$\bar{K}N$ interaction and Λ^*N interaction in chiral SU(3) dynamics

Tetsuo Hyodo[a],

Yoichi Ikeda[b], Wolfram Weise[c],

Toshitaka Uchino[a], and Makoto Oka[a]

Tokyo Tech.[a] Univ. of Tokyo/RIKEN[b] TU München[c]

supported by Global Center of Excellence Program
"Nanoscience and Quantum Physics"

2010, May 18th

Contents

- Introduction to chiral SU(3) dynamics
- $\bar{K}N$ interaction in chiral SU(3) dynamics
  - structure of the $\Lambda^* = \Lambda(1405)$
  - toward the "realistic $\bar{K}N$-$\pi\Sigma$ interaction"
- Λ^*N interaction in chiral SU(3) dynamics
  - Λ^*N potential in meson-exchange picture
  - structure of the Λ^*N bound state
- Summary

Chiral symmetry breaking in hadron physics

Chiral symmetry: QCD with massless quarks

Consequence of chiral symmetry breaking in hadron physics

- **appearance of the Nambu-Goldstone (NG) boson**

  $m_\pi \sim 140 \text{ MeV}$

- **dynamical generation of hadron masses**

  $M_p \sim 1 \text{ GeV} \sim 3M_q, \quad M_q \sim 300 \text{ MeV} \quad v.s. \quad 3-7 \text{ MeV}$

- **constraints on the interaction of NG boson and a hadron**

  low energy theorems <-- current algebra

  systematic low energy ($m, p/4\pi f_\pi$) expansion: ChPT

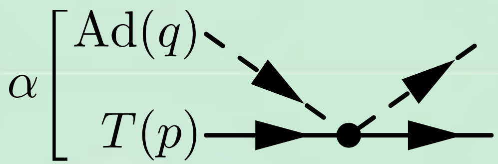
Chiral symmetry and its breaking

$$SU(3)_R \otimes SU(3)_L \to SU(3)_V$$

Underlying QCD <==> observed hadron phenomena

s-wave low energy interaction

Low energy NG boson (Ad)- target hadron (T) scattering



$$= \frac{1}{f^2}\frac{p\cdot q}{2M_T}\langle \boldsymbol{F}_T\cdot\boldsymbol{F}_{\mathrm{Ad}}\rangle_\alpha + \mathcal{O}\left(\left(\frac{m}{M_T}\right)^2\right)$$

Projection onto s-wave: Weinberg-Tomozawa term

Y. Tomozawa, Nuovo Cim. 46A, 707 (1966); S. Weinberg, Phys. Rev. Lett. 17, 616 (1966)

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

energy dependence (derivative coupling)

decay constant of π (g_V=1)

$$C_{ij} = \sum_\alpha C_{\alpha,T}\begin{pmatrix} 8 & T & \alpha \\ I_{M_i}, Y_{M_i} & I_{T_i}, Y_{T_i} & I, Y \end{pmatrix}\begin{pmatrix} 8 & T & \alpha \\ I_{M_j}, Y_{M_j} & I_{T_j}, Y_{T_j} & I, Y \end{pmatrix}$$

$$C_{\alpha,T} = \langle 2\boldsymbol{F}_T\cdot\boldsymbol{F}_{\mathrm{Ad}}\rangle = C_2(T) - C_2(\alpha) + 3$$

Group theoretical structure and flavor SU(3) symmetry determines the sign and the strength of the interaction

Low energy theorem: leading order term in ChPT

Scattering amplitude and unitarity

Unitarity of S-matrix: Optical theorem

$$\mathrm{Im}\,[T^{-1}(s)] = \frac{\rho(s)}{2}$$

phase space of two-body state

General amplitude by dispersion relation

$$T^{-1}(\sqrt{s}) = \sum_i \frac{R_i}{\sqrt{s}-W_i} + \tilde{a}(s_0) + \frac{s-s_0}{2\pi}\int_{s^+}^{\infty} ds' \frac{\rho(s')}{(s'-s)(s'-s_0)}$$

R_i, W_i, a: to be determined by chiral interaction

Identify dispersion integral = loop function G, the rest = V^{-1}

$$T(\sqrt{s}) = \frac{1}{V^{-1}(\sqrt{s}) - G(\sqrt{s};a)}$$

Scattering amplitude

V? chiral expansion of T, (conceptual) matching with ChPT

$$T^{(1)} = V^{(1)}, \quad T^{(2)} = V^{(2)}, \quad T^{(3)} = V^{(3)} - V^{(1)}GV^{(1)}, \ \ldots$$

Amplitude T: consistent with chiral symmetry + unitarity

Chiral unitary approach

Description of S = -1, $\bar{K}N$ s-wave scattering: Λ(1405) in I=0

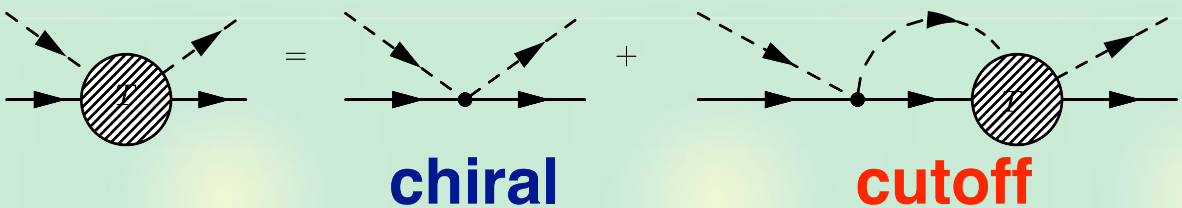
- Interaction <-- chiral symmetry

  Y. Tomozawa, Nuovo Cim. 46A, 707 (1966); S. Weinberg, Phys. Rev. Lett. 17, 616 (1966)

- Amplitude <-- unitarity in coupled channels

  R.H. Dalitz, T.C. Wong, G. Rajasekaran, Phys. Rev. 153, 1617 (1967)

$$T = \frac{1}{1 - VG} V$$

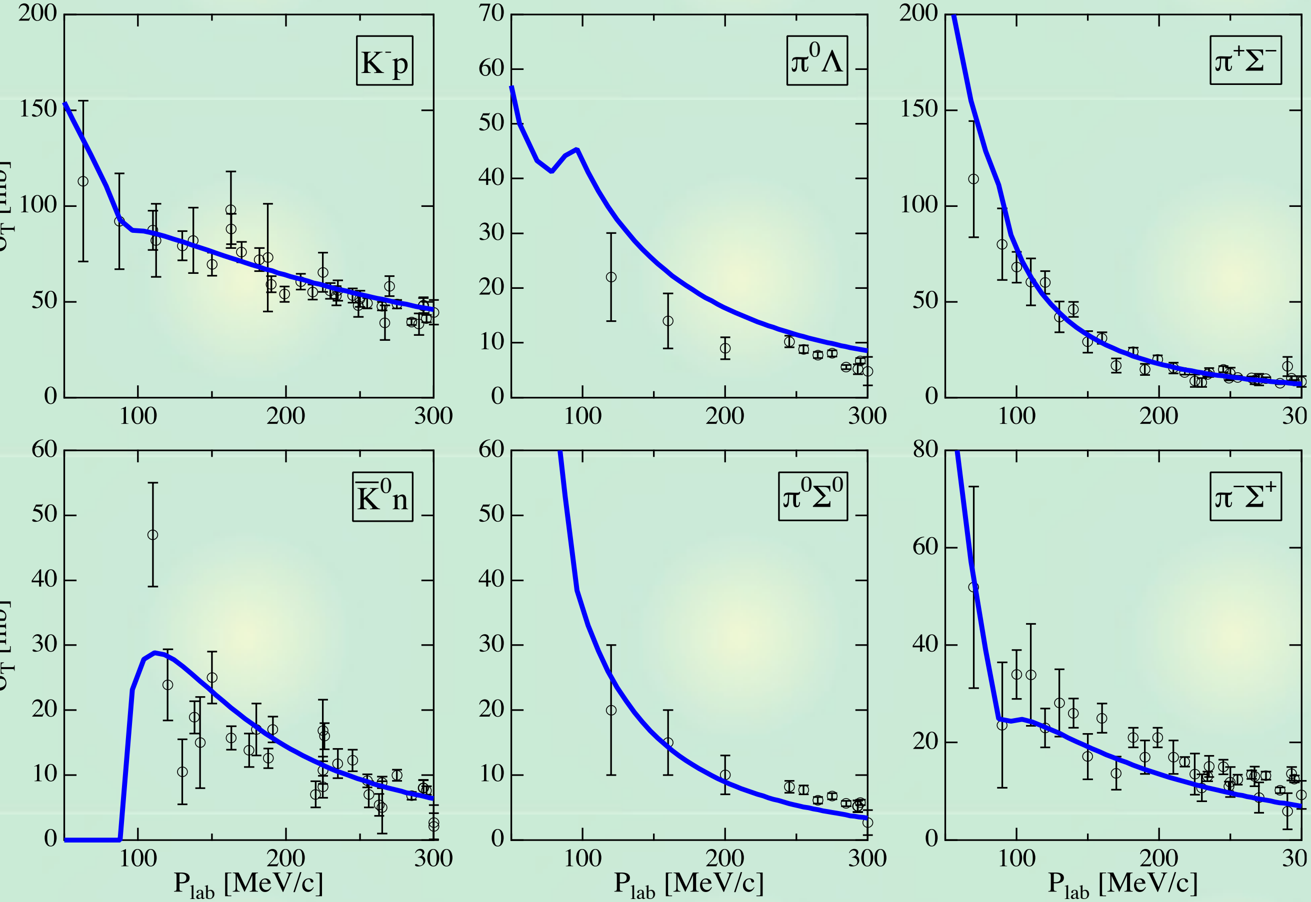


N. Kaiser, P. B. Siegel, W. Weise, Nucl. Phys. A594, 325 (1995),
E. Oset, A. Ramos, Nucl. Phys. A635, 99 (1998),
J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001),
M.F.M. Lutz, E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002), ... many others

It works successfully, also in S=0 sector, meson-meson scattering sectors, systems including heavy quarks, ...

The simplest model (1 parameter) v.s. experimental data

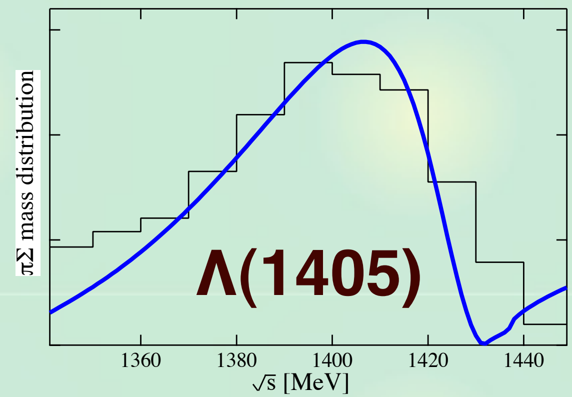
Total cross section of K-p scattering



Branching ratio

	γ	R_c	R_n
exp.	2.36	0.664	0.189
theo.	1.80	0.624	0.225

πΣ spectrum



T. Hyodo, S.I. Nam, D. Jido, A. Hosaka, PRC68, 018201 (2003); PTP 112, 73 (2004)

Good agreement with data above, at, and below $\bar{K}N$ threshold

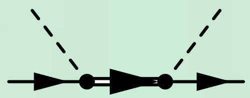
Λ(1405) mass, width, couplings: prediction of the model

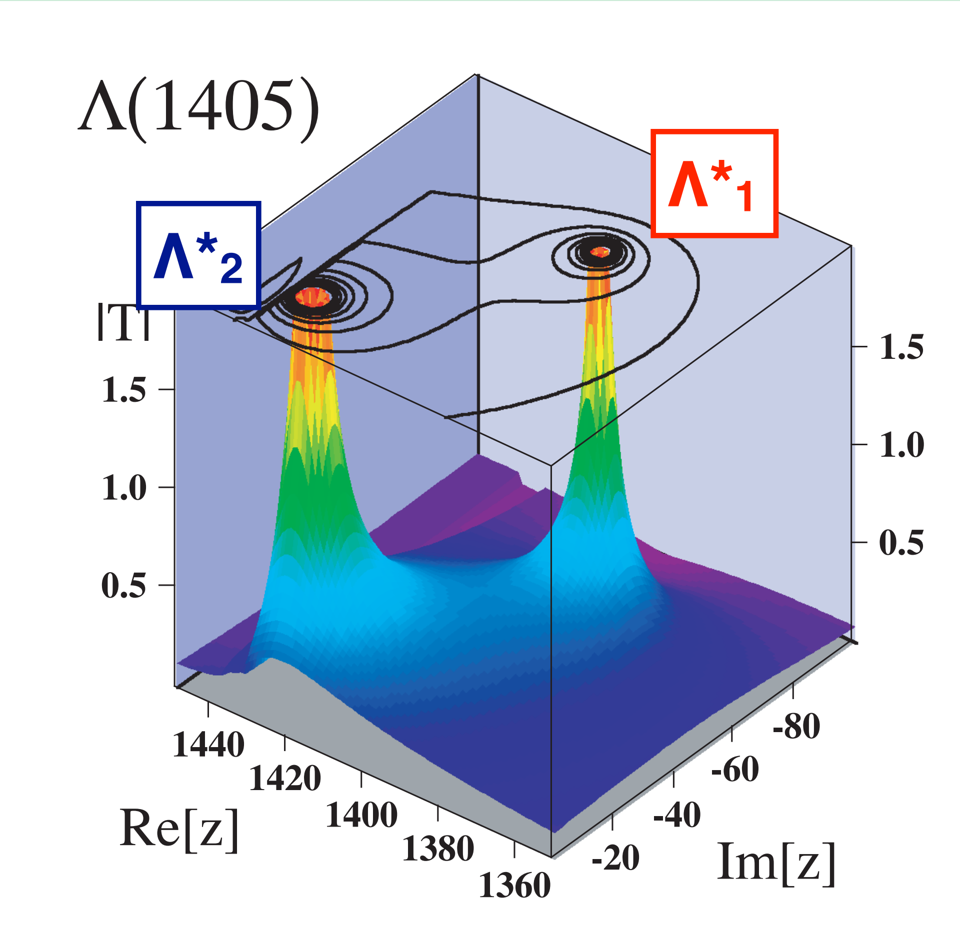
Two poles for one resonance

Poles of the amplitude in the complex plane: resonance

D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, Nucl. Phys. A 723, 205 (2003);
T. Hyodo, W. Weise, Phys. Rev. C 77, 035204 (2008)

$$T_{ij}(\sqrt{s}) \sim \frac{g_i g_j}{\sqrt{s} - M_R + i\Gamma_R/2}$$

$\sim$ 



Physical Λ* include two poles

$\bar{K}N$ bound state

+ $\pi\Sigma$ resonance

short summary
- Λ(1405): Λ^*_1, Λ^*_2
- Λ^*_i masses, widths, Λ^*_i-MB couplings predicted

c.f.) Geng's talk

Origin of the two-pole structure

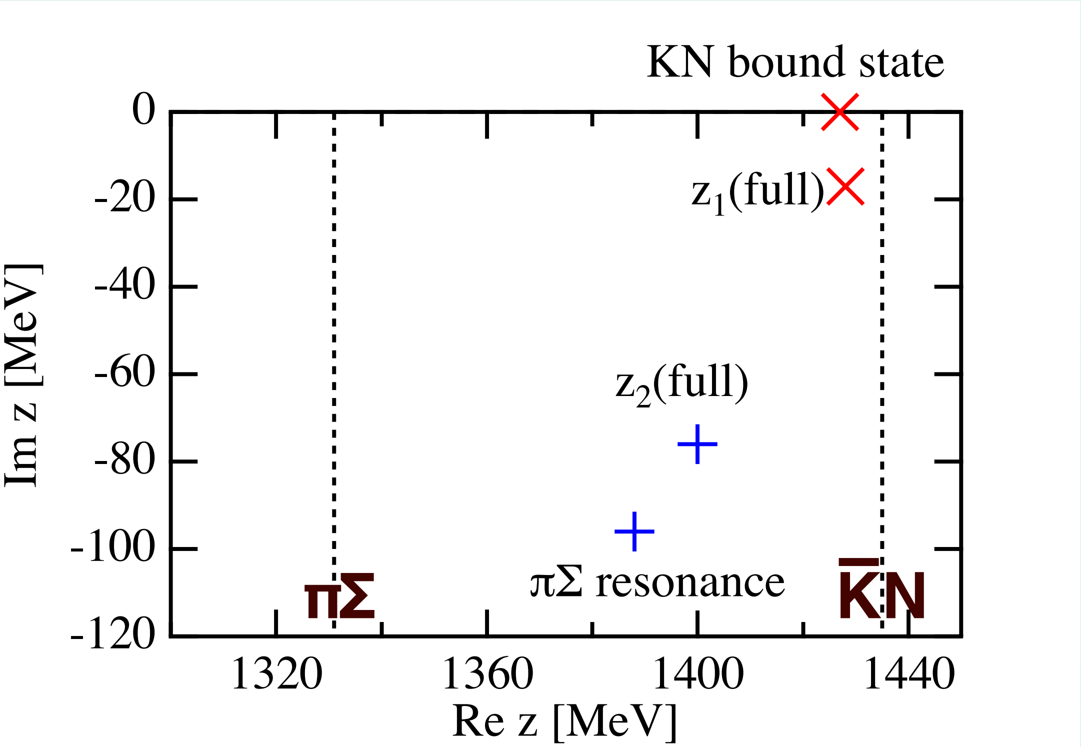
Leading order chiral interaction

T. Hyodo, W. Weise, Phys. Rev. C 77, 035204 (2008)

$$V_{ij} = -C_{ij}\frac{\omega_i + \omega_j}{4f^2}$$

K̄N πΣ

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



at threshold

$$\omega_i \sim m_i, \quad 3.3m_\pi \sim m_K$$

$$\Rightarrow V_{\bar{K}N} \sim 2.5 V_{\pi\Sigma}$$

Very strong attraction in K̄N (higher energy) --> bound state

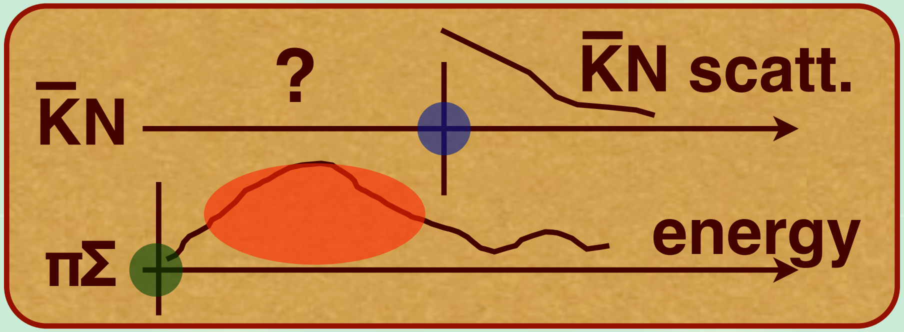
Strong attraction in πΣ (lower energy) --> resonance

"realistic KN-πΣ interaction"

Position of the second pole: model dependent

- higher order terms in the interaction kernel?
- energy dependence? (c.f. Ikeda's talk)

--> uncertainties in $\bar{K}N$ interaction below threshold



Systematic χ^2 study including NLO interactions

Y. Ikeda, T. Hyodo, W. Weise, in preparation

- Precise data of $\bar{K}N$ scattering length <-- SIDDHARTA
- Precise data of πΣ spectrum <-- FOPI (this afternoon?)
- Any information of πΣ scattering length <-- lattice QCD?

==> the "realistic $\bar{K}N$-πΣ interaction"

$\bar{K}$ in nuclei

- $\bar{K}$N interaction is strongly attractive <-- Λ(1405).
  Formation of (deeply) bound kaonic nuclei?
  Y. Akaishi, T. Yamazaki, Phys. Rev. C65, 044005 (2002)
- Structure of the Λ(1405), kaon condensation, ...

The simplest $\bar{K}$-nucleus: $\bar{K}$NN three-body system

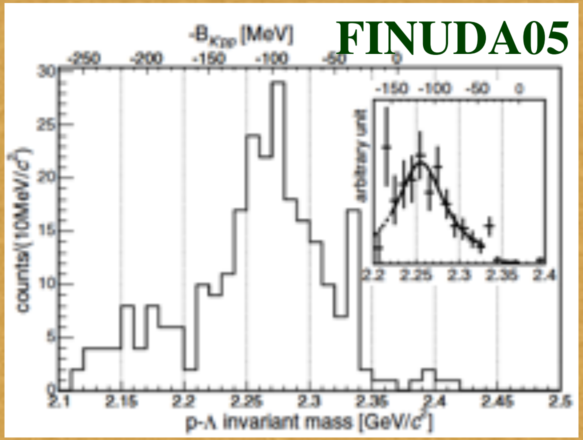
Theory: rigorous few-body calculations with realistic interactions

Yamazaki-Akaishi, Shevchenko, et al., Ikeda-Sato, Doté et al., Wycech-Green,

- System bounds
- Quantitative difference: uncertainties in $\bar{K}$N int. at far below threshold

Experiment: some "evidences" in ΛN mass spectra

FINUDA, DISTO, OBELIX, etc.

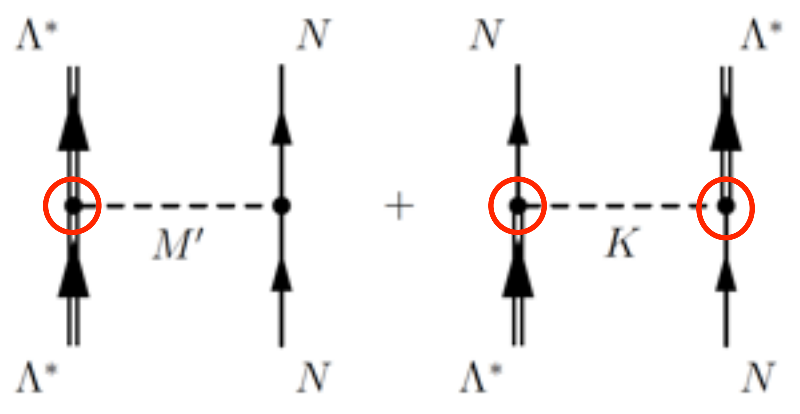


- Interpretation (πΣN?FSI?)

Λ* hypernuclei model

Regarding a $\bar{K}$N(I=0) pair as the Λ*=Λ(1405), construct the "Λ*N potential" with the meson-exchange picture

A. Arai, M. Oka, S. Yasui, Prog. Theor. Phys. 119, 103 (2008)



<== Λ* structure seems to be surviving in $\bar{K}$NN system.

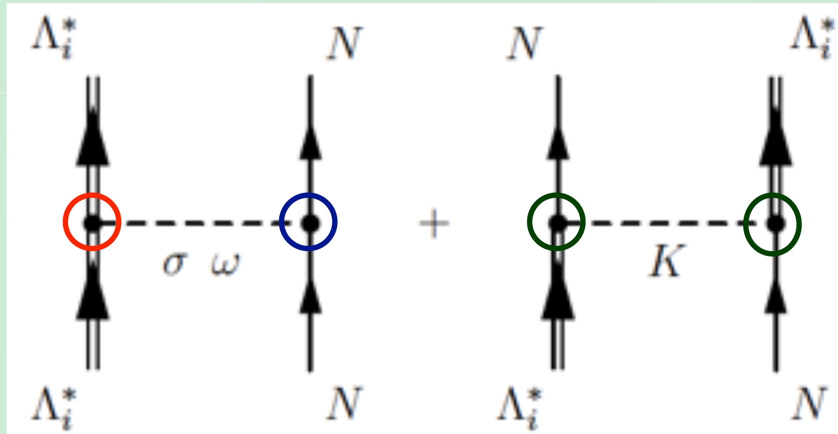
T. Yamazaki, Y. Akaishi, Phys. Rev. C76, 045201 (2007),
A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A 804, 197 (2008); Phys. Rev. C 79, 014003 (2009)

Λ* coupling constants: unknown (<-- FINUDA data).

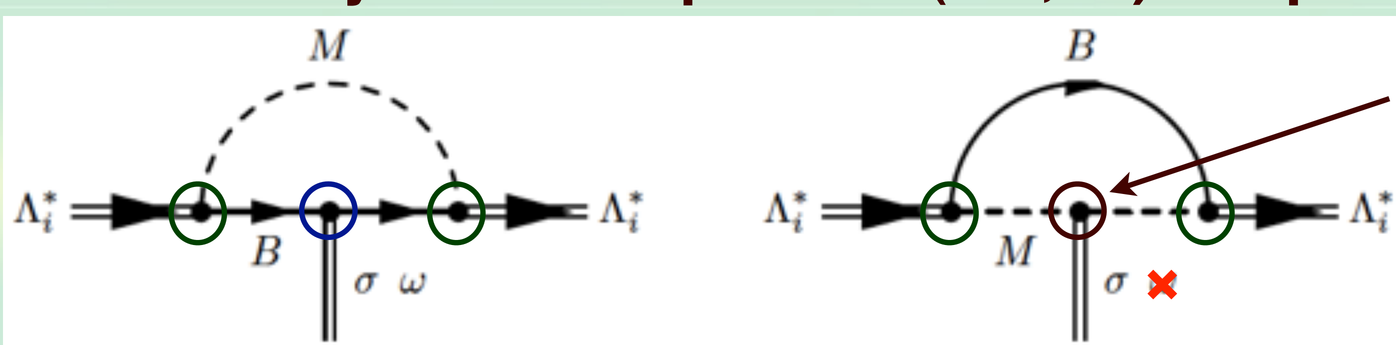
To determine the coupling and make predictions, we need a framework to describe the Λ* <-- chiral unitary approach

Λ*N potential with meson-exchange picture

$\Lambda^*_i N$ potential with one boson exchange (i=1,2)



- ○ NNσ, NNω couplings: Jülich (model A) YN potential
- ○ Λ^*_iKN coupling: chiral unitary approach (pole residue)
- ○ $\Lambda^*_i\Lambda^*_i\sigma$, $\Lambda^*_i\Lambda^*_i\omega$, couplings
  --> estimated by microscopic MB=($\bar{K}$N,πΣ) couplings

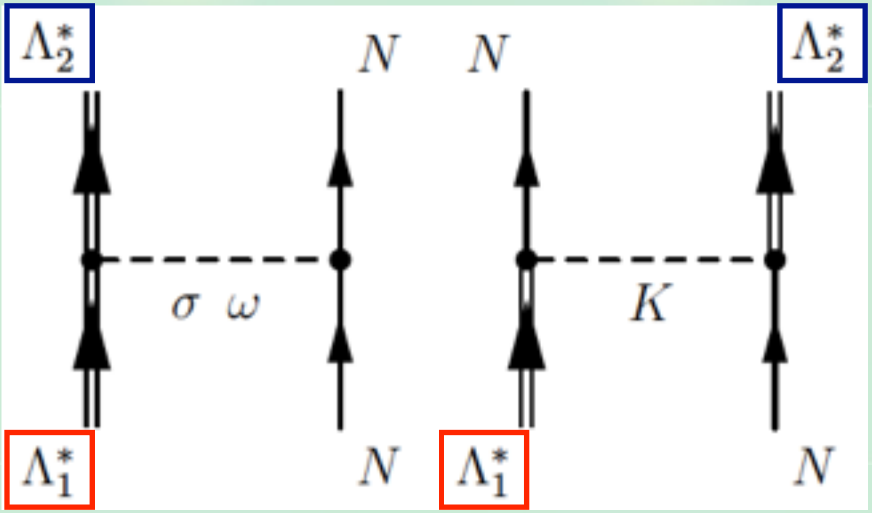


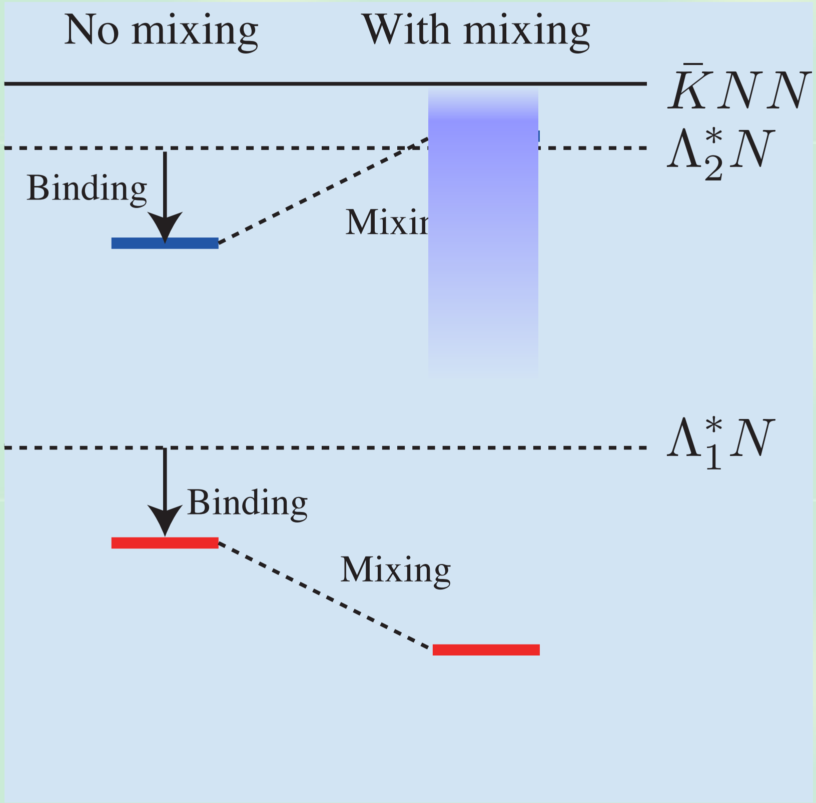
σ decay to ππ
$g_{KK\sigma} = 0$

Λ*N potential: mixing interaction

Chiral unitary approach --> two Λ* states : Λ^*_1, Λ^*_2
With sufficient attraction,
two Λ*N bound states in B=2 system : Λ^*_1N, Λ^*_2N

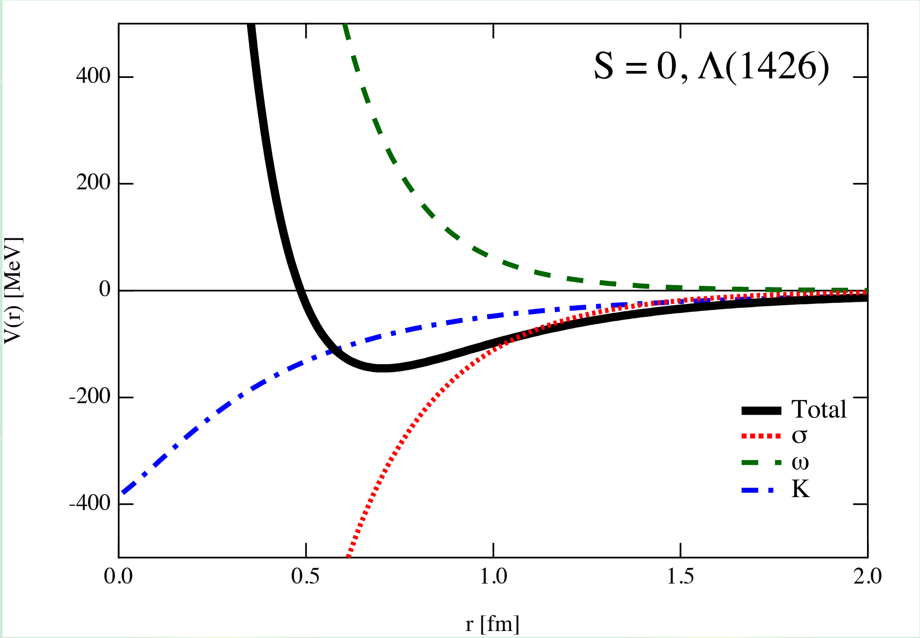
There can be the mixing of Λ^*_1N <--> Λ^*_2N

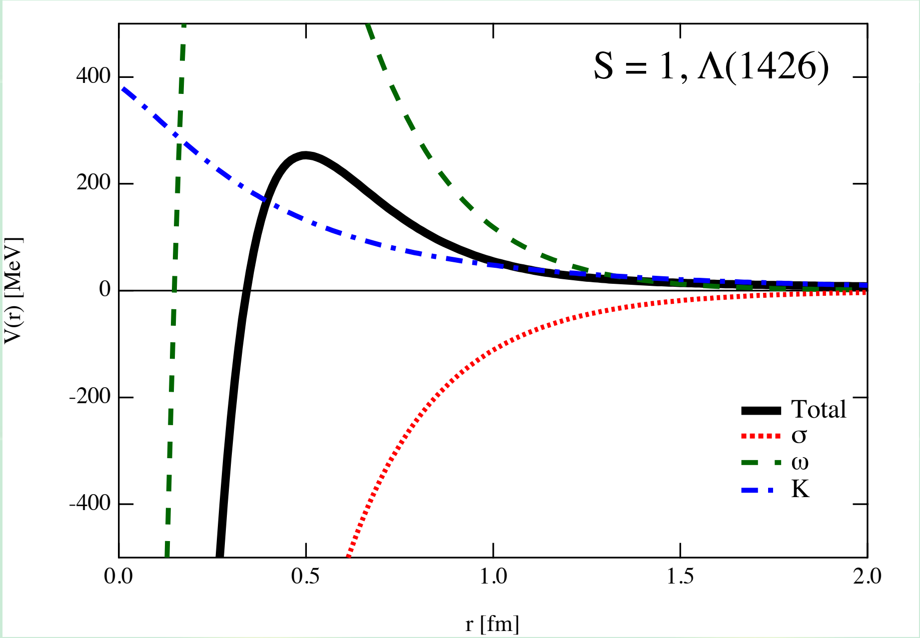




Λ*N potential: each contribution

Diagonal potentials for Λ^*_2N in S=0 and S=1, s-wave





S=0: attractive pocket at intermediate range
<-- K exchange is attractive

S=1: no intermediate attraction, but a short range dip
<-- K exchange is repulsive

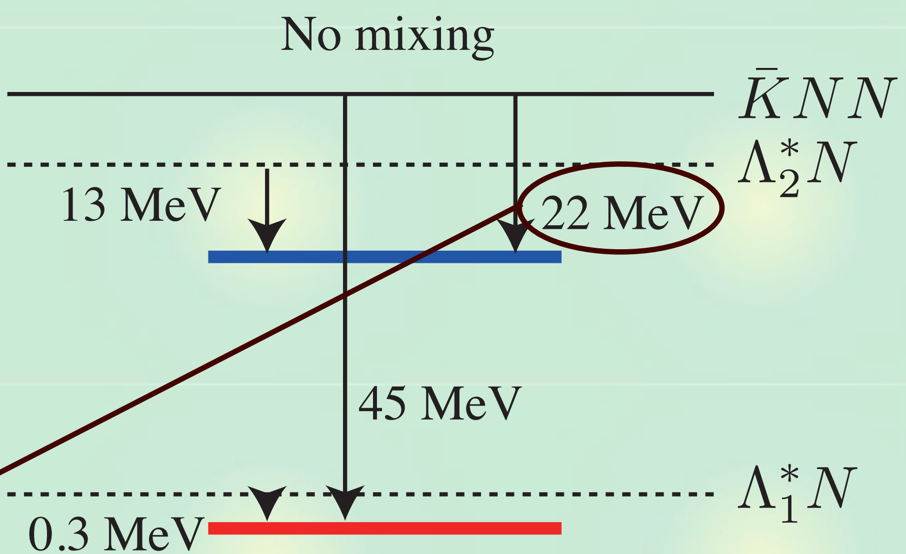
Qualitatively similar potential for Λ^*_1N

Λ*N bound states without mixing

Solve the schrödinger equation for the s-wave $\Lambda^*_i N$ potential without the mixing interaction.

- no physical bound states in S=1 channels (consistent with the analysis of the volume integral)
- for S=0 we obtain the bound states in both Λ^*_i

binding from	Λ*N th. [MeV]	K̄NN th. [MeV]
Λ^*_2 N	13.39	22.39
Λ^*_1 N	0.34	45.34



Similar value (20±3 MeV) in KNN single-channel approach

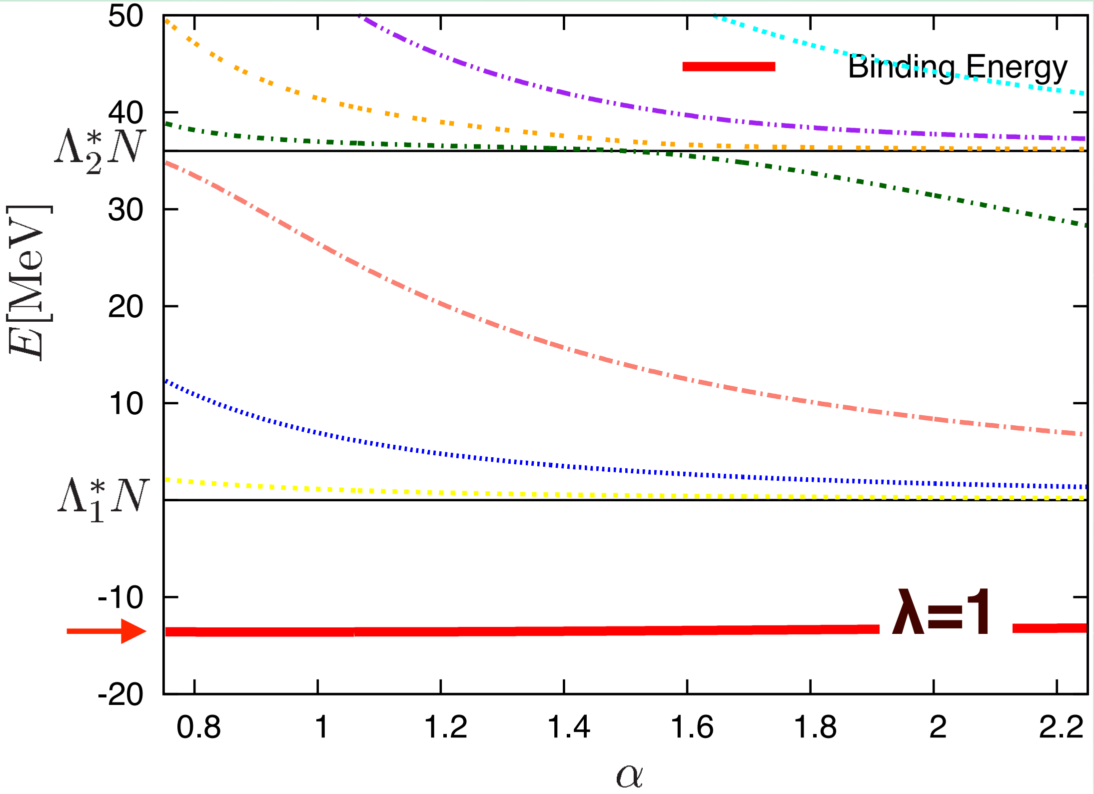
A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A 804, 197 (2008); Phys. Rev. C 79, 014003 (2009)

Λ*N bound states with mixing

With mixing, the higher state becomes a resonance.

Real scaling method ≈ changing the box size α

λ: strength of the mixing interaction, physical for λ=1



resonance
(compact object)
--> stable against
the box size

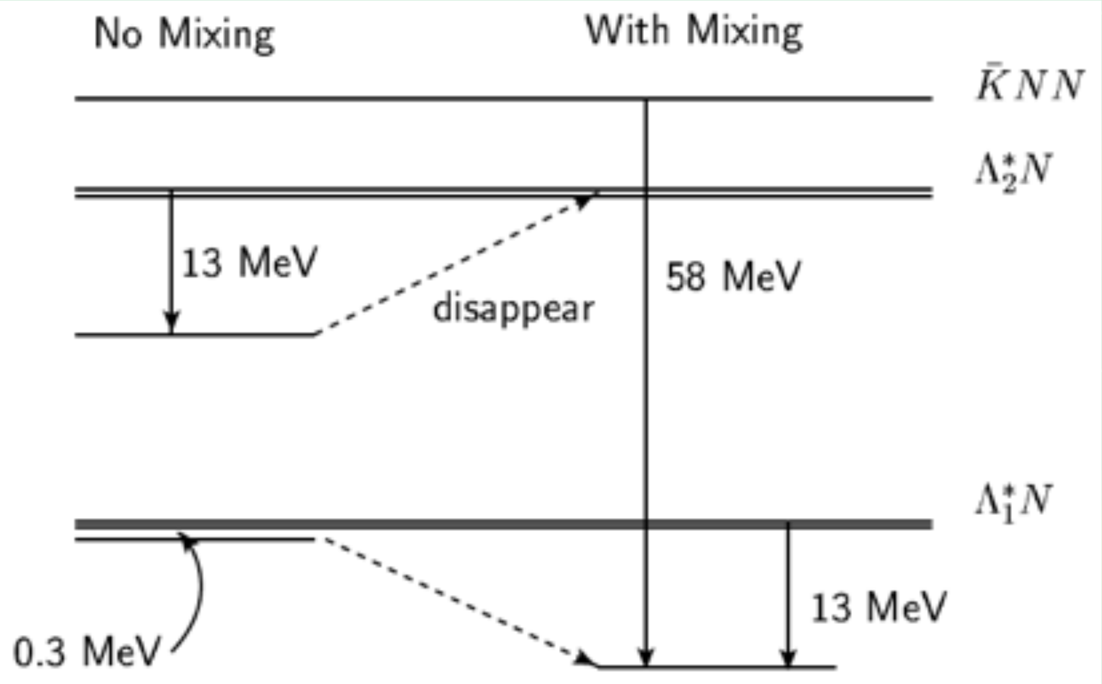
The lower energy state bounds more.

The higher energy state disappears (above Λ^*_2N threshold?).

Result of Λ*N bound states

Result in one figure:

taken from T. Uchino, Master thesis



decomposition of constituents

$$(\Lambda^* N) \sim 0.7(\Lambda_1^* N) + 0.3(\Lambda_2^* N)$$

$$\sim 0.5(\bar{K}NN) + 0.5(\pi\Sigma N)$$

substantial mixture of πΣN component

- **The Λ*N bound state decays into πΣN and YN.**
- **Disappeared state could be a very broad state.**
- **Physical Λ* (especially the lower one) has a finite width.**
- **Comparison with three-body calculation (Ikda et al)**

Summary: $\bar{K}N$ interaction

We study the $\bar{K}N$-$\pi\Sigma$ system and $\Lambda(1405)$ based on chiral SU(3) symmetry and unitarity

- Chiral low energy theorem: constrains for the NG boson dynamics
- Two poles for the $\Lambda(1405)$
  <-- attractive $\bar{K}N$ and $\pi\Sigma$ interactions

  T. Hyodo and W. Weise, Phys. Rev. C 77, 035204 (2008)
- Systematic study for the $\bar{K}N$-$\pi\Sigma$ system
  <-- new data, such as $\bar{K}N$ scattering length, $\pi\Sigma$ spectrum are called for.

  Y. Ikeda, T. Hyodo, W. Weise, in preparation

Summary: Λ*N interaction

We study the Λ*N two-body system based on the Λ*N potential with chiral SU(3) dynamics.

- Chiral dynamics: two states Λ^*_1, Λ^*_2
- Both Λ^*_i generate bound states with N in spin S=0 channels <-- K exchange
- With the mixing, the lower state bounds more, and the higher state dissolves.

  mass of Λ*N ~ 2316-2322 MeV
  <-- substantial mixture of πΣN

T. Uchino, T. Hyodo, M. Oka, in preparation