Toward realistic prediction of the Λ(1405) production in K-d reaction

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- $K^-d \rightarrow \pi\Sigma n$ **reaction for J-PARC E31**
  - S. Ohnishi, Y. Ikeda, T. Hyodo, E. Hiyama, W. Weise, arXiv:1408.0118

S. Ohnishi

Y. Ikeda

E. Hiyama

W. Weise

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

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

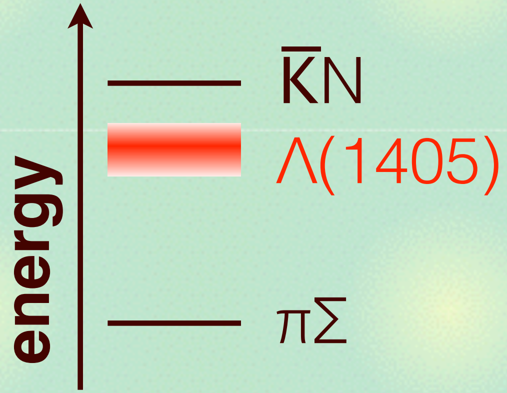
- **NG boson of chiral $SU(3)_R \otimes SU(3)_L$ --> $SU(3)_V$**
- **massive by strange quark: m_K ~ 496 MeV**

—> spontaneous/explicit symmetry breaking

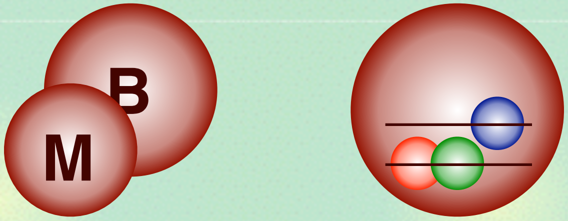
$\bar{K}N$ interaction ...

- **is coupled with $\pi\Sigma$ channel**
- **has a resonance below threshold**

—> $\Lambda(1405)$



meson-baryon v.s. qqq state, ...



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

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

$\bar{K}$ nuclei v.s. normal nuclei

$\bar{K}N$ interaction

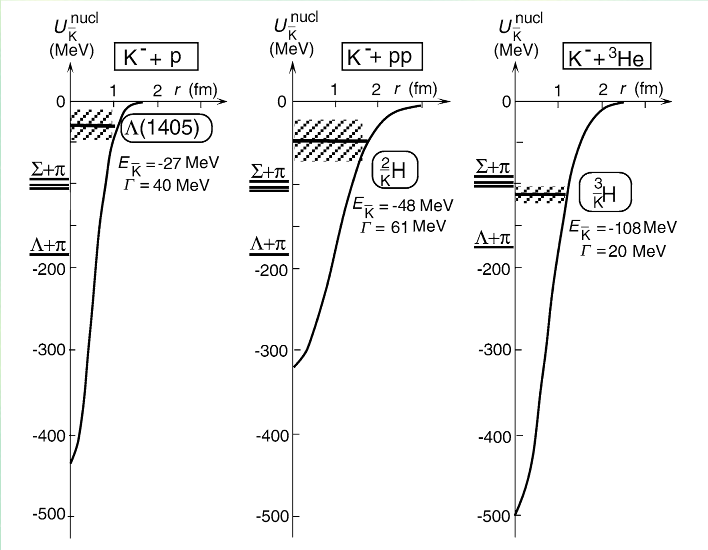
- **strong attraction**
- **no repulsive core?**

	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)



Rigolous calculations (2007-)

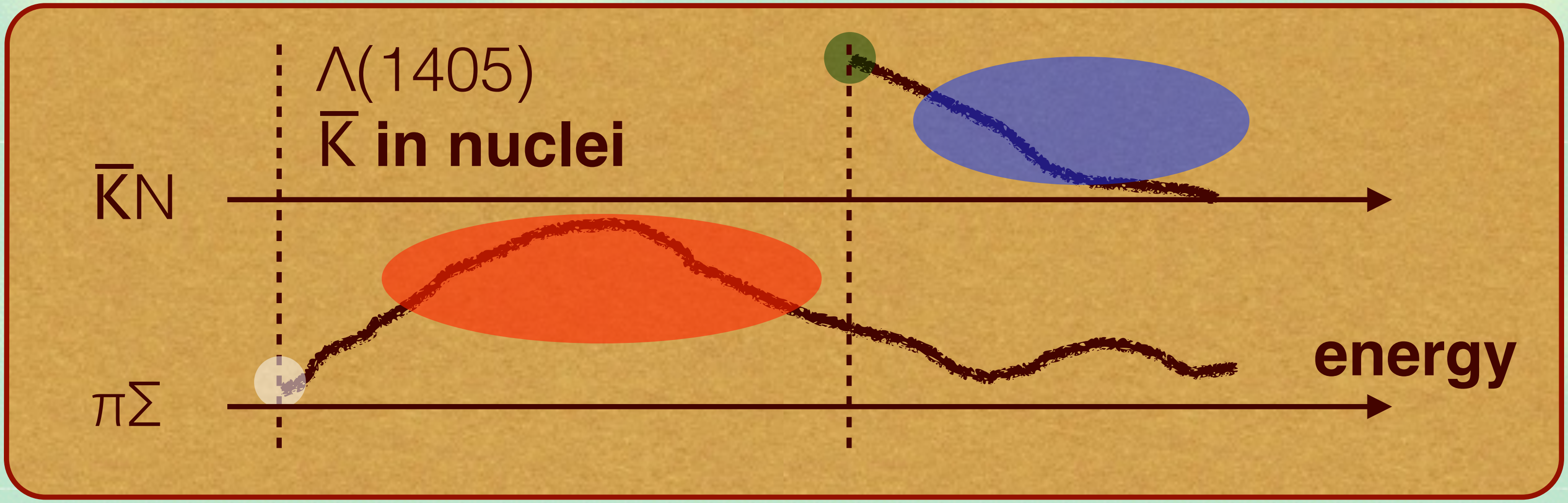
- **bound in few-nucleon systems**
- **binding energy depends on the employed $\bar{K}N$ interaction**

—> 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 by SIDDHARTA)**



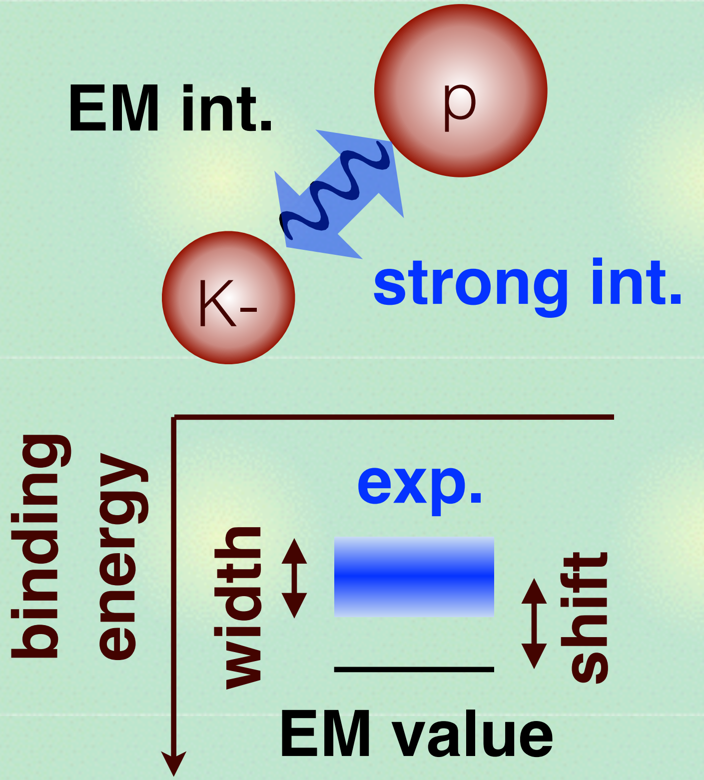
Below the $\bar{K}N$ threshold:

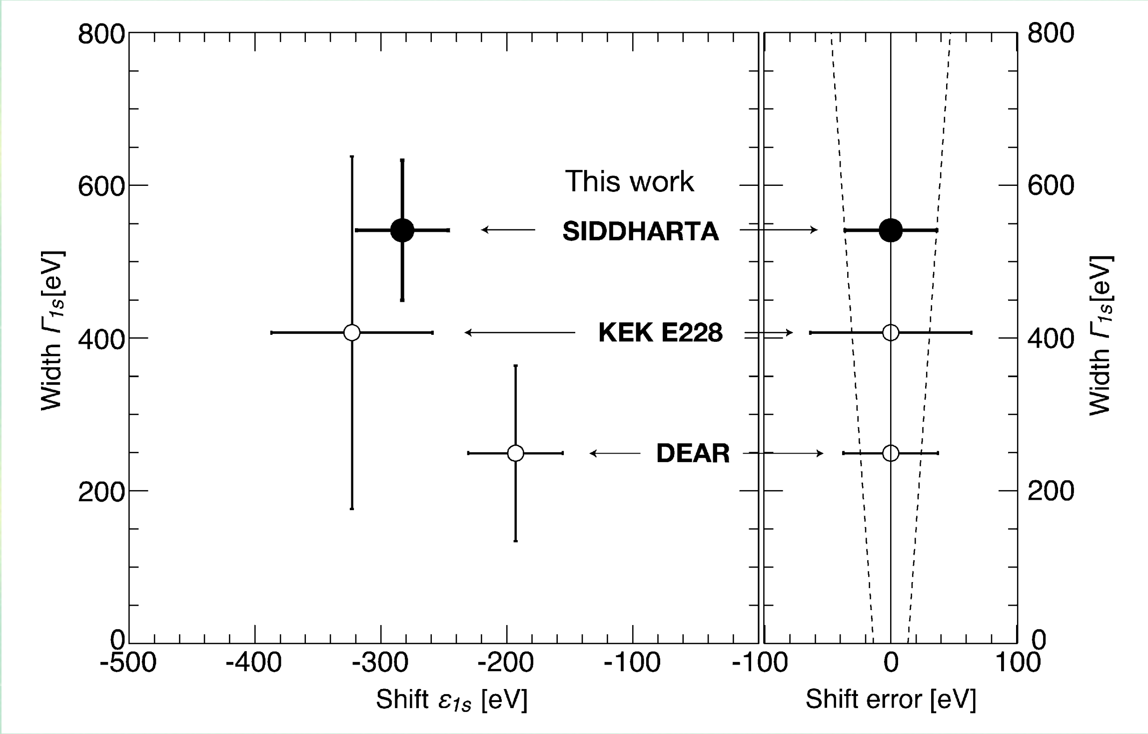
- πΣ **mass spectra (new data by LEPS, CLAS, HADES,...)**
- πΣ **scattering length (no data at present)**

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)

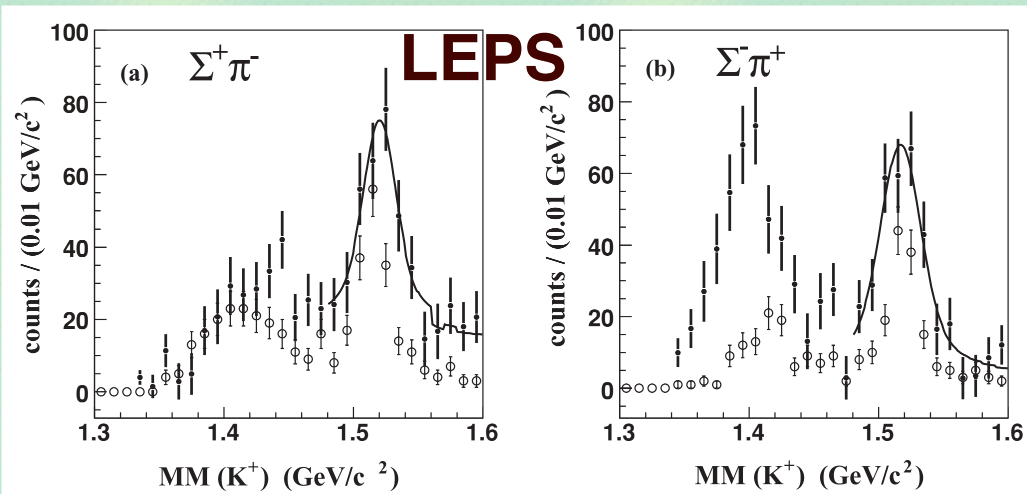
Direct constraint on the $\bar{K}N$ interaction at fixed energy

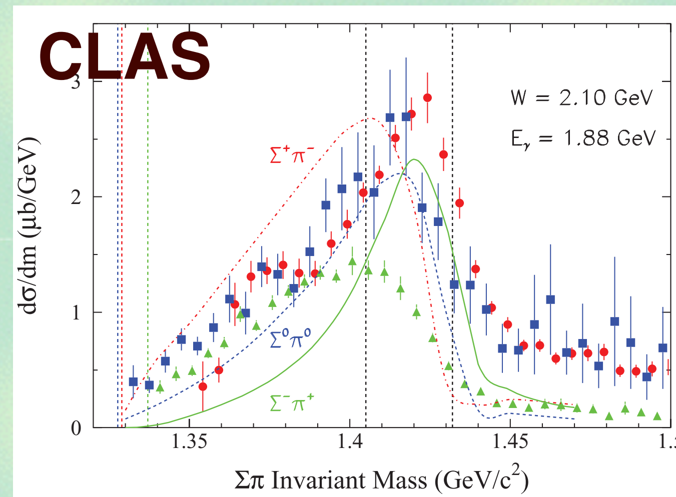
New $\pi\Sigma$ spectra

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

- **LEPS@**$1.5 < E\gamma < 2.4$ **GeV, CLAS@**$1.56 < E\gamma < 3.83$ **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):** $K^-d \to n(\pi\Sigma)^0$

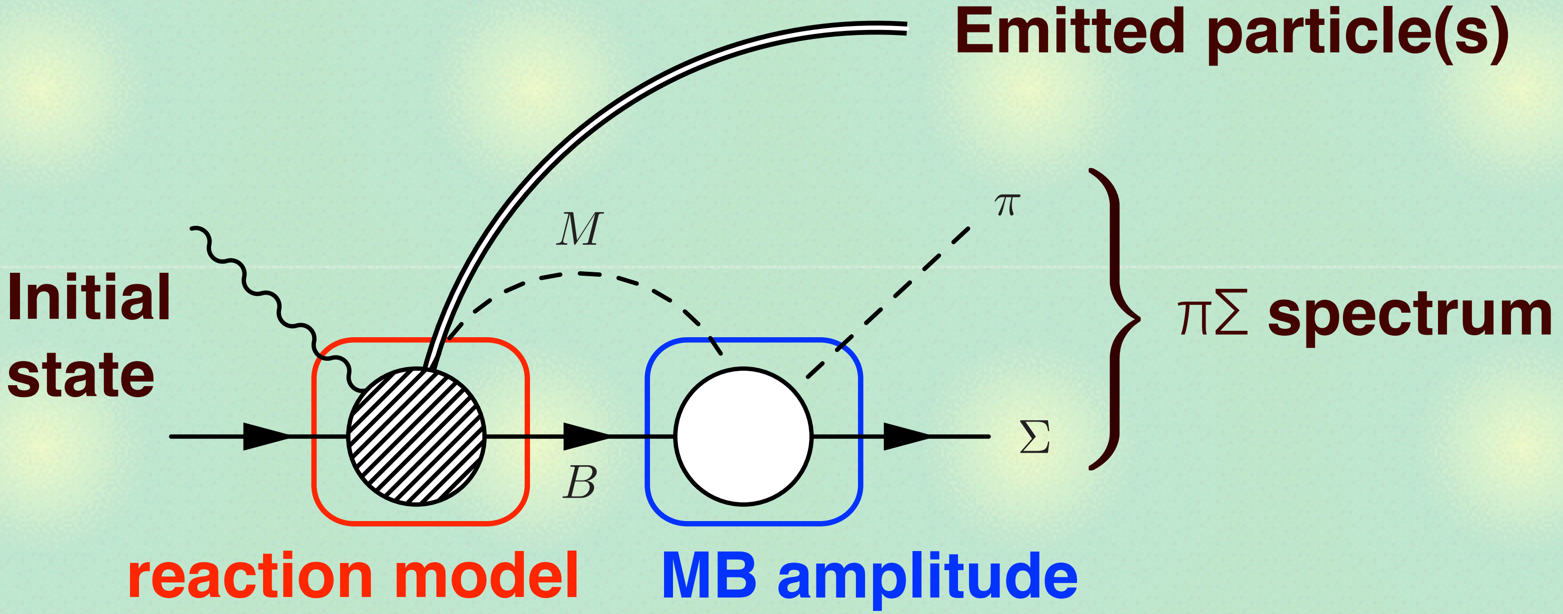
New and precise spectra are being available.

$\pi\Sigma$ 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,...).**
- **Event numbers do note constrain the absolute value.**

—> 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**

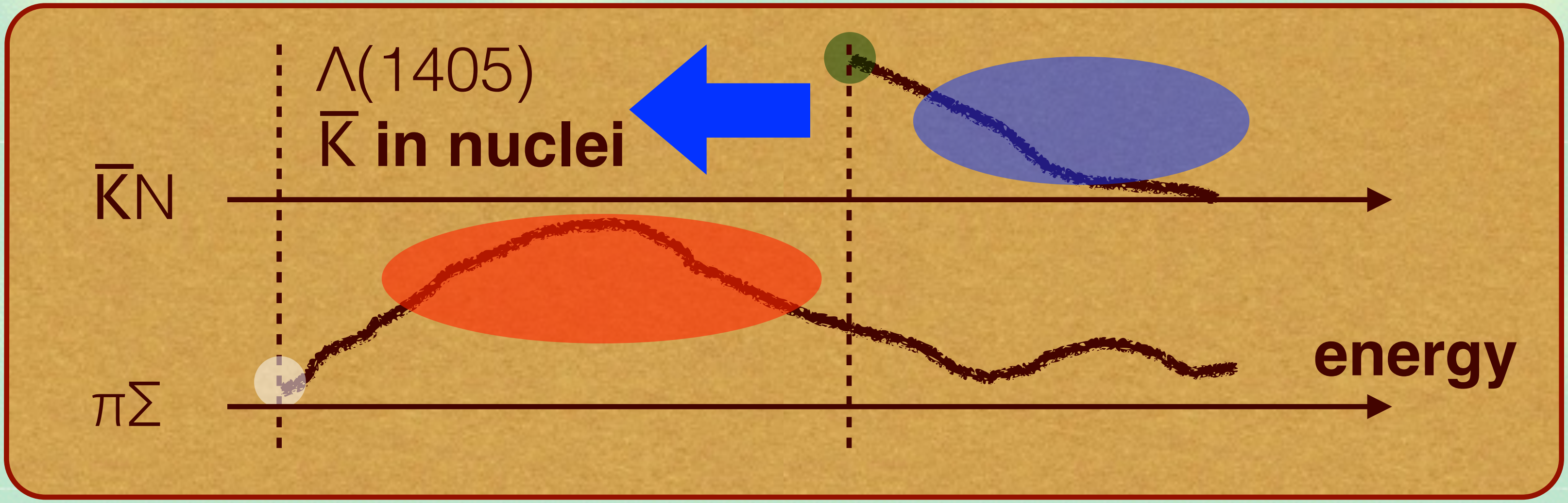
- **New $\pi\Sigma$ spectra from various reactions —> reliable reaction model required**

➡ **Construct realistic $\bar{K}N$ scattering model and predict $\pi\Sigma$ spectrum in K^-d reaction.**

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 by SIDDHARTA)**



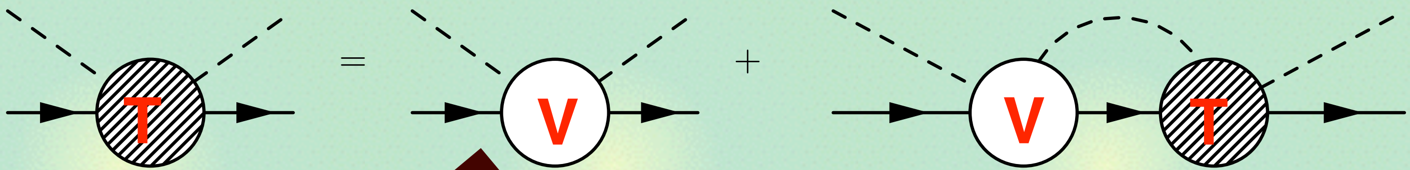
Below the $\bar{K}N$ threshold:

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

Construction of the realistic amplitude

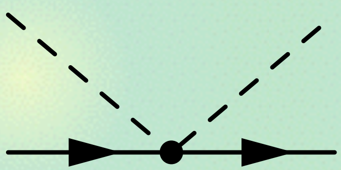
Chiral coupled-channel approach with systematic χ^2 fitting

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



ChPT

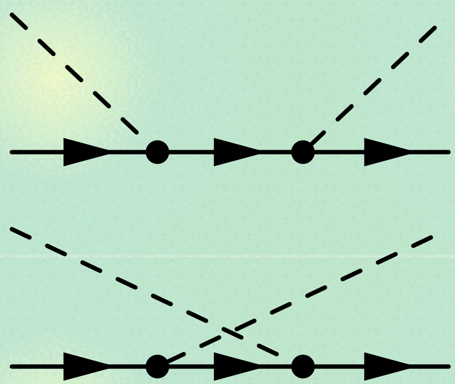
1) TW term



$\mathcal{O}(p)$

TW model

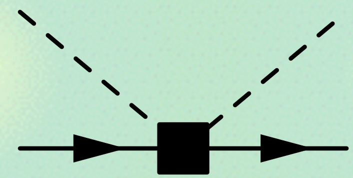
2) Born terms



$\mathcal{O}(p)$

TWB model

3) NLO terms



LECs

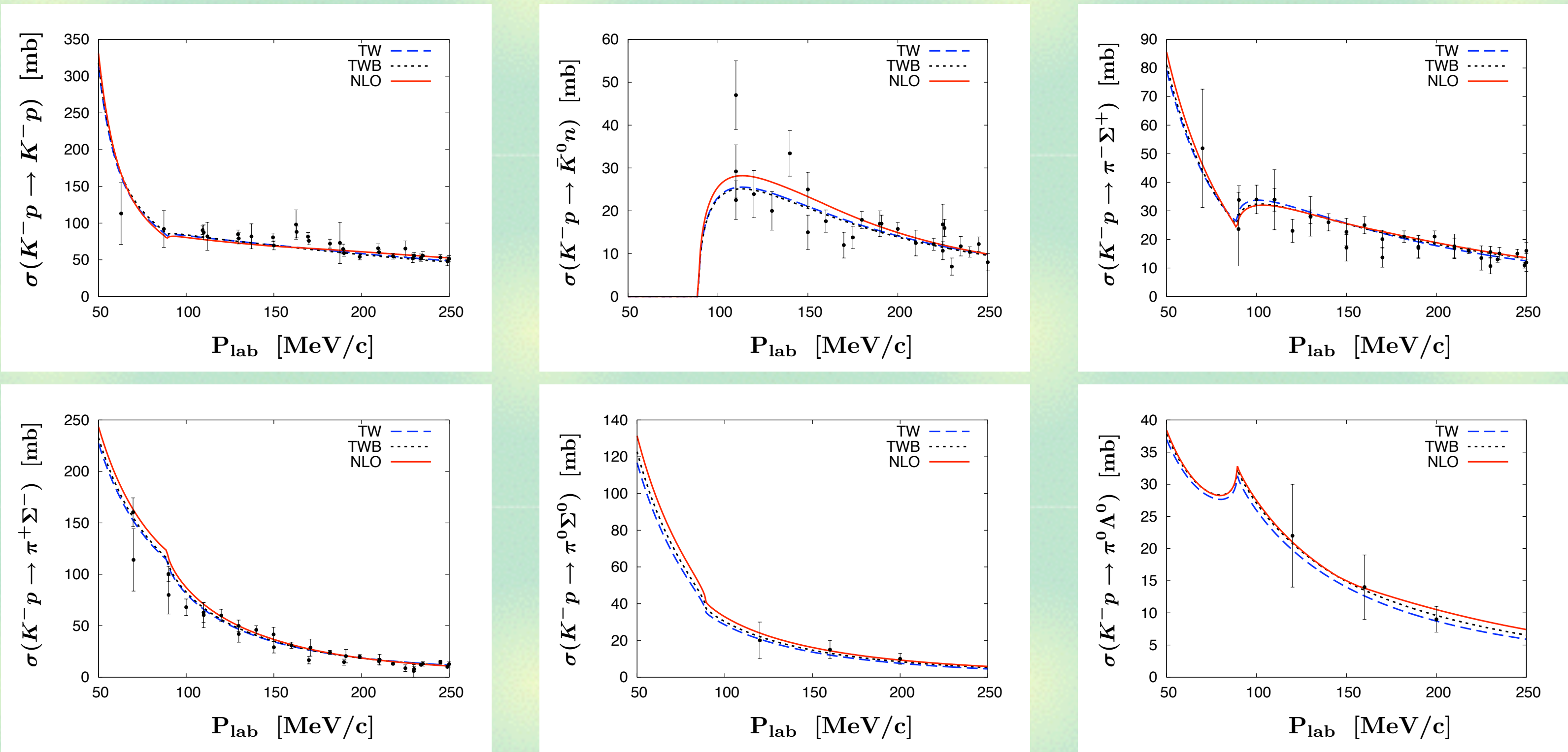
$\mathcal{O}(p^2)$

NLO model

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

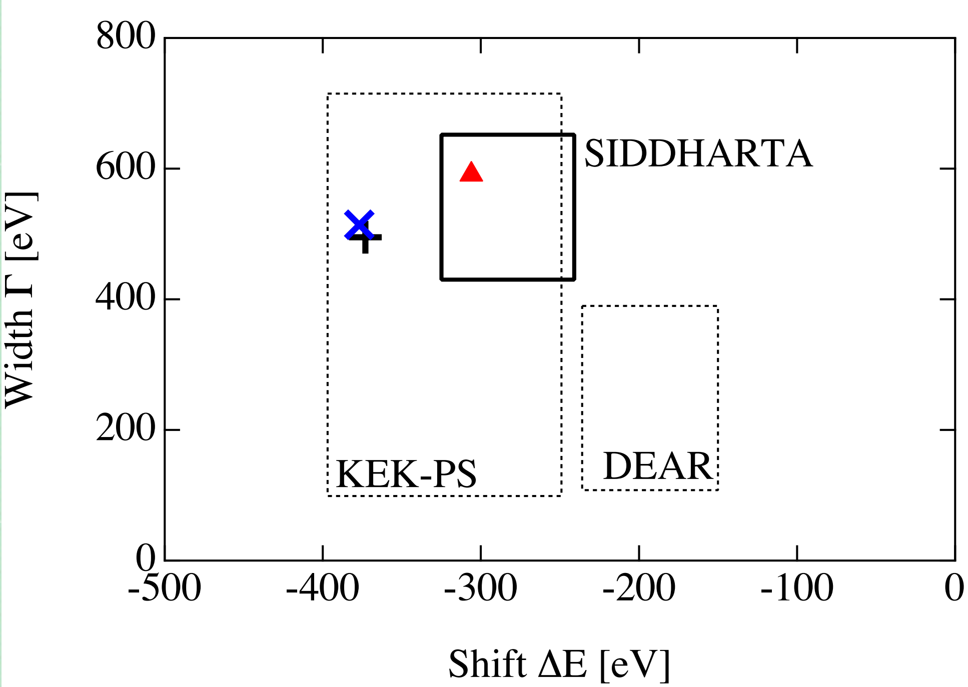


SIDDHARTA is consistent with cross sections

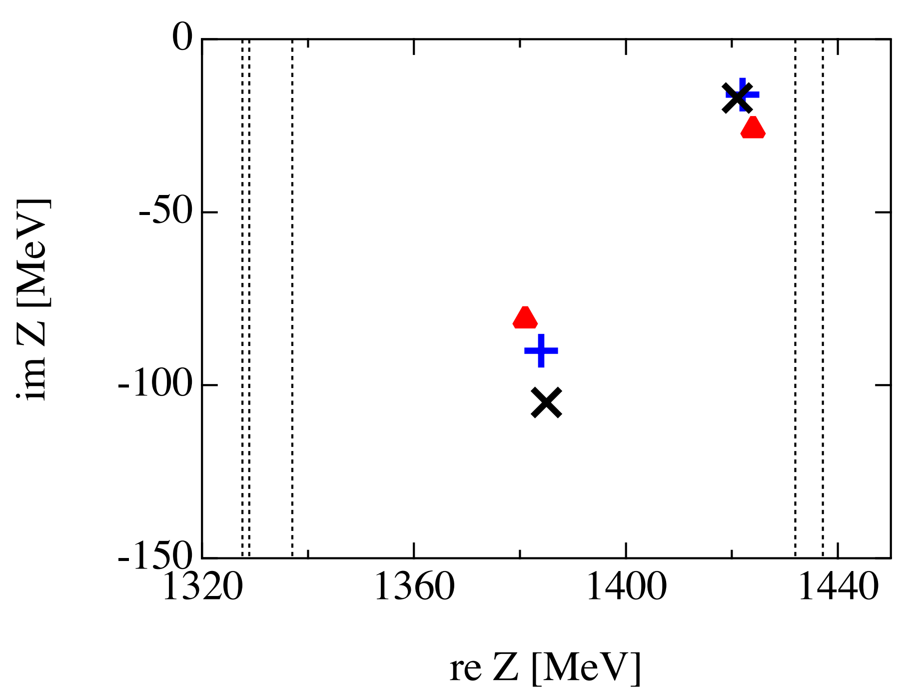
Shift, width, and pole positions

	TW	TWB	NLO
χ	1.12	1.15	0.957

Shift and width



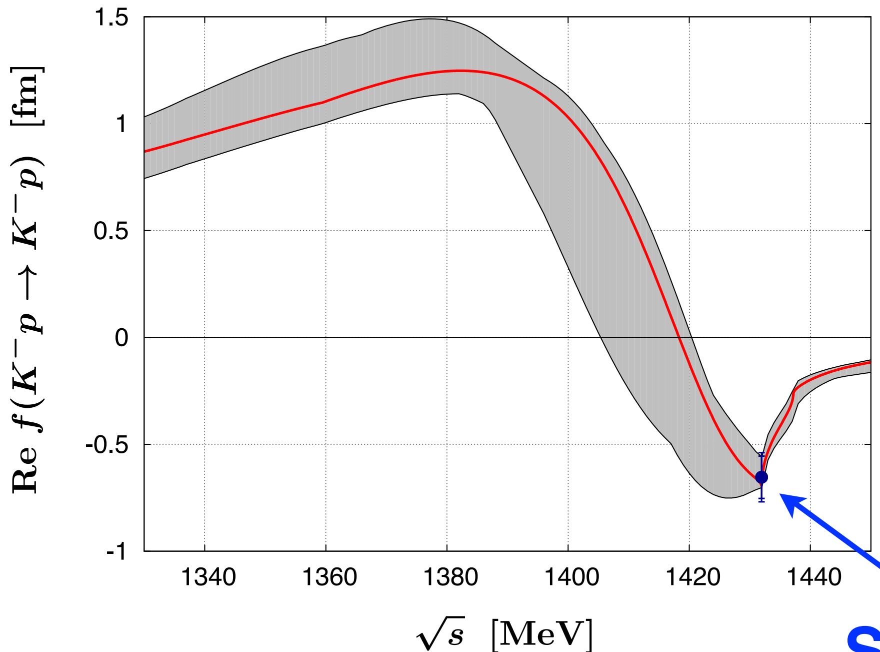
Pole positions

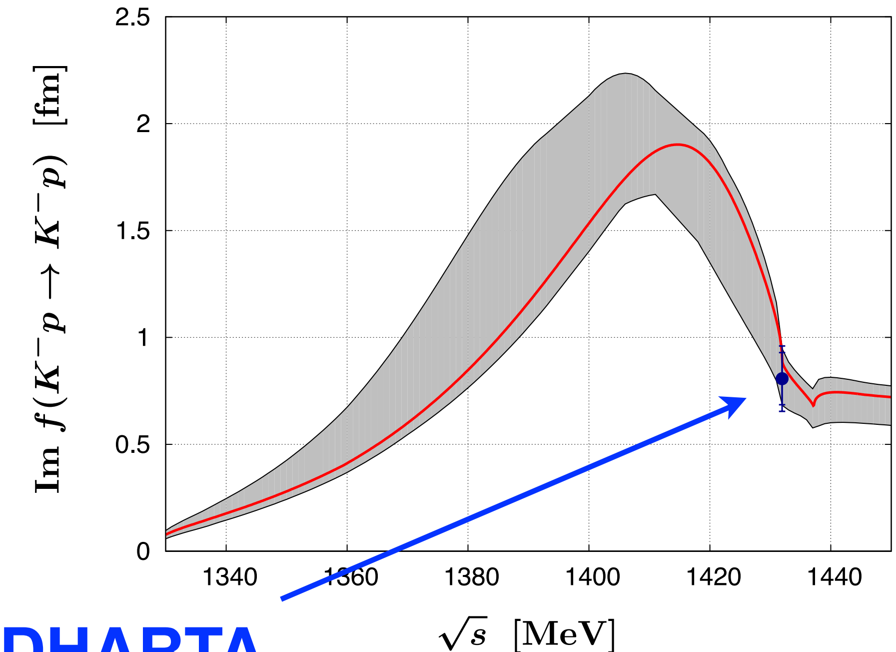


TW and TWB are reasonable, while best-fit requires NLO.
Pole positions are now converging.

Subthreshold extrapolation

Behavior of K-p amplitude below threshold

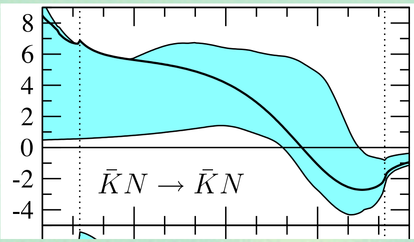




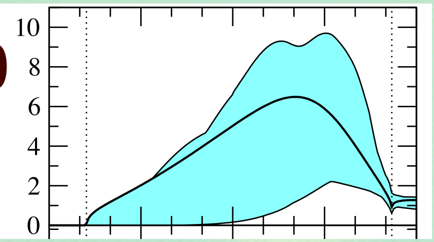
SIDDHARTA

- **c.f. without SIDDHARTA**

R. Nissler, Doctoral Thesis (2007)



I=0



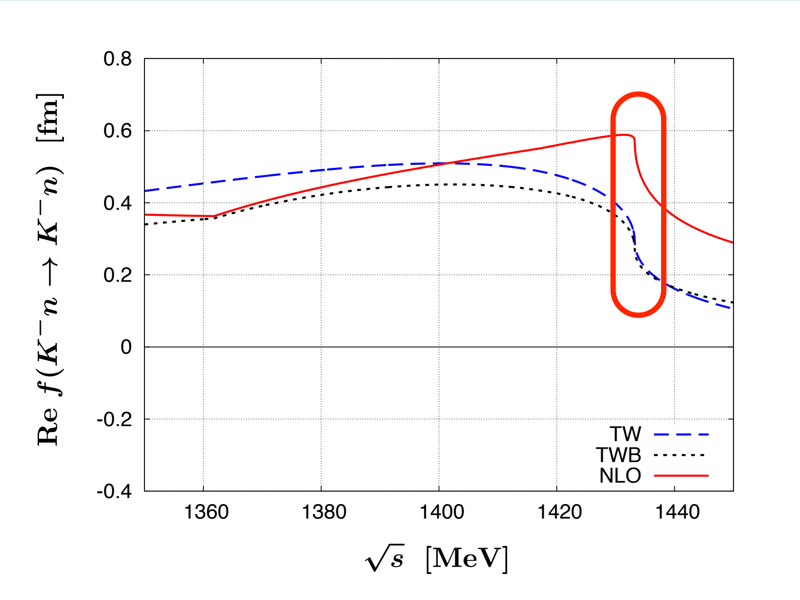
Subthreshold extrapolation is now well controlled.

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 1

We study the $\bar{K}N$-$\pi\Sigma$ interaction based on chiral coupled-channel approach.

- **With accurate kaonic hydrogen data, we can construct realistic $\bar{K}N$-$\pi\Sigma$ interaction. Ambiguity in the subthreshold extrapolation ($\Lambda(1405)$ energy region) is significantly reduced.**
- **Pole position of $\Lambda(1405)$ is converging.**
- **Future refinement: $I=1$ channel**
  <— kaonic deuterium measurement.

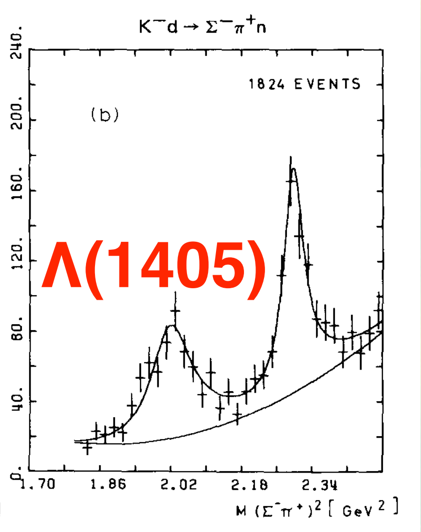
Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)

Kaon induced reaction : experiments

Bubble chamber experiment

O. Braun, *et al.*, Nucl. Phys. B129, 1 (1977)

- p_K@686-844 MeV
- $\pi^+\Sigma^-$ spectrum



J-PARC E31 (forthcoming)

http://j-parc.jp/researcher/Hadron/en/pac_0907/pdf/Noumi.pdf

- p_K@1 GeV
- Missing mass spectroscopy
- Separation of $\pi^+\Sigma^-$ / $\pi^-\Sigma^+$ / $\pi^0\Sigma^0$ spectra

Note for the K^-d reaction

$$K^-d \sim [\bar{K}[NN]_{I=0}]_{I=1/2} \sim 1[[\bar{K}N]_{I=0}N]_{I=1/2} + 3[[\bar{K}N]_{I=1}N]_{I=1/2}$$

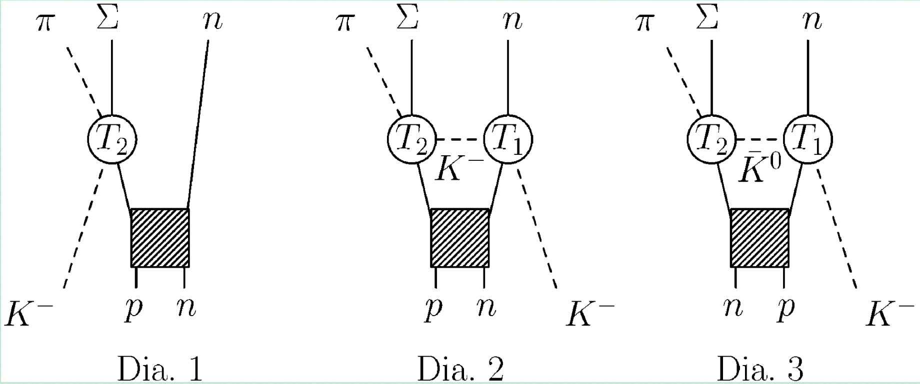
- large I=1 MB fraction

Kaon induced reaction : theory

Two-step approaches with chiral/phenomenological int.

D. Jido, E. Oset, T. Sekihara, Eur. Phys. J. A42, 257 (2009);
J. Esmaili, Y. Akaishi, T. Yamazaki, Phys. Rev. C83, 055207 (2011);
D. Jido, E. Oset, T. Sekihara, Eur. Phys. J. A47, 42 (2011);
K. Miyagawa, J. Haidenbauer, Phys. Rev. C85, 065201 (2012);
J. Yamagata-Sekihara, T. Sekihara, D. Jido, PTEP 043D02 (2013)

- **Perturbative: full three-body dynamics is not included.**



Faddeev(AGS) approach

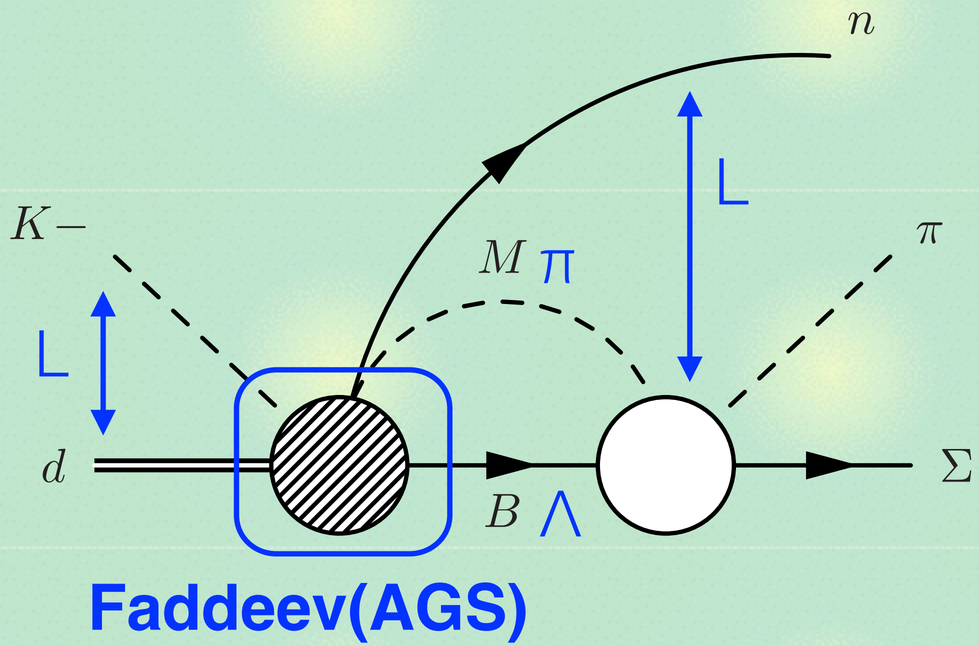
J. Revai, Few-Body Syst. 54, 1865 (2013)

- πΛN **channel is not included.**
- **s-wave interactions only (valid at low energy)**

Strategy for J-PARC E31

Our framework of K-d -> πΣn **for J-PARC E31**

- **Faddeev(AGS) amplitude: full three-body dynamics**
- **Inclusion of the** πΛN **channel: proper** I=1 **contribution**
- **Inclusion of relative** L**: 1 GeV incident momentum**

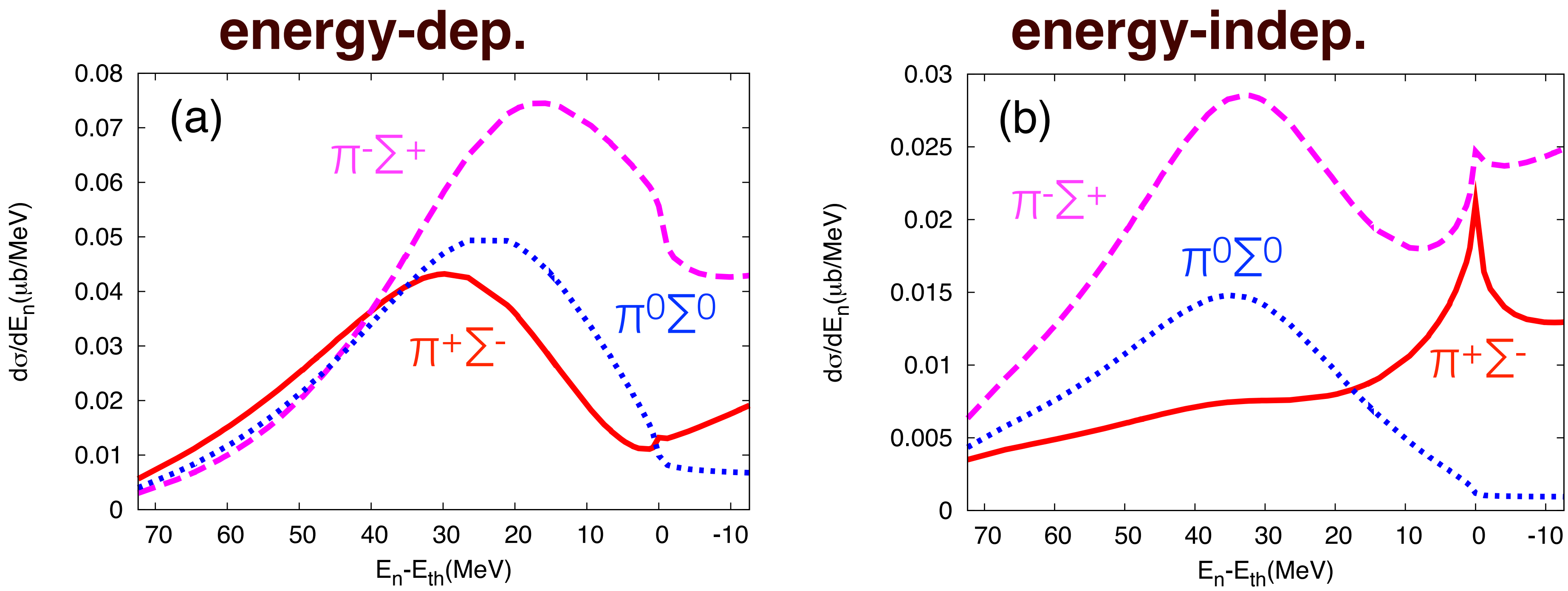


- **MB interaction: energy-dep. and energy-indep. interactions (fitted to cross sections, to be constrained by SIDDAHRTA)**

Y. Ikeda, H. Kamano, T. Sato, Prog. Theor. Phys. 124, 533 (2010)

πΣ spectra with various charge combinations

πΣ spectra @ P_{K^-} = 1 GeV



Deviation of $\pi^-\Sigma^+$ and $\pi^+\Sigma^-$ spectra

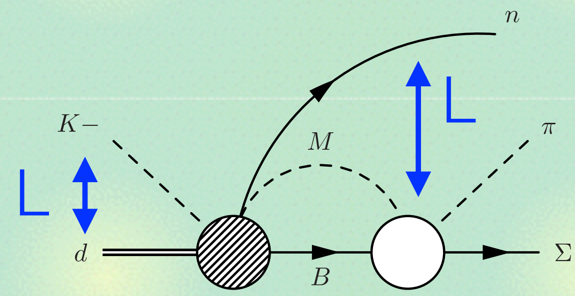
- **large interference effect with I=1 components**

Difference of energy-dep. / energy-indep. (shape, magnitude)

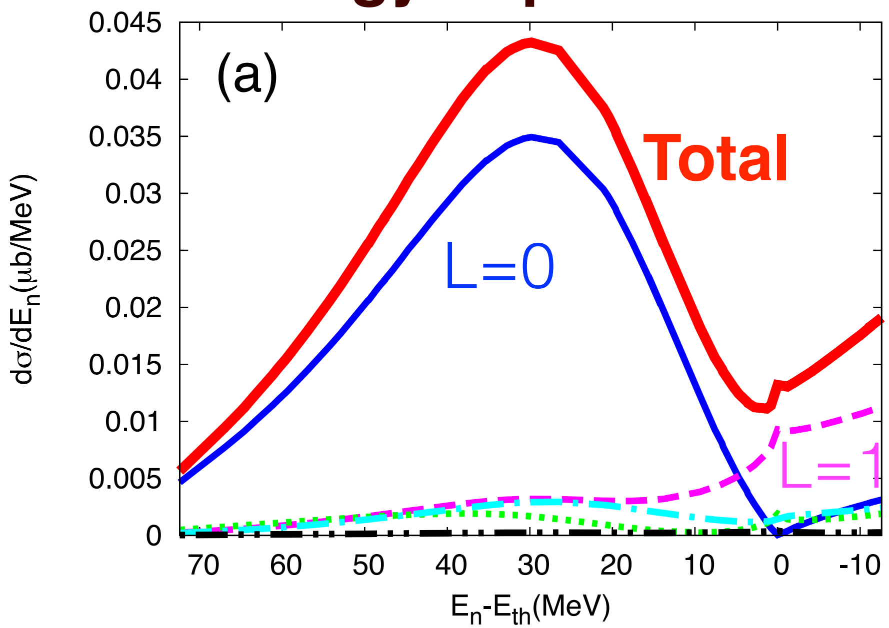
- **distinction of subthreshold $\bar{K}N$ amplitude**

Partial wave contributions

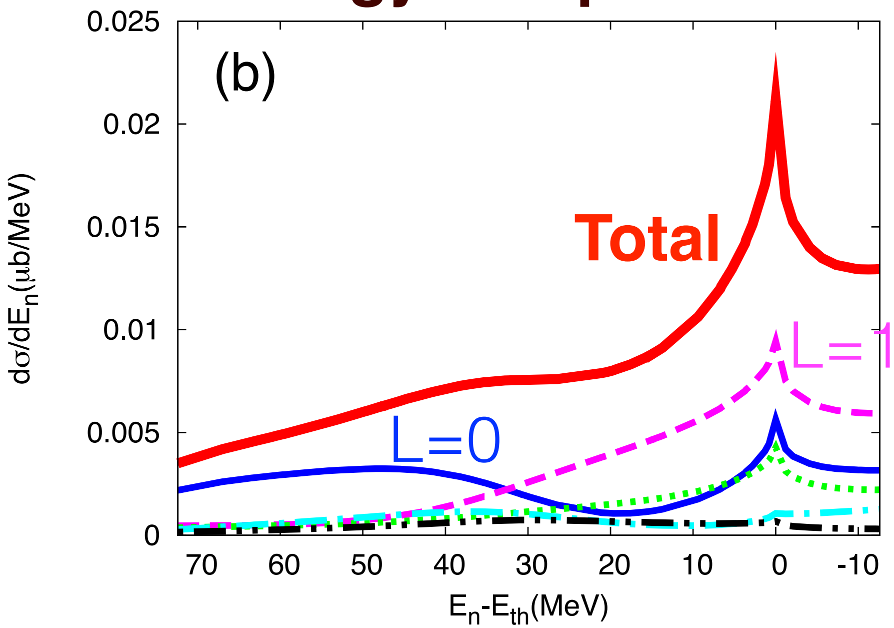
Effect of the higher partial wave components @ P_{K-} = 1 GeV



energy-dep. $\pi^+\Sigma^-$



energy-indep. $\pi^+\Sigma^-$



L≠0 **partial waves are important around threshold.**

Summary 2

We study the K-d -> πΣn reaction for J-PARC E31

- **We employ the Faddeev(AGS) amplitude with πΛN channel and relative L effects included.**

- **Deviation of different charged πΣ states indicates the large interference with I=1.**

- **Lineshape and the magnitude of πΣ spectra are sensitive to subthreshold $\bar{K}N$ interaction.**

- **Higher L components affect around threshold.**

S. Ohnishi, Y. Ikeda, T. Hyodo, E. Hiyama, W. Weise, arXiv:1408.0118