Recent developments in antikaon-nucleon dynamics

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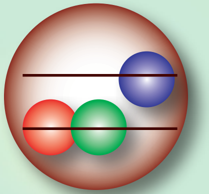
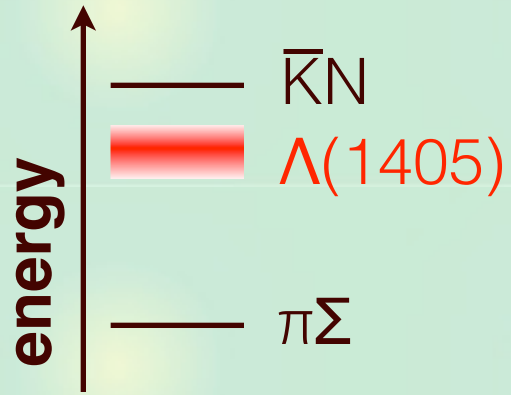
$\bar{K}$ meson and $\bar{K}N$ interaction

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

- **NG boson of chiral $SU(3)_R \otimes SU(3)_L$ --> $SU(3)_V$**
- **relatively heavy mass: $m_K \sim 496$ MeV**

--> peculiar role in hadron physics

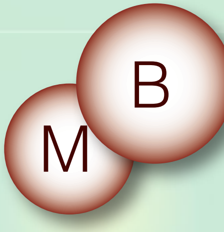




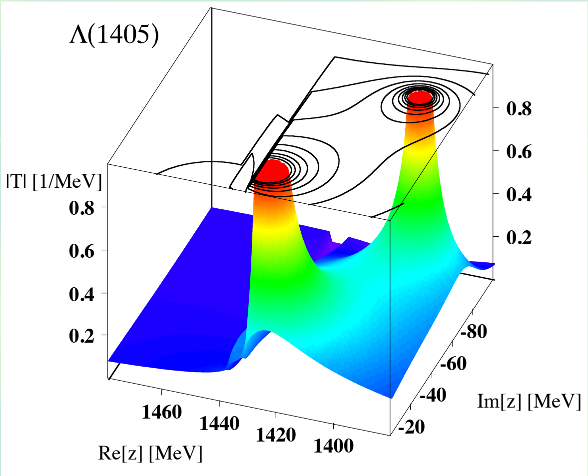
$\bar{K}N$ interaction is ...

- **coupled with $\pi\Sigma$ channel**
- **strongly attractive**

--> quasi-bound state $\Lambda(1405)$
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 $\bar{K}N$ interaction

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

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

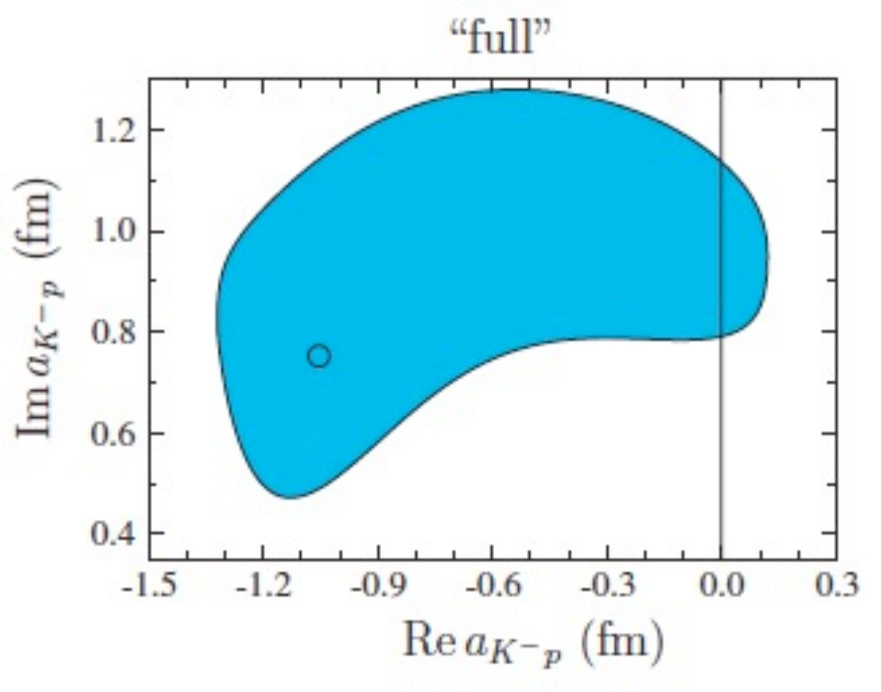
Threshold branching ratios

- **very accurate**
- **only at** $W = m_{K^-} + M_p$

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

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

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



Determination of the scattering length by these constraints

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

--> large uncertainty!

Scattering length from kaonic hydrogen

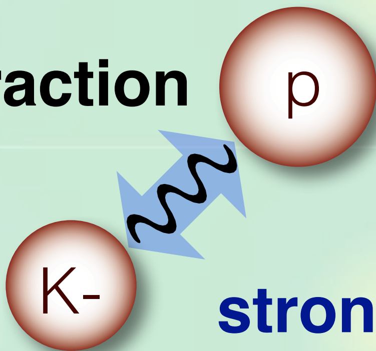
Measurements of the kaonic hydrogen

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

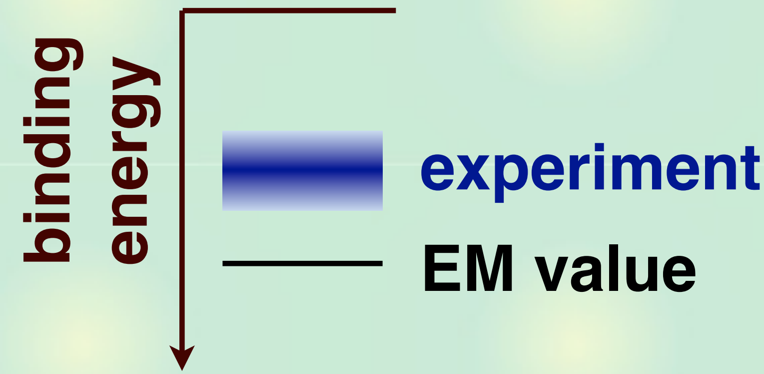
$$\Delta E - \frac{i}{2}\Gamma = -2\alpha^3\mu_c^2 a_{K^-p}[1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p}]$$ ← scattering length

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

EM interaction



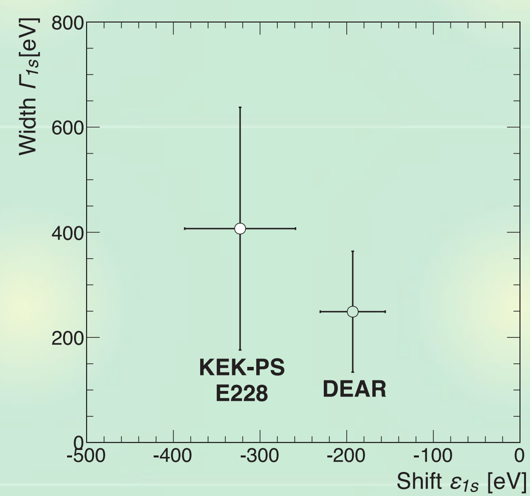
strong interaction



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?



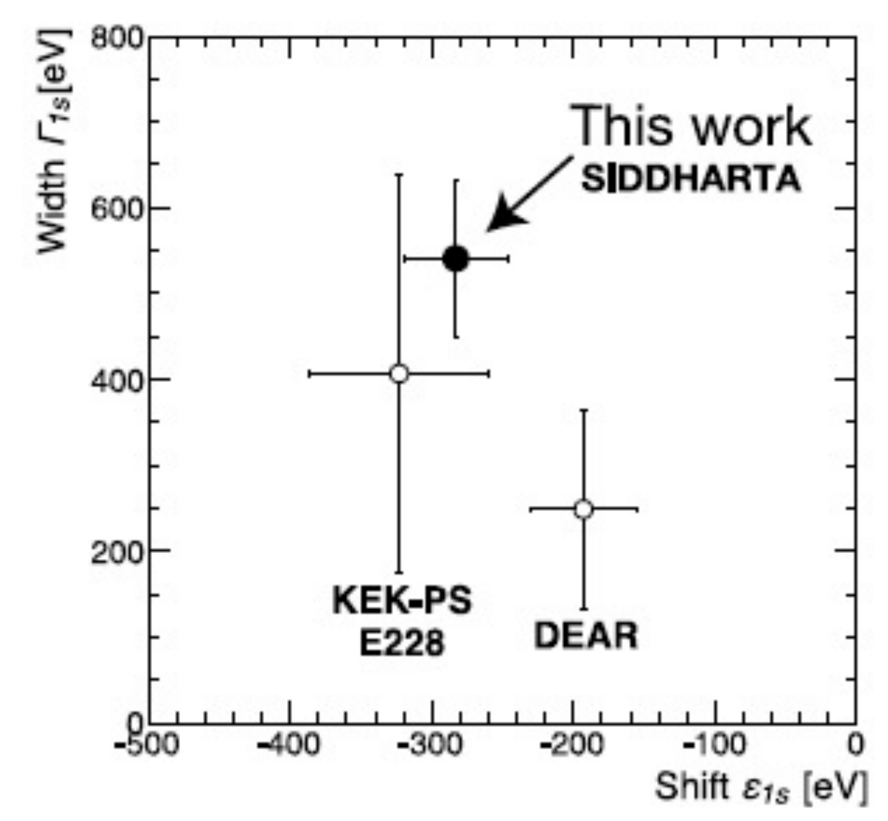
SIDDHARTA measurement

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 $\bar{\mathrm{K}}\mathrm{N}$ interaction

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); Nucl. Phys. A881 98 (2012)
- **Summary**

Chiral unitary approach

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

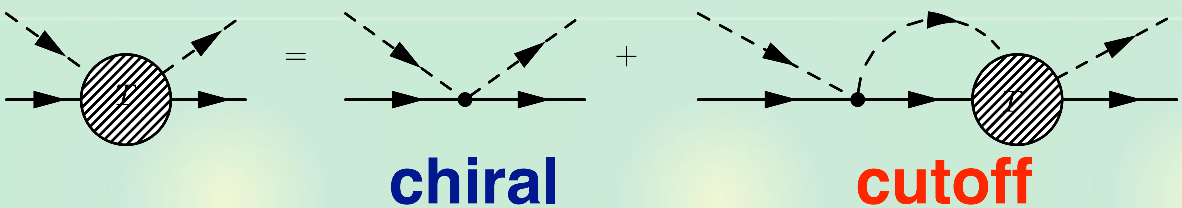
- Interaction <-- chiral symmetry

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)

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



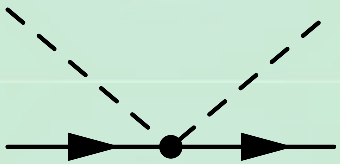
N. Kaiser, P. B. Siegel, W. Weise, Nucl. Phys. A594, 325 (1995),
E. Oset, A. Ramos, Nucl. Phys. A635, 99 (1998),
J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001),
M.F.M. Lutz, E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002), ... many others

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)

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

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

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

- **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

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

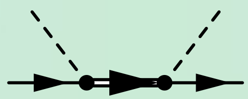
Amplitude T: consistent with chiral symmetry + unitarity

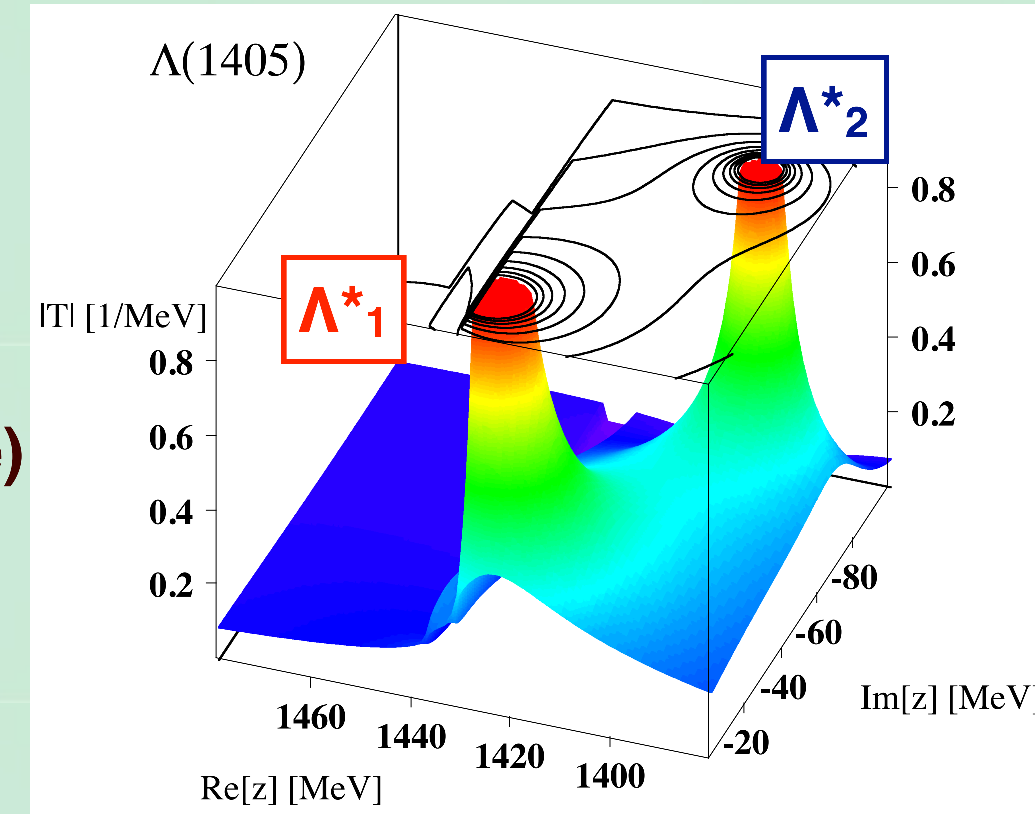
Pole structure in the complex energy plane

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)

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

$\sim$ 



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

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

Different $\pi\Sigma$ spectra?

K-d --> $\pi\Sigma N$ **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 $\bar{K}N$-$\pi\Sigma$ channel

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

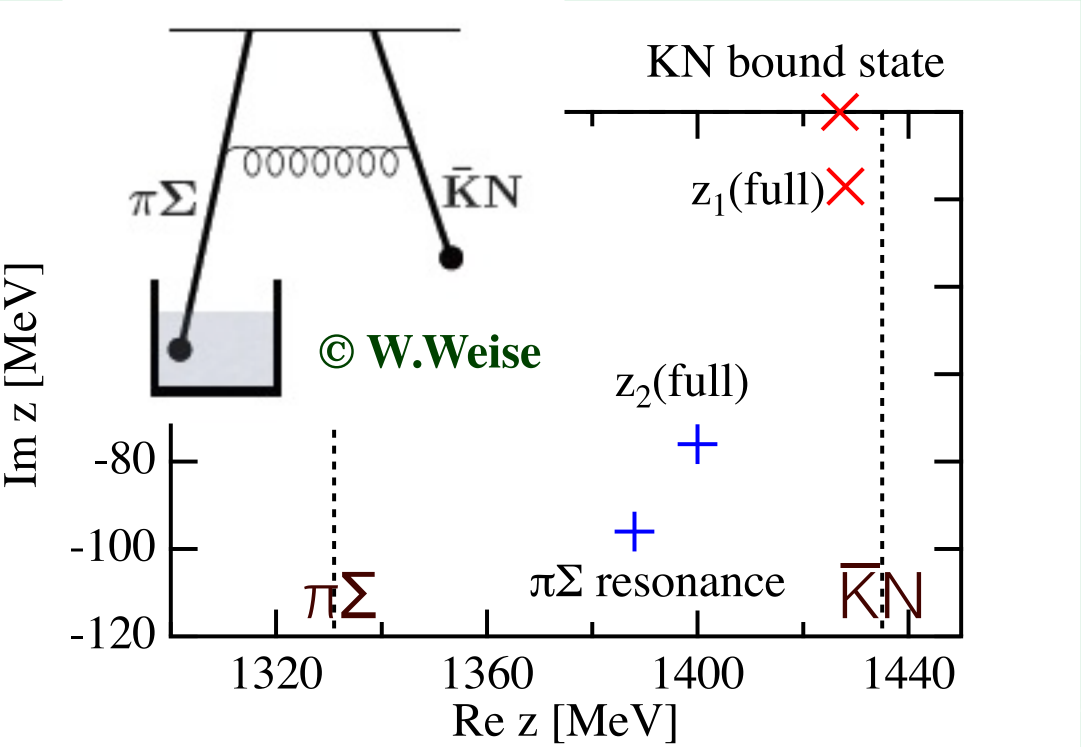
$$V_{ij} = -C_{ij}\frac{\omega_i + \omega_j}{4f^2}$$

$$\begin{array}{ccc} & \bar{K}N & \pi\Sigma \\ C_{ij} = & \left(\begin{array}{c} 3 \\ -\sqrt{\frac{3}{2}} \end{array}\right. & \left.\begin{array}{c} -\sqrt{\frac{3}{2}} \\ 4 \end{array}\right) \end{array}$$

at threshold

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

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



Very strong attraction in $\bar{K}N$ (higher energy) --> bound state
Strong attraction in $\pi\Sigma$ (lower energy) --> resonance

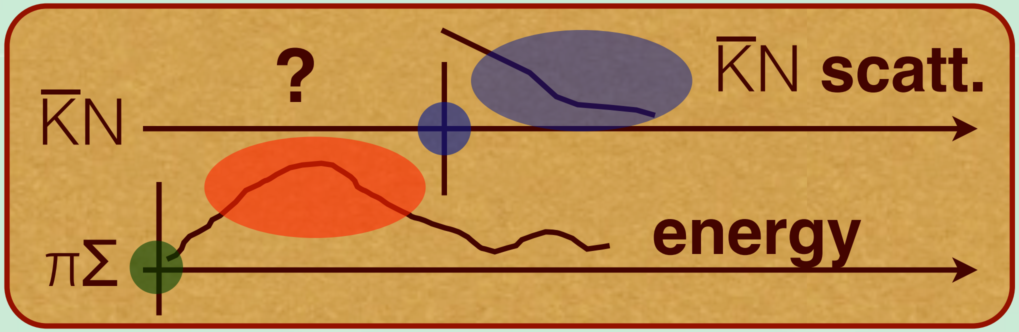
Model dependence? Effects from higher order terms?

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

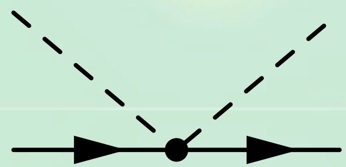
Systematic χ2 fitting with SIDDHARTA data

Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B 706, 63 (2011); Nucl. Phys. A881 98 (2012).

- Interaction kernel: NLO ChPT

B. Borasoy, R. Nissler, W. Weise, Eur. Phys. J. A25, 79-96 (2005)

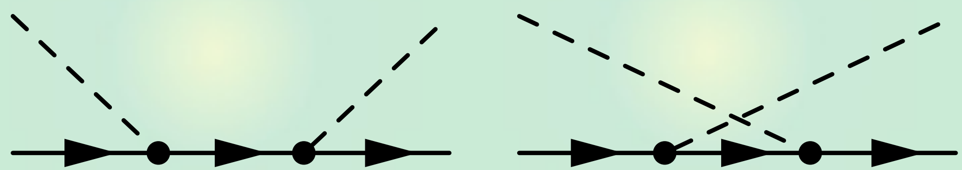
1) TW term



$\mathcal{O}(p)$

TW model

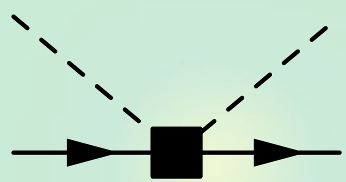
2) Born terms



$\mathcal{O}(p)$

TWB model

3) NLO terms



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

NLO model

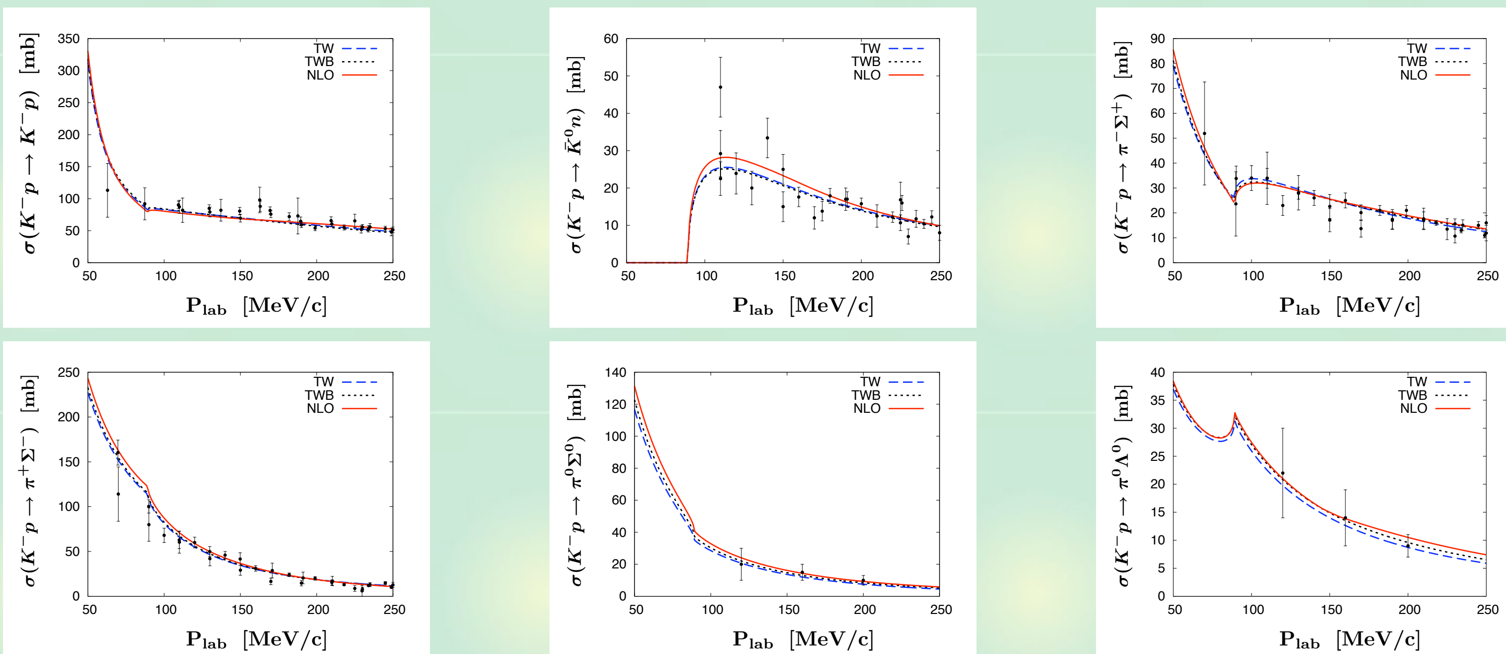
Parameters: 6 cutoffs (+ 7 low energy constants in NLO)

Systematic χ2 analysis with SIDDHARTA

Best-fit results

		TW	TWB	NLO	Experiment	
K-p	ΔE [eV]	373	377	306	$283 \pm 36 \pm 6$	[7]
	Γ [eV]	495	514	591	$541 \pm 89 \pm 22$	[7]
BR	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]	$1384 - 90i$	$1385 - 105i$	$1381 - 81i$		

cross sections

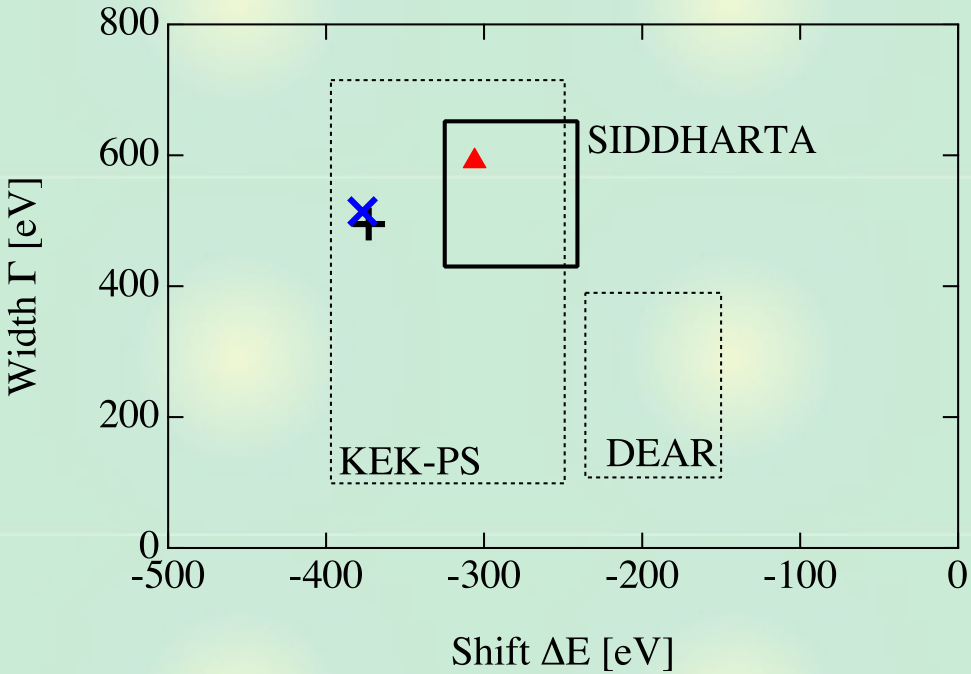


Good χ2: SIDDHARTA is consistent with cross sections

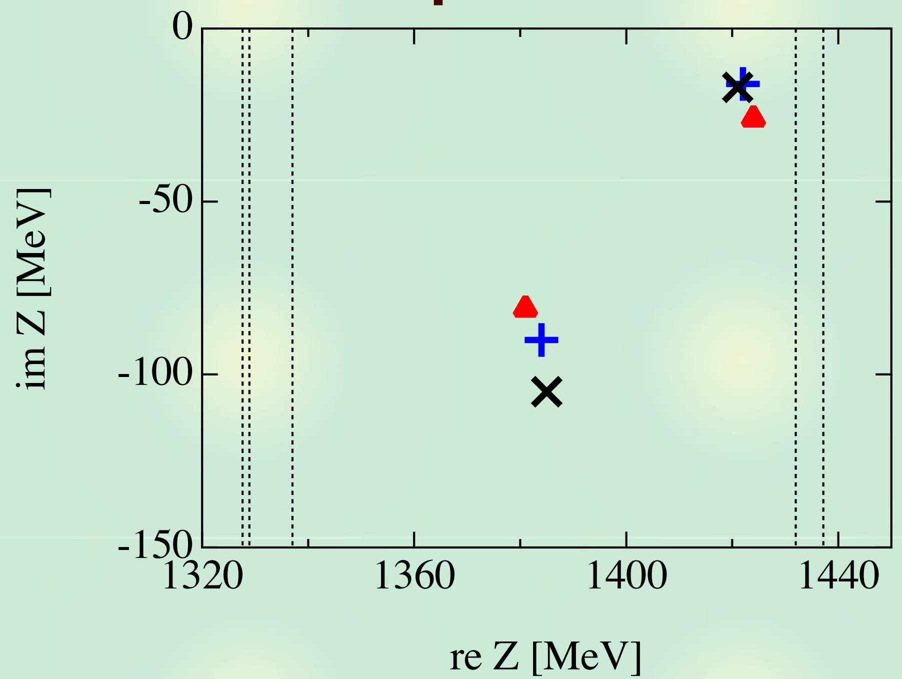
Shift, width, and pole positions

	TW	TWB	NLO
χ2/dof	1.12	1.15	0.957

Shift and width



Pole positions



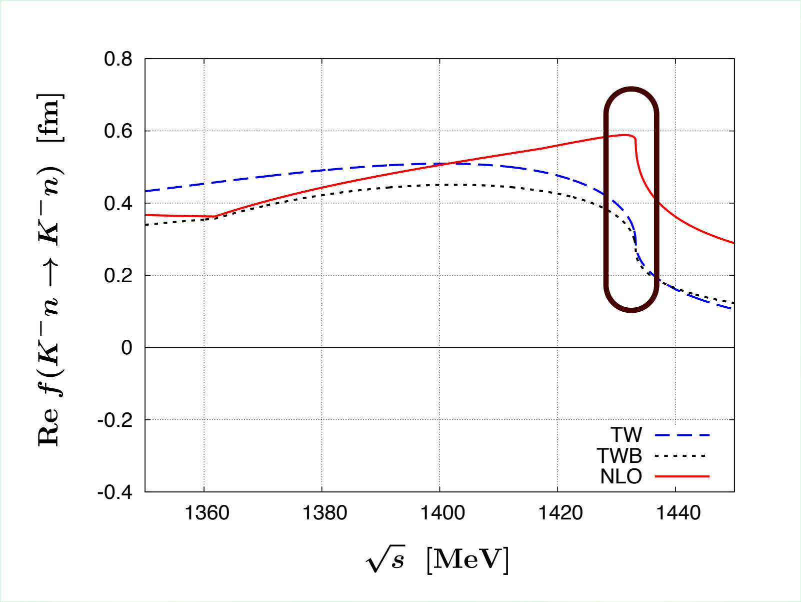
TW and TWB are reasonable, while best-fit requires NLO.
Pole positions are now converging.

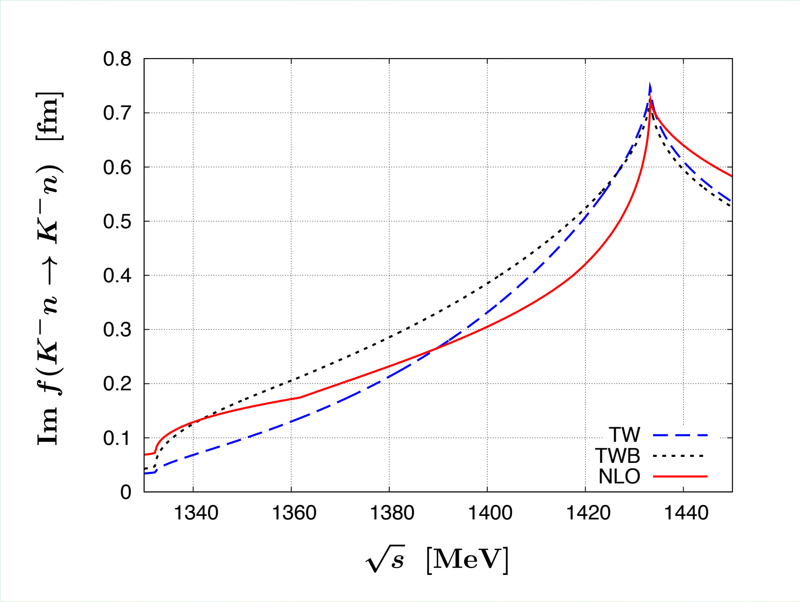
K-n scattering amplitude

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

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

$$a(K^-p) = -0.93 + i0.82 \text{ fm} \quad (\text{TW}) \quad , \qquad a(K^-n) = 0.29 + i0.76 \text{ fm} \quad (\text{TW}) \quad ,$$
$$a(K^-p) = -0.94 + i0.85 \text{ fm} \quad (\text{TWB}) \quad , \qquad a(K^-n) = 0.27 + i0.74 \text{ fm} \quad (\text{TWB}) \quad ,$$
$$a(K^-p) = -0.70 + i0.89 \text{ fm} \quad (\text{NLO}) \qquad\quad a(K^-n) = 0.57 + i0.73 \text{ fm} \quad (\text{NLO}) \quad .$$

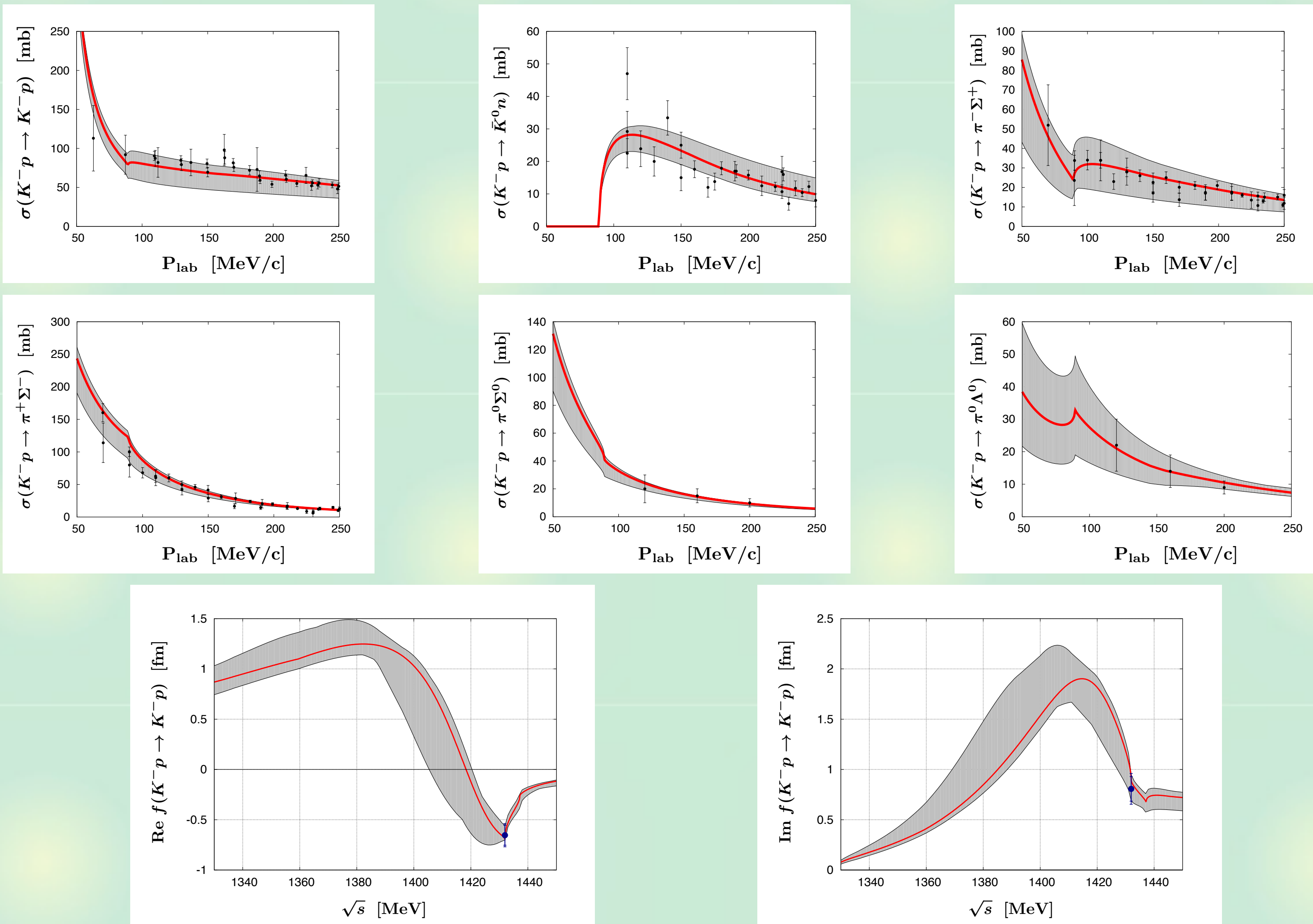




Some deviation: Constraint on K-n? (<-- kaonic deuterium?)

Error analysis

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

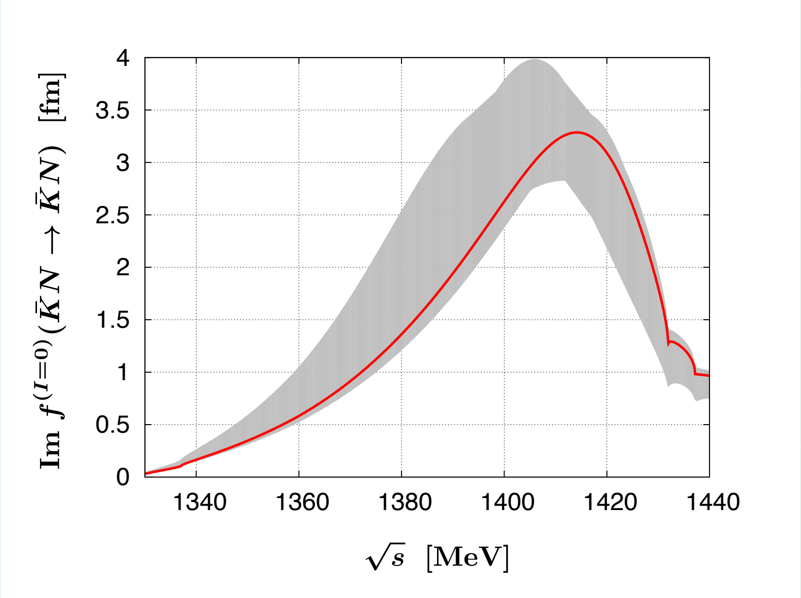


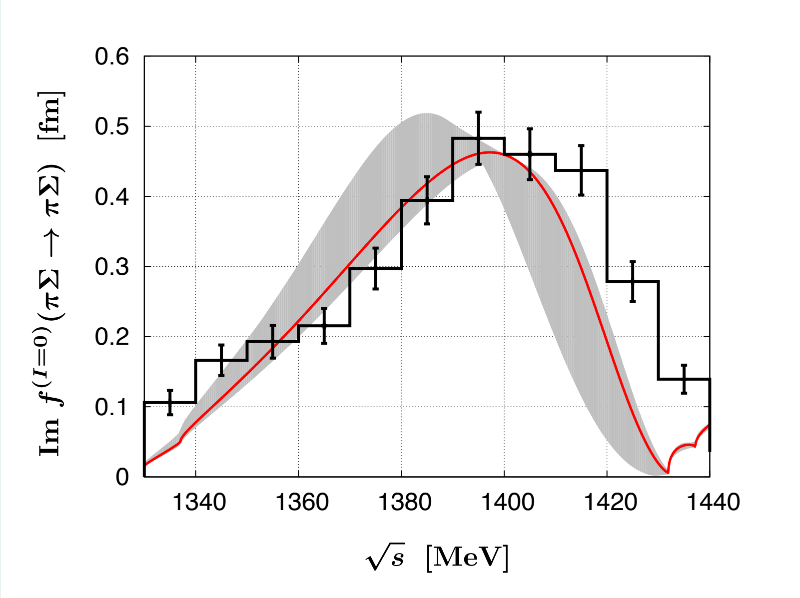
Subthreshold extrapolation of K-p **amplitude is now stable.**

Systematic χ2 analysis with SIDDHARTA

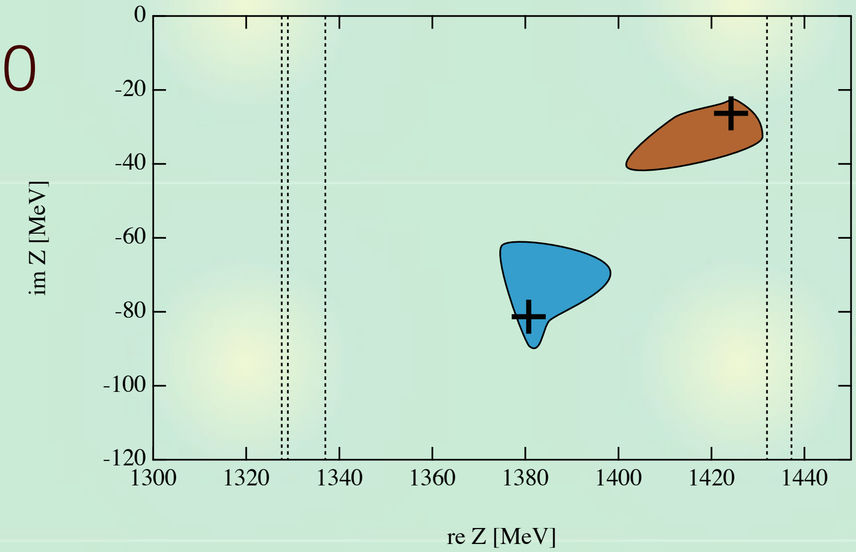
Λ(1405) properties

Predicted πΣ spectrum in comparison with $\bar{K}N$





Note: Hemingway data is not I=0



Shift of the peak position
<-- two poles

Uncertainty is reduced.

J=0 $\bar{K}NN$ system

Theoretical calculations of $\bar{K}NN$ system (~ K-pp)

	SGM	IS	YA	DHW	IKS*	BGL
Method	Fadd.	Fadd.	Var.	Var.	Fadd.	Var.
$\bar{K}N$ int.	E-indep	E-indep	E-indep	E-dep	E-dep	E-dep
$B_{\bar{K}NN}$ [MeV]	55-70	60-95	48	17-23	9-16	15.7
$\Gamma_{\pi YN}$ [MeV]	90-110	45-80	61	40-70	34-46	41.2

N.V. Shevchenko, A. Gal, J. Mares, Phys. Rev. Lett. 98, 082301 (2007),
Y. Ikeda, T. Sato, Phys. Rev. C76, 035203 (2007),
T. Yamazaki, Y. Akaishi, Phys. Rev. C76, 045201 (2007),
A. Dote, T. Hyodo, W. Weise, Phys. Rev. C79, 014003 (2009),
Y. Ikeda, Kamano, T. Sato, Prog. Thoer. Phys. 124, 533 (2010),
N. Barnea, A. Gal, E.Z. Liverts, Phys. Lett. B712 (2012)
* there is another pole at 67-89 MeV with large width.

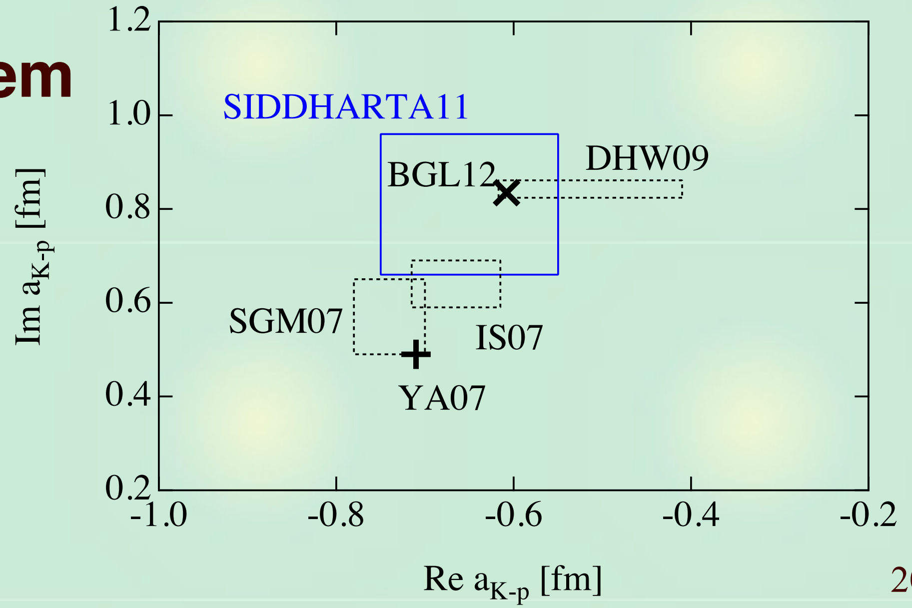
$\bar{K}NN$ system forms a quasi-bound state with large width.

Comparison of K-p scattering length

Theoretical calculations of $\bar{K}NN$ system (~ K-pp)

	SGM	IS	YA	DHW	IKS	BGL
Method	Fadd.	Fadd.	Var.	Var.	Fadd.	Var.
$\bar{K}N$ int.	E-indep	E-indep	E-indep	E-dep	E-dep	E-dep
$B_{\bar{K}NN}$ [MeV]	55-70	60-95	48	17-23	9-16	15.7
$\Gamma_{\pi YN}$ [MeV]	90-110	45-80	61	40-70	34-46	41.2

- New constraint on $\bar{K}NN$ system
- SIDDHARTA11 is obtained by the improved DT formula
- Models: isospin symmetric. Breaking is important at th.



J=1 $\bar{K}NN$ system

J=1 system (~ K-d)

- $I_{NN}=0$ --> $\bar{K}N(I=0)$:$\bar{K}N(I=1)$ = 1:3

Less attractive, but maybe weakly bound (above Λ^*N).

	UHO	Oset et al.	BGL
Model	Λ^*N potential	FCA	Three-body variational
$B_{\bar{K}NN}$ [MeV]	> M_{Λ^*N}	9	> M_{Λ^*N}
$\Gamma_{\pi YN}$ [MeV]	-	30	-

T. Uchino, T. Hyodo, M. Oka, Nucl. Phys. A868-869, 53 (2011)
E. Oset, *et al.*, Nucl. Phys. A881, 127 (2012)
N. Barnea, A. Gal, E.Z. Liverts, Phys. Lett. B712 (2012)

Small binding energy
--> Close relation with K-d scattering length?

Estimation of the K-d scattering length

K-d scattering length with EFT

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

deuteron w.f.

$$A_{Kd} = \left(1 + \frac{m_K}{M_d}\right)^{-1} \int_0^\infty dr (u^2(r) + w^2(r)) \hat{a}_{kd}(r)$$

$$\hat{a}_{kd}(r) = \frac{\tilde{a}_p + \tilde{a}_n + (2\tilde{a}_p\tilde{a}_n - b_x^2)/\tilde{r} - 2b_x^2\tilde{a}_n/\tilde{r}^2}{1 - \tilde{a}_p\tilde{a}_n/\tilde{r}^2 + b_x^2\tilde{a}_n/\tilde{r}^3} + \delta\hat{a}_{kd}$$

$\bar{\text{K}}$N scattering lengths

SIDDHARTA result + I=1 prediction + deuteron w.f.

- s-wave only

$$A_{Kd} = -1.48 \pm 0.19 + i(1.35 \pm 0.24) \text{ fm}$$

- s-wave + d-wave, short range repulsion

$$A_{Kd} = -1.56 + i1.69 \text{ fm}$$

- realistic wave function...
- three-body calculation...

Y. Ikeda, T. Hyodo, W. Weise, work in progress

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 $\bar{K}N$-$\pi\Sigma$.**

- **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 analysis with new accurate measurement of kaonic hydrogen

- New $\bar{K}N$ **threshold data** by SIDDHARTA
  - consistent with cross section data
- Implication of the improved framework:
  - **Uncertainty** in subthreshold extrapolation is significantly **reduced**.
  - $I=1$ constraint is desired.
- New input for $\bar{K}$ fey-body calculation

Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B 706, 63 (2011);
Nucl. Phys. A881 98 (2012)