Antikaon-nucleon interaction and $\Lambda(1405)$ in chiral SU(3) dynamics

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2015, Feb. 19th

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  - precise kaonic hydrogen measurement
  - new $\pi\Sigma$ spectra from various reactions
- $\bar{K}N$-$\pi\Sigma$ interaction from chiral SU(3) dynamics

  Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)
- Current status of $\Lambda(1405)$

Y. Ikeda

W. Weise

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

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

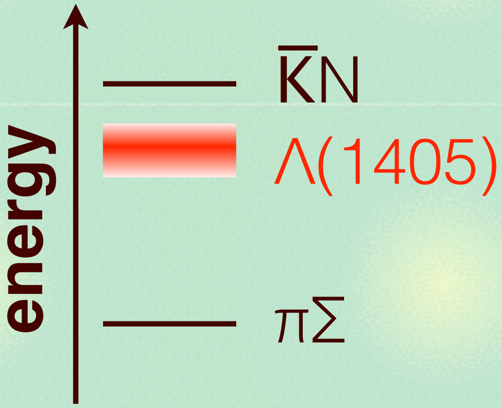
- **NG boson** of chiral $SU(3)_R \otimes SU(3)_L$ —> $SU(3)_V$
- **massive** by strange quark: $m_K \sim 496$ MeV

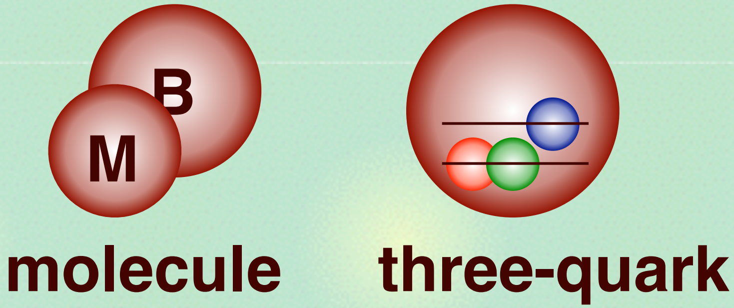
—> **spontaneous**/**explicit** symmetry breaking

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

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

- is coupled with $\pi\Sigma$ channel
- generates $\Lambda(1405)$ below threshold





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

$\bar{K}$ in nuclei

$\bar{K}$N interaction

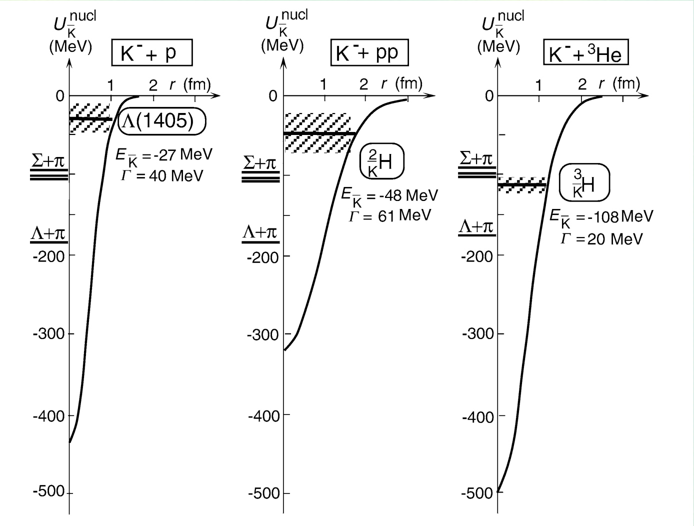
- **strong attraction**
- **no repulsive core?**

	I=0	I=1
NN	**deuteron (2 MeV)**	**attractive**
$\bar{K}$N	Λ(1405) **(15-30 MeV)**	**attractive**

Possible (quasi-)bound $\bar{K}$ in nuclei

- **deep binding, high density?**

Y. Nogami, Phys. Lett. 7, 288, (1963);
T. Yamazaki, Y. Akaishi, Phys. Lett. B535, 70 (2002);
A. Dote, *et al.*, Phys. Lett. B590, 51 (2004)



Rigorous calculations (2007-)

- **bound states in few-nucleon systems**
- **binding energy depends on the employed $\bar{K}$N interaction**

—> We need a realistic $\bar{K}$N interaction.

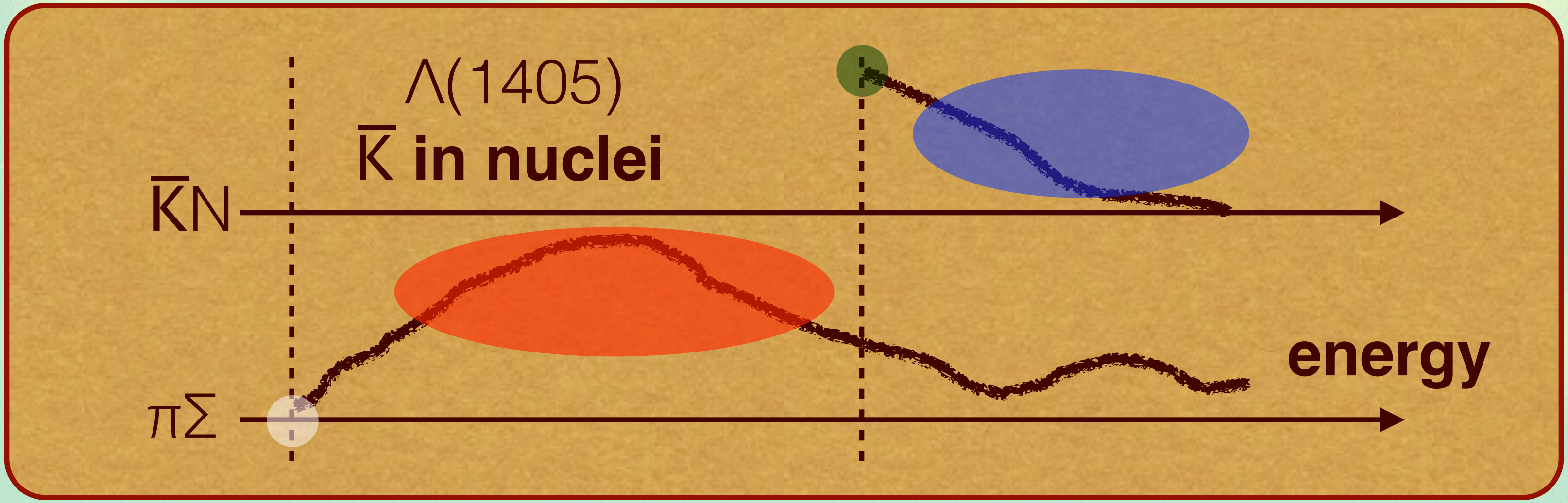
Experimental constraints for the $\bar{K}N$ interaction

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

- 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:

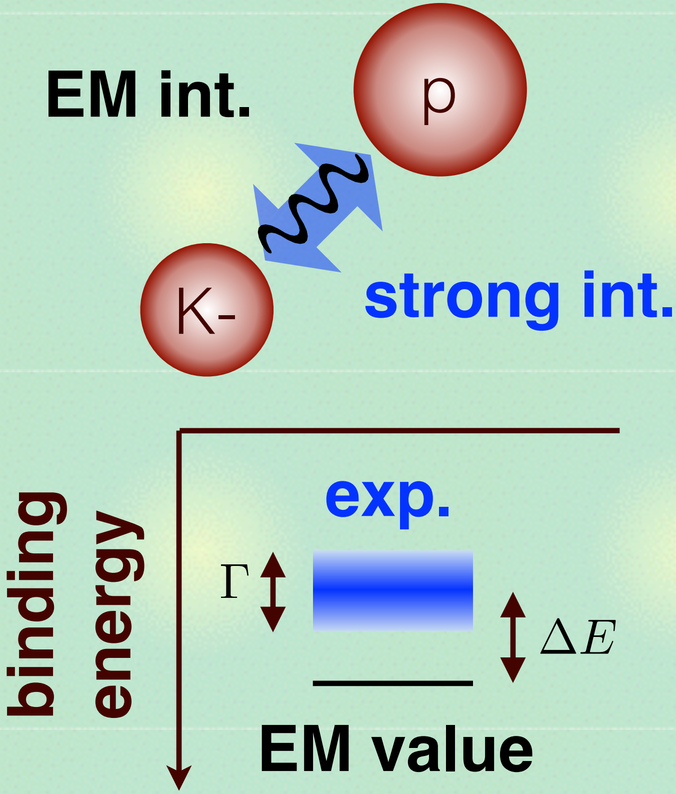
- $\pi\Sigma$ **mass spectra (new data: LEPS, CLAS, HADES,...)**
- $\pi\Sigma$ scattering length **(no data at present)**

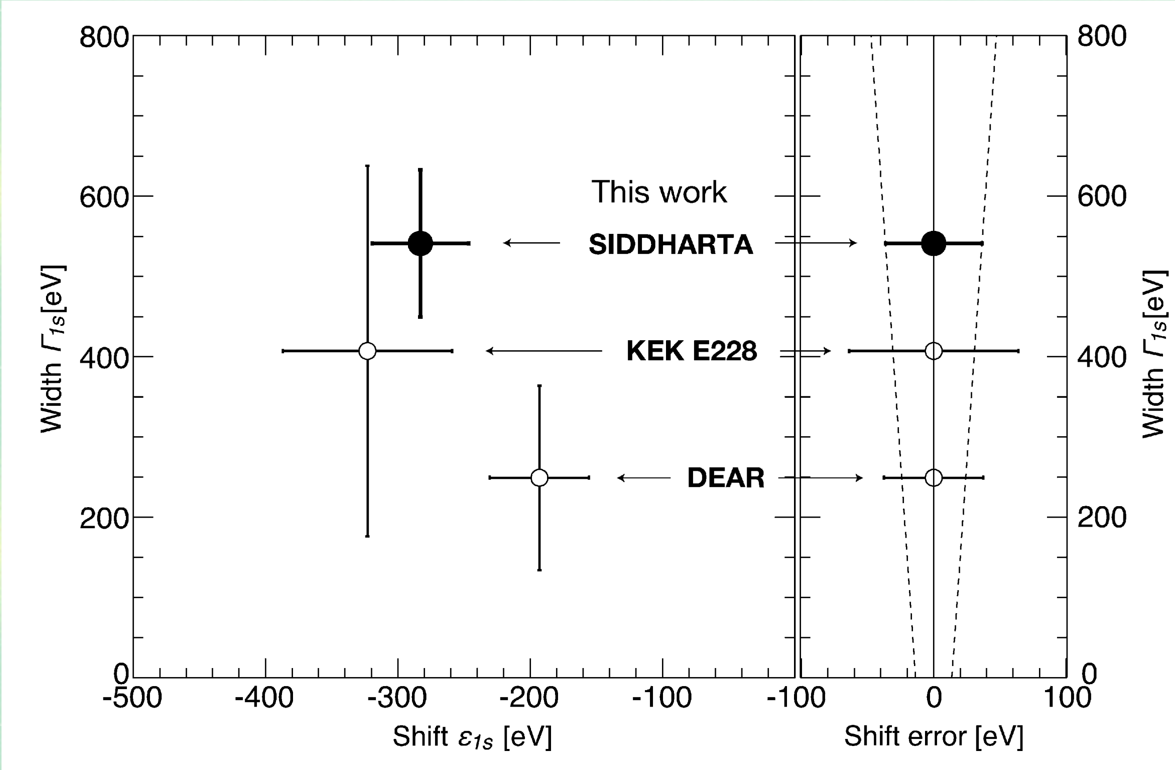


SIDDHARTA measurement

Precise measurement of the kaonic hydrogen X-rays

M. Bazzi, *et al.*, Phys. Lett. B704, 113 (2011); Nucl. Phys. A881, 88 (2012)





- shift and width of atomic state <—> K-p scattering length

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

Direct constraint on the $\bar{K}N$ interaction at fixed energy

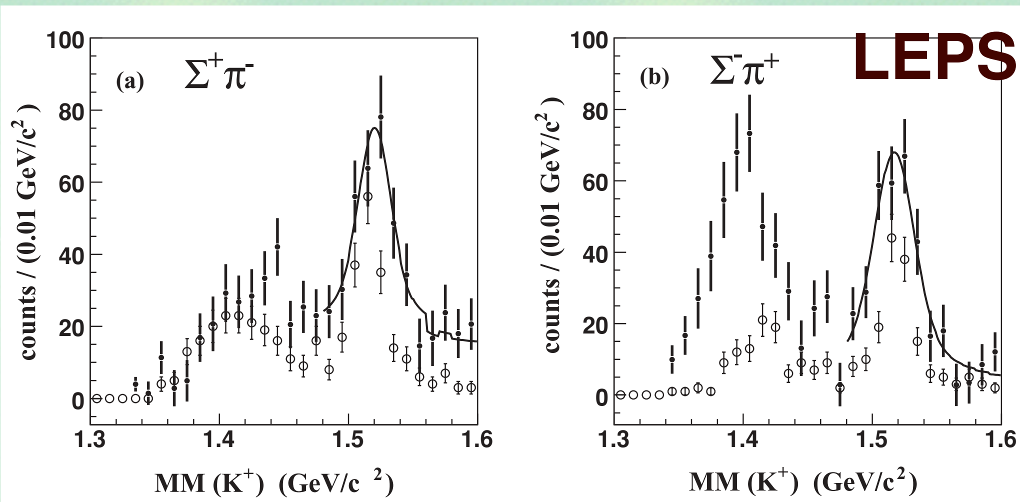
New $\pi\Sigma$ spectra

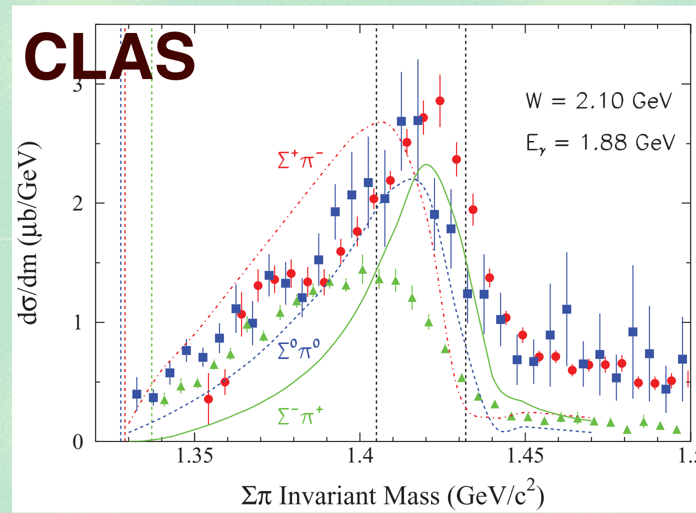
Photoproduction experiments: $\gamma p \to K^+(\pi\Sigma)^0$

- **LEPS@**1.5 < Eγ < 2.4 **GeV, CLAS@**1.56 < Eγ < 3.83 **GeV**

M. Niiyama, *et al.*, Phys. Rev. C78, 035202 (2008);

K. Moriya, *et al.*, Phys. Rev. C87, 035206 (2013)





Hadron-induced reactions:

- **HADES:** $pp \to K^+p(\pi\Sigma)^0$

G. Agakishiev, *et al.*, Phys. Rev. C87, 025201 (2013)

- **J-PARC E31(planned):** $K^-d \to n(\pi\Sigma)^0$

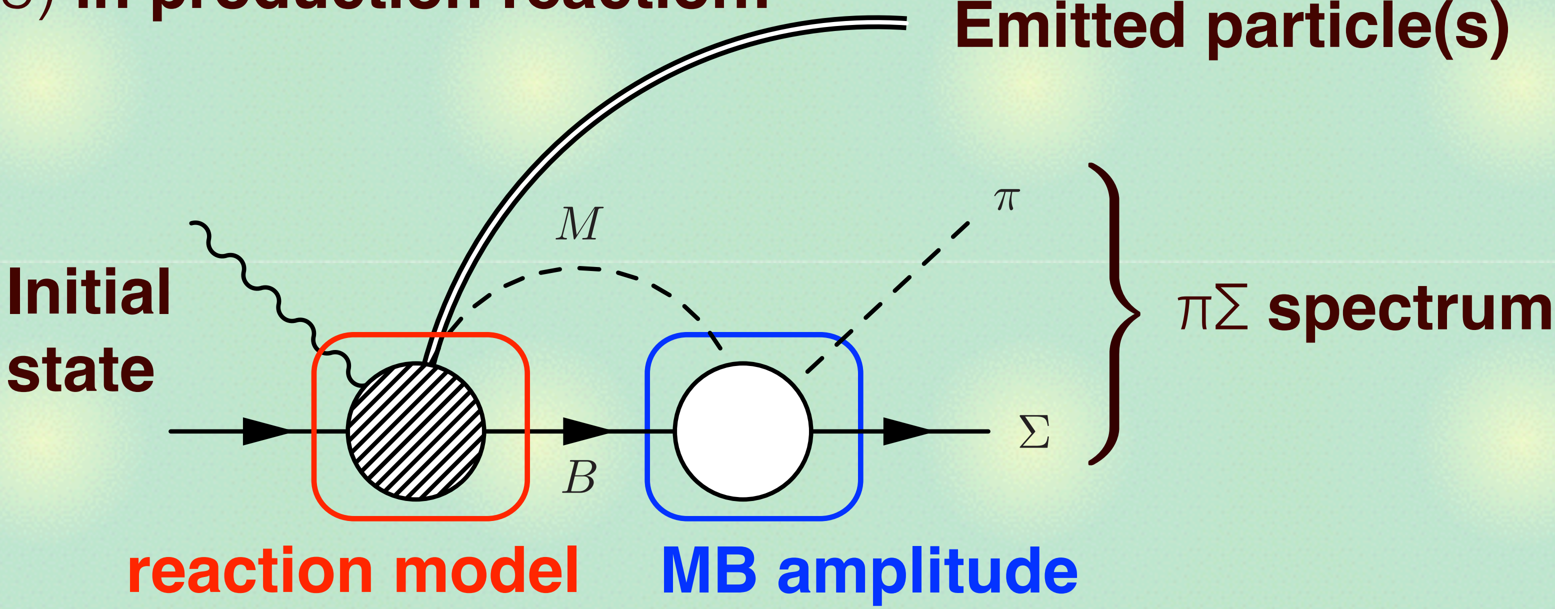
New and precise spectra are being available.

$\pi\Sigma$ spectra and $\bar{K}N$ interaction

Can spectra constrain the MB amplitude ($\bar{K}N$ interaction)?

- Not directly.

$\Lambda(1405)$ **in production reaction:**



- Spectra depend on the reaction (ratio of $\bar{K}N/\pi\Sigma$ in the intermediate state, interference with I=1,...).

—> Detailed model analysis for each reaction

Short summary of introduction

- $\bar{K}N$ **interaction** is important both for hadron physics (structure of $\Lambda(1405)$ resonance) and for nuclear physics ($\bar{K}$ in nuclei).
- Precise K^-p **scattering length** by SIDDHARTA —> quantitative **constraint** on $\bar{K}N$ interaction
- New $\pi\Sigma$ **spectra** from various reactions —> reliable **reaction model** required

➡ Construct realistic $\bar{K}N$ scattering model based on a reliable framework.

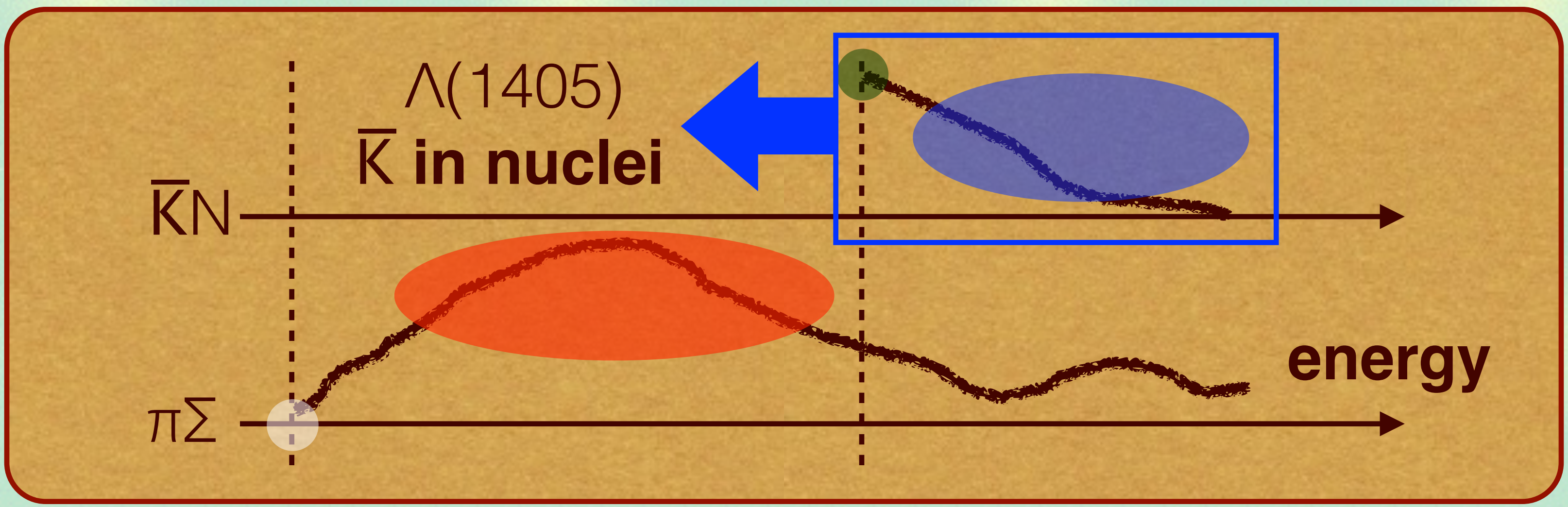
Strategy for $\bar{K}N$ interaction

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

- 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:

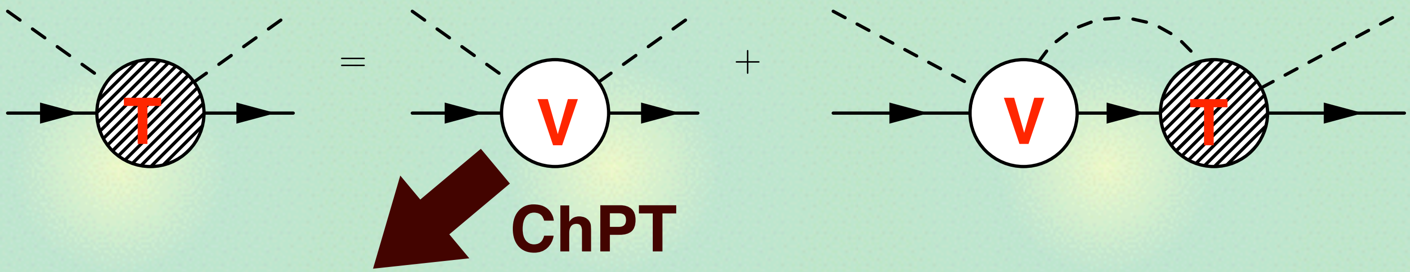
- $\pi\Sigma$ **mass spectra (new data: LEPS, CLAS, HADES,…)**
- $\pi\Sigma$ scattering length **(no data at present)**

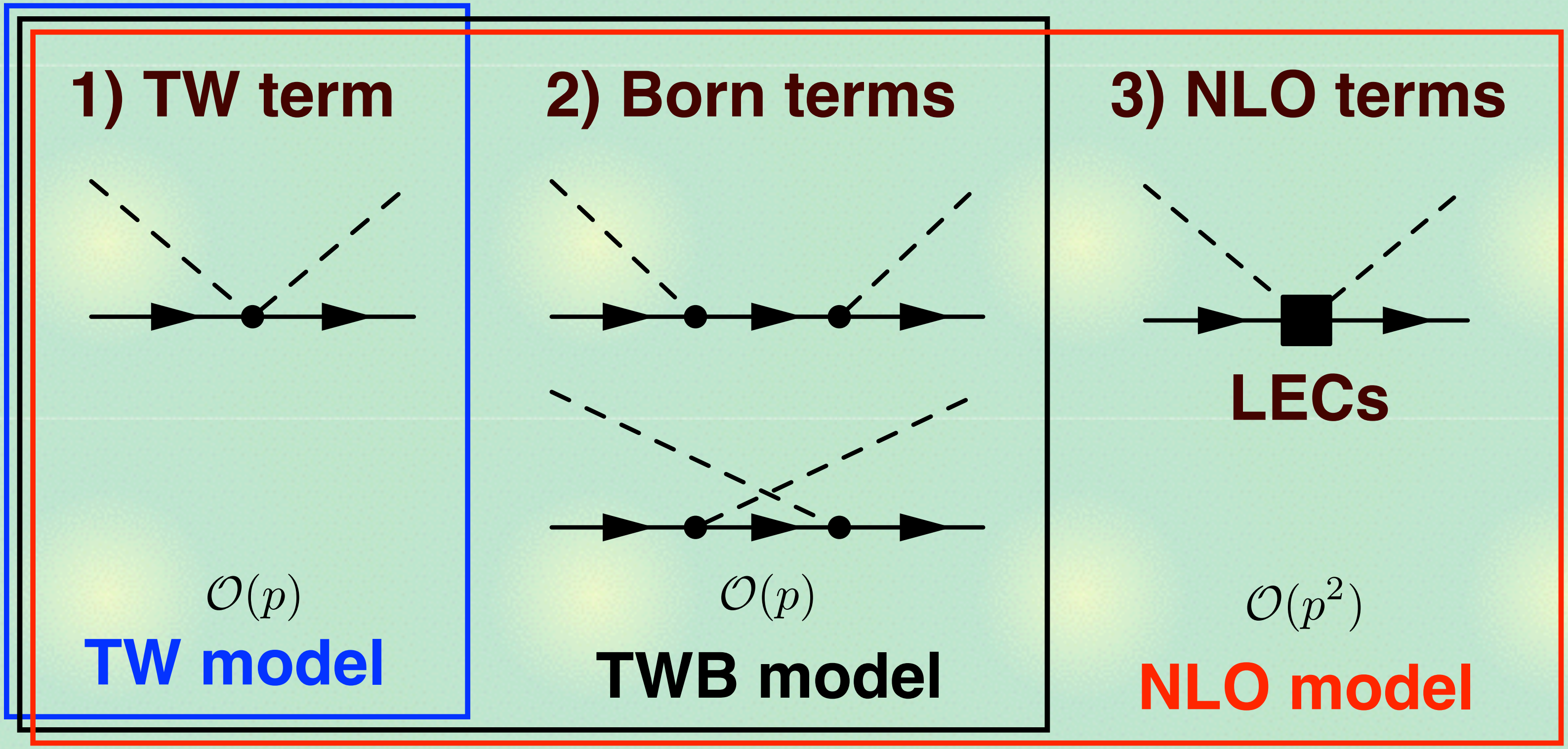


Construction of the realistic amplitude

Chiral coupled-channel approach with systematic χ^2 fitting

Y. Ikeda, T. Hyodo, W. Weise, Phys. Lett. B706, 63 (2011); Nucl. Phys. A881 98 (2012);

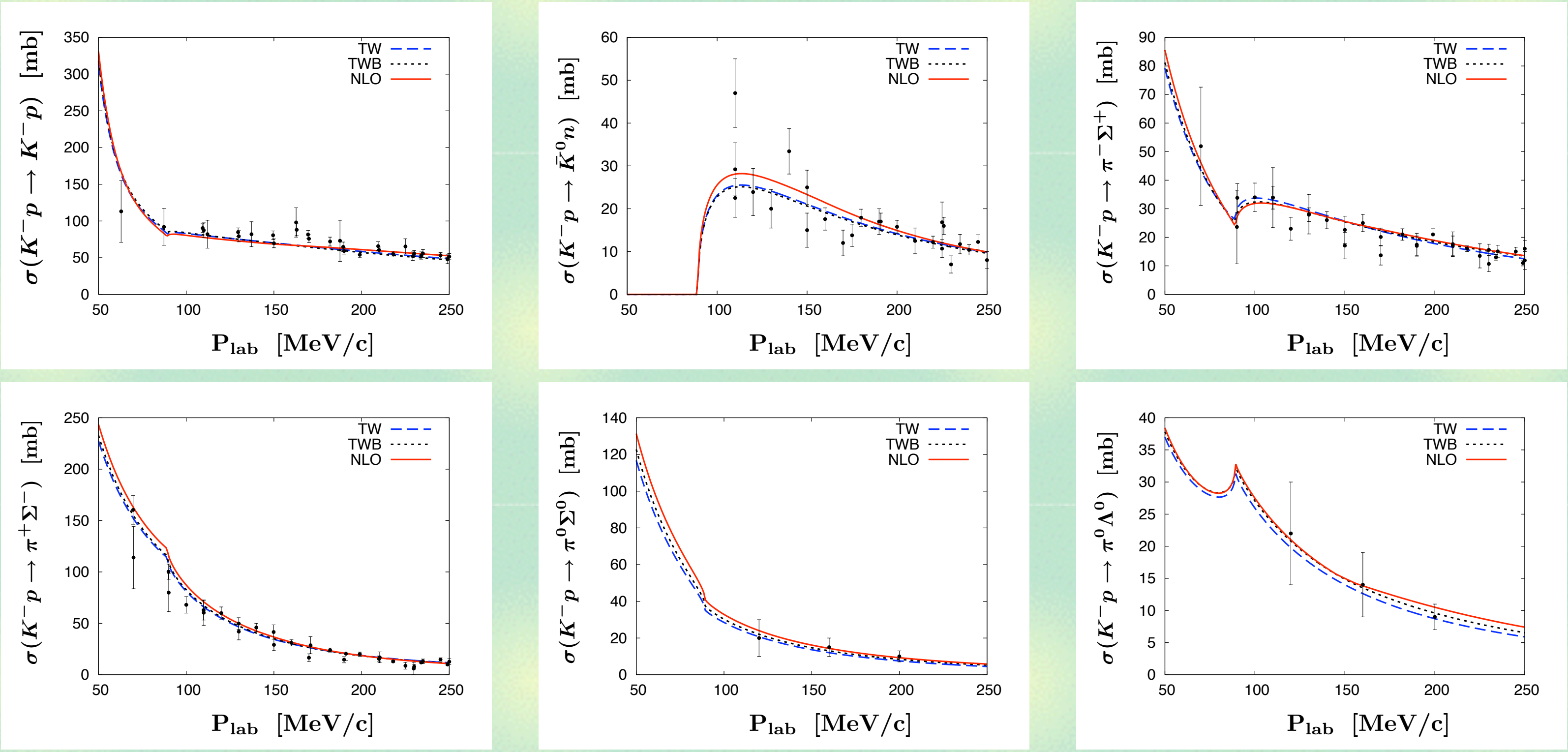




Best-fit results

		TW	TWB	NLO	Experiment	
SIDDHARTA	ΔE [eV]	373	377	306	$283 \pm 36 \pm 6$	[10]
	Γ [eV]	495	514	591	$541 \pm 89 \pm 22$	[10]
Branching ratios	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		

cross sections

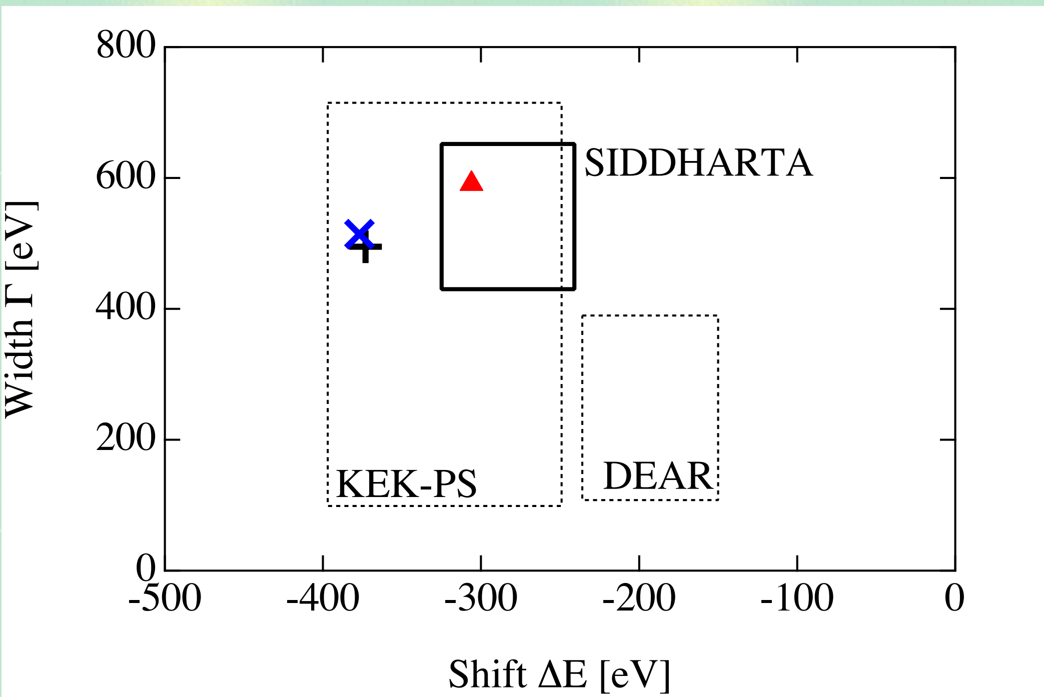


SIDDHARTA is consistent with cross sections

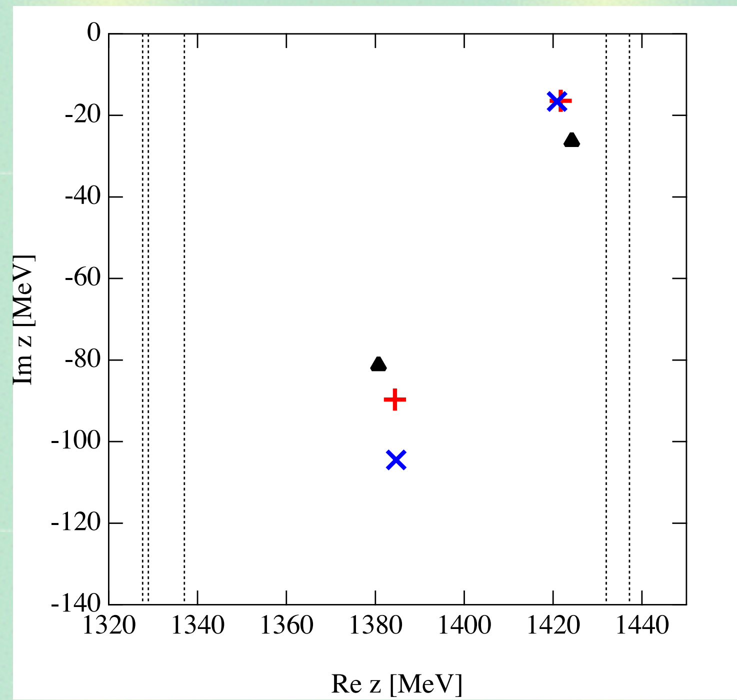
Shift, width, and pole positions

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

Shift and width



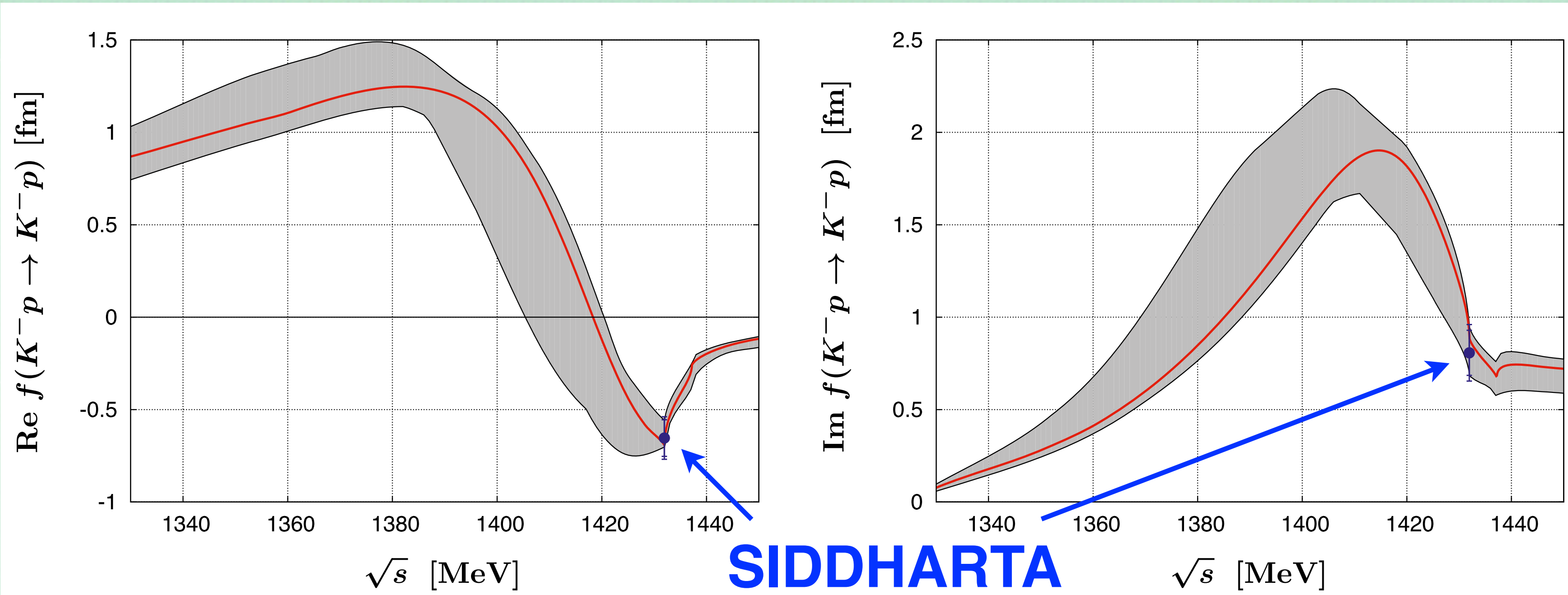
Λ(1405) Pole positions



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

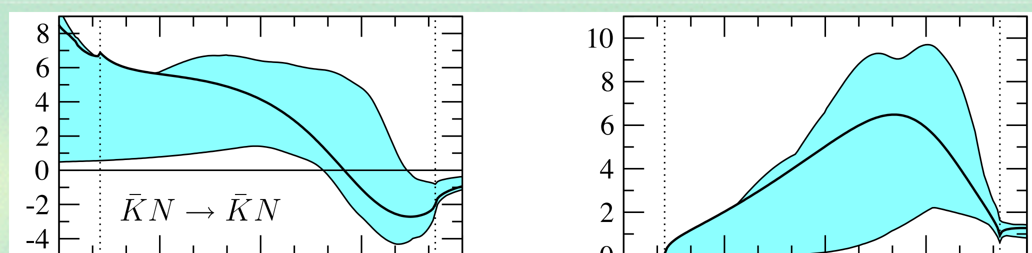
Subthreshold extrapolation

Behavior of K-p —> K-p amplitude below threshold



- c.f. $\bar{K}N$ —> $\bar{K}N$ (I=0) without SIDDHARTA

R. Nissler, Doctoral Thesis (2007)



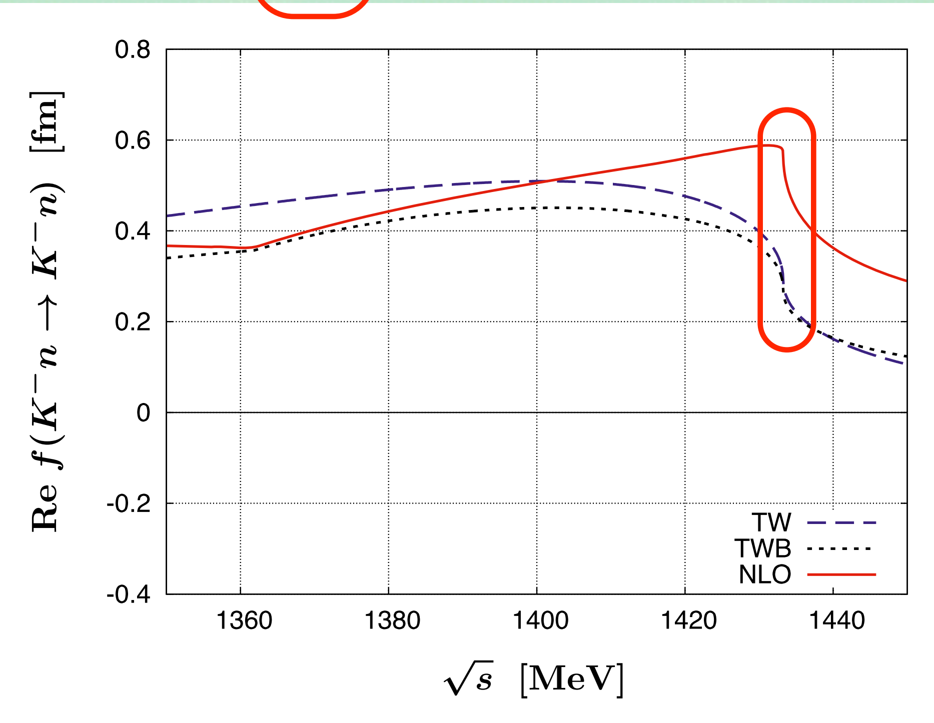
Subthreshold extrapolation is now well controlled.

Remaining ambiguity

For $\bar{K}$-nucleon interaction, we need both K-p and K-n.

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

$$a(K^-n) = 0.29 + i0.76 \text{ fm} \quad (\text{TW}) \quad ,$$
$$a(K^-n) = 0.27 + i0.74 \text{ fm} \quad (\text{TWB}) \quad ,$$
$$a(K^-n) = 0.57 + i0.73 \text{ fm} \quad (\text{NLO}) \quad .$$



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

Summary: chiral SU(3) dynamics

We perform systematic χ^2 analysis for the $\bar{K}N$-$\pi\Sigma$ interaction in chiral coupled-channel approach.

- **With accurate kaonic hydrogen data, we can construct realistic $\bar{K}N$-$\pi\Sigma$ interaction. Ambiguity in the subthreshold extrapolation for $\Lambda(1405)$ energy region is significantly reduced.**
- **Pole position of $\Lambda(1405)$ is converging.**

$$z_1 = (1424^{+7}_{-23} - i26^{+3}_{-14})\ \mathrm{MeV}, \quad z_2 = (1381^{+18}_{-6} - i81^{+19}_{-8})\ \mathrm{MeV}$$

- **Remaining ambiguity: I=1 channel**
  <— kaonic deuterium measurement.

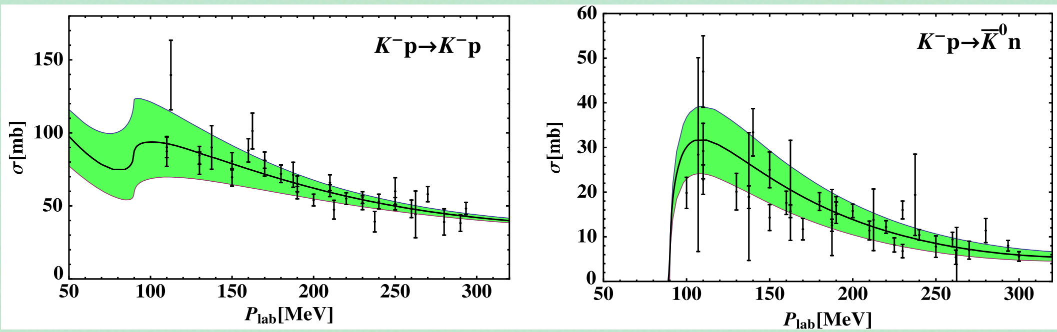
Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)

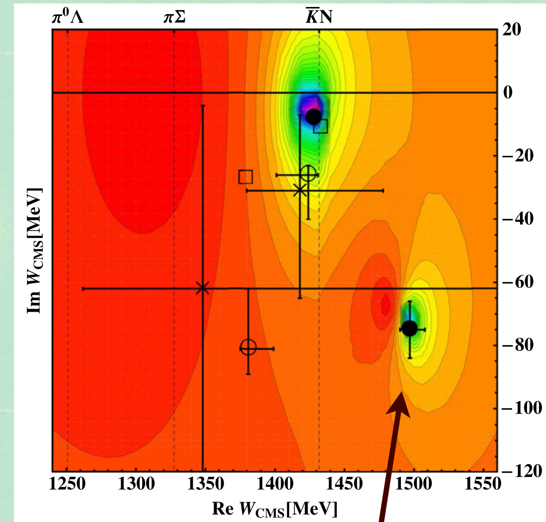
Analyses by other groups

NLO interaction + χ^2 analysis + SIDDHARTA data

- Bonn group

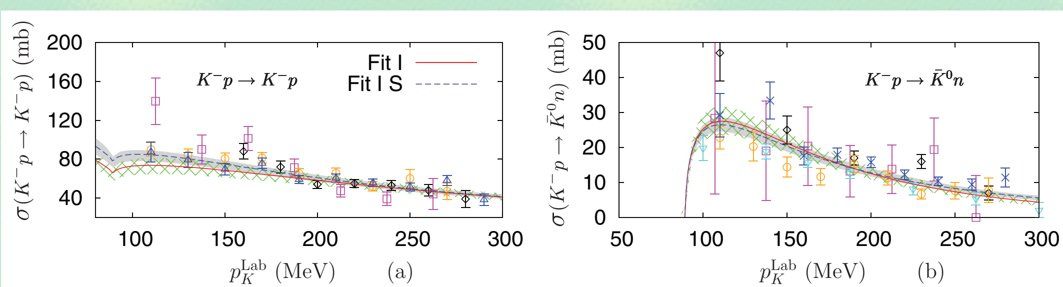
M. Mai, U.-G. Meissner, Nucl. Phys. A900, 51 (2013)





- Murcia group

Z.H. Guo, J.A. Oller, Phys. Rev. C87, 035202 (2013)



~13 parameters —> several local minima

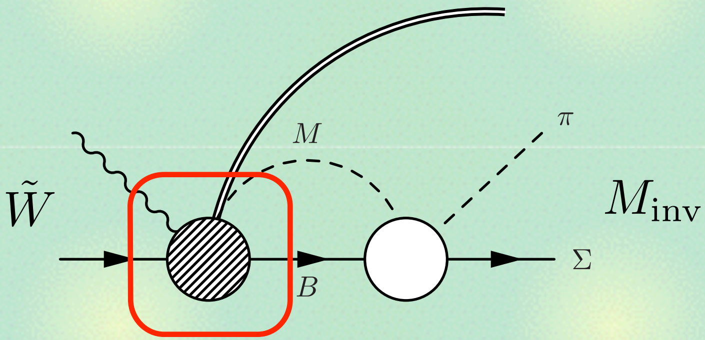
Another "exotic" solution (second pole above $\bar{K}N$)?

Constraints from the $\pi\Sigma$ spectrum

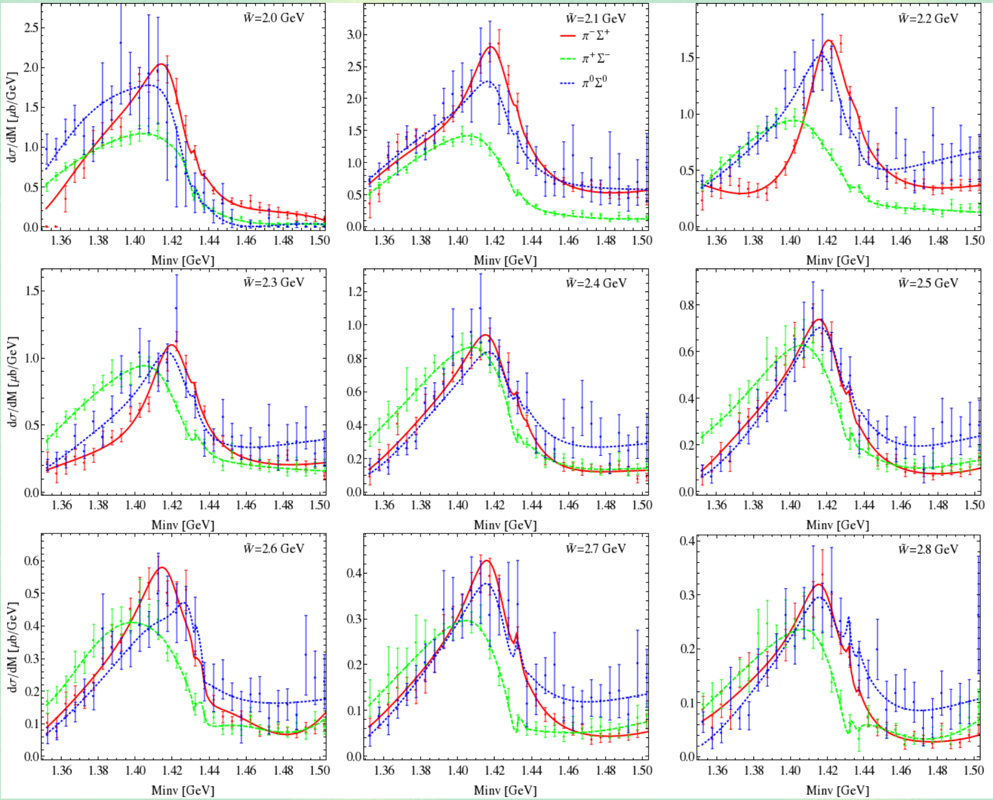
Combined analysis of scattering data + $\pi\Sigma$ spectrum

M. Mai, U.-G. Meissner, arXiv:1411.7884 [hep-ph]

- a simple model for the photoproduction $\gamma p \to K^+(\pi\Sigma)^0$
- CLAS data of the $\pi\Sigma$ spectrum



$$= \sum_{i=1}^{10} C^i(\tilde{W}) G^i(M_{\rm inv}) f_{0+}^{i,\pi\Sigma}(M_{\rm inv})$$



—> The "exotic" solution is excluded.

Pole positions of Λ(1405)

Mini-review prepared for PDG

Pole structure of the Λ(1405)

Ulf-G. Meißner, Tetsuo Hyodo

February 4, 2015

The Λ(1405) resonance emerges in the meson-baryon scattering amplitude with the strangeness $S = -1$ and isospin $I = 0$. It is the archetype of

[11,12] Ikeda-Hyodo-Weise, [14] Murcia, [15] Bonn (updated)

approach	pole 1 [MeV]	pole 2 [MeV]
Ref. [11, 12] NLO	$1424^{+7}_{-23} - i26^{+3}_{-14}$	$1381^{+18}_{-6} - i81^{+19}_{-8}$
Ref. [14] Fit I	$1417^{+4}_{-4} - i24^{+7}_{-4}$	$1436^{+14}_{-10} - i126^{+24}_{-28}$
Ref. [14] Fit II	$1421^{+3}_{-2} - i19^{+8}_{-5}$	$1388^{+9}_{-9} - i114^{+24}_{-25}$
Ref. [15] solution #2	$1434^{+2}_{-2} - i\,10^{+2}_{-1}$	$1330^{+4}_{-5} - i\,56^{+17}_{-11}$
Ref. [15] solution #4	$1429^{+8}_{-7} - i\,12^{+2}_{-3}$	$1325^{+15}_{-15} - i\,90^{+12}_{-18}$

still some deviations

Summary of current status of Λ(1405)

- To avoid "exotic" solutions, we need to check the consistency with $\pi\Sigma$ **spectra**.

- Different analyses show pole 1 (close to the $\bar{K}N$ threshold) is well determined. There is still ambiguity in pole 2 (with large imaginary part).

- Future direction:

NLO chiral interaction χ^2 error analysis **reliable reaction model**	→	$\bar{K}N$ scattering data K^-p scattering length $\pi\Sigma$ **spectrum**