$\bar{K}N$相互作用と$\Lambda(1405)$

Tetsuo Hyodo,

Tokyo Institute of Technology

supported by Global Center of Excellence Program
"Nanoscience and Quantum Physics"

2012, Nov. 30th

$\bar{K}$ meson and $\bar{K}N$ interaction

Two aspects of $K(\bar{K})$ meson

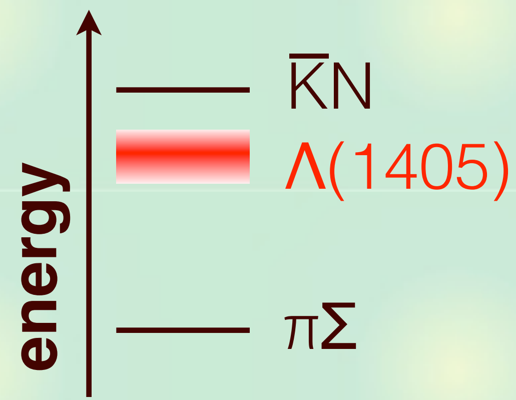
- **NG boson of chiral $SU(3)_R \otimes SU(3)_L$ --> $SU(3)_V$**
- **relatively heavy mass: m_K ~ 496 MeV**

--> peculiar role in hadron physics

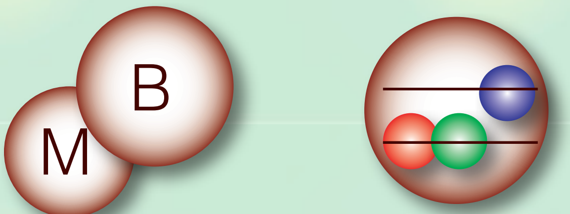
$\bar{K}N$ interaction ...

- **is coupled with $\pi\Sigma$ channel**
- **has a resonance below threshold**

--> $\Lambda(1405)$



meson-baryon v.s. qqq state, ...



- **fundamental building block for $\bar{K}$-nuclei, $\bar{K}$ in medium, ...**

T. Hyodo, D. Jido, Prog. Part. Nucl. Phys. 67, 55 (2012)

$\bar{K}$ nuclei v.s. normal nuclei

$\bar{K}N$ interaction

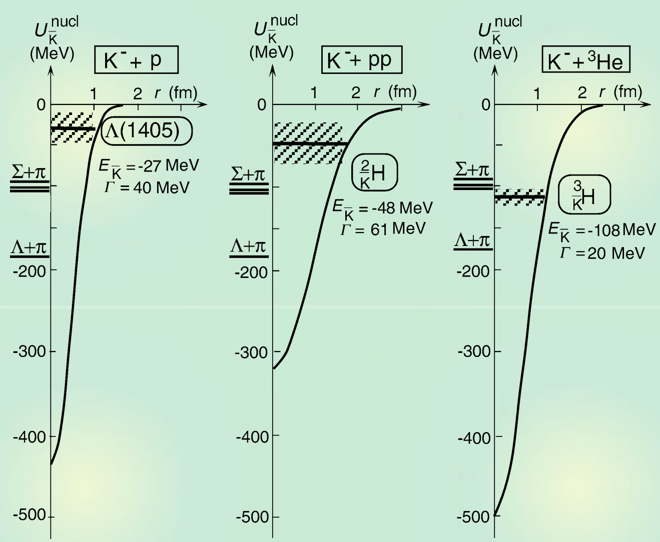
- **strong attraction**
- **no repulsive core?**

	I=0	I=1
NN	**deuteron (2 MeV)**	**attractive**
$\bar{K}N$	$\Lambda(1405)$ **(15-30 MeV)**	**attractive**

--> (quasi-)bound $\bar{K}$ in nuclei

Y. Nogami, Phys. Lett. 7, 288, (1963)

T. Yamazaki, Y. Akaishi, Phys. Lett. B535, 70 (2002)



--> we need realistic $\bar{K}N$ interaction!

Constraints for $\bar{K}N$ interaction

K-p **total cross sections to** K-p, $\bar{K}^0$n, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\pi^0\Sigma^0$, $\pi^0\Lambda$.

- **old experiments, large error bars, some contradictions**
- **wide energy range above the threshold**

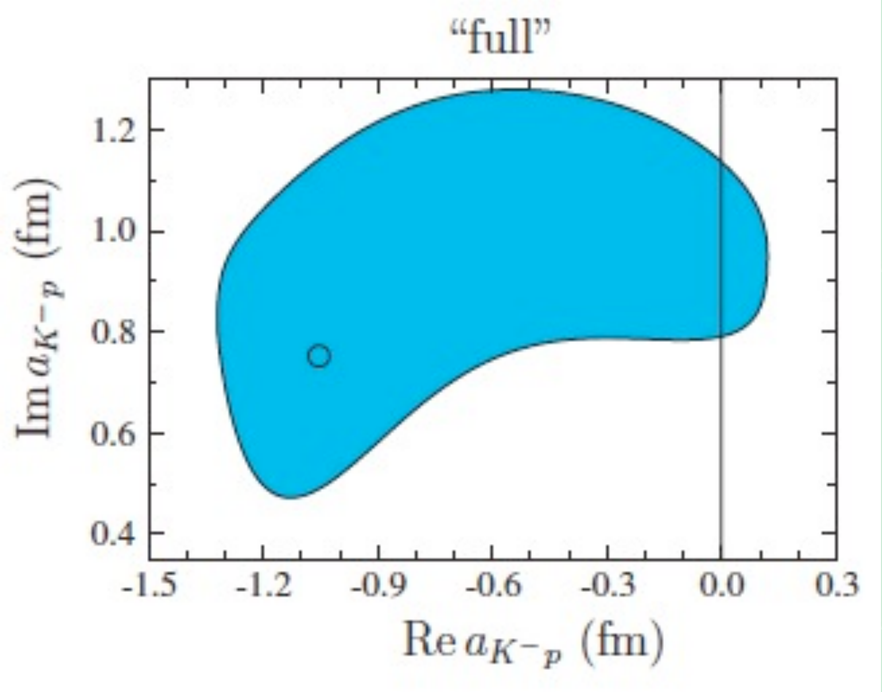
Threshold branching ratios

- **very accurate**
- **only at** $W = m_{K^-} + M_p$

$$\gamma = \frac{\Gamma(K^-p \to \pi^+\Sigma^-)}{\Gamma(K^-p \to \pi^-\Sigma^+)} = 2.36 \pm 0.04,$$

$$R_c = \frac{\Gamma(K^-p \to \text{charged})}{\Gamma(K^-p \to \text{all})} = 0.664 \pm 0.011,$$

$$R_n = \frac{\Gamma(K^-p \to \pi^0\Lambda)}{\Gamma(K^-p \to \text{neutral})} = 0.189 \pm 0.015,$$



Determination of the scattering length by these constraints

B. Borasoy, U.G. Meissner, R. Nissler, Phys. Rev. C 74, 055201 (2006)

--> large uncertainty!

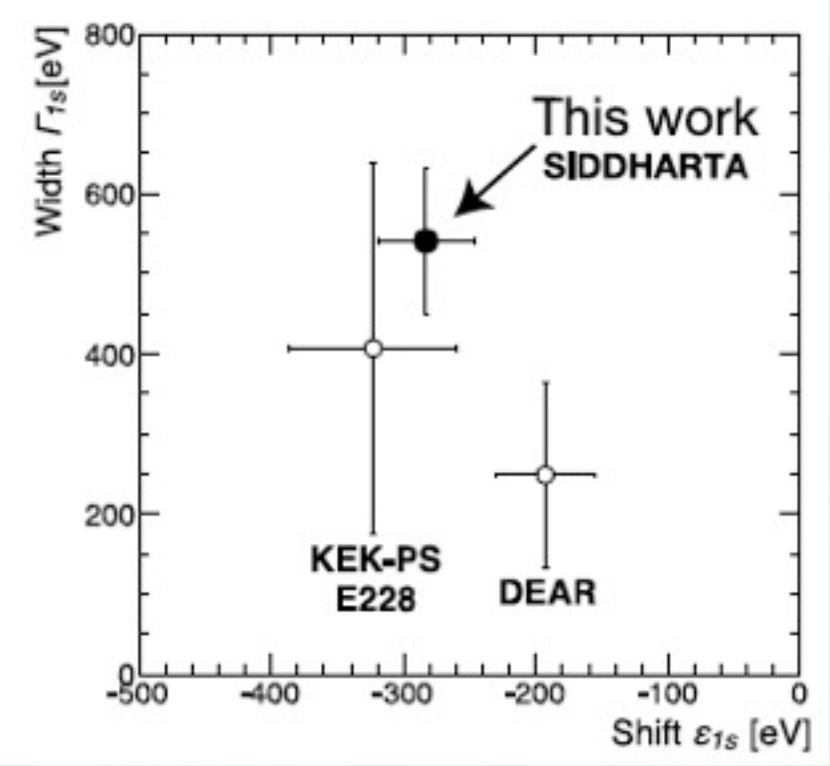
SIDDHARTA measurement

Measurements of the kaonic hydrogen

- **shift** and **width** of atomic state <--> K-p scattering length

- **SIDDHARTA experiment**

M. Bazzi, *et al.*, Phys. Lett. B704, 113 (2011)



--> New constraint on the $\bar{K}N$ interaction

Contents

Chiral unitary approach

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

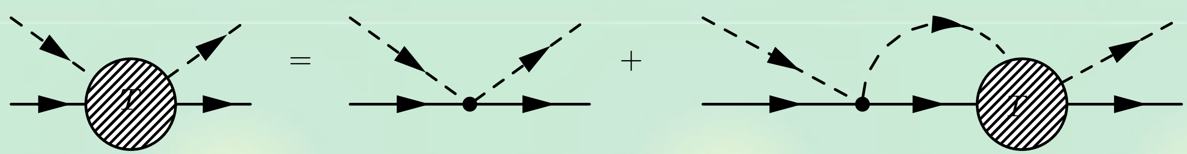
- Interaction <-- chiral symmetry

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

- Amplitude <-- unitarity in coupled channels

R.H. Dalitz, T.C. Wong, G. Rajasekaran, Phys. Rev. 153, 1617 (1967)

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



chiral

cutoff

(c.f. Chiral EFT for nuclear force)

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

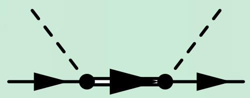
It works successfully in various hadron scatterings.

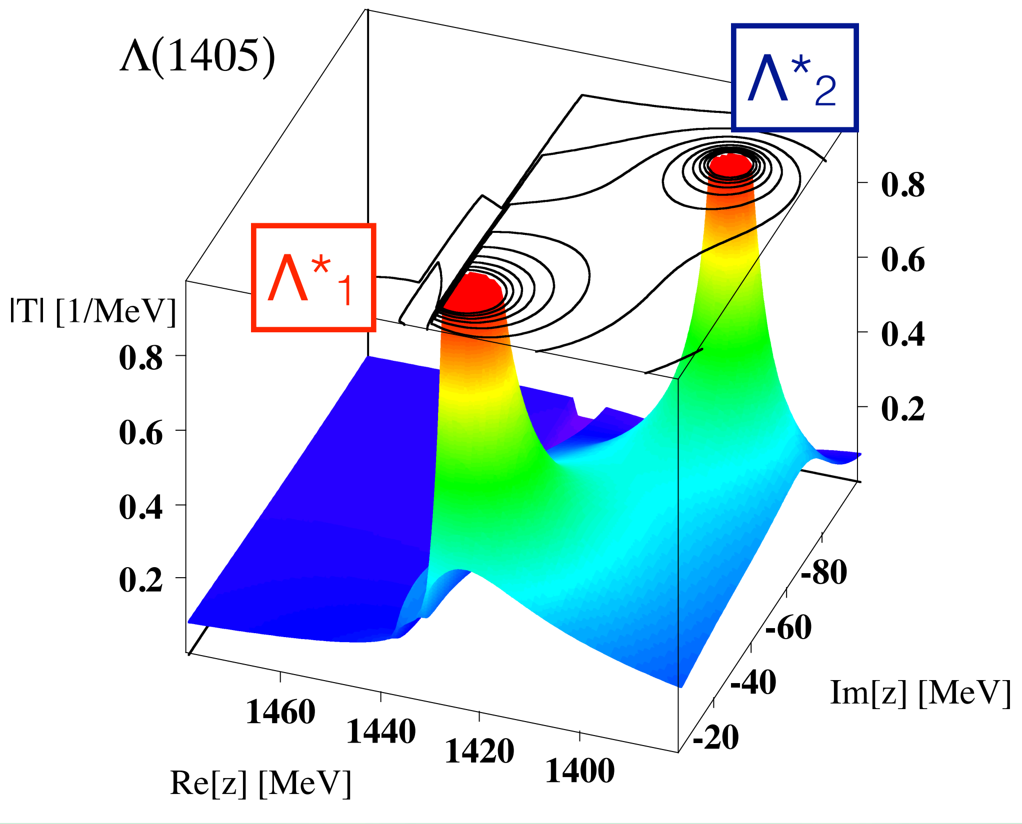
Pole structure in the complex energy plane

Resonance state ~ pole of the scattering amplitude

D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, Nucl. Phys. A723, 205 (2003)

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

$\sim$ 



T. Hyodo, D. Jido, PPNP 67, 55 (2012)

Two poles for one resonance (bump structure)

--> Superposition of two states ?

Coupling properties:

Λ^*_1 ~ $\bar{K}N$ channel, Λ^*_2 ~ πΣ channel

Origin of the two-pole structure

Leading order chiral interaction for K̄N-πΣ channel

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

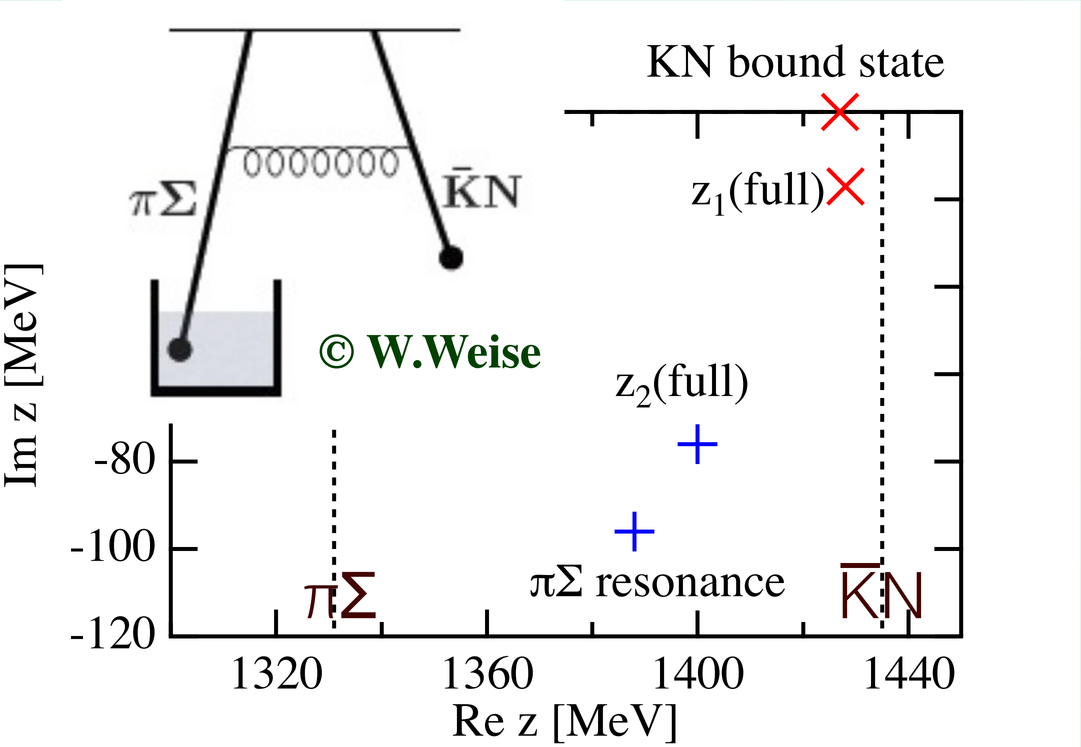
$$V_{ij} = -C_{ij}\frac{\omega_i + \omega_j}{4f^2}$$

$$\begin{array}{ccc} & \bar{K}N & \pi\Sigma \\ C_{ij} = & \left(\begin{array}{c} 3 \\ -\sqrt{\frac{3}{2}} \end{array}\right. & \left.\begin{array}{c} -\sqrt{\frac{3}{2}} \\ 4 \end{array}\right) \end{array}$$

at threshold

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

$$\Rightarrow V_{\bar{K}N} \sim 2.5 V_{\pi\Sigma}$$



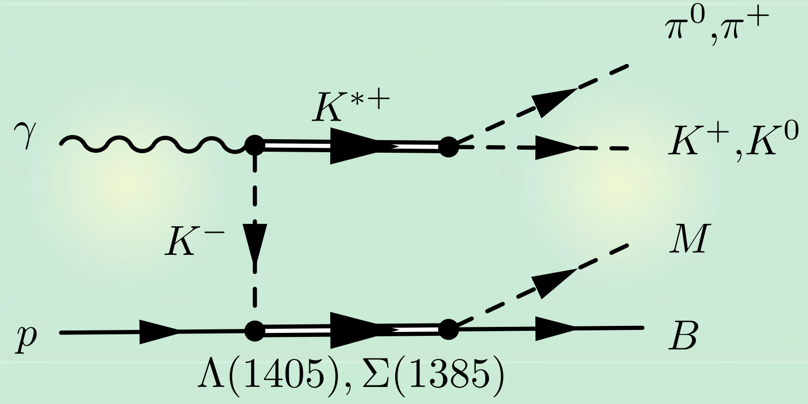
Very strong attraction in K̄N (higher energy) --> bound state
Strong attraction in πΣ (lower energy) --> resonance

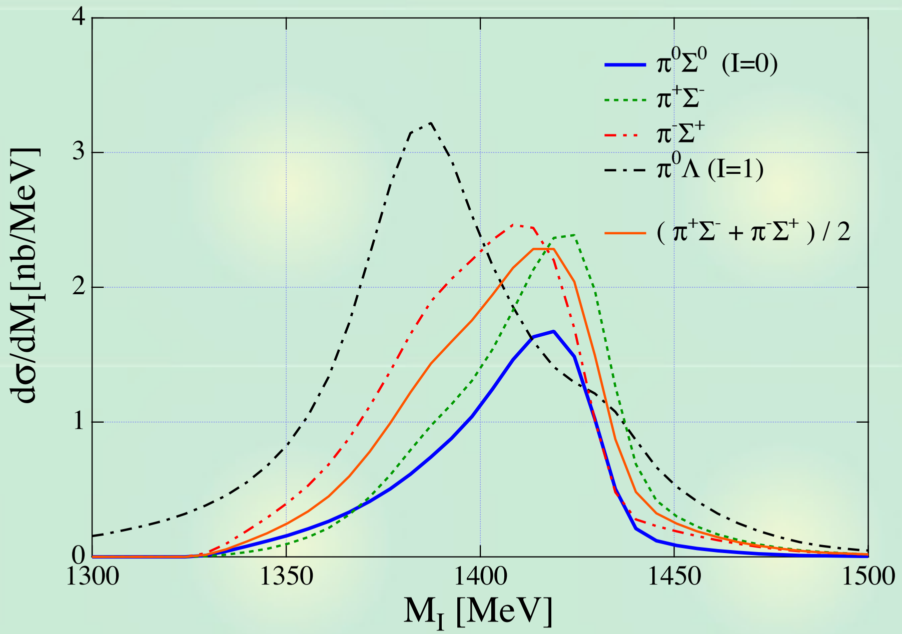
Model dependence? Effects from higher order terms?

K* photoproduction of Λ(1405)

How can we isolate one of the poles?

T. Hyodo, A. Hosaka, E. Oset, M.J. Vicente Vacas, Phys. Lett. B593, 75 (2004)





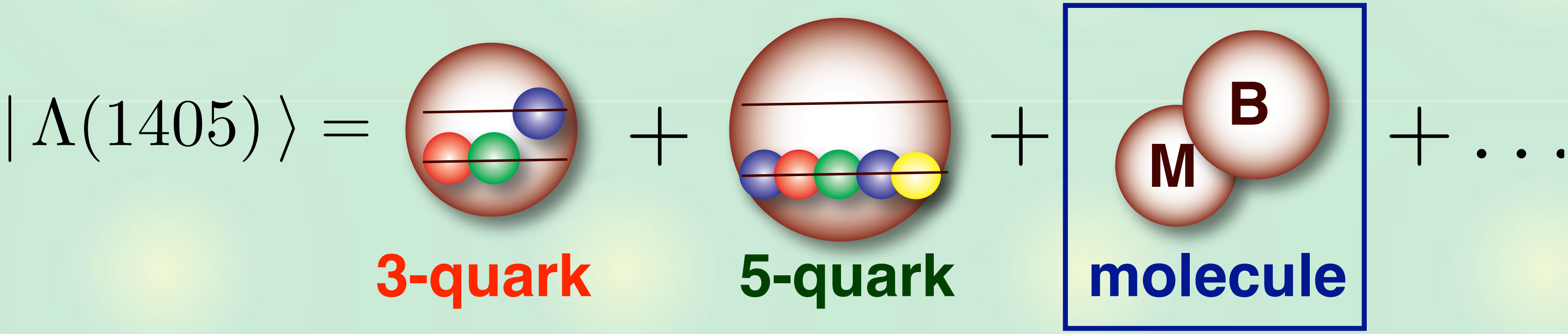
P_{lab} = 2.5 GeV, W ~ 2.35 GeV

γ polarization + K* decay --> parity of exchanged particle

K exchange picks up Λ^*_1 ($\bar{K}$N bound state)

Meson-baryon molecule strucure of Λ(1405)

What is the structure of Λ(1405)?



- **Natural renormalization condition**
  T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C 78, 025203 (2008)

- **Nc (number of colors) scaling behavior**
  T. Hyodo, D. Jido, L. Roca, Phys. Rev. D 77, 056010 (2008);
  L. Roca, T. Hyodo, D. Jido, Nucl. Phys. A809, 65 (2008)

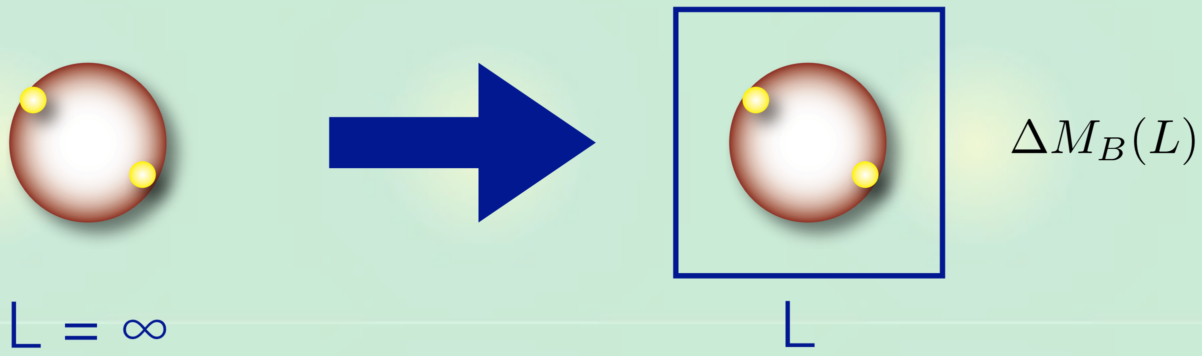
- **Electromagnetic radii/form factors**
  T. Sekihara, T. Hyodo, D. Jido, Phys. Lett. B669, 133 (2008);
  T. Sekihara, T. Hyodo, D. Jido, Phys. Rev. C 83, 055202 (2012)

--> Dominance of the molecule component
radius: complex number? (pole on the complex plane)

Size measurement of resonances

Finite volume mass shift <--> Coupling to scattering state g^2

M. Lüscher, Commun. Math. Phys. 104, 177 (1986)



g^2 **<--> compositeness <--> spatial size**

T. Sekihara, T. Hyodo, arXiv:1209.0577 [nucl-th]

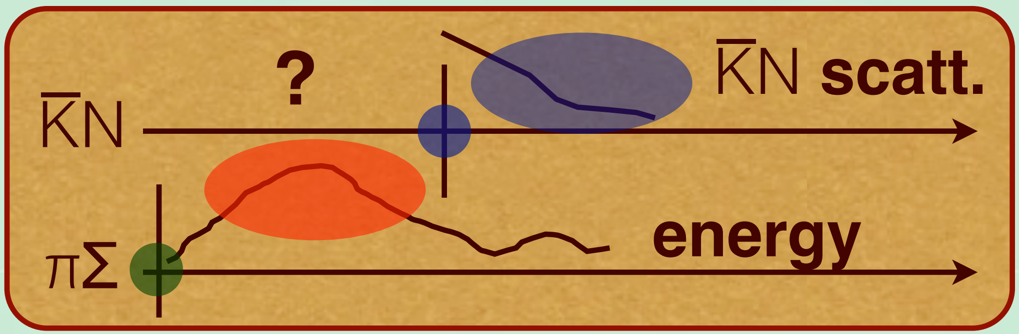
- **The relation is confirmed for bound states.**
- **Real-valued size can be defined for resonances.**
- $\bar{K}N$ **component of** $\Lambda(1405)$**:** 1.8-1.9 **fm.**

This supports the quasi-bound $\bar{K}N$ **picture of** $\Lambda(1405)$**.**

Experimental constraints for S=-1 MB scattering

K-p **total cross sections**

$\bar{K}N$ **threshold branching ratios,** K-p **scattering length**



$\pi\Sigma$ **mass spectra**

- **New data is becoming available (LEPS, CLAS, HADES,...)**
- **No model-independent way to relate two-body amplitude.**
- **Consistency of the result should be checked.**

$\pi\Sigma$ **scattering length (no data at present)**

Y. Ikeda, T. Hyodo, D. Jido, H. Kamano, T. Sato, K. Yazaki, PTP 125, 1205 (2011);
T. Hyodo, M. Oka, Phys. Rev. C 83, 055202 (2011)

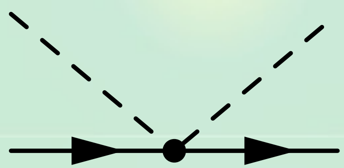
Construction of the realistic amplitude

Systematic $\chi 2$ fitting with SIDDHARTA data

Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B706, 63 (2011); Nucl. Phys. A881 98 (2012);

- Interaction kernel: NLO ChPT

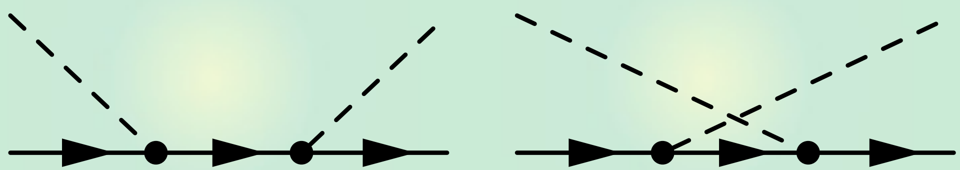
1) TW term



$\mathcal{O}(p)$

TW model

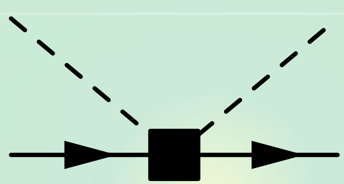
2) Born terms



$\mathcal{O}(p)$

TWB model

3) NLO terms



$\mathcal{O}(p^2)$

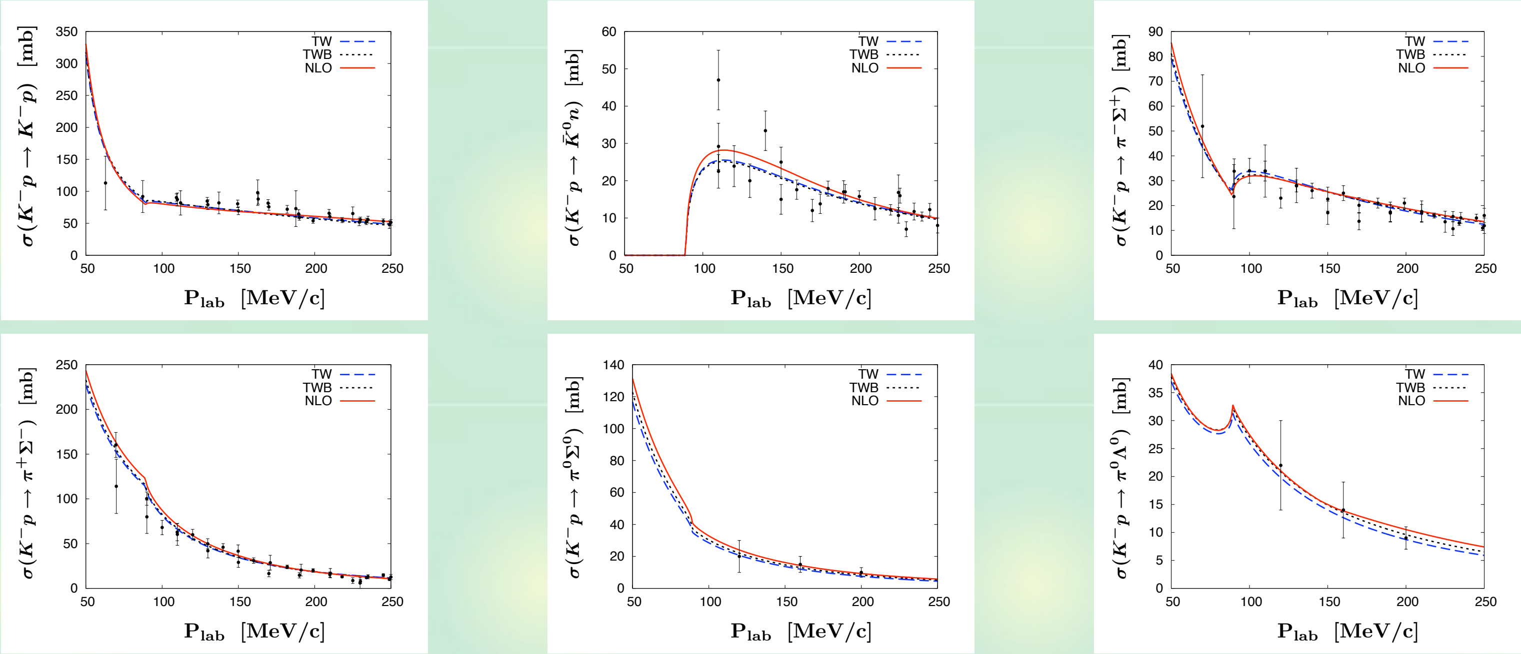
NLO model

Parameters: 6 cutoffs (+ 7 low energy constants in NLO)

Best-fit results

		TW	TWB	NLO	Experiment	
K-p	ΔE [eV]	373	377	306	$283 \pm 36 \pm 6$	[7]
	Γ [eV]	495	514	591	$541 \pm 89 \pm 22$	[7]
BR	γ	2.36	2.36	2.37	2.36 ± 0.04	[8]
	R_n	0.20	0.19	0.19	0.189 ± 0.015	[8]
	R_c	0.66	0.66	0.66	0.664 ± 0.011	[8]
	χ^2/d.o.f	1.12	1.15	0.96		
	pole positions [MeV]	$1422 - 16i$	$1421 - 17i$	$1424 - 26i$		
		$1384 - 90i$	$1385 - 105i$	$1381 - 81i$		

cross sections

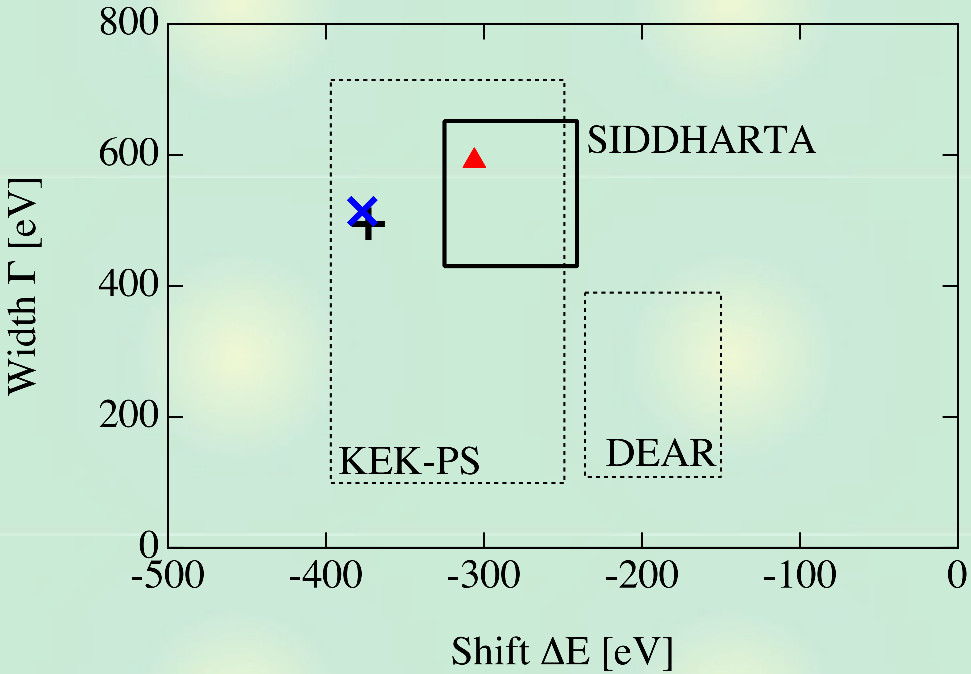


Good χ2: SIDDHARTA is consistent with cross sections

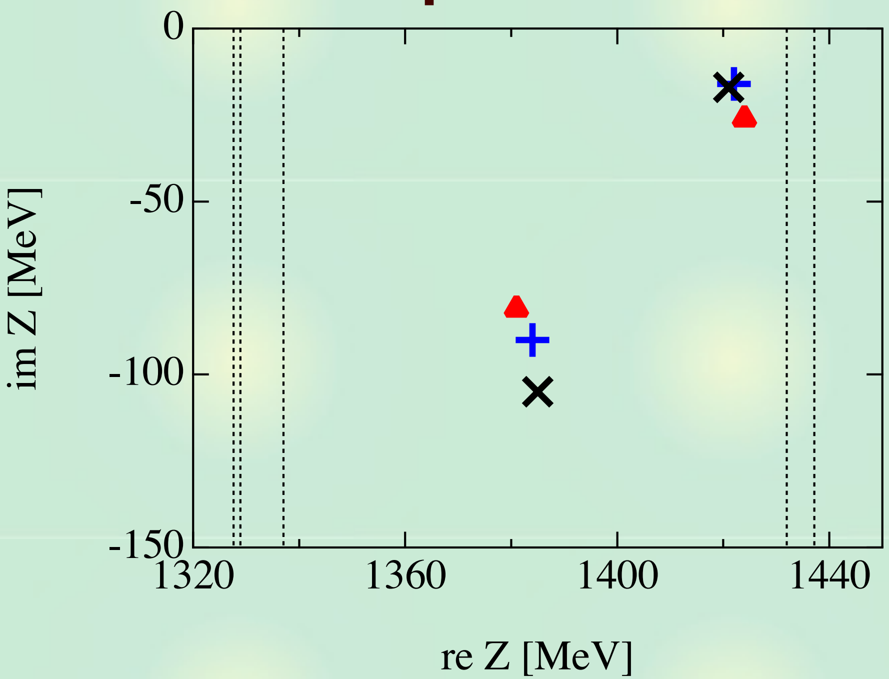
Shift, width, and pole positions

	TW	TWB	NLO
$\chi 2$/d.o.f.	1.12	1.15	0.957

Shift and width



Pole positions



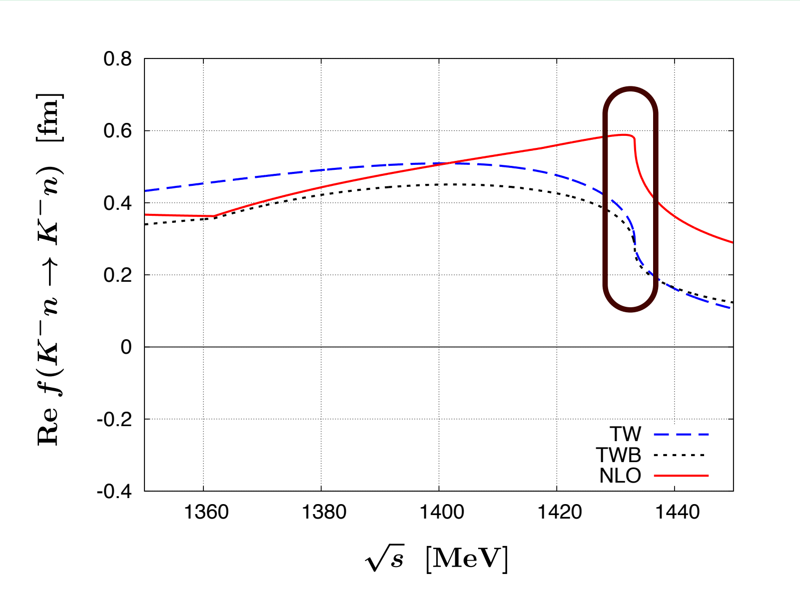
TW and TWB are reasonable, while best-fit requires NLO.
Pole positions are now converging.

Remaining ambiguity

For K-**nucleon interaction, we need both** K-p **and** K-n**.**

$$a(K^-p) = \frac{1}{2}a(I=0) + \frac{1}{2}a(I=1) + \dots, \quad a(K^-n) = a(I=1) + \dots$$

$$a(K^-n) = 0.29 + i0.76 \text{ fm} \quad (\text{TW}) \quad ,$$
$$a(K^-n) = 0.27 + i0.74 \text{ fm} \quad (\text{TWB}) \quad ,$$
$$a(K^-n) = 0.57 + i0.73 \text{ fm} \quad (\text{NLO}) \quad .$$



Some deviation: constraint on K-n**? (<-- kaonic deuterium?)**

J=0 $\bar{K}NN$ system

Theoretical calculations of $\bar{K}NN$ system (~ K^-pp)

	SGM07	IS07	YA07	DHW09	IKS10*	BGL12
Method	Fadd.	Fadd.	Var.	Var.	Fadd.	Var.
$\bar{K}N$ int.	E-indep	E-indep	E-indep	E-dep	E-dep	E-dep
$B_{\bar{K}NN}$ [MeV]	55-70	60-95	48	17-23	9-16	15.7
$\Gamma_{\pi YN}$ [MeV]	90-110	45-80	61	40-70	34-46	41.2

N.V. Shevchenko, A. Gal, J. Mares, Phys. Rev. Lett. 98, 082301 (2007),
Y. Ikeda, T. Sato, Phys. Rev. C76, 035203 (2007),
T. Yamazaki, Y. Akaishi, Phys. Rev. C76, 045201 (2007),
A. Dote, T. Hyodo, W. Weise, Phys. Rev. C79, 014003 (2009),
Y. Ikeda, Kamano, T. Sato, Prog. Thoer. Phys. 124, 533 (2010),
* there is another pole at B = 67-89 MeV with large width.
N. Barnea, A. Gal, E.Z. Liverts, Phys. Lett. B712 (2012)

$\bar{K}NN$ system forms a quasi-bound state with large width.

Comparison of K-p scattering length

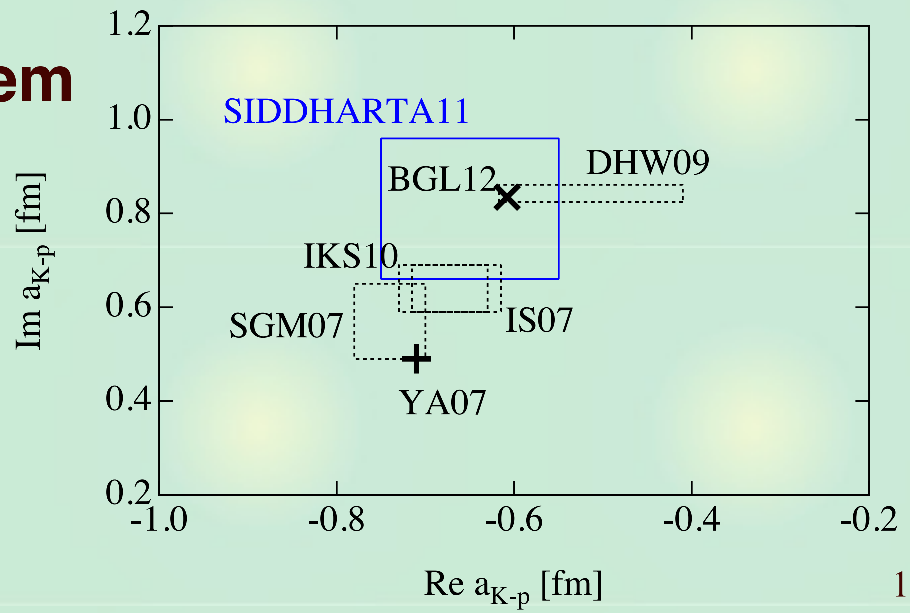
Theoretical calculations of $\bar{K}NN$ system (~ K-pp)

	SGM07	IS07	YA07	DHW09	IKS10	BGL12
Method	Fadd.	Fadd.	Var.	Var.	Fadd.	Var.
$\bar{K}N$ int.	E-indep	E-indep	E-indep	E-dep	E-dep	E-dep
$B_{\bar{K}NN}$ [MeV]	55-70	60-95	48	17-23	9-16	15.7
$\Gamma_{\pi YN}$ [MeV]	90-110	45-80	61	40-70	34-46	41.2

- New constraint on $\bar{K}NN$ system

- SIDDHARTA11 is obtained by the improved DT formula

- Models: isospin symmetric. Breaking is important at th.



Summary

We study the $\bar{K}N$-$\pi\Sigma$ interaction based on chiral coupled-channel approach.

- $\Lambda(1405)$ **is interpreted as a quasi-bound** $\bar{K}N$ **state in the resonating** $\pi\Sigma$ **continuum.**

- **Accurate** K**-hydrogen data help us to construct realistic** $\bar{K}N$-$\pi\Sigma$ **interaction.**

- **New** $\bar{K}N$ **interaction will reduce uncertainties of** $\bar{K}$ **few-nucleon systems.**