Origin of Resonances in Chiral Dynamics

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  - Dynamical or CDD pole (quark state) ?
  - Nc Behavior and quark structure
  - Electromagnetic properties
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Physics of the $\Lambda(1405)$

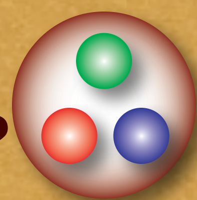
$$\Lambda(1405) : J^P = 1/2^-, I = 0$$

(PDG)

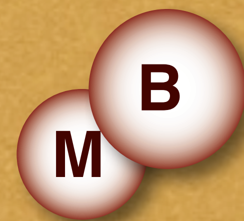
mass : 1406.5 ± 4.0 MeV, width : 50 ± 2 MeV

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

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



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



Coupled channel
multi-scattering

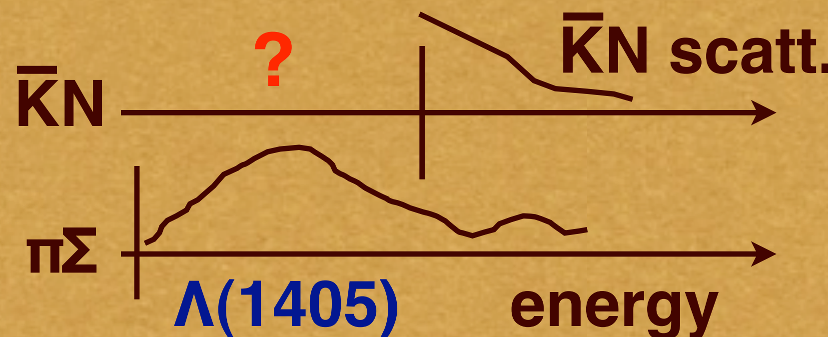
R.H. Dalitz, T.C. Wong,
G. Rajasekaran, PR153, 1617 (1967)

$\bar{K}N$ 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)



"Mass" of the 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)

Analysis of the Hemingway's data by phenomenological model with I=0 to extract mass and width.

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

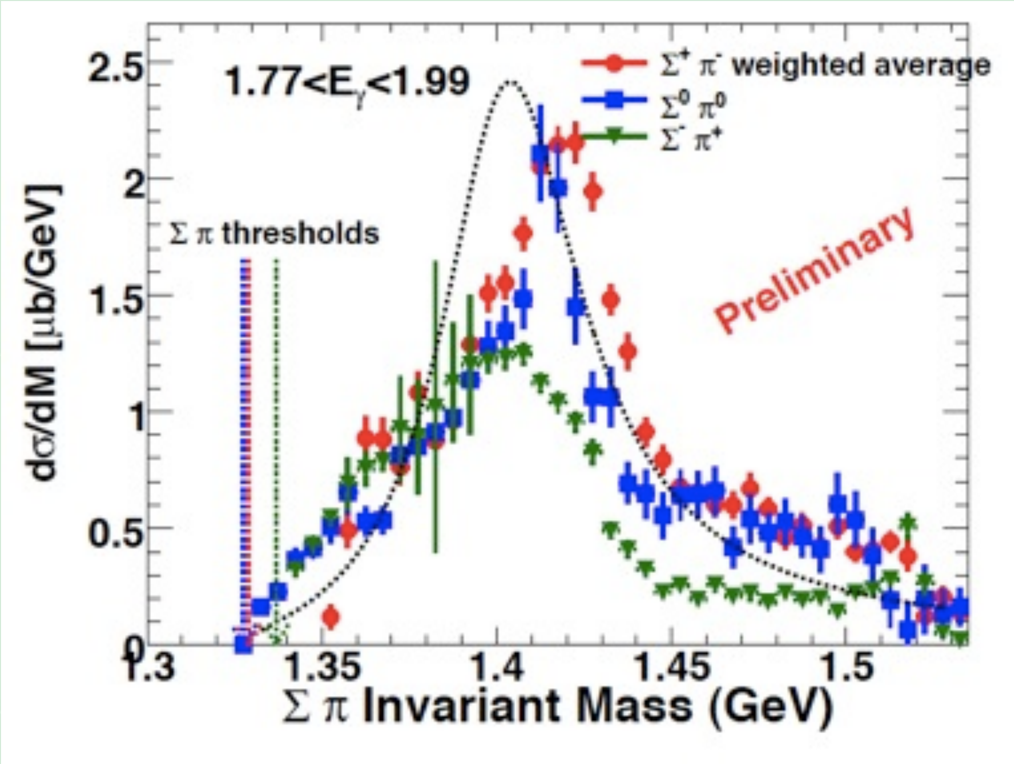
Spectrum is not purely in I=0, but with some contamination.
Analysis is valid only when $|T_{\Lambda^*}| \gg |T^{I=0,1}_{\text{non-resonant}}|$

(they knew the isospin interference and discussed it)

Isospin interference in πΣ spectrum

To select I=0 component, it is needed to observe all three πΣ charged states ($\pi^0\Sigma^0$, $\pi^\pm\Sigma^\mp$) simultaneously.

$$\gamma p \to K^+\Lambda(1405)$$



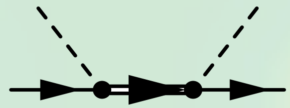
CLAS, K. Moriya@HYP-X (2009)

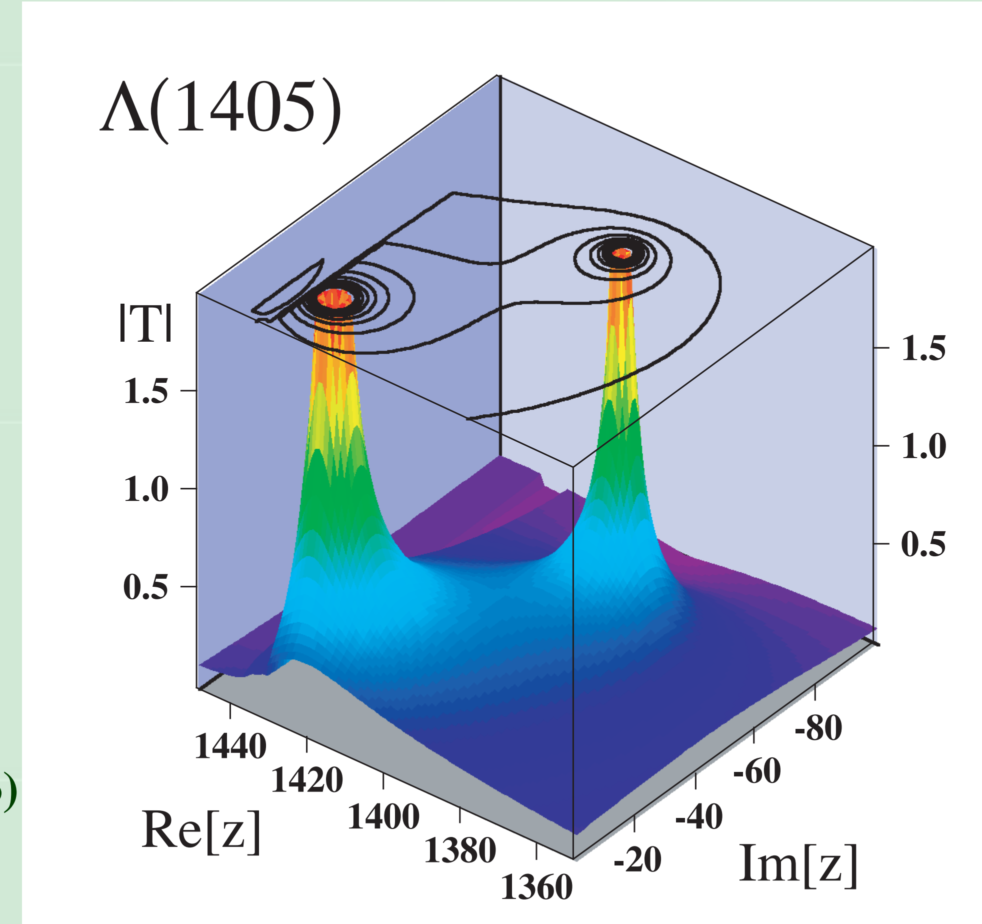
The isospin interference is observed experimentally!
The interference is strong enough to change the spectrum (peak position, width, size of cross section, etc.)!

Double-pole structure in chiral dynamics

Pole of the scattering amplitude : resonance

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

$\sim$ 



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

Different coupling to $\bar{K}N$/πΣ
--> change πΣ spectra

D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, Nucl. Phys. A 723, 205 (2003)

Origin of the two poles
<-- attractions in $\bar{K}N$ and πΣ

T. Hyodo, W. Weise, Phys. Rev. C 77, 035204 (2008)

Interference and change of the πΣ spectrum

Schematic decomposition of πΣ amplitude

$$T_{\pi\Sigma} \sim \boxed{T(\Lambda^*) + T_{\text{non-resonant}}(I=0)} + \boxed{T_{\text{non-resonant}}(I=1)}$$

Spectral change in $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\pi^0\Sigma^0$

<-- Interference between I=0 and I=1

Chiral dynamics provides $T(\Lambda^*)$ **as well as** $T_{\text{non-resonant}}(I=0,1)$

Spectral change by double-pole structure

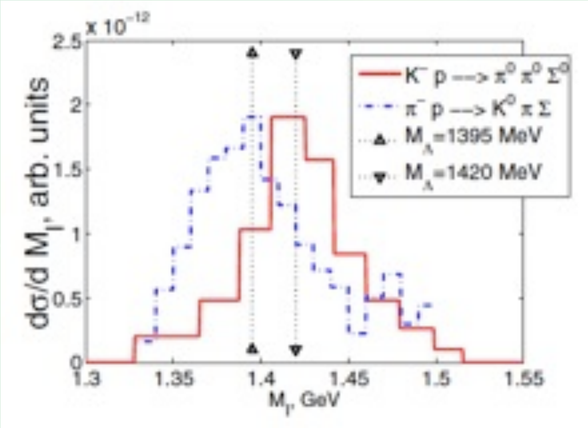
<-- different coupling to $\bar{K}N$/πΣ

$$T(\bar{K}N \to \Lambda^* \to \pi\Sigma) \neq T(\pi\Sigma \to \Lambda^* \to \pi\Sigma)$$

<-- different ratio $\bar{K}N$/πΣ in the initial state

<-- different process

$$\frac{K^-p \to \pi^0(\bar{K}N)^0}{K^-p \to \pi^0(\pi\Sigma)^0} \neq \frac{\pi^-p \to K^0(\bar{K}N)^0}{\pi^-p \to K^0(\pi\Sigma)^0}$$



V.K. Magas, E. Oset, A. Ramos, Phys. Rev. Lett. 95, 052301 (2005)

The ratio depends on the model/mechanism

Chiral symmetry breaking in hadron physics

Chiral symmetry: QCD with massless quarks

Consequence of chiral symmetry breaking in hadron physics

- **appearance of the Nambu-Goldstone (NG) boson**

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

- **dynamical generation of hadron masses**

  $M_p \sim 1 \text{ GeV} \sim 3M_q, \quad M_q \sim 300 \text{ MeV} \quad v.s. \quad m_q \sim 3\text{-}7 \text{ MeV}$

- **constraints on the interaction of NG boson-hadron**

  low energy theorems <-- current algebra

  systematic low energy ($m,p/4\pi f_\pi$) expansion : ChPT

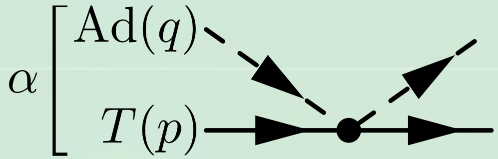
Chiral symmetry and its breaking

$$SU(3)_R \otimes SU(3)_L \to SU(3)_V$$

Underlying QCD <==> observed hadron phenomena

s-wave low energy interaction

Low energy NG boson (Ad)- target hadron (T) scattering



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

Projection onto s-wave : Weinberg-Tomozawa term

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

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

energy of π (derivative coupling)

decay constant of π (g_V=1)

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

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

Group theoretical structure of the target and flavor SU(3) symmetry determines the sign and strength of the interaction

Low energy theorem: leading order term in ChPT

Scattering amplitude and unitarity

Unitarity of S-matrix : Optical theorem

$$\mathrm{Im}\,[T^{-1}(s)] = \frac{\rho(s)}{2}$$ phase space of two-body state

General amplitude by dispersion relation

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

R_i, W_i, a : to be determined by chiral interaction

Identify dispersion integral = loop function G, the rest = V^{-1}

$$T(\sqrt{s}) = \frac{1}{V^{-1}(\sqrt{s}) - G(\sqrt{s};a)}$$ Scattering amplitude

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

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

Amplitude T : consistent with chiral symmetry + unitarity

Overview of chiral dynamics

Description of hadron-NG boson scattering

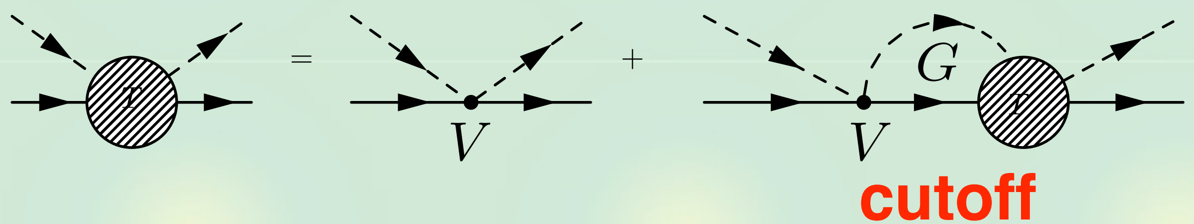
- Interaction <-- chiral symmetry

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, Phys. Rev. 153, 1617 (1967)

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



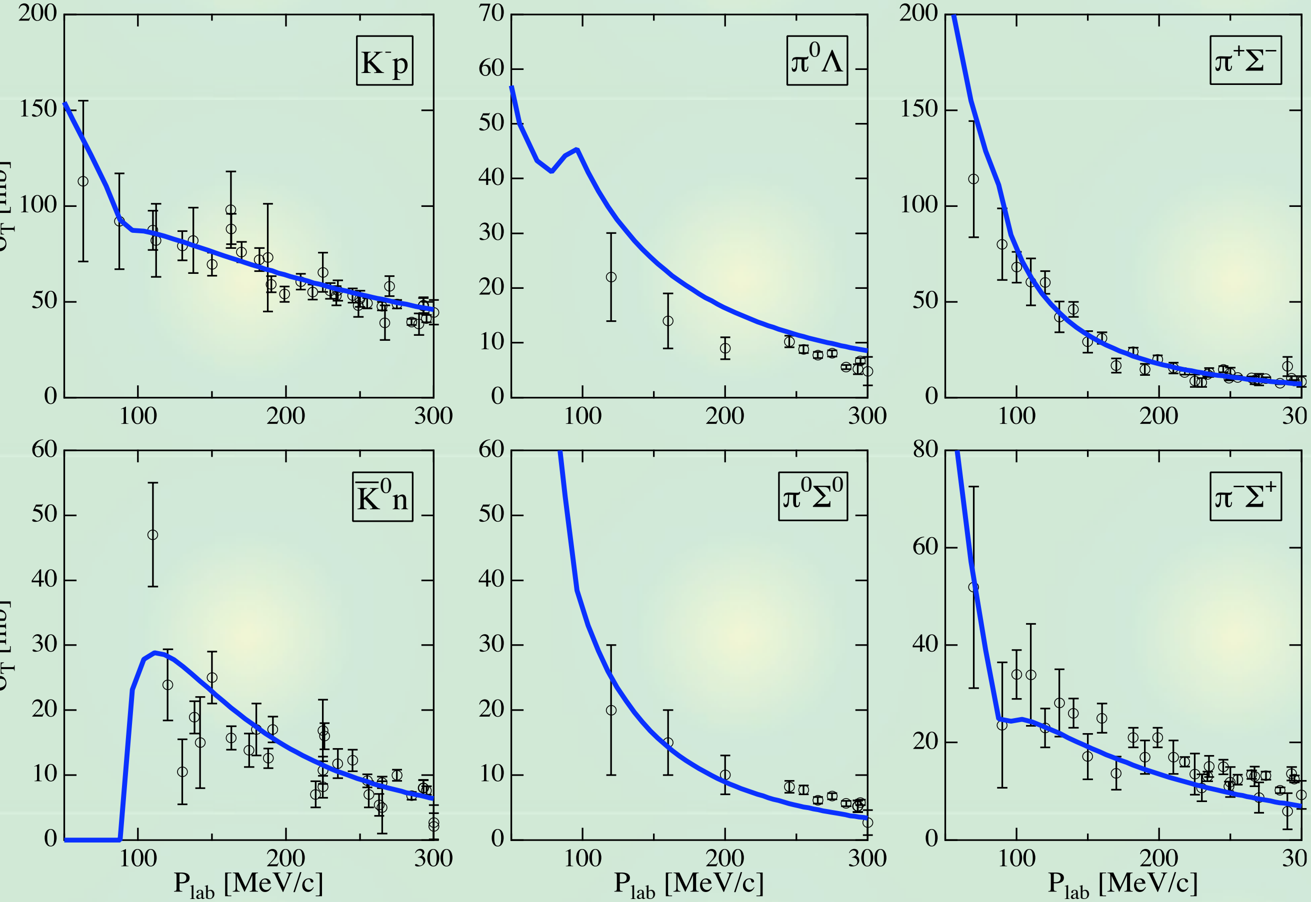
all order sum : strong interaction, resonance

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

Resonance is dynamically generated through the nonperturbative resummation.

$\bar{K}N$ scattering : comparison with data

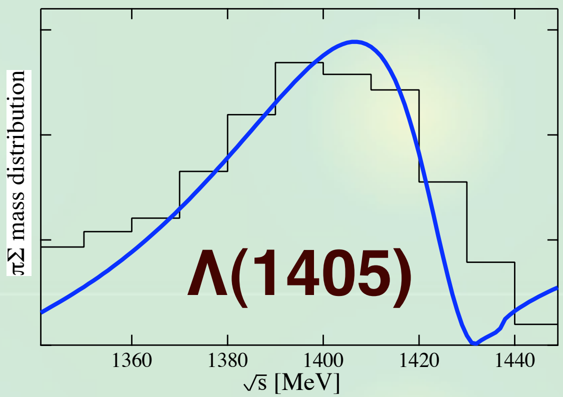
Total cross section of K-p scattering



Branching ratio

	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, PRC68, 018201 (2003); PTP 112, 73 (2004)

Good agreement with data above, at, and below $\bar{K}N$ threshold

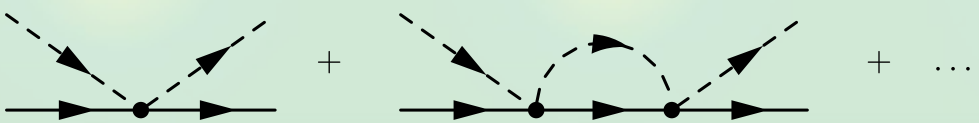
Λ(1405) mass, width, couplings : prediction of the model

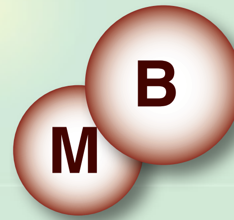
Dynamical state and CDD pole

Resonances in two-body scattering

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

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

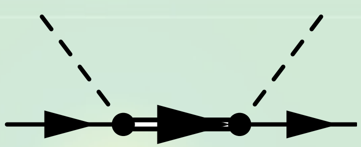


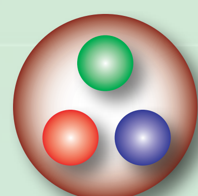


... in the present case : meson-baryon molecule

(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
G : loop integral

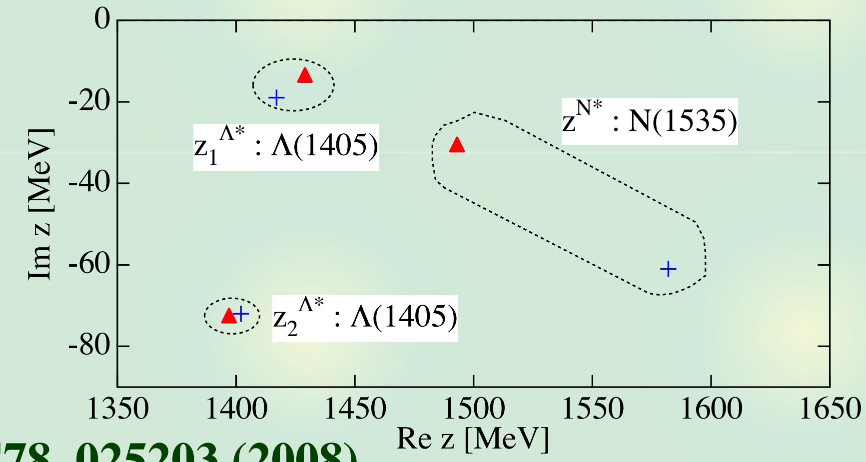
Known CDD pole contribution : those in V

We point out that the loop function G can contain the CDD pole contribution.

We propose "natural renormalization scheme" to exclude 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

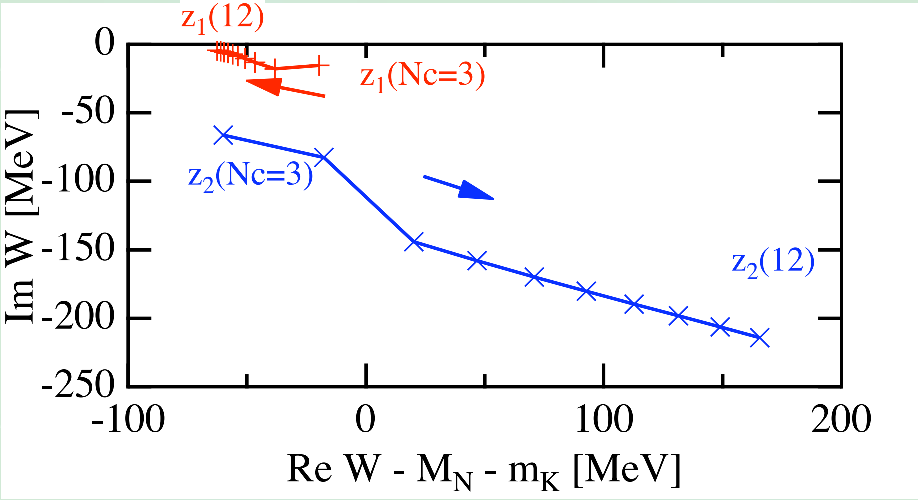
J.R. Pelaez, Phys. Rev. Lett. 92, 102001 (2004)

Nc scaling of (excited)
qq...q baryon

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

Result of chiral dynamics

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

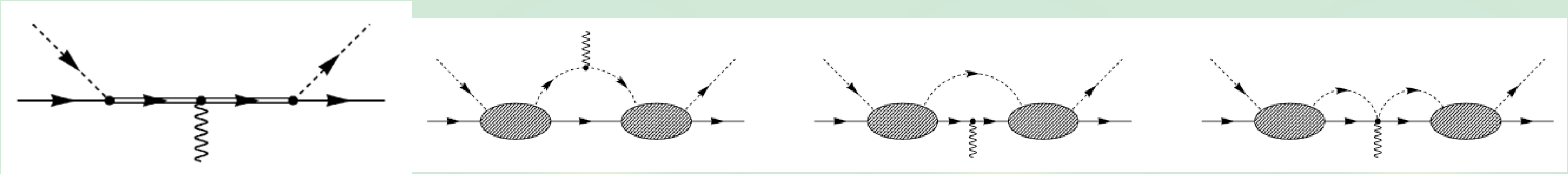


--> non-qqq structure of the Λ(1405)

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,...



Evaluated mean squared radii :

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

Λ(1405) has spatially large size. c.f. neutron: -0.12 [fm^2]

--> support the meson-baryon picture

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

Computation at finite Q^2 is now underway

--> form factor $F(Q^2)$, density distribution $\rho(r)$

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

Summary : Λ(1405) and chiral dynamics

We discuss the physics of the Λ(1405) and its description by chiral dynamics.

- Spectrum of the Λ(1405) is affected by isospin interference. Precise data from J-lab/J-PARC will be crucial for the hadron/nuclear physics.

- Chiral dynamics:
  chiral interaction + coupled-channel unitarity
  => successful description of $\bar{K}N$ scattering + the Λ(1405) resonance

- 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?** T. Hyodo, D. Jido, A. Hosaka

  => dominance of the MB components

- **Analysis of Nc scaling** T. Hyodo, D. Jido, L. Roca

  => non-qqq structure

- **Electromagnetic properties** T. Sekihara, T. Hyodo, D. Jido

  => large e.m. size

Summary : Structure of Λ(1405)

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