Improved constraints on chiral SU(3) dynamics from kaonic hydrogen

Tetsuo Hyodo[1],

Yoichi Ikeda[1,2] and Wolfram Weise[3]

Tokyo Institute of Technology[1], RIKEN[2], TU München[3]

supported by Global Center of Excellence Program
“Nanoscience and Quantum Physics”

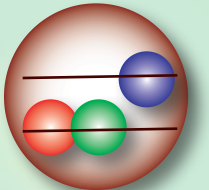
2011, Nov 26th

K meson and KN interaction

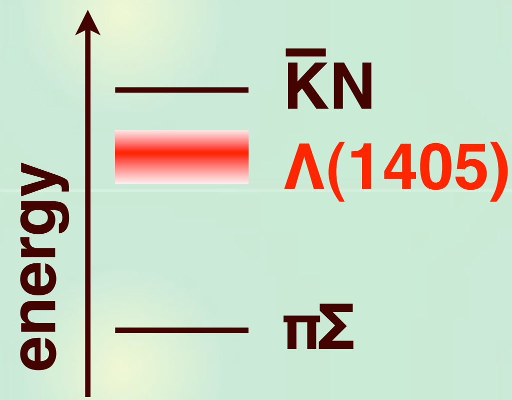
Two aspects of K($\bar{K}$) meson

- NG boson of chiral SU(3) ⊗ SU(3) --> SU(3)
- relatively heavy mass: M_K ~ 495 MeV

--> peculiar role in hadron physics

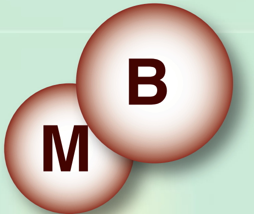


$\bar{K}$N interaction is ...

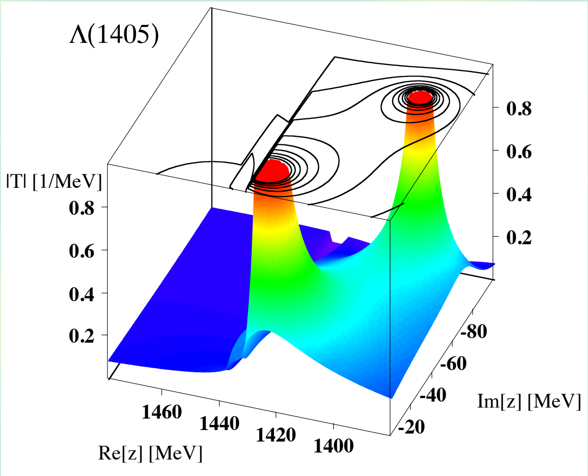


- coupled with πΣ channel
- strongly attractive

--> quasi-bound state Λ(1405)
meson-baryon v.s. qqq state,
double pole, ...



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



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

Constraints for KN interaction

K-p total cross sections to K-p, $\bar{K}^0$n, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\pi^0\Sigma^0$, $\pi^0\Lambda$.

- old experiments, large error bars, some contradictions
- wide energy range above the threshold

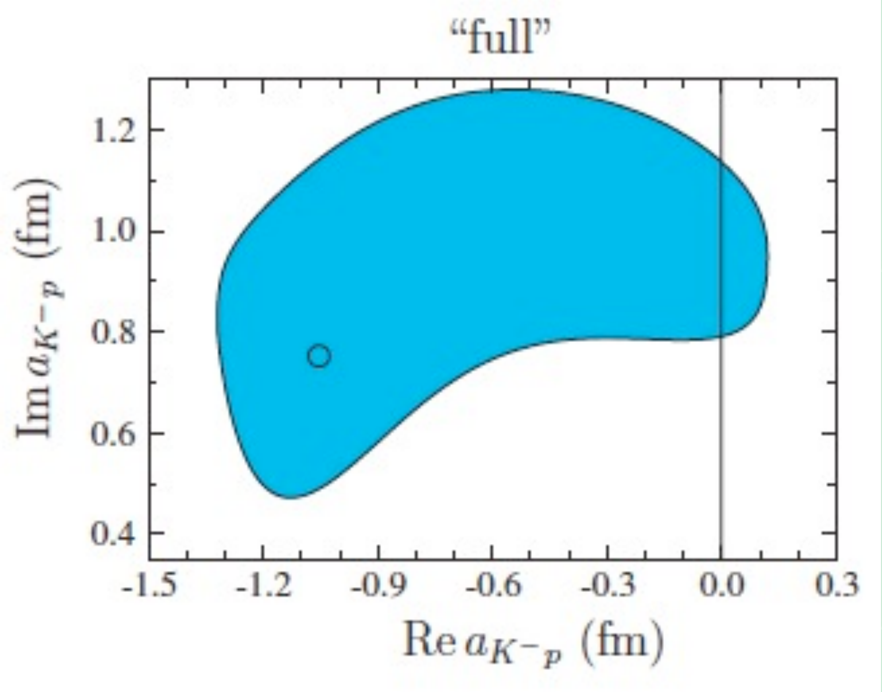
Threshold branching ratios

- very accurate
- only at $W = m_K + M_p$

$$\gamma = \frac{\Gamma(K^-p \to \pi^+\Sigma^-)}{\Gamma(K^-p \to \pi^-\Sigma^+)} = 2.36 \pm 0.04,$$

$$R_c = \frac{\Gamma(K^-p \to \text{charged})}{\Gamma(K^-p \to \text{all})} = 0.664 \pm 0.011,$$

$$R_n = \frac{\Gamma(K^-p \to \pi^0\Lambda)}{\Gamma(K^-p \to \text{neutral})} = 0.189 \pm 0.015,$$



These constraints to determine scattering length

B. Borasoy, U.G. Meissner, R. Nissler, Phys. Rev. C74, 055201 (2006)

--> large uncertainty!

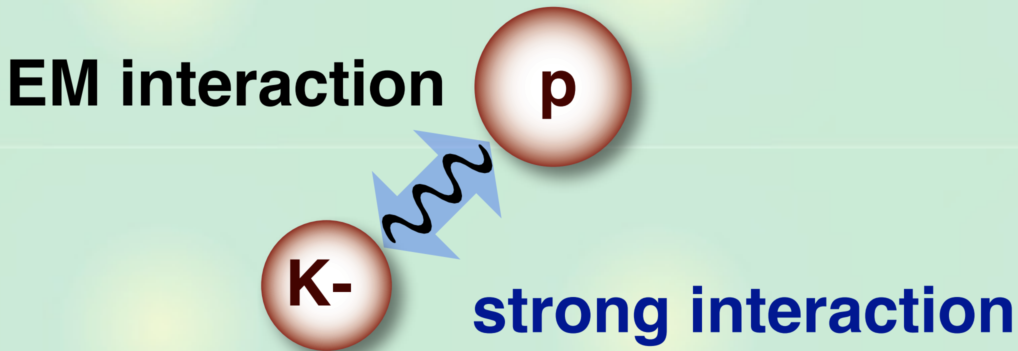
Scattering length from kaonic hydrogen

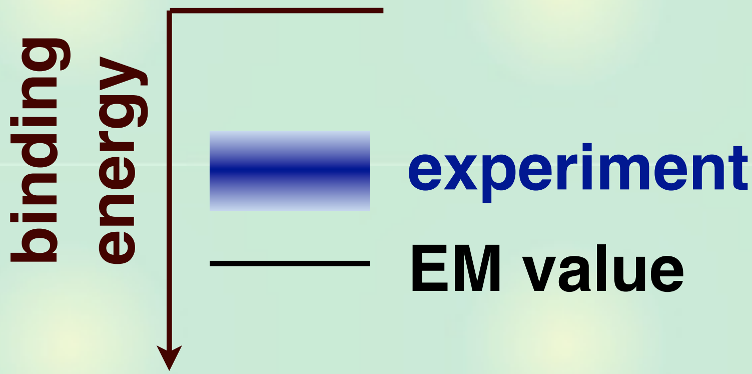
Measurements of the kaonic hydrogen

- **shift** and **width** of atomic state (Coulomb bound state)

$$\Delta E - \frac{i}{2}\Gamma = -2\alpha^3 \mu_c^2 a_{K^-p}[1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p}] \longleftarrow \text{scattering length}$$

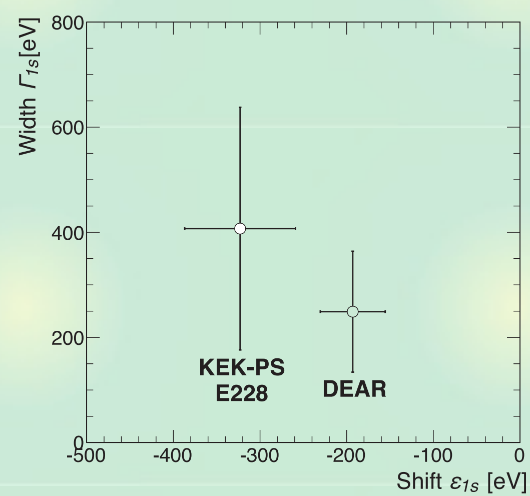
U.-G. Meissner, U. Raha, A. Rusetsky, Eur. Phys. J. C35, 349 (2004)





Experiments: KpX and DEAR

M. Iwasaki, *et al.*, Phys. Rev. Lett. 78, 3067 (1997)
G. Beer, *et al.*, Phys. Rev. Lett. 94, 212302 (2005)



- repulsive shift (existence of Λ*)
- quantitatively inconsistent?

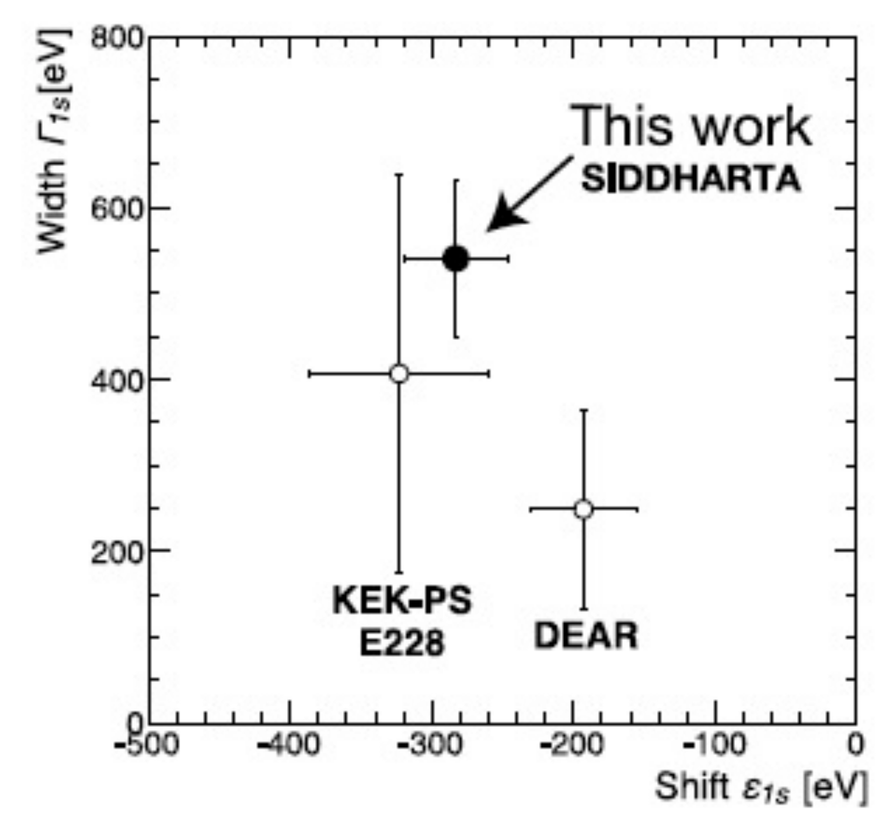
SIDDHARTA measurement

New accurate measurement by SIDDHARTA

M. Bazzi, *et al.*, Phys. Lett. B704, 113 (2011)

- smallest uncertainties

$$\Delta E = -283 \pm 36 \pm 6 \text{ eV}, \quad \Gamma = 541 \pm 89 \pm 22 \text{ eV}$$



--> New constraint on the meson-baryon amplitude

Contents

- Introduction
- Λ(1405) in meson-baryon scattering
  - Chiral SU(3) dynamics
  - Pole structure of Λ(1405)

  T. Hyodo, D. Jido, Prog. Part. Nucl. Phys. 67, 55 (2012)
- Systematic χ2 analysis with SIDDHARTA
  - Subthreshold extrapolation of $\bar{K}$N amplitude
  - Predictions (K-n scattering, πΣ spectrum)

  Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B 706, 63 (2011); in preparation
- Summary

Chiral unitary approach

Description of S = -1, $\bar{K}N$ s-wave scattering: Λ(1405) in I=0

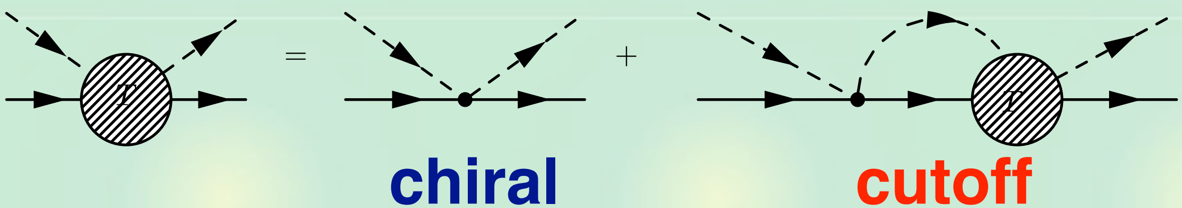
- Interaction <-- chiral symmetry

Y. Tomozawa, Nuovo Cim. 46A, 707 (1966); S. Weinberg, Phys. Rev. Lett. 17, 616 (1966)

- Amplitude <-- unitarity in coupled channels

R.H. Dalitz, T.C. Wong, G. Rajasekaran, Phys. Rev. 153, 1617 (1967)

$$T = \frac{1}{1 - VG} V$$



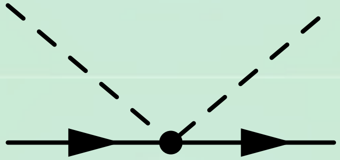
N. Kaiser, P. B. Siegel, W. Weise, Nucl. Phys. A594, 325 (1995),
E. Oset, A. Ramos, Nucl. Phys. A635, 99 (1998),
J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001),
M.F.M. Lutz, E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002), ... many others

It works successfully in various hadron scatterings.

s-wave low energy interaction in ChPT

NG boson-hadron scattering: chiral perturbation theory

$$\mathcal{L}^{\mathrm{WT}} = \frac{\boxed{1}}{4f^2}\mathrm{Tr}\left(\bar{B}i\gamma^{\mu}[\Phi\boxed{\partial_{\mu}}\Phi - (\partial_{\mu}\Phi)\Phi, B]\right)$$



s-wave contribution: Tomozawa-Weinberg (TW) term

Y. Tomozawa, Nuovo Cim. 46A, 707 (1966); S. Weinberg, Phys. Rev. Lett. 17, 616 (1966)

$$V_{ij} = -\frac{C_{ij}}{4f^2}\boxed{(\omega_i + \omega_j)} + \dots$$

$$C_{ij} = \sum_{\alpha}[6 - C_2(\alpha)]\left(\begin{array}{cc||c} 8 & 8 & \alpha \\ I_{\bar{i}}, Y_{\bar{i}} & I_i, Y_i & I, Y \end{array}\right)\left(\begin{array}{cc||c} 8 & 8 & \alpha \\ I_{\bar{j}}, Y_{\bar{j}} & I_j, Y_j & I, Y \end{array}\right)$$

$$Y = Y_{\bar{i}} + Y_i = Y_{\bar{j}} + Y_j, \quad I = I_{\bar{i}} + I_i = I_{\bar{j}} + I_j,$$

- Flavor SU(3) symmetry --> sign and strength
- Derivative coupling --> energy dependence
- Systematic improvement by higher order terms (later)

When the interaction is strong, resummation is mandatory.

Scattering amplitude and unitarity

Unitarity of S-matrix: Optical theorem

$$\mathrm{Im}[T^{-1}(s)] = \frac{\rho(s)}{2}$$ ← phase space of two-body state

General amplitude by dispersion relation

$$T^{-1}(\sqrt{s}) = \boxed{\sum_i \frac{R_i}{\sqrt{s}-W_i} + \tilde{a}(s_0)} + \frac{s-s_0}{2\pi}\int_{s^+}^{\infty} ds' \frac{\rho(s')}{(s'-s)(s'-s_0)}$$

R_i, W_i, a: to be determined by chiral interaction

Identify dispersion integral = loop function G, the rest = V^{-1}

$$\boxed{T(\sqrt{s}) = \frac{1}{V^{-1}(\sqrt{s}) - G(\sqrt{s};a)}}$$

Scattering amplitude

The function V is determined by the matching with ChPT

$$T^{(1)} = V^{(1)}, \quad T^{(2)} = V^{(2)}, \quad T^{(3)} = V^{(3)} - V^{(1)}GV^{(1)}, \quad \dots$$

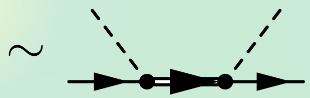
Amplitude T: consistent with chiral symmetry + unitarity

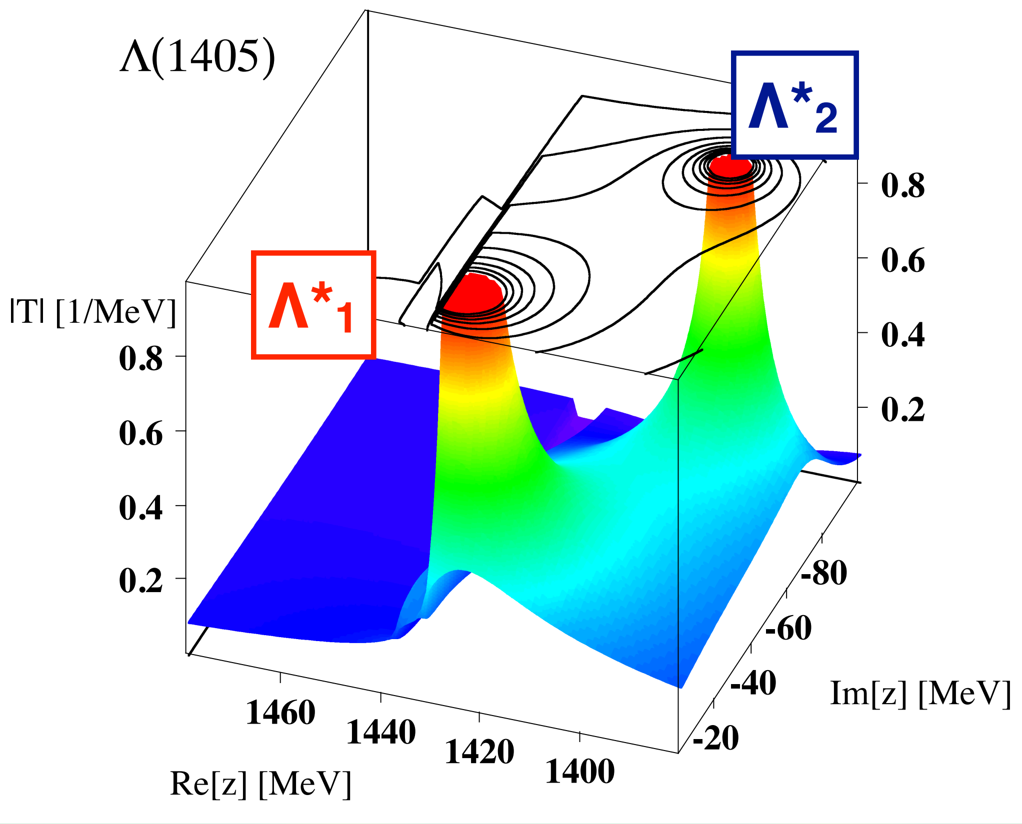
Pole structure in the complex energy plane

Resonance state ~ pole of the scattering amplitude

D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, Nucl. Phys. A 723, 205 (2003)

$$T_{ij}(\sqrt{s}) \sim \frac{g_i g_j}{\sqrt{s} - M_R + i\Gamma_R/2}$$





Two poles for one resonance (bump structure)
--> Superposition of two states ?

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

Different πΣ spectra?
K-d --> πΣN reaction

Exp.: O. Braun, et al., Nucl. Phys. B129, 715 (1977); J-PARC E31.
Theor.: D. Jido, E. Oset, T. Sekihara, Eur. Phys. J. A42, 257 (2009); A47, 42 (2011)

Origin of the two-pole structure

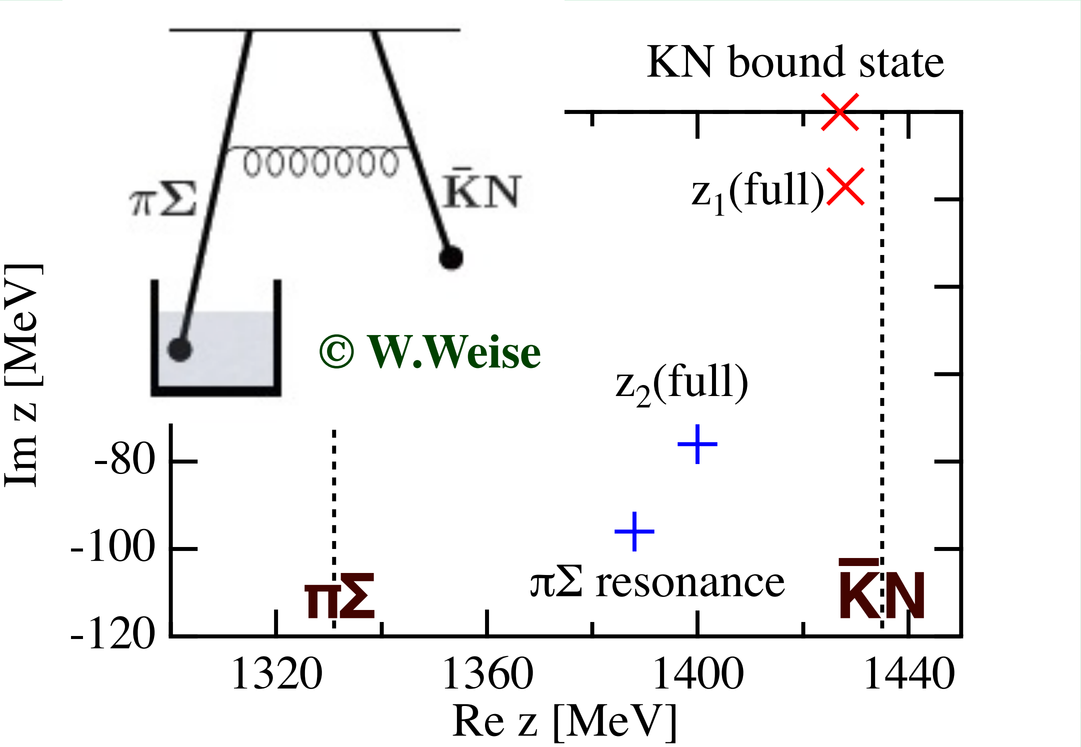
Leading order chiral interaction for K̄N-πΣ channel

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

$$V_{ij} = -C_{ij}\frac{\omega_i + \omega_j}{4f^2}$$

$$\begin{array}{cc} \bar{K}N & \pi\Sigma \end{array}$$

$$C_{ij} = \begin{pmatrix} 3 & -\sqrt{\frac{3}{2}} \\ -\sqrt{\frac{3}{2}} & 4 \end{pmatrix}$$



at threshold

$$\omega_i \sim m_i, \quad 3.3m_\pi \sim m_K$$

$$\Rightarrow V_{\bar{K}N} \sim 2.5V_{\pi\Sigma}$$

Very strong attraction in K̄N (higher energy) --> bound state

Strong attraction in πΣ (lower energy) --> resonance

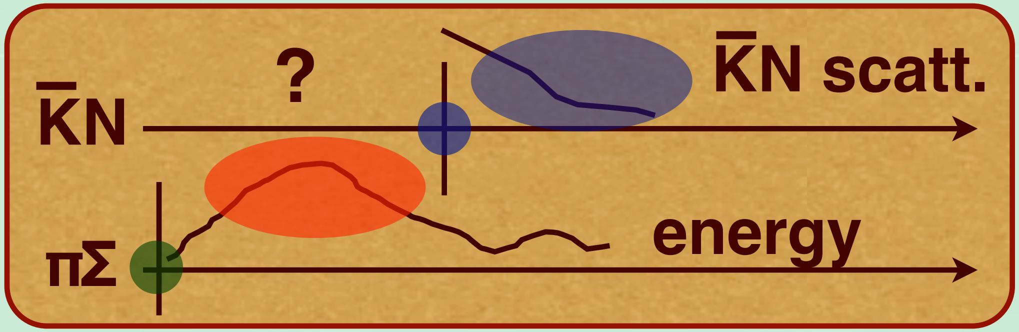
Model dependence? Effects from higher order terms?

Experimental constraints for S=-1 MB scattering

K-p total cross sections

$\bar{K}N$ threshold observables

- threshold branching ratios
- K-p scattering length <-- SIDDHARTA exp.



$\pi\Sigma$ mass spectra

- new data is becoming available (LEPS, CLAS, HADES,...)

$\pi\Sigma$ threshold observables (so far no data)

Y. Ikeda, T. Hyodo, D. Jido, H. Kamano, T. Sato, K. Yazaki, PTP 125, 1205 (2011);
T. Hyodo, M. Oka, Phys. Rev. C 83, 055202 (2011)

Construction of the realistic amplitude

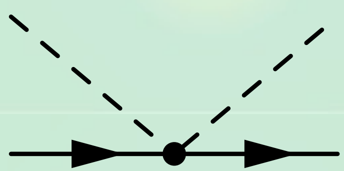
Systematic χ2 fitting with SIDDHARTA data

Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B 706, 63 (2011); in preparation

Interaction kernel: NLO ChPT

B. Borasoy, R. Nissler, W. Weise, Eur. Phys. J. A25, 79-96 (2005);
B. Borasoy, U.G. Meissner, R. Nissler, Phys. Rev. C74, 055201 (2006)

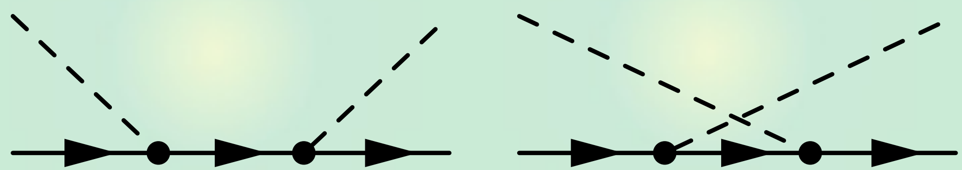
1) TW term



$\mathcal{O}(p)$

TW model

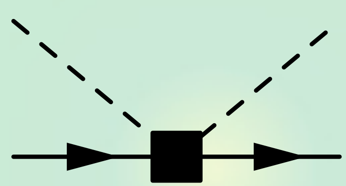
2) Born terms



$\mathcal{O}(p)$

TWB model

3) NLO terms



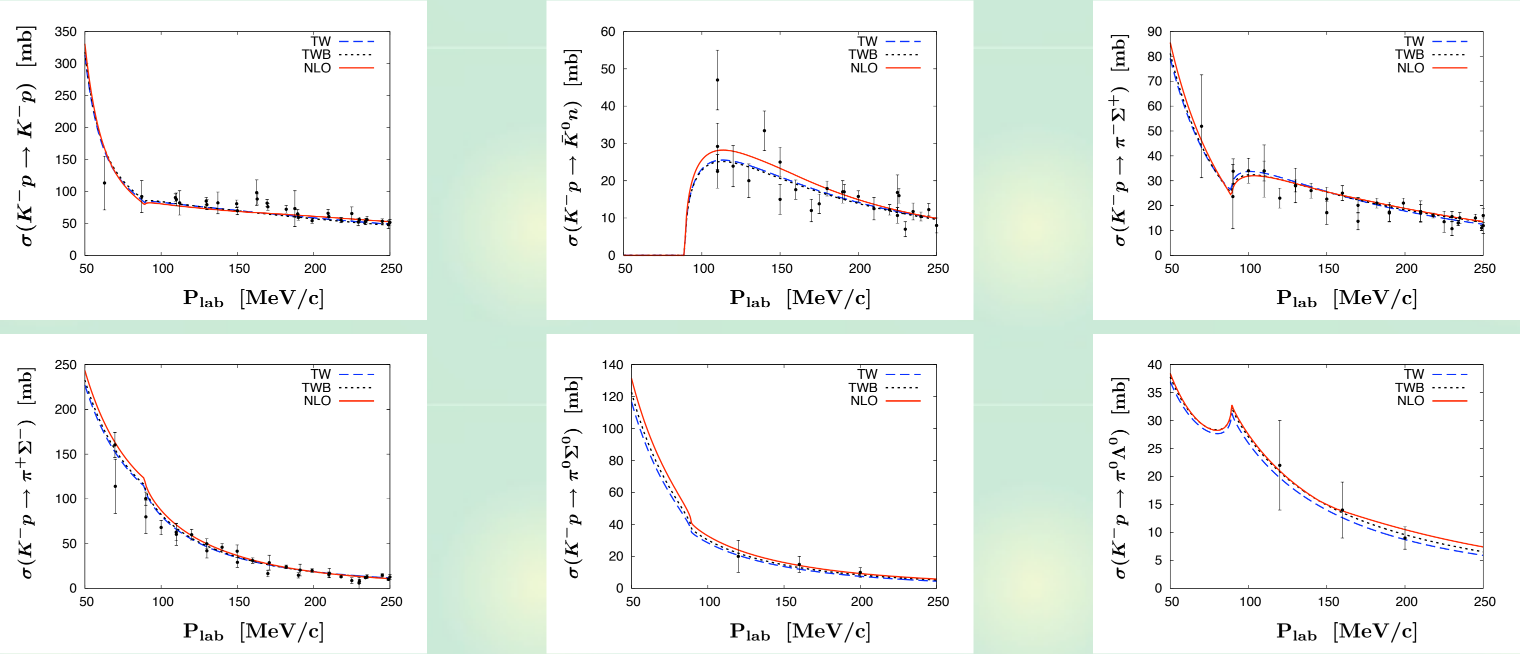
$\mathcal{O}(p^2)$

NLO model

Parameters: 6 cutoffs (+ 7 low energy constants in NLO)

Best-fit results

	TW	TWB	NLO	Experiment	
ΔE [eV]	373	377	306	$283 \pm 36 \pm 6$	[7]
Γ [eV]	495	514	591	$541 \pm 89 \pm 22$	[7]
γ	2.36	2.36	2.37	2.36 ± 0.04	[8]
R_n	0.20	0.19	0.19	0.189 ± 0.015	[8]
R_c	0.66	0.66	0.66	0.664 ± 0.011	[8]
χ^2/d.o.f	1.12	1.15	0.96		
pole positions	$1422 - 16i$	$1421 - 17i$	$1424 - 26i$		
[MeV]	$1384 - 90i$	$1385 - 105i$	$1381 - 81i$		

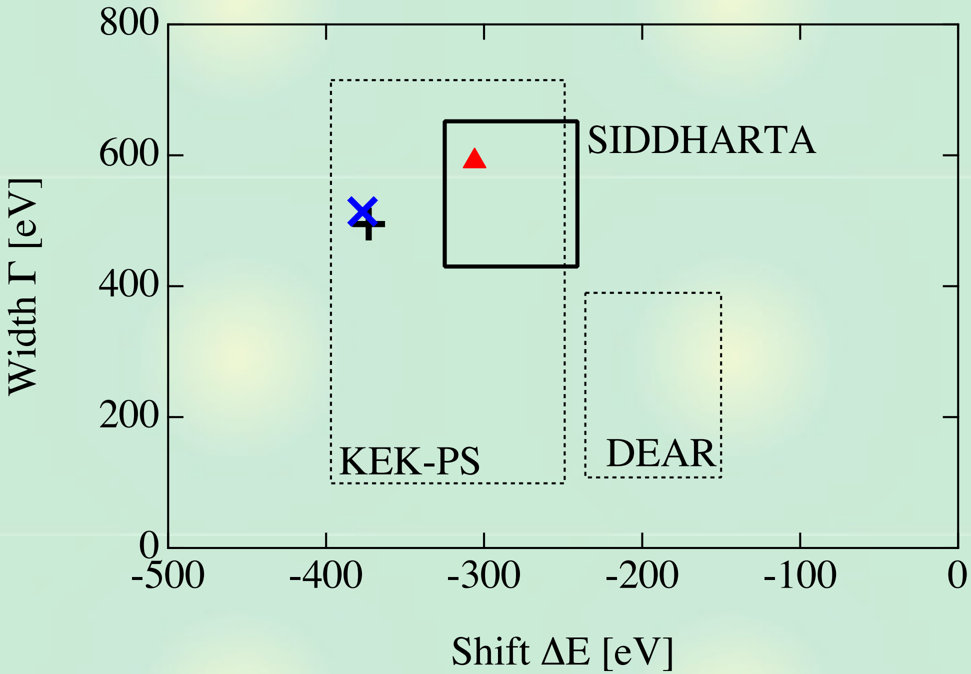


Good χ2: SIDDHARTA is consistent with cross sections

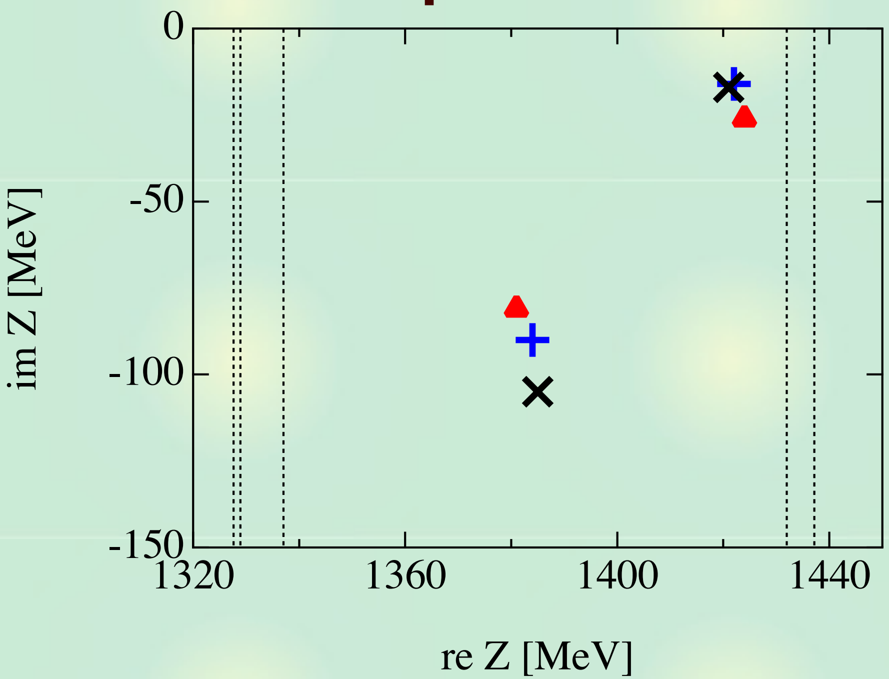
Shift, width, and pole positions

	TW	TWB	NLO
χ2/dof	1.12	1.15	0.957

Shift and width



Pole positions



TW and TWB are reasonable, while best-fit requires NLO.
Pole positions are now converging.

K-n scattering

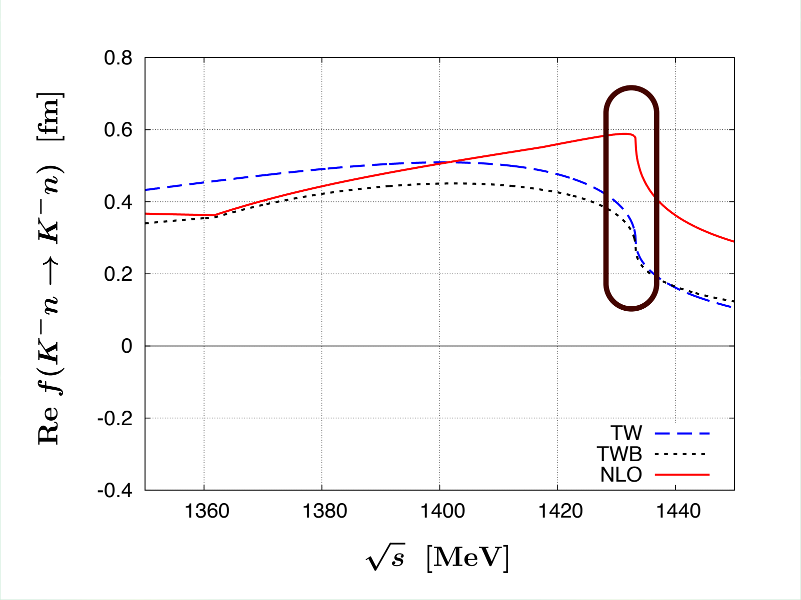
For K-Nucleon interaction, we need both K-p and K-n.

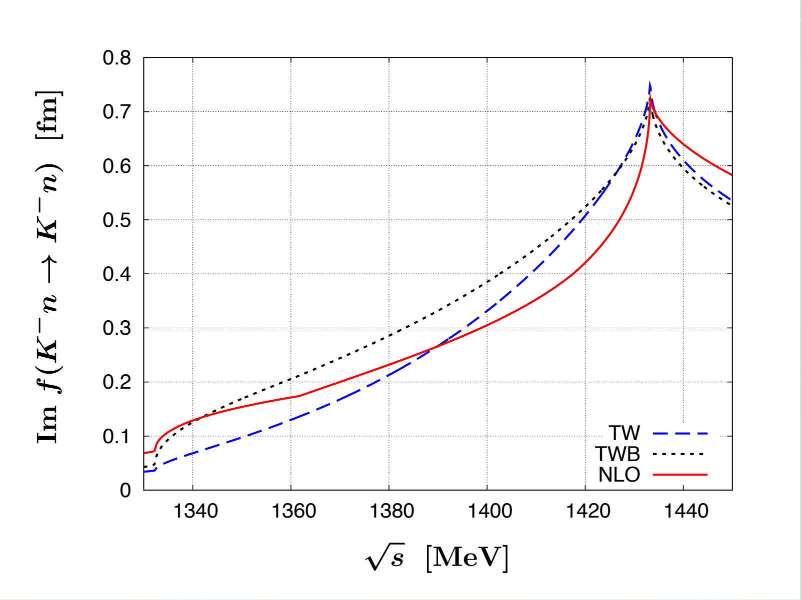
$$a(K^-p) = \frac{1}{2}a(I=0) + \frac{1}{2}a(I=1) + \dots, \quad a(K^-n) = a(I=1) + \dots$$

$$a(K^-p) = -0.93 + i0.82 \text{ fm} \quad (\text{TW}) \quad , \qquad a(K^-n) = 0.29 + i0.76 \text{ fm} \quad (\text{TW}) \quad ,$$

$$a(K^-p) = -0.94 + i0.85 \text{ fm} \quad (\text{TWB}) \quad , \qquad a(K^-n) = 0.27 + i0.74 \text{ fm} \quad (\text{TWB}) \quad ,$$

$$a(K^-p) = -0.70 + i0.89 \text{ fm} \quad (\text{NLO}) \qquad a(K^-n) = 0.57 + i0.73 \text{ fm} \quad (\text{NLO}) \quad .$$

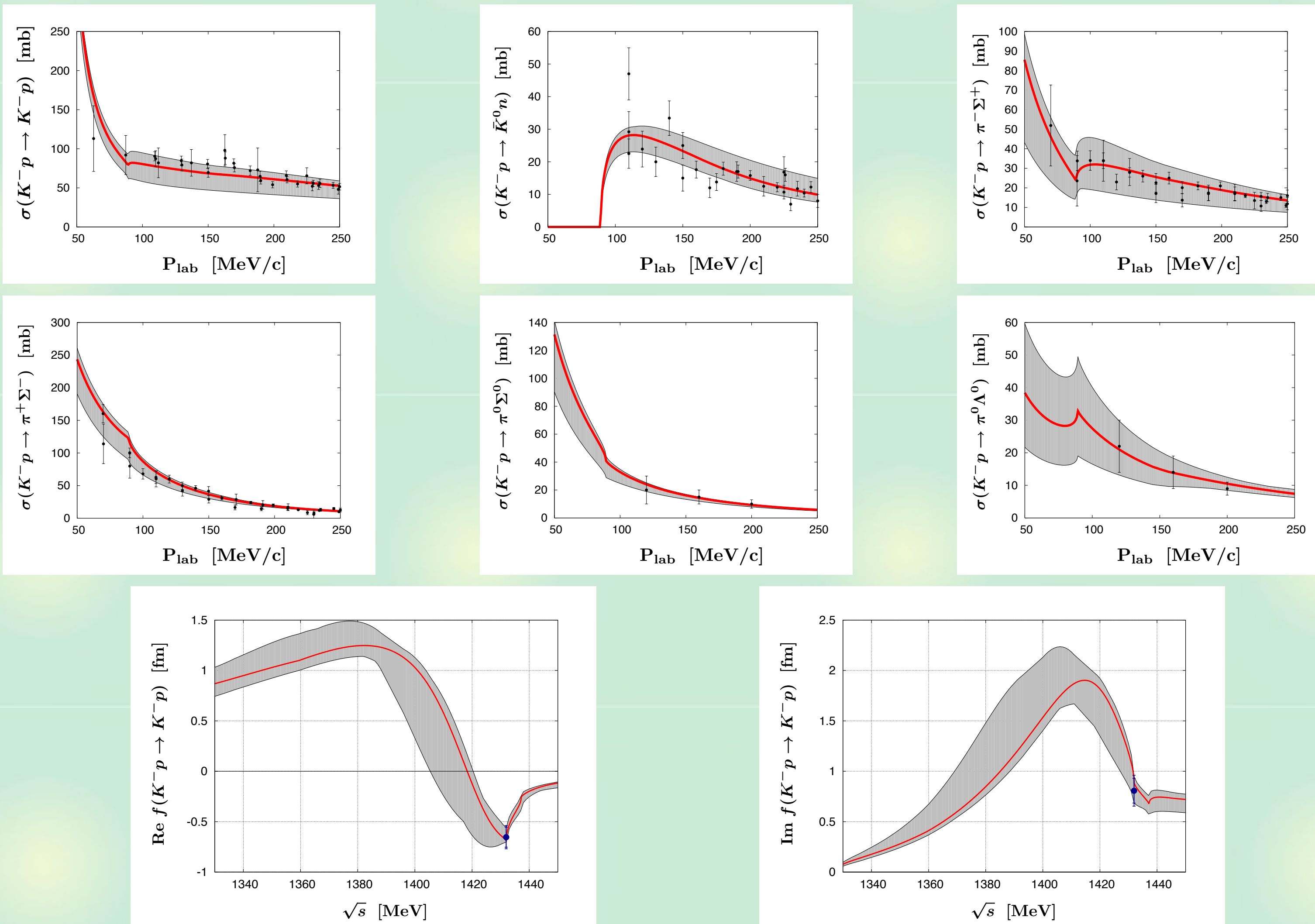




Some deviation: Constraint on K-n? (<-- kaonic deuterium?)

Error analysis

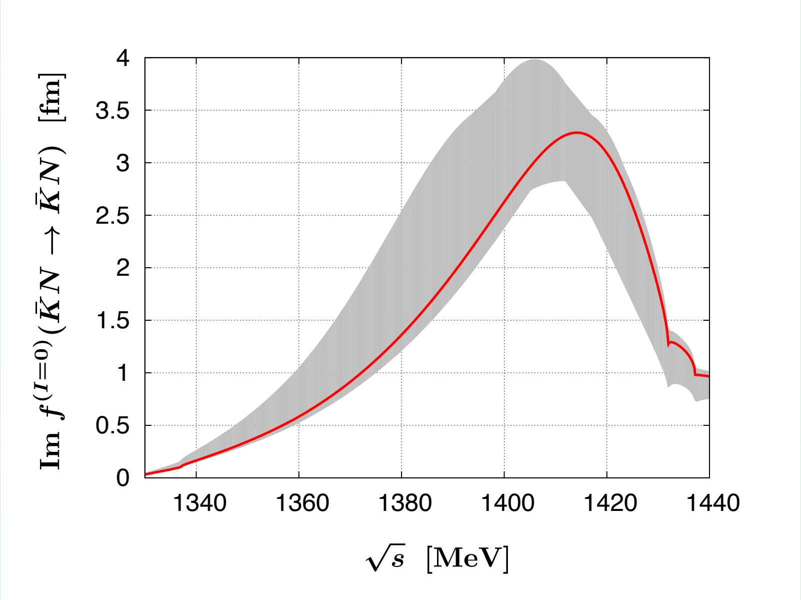
Uncertainty estimates (SIDDHARTA + $\pi^0\Lambda$ cross section)

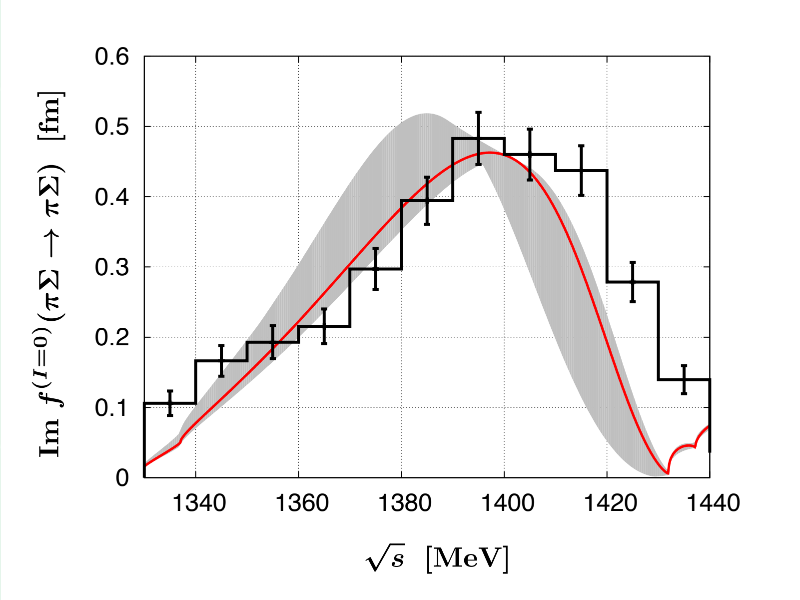


Subthreshold extrapolation of K-p amplitude is now stable.

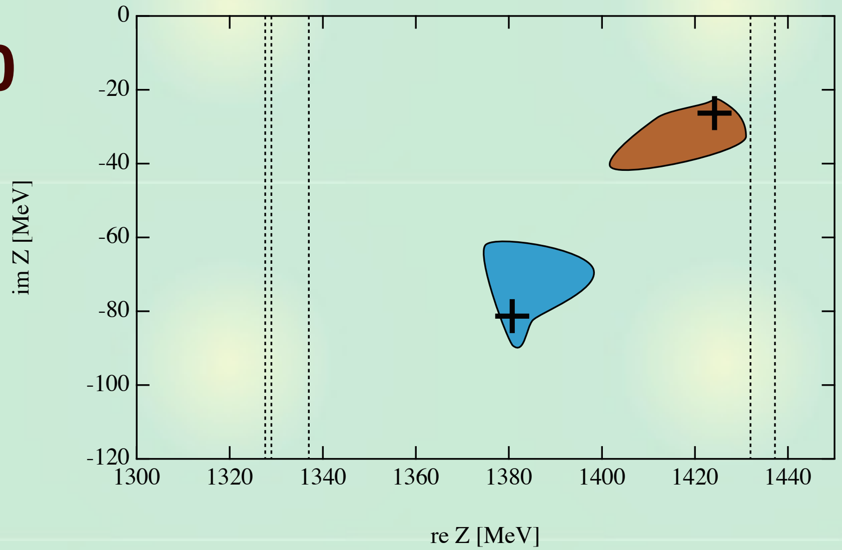
πΣ spectrum

Predicted πΣ spectrum in comparison with K̄N





Note: Hemingway data is not I=0



Shift of the peak position
<-- two poles

Uncertainty is reduced.

Summary 1

We study the $\bar{K}N$-$\pi\Sigma$ interaction and $\Lambda(1405)$ based on chiral SU(3) symmetry and unitarity

- $\bar{K}N$ interaction is closely related to the structure of $\Lambda(1405)$ and the $\bar{K}$ nuclei.

- Coupled-channel unitarity is important for the strongly interacting sector.

- Two poles for $\Lambda(1405)$ follows from attractive $\bar{K}N$ and $\pi\Sigma$ interactions

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

Summary 2

Systematic study with new accurate measurement of kaonic hydrogen

- **New $\bar{K}N$ threshold data by SIDDAHRTA**
  - consistent with cross section data

- **Implication of the improved framework:**
  - Uncertainty is significantly reduced.
  - Existence of two poles is confirmed.
  - information for I=1 is desired.

- **New input for $\bar{K}$ fey-body calculation**

Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B 706, 63 (2011); in preparation