$\Lambda(1405)$ in chiral dynamics

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2008, Mar. 21st

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

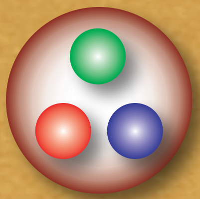
$\Lambda(1405) : J^P = 1/2^-, I = 0$

Mass : 1406.5 ± 4.0 MeV

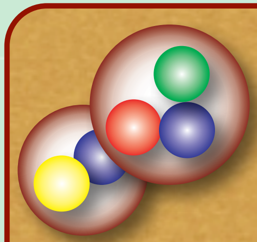
Width : 50 ± 2 MeV

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

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



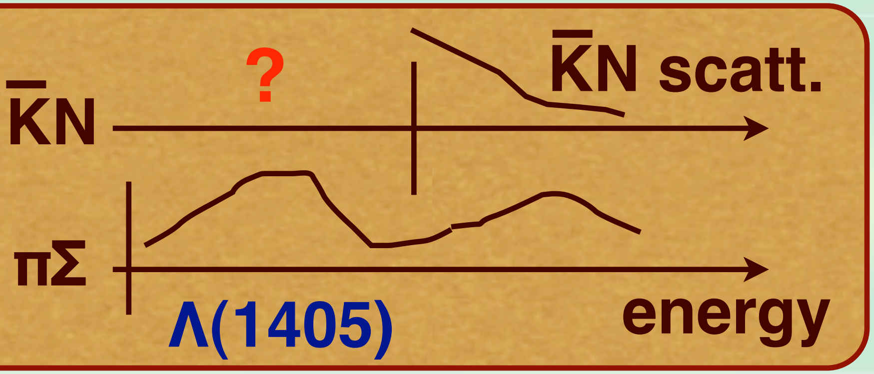
N. Isgur and G. Karl, PRD18, 4187 (1978)



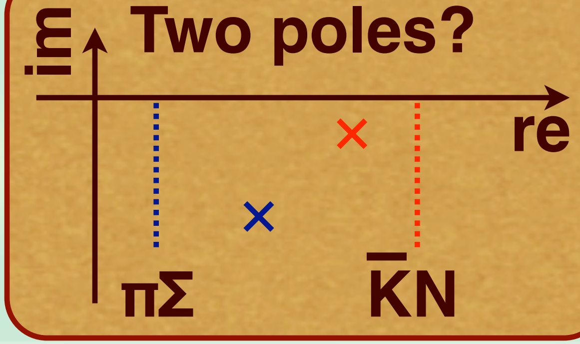
Coupled channel
multi-scattering

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

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



Two poles?



Contents

Introduction to chiral unitary appraoch

- Nc Behavior and quark structure

  T. Hyodo, D. Jido, L. Roca, 0712.3347 [hep-ph], Phys. Rev. D, in press.

- Dynamical or CDD (genuine quark state) ?

  T. Hyodo, D. Jido, A. Hosaka, 0803.2550 [nucl-th]

Phenomenology of $\bar{K}N$ interaction (main)

- Construction of local $\bar{K}N$ potential by chiral dynamics
- Implication of the two-pole structure

  T. Hyodo, W. Weise, 0712,1613 [nucl-th], Phys. Rev. C, in press.

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

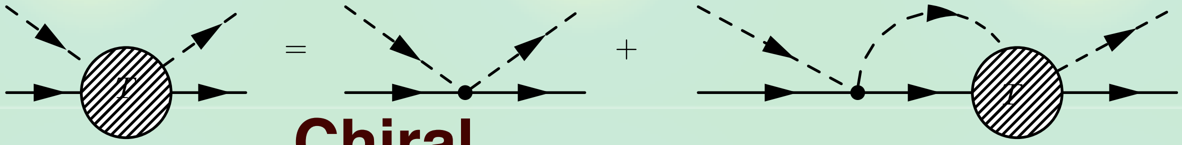
  A. Doté, T. Hyodo, W. Weise, 0802.0238 [nucl-th], Nucl. Phys. A, in press

Chiral unitary approach

S = -1, $\bar{\text{K}}$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)

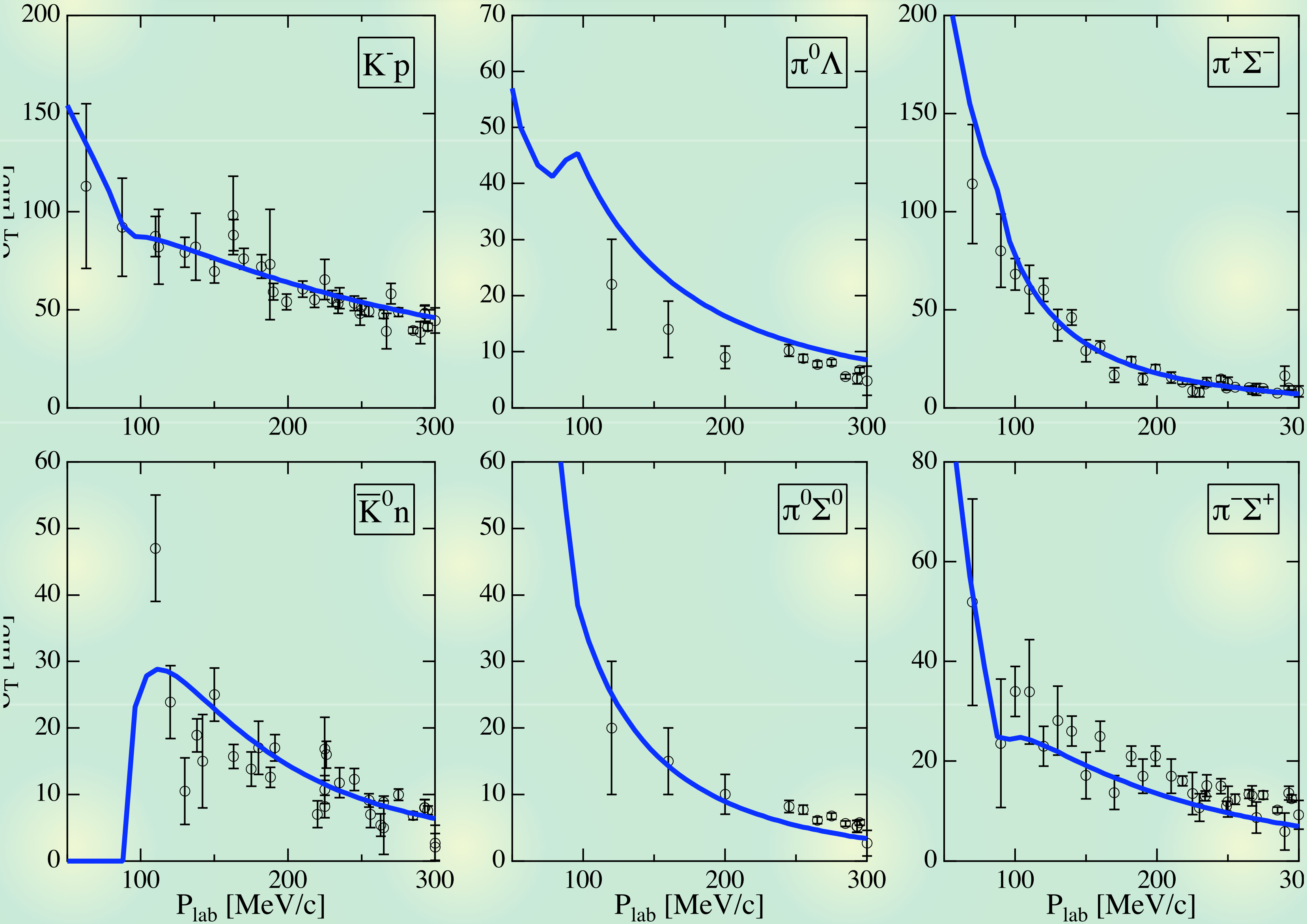
N. Kaiser, P. B. Siegel, W. Weise, Nucl. Phys. A594, 325 (1995)
E. Oset, A. Ramos, Nucl. Phys. A635, 99 (1998)
J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001)
M.F.M. Lutz, E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002),
.... many others

strong attraction (<- chiral)
bound state below threshold

➡

non-perturbative framework

Total cross sections of K^-p scattering



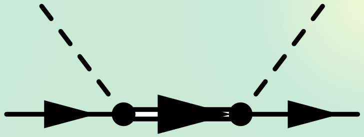
T. Hyodo, S.I. Nam, D. Jido, A. Hosaka, Phys. Rev. C68, 018201 (2003)

Description of the resonances

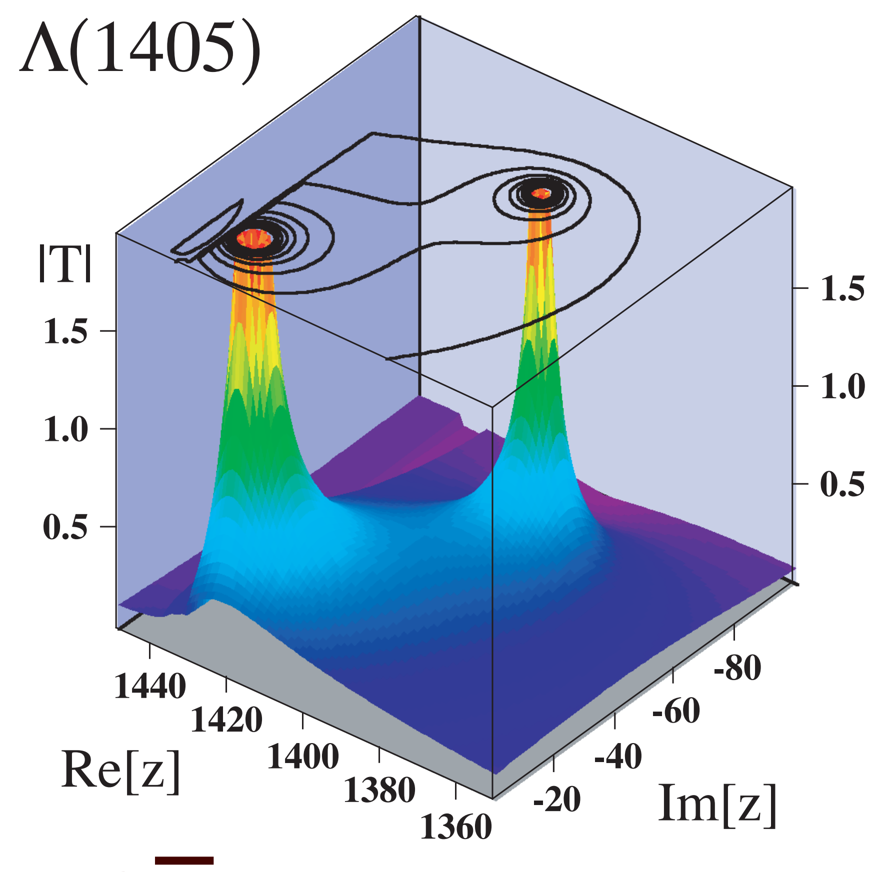
Poles of the amplitude : resonance

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

$\sim$



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



◆ **Successful description of $\bar{\text{K}}$N scattering**

◆ **Two poles for the Λ(1405)**

Structure of Λ(1405) : two analysis

Schematic decomposition of Λ(1405)

$$|\,\Lambda(1405)\,\rangle = N_{MB}|\,B\,\rangle|\,M\,\rangle + N_3|\,qqq\,\rangle + N_5|\,qqqq\bar{q}\,\rangle + \dots$$

Analysis of Nc behavior

$N_3 << 1$

T. Hyodo, D. Jido, L. Roca, 0712.3347 [hep-ph], Phys. Rev. D, in press.

Analysis of natural renormalization

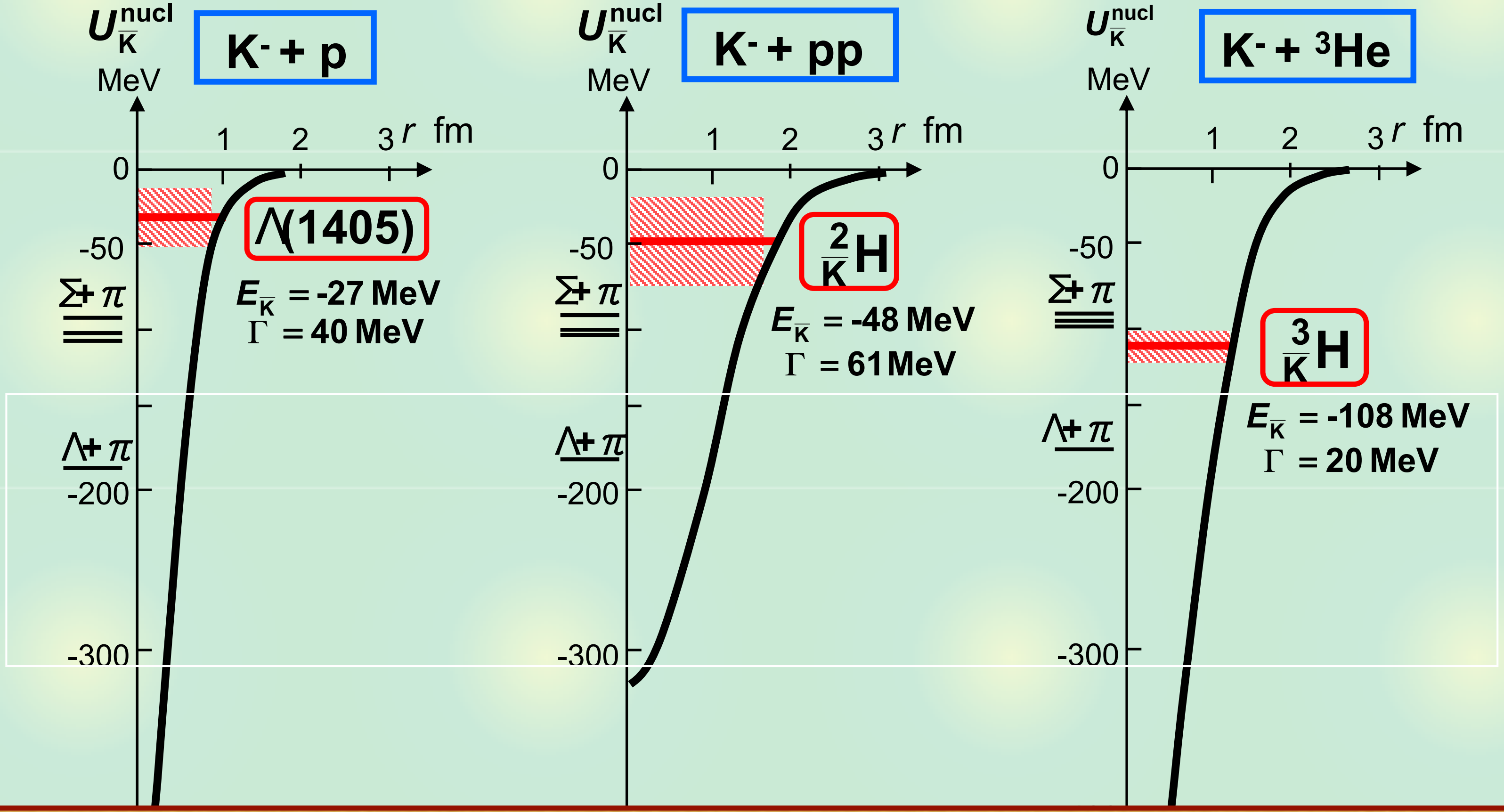
N_{MB} dominates

T. Hyodo, D. Jido, A. Hosaka, 0803.2550 [nucl-th]

→ Both analyses consistently indicate the dominance of N_{MB} component

Not trivial ! c.f. rho meson, N(1535), ...

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 --> single channel 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)**

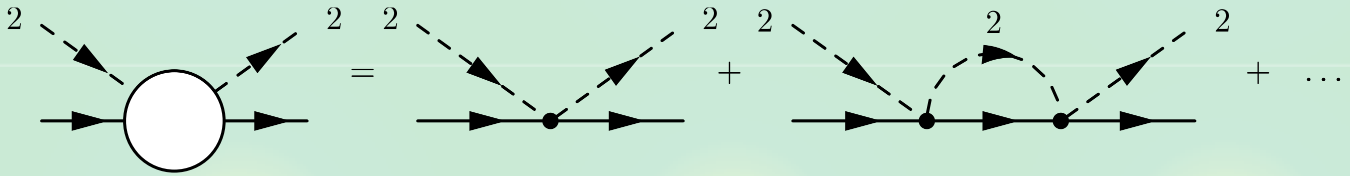
Schrödinger equation $f^{\text{eff}}(\sqrt{s}) \sim T^{\text{eff}}(\sqrt{s})$
+ local potential
complex, energy-dependent $U^{\text{eff}}(r, \sqrt{s})$

↓

few-body kaonic nuclei

Construction of the single channel interaction

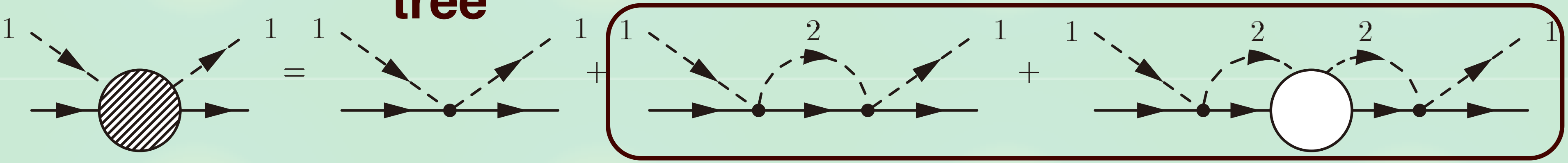
Channels 1 and 2 --> effective int. in 1



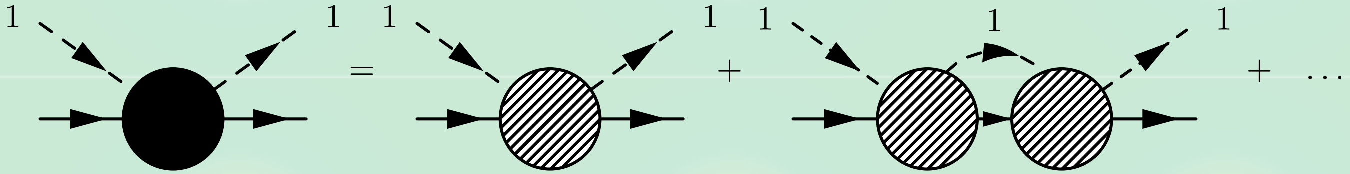
$$T_{22}^{\text{single}} = V_{22} + V_{22} G_2 T_{22}^{\text{single}}$$

effect of channel 2

tree



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

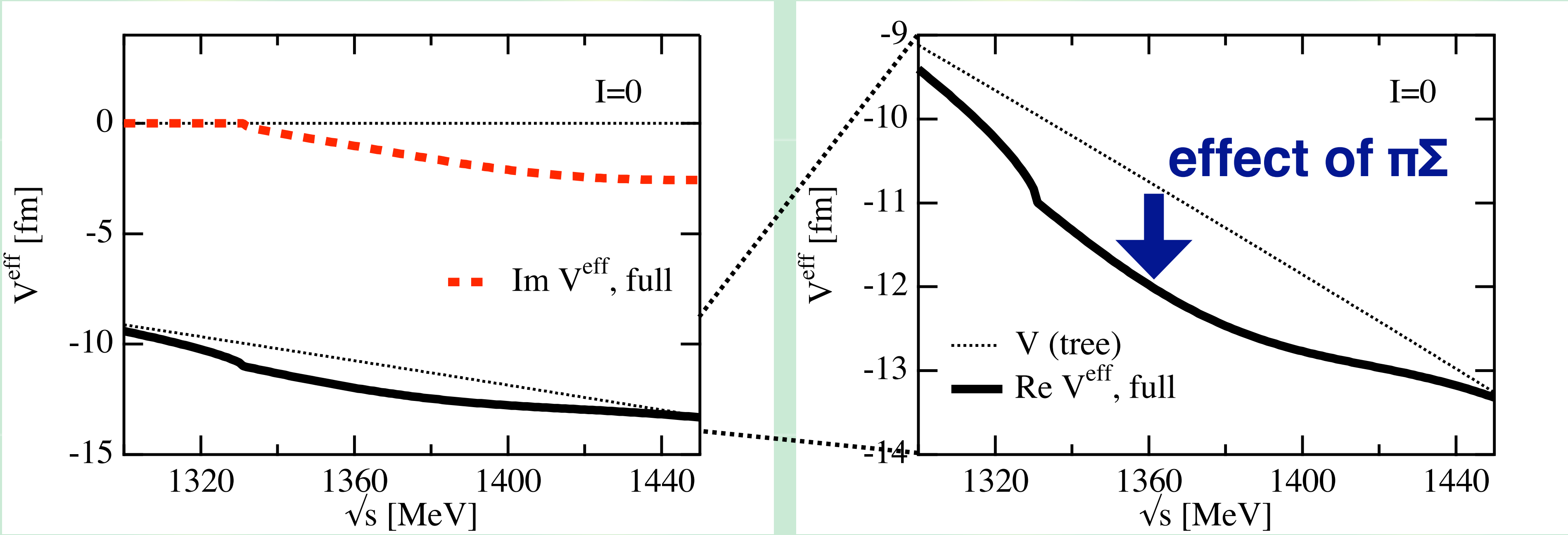


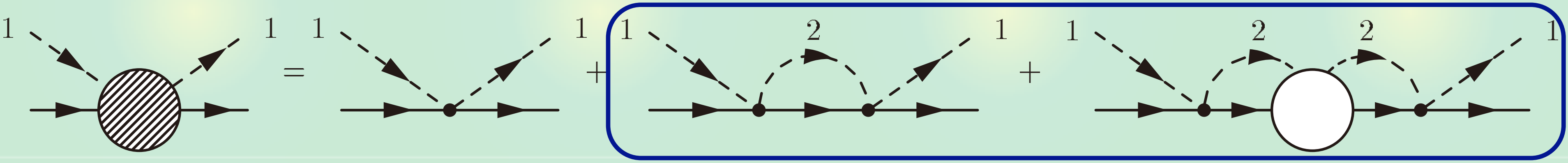
single channel

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

Equivalent to the coupled-channel equations

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

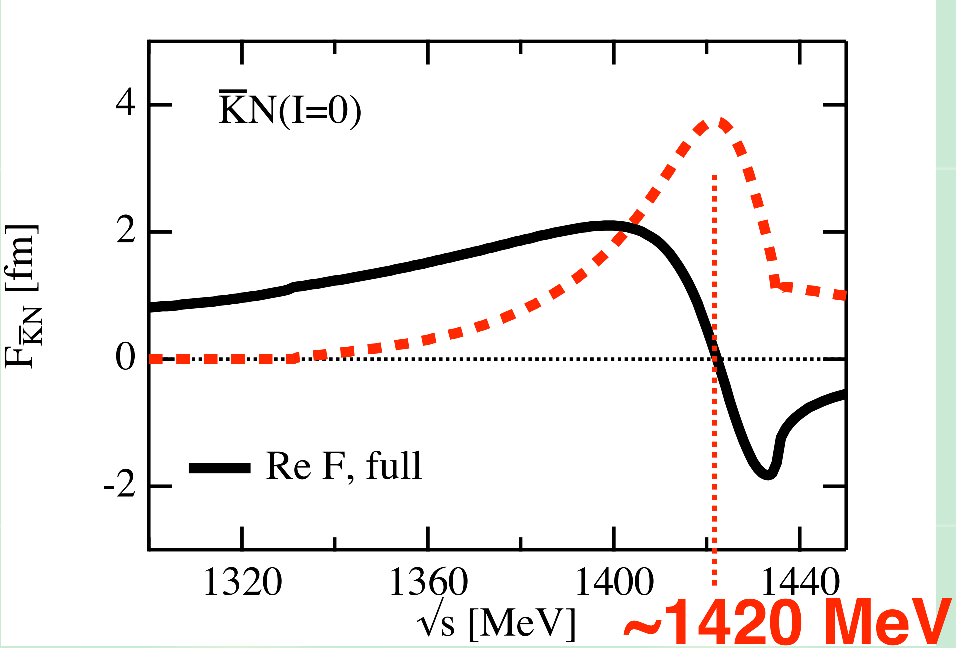


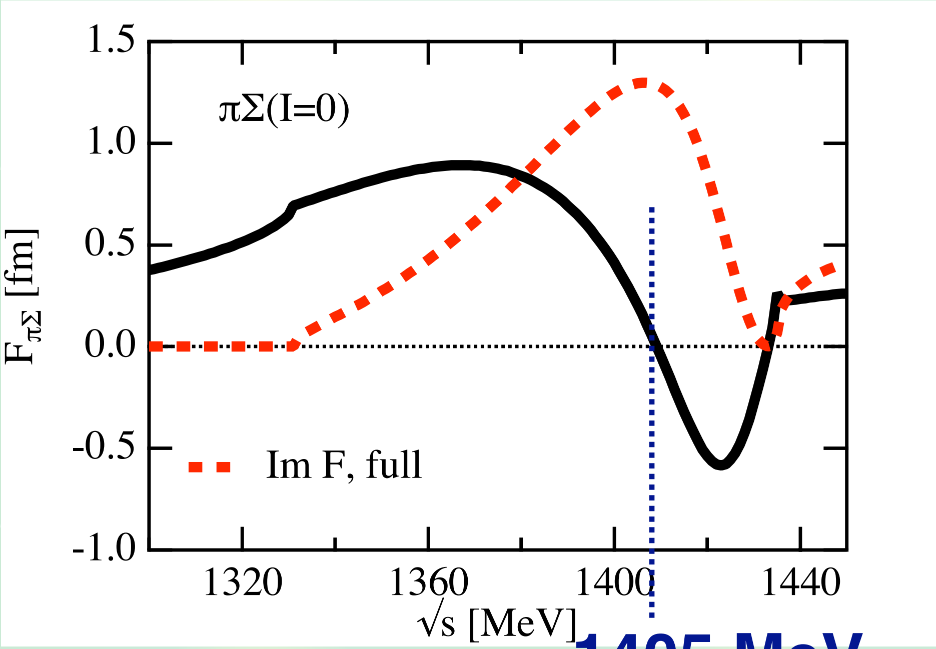


Strength : comparable with the WT term

~1/2 of phenomenological (AY) potential

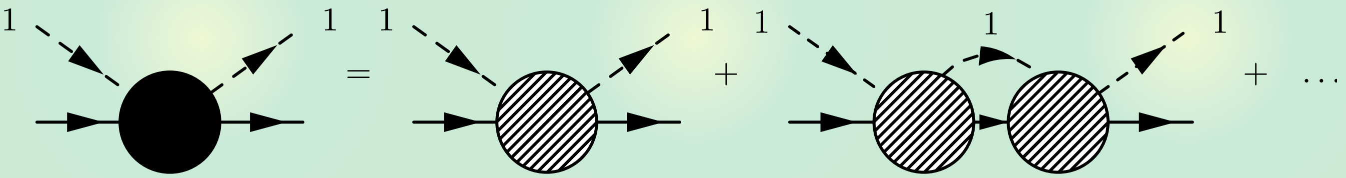
Scattering amplitude in $\bar{K}N$ and $\pi\Sigma$





~1420 MeV

~1405 MeV
Experiment



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

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

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

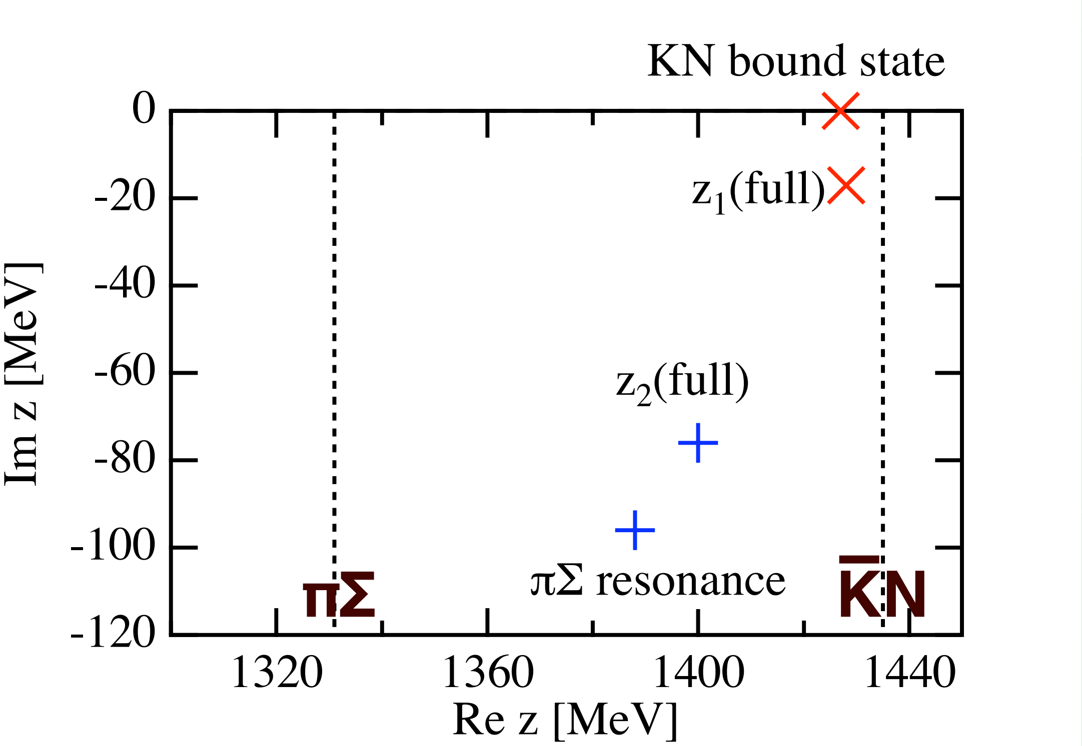
Origin of the two-pole structure

Chiral interaction

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

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

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



Very strong attraction in K̄N (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

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

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

phenomenological

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

$$v_{ij}(r) \sim -\begin{array}{cc} \bar{K}N & \pi\Sigma \\ \multicolumn{2}{c}{\left(\begin{array}{cc} 436 & 412 \\ 412 & \boxed{0} \end{array}\right)} \end{array} g(r)$$

Absence of πΣ diagonal coupling

--> absence of πΣ dynamics, resonance

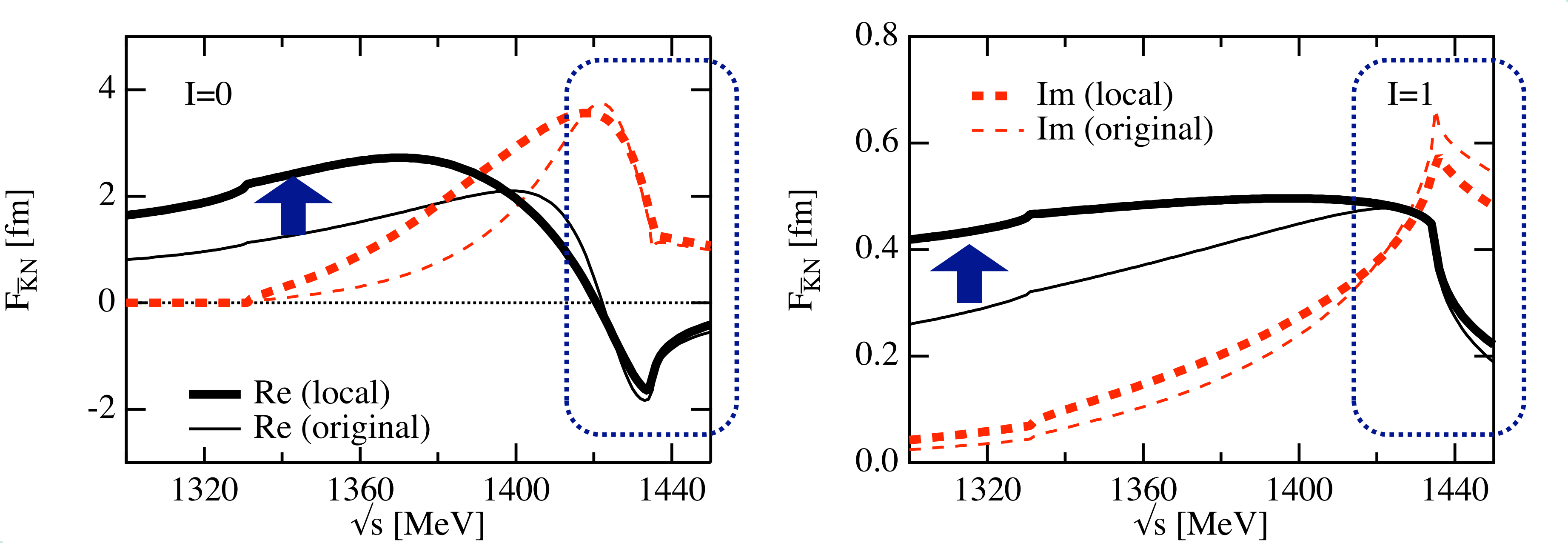
--> strong (×2) attractive interaction in K̄N

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

energy dependence : derivative coupling

Construction of the effective interaction

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



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

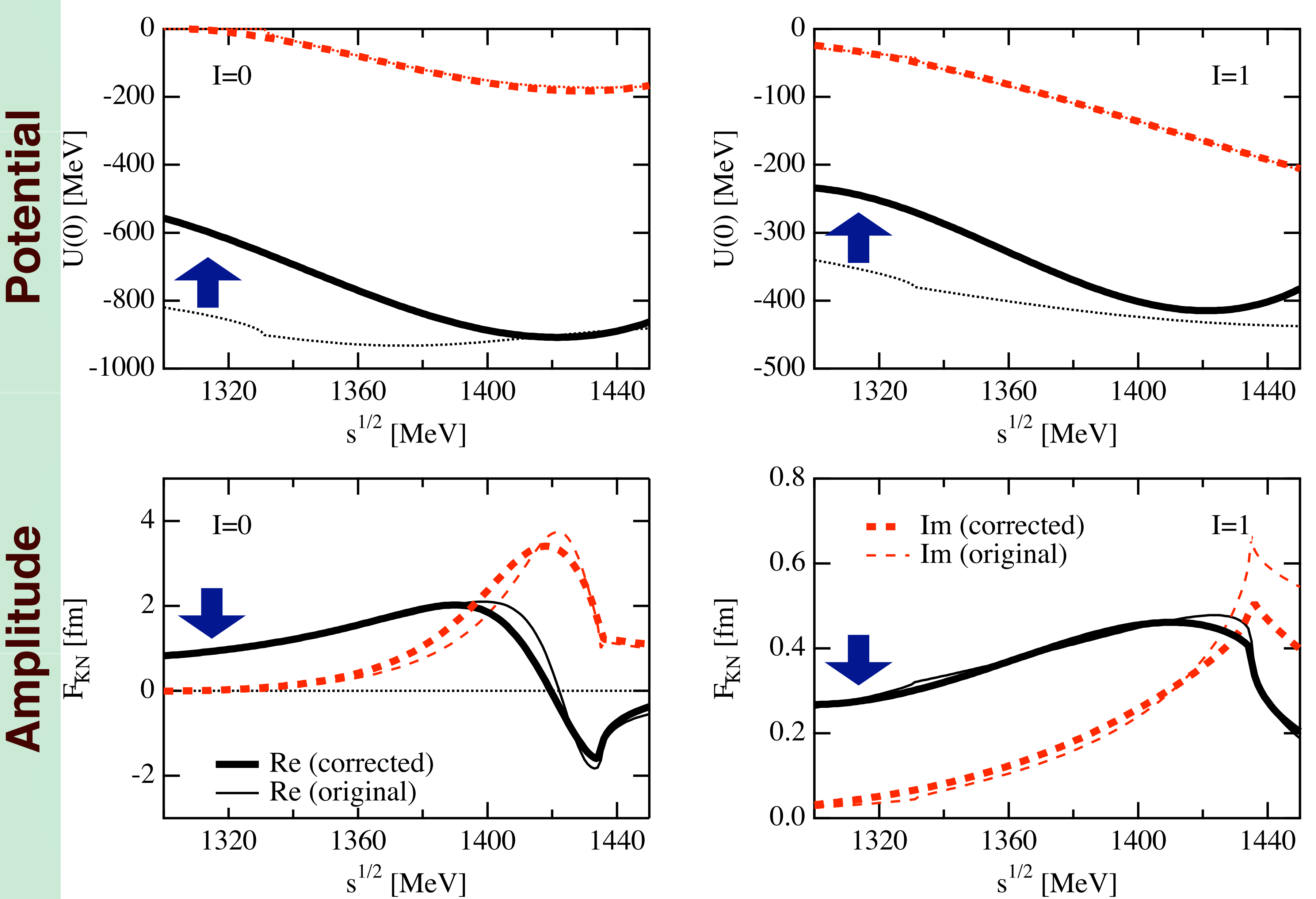
$b = 0.47\ \mathrm{fm}$ **: to reproduce the resonance**

agreement around threshold : OK

Deviation at lower energy :

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

Correction of the strength of the potential



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

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

- **Resonance structure in $\bar{K}N$ appears at around 1420 MeV <-- two-pole Λ(1405). The strength of the $\bar{K}N$ interaction is comparable with the WT term.**
- **Two poles are the consequence of two attractive interactions in $\bar{K}N$ and πΣ.**
- **Local (non-rel) potential overestimates amplitude at lower energy.**

T. Hyodo, W. Weise, 0712,1613 [nucl-th], Phys. Rev. C, in press.

Application to three-body K-pp system

Hamiltonian : Realistic interactions

$$\hat{H} = \hat{T} + \boxed{\hat{V}_{NN}} + \boxed{\mathrm{Re}\,\hat{V}_{\bar{K}N}(\sqrt{s})} - \hat{T}_{CM}$$

Realistic NN potential (Av18)

$\bar{K}N$ potential based on chiral SU(3) dynamics (real part)
dispersive effect from imaginary part
~ 3-4 MeV in two-body $\bar{K}N$ system

Self-consistency of kaon energy and $\bar{K}N$ interaction

Model wave function

$J^P = 0^-$, $T = 1/2$, $T_3 = 1/2$

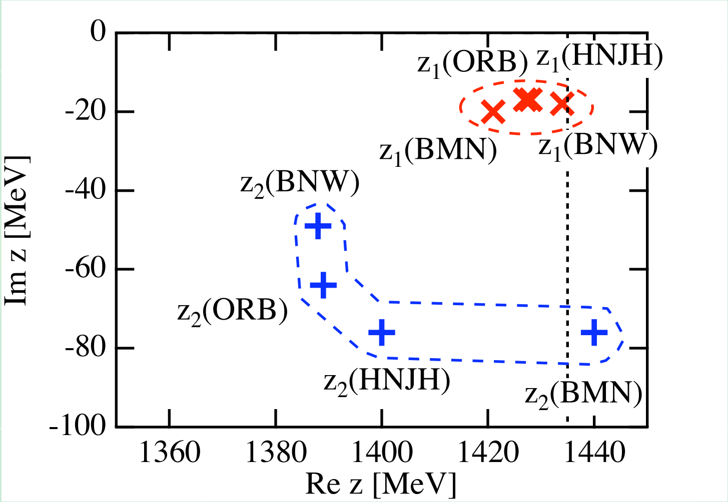
$T_N = 0$

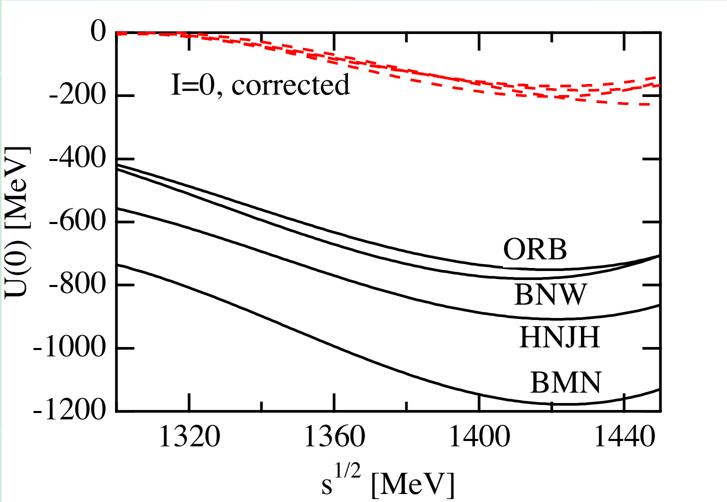
$$|\Psi\rangle = \mathcal{N}^{-1}[\,|\Phi_+\rangle + C\,|\Phi_-\rangle\,]$$

$T_N = 1$, dominant, used in Faddeev

Theoretical uncertainties

Different chrial models (leading order)





Energy dependence of $\bar{\mathrm{K}}$N interaction

Define antikaon "binding energy"

$$-B_K \equiv \langle\Psi|\hat{H}|\Psi\rangle - \langle\Psi|\hat{H}_N|\Psi\rangle$$

Two options for two-body energy

$$\text{Type I } : \sqrt{s} = M_N + m_K - B_K$$

$$\text{Type II } : \sqrt{s} = M_N + m_K - B_K/2$$

Summary 2 : K-pp system

We study the K-pp system with chiral SU(3) potentials in a variational approach.

With theoretical uncertainties,

B.E. = 19 ± 3 MeV
Γ(πYN) = 40 ~ 70 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 (2007)

No two-nucleon absorption : $\bar{K}$NN -> YN ... small?

A. Doté, T. Hyodo, W. Weise, 0802.0238 [nucl-th], Nucl. Phys. A, in press