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

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Clusters & Hierarchies

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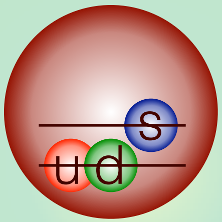
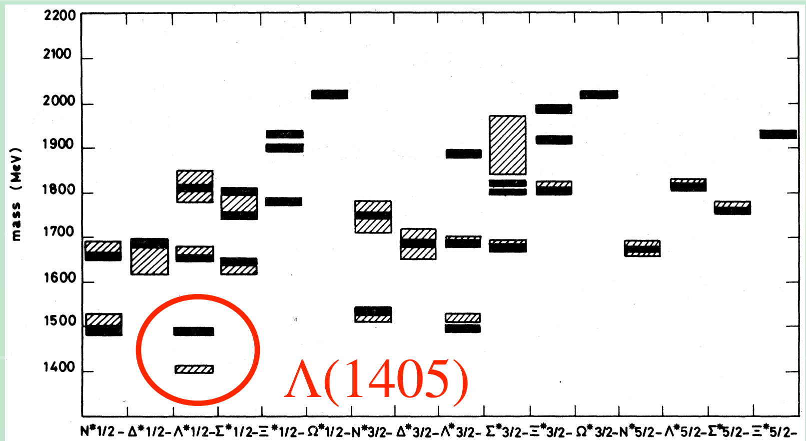
Contents

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)



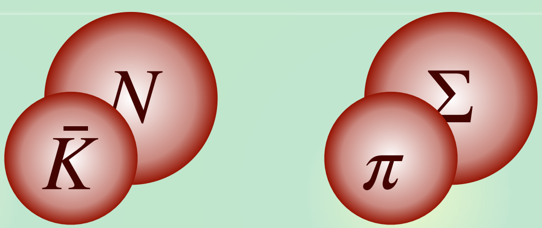


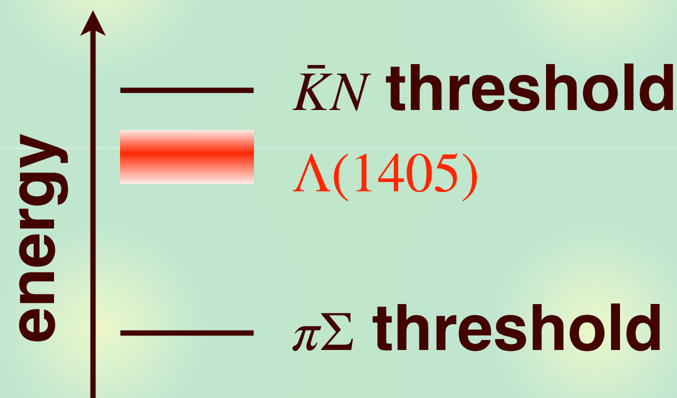
: theory

: experiment

Resonance in coupled-channel scattering

- coupling to MB states





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

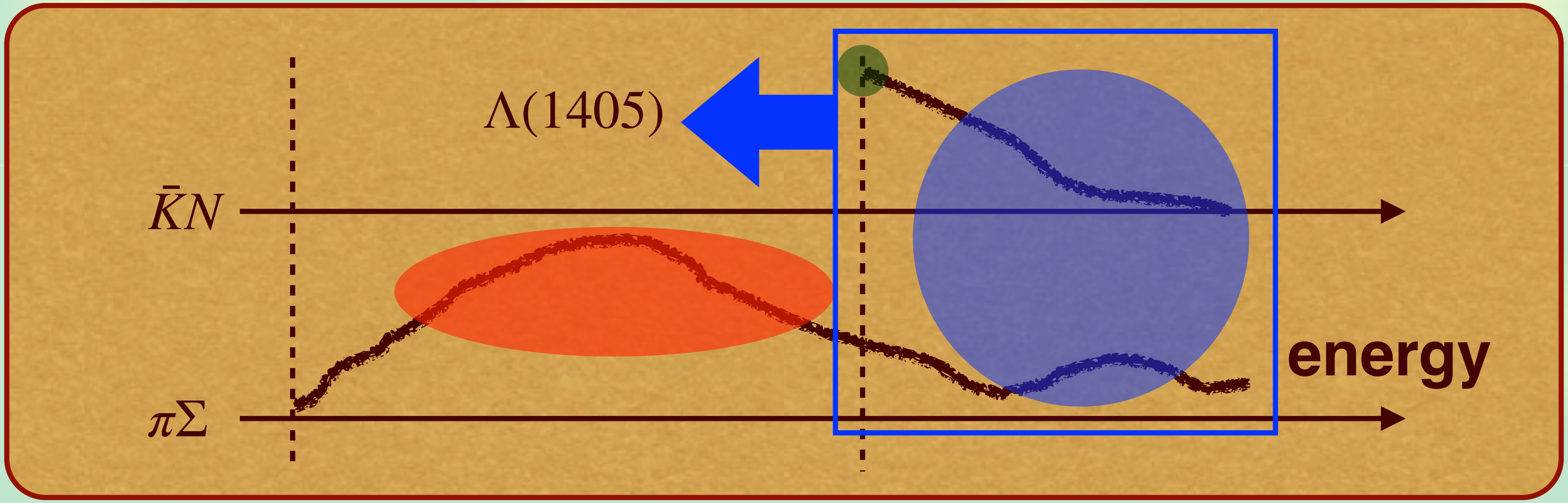
Strategy for $\bar{K}N$ interaction

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)

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

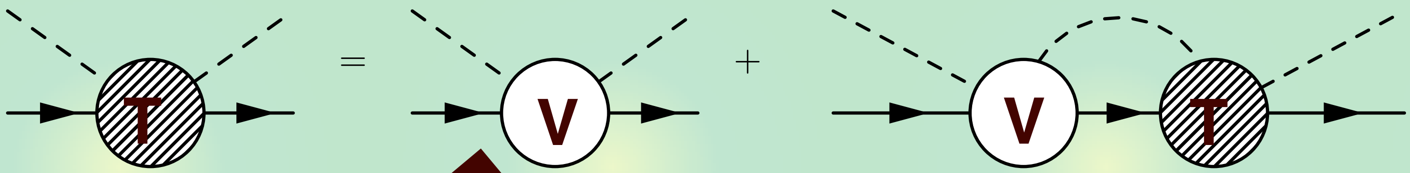
- $\pi\Sigma$ **mass spectra** (new data : LEPS, CLAS, HADES, ...)



Construction of the realistic amplitude

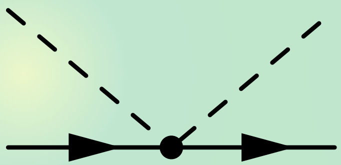
Chiral SU(3) coupled-channels $(\bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, \eta\Sigma, K\Xi)$ approach

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



Chiral perturbation theory

1) TW term

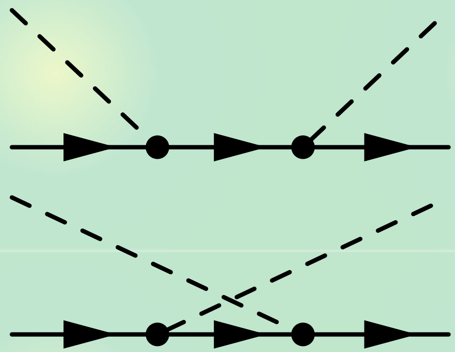


$\mathcal{O}(p)$

6 cutoffs

TW model

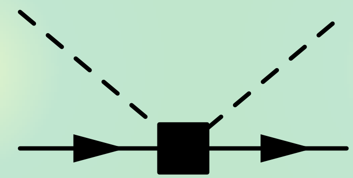
2) Born terms



$\mathcal{O}(p)$

TWB model

3) NLO terms



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

7 LECs

NLO model

Best-fit results

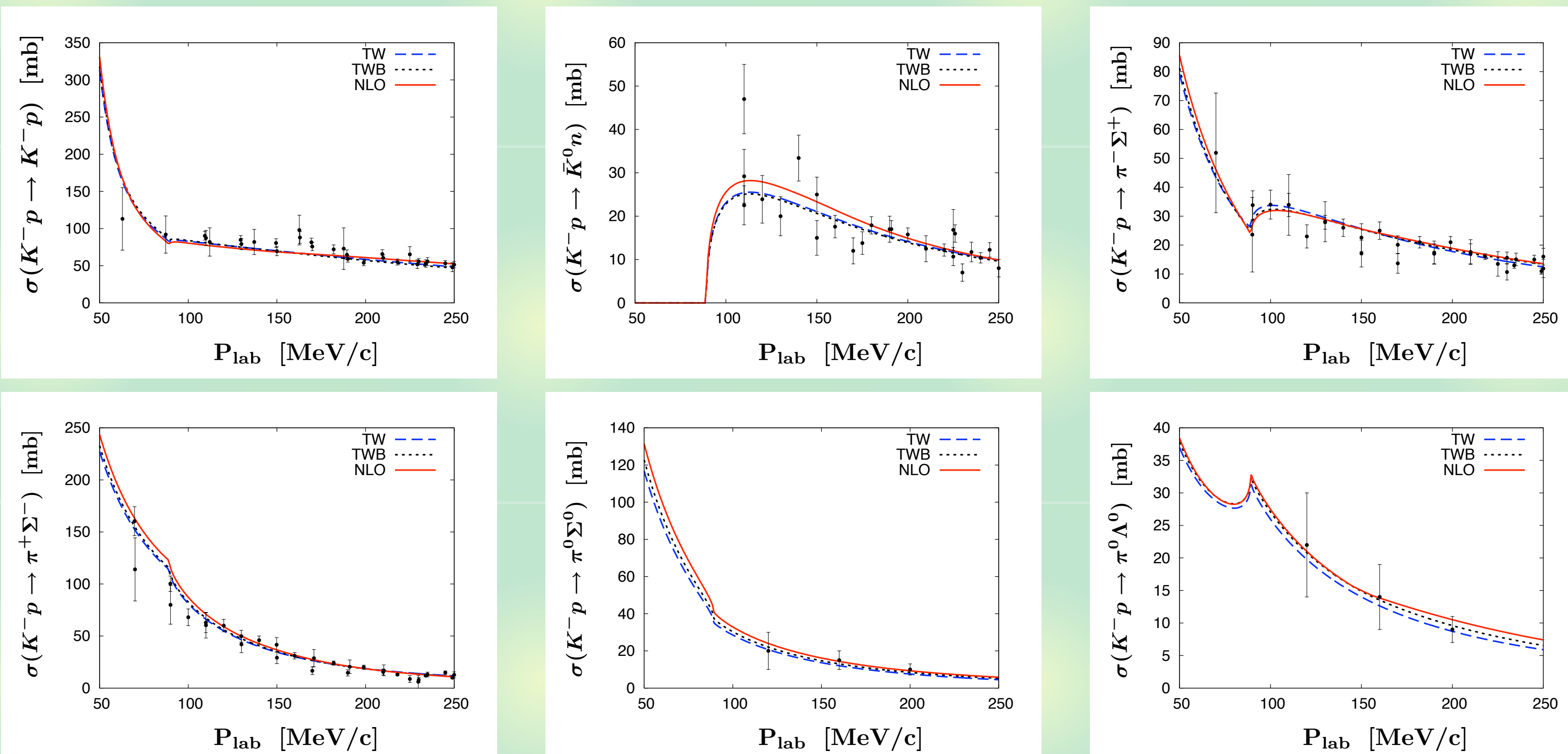
K **at rest**

	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)

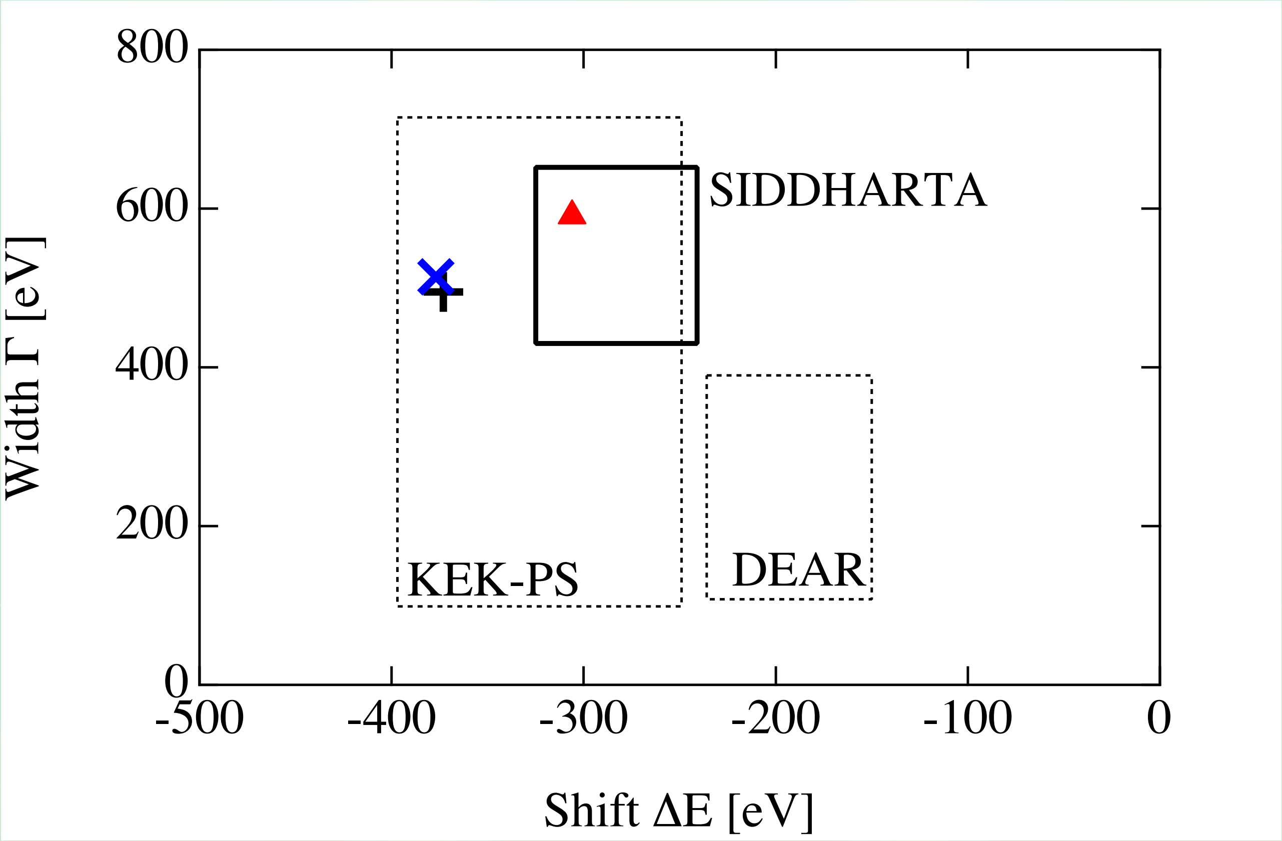
$K^- p$ **cross sections**



Accurate description of all existing data ($\chi^2/\mathrm{d.o.f} \sim 1$**)**

Comparison with SIDDHARTA

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

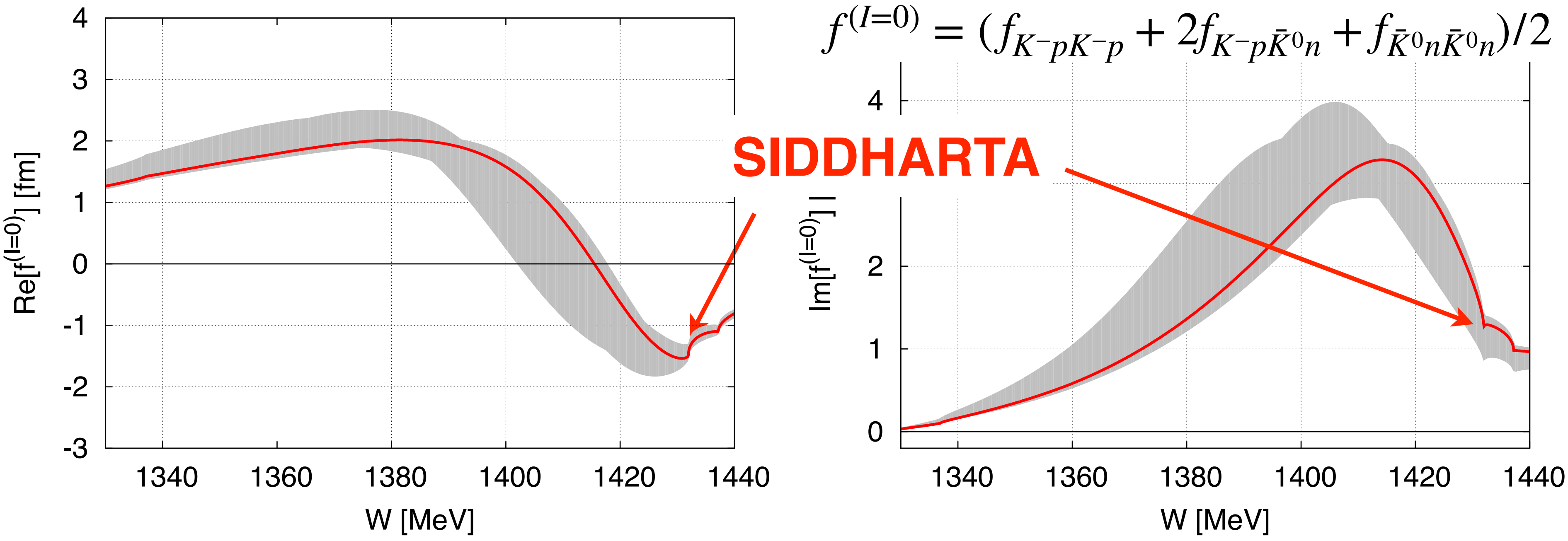


TW and TWB are reasonable, while best-fit requires NLO.

Subthreshold extrapolation

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

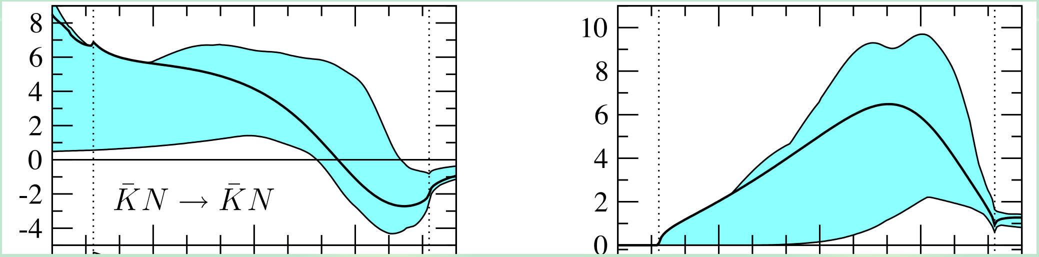
$$f^{(I=0)} = (f_{K^-pK^-p} + 2f_{K^-p\bar{K}^0n} + f_{\bar{K}^0n\bar{K}^0n})/2$$



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)

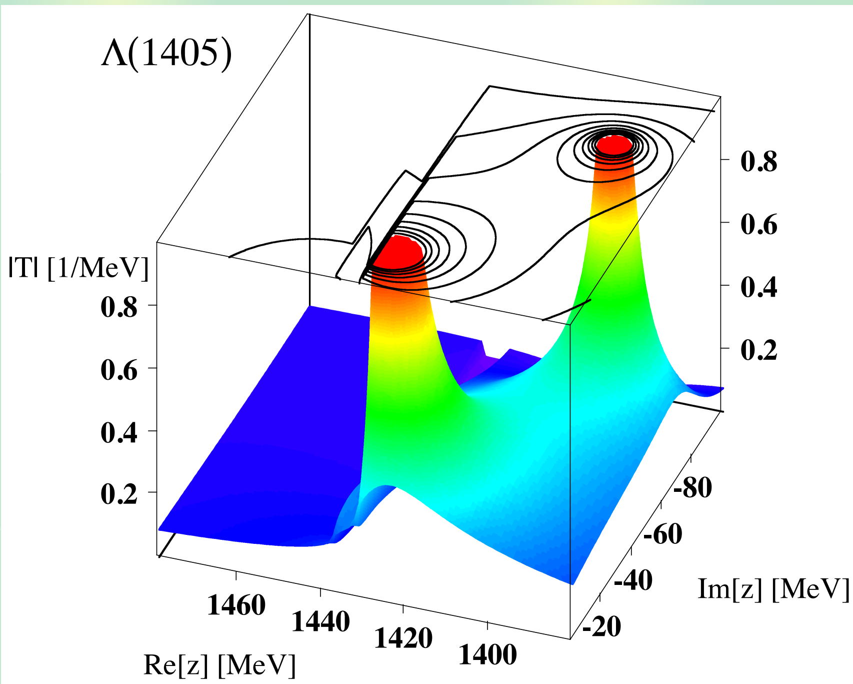


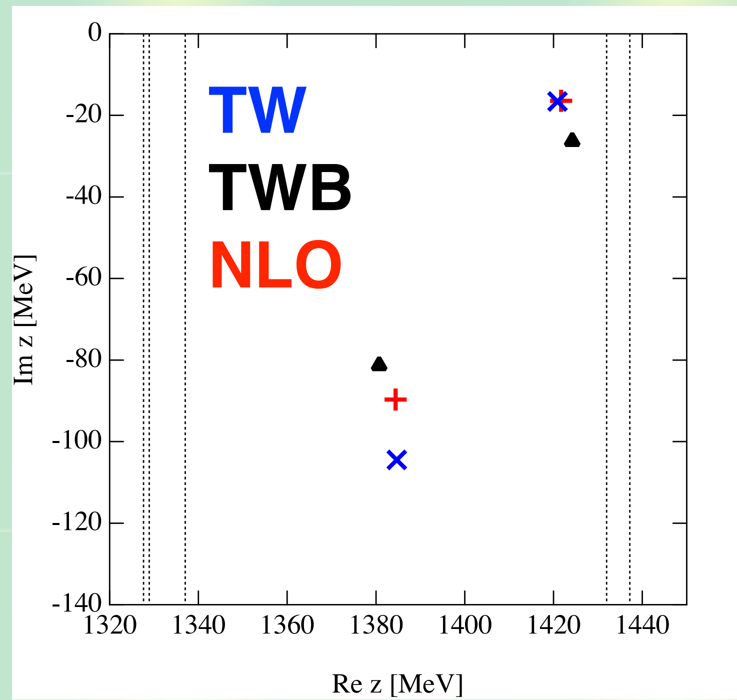
SIDDHARTA is essential for subthreshold extrapolation.

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:**

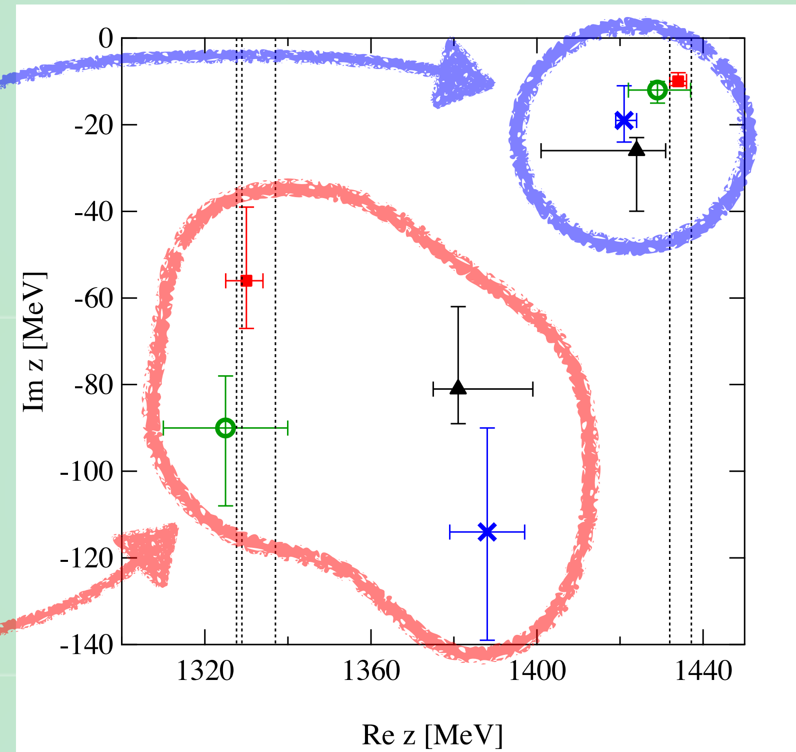
Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

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



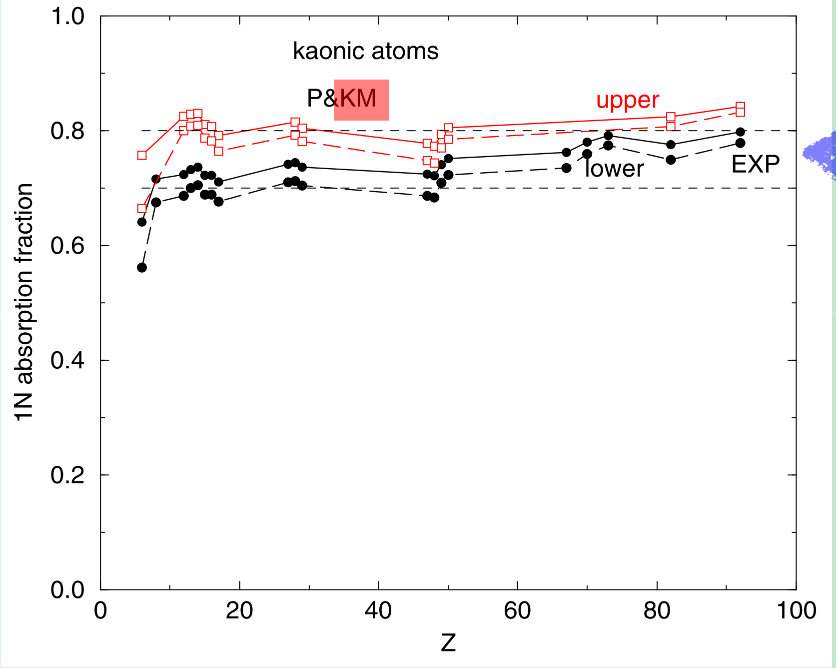
T. Hyodo, M. Niiyama, arXiv: 2010.07592 [hep-ph], to appear in PPNP

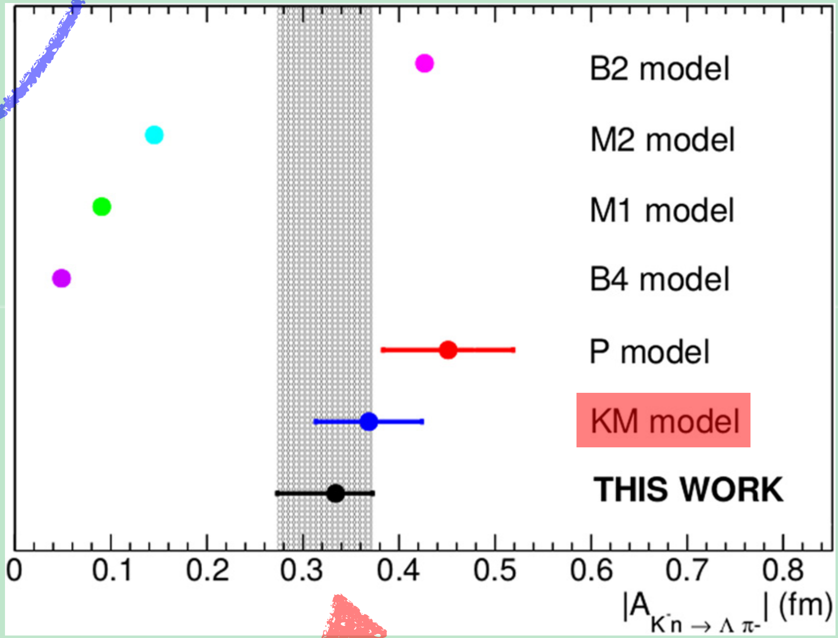
- "Λ(1405)" is no longer at 1405 MeV but ~ 1420 MeV.
- Lower pole: two-star resonance Λ(1380)

Further check of amplitude

Single-nucleon absorption on kaonic atoms

E. Friedman, A. Gal, NPA959, 66 (2017)





$|f_{K^-n\to\pi^-\Lambda}|$ from K^- absorption on $^4\mathrm{He}$ at DAΦNE

K. Piscicchia, *et al.*, PLB782, 339 (2018)

Our amplitude (KM model) is compatible with these analyses

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**

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)

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

K^-p correlation function

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

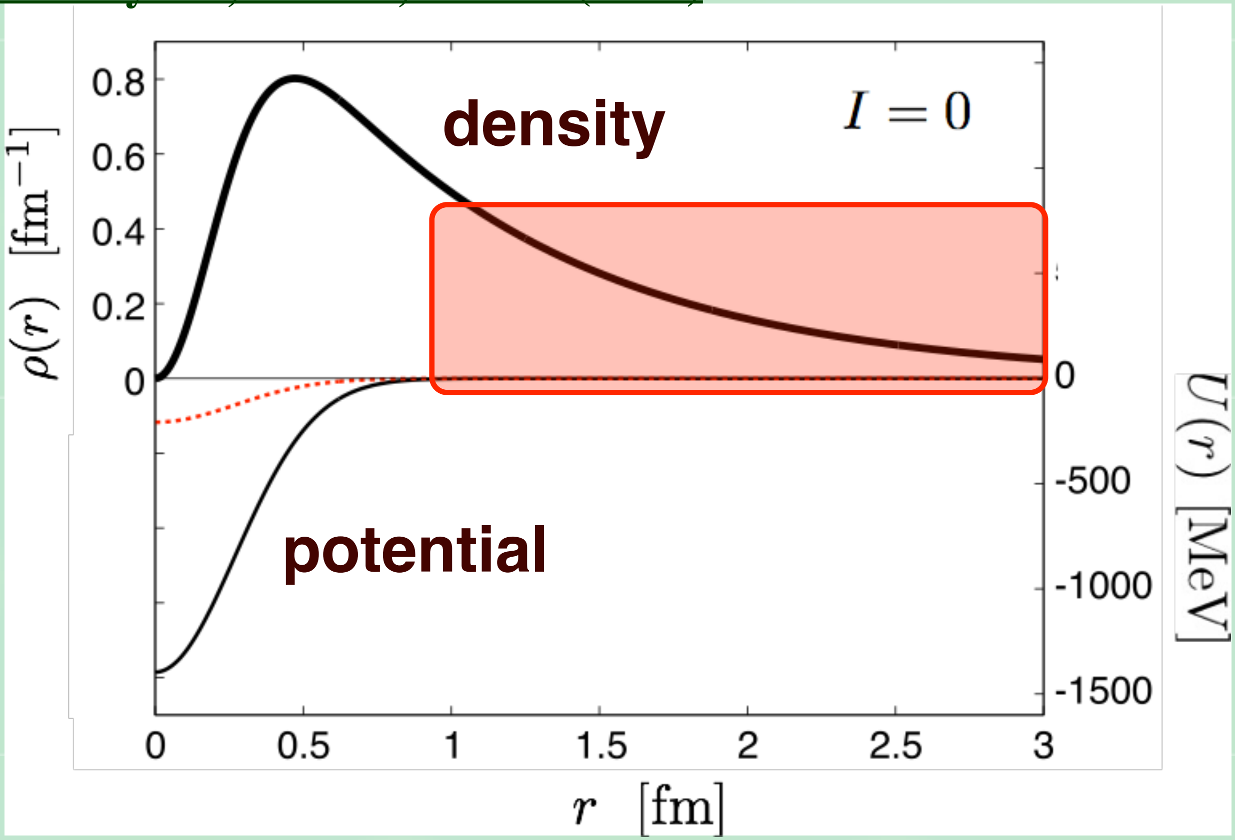
Kaonic nuclei

Kaonic deuterium

Spatial structure of $\Lambda(1405)$

$\bar{K}N$ wave function at $\Lambda(1405)$ 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 $\Lambda(1405)$ is much larger than ordinary hadrons.

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)

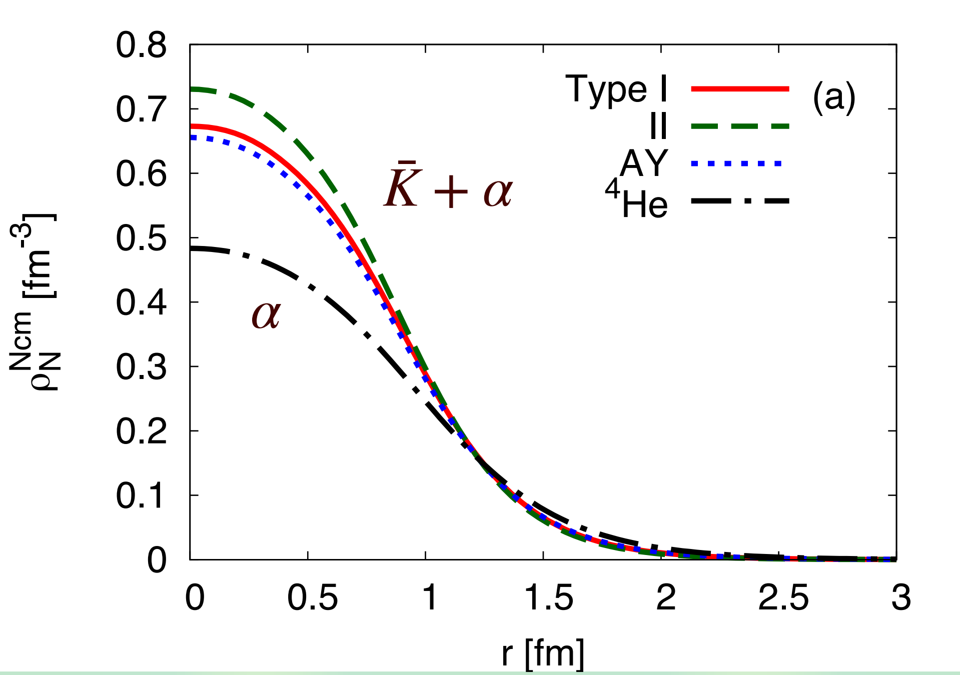
Results for kaonic nuclei with $A = 2, 3, 4, 6$

	$\bar{K}NN$	$\bar{K}NNN$	$\bar{K}NNNN$	$\bar{K}NNNNNN$
B [MeV]	25-28	45-50	68-76	70-81
$\Gamma_{\pi YN}$ [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



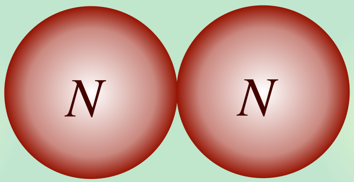
- central density increases (not substantially <— NN core)
- $B = 68$-76 MeV (Kyoto $\bar{K}N$)
- $B = 85$-87 MeV (AY)

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

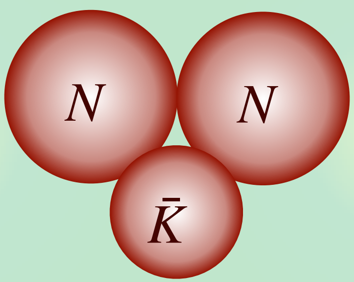
Interplay between NN and $\bar{K}N$ correlations 1

Two-nucleon system

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



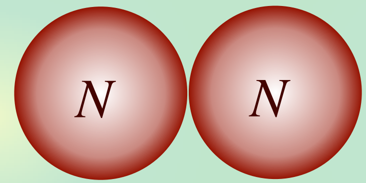
unbound



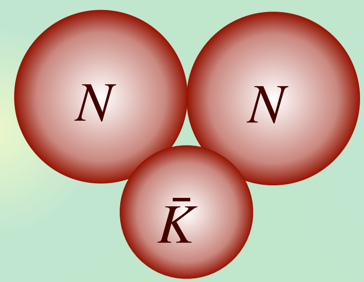
(quasi-)bound

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

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



bound (d)



$\Lambda(1405)$

unbound

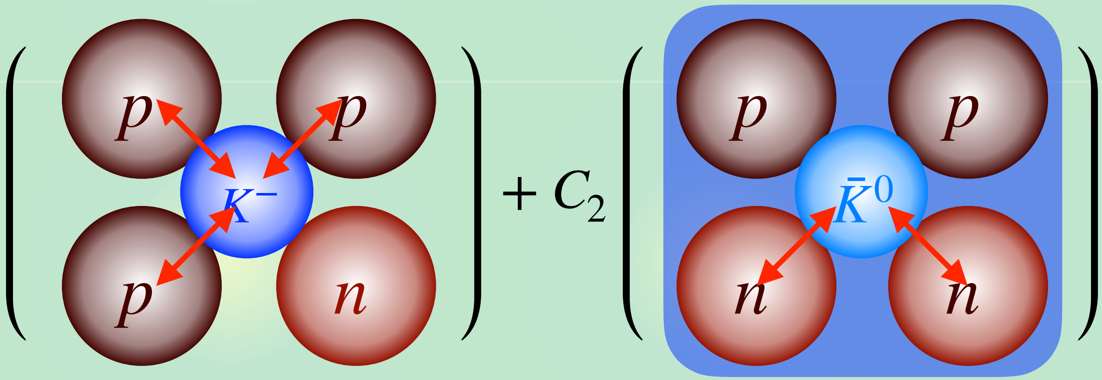
$$\frac{\bar{K}N(I=0)}{\bar{K}N(I=1)} = \frac{1}{3}$$

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

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

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

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



- **$\bar{K}N$ 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 **:** $|C_1|^2 < |C_2|^2$

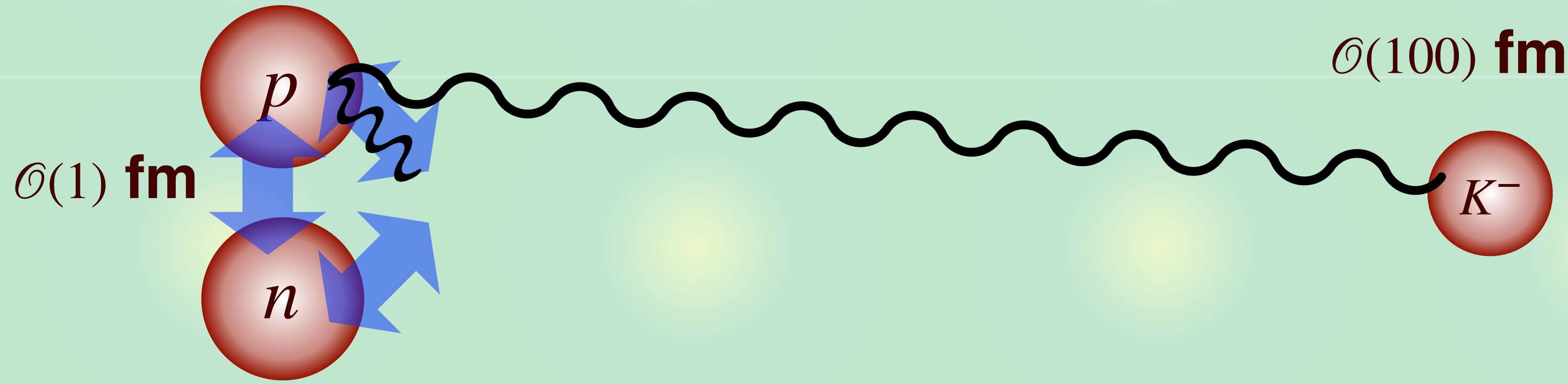
- **Numerical result**

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

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

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, PLB 744, 105 (2015);
J. Revai, PRC 94, 054001 (2016)

Check of kaonic hydrogen

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

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

Two-body calculation with physical masses

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

Result:

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

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]		$283 \pm 36 \pm 6$	$541 \pm 89 \pm 22$

	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)

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

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

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

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

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

Few-body technique

- a large number of correlated gaussian basis

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

Kaonic deuterium: shift and width

Results of the three-body calculation

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

- energy convergence

<— a 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!

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.
- 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)

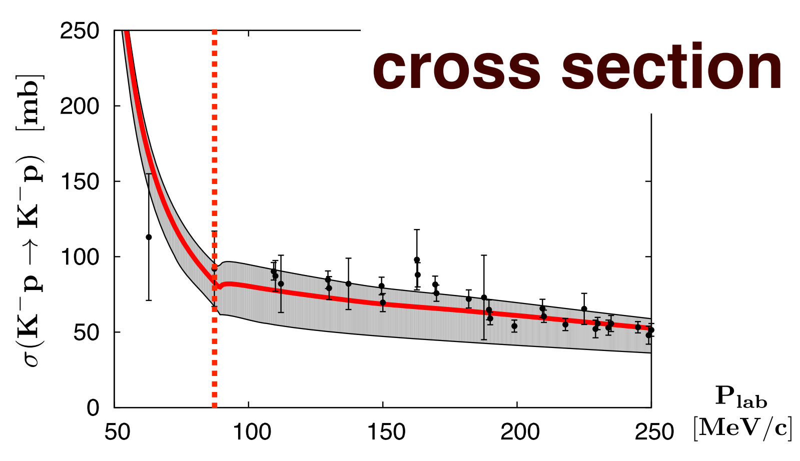
Measurement of K^-d will provide strong constraint on $I = 1$

New data : K^-p correlation function

K^-p total cross sections

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

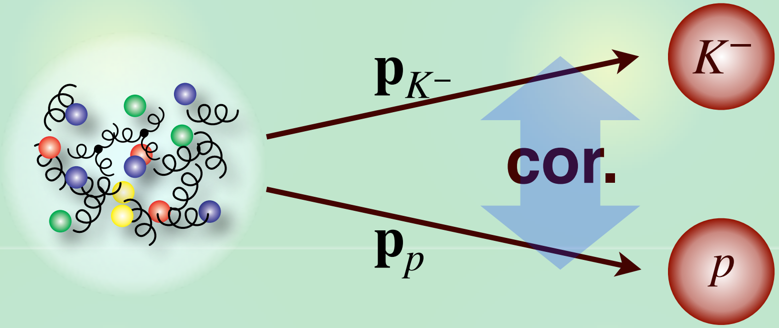
- Old bubble chamber data

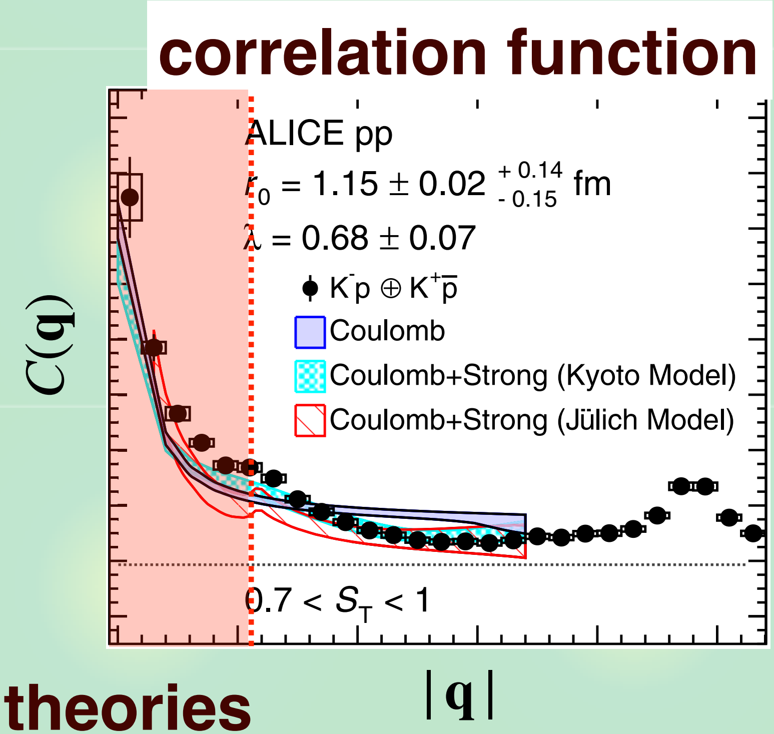


K^-p correlation function

S. Acharya *et al.* (ALICE), PRL 124, 092301 (2020)

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





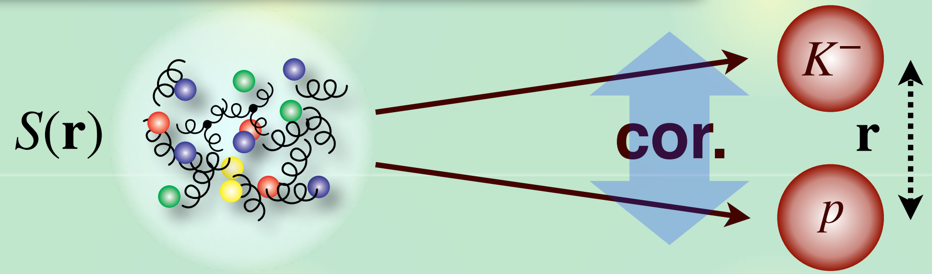
- Excellent precision ($\bar{K}^0n$ cusp)
- Low-energy data below $\bar{K}^0n$

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

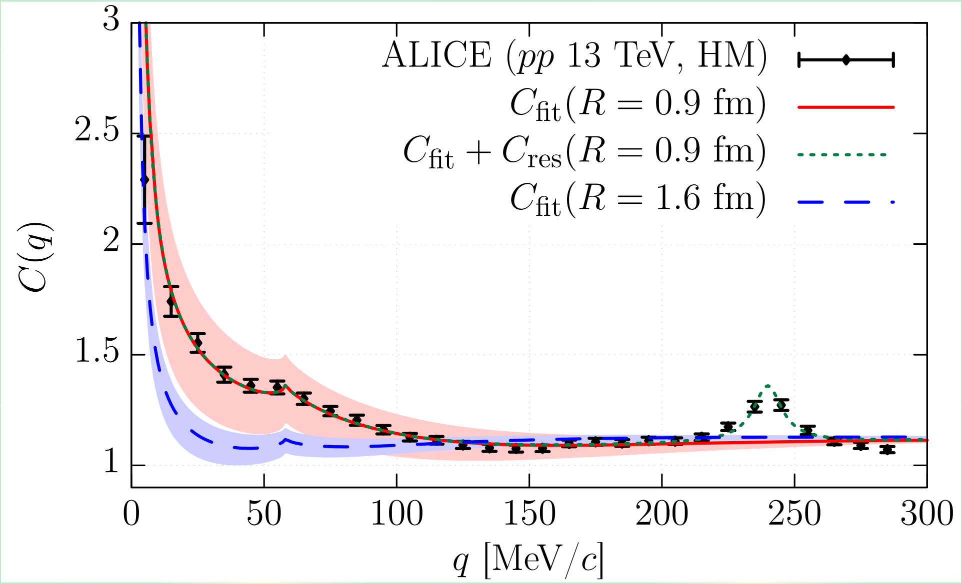
Prediction from chiral SU(3) dynamics

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 $S(\mathbf{r})$: estimated 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**

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