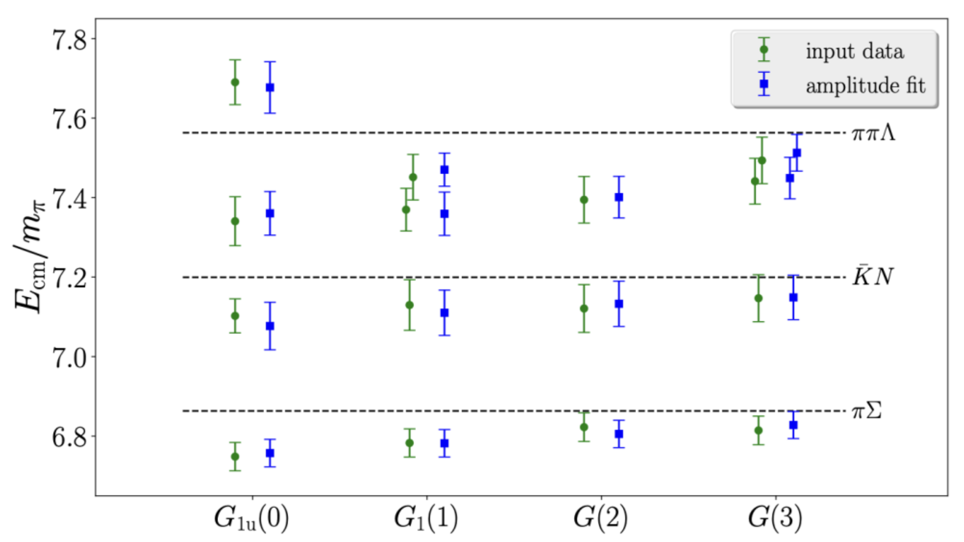
Editors' Suggestion   Open Access   Acc

Two-Pole Nature of the $\Lambda(1405)$ Resonance from Lattice QCD

John Bulava, Bárbara Cid-Mora, Andrew D. Hanlon, Ben Hörz, Daniel Mohler, Colin Morningstar, Joseph Moscoso, Amy Nicholson, Fernando Romero-López, Sarah Skinner, and André Walker-Loud (Baryon Scattering (BaSc) Collaboration)

Phys. Rev. Lett. **132**, 051901 – Published 30 January 2024

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.



Two poles are found on the $(-,+)$ sheet, which is the one closest to physical scattering in the region between the two thresholds. Their locations are

$$\begin{aligned} E_1 &= 1392(9)(2)(16)\ \text{MeV}, \\ E_2 &= [1455(13)(2)(17) - i11.5(4.4)(4)(0.1)]\ \text{MeV}, \end{aligned} \tag{6}$$

and their couplings

$$\left|\frac{c^{(1)}_{\pi\Sigma}}{c^{(1)}_{\bar{K}N}}\right| = 1.9(4)(6), \qquad \left|\frac{c^{(2)}_{\pi\Sigma}}{c^{(2)}_{\bar{K}N}}\right| = 0.53(9)(10). \tag{7}$$

$m_\pi \approx$ **200 MeV,**
a virtual bound state below $\pi\Sigma$ and a resonant (bound) state just below $\bar{K}N$,
support the two-pole structure suggested

Following up theoretical works

Pole trajectories of the $\Lambda(1405)$ helps establish its dynamical nature

#3

Zejian Zhuang (Valencia U., IFIC), Raquel Molina (Valencia U., IFIC), Jun-Xu Lu (Beihang U.), Li-Sheng Geng (Beihang U. and Peking U. and Peking U., SKLNPT and Beijing, CSRC and Lanzhou, Inst. Modern Phys.) (May 13, 2024)

e-Print: 2405.07686 [hep-ph]

Light-quark mass dependence of the Λ(1405) resonance

Xiu-Lei Ren (Helmholtz Inst., Mainz) (Apr 3, 2024)

Published in: *Phys.Lett.B* 855 (2024) 138802 • e-Print: 2404.02720 [hep-ph]

New insights into the nature of the Λ(1380) and Λ(1405) resonances away from the SU(3) limit

#17

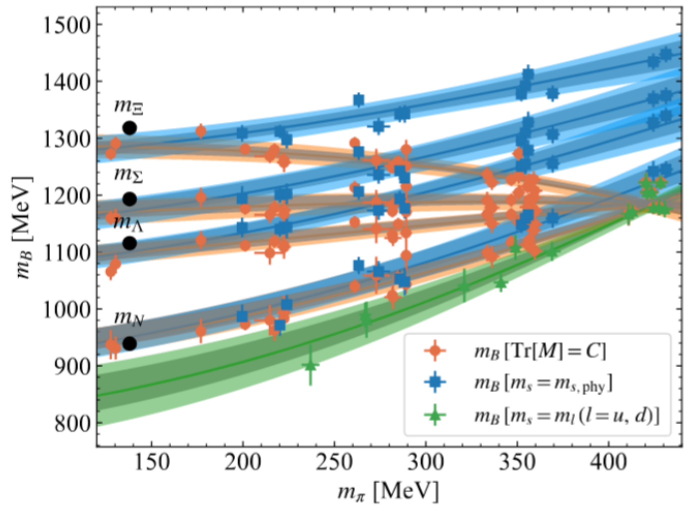
Feng-Kun Guo (Beijing, Inst. Theor. Phys. and Beijing, GUCAS and Beijing, CSRC), Yuki Kamiya (Bonn U., HISKP), Maxim Mai (Bonn U., HISKP and George Washington U.), Ulf-G. Meißner (Bonn U., HISKP and Julich, Forschungszentrum and IAS, Julich and JCHP, Julich and Tbilisi State U.) (Aug 15, 2023)

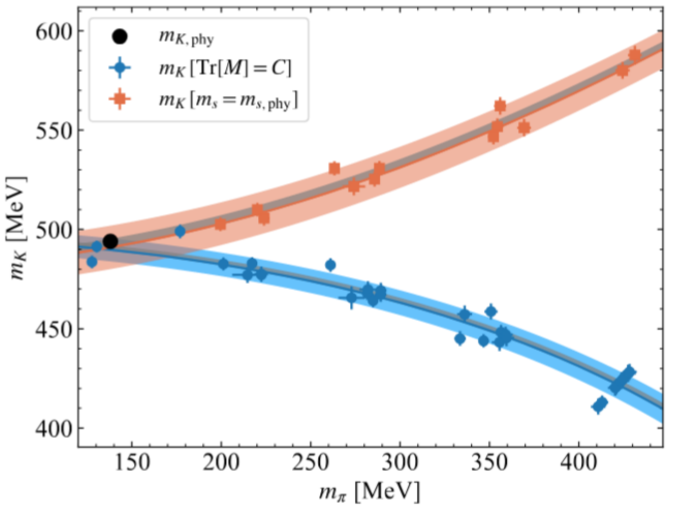
Published in: *Phys.Lett.B* 846 (2023) 138264 • e-Print: 2308.07658 [hep-ph]

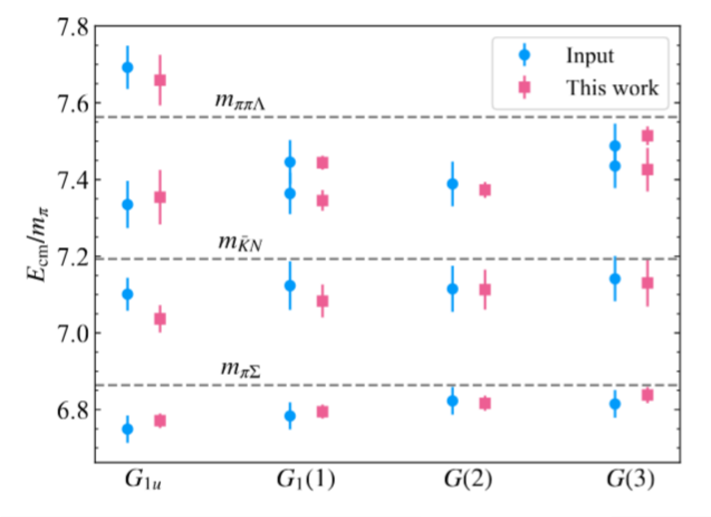
Can be described by UChPT and consistent with exp.

2405.07686, Zejian Zhuang, R. Molina*, Jun-Xu Lu, and LSG

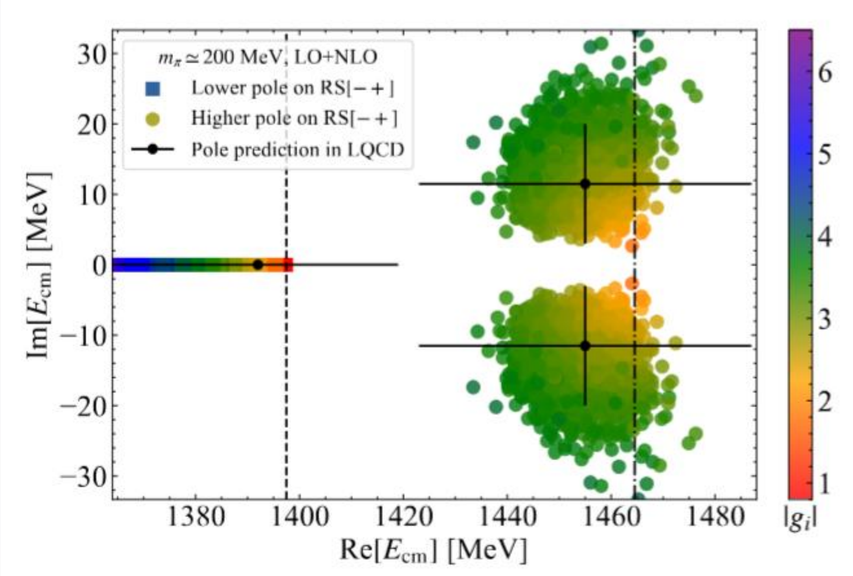
Fits

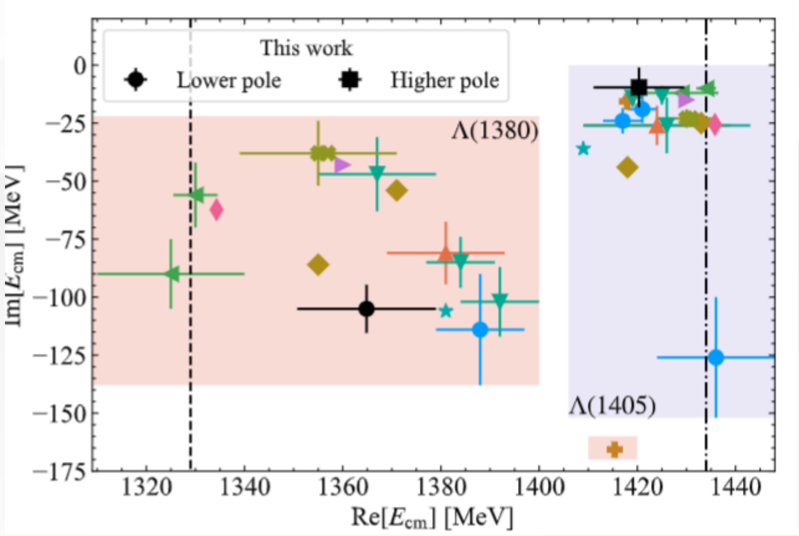


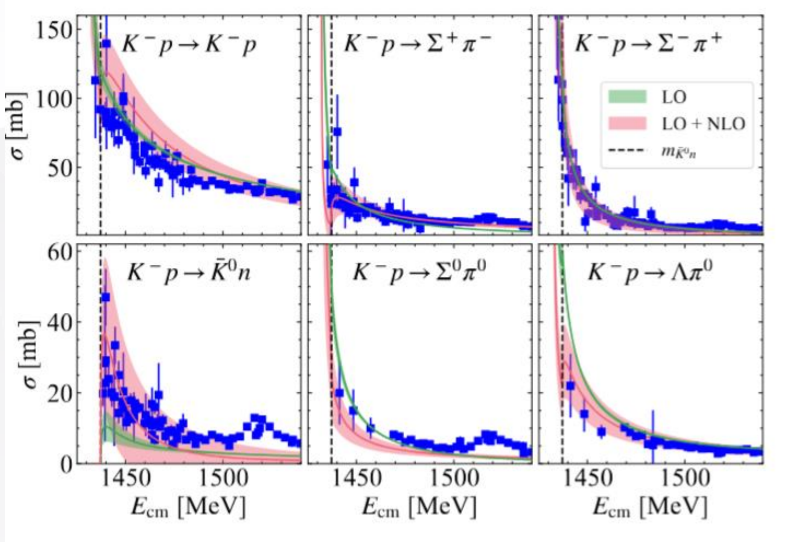




predictions



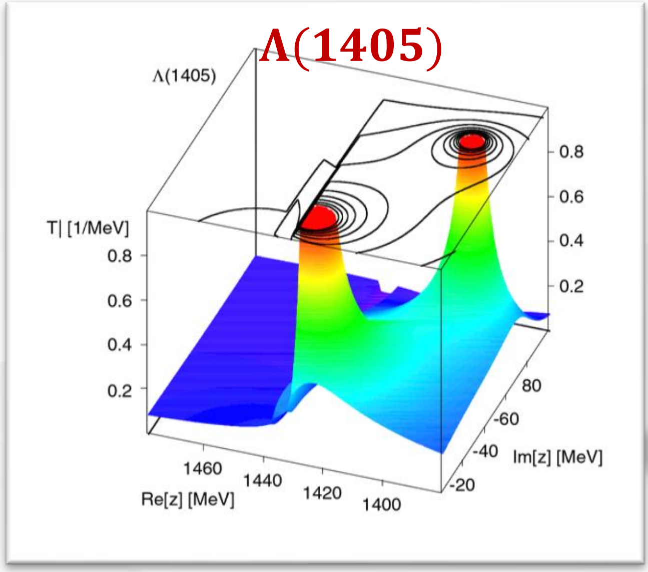




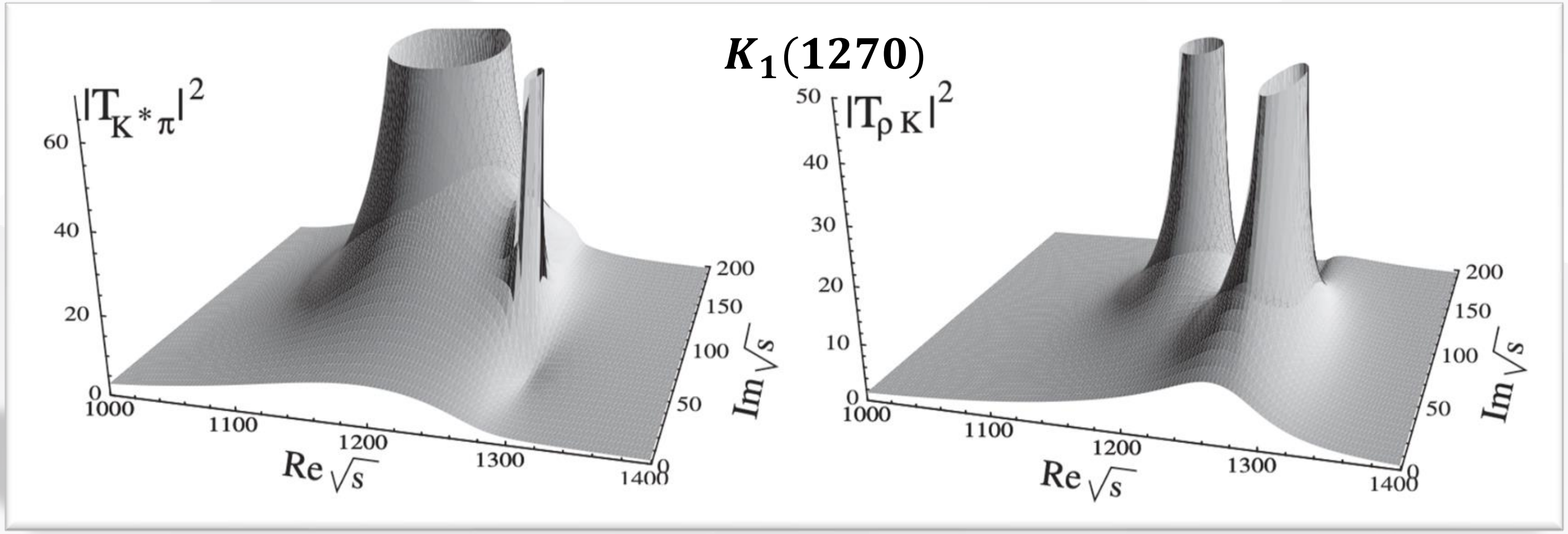
Two-pole structures are not simply two states!

① Two-pole structures refer to the fact that two dynamically generated states, **one resonant and one bound, are located close to each other** between two coupled channels and with a mass difference smaller than the sum of their widths.

② Two poles overlap, which creates the impression that **there is only one state in the invariant mass distribution** of their decay products.

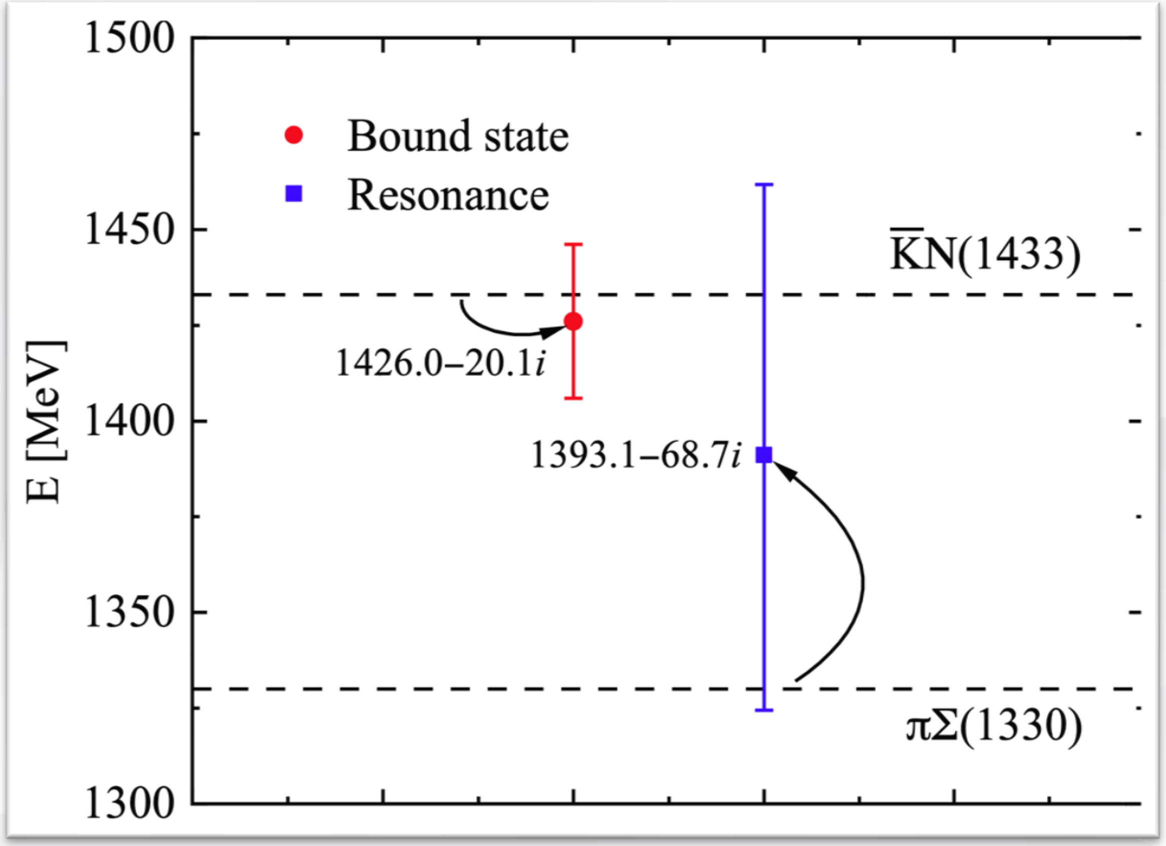


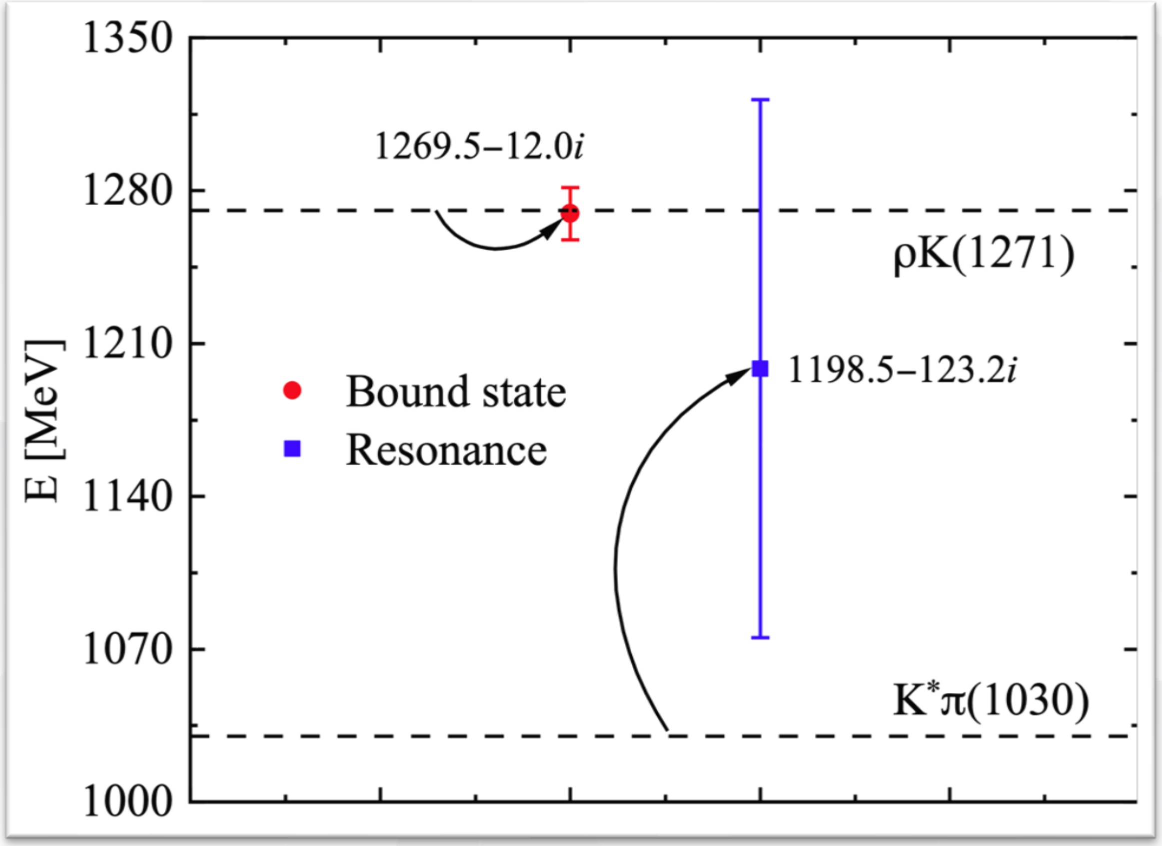
Hyodo and Jido, PPNP67, 55 (2012)



LSG, Oset, Roca, and Oller, PRD**75,** 014017 (2007)

Two prominent examples: $\Lambda(1405)$ and $K_1(1270)$





Contents

Comprehensive review from the flavor-symmetry perspective

symmetry

MDPI

Article

Two-Pole Structures in QCD: Facts, Not Fantasy!

Ulf-G. Meißner [1,2,3]

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2 Institute for Advanced Simulation, Institut für Kernphysik, and Jülich Center for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany

3 Tbilisi State University, 0186 Tbilisi, Georgia

check for updates

Received: 15 May 2020; Accepted: 4 June 2020; Published: 8 June 2020

3. The Story of the Λ(1405)

4. Meson Sector: The $D0*(2300)$ and Related States

4.1. Two-Pole Structure

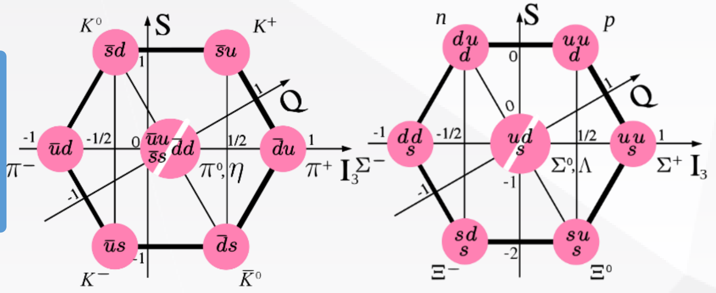
4.2. Other Candidates

4.3. Analysis of B → Dππ Data

4.4. The K1 Meson

SU(3) group-theoretical explanation

$$V_{ij} = -\frac{C_{ij}}{4f^2}(E_i + E_j)$$



◻ SU(3) symmetry decomposition

$$8 \otimes 8 = 1 \oplus 8_s \oplus 8_a \oplus 10 \oplus \overline{10} \oplus 27$$

Baryon octet-NGB octet

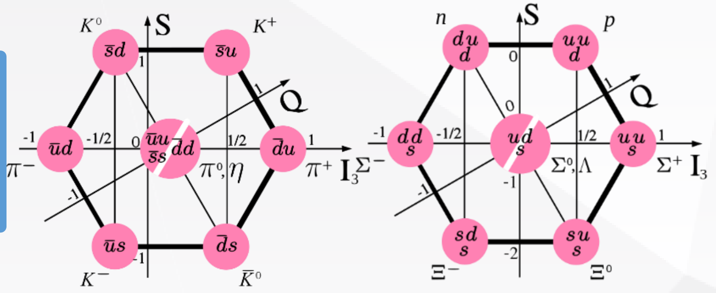
Potential in this basis

$$V_{\alpha\beta} = \mathrm{diag}(6, \underline{3, 3}, 0, 0, -2)$$

attractive

SU(3) group-theoretical explanation

$$V_{ij} = -\frac{C_{ij}}{4f^2}(E_i + E_j)$$



SU(3) symmetry decomposition

$$8 \otimes 8 = 1 \oplus 8_s \oplus 8_a \oplus 10 \oplus \overline{10} \oplus 27$$

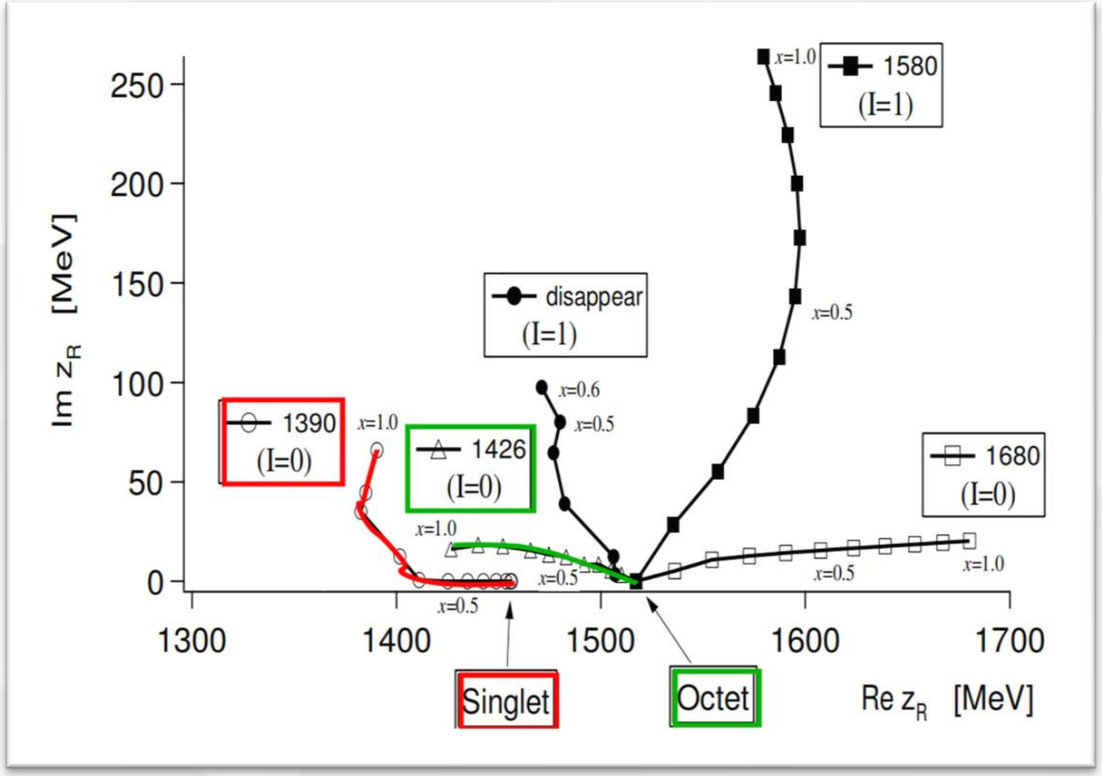
Baryon octet-NGB octet

Potential in this basis

$$V_{\alpha\beta} = \mathrm{diag}(6, \underbrace{3, 3}_{\text{attractive}}, 0, 0, -2)$$

SU(3) symmetry breaking

$$M_i(x) = M_0 + x(M_i - M_0),$$
$$m_i^2(x) = m_0^2 + x(m_i^2 - m_0^2),$$
$$a_i(x) = a_0 + x(a_i - a_0),$$



Jido, Oller, Oset, Ramos, and Meissner, NPA725, 181(2003)

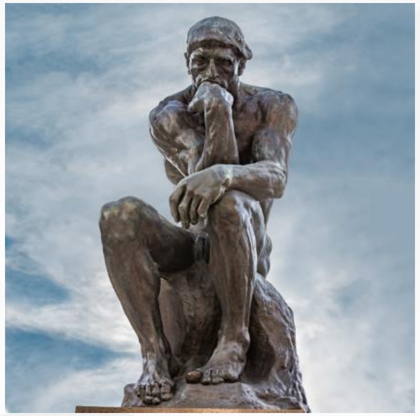
More can be asked

- ◻ **Two-pole structures are not just two states**

More can be asked

- Two-pole structures are not just two states

- Many questions can be asked



1. Why are there two?
2. Why can they be mistaken for one state?
3. Why are they located between the two channels?
4. What kind of interactions can generate such two poles?
5. ……

Three questions to ask/answer (not by flavor sym.)

$$V_{ij} = -\frac{C_{ij}}{4f^2}(E_i + E_j)$$

Q1 Is the coupling between $\bar{K}N$ and $\pi\Sigma$ important?

Q2 How does the nature of the Nambu-Goldstone bosons play a role?

Q3 Whether is the energy dependence of the WT potential relevant?

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- ☞ **Summary and outlook**

Chiral unitary approach—leading order

□Leading order interaction between a NGB and a ground-state baryon

$$\mathcal{L}_{PB}^{\mathrm{WT}} = \frac{1}{4f^2}\mathrm{Tr}\left(\bar{\mathcal{B}} i\gamma^\mu \left[\Phi\partial_\mu\Phi - \partial_\mu\Phi\Phi, \mathcal{B}\right]\right)$$

$$\Phi = \begin{bmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{bmatrix} \qquad \mathcal{B} = \begin{bmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{bmatrix}$$

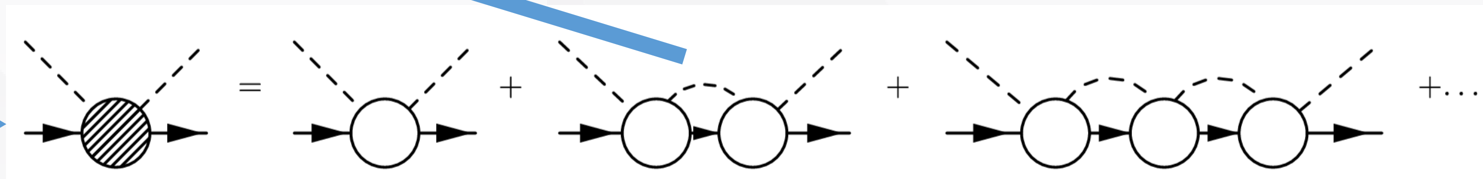
□The Weinberg-Tomozawa (WT) potential — parameter free

$$V_{ij} = -\frac{C_{ij}}{4f^2}\left(2\sqrt{s} - M_i - M_j\right) = -\frac{C_{ij}}{4f^2}\left(E_i + E_j\right)$$

$\Lambda(1405)$—dynamically generated in Chiral Unitary Approaches

- Chiral dynamics &. Coupled-channel unitarity—Bethe Salpeter equation

$$T = (1 - VG)^{-1}V$$



- Loop function

$$G_k\left(\sqrt{s}; a_k(\mu)\right) = \frac{2M_k}{16\pi^2}\left\{a_k(\mu) + \frac{m_k^2 - M_k^2 + s}{2s}\ln\frac{m_k^2}{M_k^2} + \ln\frac{M_k^2}{\mu^2} + \frac{p_k\left(\sqrt{s}\right)}{\sqrt{s}}\ln\left(\frac{\phi_{++}\phi_{+-}}{\phi_{-+}\phi_{--}}\right)\right\}$$

$$\phi_{\pm\pm} \equiv \pm s \pm \left(M_k^2 - m_k^2\right) + 2\sqrt{s}p_k\left(\sqrt{s}\right)$$

Dim. Regularization

$$G_{\text{cut}} = \int_0^{\Lambda} \frac{q^2 dq}{2\pi^2} \frac{E_M + E_m}{2E_M E_m} \frac{2M}{s - (E_M + E_m)^2 + i\epsilon}$$

Cutoff regularization

- Dynamically generated states — singularities of unitarized amplitude T

See, e.g., Oller, Oset, and Ramos, PPNP45, 157 (2000)

Q1: Is the coupling between $\bar{K}N$ and $\pi\Sigma$ important?

- **To simplify the discussion, consider only the two most relevant channels around 1400 MeV: $\bar{K}N(1433)$, $\pi\Sigma(1330)$--equivalent to the full four-body analysis**
  - With the subtraction constants: $a_{\bar{K}N} = -1.95$, $a_{\pi\Sigma} = -1.92$, **we obtain two poles:** $W_H = 1426.0 - 20.1i$, $W_L = 1393.1 - 68.7i$ (to be compared with the four-channel results) $W_H = 1424.3 - 17.1i$, $W_L = 1389.1 - 64.1\mathrm{i}$)
- **We gradually turn off the intra-channel coupling to see what happens, i.e., whether the coupling is important**

Zero-coupling limit, see, e.g.,
Hyodo et al, Phys.Rev.C 77 (2008) 035204
A. Cieplý et al, Nucl. Phys. A, 954 (2016) 17-40

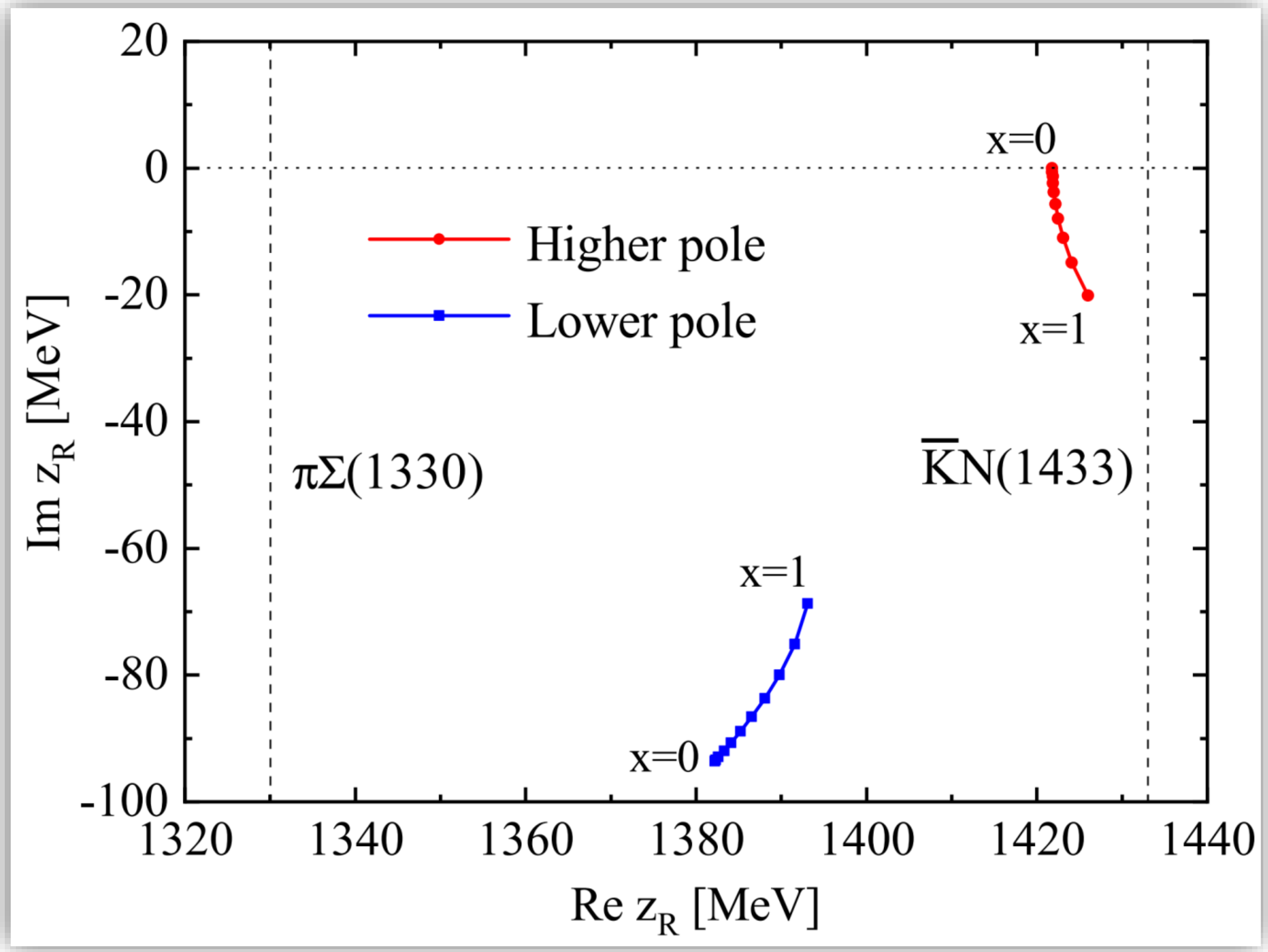
Q1: Is the coupling important?

- Multiply a factor $0 \le x \le 1$, to the off-diagonal matrix elements of the WT potential

$$C_{ij} = \begin{bmatrix} 3 & -\sqrt{\frac{3}{2}}x \\ & 4 \end{bmatrix}$$

- Even in the limit of **complete decoupling** ($x = 0$), there are still two poles between the two channels:

$$W_H = 1421.8 - 0i,$$
$$W_L = 1382.2 - 93.6i$$



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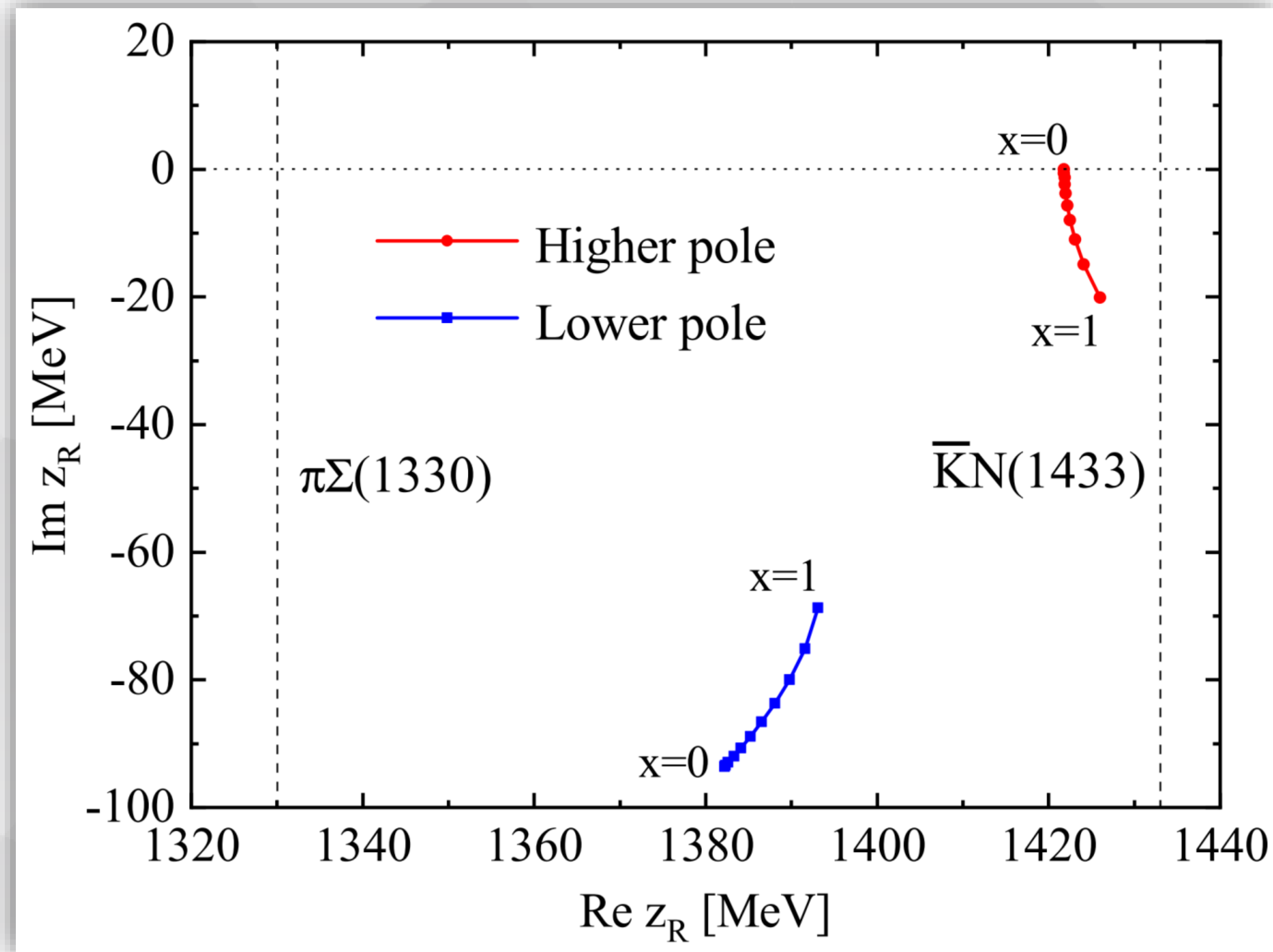

Coupling not necessary for two poles but relevant for the decay

Q2: How does the nature of NG bosons play a role?

□**The diagonal chiral WT potential (**since coupling bw two channels is less relevant**)**

$$V_{\bar{K}N-\bar{K}N}\left(\sqrt{s}\right) = -\frac{6}{4f^2}E_{\bar{K}} = -\frac{6}{4f^2}\sqrt{m_{\bar{K}}^2 + q^2},$$

$$V_{\pi\Sigma-\pi\Sigma}\left(\sqrt{s}\right) = -\frac{8}{4f^2}E_{\pi} = -\frac{8}{4f^2}\sqrt{m_{\pi}^2 + q^2}.$$

$m_K = 496$ MeV
$m_\pi = 138$ MeV

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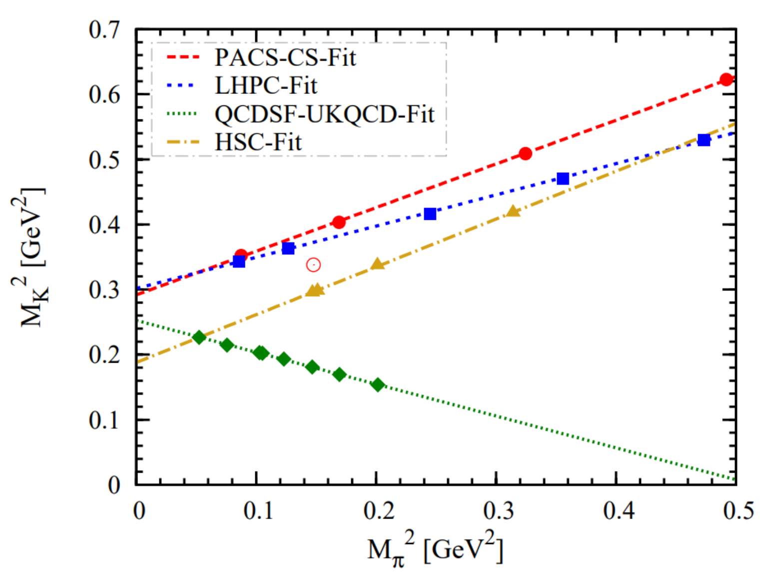
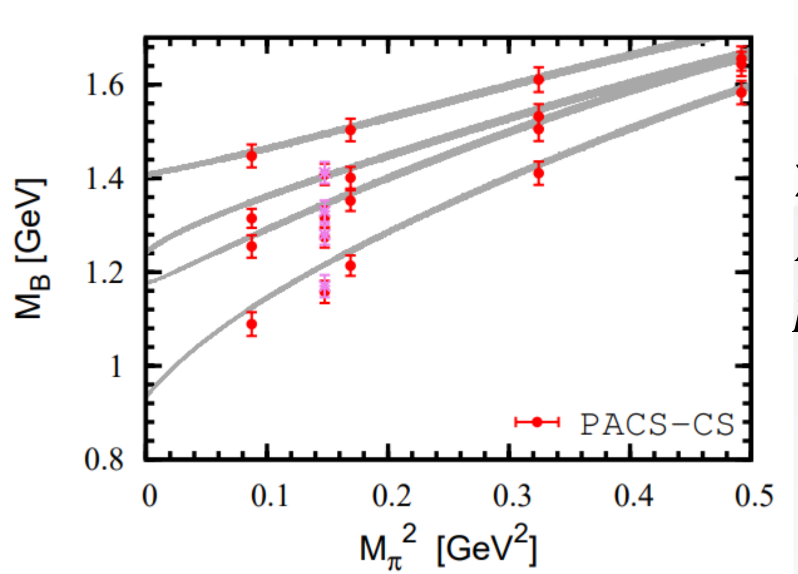
➢**The small pion mass combined with the q^2(energy)-dependence** of the interaction is responsible for the dynamical generation of **a $\pi\Sigma(1330)$ resonance**, because a momentum-independent potential cannot generate S-wave resonances

Role of explicit chiral symmetry breaking

- ◻ To better understand explicit chiral symmetry breaking, we study the **pole trajectories** as a function of the light-quark (pion) mass dependence.
- ◻ For the pion mass dependence of the mesons and baryons, we follow the PACS-CS trajectory





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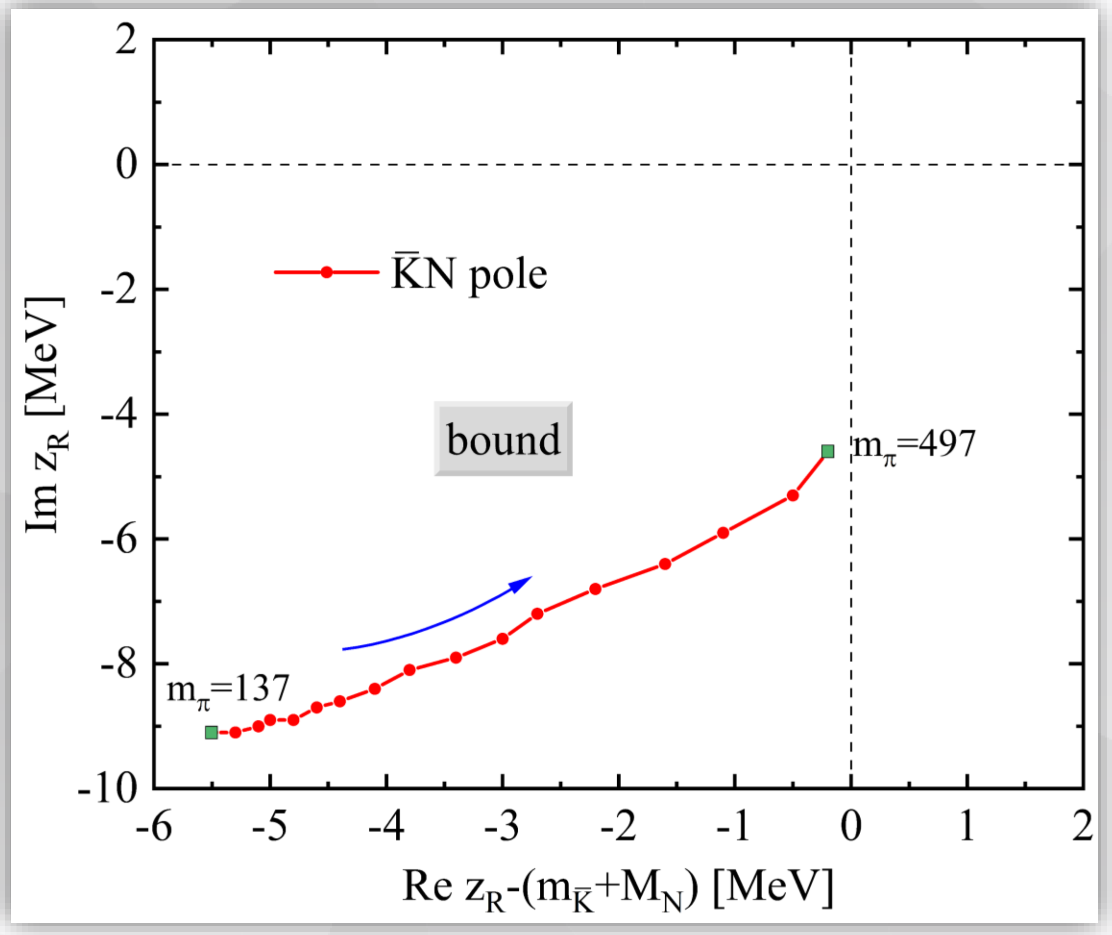
Ren, LSG*, Camalich, Meng, and Toki, JHEP**12**, 073 (2012)

Aoki et al. (PACS-CS), PRD**79**, 034503 (2009)

Variation of higher pole with m_π: simple

- **As m_π increases**, both the real and the imaginary parts of the higher pole decrease, which indicates that **the effective $\bar{K}N$ attraction becomes weaker and the coupling to $\pi\Sigma$ decreases as well.**

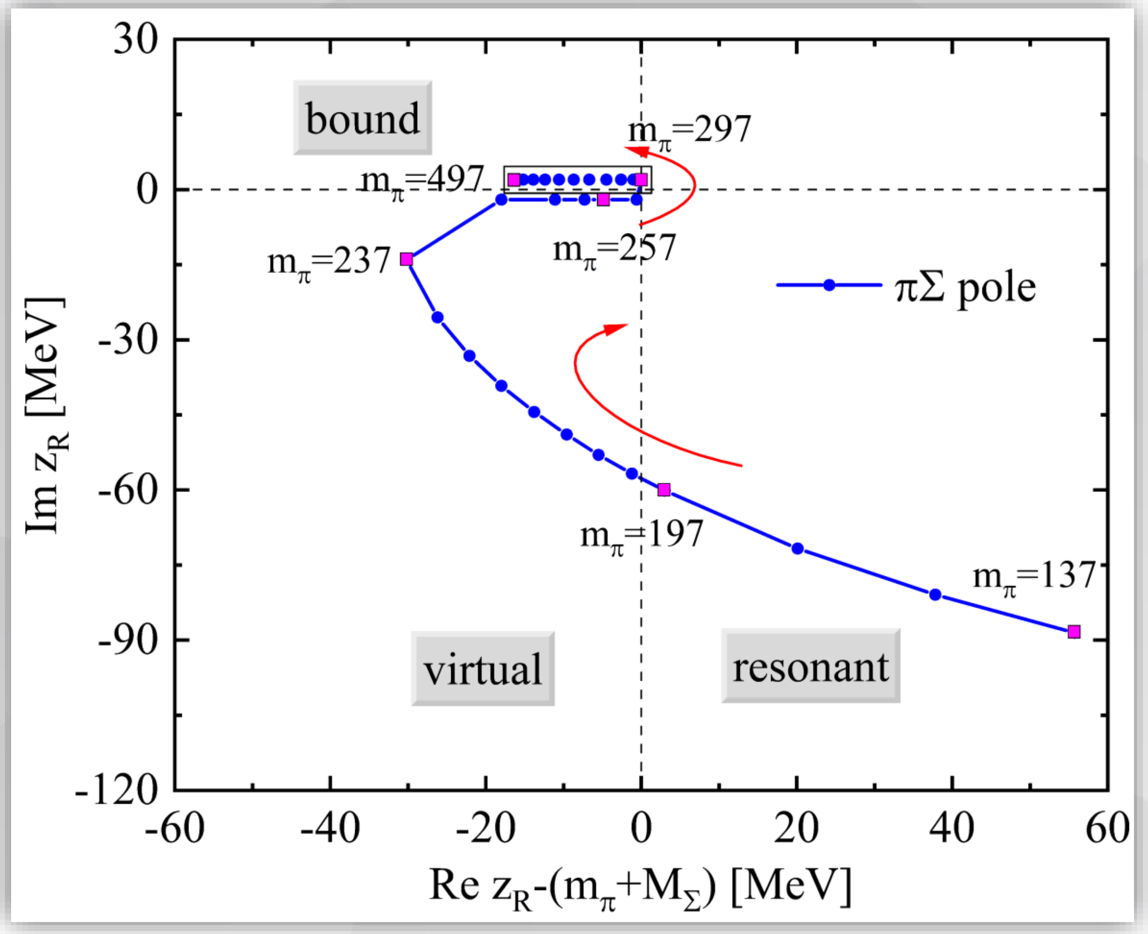
- Note that the two thresholds also increase as m_π increases.



Variation of lower pole with m_π: complicated

- For $m_\pi \approx 200$ **MeV**, it becomes **a virtual resonance** from a resonant state.

- For a pion mass of about **300 MeV**, it becomes **a bound state** and remains so up to the pion mass of **500 MeV.**



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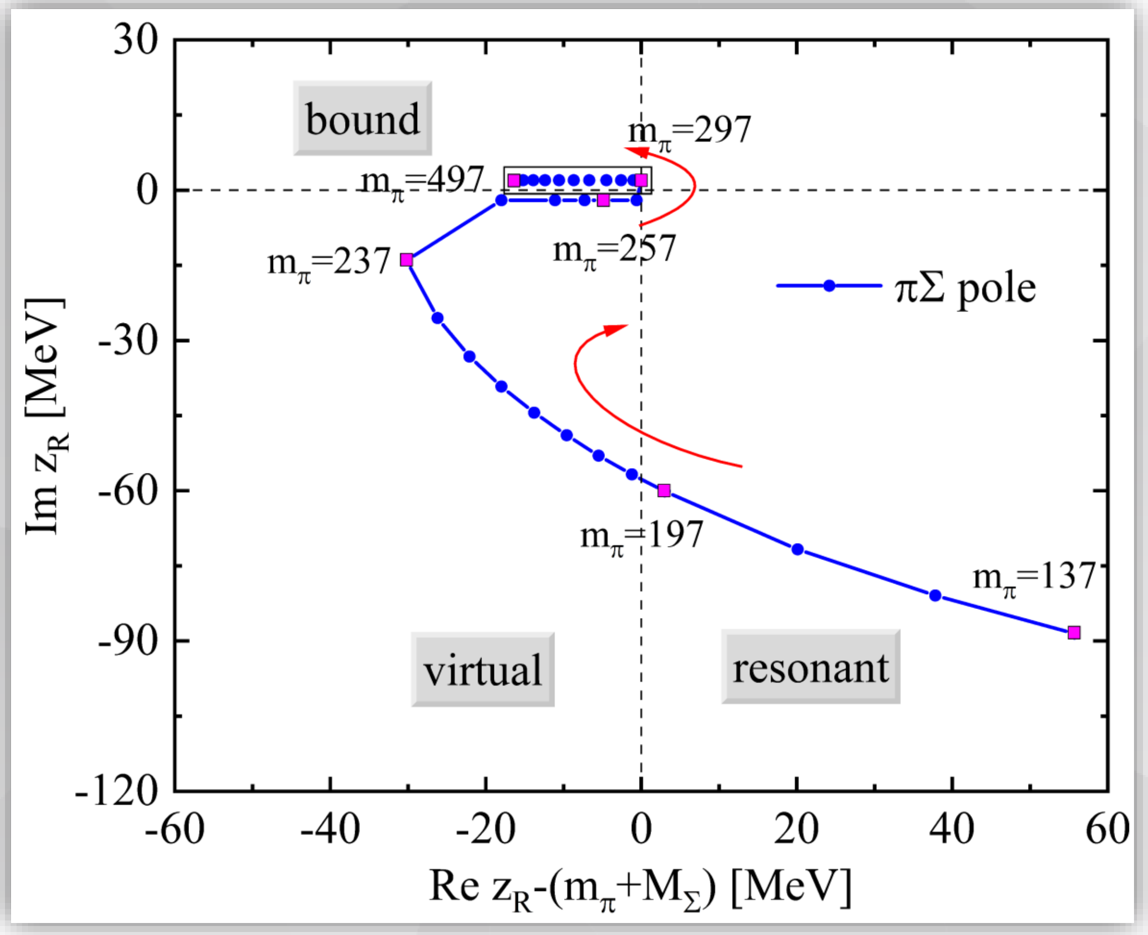

The evolution of the lower pole clearly demonstrates the chiral dynamics underlying the two-pole structure of $\Lambda(1405)$.

Q3: Is energy dependence of WT potential relevant?

$$V_{ij} = -\frac{C_{ij}}{4f^2}\left(2\sqrt{s} - M_i - M_j\right) = -\frac{C_{ij}}{4f^2}\left(E_i + E_j\right)$$

- **Replace the $E_i + E_j$ with $m_i + m_j$**, i.e. eliminate the energy dependence.

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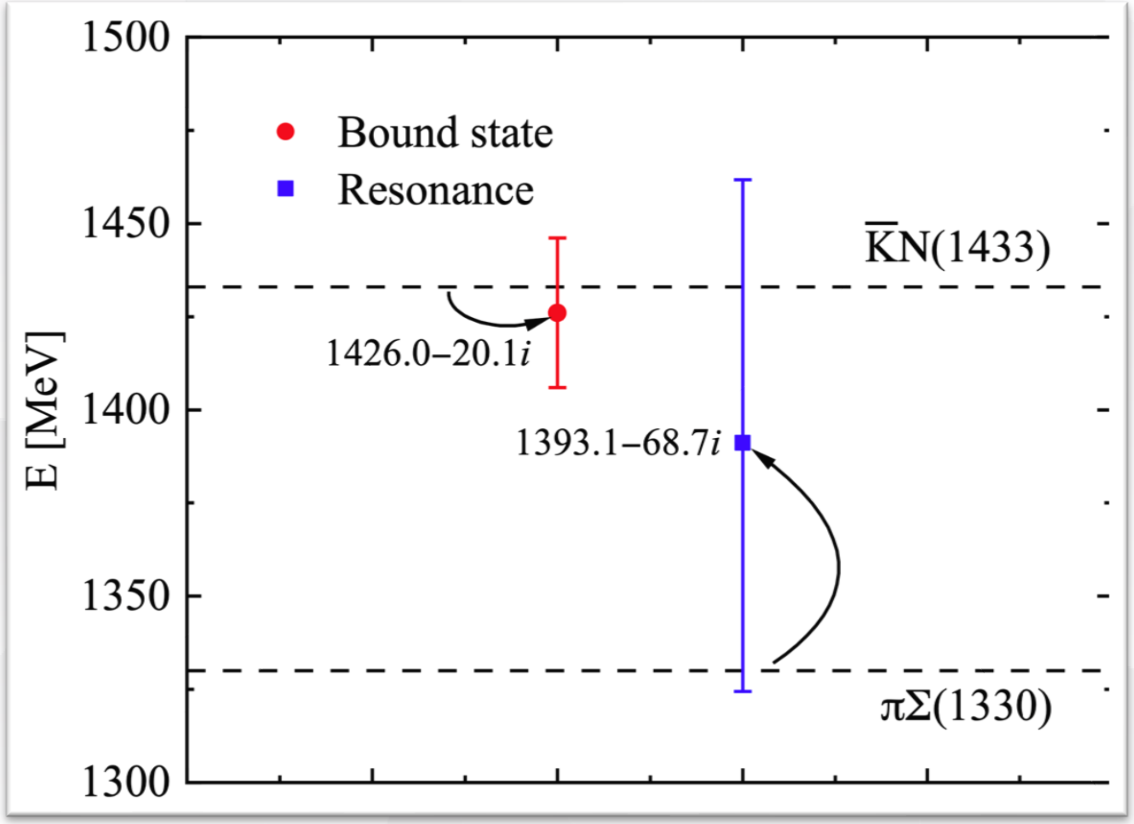
- With the original subtraction constants, we obtain only **one pole** at $1413.3 - 13.2i$, corresponding to a $\bar{K}N$ bound state.
- Switching off the off-diagonal interaction affects little our conclusion.
- As the pion mass is much smaller than the kaon mass, the attraction of the $\pi\Sigma$ channel is much weaker than that of the $\bar{K}N$ channel, **thus cannot support a bound state**.
- **If we increase the attractive potential, we can obtain two bound states, but not a bound state and a resonant state.**

Q3: Is energy dependence of WT potential relevant?

- The energy dependence of the WT potential is responsible for the emergence of two-pole structures, as we defined here.

- That is, the appearance of two states between the two relevant channels, such that they overlap.



$K_1(1270)$ $\quad I(J^P) = 1/2(1^+), S = 1;\ M = 1253 \pm 7$ MeV, $\Gamma = 90 \pm 20$ MeV

□Replace the baryon octet with the vector nonet

$$\mathcal{L}_{PV}^{\mathrm{WT}} = -\frac{1}{4f^2}\mathrm{Tr}\left([\mathcal{V}^\mu, \partial^\nu \mathcal{V}_\mu][\Phi, \partial_\nu \Phi]\right)$$

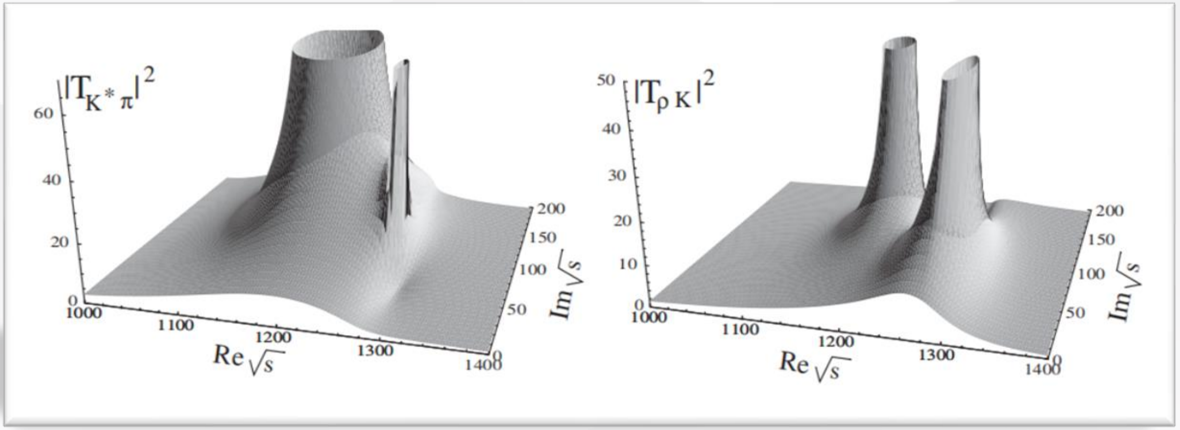
$$V_{ij}(s) = -\epsilon^i \cdot \epsilon^j \frac{C_{ij}}{8f^2}\left[3s - (M_i^2 + m_i^2 + M_j^2 + m_j^2) - \frac{1}{s}(M_i^2 - m_i^2)(M_j^2 - m_j^2)\right].$$

Simplified as the light mass of NGB and in the chiral limit of $M_i = M_j \equiv M$

$$\boxed{V_{ij}(s) = -\epsilon^i \cdot \epsilon^j \frac{C_{ij}}{8f^2} 4M(E_i + E_j)}$$

□Coupled channels: $K^*\pi(1030)$, $\rho K(1271)$, $\omega K(1278)$, $K^*\eta(1440)$, $\phi K(1515)$

$$C_{ij} = \begin{bmatrix} -2 & \frac{1}{2} & \frac{\sqrt{3}}{2} & 0 & -\sqrt{\frac{3}{2}} \\ & -2 & 0 & -\frac{3}{2} & 0 \\ & & 0 & \frac{\sqrt{3}}{2} & 0 \\ & & & 0 & -\sqrt{\frac{3}{2}} \\ & & & & 0 \end{bmatrix}$$

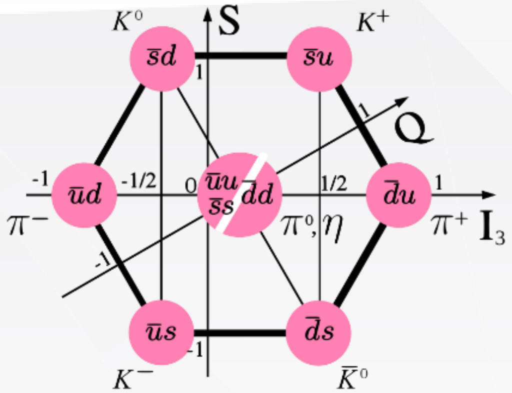


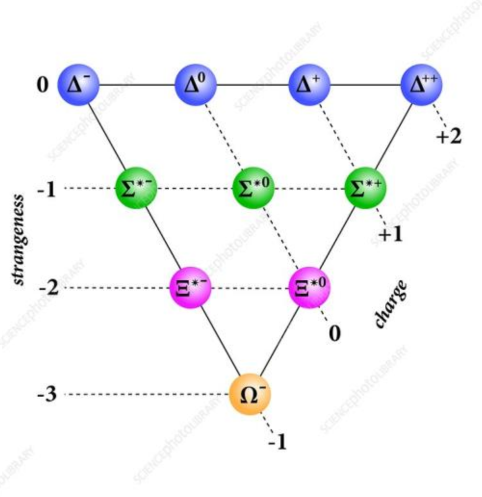
Roca, Oset, and Singh, PRD72, 014002 (2005)

LSG, Oset, Roca, and Oller, PRD**75**, 014017 (2007)

$\Xi(1820)$

$I(J^P) = 1/2(3/2^-), S = 2;\ M = 1823 \pm 5$ MeV, $\Gamma = 24^{+15}_{-10}$ MeV





$$V_{ij} = -\frac{1}{4f^2} C_{ij}\left(k^0 + k'^0\right).$$

C_{ij}	$\Sigma^*\bar{K}$	$\Xi^*\pi$	$\Xi^*\eta$	ΩK
$\Sigma^*\bar{K}$	2	1	3	0
$\Xi^*\pi$		2	0	$\frac{3}{\sqrt{2}}$
$\Xi^*\eta$			0	$\frac{3}{\sqrt{2}}$
ΩK				3

Poles	$\lvert g_i \rvert$	g_i	channels
$1824 - 31i$	3.22	$3.22 - 0.096i$	$\bar{K}\Sigma^*$
	1.71	$1.55 + 0.73i$	$\pi\Xi^*$
	2.61	$2.58 - 0.38i$	$\eta\Xi^*$
	1.62	$1.47 + 0.67i$	$K\Omega$
$1875 - 130i$	2.13	$0.29 + 2.11i$	$\bar{K}\Sigma^*$
	3.04	$-2.07 + 2.23i$	$\pi\Xi^*$
	2.20	$1.11 + 1.90i$	$\eta\Xi^*$
	3.03	$-1.77 + 2.45i$	$K\Omega$

$q_{\max} = 830$ MeV, $f = 1.28 f_\pi$

S. Sarkar, E. Oset, M.J. Vicente Vacas, NPA750 (2005) 294-323

Experimental evidence?

Phys. Lett. B 856 (2024) 138872

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Letter

Two states for the Ξ(1820) resonance

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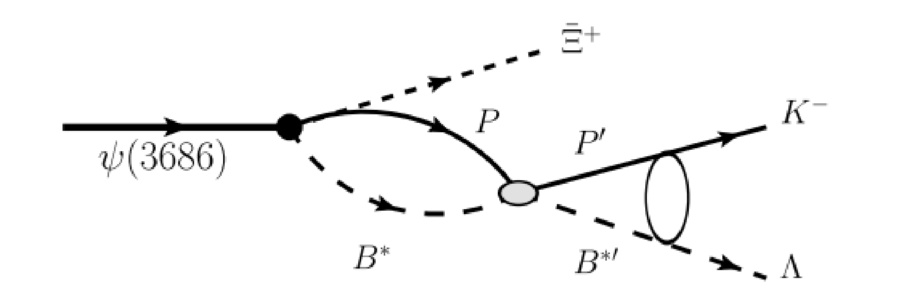
[b] Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC Institutos de Investigación de Paterna, Aptdo.22085, 46071 Valencia, Spain
[c] Guangxi Key Laboratory of Nuclear Physics and Technology, Guangxi Normal University, Guilin 541004, China
[d] Lanzhou Center for Theoretical Physics, Key Laboratory of Theoretical Physics of Gansu Province, and Key Laboratory of Quantum Theory and Applications of MoE, Lanzhou University, Lanzhou, Gansu 730000, China
[e] Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China

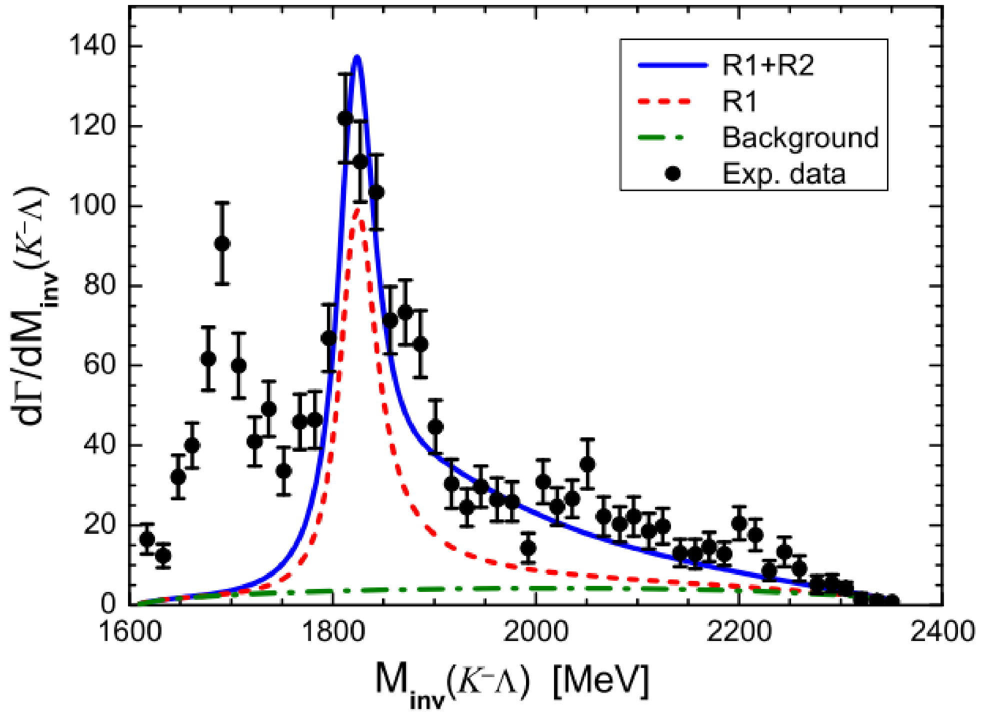
ARTICLE INFO

Editor: A. Ringwald

ABSTRACT

We recall that the chiral unitary approach for the interaction of pseudoscalar mesons with the baryons of the decuplet predicts two states for the Ξ(1820) resonance, one with a narrow width and the other one with a large width. We contrast this fact with the recent BESIII measurement of the $K^-\Lambda$ mass distribution in the $\psi(3686)$ decay to $K^-\Lambda\bar{\Xi}^+$, which demands a width much larger than the average of the PDG, and show how the consideration of the two Ξ(1820) states provides a natural explanation to the experimental data.

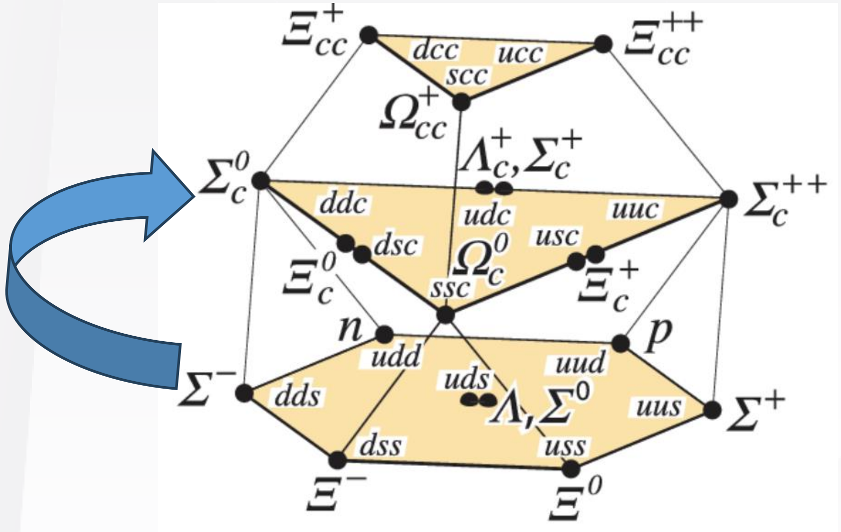




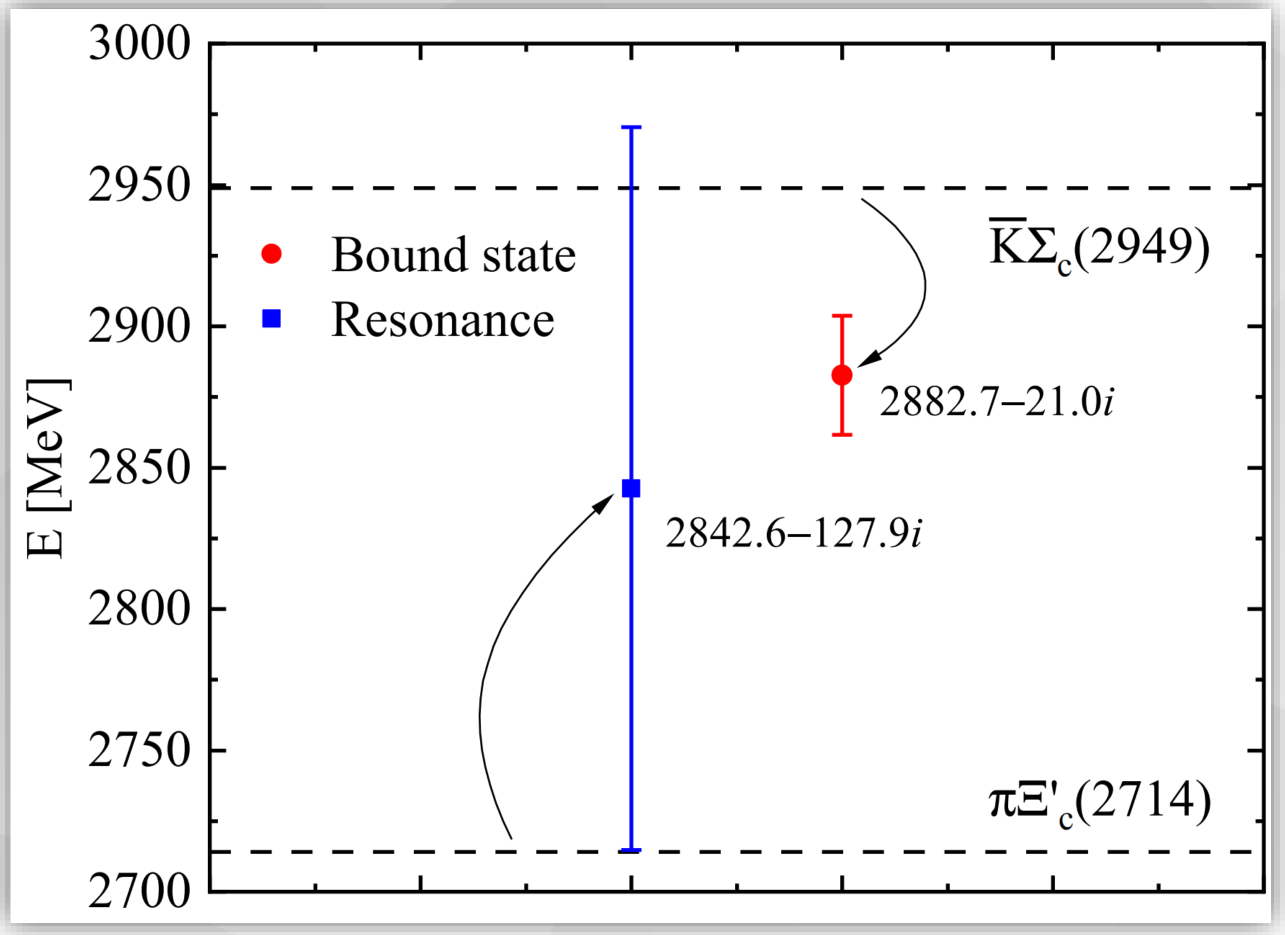
We contrast this fact with the recent BESIII measurement of the $K^-\Lambda$ mass distribution in the $\psi(3686)$ decay to $K^-\Lambda\Xi^+$, which demands a width much larger than the average of the PDG, and show how **the consideration of the two Ξ(1820) states provides a natural explanation** to the experimental data

Further two-pole structures: singly charmed baryon

- NGB scattering off a singly-charmed baryon



- $\boldsymbol{\bar{K}\Sigma_c(2949), \pi\Xi_c'(2714)}$;
  $\eta\Xi_c'(3125)$, $K\Omega_c(3191)$;
  isospin ½, strangness -1
  $\Lambda = 800$ MeV



$W_H = 2882.7 - 21.0i \quad W_L = 2842.6 - 127.9i$

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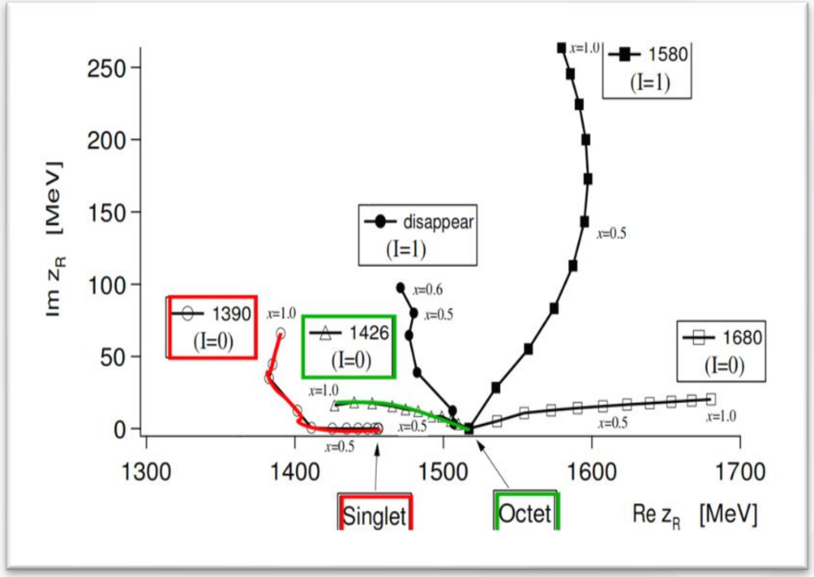
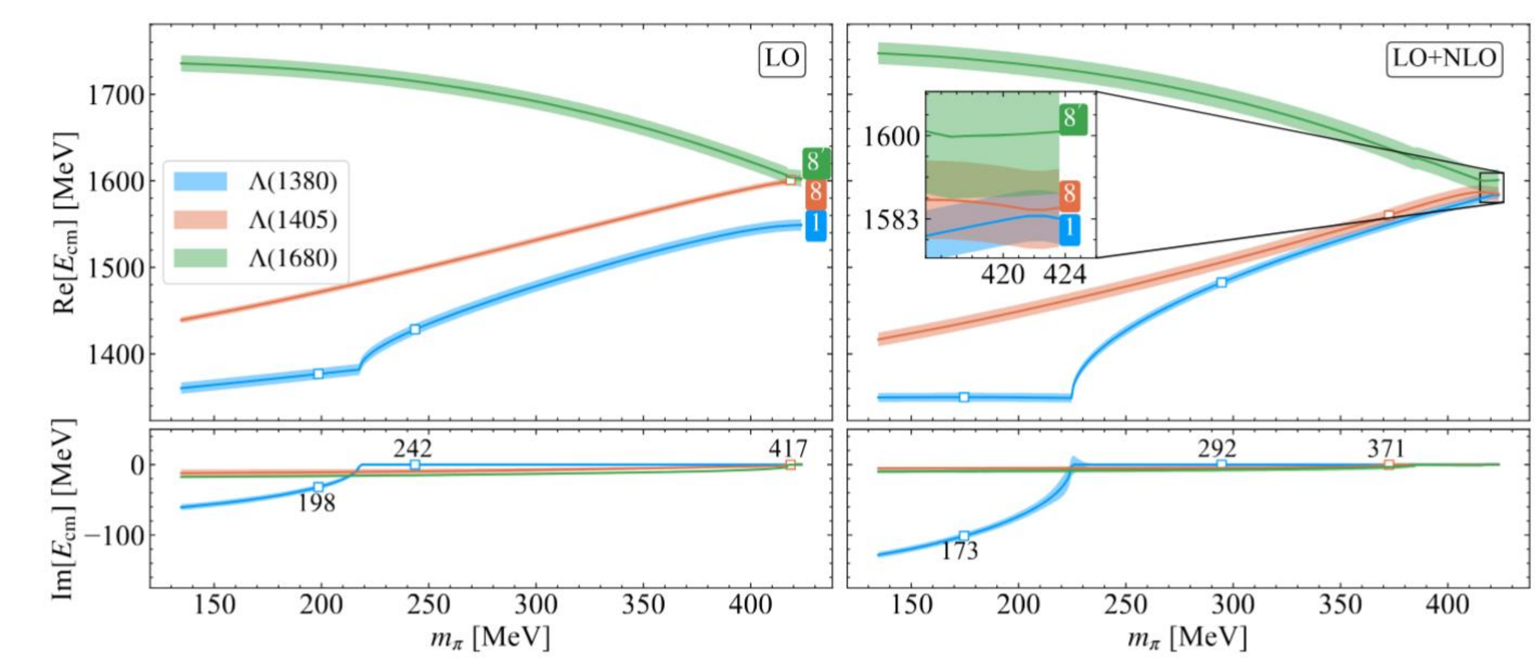
- ☞ $\Lambda(1405)$: **first exotic hadron and two-pole structures**
- ☞ **Two-pole structures: flavor symmetry/group theory**
- ☞ **Two-pole structures: chiral dynamics at work**
- ☞ **Test the flavor content of the two poles**
- ☞ **Summary and outlook**

Identifying flavor-content of the two poles of Λ(1405)

2407.13486, Ying-Bo He, Xiao-Hai Liu*, LSG*, Feng-Kun Guo*, Ju-Jun Xie*



Jido, Oller, Oset, Ramos, and Meissner, NPA725, 181(2003)



2405.07686, Zejian Zhuang, R. Molina∗, Jun-Xu Lu, and LSG

- **The higher pole is more of an SU(3) octet; the lower pole is of an SU(3) singlet.**

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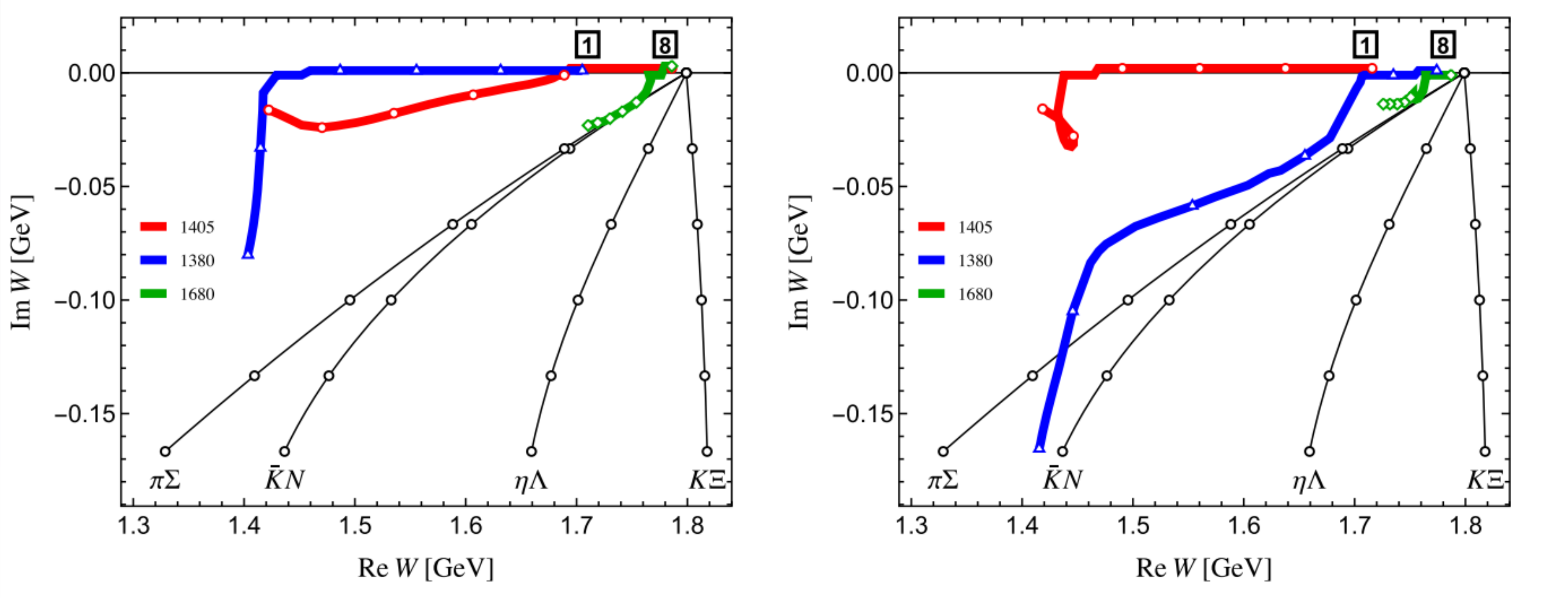
2407.13486, Ying-Bo He, Xiao-Hai Liu*, LSG*, Feng-Kun Guo*, Ju-Jun Xie*

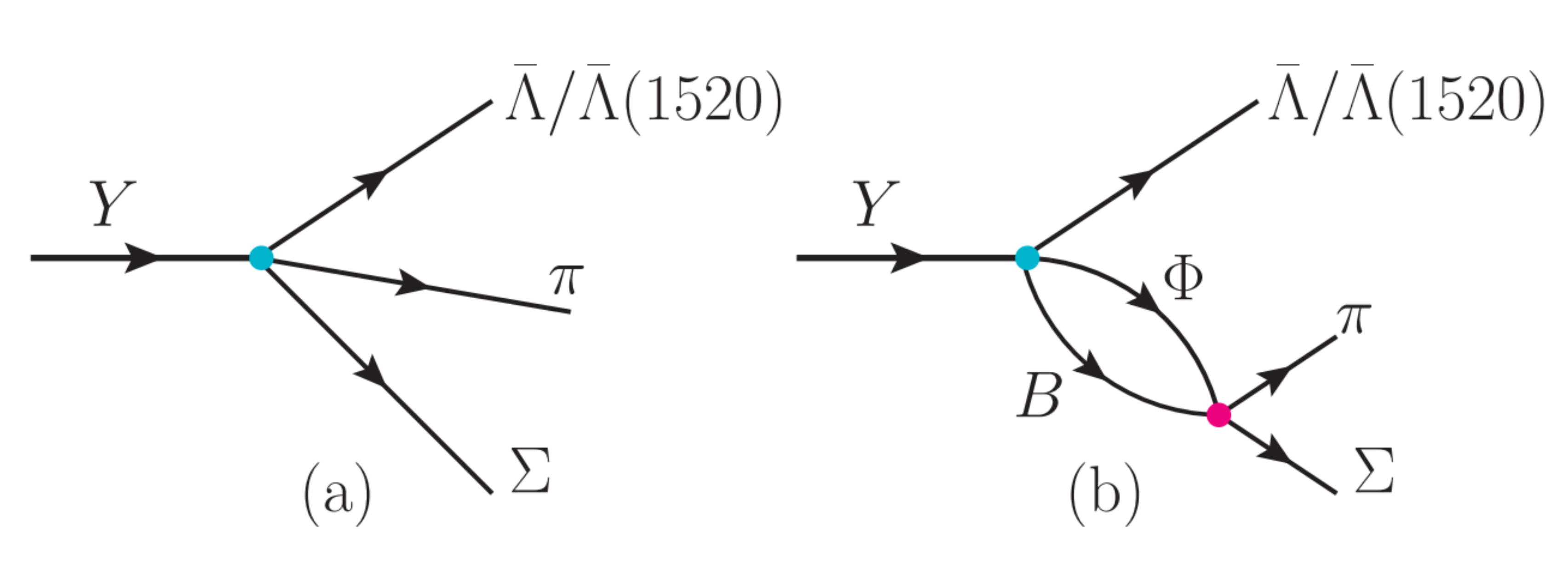


Feng-Kun Guo, Yuki Kamiya, Maxim Mai, Ulf-G. Meißner, PLB846(2023)138264

- The **higher** pole is more of an SU(3) **singlet**; the **lower** pole is of an SU(3) **octet.**

Identifying flavor-content of the two poles of $\Lambda(1405)$

2407.13486, Ying-Bo He, Xiao-Hai Liu*, LSG*, Feng-Kun Guo*, Ju-Jun Xie*



- Y is a charmonium or bottomonium, such as J/ψ, ψ_{2s}, χ_{c0}, but an SU(3) singlet
- $\bar{\Lambda}$ is an SU(3) octet, then the $\pi\Sigma$ pair must be an SU(3) octet—**higher pole**
- $\bar{\Lambda}(1520)$ is an SU(3) singlet, then the $\pi\Sigma$ pair must be an SU(3) singlet—**lower pole**

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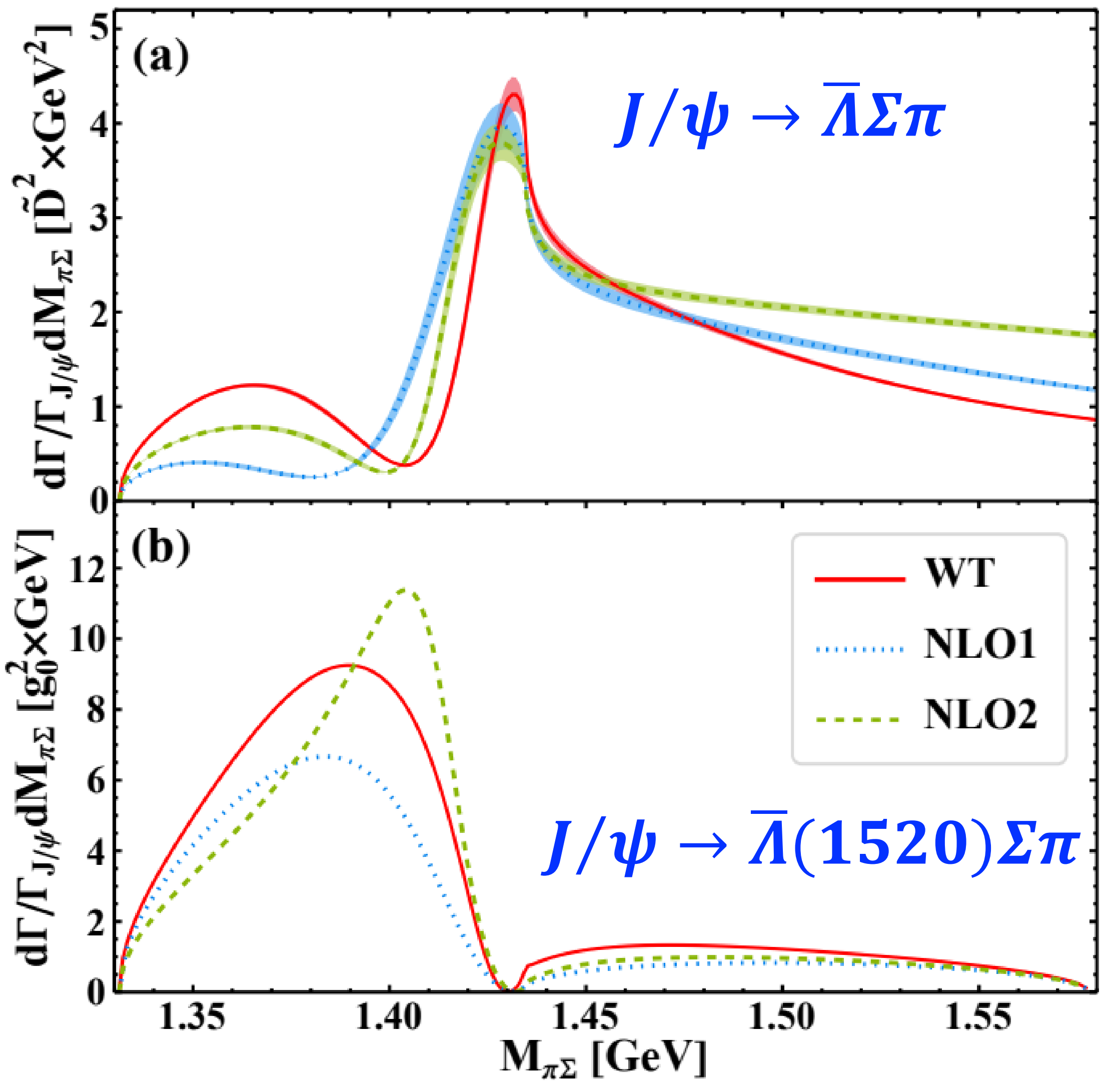


[NLO1] Y. Ikeda, T. Hyodo, and W. Weise, NPA881(2012)98

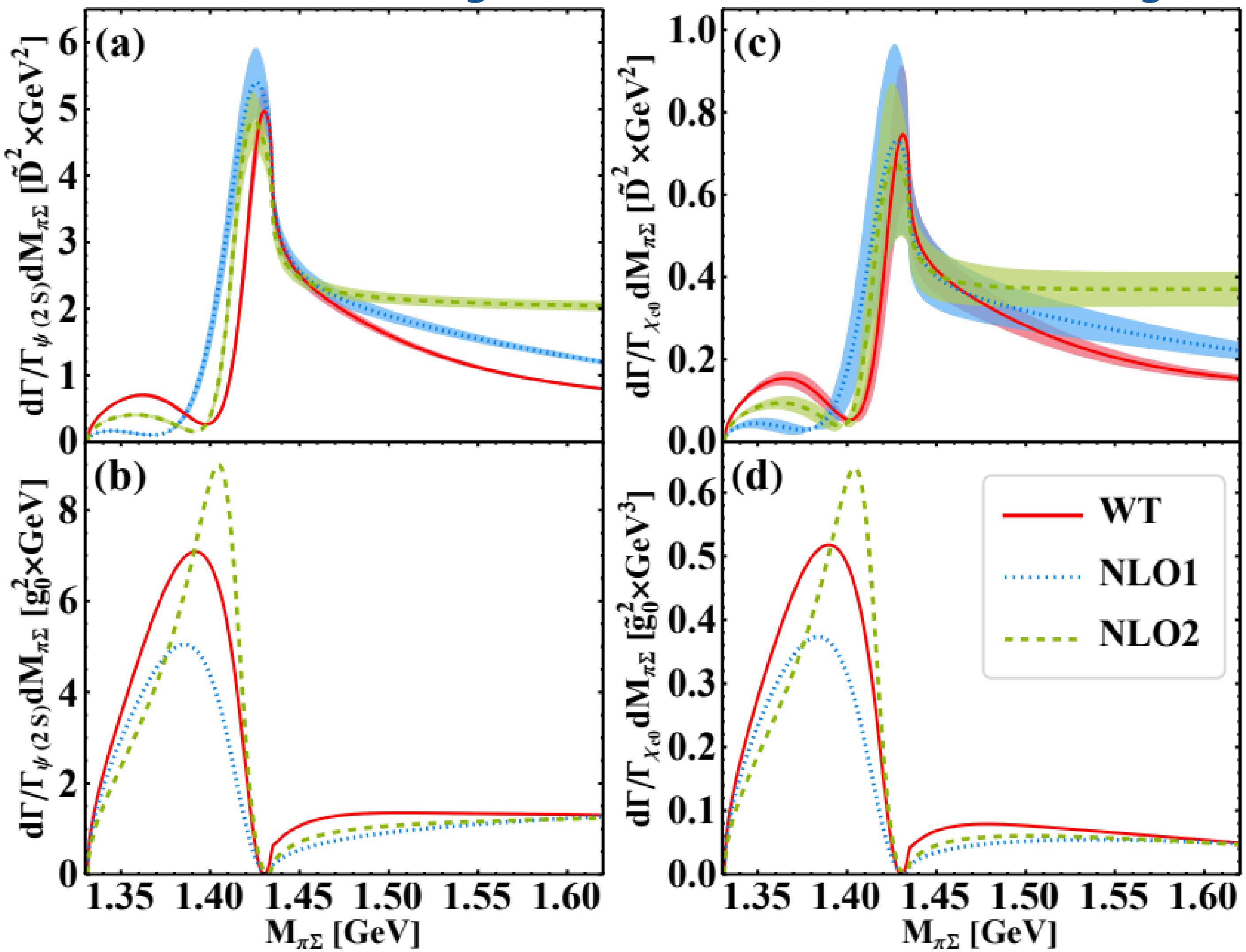
[NLO2] F.-K. Guo, Y. Kamiya, M. Mai, and U.-G. Meißner, PLB846(2023)13826

Identifying flavor-content of the two poles of $\Lambda(1405)$

2407.13486, Ying-Bo He, Xiao-Hai Liu*, LSG*, Feng-Kun Guo*, Ju-Jun Xie*

$\psi_{2s} \to \bar{\Lambda}\Sigma\pi$

$\chi_{c0} \to \bar{\Lambda}\Sigma\pi$



$\psi_{2s} \to \bar{\Lambda}(1520)\Sigma\pi$

$\chi_{c0} \to \bar{\Lambda}(1520)\Sigma\pi$

Contents

Summary and outlook

1. **Chiral symmetry** strongly constrains the interactions of a heavy matter particle with an NG boson--the Weinberg-Tomozawa potentials.
2. **The NG boson nature of π, K, (and η)** is responsible for generating two nearby poles: one bound and one resonant.
3. **The explicit chiral and SU(3) flavor symmetry breaking** dictates that the two relevant **coupled channels** are **close to each other** such that **the lineshapes** of the two states **overlap** and create the impression that there is only one state.

Summary and outlook

- We **anticipate such two-pole structures** in other systems governed by the same chiral dynamics. We encourage dedicated experimental and lattice QCD studies to verify the chiral dynamics underlying such phenomena.
- We stress that, as noted in the literature, **flavor symmetry** also plays an important role, as it **dictates the relative coupling strengths** between different channels.

Thanks a lot for your attention!

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An incomplete list of other related systems

□ $D_0^*(2300) = D_0^*(2100) + D_0^*(2450)$

1. Three channels are at play: $D\pi(2005)$, $D\eta(2415)$, $D_s\bar{K}(2464)$
2. LO results are much different from NLO results:

Guo, Shen, Chiang, Ping, and Zou, PLB**641**, 278 (2006)

LO: $W_H = 2439.8 - 43.1i$ $\quad W_L = 2100.0 - 100.9i$

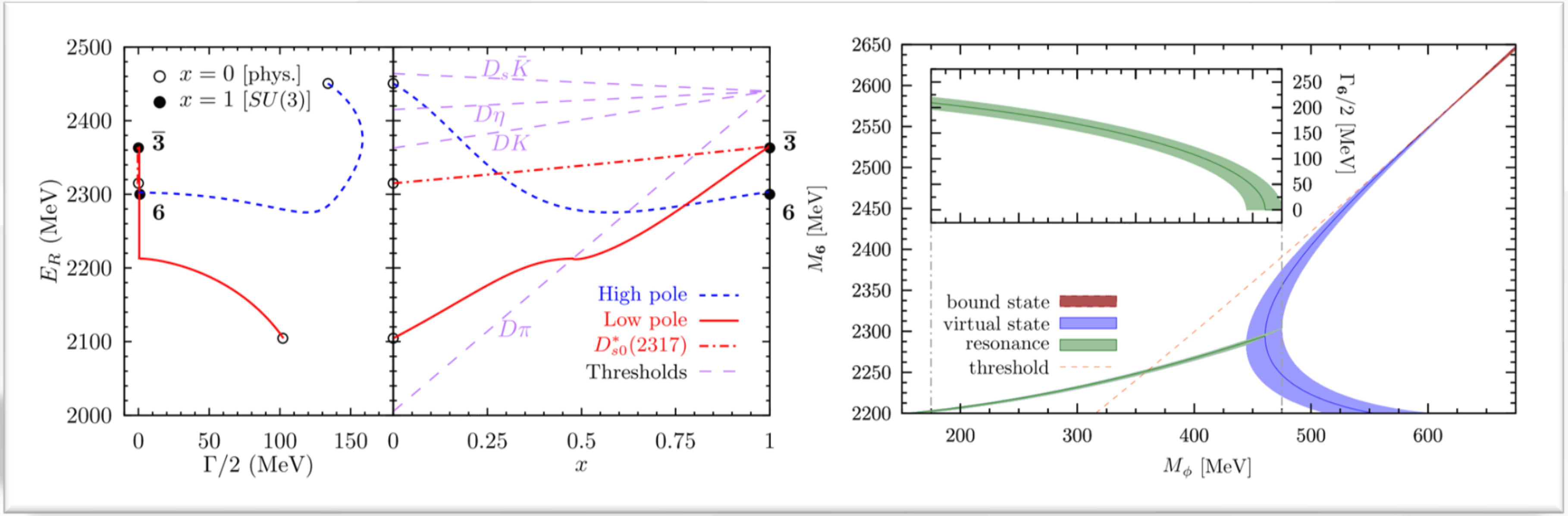
Albaladejo, Fernandez-Soler, Guo, and Nieves, PLB**767**, 465 (2017)

Distinguishable!

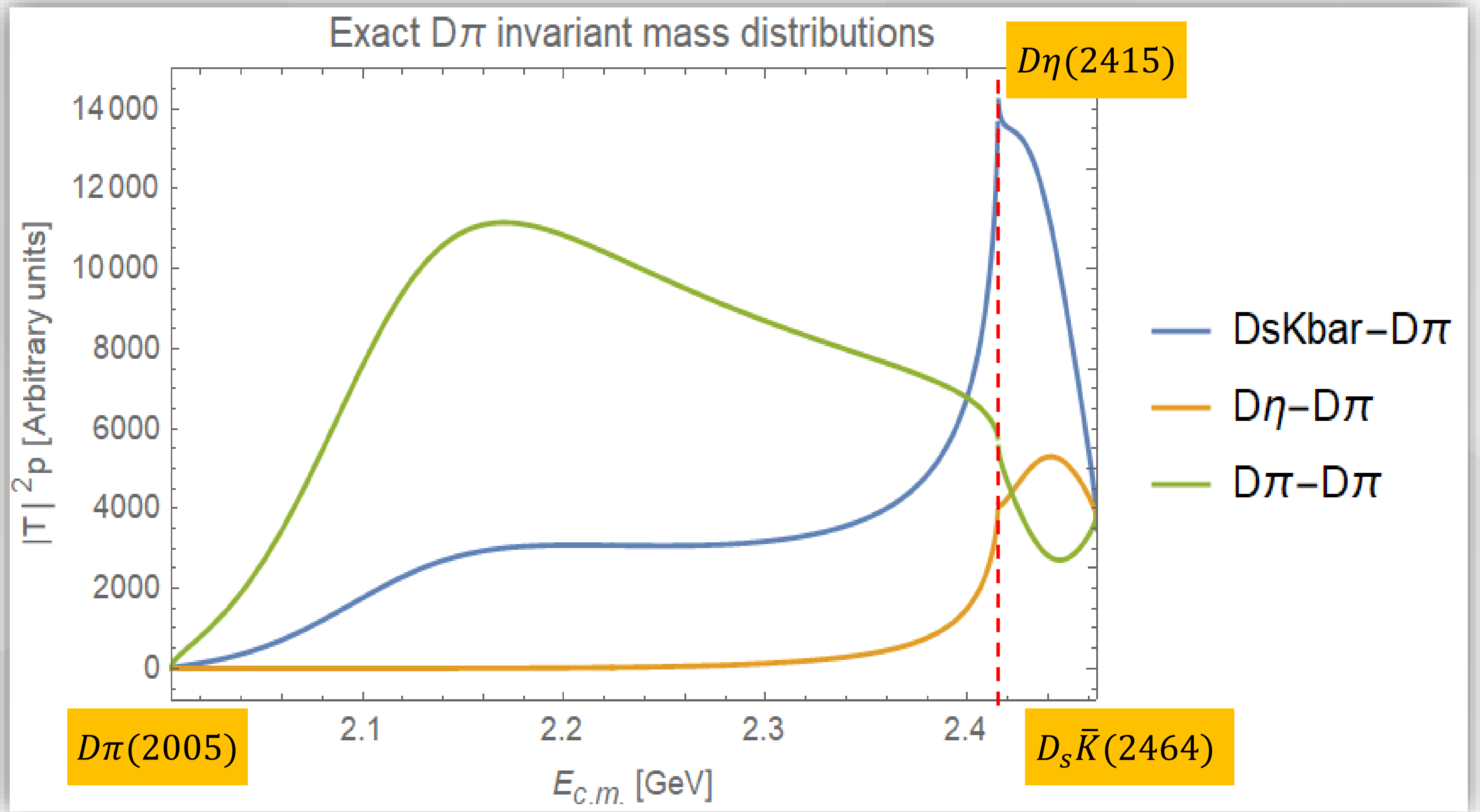
NLO: $W_H = 2451^{+36}_{-26} - 137^{+7}_{-8}i$ $\quad W_L = 2105^{+6}_{-8} - 102^{+10}_{-12}i$

$$\bar{3}\otimes 8 = \underbrace{\bar{3}\oplus 6}_{\text{attractive}} \oplus \overline{15}.$$

U.-G. Meißner, Symmetry 12, 981 (2020)



An incomplete list of other related systems



An incomplete list of other related systems

- Related to $\Lambda(1405)$ by SU(3) flavor symmetry

1. **S=-2** $\Xi(1620)$ &. $\Xi(1690)$ $\Lambda = 0.63$ MeV——natural value

   Coupled channels: $\pi\Xi(1455)$, $\bar{K}\Lambda(1610)$, $\bar{K}\Sigma(1688)$, $\eta\Xi(1865)$

   LO: $W_H = 1687.0 - 0.8i$ $W_L = 1567.8 - 127.4i$

   Questionable

   Ramos, Oset, and Bennhold, PRL**89**, 252001 (2002)

   NLO: also not good enough.

   Feijoo, Valcarce Cadenas, and Magas, PLB**841**, 137927 (2023)

2. **S=0** $\Lambda = 0.65$ GeV——natural value

   Coupled channels: $\pi N(1075)$, $\eta\mathrm{N}(1485)$, $K\Lambda(1610)$, $K\Sigma(1688)$

   LO: $W_H = 1506.8 - 80.2i$ $W_L = 1162.3 - 159.5i$

   N*(1535)?

Chen, Niu, and Zheng, CPC**46**, 081001 (2022)

An incomplete list of other related systems

- $f_0(600)$ &.$f_0(980)$

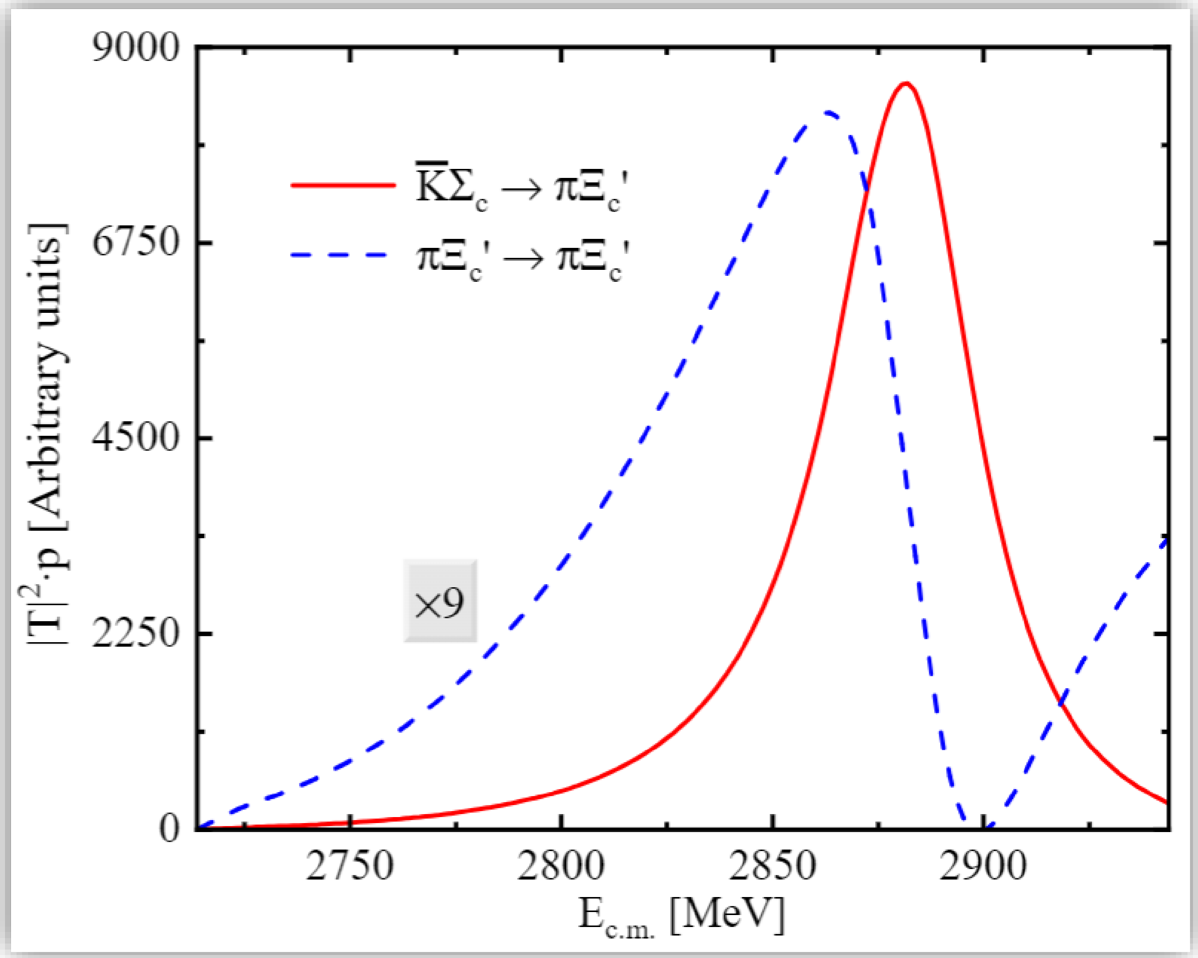
  $\pi\pi(276)$ and $\bar{K}K(990)$ molecules respectively.

  Far-separated two channels, so that two states can be distinguished.

Further two-pole structures: singly charmed baryon

- Overlapping line shapes **peak at slightly different** positions and have much different widths.

- The $\bar{\mathrm{K}}\Sigma_c \to \pi\bar{\Xi}_c$ process receives more contribution from the higher pole, while the $\pi\Xi_c' \to \pi\Xi_c'$ couples more to the lower pole.



$\pi\Xi_c'$ invariant mass distribution as functions of $E_{c.m.}$