Status of $\Lambda(1405)$ in chiral dynamics

Tetsuo Hyodo

Yukawa Institute for Theoretical Physics, Kyoto Univ.

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- Λ(1405) in chiral SU(3) dynamics
  - Precise experimental constraint
  - Determination of pole positions

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

- Kaonic nuclei
  - Local $\bar{K}N$ potential and Λ(1405) wave function

  K. Miyahara. T. Hyodo, PRC93, 015201 (2016)

  - Density of kaonic nuclei
  - $\bar{K}N$ v.s. NN correlations

  S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara, T. Hyodo, PRC95, 065202 (2017)

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

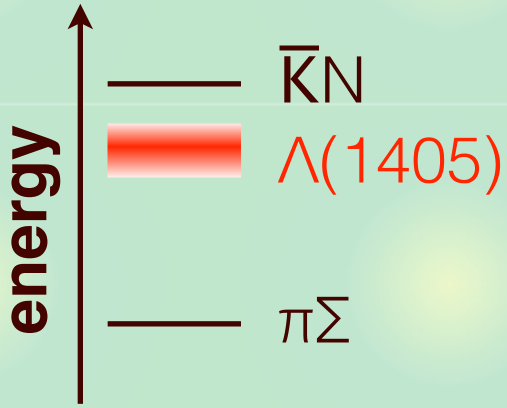
Two aspects of $K(\bar{K})$ meson

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

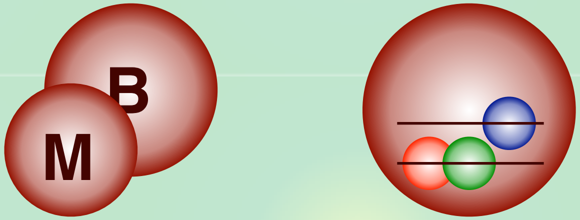
—> **Spontaneous/explicit** symmetry breaking

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

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



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



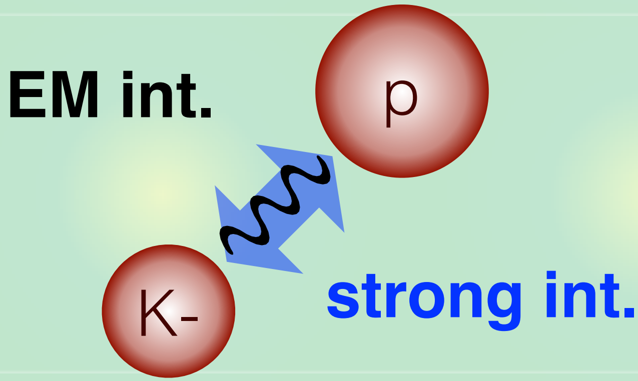
molecule three-quark

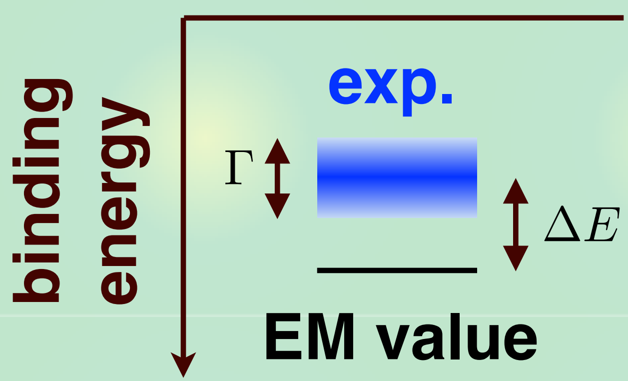
- is fundamental building block for $\bar{K}$-nuclei, $\bar{K}$ in medium, ...

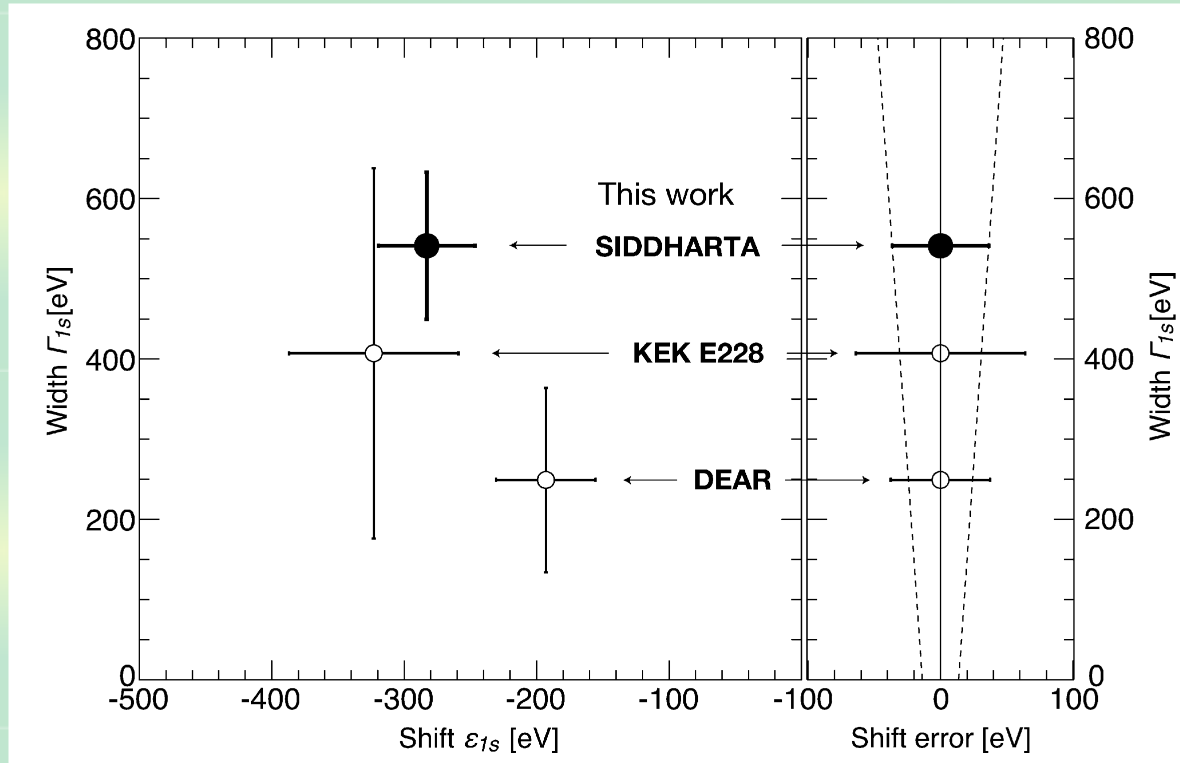
SIDDHARTA measurement

Precise measurement of the kaonic hydrogen X-rays

M. Bazzi, *et al.*, PLB 704, 113 (2011); NPA 881, 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

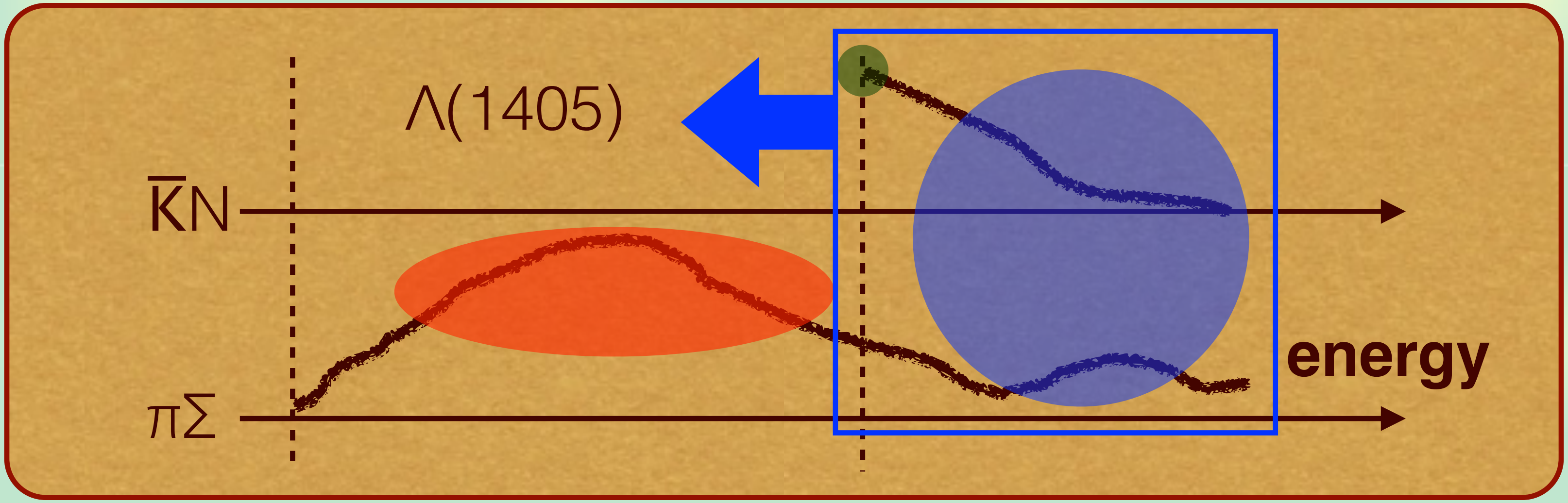
Strategy for $\bar{K}N$ interaction

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

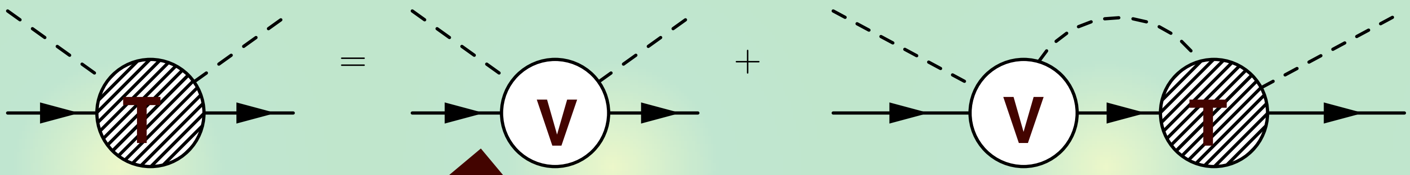
- $\pi\Sigma$ **mass spectra (new data: LEPS, CLAS, HADES,...)**



Construction of the realistic amplitude

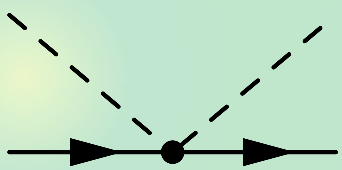
Chiral coupled-channel approach with systematic χ^2 fitting

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



Chiral perturbation theory

1) TW term

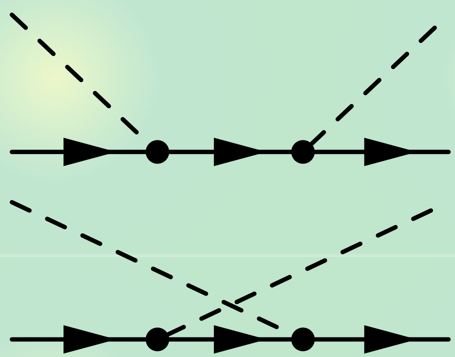


$\mathcal{O}(p)$

6 cutoffs

TW model

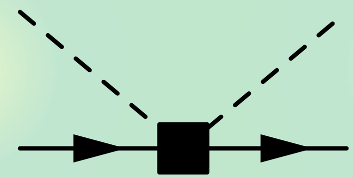
2) Born terms



$\mathcal{O}(p)$

TWB model

3) NLO terms



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

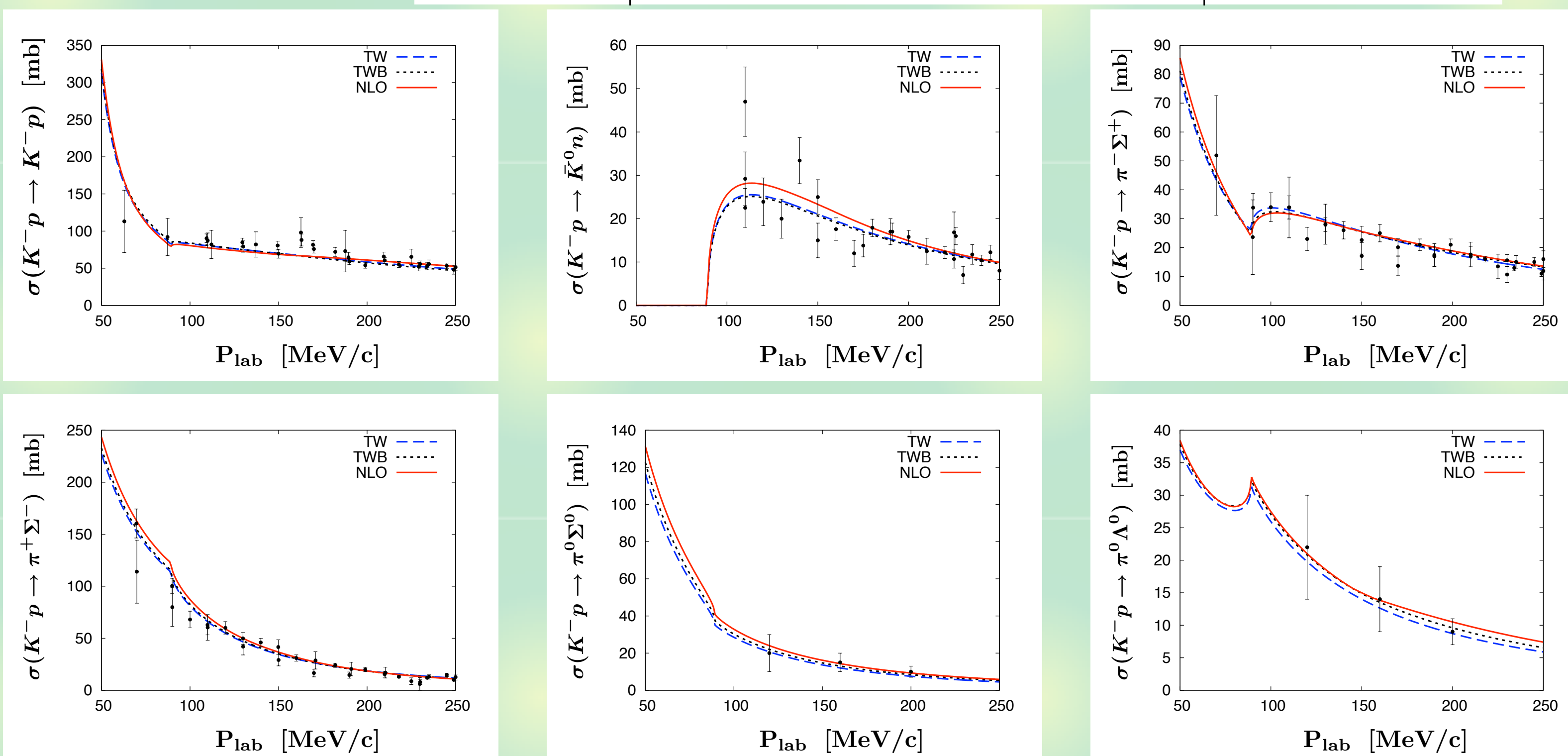
7 LECs

NLO model

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		

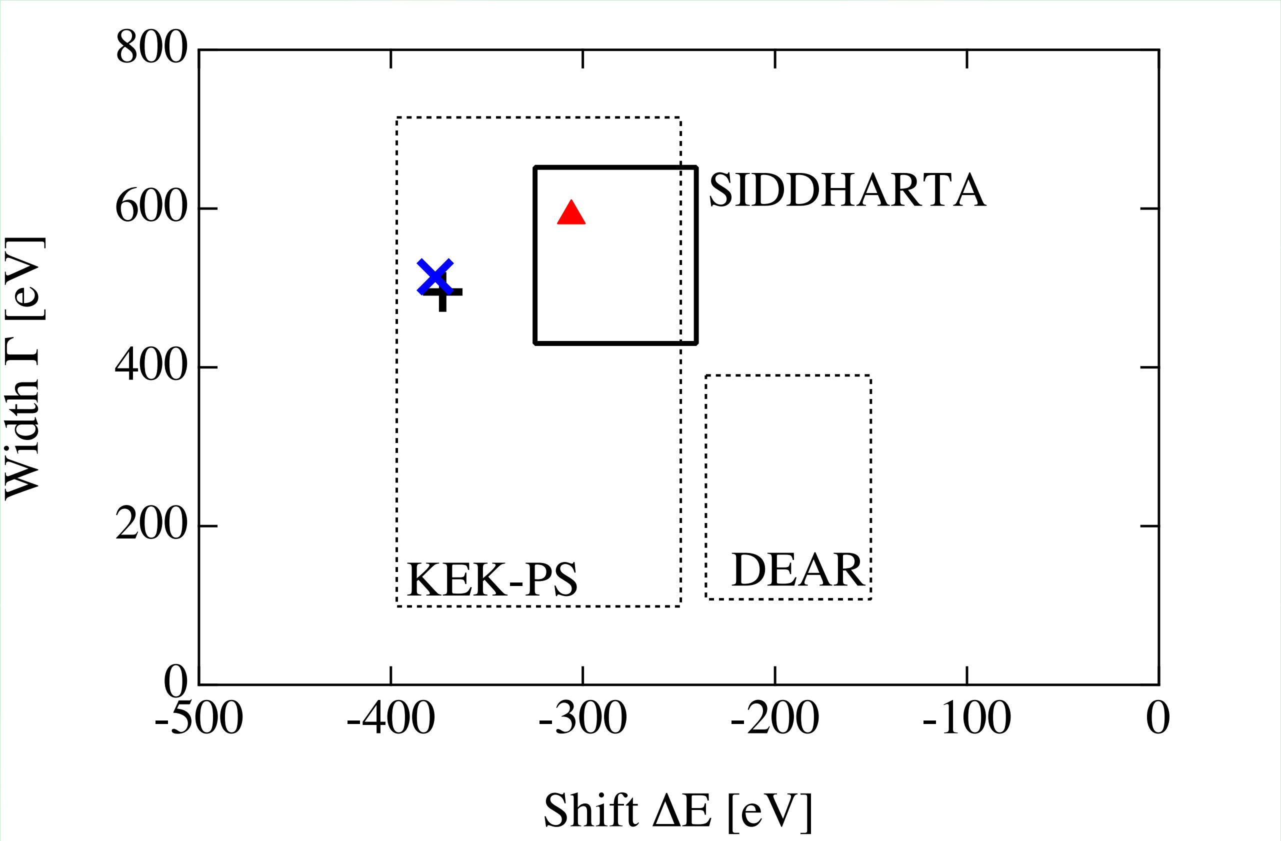
cross sections



Accurate description of all existing data (χ^2/d.o.f. ~ 1)

Comparison with SIDDHARTA

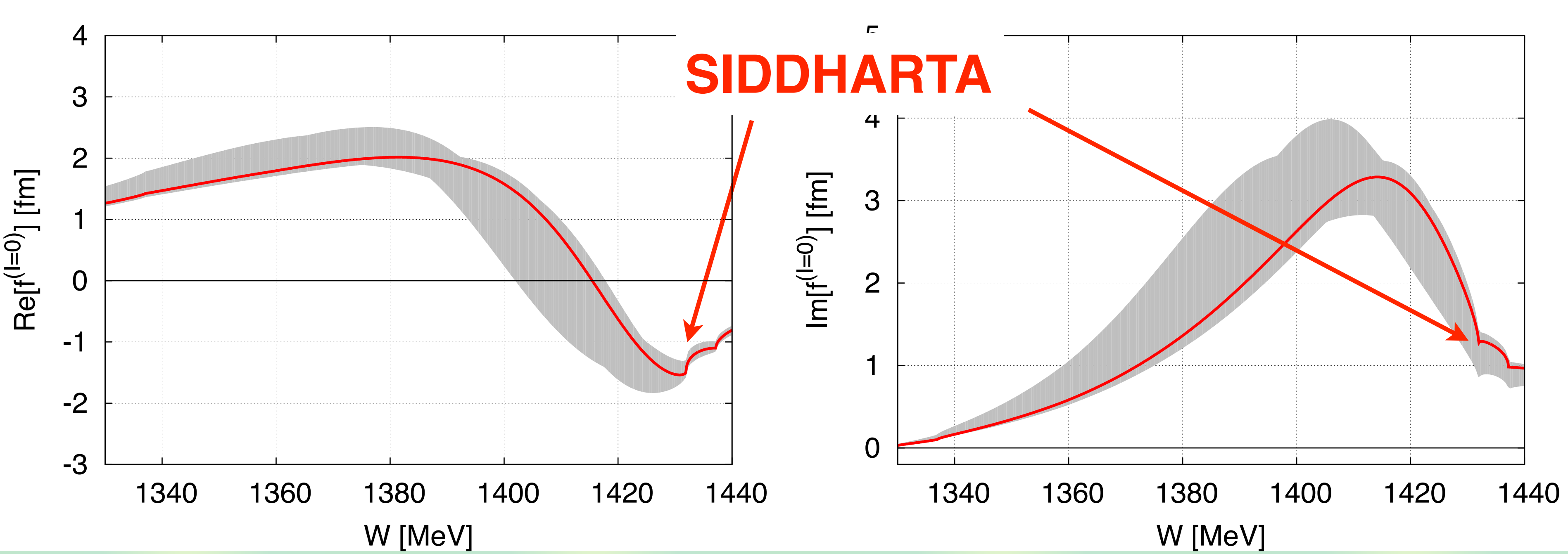
	TW	TWB	NLO
χ^2/d.o.f.	1.12	1.15	0.957



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

Subthreshold extrapolation

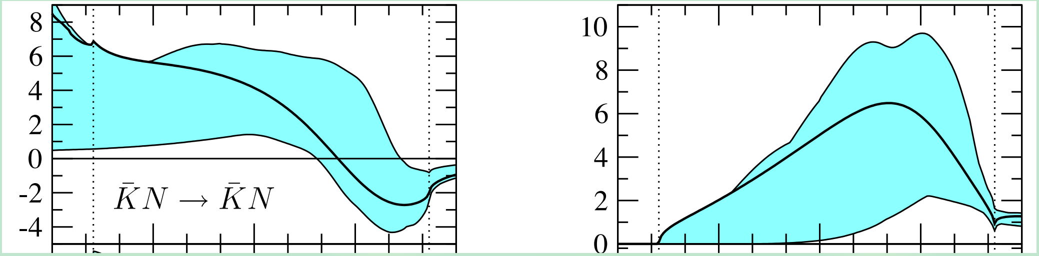
Uncertainty of $\bar{K}N \rightarrow \bar{K}N$ (I=0) amplitude below threshold



Y. Kamiya, K. Miyahara, S. Ohnishi, Y. Ikeda, T. Hyodo, E. Oset, W. Weise, NPA 954, 41 (2016)

- c.f. without SIDDHARTA

R. Nissler, Doctoral Thesis (2007)



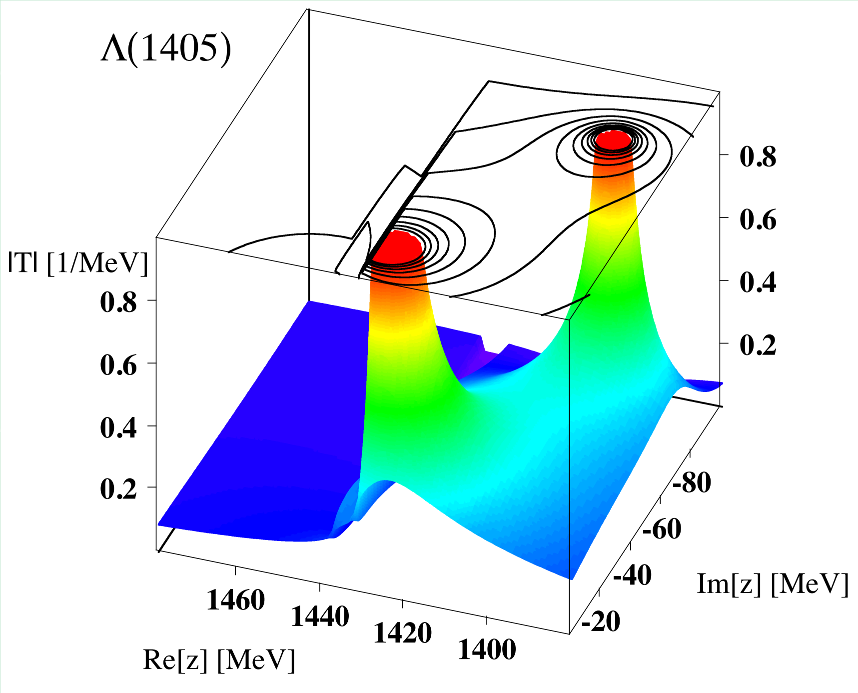
SIDDHARTA is essential for subthreshold extrapolation.

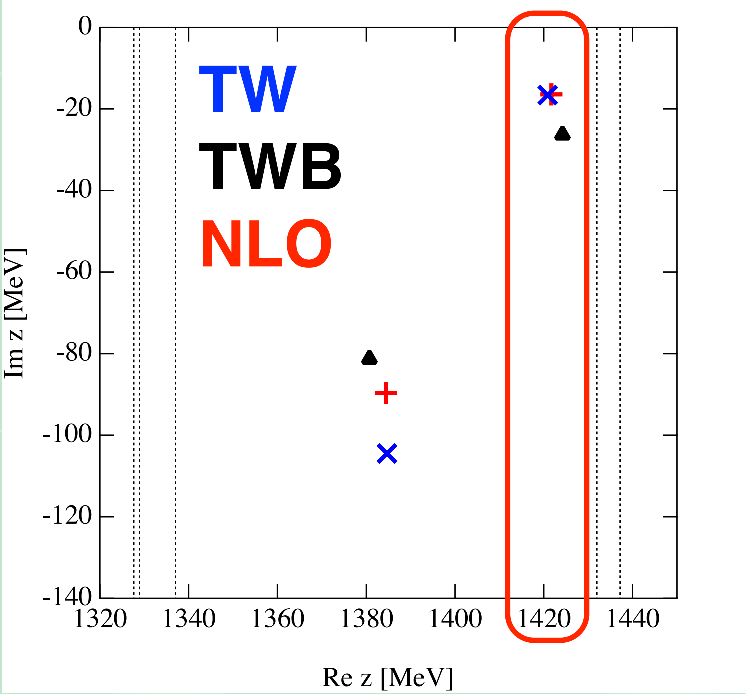
Extrapolation to complex energy: two poles

Two poles: superposition of two states

J.A. Oller, U.G. Meissner, PLB 500, 263 (2001);
D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, NPA 723, 205 (2003);
T. Hyodo, W. Weise, PRC 77, 035204 (2008)

- Higher energy pole at 1420 MeV, not at 1405 MeV
- Attractions of TW in 1 and 8 ($\bar{K}N$ and $\pi\Sigma$) channels





NLO analysis confirms the two-pole structure.

PDG changes

PDG particle listing of Λ(1405)

M. Tanabashi, *et al.*, PRD 98, 030001 (2018), http://pdg.lbl.gov/

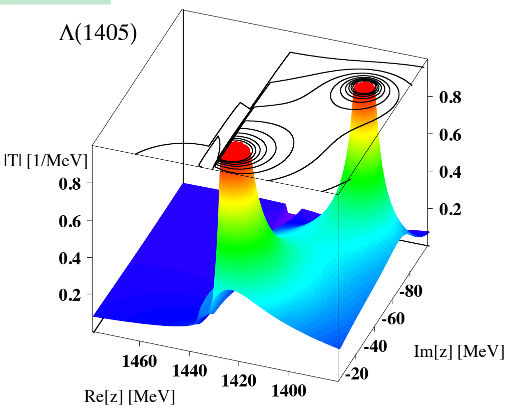
2014

$\Lambda(1405)\ 1/2^-$ $I(J^P) = 0(\frac{1}{2}^-)$ Status

The nature of the $\Lambda(1405)$ has been a puzzle for decades: t... quark state or hybrid; two poles or one. We cannot here survey the rather extensive literature. See, for example, CIEPLY 10, KISSLINGER 11, SEKIHARA 11, and SHEVCHENKO 12A for discussions and earlier references.

... of the chiral-unitary community ... 400-MeV region. ZYCHOR 08 ... inst the two-pole model, but this ... REVAI 09, which finds little basis ... o-pole models; and IKEDA 12, ...

... 1405) fits nicely into a J^P = ... ner members are the $\Lambda_c(2595)^+$, ... Fig. 1 of our note on "Charmed ...



MASS

	TECN	COMMENT
1405.1 ... 1.0 OUR AVERAGE		
1405 +11 ... HASSANVAND 13	SPEC	...

105. Pole Structure of the Λ(1405) Region

Written November 2015 by Ulf-G. Meißner (Bonn Univ. / FZ Jülich) and Tetsuo Hyodo (YITP, Kyoto Univ.).

The Λ(1405) resonance emerges in the meson-baryon scattering amplitude with the strangeness $S = -1$ and isospin $I = 0$. It is the archetype of what is called a dynamically generated resonance, as pioneered by Dalitz and Tuan [1]. The most powerful and ...

2018

$\Lambda(1405)\ 1/2^-$ $I(J^P) = 0(\frac{1}{2}^-)$ S...

In the 1998 Note on the $\Lambda(1405)$ in PDG 98, R.H. Dalitz discussed the S-shaped cusp behavior of the intensity at the N-$\overline{K}$ threshold observed in THOMAS 73 and HEMINGWAY 85. He commented that this behavior "is characteristic of S-wave coupling; the other below threshold hyperon, the $\Sigma(1385)$, has no such threshold distortion because its N-$\overline{K}$ coupling is P-wave. For $\Lambda(1405)$ this asymmetry is the sole direct evidence that $J^P = 1/2^-$."

A recent measurement by the CLAS collaboration, MORIYA 14, definitively established the long-assumed $J^P = 1/2^-$ spin-parity assignment of the $\Lambda(1405)$. The experiment produced the $\Lambda(1405)$ spin-polarized in the photoproduction process $\gamma p \to K^+\Lambda(1405)$ and measured the decay of the $\Lambda(1405)$(polarized) $\to \Sigma^+$(polarized)π^-. The observed isotropic decay of $\Lambda(1405)$ is consistent with spin $J = 1/2$. The polarization transfer to the Σ^+(polarized) direction revealed negative parity, and thus established $J^P = 1/2^-$.

See the related review(s):
Pole Structure of the $\Lambda(1405)$ Region

$\Lambda(1405)$ REGION POLE POSITIONS

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1429^{+8}_{-7}	[1] MAI	15	DPWA
1325^{+15}_{-15}	[2] MAI	15	DPWA
1434^{+2}_{-2}	[3] MAI	15	DPWA
1330^{+4}_{-5}	[4] MAI	15	DPWA
1421^{+3}_{-2}	[5] GUO	13	DPWA
1388^{+9}	[6] GUO	13	DPWA
1424^{+7}_{-23}	[7] IKEDA	12	DPWA
1381^{+18}_{-6}	[8] IKEDA	12	DPWA

- **Our analysis** (+ 2 other groups) included
- **Pole positions** are now tabulated, prior to mass/width.

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/atoms**

Strategy

Fit to experimental data (chiral SU(3) EFT)

equivalent amplitude

Single-channel complex $\bar{K}N$ potential [1] (used in $\bar{K}$-nuclei calculation)

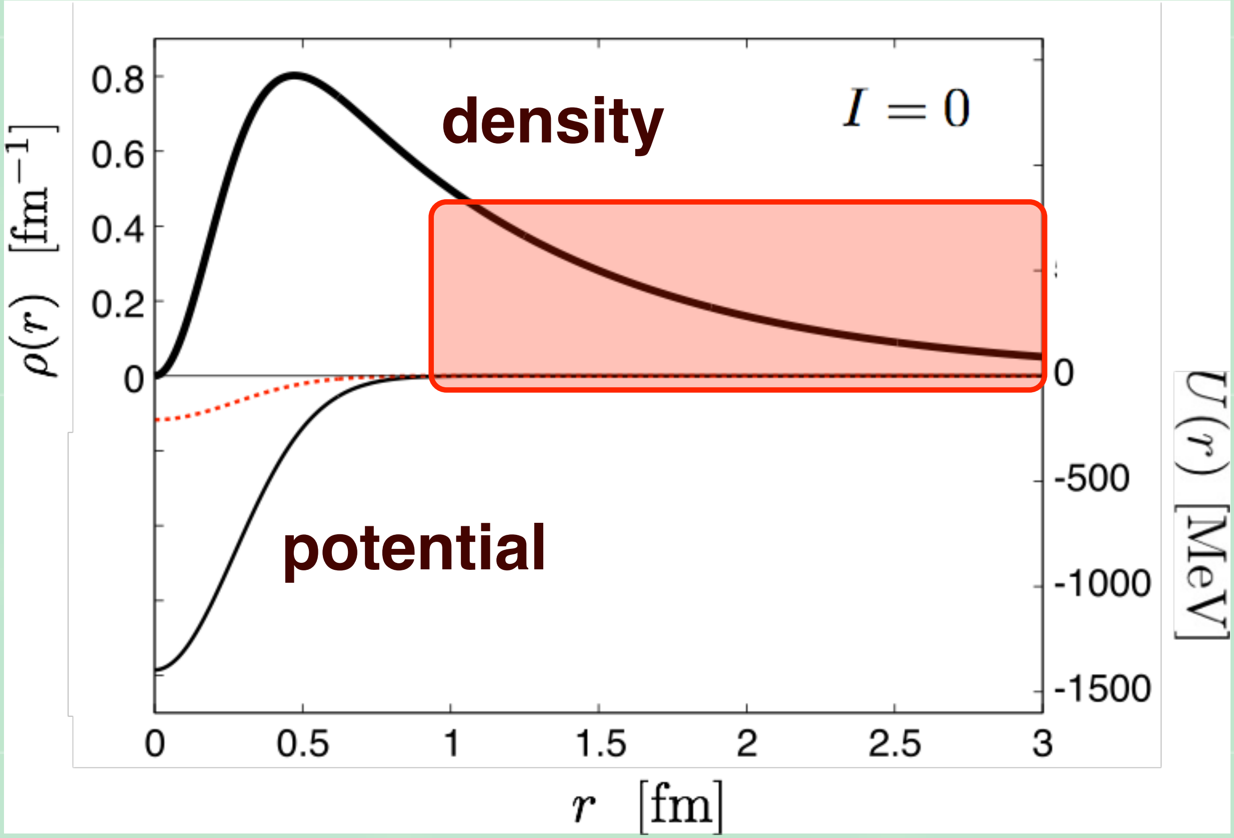
Coupled-channel real $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential [2]

[1] K. Miyahara. T. Hyodo, PRC 93, 015201 (2016);
[2] K. Miyahara, T. Hyodo, W. Weise, PRC 98, 025201 (2018).

Structure of Λ(1405)

$\bar{K}N$ wave function at Λ(1405) pole

K. Miyahara. T. Hyodo, PRC93, 015201 (2016)



- **substantial distribution at** r > 1 **fm**
- **root mean squared radius** $\sqrt{\langle r^2 \rangle} = 1.44$ fm

The size of Λ(1405) **is much larger than ordinary hadrons.**

Kaonic nuclei : current status

Recent experiment for $\bar{K}NN$ (J-PARC E15, $^3He(K^-,\Lambda p)n$)

S. Ajimura, *et al.*, arXiv:1805.12275 [nucl-ex].

$$B = 47 \pm 3^{+3}_{-6}\ \mathrm{MeV}, \quad \Gamma = 115 \pm 7^{+10}_{-9}\ \mathrm{MeV}$$

Theoretical calculation with realistic $\bar{K}N$ interaction

- **Fit to K-p cross sections and branching ratios**
- **SIDDHARTRA constraint of Kaonic hydrogen**

[1] J. Revai, N.V. Shevchenko, PRC 90, 034004 (2014),
[2] S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara. T. Hyodo, PRC95, 065202 (2017).

	V^1 [1]	V^2 [1]	V^{Chiral} [1]	[2]
B [MeV]	53.3	47.4	32.2	25-28
$\Gamma_{\pi YN}$ [MeV]	64.8	49.8	48.6	31-59

- 2N **absorption (Γ_{YN}) is NOT included.**

Kaonic nuclei

Rigorous few-body approach to $\bar{K}$ nuclear systems

S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara. T. Hyodo, PRC95, 065202 (2017).

- Stochastic variational method with correlated gaussians

$$\hat{V} = \hat{V}^{\bar{K}N}(\text{Kyoto } \bar{K}N) + \hat{V}^{NN}(\text{AV4}')$$ **(single channel)**

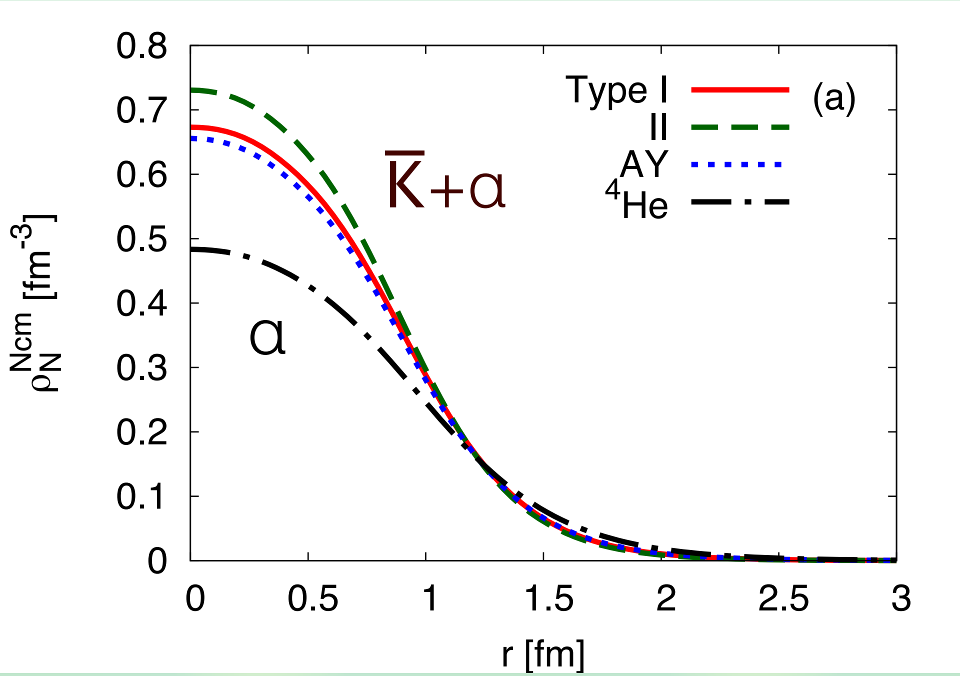
Results for A = 2, 3, 4, 6

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

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

High density?

Nucleon density distribution in four-nucleon system



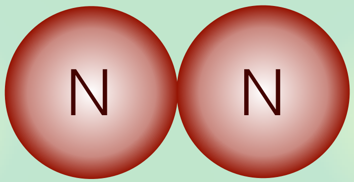
- **central density increases (not substantially <— NN core)**
- B = 68-76 **MeV (Kyoto** $\bar{K}$N**)**
- B = 85-87 **MeV (AY)**

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

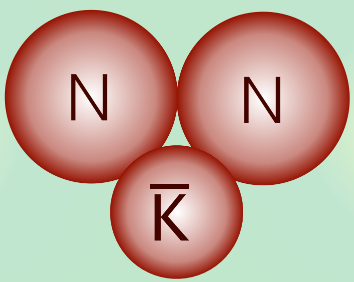
Interplay between NN and $\bar{K}$N correlations 1

Two-nucleon system

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



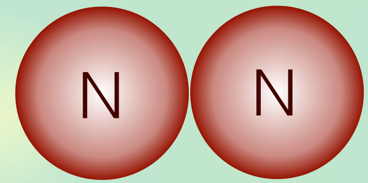
unbound



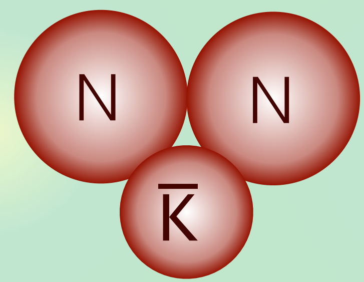
(quasi-)bound

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

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



bound (d)



Λ(1405)

unbound

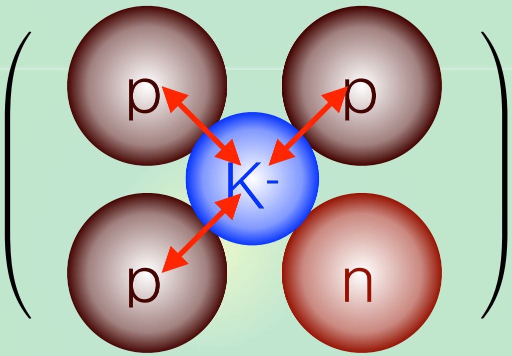
$\bar{K}N(I=0):\bar{K}N(I=1) = 1:3$

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

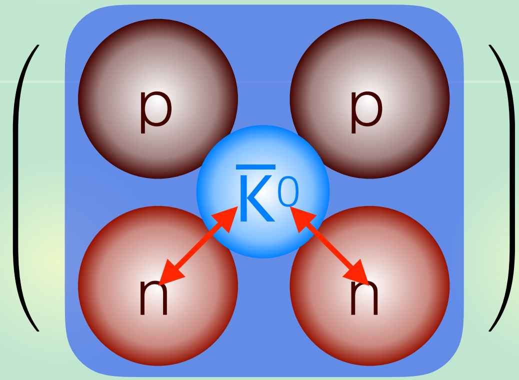
Interplay between NN and $\bar{K}$N correlations 2

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

$$|\,\bar{K}NNNN\,\rangle = C_1$$



$$+\,C_2$$



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

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

- **SIDDHARTA measurement of kaonic hydrogen reduces the ambiguity of $\bar{K}N$ amplitude.**
- **Pole positions of Λ(1405) are determined by fitting all existing data with χ^2/d.o.f. ~ 1.**

$$z_1 = (1424^{+7}_{-23} - i26^{+3}_{-14}) \text{ MeV}, \quad z_2 = (1381^{+18}_{-6} - i81^{+19}_{-8}) \text{ MeV}$$

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

- **Realistic $\bar{K}N$ potential is constructed.**

K. Miyahara. T. Hyodo, PRC93, 015201 (2016)

- **Structure of few-body kaonic nuclei reflects the interplay between NN and $\bar{K}N$ correlations.**

S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara, T. Hyodo, PRC95, 065202 (2017)