Antikaon-nucleon dynamics and its applications to few-body systems

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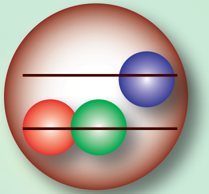
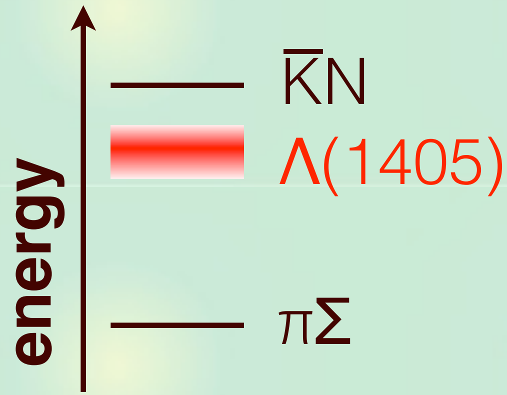
$\bar{K}$ meson and $\bar{K}N$ interaction

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

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

--> peculiar role in hadron physics

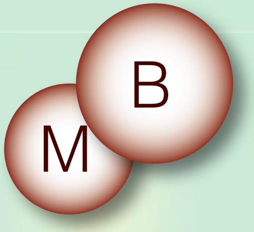




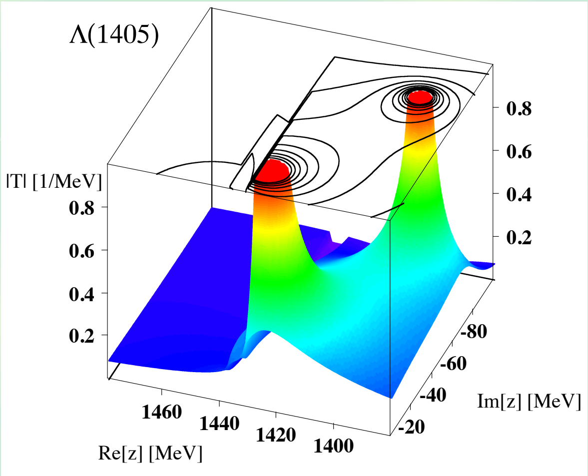
$\bar{K}N$ interaction is ...

- **coupled with $\pi\Sigma$ channel**
- **strongly attractive**

--> quasi-bound state $\Lambda(1405)$
meson-baryon v.s. qqq state,
double pole, ...



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



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

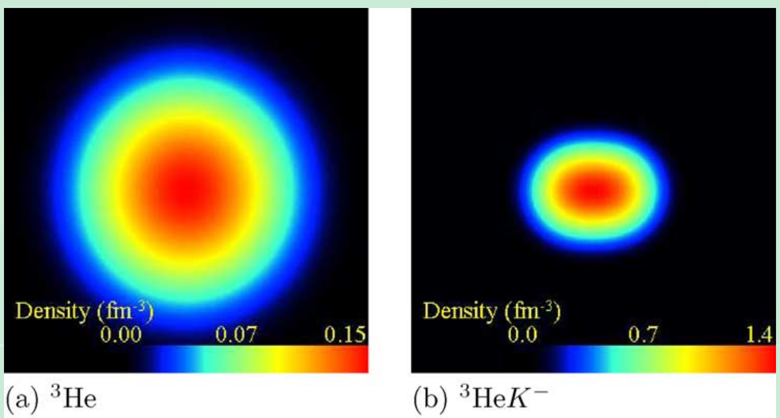
$\bar{K}$ nuclei v.s. normal nuclei

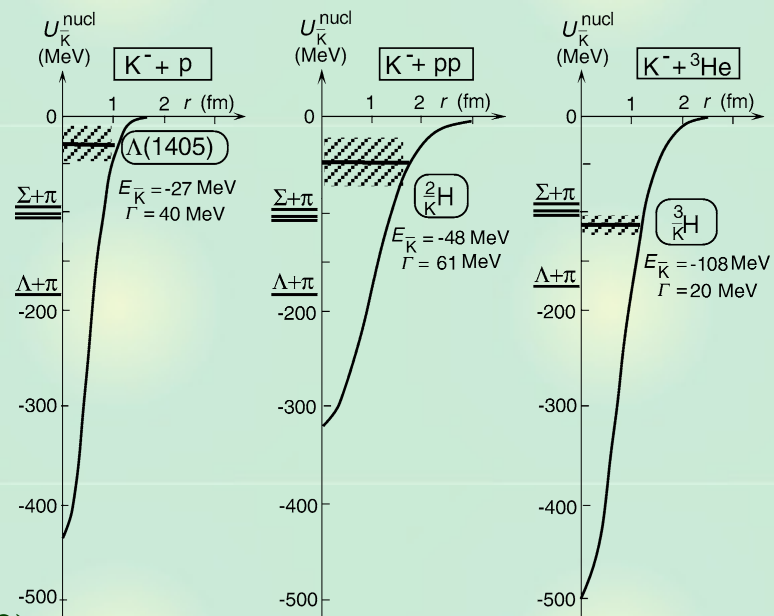
$\bar{K}N$ interaction

- strong attraction
- no repulsive core?

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

--> Strong binding of $\bar{K}$ in nuclei
High density (~10 ρ_0)?





T. Yamazaki, Y. Akaishi, Phys. Lett. B535, 70 (2002)
A. Dote, Y. Akaishi, H. Horiuchi, T. Yamazaki, Phys. Lett. B590, 51 (2004)

--> $\bar{K}N$ interaction: fundamental interaction in $\bar{K}$ nuclei

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**

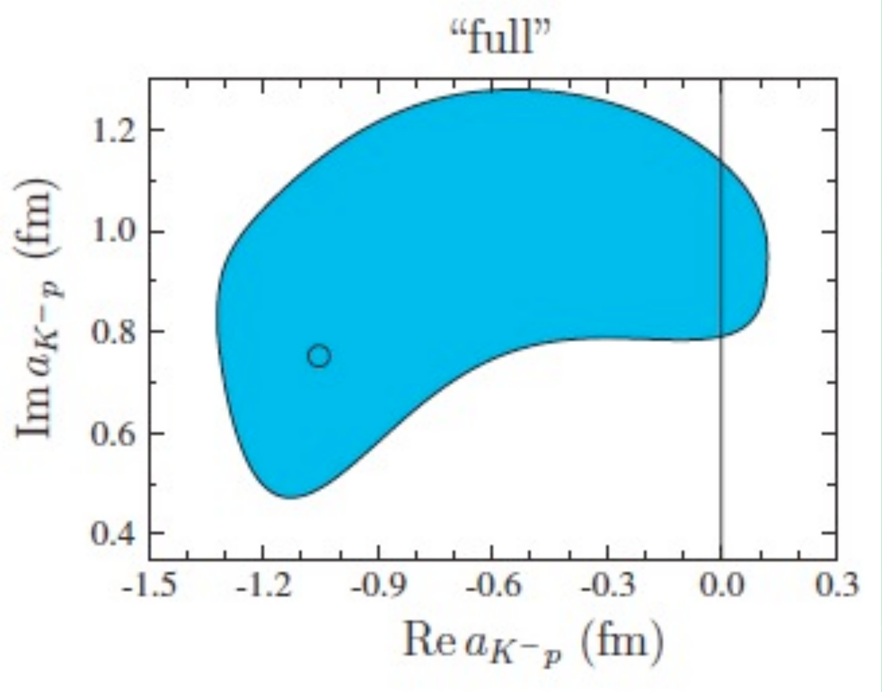
Threshold branching ratios

- **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. C74, 055201 (2006)

--> large uncertainty!

Scattering length from kaonic hydrogen

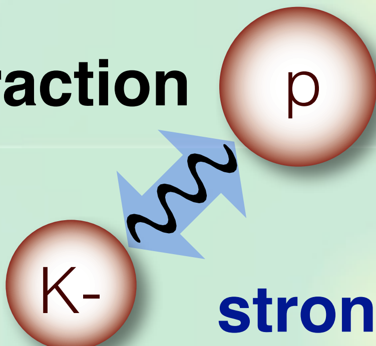
Measurements of the kaonic hydrogen

- **shift** and **width** of atomic state (Coulomb bound state)

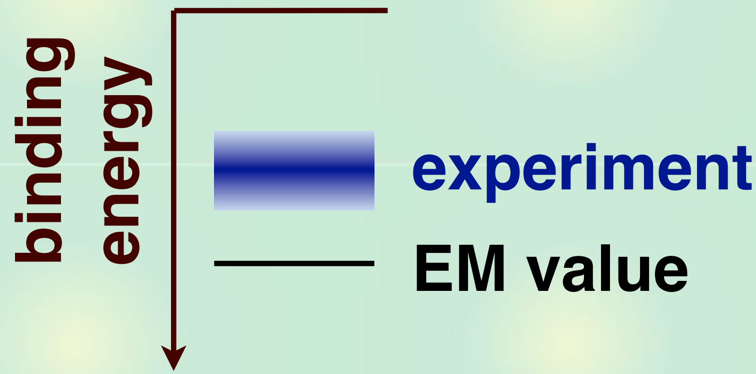
$$\Delta E - \frac{i}{2}\Gamma = -2\alpha^3\mu_c^2 a_{K^-p}[1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p}] \longleftarrow \text{scattering length}$$

U.-G. Meissner, U. Raha, A. Rusetsky, Eur. Phys. J. C35, 349 (2004)

EM interaction



strong interaction

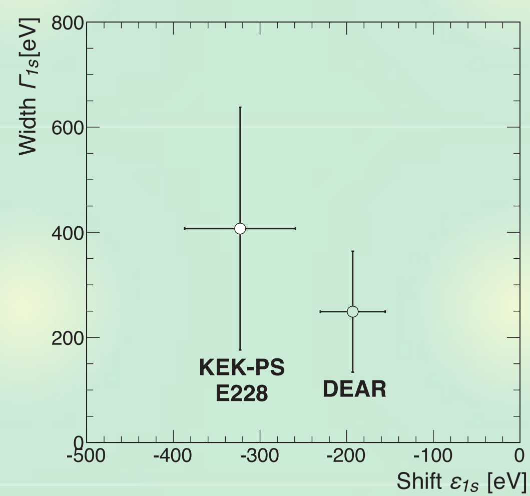


Experiments: KpX and DEAR

M. Iwasaki, *et al.*, Phys. Rev. Lett. 78, 3067 (1997)

G. Beer, *et al.*, Phys. Rev. Lett. 94, 212302 (2005)

- repulsive shift (existence of Λ^*)
- quantitatively inconsistent?



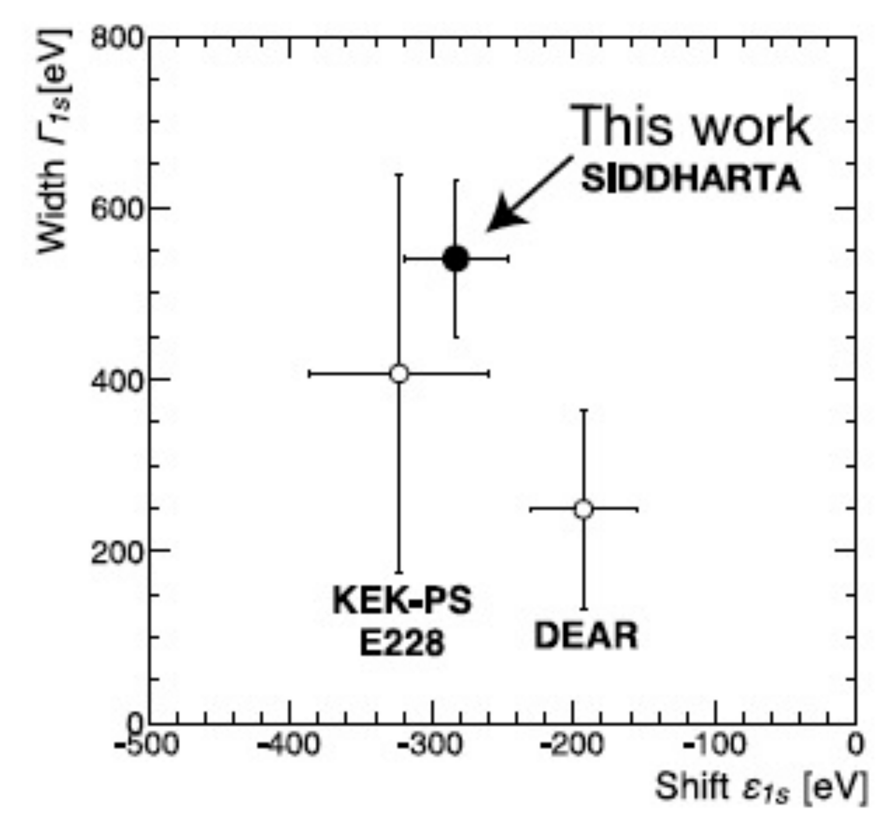
SIDDHARTA measurement

New accurate measurement by SIDDHARTA

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

Talk by M.A. Iliescu (Fri. parallel VII-a)

- smallest uncertainties



--> 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** $I = 0$

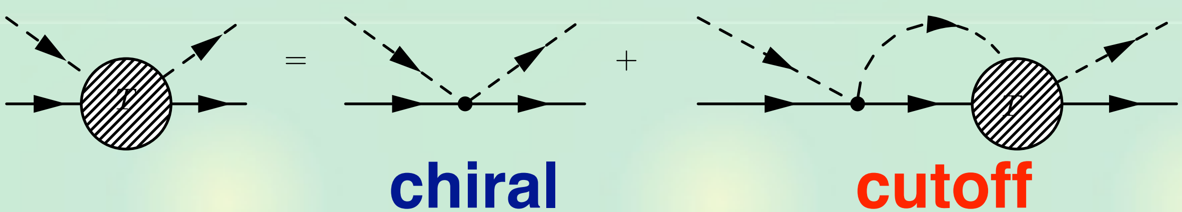
- **Interaction <-- chiral symmetry**

  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)

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



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

Talk by D. Jido (next)

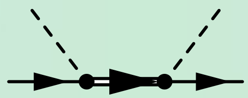
It works successfully in various hadron scatterings.

Pole structure in the complex energy plane

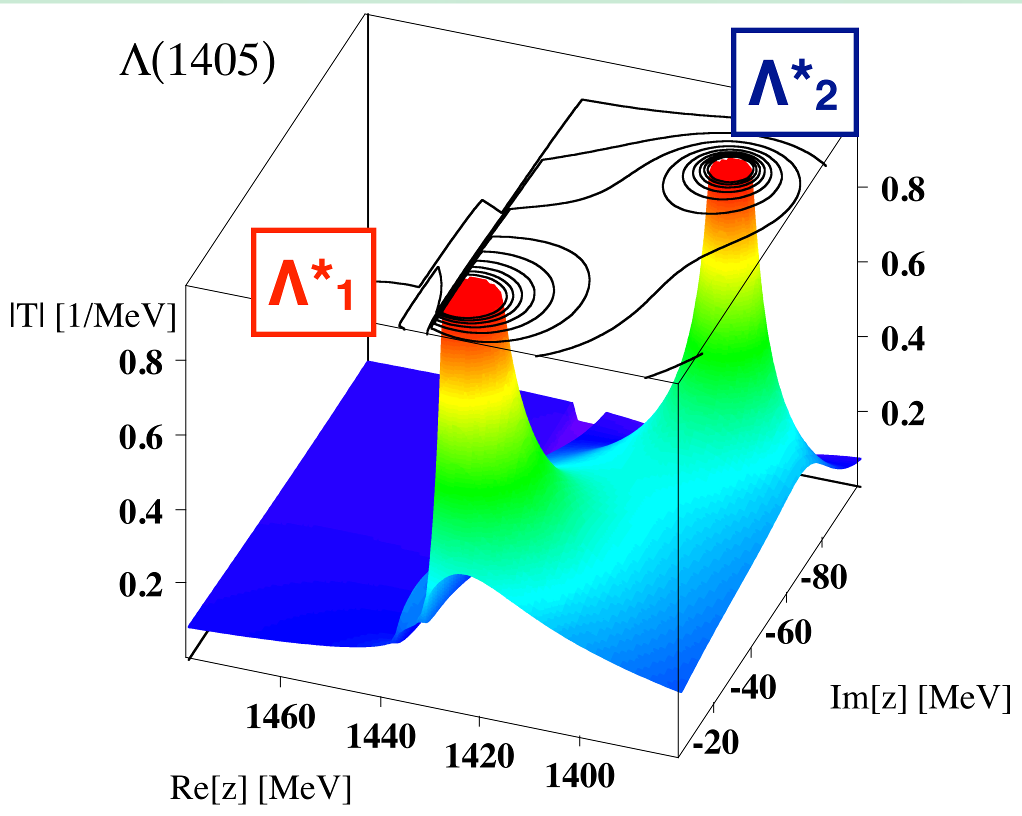
Resonance state ~ pole of the scattering amplitude

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

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

$\sim$ 

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



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

Different πΣ spectra?

K-d --> πΣN **reaction**

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)

Talk by D. Jido (next)

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)

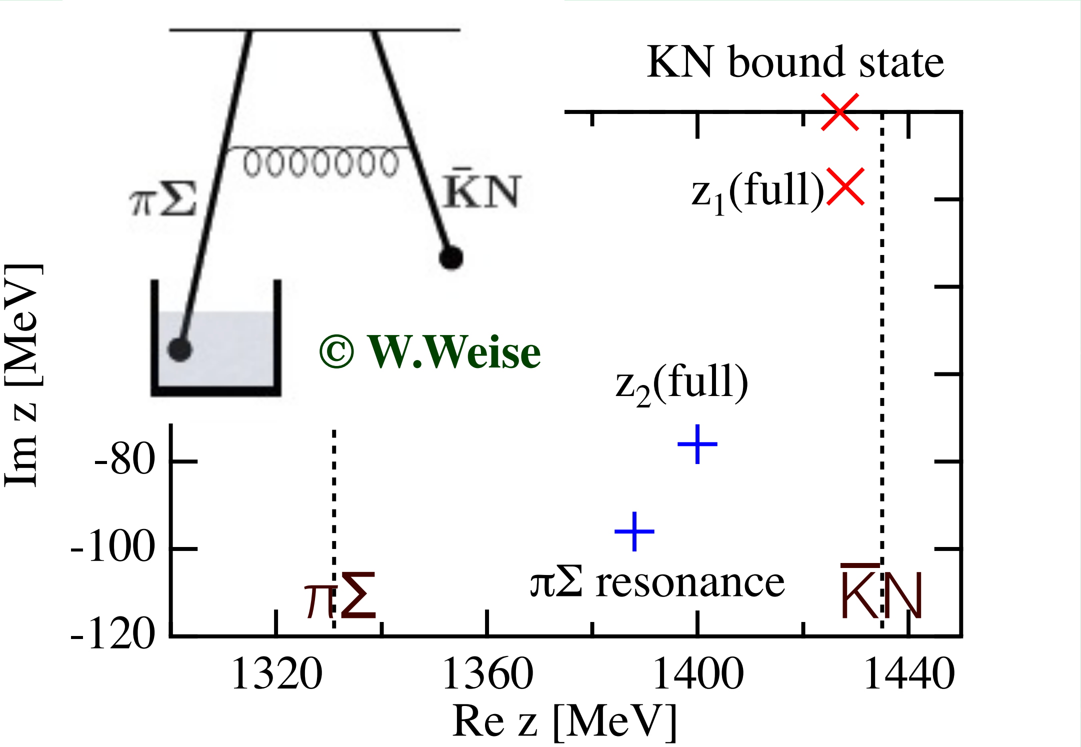
$$V_{ij} = -C_{ij}\frac{\omega_i + \omega_j}{4f^2}$$

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

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

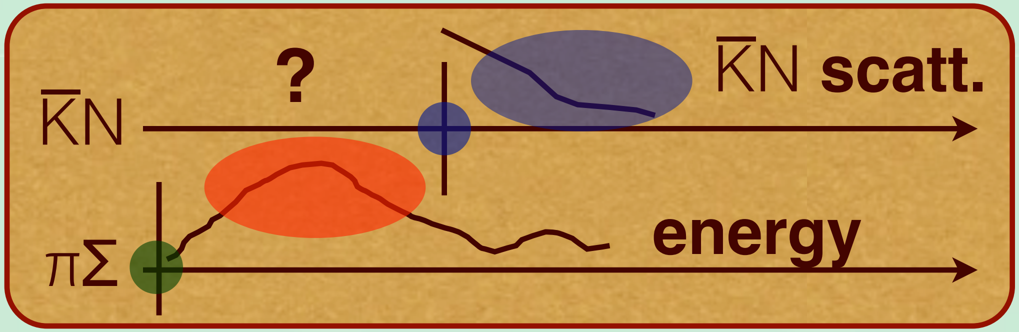
Model dependence? Effects from higher order terms?

Experimental constraints for S=-1 MB scattering

K-p **total cross sections**

$\bar{K}N$ **threshold observables**

- **threshold branching ratios**
- K-p **scattering length** **<-- SIDDHARTA exp.**



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

- **new data is becoming available (LEPS, CLAS, HADES,...)**

$\pi\Sigma$ **threshold observables (so far no data)**

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

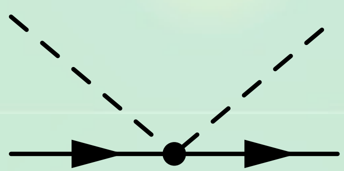
Systematic χ2 fitting with SIDDHARTA data

Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B 706, 63 (2011); Nucl. Phys. A881 98 (2012);

Talk by Y. Ikeda (Fri. parallel VII-a)

- Interaction kernel: NLO ChPT

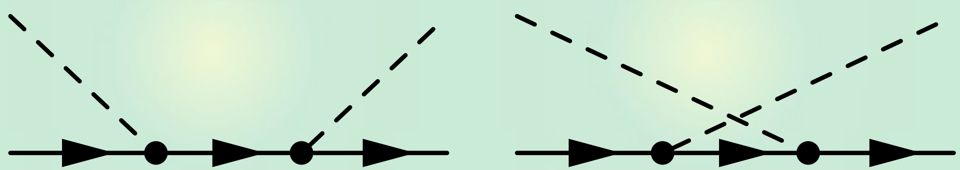
1) TW term



$\mathcal{O}(p)$

TW model

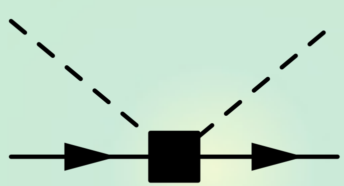
2) Born terms



$\mathcal{O}(p)$

TWB model

3) NLO terms



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

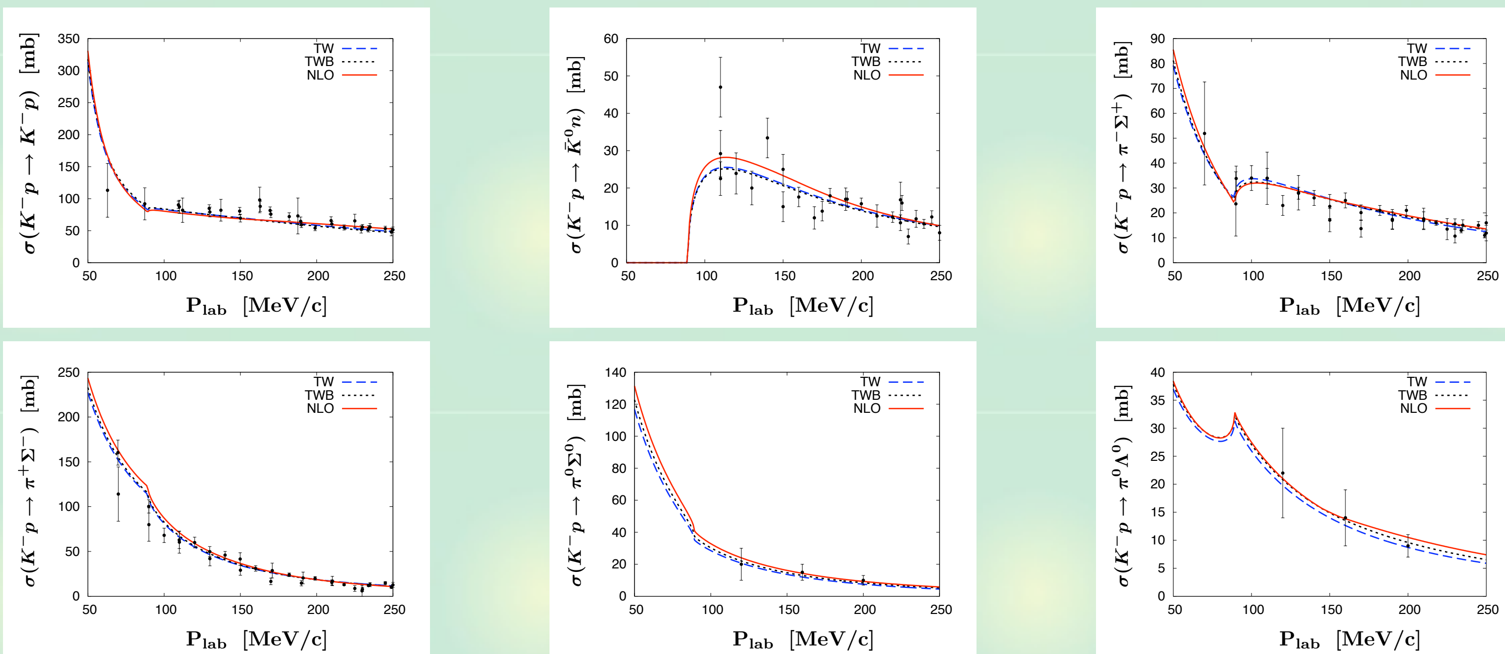
NLO model

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]	$1422 - 16i$ $1384 - 90i$	$1421 - 17i$ $1385 - 105i$	$1424 - 26i$ $1381 - 81i$		

cross sections

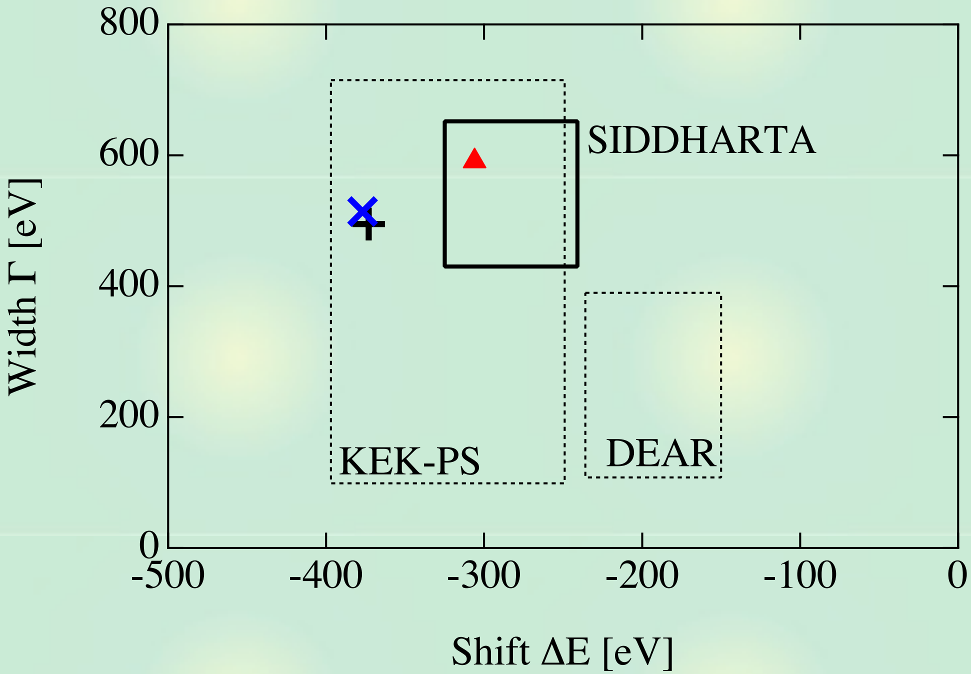


Good χ2: SIDDHARTA is consistent with cross sections

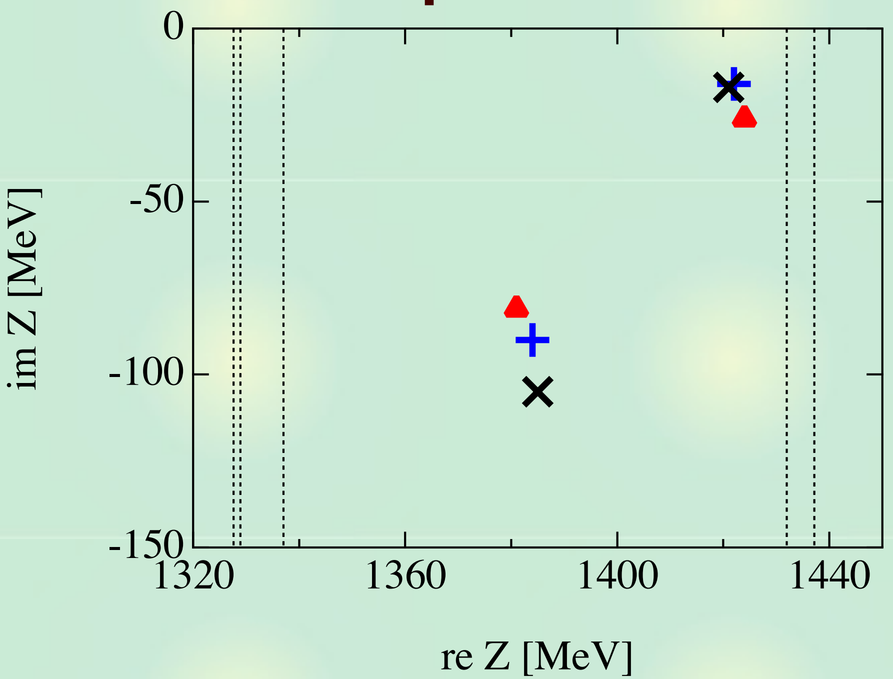
Shift, width, and pole positions

	TW	TWB	NLO
χ2/dof	1.12	1.15	0.957

Shift and width



Pole positions



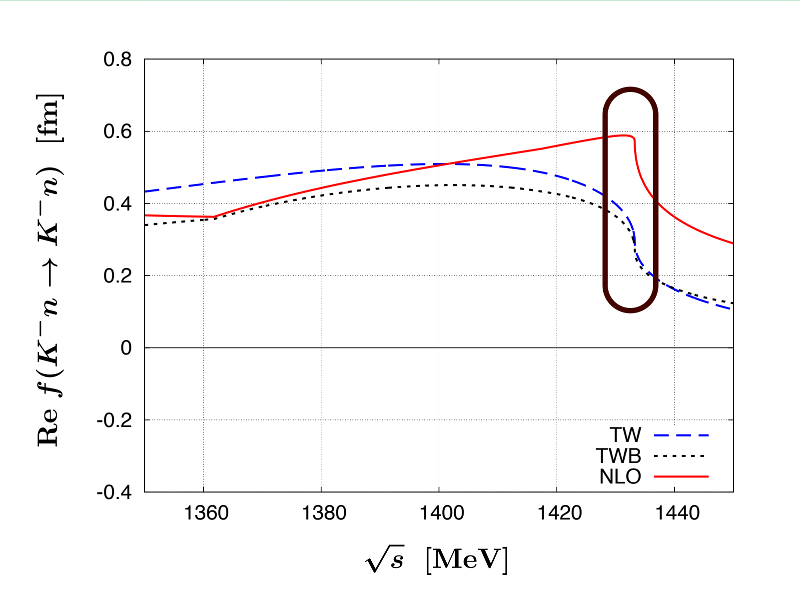
TW and TWB are reasonable, while best-fit requires NLO.
Pole positions are now converging.

K-n scattering amplitude

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
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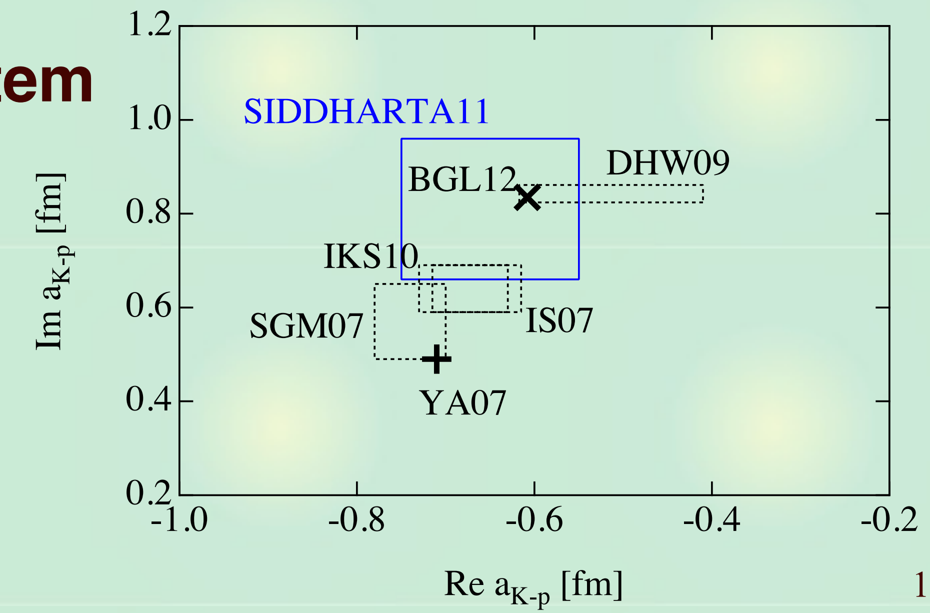
- New constraint on $\bar{K}NN$ system
- SIDDHARTA11 is obtained by the improved DT formula
- Models: isospin symmetric. Breaking is important at th.



J=1 $\bar{K}NN$ system

J=1 system (~ K-d)

- $I_{NN}=0$ --> $\bar{K}N(I=0)$:$\bar{K}N(I=1)$ = **1**:3

Less attractive, but maybe weakly bound (above Λ^*N).

	UHO11	Oset et al. (12)	BGL12
Model	Λ^*N potential	FCA	Three-body variational
$B_{\bar{K}NN}$ [MeV]	> M_{Λ^*N}	9	> M_{Λ^*N}
$\Gamma_{\pi YN}$ [MeV]	-	30	-

T. Uchino, T. Hyodo, M. Oka, Nucl. Phys. A868-869, 53 (2011)
E. Oset, *et al.*, Nucl. Phys. A881, 127 (2012)
N. Barnea, A. Gal, E.Z. Liverts, Phys. Lett. B712 (2012)

Small binding energy
--> Close relation with K-d scattering length?

Y. Ikeda, T. Hyodo, W. Weise, work in progress

DNN system

Analogous system in the charm sector: DNN system.

M. Bayar *et al.*, arXiv:1205.2275 [hep-ph], to appear in Phys. Rev. C

Talk by E. Oset (Tue. parallel III-b)

- **Replace** $\bar{K}$ **by** D
- $\Lambda(1405)$ **in** $\bar{K}N$-$\pi\Sigma$ **:** $\Lambda_c(2595)$ **in** DN -$\pi\Sigma_c$

Calculated in two different methods:

- **Fixed center approximation to Faddeev equation**
- **Variational calculation with 1-channel potential**

A quasi-bound state is found in J=0 channel.

M_{DNN} ~ 3500 MeV, B_{DNN} ~ 250 MeV, $B_{\Lambda^*_cN}$ ~ 40 MeV

Γ ~ 20-40 MeV

Narrow width: advantageous to be observed

Summary

We study the $\bar{K}N$-$\pi\Sigma$ interaction and its applications to few-body systems.

1. **$\Lambda(1405)$ is generated from the coupled-channel $\bar{K}N$-$\pi\Sigma$ dynamics.**
2. **Accurate K-hydrogen data help us to construct realistic $\bar{K}N$-$\pi\Sigma$ interaction.**
3. **Strong $\bar{K}N$ attraction will generate various $\bar{K}$ few-body systems.**