Λ^*N bound state based on chiral dynamics

Tetsuo Hyodo[a],

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

Tokyo Institute of Technology[a]

2010, Feb. 18th

$\bar{K}$ in nuclei

- $\bar{K}$N interaction is strongly attractive <-- Λ(1405).
  Formation of deeply bound state is possible.
  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

$\bar{K}$ in nuclei

- $\bar{K}N$ interaction is strongly attractive <-- Λ(1405).
  Formation of deeply bound state is possible.
  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

- System **bounds**

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

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

$\bar{K}$ in nuclei

- $\bar{K}N$ interaction is strongly attractive <-- Λ(1405).
  Formation of deeply bound state is possible.
  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

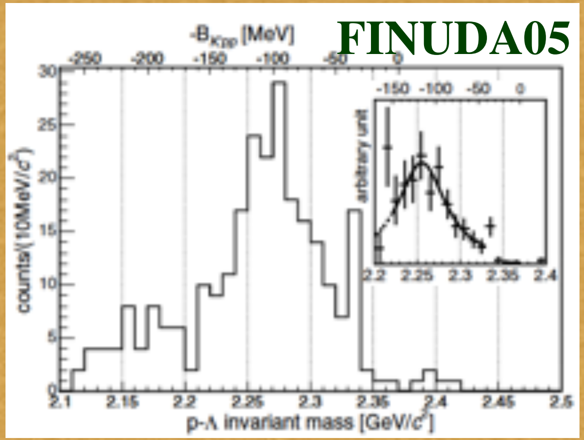
- System **bounds**

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

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

Experiments: some "evidences" in ΛN mass spectra

FINUDA, DISTO, OBELIX, etc.

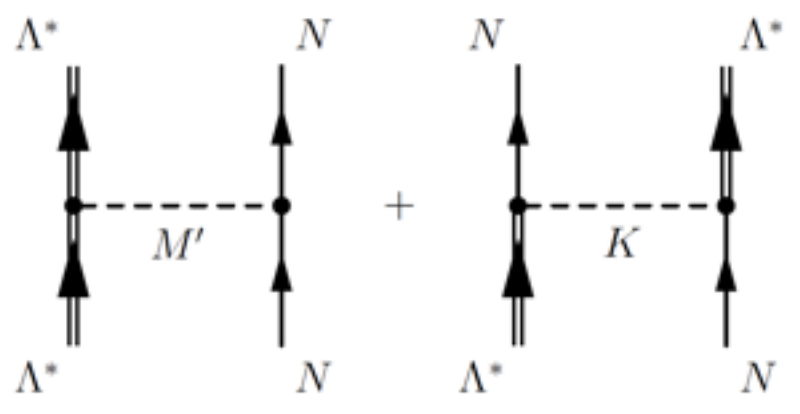


- **Interpretation**?

Λ* hypernuclei model

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

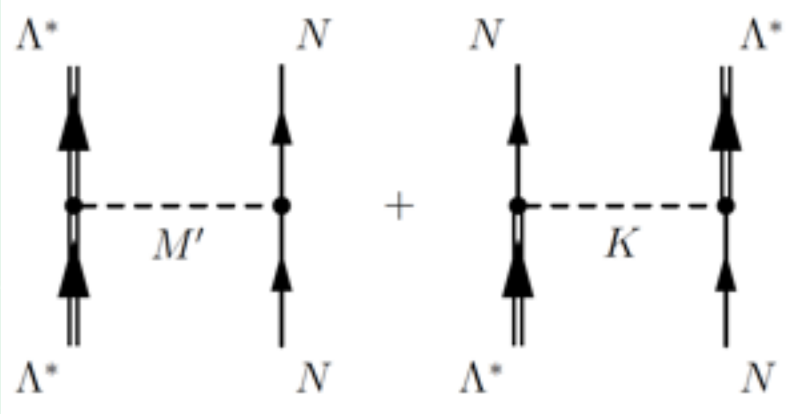
A. Arai, M. Oka, S. Yasui, Prog. Theor. Phys. 119, 103 (2008)



Λ* hypernuclei model

Regarding a K̄N 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* seems to be surviving in K̄NN system.

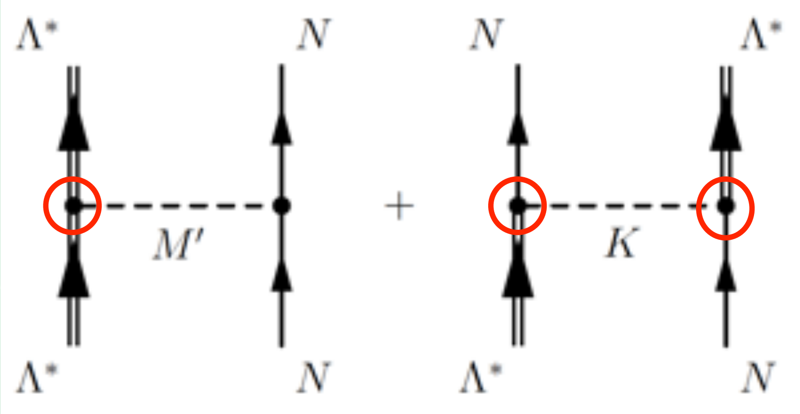
T. Yamazaki, Y. Akaishi, Phys. Rev. C76, 045201 (2007),

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

Λ* hypernuclei model

Regarding a $\bar{K}N$ 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* seems to be surviving in $\bar{K}NN$ system.

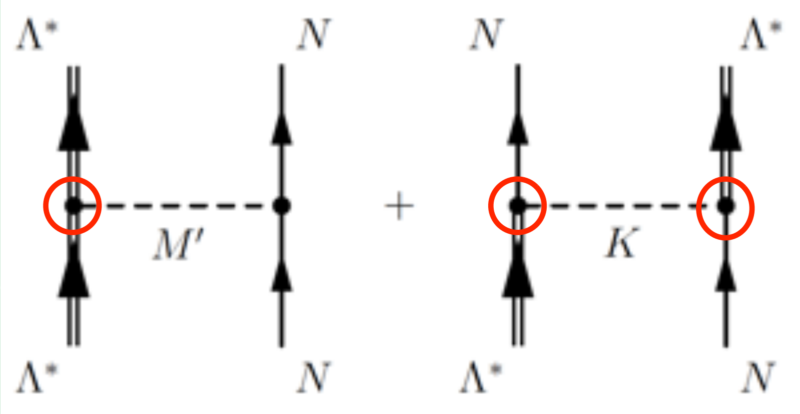
T. Yamazaki, Y. Akaishi, Phys. Rev. C76, 045201 (2007),
A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A 804, 197 (2008); Phys. Rev. C 79, 014003 (2009)

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

Λ* hypernuclei model

Regarding a $\bar{K}N$ 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* 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

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)

Chiral unitary approach

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

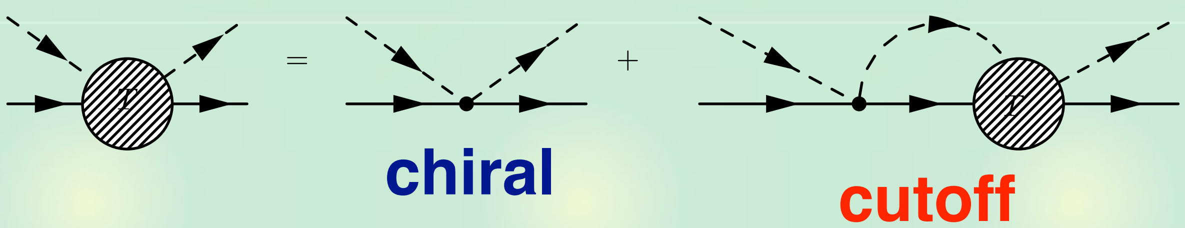
- **Interaction <-- chiral symmetry**

  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)

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

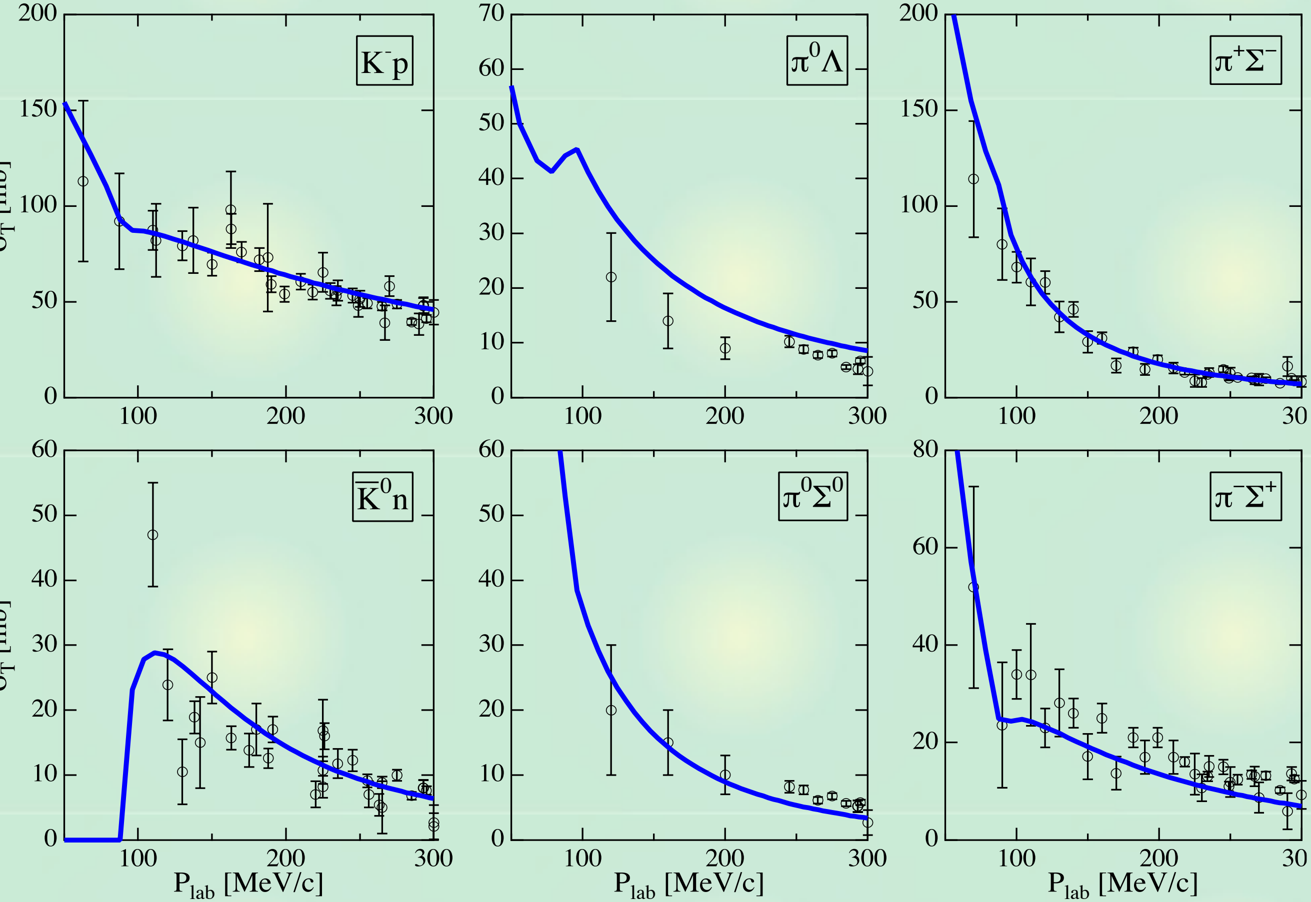


N. Kaiser, P. B. Siegel, W. Weise, Nucl. Phys. A594, 325 (1995),
E. Oset, A. Ramos, Nucl. Phys. A635, 99 (1998),
J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001),
M.F.M. Lutz, E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002), ... many others

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

$\bar{K}N$ scattering : comparison with data

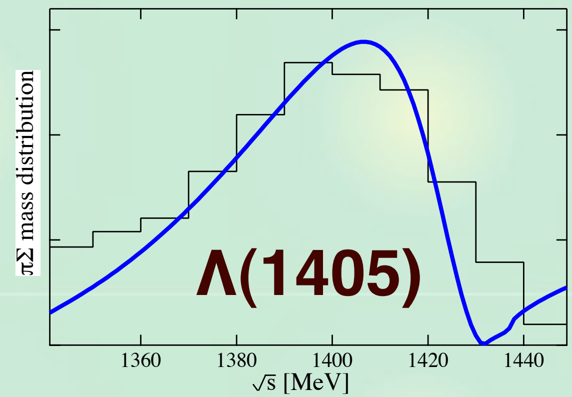
Total cross section of K-p scattering



Branching ratio

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

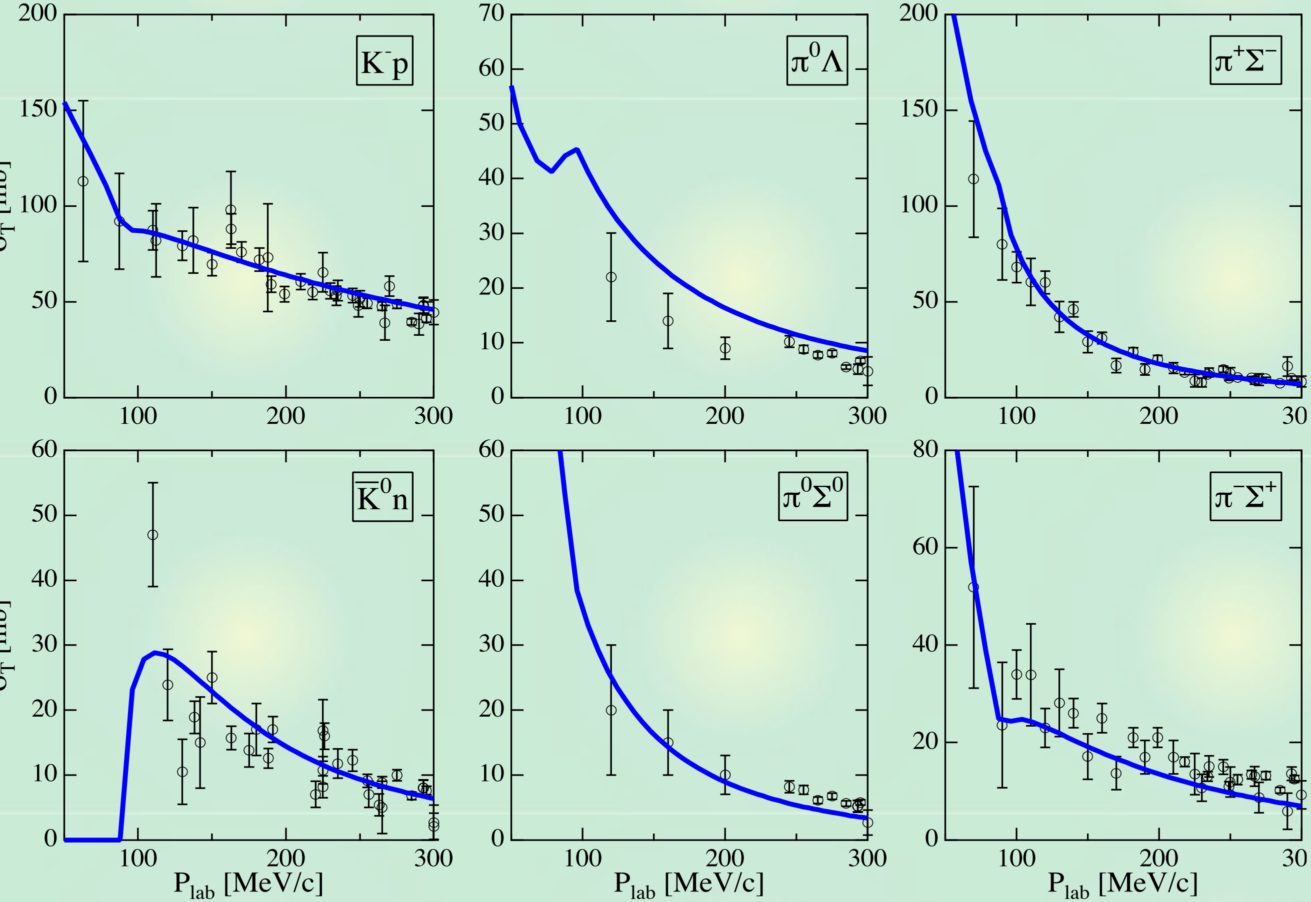
πΣ spectrum



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

$\bar{K}N$ scattering : comparison with data

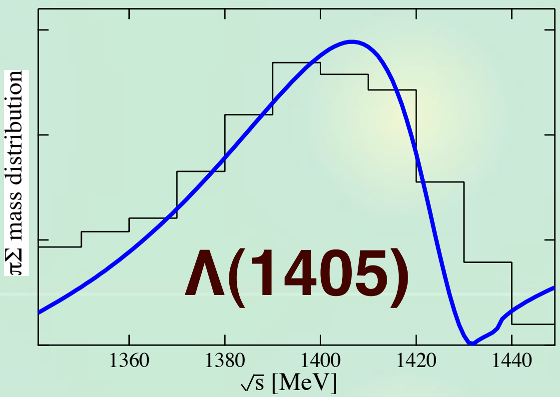
Total cross section of K-p scattering



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)

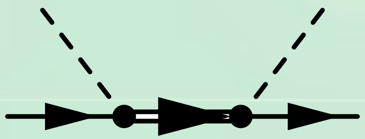
Good agreement with data above, at, and below $\bar{K}N$ threshold

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

Two poles for one resonance

Poles of the amplitude in the complex plane: resonance

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

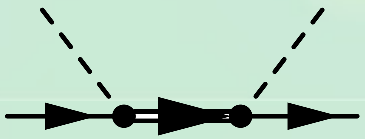
$\sim$ 

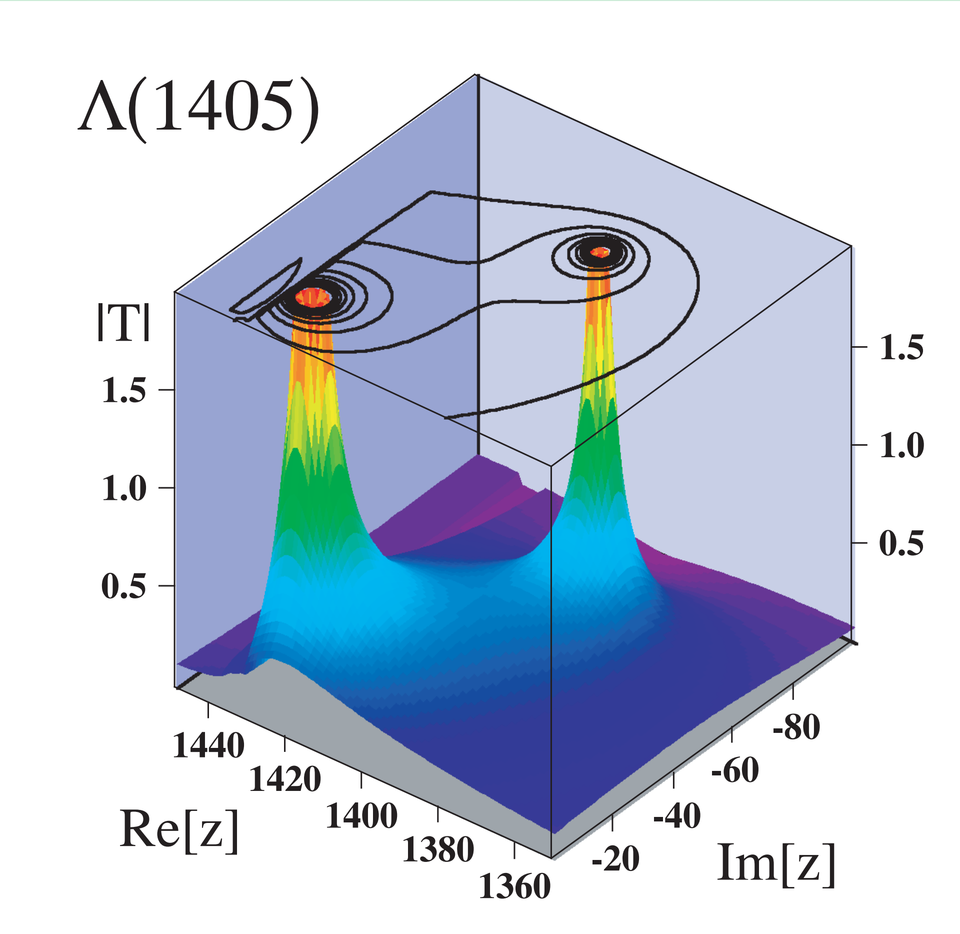
Two poles for one resonance

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)

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

$\sim$ 

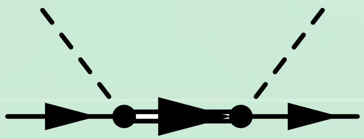


Two poles for one resonance

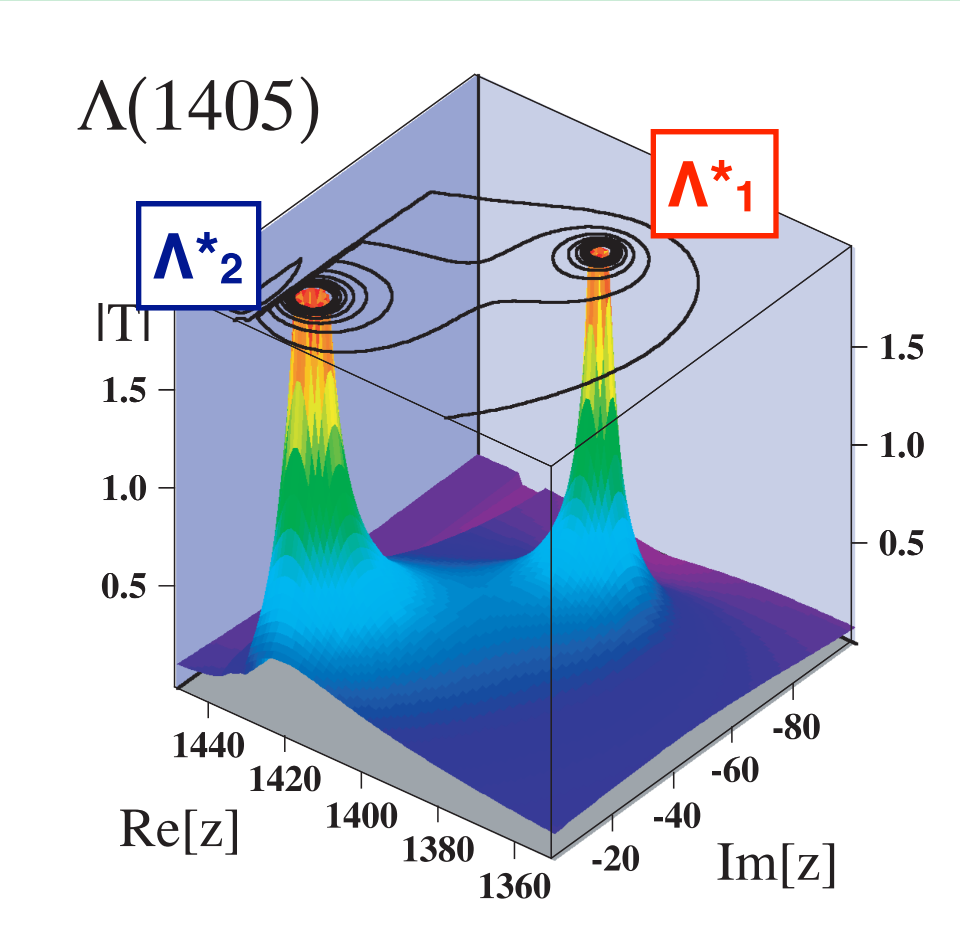
Poles of the amplitude in the complex plane: resonance

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*: two poles

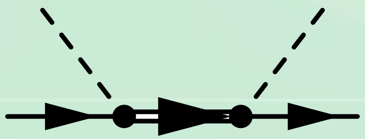


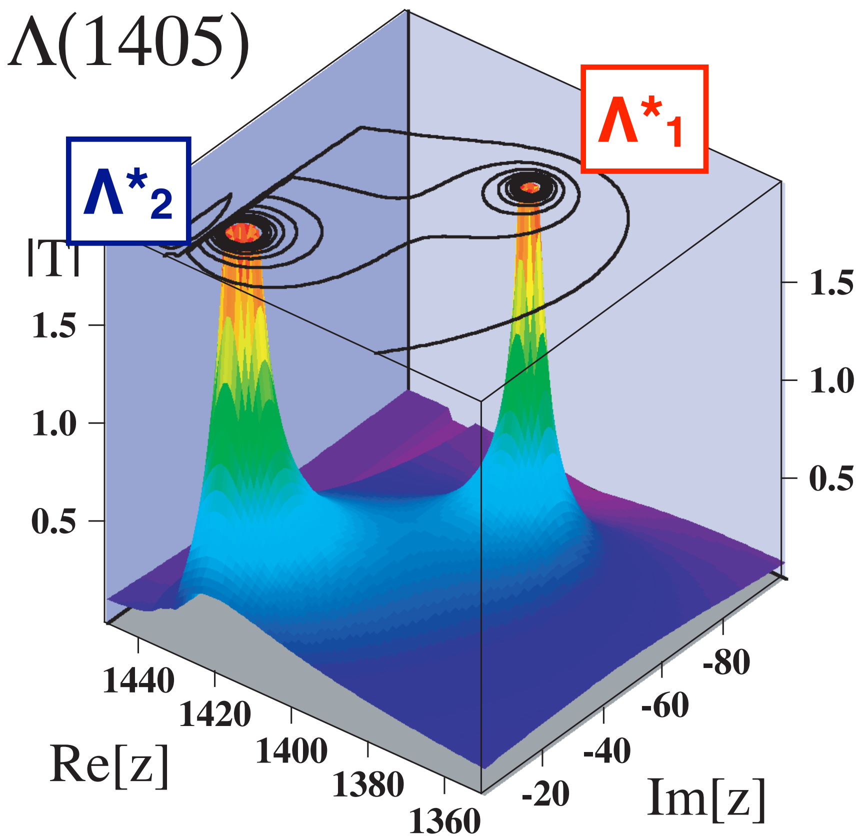
Two poles for one resonance

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)

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

$\sim$ 



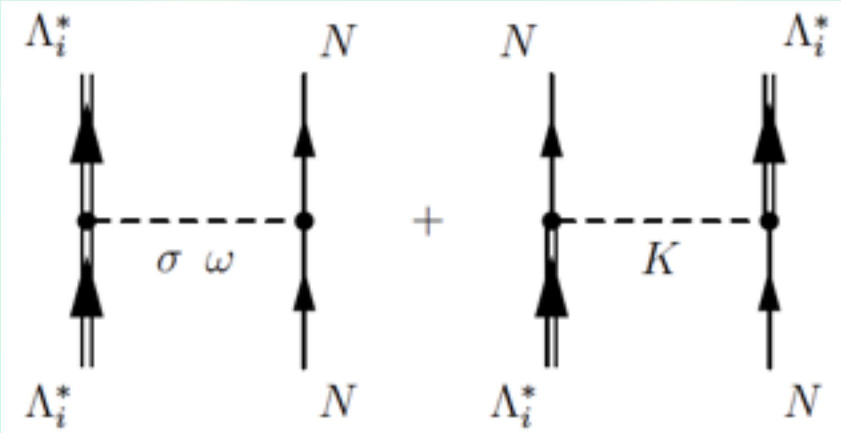
Physical Λ*: two poles

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

--> Λ* hypernuclei based on chiral dynamics

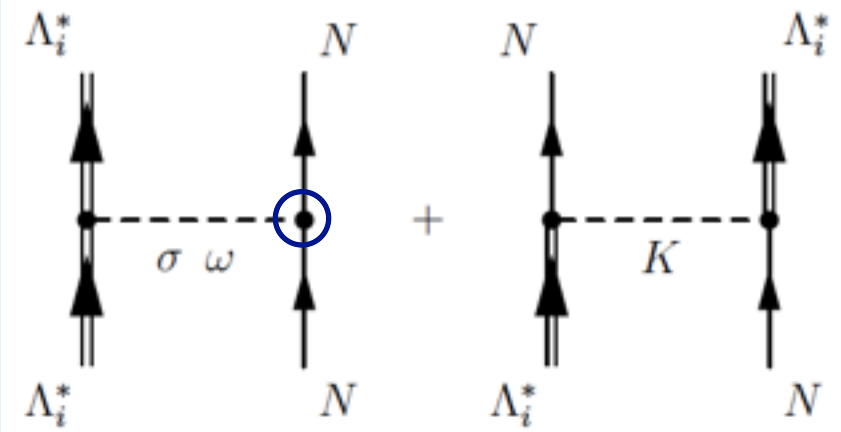
Λ*N potential with meson-exchange picture

Λ^*_iN potential with one boson exchange (i=1,2)



Λ*N potential with meson-exchange picture

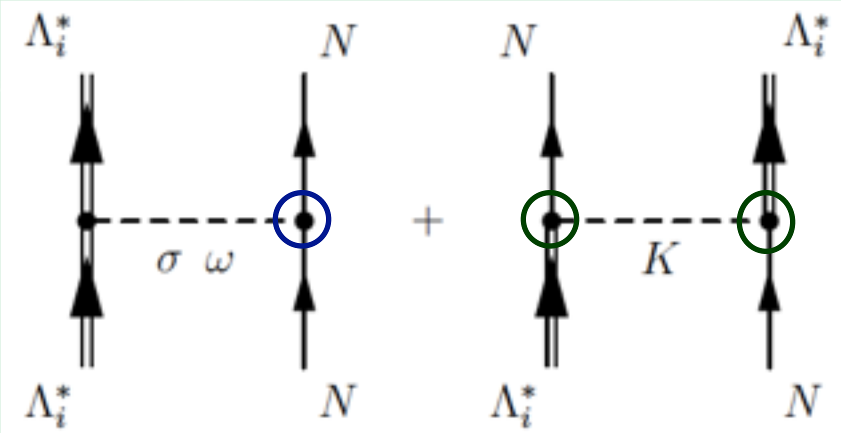
$\Lambda^*_i N$ potential with one boson exchange (i=1,2)



○ NNσ, NNω couplings: Jülich (model A) YN potential

Λ*N potential with meson-exchange picture

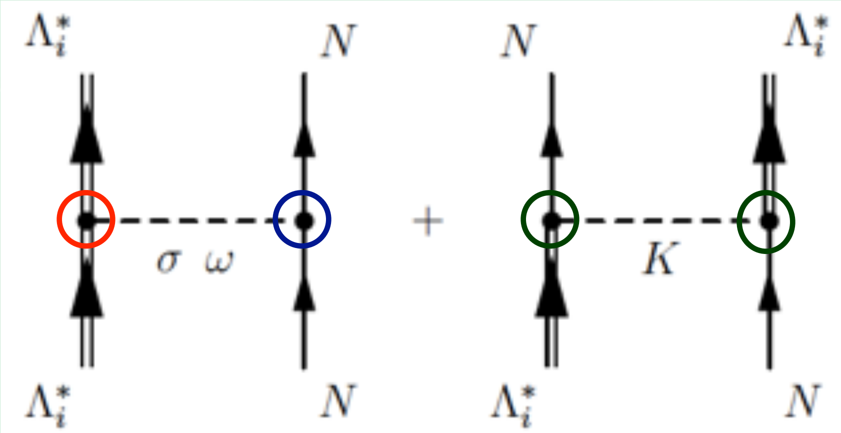
Λ^*_iN potential with one boson exchange (i=1,2)



- ◯ NNσ, NNω couplings: Jülich (model A) YN potential
- ◯ Λ^*_iKN coupling: Chiral unitary approach

Λ*N potential with meson-exchange picture

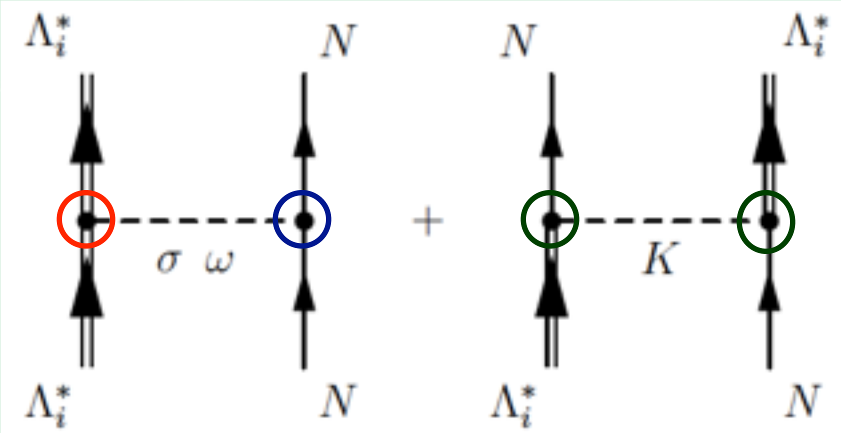
$\Lambda^*_i N$ potential with one boson exchange (i=1,2)



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

Λ*N potential with meson-exchange picture

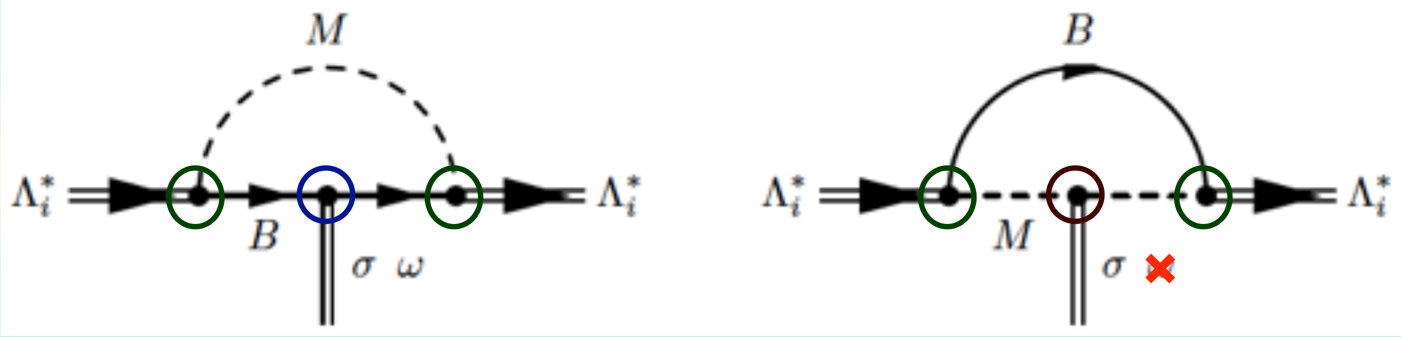
$\Lambda^*_i N$ potential with one boson exchange (i=1,2)



○ NNσ, NNω couplings: Jülich (model A) YN potential

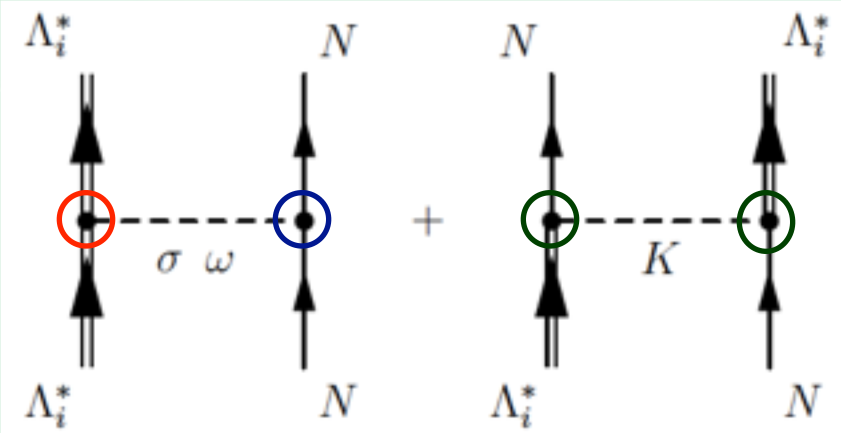
○ $\Lambda^*_i KN$ coupling: Chiral unitary approach

○ $\Lambda^*_i\Lambda^*_i\sigma$, $\Lambda^*_i\Lambda^*_i\omega$, couplings
--> estimated by microscopic MB=($\bar{K}N$,πΣ,ηΛ) couplings

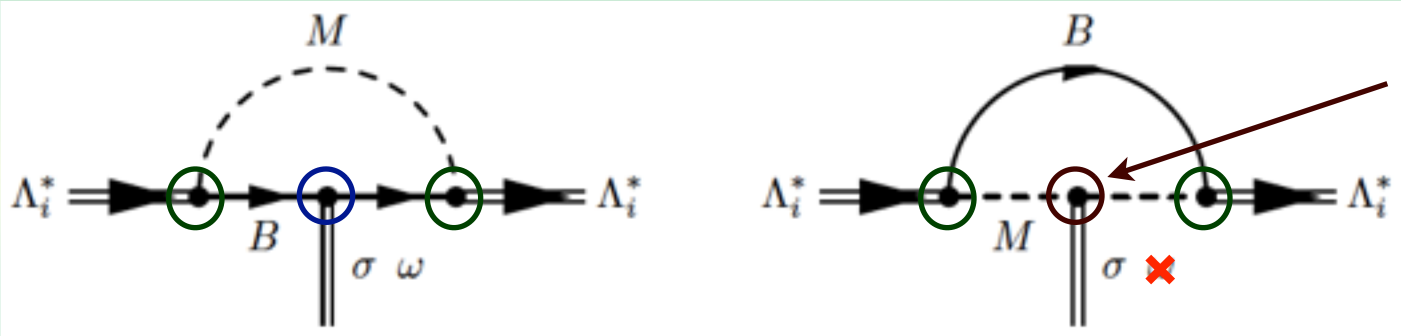


Λ*N potential with meson-exchange picture

Λ^*_iN potential with one boson exchange (i=1,2)



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

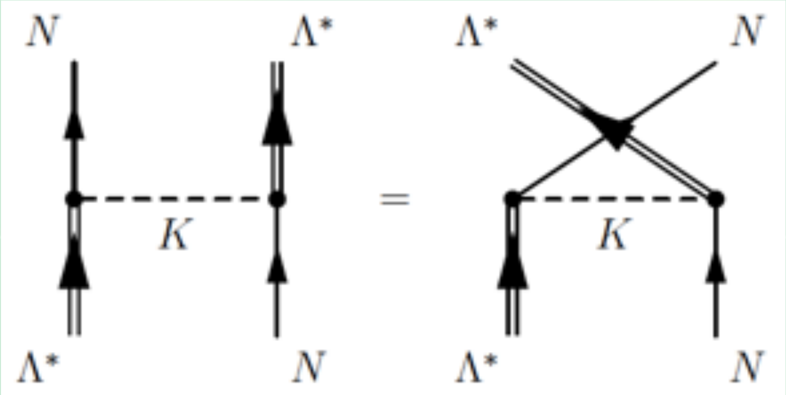


Λ*N potential: K exchange

Λ*KN vertex: scalar type (Λ*=1/2⁻)

$$\mathcal{H}_{\Lambda^* NK} = g_{\Lambda^* KN}(\bar{\Lambda}^* \bar{K} N + \bar{N} K \Lambda^*)$$

Exchange factor

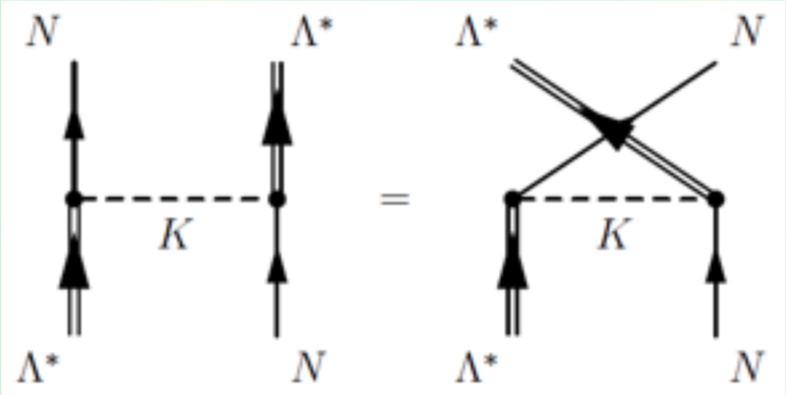


Λ*N potential: K exchange

Λ*KN vertex: scalar type (Λ*=1/2⁻)

$$\mathcal{H}_{\Lambda^* NK} = g_{\Lambda^* KN}(\bar{\Lambda}^* \bar{K} N + \bar{N} K \Lambda^*)$$

Exchange factor



$$-\mathcal{P}_x \frac{1 + \vec{\sigma}_{\Lambda^*} \cdot \vec{\sigma}_N}{2}$$

spin dependence
(P_x=1 for s-wave)

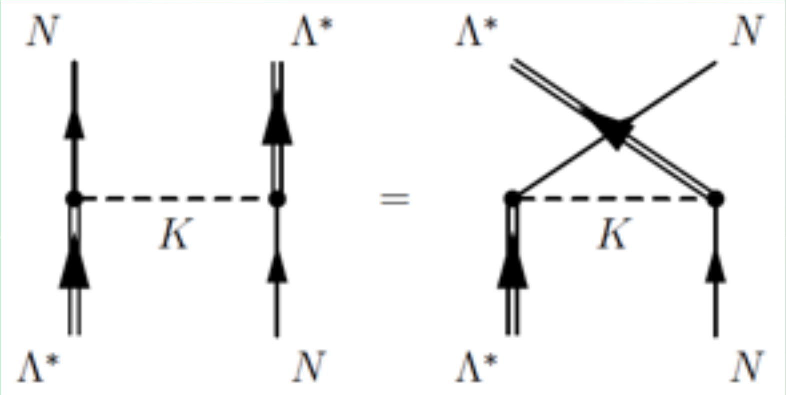
In total, S=0 (σσ=-3) attractive, S=1 (σσ=1) repulsive.

Λ*N potential: K exchange

Λ*KN vertex: scalar type ($\Lambda^*=1/2^-$)

$$\mathcal{H}_{\Lambda^* NK} = g_{\Lambda^* KN}(\bar{\Lambda}^* \bar{K} N + \bar{N} K \Lambda^*)$$

Exchange factor



$$-\mathcal{P}_x \frac{1 + \vec{\sigma}_{\Lambda^*} \cdot \vec{\sigma}_N}{2}$$

spin dependence
(P_x=1 for s-wave)

In total, S=0 (σσ=-3) attractive, S=1 (σσ=1) repulsive.

Mass difference of Λ* and N
--> effective K mass

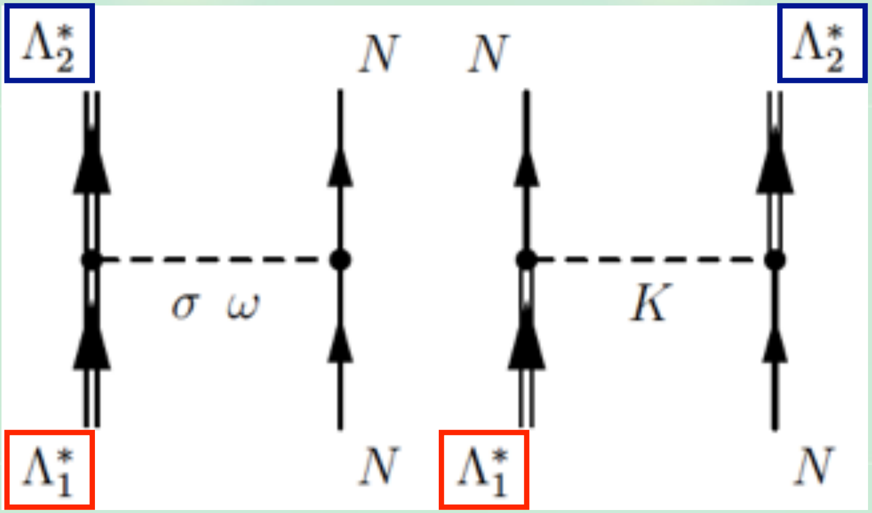
$$\tilde{m}_K = \sqrt{m_K^2 - (M_{\Lambda^*} - M_N)^2}$$

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

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

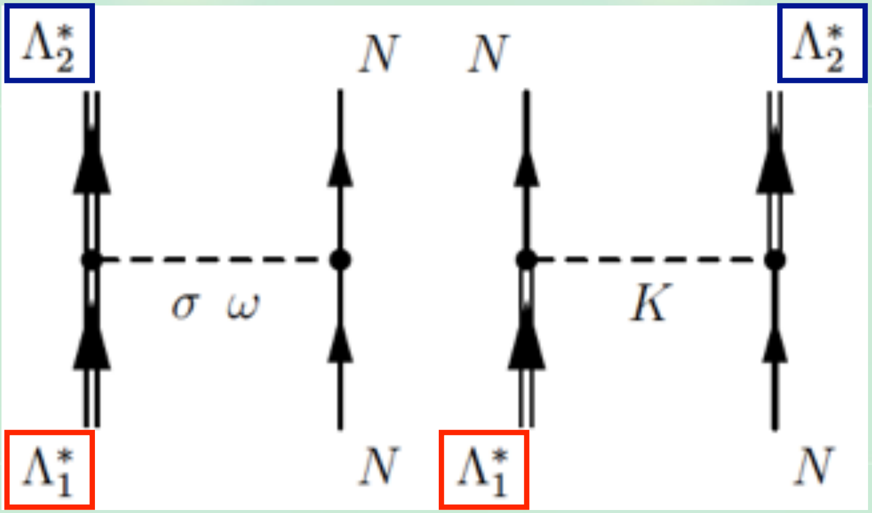
There can be the mixing of Λ^*_1N <--> Λ^*_2N

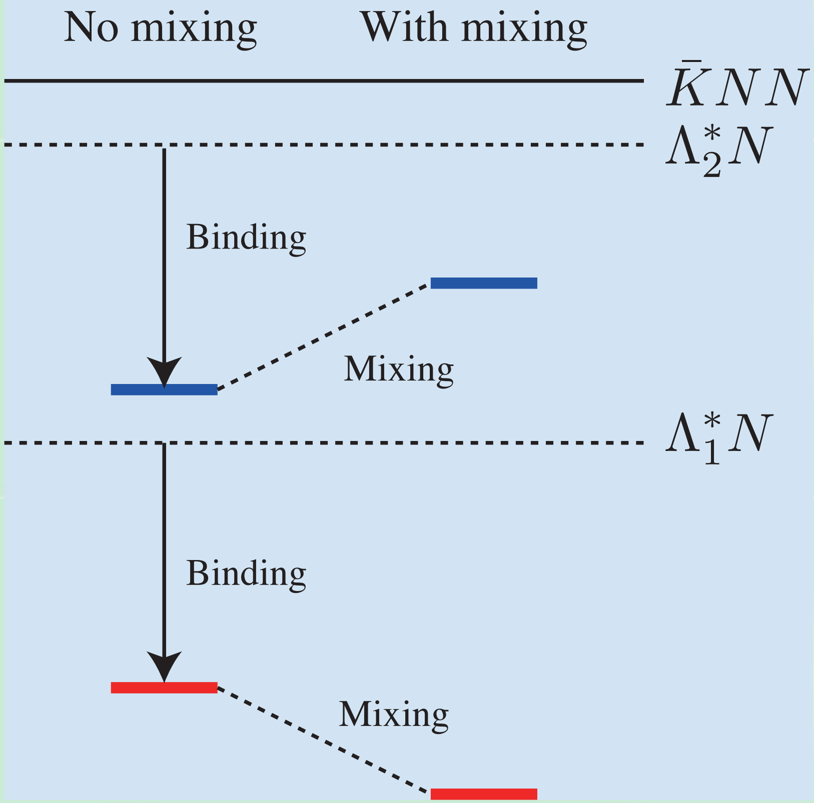


Λ*N potential: mixing interaction

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

There can be the mixing of $\Lambda^*_1 N$ <--> $\Lambda^*_2 N$

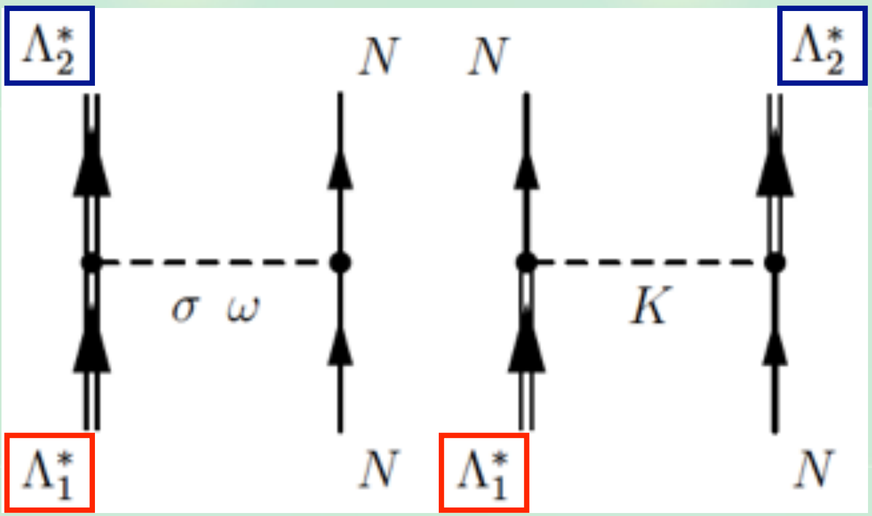


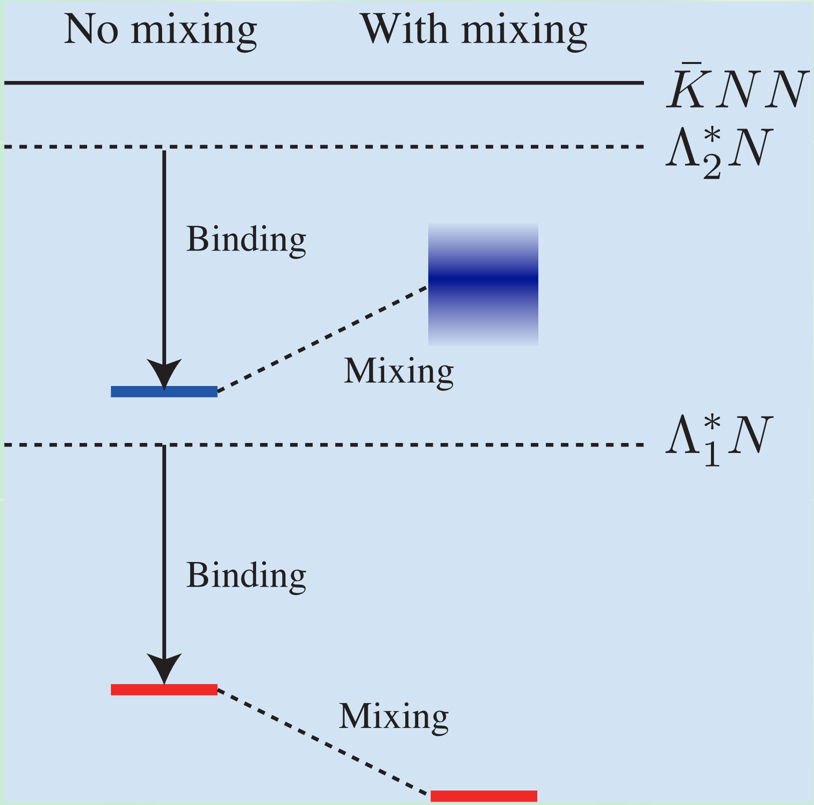


Λ*N potential: mixing interaction

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

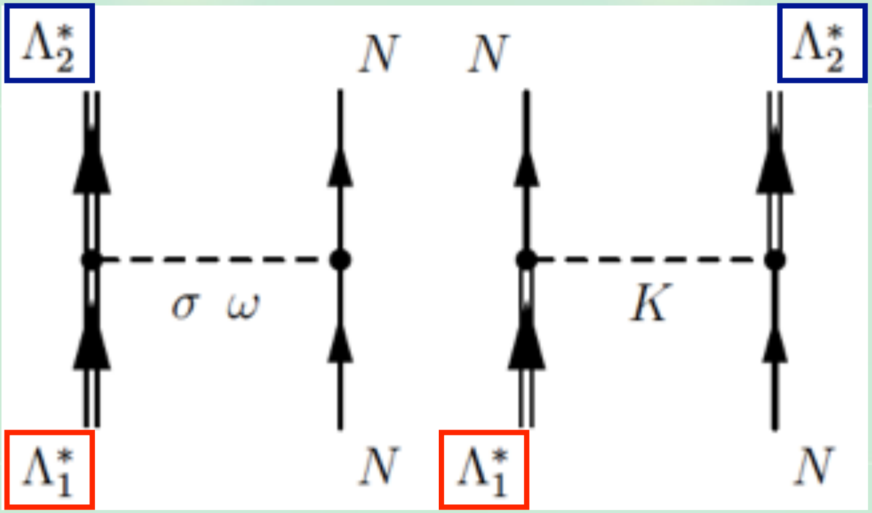


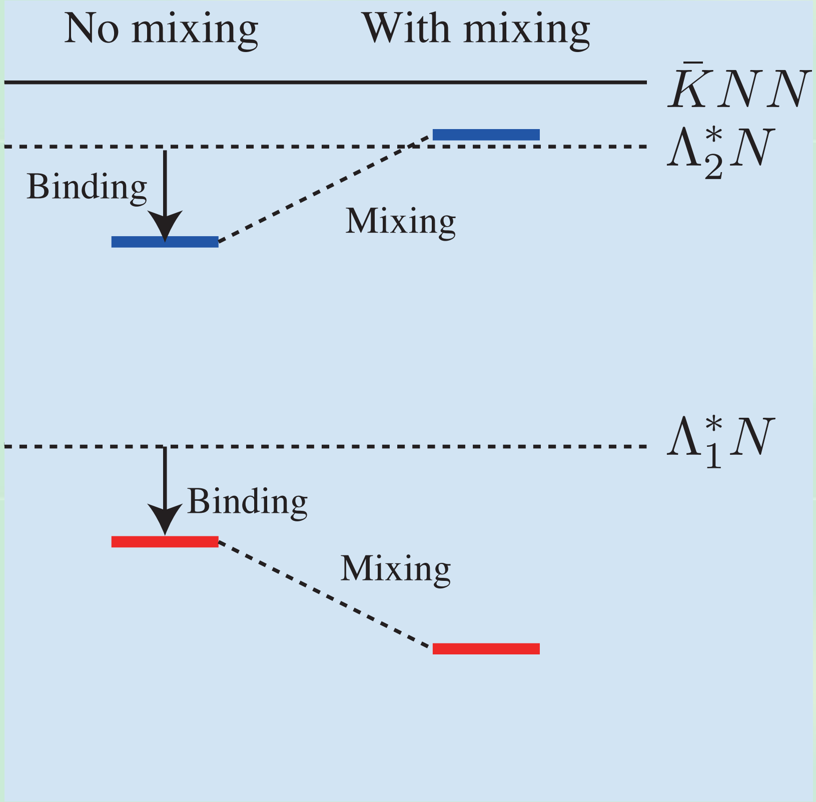


Λ*N potential: mixing interaction

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

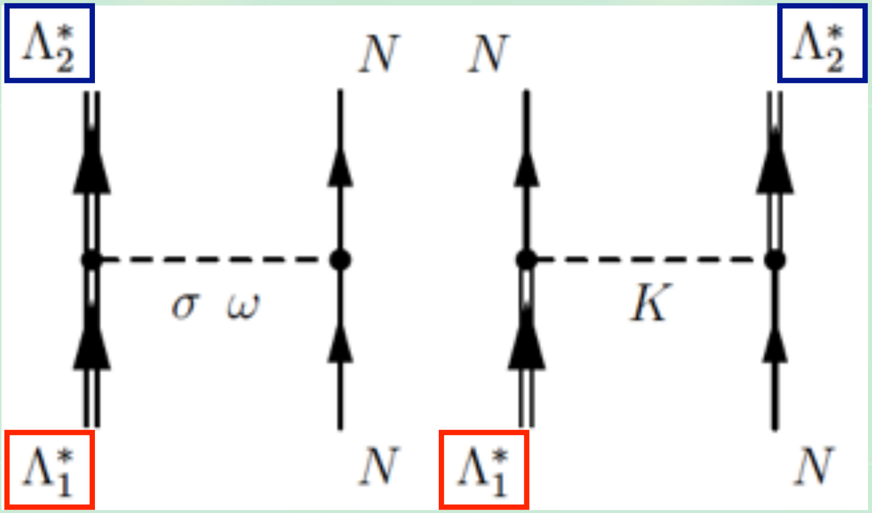


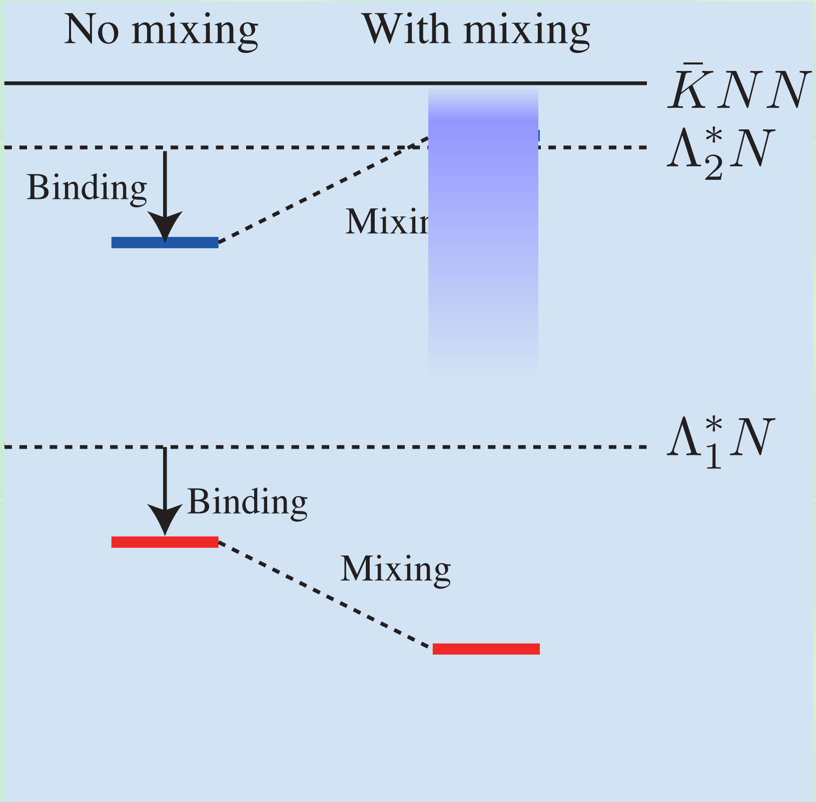


Λ*N potential: mixing interaction

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

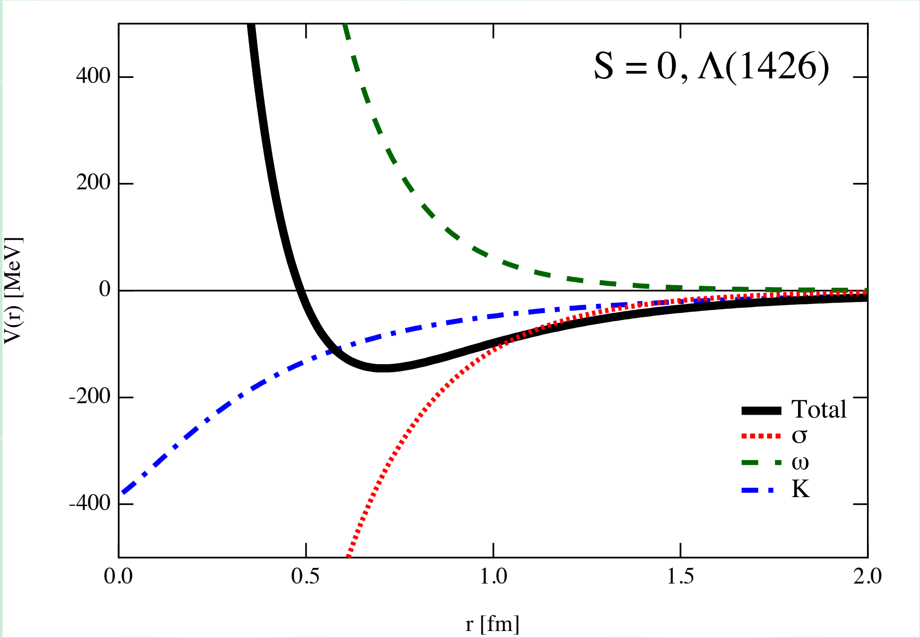
There can be the mixing of Λ^*_1N <--> Λ^*_2N

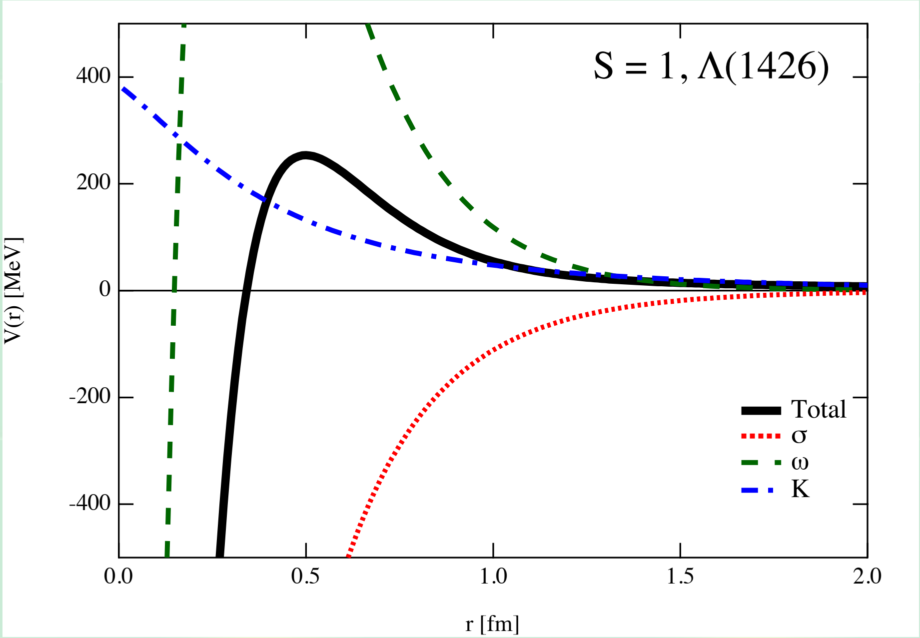




Λ*N potential

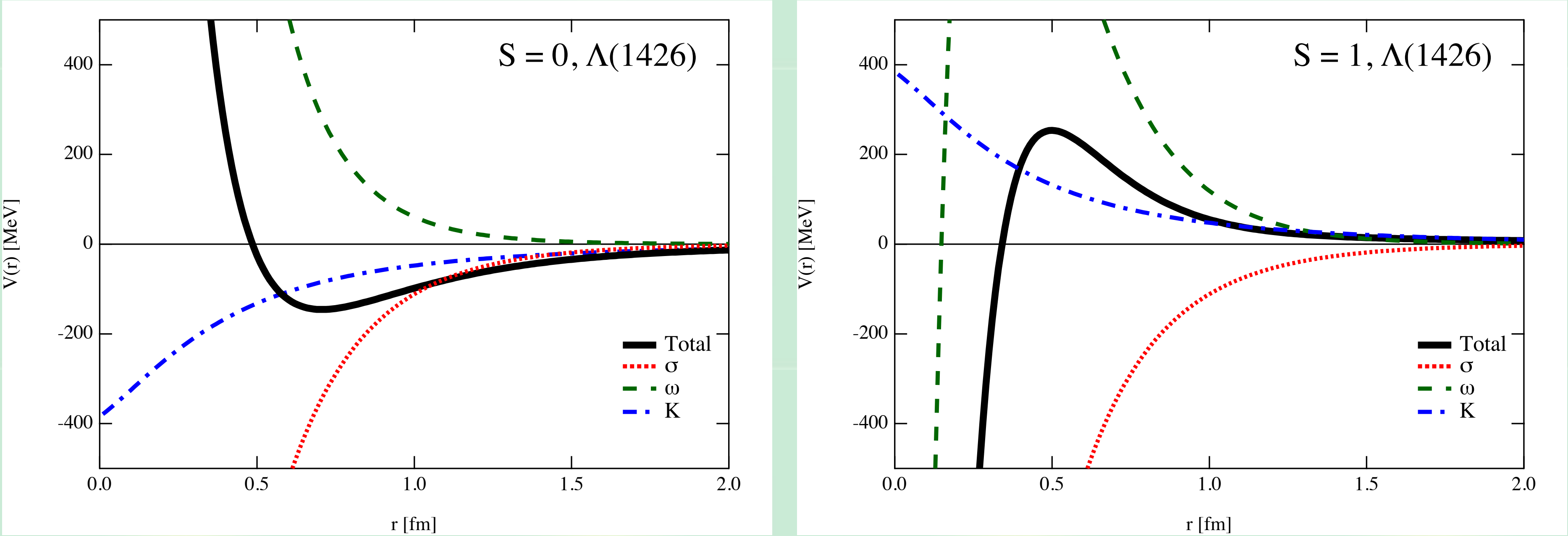
Diagonal potentials for Λ^*_2N in S=0 and S=1, s-wave





Λ*N potential

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

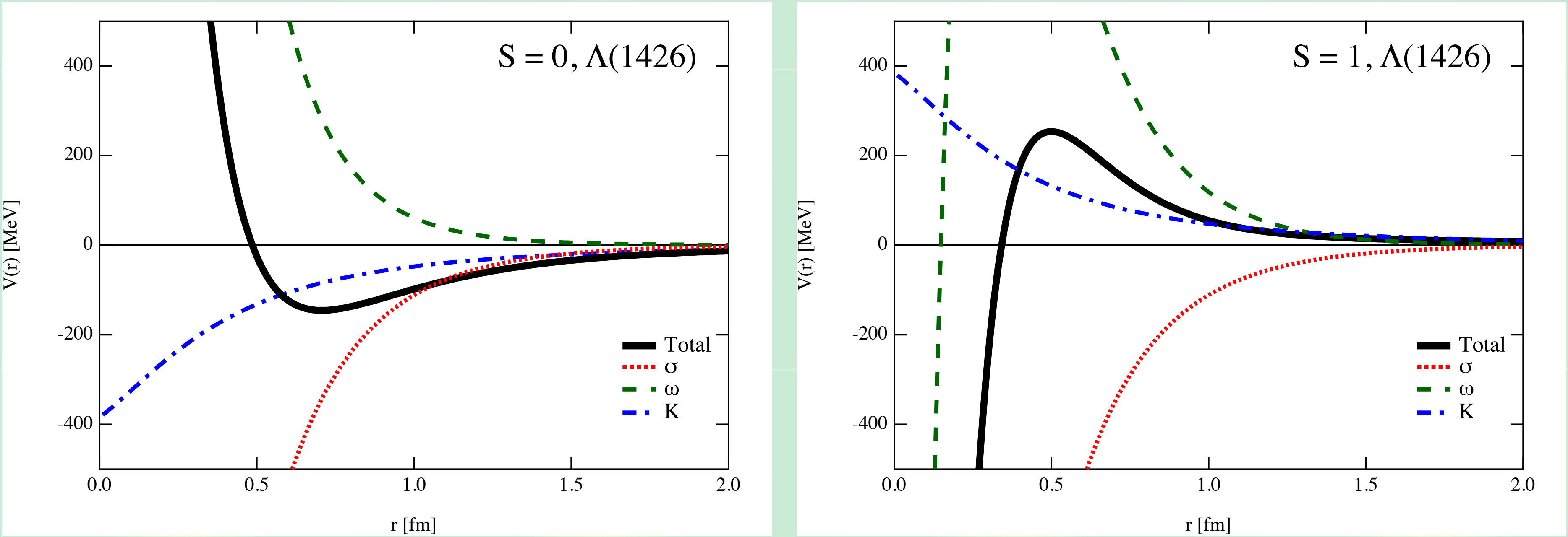


S=0: K exchange is attractive

--> attractive pocket at intermediate range

Λ*N potential

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



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

S=1: K exchange is repulsive
--> no intermediate attraction.
(short range dip: artificial, not physical)

Λ*N bound states without mixing

Solve the schrödinger equation for the s-wave Λ*¡N potential without the mixing interaction.

$\Lambda^* N$ bound states without mixing

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

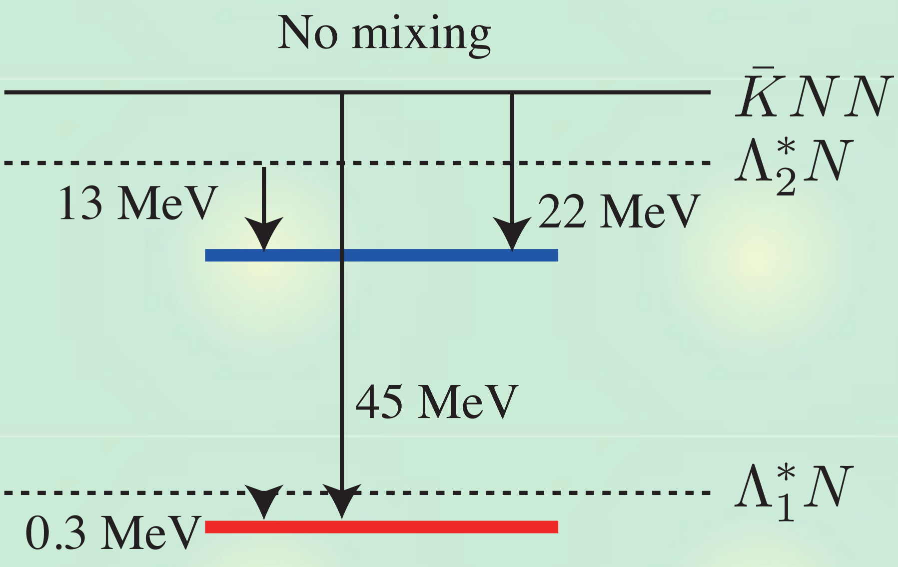
- no physical bound states in S=1 channels

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
- for S=0 we obtain the bound states in both Λ^*_i

binding from	Λ*N th. [MeV]	$\bar{K}$NN th. [MeV]
Λ^*_2 N	13.39	22.39
Λ^*_1 N	0.34	45.34

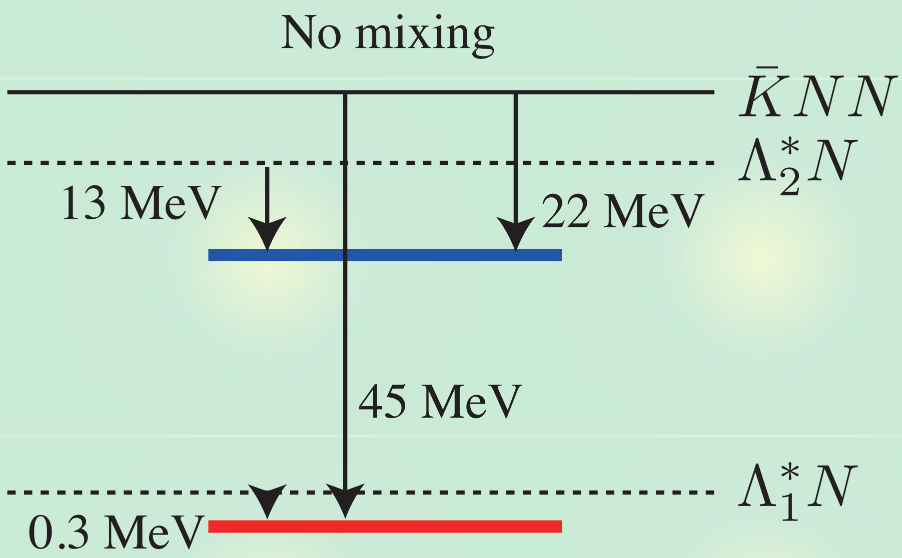


Λ*N bound states without mixing

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

- no physical bound states in S=1 channels
- for S=0 we obtain the bound states in both Λ^*_i

binding from	Λ*N th. [MeV]	$\bar{K}$NN th. [MeV]
Λ^*_2 N	13.39	22.39
Λ^*_1 N	0.34	45.34



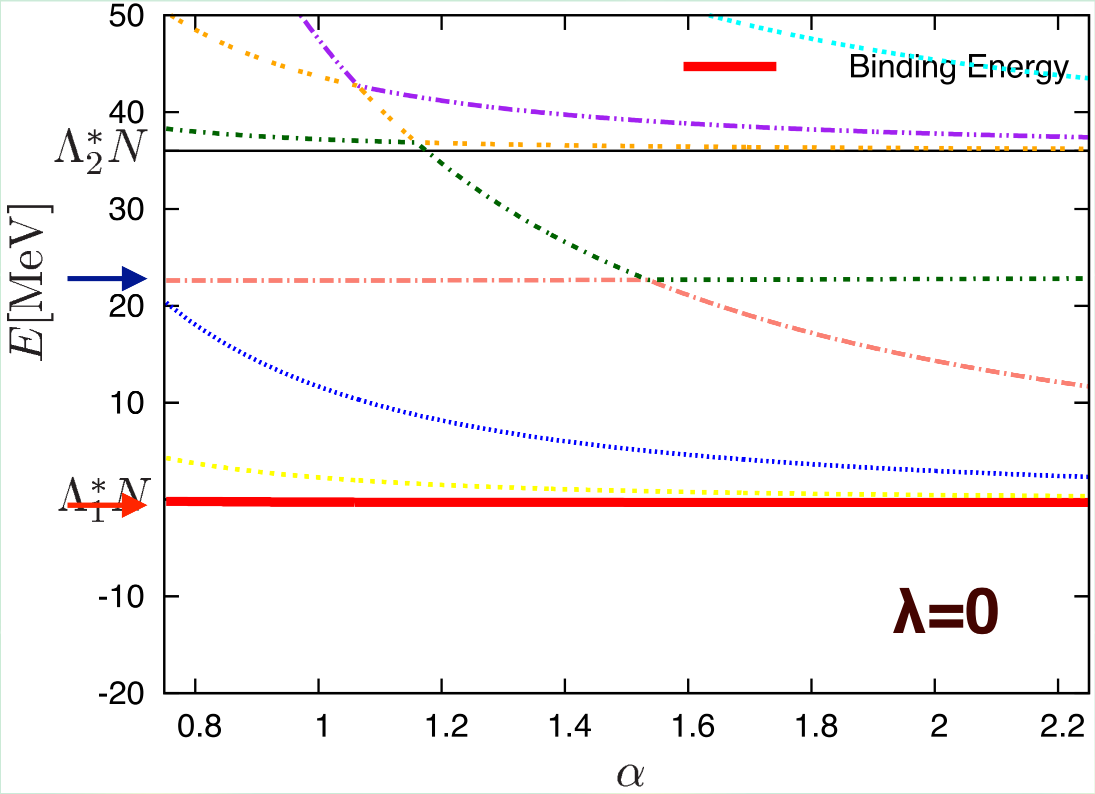
Two Λ*N states in spin S=0 channel

Λ*N bound states with mixing

With mixing, the higher state becomes a resonance.
Real scaling method ≈ changing the box size.
λ: strength of the mixing interaction, physical for λ=1

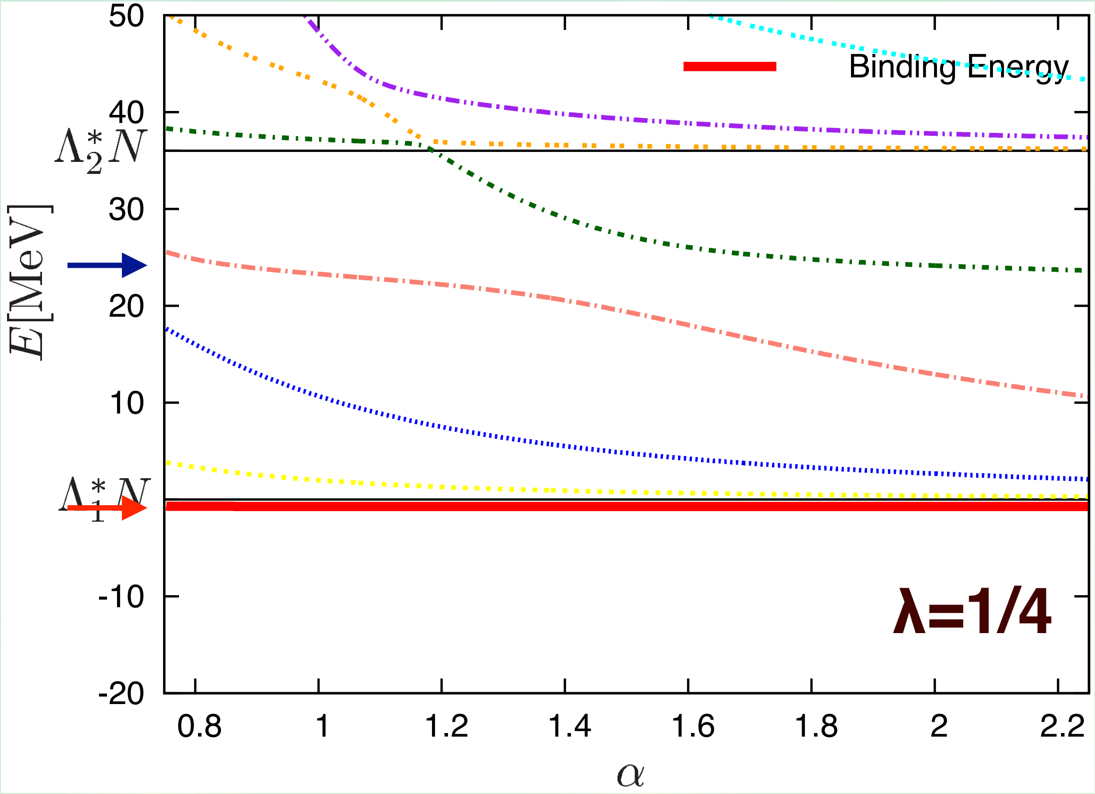
Λ*N bound states with mixing

With mixing, the higher state becomes a resonance.
Real scaling method ≈ changing the box size.
λ: strength of the mixing interaction, physical for λ=1



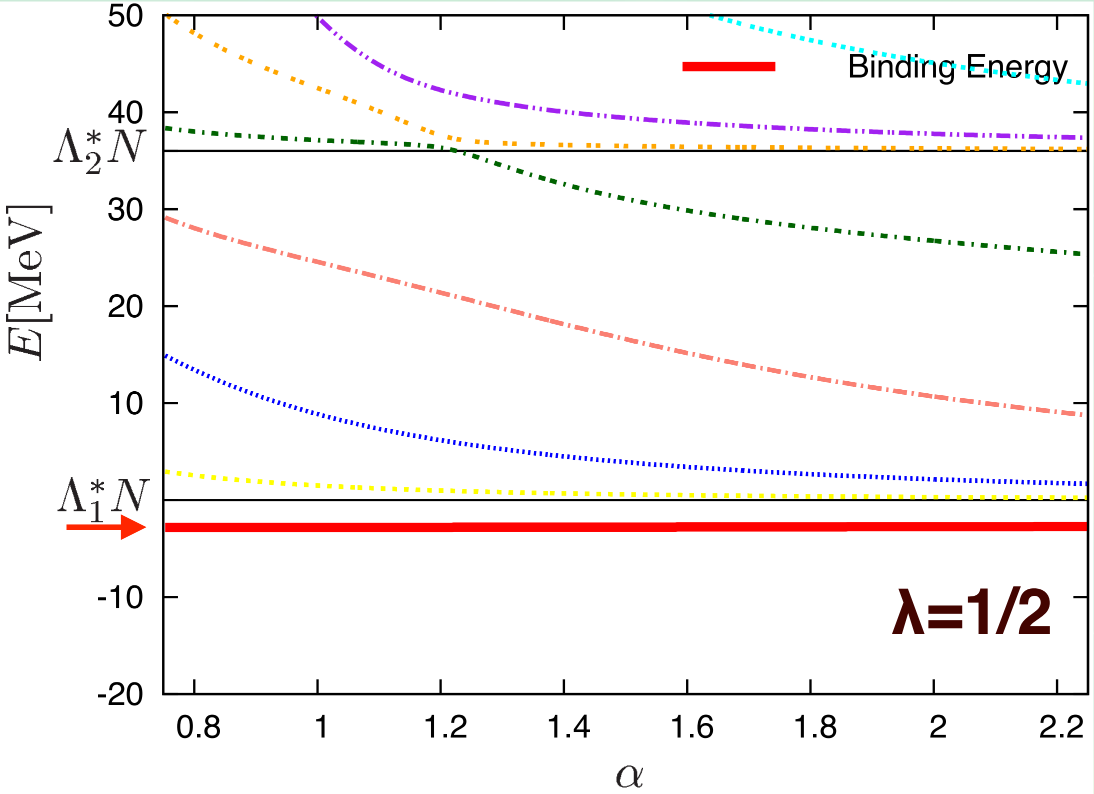
Λ*N bound states with mixing

With mixing, the higher state becomes a resonance.
Real scaling method ≈ changing the box size.
λ: strength of the mixing interaction, physical for λ=1



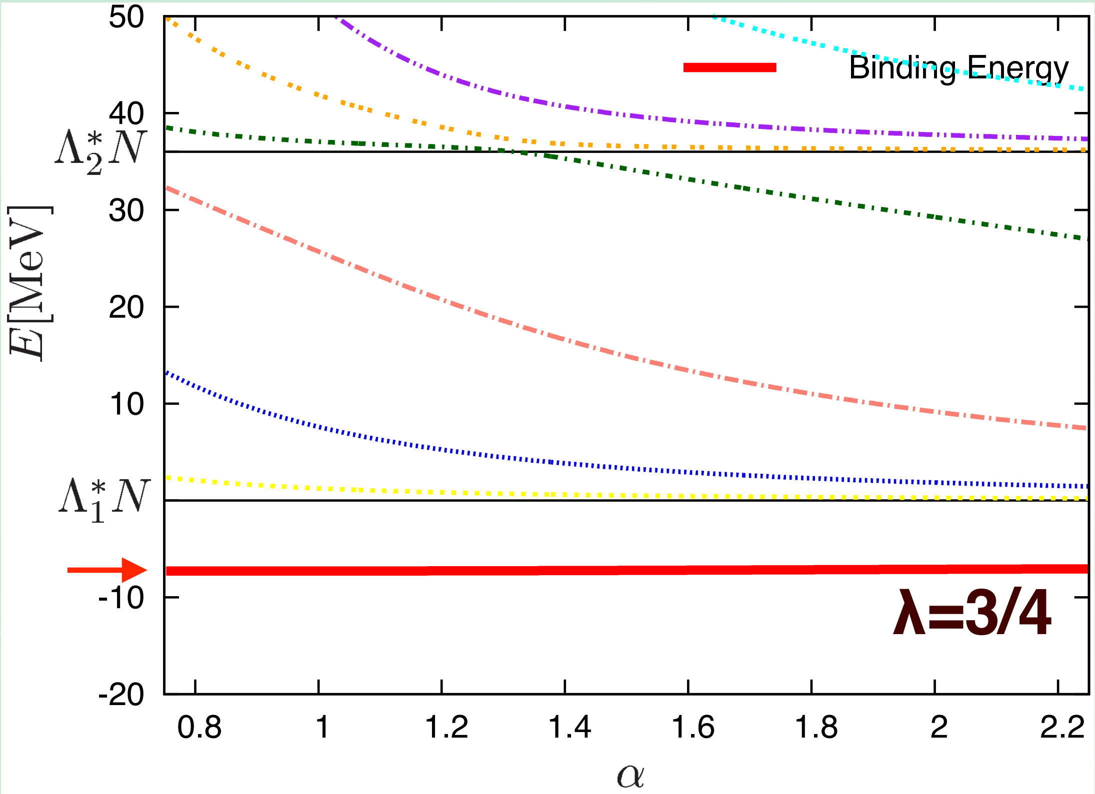
Λ*N bound states with mixing

With mixing, the higher state becomes a resonance.
Real scaling method ≈ changing the box size.
λ: strength of the mixing interaction, physical for λ=1



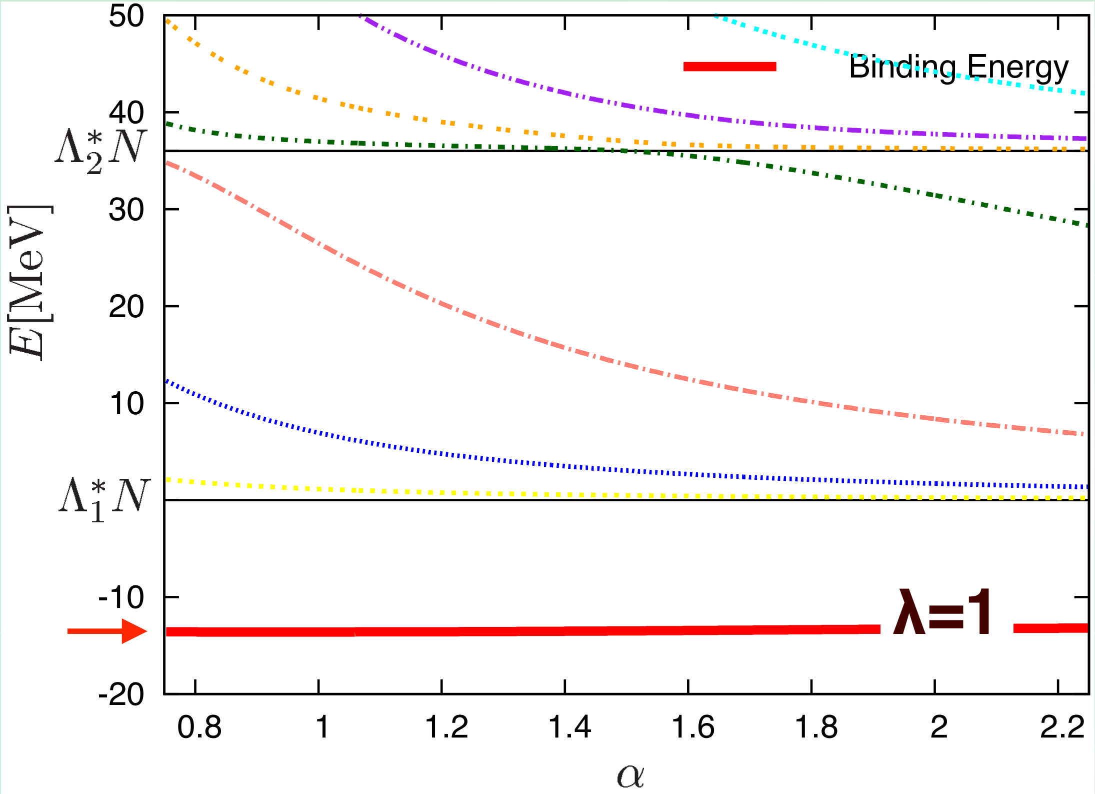
Λ*N bound states with mixing

With mixing, the higher state becomes a resonance.
Real scaling method ≈ changing the box size.
λ: strength of the mixing interaction, physical for λ=1



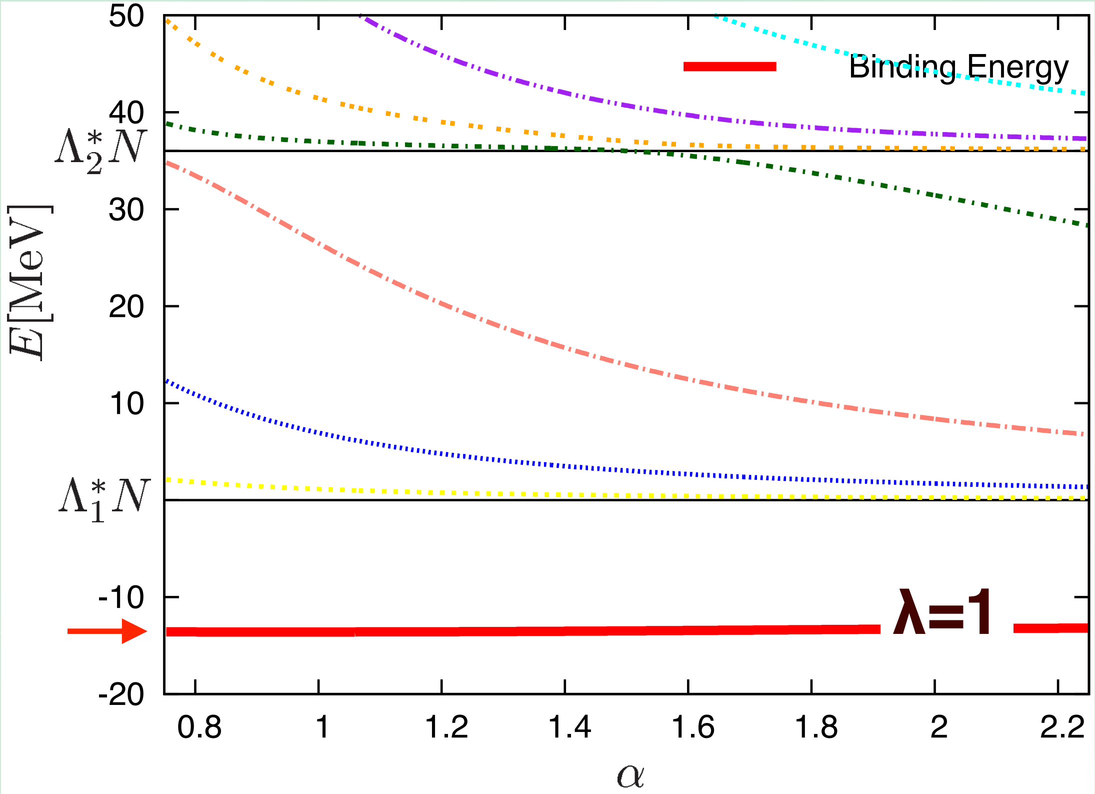
Λ*N bound states with mixing

With mixing, the higher state becomes a resonance.
Real scaling method ≈ changing the box size.
λ: strength of the mixing interaction, physical for λ=1



Λ*N bound states with mixing

With mixing, the higher state becomes a resonance.
Real scaling method ≈ changing the box size.
λ: strength of the mixing interaction, physical for λ=1



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

Summary

We study the Λ^*N two-body system based on the Λ^*N potential with chiral dynamics.

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

B.E.(from $\bar{K}NN$) = 52-58 MeV
<-- strong mixing between Λ^*_1N - Λ^*_2N

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

Summary

taken from T. Uchino, Master thesis