$\Lambda(1405)$ and kaon-nuclear systems

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2026, Jun. 1st

(Personal) history

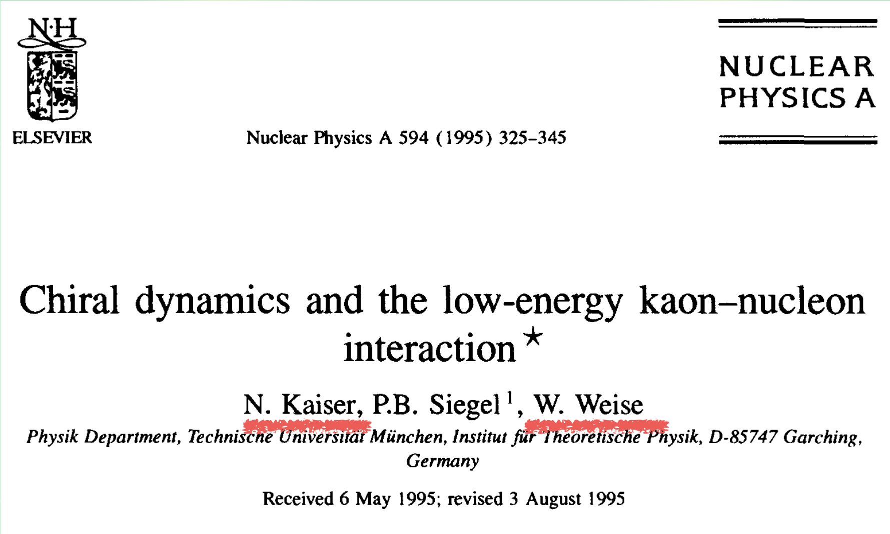
~2003: on the paper

2006: in person@YKIS2006

2007-8: posdoc@TUM

- The first paper

T. Hyodo, W. Weise, PRC 77, 035204 (2008)


NUCLEAR PHYSICS A

ELSEVIER

Nuclear Physics A 594 (1995) 325–345

Chiral dynamics and the low-energy kaon–nucleon interaction ★

N. Kaiser, P.B. Siegel [1], W. Weise

Physik Department, Technische Universität München, Institut für Theoretische Physik, D-85747 Garching, Germany

Received 6 May 1995; revised 3 August 1995

Subsequent papers

A. Dote, T. Hyodo, W. Weise, NPA 804, 197 (2008);

A. Dote, T. Hyodo, W. Weise, PRC 79, 014003 (2009);

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011);

Y. Ikeda, T. Hyodo, W. Weise, NPA 881, 98 (2012);

S. Ohnishi, Y. Ikeda, T. Hyodo, W. Weise, PRC 93, 025207 (2016);

T. Hoshino, S. Ohnishi, W. Horiuchi, T. Hyodo, W. Weise, PRC 96, 045204 (2017);

K. Miyahara, T. Hyodo, W. Weise, PRC 98, 025201 (2018);

Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise. PRL 124, 132501 (2020)

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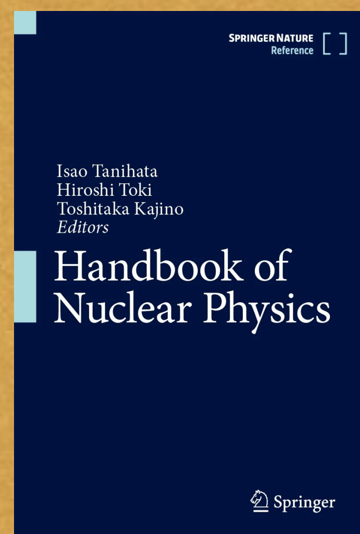
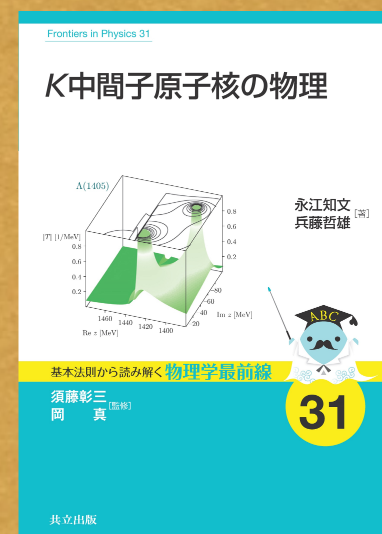


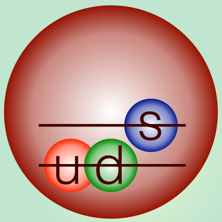


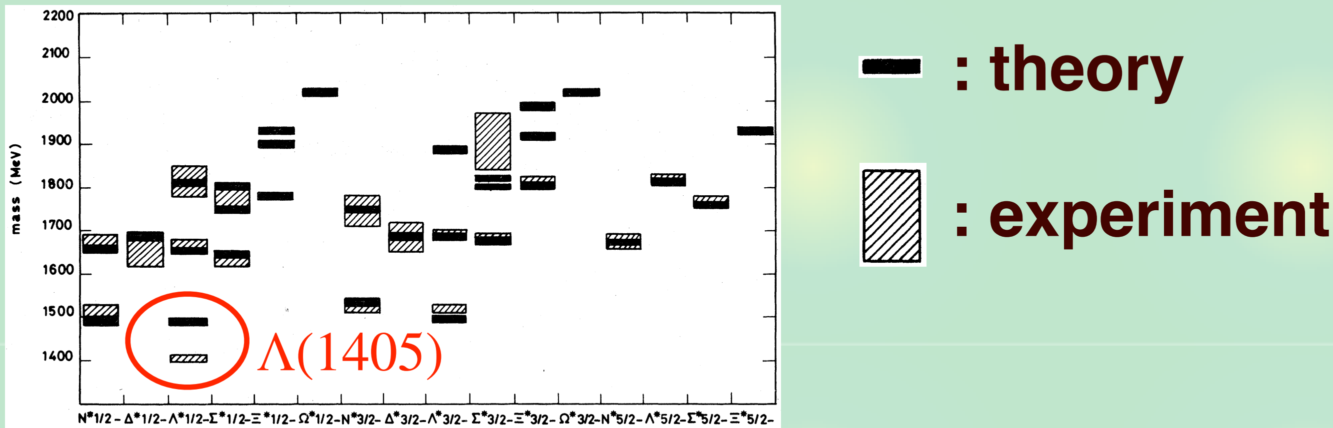
T. Hyodo, W. Weise, "Theory of kaon-nuclear systems", arXiv:2202.06181 [nucl-th]
T. Nagae, T. Hyodo, "Theory of kaonic nuclei", (in Japanese, Kyoritsu Shuppan, 2023)

$\Lambda(1405)$ and $\bar{K}N$ scattering

$\Lambda(1405)$ does not fit in standard picture —> exotic candidate

N. Isgur, G. Karl, PRD 18, 4187 (1978)

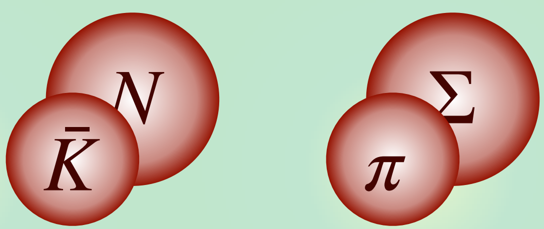


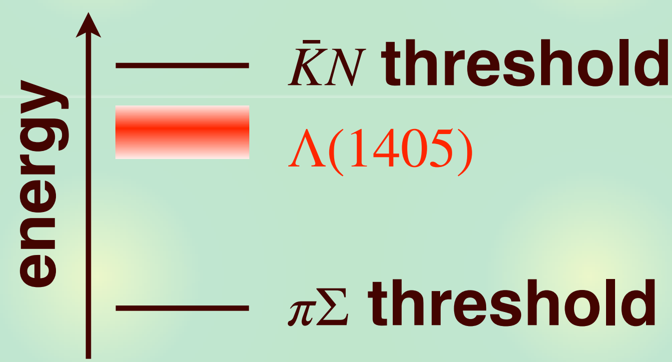


Resonance in coupled-channel scattering

R.H. Dalitz, S.F. Tuan, PRL 10, 425 (1959); Ann. Phys. 10, 307 (1960)

- Coupling to MB states





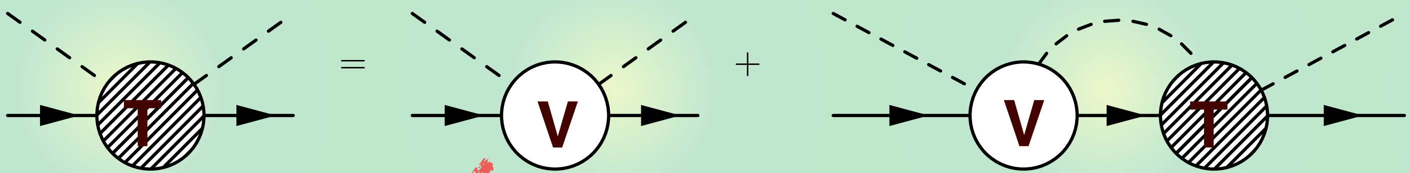
Detailed analysis of $\bar{K}N$-$\pi\Sigma$ scattering is necessary

Chiral coupled-channel analysis

Chiral SU(3) coupled-channels $(\bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, \eta\Sigma, K\Xi)$ approach

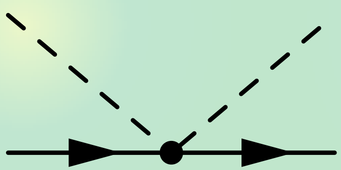
N. Kaiser, P.B. Siegel, W. Weise, NPA594, 325 (1995)

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



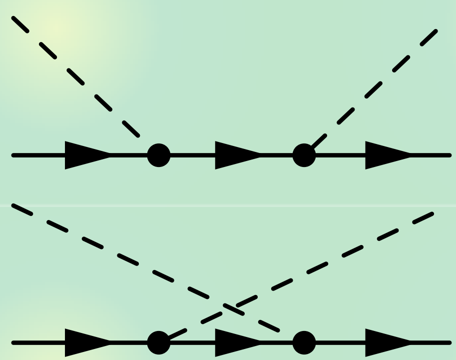
Chiral perturbation theory (3-flavor)

1) TW term



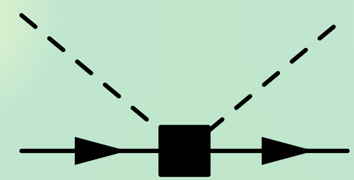
$\mathcal{O}(p)$

2) Born terms



$\mathcal{O}(p)$

3) NLO terms



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

Dominant contribution from TW interaction

Chiral symmetry and TW interaction

TW interaction: low-energy theorem (model independent)

D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meißner, NPA725, 181 (2003);
T. Hyodo, W. Weise, PRC 77, 035204 (2008)

- **Interaction at threshold:** $V \propto m_i$ **(spontaneous breaking)**

$$V_{ii}(E=0) = -\frac{C_{ii} m_i}{2f^2}$$

$$C_{ij}^{\mathrm{SU}(3)} = \begin{pmatrix} 6 & & & \\ & 3 & & \\ & & 3 & \\ & & & -2 \end{pmatrix} \begin{matrix} \mathbf{1} \\ \mathbf{8} \\ \mathbf{8}' \\ \mathbf{27} \end{matrix}$$

$$C_{ij}^{I=0} = \begin{pmatrix} 3 & -\sqrt{\frac{3}{2}} & \frac{3}{\sqrt{2}} & 0 \\ & 4 & 0 & \sqrt{\frac{3}{2}} \\ & & 0 & -\frac{3}{\sqrt{2}} \\ & & & 3 \end{pmatrix} \begin{matrix} \bar{K}N \\ \pi\Sigma \\ \eta\Lambda \\ K\Xi \end{matrix}$$

$$V_{\bar{K}N(I=0)} = \frac{3m_K}{2f^2} \sim -12.1 \text{ fm}, \quad V_{\pi\Sigma(I=0)} = \frac{4m_\pi}{2f^2} \sim -6.4 \text{ fm},$$

- **Two attractive components in $\bar{K}N$ and $\pi\Sigma$ —> two states**

- $m_K \sim 3.5 m_\pi$ **(explicit breaking) —>** $|V_{\bar{K}N(I=0)}| > |V_{\pi\Sigma(I=0)}|$

Fit to experimental data

K at rest

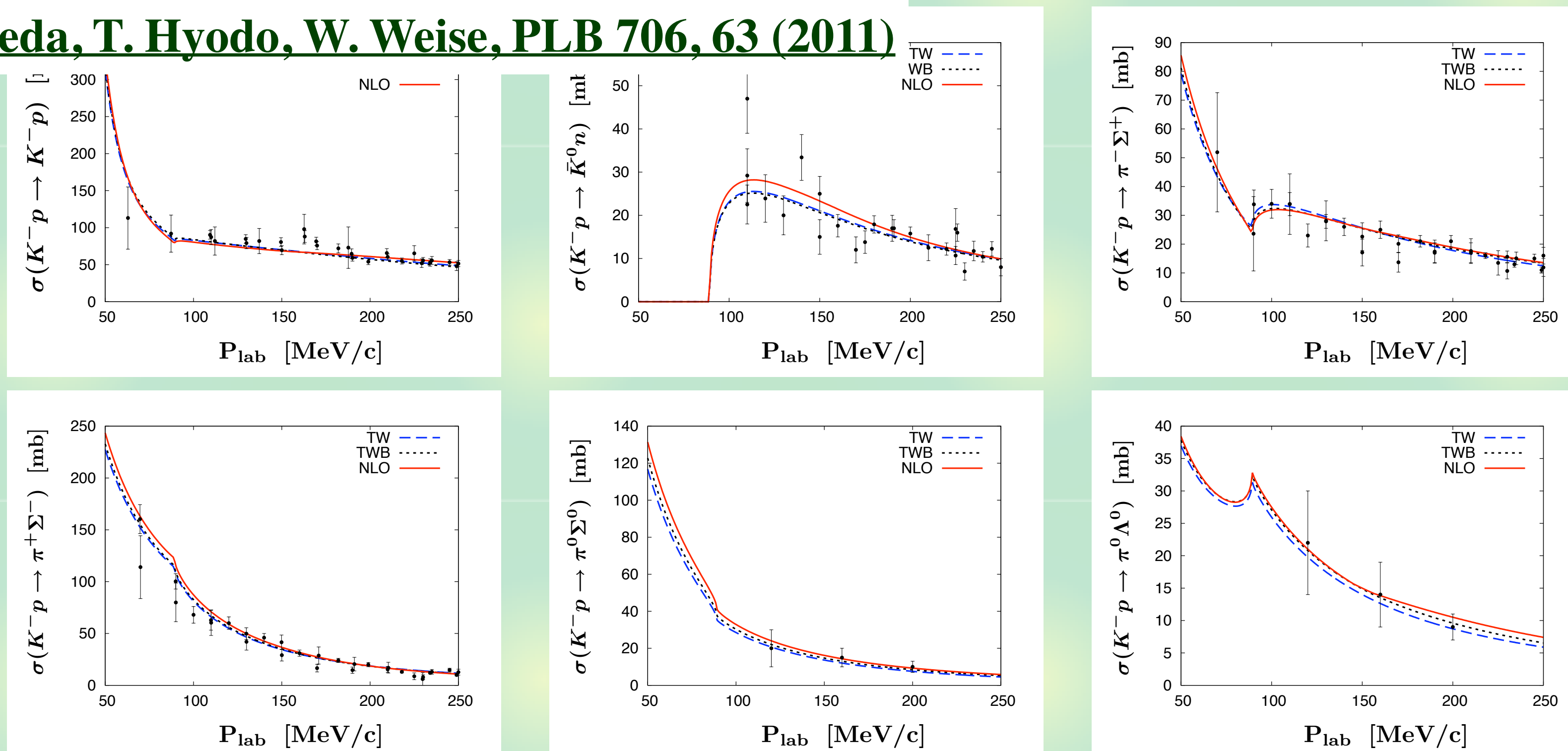
	TW	TWB	NLO	Experiment	
ΔE [eV]	373	377	306	$283 \pm 36 \pm 6$	[10]
Γ [eV]	495	514	591	$541 \pm 89 \pm 22$	[10]
γ	2.36	2.36	2.37	2.36 ± 0.04	[11]
R_n	0.20	0.19	0.19	0.189 ± 0.015	[11]
R_c	0.66	0.66	0.66	0.664 ± 0.011	[11]
χ^2/d.o.f	1.12	1.15	0.96		

} **SIDDHARTA** (ΔE, Γ)

} **Branching ratios** (γ, R_n, R_c)

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011)

$K^- p$ cross sections



—> **Two poles at 1424-26i MeV and 1381-81i MeV**

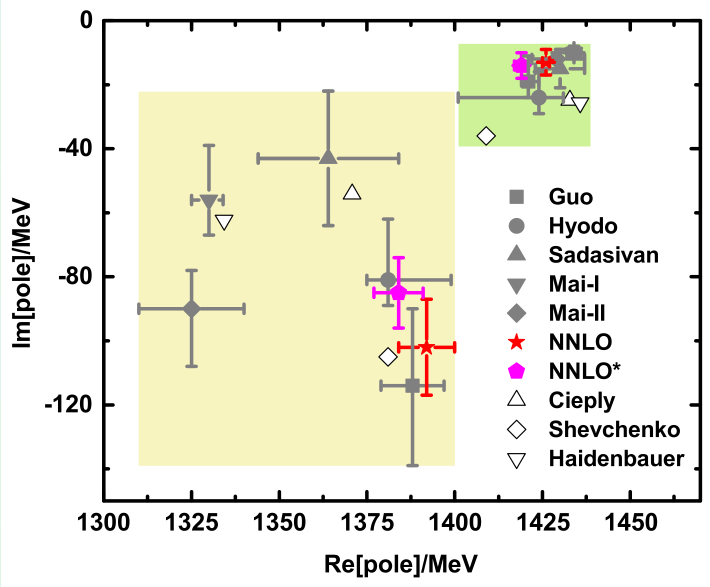
NNLO analysis and lattice QCD

Analysis at NNLO chiral SU(3) dynamics (KN and πN included)

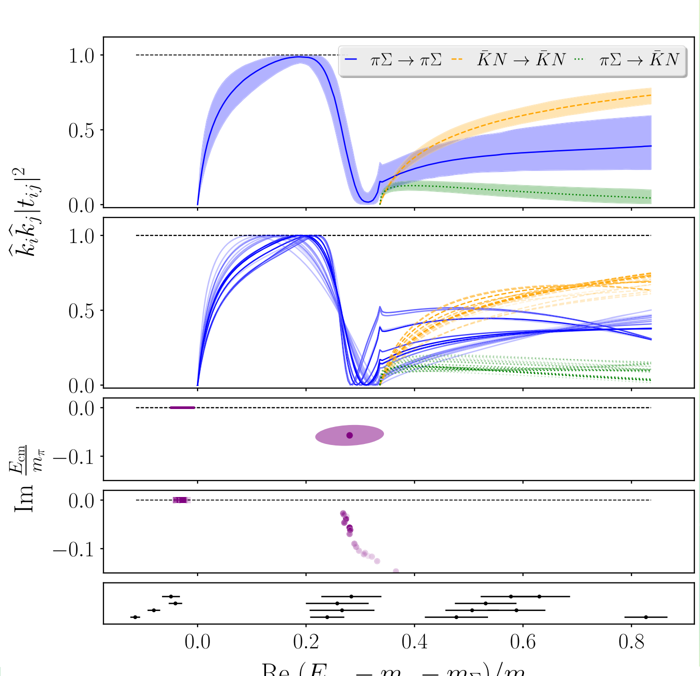
J.-X. Lu, L.S. Geng, M. Doering, M. Mai, PRL 130, 071902 (2023)

Lattice QCD calculation of $\bar{K}N$-$\pi\Sigma$ scattering ($m_\pi \sim 200$ MeV)

J. Bulava, *et al.* (Baryon Scattering collaboration), PRL 132, 051901 (2023)



	Pole positions (MeV)
$\Lambda(1380)$	$1392 \pm 8 - i(102 \pm 15)$
$\Lambda(1405)$	$1425 \pm 1 - i(13 \pm 4)$



$$E_1 = 1392(9)(2)(16)\ \mathrm{MeV},$$

$$E_2 = [1455(13)(2)(17) - i11.5(4.4)(4)(0.1)]\ \mathrm{MeV},$$

Two poles are confirmed at NNLO and lattice QCD

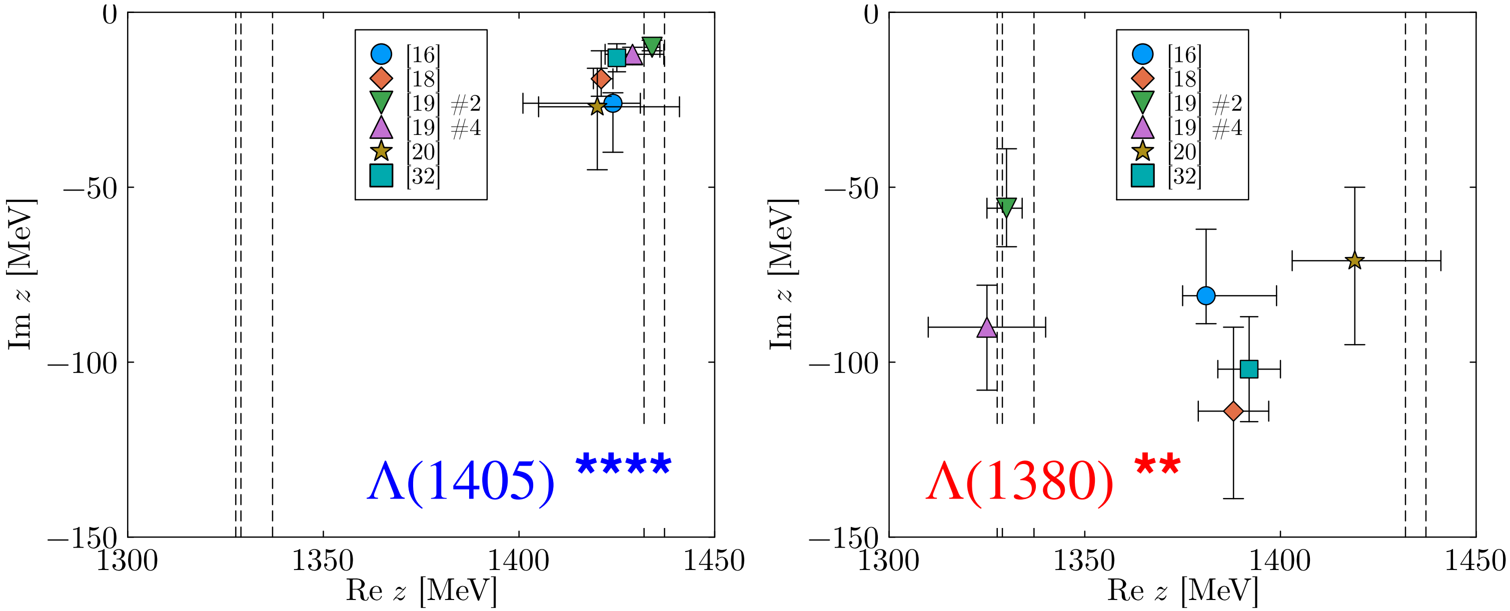
Current PDG

Since 2020 edition of PDG, two Λ resonances are listed

http://pdg.lbl.gov/

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

Revised Feb. 2025 by T. Hyodo (RCNP, Osaka U.; Tokyo Metropolitan U.) and U.-G. Meißner (Bonn U.; FZ Jülich).



- “$\Lambda(1405)$” is no longer at 1405 MeV but ~ 1420 MeV.
- Lower pole: two-star resonance $\Lambda(1380)$

Kaonic nuclei

NN and $\bar{K}N$ interactions share common features:

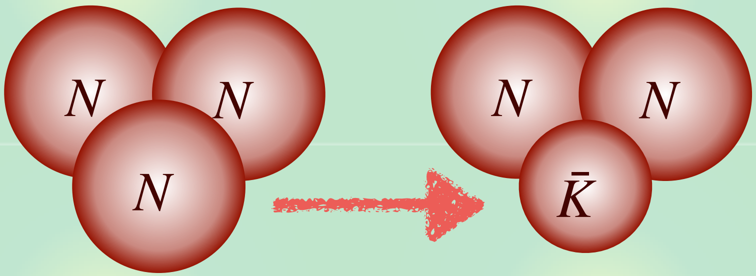
	$I=0$	$I=1$
NN	d (bound state)	attractive
$\bar{K}N$	$\Lambda(1405)$ (quasi-bound state)	attractive

—> (quasi-)bound states of $\bar{K}$ + nuclei?

Y. Nogami, PL 7, 288 (1963)

- possible "deeply-bound" nuclei

Y. Akaishi, T. Yamazaki, PRC 65, 044005 (2002)



A question:

- Does kaonic nculei exist with realistic $\bar{K}N$ interaction?

Construction of $\bar{K}N$ potentials

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

meson-baryon amplitude (chiral SU(3) EFT)

T. Hyodo, W. Weise, PRC 77, 035204 (2008)

Kyoto $\bar{K}N$ potential (single-channel, complex)

K. Miyahara. T. Hyodo, PRC 93, 015201 (2016)

Kyoto $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential (coupled-channel, real)

K. Miyahara, T. Hyodo, W. Weise, PRC 98, 025201 (2018)

Kaonic nuclei

Kaonic deuterium

$K^- p$ correlation function

$\bar{K}NN$ system: simplest kaonic nucleus

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)

Potential	$\Lambda(1405)$ [MeV]	$\Lambda(1380)$ [MeV]	$B_{\bar{K}NN}$ [MeV]	$\Gamma_{\bar{K}NN\to\pi YN}$ [MeV]
$V^{1,\mathrm{SIDD}}_{\bar{K}N\text{-}\pi\Sigma}$	$1426-48i$ [3]	-	53.3 [1]	64.8 [1]
$V^{2,\mathrm{SIDD}}_{\bar{K}N\text{-}\pi\Sigma}$	$1414-58i$ [3]	$1386-104i$ [3]	47.4 [1]	49.8 [1]
$V^{\mathrm{chiral}}_{\bar{K}N\text{-}\pi\Sigma\text{-}\pi\Lambda}$	$1417-33i$ [4]	$1406-89i$ [4]	32.2 [1]	48.6 [1]
Kyoto $\bar{K}N$	$1424-26i$ [5]	$1381-81i$ [5]	25.3-27.9 [2]	30.9-59.4 [2]

[3] N.V. Shevchenko, NPA 890-891, 50 (2012)
[4] N.V. Shevchenko, J. Revai, PRC 90, 034003 (2014)
[5] K. Miyahara. T. Hyodo, PRC 93, 015201 (2016)

- **Caution: $2N$ absorption (Γ_{YN}) is NOT included!!**

Kaonic nuclei up to $A = 6$

Rigorous few-body approach up to $A = 6$ systems

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

- Stochastic variational method with correlated gaussians

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

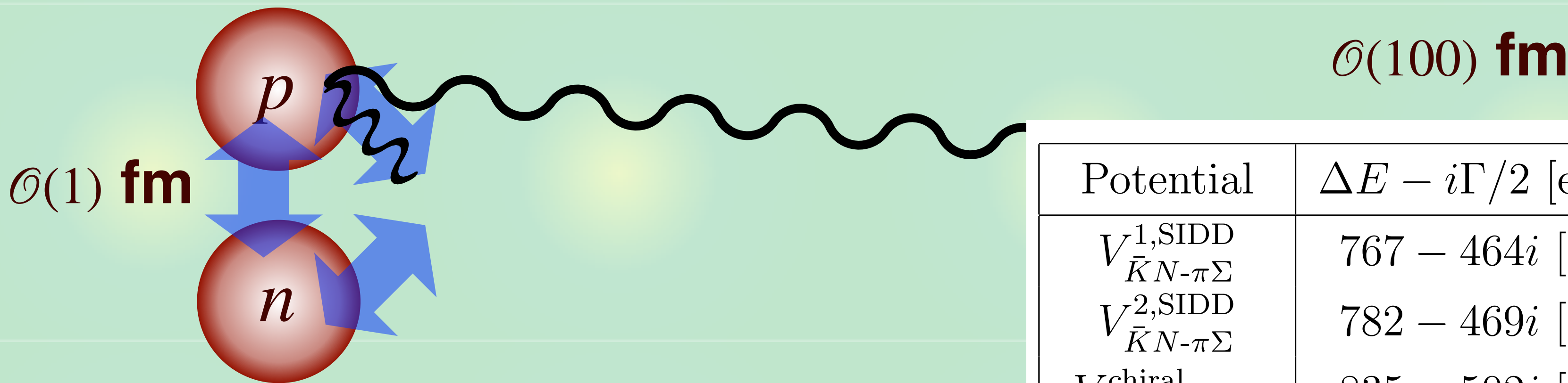
Results for kaonic nuclei with $A = 2, 3, 4, 6$

	$\bar{K}NN$	$\bar{K}NNN$	$\bar{K}NNNN$	$\bar{K}NNNNNN$
$I(J^P)$	$1/2(0^-)$	$0(1/2^-)$	$1/2(0^-)$	$1/2(0^-, 1^-)$
B [MeV]	25.3-27.9	45.3-49.7	67.9-75.5	69.8-80.7
$\Gamma_{\text{mes.}}$ [MeV]	30.9-59.4	25.5-69.4	28.0-74.5	23.7-75.6

- for $A = 6$ system, 0^- and 1^- are almost degenerated
- quasi-bound state below the lowest threshold
- decay width (without multi-N absorption) ~ binding energy

Kaonic deuterium

$K^- pn$ system with strong + Coulomb interaction



Potential	$\Delta E - i\Gamma/2$ [eV]
$V^{1,\mathrm{SIDD}}_{\bar{K}N\text{-}\pi\Sigma}$	$767 - 464i$ [1]
$V^{2,\mathrm{SIDD}}_{\bar{K}N\text{-}\pi\Sigma}$	$782 - 469i$ [1]
$V^{\mathrm{chiral}}_{\bar{K}N\text{-}\pi\Sigma\text{-}\pi\Lambda}$	$835 - 502i$ [1]
Kyoto $\bar{K}N$	$670 - 508i$ [2]

Theoretical requirements:

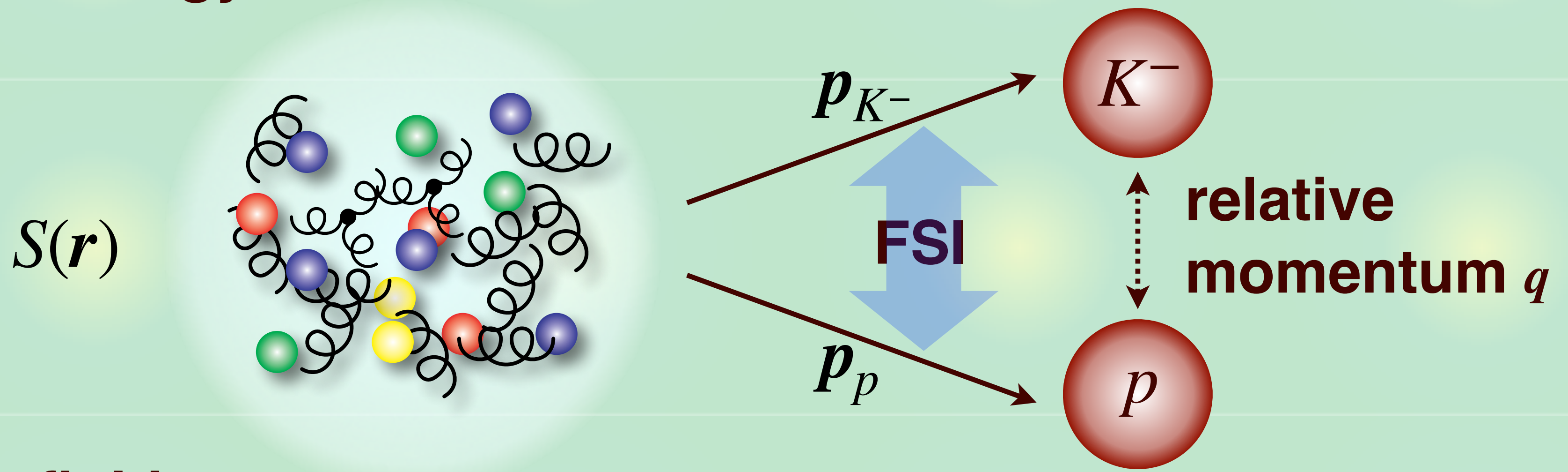
- **Rigorous three-body treatment of strong + Coulomb**
- **Inclusion of SIDDHARTRA constraint (realistic $\bar{K}N$)**

[1] J. Revai, PRC 94, 054001 (2016)
[2] T. Hoshino, S. Ohnishi, W. Horiuchi, T. Hyodo, W. Weise, PRC96, 045204 (2017)

- **Experiments: J-PARC E57, SIDDHARTA-2**

Correlation function and hadron interaction

High-energy collision: chaotic source $S(\mathbf{r})$ of hadron emission



- Definition

$$C(\mathbf{q}) = \frac{N_{K^-p}(\mathbf{p}_{K^-}, \mathbf{p}_p)}{N_{K^-}(\mathbf{p}_{K^-}) N_p(\mathbf{p}_p)}$$ **(= 1 in the absence of FSI/QS)**

- Theory (Koonin-Pratt formula)

S.E. Koonin PLB 70, 43 (1977); S. Pratt, PRD 33, 1314 (1986)

$$C(\mathbf{q}) \simeq \int d^3\mathbf{r}\, S(\mathbf{r})\, |\Psi_{\mathbf{q}}^{(-)}(\mathbf{r})|^2$$

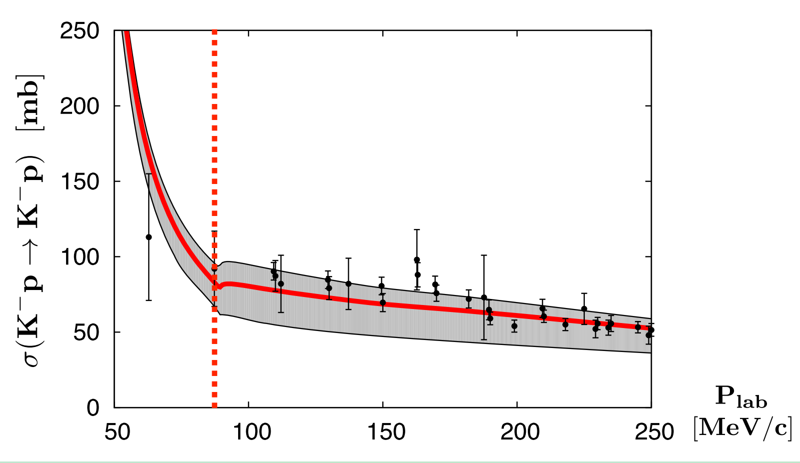
Source function $S(\mathbf{r})$ <—> wave function $\Psi_{\mathbf{q}}^{(-)}(\mathbf{r})$ (FSI)

Experimental data of K^-p correlation

K^-p total cross sections

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011)

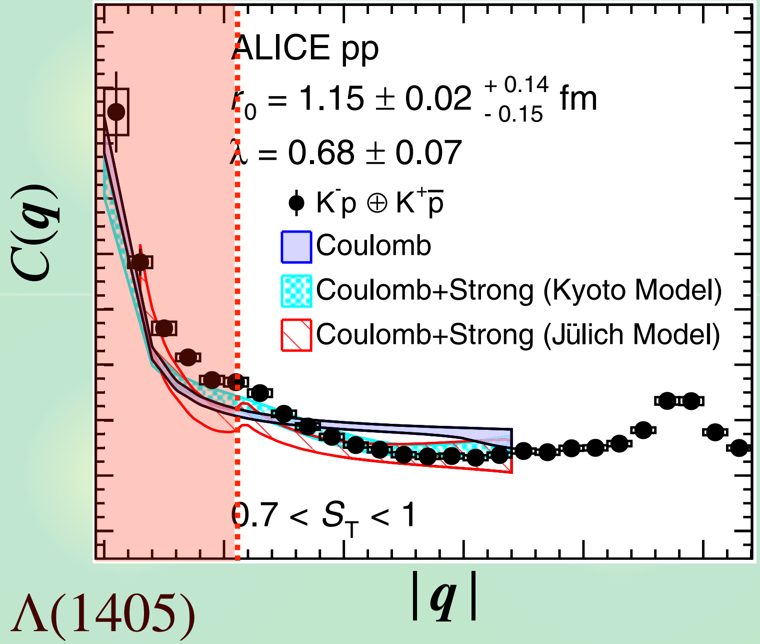
- Old bubble chamber data
- Resolution is not good
- Threshold cusp is not visible



K^-p correlation function

ALICE collaboration, PRL 124, 092301 (2020)

- Excellent precision ($\bar{K}^0 n$ cusp)
- Low-energy data below $\bar{K}^0 n$



—> Important constraint on $\bar{K}N$ and $\Lambda(1405)$

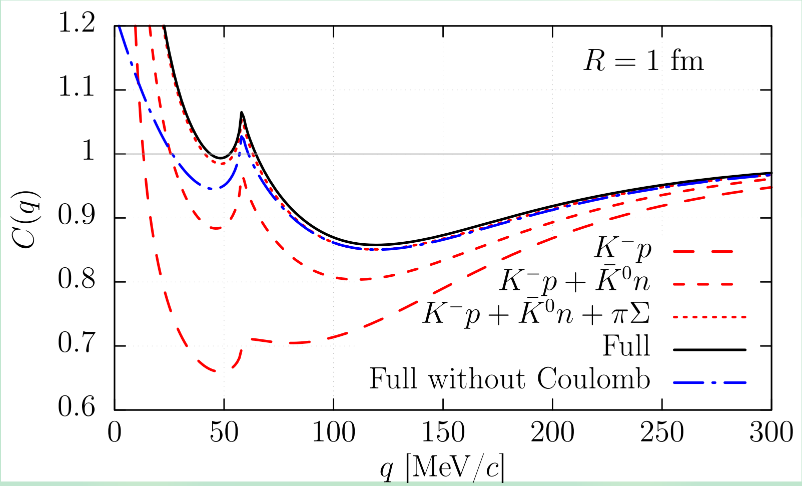
Coupled-channel correlation function

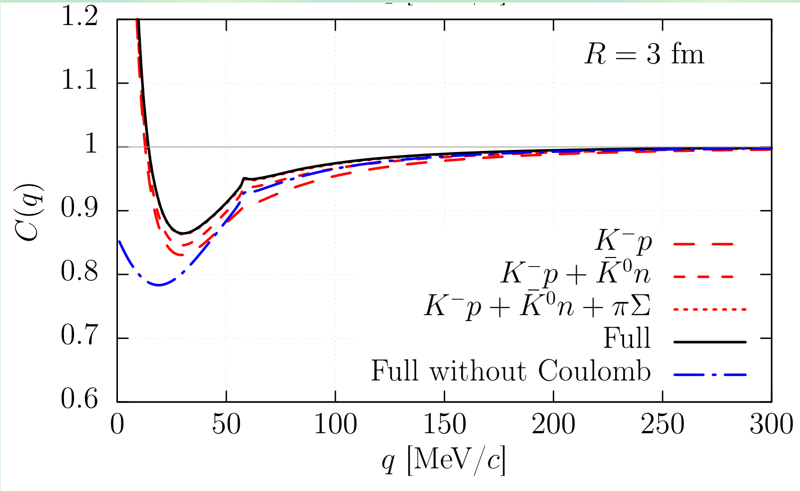
Coupled-channel Koonin-Pratt formula

R. Lednicky, V.V. Lyuboshitz, V.L.Lyuboshitz, Phys. Atom. Nucl. 61, 2950 (1998);
J. Haidenbauer, NPA 981, 1 (2019);
Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise, PRL124, 132501 (2020)

$$C_{K^-p}(\boldsymbol{q}) \simeq \int d^3\boldsymbol{r}\, S_{K^-p}(\boldsymbol{r})\,|\,\Psi^{(-)}_{K^-p,\boldsymbol{q}}(\boldsymbol{r})\,|^2 + \sum_{i\neq K^-p} \omega_i \int d^3\boldsymbol{r}\, S_i(\boldsymbol{r})\,|\,\Psi^{(-)}_{i,\boldsymbol{q}}(\boldsymbol{r})\,|^2$$

- **Transition from** $\bar{K}^0 n, \pi^+\Sigma^-, \pi^0\Sigma^0, \pi^-\Sigma^+, \pi^0\Lambda$
- ω_i **: weight of source channel** i **relative to** K^-p





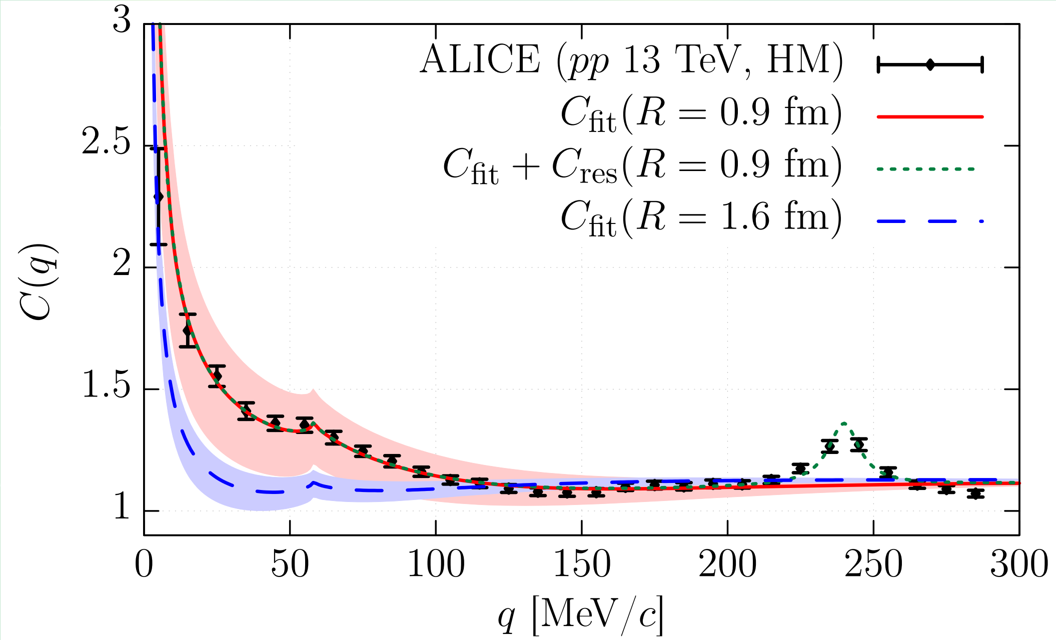
Coupled-channel effect is enhanced for small sources

Correlation from chiral SU(3) dynamics

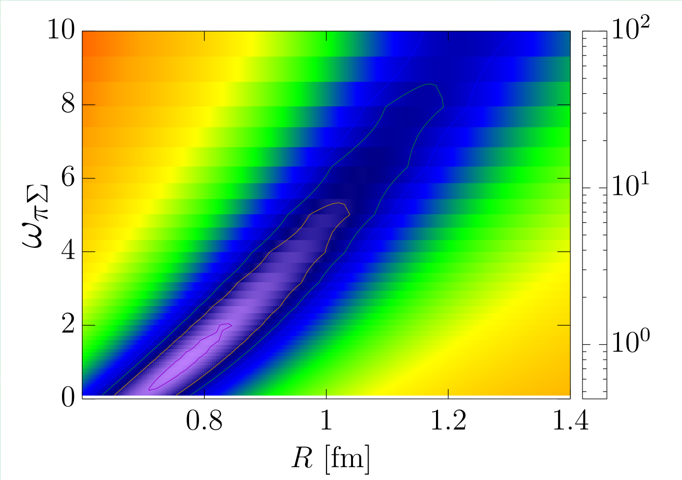
Wave function $\Psi^{(-)}_{i,\boldsymbol{q}}(\boldsymbol{r})$: coupled-channel $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential

K. Miyahara, T. Hyodo, W. Weise, PRC 98, 025201 (2018)

- **Source function $S(\boldsymbol{r})$: Gaussian, $R \sim 1$ fm in K^+p data**
- **Source weight $\omega_{\pi\Sigma} \sim 2$ by simple statistical model estimate**



reduced χ^2



Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise, PRL 124, 132501 (2020)

Correlation function by ALICE is well reproduced

Summary

- $\Lambda(1405)$ and $\Lambda(1380)$ arise from chiral SU(3) coupled-channel dynamics.

  N. Kaiser, P.B. Siegel, W. Weise, NPA594, 325 (1995)
  Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012)

- Kaonic nuclei and kaonic atoms are systematically studied based on realistic $\bar{K}N$ interactions.

  T. Hyodo, W. Weise, "Theory of kaon-nuclear systems", arXiv:2202.06181 [nucl-th]

- K^-p correlation measurements provide a novel and precise probe of the $\bar{K}N$ interaction.

  Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise. PRL124, 132501 (2020)