Λ(1405) in chiral dynamics

Tetsuo Hyodo[a,b]

TU München[a] *YITP, Kyoto*[b]

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

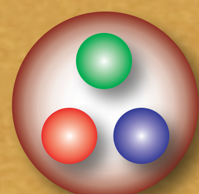
$\Lambda(1405) : J^P = 1/2^-, I = 0$

Mass : 1406.5 ± 4.0 MeV

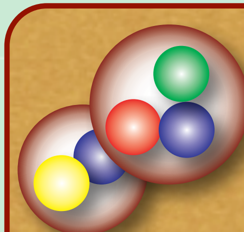
Width : 50 ± 2 MeV

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

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



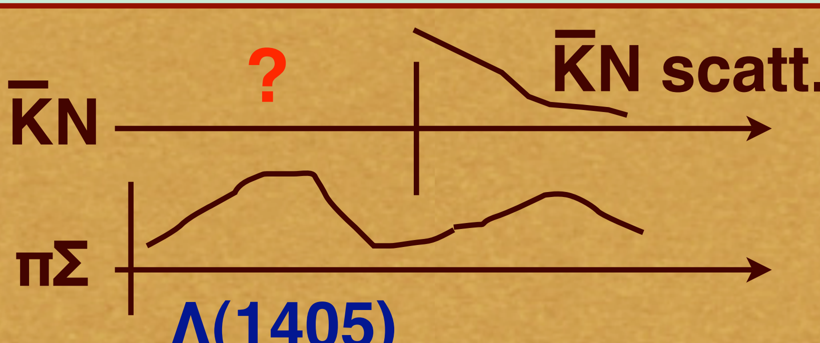
N. Isgur and G. Karl, PRD18, 4187 (1978)



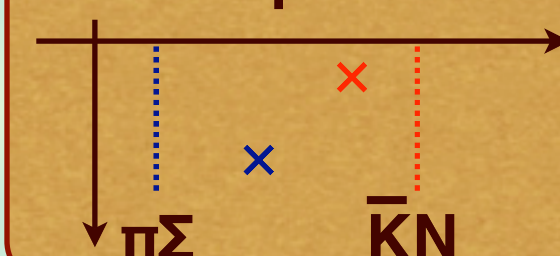
Coupled channel multi-scattering

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

With W. Weise, in preparation

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

With A. Doté, W. Weise, in preparation → Talk by Doté-san

Structure of the Λ(1405)

Behavior at large Nc

With D. Jido, L. Roca, in preparation

Dynamical or CDD (genuine quark state) ?

With D. Jido, A. Hosaka, in preparation (Talk by Jido-san)

Electromagnetic properties

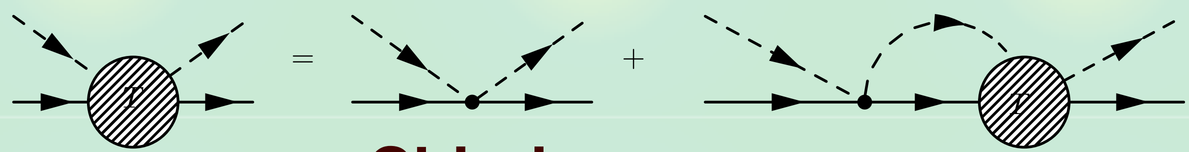
With T. Sekihara, D. Jido, in preparation → Poster by Sekihara-san

Chiral unitary approach

Hadron + NG boson scattering

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

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



Chiral

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

Successful description!!

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

Effective interaction based on chiral SU(3) dynamics

Result of chiral dynamics --> local potential

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

↓ (exact)

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

↓ (approximate)

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

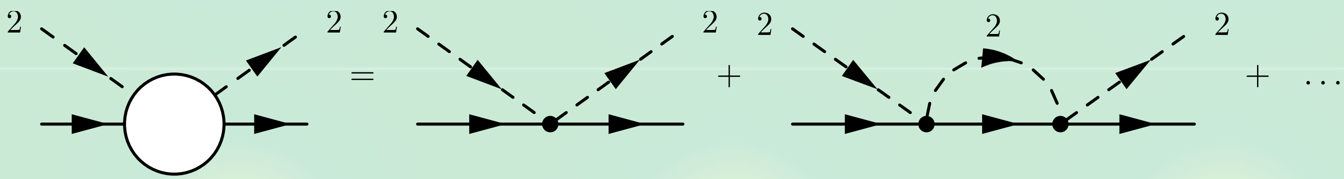
↓

few-body kaonic nuclei

** no medium effect **

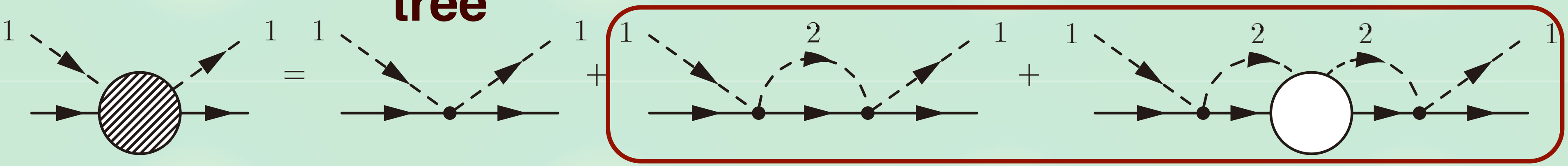
Construction of the single channel interaction

Resummation of the channel to be eliminated

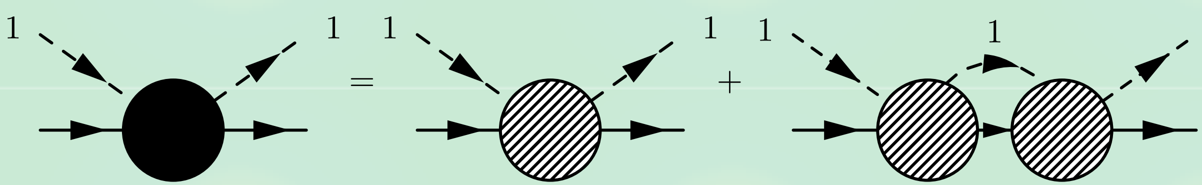


$$T_{22}^{\text{single}} = V_{22} + V_{22} G_2 T_{22}^{\text{single}}$$

tree **effect of channel 2**



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

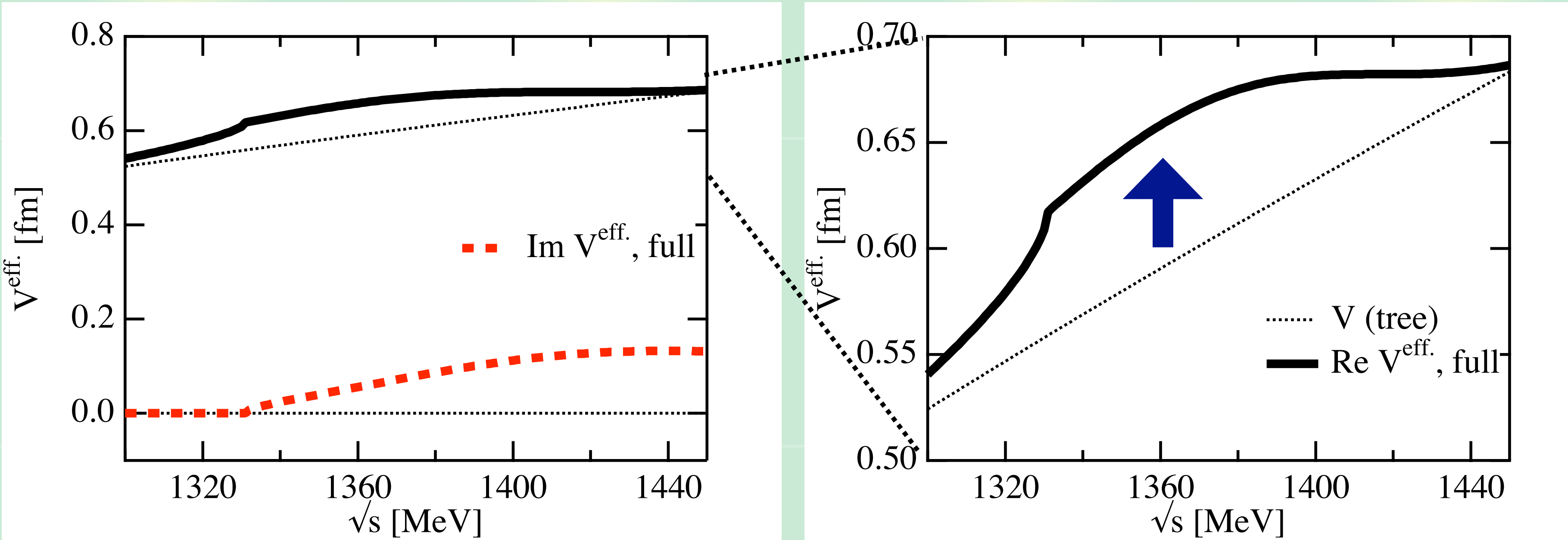


single channel

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

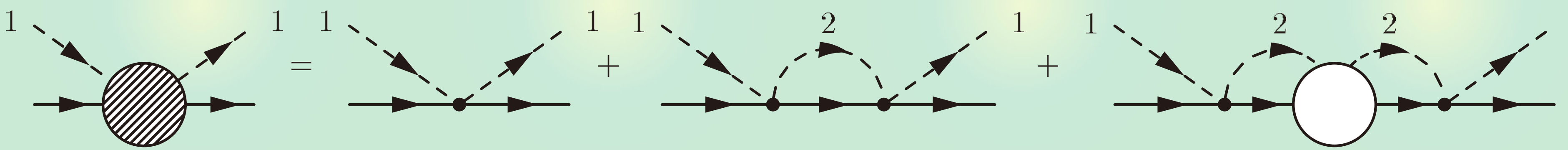
Equivalent to the coupled-channel equation

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



tree

effect of channel 2



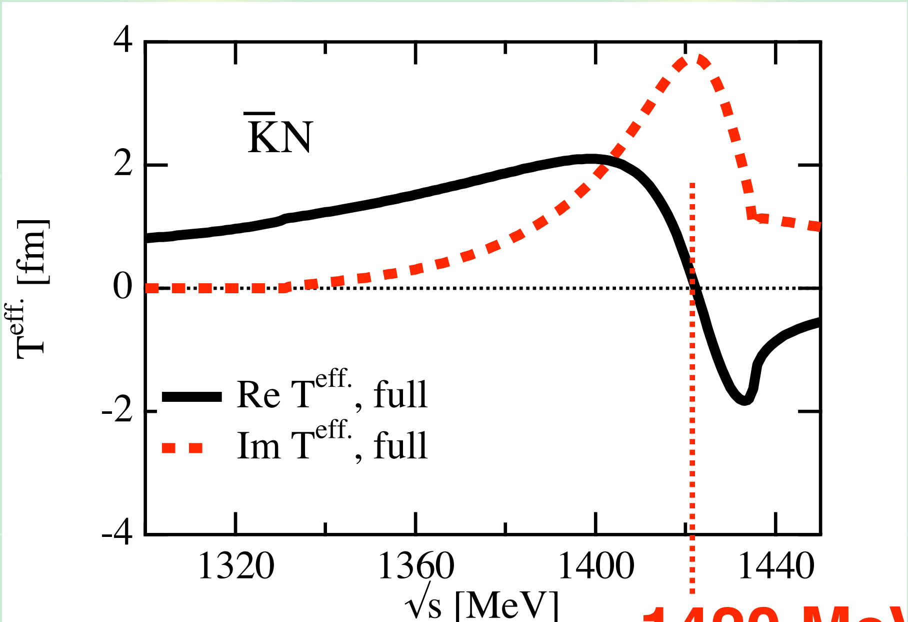
Not very much different from the WT term

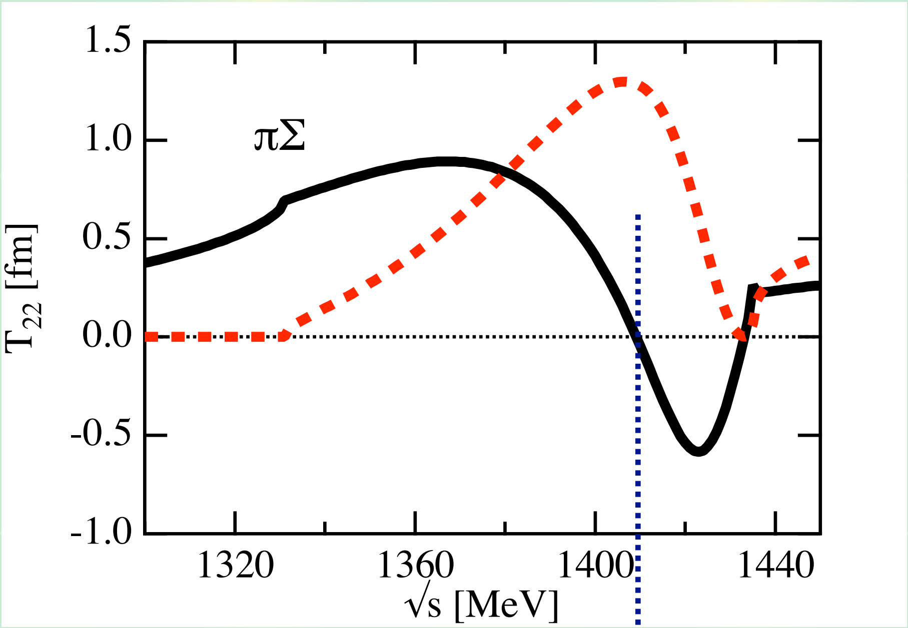
~ 1/2 of Akaishi-Yamazaki potential

πΣ resummation : small but pole exists

Small imaginary part : treated as perturbation

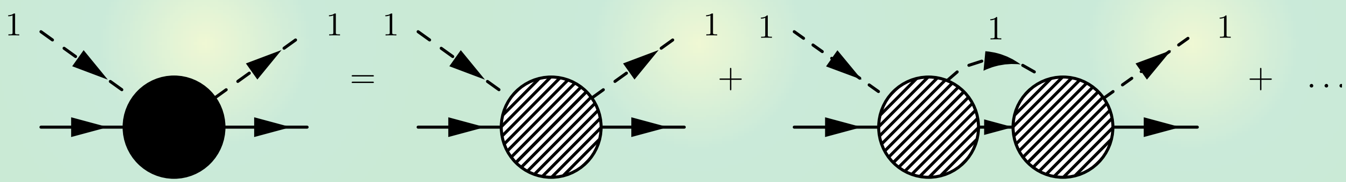
Scattering amplitude in $\bar{K}N$ and $\pi\Sigma$





~1420 MeV

~1405 MeV
Experiment



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

<-- two-pole structure (coupled-channel)
independent of the position of second pole

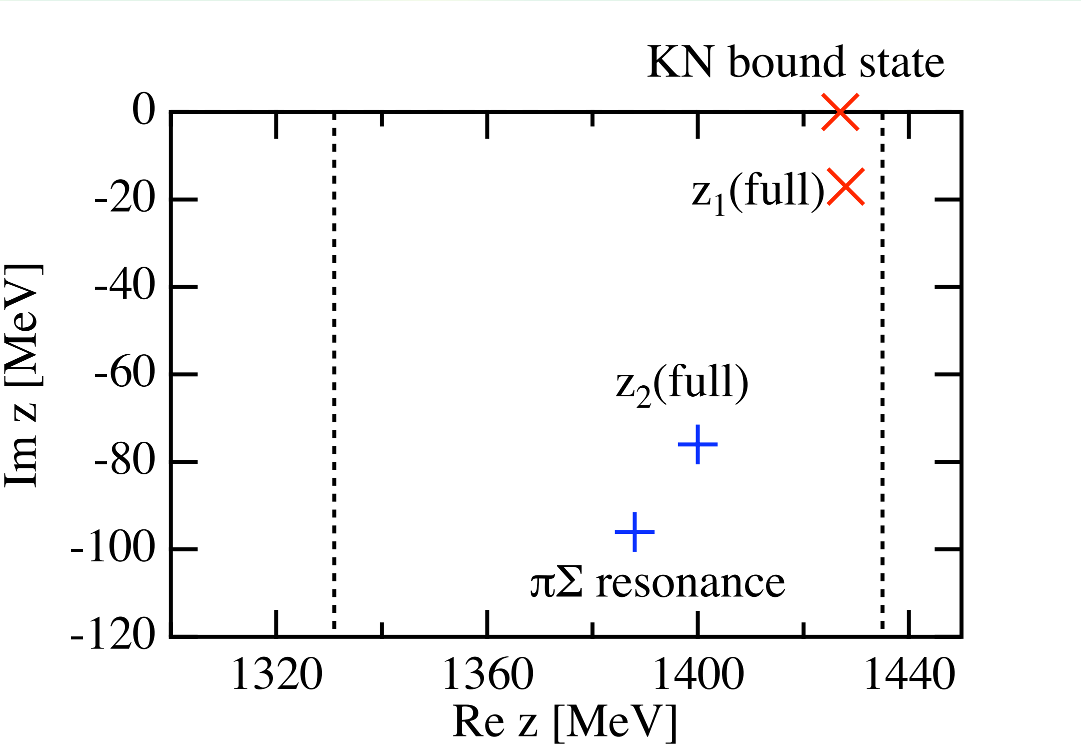
Origin of the two-pole structure

Chiral interaction

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

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

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

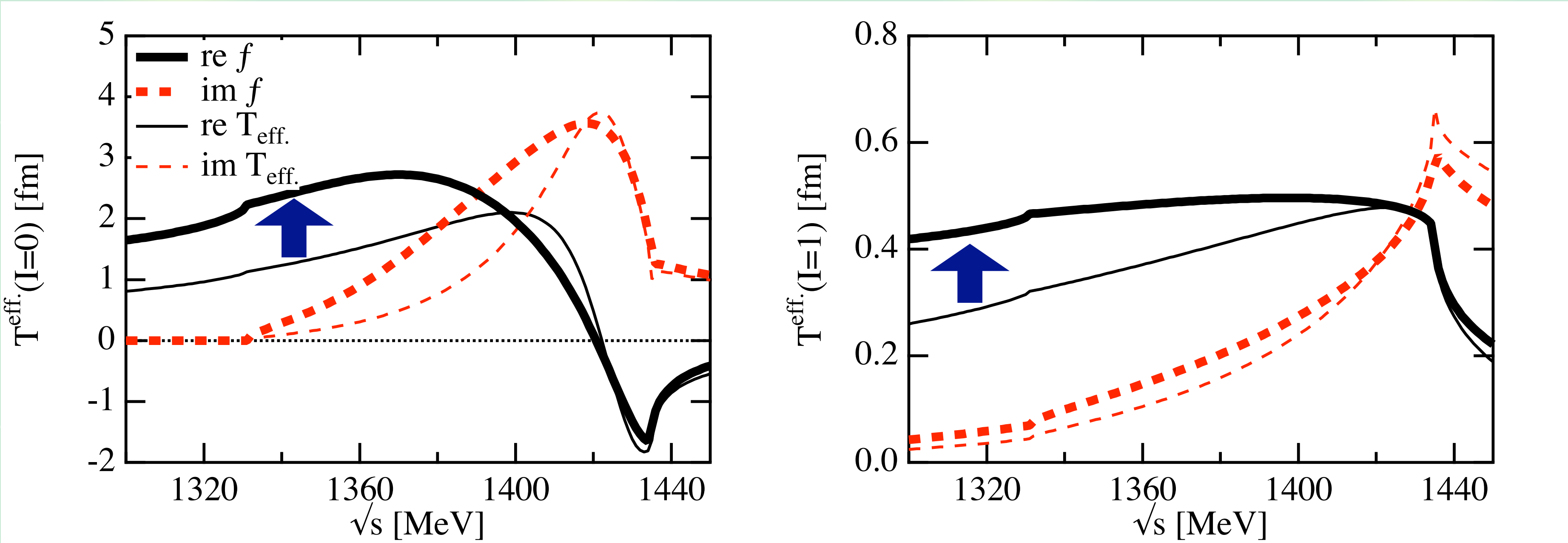


Strong attraction in K̄N (higher energy) --> bound state
Moderate attraction in πΣ (lower energy) --> resonance
==> two states in between two thresholds.

Two poles : natural consequence of chiral int.

c.f. σ and f0(980) in ππ and KK̄ ?

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



$$U(r,\sqrt{s}) = -\frac{4\pi \tilde{V}^{\mathrm{eff.}}(\sqrt{s})}{2\tilde{\omega}(\sqrt{s})} g(r) \qquad g(r) = \frac{e^{-r^2/b^2}}{\pi^{3/2} b^3}$$

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

==> agreement around threshold : OK

Deviation at lower energy

<-- Ambiguity of the extrapolation

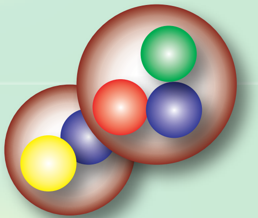
Summary 1 : $\bar{K}N$ interaction

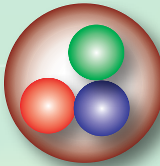
We derive a single-channel local potential based on chiral SU(3) dynamics.

- 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 poles.
- Two poles are the consequence of two attractive interactions in $\bar{K}N$ and $\pi\Sigma$.
- Extrapolation of local potential to the deep region is model-dependent.

Structure of dynamically generated resonances

Resonances ~ quasi-bound two-body states





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

c.f. ρ meson in $\pi\pi$ 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?

1 : analysis of Nc scaling

2 : extraction of the low energy structure

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.

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

(for baryon and Nf > 2)

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.

Excited qqq baryon

$$M_R \sim \mathcal{O}(N_c), \quad \Gamma_R \sim \mathcal{O}(1)$$ **should not be narrow**

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

S = -1 I = 0 channel in Isospin basis

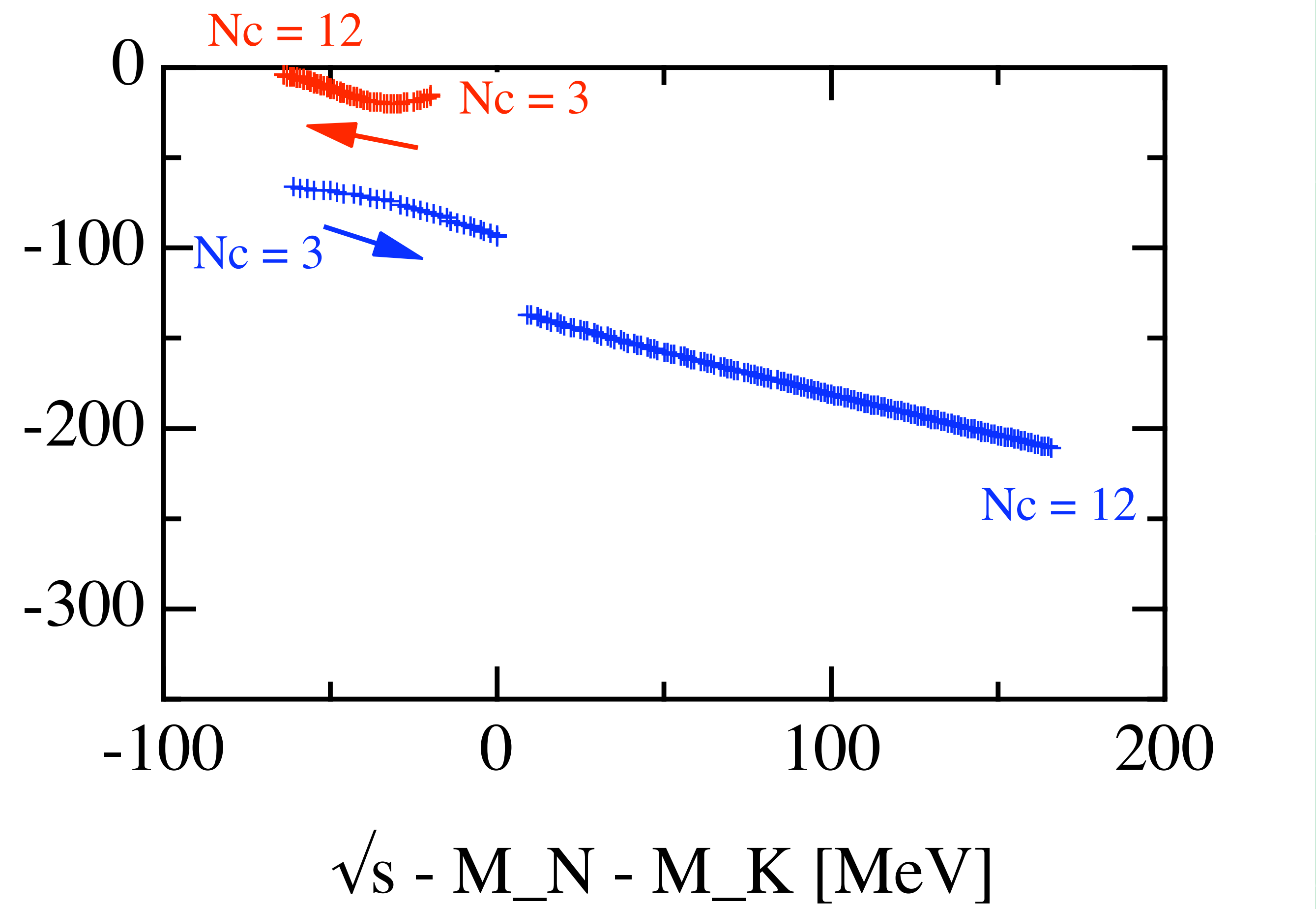
Coupling strengths with Nc dependence

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

Combining with the 1/Nc factor of 1/f^2,

- $\bar{K}N \to \bar{K}N$: **attractive** at large Nc
- $\bar{K}N \to \pi\Sigma$: $\mathcal{O}(1/\sqrt{N_c})$
- $\pi\Sigma \to \pi\Sigma$: $\mathcal{O}(1/N_c)$

Pole trajectories with varying Nc



1 bound state and 1 (desolving) resonance

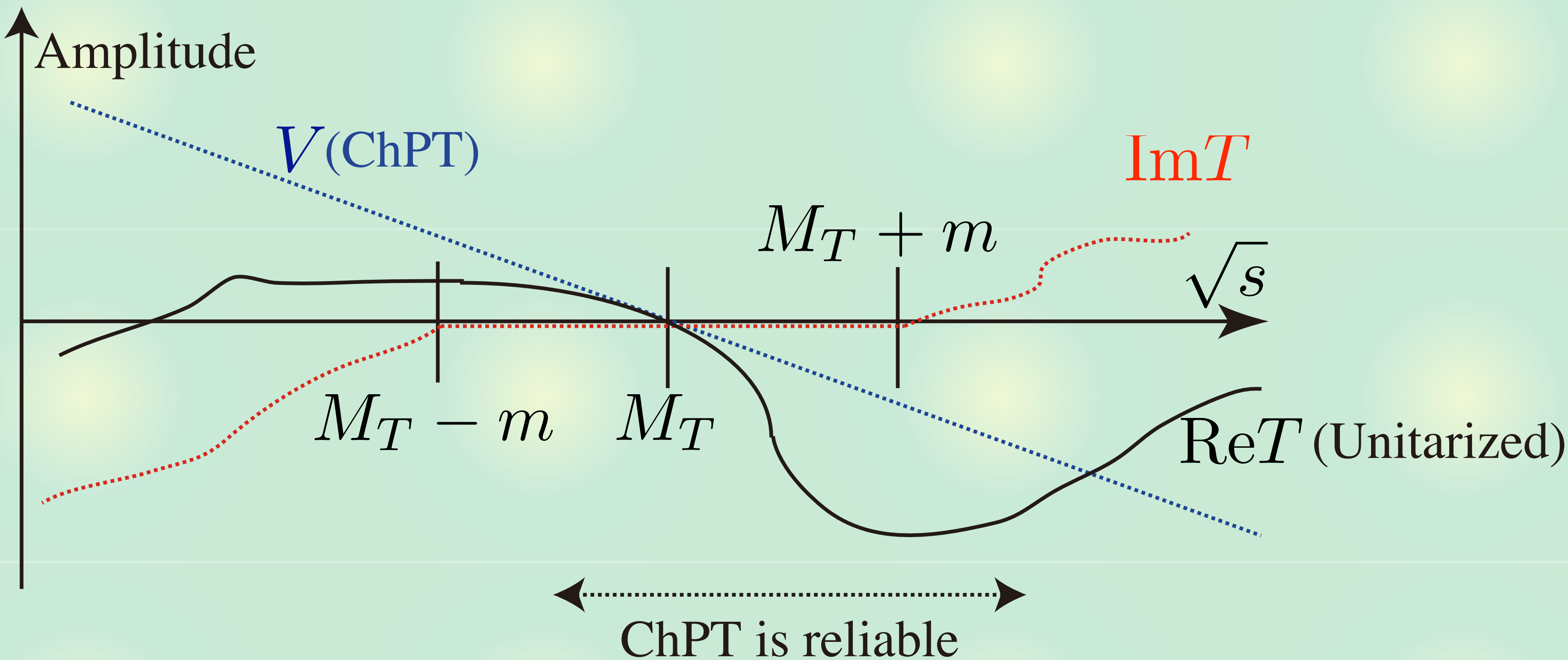
$\Gamma_R \neq \mathcal{O}(1)$

~ signal of the non-qqq (dynamical) structure

Renormalization condition : matching with ChPT

Match the unitarized amplitude with ChPT
--> fix the renormalization condition

$$G(\mu_m) = 0, \quad \Leftrightarrow \quad T(\mu_m) = V(\mu_m)$$



subtraction constant : real

$\Rightarrow \mu_m = M_T$ **natural unitarization**

Pole in the effective interaction

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

↑phenomonological ↑natural

Effective interaction

$$V' = -\frac{8\pi^2}{M\Delta a}\frac{\sqrt{s}-M}{\sqrt{s}-M_{\text{eff.}}}$$

$$= -\frac{C}{2f^2}(\sqrt{s}-M_T) + \boxed{\frac{C}{2f^2}\frac{(\sqrt{s}-M_T)^2}{\sqrt{s}-M_{\text{eff.}}}}$$

pole!

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

Physically meaningful pole :

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

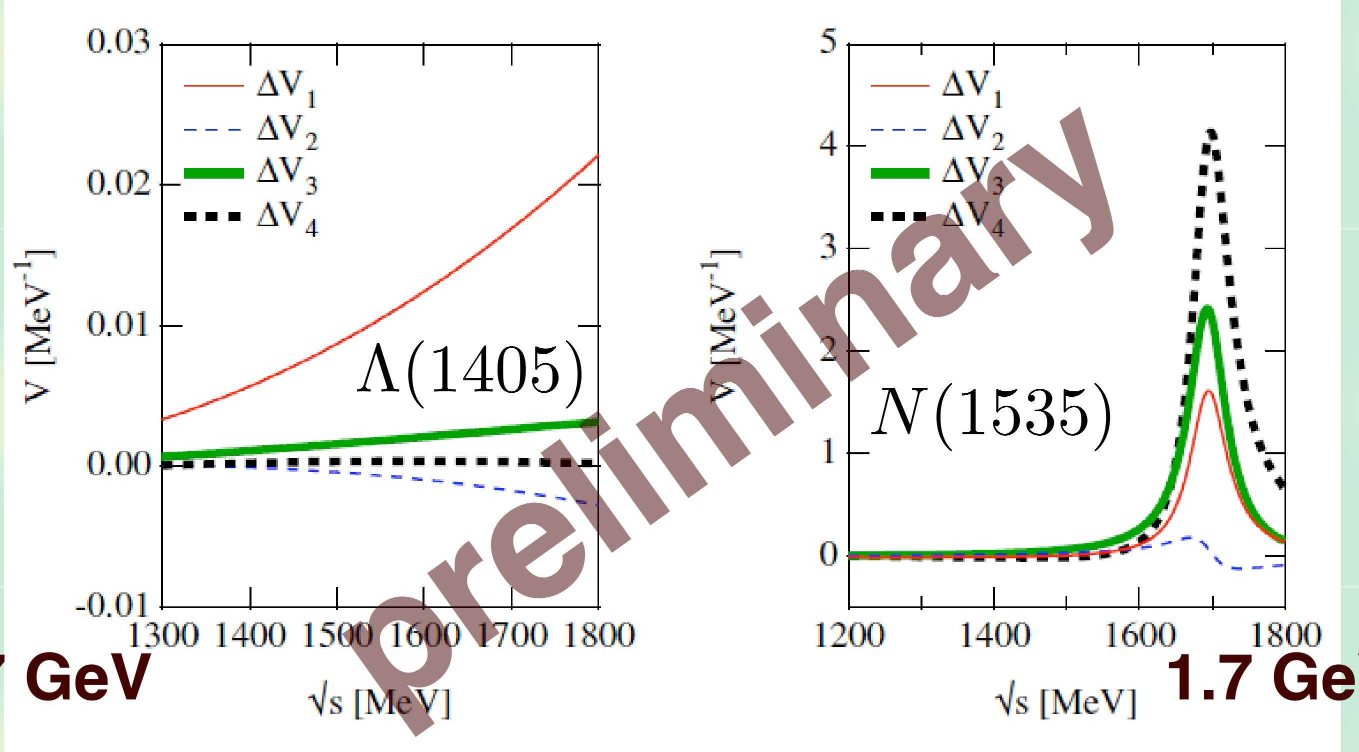
** energy scale of the effective pole **

Example : Λ(1405) and N(1535)

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

↑phenomonological ↑natural

Absorb Δa into effective interaction



17 GeV

1.7 GeV

Origin of dynamical pole?

Summary 2 : Structure of Λ(1405)

- **Large Nc behavior**

  Existence of a bound state in "1" or $\bar{K}N$ channel even in the large Nc limit
  : signal of the non-qqq state.

- **Matching with the low energy structure**

  Even if we use the LO chiral interaction, a choice of the subtraction constant may introduce a pole in the kernel interaction.

  Λ(1405) ~ dynamical?
  N(1535) ~ with CDD pole structure?