# $\bar{K}N$ interaction in chiral dynamics

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2017, Dec. 6th

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

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

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

  - Coupled-channel $\bar{K}N$-$\pi\Sigma$(-$\pi\Lambda$) potential

    K. Miyahara, T. Hyodo, W. Weise, in preparation

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

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    T. Hoshino, S. Ohnishi, W. Horiuchi, T. Hyodo, W. Weise, PRC96, 045204 (2017)

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

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

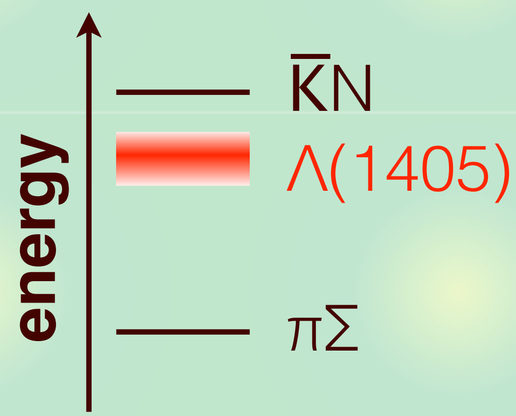
- NG boson of chiral $SU(3)_R \otimes SU(3)_L$ —> $SU(3)_V$
- Massive by strange quark: $m_K \sim 496$ MeV

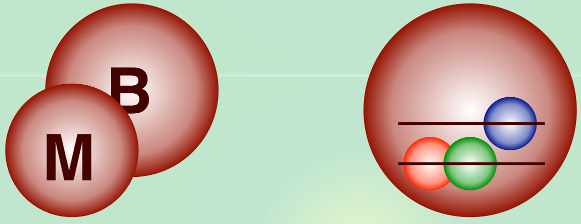
—> Spontaneous/explicit symmetry breaking

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

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

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



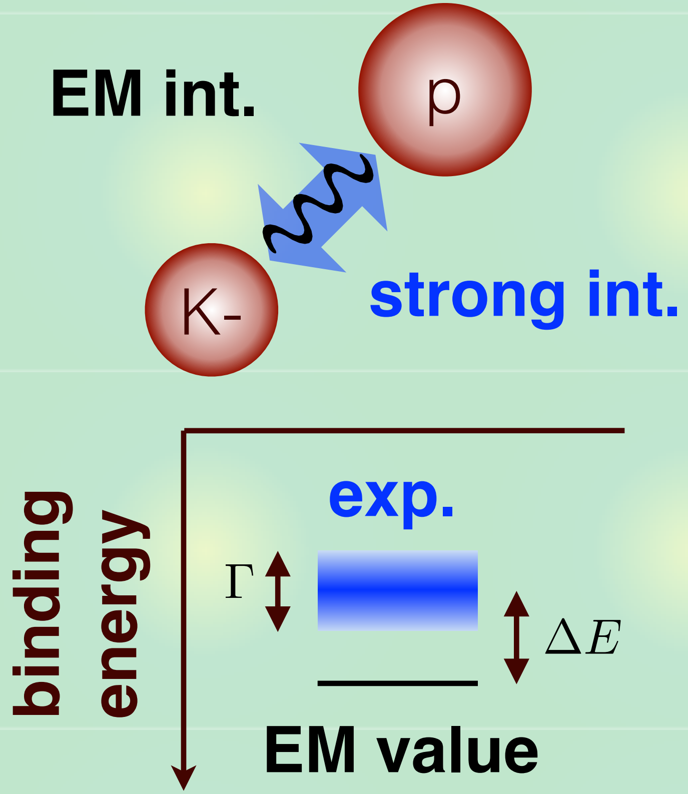

molecule three-quark

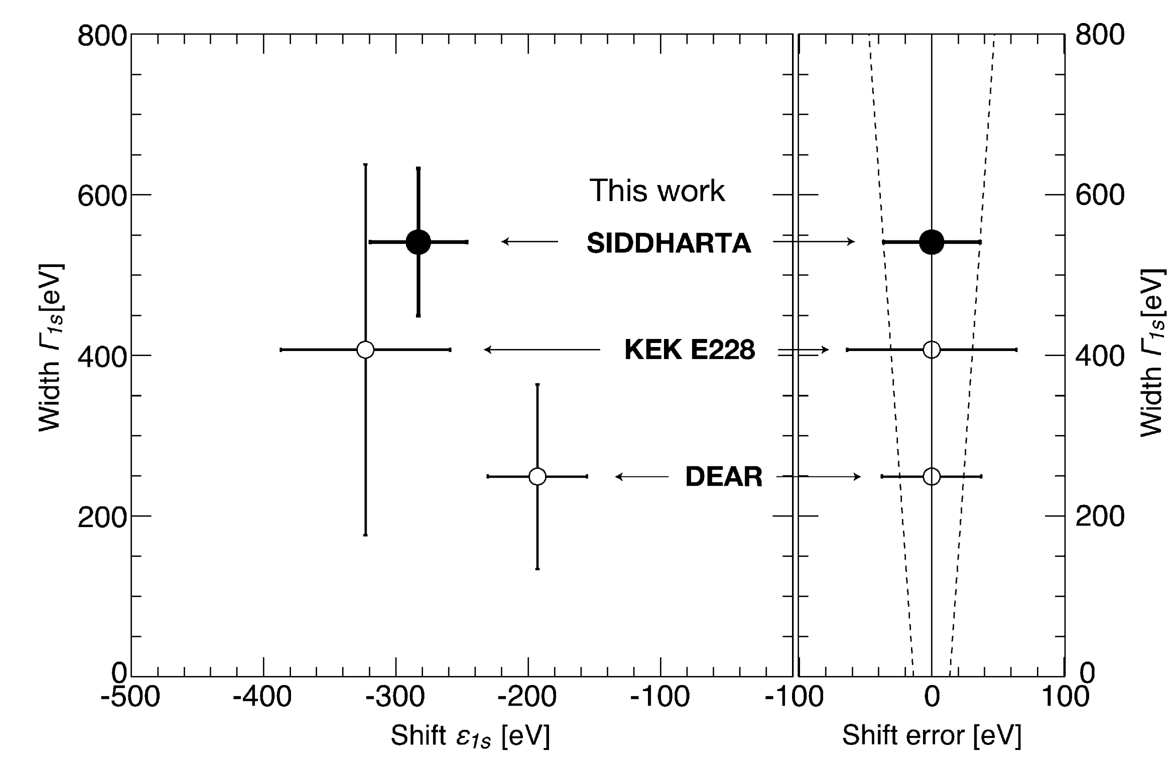
- is fundamental building block for $\bar{K}$-nuclei, $\bar{K}$ in medium, ...

# SIDDHARTA measurement

## Precise measurement of the kaonic hydrogen X-rays

**M. Bazzi, *et al.*, 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**

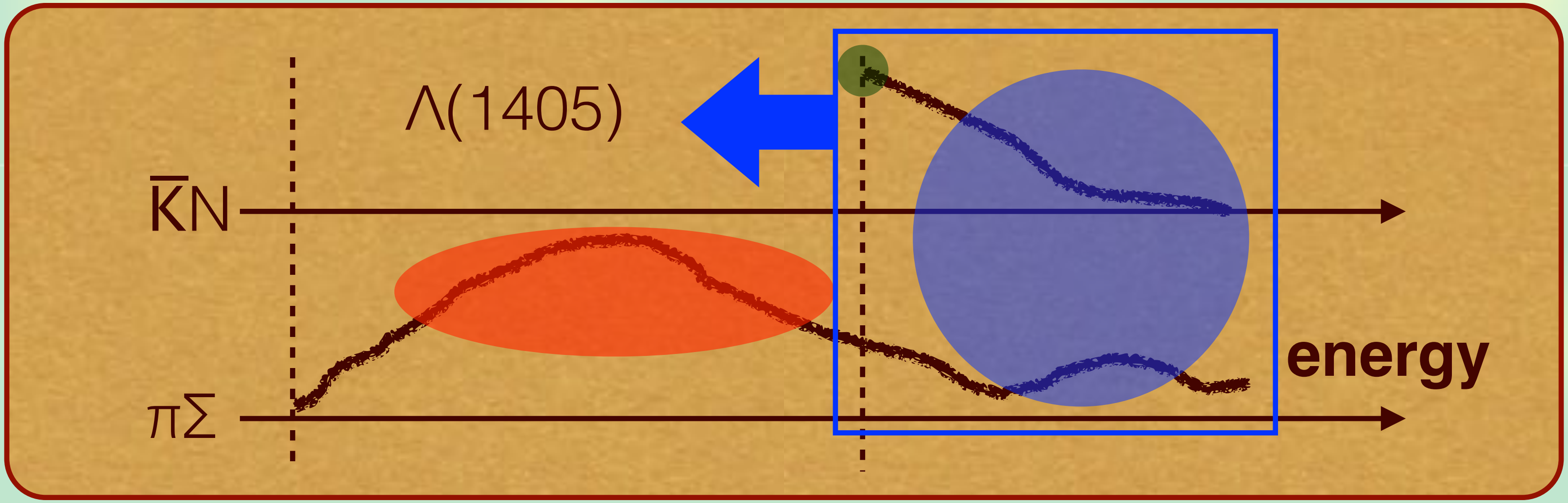
# Strategy for $\bar{K}N$ interaction

**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**

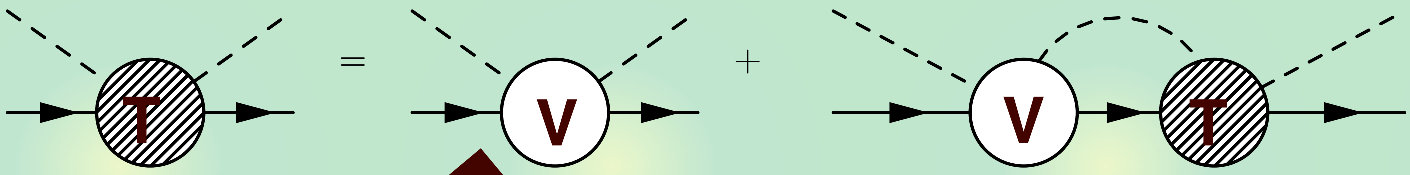
- $\pi\Sigma$ **mass spectra** **(new data: LEPS, CLAS, HADES,…)**



# Construction of the realistic amplitude

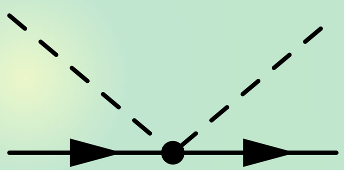
## Chiral coupled-channel approach with systematic $\chi^2$ fitting

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




Chiral perturbation theory

### 1) TW term

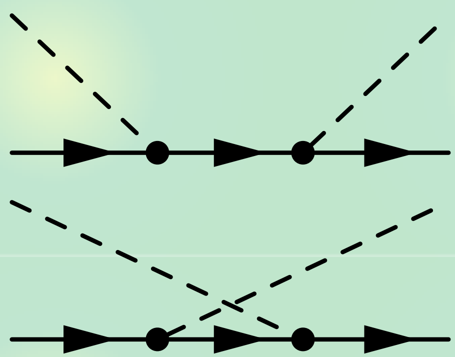


$\mathcal{O}(p)$

6 cutoffs

**TW model**

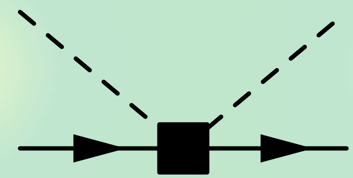
### 2) Born terms



$\mathcal{O}(p)$

**TWB model**

### 3) NLO terms



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

7 LECs

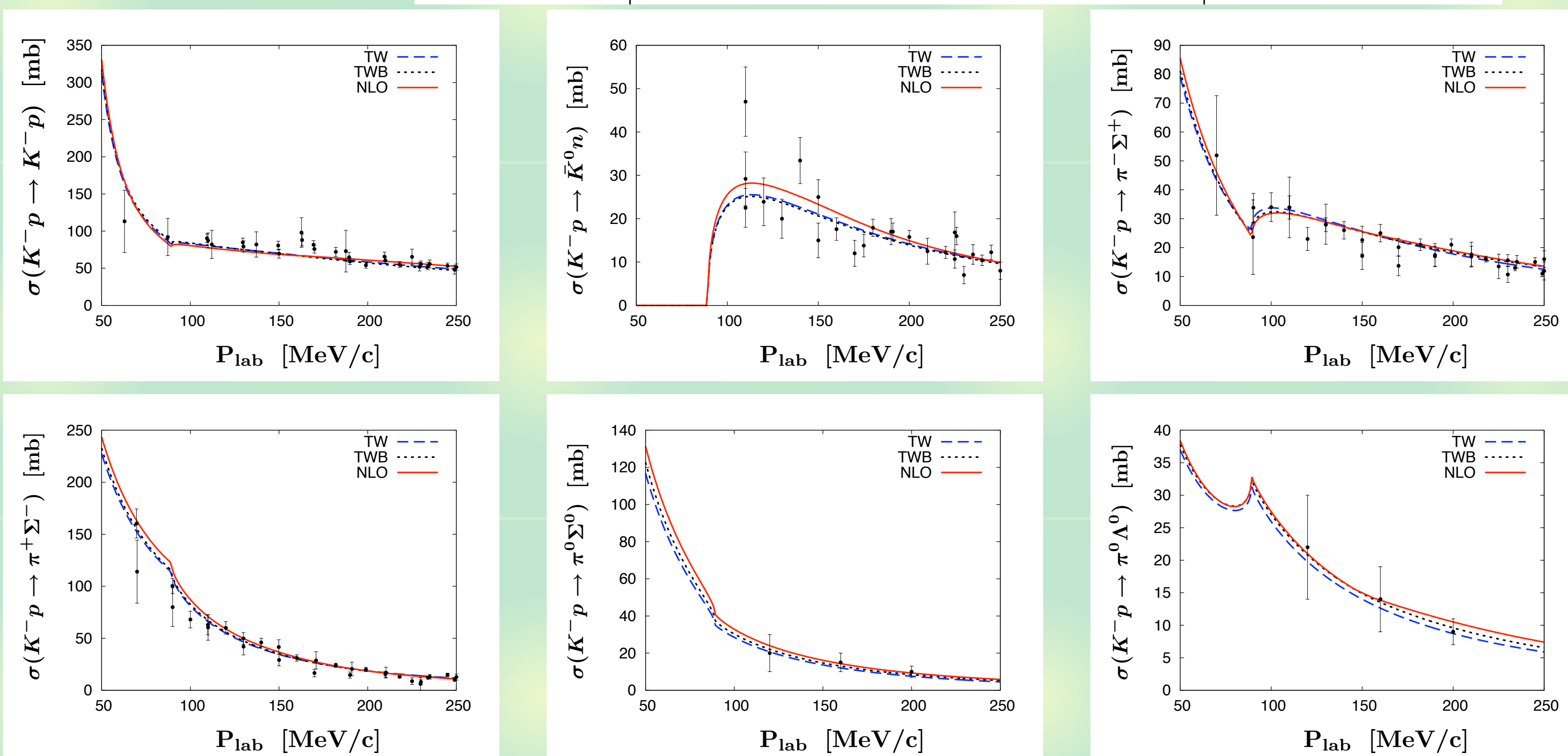
**NLO model**

$\overline{\mathrm{K}}$N interaction in chiral SU(3) dynamics

# Best-fit results

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

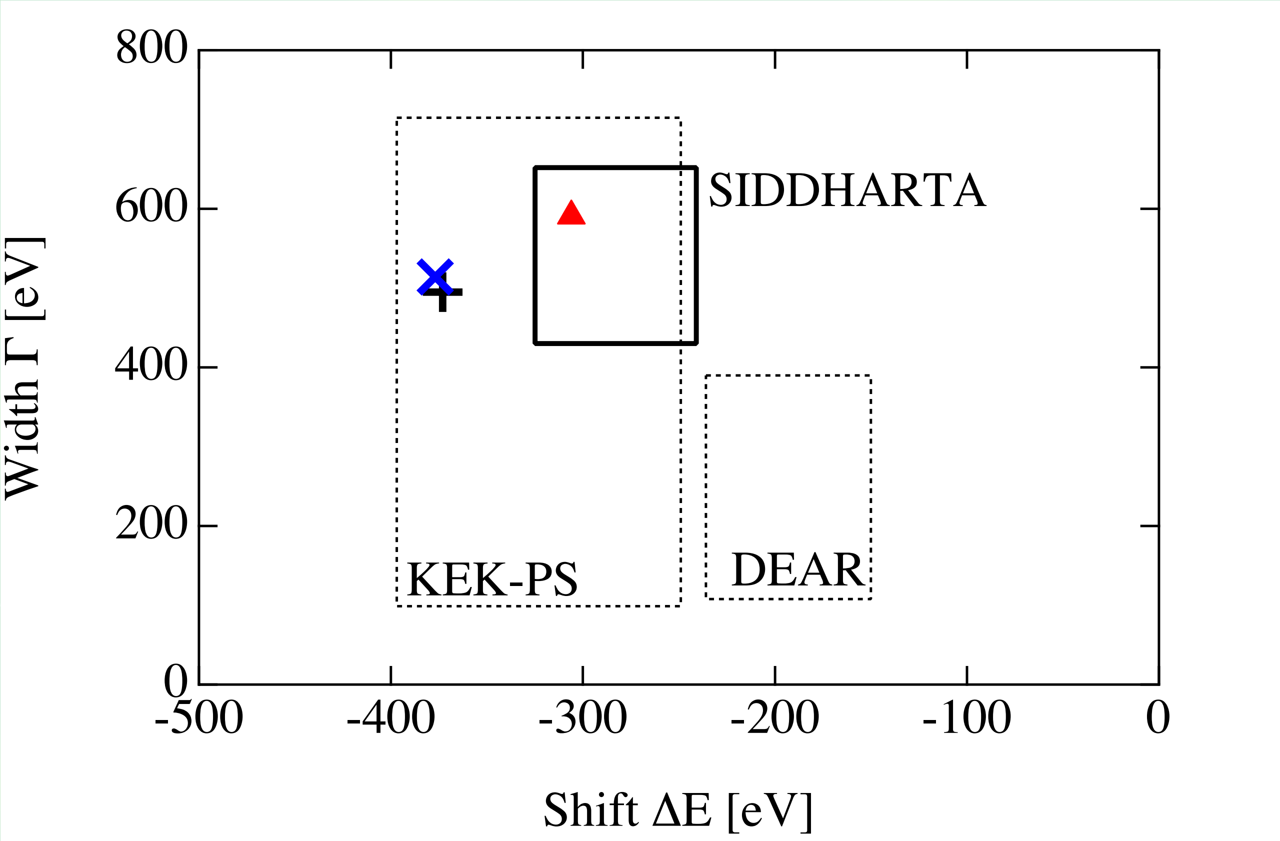
cross sections




$\overline{\mathrm{K}}$-hydrogen and cross sections are consistent (c.f. DEAR).

# Comparison with SIDDHARTA

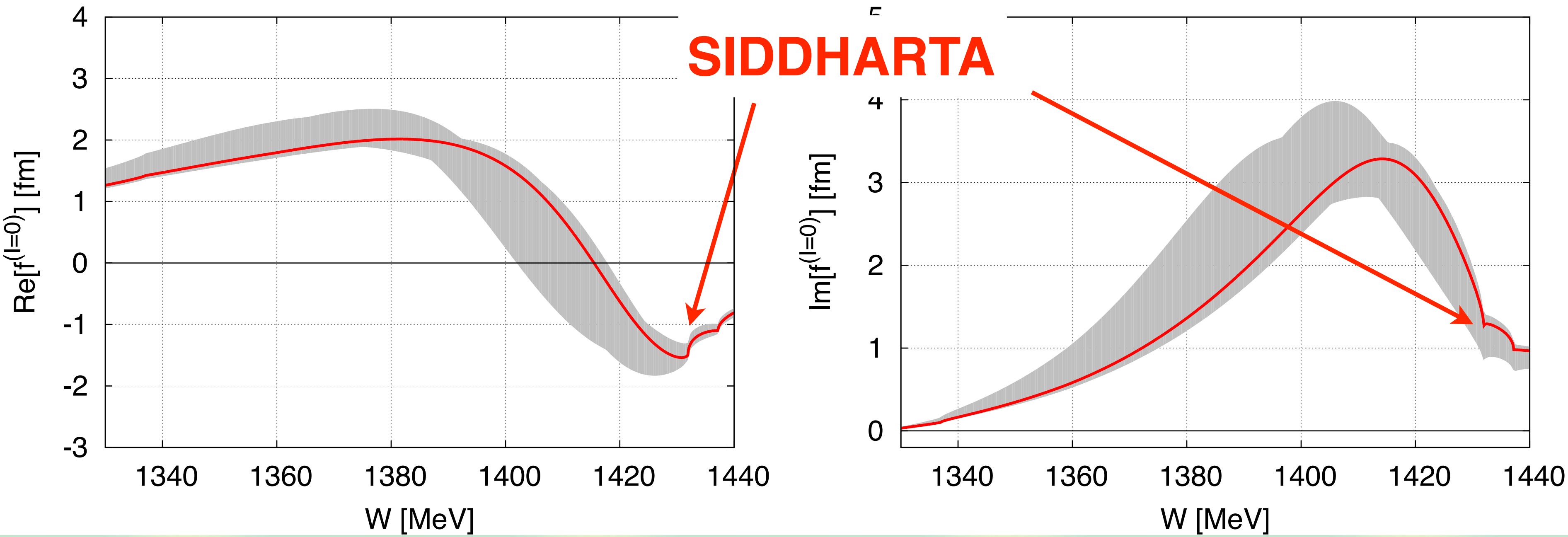
| | TW | TWB | NLO |
|---|---|---|---|
| $\chi^2$/d.o.f. | 1.12 | 1.15 | 0.957 |




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

# Subthreshold extrapolation

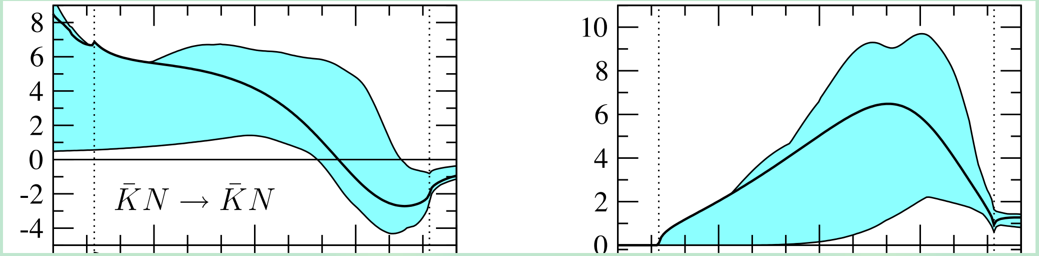
## Uncertainty of $\bar{K}N \longrightarrow \bar{K}N$ (I=0) amplitude below threshold




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)



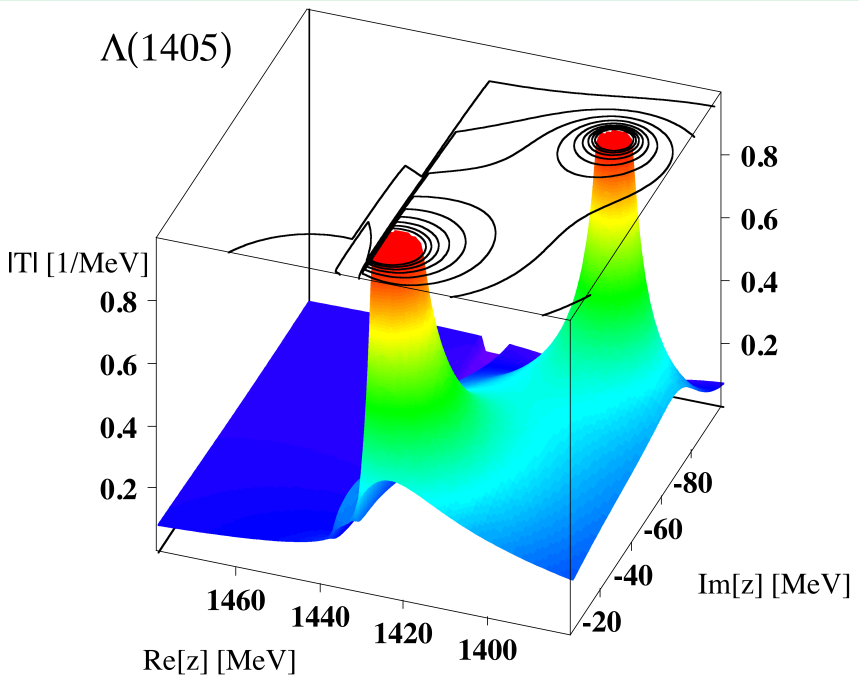

**SIDDHARTA is essential for subthreshold extrapolation.**

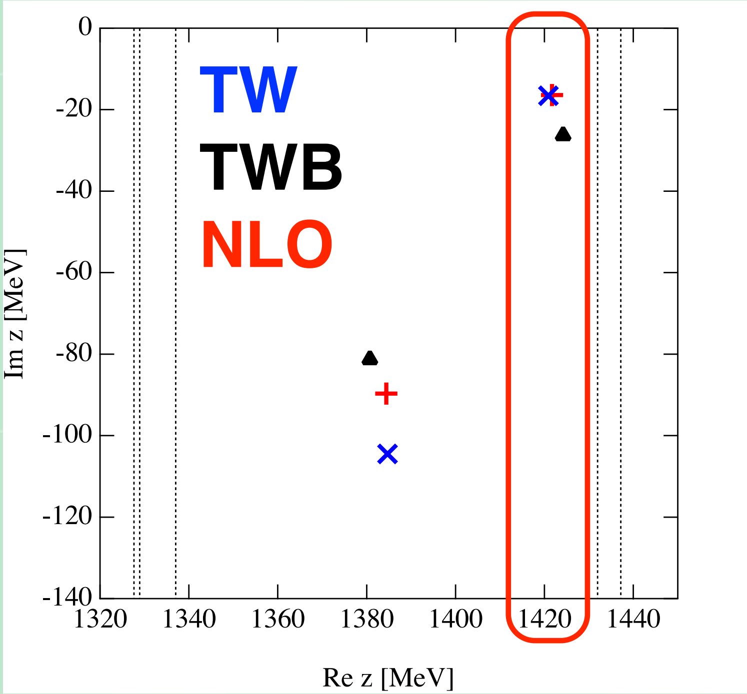
# Extrapolation to complex energy: two poles

## Two poles: superposition of two states

J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001);
D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, Nucl. Phys. A 723, 205 (2003);
T. Hyodo, W. Weise, Phys. Rev. C 77, 035204 (2008)

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




**NLO analysis confirms the two-pole structure.**

# PDG changes

## PDG particle listing

C. Patrignani, *et al.*, Chin. Phys. C40, 100001 (2016), http://pdg.lbl.gov/

**2014**

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

It seems to be the universal opinion of the chiral-unitary community that there are two poles in the 1400-MeV region. ZYCHOR 08 presents experimental evidence against the two-pole model, but this is disputed by GENG 07A. See also REVAI 09, which finds little basis for choosing between one- and two-pole models; and IKEDA 12, which favors the two-pole model.

A single, ordinary three-quark $\Lambda(1405)$ fits nicely into a $J^P = 1/2^-$ SU(4) $\bar{4}$ multiplet, whose other members are the $\Lambda_c(2595)^+$, $\Xi_c(2790)^+$, and $\Xi_c(2790)^0$; see Fig. 1 of our note on "Charmed Baryons."

**$\Lambda(1405)$ MASS**

**105. Pole Structure of the $\Lambda(1405)$ Region**

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

The $\Lambda(1405)$ 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

**2017**

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

In the 1998 Note on the $\Lambda(1405)$ in PDG 98, R.H. Dalitz disc... the S-shaped cusp behavior of the intensity at the $N$-$\bar{K}$ 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 $N$-$\bar{K}$ 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)$\pi^-$. The observed isotropic decay of $\Lambda(1405)$ is consistent with spin $J = 1/2$. The polarization transfer to the $\Sigma^+$(polarized) direction revealed negative parity, and thus established $J^P = 1/2^-$.

A REVIEW GOES HERE – Check our WWW List of Reviews

**$\Lambda(1405)$ REGION POLE POSITIONS**

**REAL PART**

• • • We do not use the following data for averages, fits, limits, etc. • • •

| VALUE (MeV) | DOCUMENT ID | | TECN |
|---|---|---|---|
| $1429^{+8}_{-7}$ | [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 |
| $1388 \pm 9$ | [6] GUO | 13 | DPWA |
| $1424^{+7}_{-23}$ | [7] IKEDA | 12 | DPWA |
| $1381^{+18}_{-6}$ | [8] IKEDA | 12 | DPWA |

- **Pole positions** are now tabulated, prior to mass/width.
- **Mini-review** on the pole structure is included.
- **Funny statements** are replaced by experimental info.

# 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**

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

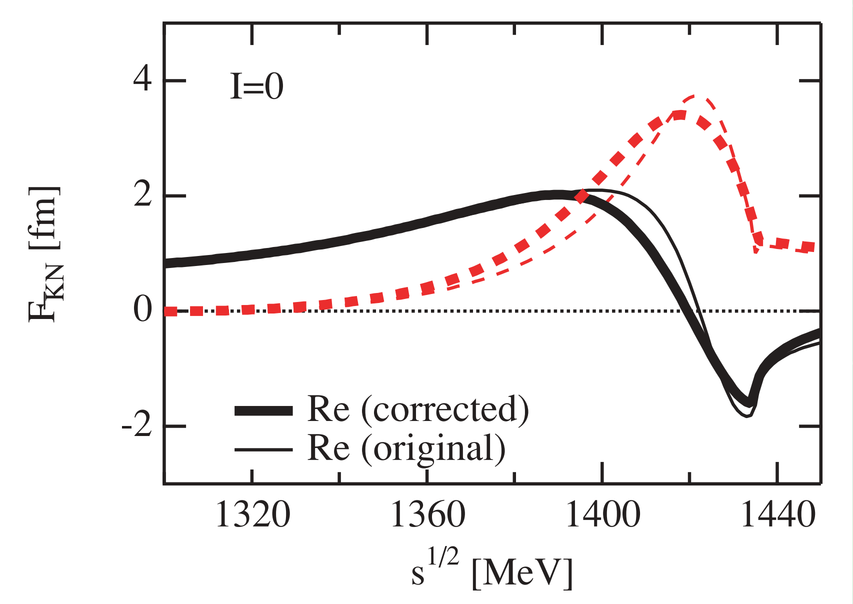
T. Hyodo, W. Weise, Phys. Rev. C 77, 035204 (2008)

- **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

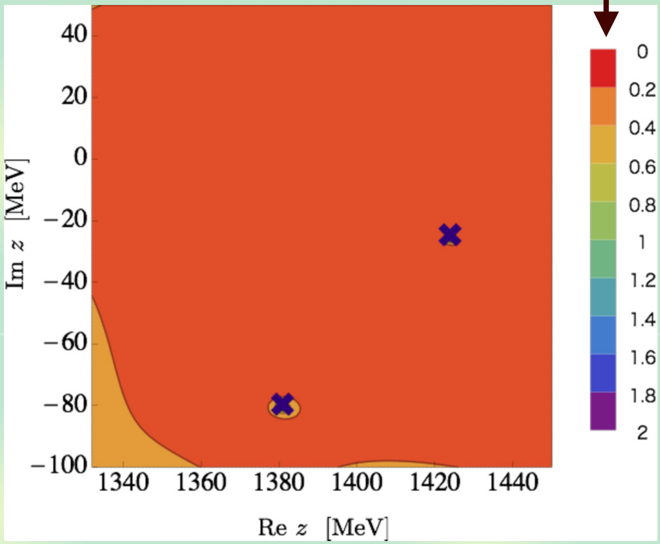
## Issues to be improved:

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

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

| Model | Pole position (MeV) original $F^{Ch}_{\bar{K}N}$ | 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



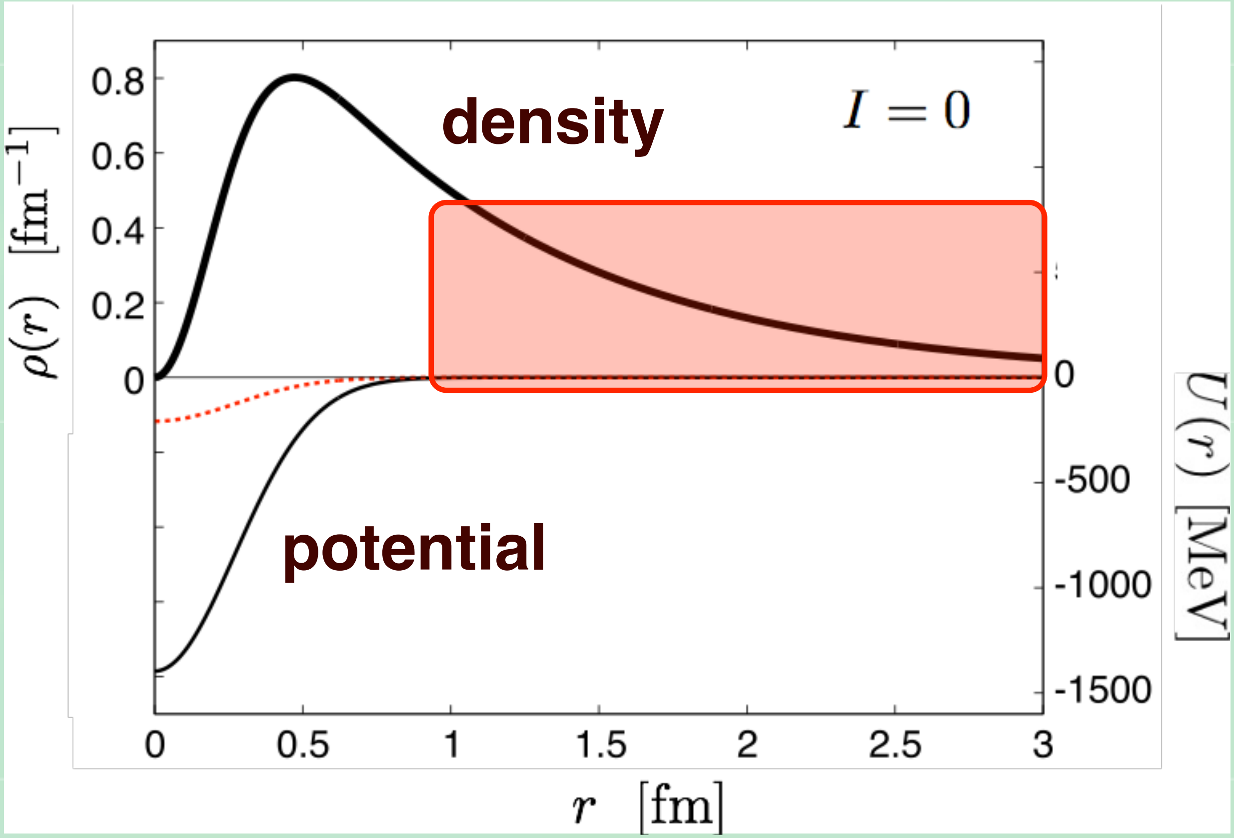

## New potential (Kyoto $\bar{K}N$ potential)

- Chiral SU(3) at NLO with SIDDHARTA
- Pole positions are reproduced with 1 MeV precision

**It reproduces data with $\chi^2$/d.o.f. ~ 1: realistic potential**

# Structure of Λ(1405)

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



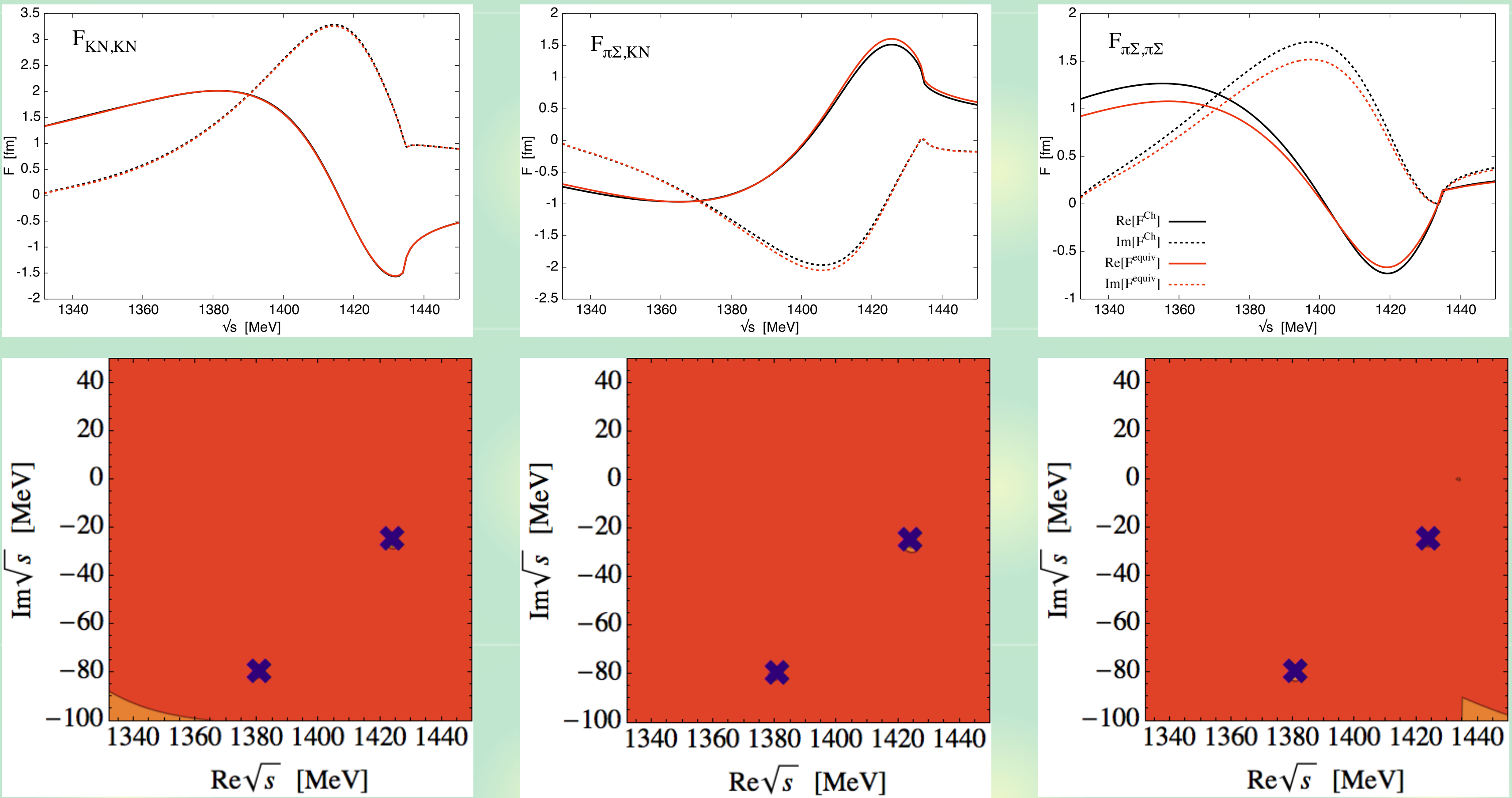

- **substantial distribution at** r > 1 **fm**
- **root mean squared radius** $\sqrt{\langle r^2 \rangle} = 1.44$ fm

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

# Coupled-channel potential

## Coupled-channel $\bar{K}N$-$\pi\Sigma$ potential

**K. Miyahara, T. Hyodo, W. Weise, in preparation**




- Simpler parametrization of E-dependence is possible.
- Pole positions are well reproduced.

# Kaonic nuclei

## Rigorous few-body approach to $\bar{\text{K}}$ 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

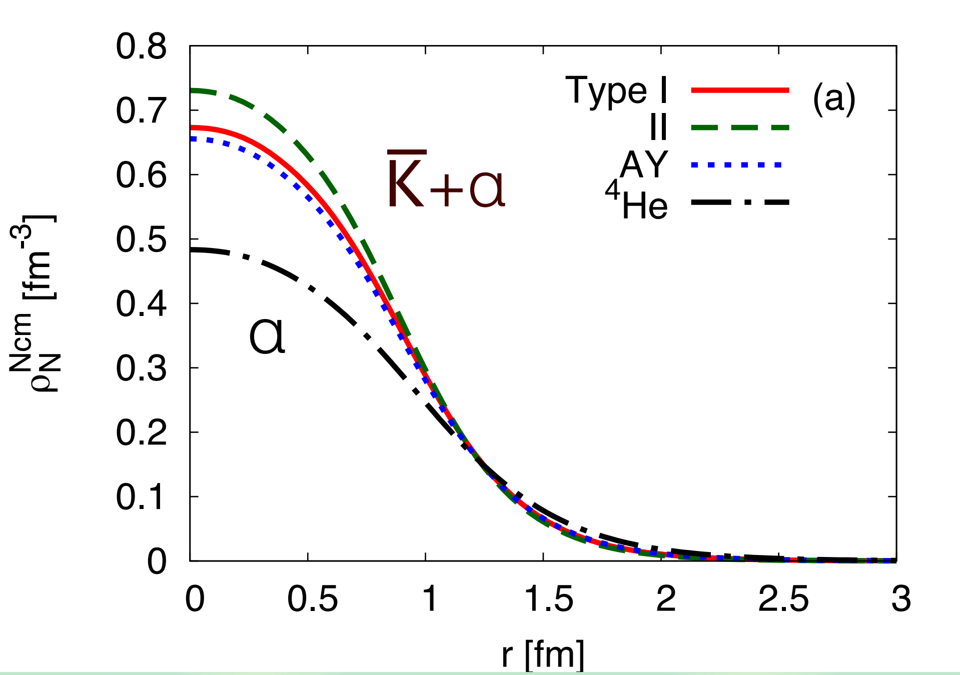
| | $\bar{\text{K}}$NN | $\bar{\text{K}}$NNN | $\bar{\text{K}}$NNNN | $\bar{\text{K}}$NNNNNN |
|---|---|---|---|---|
| B [MeV] | 25-28 | 45-50 | 68-76 | 70-81 |
| Γ [MeV] | 31-59 | 26-70 | 28-74 | 24-76 |

**- quasi-bound state below the lowest threshold**

**- decay width (without multi-N absorption) ~ binding energy**

# High density?

## Nucleon density distribution in four-nucleon system



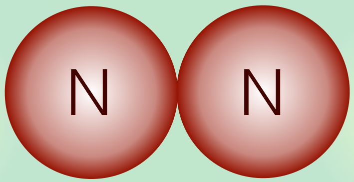

- **central density increases (not substantially <— NN core)**
- **B = 68-76 MeV (Kyoto $\bar{K}N$)**
- **B = 85-87 MeV (AY)**

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

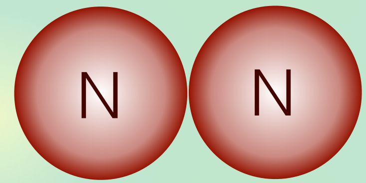
# Interplay between NN and $\bar{K}N$ correlations 1

## Two-nucleon system

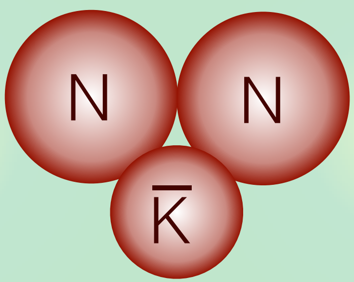
| $^1S_0$ ($I_{NN}$=1) | $^3S_1$ ($I_{NN}$=0) |
|---|---|




**unbound**

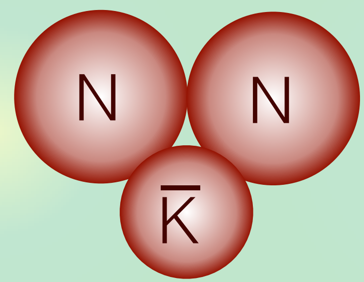



**bound (d)**




**(quasi-)bound**

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




$\Lambda(1405)$

**unbound**

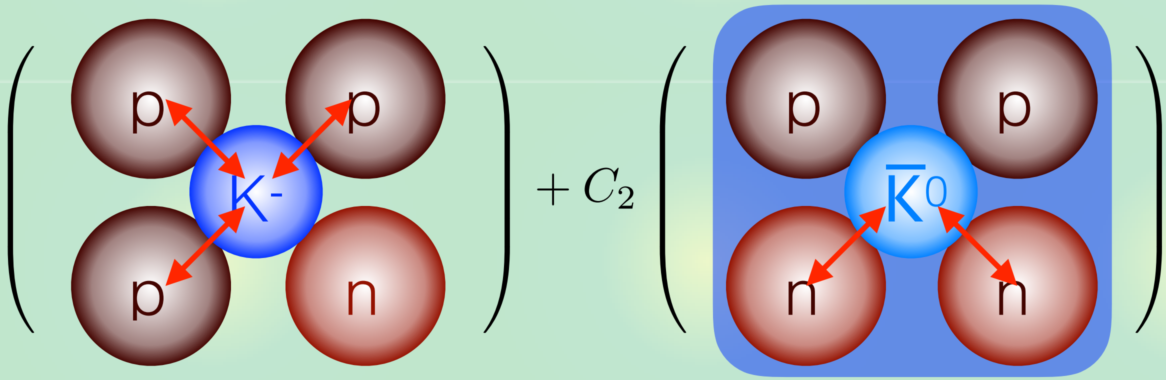
$\bar{K}N(I=0):\bar{K}N(I=1) = 1:3$

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

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

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

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




- $\bar{K}$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 **:** $C_1 < C_2$

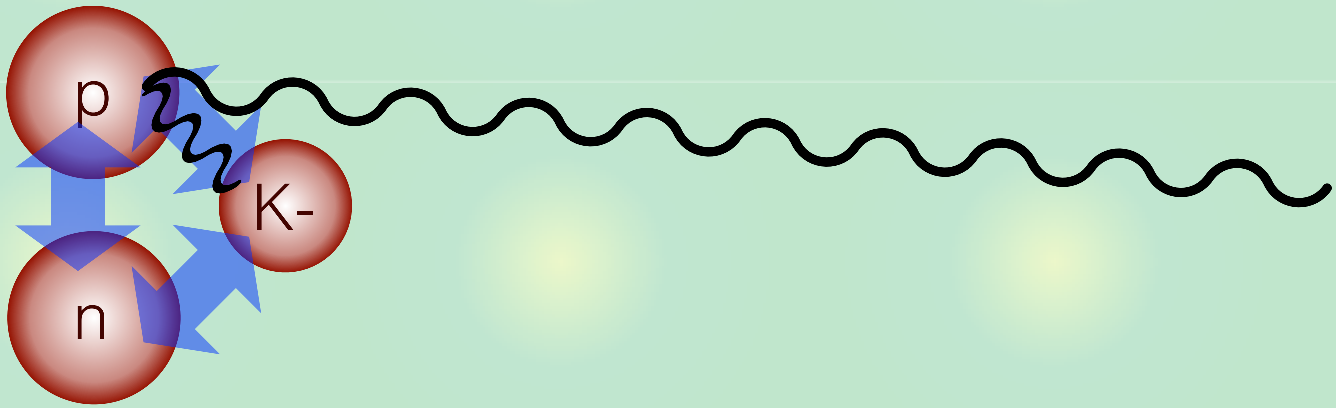
- **Numerical result**

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

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

# Kaonic deuterium: background

K-pn **system with strong + Coulomb interaction**




**- Experiments are planned at J-PARC E57, SIDDHARTA-2**

**- Complementary to** K-p **for** $\bar{K}N$ **isospin decomposition**

## Previous studies

**- Rigorous treatment of strong+Coulomb is not easy**
**-> two-body** K-d **treatment, EFT (expansion), etc.**

**- Recent (advanced) Faddeev calculation:**

**J. Revai, Phys. Rev. C 94, 054001 (2016)**

# Kaonic deuterium: results

## Rigorous three-body calculation with isospin breaking

T. Hoshino, S. Ohnishi, W. Horiuchi, T. Hyodo, W. Weise, PRC96, 045204 (2017)

$$\hat{V} = \hat{V}^{\bar{K}N}(\text{Kyoto } \bar{K}N) + \hat{V}^{NN}(\text{Minnesota}) + \hat{V}^{\text{EM}}$$

## Results

- **Shift-width of the 1S state:**

$$\Delta E - i\Gamma/2 = (670 - i508)\ \text{eV}$$

- **No shift in 2P state is shown by explicit calculation.**

## Varying I=1 potential within SIDDHARTA uncertainty of K-p

| $\beta$ | $K^-p$ | | $K^-d$ | |
|---|---|---|---|---|
| | $\Delta E$ | $\Gamma$ | $\Delta E$ | $\Gamma$ |
| 1.08 | 287 | 648 | 676 | 1020 |
| 1.00 | 283 | 607 | 670 | 1016 |
| −0.17 | 310 | 430 | 506 | 980 |

- **Precision 30-60 eV for ΔE gives a strong constraint on I=1**

# Summary: $\Lambda(1405)$

- $\bar{K}N$ **scattering is quantitatively described by NLO chiral coupled-channel approach.**

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

- **Realistic** $\bar{K}N$ **potential** ($\chi^2$**/d.o.f. ~ 1) is available.**

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

- **Few-body kaonic nuclei exist as quasi-bound states. Structure is determined by the interplay between NN and** $\bar{K}N$ **correlations.**

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

- **Shift-width of kaonic deuterium is found to be**

  $$\Delta E - i\Gamma/2 = (670 - i508)\ \mathrm{eV}$$

  T. Hoshino, S. Ohnishi, W. Horiuchi, T. Hyodo, W. Weise, PRC96, 045204 (2017)