S-wave resonances in meson-baryon scattering induced by Weinberg-Tomozawa interaction

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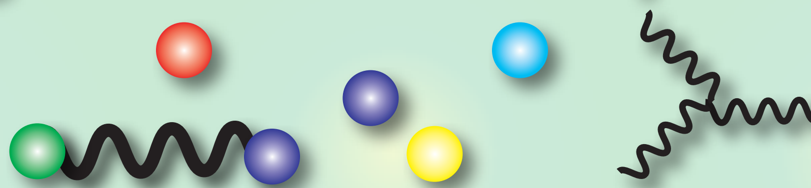
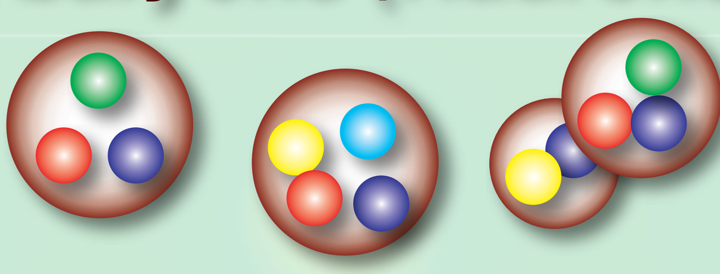
Introduction : QCD at low energy

Quantum chromodynamics (QCD)
: strong interaction of quarks and gluons



At low energies...
Color confinement
Chiral symmetry breaking

Mesons, baryons (Hadrons)

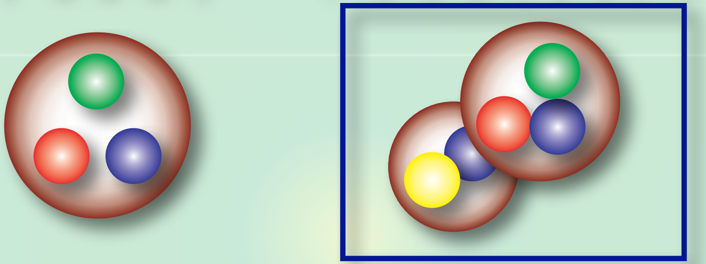


"exotics"

: elementary excitations of QCD vacuum

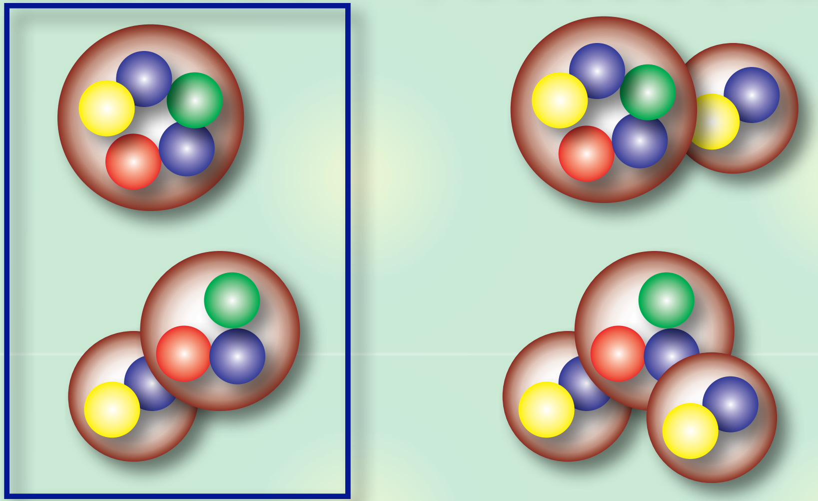
Introduction : Exotics and hadron dynamics

$$|\,B\,\rangle = |\,qqq\,\rangle + |\,qqq(q\bar{q})\,\rangle + \cdots$$



meson-baryon molecule

$$|\,P\,\rangle = |\,qqqq\bar{q}\,\rangle + |\,qqqq\bar{q}(q\bar{q})\,\rangle + \cdots$$



Hadron structure ↔ meson-baryon dynamics

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  - Two-pole structure of Λ(1405)
  - Experimental verification
- Bound states in SU(3) limit
  - Weinberg-Tomozawa interaction
  - Large Nc limit
  - Bound states in exotic channels

Chiral unitary model and two-pole structure of the $\Lambda(1405)$

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Hyodo, Hosaka, Oset, Ramos, Vacas, Phys. Rev. C 68, 065203 (2003)

Hyodo, Hosaka, Vacas, Oset, Phys. Lett. B593, 75-81 (2004)

Chiral unitary model

Flavor SU(3) meson-baryon scatterings (s-wave)

Chiral symmetry

Low energy behavior

+

Unitarity of S-matrix

Non-perturbative resummation

→

Scattering amplitude

$J^P = 1/2^-$ resonances

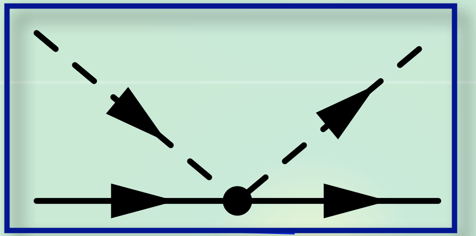
- Theoretical foundation based on chiral symmetry
- Analytically solvable

  --> information of the complex energy plane

Framework of the chiral unitary model : Interaction

Chiral perturbation theory

$$\mathcal{L}_{WT} = \frac{1}{4f^2}\mathrm{Tr}(\bar{B}i\gamma^\mu[(\Phi\partial_\mu\Phi - \partial_\mu\Phi\Phi), B])$$



chiral symmetry

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

SU(3) symmetry

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

Ex.)

$$V^{(WT)}(\bar{K}N \to \bar{K}N, I=0) = -\frac{3}{4f^2}(2\sqrt{s} - M_N - M_N)\sqrt{\frac{E_N + M_N}{2M_N}}\sqrt{\frac{E_N + M_N}{2M_N}}$$

$$V^{(WT)}(\bar{K}N \to \pi\Sigma, I=0) = \sqrt{\frac{3}{2}}\frac{1}{4f^2}(2\sqrt{s} - M_N - M_\Sigma)\sqrt{\frac{E_N + M_N}{2M_N}}\sqrt{\frac{E_\Sigma + M_\Sigma}{2M_\Sigma}}$$

Framework of the chiral unitary model : Unitarization

Unitarization

N/D method : general form of amplitude

$$T_{ij}^{-1}(\sqrt{s}) = \delta_{ij}\left(\tilde{a}_i(s_0) + \frac{s-s_0}{2\pi}\int_{s_i^+}^{\infty} ds' \frac{\rho_i(s')}{(s'-s)(s'-s_0)}\right) + \mathcal{T}_{ij}^{-1}$$

$$-G_i(\sqrt{s}) = -i\int \frac{d^4q}{(2\pi)^4}\frac{2M_i}{(P-q)^2 - M_i^2 + i\epsilon}\frac{1}{q^2 - m_i^2 + i\epsilon}$$

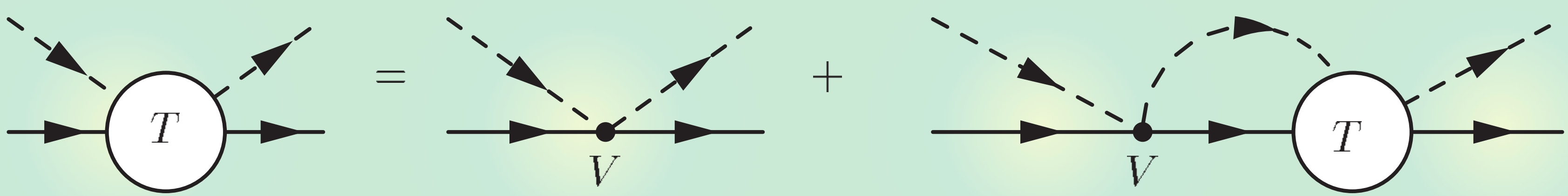
$$V^{(WT)}$$

$$T^{-1} = -G + (V^{(WT)})^{-1}$$

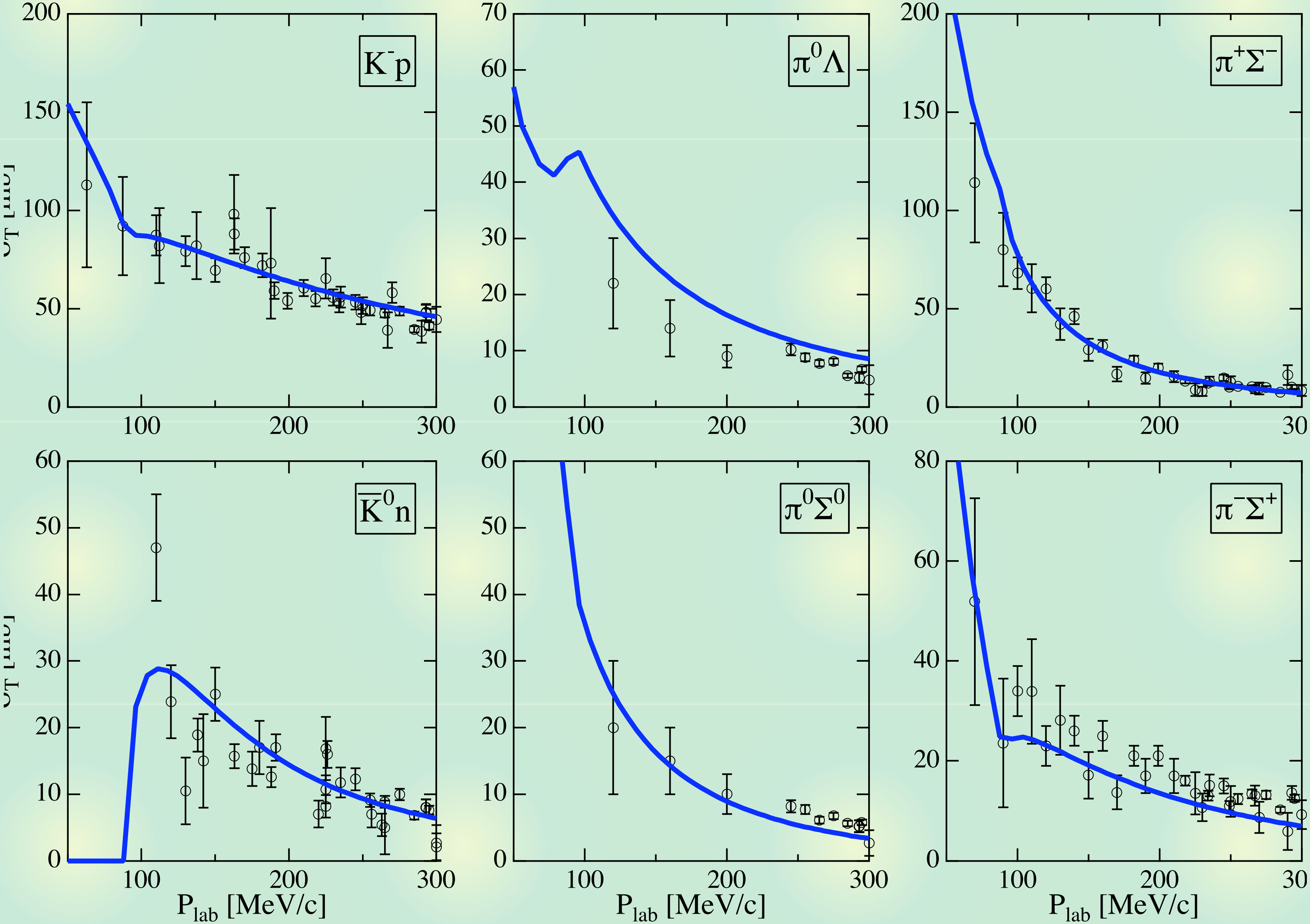
$$T = V^{(WT)} + V^{(WT)}GT$$

physical masses

regularization of loop



Total cross sections of K^-p scattering

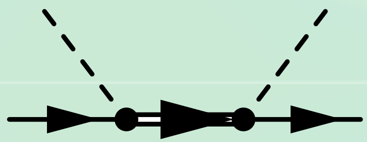


T. Hyodo, Nam, Jido, Hosaka, PRC (2003), PTP (2004)

Resonance state

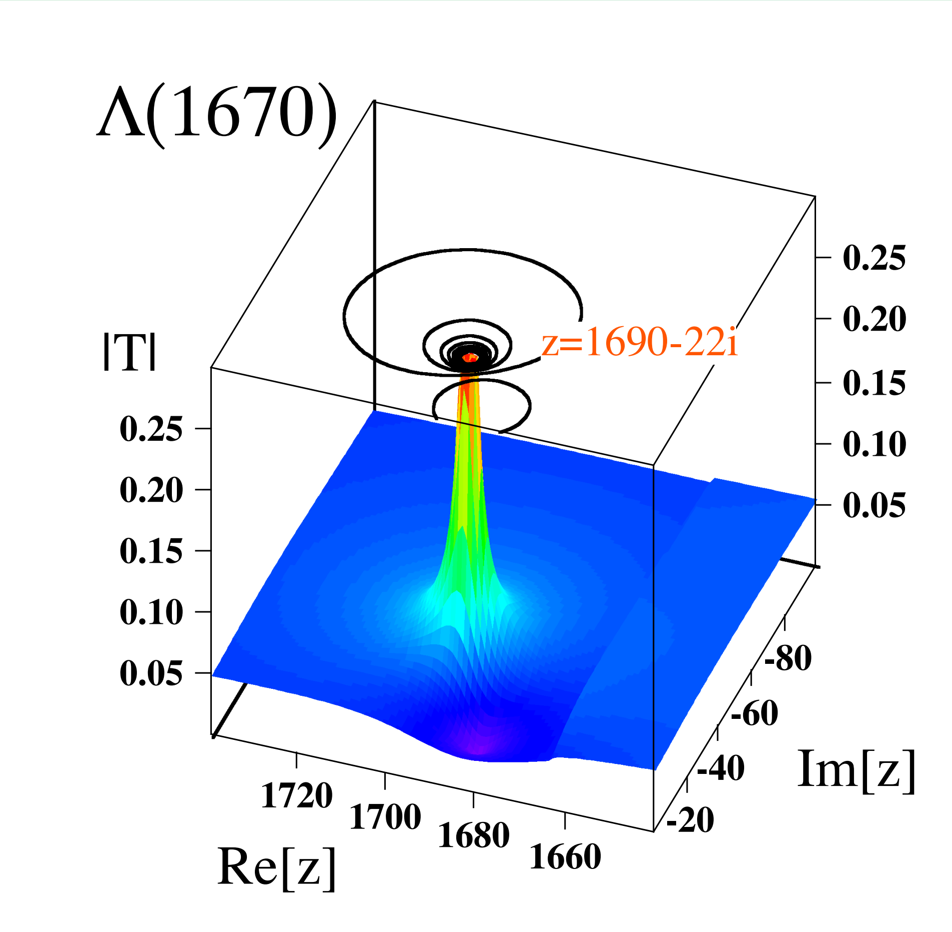
If there is a sufficient attraction, resonances can be dynamically generated.

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

$\sim$ 

Position of the pole, Residues

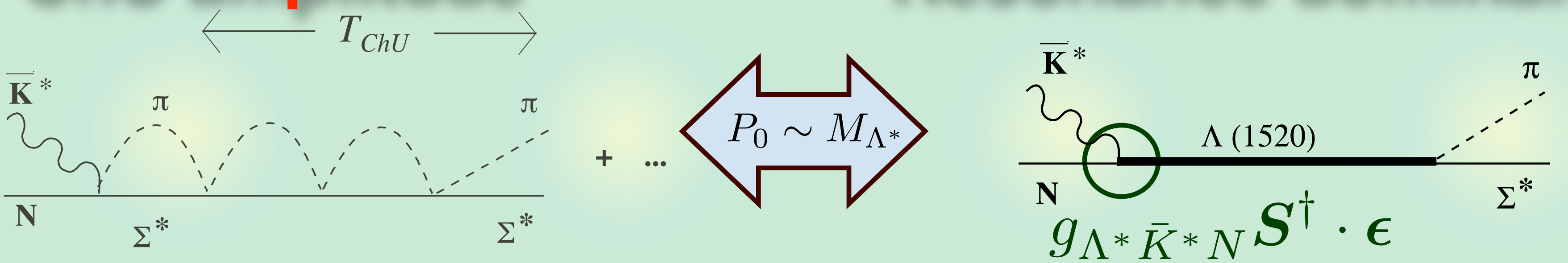
-> Mass, Width, Coupling strengths



Application : Evaluation of coupling constant

Compare two amplitudes for the same process

ChU amplitude — **Resonance dominance**



--> Extract the coupling constants

- **K*N Λ(1520) coupling**

Hyodo, Sarkar, Hosaka, Oset, Phys. Rev. C 73, 035209 (2006)

- **Magnetic moments**

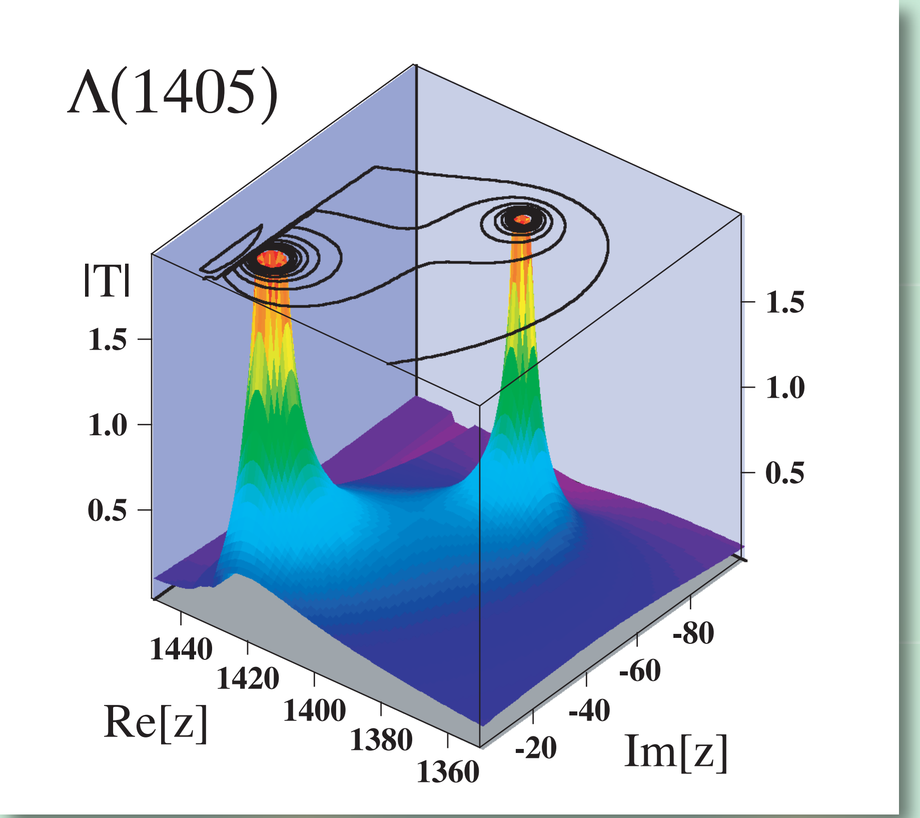
Jido, Hosaka, Nacher, Oset, Ramos, Phys. Rev. C 66, 025203 (2003)

Hyodo, Nam, Jido, Hosaka, nucl-th/0305023

Two poles?

Two poles of the scattering amplitude were found around nominal Λ(1405) energy region.

- **Cloudy bag model**
- **Chiral unitary model**



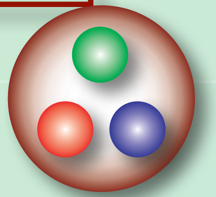
Λ(1405) : superposition of two states?

Introduction : Λ(1405)

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

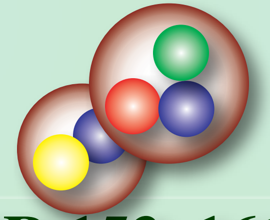
Mass : 1406.5 ± 4.0 MeV
Width : 50 ± 2 MeV
Decay mode : $\Lambda(1405) \to (\pi\Sigma)_{I=0}$ **100%**

Quark model : p-wave, ~1600 MeV?



N. Isgur, and G. Karl, PRD 18, 4187 (1978)

Coupled channel multi-scattering



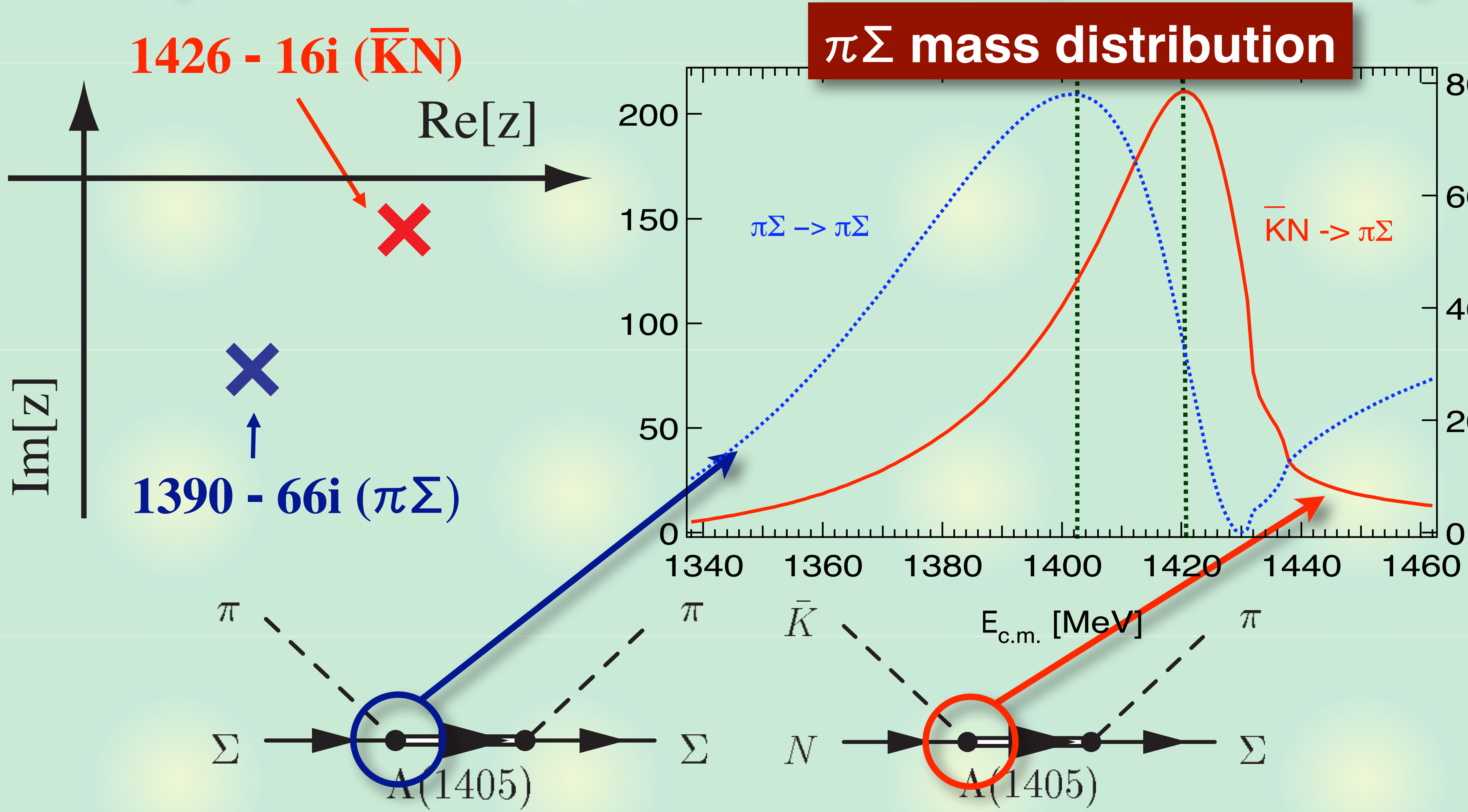
R.H. Dalitz, T.C. Wong and G. Rajasekaran PR 153, 1617 (1967)

Deeply bound Kaonic nuclei?

Y. Akaishi, T. Yamazaki PRC 65, 044005 (2002)

Λ(1405) in the chiral unitary model

Two poles? -> to be checked experimentally



Shape of πΣ spectrum depends on initial state

Production reaction for the Λ(1405)

$$\frac{d\sigma}{dM_I} = C|t_{\pi\Sigma\to\pi\Sigma}|^2 p_{CM} \Rightarrow \frac{d\sigma}{dM_I} = |\sum_i C_i t_{i\to\pi\Sigma}|^2 p_{CM}$$

In order to clarify the two-pole structure, we study two reactions.

$$\pi^- p \to K^0 \Lambda(1405) \to K^0 \pi\Sigma$$

- **Experimental result -> lower energy pole**

Hyodo, Hosaka, Oset, Ramos, Vacas, Phys. Rev. C 68, 065203 (2003)

$$\gamma p \to K^* \Lambda(1405) \to K^0 \pi^+ \pi\Sigma$$

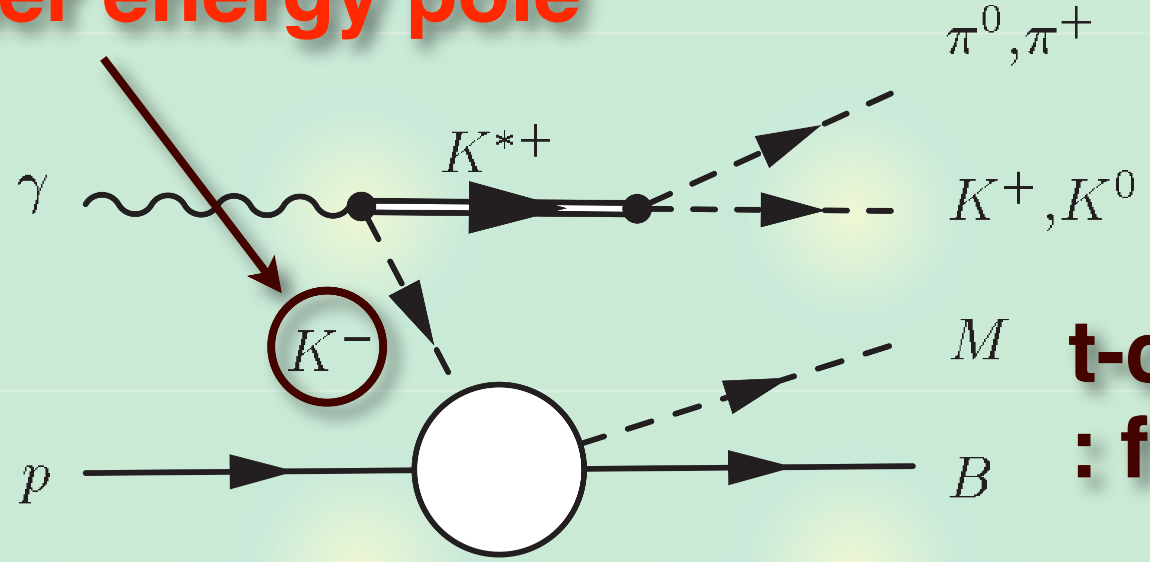
- **higher energy pole?**

Hyodo, Hosaka, Vacas, Oset, Phys. Lett. B593, 75-81 (2004)

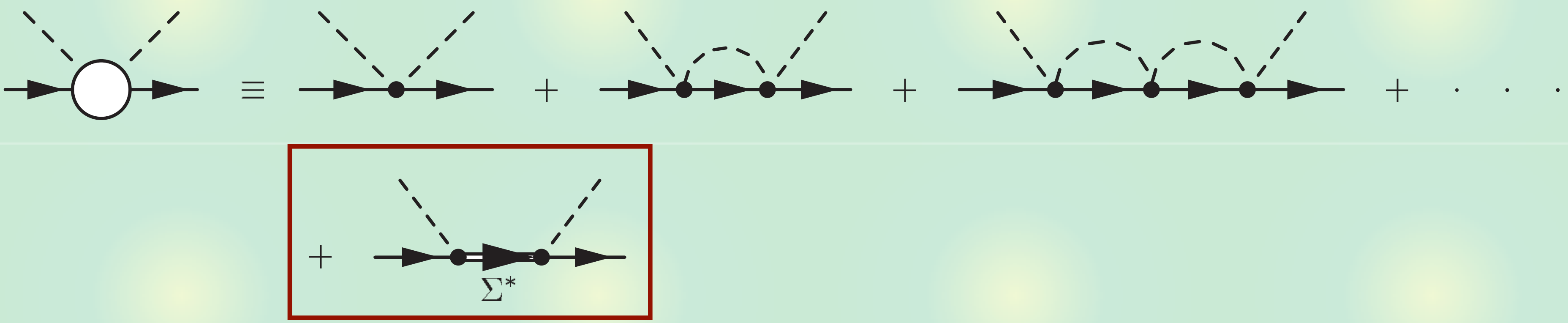
Photoproduction of K* and Λ(1405)

Only K⁻p channel appears at the initial stage

--> higher energy pole



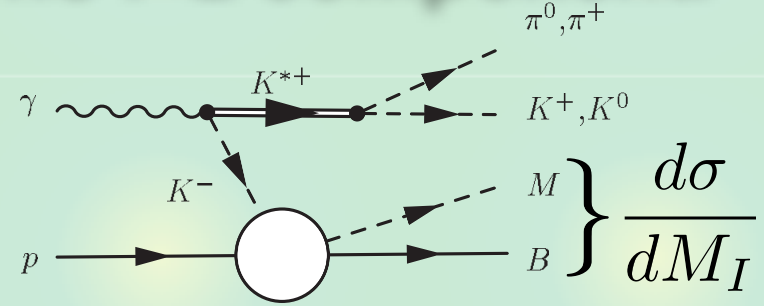
t-channel
: forward



Σ(1385) is included <- background estimation

Isospin decomposition of final states

Since initial state is $\overline{\text{K}}$N, no I=2 component.



$$\sigma(\pi^0\Sigma^0) \propto \frac{1}{3}|T^{(0)}|^2$$

- **Pure I=0 amplitude <-- Λ(1405)**

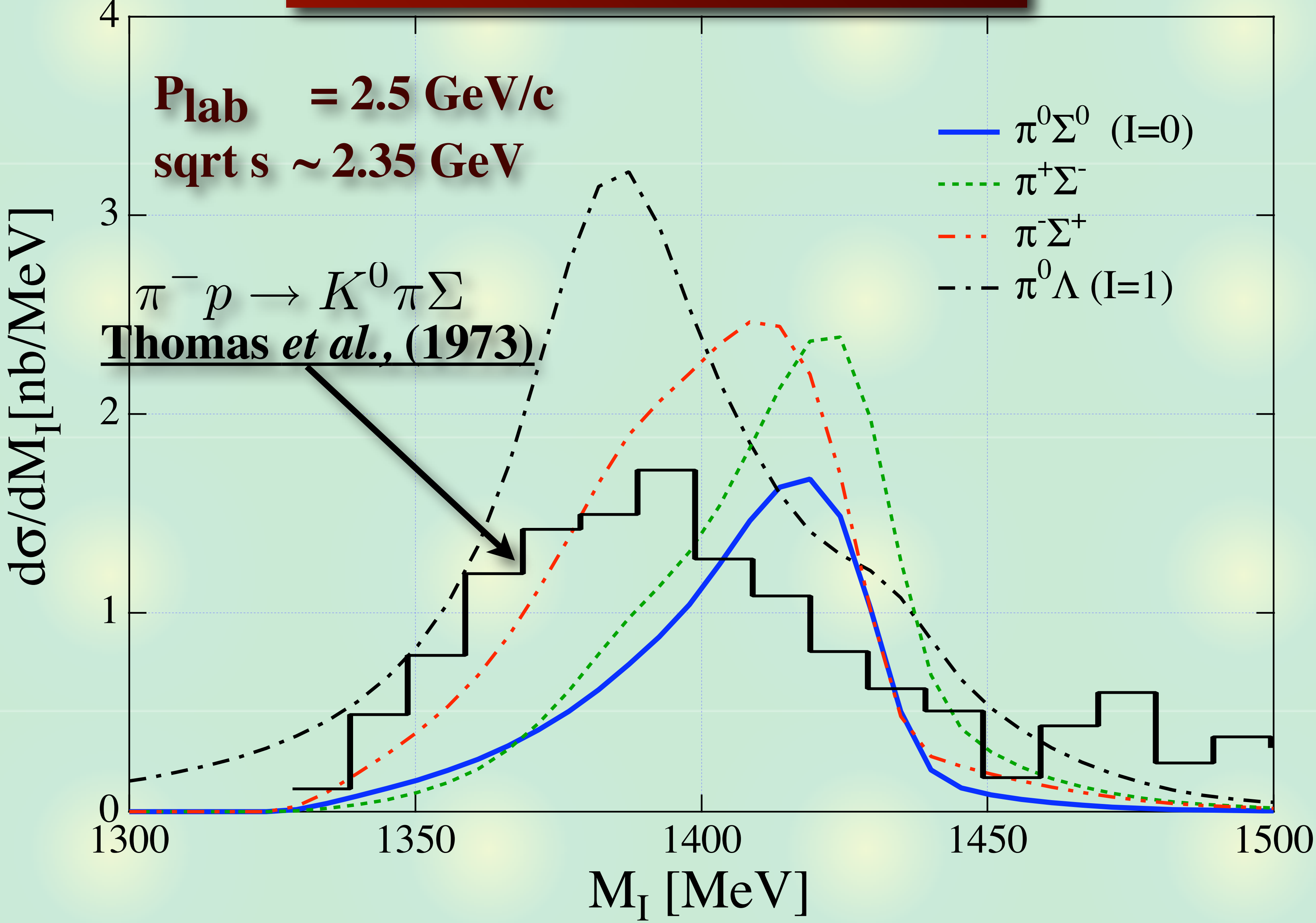
$$\sigma(\pi^0\Lambda) \propto |T^{(1)}|^2$$

- **Pure I=1 amplitude <-- Σ(1385)**

$$\sigma(\pi^\pm\Sigma^\mp) \propto \frac{1}{3}|T^{(0)}|^2 + \frac{1}{2}|T^{(1)}|^2 \pm \frac{2}{\sqrt{6}}\mathrm{Re}(T^{(0)}T^{(1)*})$$

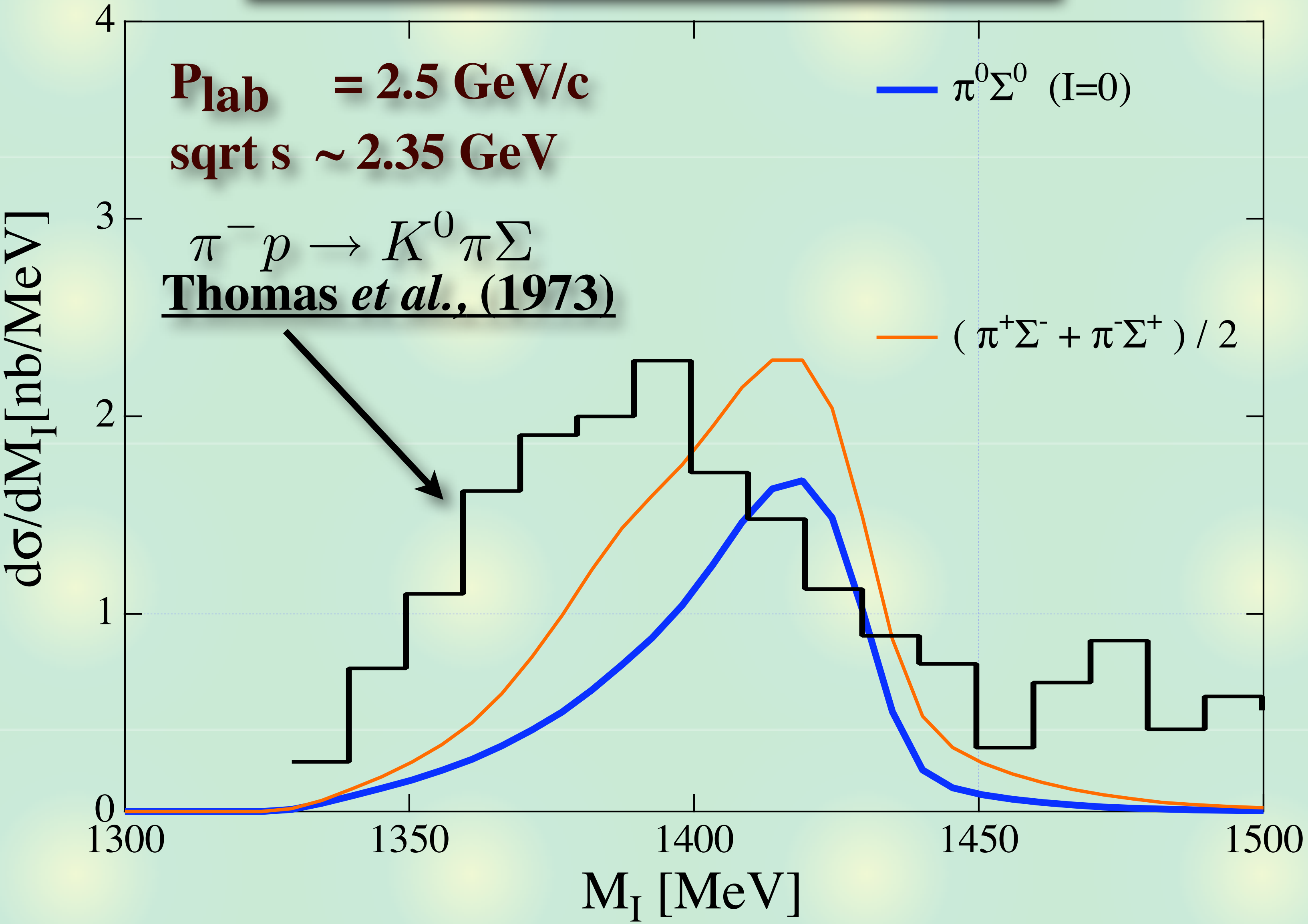
- **Mixture of I=0 and I=1**

Invariant mass distributions



- **dominance of higher pole -> different shape**

Invariant mass distributions 2



Σ(1385) contribution is small

Conclusion for part I

We study the structure of Λ(1405) using the chiral unitary model.

- In this model, Λ(1405) is generated as a quasi-bound state in coupled channel meson-baryon scattering.
- Two poles of the scattering amplitude are found around the Λ(1405) energy region.

Pole 1 (1426-16i) : strongly couples to $\bar{K}N$ state

Pole 2 (1390-66i) : strongly couples to $\pi\Sigma$ state

Conclusion for part I

- We propose the $\gamma p \rightarrow K^* \Lambda(1405)$ reaction, which provides a **different shape** of spectrum from the nominal one. Observation of this feature give a support of the two-pole structure.
- We estimate the effect of **Σ(1385)** in I=1 channel, which is found to be **small for the πΣ spectrum**.

s-wave exotic bound states in the SU(3) symmetric limit

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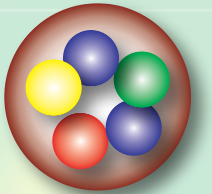
in preparation...

Pentaquark Θ

LEPS, T. Nakano, *et al.*, Phys. Rev. Lett. 91, 012002 (2003)

$$|\,\Theta\,\rangle = |\,uudd\bar{s}\,\rangle$$



S = +1, manifestly exotic

light mass 1540 MeV

$$M_\Theta \sim 4m_{ud} + m_s \sim 1700\ \mathrm{MeV}$$

narrow width < 15 MeV (1 MeV)

$$\Gamma_{B^*} \sim 100\ \mathrm{MeV}$$

Experimental situation is still controversial

Exotic hadrons

QCD does not forbid exotic states.

Effective models, lattice simulations, ...

Experimentally, (almost?) completely absent
--> highly non-trivial fact

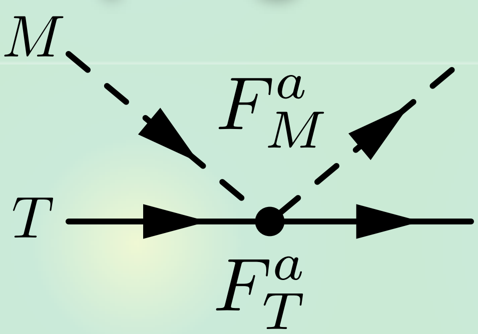
We need theoretical explanation.

Does exotic states exist in the chiral unitary model?

--> In the simplest case : flavor SU(3) limit.

Weinberg-Tomozawa interaction

Coupling structure : chiral symmetry



current-current interaction

--> universal for any target particles

In SU(3) basis, channel coupling disappears.

$$V_{\alpha\beta}^{(WT)} = -\frac{1}{2f^2} C_\alpha (\sqrt{s} - M_\alpha) \frac{E_\alpha + M_\alpha}{2M_\alpha} \delta_{\alpha\beta}$$

Coupling strength : SU(3) symmetry

$$\begin{aligned} C_\alpha &= -2 \langle\, [MT]_\alpha \,| F_M^a F_T^a |\, [MT]_\alpha \,\rangle \\ &= -\left[C(\alpha) - C(M) - C(T) \right] \end{aligned}$$

Coupling strengths

Examples of C_α : (positive is attractive)

α	1	8	10	$\overline{10}$	27	35
T=8	6	3	0	0	-2	
T=10		6	3		1	-3

α	$\bar{3}$	6	$\overline{15}$	24
T=$\bar{3}$	3	1	-1	
T=6	5	3	1	-2

Can these attraction generate a bound state?

Coupling strengths in large Nc limit

Take large Nc limit

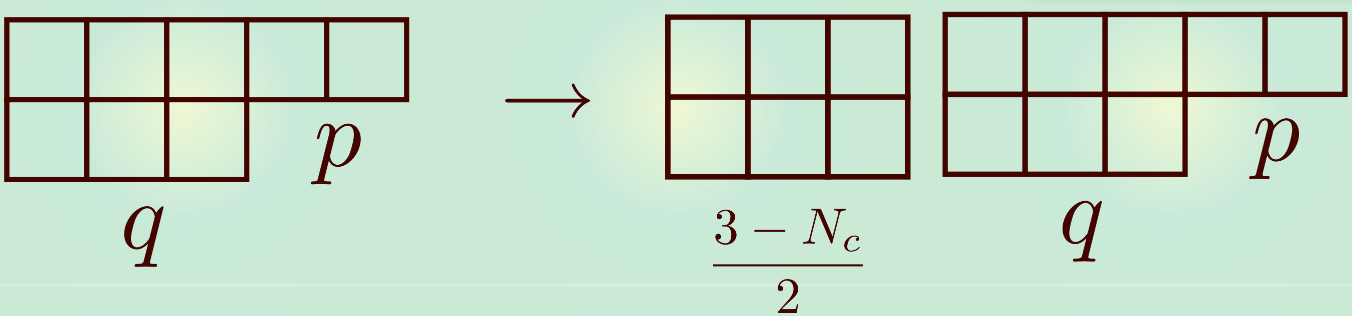
$$V^{(WT)}_{\alpha\beta} \sim -\frac{1}{2f^2} C_\alpha \omega_\alpha \delta_{\alpha\beta} \sim \frac{1}{N_c} \times C_\alpha$$

Flavor representation

$$\begin{aligned} C_\alpha &= -2\langle\, [MT]_\alpha \,|F^a_M F^a_T|\, [MT]_\alpha \,\rangle \\ &= -\,[C(\alpha) - C(M) - C(T)] \end{aligned}$$

$C(M)$ =3

$$[p, q] \rightarrow [p, q + \frac{3 - N_c}{2}]$$



$$C([p, q + \frac{3 - N_c}{2}]) = \frac{1}{3}\left(-\frac{9}{4} + p^2 + \frac{3q}{2} + pq + q^2\right) + \frac{1}{3}\left(p + \frac{q}{2}\right) N_c + \frac{N_c^2}{12}$$

Non-trivial Nc dependence

Coupling strengths in large Nc limit

Cα in large Nc : (positive is attractive)

α	1	8	10	$\overline{10}$	27	35
T=8	$\frac{9}{2}+\frac{N_c}{2}$	3	0	$\frac{3}{2}-\frac{N_c}{2}$	$-\frac{1}{2}-\frac{N_c}{2}$	
T=10		6	3		$\frac{5}{2}-\frac{N_c}{2}$	$-\frac{1}{2}-\frac{N_c}{2}$

α	$\overline{3}$	6	$\overline{15}$	24
T=$\overline{3}$	3	1	$-\frac{N_c}{3}$	
T=6	5	3	$\frac{5}{2}-\frac{N_c}{2}$	$\frac{1}{2}-\frac{5N_c}{6}$

Exotic attractions --> repulsions

Renormalization and bound states

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

Renomalization condition :

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

M.F.M. Lutz, and E. Kolomeitsev, NPA 700, 193-308 (2002)

Condition is fixed by the mass of target.
It almost agrees with the natural value of cutoff.

Bound state:

--> $1 - V(M_b)G(M_b) = 0 \qquad M < M_b < M + m$

Parameters for numerical analysis

Mass of the target

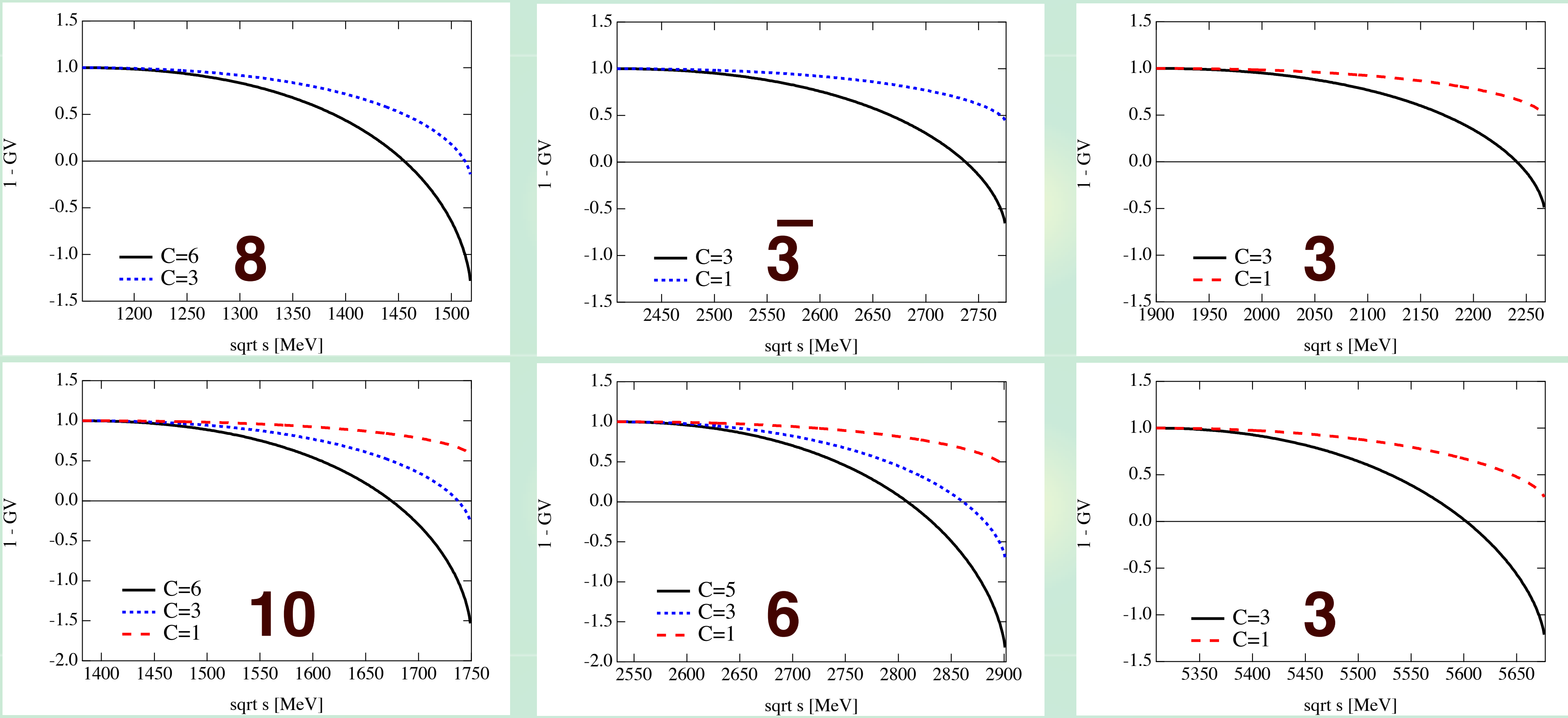
Target	Irrep.	M [MeV]
light baryon	8	1151
	10	1382
charm baryon	$\bar{3}$	2408
	6	2534
D meson	3	1900
B meson	3	5309

Mass of NG boson : m=368 MeV

Meson decay constant : f=93 MeV

Numerical result for 1-VG

$$1 - V(M_b)G(M_b) = 0$$



No bound state for exotic channel :

Strength of the attraction in exotic channel is not enough to generate a bound state.

Critical attraction and applicability of the model

Since G(M)=0 by renormalization, 1-V(M)G(M) = 1
1-VG is monotonically decreasing.

--> Critical attraction : 1 - VG = 0 at M+m

$$C_{\mathrm{crit}} = -\frac{2f^2}{mG(M+m)}$$

No appearance of artificial pole

--> Maximal attraction : 1 - VG = 0 at M-m

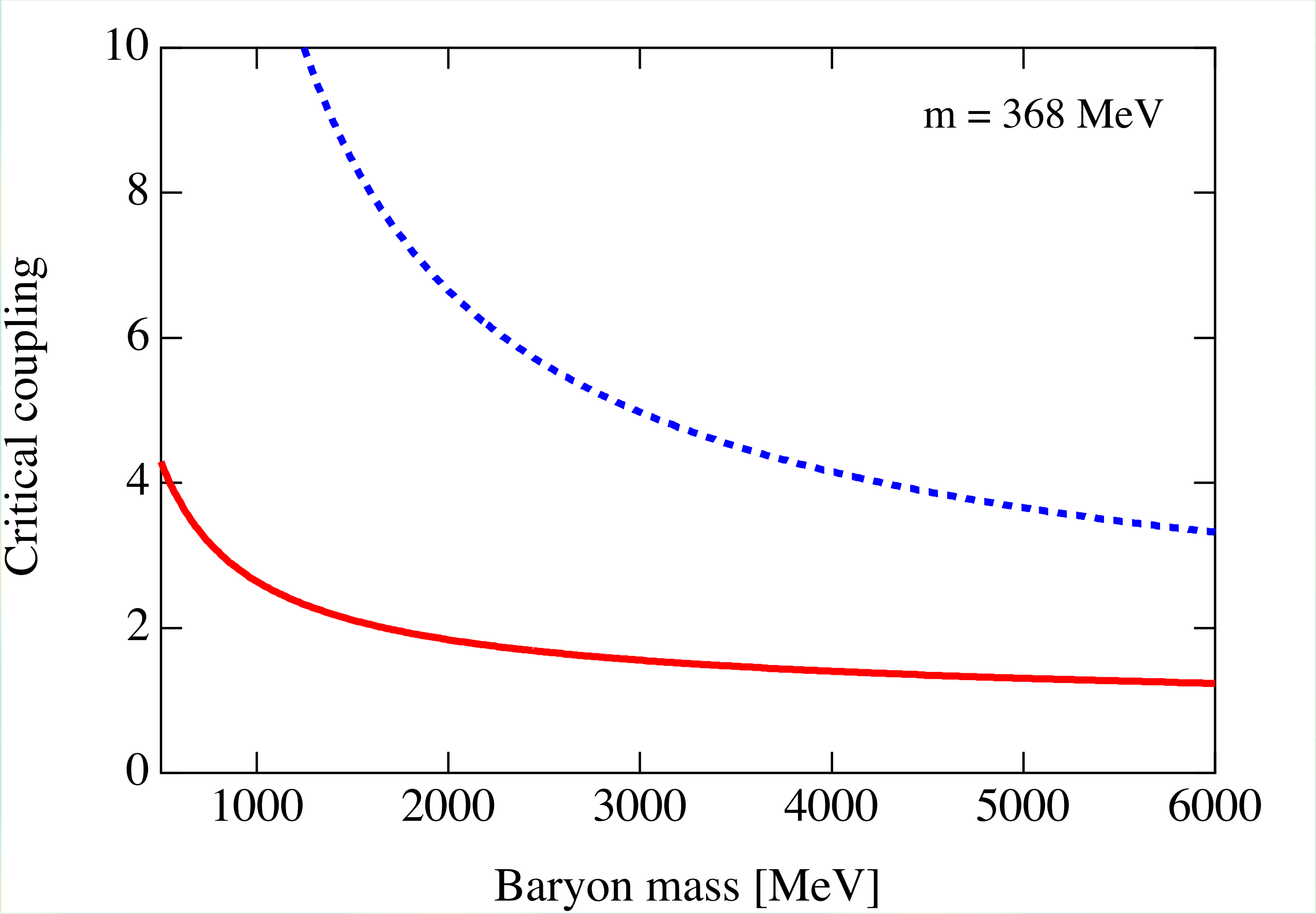
$$C_{\mathrm{Max}} = \frac{2f^2}{mG(M-m)}$$

Physically meaningful bound state appears when

$$C_{\mathrm{crit}} < C < C_{\mathrm{Max}}$$

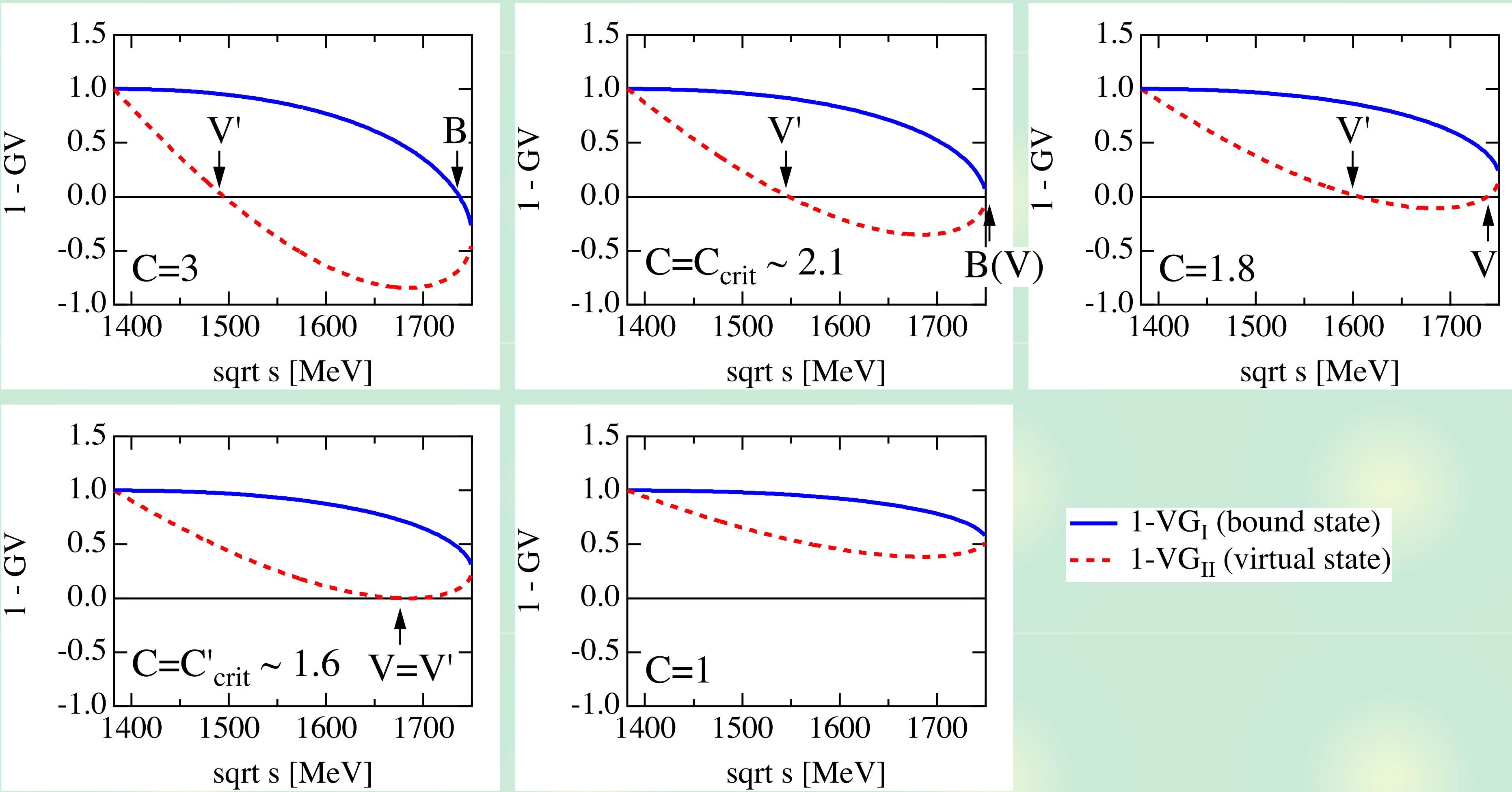
On the fate of the bound state

Plot of critical attraction.



On the fate of the bound state

It turns into virtual state.



Another state V’ <-- due to V(M)=0 ?

Summary

We study the exotics bound states in chiral unitary model in flavor SU(3) limit.

- **We give the general formula of coupling strength of WT interaction.**
- **There are attractions in exotic channels, though the strength is week.**
- **In large Nc limit, these attractions turns into repulsive.**

Summary

- We give **the critical and maximal attractions** which determine the region of coupling constant for physically meaningful bound states. Attraction in exotic channel is **beyond this region**.
- For the less attraction than the critical value, bound state becomes **virtual state**.