

# Recent developments in antikaon-nucleon dynamics



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

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

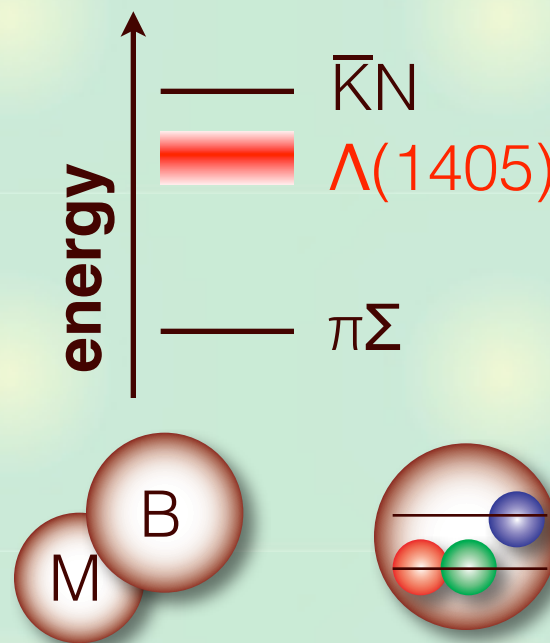
- NG boson of chiral  $SU(3)_R \otimes SU(3)_L \rightarrow SU(3)_V$
- relatively heavy mass:  $m_K \sim 496 \text{ MeV}$
- > peculiar role in hadron physics

## $\bar{K}N$ 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, ...



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

## $\bar{K}N$ interaction

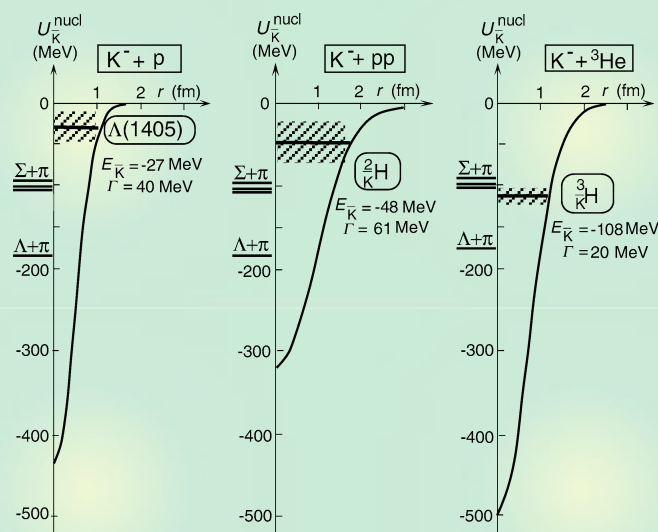
- strong attraction
- no repulsive core?

	$l=0$	$l=1$
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  $K^-p$ ,  $\bar{K}^0n$ ,  $\pi^+\Sigma^-$ ,  $\pi^-\Sigma^+$ ,  $\pi^0\Sigma^0$ ,  $\pi^0\Lambda$ .

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

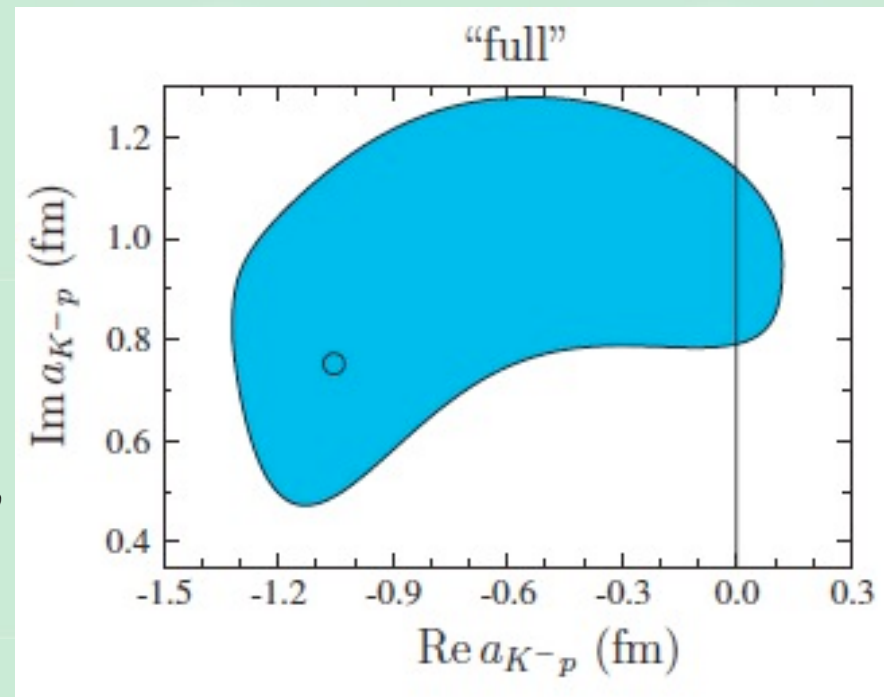
## Threshold branching ratios

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

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

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

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



## Determination of the scattering length by these constraints

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

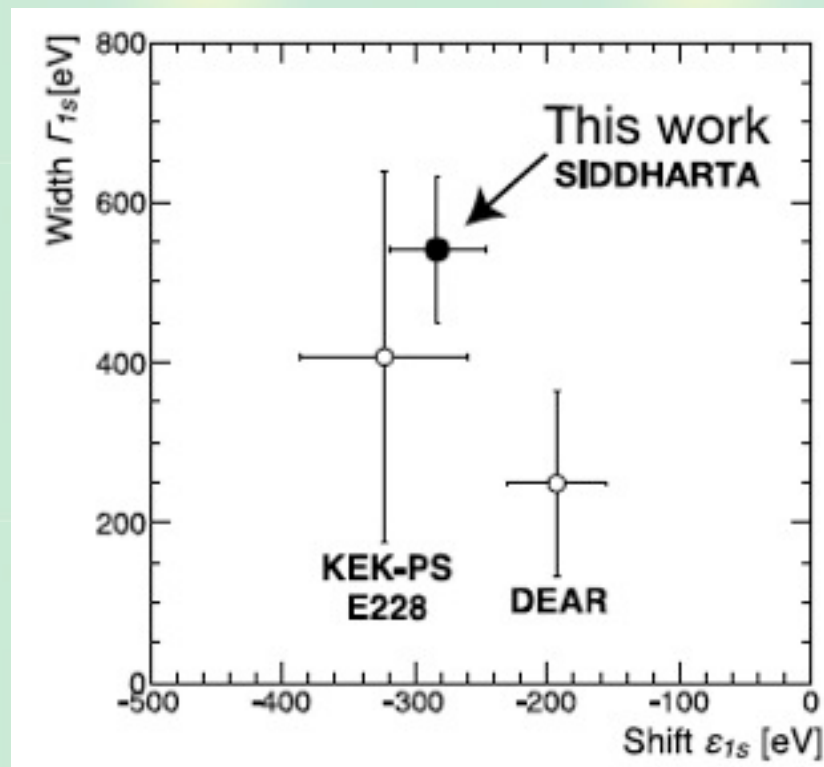
--> **large uncertainty!**

# SIDDHARTA measurement

## Measurements of the kaonic hydrogen

- **shift** and **width** of atomic state  $\leftrightarrow$  K-p scattering length
- **SIDDHARTA** experiment

M. Bazzi, *et al.*, Phys. Lett. B704, 113 (2011); **Talk by C. Curceanu**



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



# Contents



**Introduction**



**1.  $\Lambda(1405)$  in  $\bar{K}N$ - $\pi\Sigma$  scattering**



**2. Realistic  $\bar{K}N$ - $\pi\Sigma$  interaction with SIDDHARTA**



**(3. Applications to few-body systems)**

**Talk by A. Gal**



**Summary**

# 1. $\Lambda(1405)$ in $\bar{K}N$ - $\pi\Sigma$ scattering

## Chiral unitary approach

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

- Interaction  $\leftarrow$  chiral symmetry

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

- Amplitude  $\leftarrow$  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

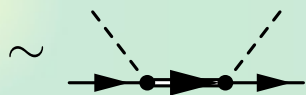
It works successfully in various hadron scatterings.

# Pole structure in the complex energy plane

Resonance state  $\sim$  pole of the scattering amplitude

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

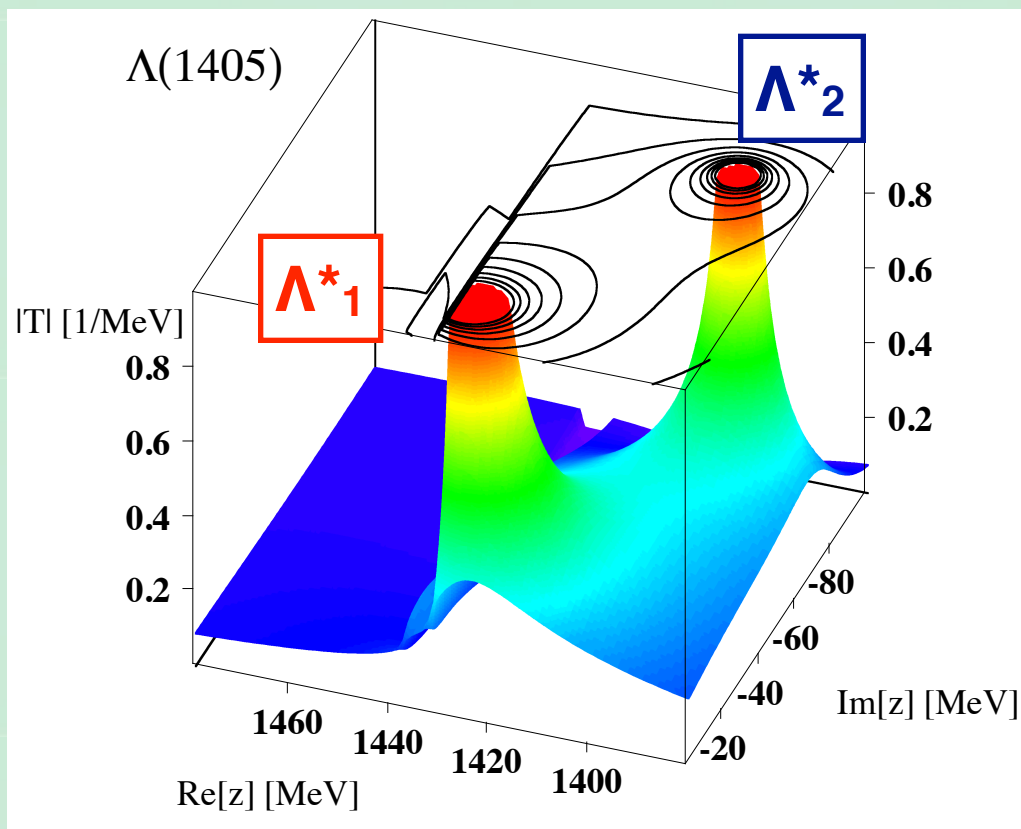
$$T_{ij}(\sqrt{s}) \sim \frac{g_i g_j}{\sqrt{s} - M_R + i\Gamma_R/2}$$



**Two poles for one resonance (bump structure)**  
**--> Superposition of two states ?**

**Different  $\pi\Sigma$  spectra?**

**K-d -->  $\pi\Sigma N$  reaction**



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

Exp.: O. Braun, et al., Nucl. Phys. B129, 715 (1977); J-PARC E31.

Theor.: D. Jido, E. Oset, T. Sekihara, Eur. Phys. J. A42, 257 (2009); A47, 42 (2011)



# Origin of the two-pole structure

## Leading order chiral interaction for $\bar{K}N$ - $\pi\Sigma$ channel

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

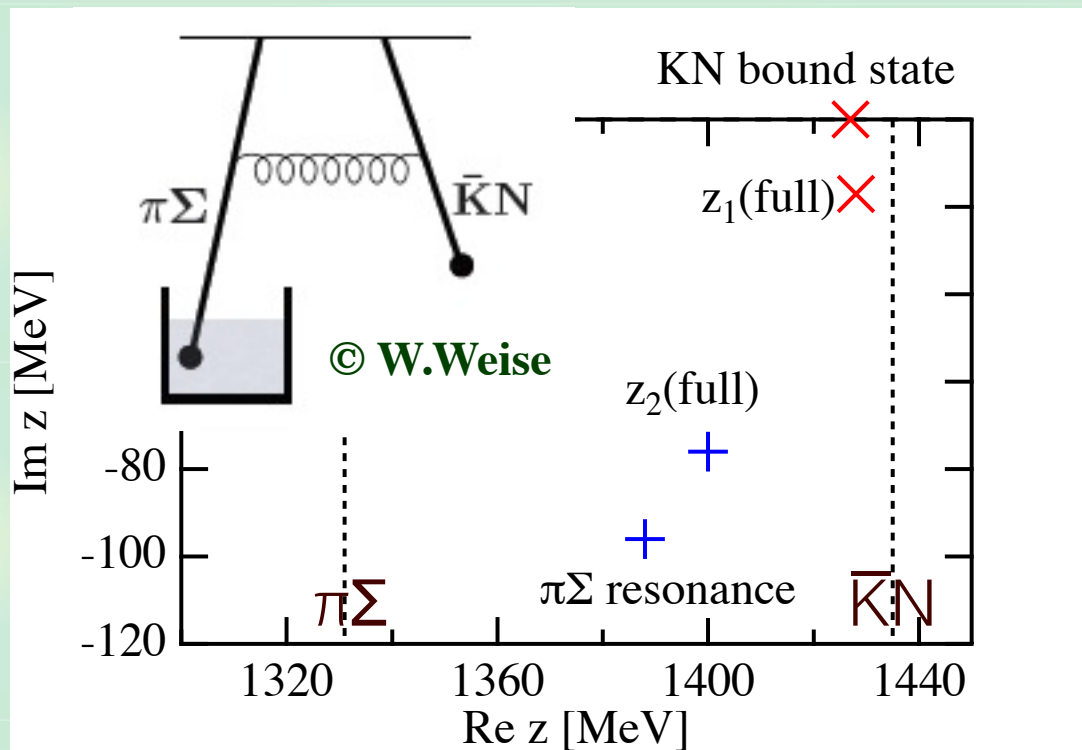
$$V_{ij} = -C_{ij} \frac{\omega_i + \omega_j}{4f^2}$$

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

at threshold

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

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



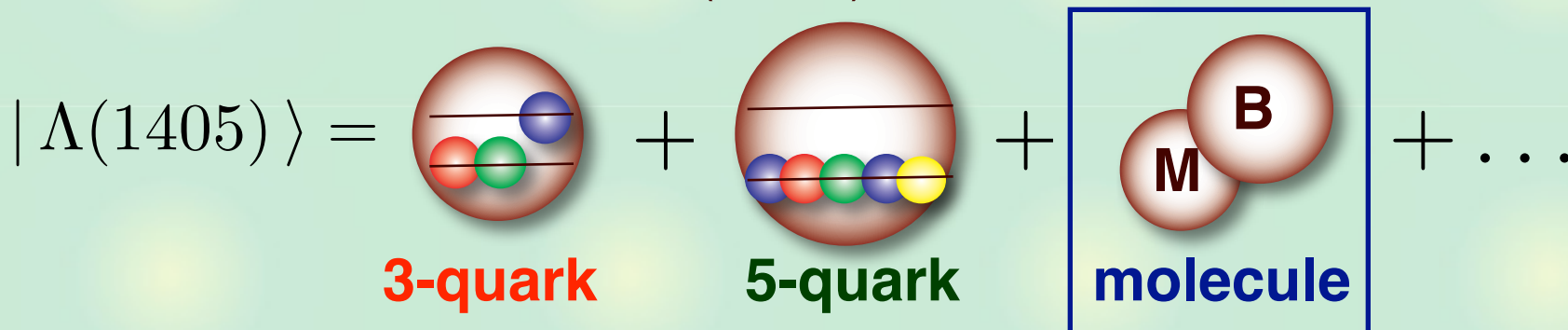
Very strong attraction in  $\bar{K}N$  (higher energy) --> bound state

Strong attraction in  $\pi\Sigma$  (lower energy) --> resonance

Model dependence? Effects from higher order terms?

# Meson-baryon molecule structure of $\Lambda(1405)$

What is the structure of  $\Lambda(1405)$ ?



- Natural renormalization condition

T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C 78, 025203 (2008)

-  $N_c$  (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)

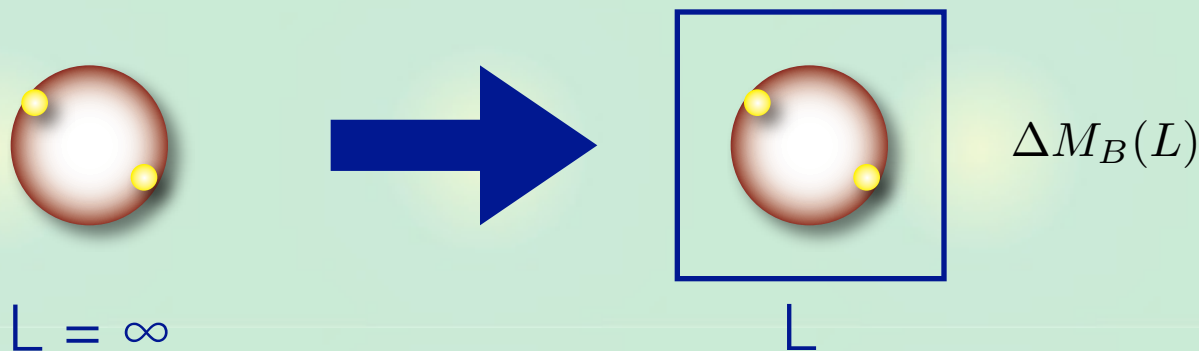
--> Dominance of the **molecule** component

radius: **complex** number? (pole on the complex plane)

## Size measurement of resonances

Finite volume mass shift  $\leftrightarrow$  Coupling to scattering state  $g^2$

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



$g^2 \leftrightarrow$  compositeness  $\leftrightarrow$  spatial size

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

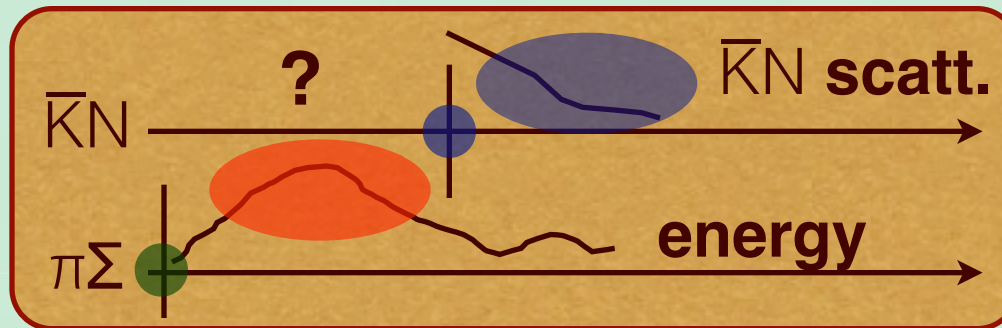
- The relation is confirmed for bound states.
- **Real-valued size can be defined for resonances.**
- $\bar{K}N$  component of  $\Lambda(1405)$ : 1.8-1.9 fm.

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)

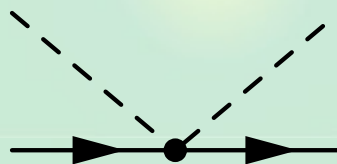
# Construction of the realistic amplitude

## 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

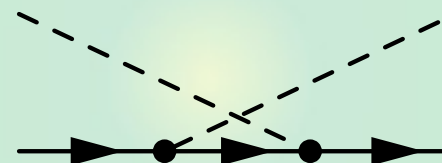
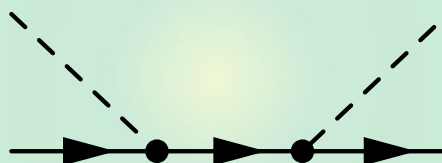
1) TW term



$\mathcal{O}(p)$

**TW model**

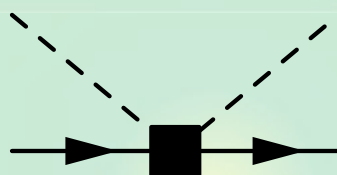
2) Born terms



$\mathcal{O}(p)$

**TWB model**

3) NLO terms



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

**NLO model**

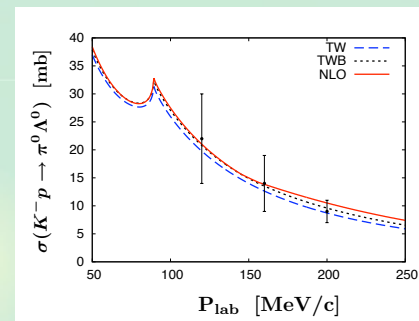
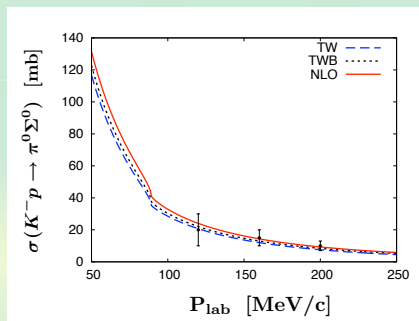
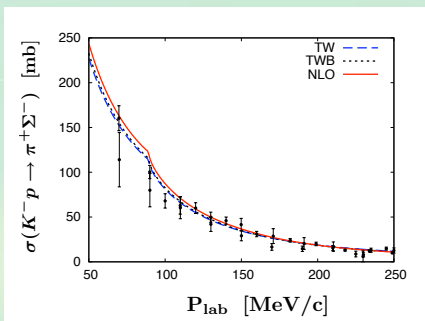
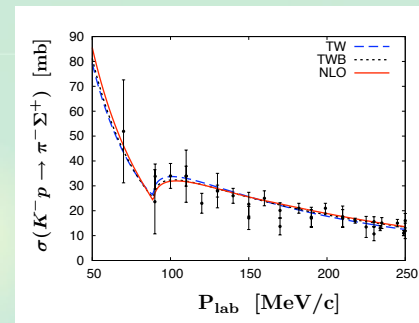
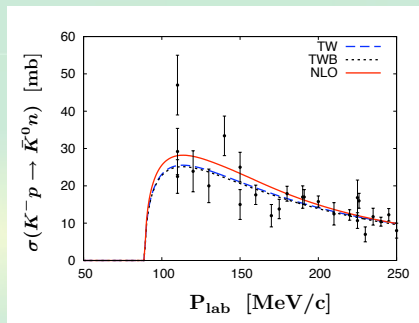
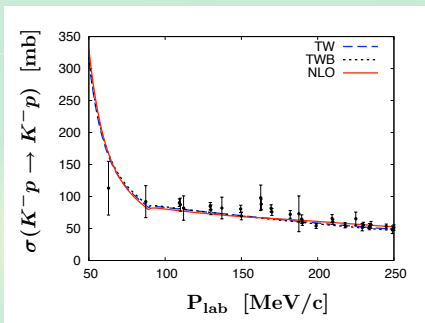
Parameters: 6 cutoffs (+ 7 low energy constants in NLO)

## 2. Realistic $\bar{K}N$ - $\pi\Sigma$ interaction with SIDDHARTA

# Best-fit results

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

cross sections



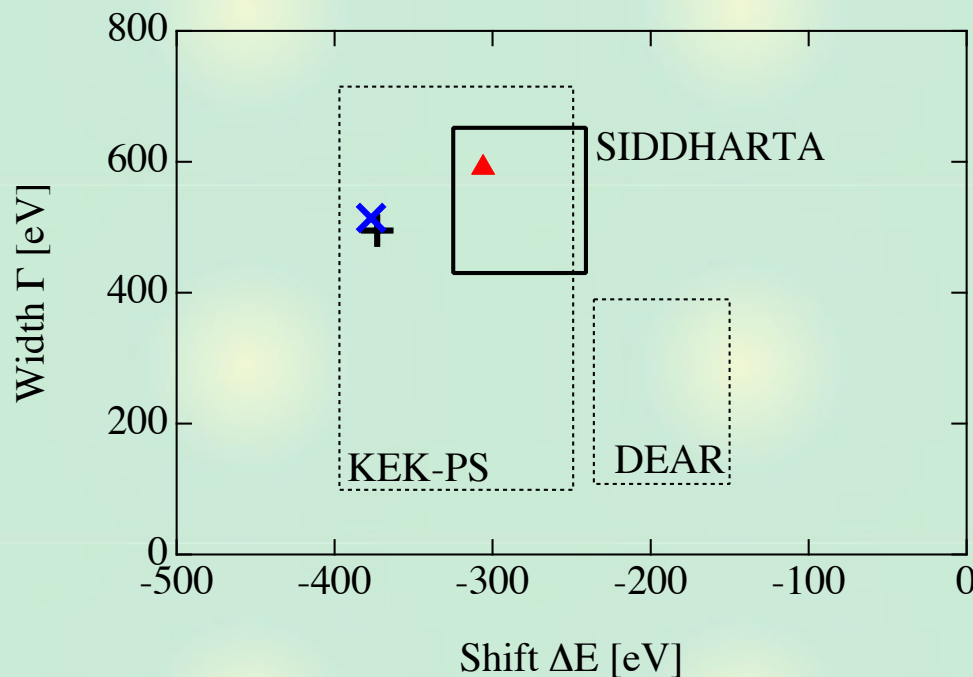
Good  $\chi^2$ : SIDDHARTA is consistent with cross sections



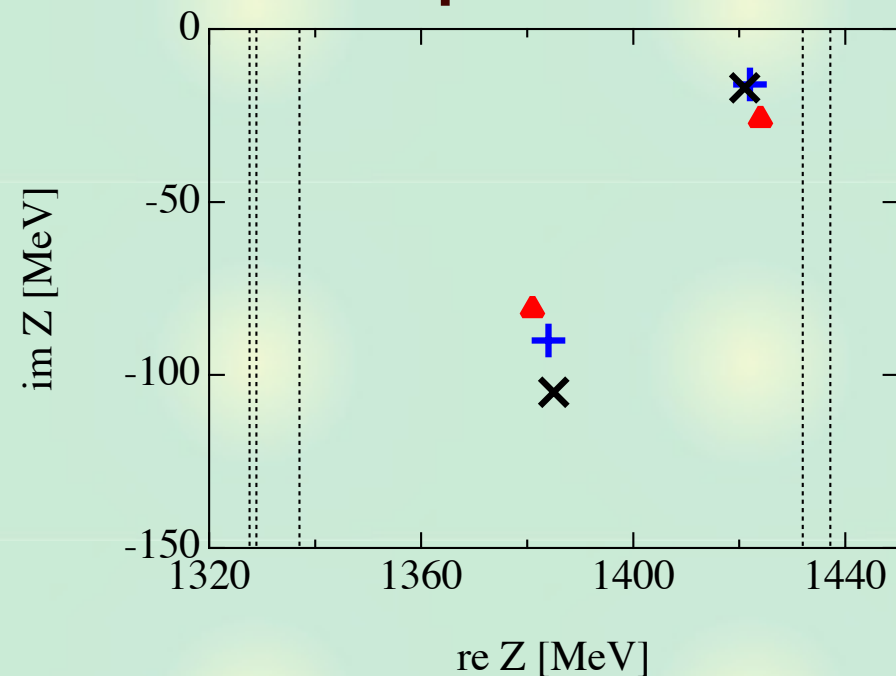
# Shift, width, and pole positions

	<b>TW</b>	<b>TWB</b>	<b>NLO</b>
$\chi^2/\text{d.o.f.}$	<b>1.12</b>	<b>1.15</b>	<b>0.957</b>

## Shift and width



## Pole positions



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

### Remaining ambiguity

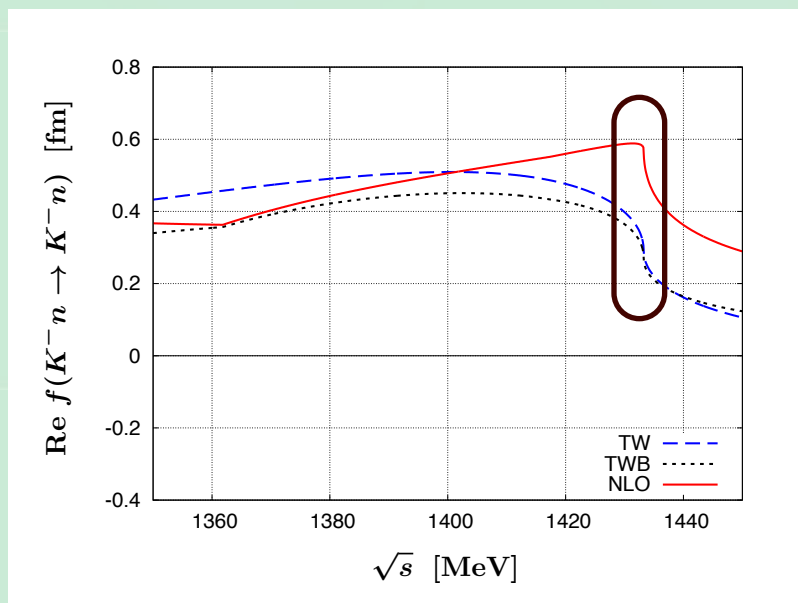
For  $K$ -nucleon interaction, we need both  $K$ - $p$  and  $K$ - $n$ .

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

$$a(K^-n) = 0.29 + i0.76 \text{ fm (TW) ,}$$

$$a(K^-n) = 0.27 + i0.74 \text{ fm (TWB) ,}$$

$$a(K^-n) = 0.57 + i0.73 \text{ fm (NLO) .}$$



Some deviation: constraint on  $K$ - $n$ ? ( $\leftarrow$  kaonic deuterium?)

### 3. Applications to few-body systems

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

### Theoretical calculations of $\bar{K}NN$ system ( $\sim K$ -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
$\Gamma_{\pi NN}$ [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. Theor. 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)

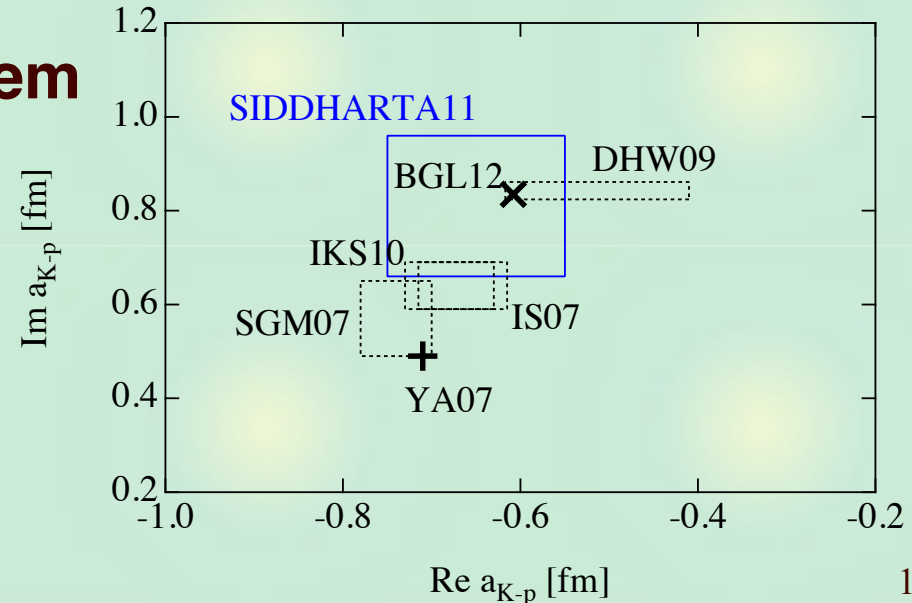
$\bar{K}NN$  system forms a quasi-bound state with large width.

# Comparison of $K$ - $p$ scattering length

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




	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
$\Gamma_{\pi NN}$ [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.**