Structure of the Λ(1405) baryon resonance from its large Nc behavior

Tetsuo Hyodo[a],

Daisuke Jido[b], and Luis Roca[c]

Tokyo Institute of Technology[a] *YITP, Kyoto[b]* *Murcia Univ.[c]*

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Λ(1405) and $\bar{K}N$ dynamics

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

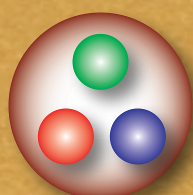
PDG

Mass : 1406.5 ± 4.0 MeV

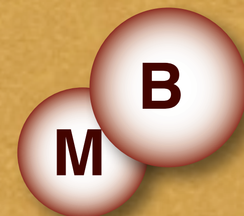
Width : 50 ± 2 MeV

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

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



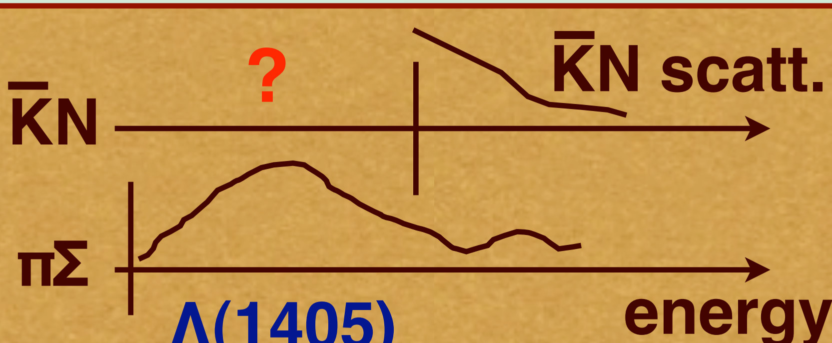
N. Isgur, G. Karl, PRD18, 4187 (1978)



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

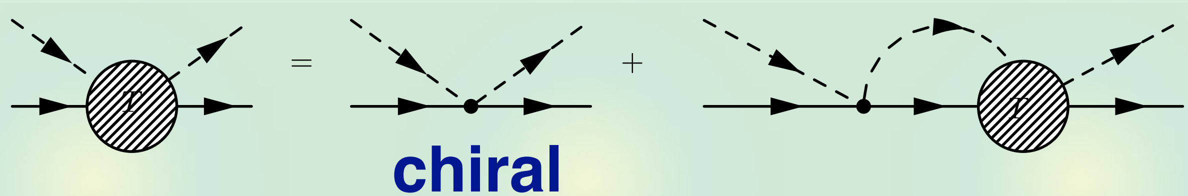
- Interaction <-- chiral symmetry

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

- Amplitude <-- unitarity (coupled channel)

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

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



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, ...

Nc scaling and quark structure : meson case

Origin of meson resonances?
General Nc scaling of $q\bar{q}$ meson

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

can be used to disentangle $q\bar{q}$.

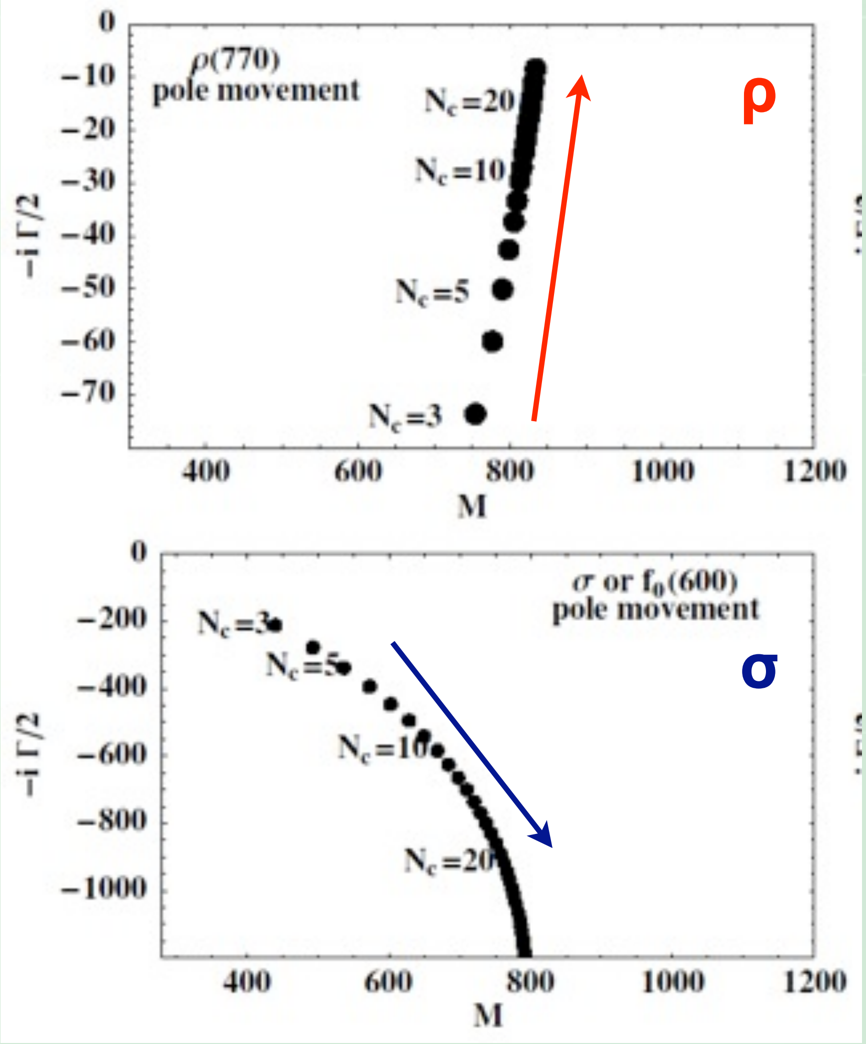
J.R. Pelaez, Phys. Rev. Lett. 92, 102001 (2004); Mod. Phys. Lett. A19, 2879 (2004)

Introducing Nc scaling in mass and low-energy constants, behavior of the resonance pole was studied.

$\rho \sim q\bar{q}$, $\sigma \neq q\bar{q}$

Nc scaling enables us to extract quark structure of resonances in hadron effective theory

pole position



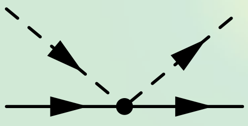
Nc scaling : baryon case

Nc dependence for hadron masses and decay constant

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

Leading order WT interaction has Nc dependence

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



(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)

Expression of the coupling strength

$$C = C.G. \times [C_2(T) - C_2(\alpha) + 3]$$

flavor representation <-- Nc dependence

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

Coupling strengths with Nc dependence

$$V = -C\frac{\omega}{2f^2}$$

“1” “8” “8” “27”

$$C_{ij}^{SU(3)}(N_c) = \begin{pmatrix} \frac{9}{2}+\frac{N_c}{2} & 0 & 0 & 0 \\ & 3 & 0 & 0 \\ & & 3 & 0 \\ & & & -\frac{1}{2}-\frac{N_c}{2} \end{pmatrix}$$

Linear dependence of Nc
--> finite interaction at large Nc limit.

$$f \sim \mathcal{O}(\sqrt{N_c})$$

Attractive interaction in “1” channel
Repulsive interaction in “27” channel

(Any exotic channels have nonpositive Nc dependence.)

S = -1, I = 0 channel in Isospin basis

Coupling strengths with Nc dependence

$$
\begin{array}{ccccc}
 & \bar{K}N & \pi\Sigma & \eta\Lambda & K\Xi
\end{array}
$$

$$
C^{I}_{ij}(N_c) = \begin{pmatrix}
\frac{1}{2}(3+N_c) & -\frac{\sqrt{3}}{2}\sqrt{-1+N_c} & \frac{\sqrt{3}}{2}\sqrt{3+N_c} & 0 \\
 & 4 & 0 & \frac{\sqrt{3+N_c}}{2} \\
 & & 0 & -\frac{3}{2}\sqrt{-1+N_c} \\
 & & & \frac{1}{2}(9-N_c)
\end{pmatrix}
$$

$O(Nc^{1/2})$ dependence <-- C.G. coefficients

Off-diagonal couplings < $O(Nc^{1})$
single-channel scattering in large Nc limit.

Attractive interaction in $\bar{K}N$ -> $\bar{K}N$ channel
Repulsive interaction in $K\Xi$ -> $K\Xi$ channel (for Nc > 9)

In the large Nc limit

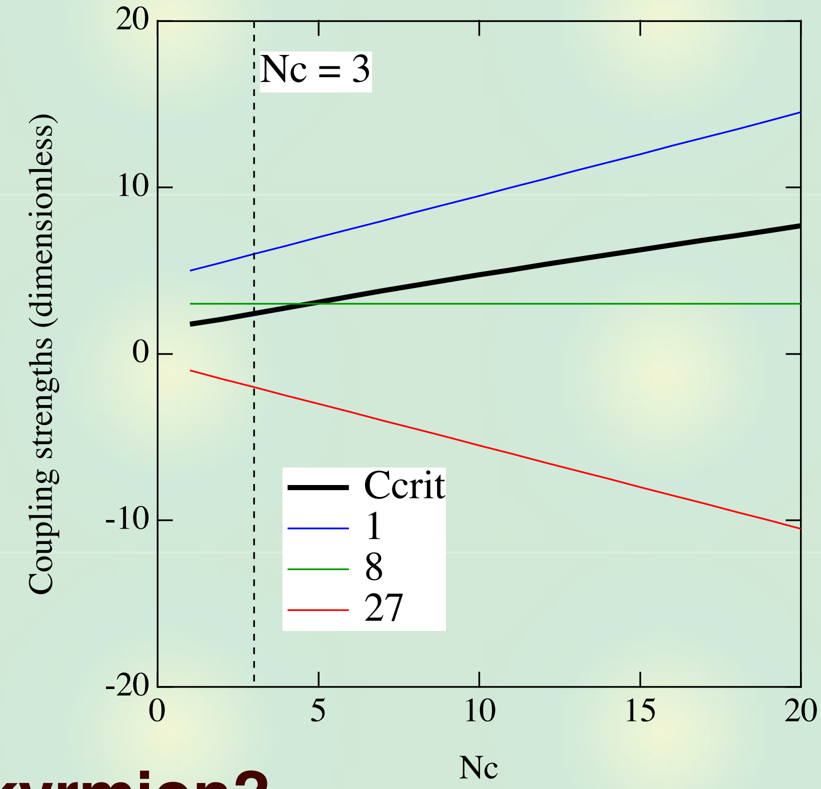
Attractive interaction in $\bar{K}N$("1") channel

$$C \sim N_c/2$$

Critical coupling strength (with Nc dependence)

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

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



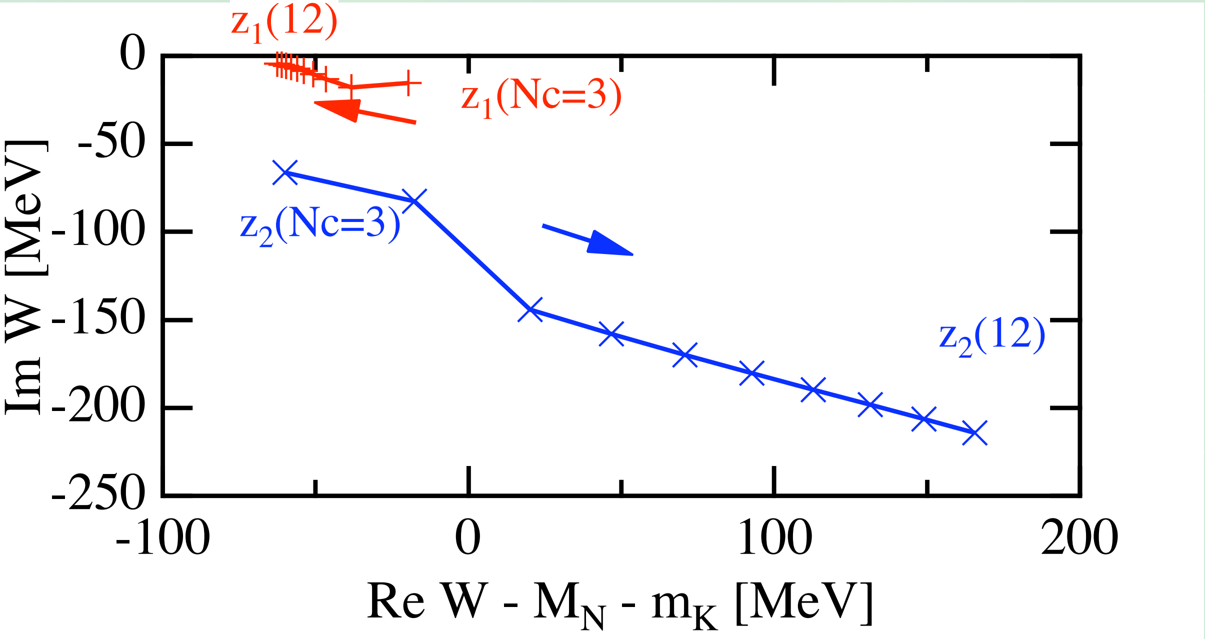
Bound state in $\bar{K}N$("1") channel

Kaon bound state approach for Skyrmion?

C.G. Callan and I.R. Klebanov, Nucl. Phys. B262, 365 (1985)

Pole trajectories with varying Nc

Λ(1405) poles in the unitarized amplitude (excitation energy)



1 bound state and 1 dissolving resonance

General 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)

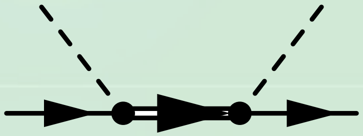
Result of chiral unitary approach

$\Gamma_R \neq \mathcal{O}(1)$ **=> Λ(1405) ~ non-qqq structure**

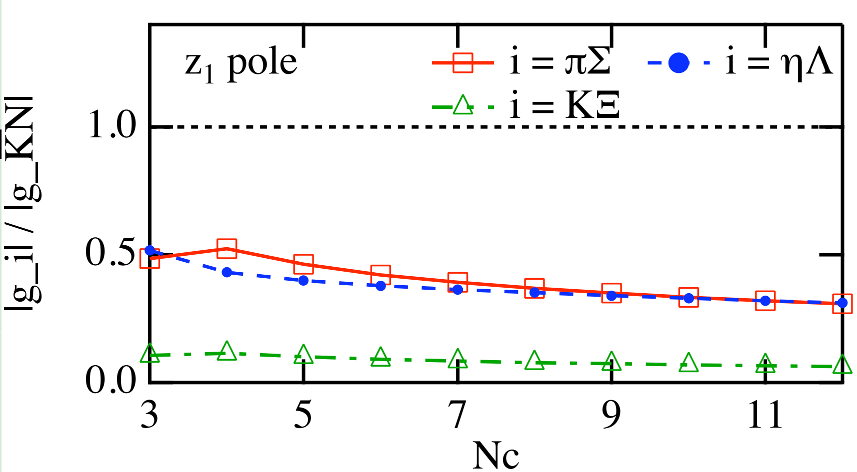
Isospin components of the poles

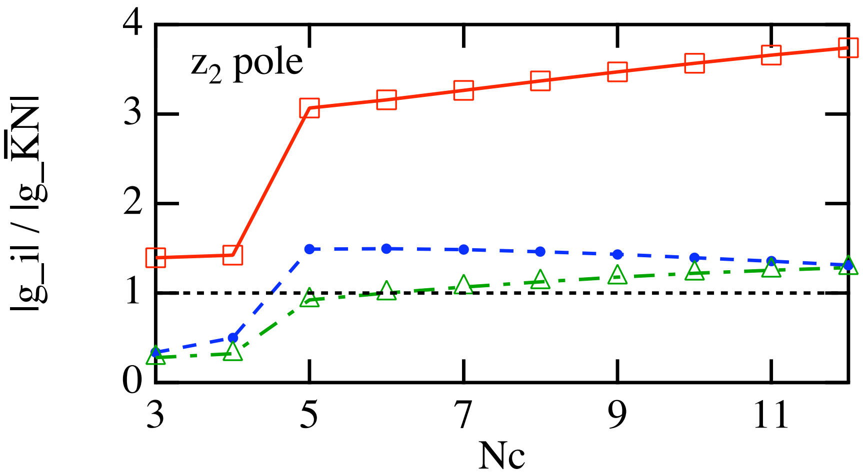
Residues (coupling strengths) in isospin basis

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



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

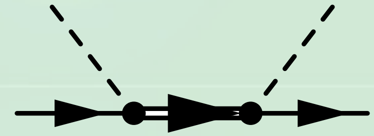




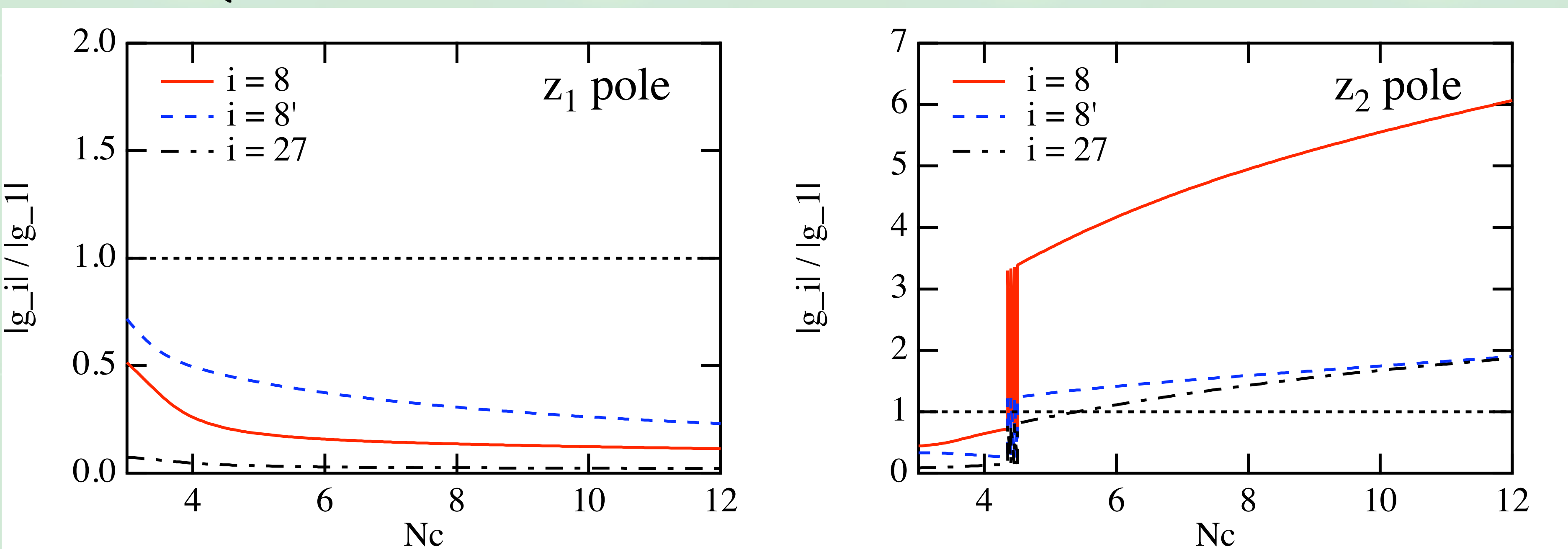
bound state : $\bar{\text{K}}$N dominant dissolving : other components

SU(3) components of the poles

Residues in SU(3) basis

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

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



bound state : “1” dominant **dissolving : other components**

Summary

We study the Nc scaling of the Λ(1405)

- Large Nc limit

  Bound state in $\bar{K}N$("1") channel

- Behavior around Nc = 3

  1 bound state and 1 dissolving resonance

  Nc dep. of Γ : evidence for non-qqq state

  Components of would-be-bound-state
  : dominated by $\bar{K}N$("1")
  --> consistent with large Nc limit

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

Appendix

ChU

Nc dependence in flavor representation?

For arbitrary Nc, a baryon should consist of Nc quarks.
Consider a ground state baryon (all quarks in s-state)

orbital : symmetric
color : antisymmetric

=> spin-flavor should be symmetric.

Assume spin is fixed --> flavor should be changed.
For instance, at Nc = 5,

spin : $(2 \times 2 \times 2) \times 2 \times 2 = (2 \times 2 \times 2) \times (1 + 3)$

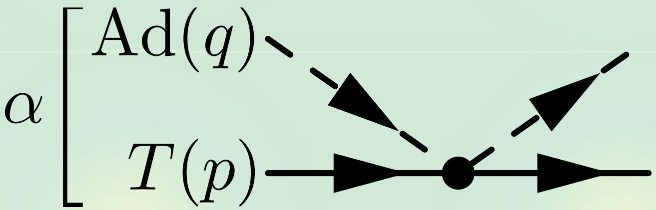
flavor : $(3 \times 3 \times 3) \times 3 \times 3 = (3 \times 3 \times 3) \times (\bar{3} + 6)$

Thus, flavor (or spin) representation should be changed **for baryons with Nf > 2**.

K. Piesciuk and M. Praszalowicz, Prog. Theor. Phys. Suppl. 168, 70 (2007)

Low energy theorem for s-wave interaction

Scattering of a target hadron (T) with the NG boson (Ad)



$$= \frac{1}{f^2}\frac{p\cdot q}{2M_T}\langle \boldsymbol{F}_T\cdot\boldsymbol{F}_{\mathrm{Ad}}\rangle_\alpha + \mathcal{O}\left(\left(\frac{m}{M_T}\right)^2\right)$$

s-wave : Weinberg-Tomozawa term

$$V_\alpha = -\frac{\omega}{2f^2}C_{\alpha,T}$$

$$C_{\alpha,T} \equiv -\langle 2\boldsymbol{F}_T\cdot\boldsymbol{F}_{\mathrm{Ad}}\rangle_\alpha = C_2(T) - C_2(\alpha) + 3 \quad (\text{for } N_f = 3)$$

coupling : pion decay constant
--> only flavor (group theoretical) structure is relevant
c.f. p-wave interaction ∈ axial charge g_A

The theorem well reproduces the πN scattering lengths

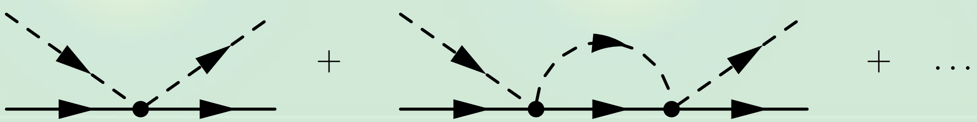
Y. Tomozawa, Nuovo Cim. 46A, 707 (1966); S. Weinberg, Phys. Rev. Lett. 17, 616 (1966)

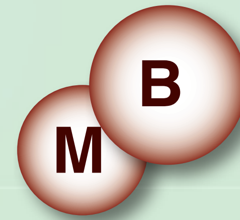
Dynamical state and CDD pole

Resonances in two-body scattering

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

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

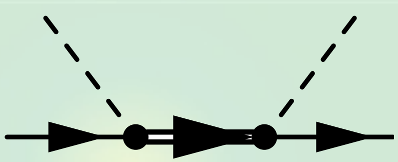


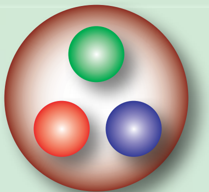


e.g.) Deuteron in NN, positronium in e^+e^-, (σ in π π), ...

(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

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

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

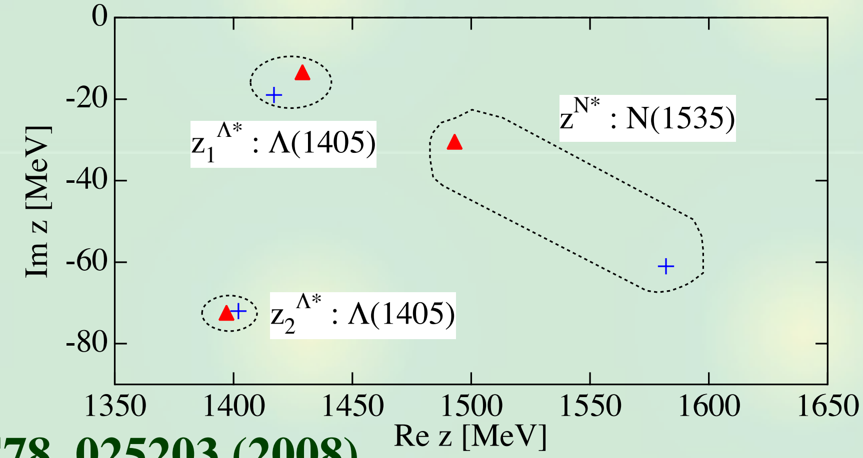
Known CDD pole contribution

(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).

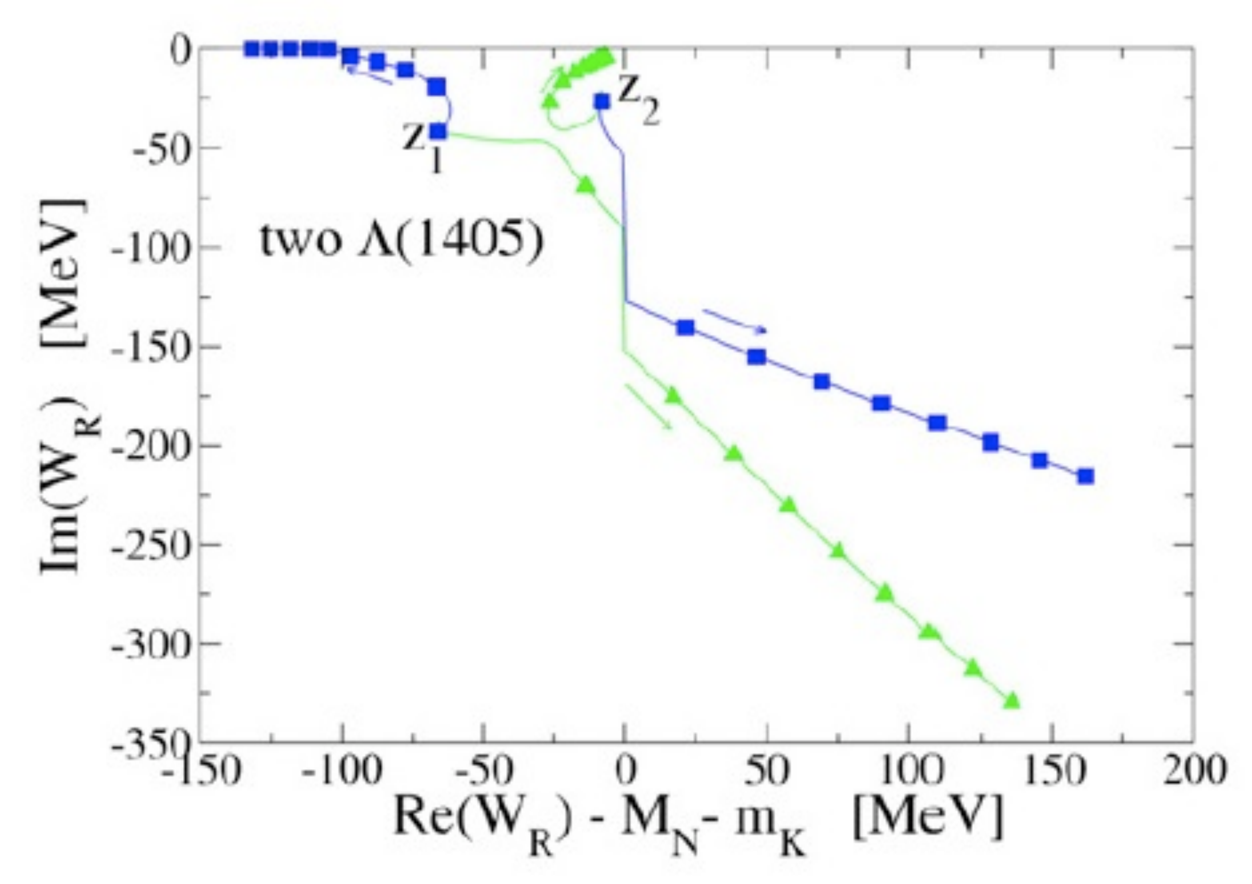
N(1535) in πN scattering
--> dynamical + CDD pole

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



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

Results in cutoff regularization



Pole trajectories in cutoff regularization

Difference : scaling of cutoff, 1 (mass) or $Nc^{1/2}$ (f)

Residue : bound state is dominated by