Λ(1405) in chiral dynamics

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

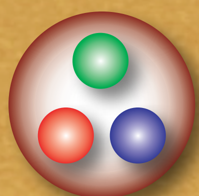
$\Lambda(1405) : J^P = 1/2^-, I = 0$

Mass : 1406.5 ± 4.0 MeV

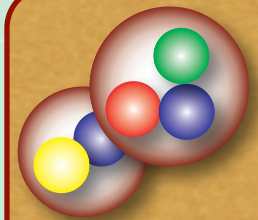
Width : 50 ± 2 MeV

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

“naive” quark model
: p-wave
~1600 MeV?



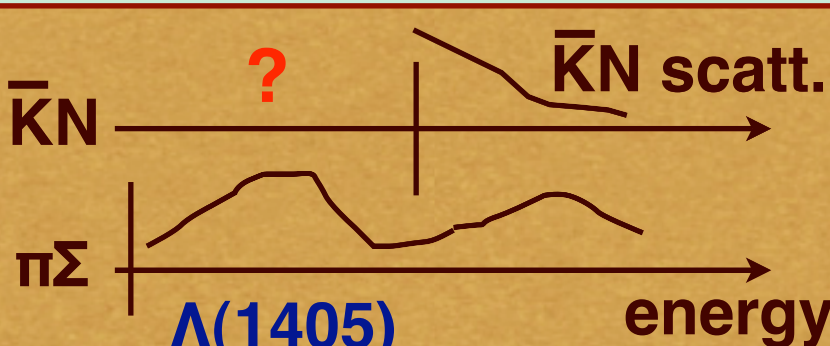
N. Isgur and G. Karl, PRD18, 4187 (1978)

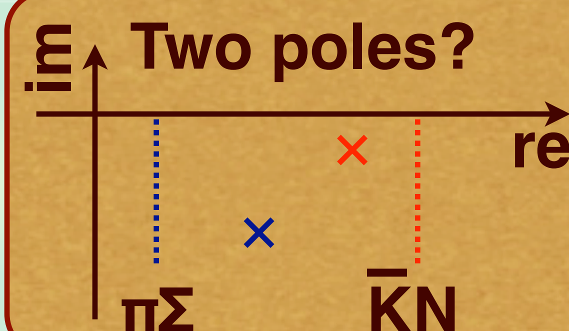


Coupled channel multi-scattering

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

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





Introduction : *less* known facts on Λ(1405)

PDG

Λ(1405) MASS

PRODUCTION EXPERIMENTS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1406.5 ± 4.0		[1] DALITZ	91		M-matrix fit
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1391 ± 1	700	[1] HEMINGWAY	85	HBC	$K^- p$ 4.2 GeV/c

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

analyze Hemingway data by phenomenological model with I=0 to extract mass and width.

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

Spectrum is not in I=0, but with the cross term, which may change the shape of the spectrum.

Contents

Phenomenology of $\bar{K}N$ interaction

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

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

Structure of the Λ(1405)

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, in preparation

(Electromagnetic properties

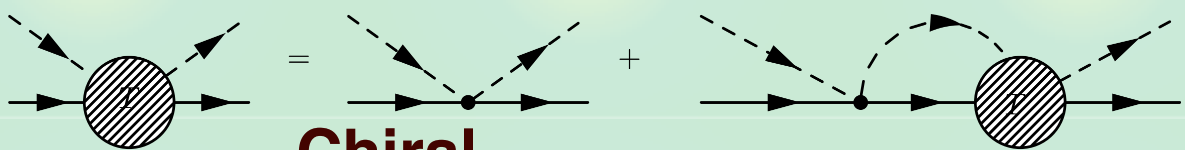
T. Sekihara, T. Hyodo, D. Jido, in preparation)

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)

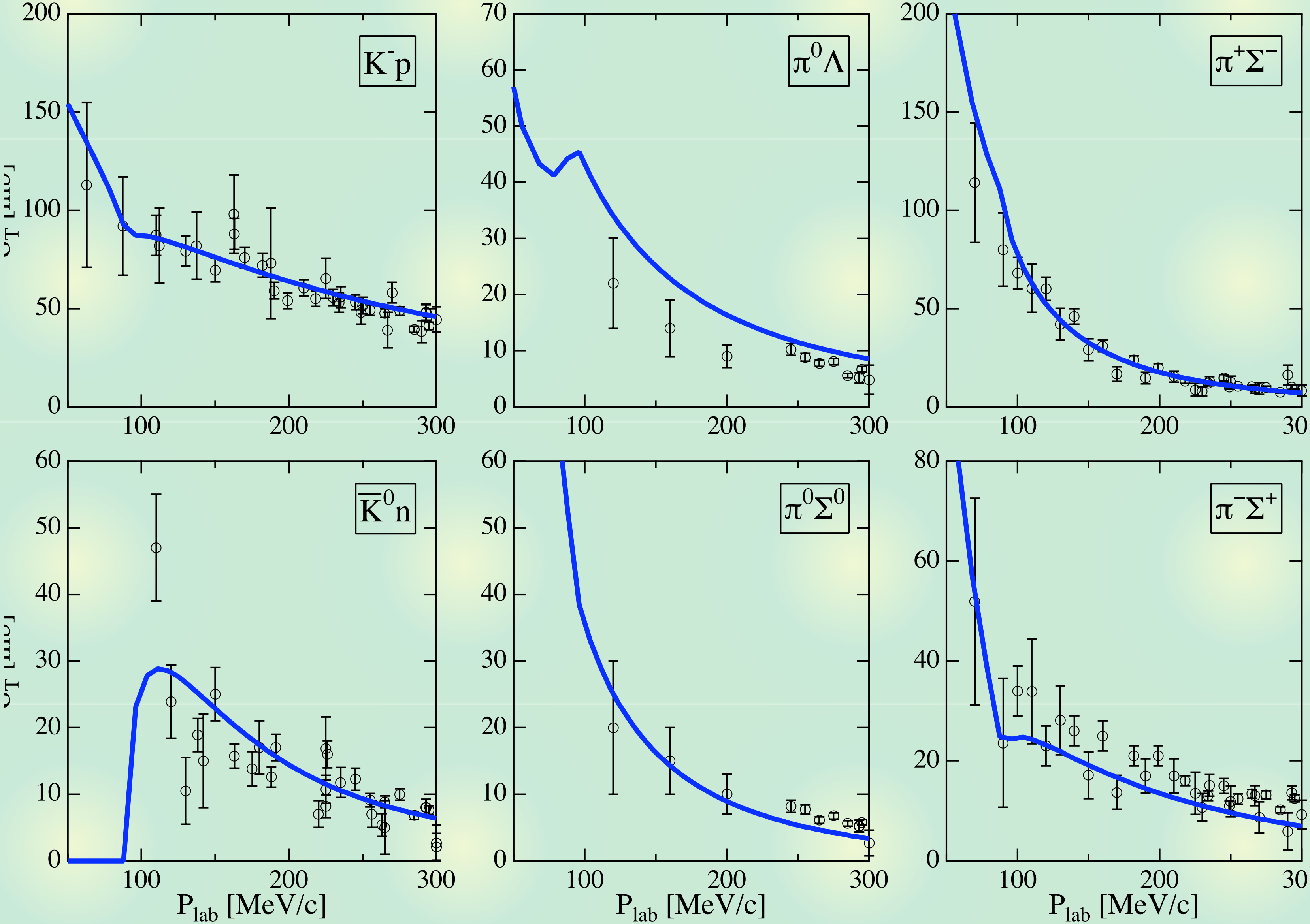
cutoff
(subtraction
constant)

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

strong attraction (<- chiral)
bound state below threshold

➡ non-perturbative framework

Total cross sections of K^-p scattering

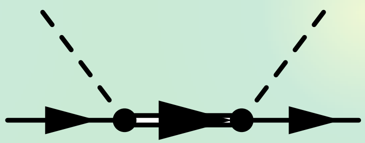


T. Hyodo, S.I. Nam, D. Jido, A. Hosaka, Phys. Rev. C68, 018201 (2003)

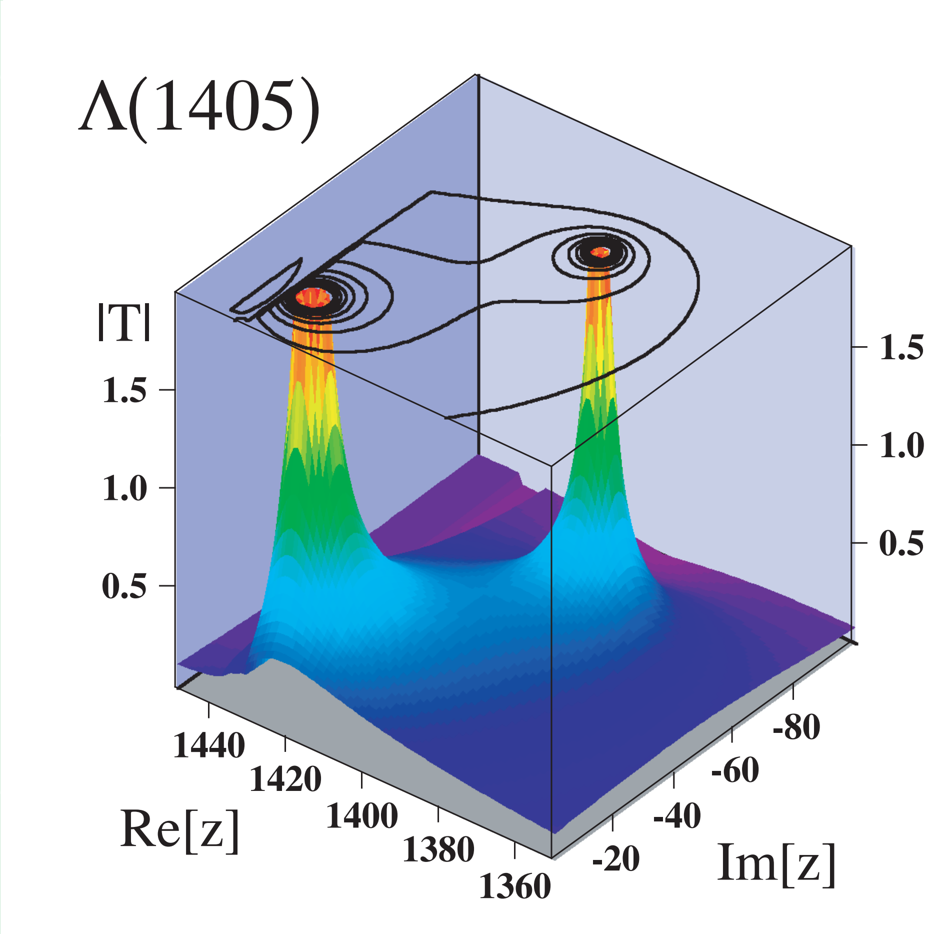
Description of the resonances

Poles of the amplitude : resonance

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

$\sim$ 

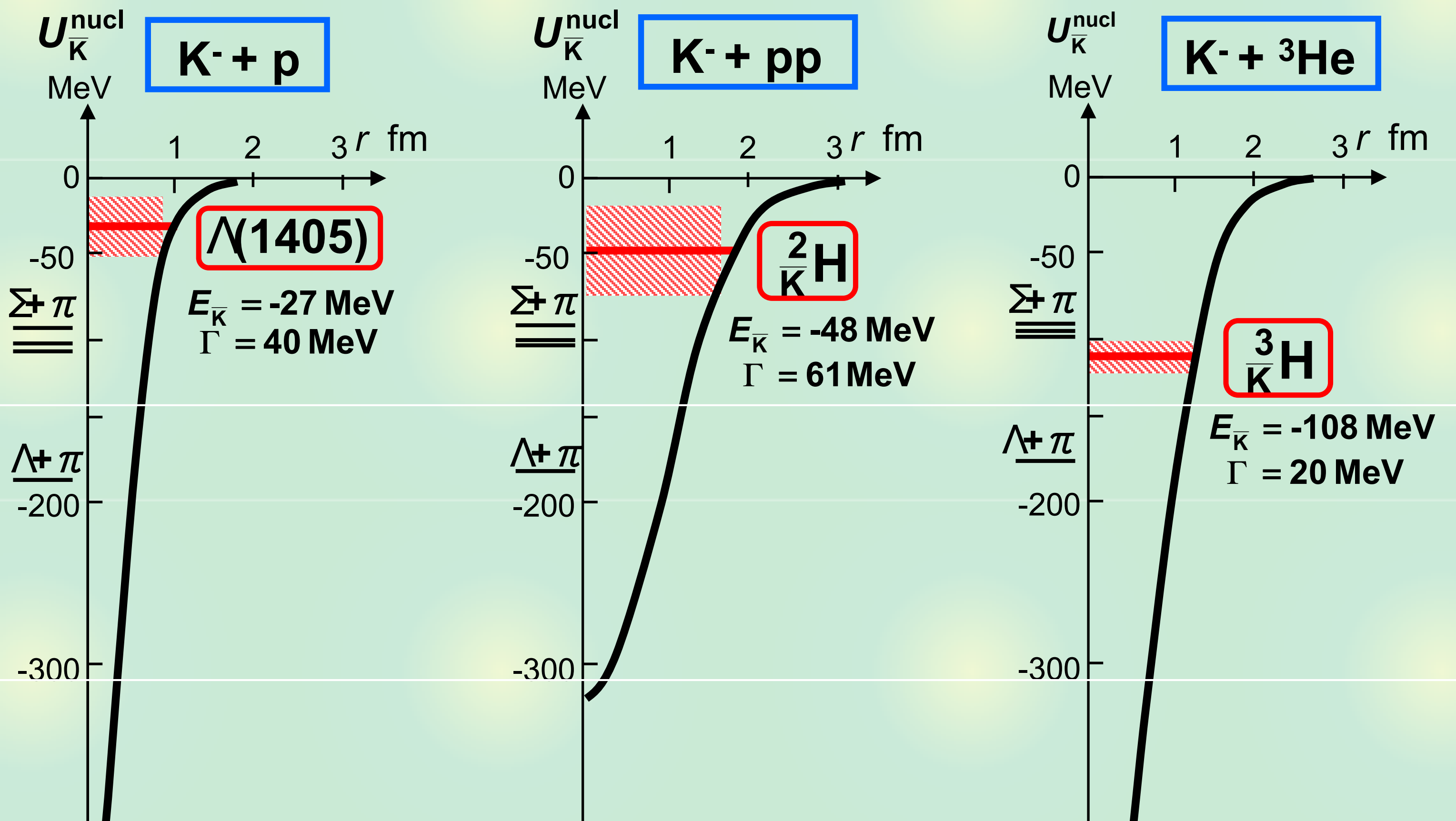
Real part	Mass
Imaginary part	Width/2
Residues	Couplings



Successful description of $\bar{K}N$ scattering

Two poles 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 --> 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 $V^{\text{eff}}(\sqrt{s})$

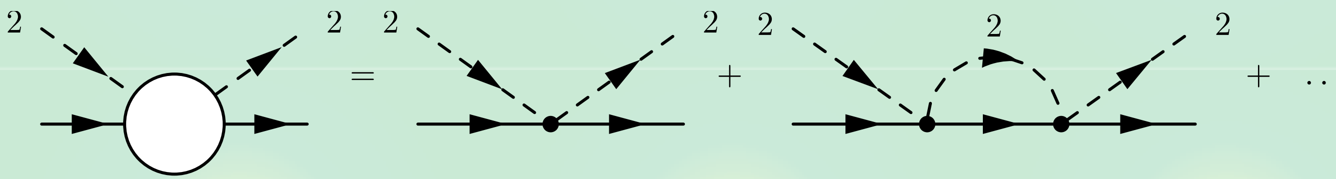
(approximate)

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

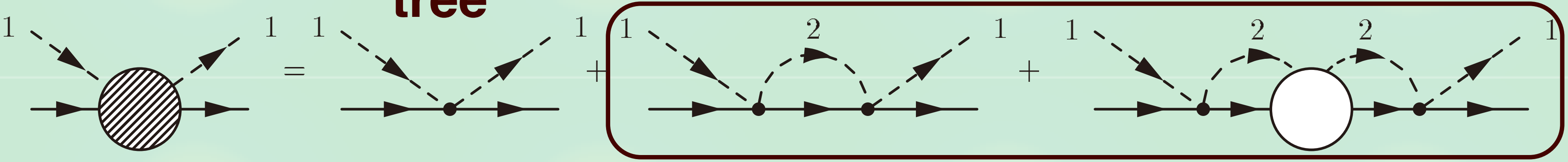
Resummation of the channel to be eliminated



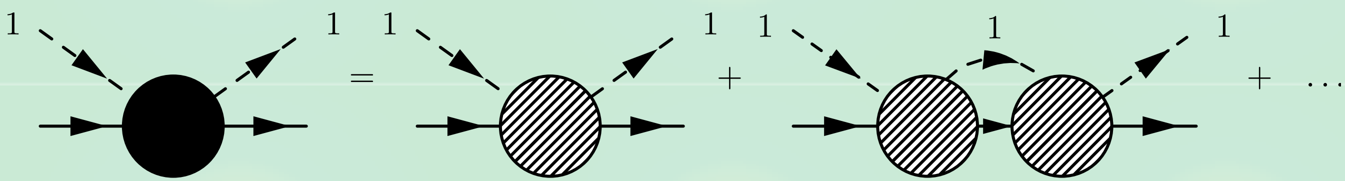
$$T_{22}^{\rm single} = V_{22} + V_{22} G_2 T_{22}^{\rm single}$$

tree

effect of channel 2



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

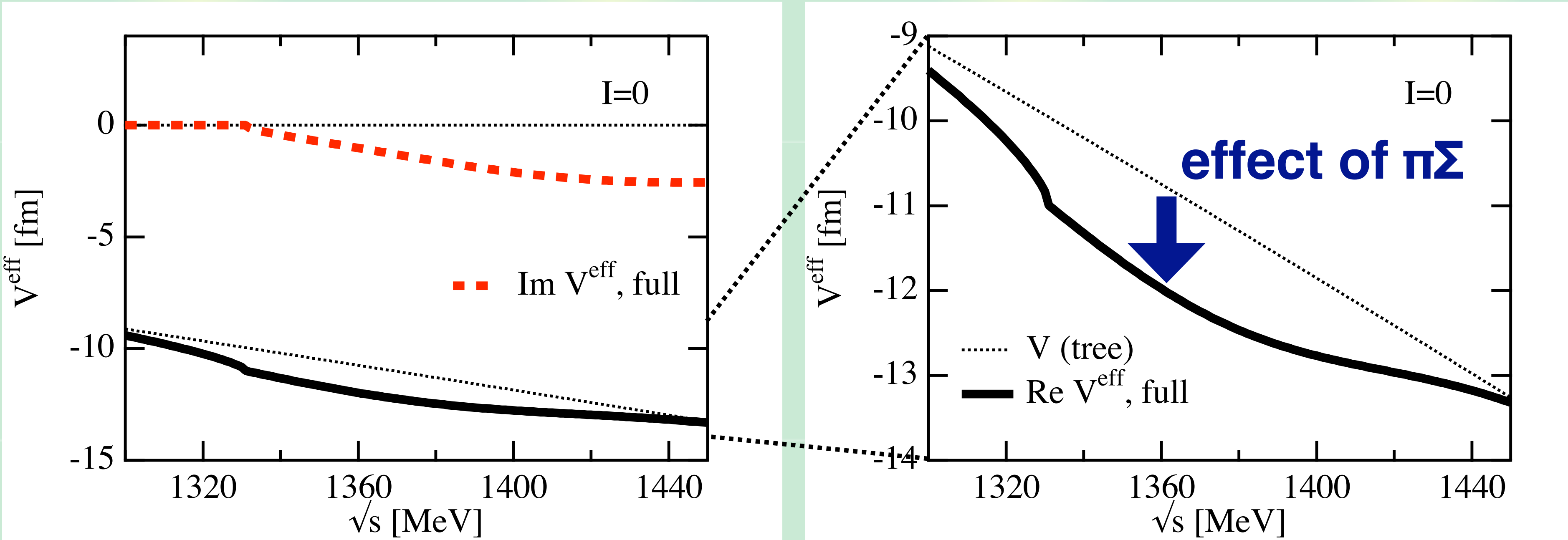


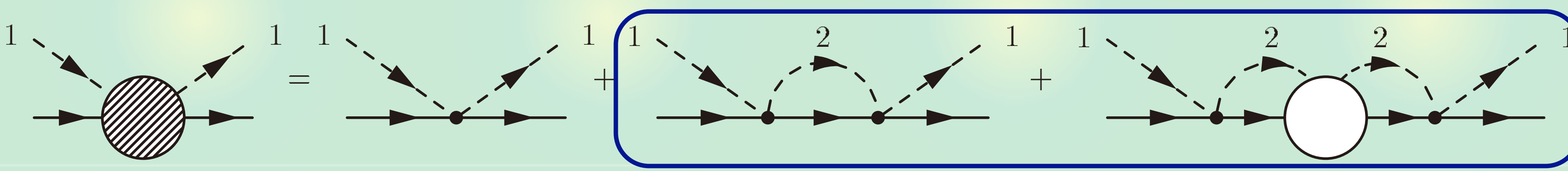
single channel

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

Equivalent to the coupled-channel equations

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

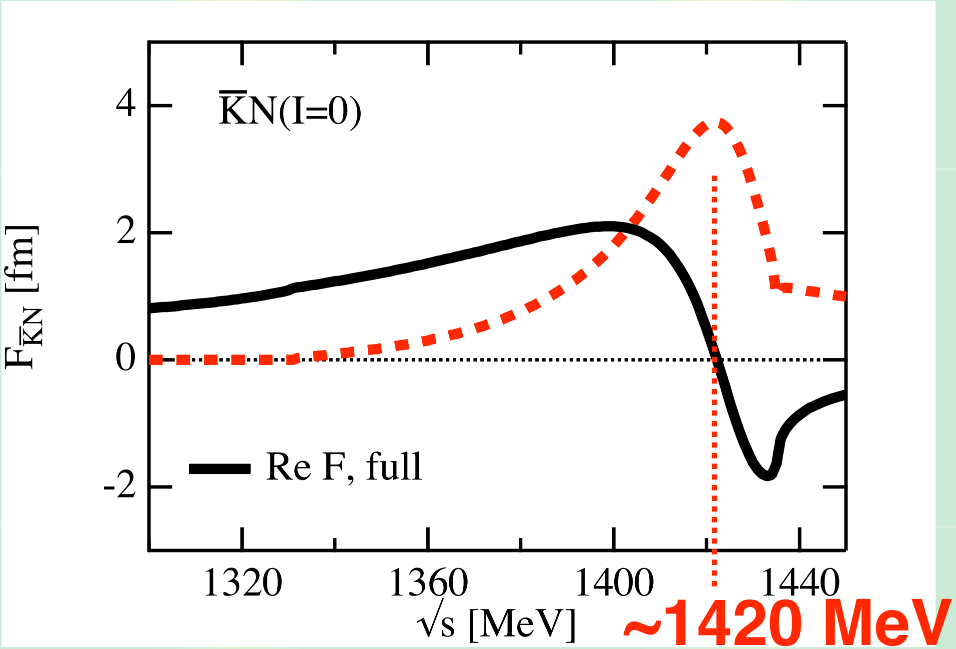


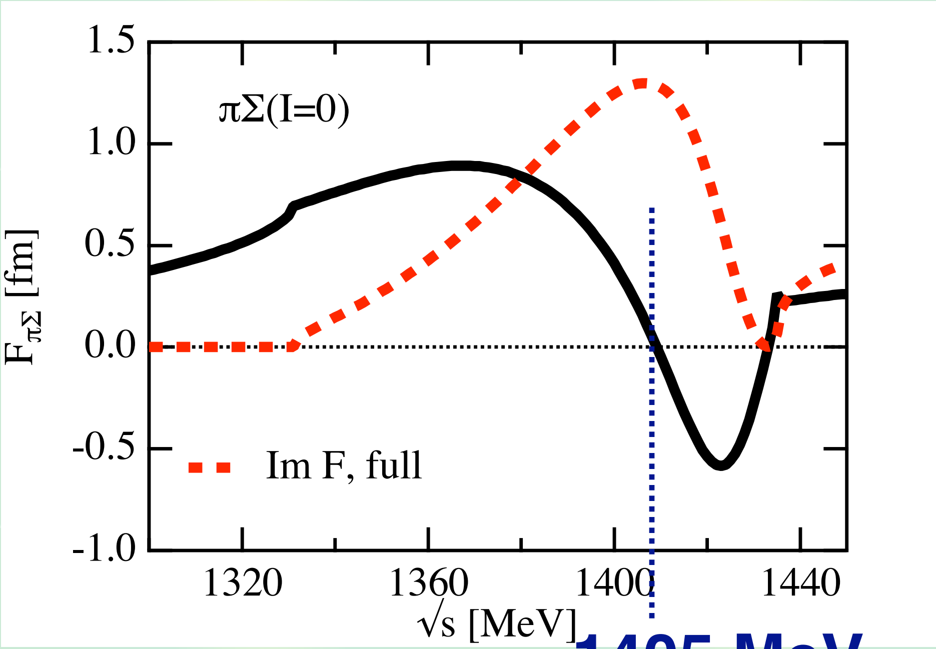


Strength : comparable with the WT term

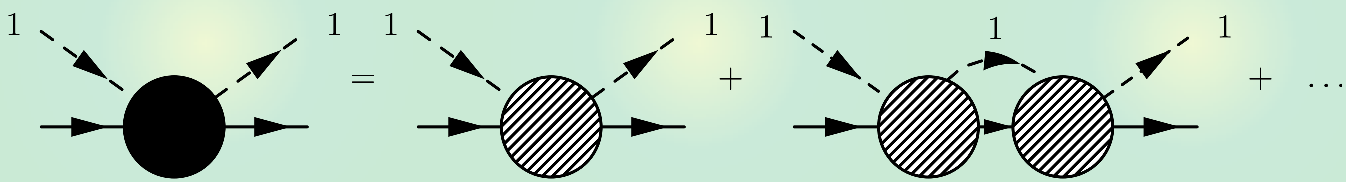
- ~ 1/2 of phenomenological (Akaishi-Yamazaki) potential
- $\pi\Sigma$ resummation : small but pole exists

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 = 15 MeV <--> 30 MeV

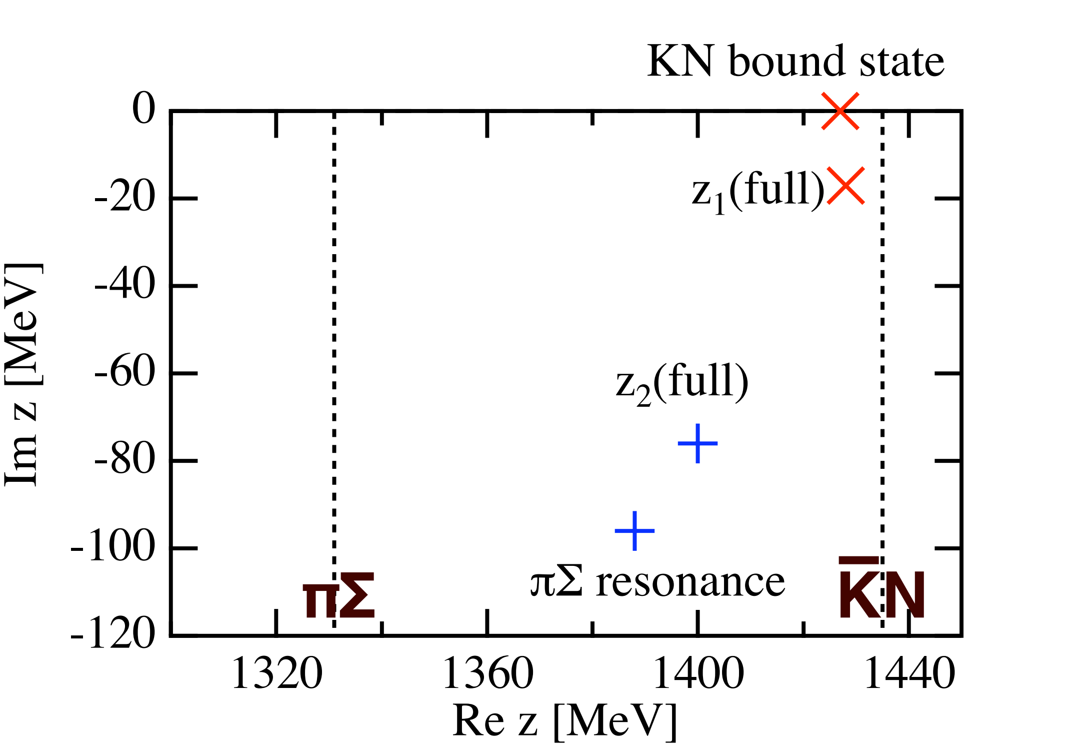
Origin of the two-pole structure

Chiral interaction

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

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

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



Very strong attraction in 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

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

$$\begin{array}{cc} \bar{K}N & \pi\Sigma \end{array}$$

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

phenomenological

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

$$\begin{array}{cc} \bar{K}N & \pi\Sigma \end{array}$$

$$v_{ij}(r) \sim -\begin{pmatrix} 436 & 412 \\ 412 & 0 \end{pmatrix} g(r)$$

Absence of πΣ diagonal coupling

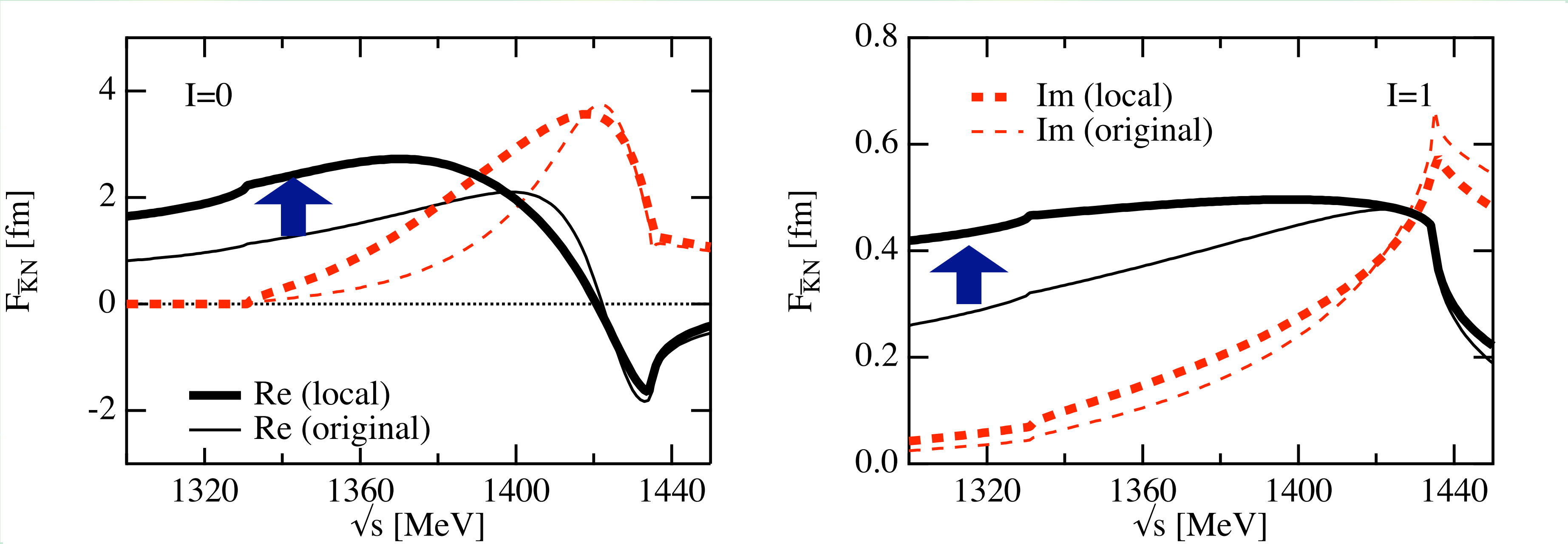
--> absence of πΣ dynamics, resonance

--> 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



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

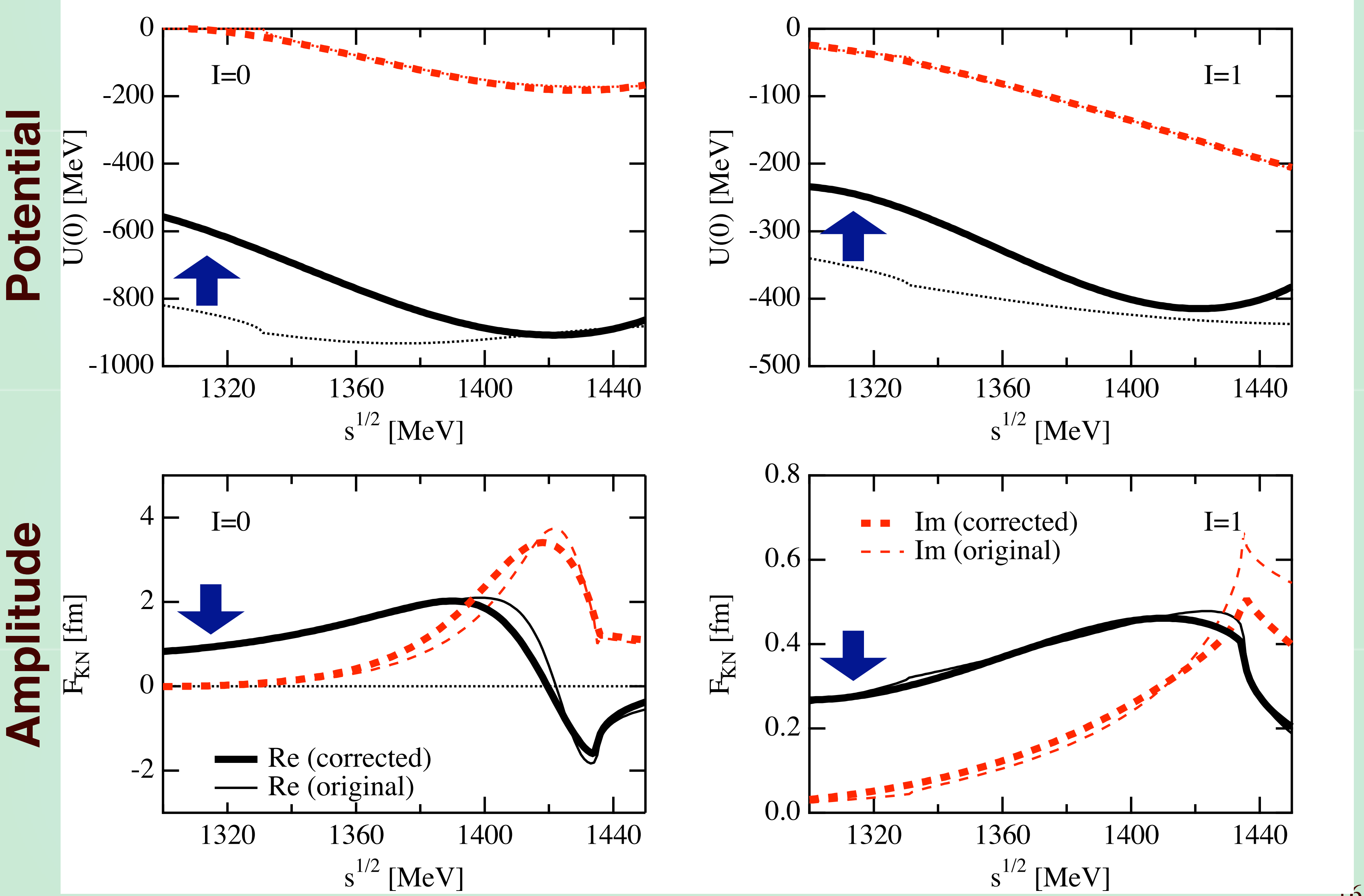
$b = 0.47$ fm **: to reproduce the resonance**

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

Application to three-body K-pp system

Hamiltonian : Realistic interactions

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

Realistic NN potential (Av18)

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

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

Variational calculation

Model wave function : $J^P = 0^-$, $T = 1/2$, $T_3 = 1/2$

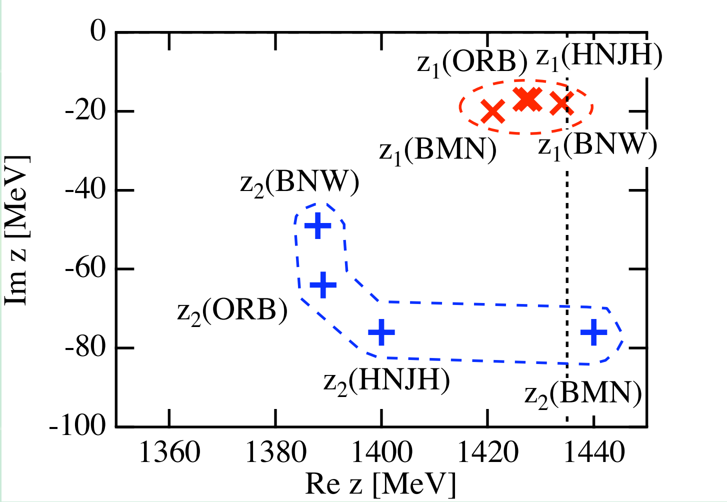
$$|\Psi\rangle = \mathcal{N}^{-1}[\,|\Phi_+\rangle + C\,|\Phi_-\rangle\,]$$

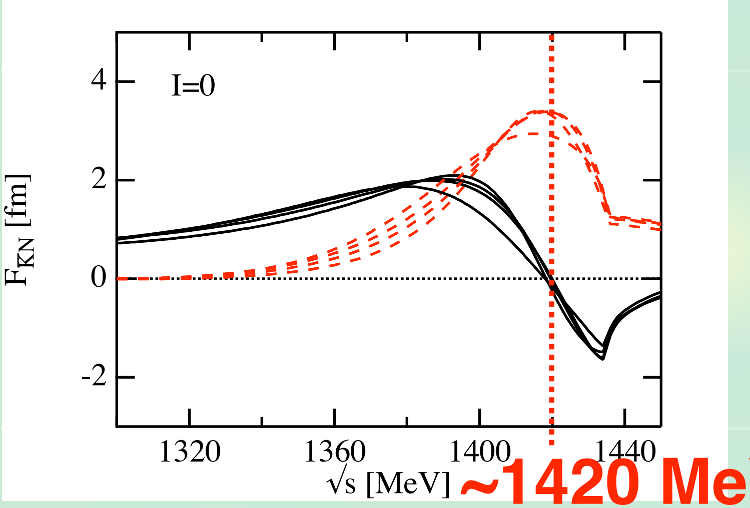
$T_N = 0$

$T_N = 1$, dominant, used in Faddeev

Theoretical uncertainties

Different models of chiral dynamics





~1420 MeV

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 : $\bar{K}$NN system

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

With theoretical uncertainties,

$$\text{B.E.} = 19 \pm 3 \;\text{MeV}$$
$$\Gamma(\pi YN) = 40 \sim 70 \;\text{MeV}$$

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

Structure of dynamically generated resonances

Quark structure of resonances?
<-- known Nc scaling of $q\bar{q}$ meson

$$m \sim \mathcal{O}(1), \quad \Gamma \sim \mathcal{O}(1/N_c),$$

can be used to distinguish $q\bar{q}$ from others

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 --> ρ ~ $q\bar{q}$

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

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

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

C ∝ Nc : finite interaction at Nc -> ∞

Attractive interaction in singlet channel

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 -> ∞
--> single-channel problem @ large Nc limit

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

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

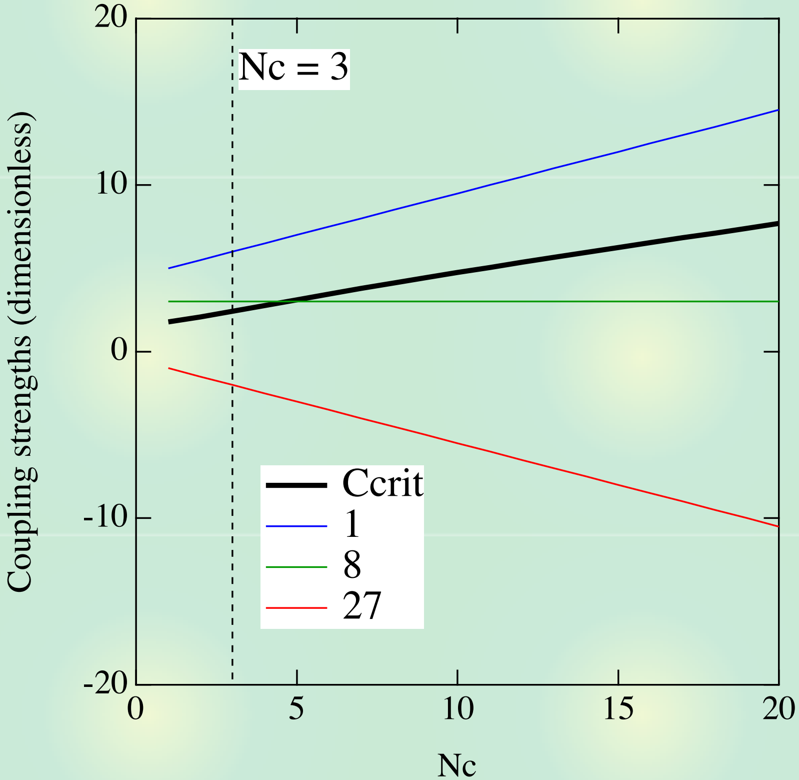
In the large Nc limit

Attractive interaction in KN(singlet) channels

$$C \sim N_c/2$$

Critical coupling strength (with Nc dep)

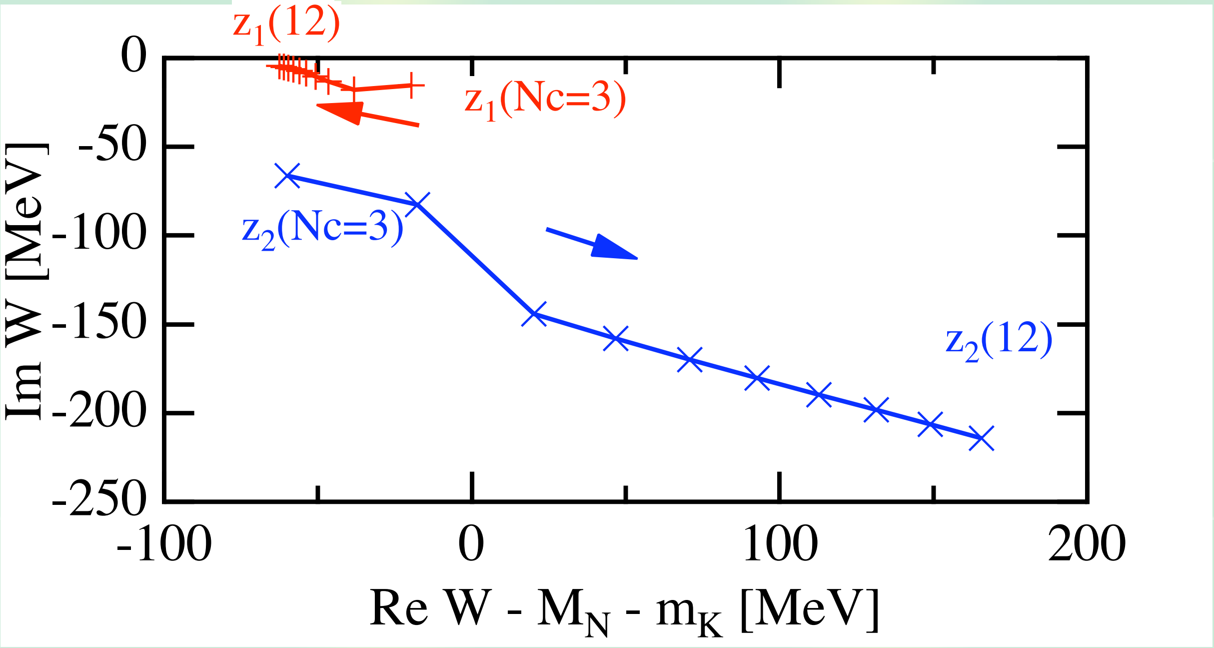
$$C_{\rm crit}(N_c) = \frac{2[f(N_c)]^2}{m[-G(M_T(N_c)+m)]}$$



$$N_c/2 > C_{\rm crit}(N_c)$$

Bound state in "1" or KN channels

With SU(3) breaking : Pole trajectories with varying Nc



1 bound state and 1 dissolving resonance

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

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

Nc scaling of excited qqq baryon

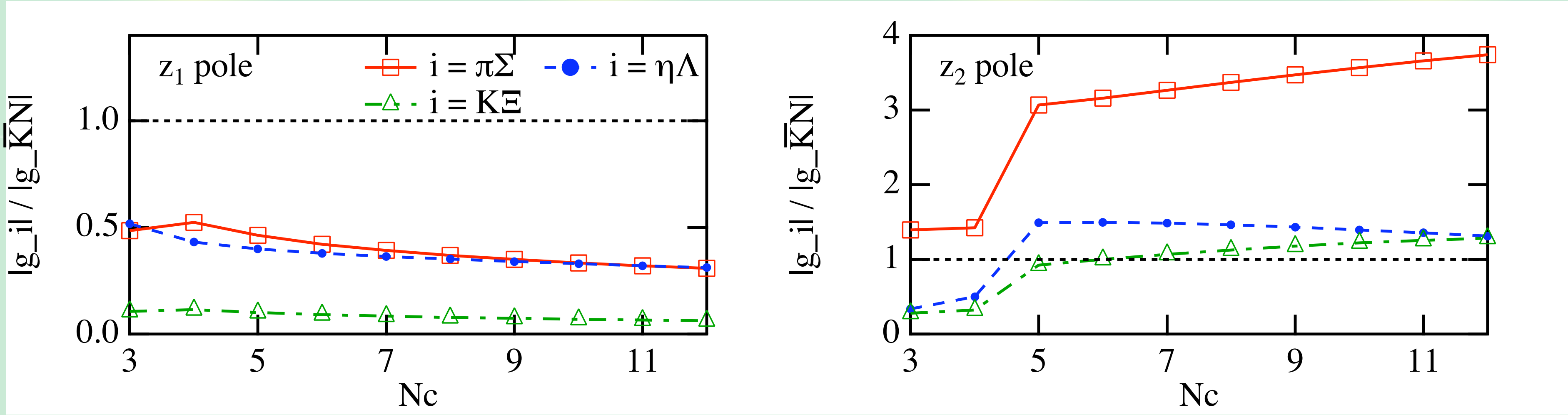
$$M_R \sim \mathcal{O}(N_c), \quad \Gamma_R \sim \mathcal{O}(1)$$

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

Isospin conponents of the poles

Residues in the isospin basis

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



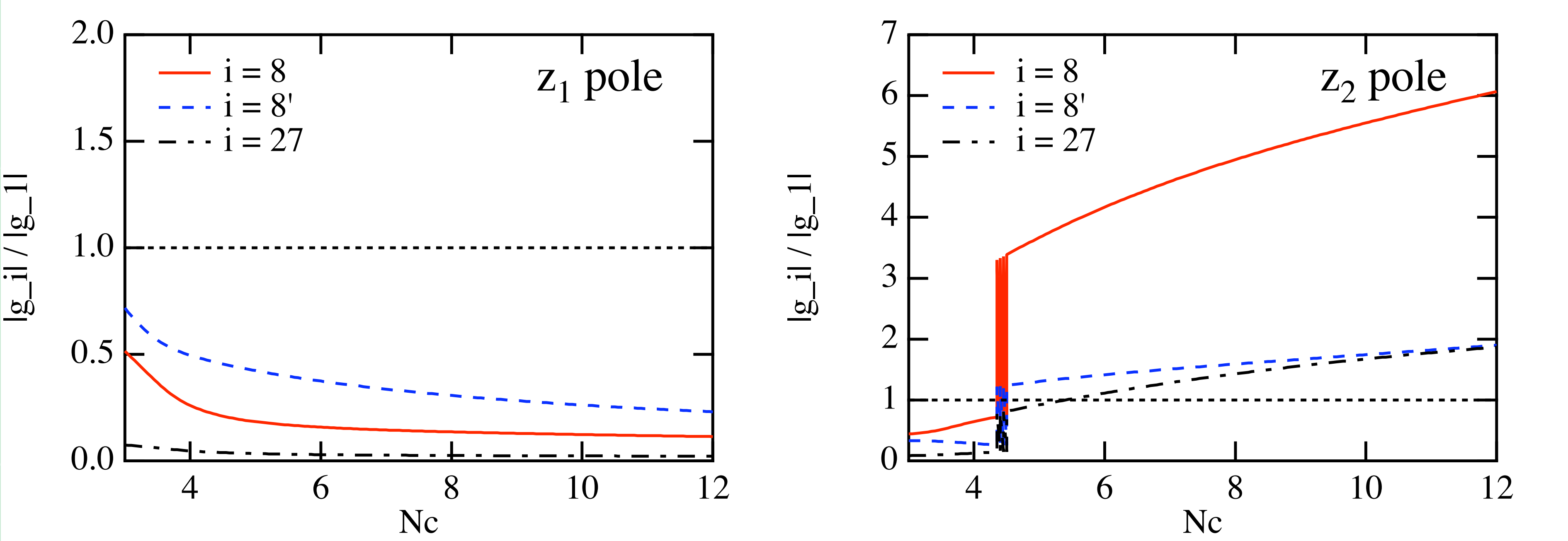
bound state
$\bar{\text{K}}$N dominant

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" or $\bar{K}N$ channel even in the large Nc limit

- **Behavior around Nc = 3**

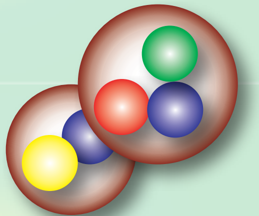
  1 bound state and 1 dissolving pole
  : signal of the non-qqq state.

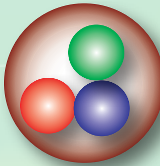
  Residues of the would-be-bound-state
  : dominated by "1" or $\bar{K}N$
  : consistent with large Nc limit.

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

Structure of dynamically generated resonances

Resonances ~ quasi-bound two-body states





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

Renormalization
change of loop function
~ change of interaction kernel

Formulation of the N/D method
and the structure of low energy interaction

Renormalization schemes

Scattering amplitude in N/D method

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

V : interaction   G : loop function (cutoff)

Phenomenological scheme

: V is given by ChPT, fit cutoff to data

N/D method : CDD pole contribution --> V

Natural renormalization scheme

: exclude CDD pole contribution from G

$$G(\mu) = 0, \quad \Leftrightarrow \quad T(\mu) = V(\mu) \quad \text{at} \quad \mu = M_T$$

K. Igi, and K. Hikasa, Phys. Rev. D59, 034005 (1999)
M.F.M. Lutz, and E. Kolomeitsev, Nucl. Phys. A700, 193-308 (2002)

Pole in the effective interaction

$$T = (V^{-1} - G(a+\Delta a))^{-1} = ((V')^{-1} - G(a))^{-1}$$

↑phenomonological ↑natural

Effective interaction in natural scheme

$$\begin{aligned} V' &= -\frac{8\pi^2}{M\Delta a}\frac{\sqrt{s}-M}{\sqrt{s}-M_{\rm eff}} \\ &= -\frac{C}{2f^2}(\sqrt{s}-M_T) + \boxed{\frac{C}{2f^2}\frac{(\sqrt{s}-M_T)^2}{\sqrt{s}-M_{\rm eff}}} \end{aligned}$$

pole!

$$M_{\rm eff} = M - \frac{16\pi^2 f^2}{CM\Delta a}$$

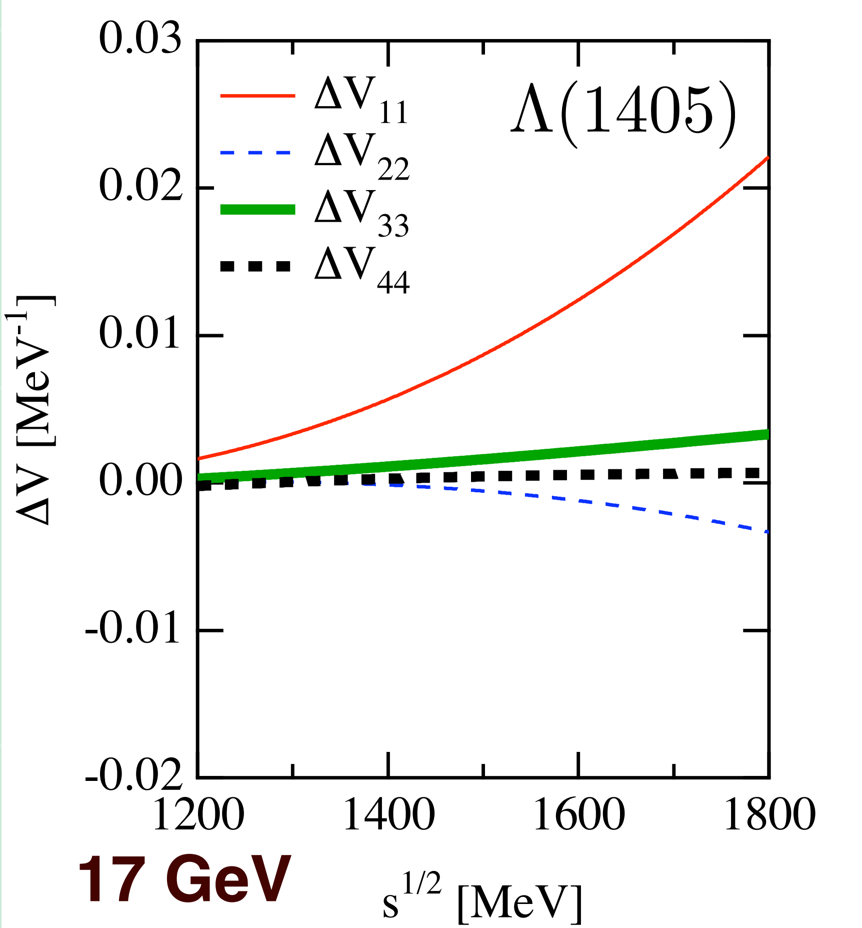
Physically meaningful pole :

$$C > 0, \quad \Delta a < 0$$

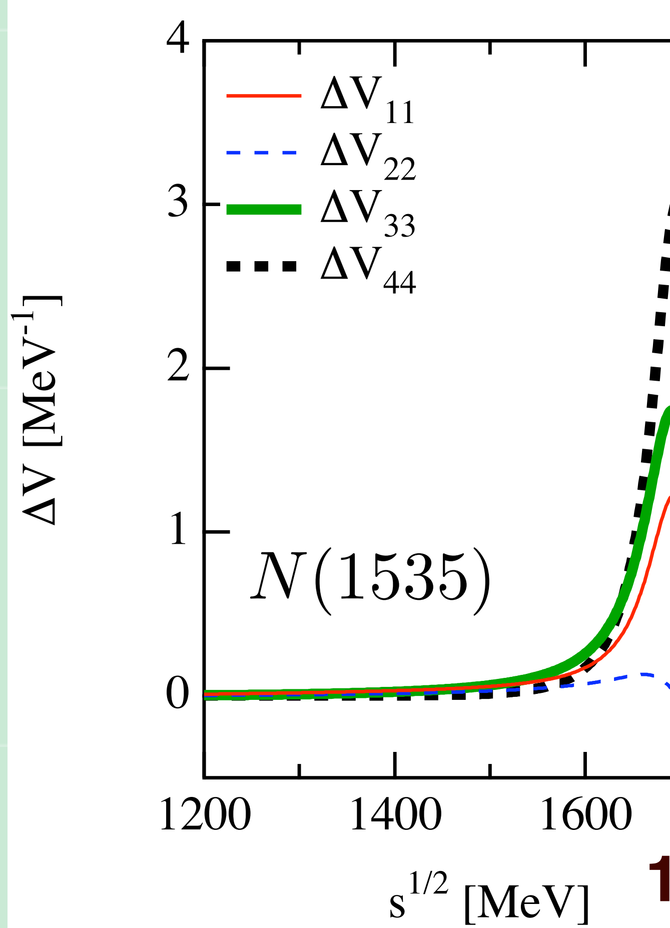
** energy scale of the effective pole **

Example : Λ(1405) and N(1535)

$$\Delta V \equiv V' - V_{WT}$$



17 GeV



1.7 GeV

Origin of dynamical pole?

Summary 4 : dynamical or CDD?

We study the origin of the resonances in the chiral unitary approach

- Natural renormalization

  Exclude CDD pole contribution from the loop function, consistent with N/D

- Analysis of Λ(1405) and N(1535)

  Λ(1405) : CDD pole would be small
  N(1535) : appreciable contribution from CDD pole

T. Hyodo, D. Jido, A. Hosaka, in preparation

Summary 5 : Structure of Λ(1405)

Schematic decomposition of Λ(1405)

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

- **Analysis of Nc behavior**

  N_3 << 1

- **Analysis of natural renormalization**

  N_{MB} dominates

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

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