$\bar{K}N$ interaction and Kaonic nuclei

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  - Systematic analysis in chiral SU(3) dynamics

    Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)

  - Realistic $\bar{K}N$ potential

    T. Hyodo, W. Weise, PRC77, 035204 (2008)
    K. Miyahara. T. Hyodo, PRC93, 015201 (2016)

- (Selected topics of) Kaonic nuclei

  - Few-body systems up to A=6

    S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara, T. Hyodo,
    arXiv:1701.07589 [nucl-th], PRC in press.

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

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

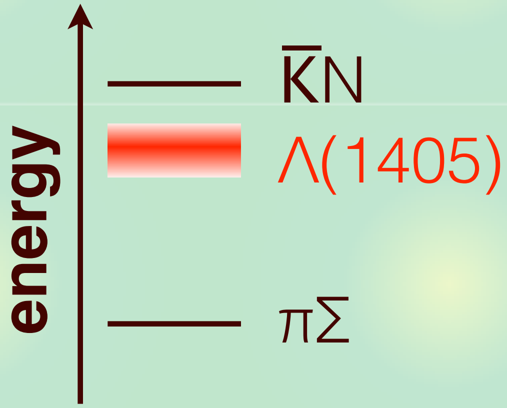
- **NG boson** of chiral $SU(3)_R \otimes SU(3)_L \longrightarrow SU(3)_V$
- **Massive** by strange quark: $m_K \sim 496$ MeV

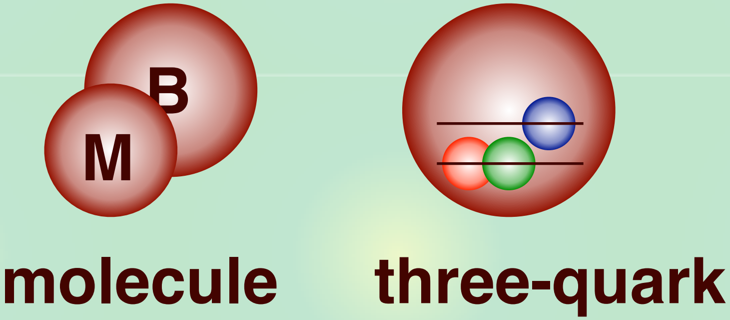
—> **Spontaneous**/**explicit** symmetry breaking

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

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

- is coupled with $\pi\Sigma$ channel
- generates $\Lambda(1405)$ below threshold



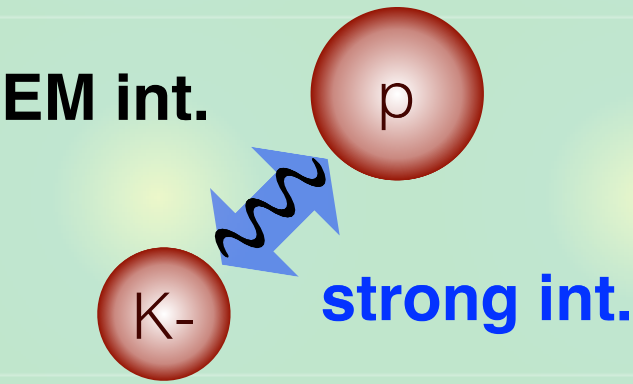


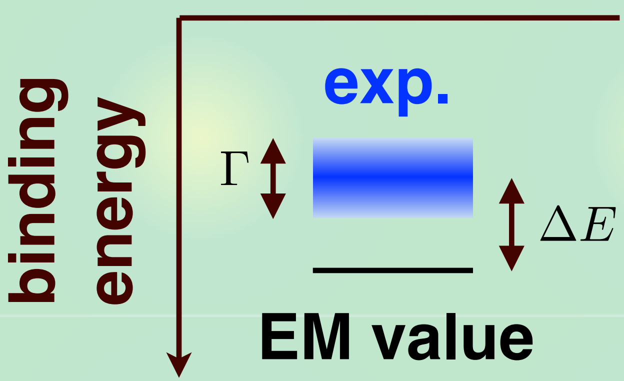
- is fundamental building block for $\bar{K}$-nuclei, $\bar{K}$ in medium, ...

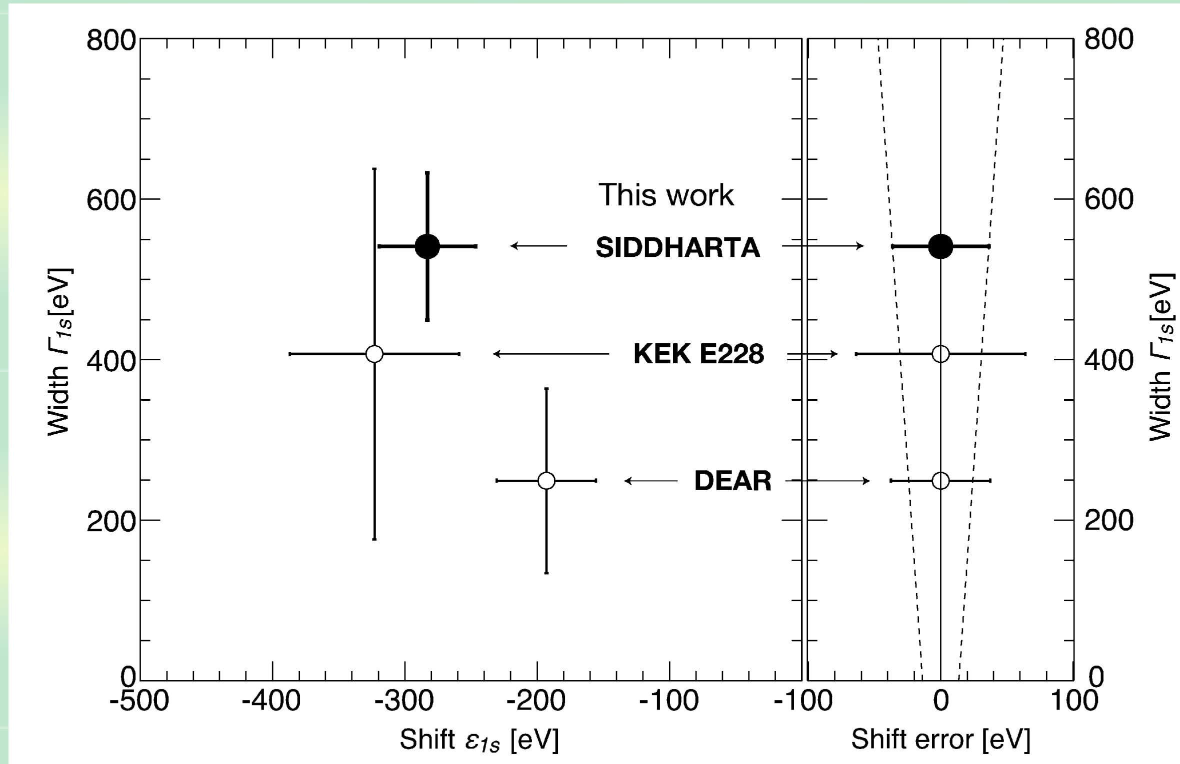
SIDDHARTA measurement

Precise measurement of the kaonic hydrogen X-rays

M. Bazzi, *et al.*, Phys. Lett. B704, 113 (2011); Nucl. Phys. A881, 88 (2012)







- Shift and width of atomic state <—> K-p scattering length

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

Quantitative constraint on the $\bar{K}N$ interaction at fixed energy

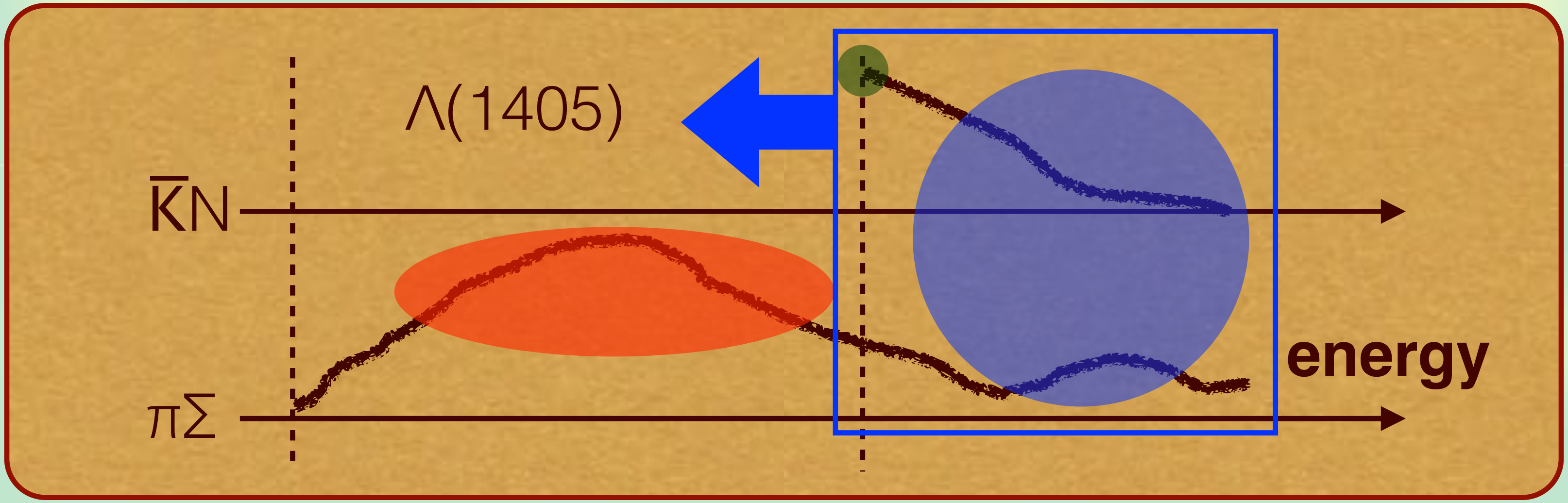
Strategy for $\bar{K}N$ interaction

Above the $\bar{K}N$ threshold: direct constraints

- K-p **total cross sections (old data)**
- $\bar{K}N$ **threshold branching ratios (old data)**
- K-p **scattering length (new data: SIDDHARTA)**

Below the $\bar{K}N$ threshold: indirect constraints

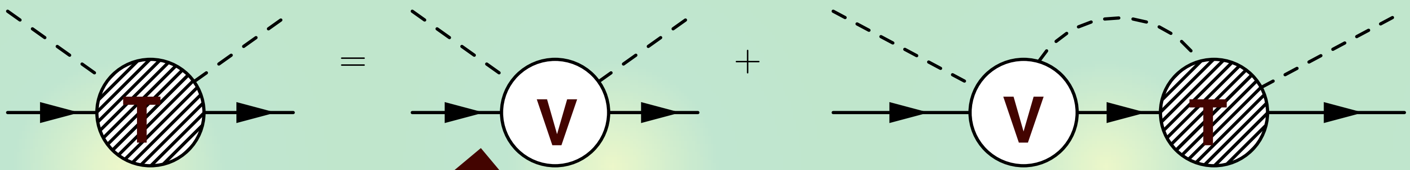
- $\pi\Sigma$ **mass spectra (new data: LEPS, CLAS, HADES,…)**



Construction of the realistic amplitude

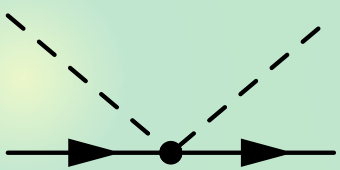
Chiral coupled-channel approach with systematic χ^2 fitting

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



Chiral perturbation theory

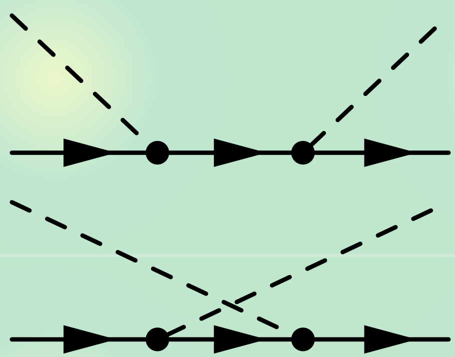
1) TW term



$\mathcal{O}(p)$

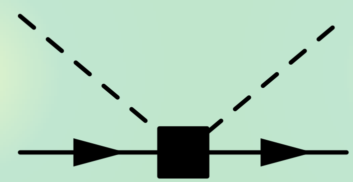
6 cutoffs

2) Born terms



$\mathcal{O}(p)$

3) NLO terms



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

7 LECs

TW model

TWB model

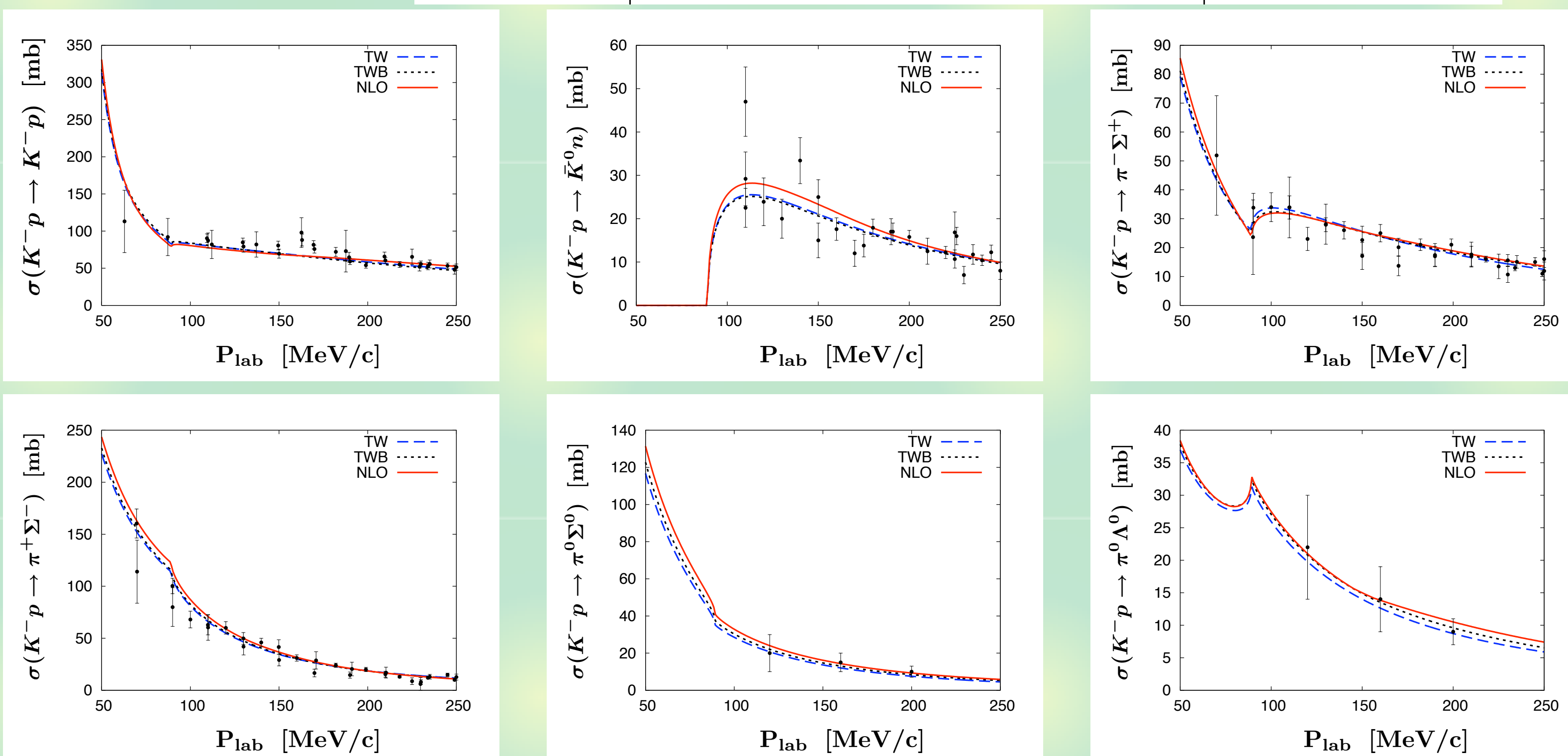
NLO model

Systematic analysis in chiral SU(3) dynamics

Best-fit results

		TW	TWB	NLO	Experiment	
SIDDHARTA	ΔE [eV]	373	377	306	$283 \pm 36 \pm 6$	[10]
	Γ [eV]	495	514	591	$541 \pm 89 \pm 22$	[10]
Branching ratios	γ	2.36	2.36	2.37	2.36 ± 0.04	[11]
	R_n	0.20	0.19	0.19	0.189 ± 0.015	[11]
	R_c	0.66	0.66	0.66	0.664 ± 0.011	[11]
	χ^2/d.o.f	1.12	1.15	0.96		

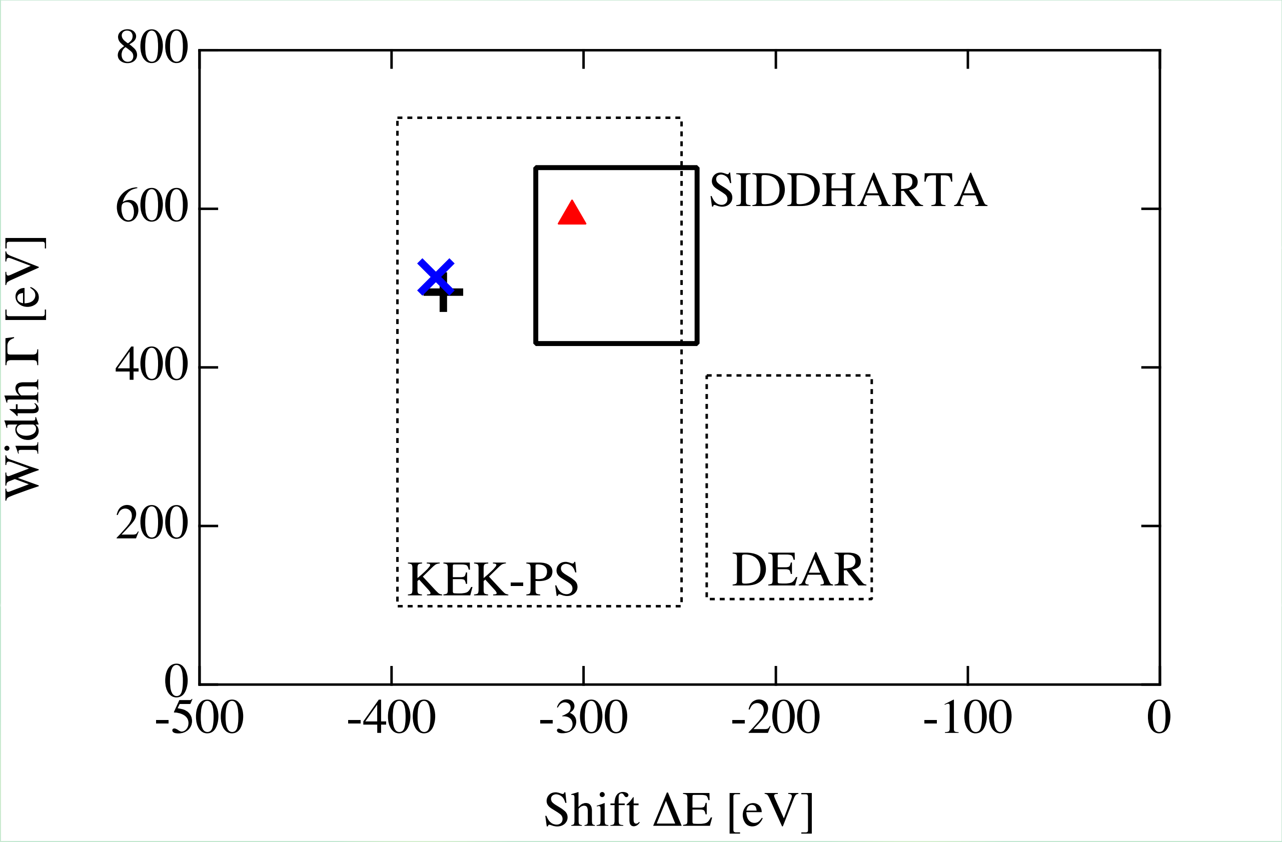
cross sections



K-hydrogen and cross sections are consistent (c.f. DEAR).

Comparison with SIDDHARTA

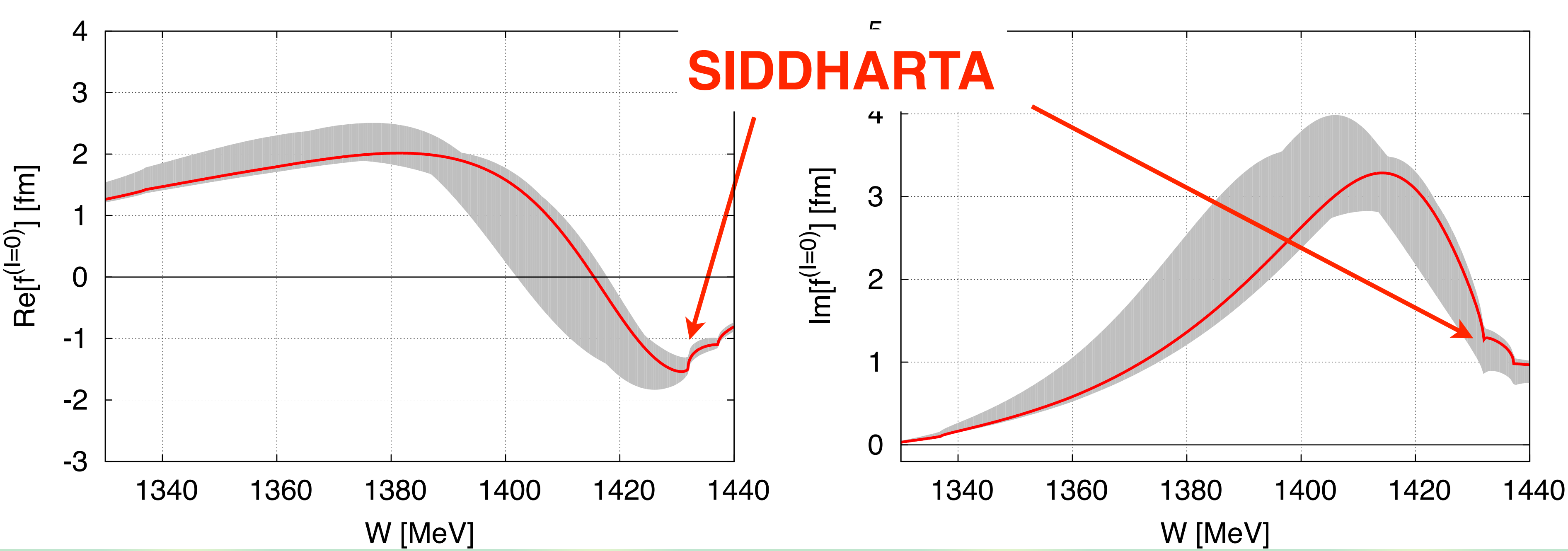
	TW	TWB	NLO
χ^2/d.o.f.	1.12	1.15	0.957



TW and TWB are reasonable, while best-fit requires NLO.

Subthreshold extrapolation

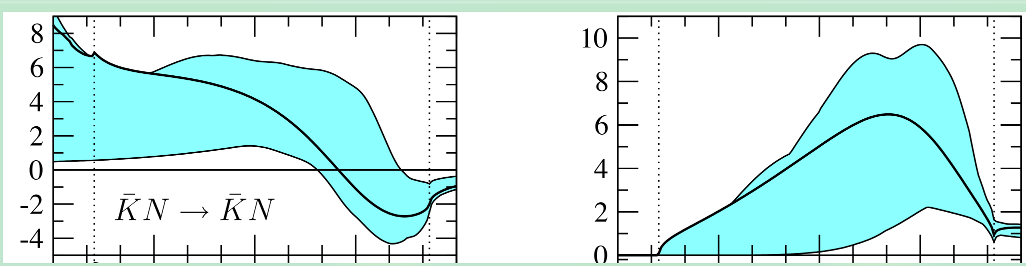
Uncertainty of $\bar{K}N \longrightarrow \bar{K}N$ (I=0) amplitude below threshold



Y. Kamiya, K. Miyahara, S. Ohnishi, Y. Ikeda, T. Hyodo, E. Oset, W. Weise, Nucl. Phys. A954, 41 (2016)

- c.f. without SIDDHARTA

R. Nissler, Doctoral Thesis (2007)



SIDDHARTA is essential for subthreshold extrapolation.

Construction of $\bar{K}N$ potential

Local $\bar{K}N$ potential is useful for

- extraction of the wave function of $\Lambda(1405)$
- application to few-body Kaonic nuclei

Single-channel energy-dependent $\bar{K}N$ potential

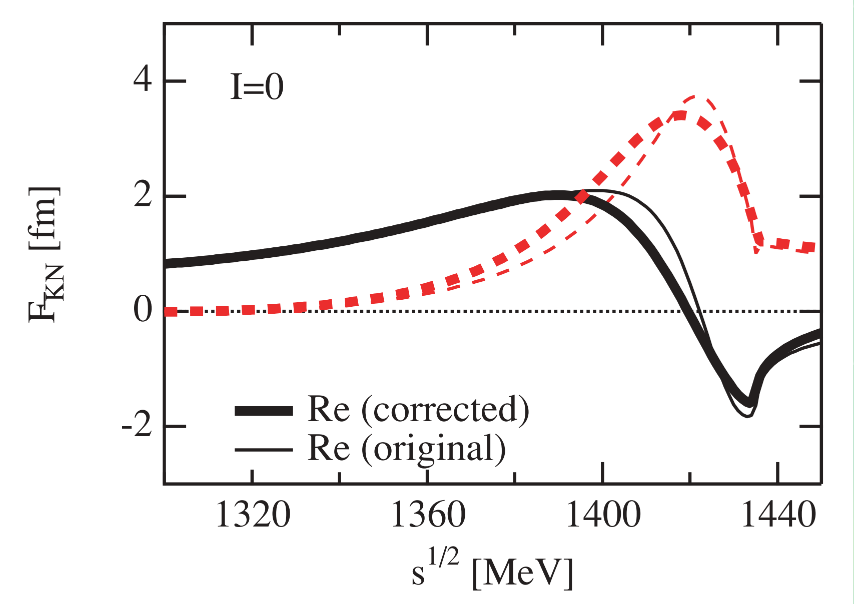
T. Hyodo, W. Weise, Phys. Rev. C 77, 035204 (2008)

- Chiral dynamics (thin)

$$T(W) = V(W) + V(W)G(W)T(W)$$

- Potential (thick)

$U(W, r)$ + Schrödinger eq.



- Reasonable on-shell scattering amplitude on real axis

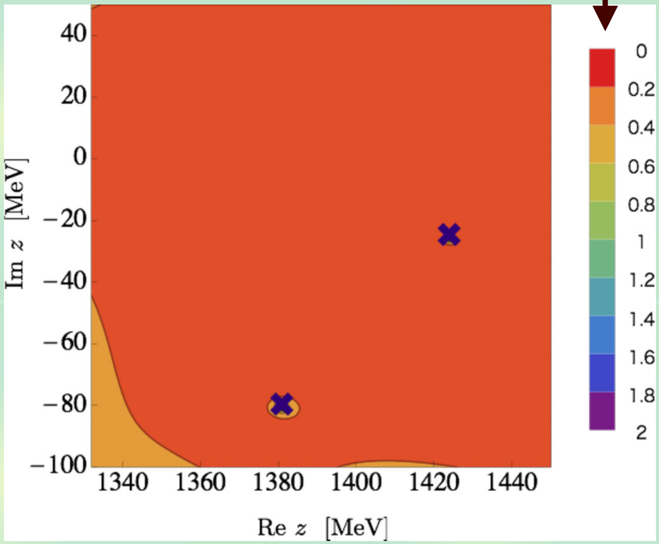
Realistic $\bar{K}N$ potential

Issues to be improved:

- Amplitude was not constrained by SIDDHARTA
- Pole structure of the amplitude was not reproduced.

Model	Pole position (MeV) original $F^{\mathrm{Ch}}_{\bar{K}N}$	potential $F_{\bar{K}N}$
ORB [68]	$1427-17i$, $1389-64i$	$1419-42i$
HNJH [66,67]	$1428-17i$, $1400-76i$	$1421-35i$
BNW [57,59]	$1434-18i$, $1388-49i$	$1404-46i$
BMN [58]	$1421-20i$, $1440-76i$	$1416-27i$

deviation from original amplitude



Construction of realistic potential

K. Miyahara, T. Hyodo, Phys. Rev. C93, 015201 (2016)

- Chiral SU(3) at NLO with SIDDHARTA
- Equivalent amplitude in the complex energy plane

Kyoto $\bar{K}N$ potential reproduces data $\chi^2/\mathrm{dof} \sim 1$: realistic

Kaonic nuclei

Few-body $\bar{K}$ nuclear systems

S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara. T. Hyodo, arXiv:1701.07589 [nucl-th], PRC in press.

- **Stochastic variational method with correlated gaussians**
- $\bar{K}N$ **: Kyoto** $\bar{K}N$ **potential,** NN**: AV4' (hard core)**

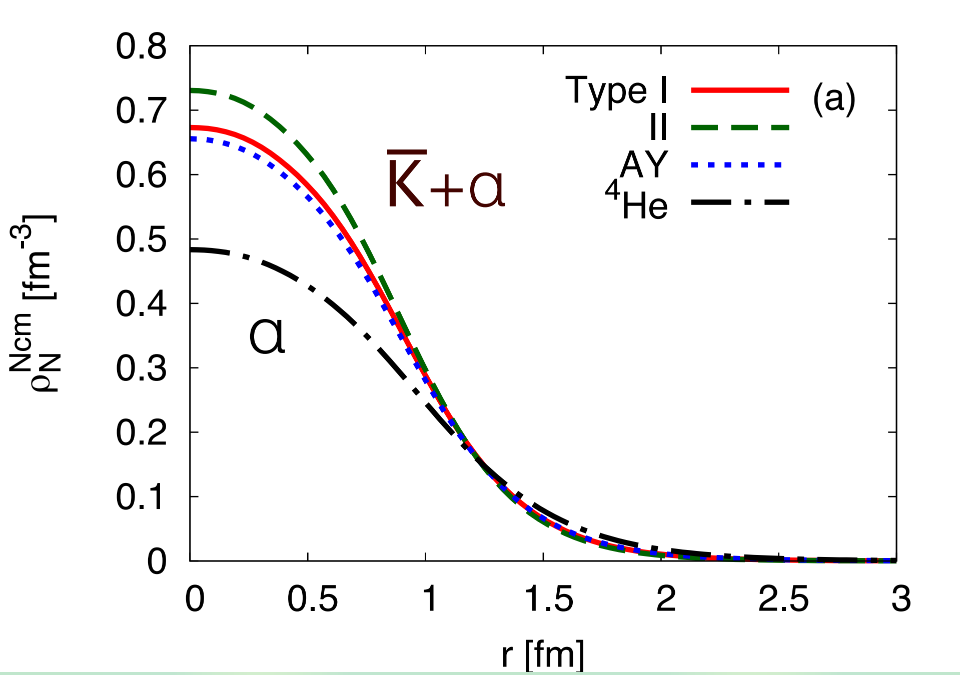
Few-body $\bar{K}$ nuclear systems

	$\bar{K}NN$	$\bar{K}NNN$	$\bar{K}NNNN$	$\bar{K}NNNNNN$
B [MeV]	25-28	45-50	68-76	70-81
Γ [MeV]	31-59	26-70	28-74	24-76

- **bound below the lowest threshold**
- **decay width (without multi-N absorption) ~ binding energy**

High density?

Nucleon density distribution in four-nucleon system



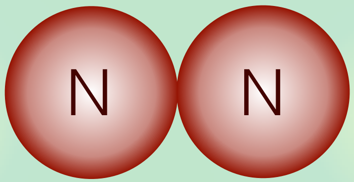
- **central density increases (not substantially <— NN core)**
- B = 68-76 **MeV (Kyoto** $\bar{K}$N**)**
- B = 85-87 **MeV (AY)**

Central density is not always proportional to B **<— tail of w.f.**

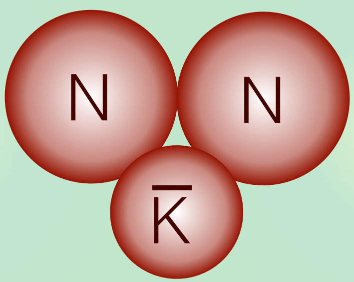
Interplay between NN and $\bar{K}N$ correlations 1

Two-nucleon system

$^1S_0$ (I_{NN}=1)



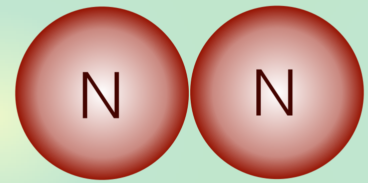
unbound



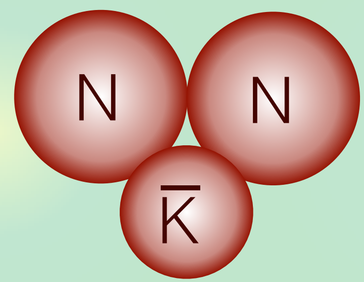
bound

$\bar{K}N(I=0):\bar{K}N(I=1) = 3:1$

$^3S_1$ (I_{NN}=0)



bound (d)



$\Lambda(1405)$

unbound

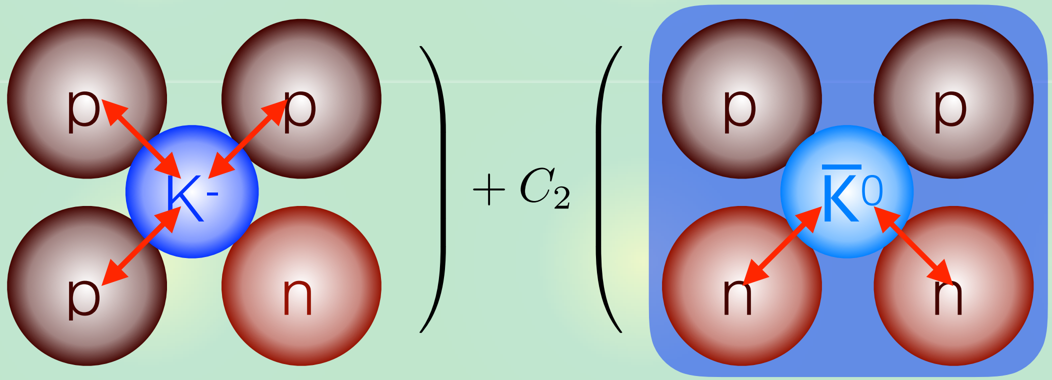
$\bar{K}N(I=0):\bar{K}N(I=1) = 1:3$

NN **correlation <** $\bar{K}N$ **correlation (also in A=6)**

Interplay between NN and $\bar{K}N$ correlations 2

Four-nucleon system with $J^\pi=0^-$, $I=1/2$, $I_3=+1/2$

$$|\bar{K}NNNN\rangle = C_1 \left(\right) + C_2 \left(\right)$$



- $\bar{K}N$ **correlation**

  I=0 **pair in** K^-p **(3 pairs) or** $\bar{K}^0n$ **(2 pairs) :** $C_1 > C_2$

- NN **correlation**

  ppnn **forms** α **:** $C_1 < C_2$

- **Numerical result**

  $|C_1|^2 = 0.08$, $|C_2|^2 = 0.92$

NN **correlation >** $\bar{K}N$ **correlation**

Summary: Λ(1405)

- $\bar{K}N$ scattering is quantitatively described (χ^2/d.o.f. ~ 1) by **NLO chiral coupled-channel approach** with accurate K-p scattering length.
- **Realistic $\bar{K}N$ potential** is now available.
- Few-body kaonic nuclei exist as quasi-bound states. Structure is determined by the **interplay between NN and $\bar{K}N$ correlations**.