Chiral dynamics, structure of Λ(1405), and $\bar{K}N$ phenomenology

Tetsuo Hyodo[a]

Tokyo Institute of Technology[a]

2009, Feb. 27th

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

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

PDG

Mass : 1406.5 ± 4.0 MeV

Width : 50 ± 2 MeV

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

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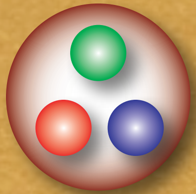
: p-wave
~1600 MeV?



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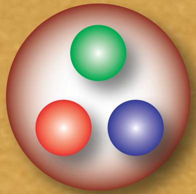

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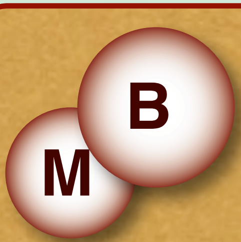

Coupled channel
multi-scattering
<-- strong $\bar{\mathrm{K}}$N int.

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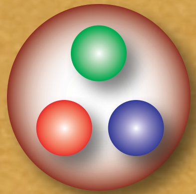

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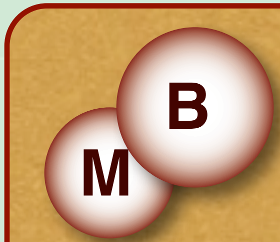

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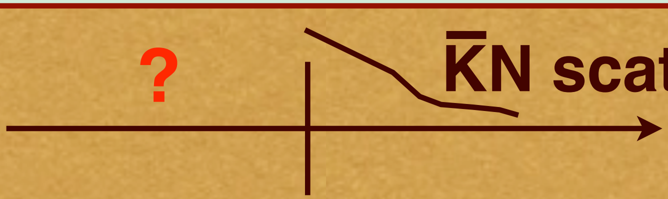

$\bar{\text{K}}$N

?

$\bar{\text{K}}$N scatt.

energy

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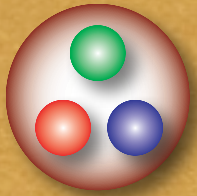

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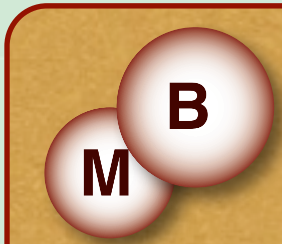

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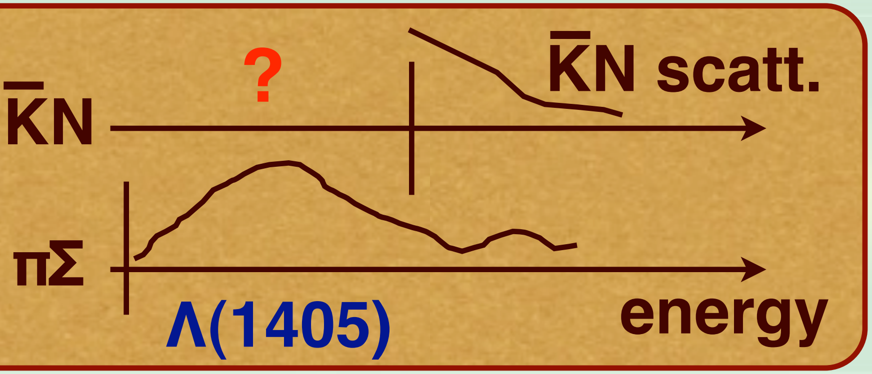

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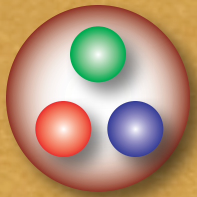

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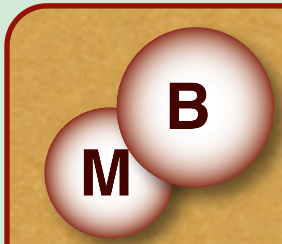

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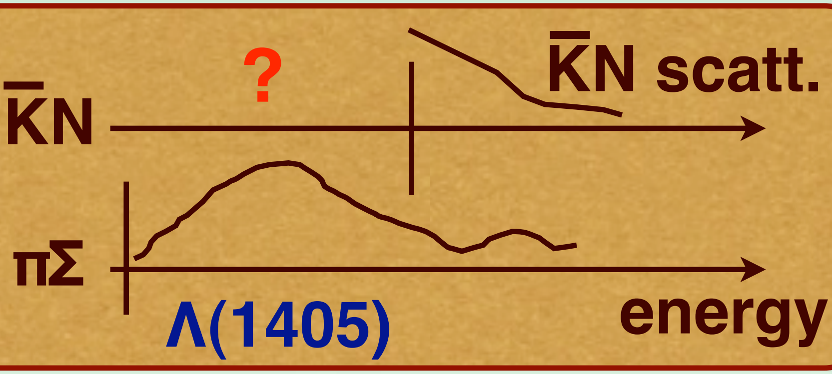

kaonic nuclei,
Λ(1405), ...
-->
exp. @ J-PARC

Chiral dynamics

Description of S = -1, $\bar{K}N$ s-wave scattering : Λ(1405) in I=0

- Interaction <-- chiral symmetry <-- kaon as NG boson

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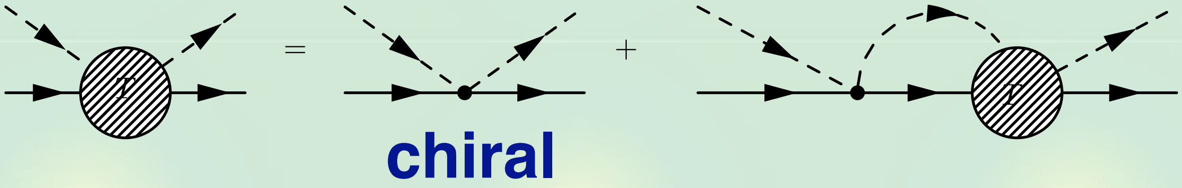
$$T = \frac{1}{1 - VG} V$$



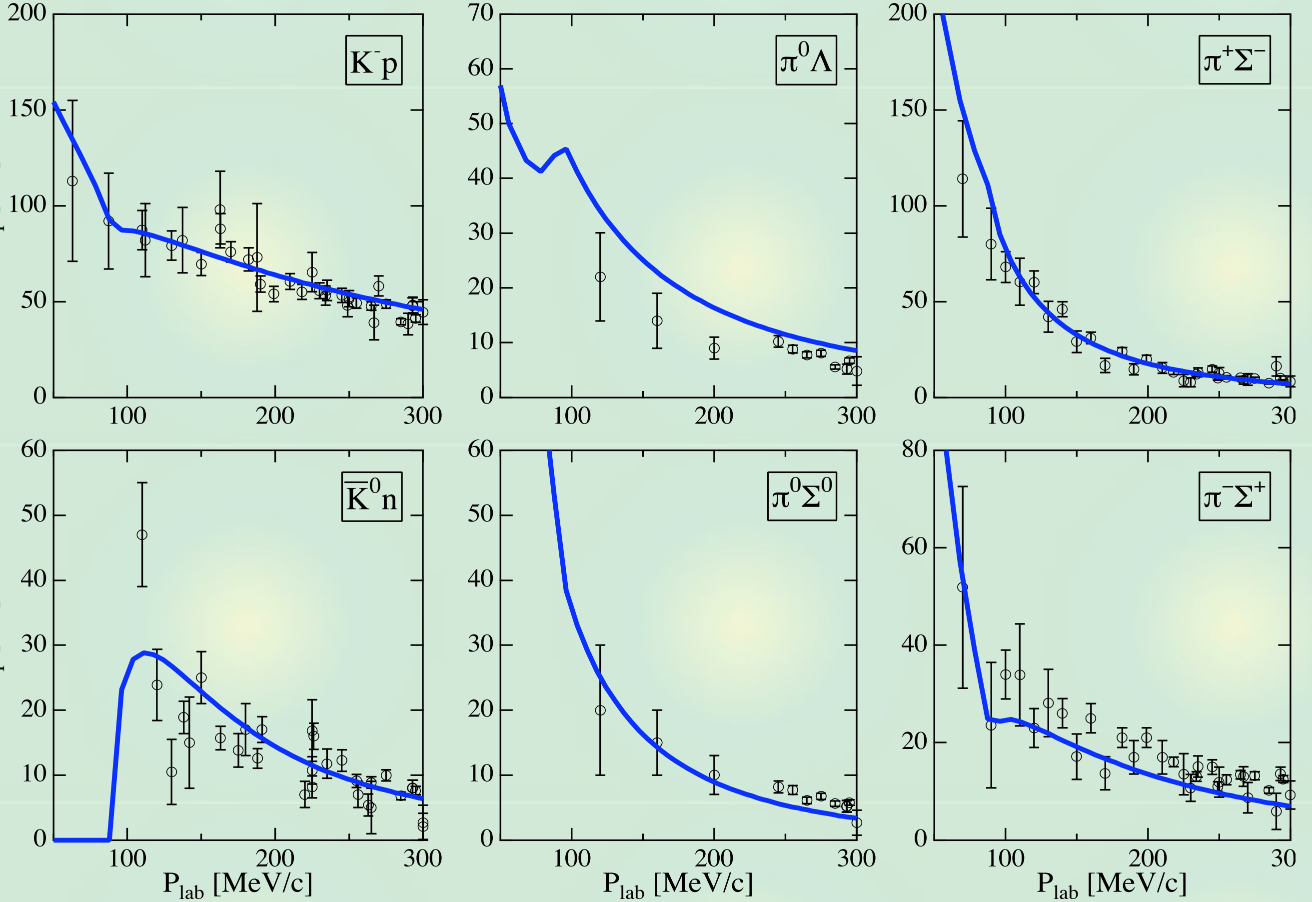
N. Kaiser, P. B. Siegel, W. Weise, Nucl. Phys. A594, 325 (1995),
E. Oset, A. Ramos, Nucl. Phys. A635, 99 (1998),
J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001),
M.F.M. Lutz, E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002), ... many others

works successfully, also in S=0 sector, meson-meson scattering sectors, systems including heavy quarks, ...

T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. Lett. 97, 192002 (2006)
T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. D 75, 034002 (2007)

How it works? vs experimental data

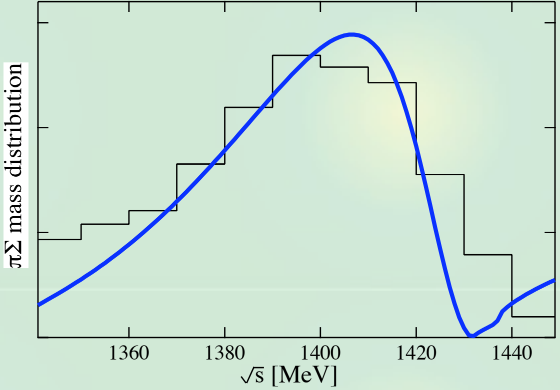
Total cross sections



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)

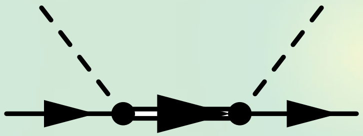
Good agreement in wide energy region (E >, =, < threshold).

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

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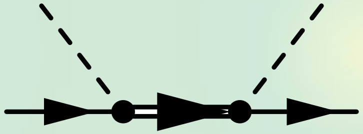

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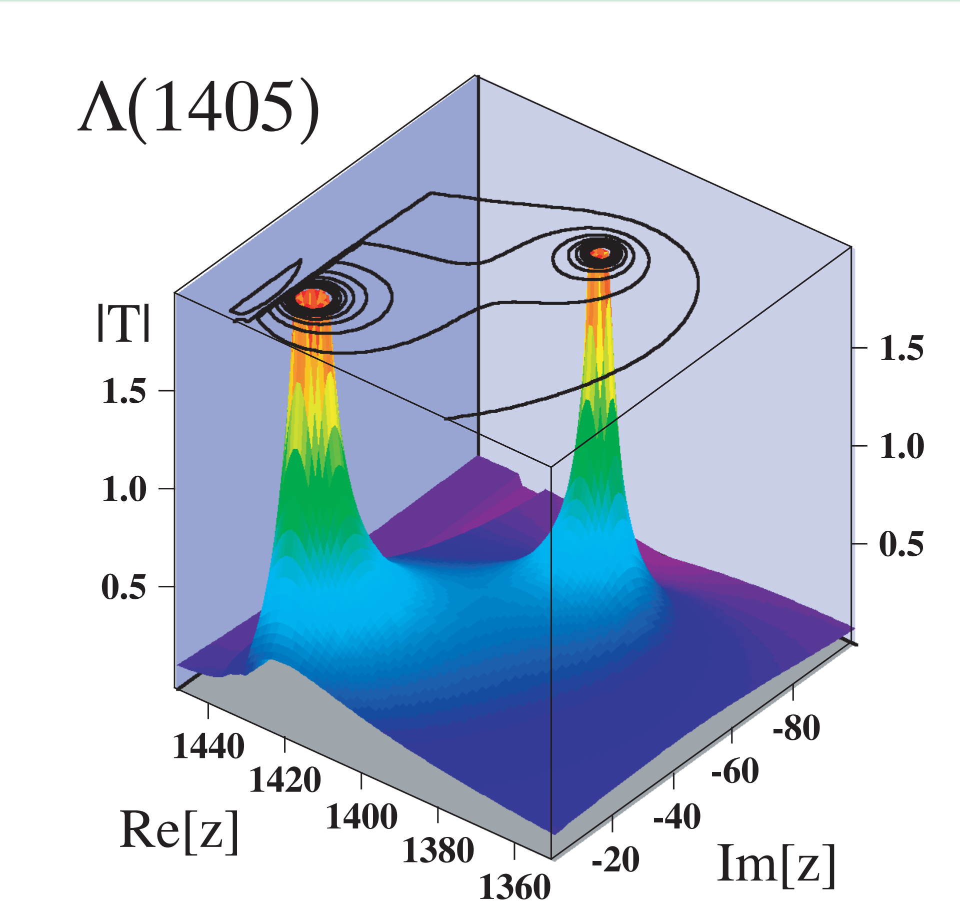
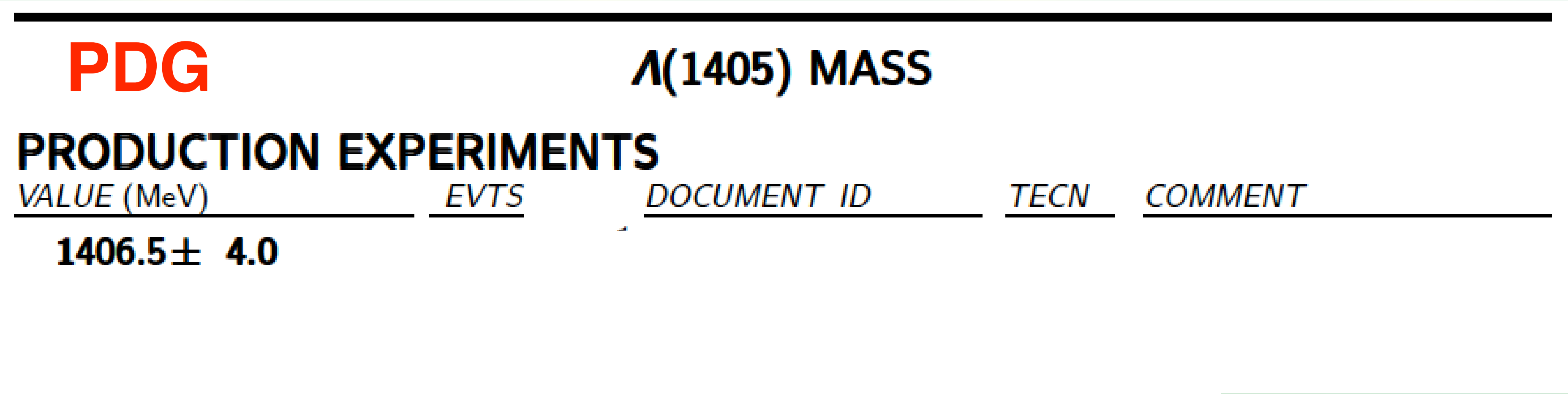


Physical state: superposition

$$|\Lambda(1405)\rangle = a|\Lambda_1^*\rangle + b|\Lambda_2^*\rangle$$

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)

Λ(1405) in PDG



PDG

Λ(1405) MASS

PRODUCTION EXPERIMENTS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
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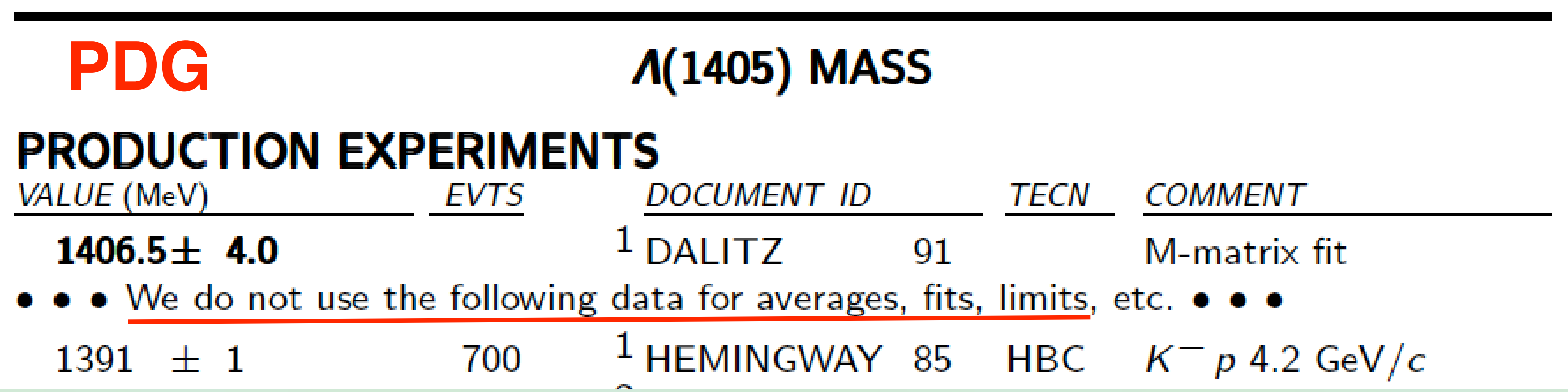

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R.H. Dalitz, A. Deloff, J. Phys G17, 289 (1991)

Analysis of Hemingway data by I=0 model. Spectrum ($\pi^-\Sigma^+$) is not in I=0.

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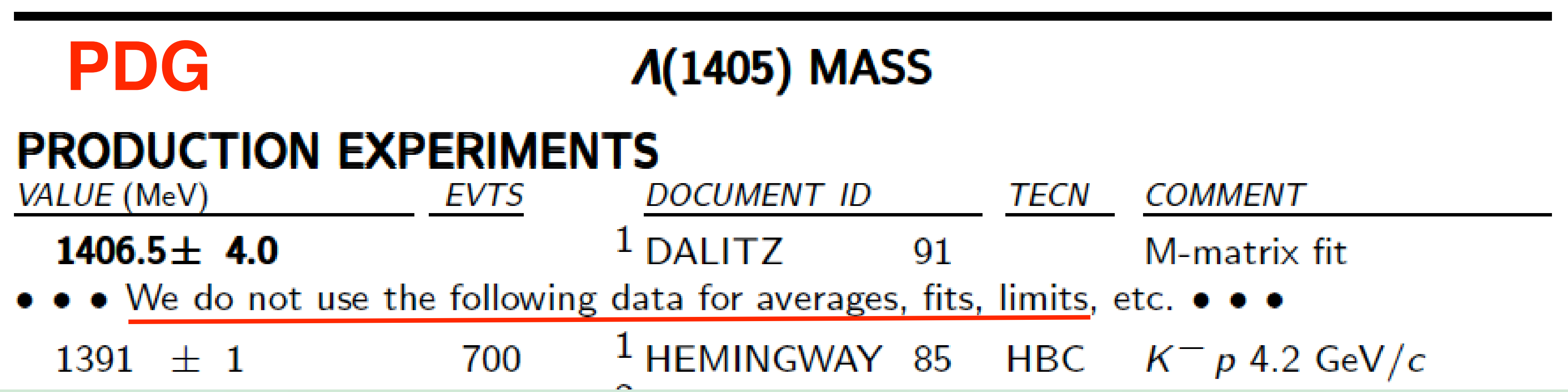

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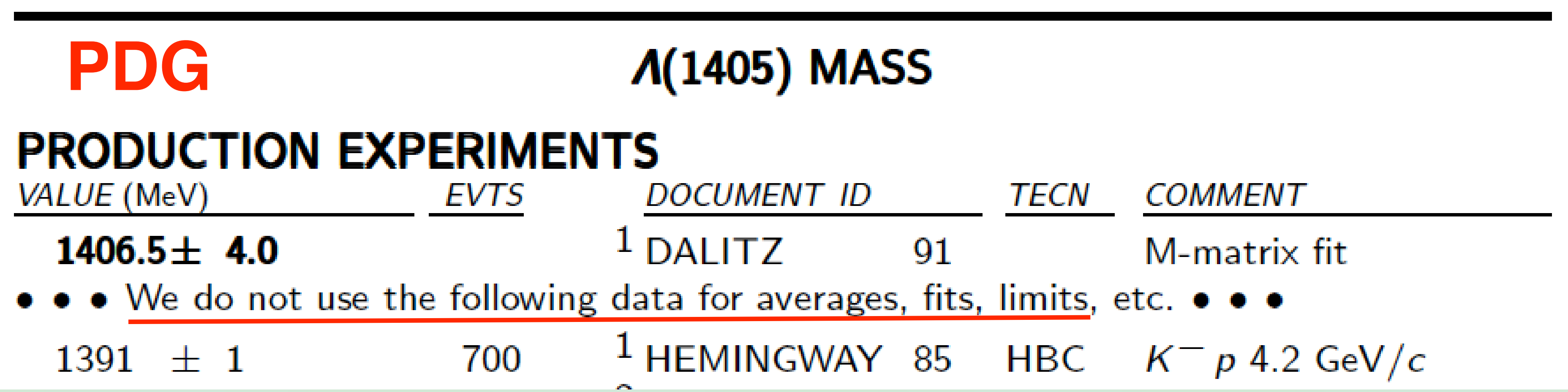
I=1
Σ(1385)

interference

Λ(1405) in PDG



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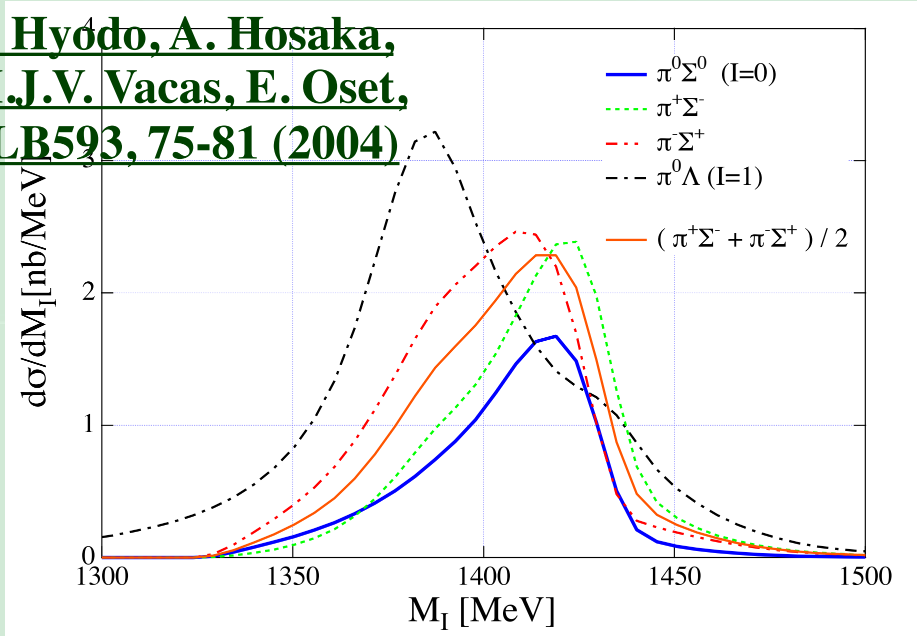

T. Hyodo, A. Hosaka, M.J.V. Vacas, E. Oset, PLB593, 75-81 (2004)

A note on the πΣ spectrum

アイソスピンの正しい状態（I=0）を選ぶにはπΣの３つの荷電状態（$\pi^0\Sigma^0$, $\pi^\pm\Sigma^\mp$）を全て同時に測定する必要がある（未達成）。

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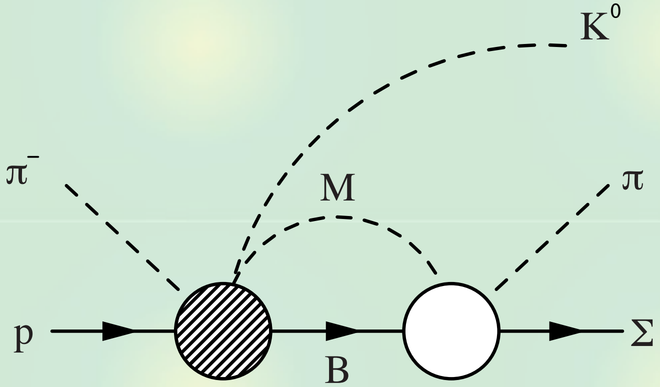

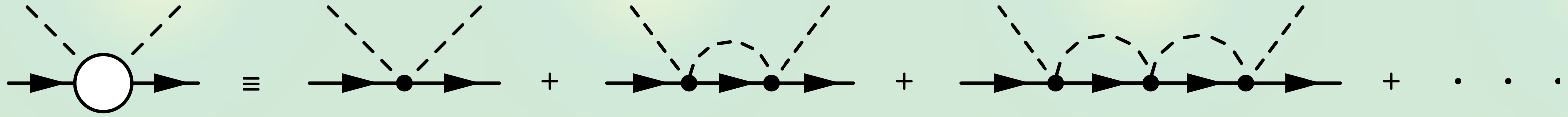

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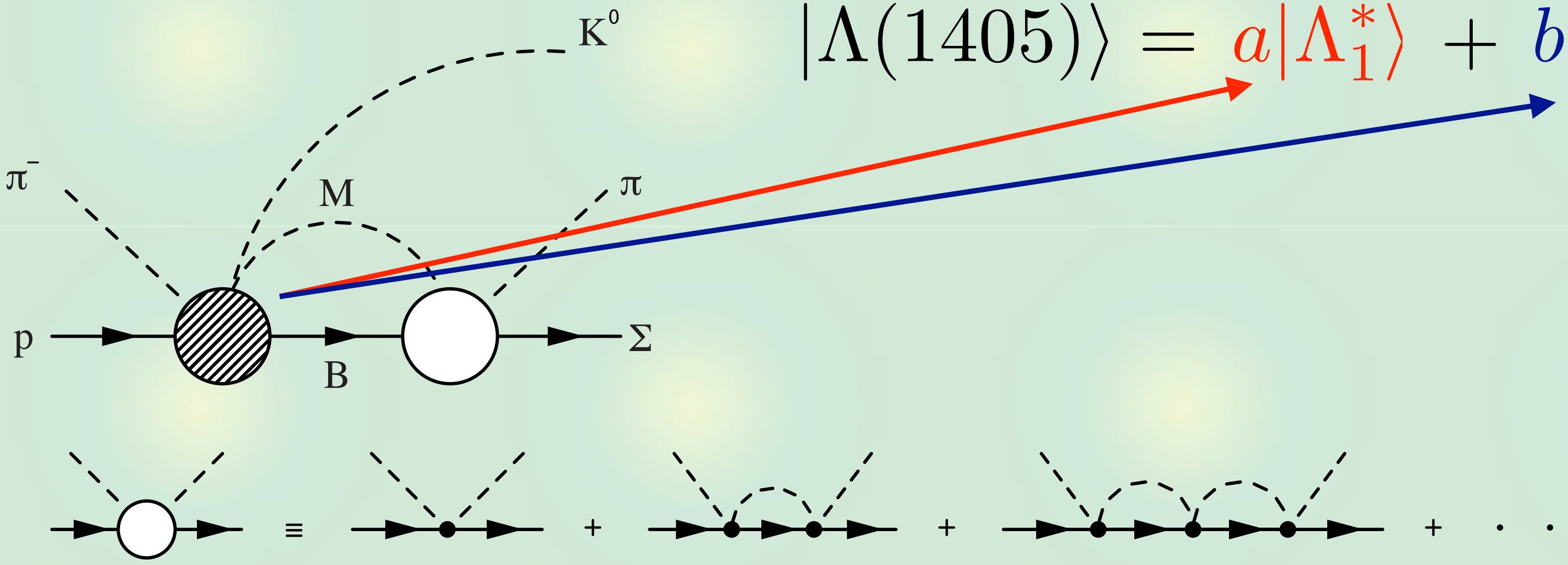

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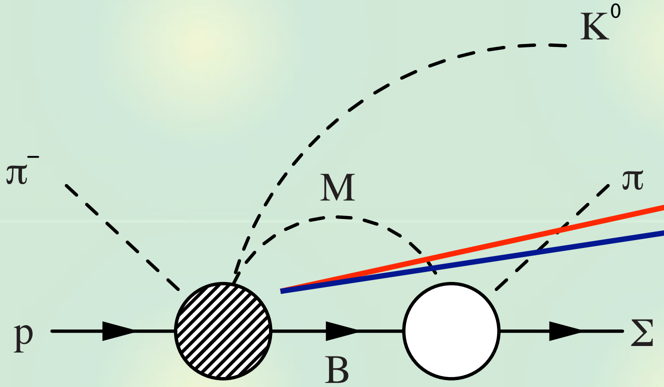

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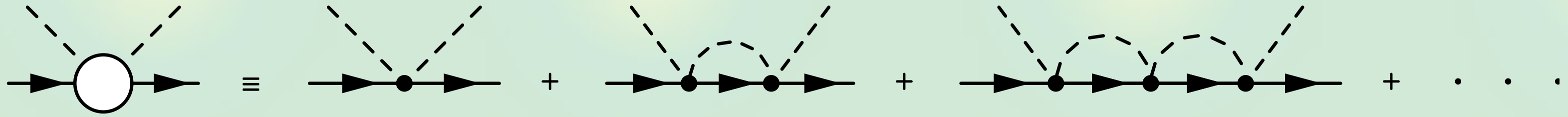
ただし反応計算は模型依存。

１ポールでも干渉でピーク位置が変化。



Contents

Structure of Λ(1405) resonance (Bグループ)

- Dynamical or CDD (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 (2008).

- Electromagnetic properties

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

Phenomenology of $\bar{K}N$ interaction

- Construction of local $\bar{K}N$ potential (Cグループ)

  T. Hyodo, W. Weise, Phys. Rev. C77, 035204 (2008).

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

  A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A804, 197 (2008)
  A. Doté, T. Hyodo, W. Weise, Phys. Rev. C 79, 014003 (2009)

+α

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, ...

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

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

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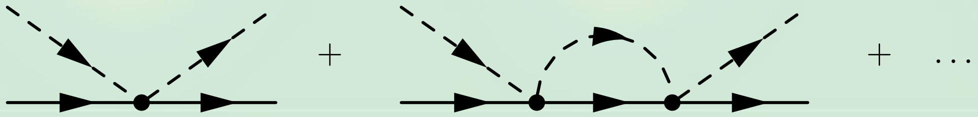

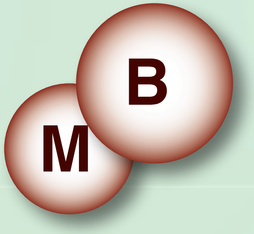

e.g.) Deuteron in NN, positronium in e^+e^-, (σ in π π), ...

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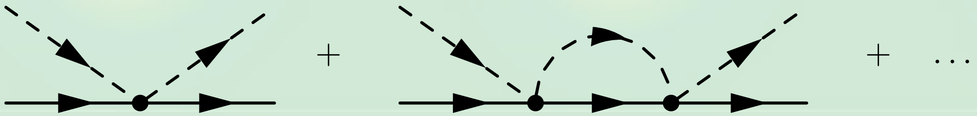

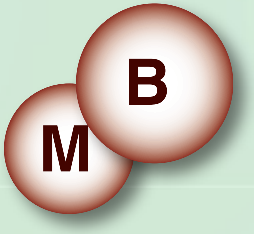

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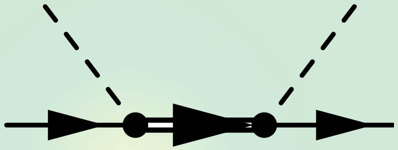
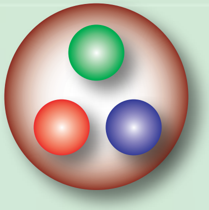




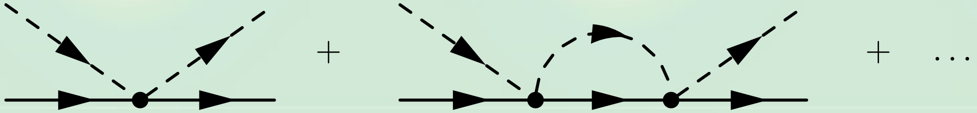
e.g.) J/Ψ in e^+e^-, (ρ in π π), ...

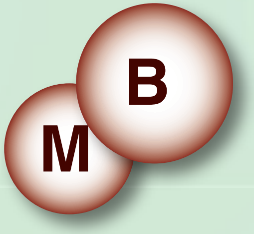
Dynamical state and CDD pole

Resonances in two-body scattering

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

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

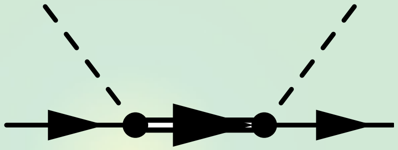


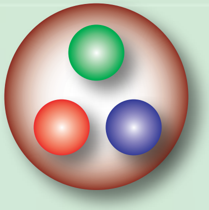


e.g.) Deuteron in NN, positronium in e^+e^-, (σ in π π), ...

(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

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

CDD pole contribution in chiral unitary approach

Amplitude in chiral unitary model

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

V : interaction kernel (potential)

G : loop integral (Green’s function)

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Known CDD pole contribution

(1) Explicit resonance field in **V**
(2) Contracted resonance propagator in **V**

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Defining "natural renormalization scheme",
we find **CDD pole contribution in G** (subtraction constant).

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Defining "natural renormalization scheme",
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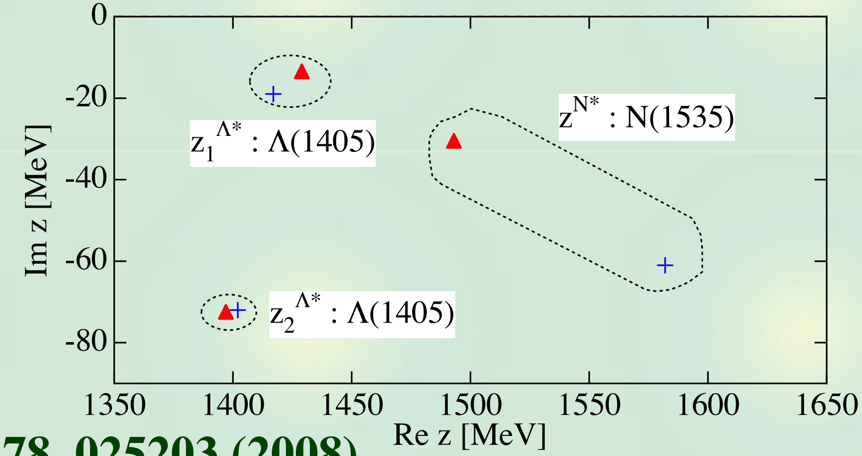
N(1535) in πN scattering
--> dynamical + CDD pole

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

Nc scaling in the model

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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)

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Nc scaling of (excited)
qqq baryon

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

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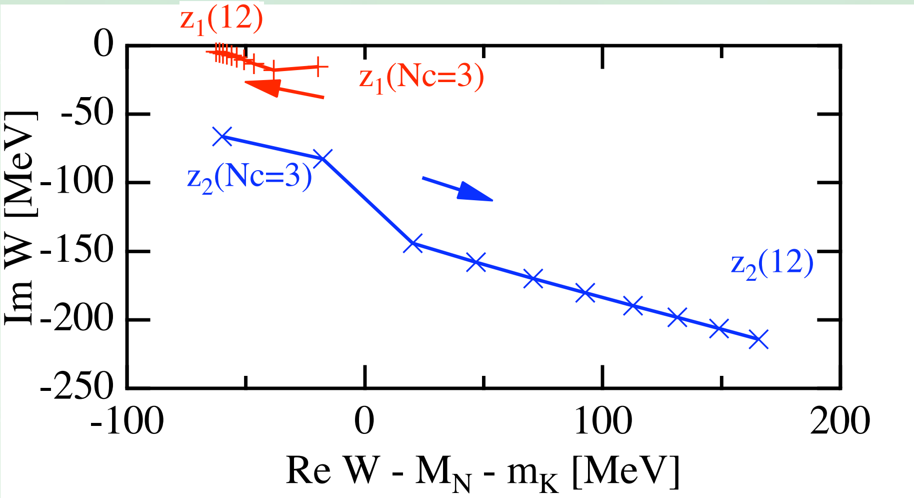


Nc scaling of (excited) qqq baryon

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

Result : $\Gamma_R \neq \mathcal{O}(1)$
~ non-qqq (i.e. dynamical) structure

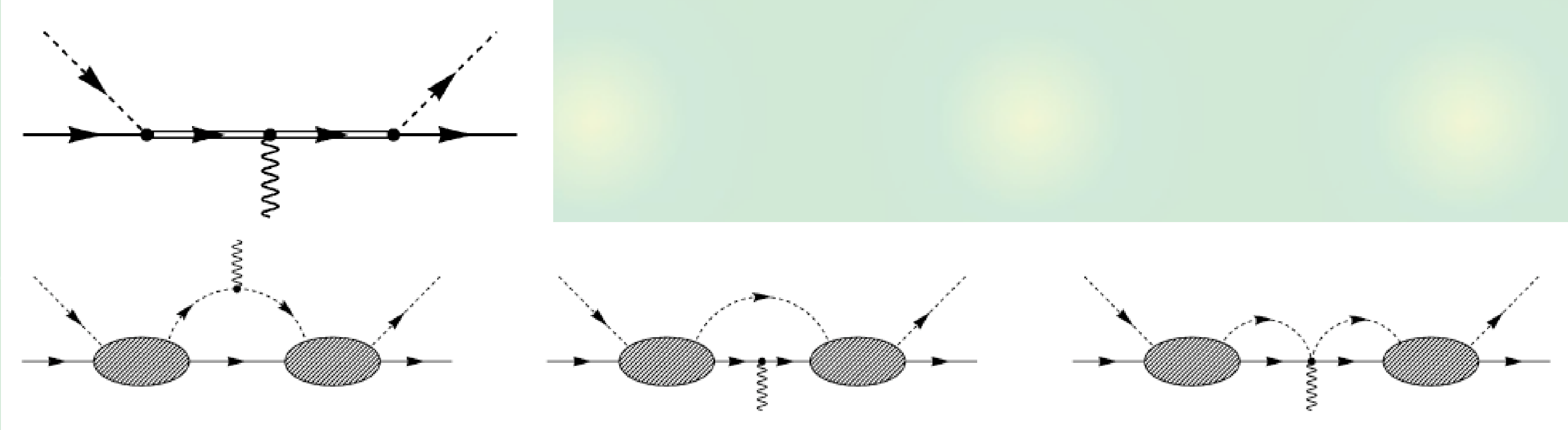
T. Hyodo, D. Jido, L. Roca, Phys. Rev. D77, 056010 (2008).
L. Roca, T. Hyodo, D. Jido, Nucl. Phys. A809, 65 (2008).

詳細は学会で

29pSJ-2

Electromagnetic properties

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



result of mean squared radii :

$$< r^2 >_E = -2.193 \text{ fm}^2$$

large (em) size of the Λ(1405)
--> meson-baryon picture

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

Summary 1 : Structure of Λ(1405)

We study the structure of the Λ(1405)

- Dynamical or CDD?

  => dominance of the MB components

- Analysis of Nc scaling

  => non-qqq structure

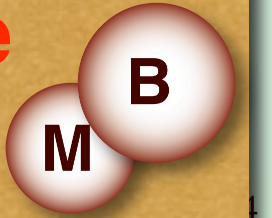
- Electromagnetic properties

  => large e.m. size

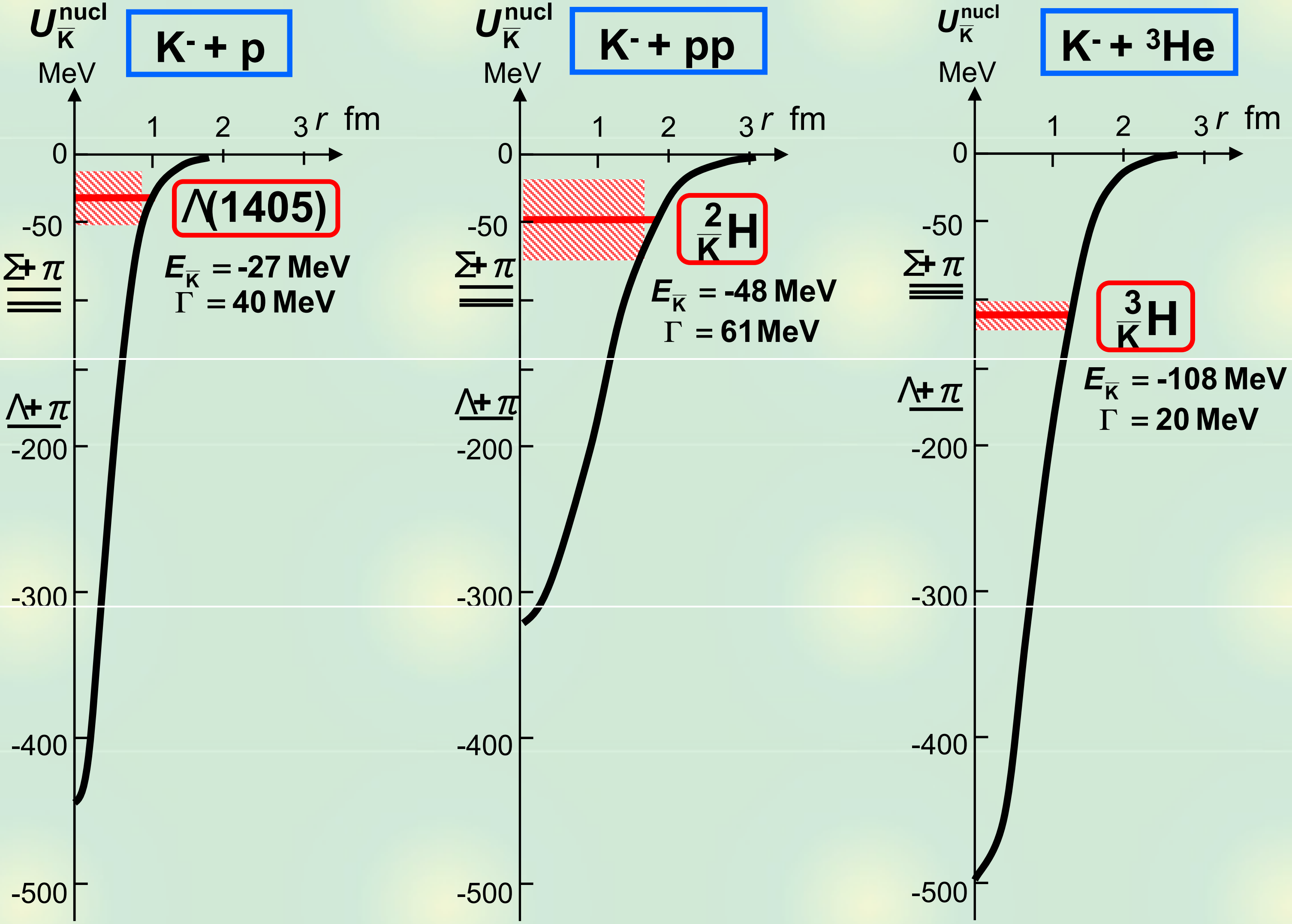
Summary 1 : Structure of Λ(1405)

We study the structure of the Λ(1405)

- **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 of the Λ(1405)**



Deeply bound (few-body) kaonic nuclei?



Y. Akaishi & T. Yamazaki, Phys. Rev. C 65 (2002) 044005
T. Yamazaki & Y. Akaishi, Phys. Lett. B 535 (2002) 70

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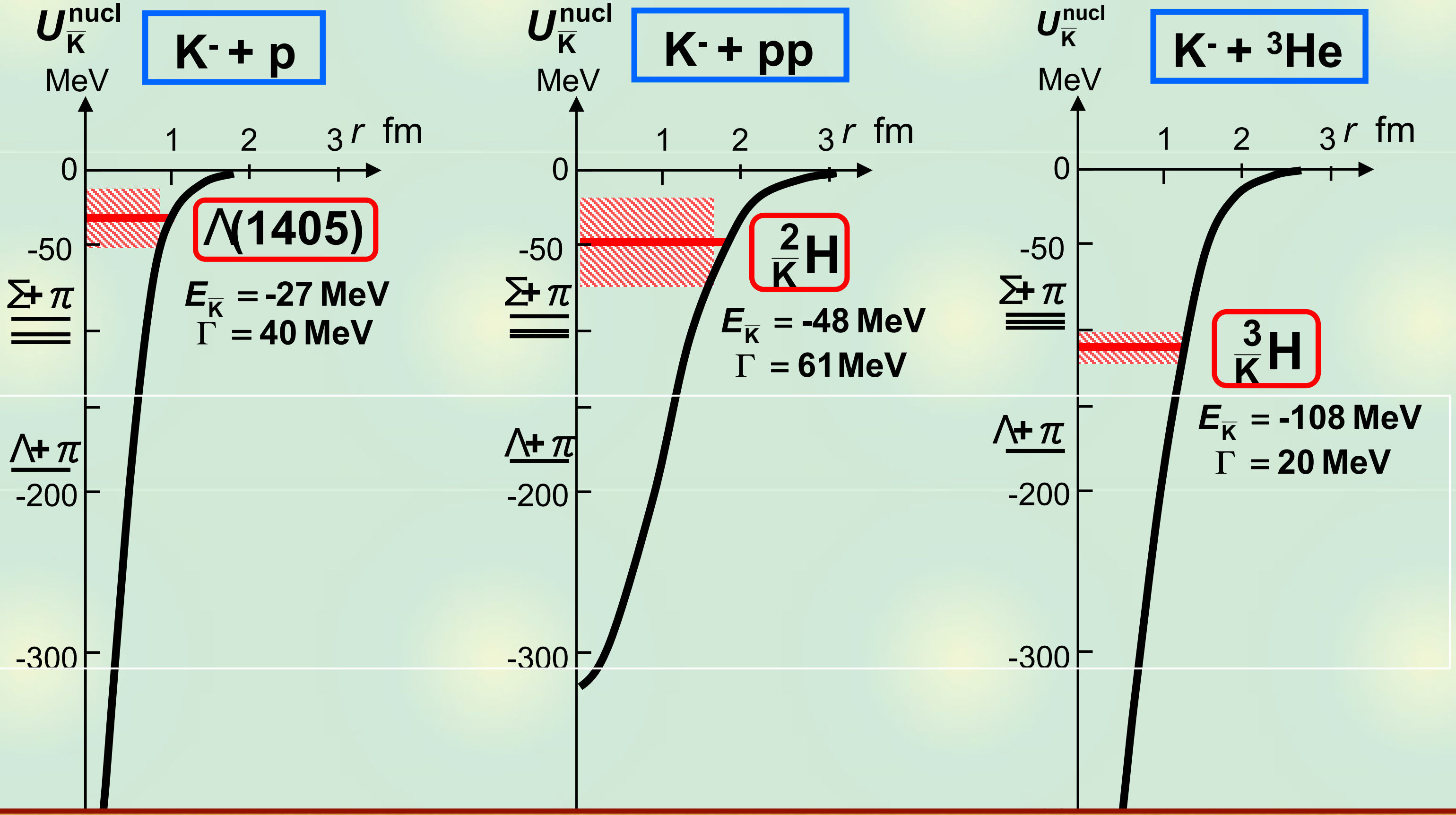

Potential is purely phenomenological.
What does chiral dynamics tell us about it?

Y. Akaishi & T. Yamazaki, Phys. Rev. C 65 (2002) 044005
T. Yamazaki & Y. Akaishi, Phys. Lett. B 535 (2002) 70

Effective interaction based on chiral SU(3) dynamics

Few-body kaonic nuclei in chiral dynamics

- single-channel $\bar{K}N$ potential

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Construction of effective single-channel potential

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

1) Coupled-channel --> single $\bar{K}N$ channel BS equation
incorporation of πΣ channel (exact)

2) Local potential in Schrödinger equation (approximate)

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Application to K-pp system : bound, but B ~ 20 MeV

A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A 804, 197 (2008); Phys. Rev. C 79, 014003 (2009)

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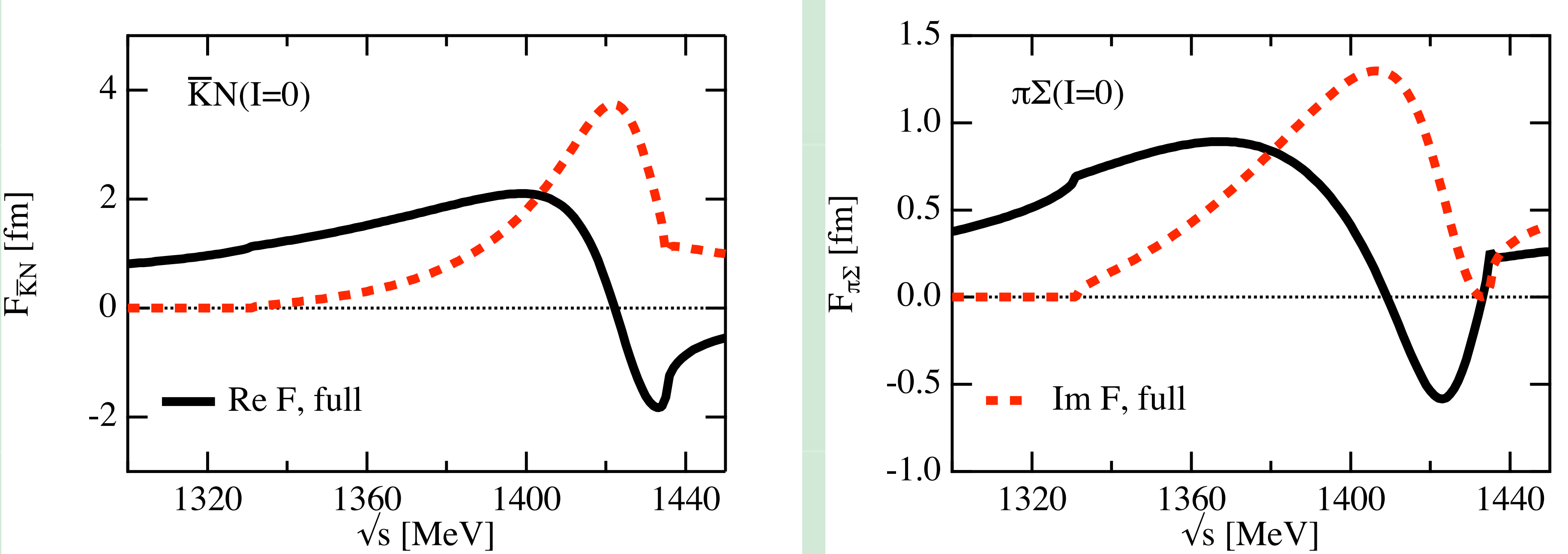
Why the interaction is weaker? --> structure of the Λ(1405)

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



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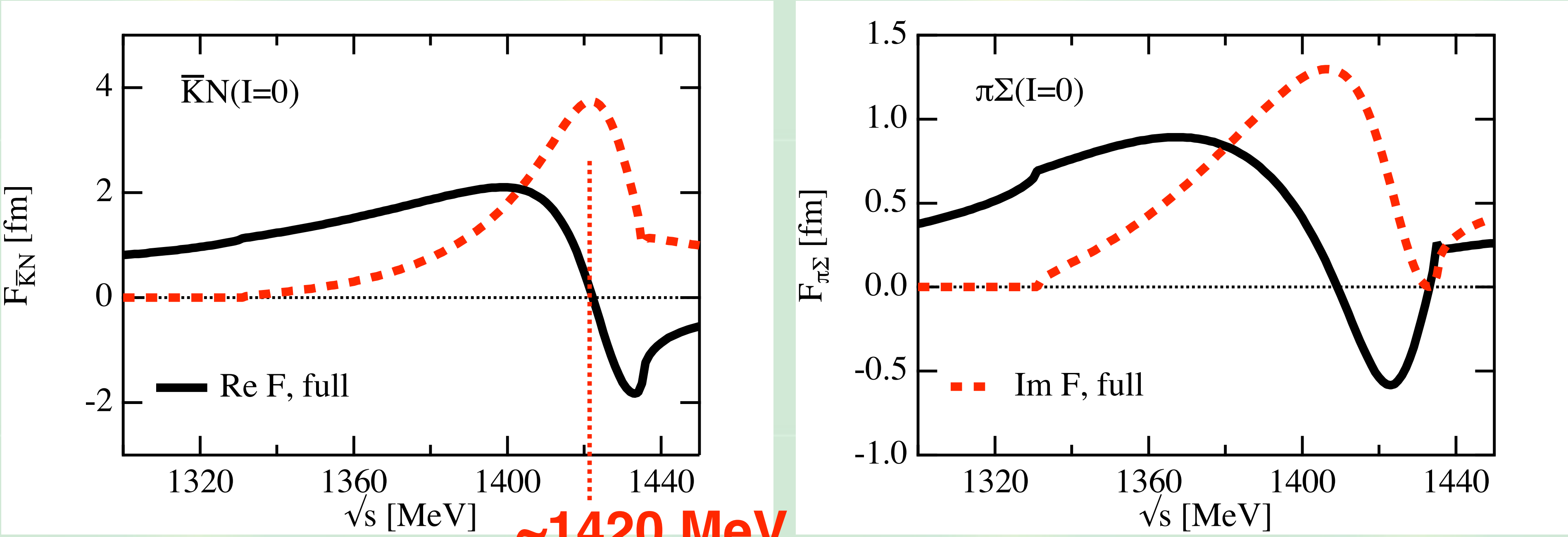

~1420 MeV

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

<-- strong πΣ dynamics (coupled-channel)

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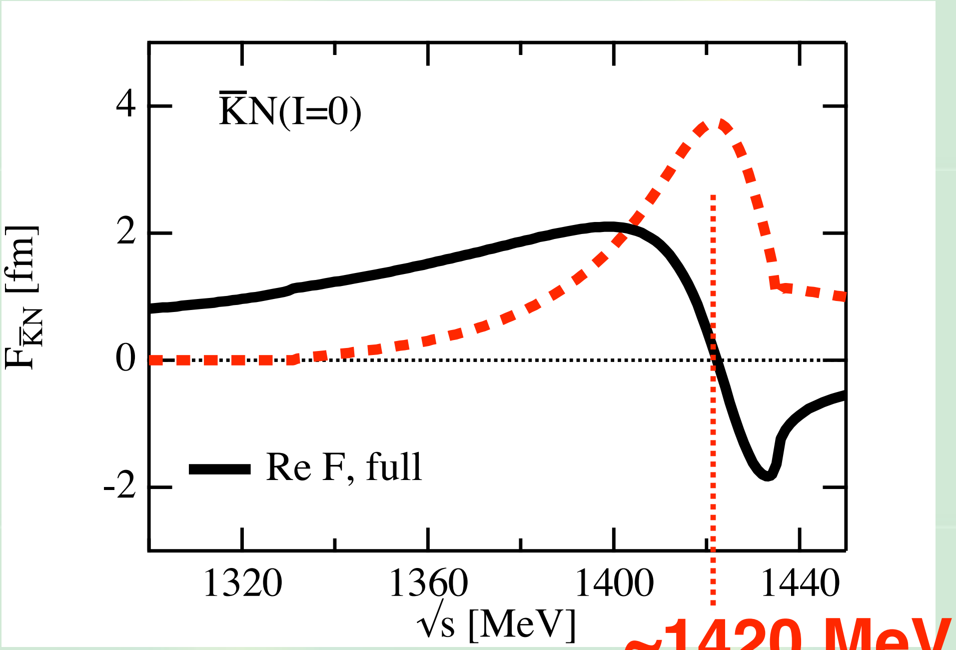

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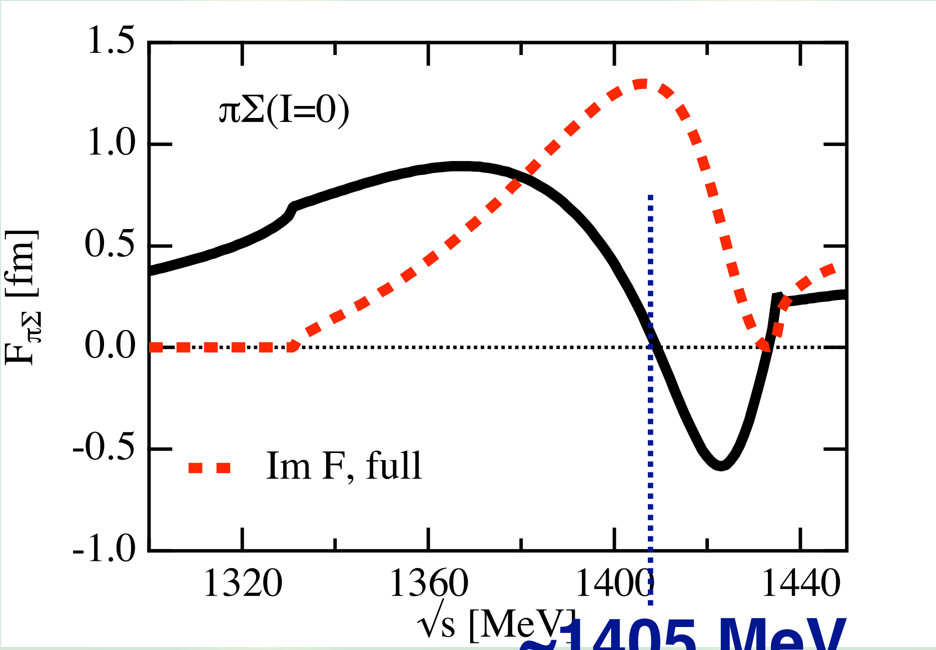

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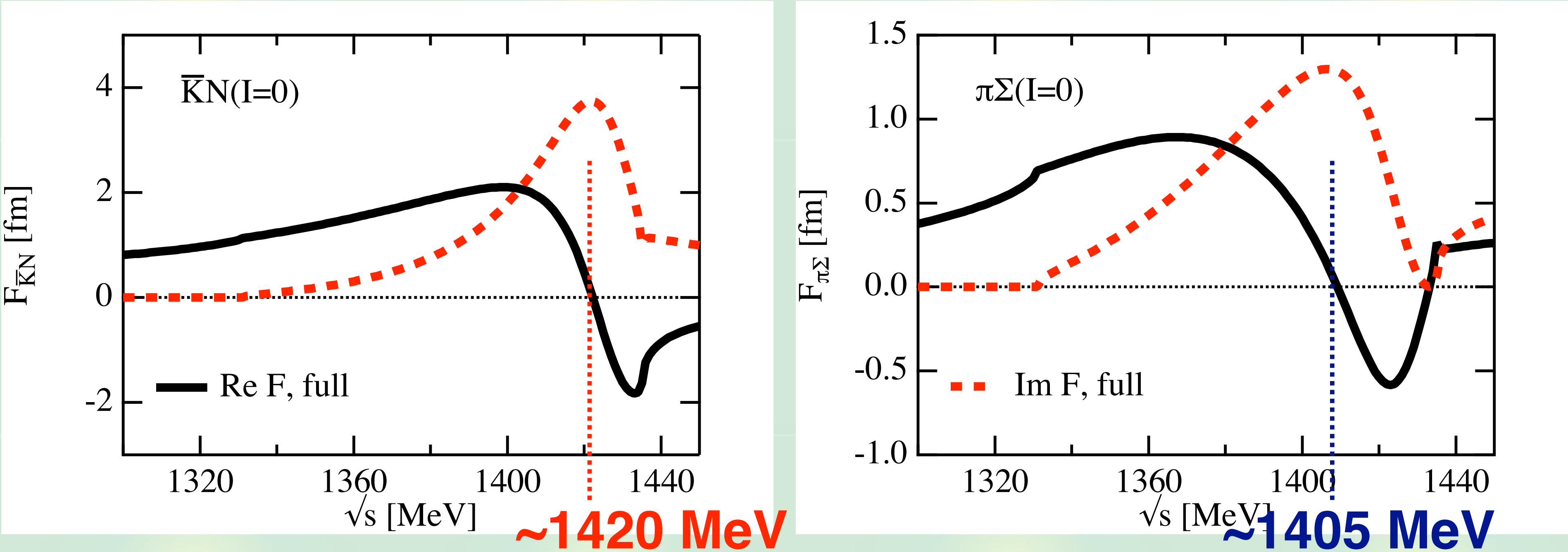

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Binding energy : B = 15 MeV <--> 30 MeV

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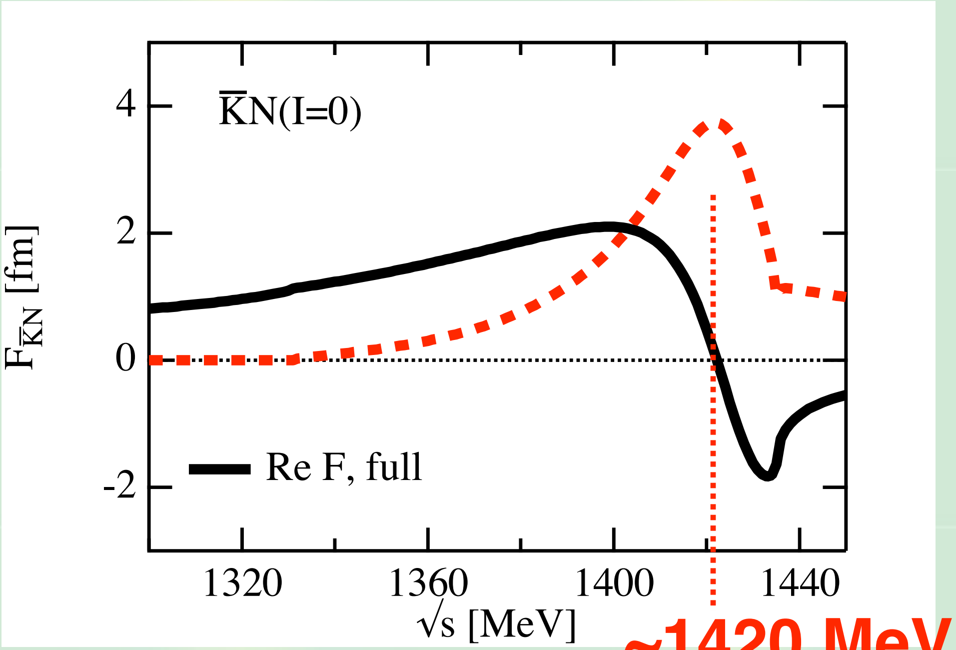

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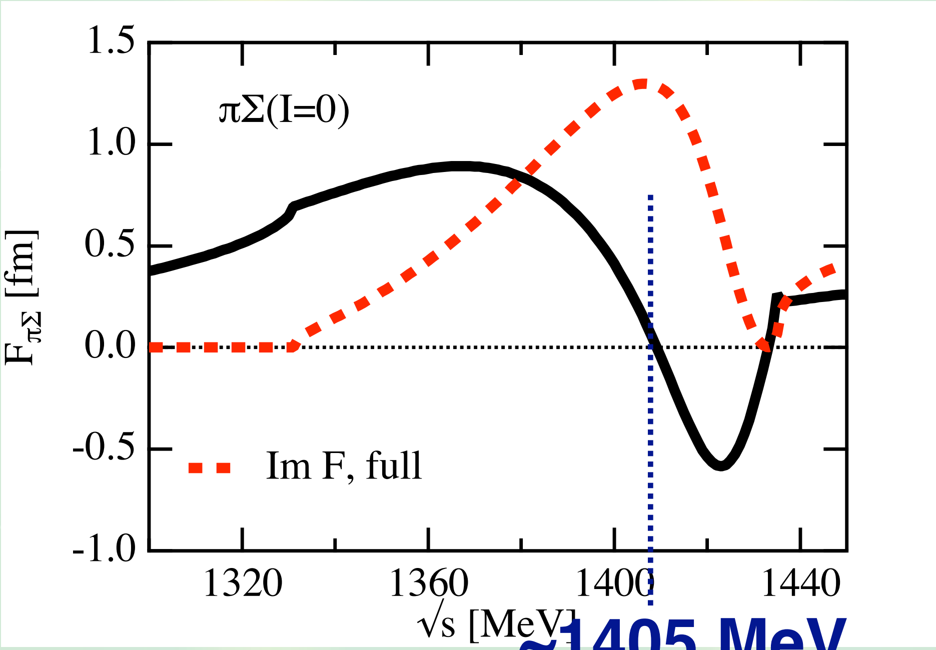

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Resonance in $\bar{K}$N : around 1420 MeV
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Two poles with same quantum numbers
Different weights of the pole residues --> different spectra

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

Origin of the two-pole structure

Chiral interaction

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

$$C_{ij} = \begin{array}{cc} \bar{K}N & \pi\Sigma \\ \end{array}$$

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

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

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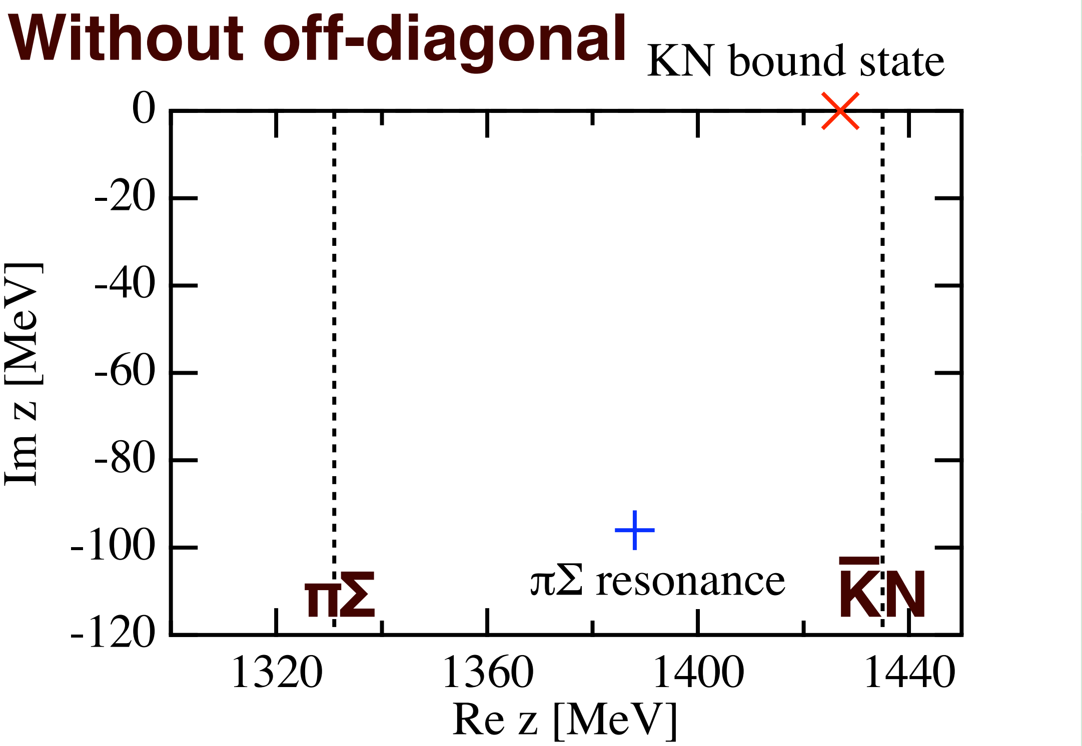

Without off-diagonal

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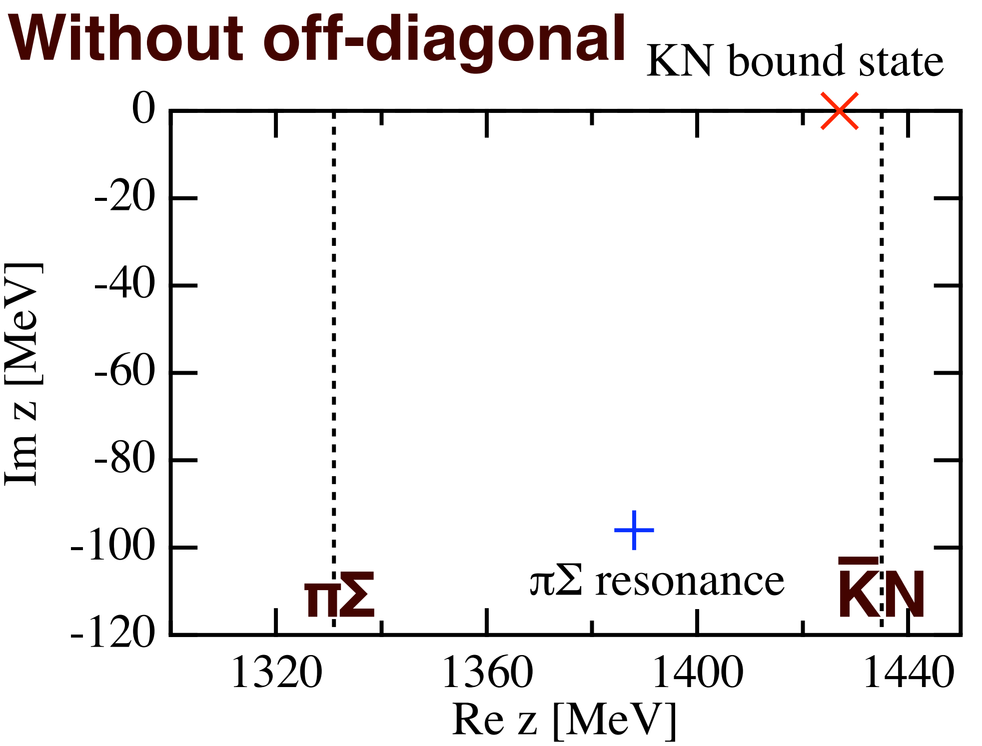

Very strong attraction in K̄N (higher energy) --> bound state

Strong attraction in πΣ (lower energy) --> resonance

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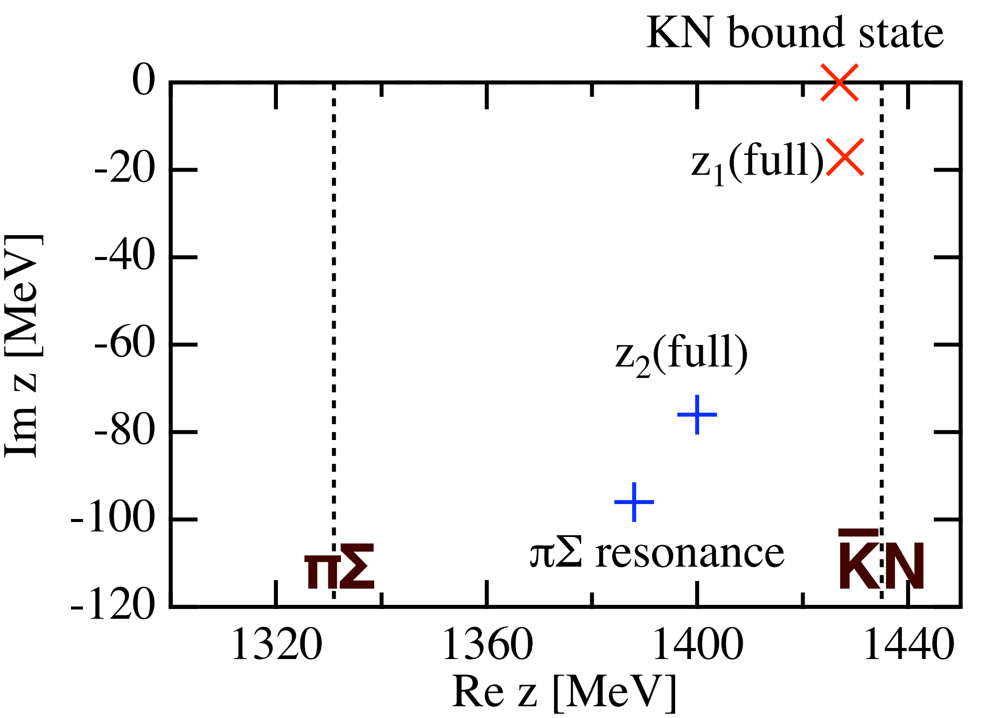

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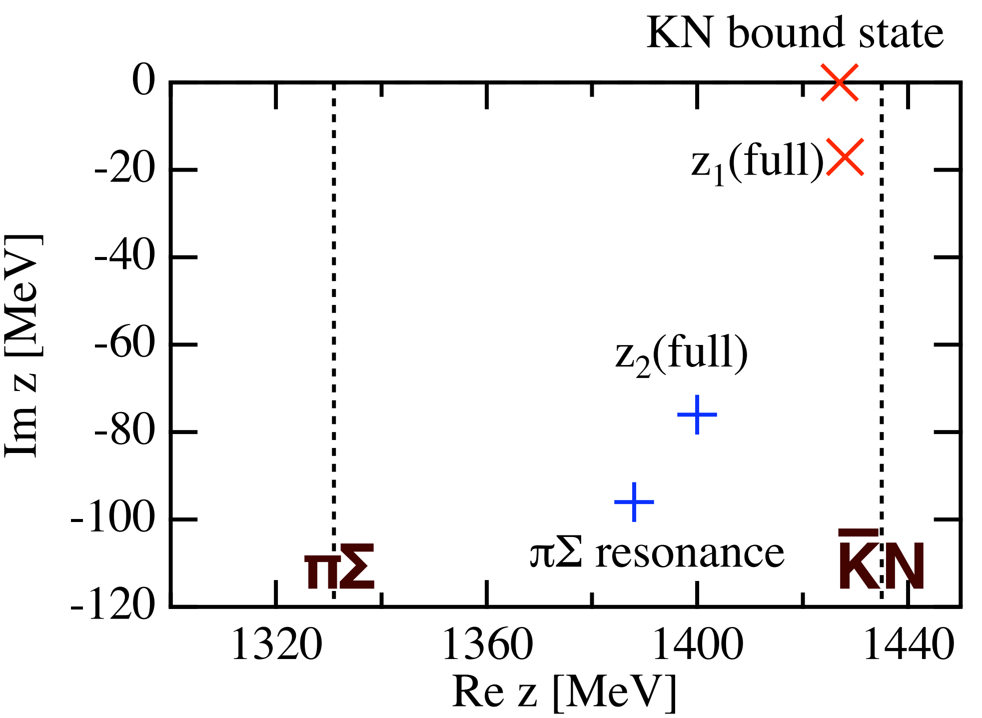

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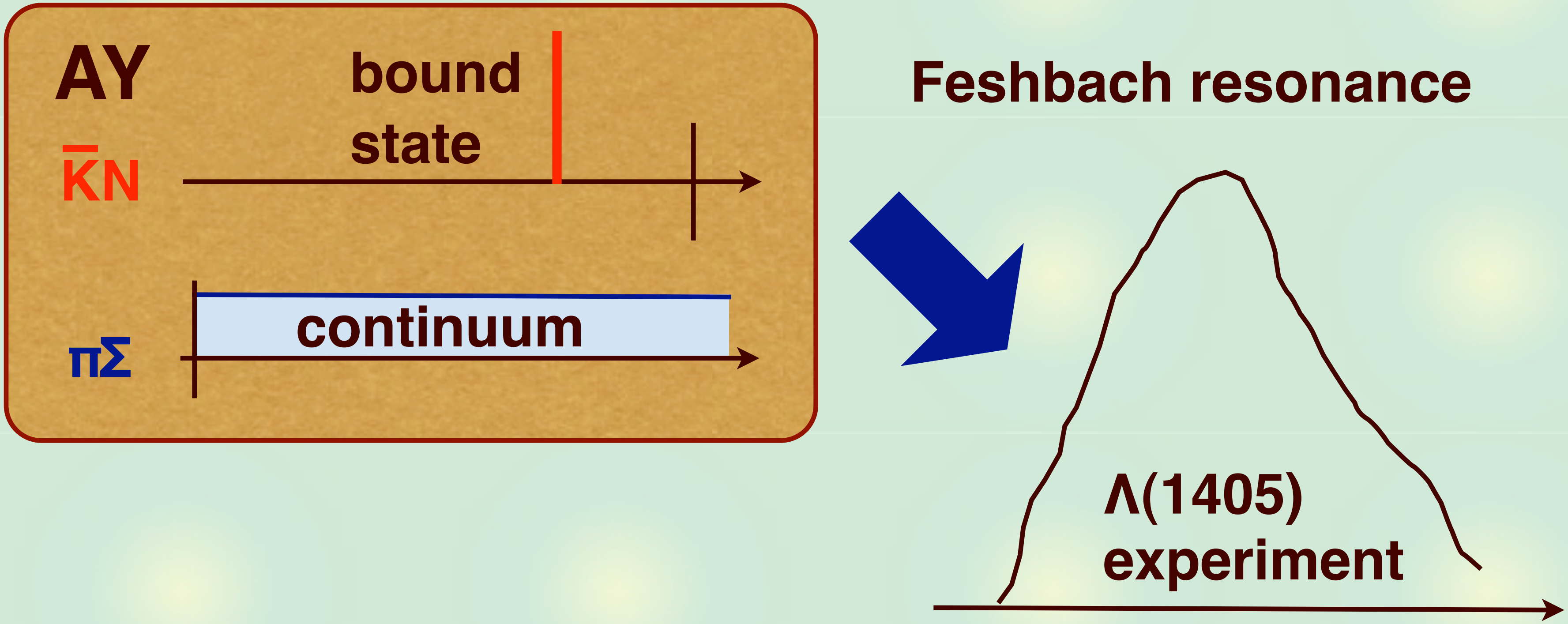
Two attractive interactions --> Two states
πΣ -> πΣ attraction : chiral SU(3) symmetry

Schematic illustration : AY vs Chiral



AY

$\bar{K}N$

bound state

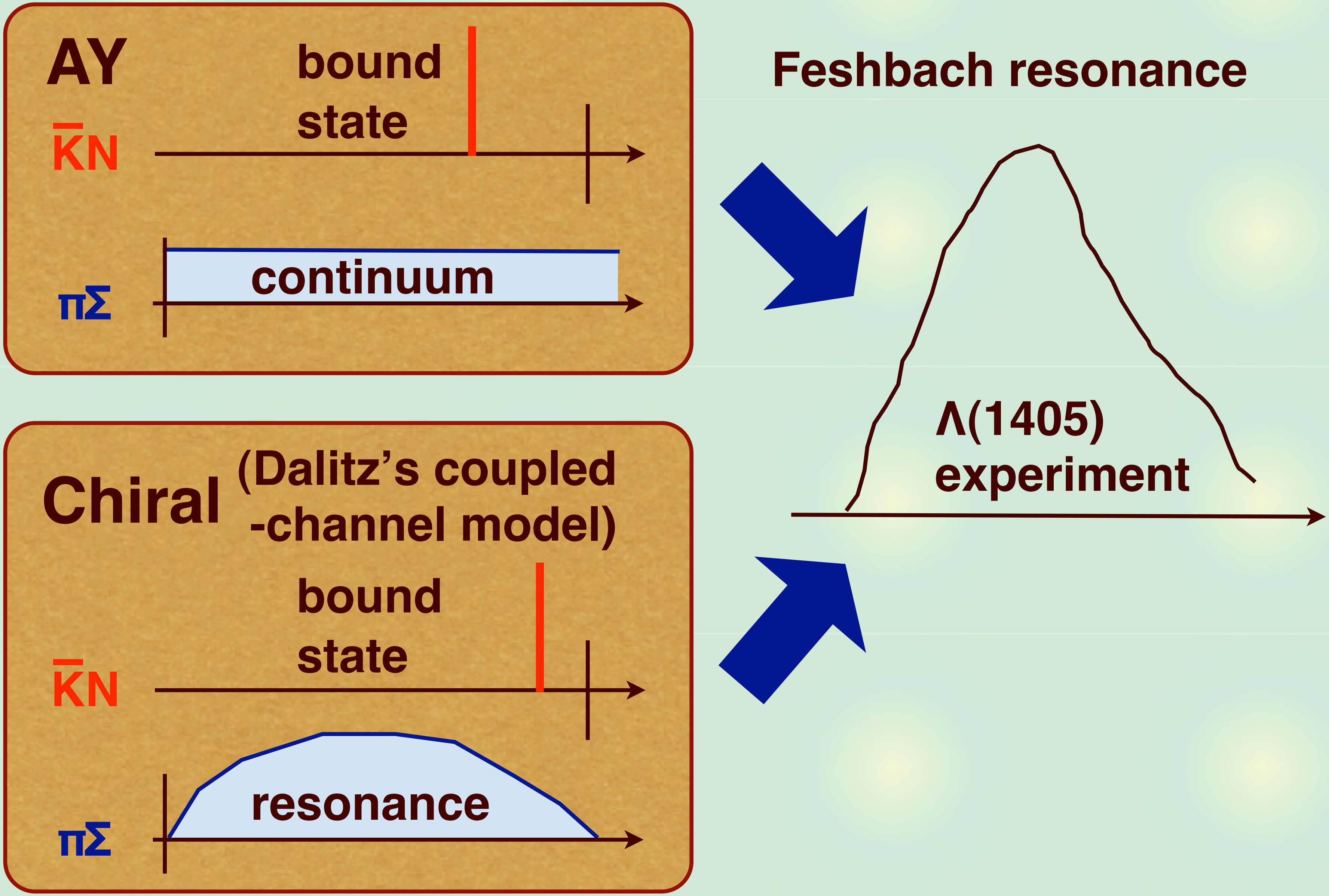
$\pi\Sigma$

continuum

Feshbach resonance

Λ(1405) experiment

Schematic illustration : AY vs Chiral



AY

$\bar{K}N$ bound state

$\pi\Sigma$ continuum

Chiral (Dalitz's coupled -channel model)

$\bar{K}N$ bound state

$\pi\Sigma$ resonance

Feshbach resonance

Λ(1405) experiment

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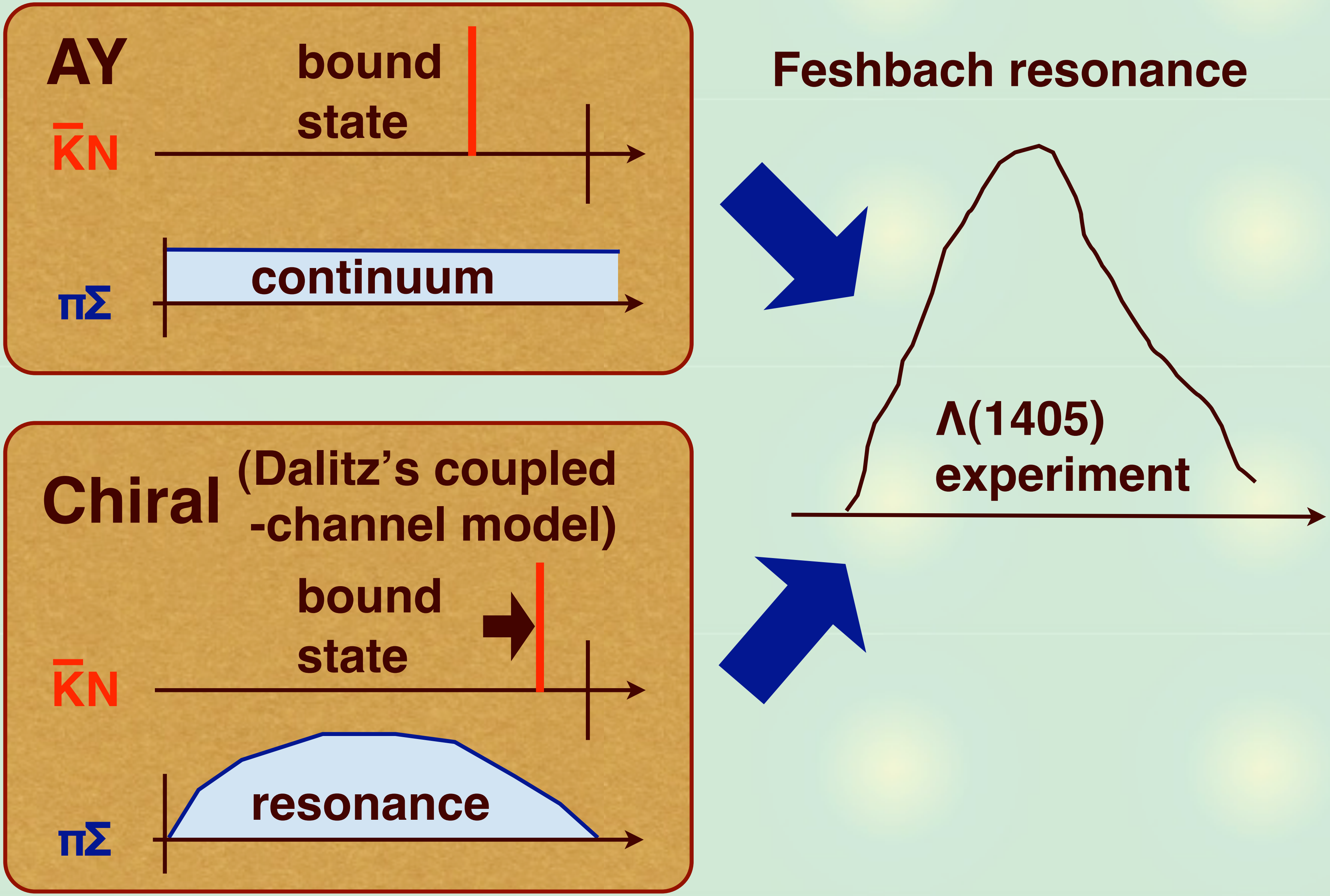

AY

bound state

$\bar{K}N$

continuum

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$\Lambda(1405)$ experiment

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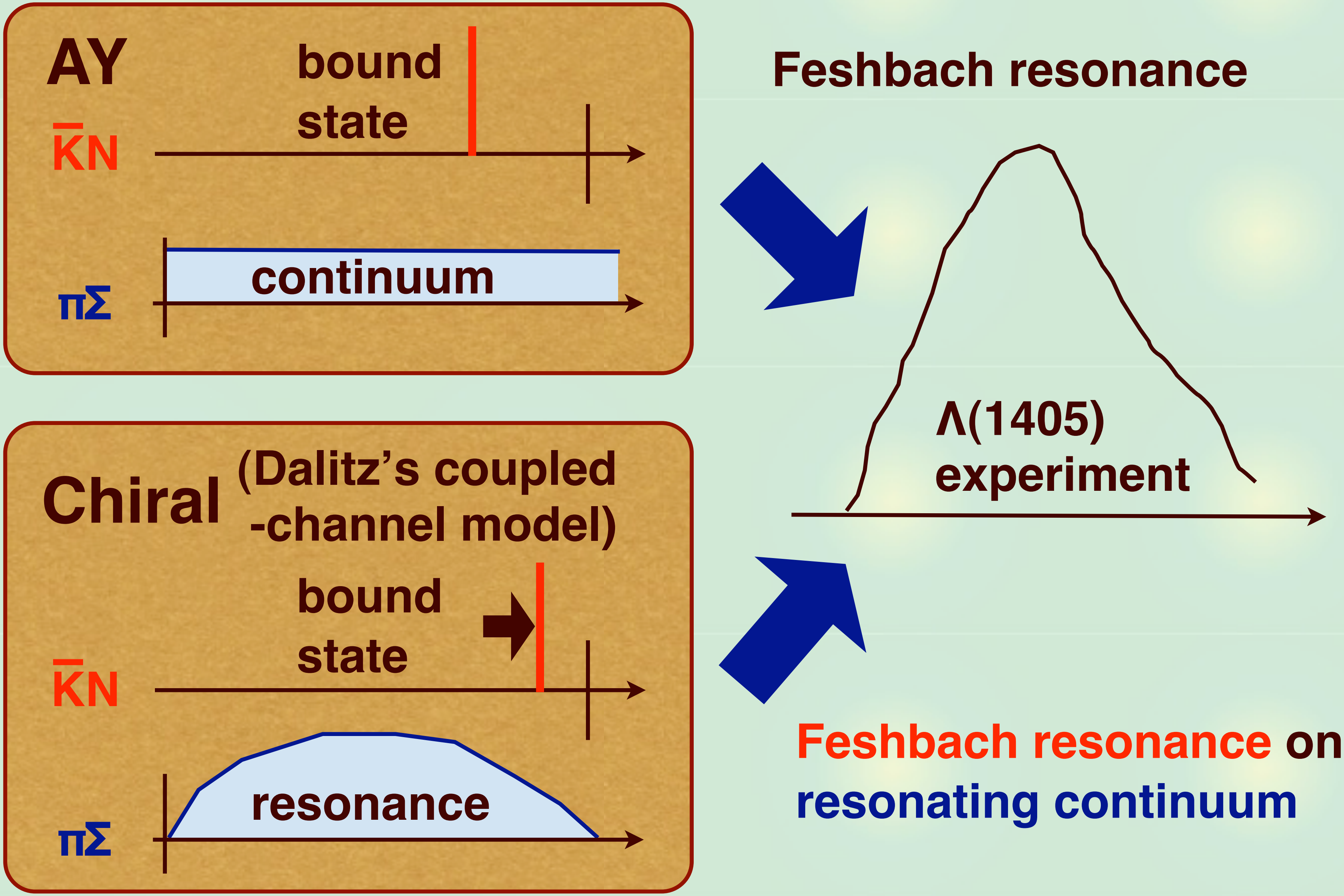

AY

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$\bar{K}N$

continuum

$\pi\Sigma$

Chiral (Dalitz's coupled -channel model)

bound state

$\bar{K}N$

resonance

$\pi\Sigma$

Feshbach resonance

Λ(1405) experiment

Feshbach resonance on resonating continuum

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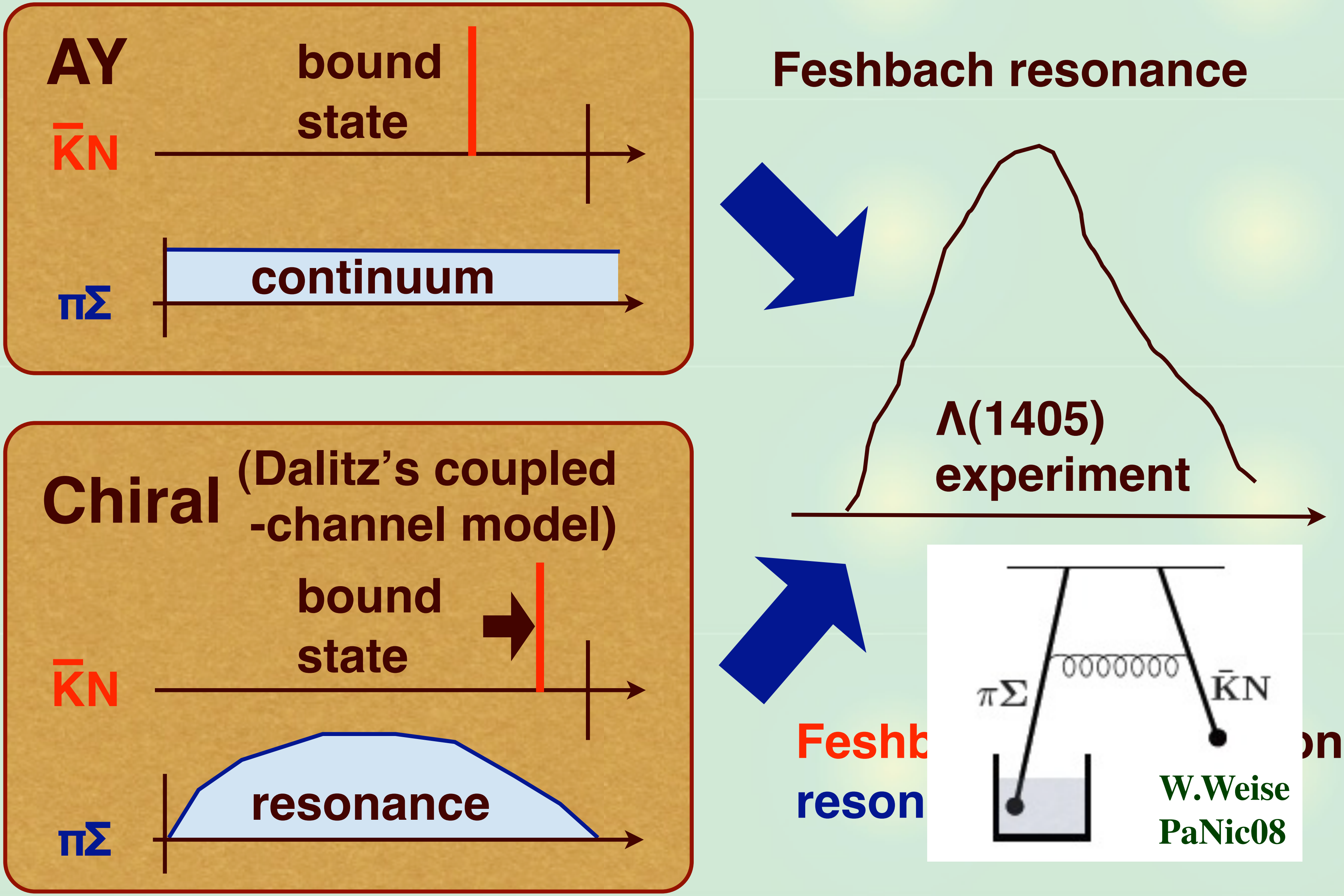

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Chiral (Dalitz's coupled -channel model)

$\bar{K}N$

bound state

$\pi\Sigma$

resonance

Feshbach resonance

Λ(1405) experiment

Feshb on

reson

Summary 2 : $\bar{K}N$ interaction

We study the consequence of chiral SU(3) dynamics in $\bar{K}N$ phenomenology.

- Single-channel effective $\bar{K}N$ interaction is **attractive** and forms K-pp bound system, about 20 MeV binding.
- Resonance structure in $\bar{K}N$ appears at around **1420 MeV** <-- **strong πΣ dynamics**
- Two attractive interactions in **$\bar{K}N$** and **πΣ** --> **weaker** effective $\bar{K}N$ interaction.

T. Hyodo and W. Weise, Phys. Rev. C 77, 035204 (2008)
A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A804, 197 (2008)
A. Doté, T. Hyodo, W. Weise, Phys. Rev. C 79, 014003 (2009)

Three-body calculations for $\bar{K}NN$

Single-channel variational calculation (DHW)

B.E. = 20 ± 3 MeV, Γ(πYN) = 40 ~ 70 MeV

Coupled-channel Faddeev calculation (IS)
using chiral interaction

Y. Ikeda and T. Sato, Phys. Rev. C 77, 035204 (2008)

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B.E. ~ 79 MeV, Γ(πYN) ~ 74 MeV

Why are they so different?
Inconsistency in theoretical calculations?

- **πΣN dynamics?**
  (existence of another N when eliminating πΣ channel)

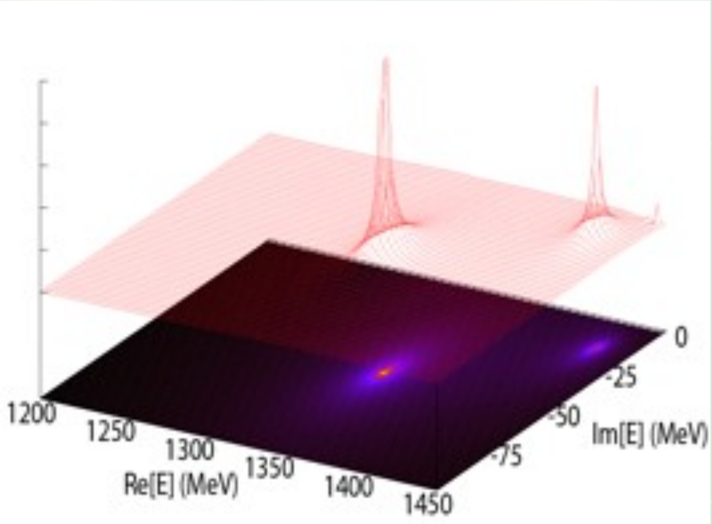
Y. Ikeda and T. Sato, arXiv:0809.1285 [nucl-th]

Two-pole structure for $\bar{K}NN$

Y. Ikeda, H. Kamano, T. Sato

Y. Ikeda, RCNP workshop, Dec. 25, 2008

“Chiral unitary like” model
: two poles in $\bar{K}N$-$\pi\Sigma$ amplitude



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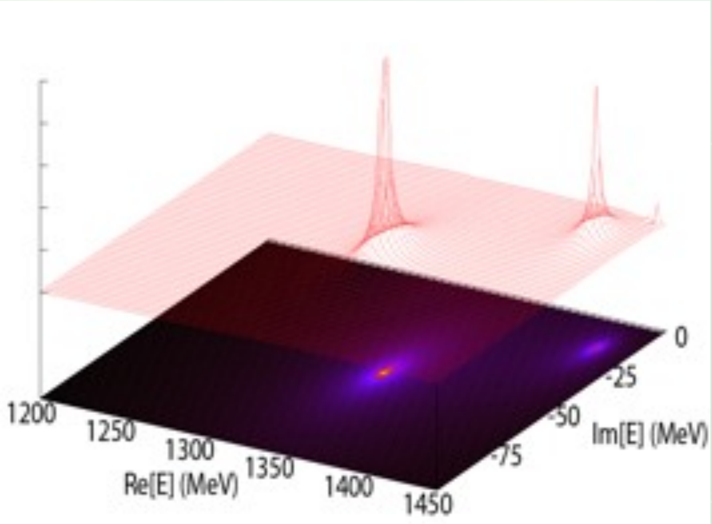
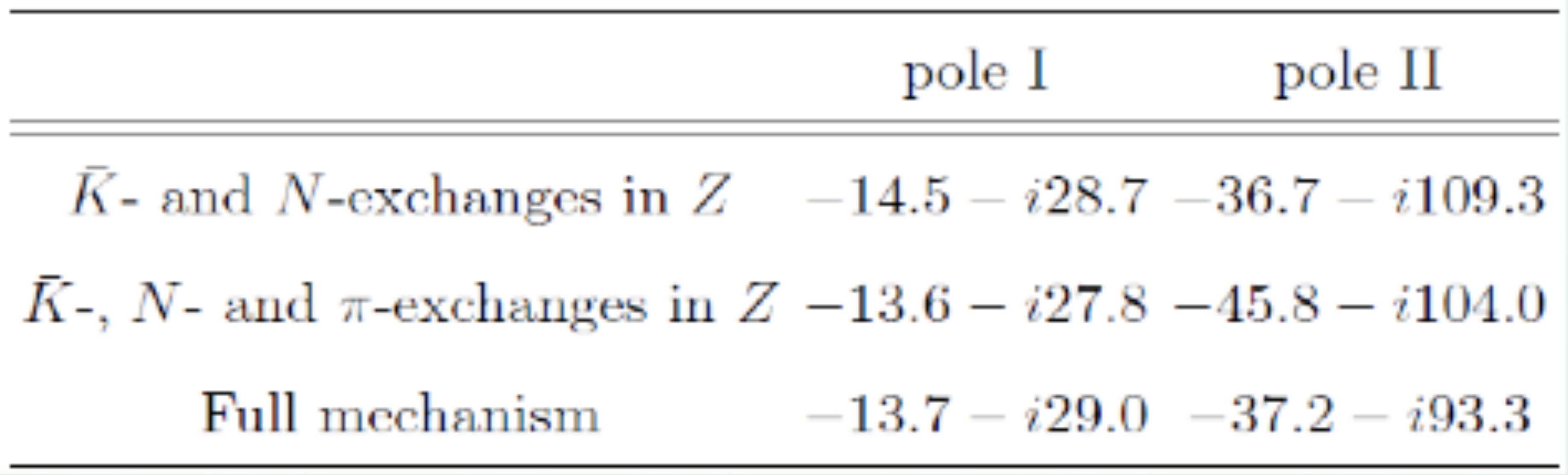
Solving Faddeev equation, they find
two poles in **$\bar{K}$NN-πΣN amplitude**





	pole I	pole II
$\bar{K}$- and N-exchanges in Z	$-14.5 - i28.7$	$-36.7 - i109.3$
$\bar{K}$-, N- and π-exchanges in Z	$-13.6 - i27.8$	$-45.8 - i104.0$
Full mechanism	$-13.7 - i29.0$	$-37.2 - i93.3$

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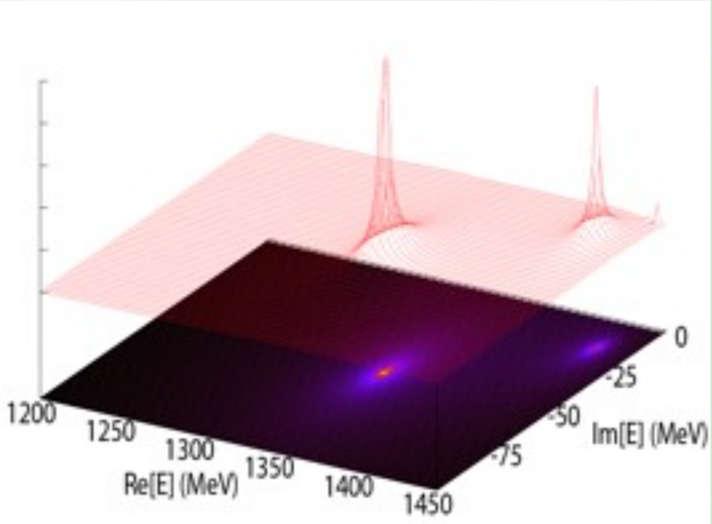
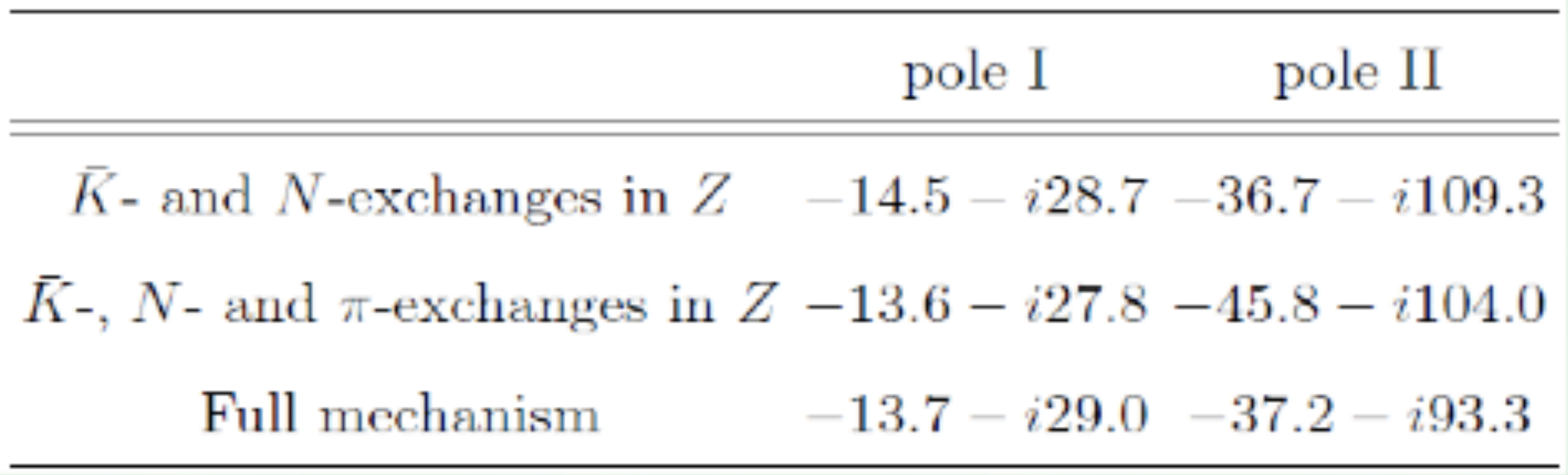


"Chiral unitary like" model
: two poles in $\bar{K}N$-$\pi\Sigma$ amplitude

Solving Faddeev equation, they find two poles in $\bar{K}NN$-$\pi\Sigma N$ amplitude



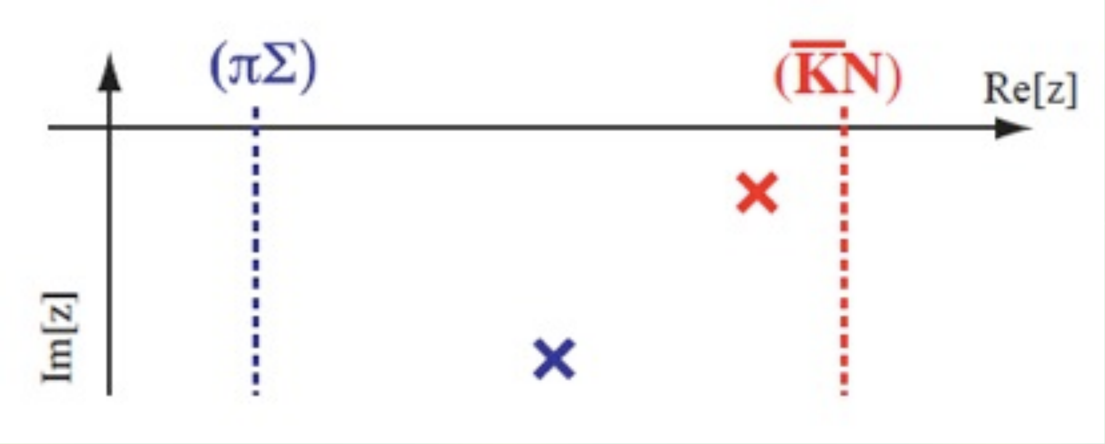
	pole I	pole II
$\bar{K}$- and N-exchanges in Z	$-14.5 - i28.7$	$-36.7 - i109.3$
$\bar{K}$-, N- and π-exchanges in Z	$-13.6 - i27.8$	$-45.8 - i104.0$
Full mechanism	$-13.7 - i29.0$	$-37.2 - i93.3$

--> Two poles for three-body system?

Two-pole structure for $\bar{K}NN$

Two poles in two-body scattering:

higher energy pole --> $\bar{K}N$ bound state
lower energy pole --> πΣ resonance



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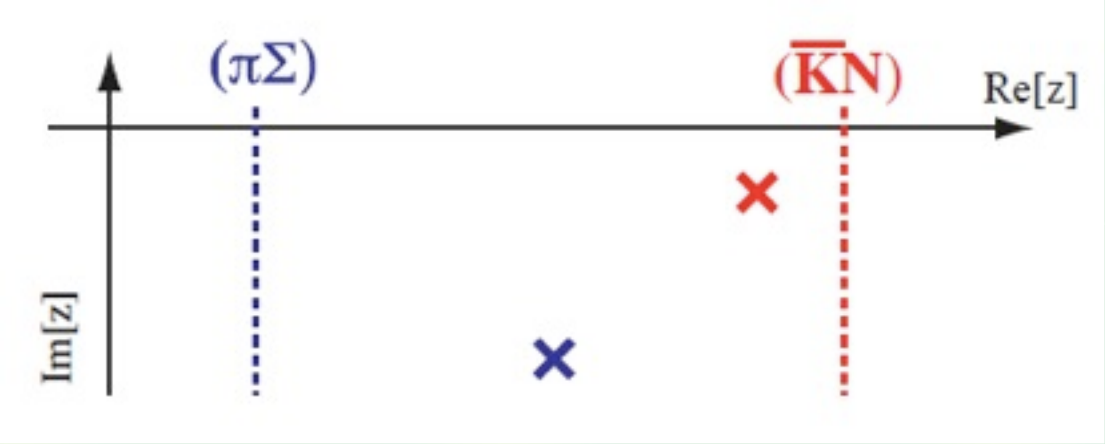

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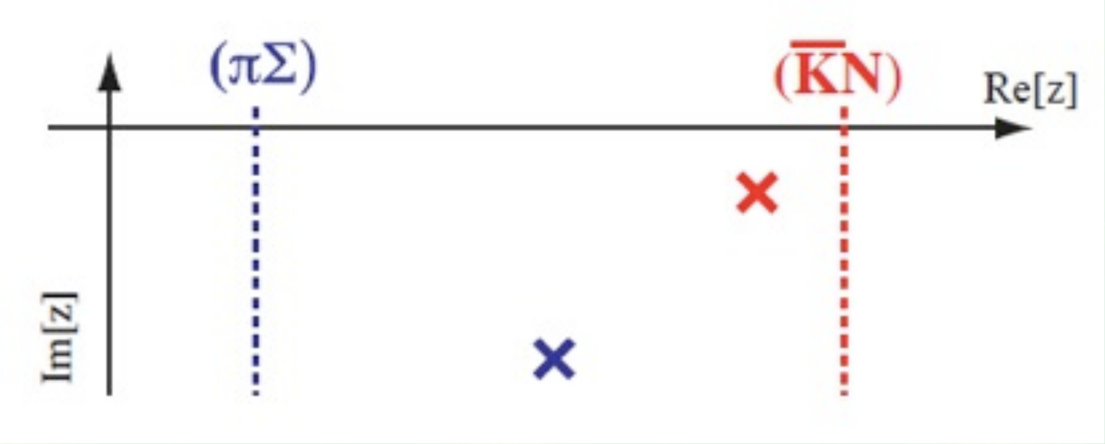


If there are two poles in three-body system, “single-channel” approach of DHW focuses on the higher energy pole of $\bar{K}NN$, since the πΣN channel has been eliminated.

Then, where is the lower energy state in three-body system?

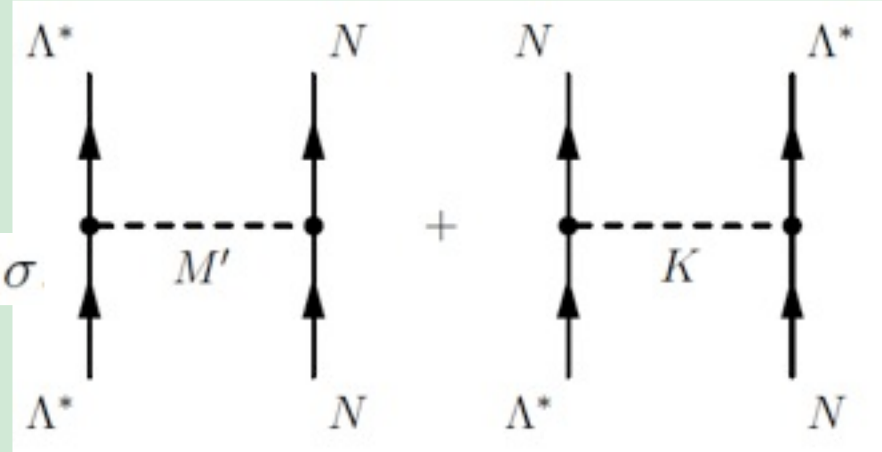
--> Schematic model calculation

Λ* hypernuclei model

Treating Λ(1405) as an elementary field, construct "Λ*N potential" through meson exchange

A. Arai, M. Oka and S. Yasui, Prog. Theor. Phys. 119, 103 (2008)

$M' = \eta, \omega, \sigma$



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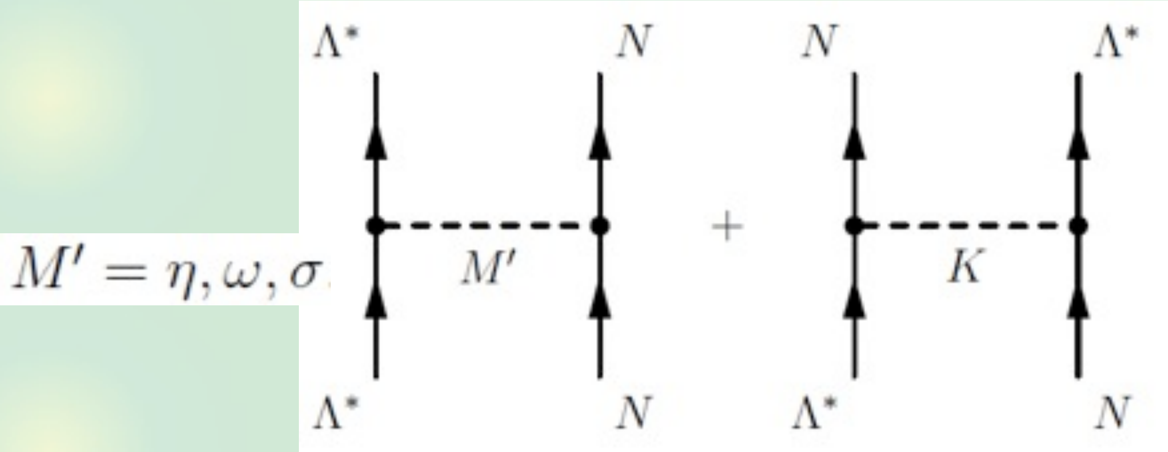

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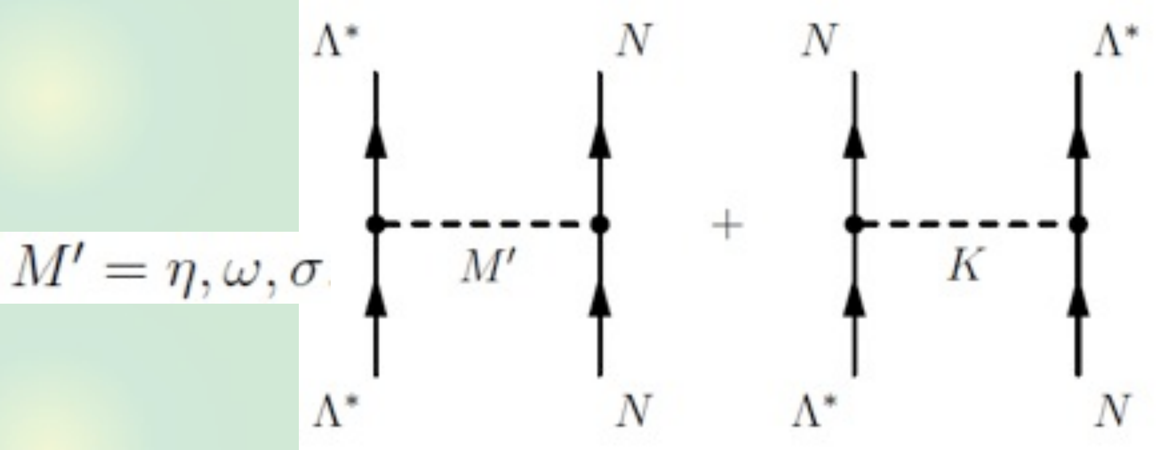

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Attractive interaction (mainly from σ exchange)
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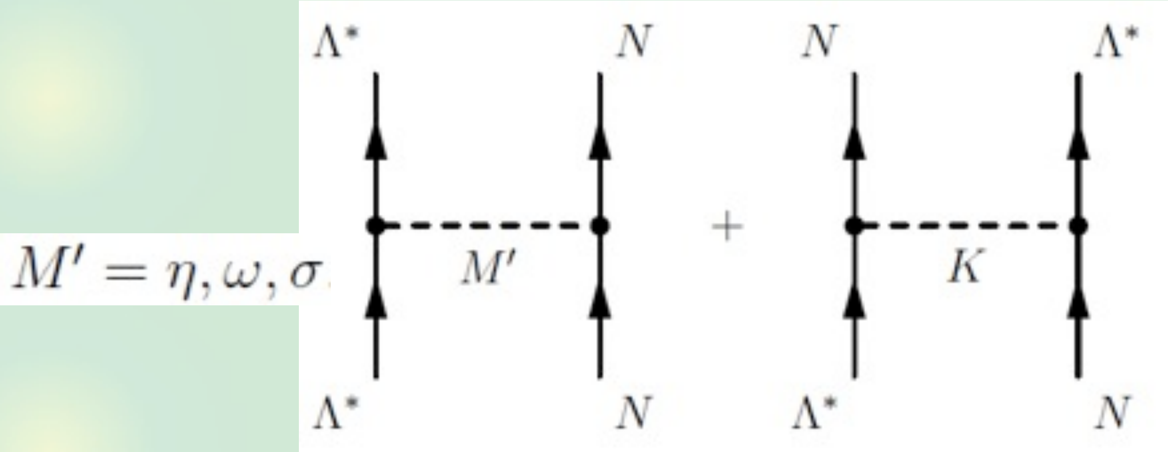

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Attractive interaction (mainly from σ exchange) --> bound Λ*N, Λ*NN systems

Λ* coupling constant : unknown (<-- FINUDA data).

Λ*N state in chiral model

Chiral dynamics --> two Λ* states : Λ^*_1, Λ^*_2

With sufficient attraction (σ exchange),
--> two Λ*N bound states in B=2 system : Λ^*_1N, Λ^*_2N

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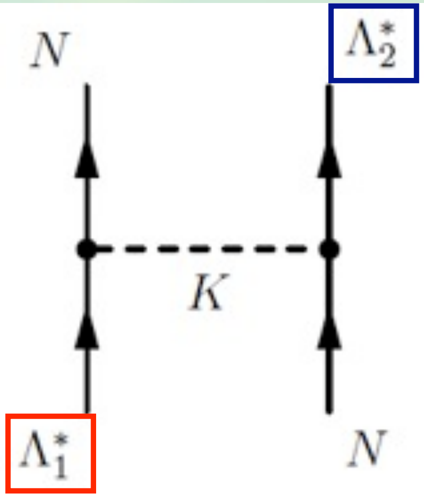

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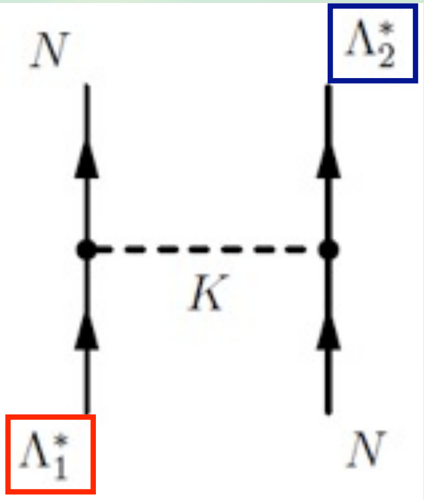
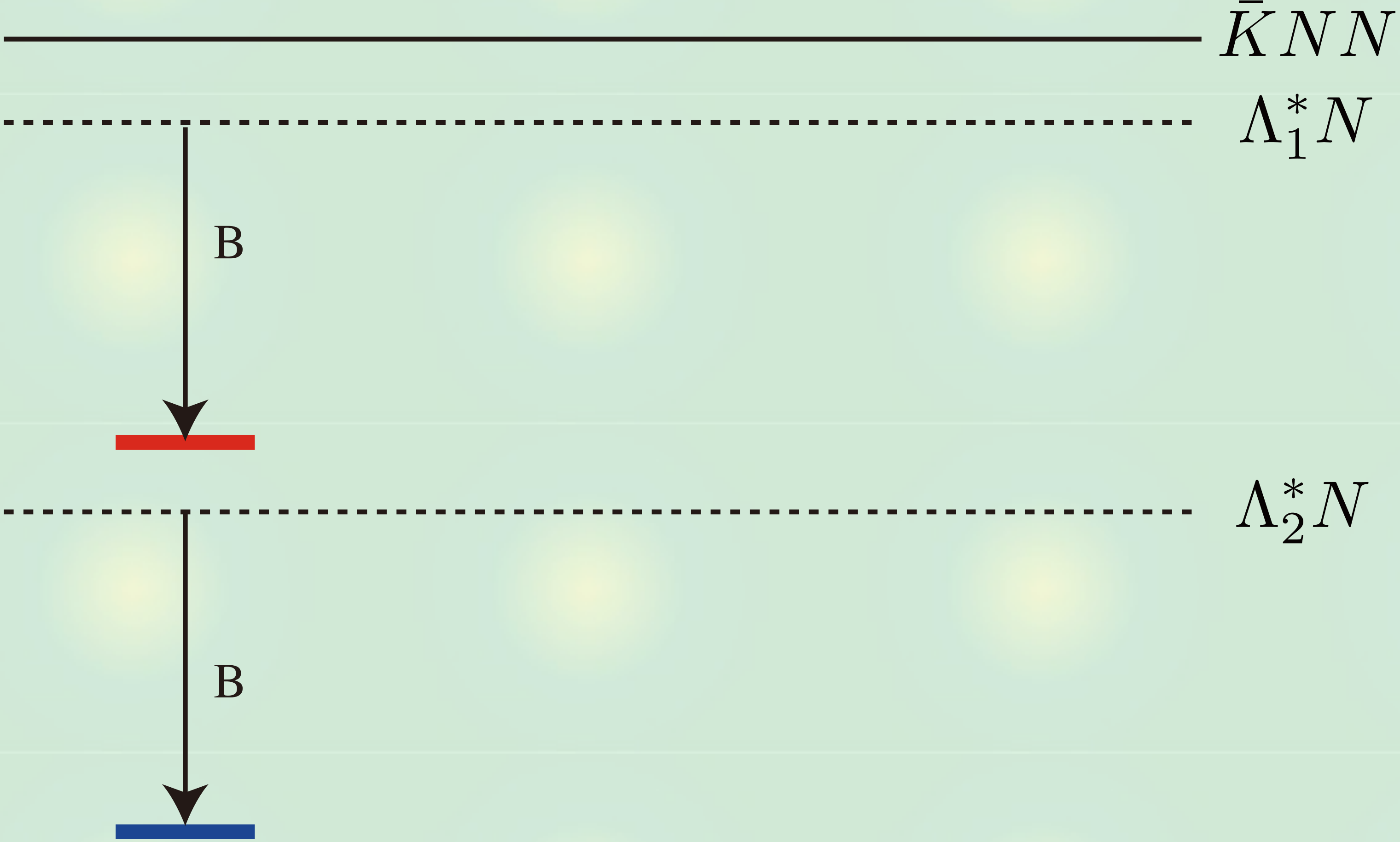


Λ* coupling constant : unknown
We consider this model simulates the thee-body calculation
--> DHW result = Λ^*_1N

Λ*N state in chiral model : result would be...

No mixing



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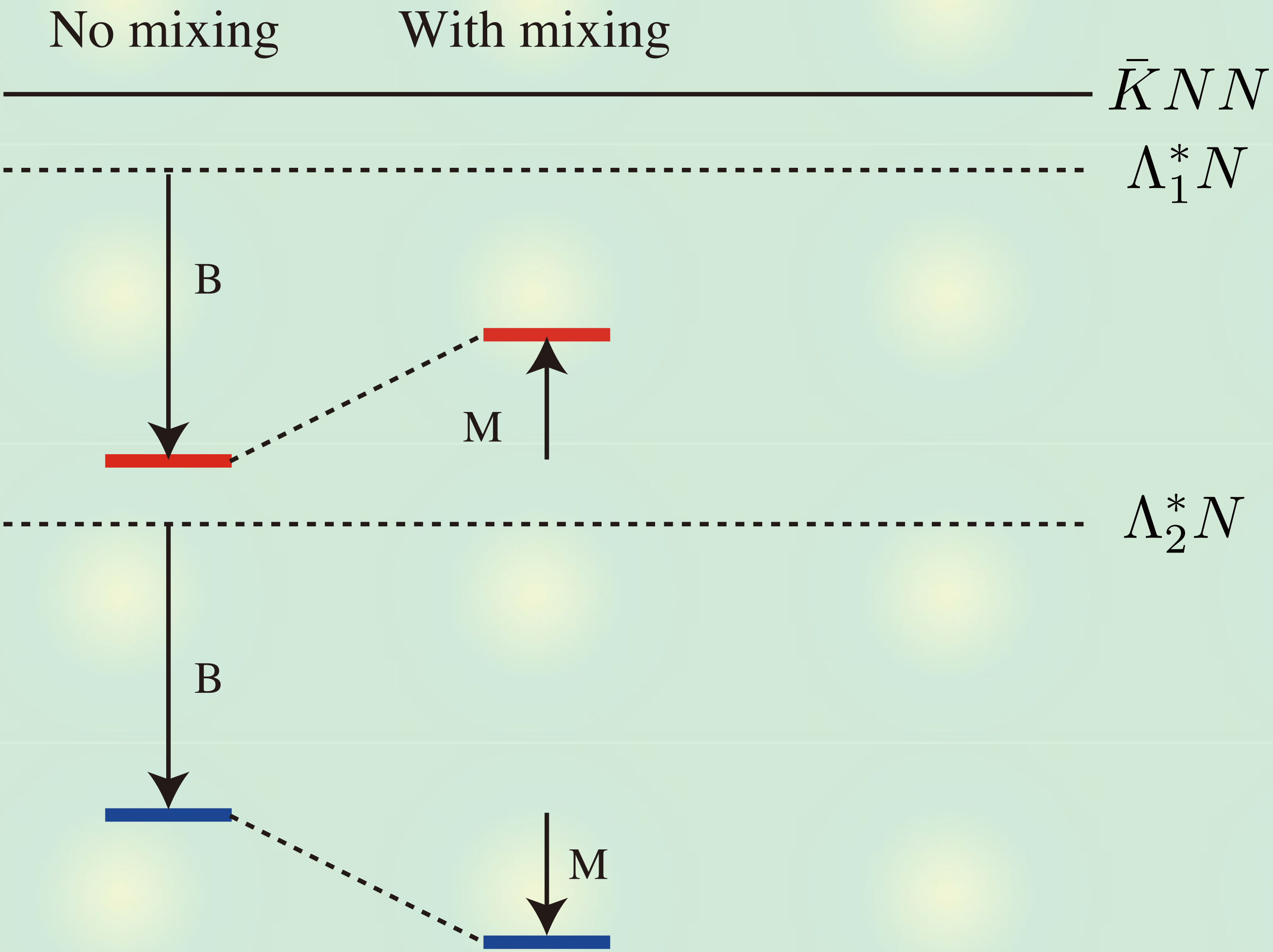


No mixing

With mixing

$\bar{K}NN$

$\Lambda_1^* N$

B

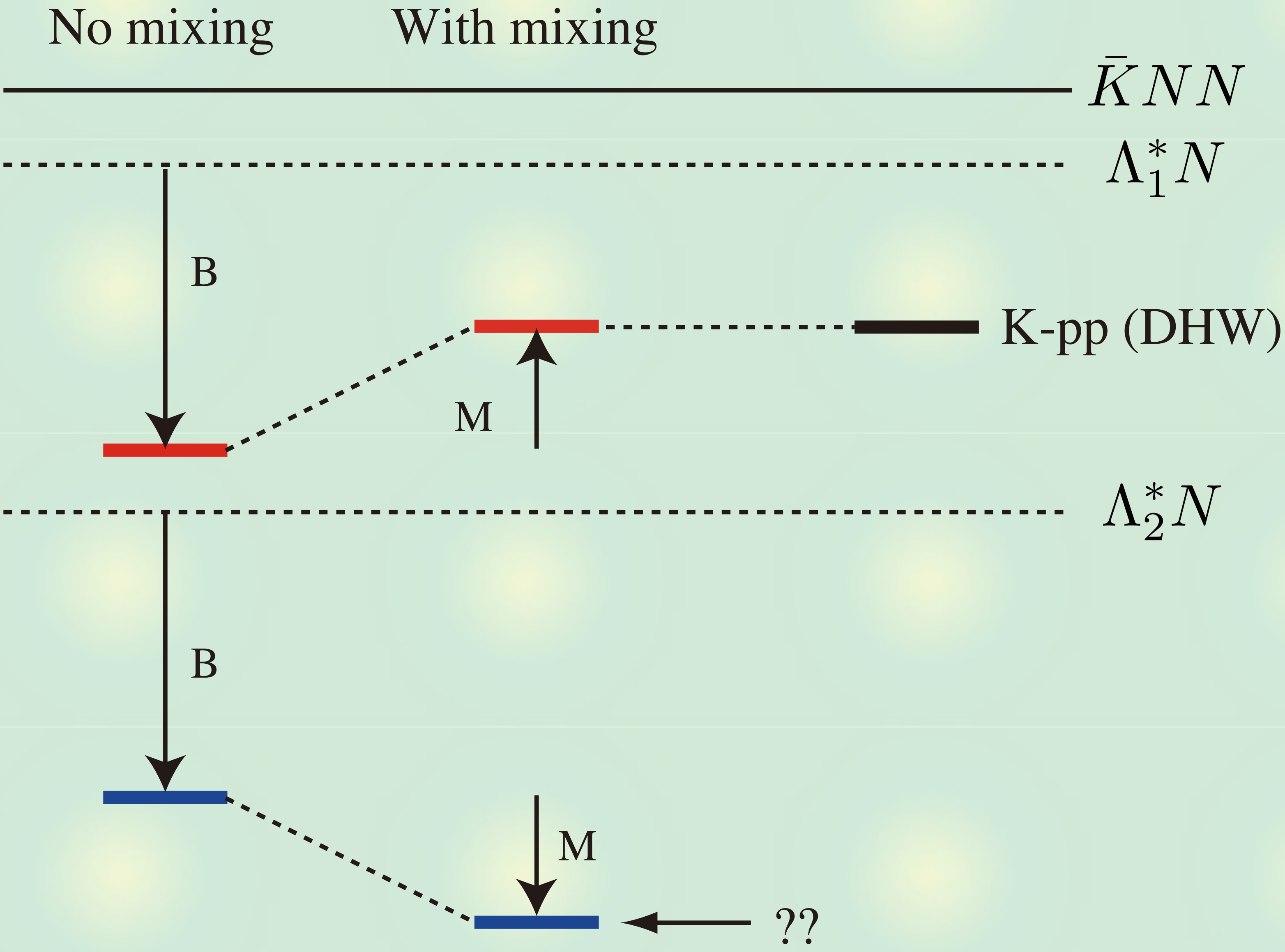
M

$\Lambda_2^* N$

B

M

Λ*N state in chiral model : result would be...



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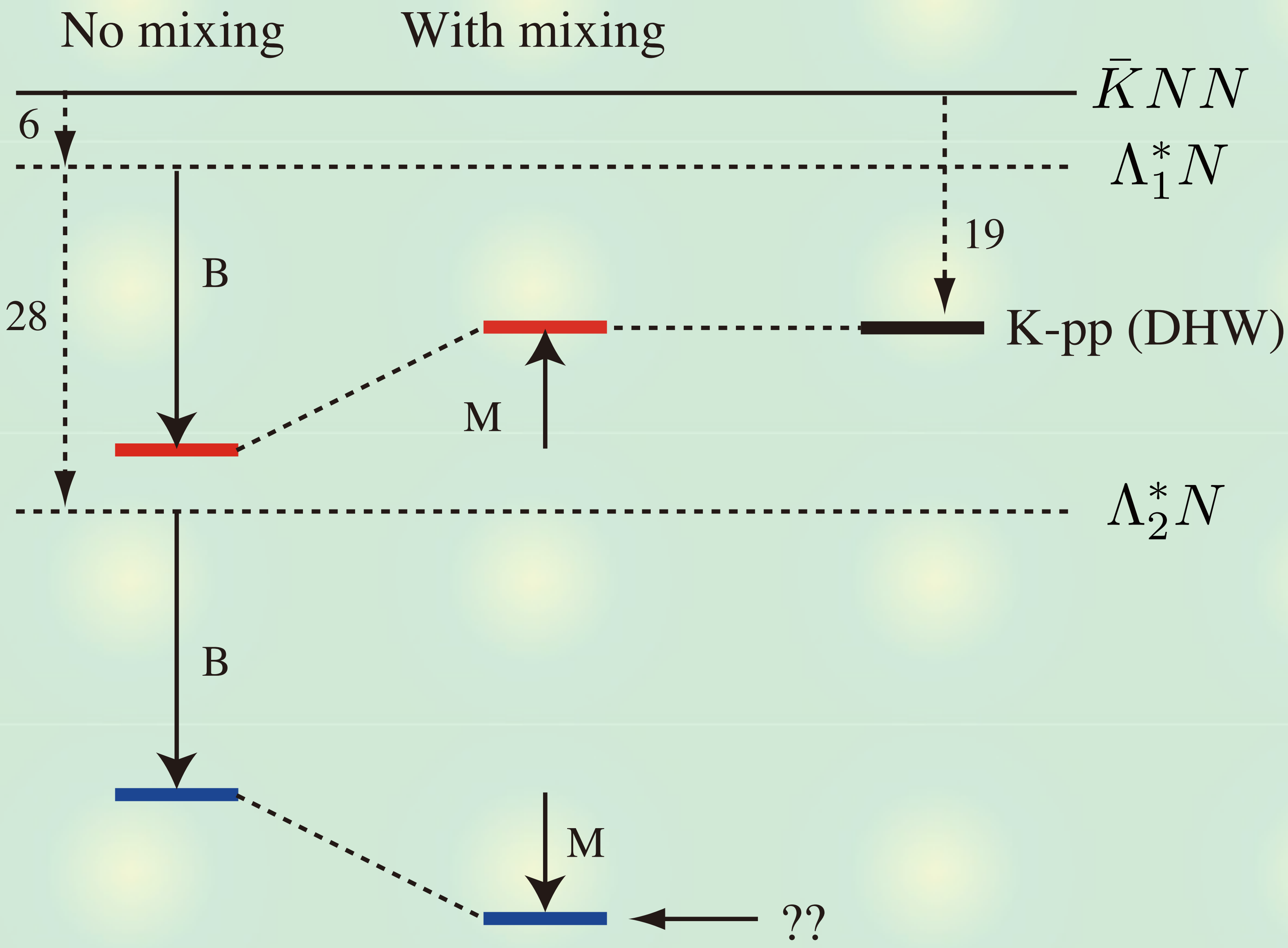

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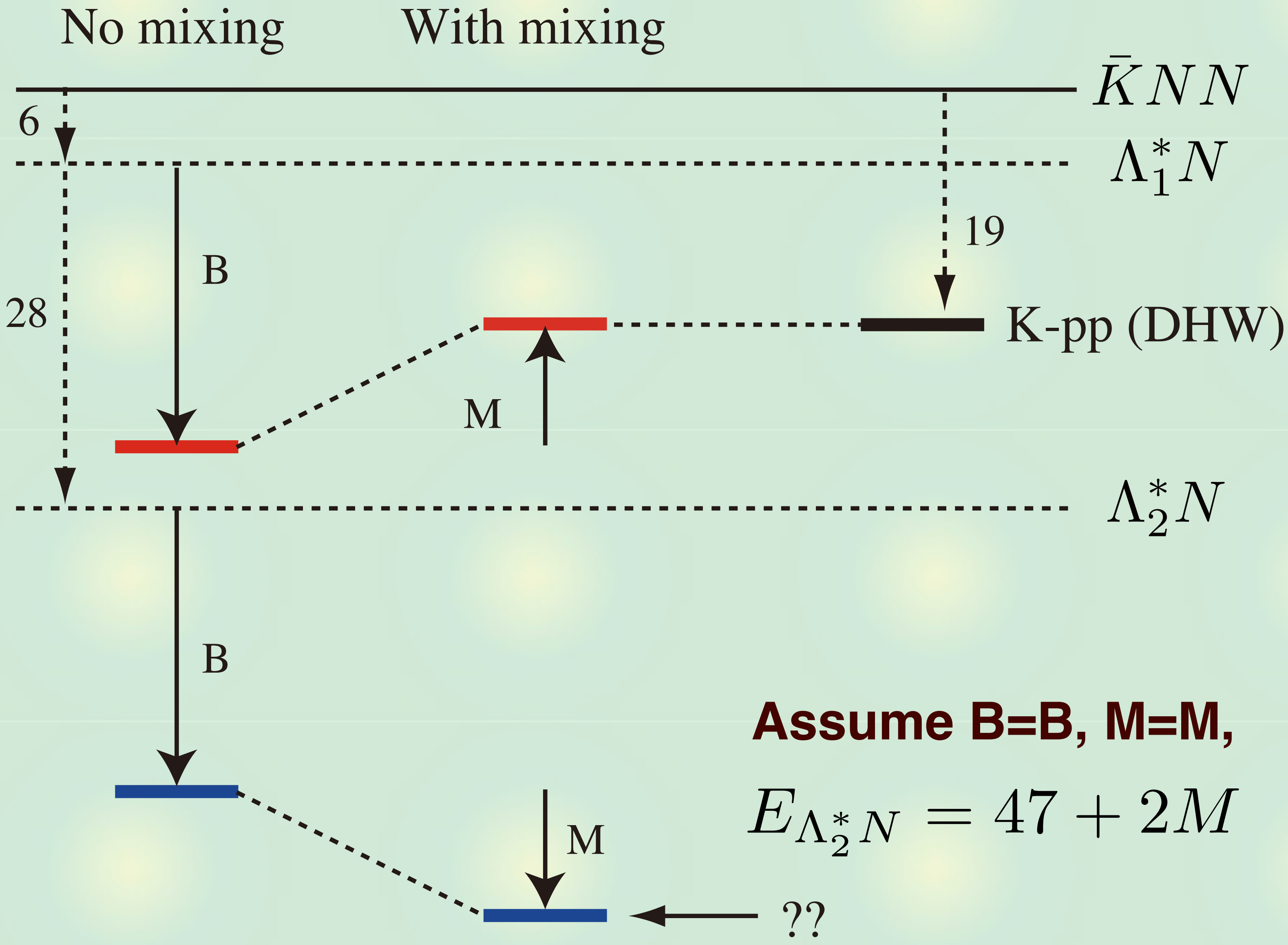

Assume B=B, M=M,

$$E_{\Lambda_2^*N} = 47 + 2M \quad [\mathrm{MeV}]$$

Λ*N state in chiral model

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$$|\Lambda(1405)\rangle = \underbrace{a|\Lambda_1^*\rangle}_{\bar{K}N} + \underbrace{b|\Lambda_2^*\rangle}_{\pi\Sigma}$$

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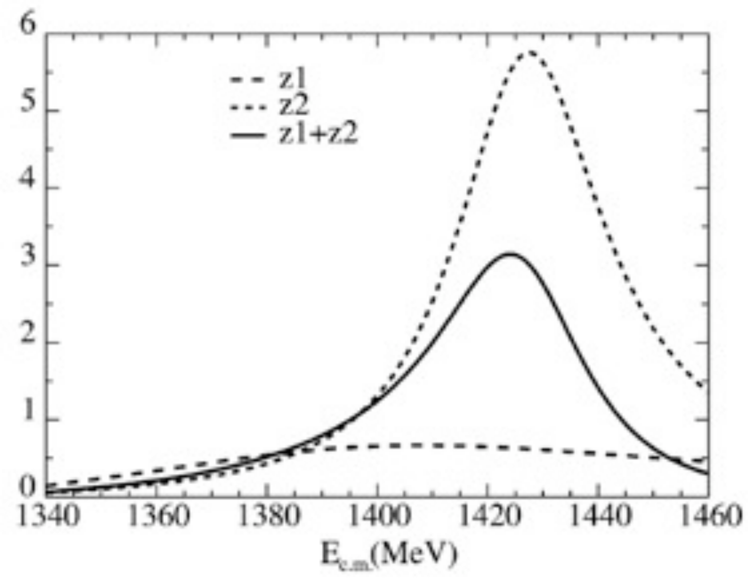
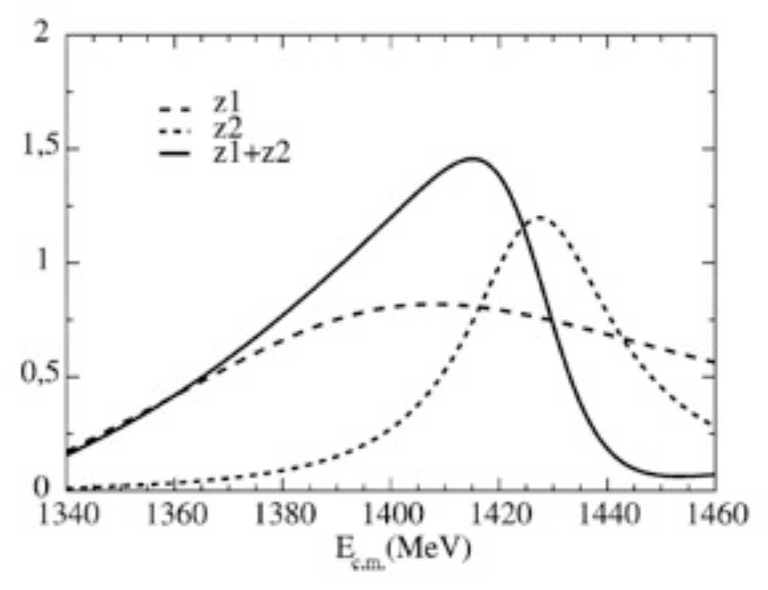
$\bar{K}N$ $\pi\Sigma$





D. Jido, *et al*, Nucl. Phys. Rev. A725, 181 (2003)

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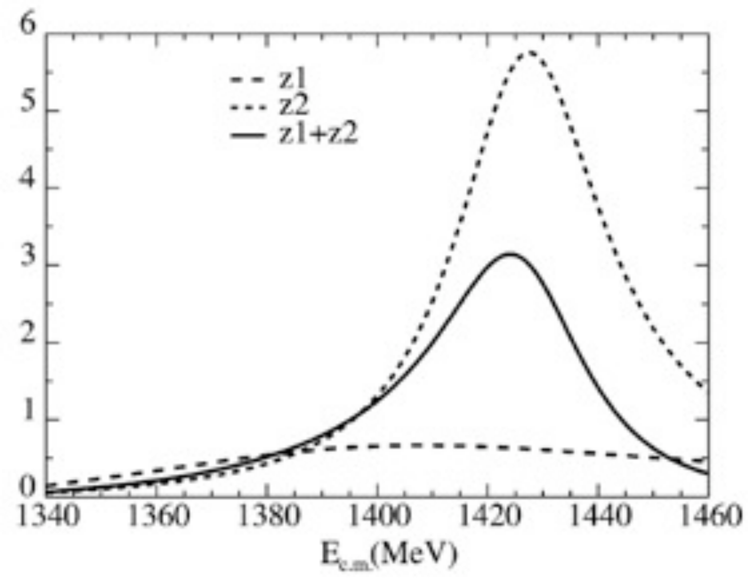
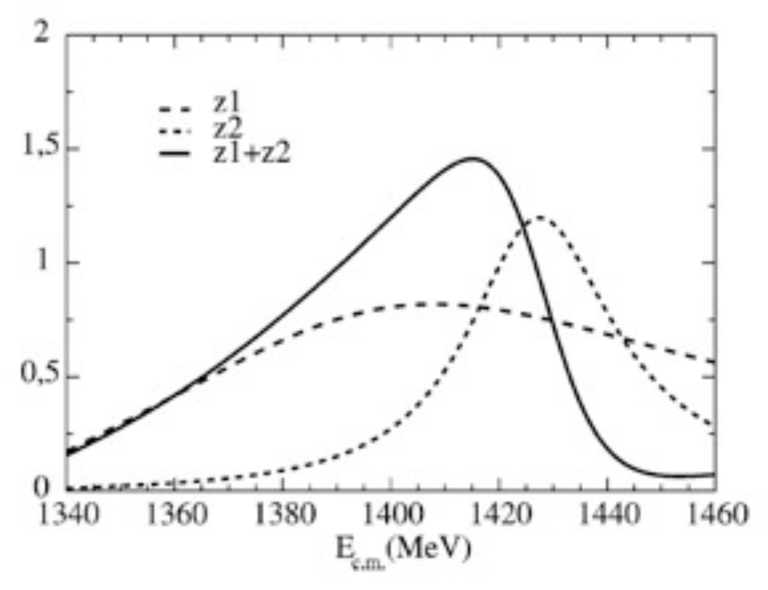
$\bar{K}N$ πΣ





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B=2 system : Λ^*_1N, Λ^*_2N

$$|B=2, S=-1\rangle = a'|\Lambda^*_1 N\rangle + b'|\Lambda^*_2 N\rangle$$

Summary 3 : $\bar{K}NN$ system

B=2 and S=-1 system in chiral dynamics

- Possibility of two poles for three-body $\bar{K}NN$ state in Faddeev approach.

  Y. Ikeda, RCNP workshop, Dec. 25, 2008

- If this is the case, DHW result may corresponds to higher energy $\Lambda^*_1 N$ state.

  estimate of $\Lambda^*_2 N$ ~ 47 + 2M MeV?

  T. Uchino, T. Hyodo, M. Oka, in preparation

- When the lower energy channel is strongly interacting, coupled-channel approach would be mandatory.