$\Lambda(1405)$ and the antikaon-nucleon potential

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Clusters & Hierarchies

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Contents

- $\Lambda(1405)$ **in meson-baryon scattering**

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012);
T. Hyodo, M. Niiyama, arXiv: 2010.07592 [hep-ph], to appear in PPNP

- $\bar{K}N$ **potentials and their applications**

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

- Kaonic nuclei

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

- Kaonic deuterium

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

- $K^{-}p$ **correlation function**

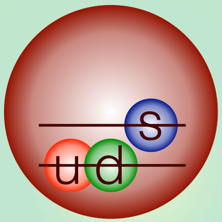
Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise. PRL124, 132501 (2020)

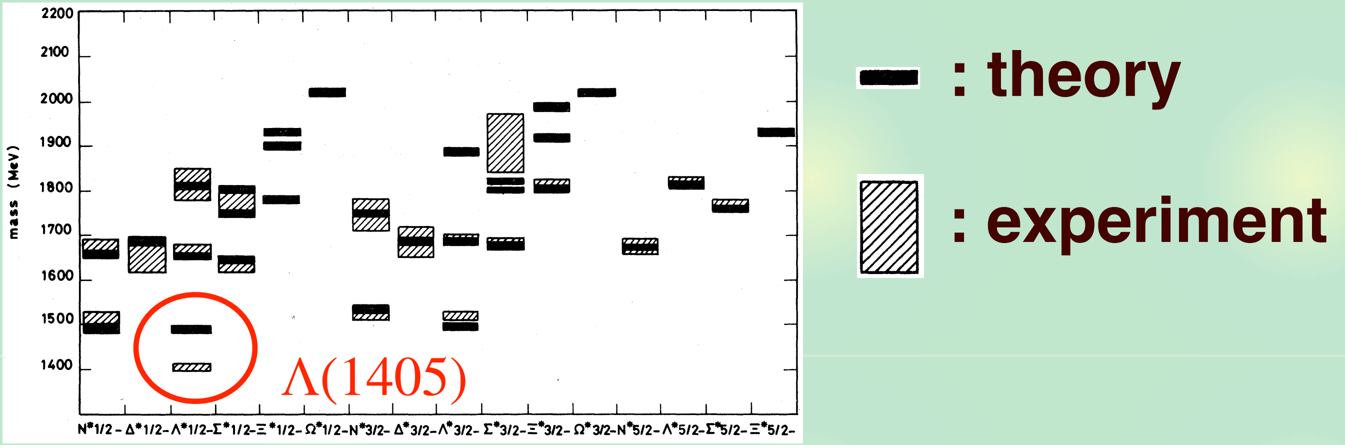
- **Summary** **(THEIA-REIMEI Seminar on 17 Mar.)**

Λ(1405) and $\bar{K}N$ scattering

Λ(1405) does not fit in standard picture —> exotic candidate

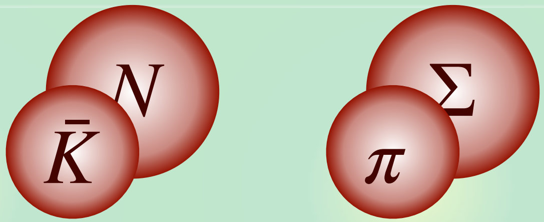
N. Isgur and G. Karl, Phys. Rev. D18, 4187 (1978)

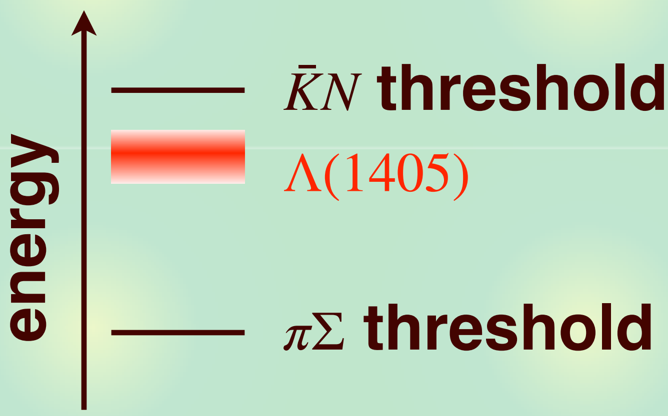




Resonance in coupled-channel scattering

- coupling to MB states





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

Strategy for $\bar{K}N$ interaction

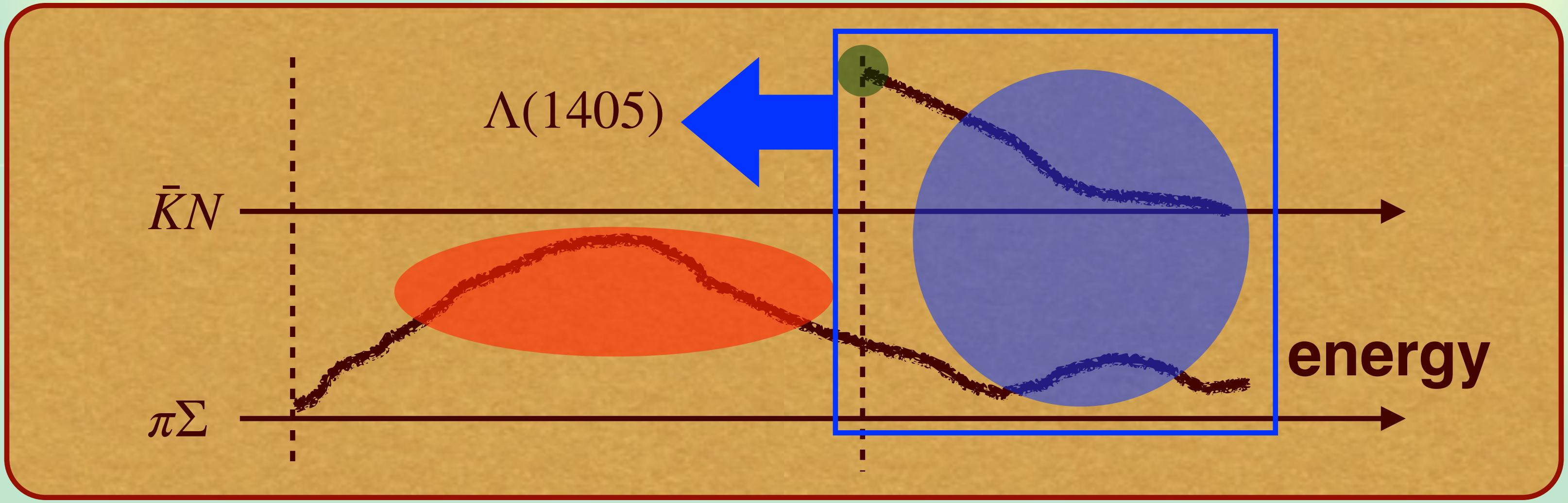
Above the $\bar{K}N$ threshold : direct constraints

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

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

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

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



Best-fit results

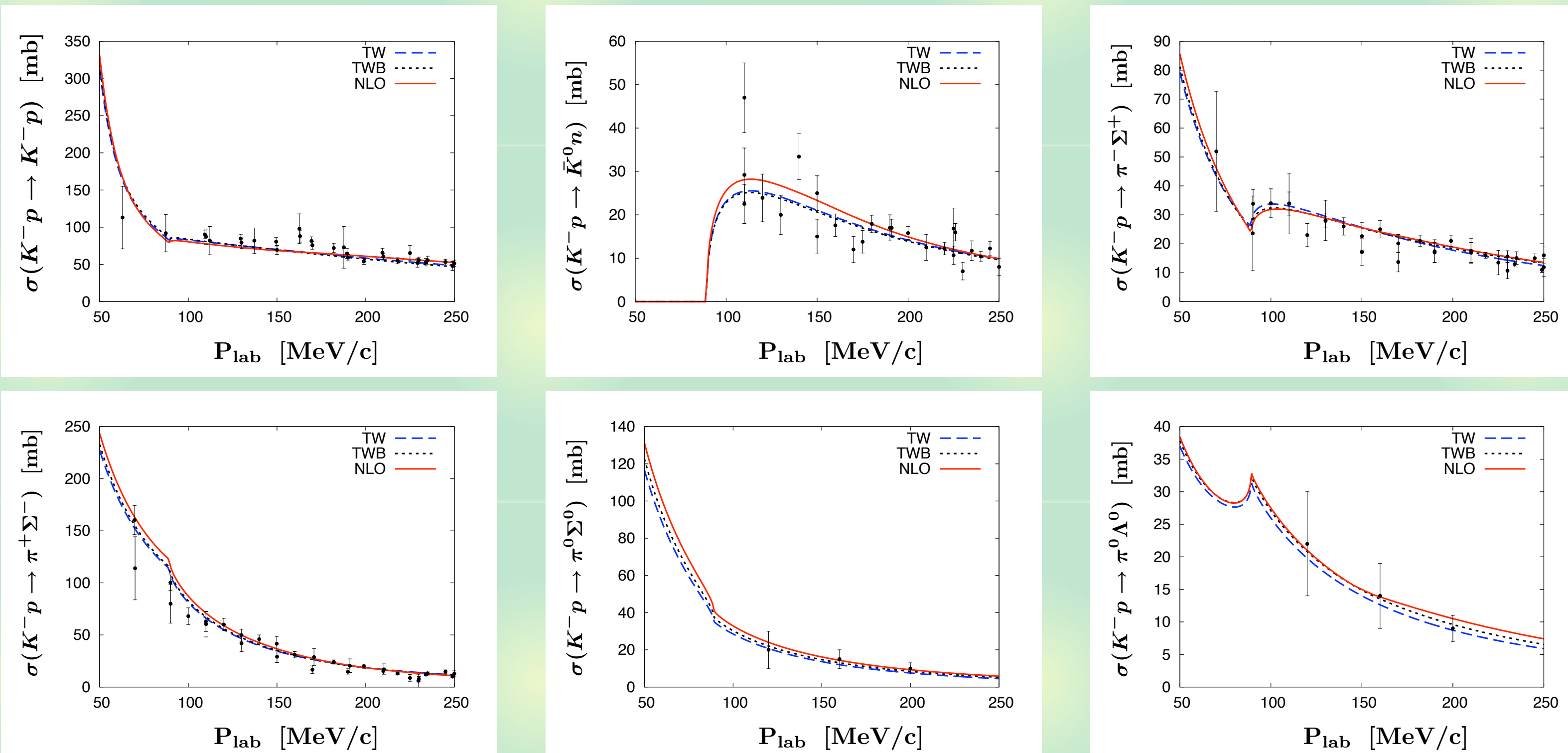
***K* at rest**

	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)

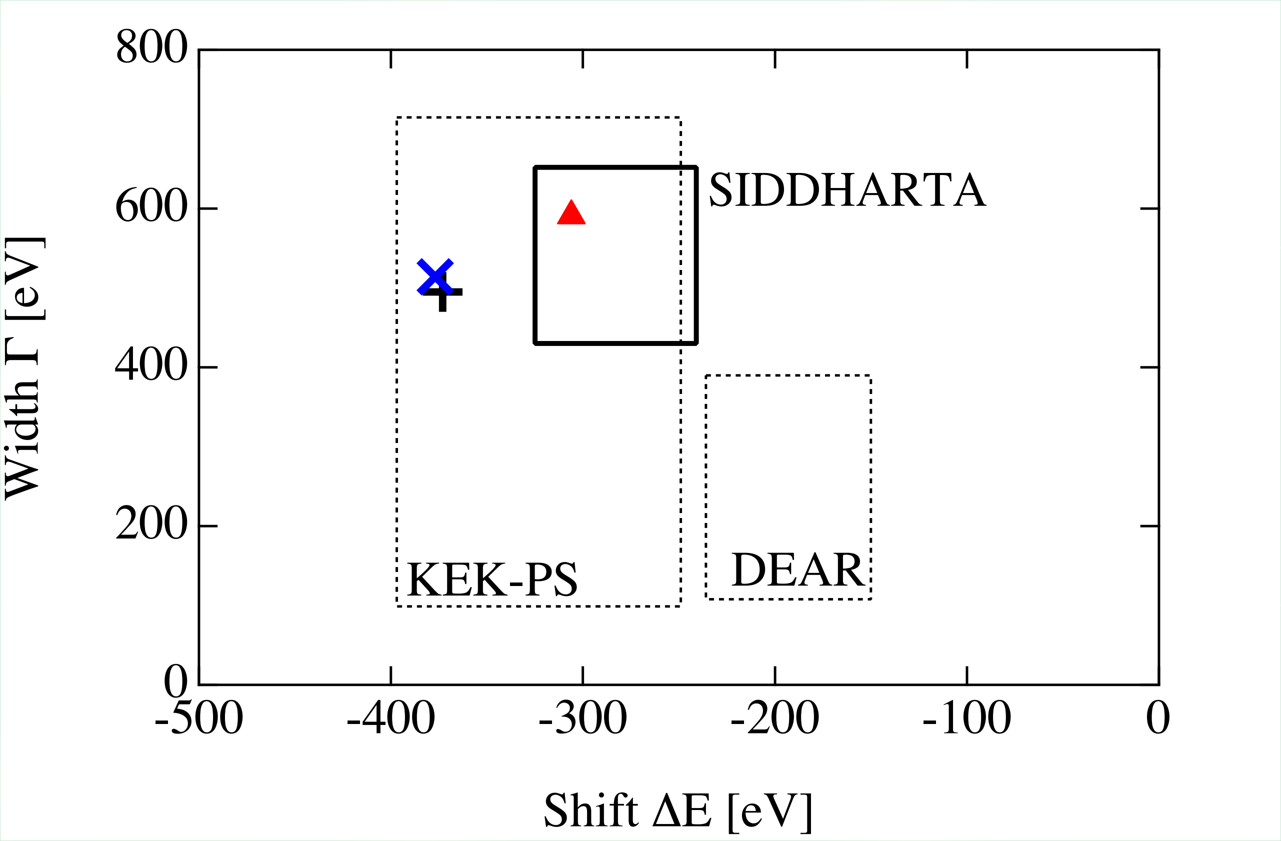
K^-p cross sections



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

Comparison with SIDDHARTA

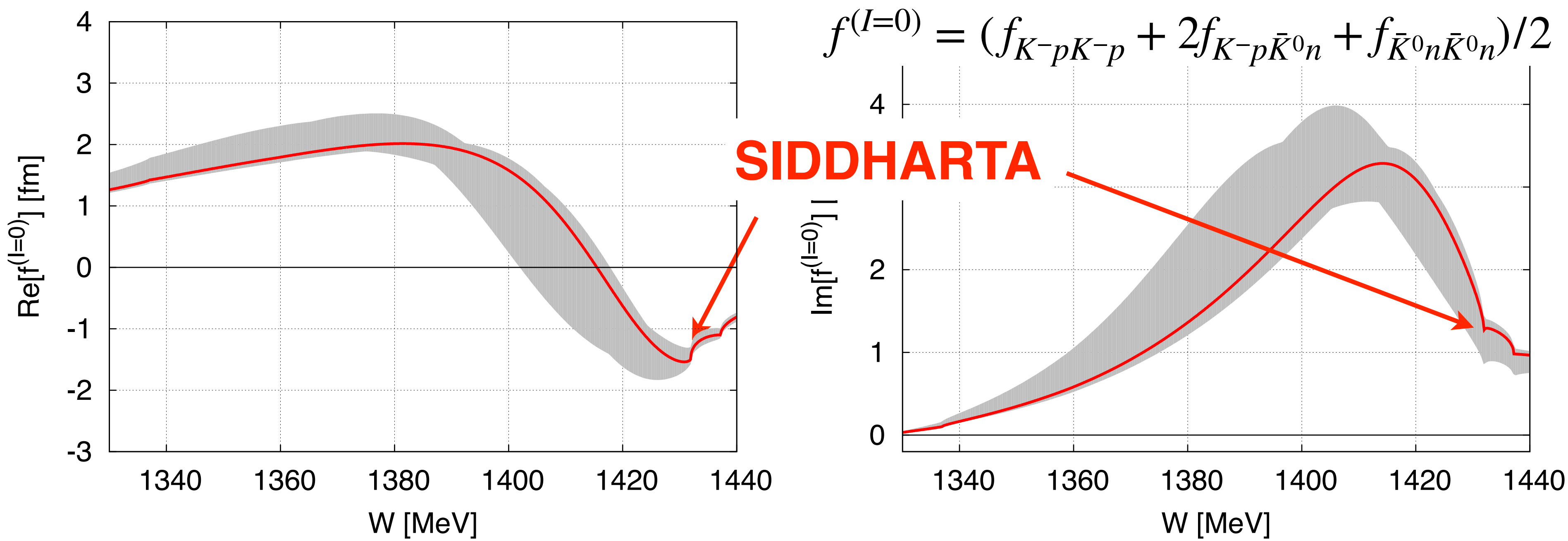
	TW	TWB	NLO
χ^2/d.o.f.	1.12	1.15	0.957



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

Subthreshold extrapolation

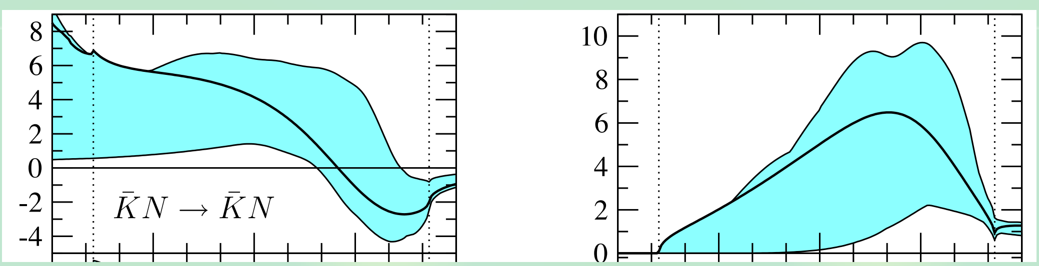
Uncertainty of $\bar{K}N \to \bar{K}N(I=0)$ amplitude below threshold



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)

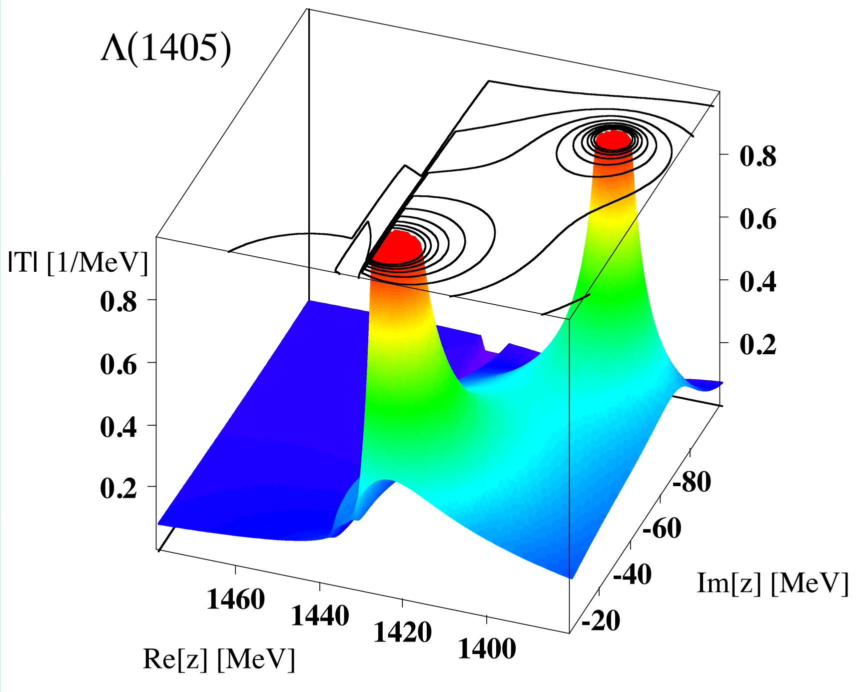


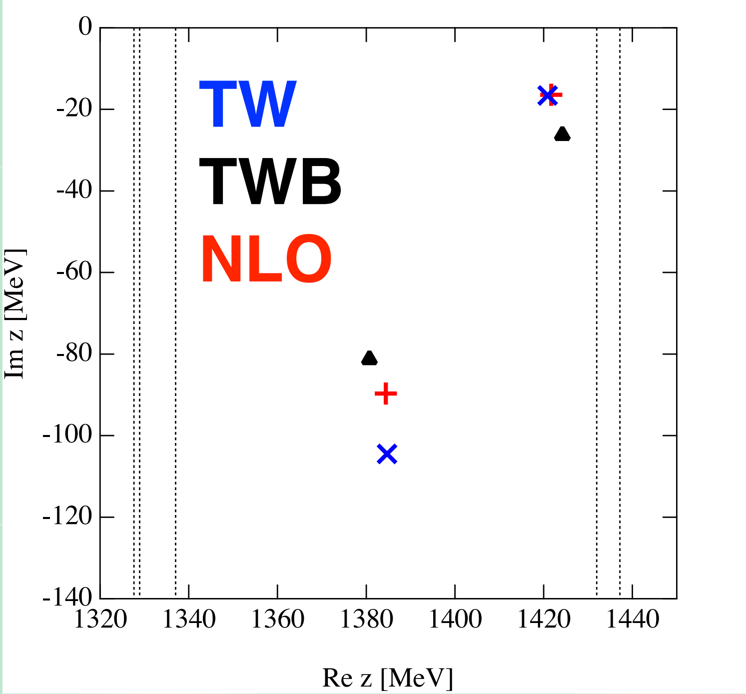
SIDDHARTA is essential for subthreshold extrapolation.

Extrapolation to complex energy: two poles

Two poles : superposition of two eigenstates

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);
U.G. Meißner, Symmetry 12, 981 (2020); M. Mai, arXiv: 2010.00056 [nucl-th];
T. Hyodo, M. Niiyama, arXiv: 2010.07592 [hep-ph], to appear in PPNP





T. Hyodo, D. Jido, PPNP 67, 55 (2012)

NLO analysis confirms the two-pole structure.

PDG has changed

2020 update of PDG

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012);
Z.H. Guo, J.A. Oller, PRC87, 035202 (2013);
M. Mai, U.G. Meißner, EPJA51, 30 (2015)

- Particle Listing section:

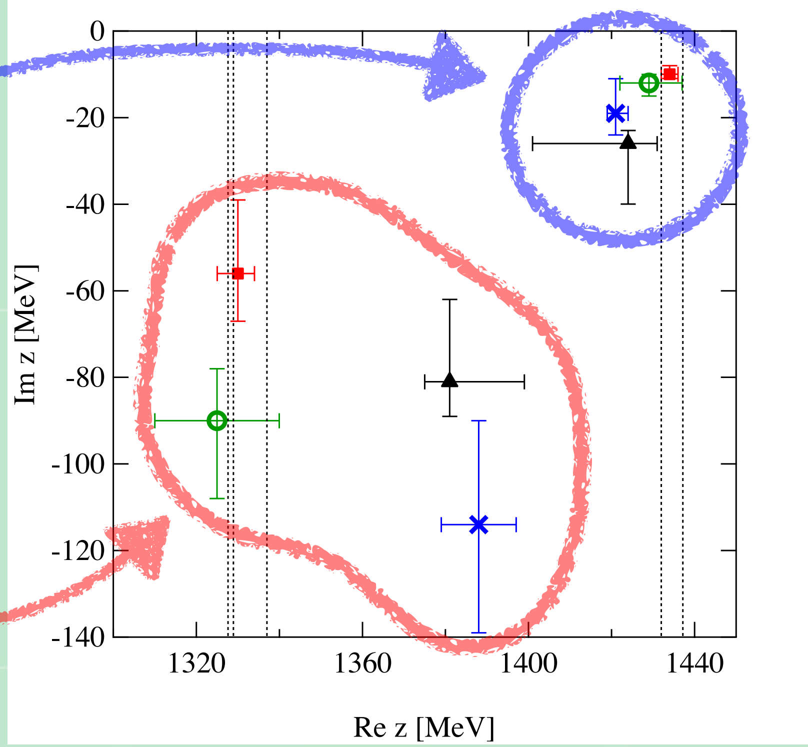
Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

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

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

$\Lambda(1380)\ 1/2^-$ $J^P = \frac{1}{2}^-$ Status: ∗∗

new!



T. Hyodo, M. Niiyama, arXiv: 2010.07592 [hep-ph], to appear in PPNP

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

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

- $K^{-}p$ **correlation function**

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

- **Summary** **(THEIA-REIMEI Seminar on 17 Mar.)**

Construction of $\bar{K}N$ potentials

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

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

→ **Coupled-channel real $\bar{K}N$ $\pi\Sigma$ $\pi\Lambda$ potential**

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

→ **K^-p correlation function**

↓ **Single-channel complex $\bar{K}N$ potential**

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

→ **Kaonic nuclei**

→ **Kaonic deuterium**

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

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

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

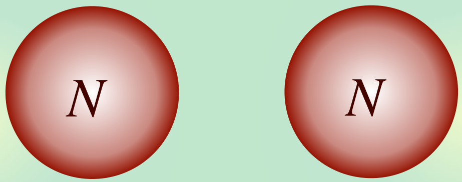
	$\bar{K}$NN	$\bar{K}$NNN	$\bar{K}$NNNN	$\bar{K}$NNNNNN
B [MeV]	25-28	45-50	68-76	70-81
Γ [MeV]	31-59	26-70	28-74	24-76

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

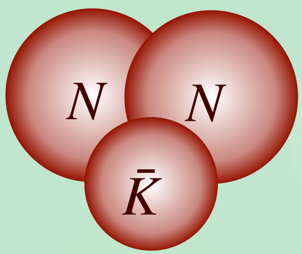
Interplay between NN and $\bar{K}N$ correlations 1

Two-nucleon system

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



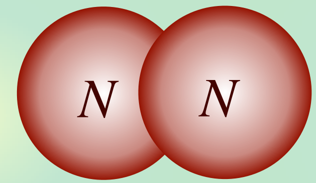
unbound



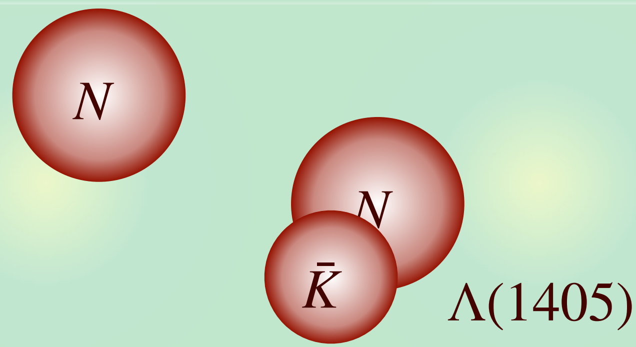
(quasi-)bound

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

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



bound (d)



unbound

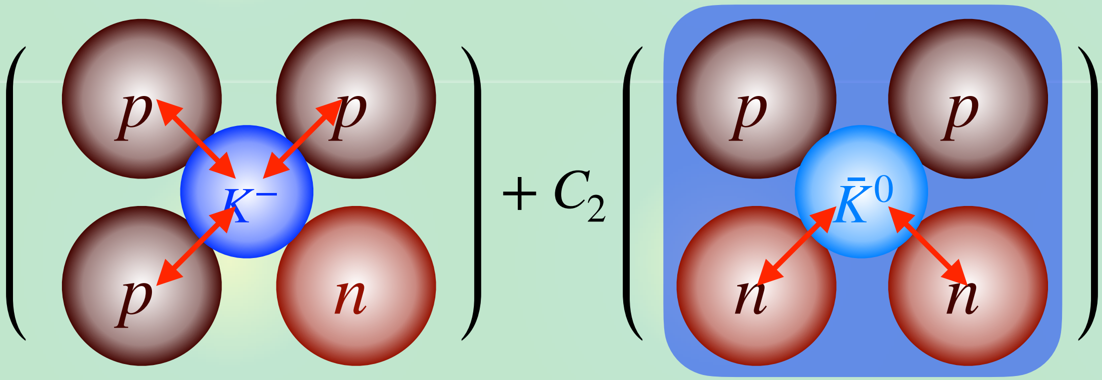
$$\frac{\bar{K}N(I=0)}{\bar{K}N(I=1)}=\frac{1}{3}$$

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

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

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

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



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

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

- NN **correlation**

  $ppnn$ **forms** α **:** $|C_1|^2 < |C_2|^2$

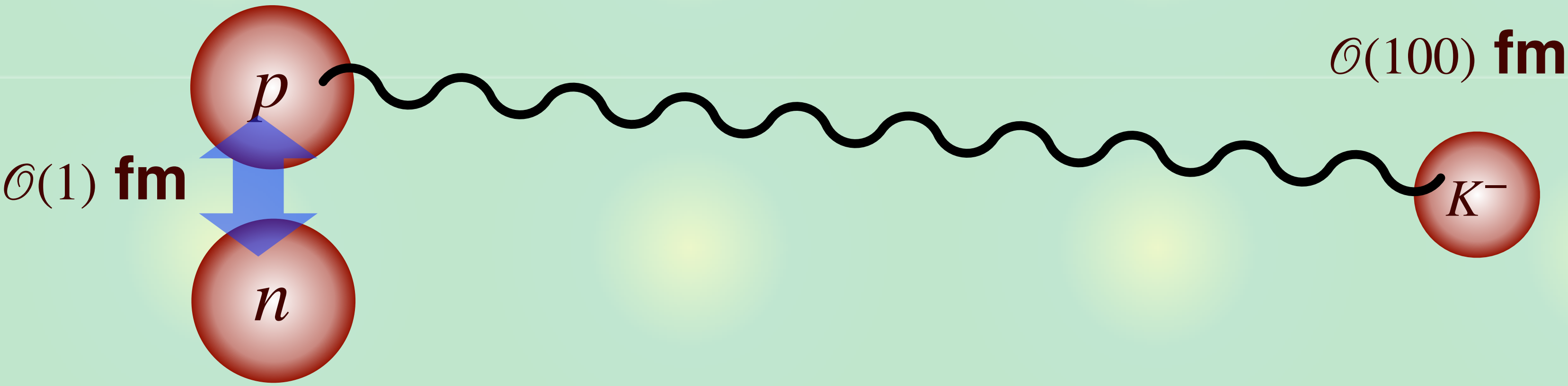
- **Numerical result**

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

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

Shift-width of the $1S$ state:

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

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

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

c.f.) J. Revai, PRC 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

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

Vary β within SIDDHARTA uncertainty of $K^- p$

- allowed region: $-0.17 < \beta < 1.08$

(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

- deviation of ΔE of $K^- d$ ~ 170 eV

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

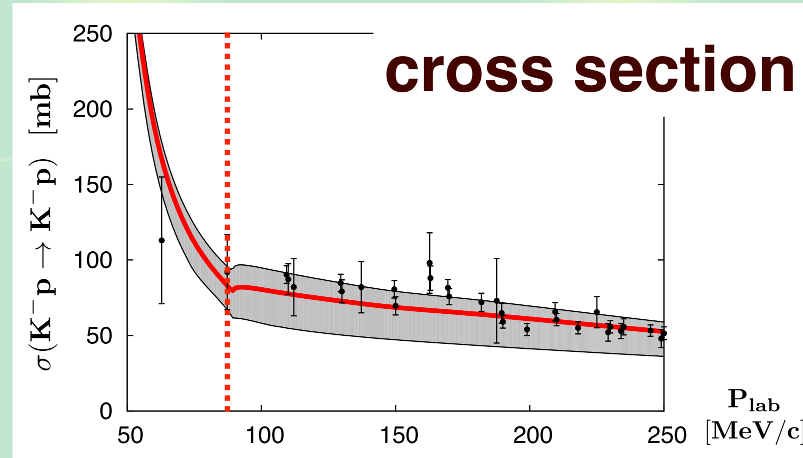
Measurement of $K^- d$ will provide strong constraint on $I = 1$

New data : K^-p correlation function

K^-p total cross sections

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

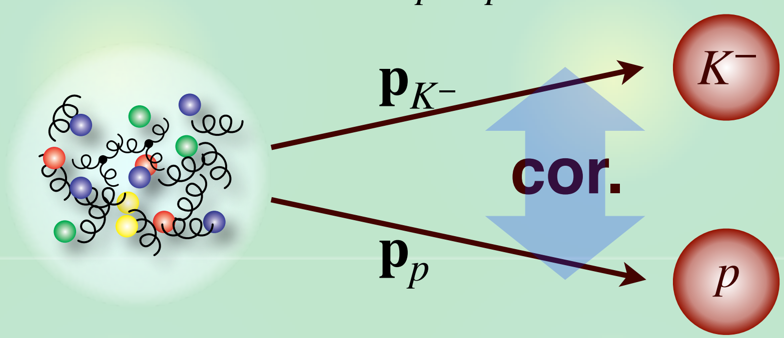
- Old bubble chamber data

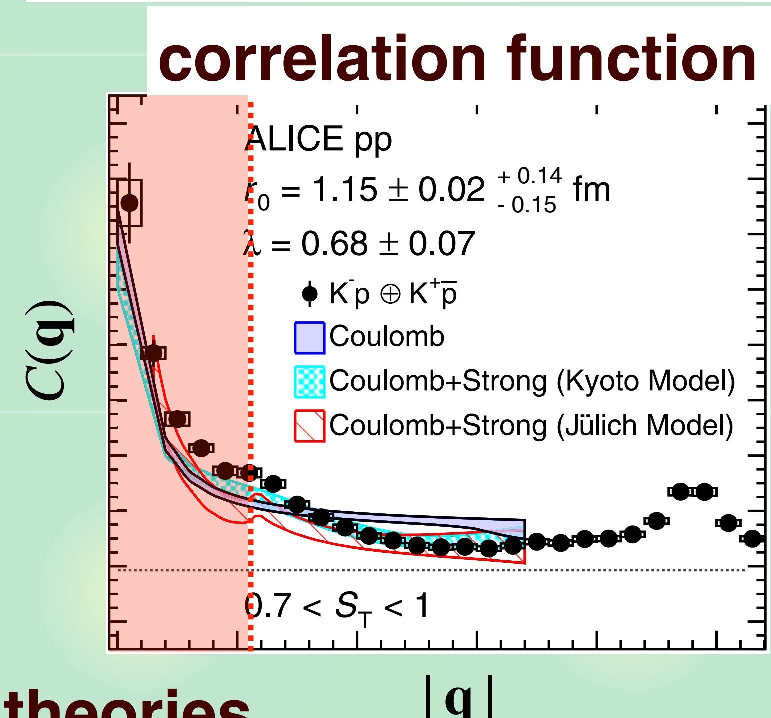


K^-p correlation function

ALICE collaboration, PRL 124, 092301 (2020)

$$C(\mathbf{q}) = \frac{N_{K^-p}(\mathbf{p}_{K^-}, \mathbf{p}_p)}{N_{K^-}(\mathbf{p}_{K^-})N_p(\mathbf{p}_p)}$$





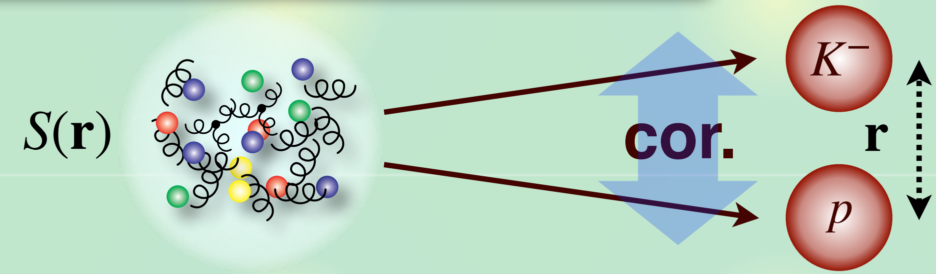
- Excellent precision ($\bar{K}^0n$ cusp)
- Low-energy data below $\bar{K}^0n$

—> important constraint on $\Lambda(1405)$ theories

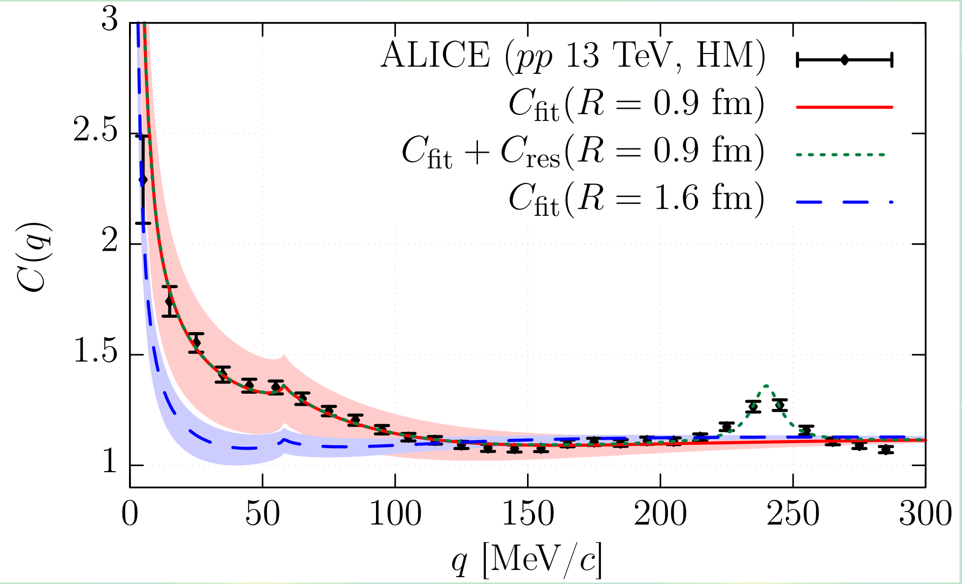
Prediction from chiral SU(3) dynamics

Theoretical calculation of $C(q)$

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



- wave function $\Psi^{(-)}_{\mathbf{q}}(\mathbf{r})$: coupled-channel $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential
- source function $S(\mathbf{r})$: determined by K^+p data



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

Correlation function is well reproduced.

Summary

- **Pole structure of the $\Lambda(1405)$ region is now well constrained by the experimental data.**

  "$\Lambda(1405)$" **—>** $\Lambda(1405)$ **and** $\Lambda(1380)$

  Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012);
  T. Hyodo, M. Niiyama, arXiv: 2010.07592 [hep-ph], to appear in PPNP

- **$\bar{K}N$ potentials are useful for various applications, Kaonic nuclei, Kaonic deuterium, and K^-p correlation function**

  K. Miyahara. T. Hyodo, PRC 93, 015201 (2016);
  K. Miyahara, T. Hyodo, W. Weise, PRC 98, 025201 (2018);
  S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara. T. Hyodo, PRC95, 065202 (2017);
  T. Hoshino, S. Ohnishi, W. Horiuchi, T. Hyodo, W. Weise, PRC96, 045204 (2017);
  Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise. PRL124, 132501 (2020)