Kaonic deuterium from realistic antikaon-nucleon interaction

Tetsuo Hyodo

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2018, Jun. 7th

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

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

    K. Miyahara, T. Hyodo, W. Weise, arXiv:1804.08269 [nucl-th]

- Application to kaonic deuterium

  - Prediction of shift and width

  - Sensitivity to $I=1$ component

    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

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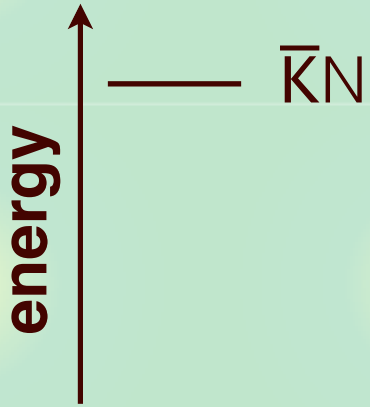
T. Hyodo, D. Jido, Prog. Part. Nucl. Phys. 67, 55 (2012)



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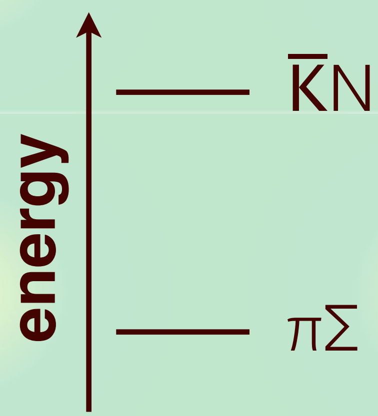

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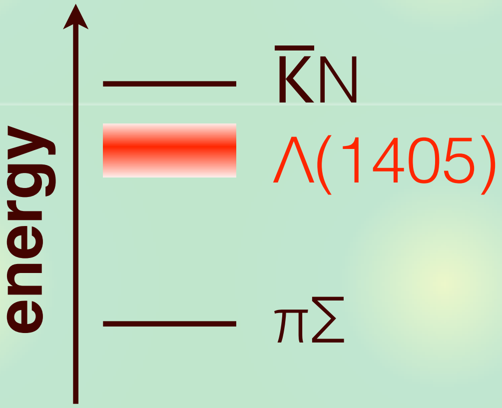

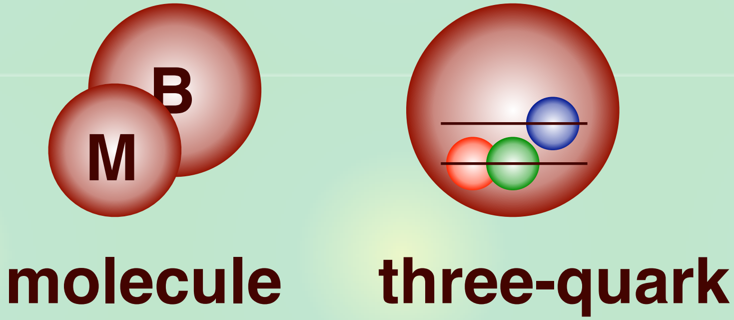

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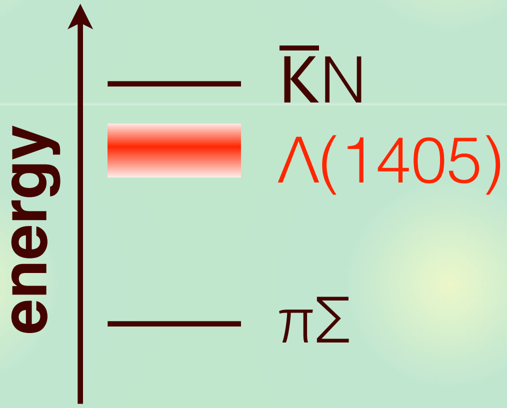
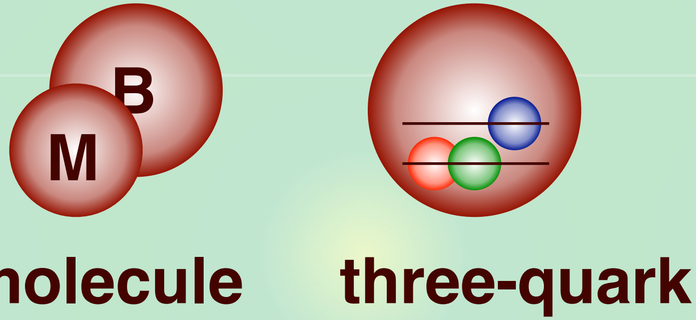


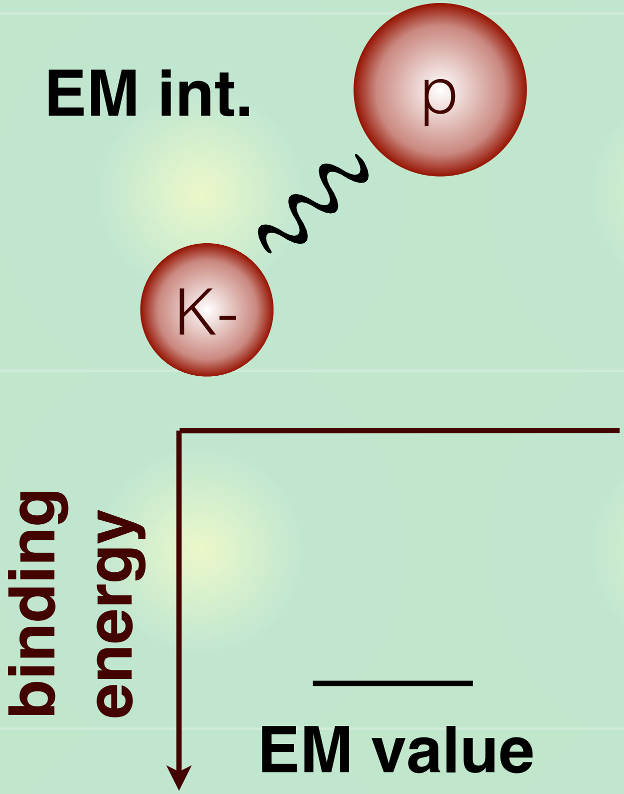


- is fundamental building block for $\bar{K}$-nuclei, $\bar{K}$-atoms, ...

SIDDHARTA measurement

Precise measurement of the kaonic hydrogen X-rays

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



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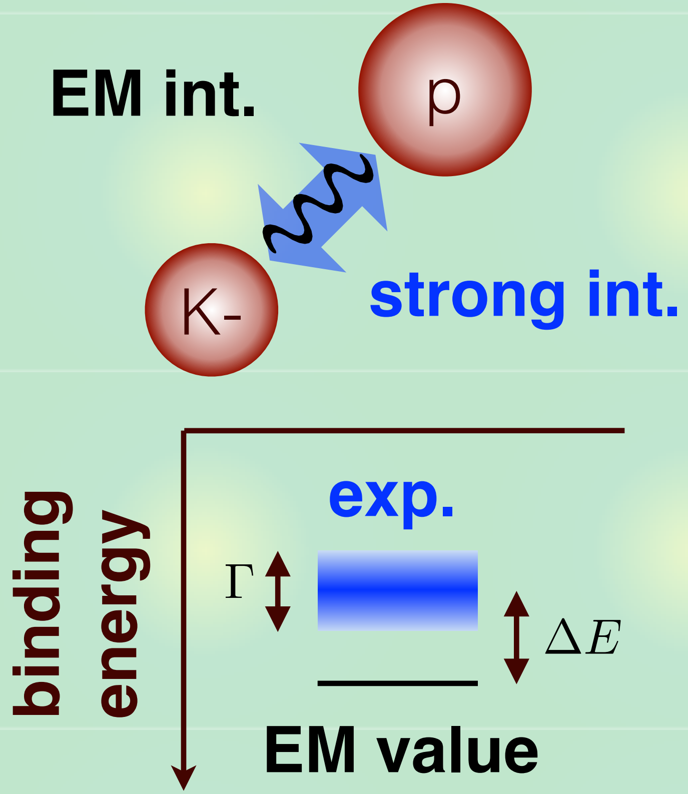

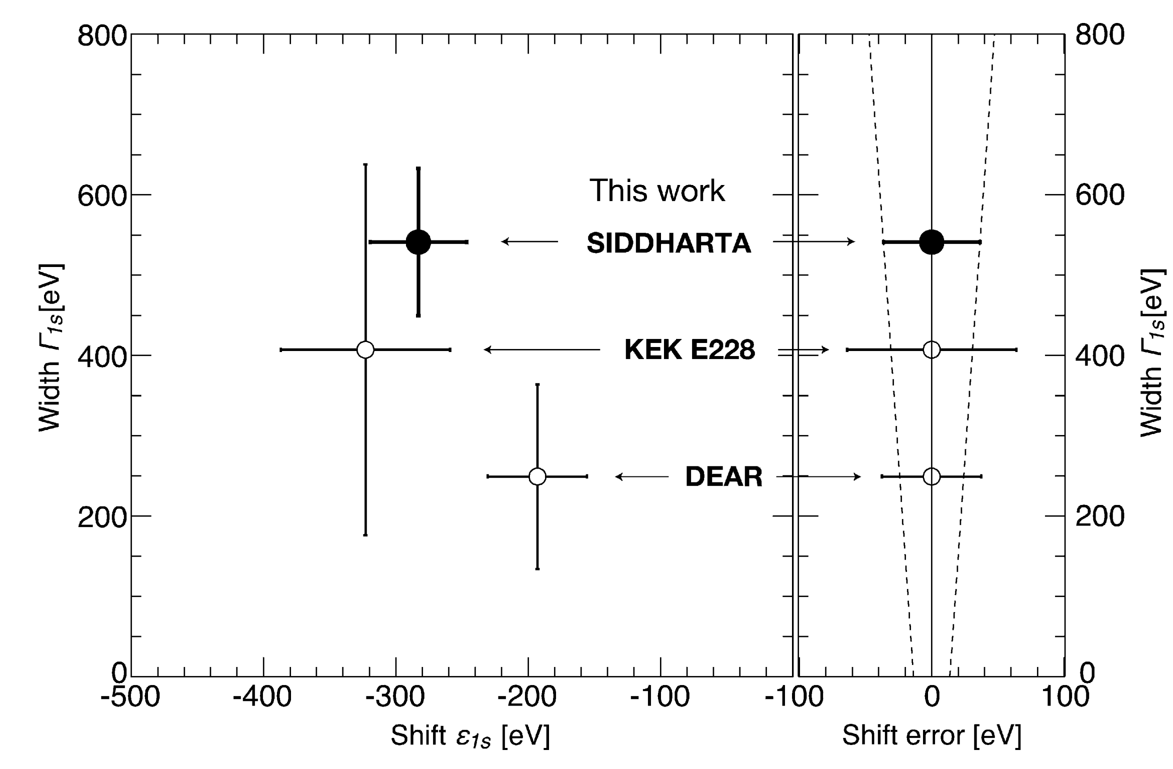

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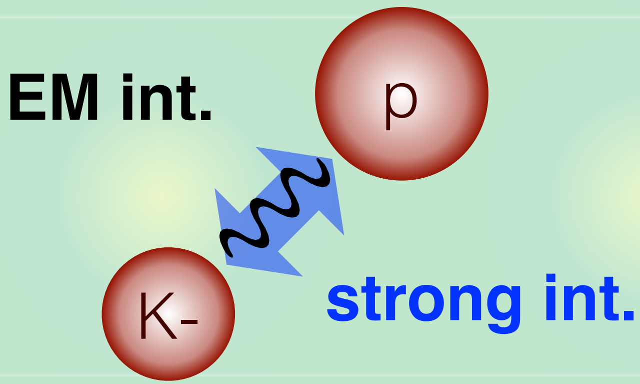
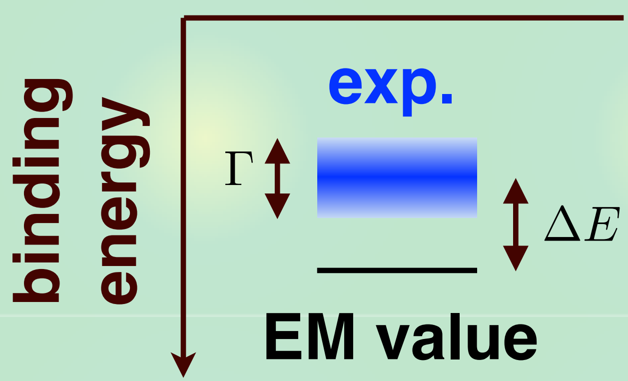
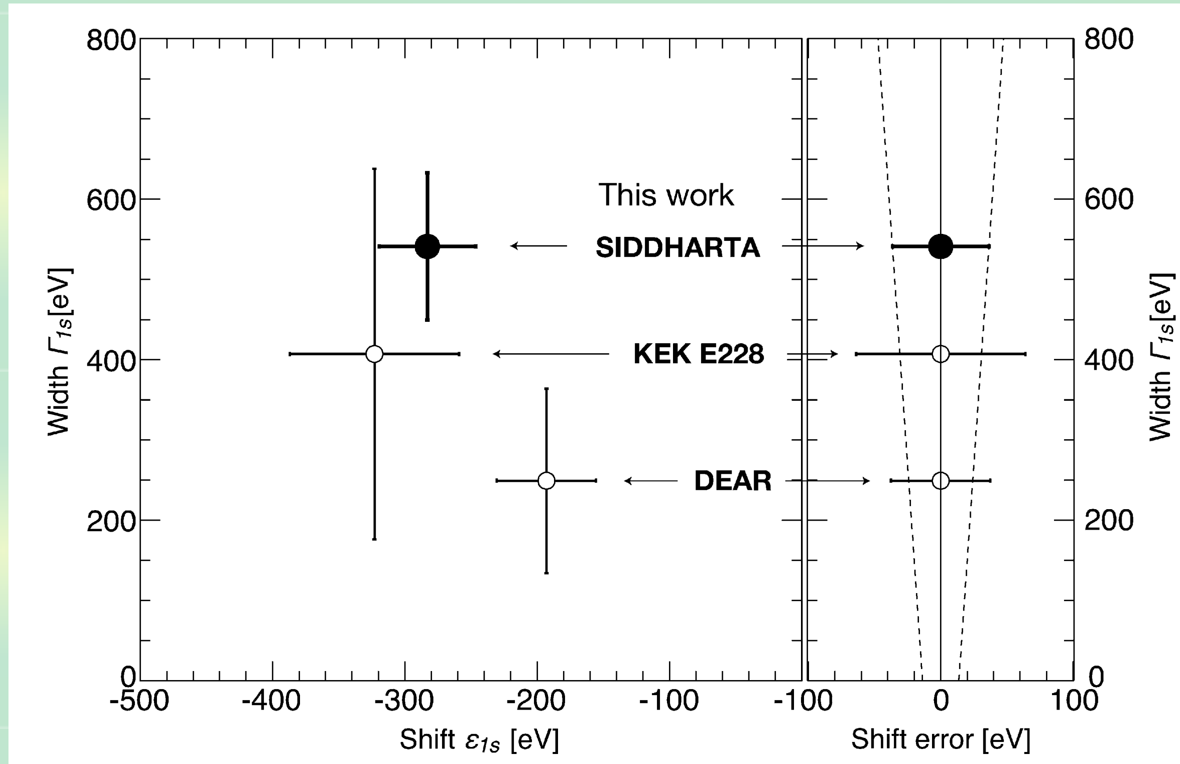






- Shift and width of atomic state <—> K-p scattering length

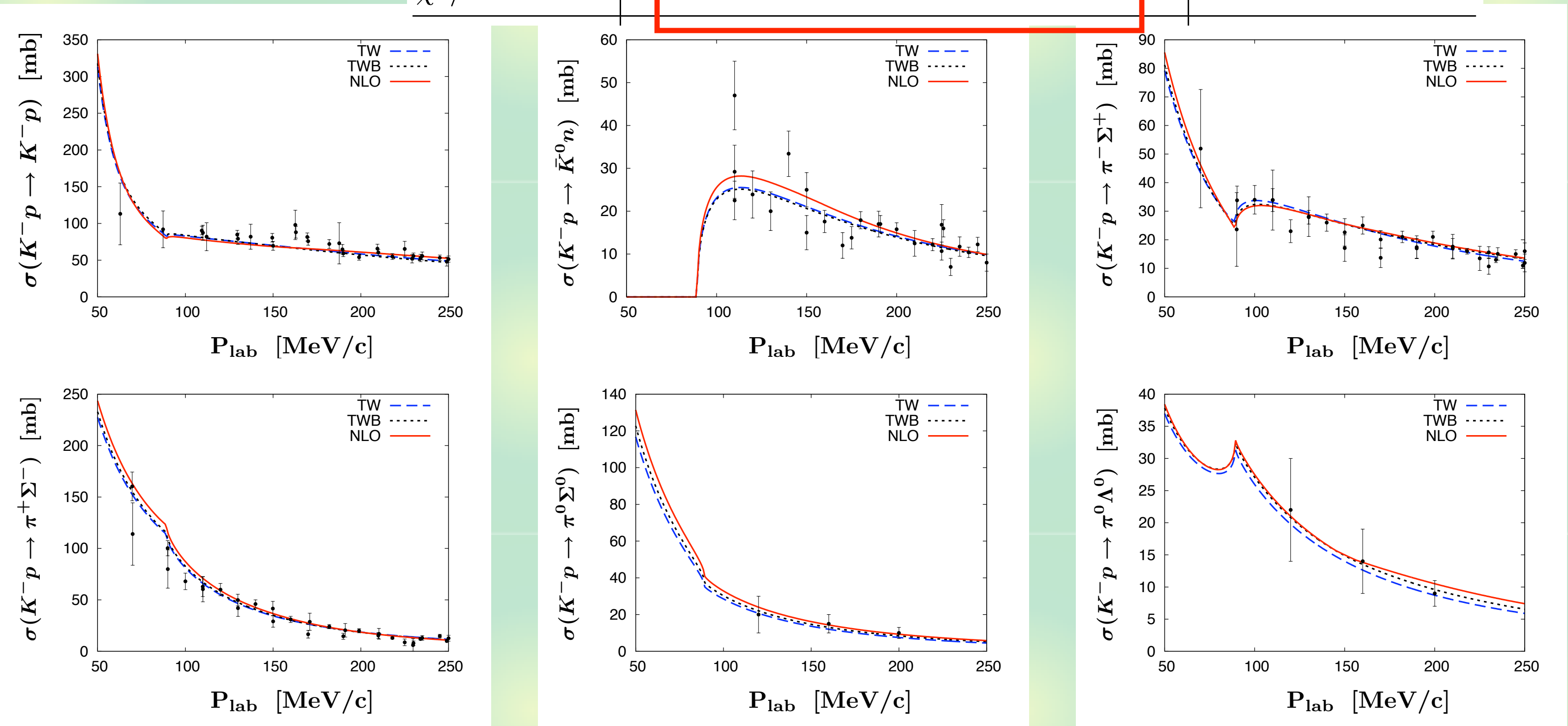
U.-G. Meissner, U. Raha, A. Rusetsky, Eur. Phys. J. C35, 349 (2004)

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

Best-fit results of chiral SU(3) dynamics

		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

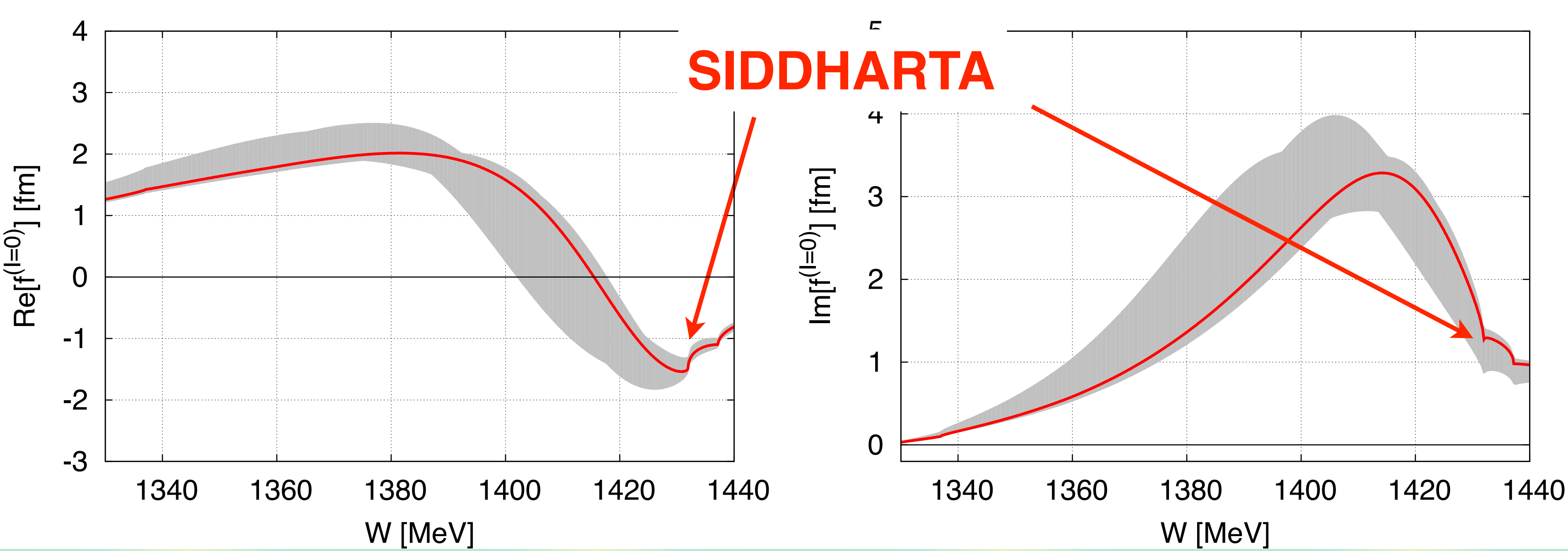


Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)

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

Subthreshold extrapolation

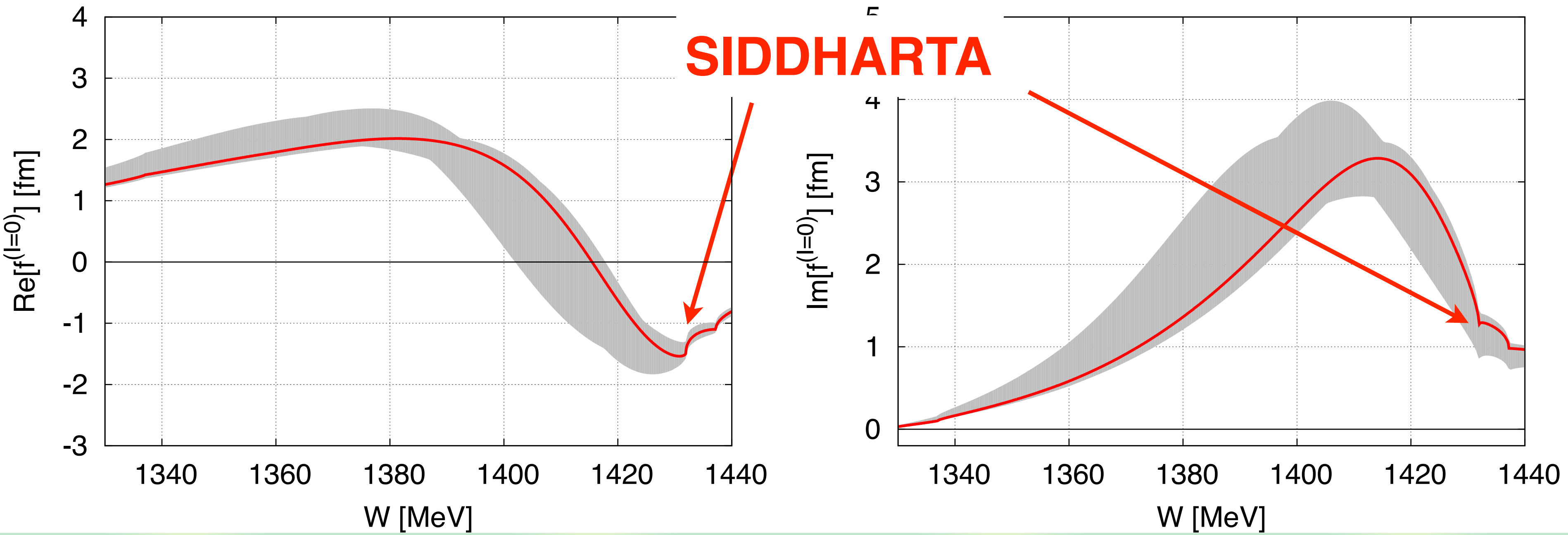
Uncertainty of $\bar{K}N$ —> $\bar{K}N$ (I=0) amplitude below threshold



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

Subthreshold extrapolation

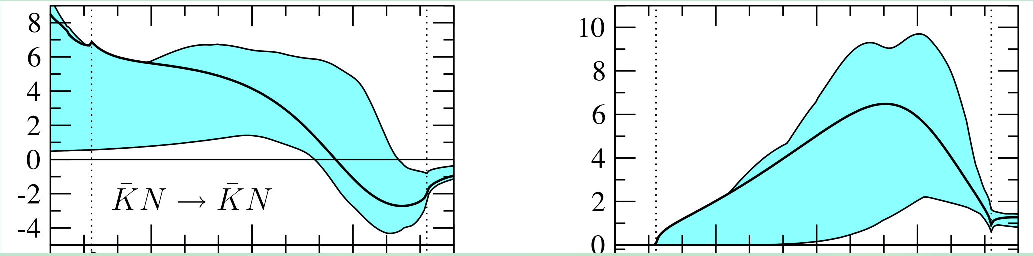
Uncertainty of K̄N —> K̄N (I=0) amplitude below threshold



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)

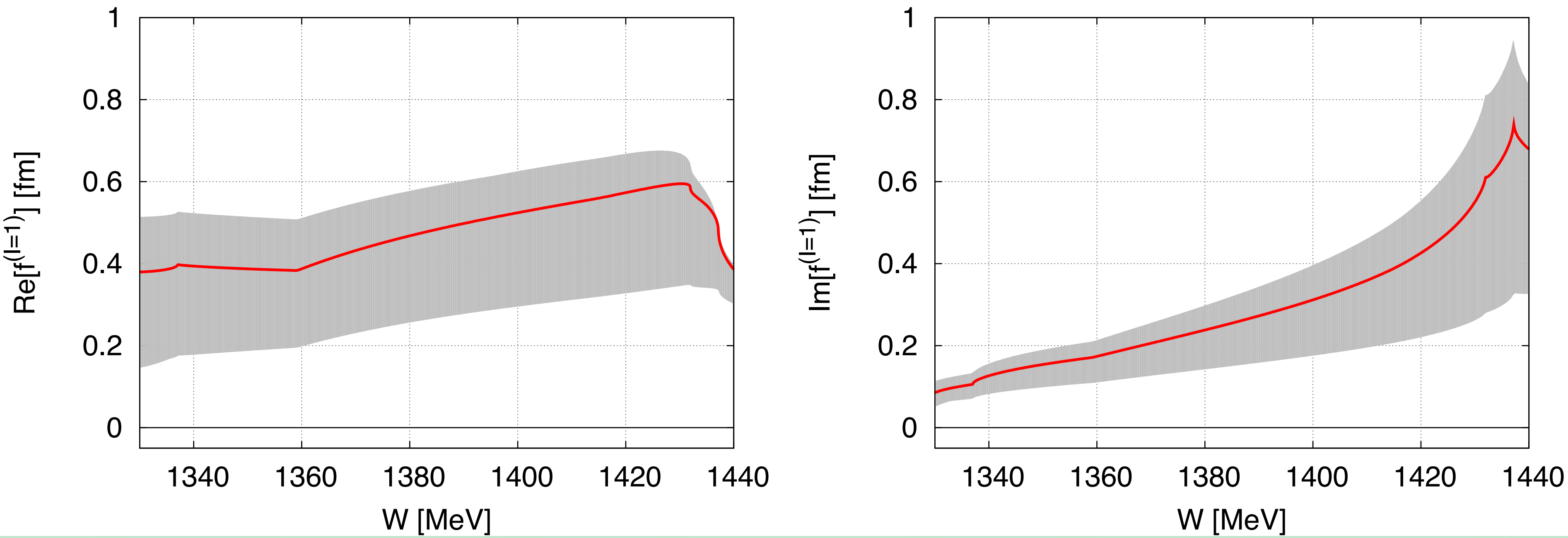


Accurate data is essential to reduce theoretical uncertainty.

Remaining ambiguity

$\bar{K}N$ interaction has two isospin components (I=0, I=1).

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



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Relatively large uncertainty in I=1 sector

- More constraints required (<— kaonic deuterium?)

PDG changes

PDG particle listing of $\Lambda(1405)$

M. Tanabashi, *et al.*, Phys. Rev. D98, 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.

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) $\overline{4}$ 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

PRODUCTION EXPERIMENTS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$1405.1^{+1.3}_{-1.0}$ OUR AVERAGE					
1405^{+11}_{-9}		HASSANVAND	13	SPEC	$pp \to p\Lambda(1405)K^+$
$1405^{+1.4}_{-1.0}$		ESMAILI	10	RVUE	^{4}He $K^- \to \Sigma^\pm\pi^\mp X$ at rest
1406.5 ± 4.0		[1] DALITZ	91		M-matrix fit

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

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

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- **Our analysis** (+ 2 other groups) included

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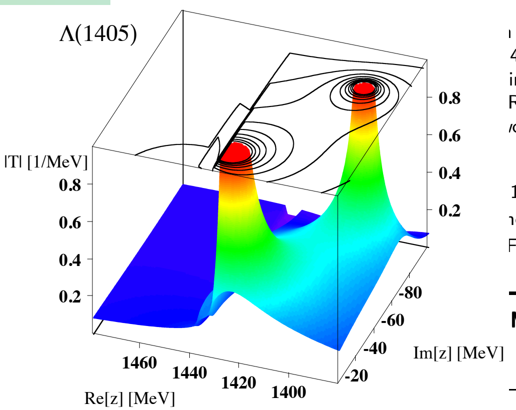

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MASS

TECN COMMENT

1.0

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

2018

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

Construction of $\bar{K}N$ potential

Accurate scattering amplitude is now available.

- local $\bar{K}N$ potential in Schrödinger eq.

—> device to be used in few-body calculations

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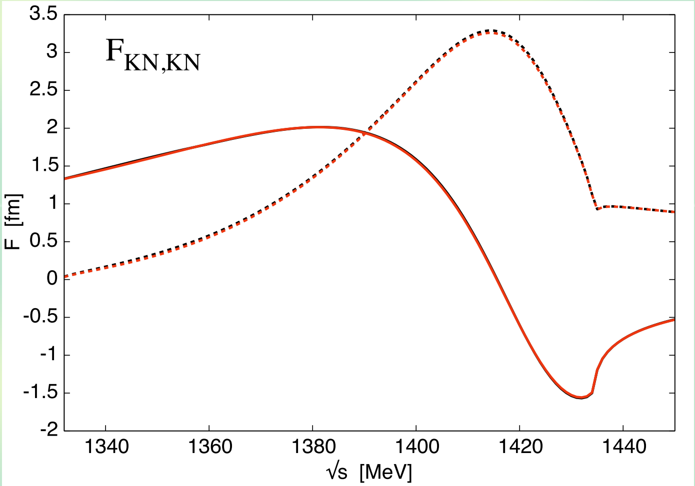

Construction of equivalent potential

- **single-channel $\bar{K}N$ potential**

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

- **coupled-channel $\bar{K}N$-$\pi\Sigma$ potential**

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- **original (black) v.s. potential (red)**

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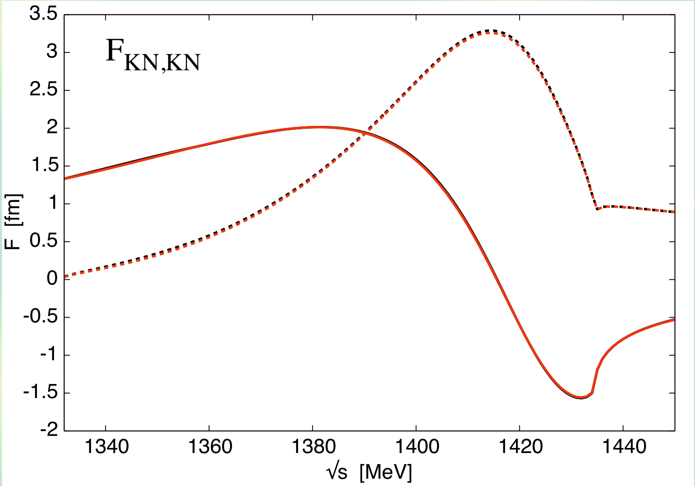

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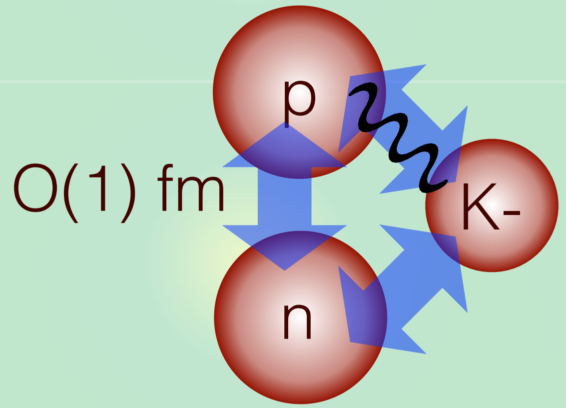
These potentials accurately reproduces data (χ^2/d.o.f. ~ 1)

—> realistic $\bar{K}N$ potential

Kaonic deuterium: background

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



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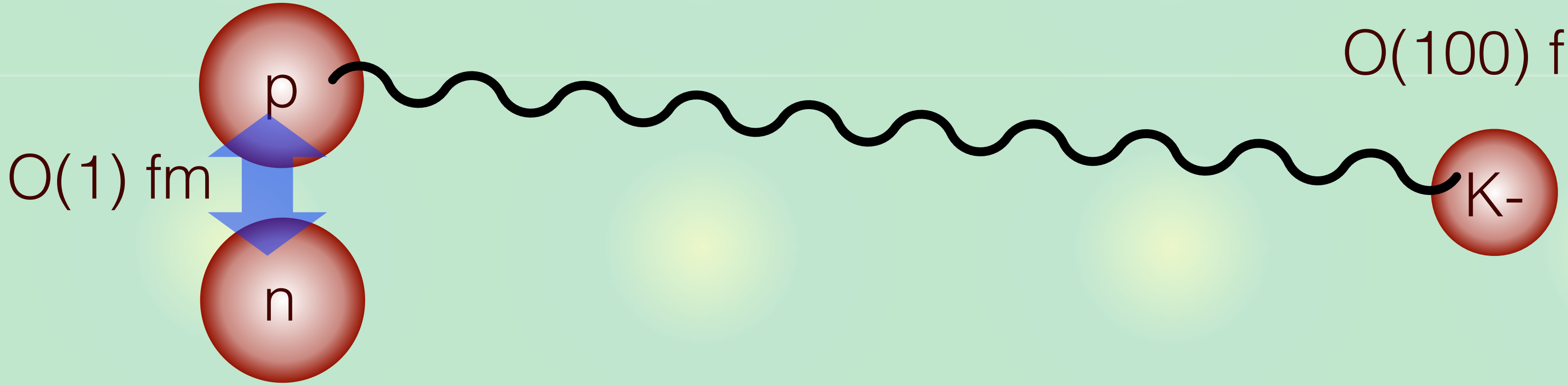

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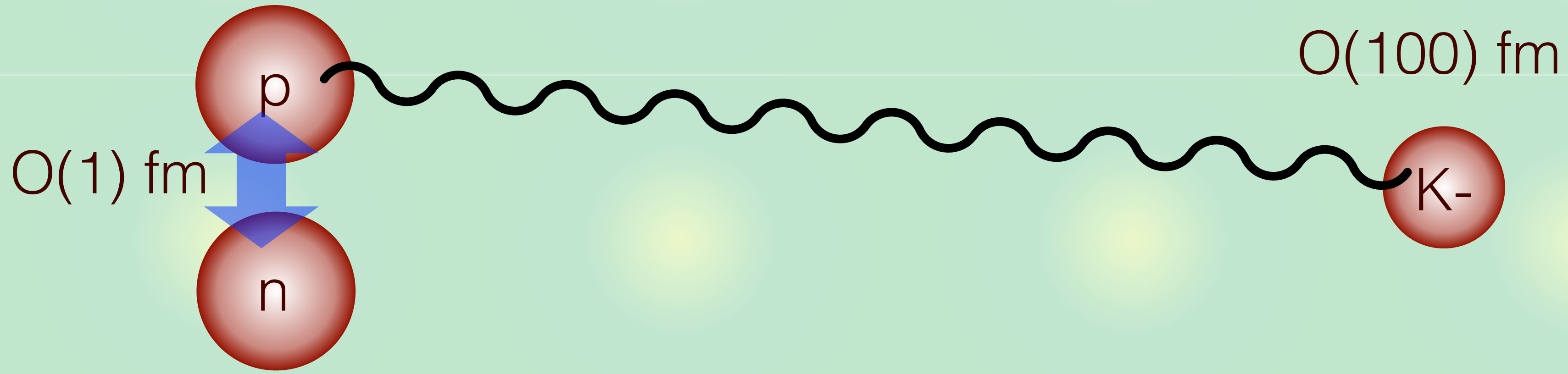

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Theoretical requirements:

- Rigorous three-body treatment of strong + Coulomb

- Inclusion of SIDDHARTRA constraint (realistic $\bar{K}N$)

- c.f. advanced Faddeev calculations

P. Doleschall, J. Revai, N.V. Shevchenko, Phys. Lett. B 744, 105 (2015);
J. Revai, Phys. Rev. C 94, 054001 (2016)

Check of kaonic hydrogen

Kaonic hydrogen (K-p) in the present setup?

- **Deser-type formula is based on (systematic) expansion.**
- $\bar{\text{K}}$N **potential is formulated with isospin symmetry.**

Two-body calculation with physical masses

$$\begin{pmatrix} \hat{T} + \hat{V}^{\bar{K}N} + \hat{V}^{\text{EM}} & \hat{V}^{\bar{K}N} \\ \hat{V}^{\bar{K}N} & \hat{T} + \hat{V}^{\bar{K}N} + \Delta m \end{pmatrix} \begin{pmatrix} |K^- p\rangle \\ |\bar{K}^0 n\rangle \end{pmatrix} = E \begin{pmatrix} |K^- p\rangle \\ |\bar{K}^0 n\rangle \end{pmatrix}$$

Check of kaonic hydrogen

Kaonic hydrogen (K-p) in the present setup?

- Deser-type formula is based on (systematic) expansion.
- $\bar{\text{K}}$N potential is formulated with isospin symmetry.

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Result:

- consistent with SIDDHARTA constraint

Mass	E dependence	ΔE (eV)	Γ (eV)
Physical	Self-consistent	283	607
Isospin	Self-consistent	163	574
Physical	$E_{\bar{K}N} = 0$	283	607
Expt. [31,32]		$283 \pm 36 \pm 6$	$541 \pm 89 \pm 22$

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Result:

- **consistent with SIDDHARTA constraint**
- **Ressumed Deser-type formula works reasonably for K-p.**

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Expt. [31,32]		283 ± 36 ± 6	541 ± 89 ±22

	ΔE (eV)	Γ (eV)
Full Schrödinger equation	283	607
Improved Deser formula (18)	293	596
Resummed formula (19)	284	605

Formulation

Three-body calculation of K-d with physical masses

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

$$\begin{pmatrix} \hat{H}_{K^-pn} & \hat{V}_{12}^{\bar{K}N} + \hat{V}_{13}^{\bar{K}N} \\ \hat{V}_{12}^{\bar{K}N} + \hat{V}_{13}^{\bar{K}N} & \hat{H}_{\bar{K}^0nn} \end{pmatrix} \begin{pmatrix} |K^-pn\rangle \\ |\bar{K}^0nn\rangle \end{pmatrix} = E \begin{pmatrix} |K^-pn\rangle \\ |\bar{K}^0nn\rangle \end{pmatrix}$$

$$\hat{H}_{K^-pn} = \sum_{i=1}^{3} \hat{T}_i - \hat{T}_{\rm cm} + \hat{V}_{23}^{NN} + \sum_{i=2}^{3} (\hat{V}_{1i}^{\bar{K}N} + \underline{\hat{V}_{1i}^{\rm EM}})$$ **Coulomb**

$$\hat{H}_{\bar{K}^0nn} = \sum_{i=1}^{3} \hat{T}_i - \hat{T}_{\rm cm} + \hat{V}_{23}^{NN} + \sum_{i=2}^{3} \hat{V}_{1i}^{\bar{K}N} + \underline{\Delta M}$$ **threshold difference**

- (single-channel) realistic $\bar{\rm K}$N potential

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

Few-body technique

- stochastic variational method + correlated gaussian basis

Y. Suzuki, K. Varga, Lect. Notes Phys. M54, (1998)

Kaonic deuterium: shift and width

Results of the three-body calculation

- energy convergence

<— large number of basis

N	Re[E] (MeV)
1677	−2.211689436
2194	−2.211722964
2377	−2.211732072
2511	−2.211735493
2621	−2.211737242
2721	−2.211737609
2806	−2.211737677
2879	−2.211737682

keV **eV!**

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keV eV!

Shift-width of the 1S state:

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

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

- Deser-type formula does not work accurately for K-d

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

	ΔE (eV)	Γ (eV)
Full Schrödinger equation	670	1016
Improved Deser formula (18)	910	989
Resummed formula (19)	818	1188

I=1 dependence

Study sensitivity to I=1 interaction

- introduce parameter β to control the potential strength

$$\mathrm{Re}\ \hat{V}^{\bar{K}N(I=1)}(r) \to \beta[\mathrm{Re}\ \hat{V}^{\bar{K}N(I=1)}(r)]$$

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Vary β within SIDDHARTA uncertainty of K-p

- allowed region: -0.17< β < 1.08
  (negative β may contradict with scattering data)

β	$K^- p$		$K^- d$	
	ΔE	Γ	ΔE	Γ
1.08	287	648	676	1020
1.00	283	607	670	1016
−0.17	310	430	506	980

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- deviation of ΔE of K-d ~ 170 eV

- Planned precision: 60 eV (30 eV) at J-PARC (SIDDHARTA-2)

Measurement of K-d will provide strong constraint on I=1

Summary: $\Lambda(1405)$

- **Realistic $\bar{K}N$ potentials** (χ^2/d.o.f. ~ 1) based on NLO chiral SU(3) dynamics are now available, thanks to precise kaonic hydrogen data.

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)
K. Miyahara. T. Hyodo, PRC93, 015201 (2016)
K. Miyahara, T. Hyodo, W. Weise, arXiv:1804.08269 [nucl-th]

- We study **kaonic dueterium** as
  - Prediction of shift and width

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

  - sensitive to I=1 component

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