

Pole trajectories of the exotic baryons help establish their dynamical nature

Zejian Zhuang (庄泽坚)

In collaboration with Raquel Molina, Jun-Xu Lu, and Li-Sheng Geng



A bit of history: $\Lambda(1405)$

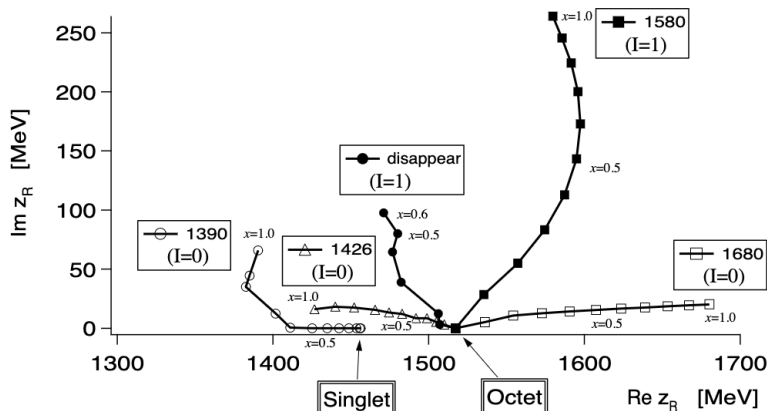
$\Lambda(1405) \ 1/2^-$

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ***

In the 1998 Note on the $\Lambda(1405)$ in PDG 98, R.H. Dalitz discussed the S-shaped cusp behavior of the intensity at the $N\bar{K}$ threshold observed in THOMAS 73 and HEMINGWAY 85. He commented that this behavior "is characteristic of S-wave coupling; the other below threshold hyperon, the $\Sigma(1385)$, has no such threshold distortion because its $N\bar{K}$ coupling is P-wave. For $\Lambda(1405)$ this asymmetry is the sole direct evidence that $J^P = 1/2^-$."

$\Lambda(1380) \ 1/2^-$

$J^P = \frac{1}{2}^-$ Status: **



D. Jido, J.A. Oller, E. Oset et al, NPA725 (2003) 181-200

□ Theoretical prediction $K^-p \rightarrow \pi\Sigma$

▪ Dalitz et al, PRL 2 (1959) 425

□ Discovered in bubble chamber experiments

□ Two-pole structure of $\Lambda(1405)$

▪ Coupled-channel model

$\{\pi\Sigma, \bar{K}N, \eta\Lambda, K\Xi\}$

▪ Chiral unitary approach ...

□ SU3 flavor symmetry

$$8 \otimes 8 = 1 \oplus 8_s \oplus 8_a \oplus 27 \oplus \dots$$

$$\Lambda(1380) \rightarrow \mathbf{1} \quad \Lambda(1405)/\Lambda(1670) \rightarrow \mathbf{8}_{s(a)}$$

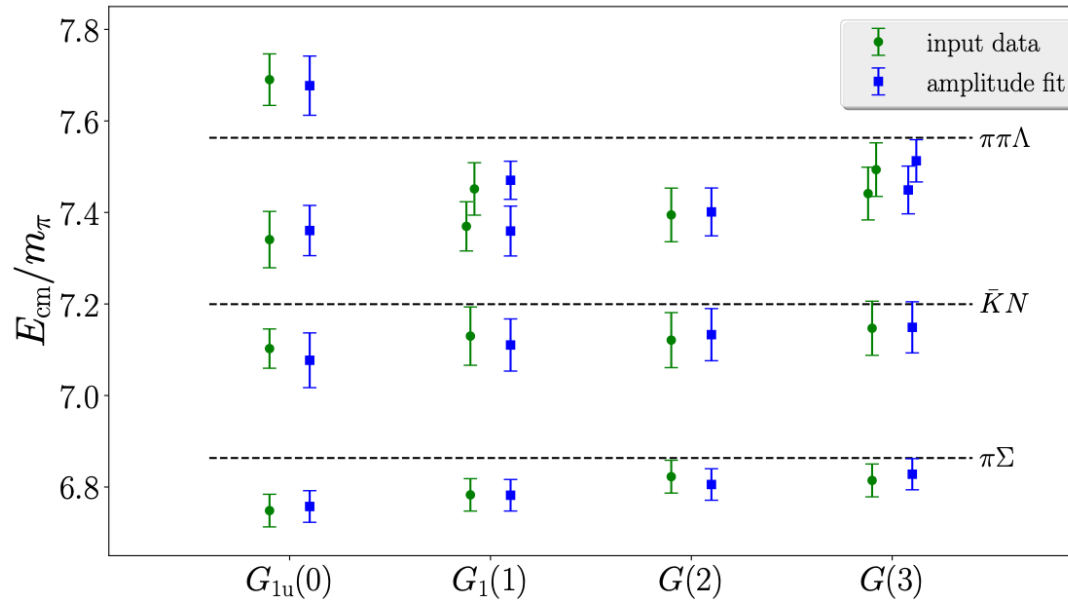
$$C_{\text{SU}(3)}^{\text{WT}} = \begin{bmatrix} 6 & & \\ & 3 & \\ & & 3 \\ & & & -2 \end{bmatrix}$$

□ Decouple is broken by the Born term and NLO

$\Lambda(1405)$ in LQCD simulation

$$\pi\Sigma - \bar{K}N$$

$$m_\pi = 200 \text{ MeV}$$



J. Bulava et al, (BaSc), PRD 109, 014511 (2024)

J. Bulava et al, (BaSc), PRL 132, 051901 (2024)

□ Luscher method

□ Two-pole structure

- The virtual state: $z_1 = 1392(9)(2)(16) \text{ MeV}$
- The resonance: $z_2 = 1455(13)(2)(17) - i11.5(4.4)(4)(0.1) \text{ MeV}$

A bit history: $N(1535)$

Chiral dynamics and the $S_{11}(1535)$ nucleon resonance [★]

N. Kaiser, P.B. Siegel ¹, W. Weise

*Physik Department, Technische Universität München,
Institut für Theoretische Physik, D-85747 Garching, Germany*

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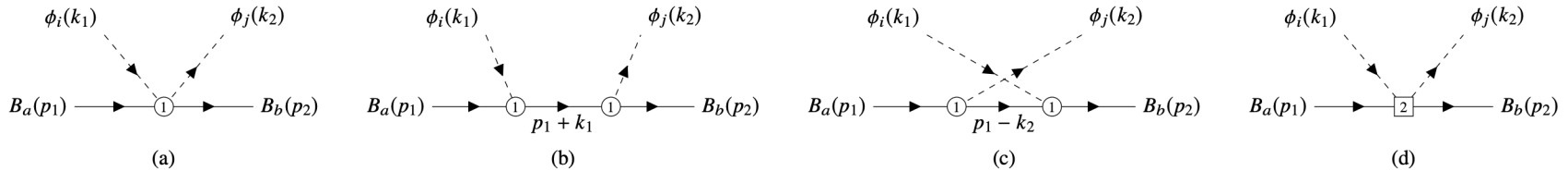
Editor: C. Mahaux

Abstract

The $SU(3)$ chiral effective lagrangian at next-to-leading order is applied to the S-wave meson-baryon interaction in the energy range around the ηN threshold. A potential is derived from this lagrangian and used in a coupled channel calculation of the πN , ηN , $K\Lambda$, $K\Sigma$ system in the isospin- $\frac{1}{2}$, $l = 0$ partial wave. Using the same parameters as obtained previously from a fit to the low energy $\bar{K}N$ data it is found that a quasi-bound $K\Sigma$ - $K\Lambda$ -state is formed, with properties remarkably similar to the $S_{11}(1535)$ nucleon resonance. In particular, we find a large partial decay width into ηN consistent with the empirical data.

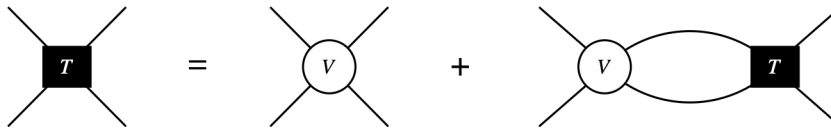
- $N(1535)$ predicted by the Chiral approach up to NLO
- $J^P = \frac{1}{2}^-$, $(S, I) = (0, \frac{1}{2})$
- $N(1650)$ also as a dynamical generation of the resonance
- $N(1440)$ difficult to be understood by simple three-quark picture

Chiral approach up to NLO



□ Meson-baryon interaction kernels up to NLO

- Weinberg-Tomozawa interaction (a)
 - Born term (b-c)
 - NLO contact term (d)
- } LO interaction



□ Couple-channel scattering matrix

$$T = V + VGT = [\mathbb{I} - VG]^{-1}V$$

$$G_j = i \int \frac{d^4 q}{(2\pi)^4} \frac{1}{(P - q)^2 - m_j^2 + i\epsilon} \frac{1}{q^2 - M_j^2 + i\epsilon}$$

J. A. Oller et al, PRD.60.074023

J. A. Oller, Prog. Part. Nucl. Phys. 110.103728 (2020)

□ Scattering Matrix in the finite volume

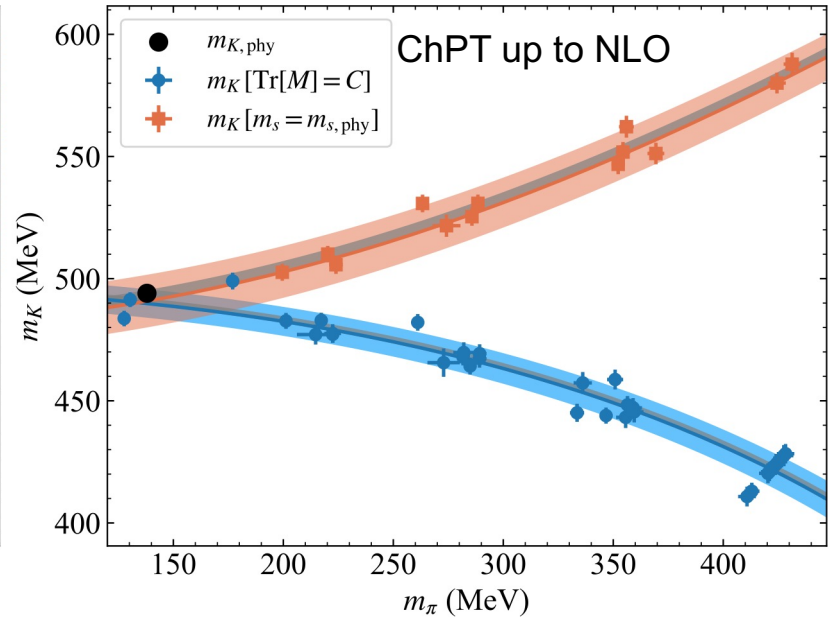
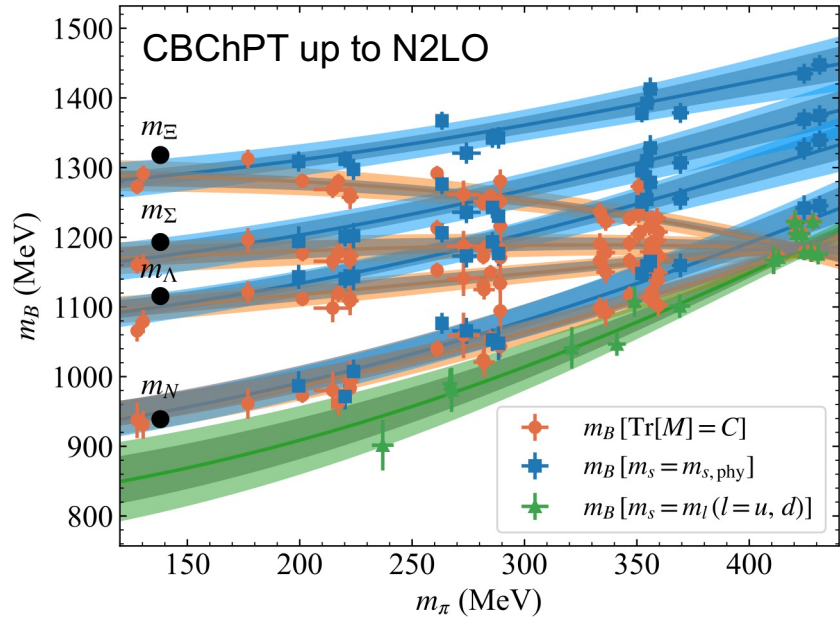
$$\tilde{T} = [\mathbb{I} - V\tilde{G}]^{-1}V$$

□ The energy levels in the finite volume

$$\det [\mathbb{I} - V\tilde{G}] = 0$$

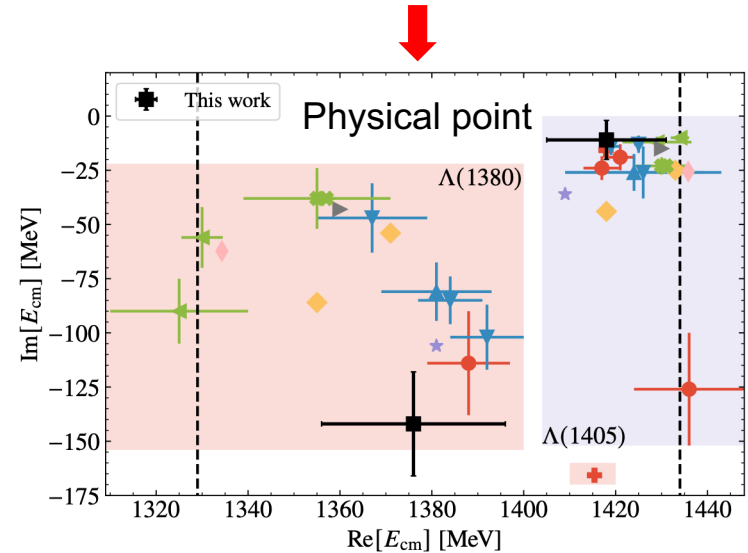
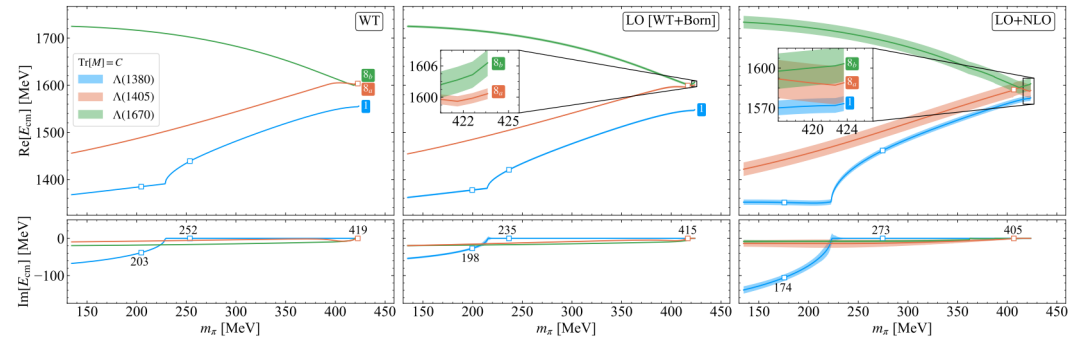
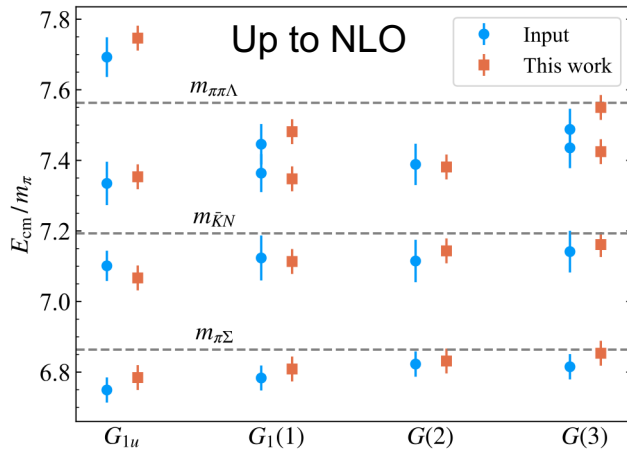
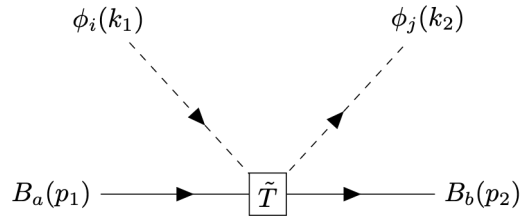
M. Doring et al, EPJA (2012) 48: 114

Pion mass dependence: three types of chiral trajectories



- Chiral-trajectory setup in LQCD: $\text{Tr}[M] = 2m_{u(d)} + m_s = C$, $m_s = m_{s,\text{phy}}$, and $m_s = m_{u(d)}$
- The trajectory of m_K **increasing** over $m_s = m_{s,\text{phy}}$ but **decreasing** over $\text{Tr}[M] = C$
- The trajectory of $m_{\Lambda(\Sigma)}(sqq)$ increasing but almost flat over $\text{Tr}[M] = C$
- The trajectory of $m_{\Xi}(ssq)$ **increasing** over $m_s = m_{s,\text{phy}}$ but **decreasing** over $\text{Tr}[M] = C$
- The trajectories of the Nucleon mass over $\text{Tr}[M] = C$ and $m_s = m_{s,\text{phy}}$ are compatible up to ~ 420 MeV

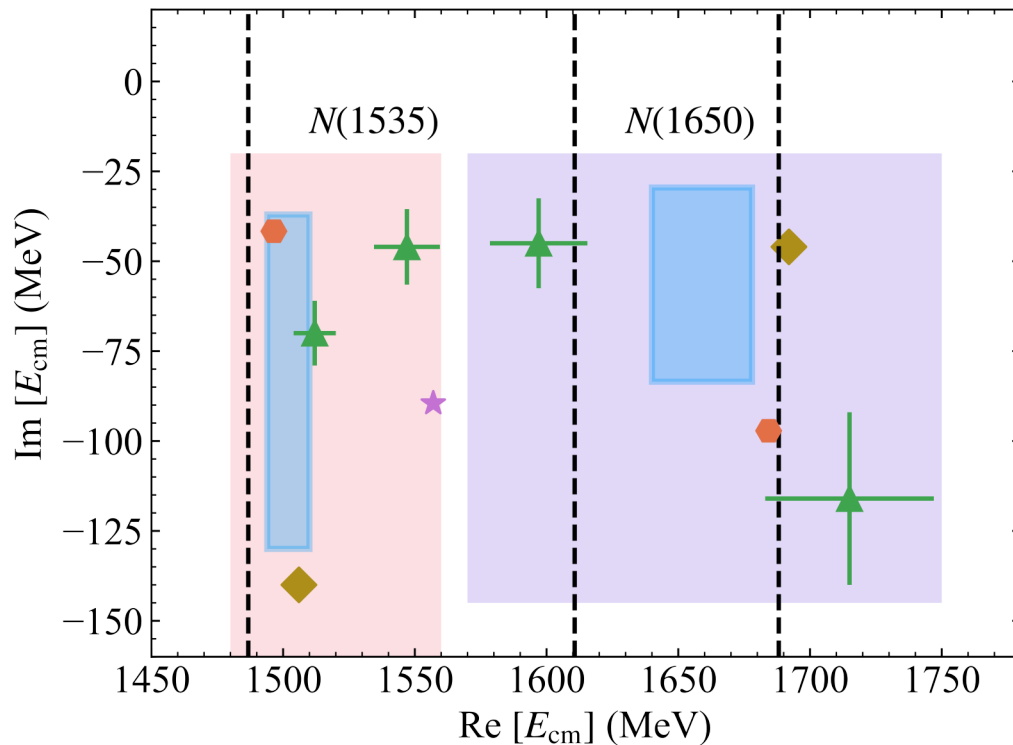
UChPT in the finite volume



- Two-pole structure of $\Lambda(1405)$ at physical point
- The $\Lambda(1380)$ connected to the **Singlet** in the flavor symmetry
- The $\Lambda(1405)/\Lambda(1670)$ coupled to the **Octet** in the flavor symmetry

Over $\text{Tr}[M] = C$

$N(1535)/N(1650)$ in UChPT



$\{\pi N, \eta N, K\Lambda, K\Sigma\}$

Peter, et al, PLB.697.2011, 254-259

J. Nieves, et al, PRD.64.116008

Maxim Mai et al, PRD.86.094033

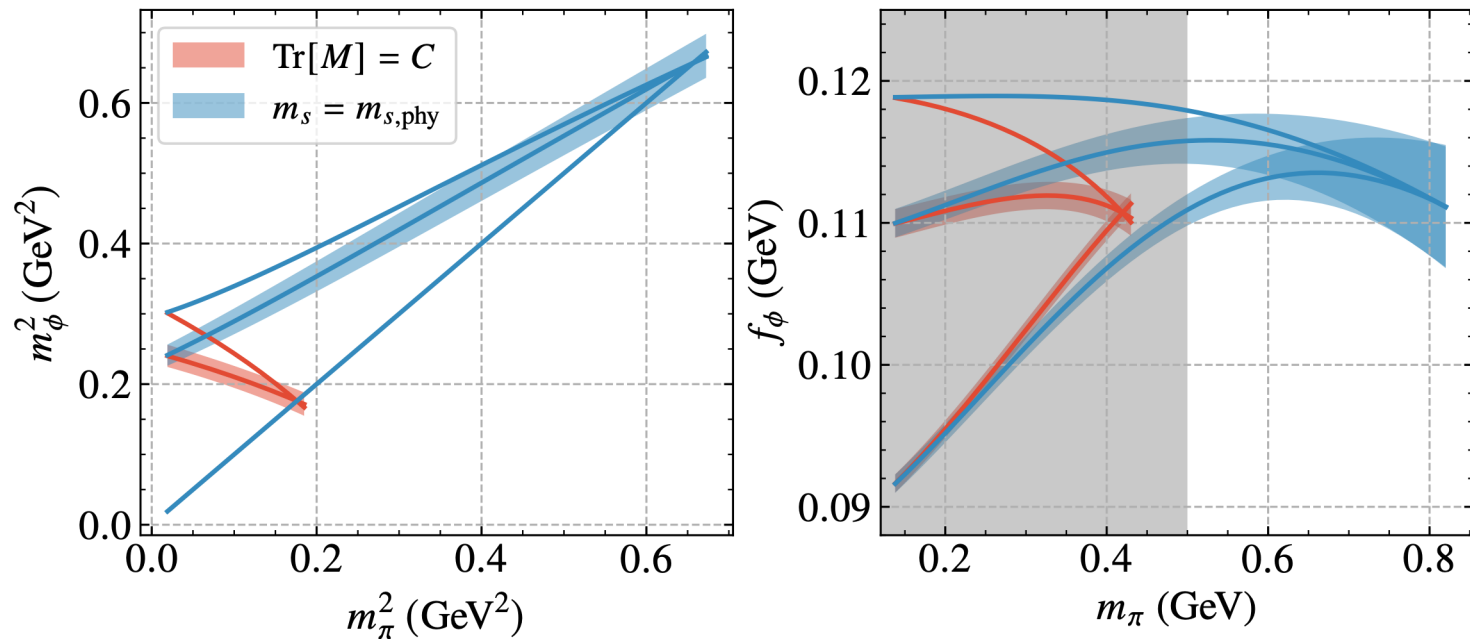
N. Kaiser, et al, PLB.362.1995, 23-28

PDG

...

- ❑ Pole positions of the $N(1535)$ and $N(1650)$ up to NLO
- ❑ Reference results: **Re [Pole 1] = [1480, 1560] MeV, Re [Pole 2] = [1580, 1750] MeV**
- ❑ My result for N1535 up to NLO is still going 🤔

NLO ChPT works up to $m_\pi = 450$ MeV

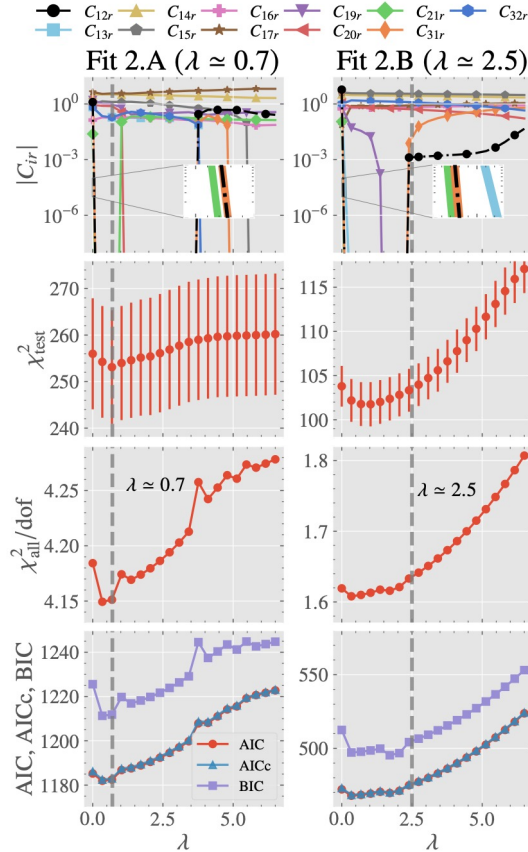


- Could we correctly recover the chiral trajectories of m_ϕ and f_ϕ over $m_{s,\text{phy}}$?
- ChPT up to N2LO

$$m_\phi^2 = m_{0,\phi}^2 + m_{4,\phi}^2(L_{ir}) + m_{6\text{ct},a}^2(C_{ir}) + m_{6\text{loop},a}^2(L_{ir})$$

$$f_\phi = f_0(1 + f_{4,a}(L_{ir}) + f_{6\text{ct},a}(C_{ir}) + f_{6\text{loop},a}(L_{ir}))$$

- ~ 90 C_{ir} s in scattering but 13 C_{ir} s in m_ϕ and f_ϕ



Lasso regression

$$\chi^2 = \chi^2_{\text{dof}} + \lambda \sum_{i=1}^n |p_i|$$

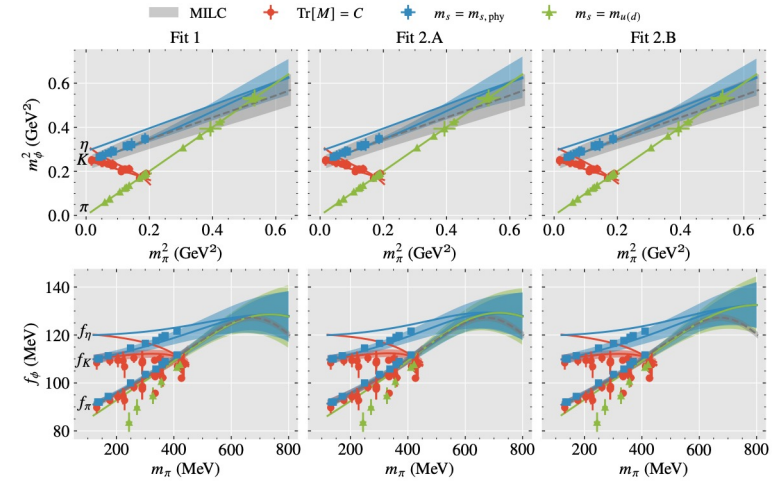
$$p_i = C_{ir}$$



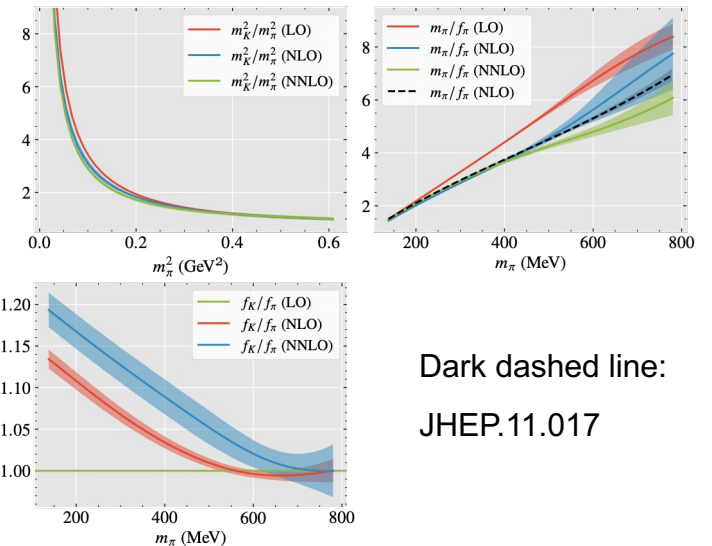
Shrinking less relevant C_{ir} to 0

Fit 2.A: $\{C_{12r}, C_{21r}, C_{31r}\} \rightarrow 0$

Fit 2.B: $\{C_{13r}, C_{21r}, C_{31r}\} \rightarrow 0$



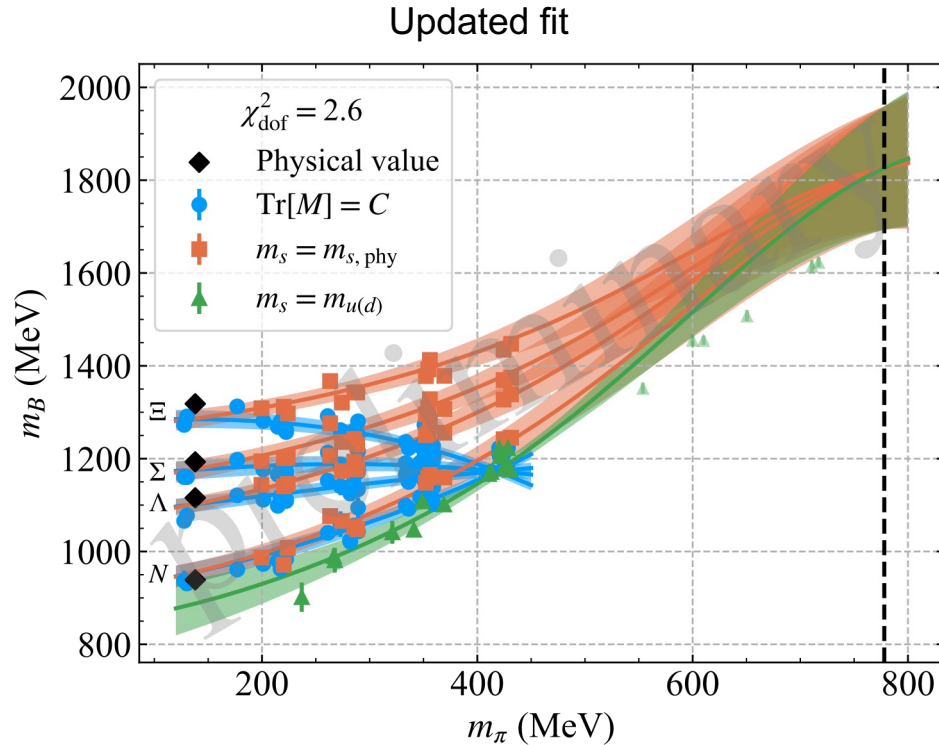
Convergence of the chiral expansion



- Fit 1: Fitting L_{ir} and C_{ir} to data as comparison
- Fit 2.A: Set $C_{ir} = 0$ and fix L_{ir} by data. Then perform the Lasso on C_{ir}
- Fit 2.B: Fit to data with C_{ir} and L_{ir} , Then fix L_{ir} and perform the Lasso on C_{ir}

Dark dashed line:
JHEP.11.017

Pion mass dependence of the baryon-octet mass up to $\sim m_\pi = 800$ MeV



Trajectory	m_π (MeV)	f_π (MeV)	m_B (MeV)
$\text{Tr}[M] = C$	420	110	1174
$m_s = m_{s, \text{phy.}}$	780	128	1827

□ Could be as input for studying the properties of the exotic baryon resonances. Λ^* , N^* , $\Sigma^*(I = 1)$...

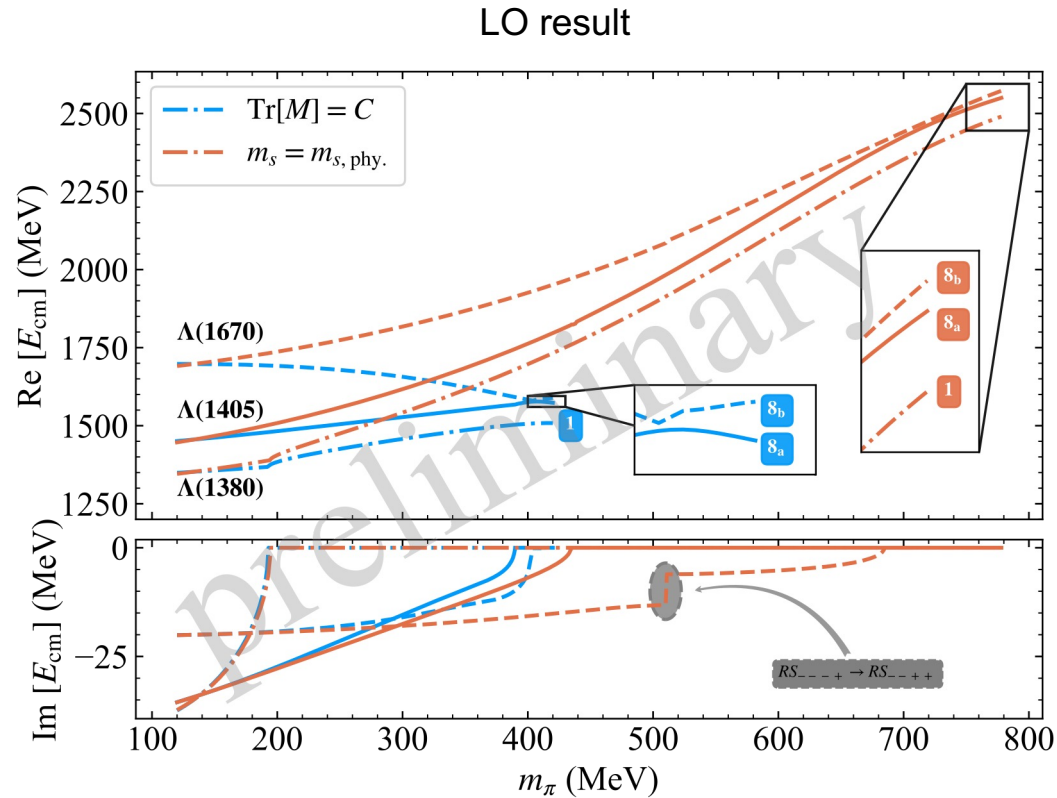


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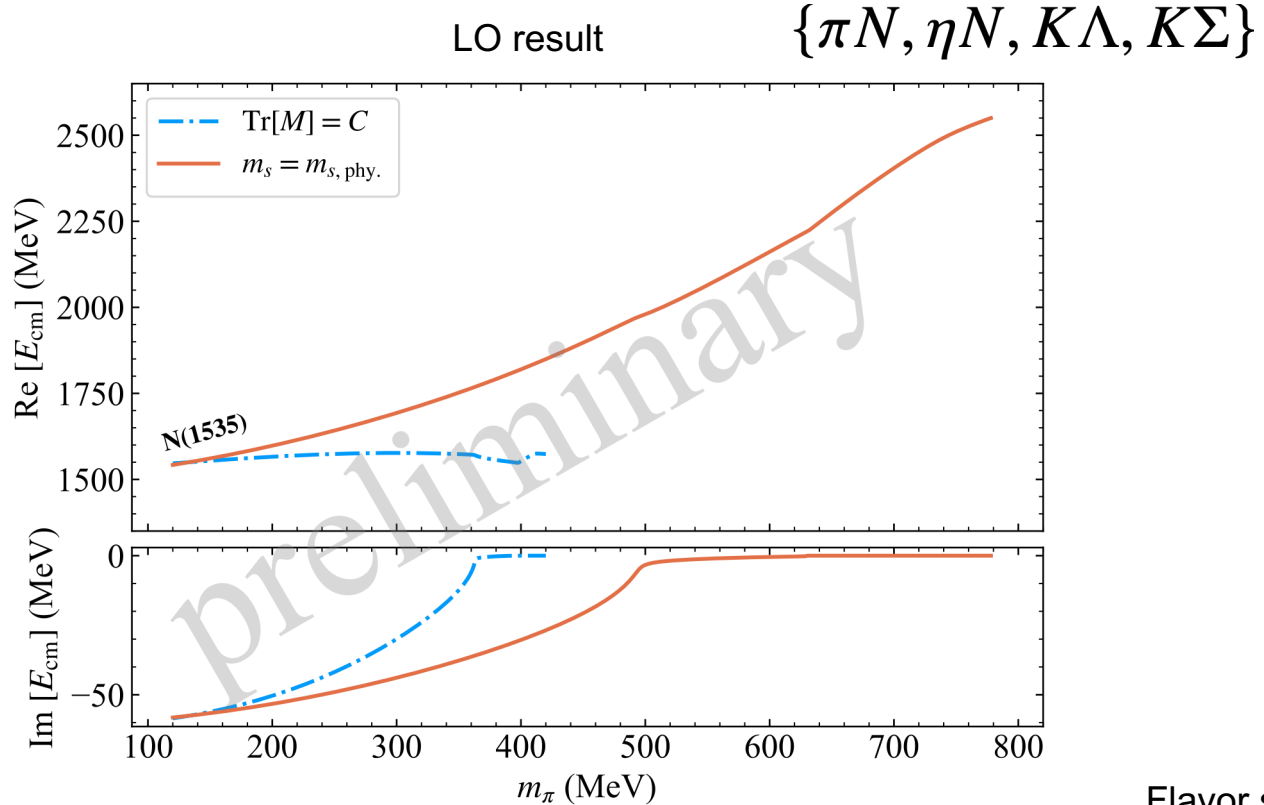
Revealing the s or $s\bar{s}$ component in exotic hadrons

Revealing the s -quark component in exotic hadrons: a trivial example



- The trajectories of the two poles smoothly increasing over m_s but almost flat over $\text{Tr}[M] = C$
- s -quark and $s\bar{s}$ component play important role in $\Lambda(1670)$

Observing $s\bar{s}$ component in $N(1535)$ by trajectories



Flavor symmetry

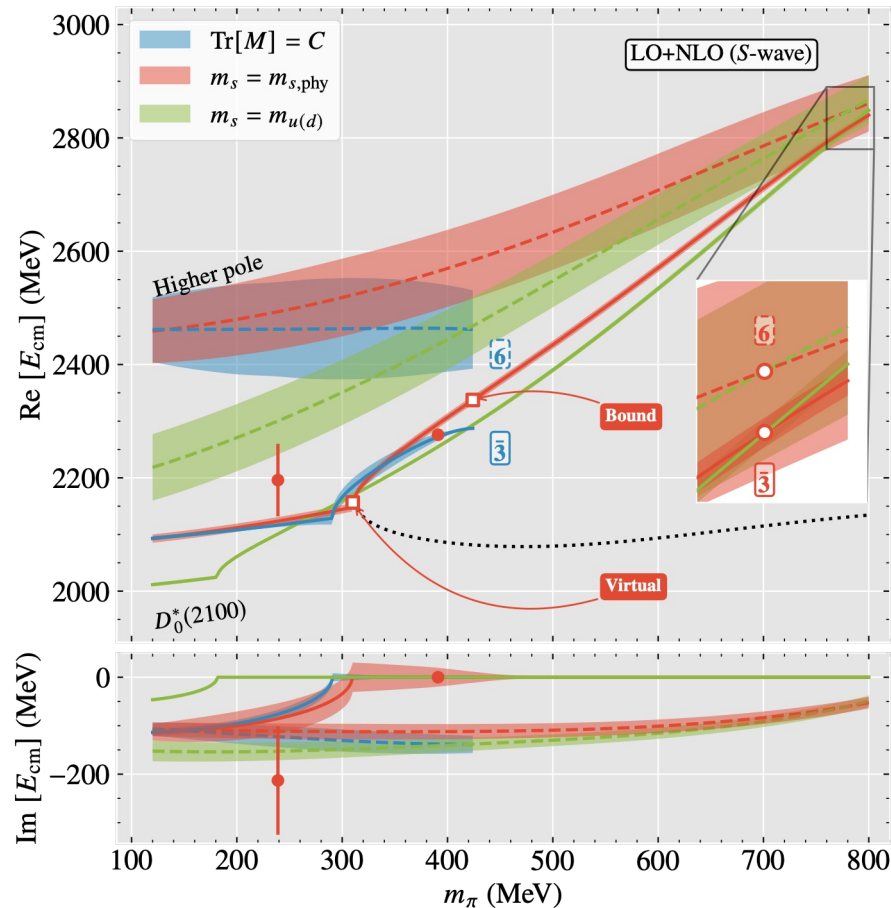
- The transitions of the R.S. with respect to m_π : $[- \ - \ + \ +] \rightarrow [- \ + \ + \ +] \rightarrow [+]$
- The trajectory over $\text{Tr}[M] = C$ is approximately constant by varying the pion mass
- The trajectory over $m_s = m_{s, \text{phy.}}$ is increasing when increasing the pion mass
- **The distinction between trajectories over $\text{Tr}[M] = C$ and $m_s = m_{s, \text{phy.}}$ exhibits the hidden s -quark component in $N(1535)$!!!**

Another example: $D_0^*(2300)$ $(S, I) = (0, \frac{1}{2})$

$\{D\pi, D\eta, D_s\bar{K}\}$

$$\bar{3} \otimes 8 = \bar{3} \oplus 6 \oplus \bar{15}$$

See Raquel Molina's talk on Monday for detail



Z. Zhuang et al, ArXiv: 2606.03826

- Less hidden s -quark component in the $D_0^*(2100)$
- The higher pole has $s\bar{s}$ component

Summary

- ❑ Pole trajectory as another point of view revealing the quark component of the exotic resonances
- ❑ $N(1535)$ as a dynamically generated state has hidden s-quark component
- ❑ Trajectories of the poles up to NLO are still going
- ❑ New results are coming soon

Thank you for your attention !!!