Chiral dynamics, structure of Λ(1405), and $\bar{K}N$ phenomenology

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2009, Feb. 27th

Λ(1405) and $\bar{K}N$ dynamics

$\Lambda(1405) : J^P = 1/2^-, I = 0$

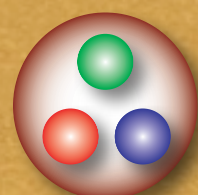
PDG

Mass : 1406.5 ± 4.0 MeV

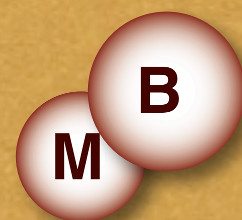
Width : 50 ± 2 MeV

Decay mode : $\Lambda(1405) \to (\pi\Sigma)_{I=0}$ **100%**

"naive" quark model
: p-wave
~1600 MeV?



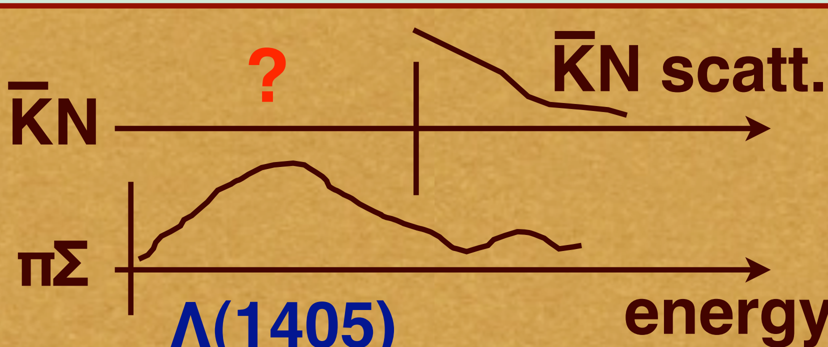
N. Isgur, G. Karl, PRD18, 4187 (1978)



Coupled channel
multi-scattering
<-- strong $\bar{K}N$ int.

R.H. Dalitz, T.C. Wong,
G. Rajasekaran, PR153, 1617 (1967)

$\bar{K}N$ int.
below
threshold



kaonic nuclei,
Λ(1405), ...
-->
exp. @ J-PARC

Chiral dynamics

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

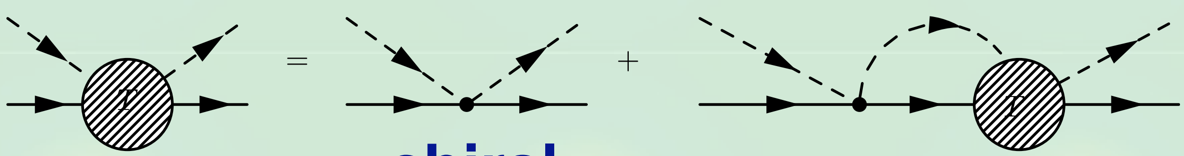
- Interaction <-- chiral symmetry <-- kaon as NG boson

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

- Amplitude <-- unitarity (coupled channel) <-- strong int.

R.H. Dalitz, T.C. Wong, G. Rajasekaran, PR153, 1617 (1967)

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



chiral

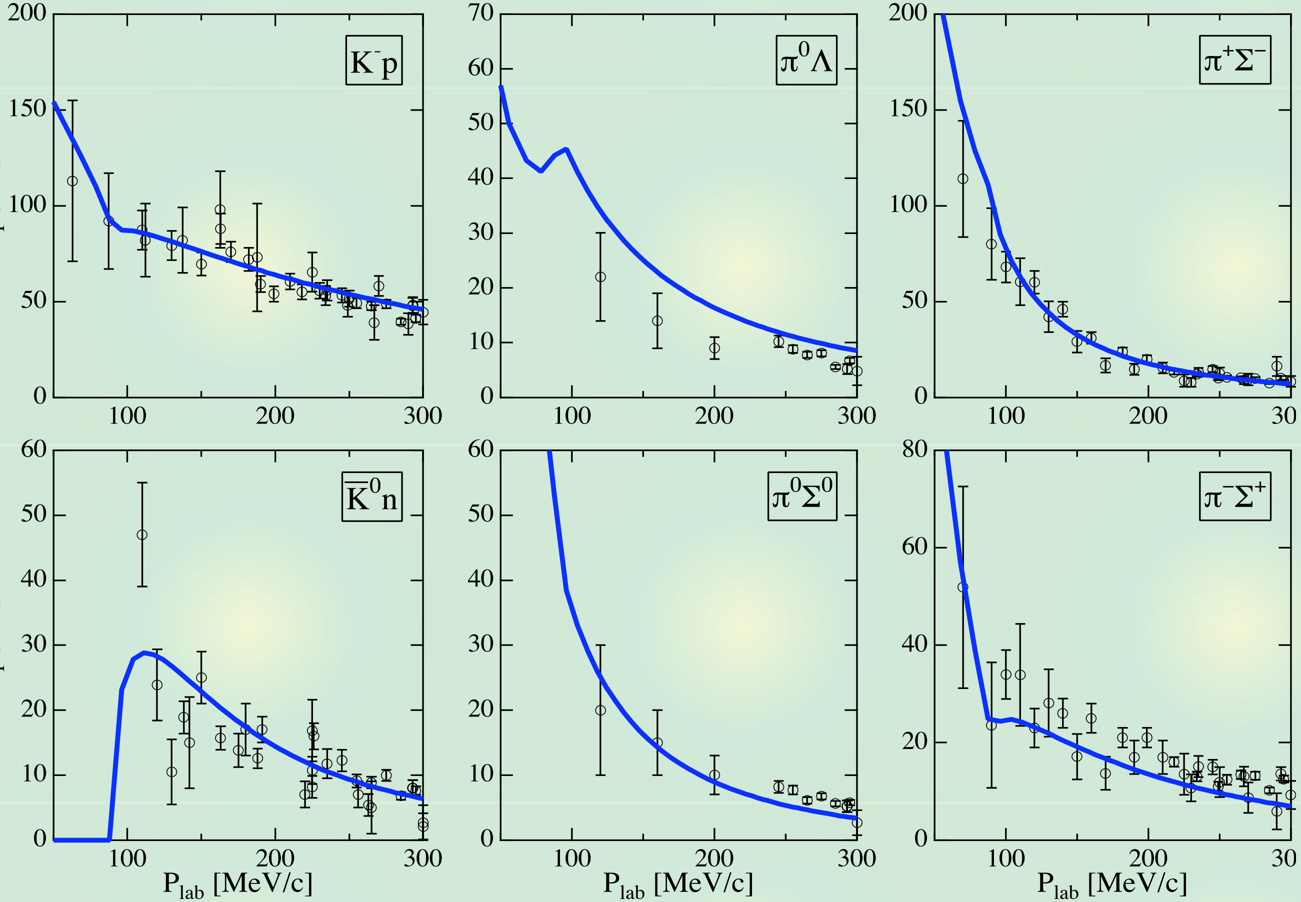
N. Kaiser, P. B. Siegel, W. Weise, Nucl. Phys. A594, 325 (1995),
E. Oset, A. Ramos, Nucl. Phys. A635, 99 (1998),
J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001),
M.F.M. Lutz, E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002), ... many others

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

<u>T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. Lett. 97, 192002 (2006)</u>
<u>T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. D 75, 034002 (2007)</u>

How it works? vs experimental data

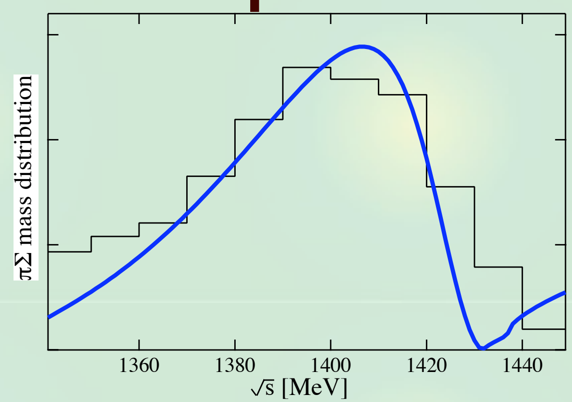
Total cross sections



threshold ratios

	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, Phys. Rev. C68, 018201 (2003),
T. Hyodo, S.I. Nam, D. Jido, A. Hosaka, Prog. Theor. Phys. 112, 73 (2004)

Good agreement in wide energy region (E >, =, < threshold).

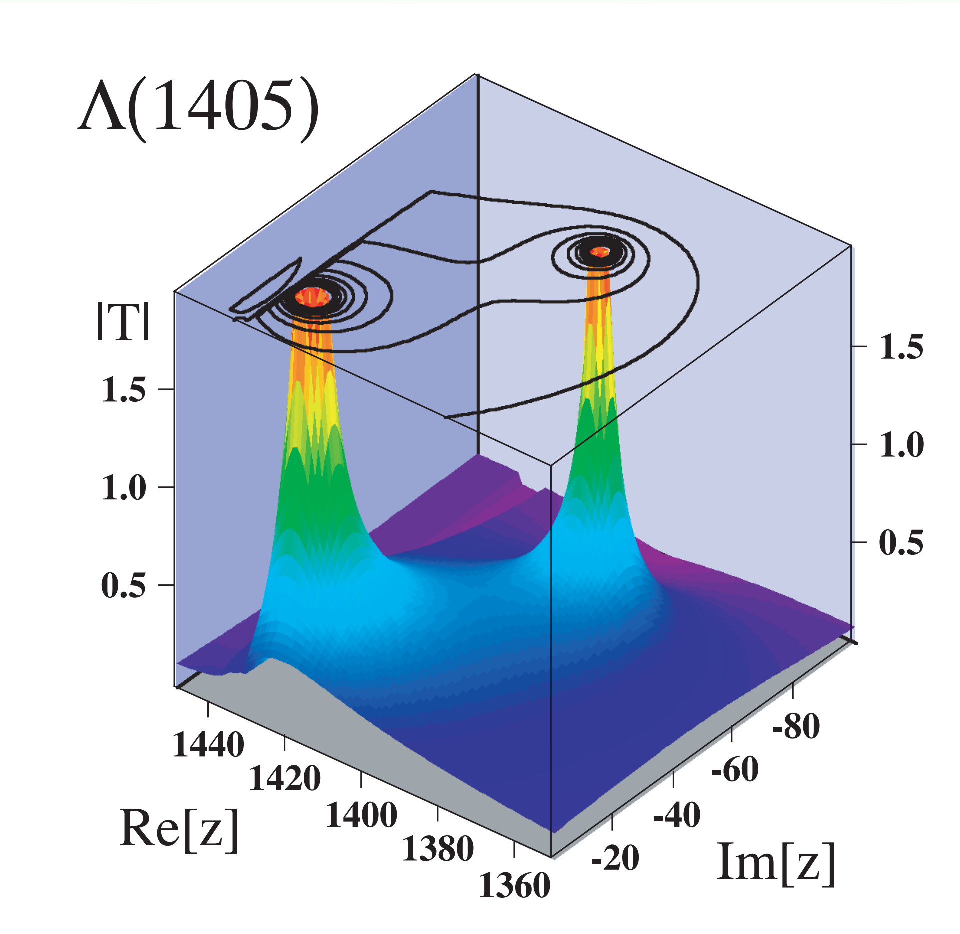
Two poles for one resonance

Poles of the amplitude in the complex plane : resonance

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

$\sim$

Real part	**Mass**
Imaginary part	**Width/2**
Residues	**Couplings**



Physical state: superposition

$$|\Lambda(1405)\rangle = a|\Lambda_1^*\rangle + b|\Lambda_2^*\rangle$$

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)

Λ(1405) in PDG

PDG

Λ(1405) MASS

PRODUCTION EXPERIMENTS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1406.5 ± 4.0				

R.H. Dalitz, A. Deloff, J. Phys G17, 289 (1991)

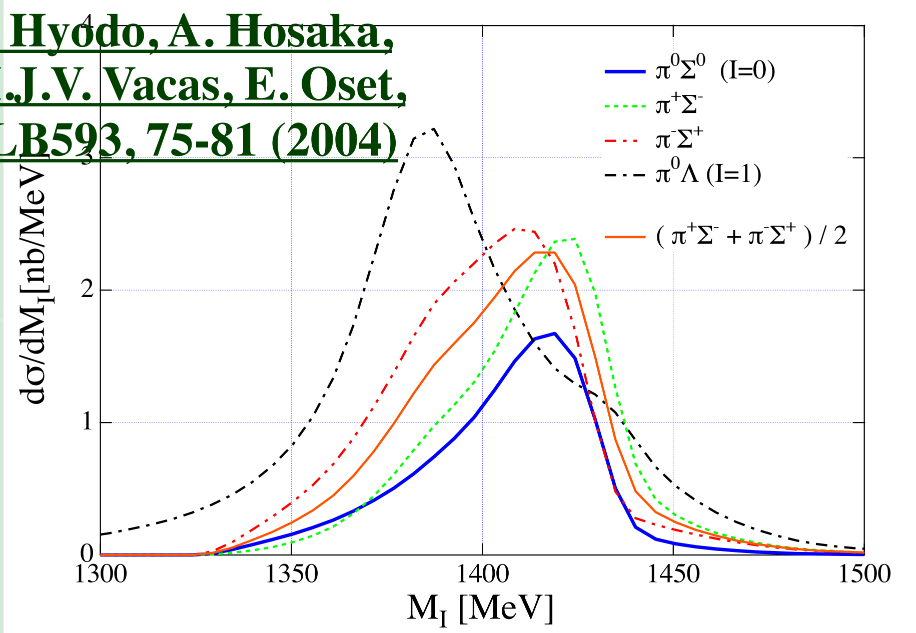
Analysis of Hemingway data by I=0 model. Spectrum ($\pi^-\Sigma^+$) is not in I=0.

$$\sigma(\pi^-\Sigma^+) \propto \frac{1}{3}|T^{I=0}|^2 + \frac{1}{2}|T^{I=1}|^2 - \frac{2}{\sqrt{6}}\mathrm{Re}(T^{I=0}\cdot T^{I=1})$$

I=1 Σ(1385)

interference

T. Hyodo, A. Hosaka, M.J.V. Vacas, E. Oset, PLB593, 75-81 (2004)



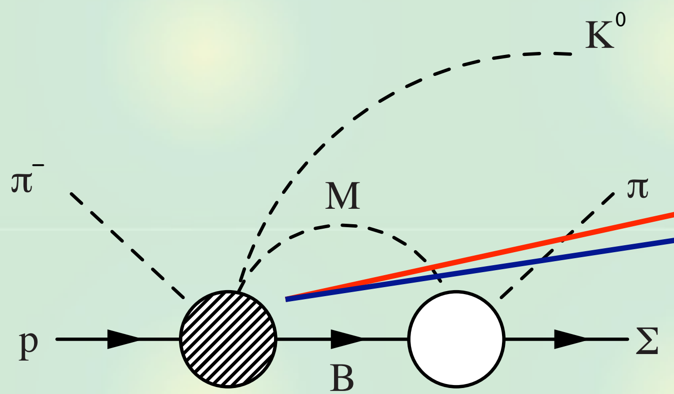
A note on the πΣ spectrum

アイソスピンの正しい状態（I=0）を選ぶにはπΣの３つの荷電状態（$\pi^0\Sigma^0$, $\pi^\pm\Sigma^\mp$）を全て同時に測定する必要がある（未達成）。

（現実的には$\pi^0\Sigma^0$はI=1がないので理想的？）

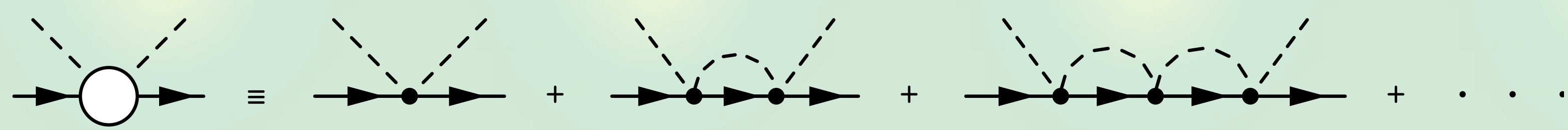
ポールが２つある効果は、スペクトルが反応によって変化することを調べる必要がある。=> １つの実験で検証／排除は不可能

$$|\Lambda(1405)\rangle = a|\Lambda_1^*\rangle + b|\Lambda_2^*\rangle$$



ただし反応計算は模型依存。

１ポールでも干渉でピーク位置が変化。



Contents

Structure of Λ(1405) resonance (Bグループ)

- Dynamical or CDD (genuine quark state) ?

  T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C78, 025203 (2008).

- Nc Behavior and quark structure

  T. Hyodo, D. Jido, L. Roca, Phys. Rev. D77, 056010 (2008).
  L. Roca, T. Hyodo, D. Jido, Nucl. Phys. A809, 65 (2008).

- Electromagnetic properties

  T. Sekihara, T. Hyodo, D. Jido, Phys. Lett. B669, 133-138 (2008).

Phenomenology of $\bar{K}N$ interaction

- Construction of local $\bar{K}N$ potential (Cグループ)

  T. Hyodo, W. Weise, Phys. Rev. C77, 035204 (2008).

- Application to three-body $\bar{K}NN$ system

  A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A804, 197 (2008)
  A. Doté, T. Hyodo, W. Weise, Phys. Rev. C 79, 014003 (2009)

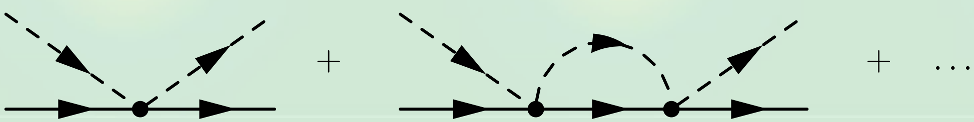
+α

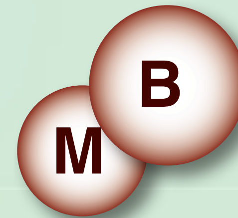
Dynamical state and CDD pole

Resonances in two-body scattering

- Knowledge of interaction (potential)
- Experimental data (cross section, phase shift,...)

(a) dynamical state: molecule, quasi-bound, ...

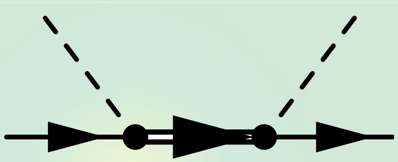


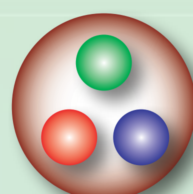


e.g.) Deuteron in NN, positronium in e^+e^-, (σ in π π), ...

(b) CDD pole: elementary, independent, ...

L. Castillejo, R.H. Dalitz, F.J. Dyson, Phys. Rev. 101, 453 (1956)





e.g.) J/Ψ in e^+e^-, (ρ in π π), ...

Resonances in chiral unitary approach -> (a) dynamical?

CDD pole contribution in chiral unitary approach

Amplitude in chiral unitary model

$$T = \frac{1}{\boxed{V^{-1}} - \boxed{G}}$$

V : interaction kernel (potential)
G : loop integral (Green's function)

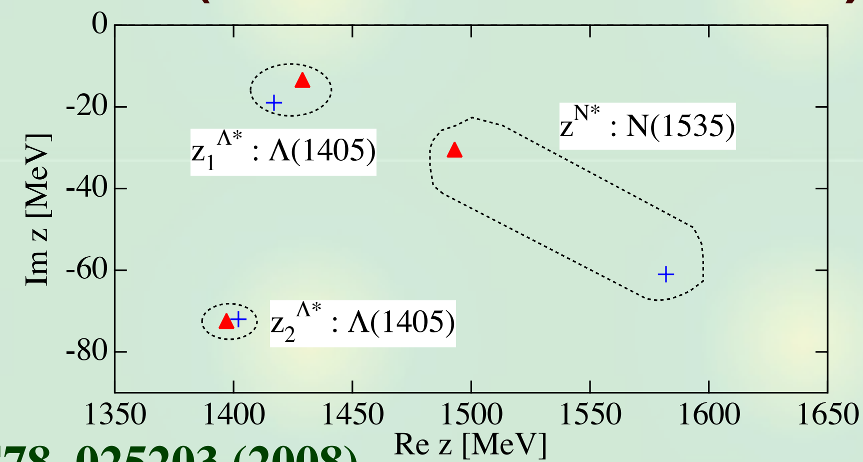
Known CDD pole contribution

(1) Explicit resonance field in **V**
(2) Contracted resonance propagator in **V**

Defining "natural renormalization scheme",
we find **CDD pole contribution in G** (subtraction constant).

N(1535) in πN scattering
--> dynamical + CDD pole

Λ(1405) in $\bar{K}N$ scattering
--> **mostly dynamical**



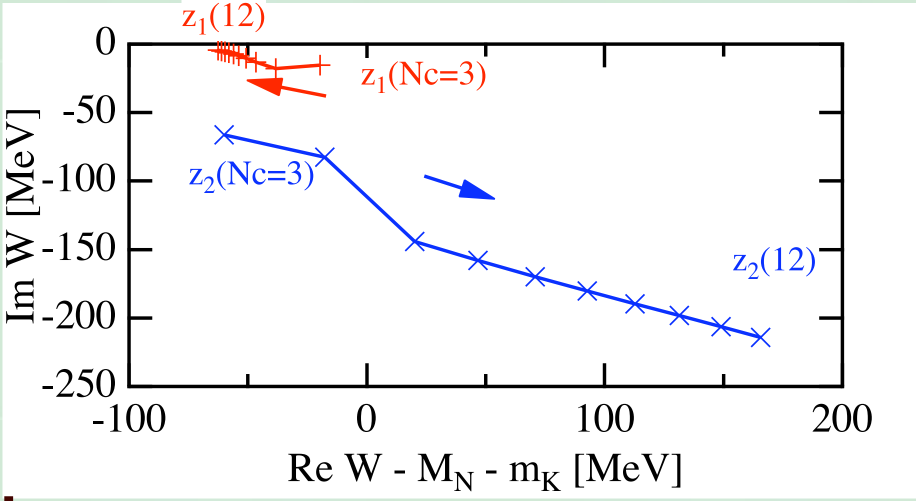
T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C78, 025203 (2008).

Nc scaling in the model

Nc : number of color in QCD
Hadron effective theory / quark structure

The Nc behavior is known from the general argument.
<-- introducing Nc dependence in the model,
analyze the resonance properties with respect to Nc

J.R. Pelaez, Phys. Rev. Lett. 92, 102001 (2004)



Nc scaling of (excited) qqq baryon

$$M_R \sim \mathcal{O}(N_c), \quad \Gamma_R \sim \mathcal{O}(1)$$

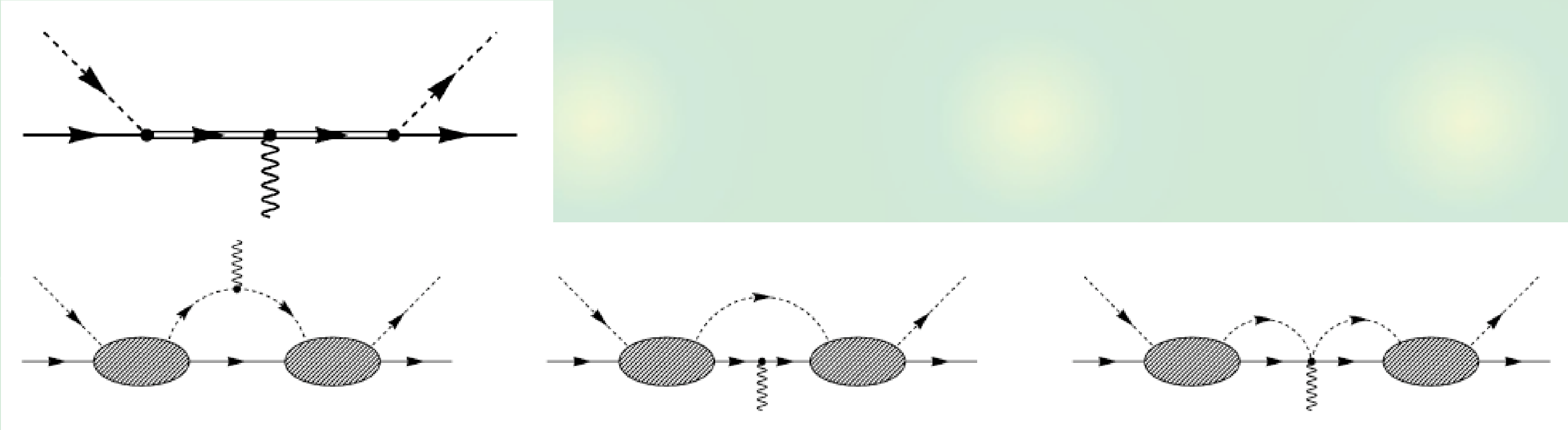
Result : $\Gamma_R \neq \mathcal{O}(1)$
~ non-qqq (i.e. dynamical) structure

詳細は学会で
29pSJ-2

T. Hyodo, D. Jido, L. Roca, Phys. Rev. D77, 056010 (2008).
L. Roca, T. Hyodo, D. Jido, Nucl. Phys. A809, 65 (2008).

Electromagnetic properties

Attaching photon to resonance
--> em properties : rms, form factors,...



result of mean squared radii :

$$< r^2 >_E = -2.193 \text{ fm}^2$$

large (em) size of the Λ(1405)
--> meson-baryon picture

T. Sekihara, T. Hyodo, D. Jido, Phys. Lett. B669, 133-138 (2008).

Summary 1 : Structure of Λ(1405)

We study the structure of the Λ(1405)

- Dynamical or CDD?
  - => dominance of the MB components
- Analysis of Nc scaling
  - => non-qqq structure
- Electromagnetic properties
  - => large e.m. size

Summary 1 : Structure of Λ(1405)

We study the structure of the Λ(1405)

- **Dynamical or CDD?**

  => dominance of the MB components

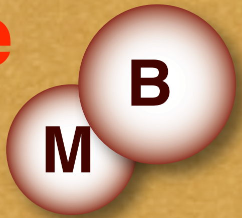
- **Analysis of Nc scaling**

  => non-qqq structure

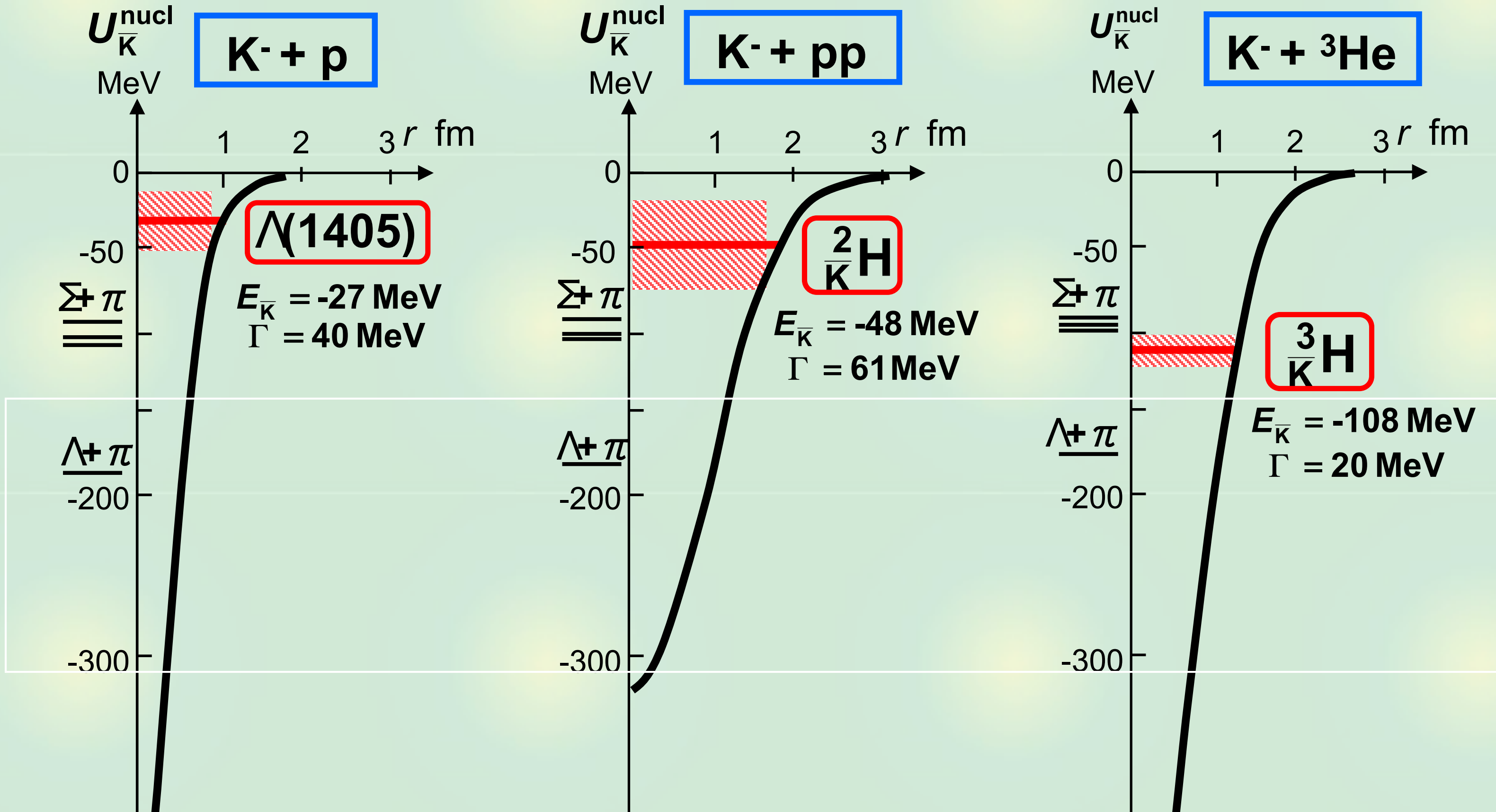
- **Electromagnetic properties**

  => large e.m. size

- **Independent analyses consistently support the meson-baryon molecule picture of the Λ(1405)**



Deeply bound (few-body) kaonic nuclei?



Potential is purely phenomenological.
What does chiral dynamics tell us about it?

Y. Akaishi & T. Yamazaki, Phys. Rev. C 65 (2002) 044005
T. Yamazaki & Y. Akaishi, Phys. Lett. B 535 (2002) 70

Effective interaction based on chiral SU(3) dynamics

Few-body kaonic nuclei in chiral dynamics

- single-channel $\bar{K}N$ potential

Construction of effective single-channel potential

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

1) Coupled-channel --> single $\bar{K}N$ channel BS equation
   incorporation of $\pi\Sigma$ channel (exact)

2) Local potential in Schrödinger equation (approximate)

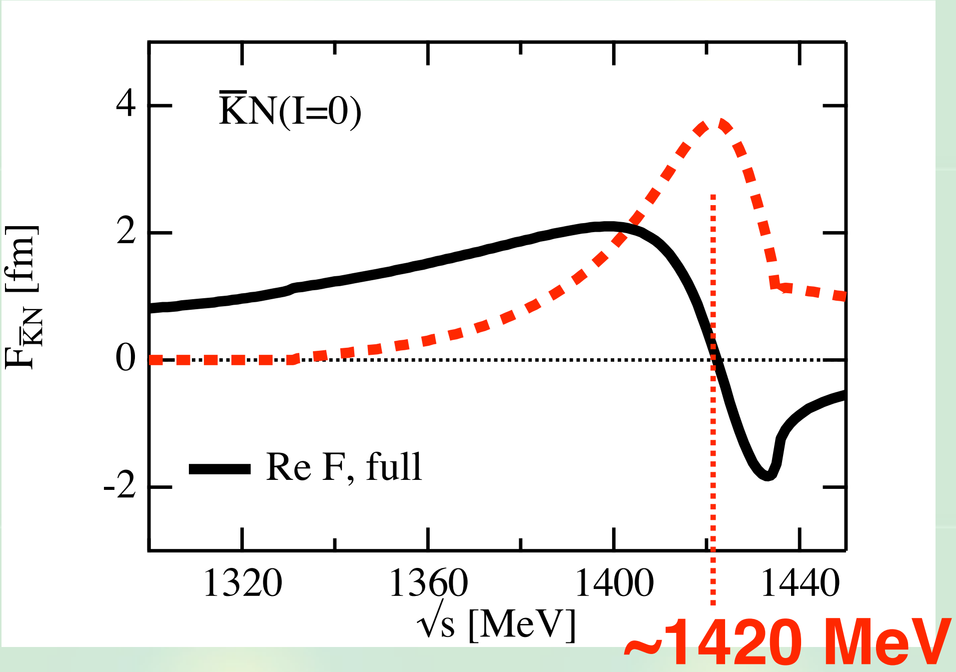
--> $\bar{K}N$ interaction : attractive, but weaker than the phenomenological potential.

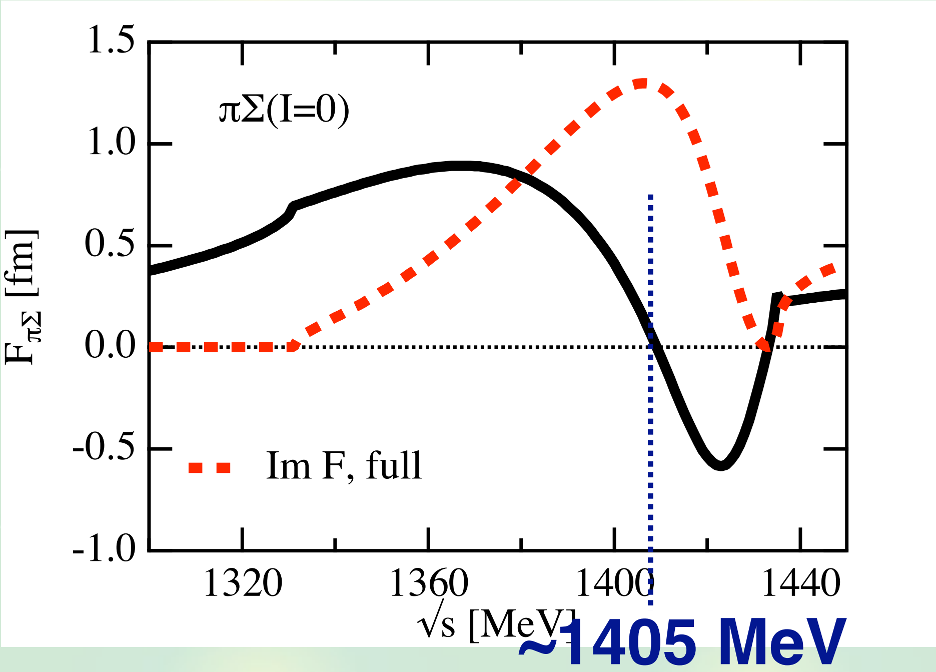
Application to K-pp system : bound, but B ~ 20 MeV

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

Why the interaction is weaker? --> structure of the Λ(1405)

Scattering amplitude in $\bar{K}N$ and $\pi\Sigma$





Resonance in $\bar{K}N$: around 1420 MeV
<-- strong πΣ dynamics (coupled-channel)

Binding energy : B = 15 MeV <--> 30 MeV

Two poles with same quantum numbers
Different weights of the pole residues --> different spectra

D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, Nucl. Phys. A 723, 205 (2003)

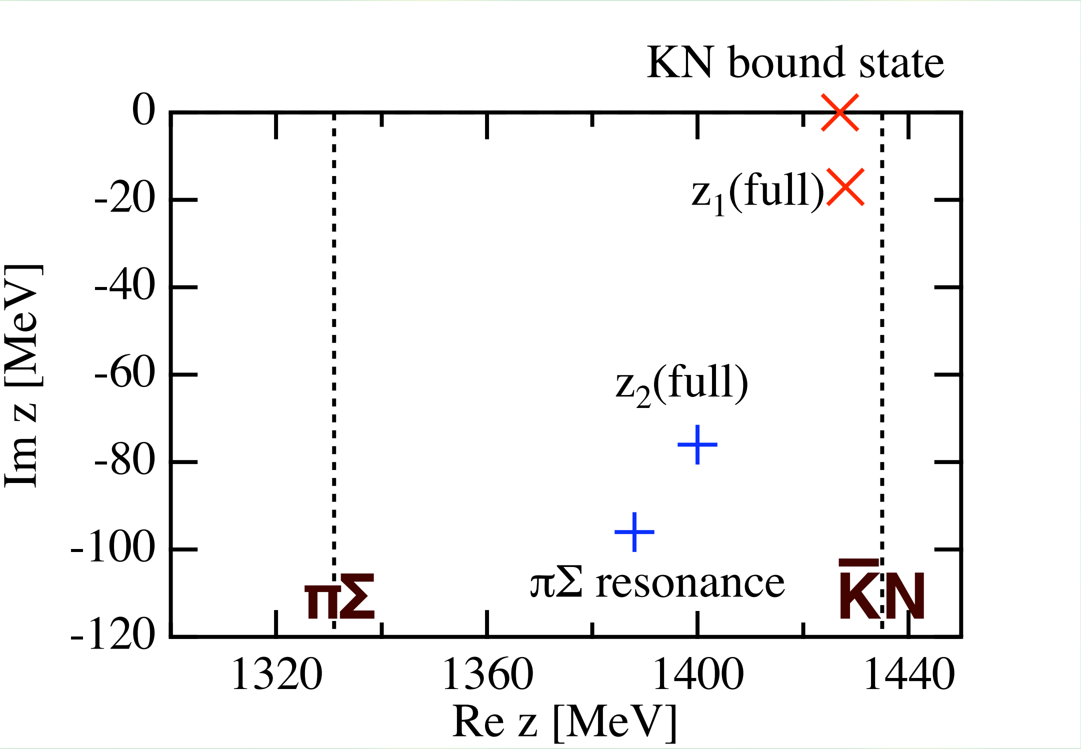
Origin of the two-pole structure

Chiral interaction

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

$$C_{ij} = \begin{array}{cc} \bar{K}N & \pi\Sigma \\ \end{array}$$
$$\begin{pmatrix} 3 & -\sqrt{\frac{3}{2}} \\ -\sqrt{\frac{3}{2}} & 4 \end{pmatrix}$$

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



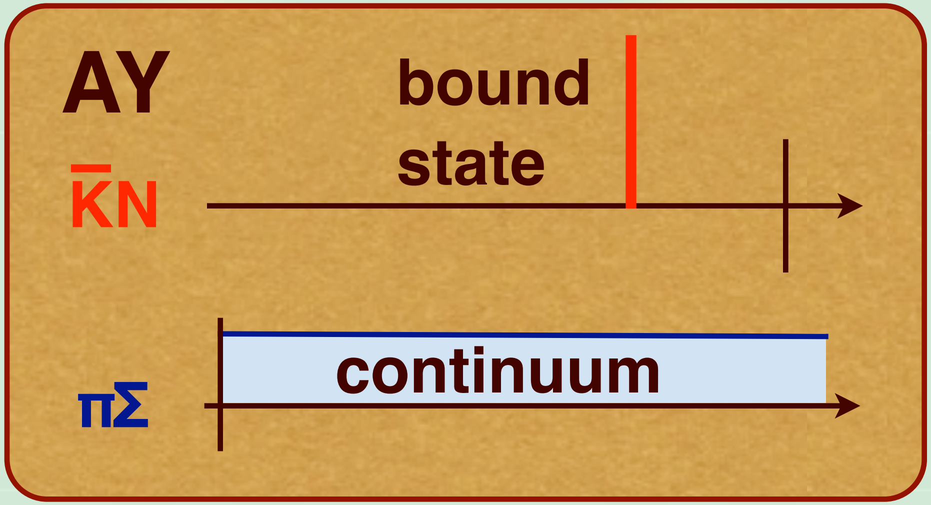
Very strong attraction in $\bar{K}$N (higher energy) --> bound state

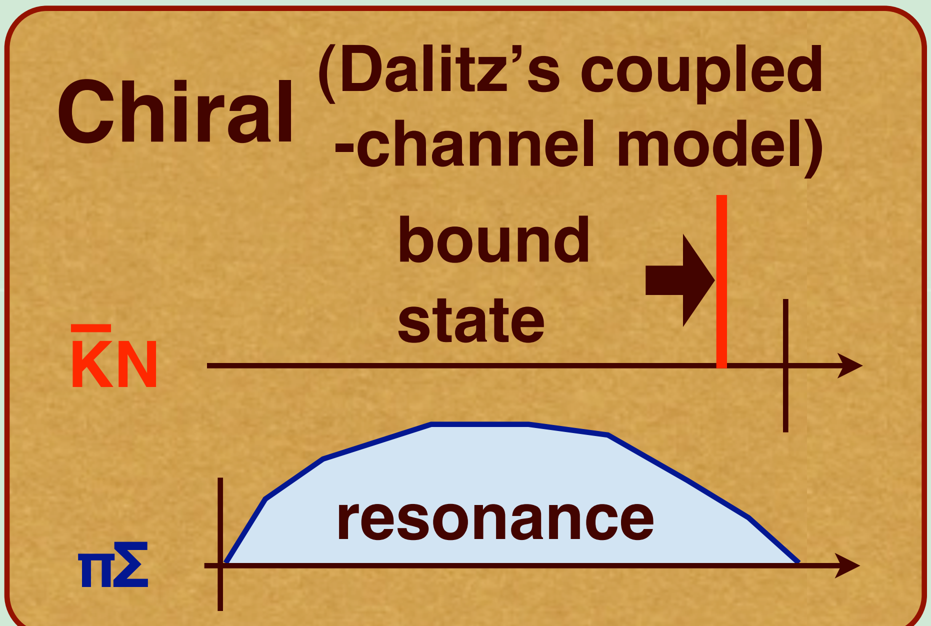
Strong attraction in πΣ (lower energy) --> resonance

Two attractive interactions --> Two states

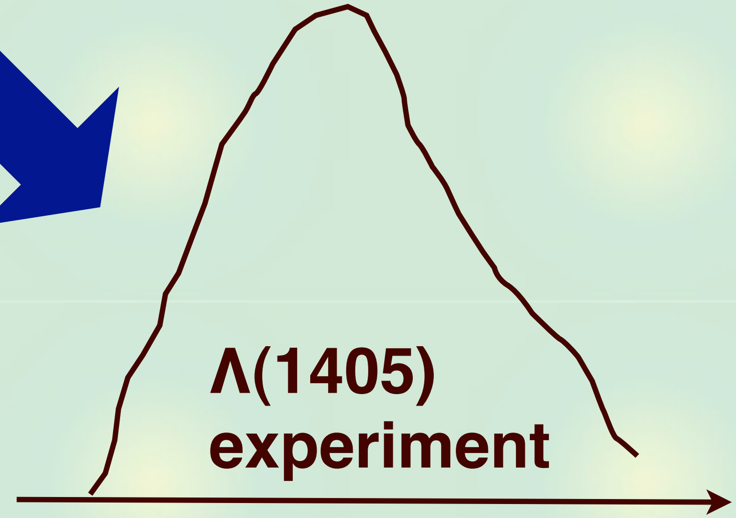
πΣ -> πΣ attraction : chiral SU(3) symmetry

Schematic illustration : AY vs Chiral



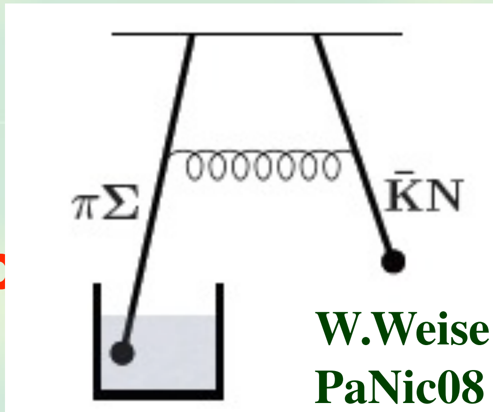


Feshbach resonance



Feshb on

reson



Summary 2 : $\bar{K}N$ interaction

We study the consequence of chiral SU(3) dynamics in $\bar{K}N$ phenomenology.

- **Single-channel effective $\bar{K}N$ interaction is attractive and forms K-pp bound system, about 20 MeV binding.**
- **Resonance structure in $\bar{K}N$ appears at around 1420 MeV <-- strong πΣ dynamics**
- **Two attractive interactions in $\bar{K}N$ and πΣ --> weaker effective $\bar{K}N$ interaction.**

T. Hyodo and W. Weise, Phys. Rev. C 77, 035204 (2008)
A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A804, 197 (2008)
A. Doté, T. Hyodo, W. Weise, Phys. Rev. C 79, 014003 (2009)

Three-body calculations for $\bar{K}NN$

Single-channel variational calculation (DHW)

B.E. = 20 ± 3 MeV, Γ(πYN) = 40 ~ 70 MeV

Coupled-channel Faddeev calculation (IS)
using chiral interaction

Y. Ikeda and T. Sato, Phys. Rev. C 77, 035204 (2008)

B.E. ~ 79 MeV, Γ(πYN) ~ 74 MeV

Why are they so different?
Inconsistency in theoretical calculations?

- πΣN dynamics?
  (existence of another N when eliminating πΣ channel)

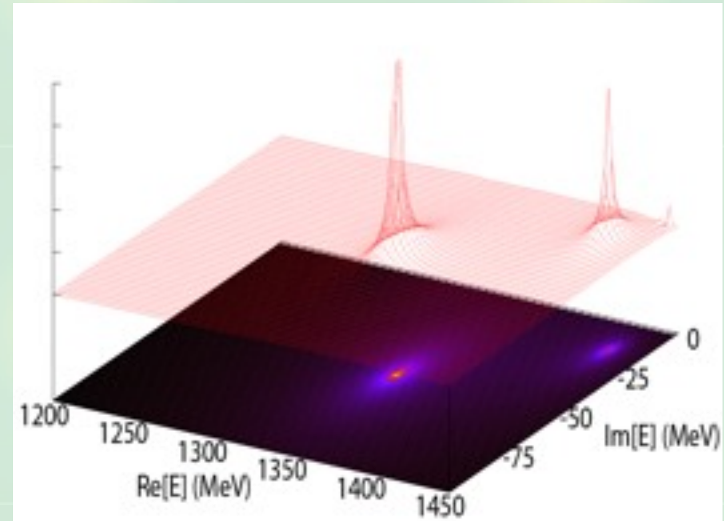
Y. Ikeda and T. Sato, arXiv:0809.1285 [nucl-th]

Two-pole structure for $\bar{K}NN$

Y. Ikeda, H. Kamano, T. Sato

Y. Ikeda, RCNP workshop, Dec. 25, 2008

"Chiral unitary like" model
: two poles in $\bar{K}N$-$\pi\Sigma$ amplitude



Solving Faddeev equation, they find
two poles in $\bar{K}NN$-$\pi\Sigma N$ amplitude

	pole I	pole II
$\bar{K}$- and N-exchanges in Z	$-14.5 - i28.7$	$-36.7 - i109.3$
$\bar{K}$-, N- and π-exchanges in Z	$-13.6 - i27.8$	$-45.8 - i104.0$
Full mechanism	$-13.7 - i29.0$	$-37.2 - i93.3$

--> Two poles for three-body system?

Two-pole structure for $\bar{K}NN$

Two poles in two-body scattering:

higher energy pole --> $\bar{K}N$ bound state
lower energy pole --> πΣ resonance

If there are two poles in three-body system, "single-channel" approach of DHW focuses on the higher energy pole of $\bar{K}NN$, since the πΣN channel has been eliminated.

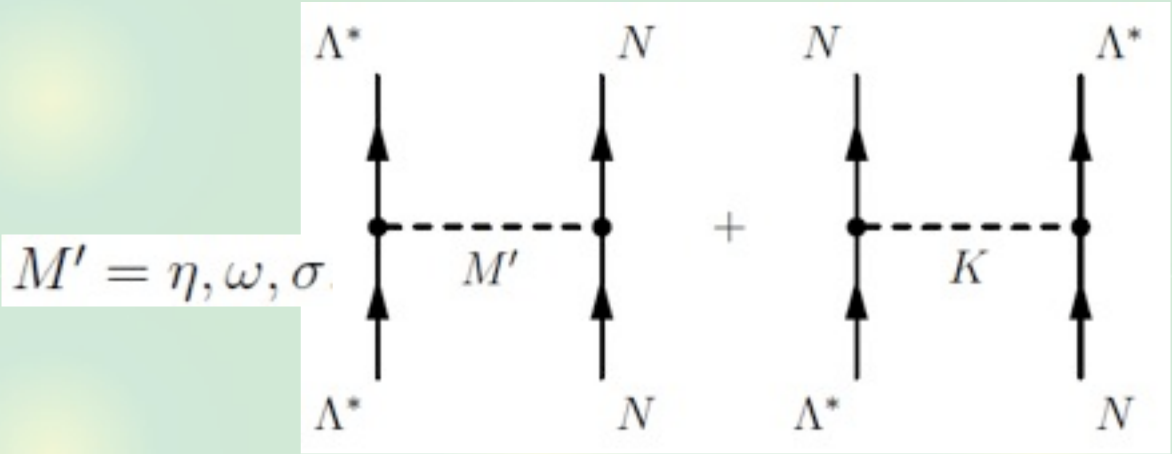
Then, where is the lower energy state in three-body system?

--> Schematic model calculation

Λ* hypernuclei model

Treating Λ(1405) as an elementary field, construct "Λ*N potential" through meson exchange

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



This approach may be justified by the observation that the Λ* seems to be surviving in K-pp system.

Attractive interaction (mainly from σ exchange) --> bound Λ*N, Λ*NN systems

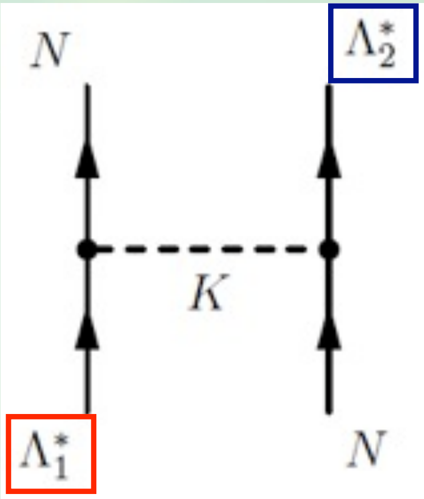
Λ* coupling constant : unknown (<-- FINUDA data).

Λ*N state in chiral model

Chiral dynamics --> two Λ* states : Λ^*_1, Λ^*_2

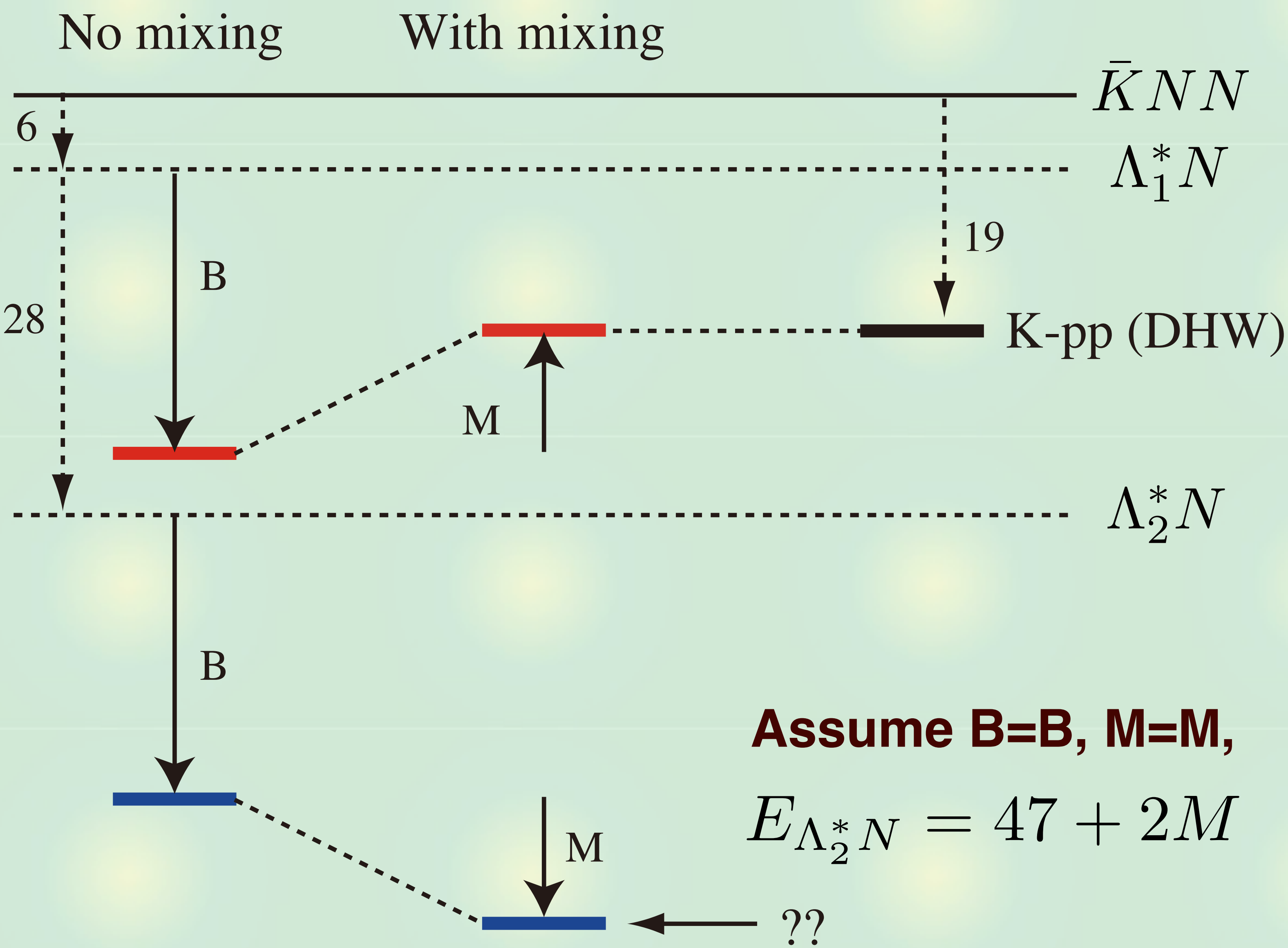
With sufficient attraction (σ exchange),
--> two Λ*N bound states in B=2 system : $\Lambda^*_1 N$, $\Lambda^*_2 N$

In addition, mixing of $\Lambda^*_1 N$ <--> $\Lambda^*_2 N$: level repulsion



Λ* coupling constant : unknown
We consider this model simulates the thee-body calculation
--> DHW result = $\Lambda^*_1 N$

Λ*N state in chiral model : result would be...



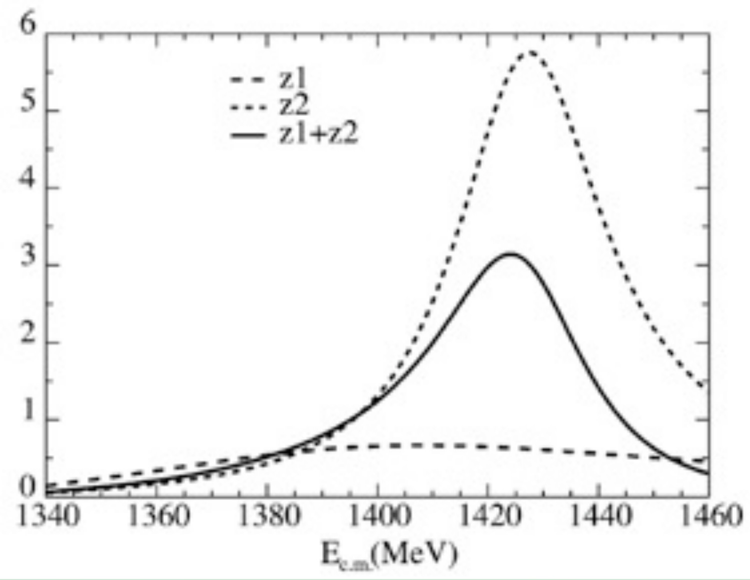
Assume B=B, M=M,

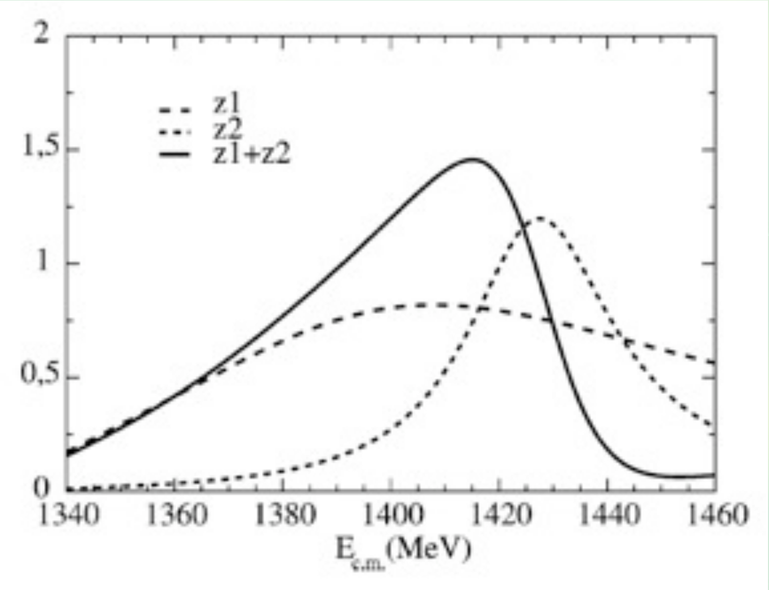
$$E_{\Lambda_2^* N} = 47 + 2M \quad [\mathrm{MeV}]$$

Λ*N state in chiral model

Chiral dynamics --> two Λ* states : Λ^*_1, Λ^*_2

$$|\Lambda(1405)\rangle = \underbrace{a|\Lambda^*_1\rangle}_{\bar{K}N} + \underbrace{b|\Lambda^*_2\rangle}_{\pi\Sigma}$$





D. Jido, *et al*, Nucl. Phys. Rev. A725, 181 (2003)

B=2 system : $\Lambda^*_1 N$, $\Lambda^*_2 N$

$$|B=2, S=-1\rangle = a'|\Lambda^*_1 N\rangle + b'|\Lambda^*_2 N\rangle$$

Summary 3 : $\bar{K}$NN system

B=2 and S=-1 system in chiral dynamics

- Possibility of two poles for three-body $\bar{K}$NN state in Faddeev approach.

  Y. Ikeda, RCNP workshop, Dec. 25, 2008

- If this is the case, DHW result may corresponds to higher energy Λ^*_1N state.

  estimate of Λ^*_2N ~ 47 + 2M MeV?

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

- When the lower energy channel is strongly interacting, coupled-channel approach would be mandatory.