$\Lambda(1405)$ Resonance in Chiral SU(3)-Dynamics

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Introduction : (well) known facts on Λ(1405)

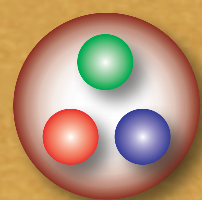
$\Lambda(1405) : J^P = 1/2^-, I = 0$

Mass : 1406.5 ± 4.0 MeV

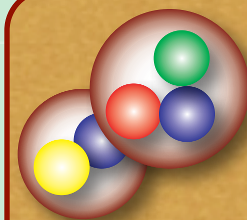
Width : 50 ± 2 MeV

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

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



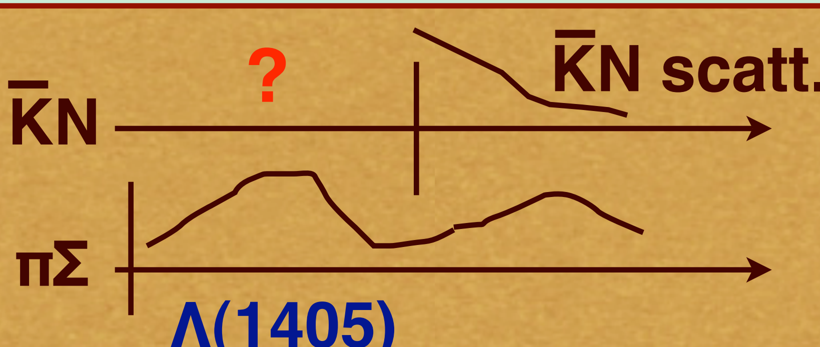
N. Isgur and G. Karl, PRD18, 4187 (1978)



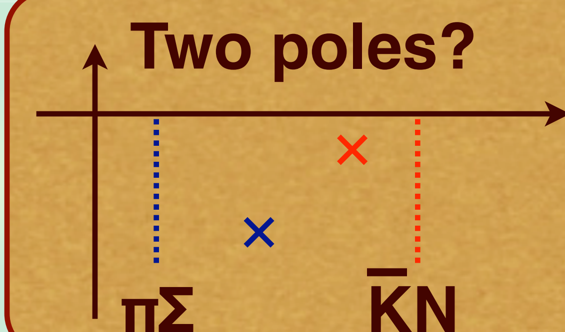
Coupled channel
multi-scattering

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

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



Two poles?



Contents

Phenomenology of $\bar{K}N$ interaction

Construction of local $\bar{K}N$ potential by chiral dynamics

With W. Weise, in preparation (about to submit)

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

With A. Doté, W. Weise, in preparation

Structure of the $\Lambda(1405)$

Behavior at large Nc

With L. Roca, D. Jido, in preparation

(Dynamical or CDD (genuine quark state) ?

With D. Jido, A. Hosaka, in preparation

Electromagnetic properties

With T. Sekihara, D. Jido, in preparation)

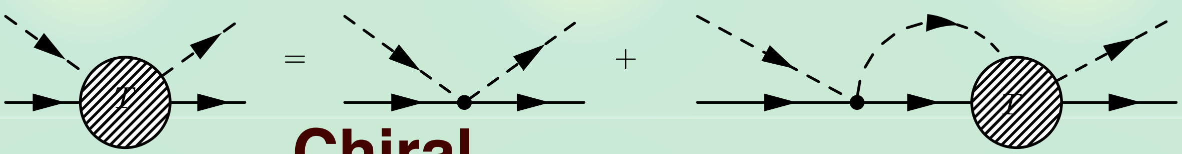
next opportunity...

Chiral unitary approach

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

- ○ Interaction <-- chiral symmetry
- ○ Amplitude <-- unitarity (coupled channel)

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



Chiral
(WT interaction)

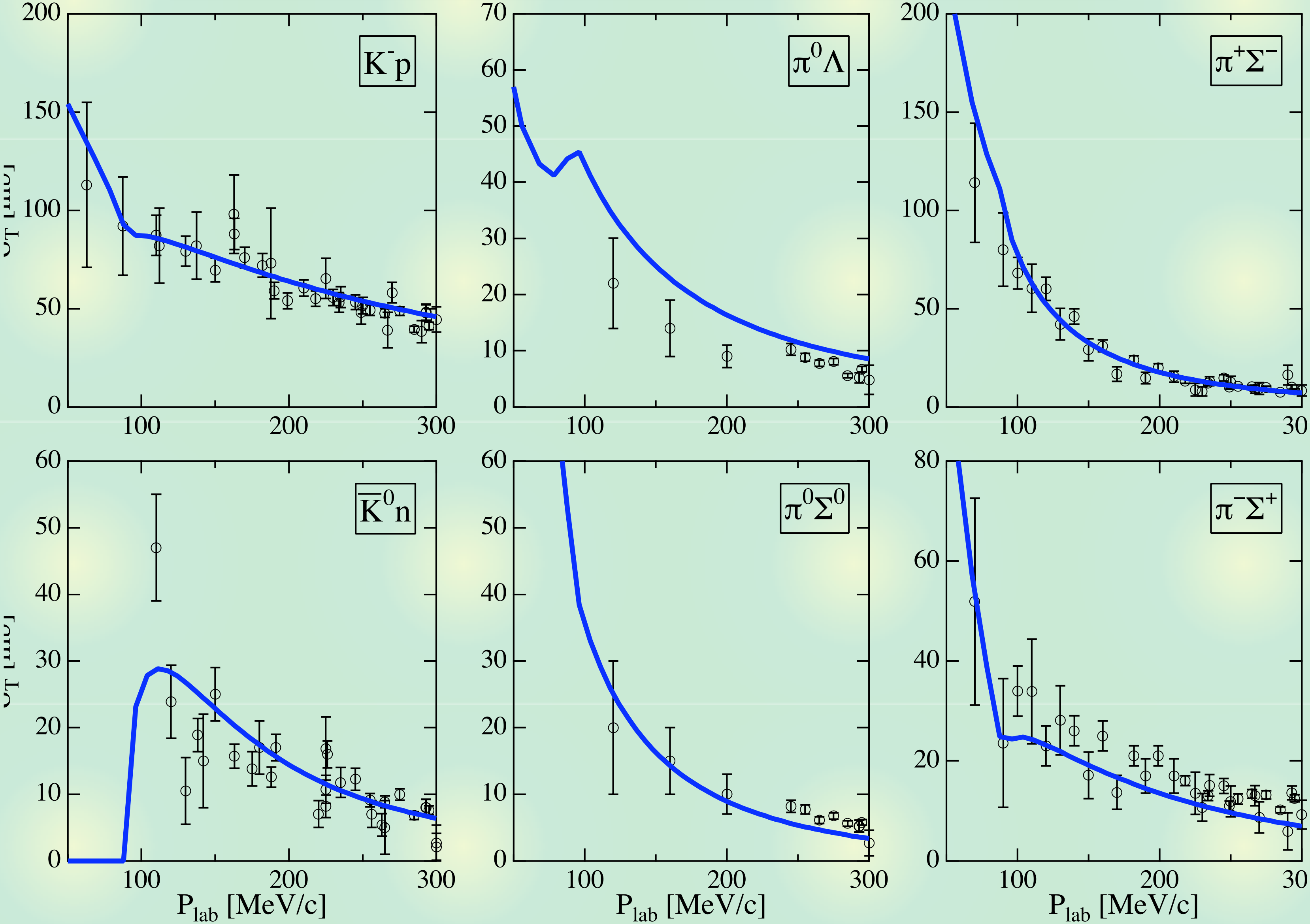
cutoff
(subtraction
constant)

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

Interaction is strong
Bound state below threshold

➡ **non-perturbative framework**

Total cross sections of K^-p scattering



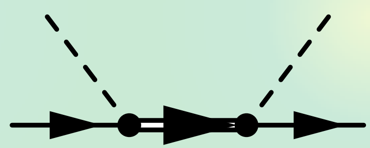
T. Hyodo, S.I. Nam, D. Jido, A. Hosaka, Phys. Rev. C68, 018201 (2003)

Description of the resonances

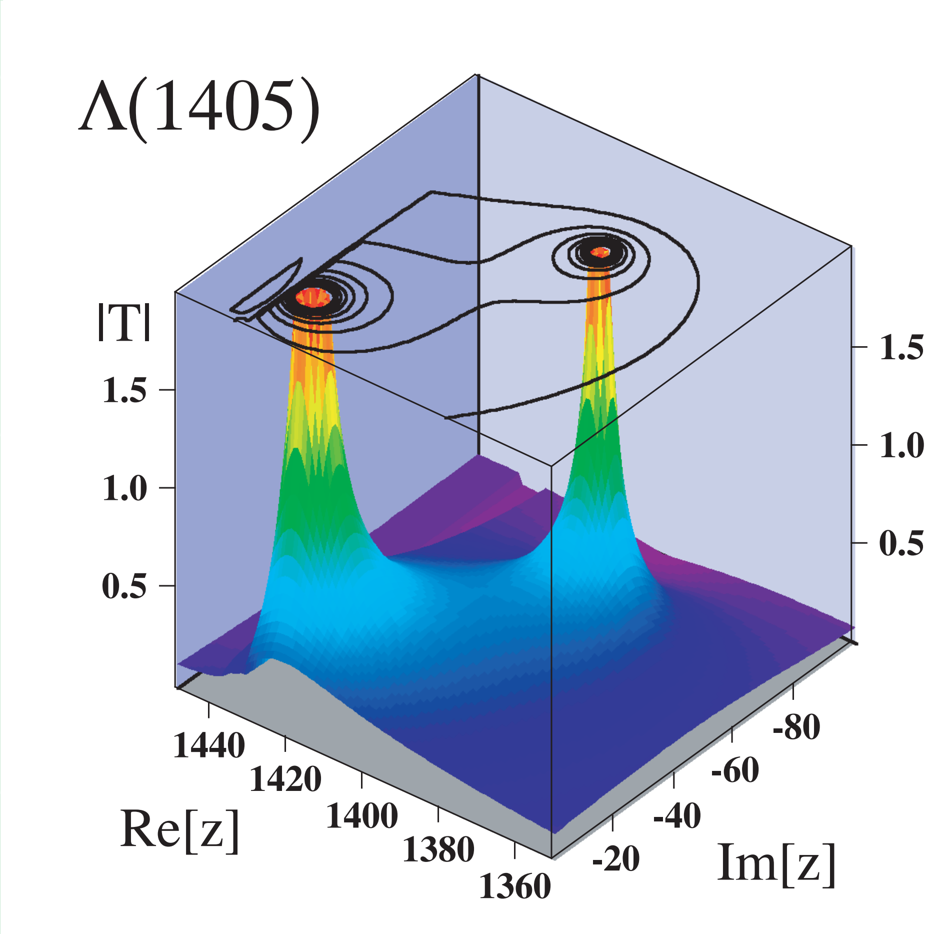
Poles of the amplitude : resonance

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

$\sim$

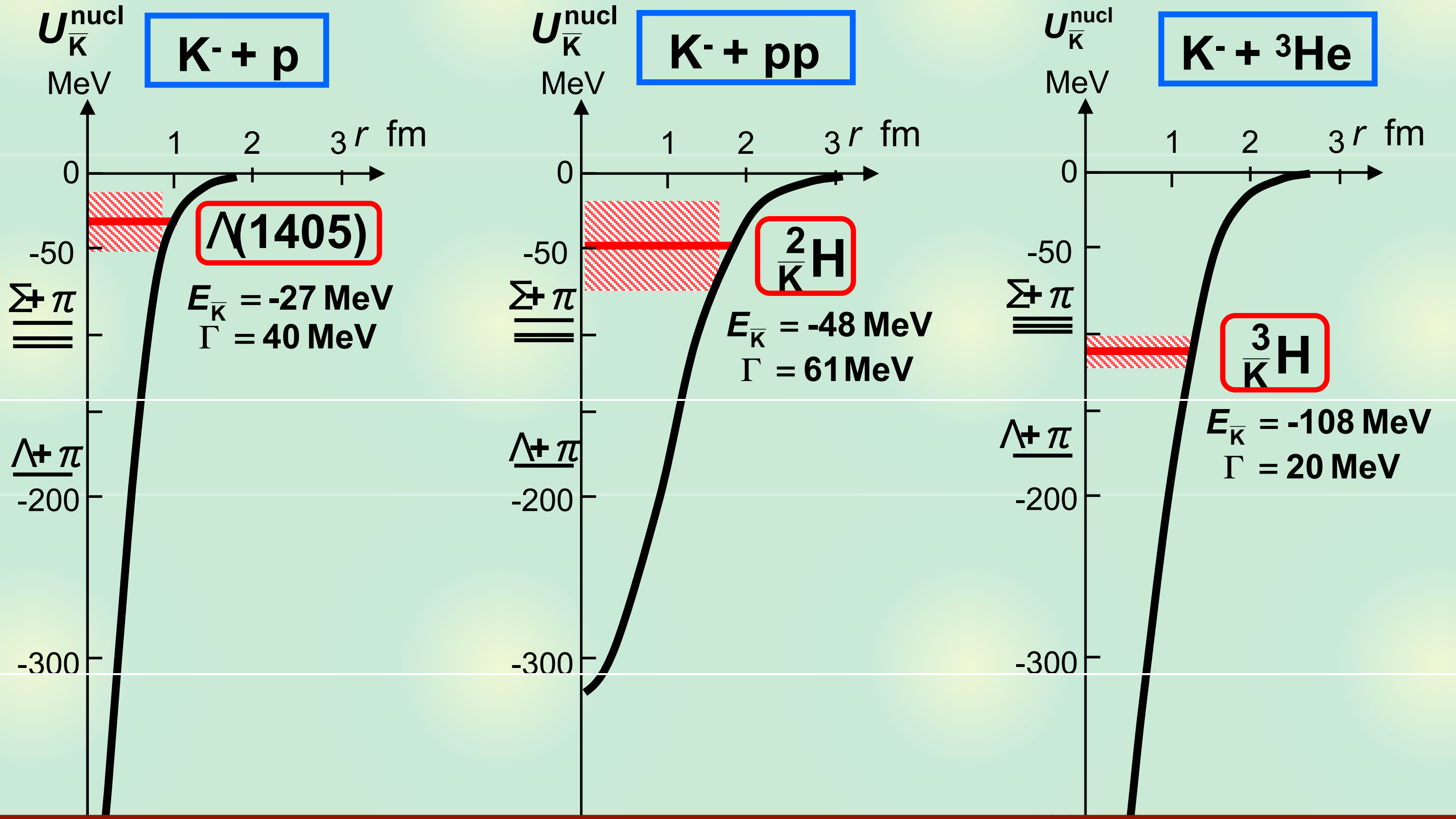


Real part	**Mass**
Imaginary part	**Width/2**
Residues	**Couplings**



Successful description of $\bar{K}N$ scattering
Two poles are found for 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

Result of chiral dynamics --> local potential

Coupled-channel BS $T_{ij}(\sqrt{s})$
+ real interaction $V_{ij}(\sqrt{s})$

(exact)

Single-channel BS $T^{\text{eff}}(\sqrt{s}) = T_{ii}(\sqrt{s})$
+ complex interaction $V^{\text{eff}}(\sqrt{s})$

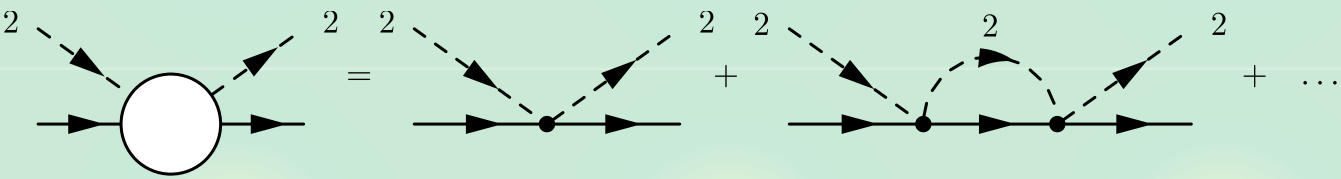
(approximate)

Schrödinger equation $f^{\text{eff}}(\sqrt{s}) \sim T^{\text{eff}}(\sqrt{s})$
+ local potential
complex, energy-dependent $U^{\text{eff}}(r, \sqrt{s})$

few-body kaonic nuclei

Construction of the single channel interaction

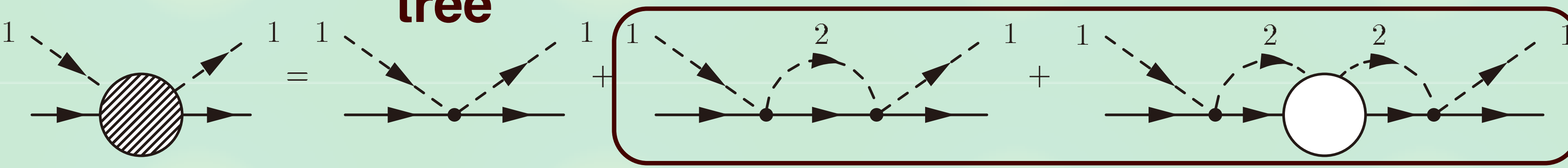
Resummation of the channel to be eliminated



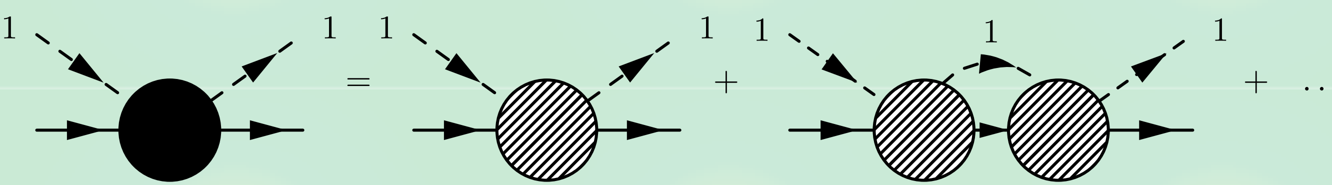
$$T_{22}^{\mathrm{single}} = V_{22} + V_{22} G_2 T_{22}^{\mathrm{single}}$$

tree

effect of channel 2



$$V^{\mathrm{eff}} = V_{11} + V_{12} G_2 V_{21} + V_{12} G_2 T_{22}^{\mathrm{single}} G_2 V_{21}$$

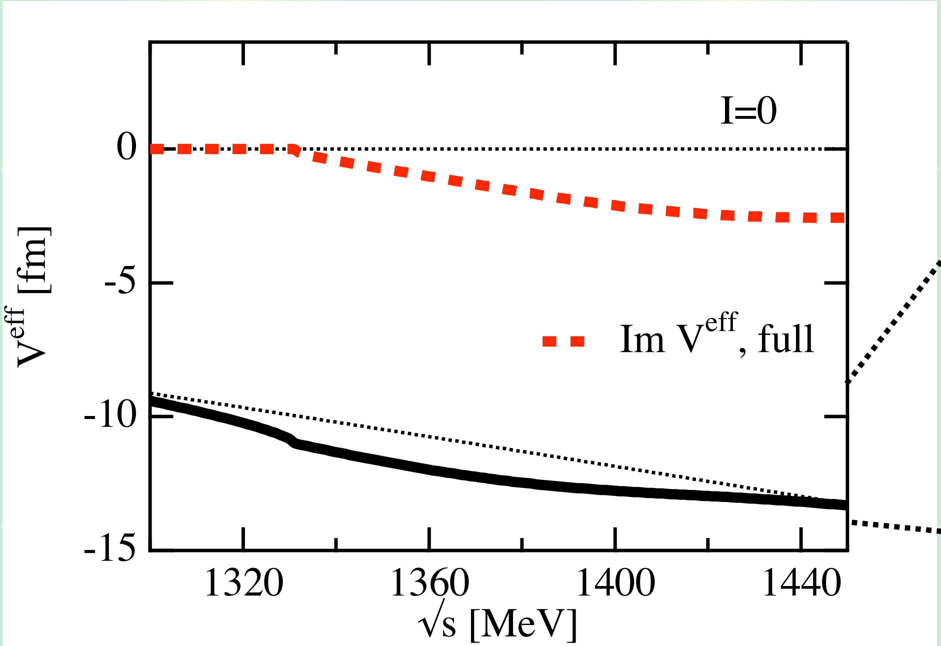


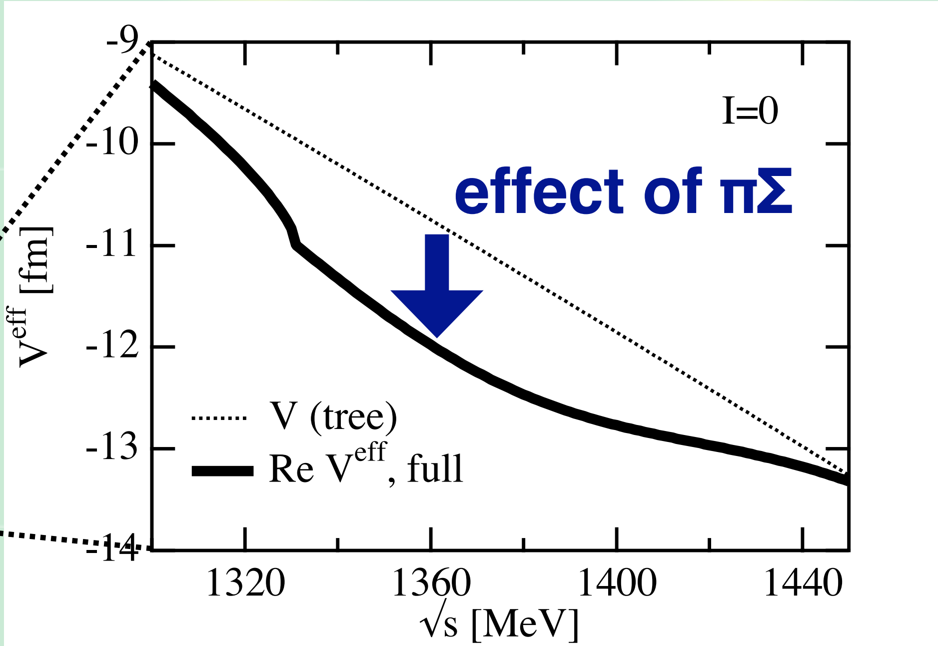
single channel

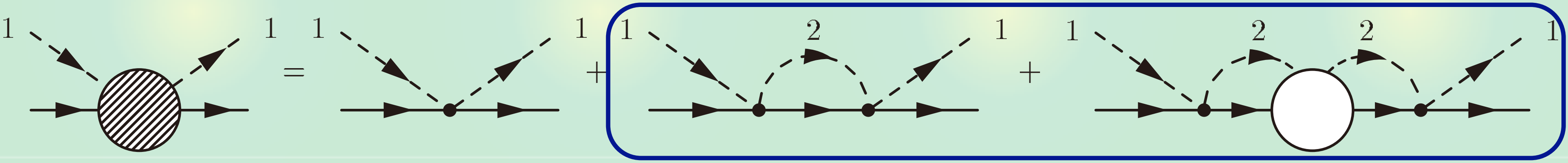
$$T_{11} = T^{\mathrm{eff}} = V^{\mathrm{eff}} + V^{\mathrm{eff}} G_1 T^{\mathrm{eff}}$$

Equivalent to the coupled-channel equations

Single channel $\bar{K}N$ interaction with $\pi\Sigma$ dynamics



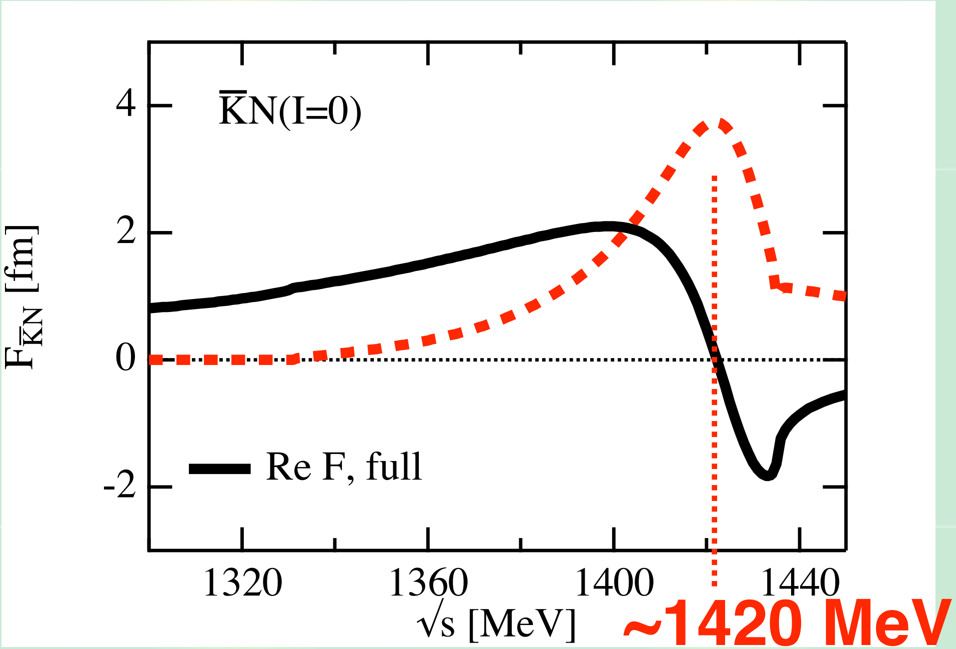


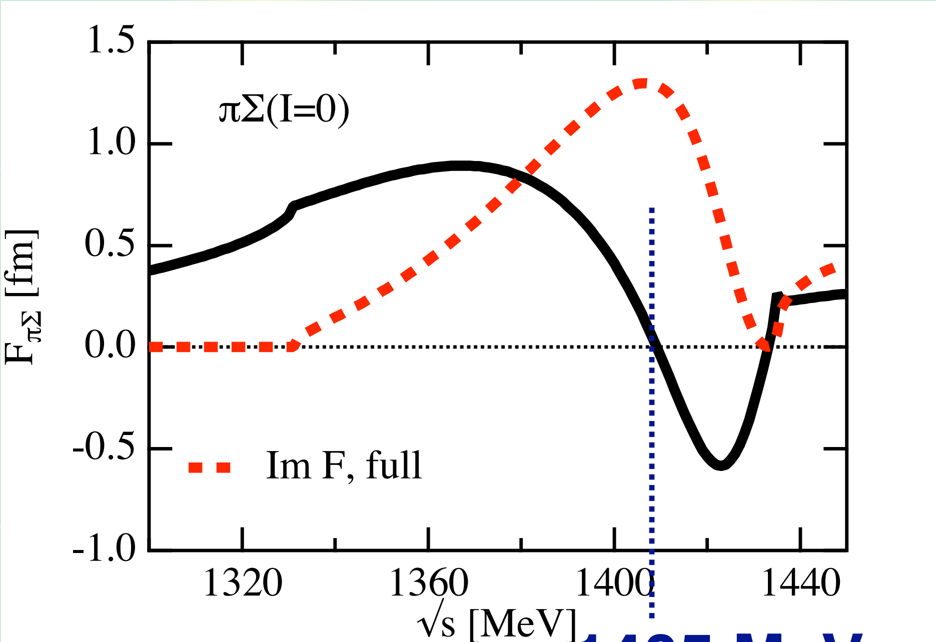


Strength : comparable with the WT term

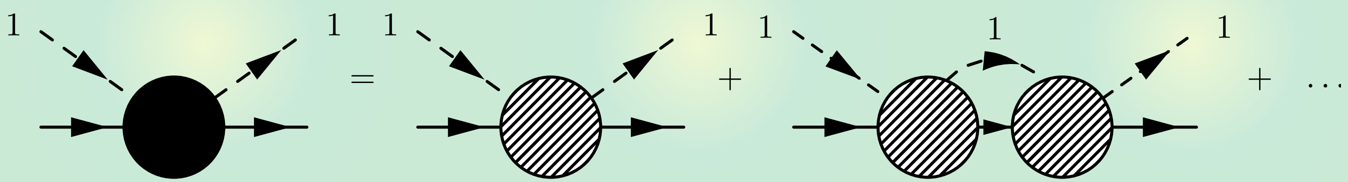
- ~ 1/2 of phenomenological (Akaishi-Yamazaki) potential
- $\pi\Sigma$ resummation : small but pole exists

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





~1405 MeV Experiment



Resonance in $\bar{K}N$: around 1420 MeV

<-- two-pole structure (coupled-channel)

Binding energy : B = 12 MeV <--> 27 MeV

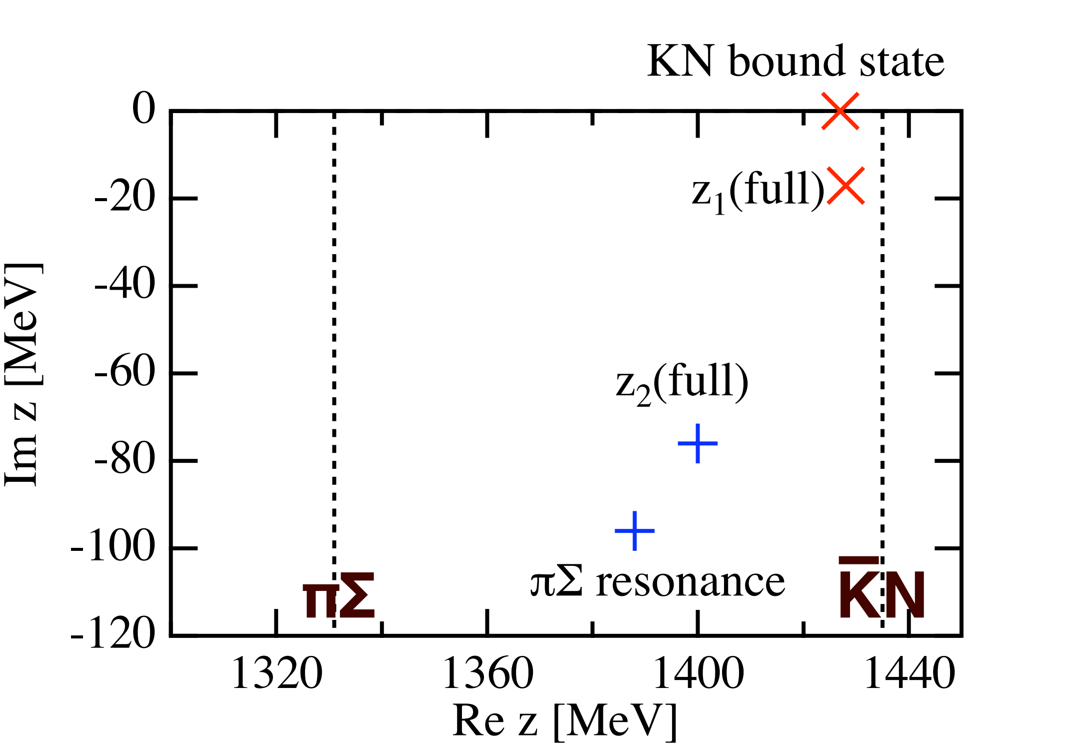
Origin of the two-pole structure

Chiral interaction

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

$$\begin{array}{ccc} & \bar{K}N & \pi\Sigma \\ C_{ij} = & \left(\begin{array}{c} 3 \\ -\sqrt{\frac{3}{2}} \end{array}\right. & \left.\begin{array}{c} -\sqrt{\frac{3}{2}} \\ 4 \end{array}\right) \end{array}$$

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



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

Two poles : natural consequence of chiral interaction

higher order correction? --> theoretical uncertainty (later)

B. Borasoy, R. Nissler, W. Weise, Eur. Phys. J. A25, 79-96 (2005)

Comparison with phenomenological potential

Chiral interaction

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

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

phenomenological

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

$$\begin{array}{cc} & \begin{array}{cc} \bar{K}N & \pi\Sigma \end{array} \\ v_{ij}(r) \sim - & \begin{pmatrix} 436 & 412 \\ 412 & 0 \end{pmatrix} g(r) \end{array}$$

Absence of πΣ diagonal coupling

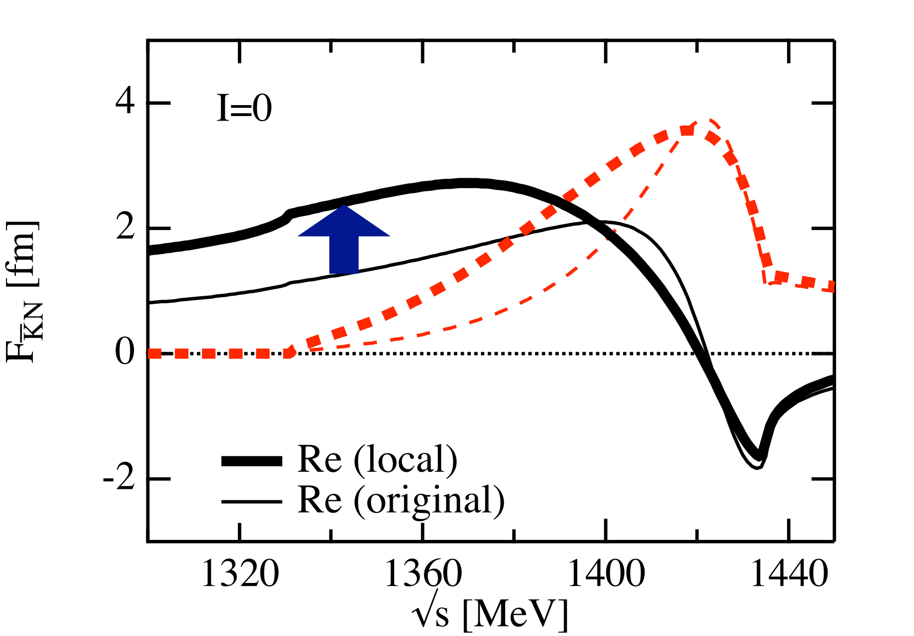
--> absence of πΣ dynamics, resonance

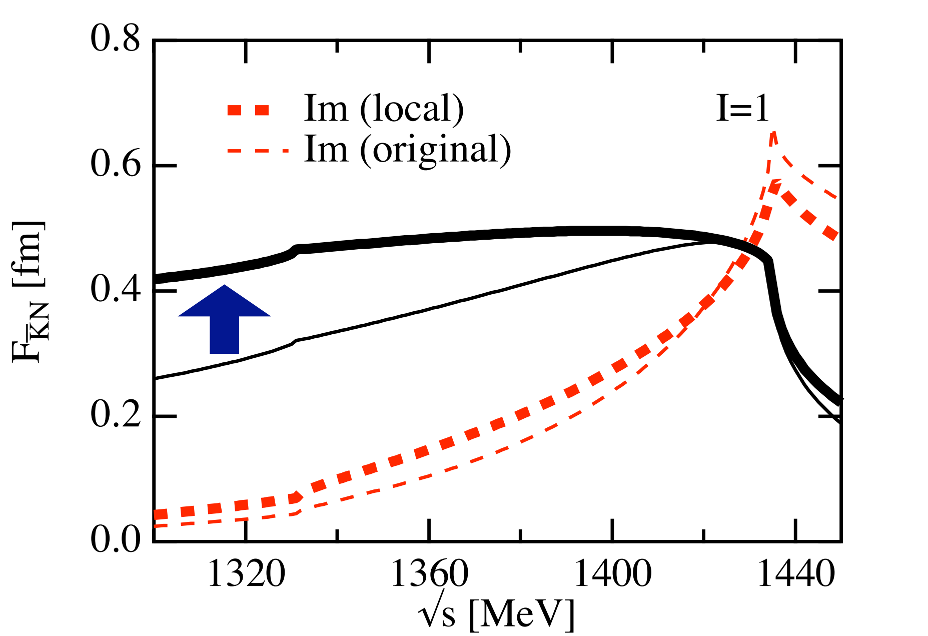
--> strong (×2) attractive interaction in $\bar{K}$N

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

energy dependence : derivative coupling

$\bar{K}N$ amplitude with local potential





$$U(r,\sqrt{s}) = \frac{M_N V^{\text{eff}}(\sqrt{s})}{2\sqrt{s}\tilde{\omega}(\sqrt{s})} g(r) \qquad g(r) = \frac{e^{-r^2/b^2}}{\pi^{3/2}b^3}$$

$b = 0.47$ fm **: to reproduce the resonance**

agreement around threshold : OK

Deviation at lower energy : model dependence

BS eq. <--> local potential + Schrödinger eq.

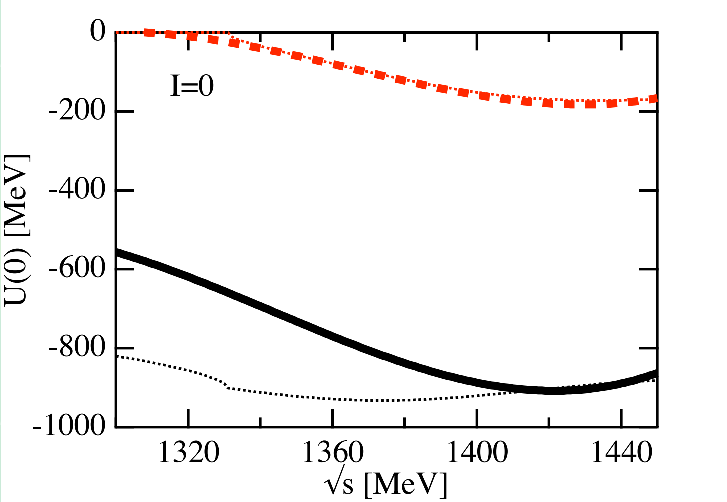
Summary 1 : $\bar{K}N$ interaction

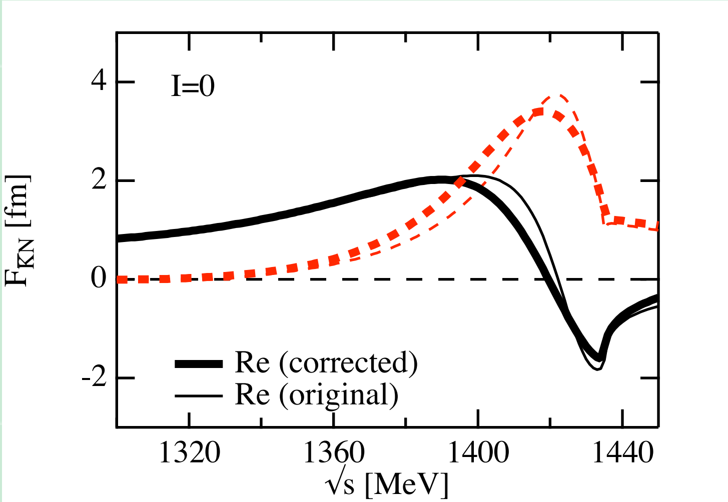
We derive single-channel local potentials based on chiral SU(3) dynamics.

- The strength of the $\bar{K}N$ interaction is **comparable with the WT term**.
- Resonance structure in $\bar{K}N$ appears at around **1420 MeV** <-- two-pole Λ(1405).
- Two poles are the consequence of **two attractive interactions in $\bar{K}N$ and πΣ**.
- Extrapolation of local potential to the deep region is **model dependent**.

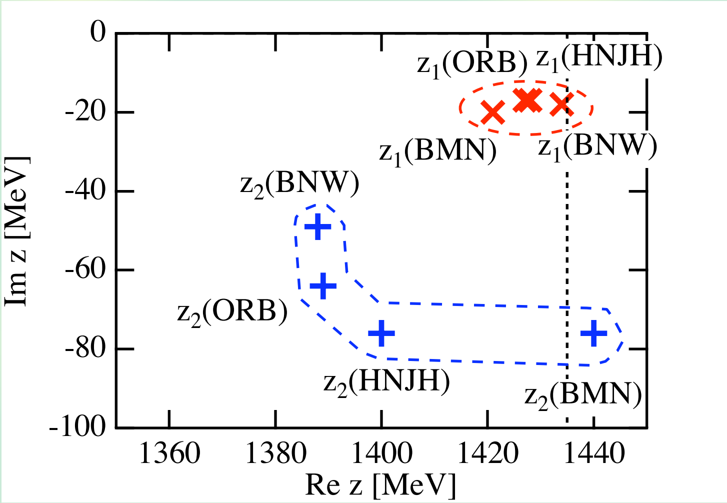
Theoretical uncertainties

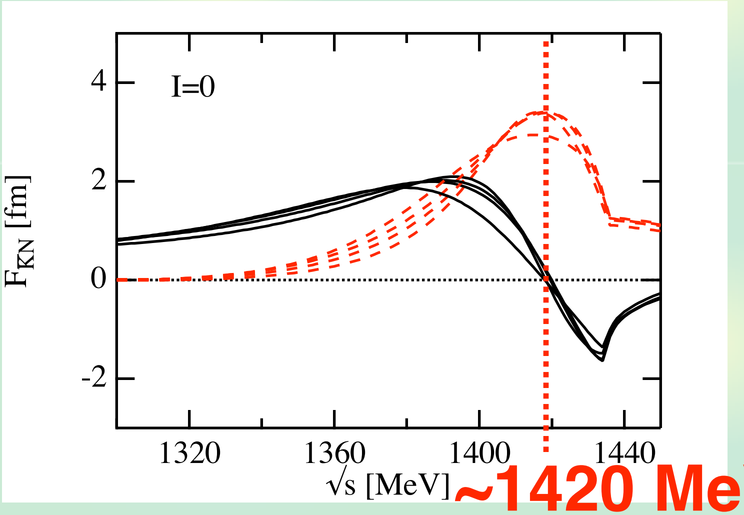
Strength of the potential





Different models of chiral dynamics

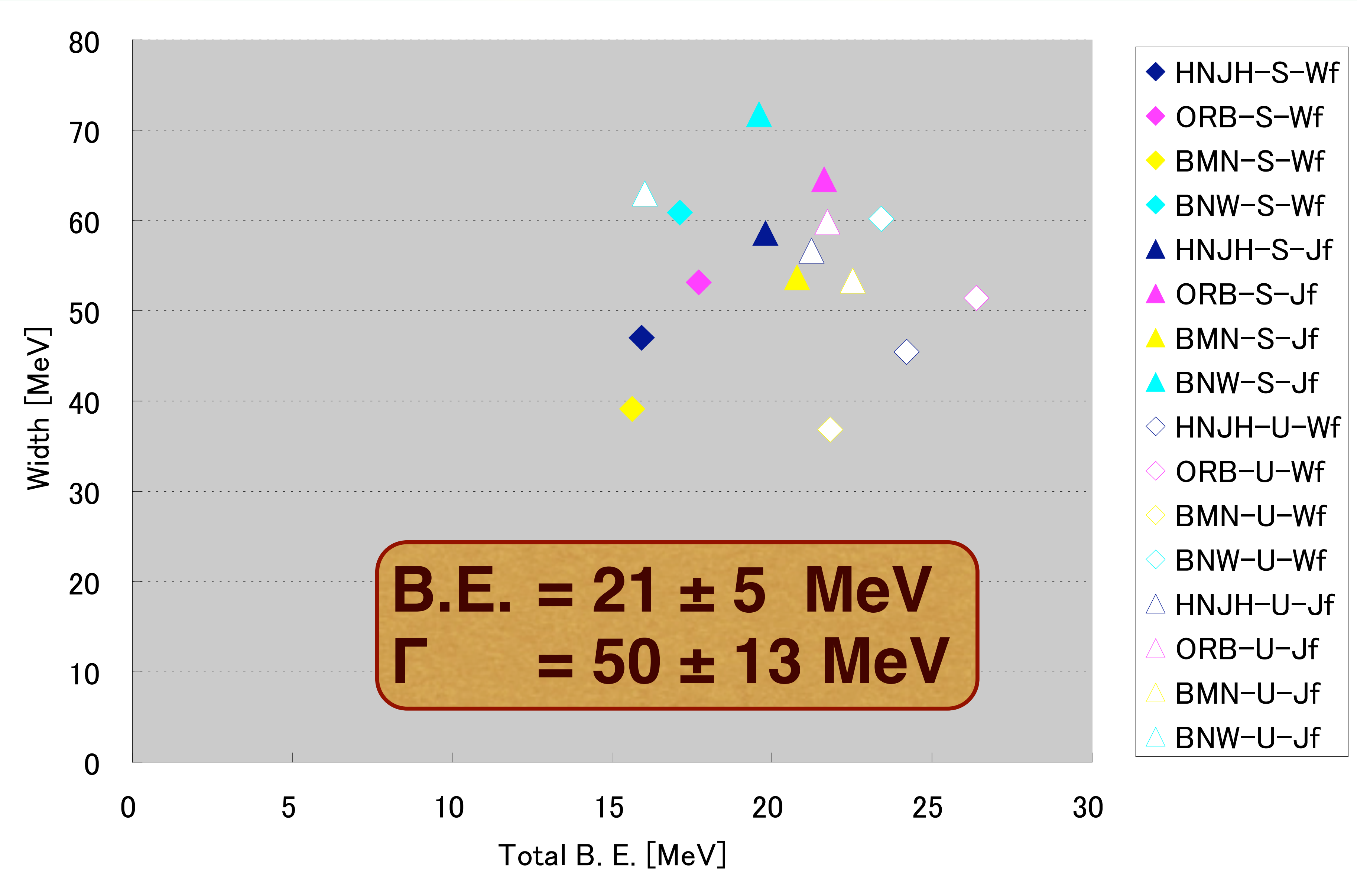




~1420 MeV

Application to the few-body anti-K system

$\bar{K}NN$ state with local potential



B.E. = 21 ± 5 MeV

Γ = 50 ± 13 MeV

Summary 2 : $\bar{K}$NN system

We study the $\bar{K}$NN system with chiral SU(3) potentials in a variational approach.

With theoretical uncertainties,

B.E. = 21 ± 5 MeV
Γ = 50 ± 13 MeV

Phenomenological potential (~ 2 times stronger than ours)	B.E. ~ 48 MeV Γ ~ 60 MeV

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

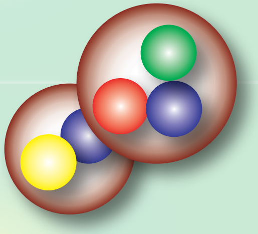
Faddeev with chiral interaction (separable, non-rel, ...?)	B.E. ~ 79 MeV Γ ~ 74 MeV

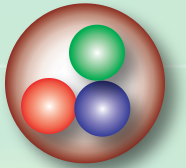
Y. Ikeda, T. Sato, Phys. Rev. C76, 035203 (2003)

Width : $\bar{K}$NN -> πYN
No two-nucleon absorption : $\bar{K}$NN -> YN

Structure of dynamically generated resonances

Resonances ~ quasi-bound two-body states





<--> in some case, CDD pole (genuine state).

c.f. ρ meson in ππ scattering

<-- originate from the contracted resonance propagator in higher order terms

J.A. Oller, E. Oset and J.R. Pelaez, Phys. Rev. D59, 074001 (1999)

G. Ecker, J. Gasser, A. Pich, and E. de Rafael, Nucl. Phys. B321, 311 (1989)

analysis of Nc scaling --> $\rho \sim q\bar{q}$

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

Baryon resonances?

--> analysis of Nc scaling

Nc scaling in the model

Introduce the Nc scaling into the model and study the behavior of resonance.

$$m \sim \mathcal{O}(1), \quad M \sim \mathcal{O}(N_c), \quad f \sim \mathcal{O}(\sqrt{N_c})$$

Leading order WT interaction has Nc dep.

$$V = -C\frac{\omega}{2f^2} \sim \mathcal{O}(1/N_c) \quad (\Leftarrow C \sim \mathcal{O}(1))$$

(for baryon and Nf > 2)

$$V = -C\frac{\omega}{2f^2}, \quad \underline{C \sim \mathcal{O}(N_c)} \quad \Rightarrow V \sim \mathcal{O}(1)$$

T. Hyodo, D. Jido and A. Hosaka, Phys. Rev. Lett. 97, 192002 (2006)
T. Hyodo, D. Jido and A. Hosaka, Phys. Rev. D75, 034002 (2007)

c.f. meson-meson scattering : $V_{\mathrm{LO}} \sim \mathcal{O}(1/N_c)$ **= trivial**
Nontrivial Nc dependence of the interaction is in NLO.

S = -1 I = 0 channel in SU(3) basis

Coupling strengths with Nc dependence

$$V = -C\frac{\omega}{2f^2} \qquad f \sim \mathcal{O}(\sqrt{N_c})$$

$$C_{ij}^{SU(3)}(N_c) = \begin{array}{c} \begin{matrix} \mathbf{1} & \mathbf{8} & \mathbf{8} & \mathbf{27} \end{matrix} \\ \begin{pmatrix} \boxed{\frac{9}{2}+\frac{N_c}{2}} & 0 & 0 & 0 \\ & 3 & 0 & 0 \\ & & 3 & 0 \\ & & & -\frac{1}{2}-\frac{N_c}{2} \end{pmatrix} \end{array}$$

C ∝ Nc : finite interaction at Nc -> ∞

Attractive interaction in singlet channel
: strong enough to make a bound state

S = -1 I = 0 channel in Isospin basis

Coupling strengths with Nc dependence

$$
\begin{array}{cc}
 & \begin{array}{cccc} \bar{K}N & \pi\Sigma & \eta\Lambda & K\Xi \end{array} \\
C^{I}_{ij}(N_c) = & \begin{pmatrix}
\frac{1}{2}(3+N_c) & -\frac{\sqrt{3}}{2}\sqrt{-1+N_c} & \frac{\sqrt{3}}{2}\sqrt{3+N_c} & 0 \\
 & 4 & 0 & \frac{\sqrt{3+N_c}}{2} \\
 & & 0 & -\frac{3}{2}\sqrt{-1+N_c} \\
 & & & \frac{1}{2}(9-N_c)
\end{pmatrix}
\end{array}
$$

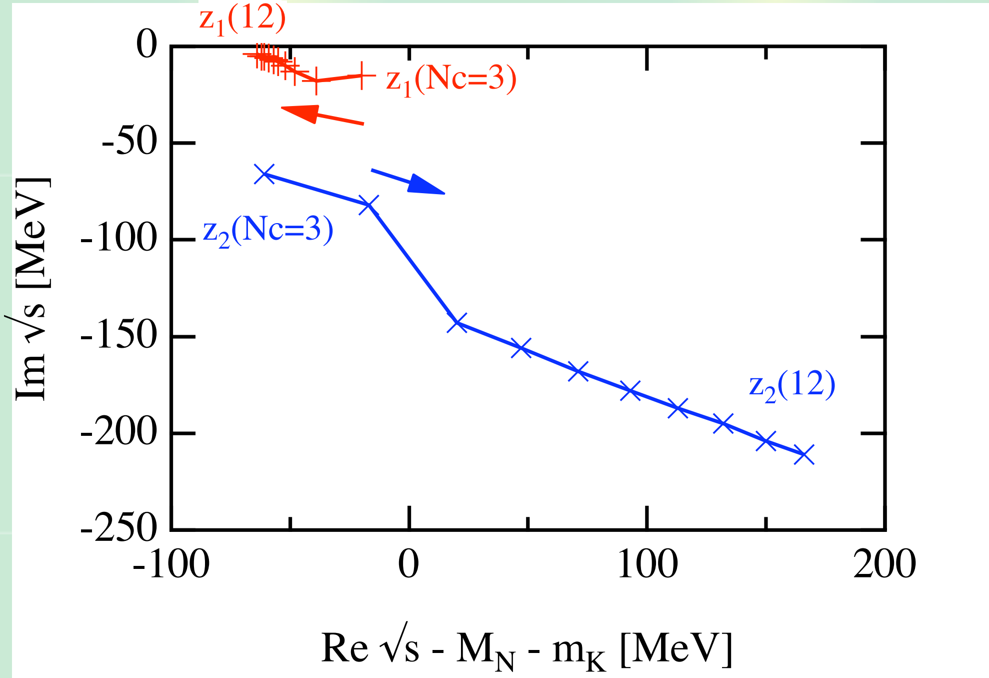
Off-diagonal couplings vanish at Nc -> ∞

Attractive interaction in $\bar{K}$N -> $\bar{K}$N

: strong enough to make a bound state

KΞ -> KΞ : attractive -> repulsive for Nc > 9

Pole trajectories with varying Nc



1 bound state and 1 dissolving resonance

$$\Gamma_R \neq \mathcal{O}(1)$$

~ non-qqq (i.e. dynamical) structure

Excited qqq baryon in large Nc

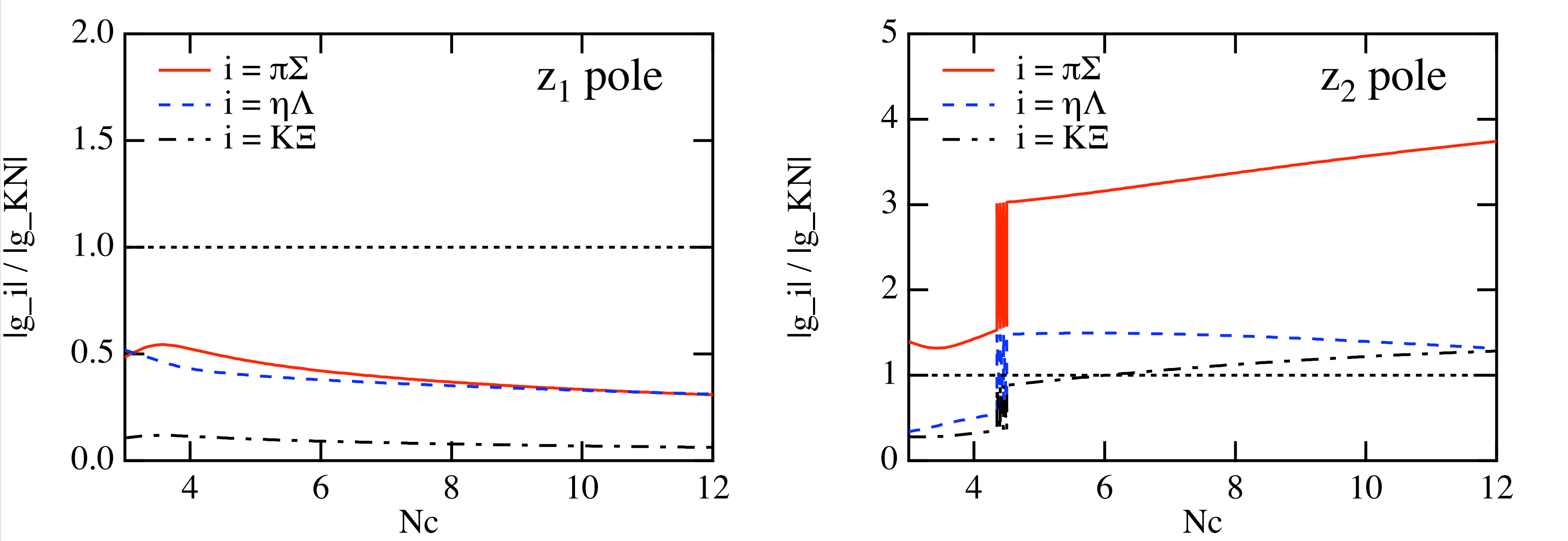
$$M_R \sim \mathcal{O}(N_c), \quad \Gamma_R \sim \mathcal{O}(1)$$

T.D. Cohen, D.C. Dakin and A. Nellore, Phys. Rev. D69, 056001 (2004)

Isospin conponents of the poles

Residues in the isospin basis

$$\frac{|g_i|}{|g_{\bar{K}N}|}\begin{cases}< 1 : \bar{K}N \text{ dominant}\\ > 1 : \text{non } \bar{K}N \text{ dominant}\end{cases}$$



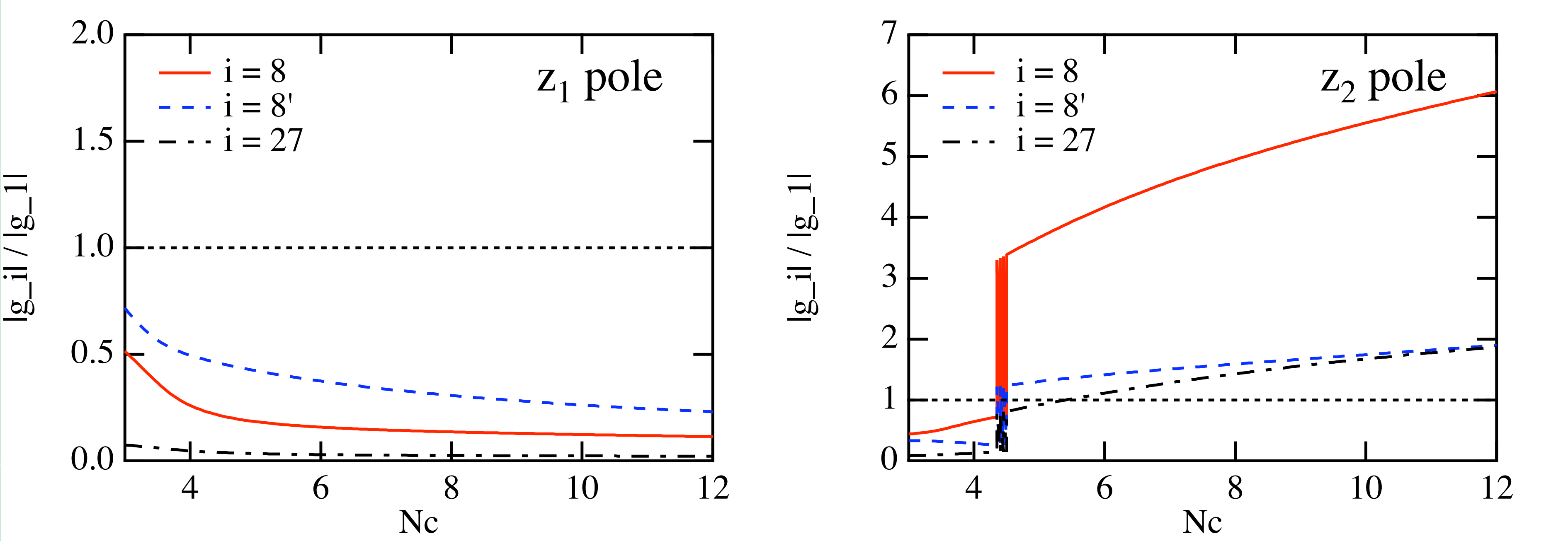
bound state
$\bar{K}$N dominant

dissolving
other components

SU(3) components of the poles

Residues in the SU(3) basis

$$\frac{|g_i|}{|g_{\mathbf{1}}|}\begin{cases} < 1 : \text{singlet dominant} \\ > 1 : \text{non singlet dominant} \end{cases}$$



bound state
1 dominant

dissolving
other components

Summary 3 : Nc behavior of Λ(1405)

We study the Nc scaling of the Λ(1405)

- **Large Nc limit**

  Existence of a bound state in "1" and $\bar{K}N$ channel even in the large Nc limit

- **Behavior around Nc = 3**

  1 bound state and 1 dissolving pole
  : signal of the non-qqq state.

  Residues of the would-be-bound-state
  : dominated by "1" and $\bar{K}N$
  : consistent with large Nc limit.