Yuki Kamiya
HISKP, Bonn Univ.

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

in collaboration with
FengKun Guo
Maxim Mai
Ulf-G Meißner

Hadron spectroscopy with strangeness
@ Glasgow, UK, 4.4.2024,

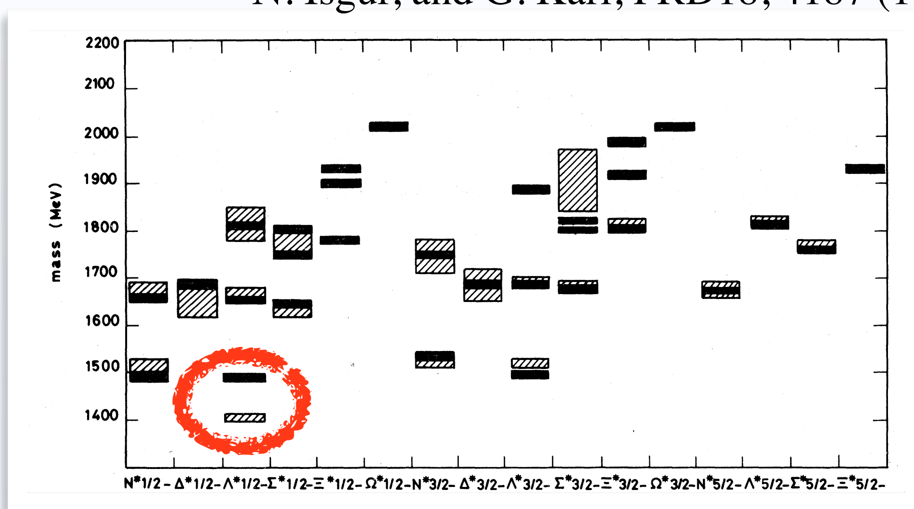
Contents

$\bar{K}N$ interaction and $\Lambda(1405)$

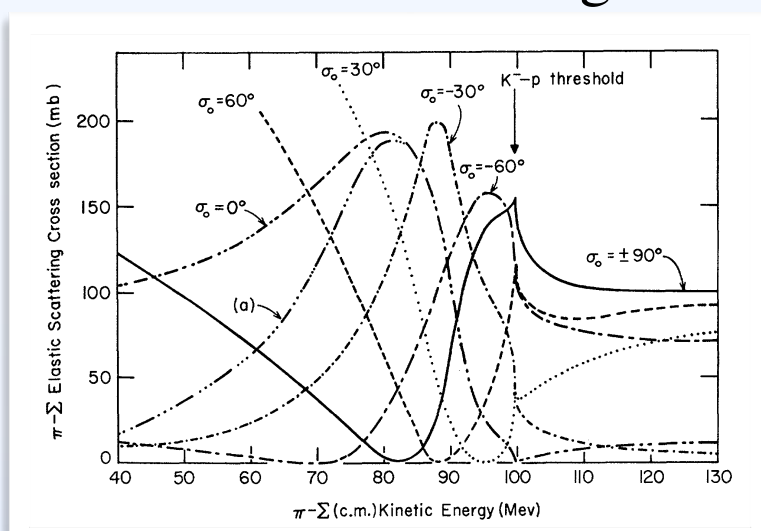
$\Lambda(1405)$

- Large discrepancy from qurak model

N. Isgur, and G. Karl, PRD18, 4187 (1978)



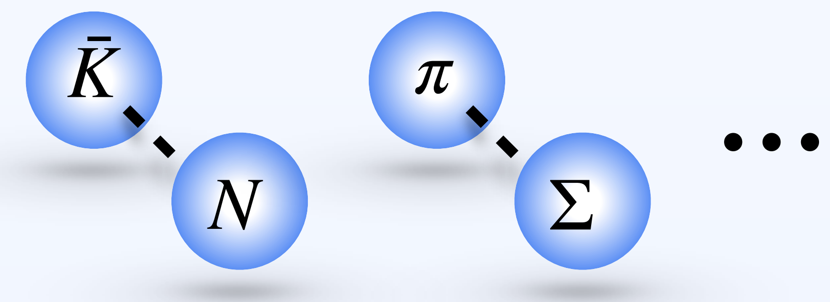
- Predicted in the $\pi\Sigma$ scattering below $\bar{K}N$



R. H. Dalitz and S. F. Tuan, PRL2, 425 (1959)

R. H. Dalitz and S. F. Tuan, Annals Phys. 10, 307 (1960).

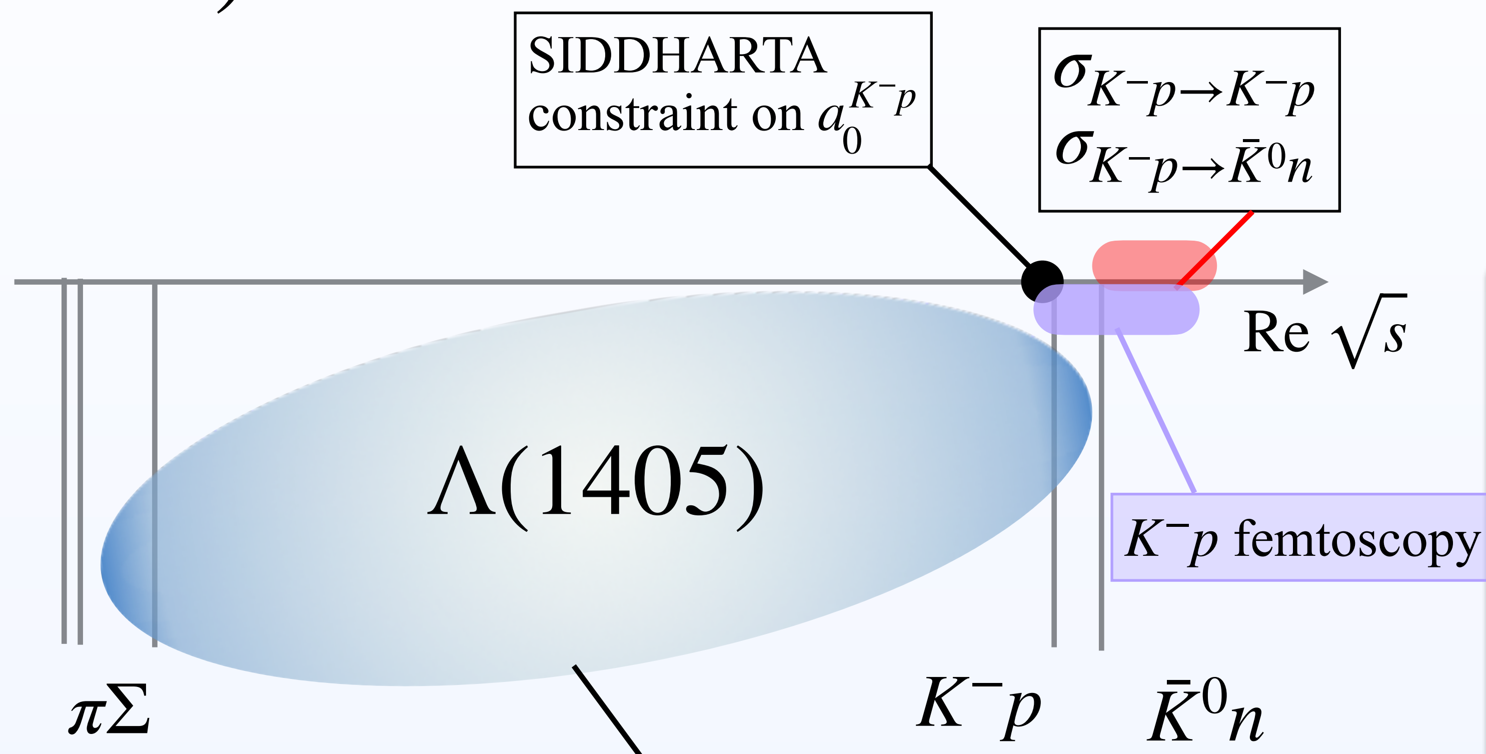
- Exotics candidate
  - Quest for internal structure



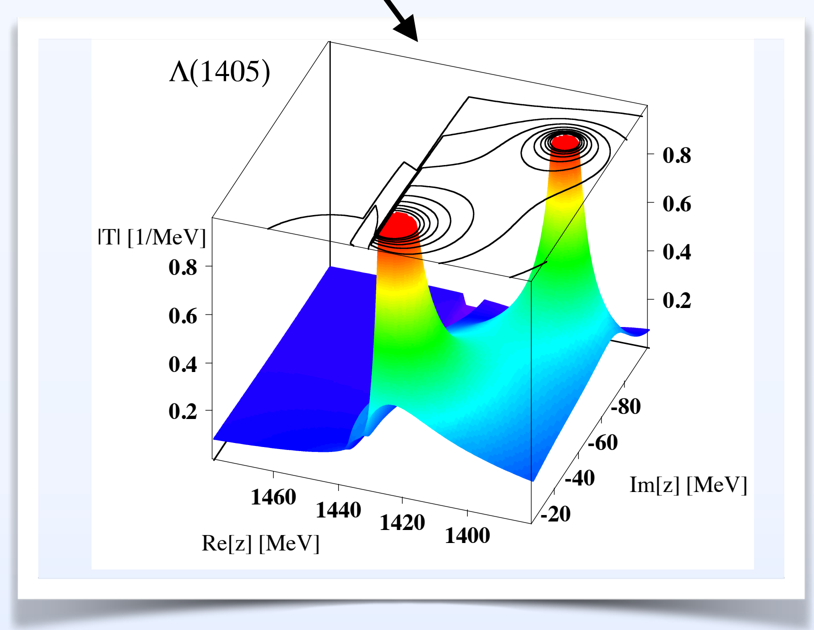
$\longrightarrow$ Detailed analysis of $\pi\Sigma$-$\bar{K}N$ interaction

$\bar{K}N$ interaction and $\Lambda(1405)$

$\bar{K}N$ interaction data and $\Lambda(1405)$ resonance



- Experimental data for $\pi\Sigma$-$\bar{K}N$ system
  - K^-p total cross sections
  - Branching rations
  - K^-p scattering length from Kaonic nuclei
  - $\pi\Sigma$ mass spectra
  - <u>K^-p femtoscopy</u>



T. Hyodo, D. Jido - PPNP 67 (2012) 55

- Recent analysis with chiral SU(3) dynamics
  - <u>Two pole structure</u>

    J. A. Oller and U. G. Meißner, PLB500, 263 (2001)

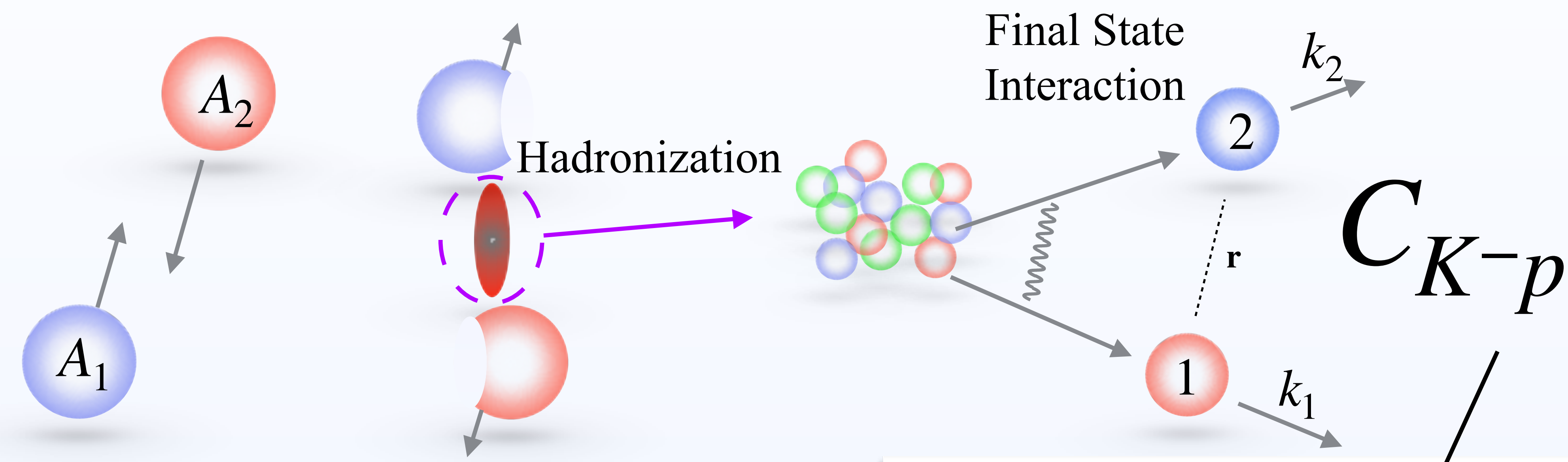
    Peak in mass spectra

    $\rightarrow$ two poles in complex E-plane $\left\{\begin{array}{l}\Lambda(1380)\\ \Lambda(1405)\end{array}\right.$

Detailed nature of two Λ resonances

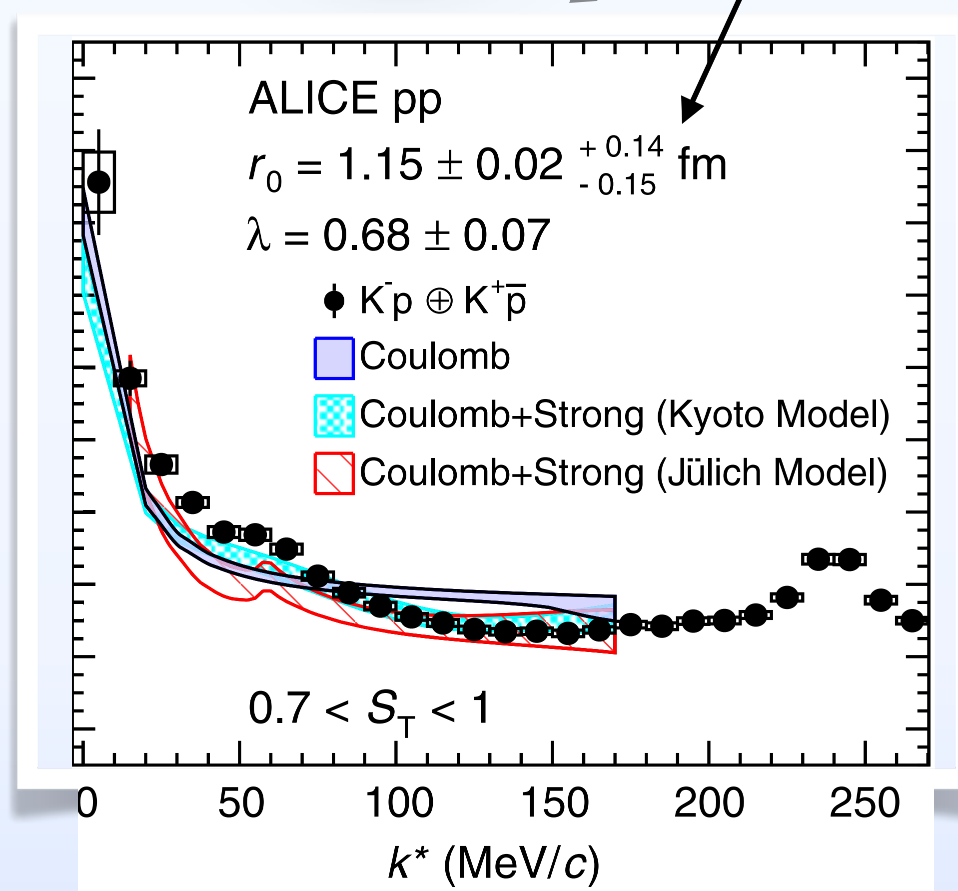
$\bar{K}N$ interaction and K^-p correlation

- K^-p correlation function in high-energy collisions



- Good resolution thanks to high statistics
- Sensitive to $k^* \lesssim 200$ MeV/c
- Detailed coupled-channel effect

⇨ Complementary data for $\bar{K}N$ interaction

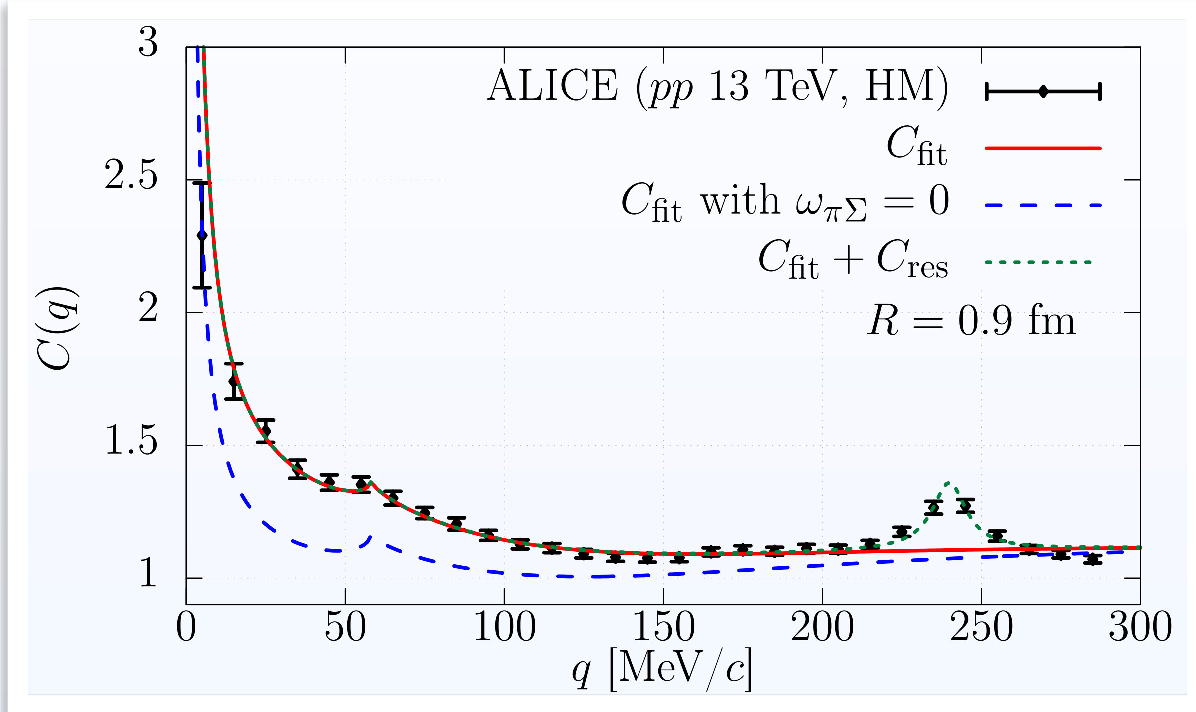


ALICE PRL 124, 092301 (2020)

$\bar{K}N$ interaction and K^-p correlation

- ALICE *pp* collision data

ALICE PRL 124, 092301 (2020)

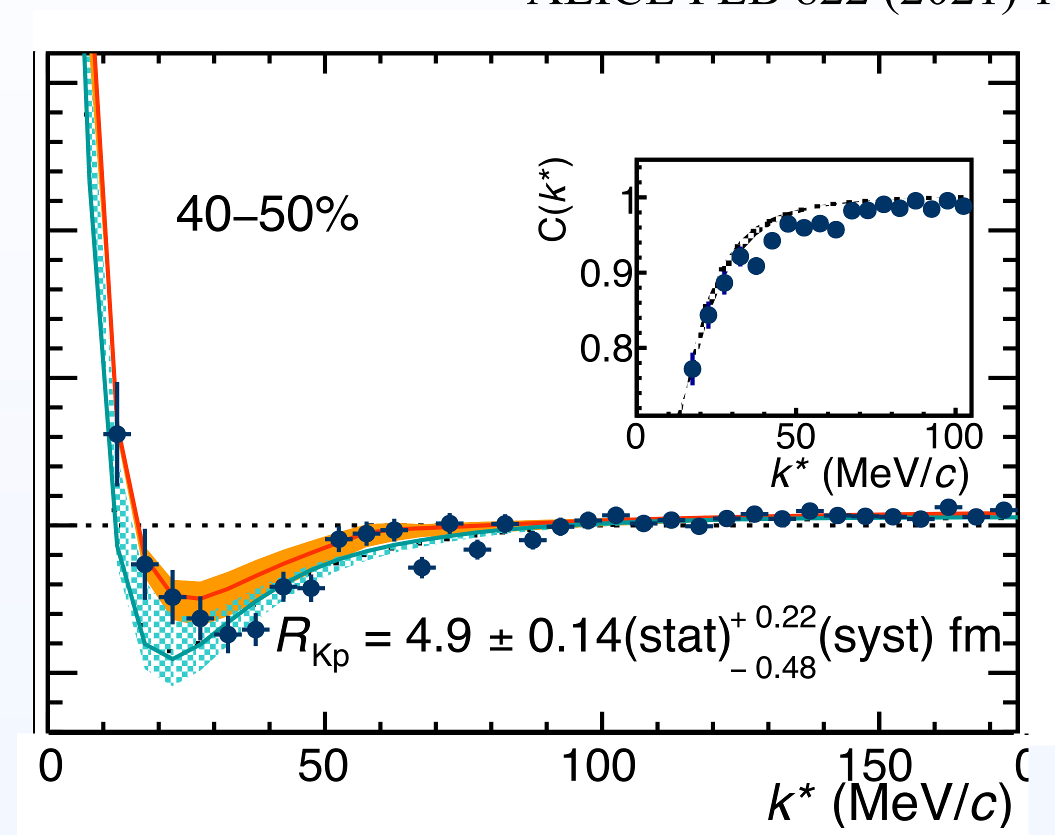


YK et al , PRL 124 (2020) 13, 132501

- Small source
  - Clear $\bar{K}^0 n$ cusp structure
  - Sizable contribution from coupled-channel source required to reproduce data

- ALICE PbPb collision data

ALICE PLB 822 (2021) 136708



- Large source
  - Weaker cusp
  - Scattering length fitting
    —> Consistent with Kaonic hydrogen

- Chiral SU(3) model reproduces both source data

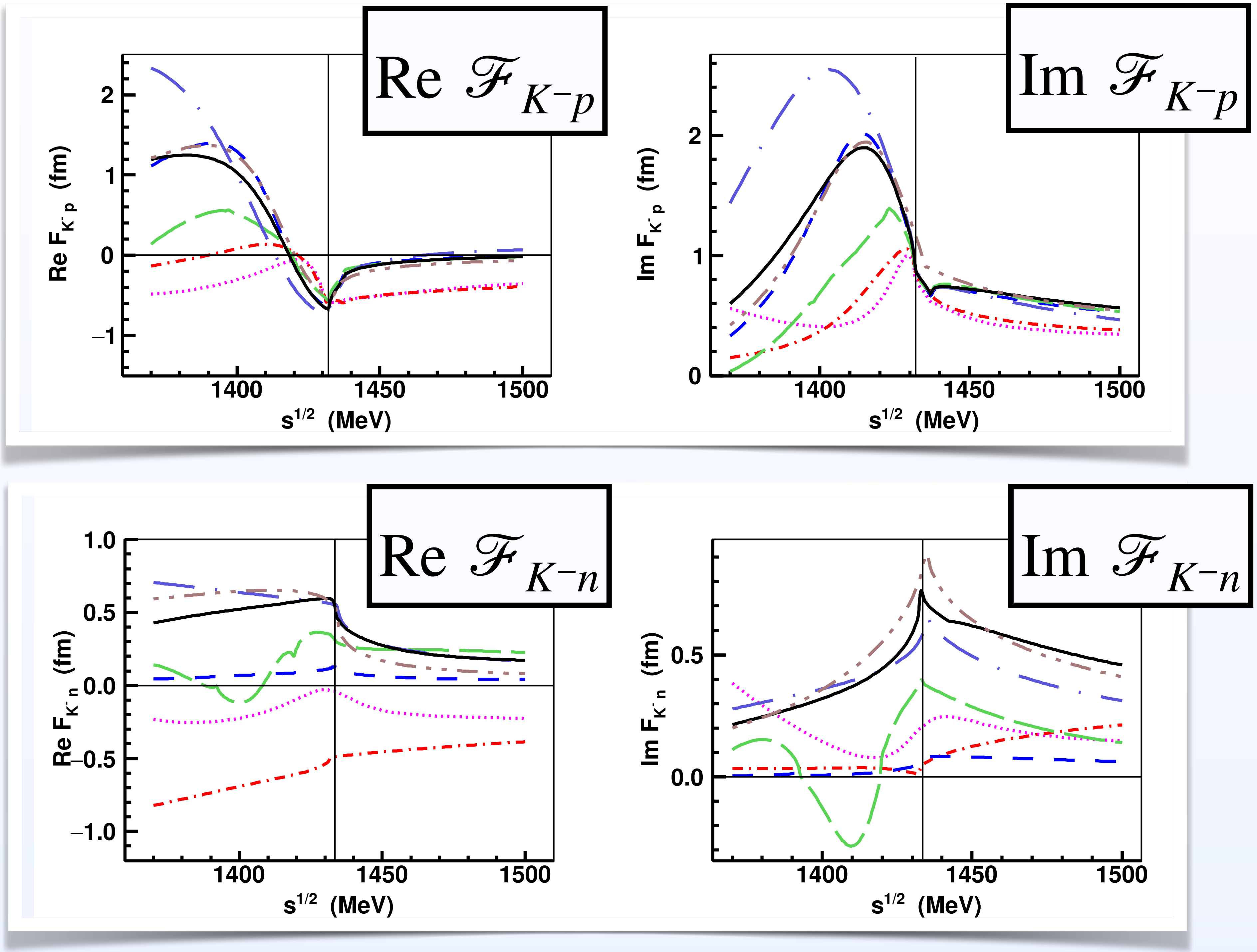
- Chiral SU(3) dynamics describes the low-energy $\bar{K}N$ scattering

$\bar{K}N$-$\pi\Sigma$ interaction and two pole structure

- $\bar{K}N$ interaction

$\mathscr{F}_{\bar{K}N,I=0}$

$\mathscr{F}_{\bar{K}N,I=1}$



B2, B4: Mai, Meißner, EPJA 51 (2015)

MI, MII: Guo, Oller, PRC 87 (2013)

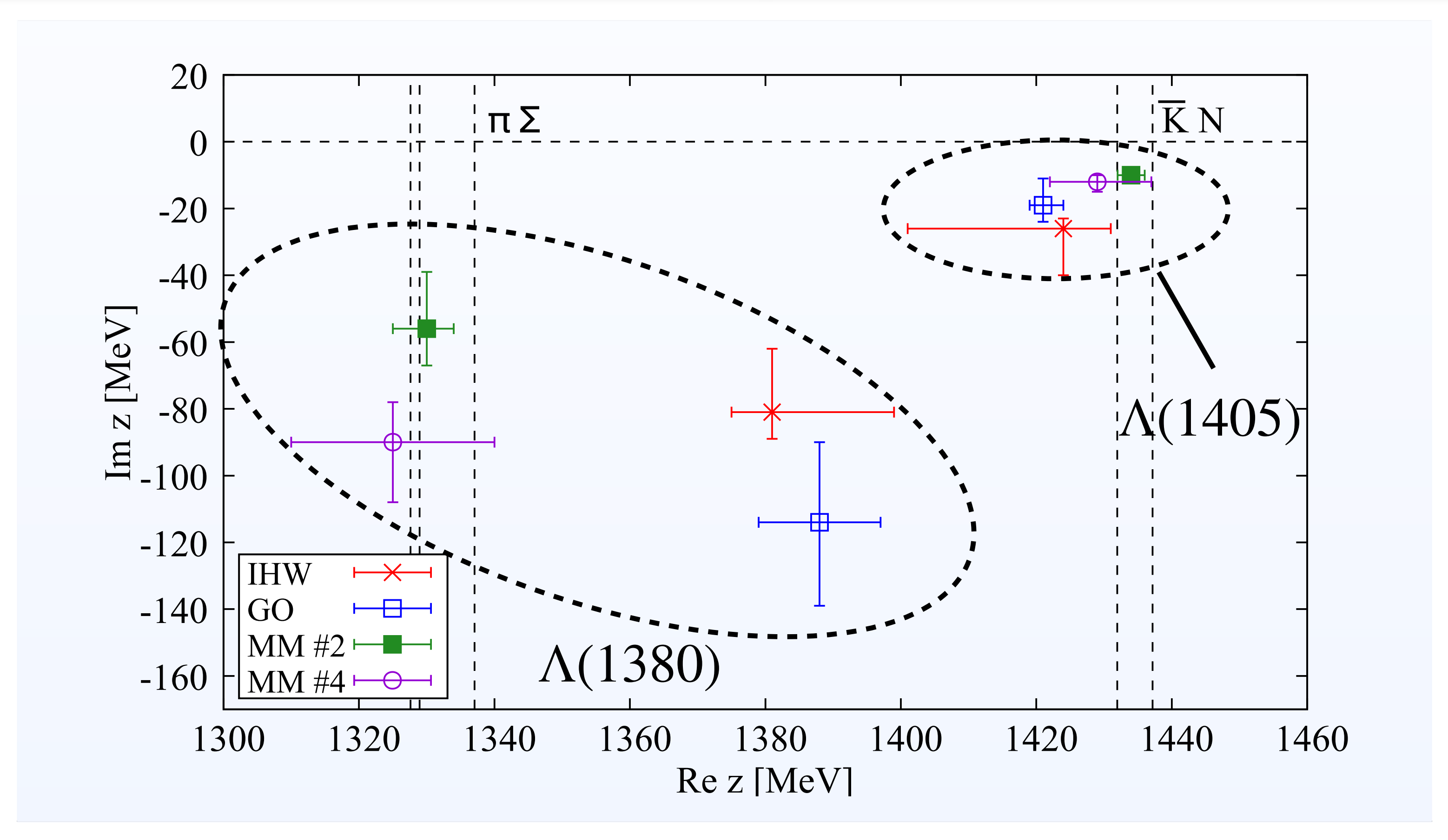
PNLO: Cieplý, Smejkal, NPA 881 (2012)

KMNLO: Ikeda, Hyodo Weise NPA 881 (2012)

Ciepiy and Mai, EPJ Web Conf. 130, 02001 (2016)

$\bar{K}N$-$\pi\Sigma$ interaction and two pole structure

- Pole structure with chiral NLO models



Ikeda, Hyodo Weise NPA 881 (2012)

Mai, Meißner, EPJA 51 (2015)

Guo, Oller, PRC 87 (2013)

- $\Lambda(1405)$: Good consensus on $\underline{\bar{K}N \text{ threshold pole}}$

 Strong constraint from SIDDHARTA data

- $\Lambda(1380)$: lying close to $\pi\Sigma$ but the poles are scattered

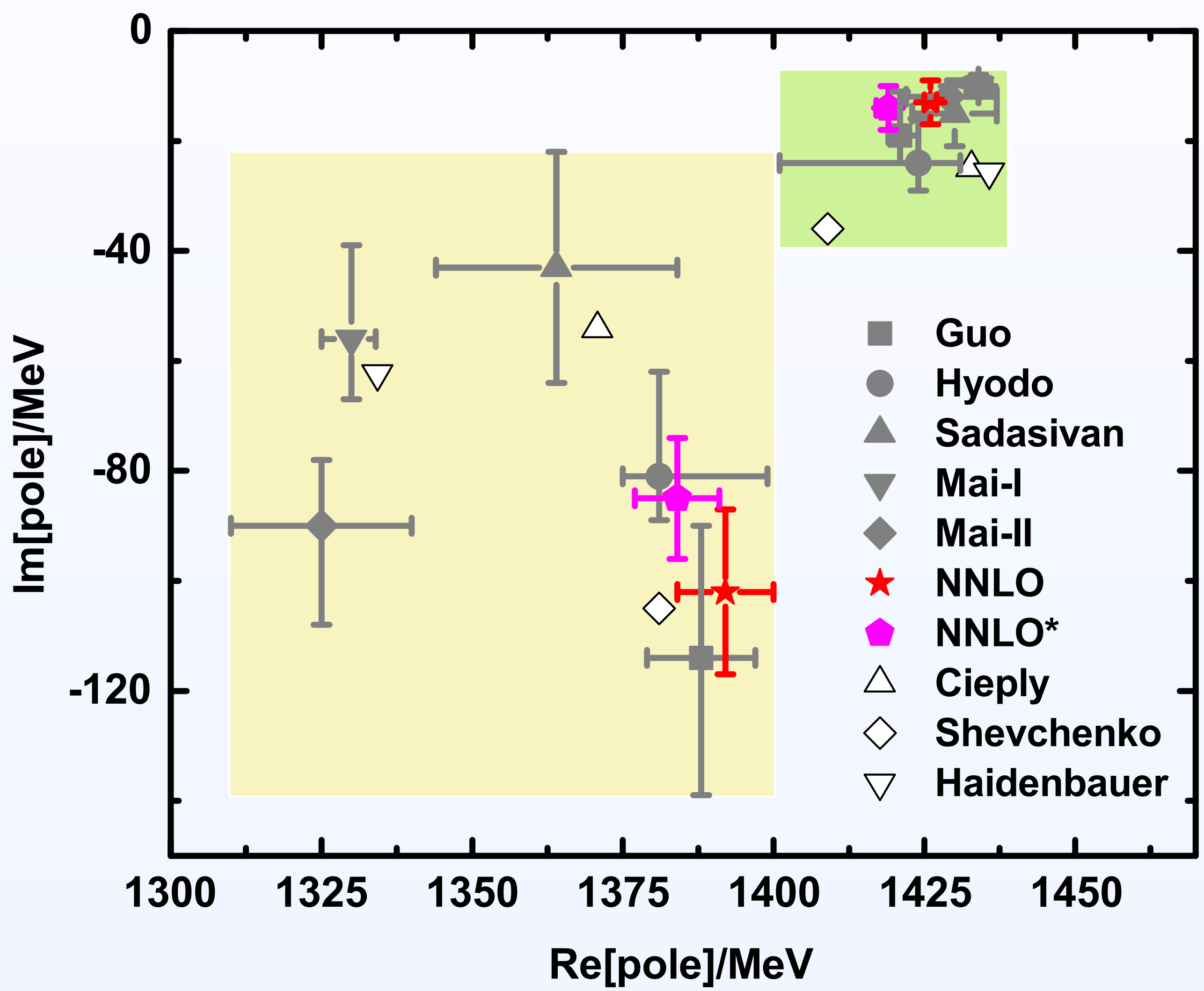
 $\rightarrow$ Further constraint needed…

 - Are they stable with the higher-terms of chiral order?
 - What are their origin?

$\bar{K}N$-$\pi\Sigma$ interaction and two pole structure

- New chiral <u>NNLO</u> analysis

J.-X. Lu, L.-S. Geng, M. Doering, M. Mai, PRL 130 (7) (2023) 071902.



- Two pole structure is found in the latest NNLO analysis
- $\Lambda(1405)$ pole is consistent in NLO and NNLO models
- $\Lambda(1380)$ is also in the range of errors

Origin of poles ~Compositeness~

- Compositeness for bound state

$$\boxed{a_0 = R\left\{\frac{2X}{1+X} + \mathcal{O}\left(R_{\rm typ}/R\right)\right\}} \quad R = \frac{1}{\sqrt{2\mu B}}$$

S. Weinberg, Phys. Rev. 137, B672 (1965)

Observables → Indication of structure

a_0: Scattering length

B : Binding energy

<u>X : Compositeness</u>

- Extension to unstable states and application Λ(1405)

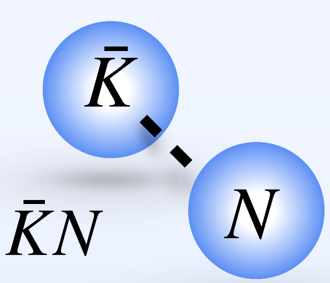
- Extended weak binding relation for unstable states
- Interpretation of complex value of X

$$a_0 = R\left[\frac{2X}{1+X} + \mathcal{O}\left(\left|\frac{R_{\rm typ}}{R}\right|\right) + \mathcal{O}\left(\left|\frac{l}{R}\right|^3\right)\right] \Rightarrow \tilde{X} \equiv \frac{1-|Z|+|X|}{2}$$

- Applications to Λ(1405) with chiral models

Models	B [MeV]	a_0 [fm]	X	$\tilde{X}$	$U/2$
IHW	-10-i26	1.39-i0.85	1.3+i0.1	1.0	0.3
MM(2013)	-4-i8	1.81-i0.92	0.6+i0.1	0.6	0.0
GO	-13-i20	1.30-i0.85	0.9-i0.2	0.9	0.1
MM(2015)	2-i10	1.21-i1.47	0.6+i0.0	0.6	0.0
MM(2015)	- 3-i12	1.52-i1.85	1.0+i0.5	0.8	0.3

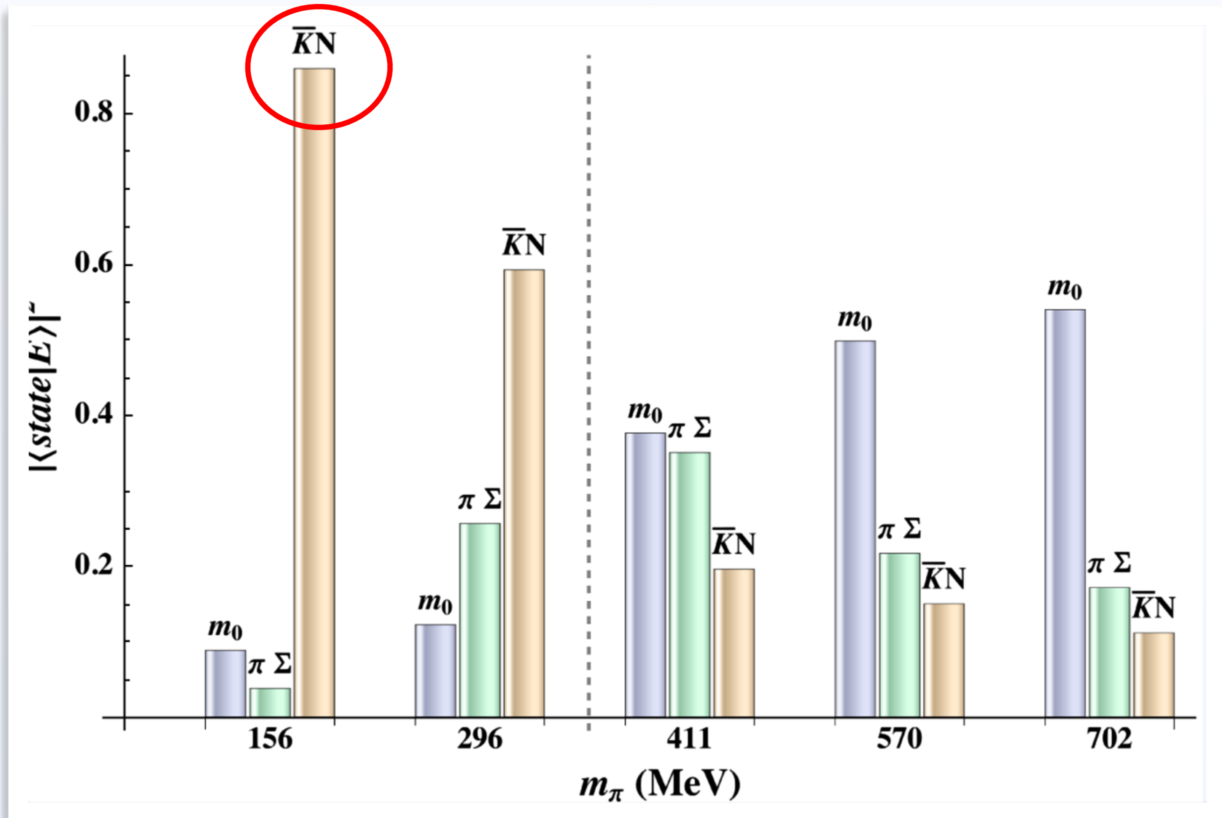
⇒ Λ(1405) is $\bar{K}N$ dominated state



Origin of poles ~lattice QCD analysis~

- Component of Λ(1405)

J.M.M.Hall, et al,, PRL 114 (13) (2015)

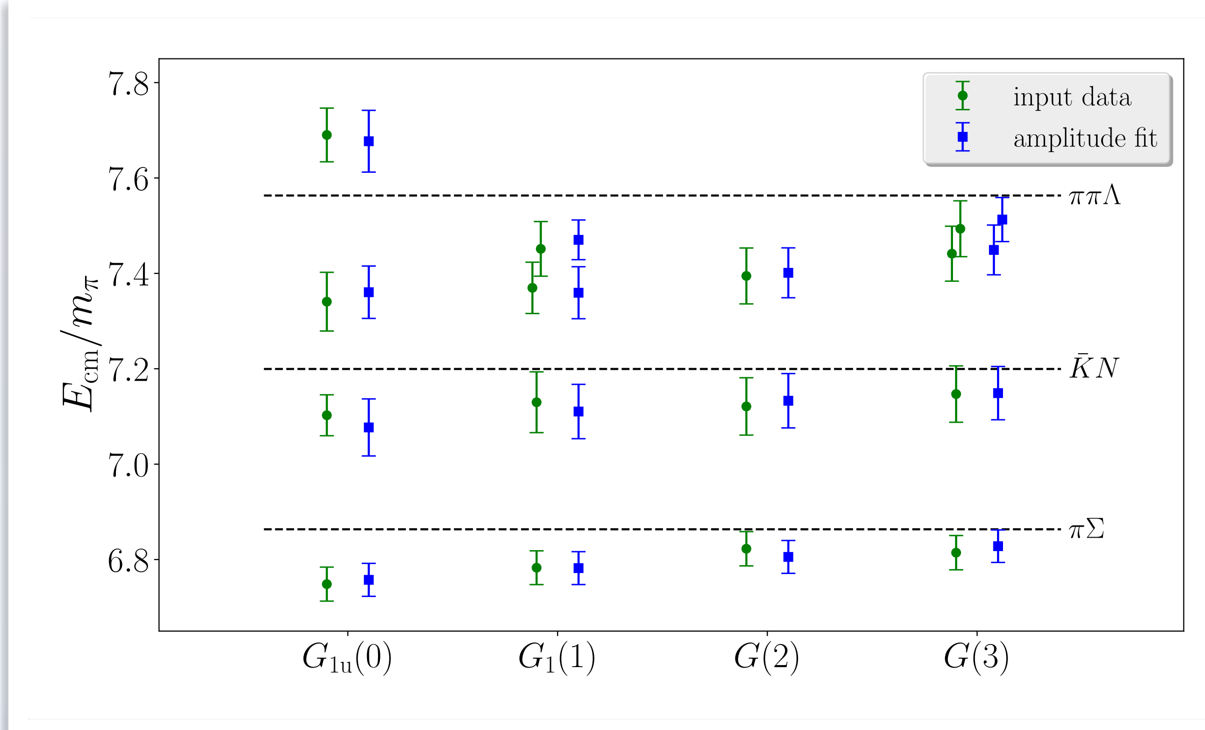


- Structure identification by strange magnetic form factor
- $\bar{K}N$ component dominant at the near physical point

Nature of Λs can be accessed in lattices

- Two pole structure

J.Bulava PRL. 132 (2024) 5, 051901



- Two pole structure is found at $m_\pi \approx$ 200 MeV

$$\mathrm{Re}\, E_1 = 1325 - 1380\,\mathrm{MeV}$$

$$\mathrm{Re}\, E_2 = 1421 - 1434\,\mathrm{MeV}.$$

Origin of poles ~Representations~

- **Extrapolation of chiral model** D. Jido, J.A. Oller, E. Oset, A. Ramos, U.-G. Meißner, NPA 725 (2003)
  - Weinberg-Tomozawa term and extrapolation

$$V_{ij}^{WT} = -\frac{C_{ij}^{\mathrm{WT}}}{8F^2}\mathcal{N}_i\mathcal{N}_j(2\sqrt{s} - m_i - m_j)$$

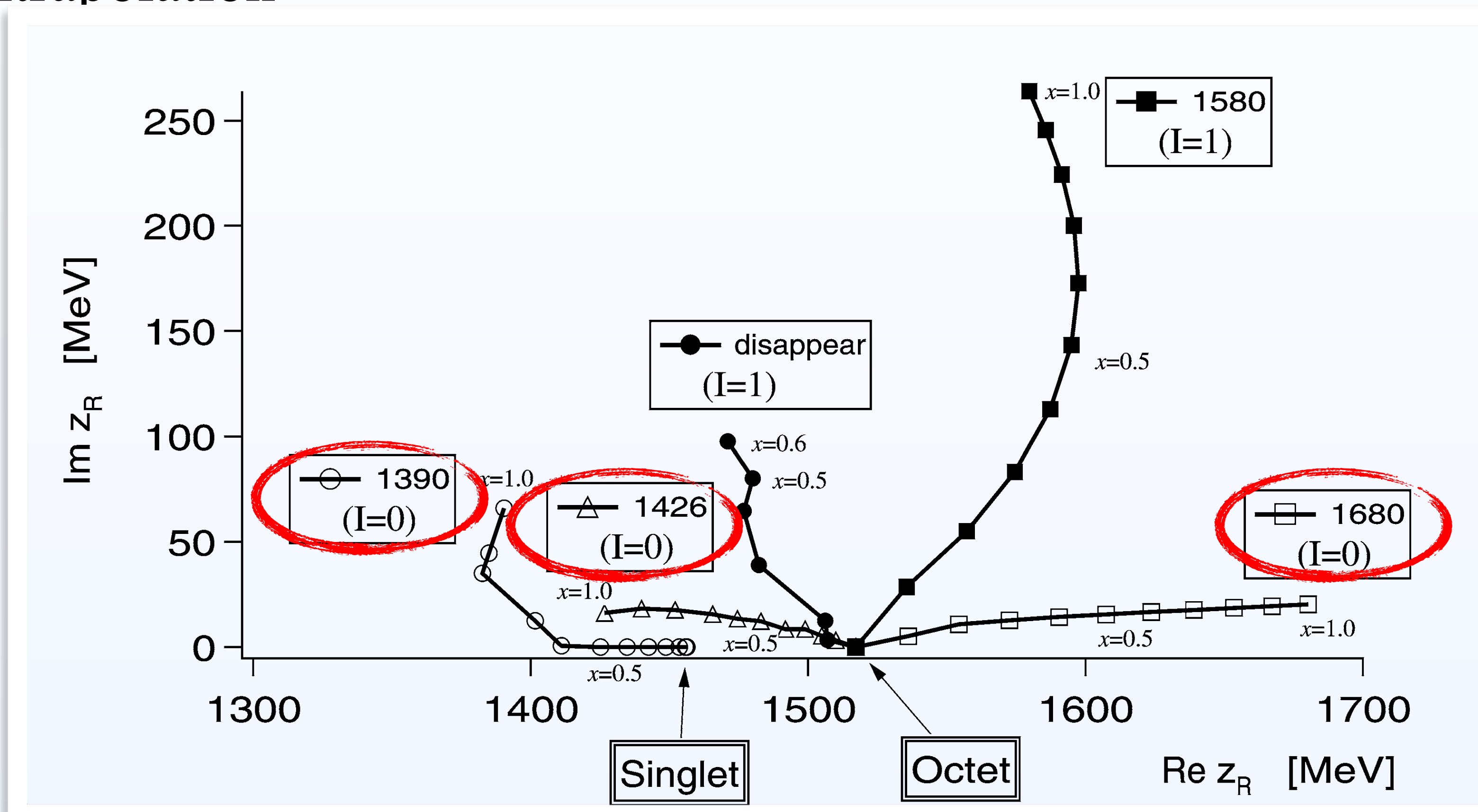
$$M_i(x) = M_0 + x(M_i - M_0),\ \cdots$$

$x = 0$: physical point

$x = 1$: SU(3) limit

  - Projection to multiplets
    decomposition of multiplets
    (1,8,8',27) in SU(3) limit

$$C_{ij}^{\mathrm{WT}} \xrightarrow{U} C_{\alpha\beta} = \begin{array}{cccc} 1 & 8 & 8' & \\ \left(\begin{matrix} 6 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & -2 \end{matrix}\right) \end{array}$$



Origin of Int.	SU(3) limit	Physical point
Singlet (1)	Deep bound state	Λ(1380)
Octet (8, 8')	Weekly bound states (degenerated)	Λ(1405), Λ(1680)

- Resonant poles are related to the interaction multiplets
- Trajectories depend on extrapolation detail—> More detaield extrapolation towards lattice?
- How trajectories change with NLO terms ?

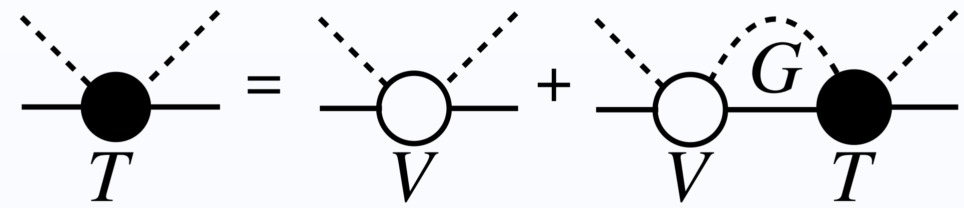
Motivation of this study

Model extrapolation to unphysical point

- Chiral unitary dynamics ~Weinberg-Tomozawa term model ~

- Bethe-Salpeter equation

$$T_{ij} = V_{ij} + V_{ik}G_kT_{kj} \qquad i,j,k \in \{\pi\Sigma, \bar{K}N, \eta\Lambda, K\Xi\}$$



- Interaction kernel: Weinberg-Tomozawa term

$$V_{ij}^{WT} = -\frac{C_{ij}}{8F^2}\mathcal{N}_i\mathcal{N}_j(2\sqrt{s} - m_i - m_j) \qquad \mathcal{N}_i = \mathcal{N}_i(m_i, M_i)$$

  - m_i, M_i, F ; Depends on the bare pion/Kaon masses ($M_{0\pi}$, M_{0K})

  $\longrightarrow$ Relations (m_i, M_i, F) $\longleftrightarrow$($M_{0\pi}$, $M_{0,K}$) required ⇨ (next page)

- Loop function

$$G_i(\sqrt{s}) = \frac{2m_i}{16\pi^2}\left\{a_i(\mu) + \ln\frac{m_i^2}{\mu^2}\frac{M_i^2 - m_i^2 + s}{2s}\ln\frac{M_i^2}{m_i^2} + (\text{log terms})\right\}$$

  - Natural normalization scheme M.F.M. Lutz, E.E. Kolomeitsev, Nucl. Phys. A 700 (2002) 193–308, T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C 78 (2008) 025203

$$\boxed{G(\sqrt{s} = m_B; a(\mu)) = 0 \Longleftrightarrow T(\mu) = V(\mu) \quad \text{with } \mu = m_B}$$

Given the hadron masses m_B, $a(\mu)$ can be determined.

Model extrapolation to unphysical point

- Quark mass dependence of NG bosons and octet baryons

Hadron masses are needed for calculations at unphysical point with $m_{0,\pi,K}$

$\longleftarrow$ Relations from chiral perturbation models

- NG bosons J. Gasser, H. Leutwyler, NPB 250 (1985) 465–516

$$M_\pi^2 = M_{0\pi}\left[1 + \mu_\pi - \frac{\mu_\eta}{3} + \frac{16M_{0K}^2}{F_0^2}(2L_6^r - L_4^r) + \frac{8M_{0\pi}^2}{\underline{F_0^2}}(2L_6^r + 2L_8^r - L_4^r - L_5^r)\right]$$

Decay const. in chiral limit

  - $M_\pi \leftrightarrow M_{0,\pi,K}, F_0$
  - LECs (L_i^r): determined with the lattice meson-meson scattering data

- Octet baryons M. Frink, U.-G. Meißner, JHEP 07 (2004) 028.

$$m_B = \underline{m_0} + m^{(2)}\underline{(b_0, b_D, b_F)}$$

chiral limit mass LECs

- Determination of LECs and bare parameters

$F_0, b_0, b_D, b_F \rightarrow$ fitted to the hadron masses at the physical point

$m_0 \rightarrow$ hadron mass at the unphysical point (lattice) [$M_\phi = 659.4$ MeV, $m_B = 1444.2$ MeV]

J.M.M.Hall, et al, PRL114 (13) (2015) 132002.

Chiral SU(3) amplitude and poles can be calculated at any unphysical point (M_π, M_K) with systematic model

$M_\pi, M_K \rightarrow (M_{0,\pi}, M_{0,K}) \rightarrow m_N, m_\Lambda, m_\Sigma, F \rightarrow \mathscr{F}^{\text{chiral}} \rightarrow E_{\Lambda^*}$

Pole trajectory with WT model

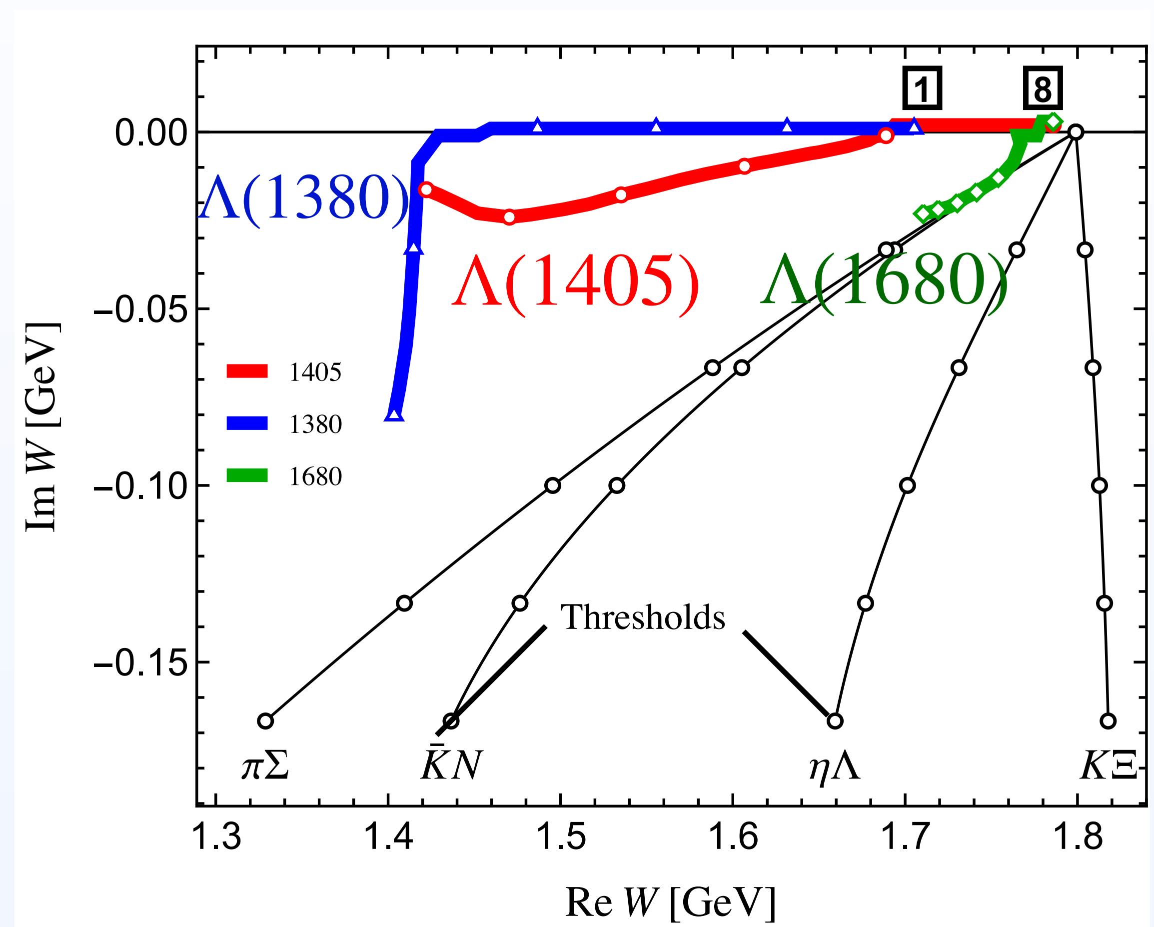
- Extrapolation from physical point to SU(3) limit
  - Poles at physical point

$$E^{\rm LO}_{\Lambda(1380)} = 1403.3 - i\,80.3 \text{ MeV},$$
$$E^{\rm LO}_{\Lambda(1405)} = 1422.7 - i\,16.2 \text{ MeV},$$
$$E^{\rm LO}_{\Lambda(1680)} = 1717.4 - i\,22.9 \text{ MeV},$$

Consistent with the latest chiral models
→ Model describes the Λ*s well

  - Extrapolation to unphysical point

$$\underbrace{(m^{\rm phys}_{0,\pi}, m^{\rm phys}_{0,K})}_{\text{Physi. point}} \to \underbrace{(m^{\rm phys}_{0,K}, m^{\rm phys}_{0,K})}_{\text{SU(3) limit}}$$



F-K, Guo, YK, M Mai, U-G Meißner, PL B 846 (2023) 138264

- Pole trajectories
  - Λ(1380) connected to singlet pole
  - Λ(1405)/Λ(1680) connected to degenerated octet pole

Consistent with simple extrapolation
D. Jido, et al, NPA 725 (2003)

- Pole origins are well related to representations of interactions with detailed extrapolation

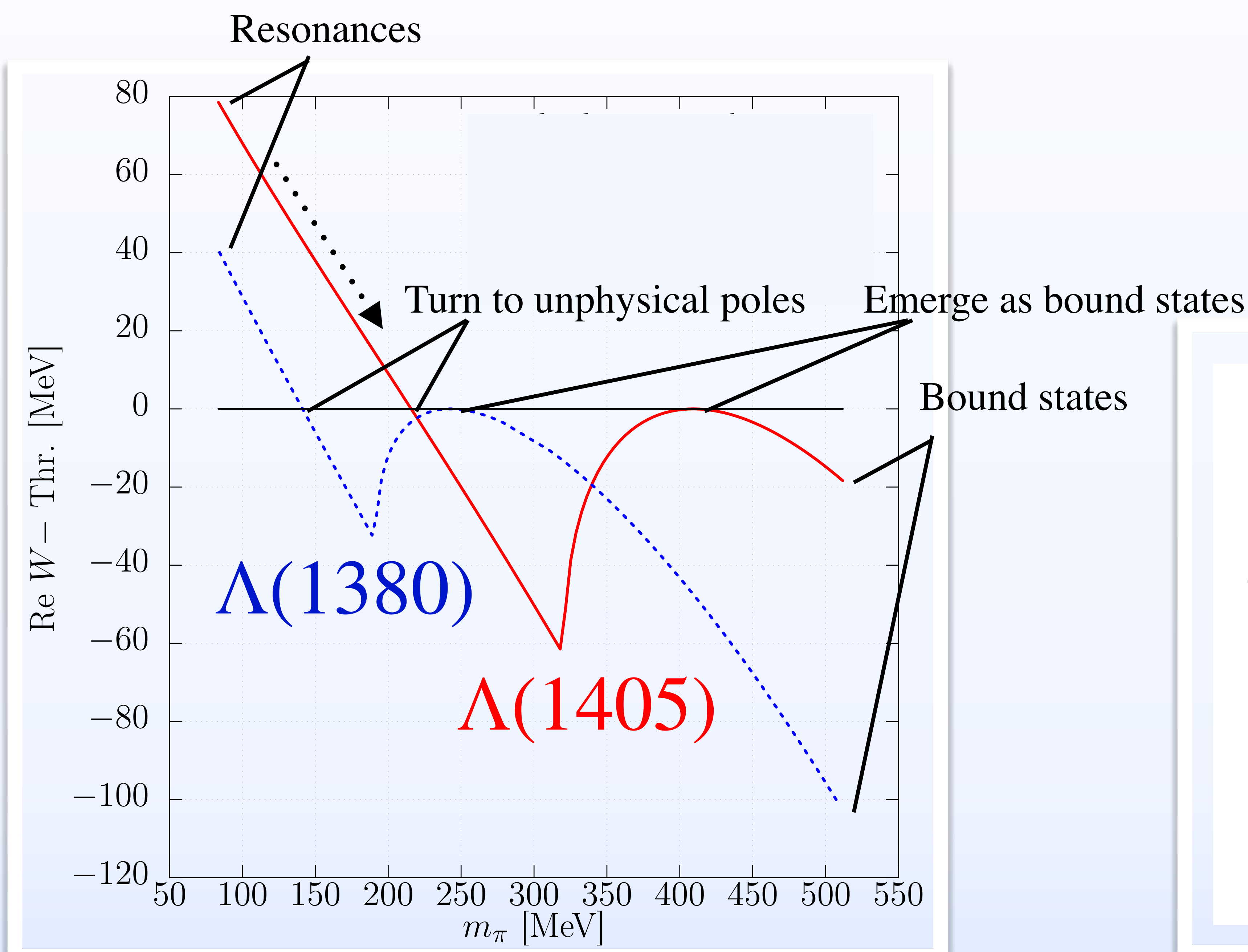
Model parameters

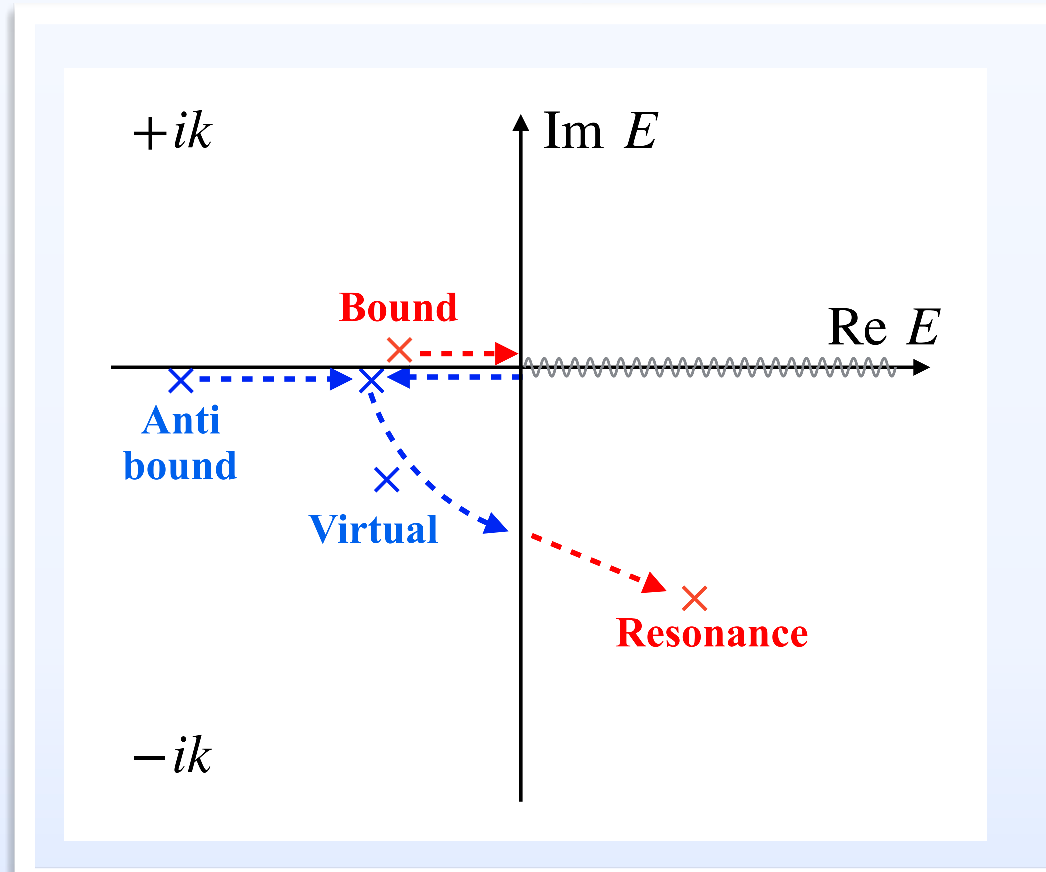
- Trajectory of SU(3) limit (Re E vs. pion mass)

With WT model

$(m_{0,\pi}, m_{0,K} = m_{0,\pi})$ $\rightarrow$Vary $m_{0,\pi}$

In SU(3) limit,
$\Rightarrow$Two (physical, unphysical) Riemann sheets exit



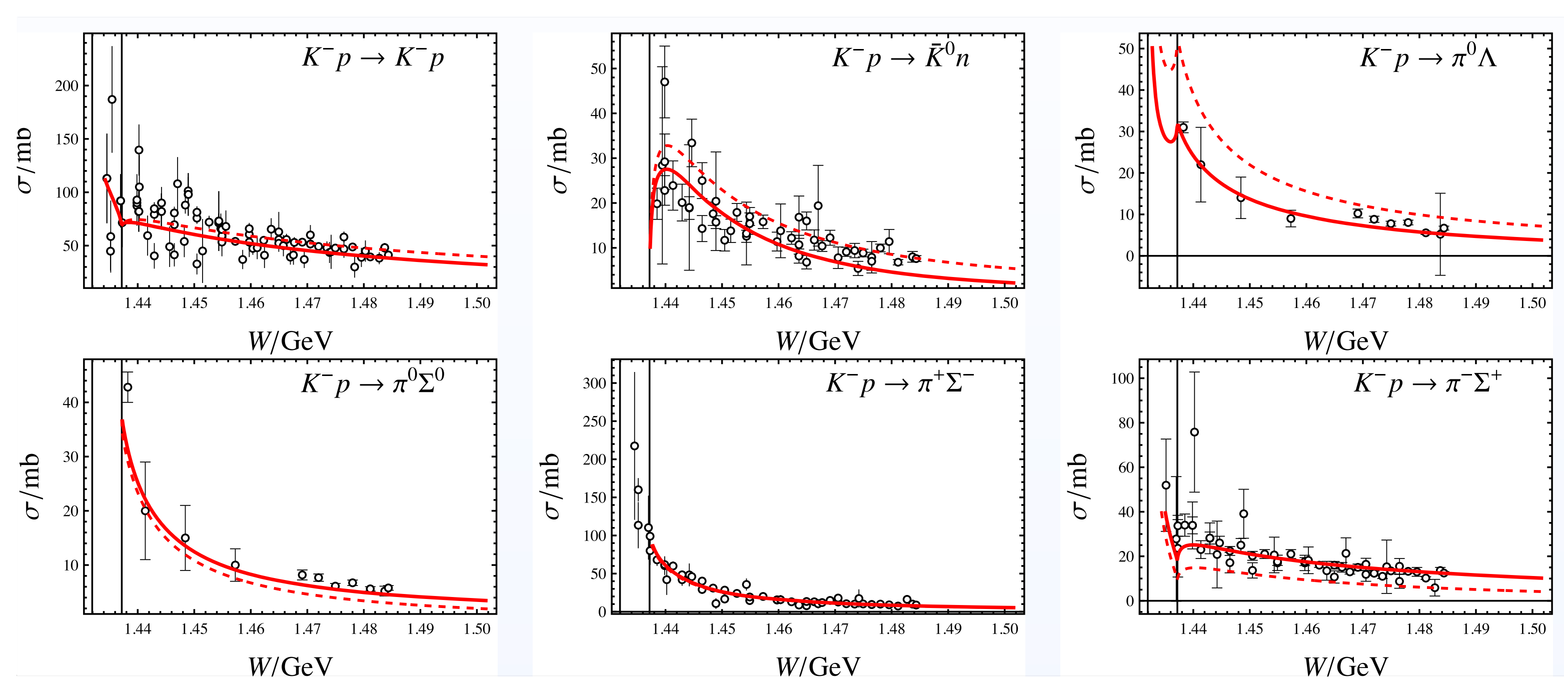


Addition of NLO terms

- NLO interaction

$$V_{ij}^{\rm NLO}(\sqrt{s}) = \frac{\mathcal{N}_i\mathcal{N}_j}{F^2}\left(C_{ij}^{\rm NLO1} - 2C_{ij}^{\rm NLO2}\left(E_iE_j + \frac{q_i^2q_j^2}{3\mathcal{N}_i\mathcal{N}_j}\right)\right)$$

  - Born terms are neglected.
    small contribution for s-wave
  - Additional LECs (d_1, d_2, d_3, d_4)
    → fitted to the experimental data
    χ^2/d.o.f ≈ 2.1



F-K, Guo, YK, M Mai, U-G Meißner, PL B 846 (2023) 138264

  - LECs and subt. const. are consistent with WT model

- Projection to representations

$$C_{ij}^{\rm NLO1} \xrightarrow{\quad} \begin{pmatrix} \frac{4}{3}(3b_0+7b_D)m_q & 0 & 0 & 0 \\ 0 & \frac{2}{3}(6b_0+b_D)m_q & -\sqrt{20}b_Fm_q & 0 \\ 0 & -\sqrt{20}b_Fm_q & 2(2b_0+3b_D)m_q & 0 \\ 0 & 0 & 0 & 4(b_0+b_D)m_q \end{pmatrix},$$

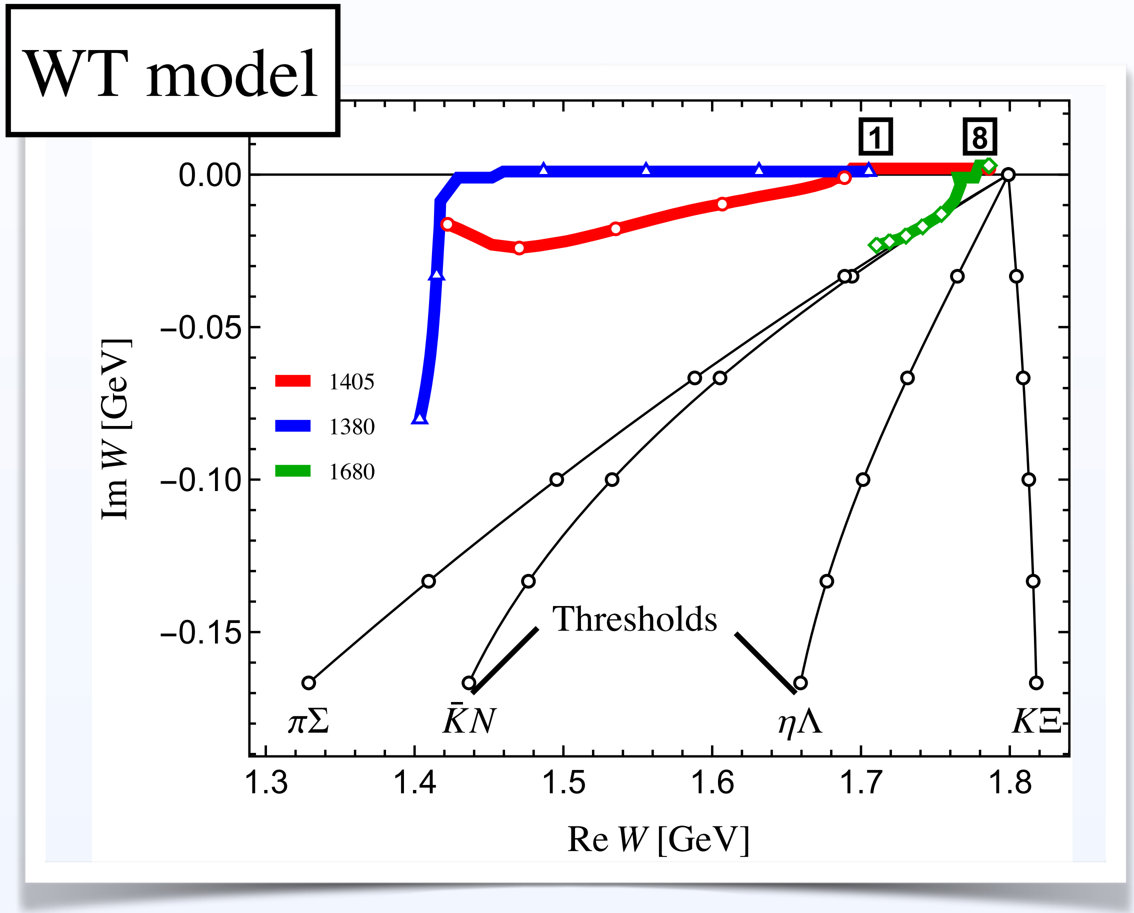
U

$$C_{ij}^{\rm NLO2} \xrightarrow{\quad} \begin{pmatrix} -3d_2+\frac{9}{2}d_3+d_4 & 0 & 0 & 0 \\ 0 & \frac{1}{2}(-3d_2+d_3+2d_4) & -\frac{\sqrt{5}}{2}d_1 & 0 \\ 0 & -\frac{\sqrt{5}}{2}d_1 & \frac{1}{2}(9d_2-d_3+2d_4) & 0 \\ 0 & 0 & 0 & \frac{1}{2}(2d_2+d_3+2d_4) \end{pmatrix}.$$

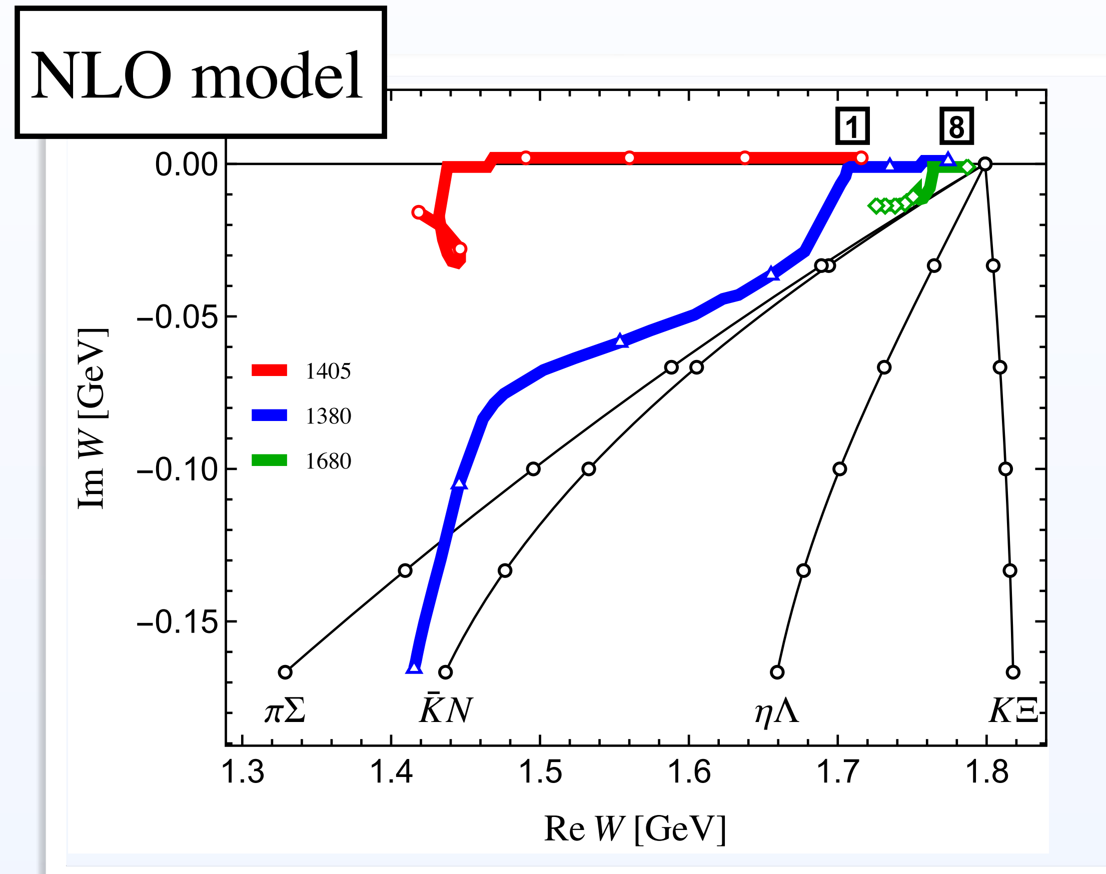
  - Two octet representations (8, 8’) are mixed.
    →Degeneration of 8, 8’ poles?

Addition of NLO terms

- Pole trajectories with NLO model



Addition of NLO terms →



F-K, Guo, YK, M Mai, U-G Meißner, PL B 846 (2023) 138264

Model	*E1*	*E8*	*E8'*
WT	1704	1788	1788
NLO	1716	1772	1787

- Trajectories with NLO terms
  - Two octet poles are not degenerated and remained as two separated poles
  - Λ(1405) is now connected to singlet and Λ(1380) is connected to octet

- Connection to SU(3) limit poles may be exchanged by the detailed interaction
- Mixing effect of 8 and 8' interaction is moderate

Summary

- For understanding of nature of $\Lambda(1380)/\Lambda(1405)$, detailed analysis of $\pi\Sigma$-$\bar{K}N$ interaction is required.

- Extrapolation to the unphysical point was performed with the quark mass dependence relation and the natural renormalization scheme.

- With WT model, $\Lambda(1380)/\Lambda(1405)$ are connected to singlet/octet.

- With NLO model, $\Lambda(1380)/\Lambda(1405)$ are connected to octet/singlet and two octets state in SU(3) are separated due to breaking term in V_{NLO}

Thank you for your attention!

Thank you!

Addition of NLO terms

- Pole trajectory change by NLO terms