Chiral symmetry in hadron physics

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Contents

Chiral dynamics

- Chiral symmetry and low energy theorem
- Unitarity of S-matrix and dispersion theory
- Baryon resonances in meson-baryon scattering

Structure of Λ(1405) resonance

- Dynamical or CDD pole (genuine quark state) ?

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

- Nc Behavior and quark structure

  T. Hyodo, D. Jido, L. Roca, Phys. Rev. D77, 056010 (2008);
  L. Roca, T. Hyodo, D. Jido, Nucl. Phys. A809, 65-87 (2008).

- Electromagnetic properties

  T. Sekihara, T. Hyodo, D. Jido, Phys. Lett. B669, 133-138 (2008).

Chiral symmetry

Chiral symmetry: symmetry of massless fermion

$$\mathcal{L} = \bar{q}(i\partial\!\!\!/ - m)q$$

Chiral projection operators and Left-(Right-)handed fermions

$$P_L = \frac{1}{2}(1-\gamma_5), \quad P_R = \frac{1}{2}(1+\gamma_5), \quad q_L \equiv P_L q \quad q_R \equiv P_R q$$

Lagrangian can be decomposed as

$$\mathcal{L} = \bar{q}_{\underline{L}} i\partial\!\!\!/ q_{\underline{L}} + \bar{q}_{\underline{R}} i\partial\!\!\!/ q_{\underline{R}} - \bar{q}_{\underline{L}} m q_{\underline{R}} - \bar{q}_{\underline{R}} m q_{\underline{L}}$$

If m=0, L and R fields independently have global symmetries, such as phase transformations and flavor rotations:

$$q_R \to \exp\{i\sum_{a=0}^{N_F} t^a\theta_R^a\}q_R, \quad q_L \to \exp\{i\sum_{a=0}^{N_F} t^a\theta_L^a\}q_L$$

$$G = U(N_F)_R \otimes U(N_F)_L$$

$$= U(1)_V \otimes U(1)_A \otimes \boxed{SU(N_F)_R \otimes SU(N_F)_L}$$

chiral symmetry

QCD and chiral symmetry breaking

QCD : up, down, and strange quarks are light.
In the limit of vanishing quark masses,
QCD Lagrangian has 3-flavor chiral symmetry

$$G = SU(3)_R \otimes SU(3)_L$$

Chiral symmetry is broken in two ways:

- **spontaneous breaking**
- **explicit breaking (treated perturbatively)**

Spontaneous breaking: symmetry in the Lagrangain is not manifested in the vacuum (states).

$$\langle 0 | \bar{q}q | 0 \rangle = v \neq 0$$

not chiral invariant. For u,d quarks, v ~ -(250 MeV)^3

$$SU(3)_R \otimes SU(3)_L \to \boxed{SU(3)_V}$$

flavor symmetry

Chiral symmetry breaking in hadron physics

Why important, although it is broken anyway?

Consequence of spontaneous breaking:

- appearance of the Nambu-Goldstone (NG) boson

  $m_\pi \sim 140 \text{ MeV}$

- hadron mass generation

  $m_p \sim 1 \text{ GeV}$

- constraint for hadron-NG boson interaction
  low energy theorem

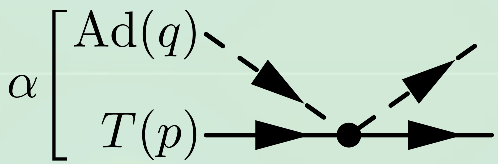
PCAC + commutation relation --> current algebra
more systematic low-energy expansion --> ChPT

Chiral symmetry and its breaking

QCD <==> hadron phenomena

Low energy s-wave interaction

Low energy theorem for pion (Ad) scattering with a target (T)



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

s-wave : Weinberg-Tomozawa term

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

$$V_{ij} = -\frac{C_{ij}}{4f^2}(\omega_i+\omega_j)$$ **pion energy**

pion decay constant (g_V=1)

$$C_{ij} = \sum_\alpha C_{\alpha,T}\begin{pmatrix} 8 & T & \| & \alpha \\ I_{M_i}, Y_{M_i} & I_{T_i}, Y_{T_i} & \| & I, Y\end{pmatrix}\begin{pmatrix} 8 & T & \| & \alpha \\ I_{M_j}, Y_{M_j} & I_{T_j}, Y_{T_j} & \| & I, Y\end{pmatrix}$$

$$C_{\alpha,T} = \langle 2\boldsymbol{F}_T\cdot\boldsymbol{F}_{\mathrm{Ad}}\rangle = C_2(T) - C_2(\alpha) + 3$$

flavor SU(3) --> sign and strength

The result corresponds to the leading order term in ChPT

Chiral dynamics : overview

Description of hadron-NG boson scattering and resonance

- interaction <-- chiral symmetry

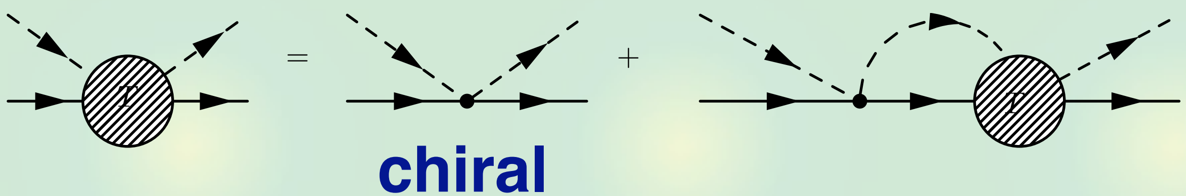
Y. Tomozawa, Nuovo Cim. 46A, 707 (1966); S. Weinberg, Phys. Rev. Lett. 17, 616 (1966)

- scattering amplitude <-- unitarity in coupled channels

chiral interaction is strong, especially for 3-flavor case

R.H. Dalitz, T.C. Wong, G. Rajasekaran, Phys. Rev. 153, 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, ...

Scattering theory : N/D method

Single-channel scattering, masses: M_T and m

G.F. Chew, S. Mandelstam, Phys. Rev. 119, 467 (1960)

$s = W^2$

N/D method:
Divide T into N(umerator) and D(enominator)
unitarity cut --> D, unphysical cut(s) --> N

$$T(s) = N(s)/D(s)$$

phase space (optical theorem)

$$\mathrm{Im}D(s) = \mathrm{Im}[T^{-1}(s)]N(s) = \rho(s)N(s)/2 \quad \text{for } s > s^+$$

$$\mathrm{Im}N(s) = \mathrm{Im}[T(s)]D(s) \quad \text{for } s < s^-$$

Dispersion relation for N and D
--> set of integral equations, input : $\mathrm{Im}[T(s)] \quad \text{for } s < s^-$

General form of the (s-wave) amplitude

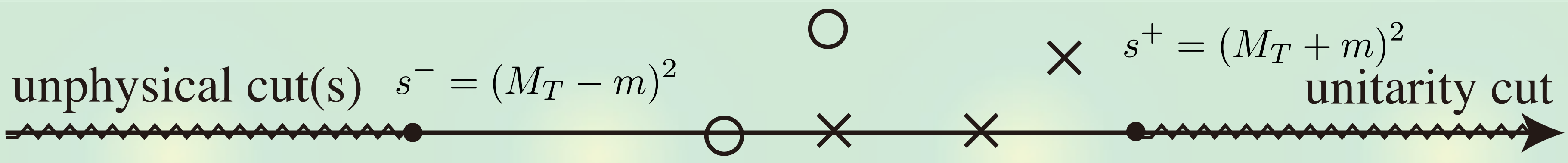
Neglect unphysical cut (crossed diagrams), set N=1

U. G. Meissner, J. A. Oller, Nucl. Phys. A673, 311 (2000)

$$T^{-1}(\sqrt{s}) = \tilde{a}(s_0) + \frac{s-s_0}{2\pi}\int_{s^+}^{\infty} ds' \frac{\rho(s')}{(s'-s)(s'-s_0)}$$

- pole (and zero) of the amplitude

L. Castillejo, R.H. Dalitz, F.J. Dyson, Phys. Rev. 101, 453 (1956)



CDD pole(s), R_i, W_i : not known in advance

$$T^{-1}(\sqrt{s}) = \sum_i \frac{R_i}{\sqrt{s}-W_i} + \tilde{a}(s_0) + \frac{s-s_0}{2\pi}\int_{s^+}^{\infty} ds' \frac{\rho(s')}{(s'-s)(s'-s_0)}$$

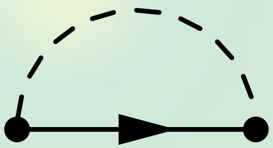
CDD pole contribution --> independent particle

G.F. Chew, S.C. Frautschi, Phys. Rev. 124, 264 (1961)

Order by order matching with ChPT

Identify loop function G, the rest contribution --> V^{-1}

$$T^{-1}(\sqrt{s}) = \sum_i \frac{R_i}{\sqrt{s}-W_i} + \tilde{a}(s_0) + \frac{s-s_0}{2\pi}\int_{s+}^{\infty} ds' \frac{\rho(s')}{(s'-s)(s'-s_0)}$$

$-$ 

$$= -i\int \frac{d^4q}{(2\pi)^4}\frac{2M_T}{(P-q)^2-M_T^2+i\epsilon}\frac{1}{q^2-m^2+i\epsilon}\Big|_{\text{dim.reg.}}$$

$$= -\frac{2M_T}{(4\pi)^2}\left\{a + \frac{m^2-M_T^2+s}{2s}\ln\frac{m^2}{M_T^2} + \frac{\bar{q}}{\sqrt{s}}\ln\frac{\phi_{++}(s)\,\phi_{+-}(s)}{\phi_{-+}(s)\,\phi_{--}(s)}\right\}$$

$$= -G(\sqrt{s};a)$$

subtraction constant (cutoff)

$$T(\sqrt{s}) = [V^{-1}(\sqrt{s}) - G(\sqrt{s};a)]^{-1}$$

scattering amplitude

V? chiral expansion of T, (conceptual) matching with ChPT

J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001)

$$T^{(1)} = V^{(1)}, \quad T^{(2)} = V^{(2)}, \quad T^{(3)} = V^{(3)} - V^{(1)}GV^{(1)}, \ \ldots$$

$\bar{K}N$ scattering and $\Lambda(1405)$

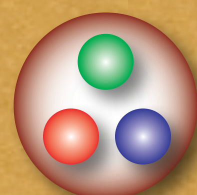
$\Lambda(1405) : J^P = 1/2^-, I = 0$

(PDG)

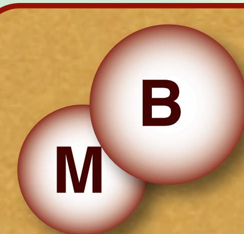
mass: 1406.5 ± 4.0 MeV, width: 50 ± 2 MeV

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

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



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



Coupled channel multi-scattering

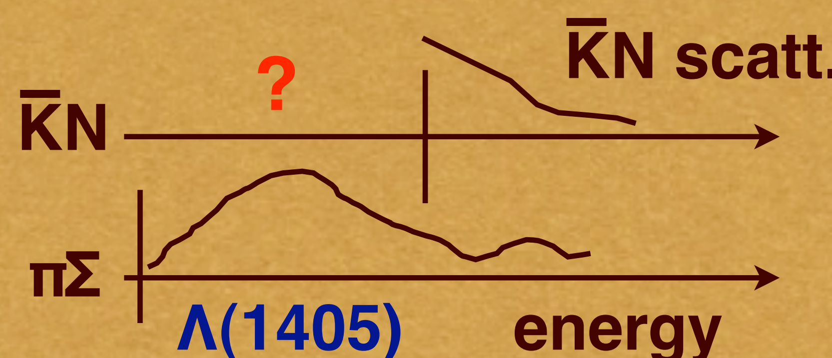
R.H. Dalitz, T.C. Wong,
G. Rajasekaran, PR153, 1617 (1967)

$\bar{K}N$ interaction below threshold

T. Hyodo, W. Weise, PRC 77, 035204 (2008)

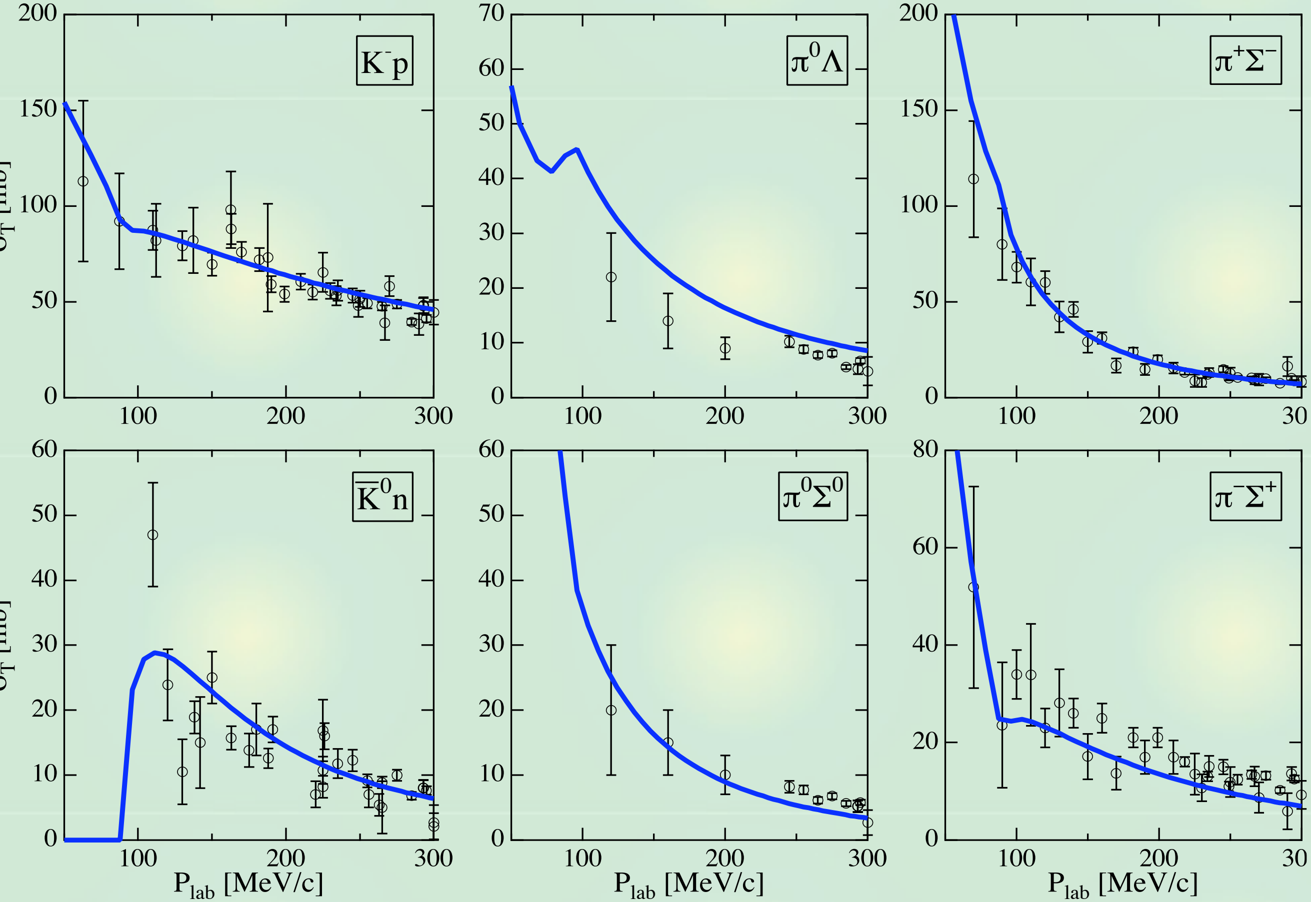
--> $\bar{K}N$ potential, kaonic nuclei

A. Dote, T. Hyodo, W. Weise,
NPA804, 197 (2008); PRC 79, 014003 (2009)



How it works? vs experimental data

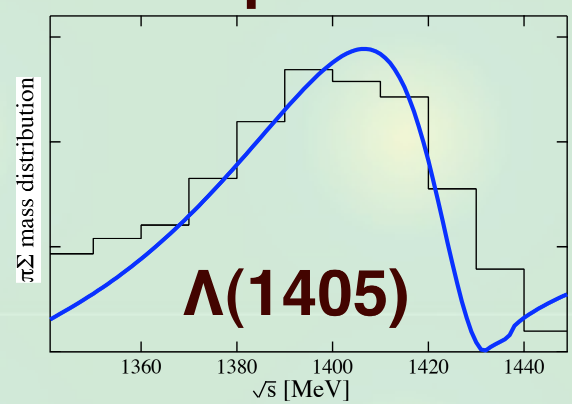
Total cross sections



threshold ratios

	γ	R_c	R_n
exp.	2.36	0.664	0.189
theo.	1.80	0.624	0.225

πΣ spectrum



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

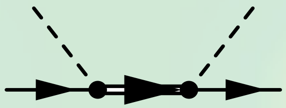
T. Hyodo, S.I. Nam, D. Jido, A. Hosaka, Prog. Theor. Phys. 112, 73 (2004)

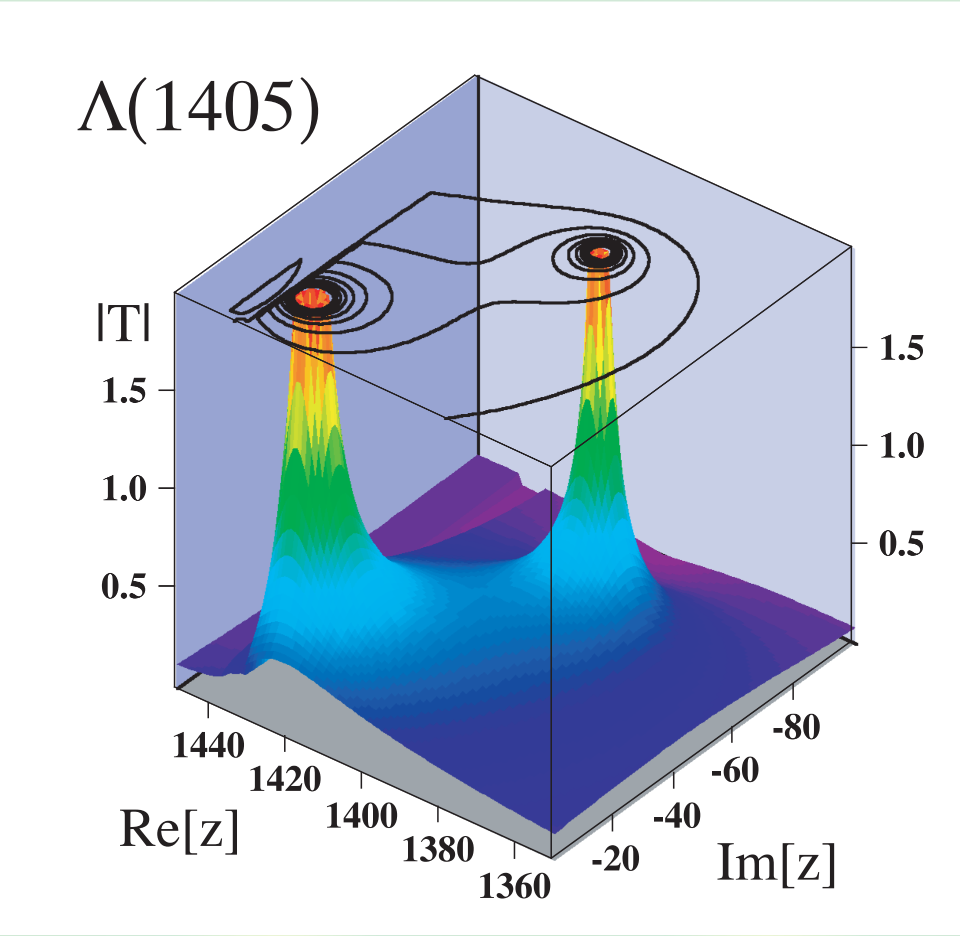
Good agreement with data above, at, and below threshold

Two poles for one resonance

Poles of the amplitude in the complex plane : 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**

Physical "Λ(1405)"
: superposition of two states

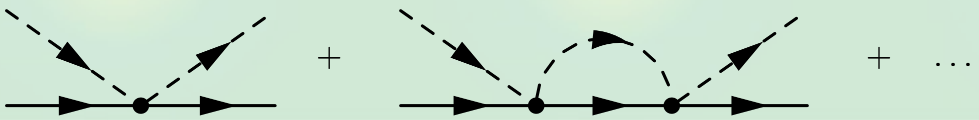
D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, Nucl. Phys. A 723, 205 (2003);
T. Hyodo, W. Weise, Phys. Rev. C 77, 035204 (2008)

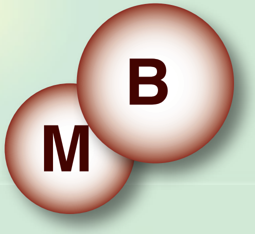
Dynamical state and CDD pole

Resonances in two-body scattering

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

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

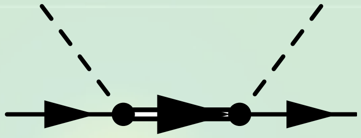


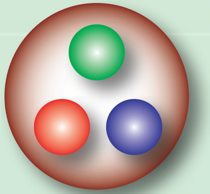


... in the present case : meson-baryon molecule

(b) CDD pole: elementary, independent, ...

L. Castillejo, R.H. Dalitz, F.J. Dyson, Phys. Rev. 101, 453 (1956)





... in the present case : three-quark state

Resonances in chiral dynamics -> (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)

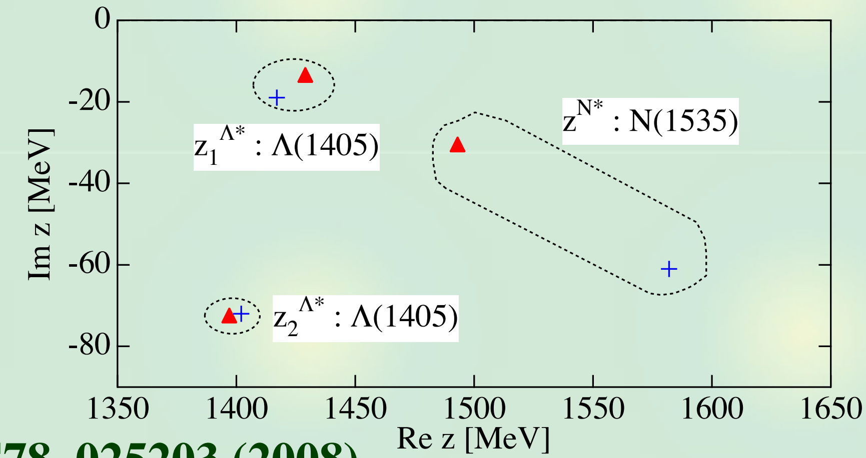
Known CDD pole contribution

(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**



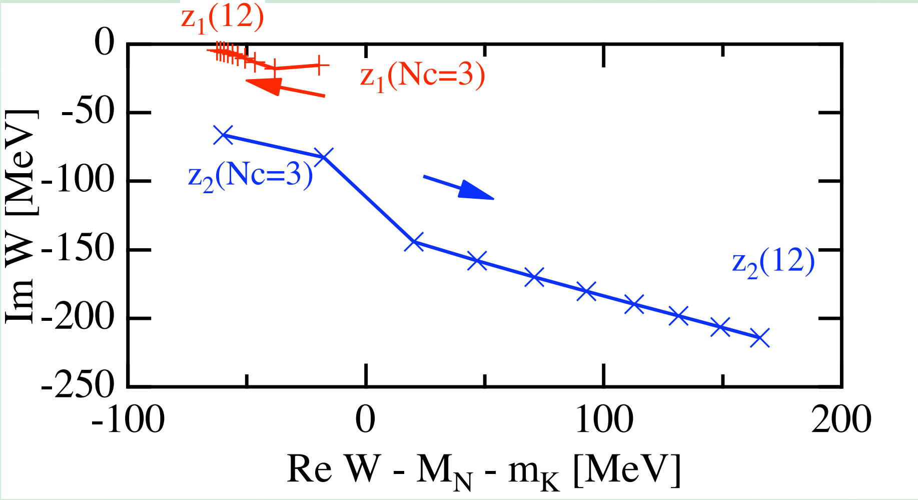
T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C78, 025203 (2008).

Nc scaling in the model

Nc : number of color in QCD
Hadron effective theory / quark structure

The Nc behavior is known from the general argument.
<-- introducing Nc dependence in the model,
analyze the resonance properties with respect to Nc

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



Nc scaling of (excited) qqq baryon

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

Result of chiral dynamics

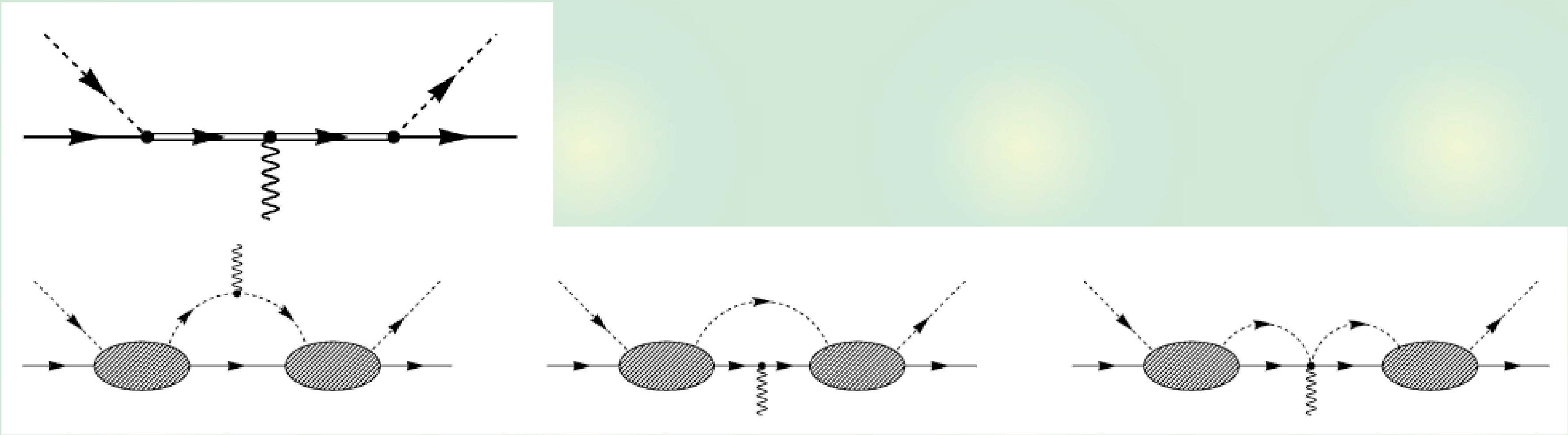
$$\Gamma_R \neq \mathcal{O}(1)$$

--> non-qqq (i.e. dynamical) structure of the Λ(1405)

T. Hyodo, D. Jido, L. Roca, Phys. Rev. D77, 056010 (2008).
L. Roca, T. Hyodo, D. Jido, Nucl. Phys. A809, 65-87 (2008).

Electromagnetic properties

Attaching photon to resonance
--> em properties : rms, form factors,...



result of mean squared radii :

$$|\langle r^2 \rangle_{\mathrm{E}}| = 0.33 \ [\mathrm{fm}^2]$$

large (em) size of the Λ(1405) : c.f. -0.12 [fm²] for neutron
--> meson-baryon picture

T. Sekihara, T. Hyodo, D. Jido, Phys. Lett. B669, 133-138 (2008);
T. Sekihara, T. Hyodo, D. Jido, in preparation.

Summary : Chiral dynamics

Chiral symmetry in QCD, its spontaneous breaking, and dynamical scattering model are reviewed.

- **Chiral symmetry enables us to connect hadron phenomena with underlying theory of QCD.**
- **Interaction constrained by chiral symmetry + coupled-channel unitarity condition**

  => successful description of hadron scattering and resonances: e.g. Λ(1405) in $\bar{K}N$ scattering.
- **Internal structure of resonances can be investigated in several ways.**

Summary : Structure of Λ(1405)

The structure of the Λ(1405) is studied:

- Dynamical or CDD?

  => dominance of the MB components

- Analysis of Nc scaling

  => non-qqq structure

- Electromagnetic properties

  => large e.m. size

- Independent analyses consistently support the meson-baryon molecule picture for the Λ(1405)