What we know about the Λ(1405)

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Yukawa Institute for Theoretical Physics, Kyoto Univ.

2015, Sep. 15th

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- **Current status of** Λ(1405) **and** $\bar{K}N$ **interaction**
  - **Recent experimental achievements**
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    Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)
  - Λ(1405) **in** πΣ **spectrum**

    S. Ohnishi, Y. Ikeda, T. Hyodo, E. Hiyama, W. Weise,
    J. Phys. Conf. Ser. 569, 012077 (2014) + in prepărataion;
    K. Miyahara, T. Hyodo, E. Oset, arXiv:1508.04882 [nucl-th]
- **Structure of** Λ(1405)
  - $\bar{K}N$ **molecule?**

    K. Miyahara, T. Hyodo, arXiv:1506.05724 [nucl-th];
    Y. Kamiya, T. Hyodo, arXiv:1509.00146 [hep-ph]

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

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

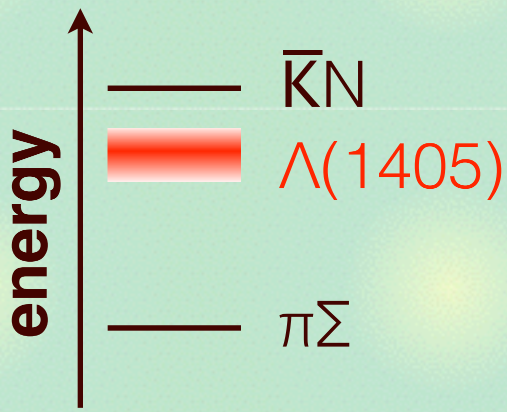
- **NG boson** of chiral $SU(3)_R \otimes SU(3)_L$ —> $SU(3)_V$
- **massive** by strange quark: $m_K \sim 496$ MeV

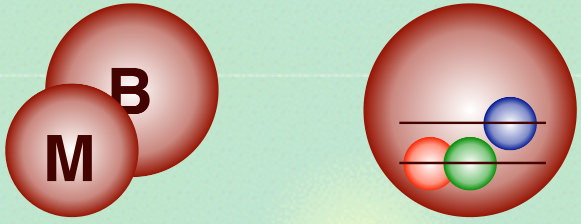
—> **spontaneous**/**explicit** symmetry breaking

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

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

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





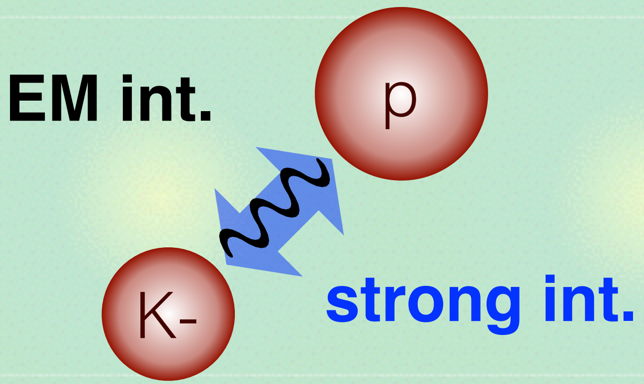
molecule three-quark

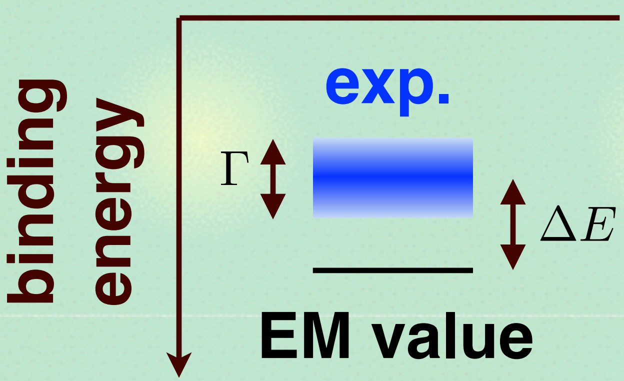
- is fundamental building block for $\bar{K}$-nuclei, $\bar{K}$ in medium, ...

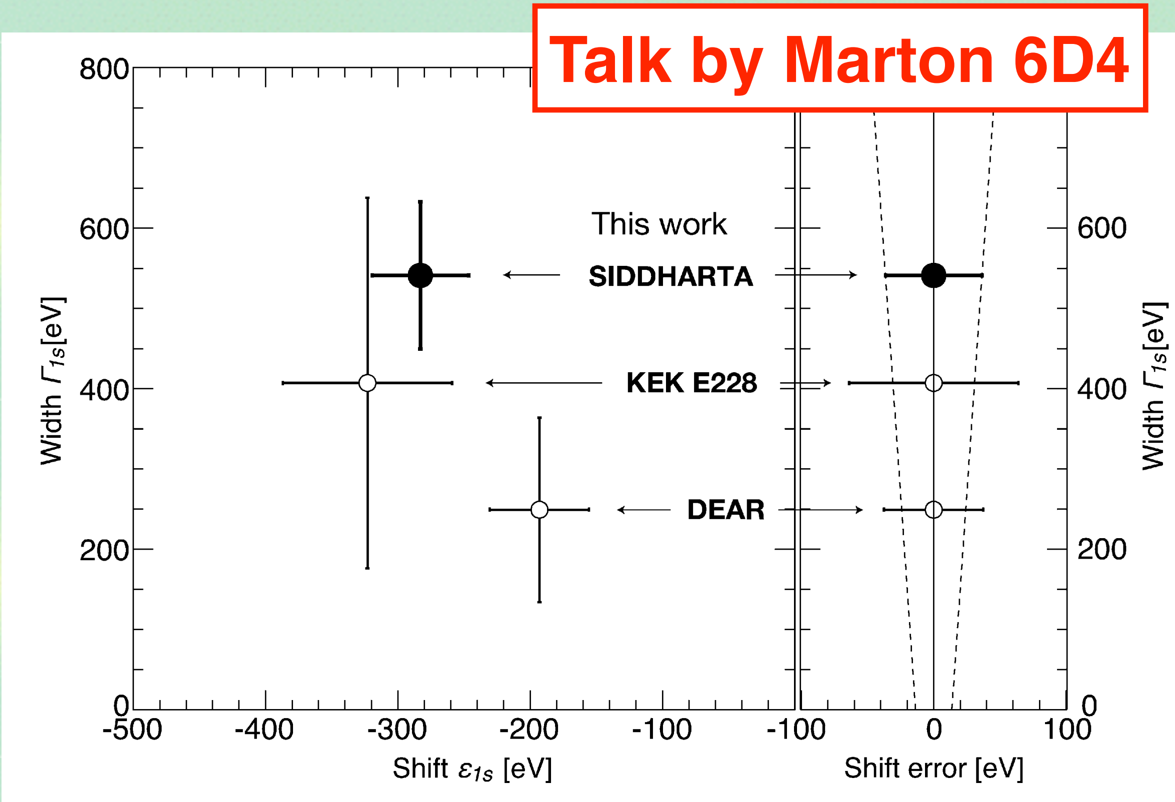
SIDDHARTA measurement

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

$\pi\Sigma$ invarint mass spectra

$\pi\Sigma$ spectrum before 2008: single mode, no absolute values

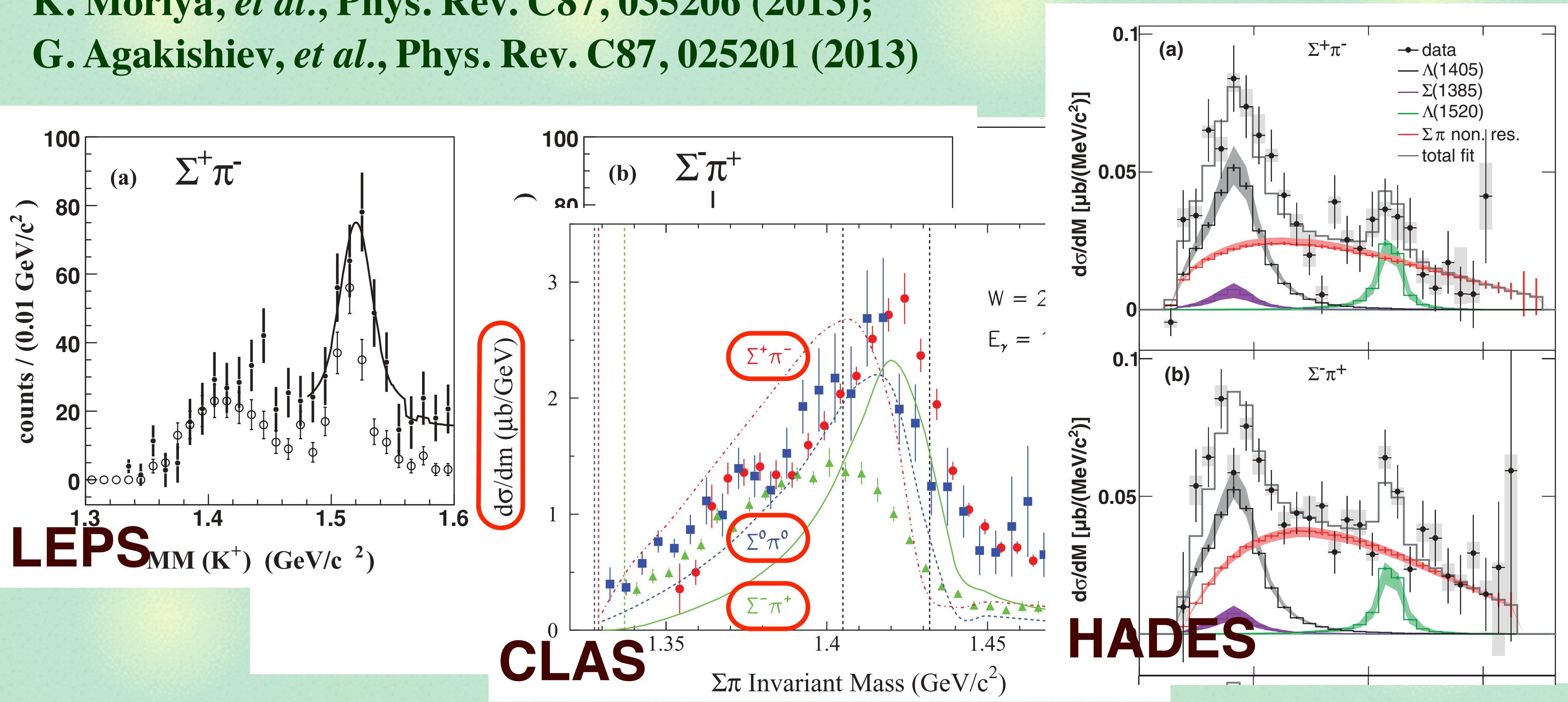
R.J. Hemingway, Nucl. Phys. B253, 742 (1985)

After 2008: $\gamma p \to K^+(\pi\Sigma)^0$ LEPS, CLAS, $pp \to K^+p(\pi\Sigma)^0$ HADES

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

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

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



Cross sections in different charge modes are available.

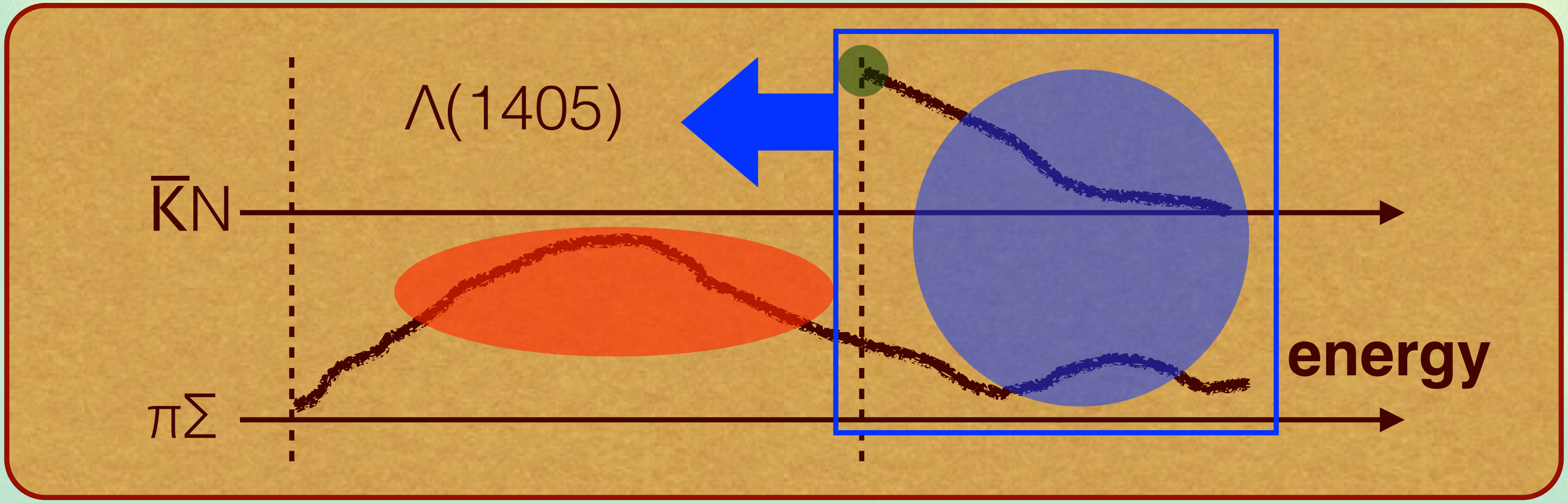
Strategy for $\bar{K}N$ interaction

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

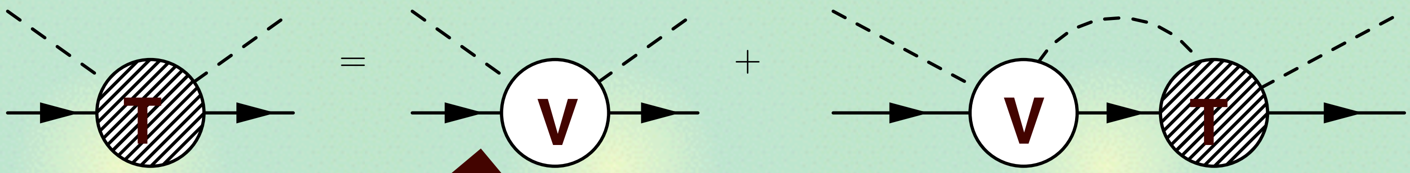
- πΣ **mass spectra (new data: LEPS, CLAS, HADES,…)**



Construction of the realistic amplitude

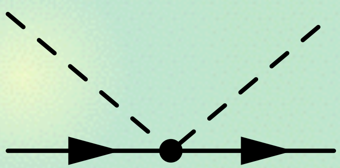
Chiral coupled-channel approach with systematic χ^2 fitting

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



Chiral perturbation theory

1) TW term

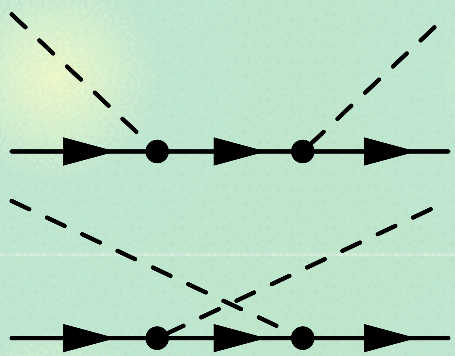


$\mathcal{O}(p)$

6 cutoffs

TW model

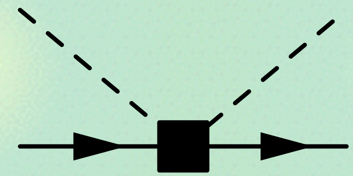
2) Born terms



$\mathcal{O}(p)$

TWB model

3) NLO terms



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

7 LECs

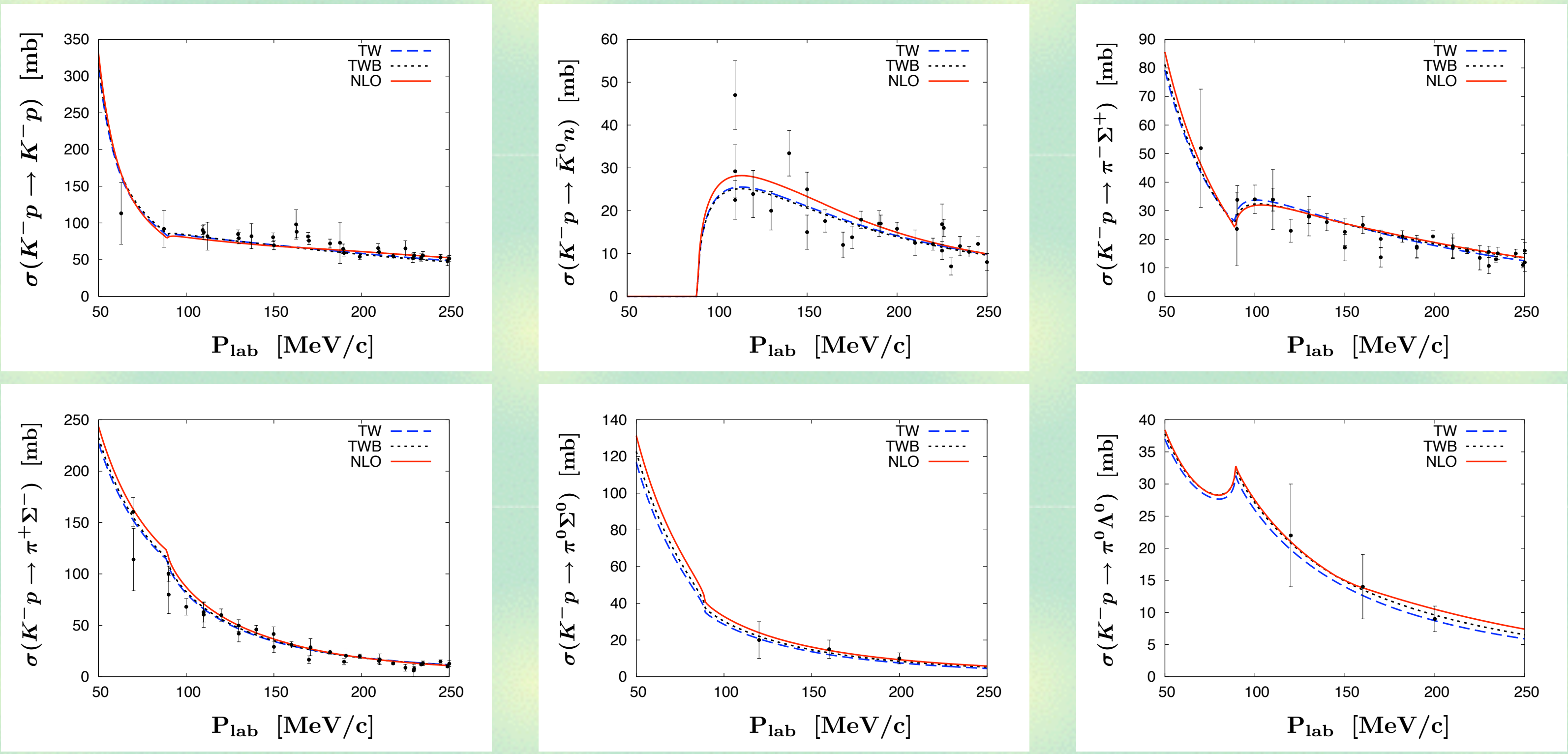
NLO model

Systematic analysis in chiral dynamics

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		

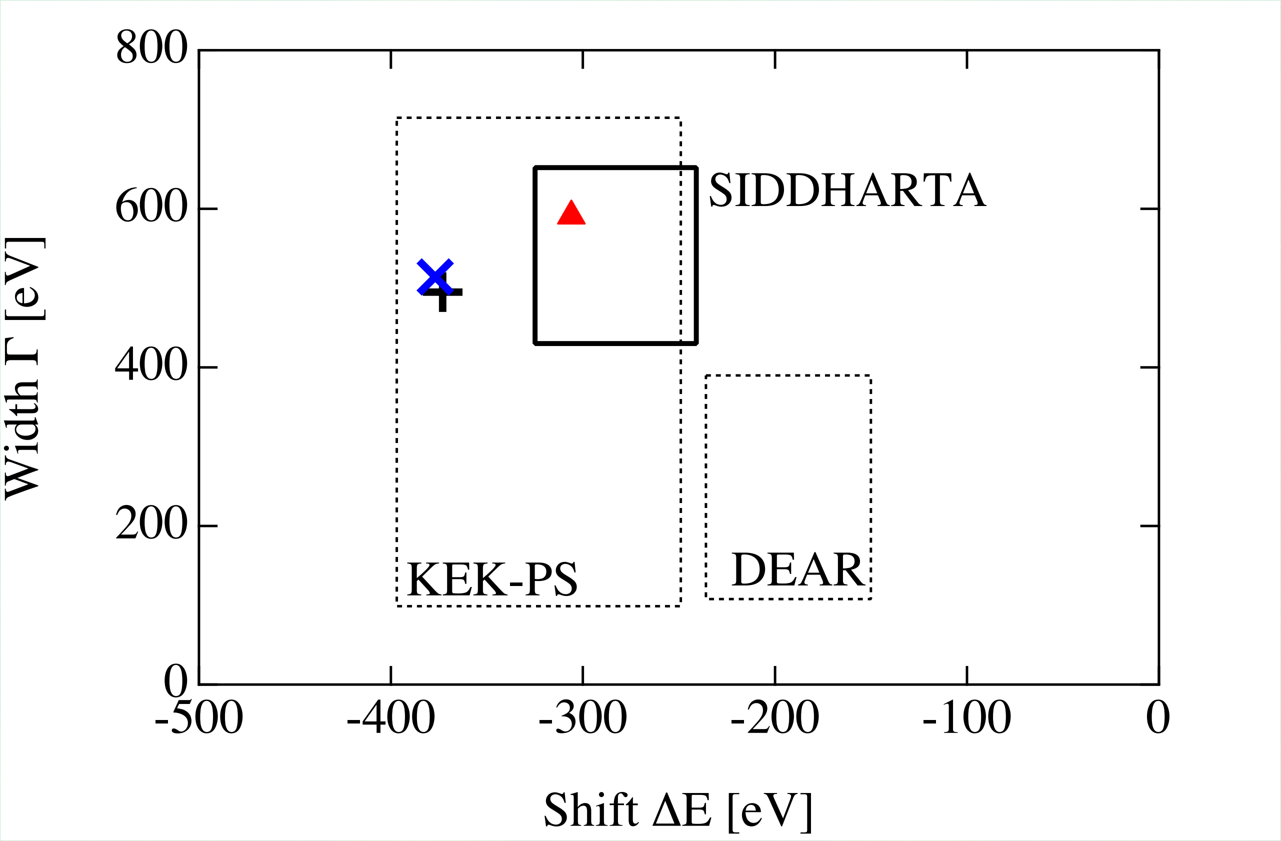
cross sections



SIDDHARTA is consistent with cross sections (c.f. DEAR).

Comparison with SIDDHARTA

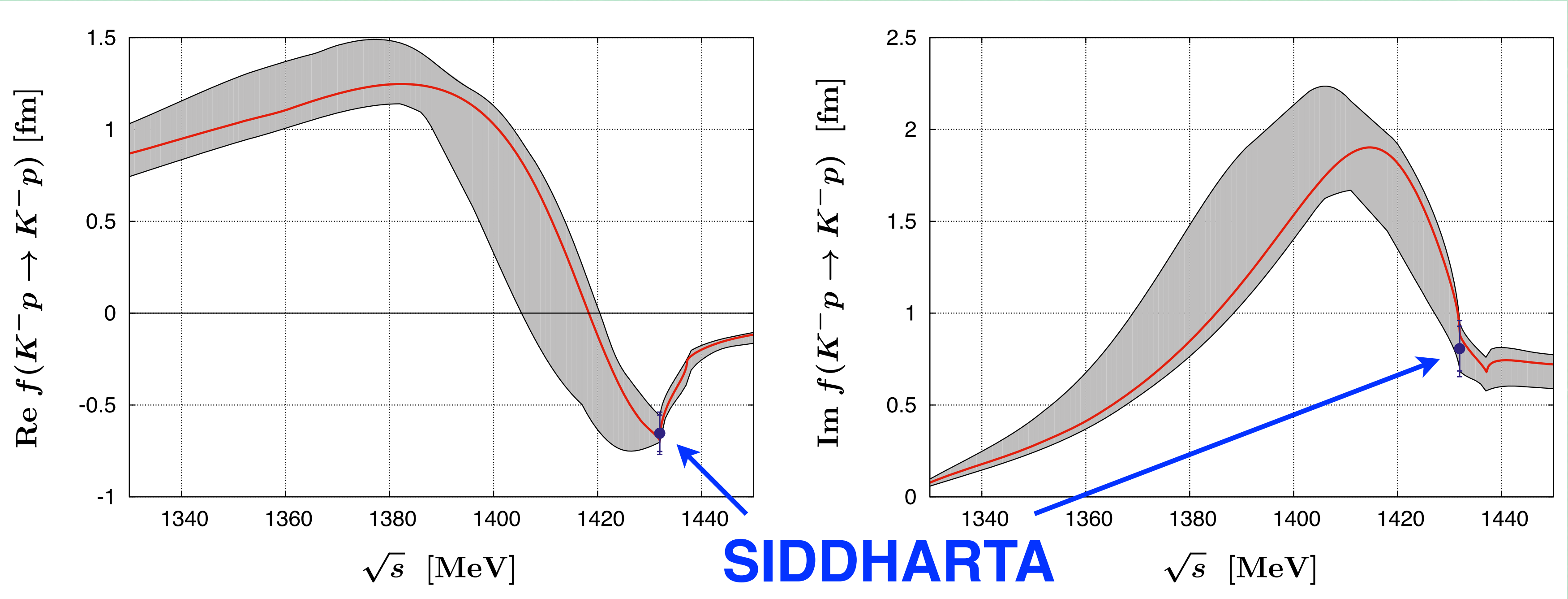
	TW	TWB	NLO
χ^2/d.o.f.	1.12	1.15	0.957



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

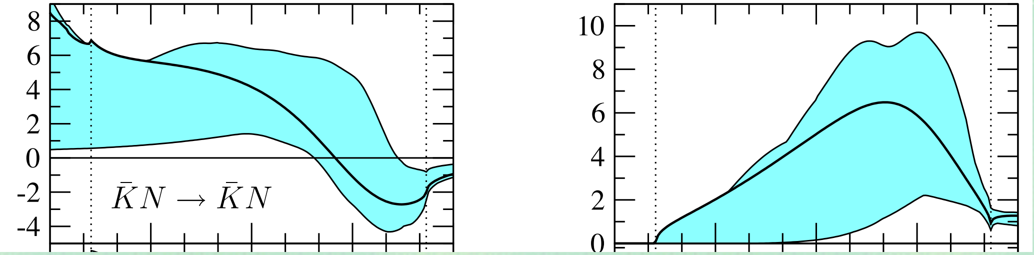
Subthreshold extrapolation

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)



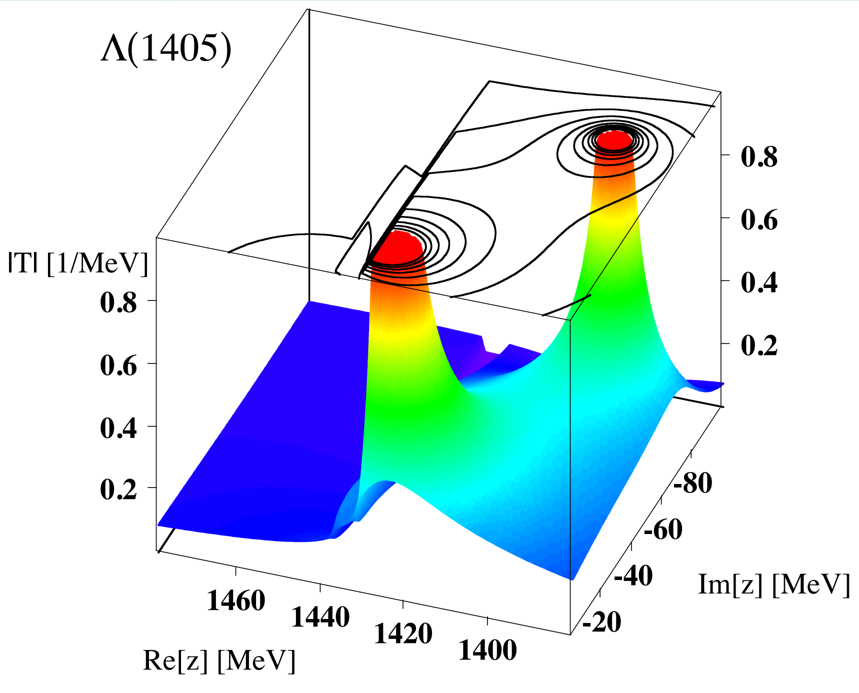
Subthreshold extrapolation is better controlled.

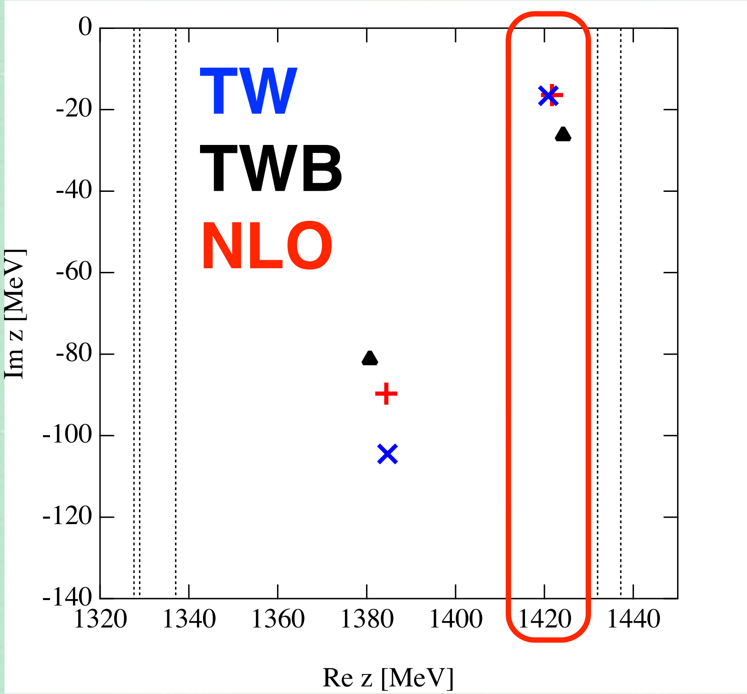
Extrapolation to complex energy: two poles

Two poles: superposition of two states

J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001);
D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, Nucl. Phys. A 723, 205 (2003);
T. Hyodo, W. Weise, Phys. Rev. C 77, 035204 (2008)

- Higher energy pole at 1420 MeV, not at 1405 MeV
- Attractions of WT in 1 and 8 ($\bar{K}N$ and $\pi\Sigma$) channels





NLO analysis confirms the two-pole structure.

Remaining ambiguity

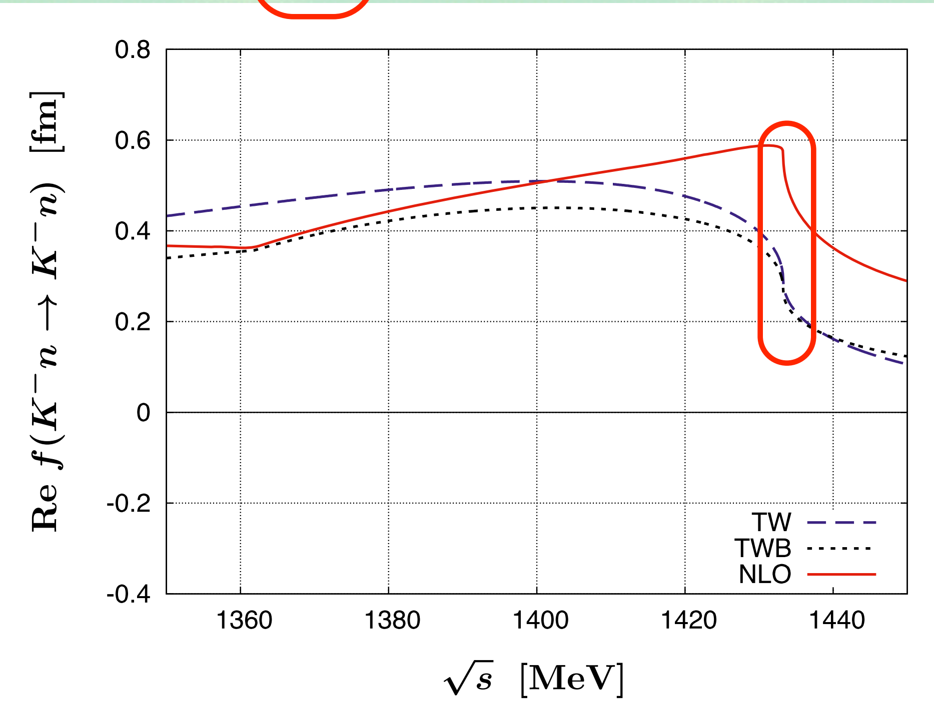
$\bar{K}N$ interaction has two isospin components (I=0, I=1).

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

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

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

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



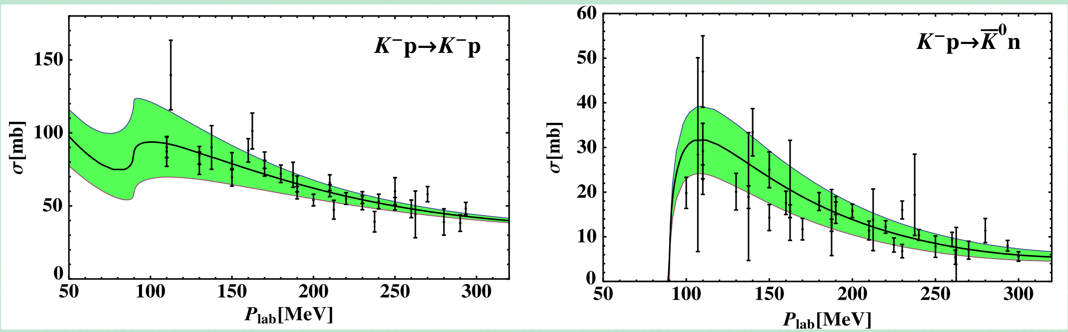
Some deviation: constraint on I=1 (<— kaonic deuterium?)

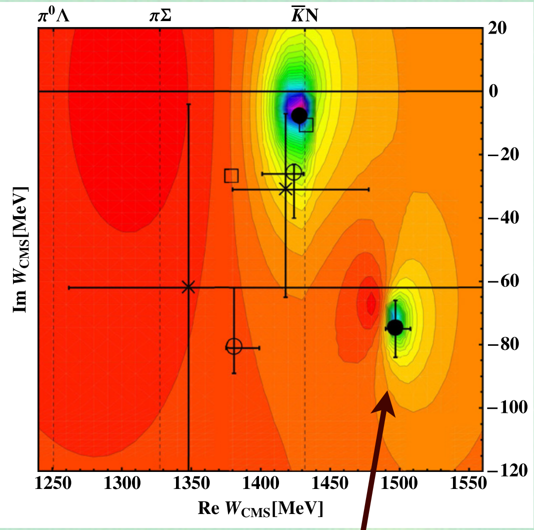
Analyses by other groups

Further studies with NLO + χ^2 analysis + SIDDHARTA data

- Bonn group

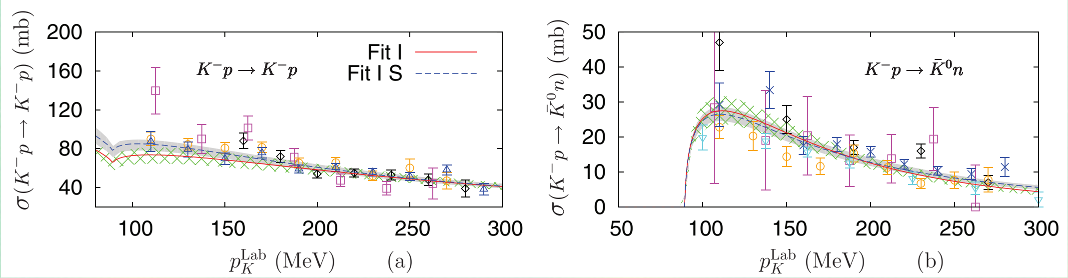
M. Mai, U.-G. Meissner, Nucl. Phys. A900, 51 (2013)





- Murcia group

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



~13 parameters —> several local minima

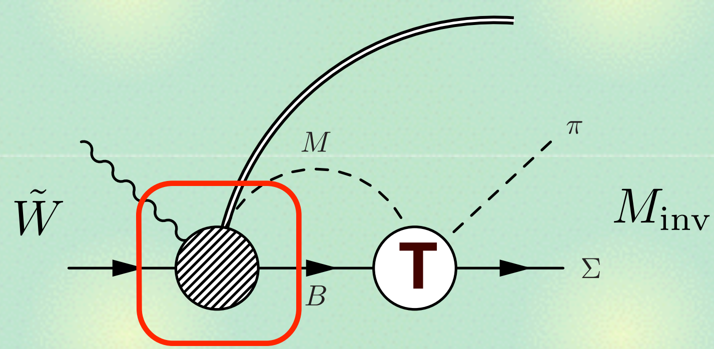
“exotic” solution by Bonn group (second pole above $\bar{K}N$)?

Constraints from the $\pi\Sigma$ spectrum

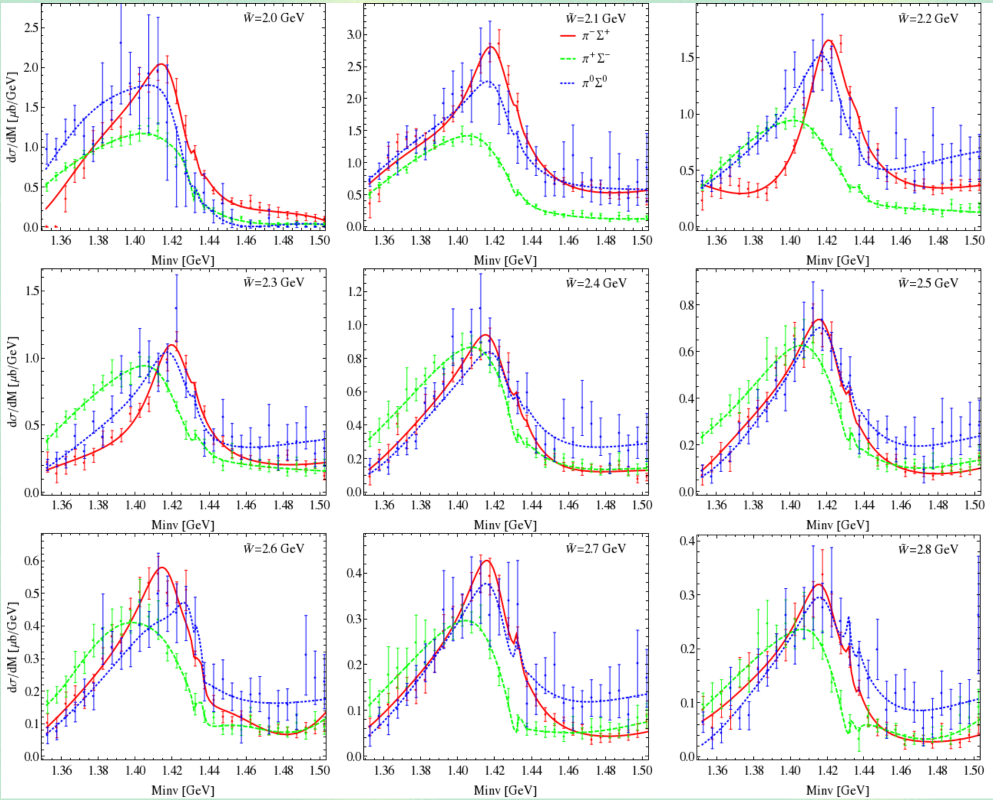
Combined analysis of scattering data + $\pi\Sigma$ spectrum

M. Mai, U.-G. Meissner, Eur. Phys. J. A 51, 30 (2015)

- 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] Guo-Oller, [15] Mai-Meissner

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	$1429^{+8}_{-7} - i\,12^{+2}_{-3}$	$1325^{+15}_{-15} - i\,90^{+12}_{-18}$

converge around 1420 **still some deviations**

c.f. comprehensive analysis of the CLAS data (at LO)

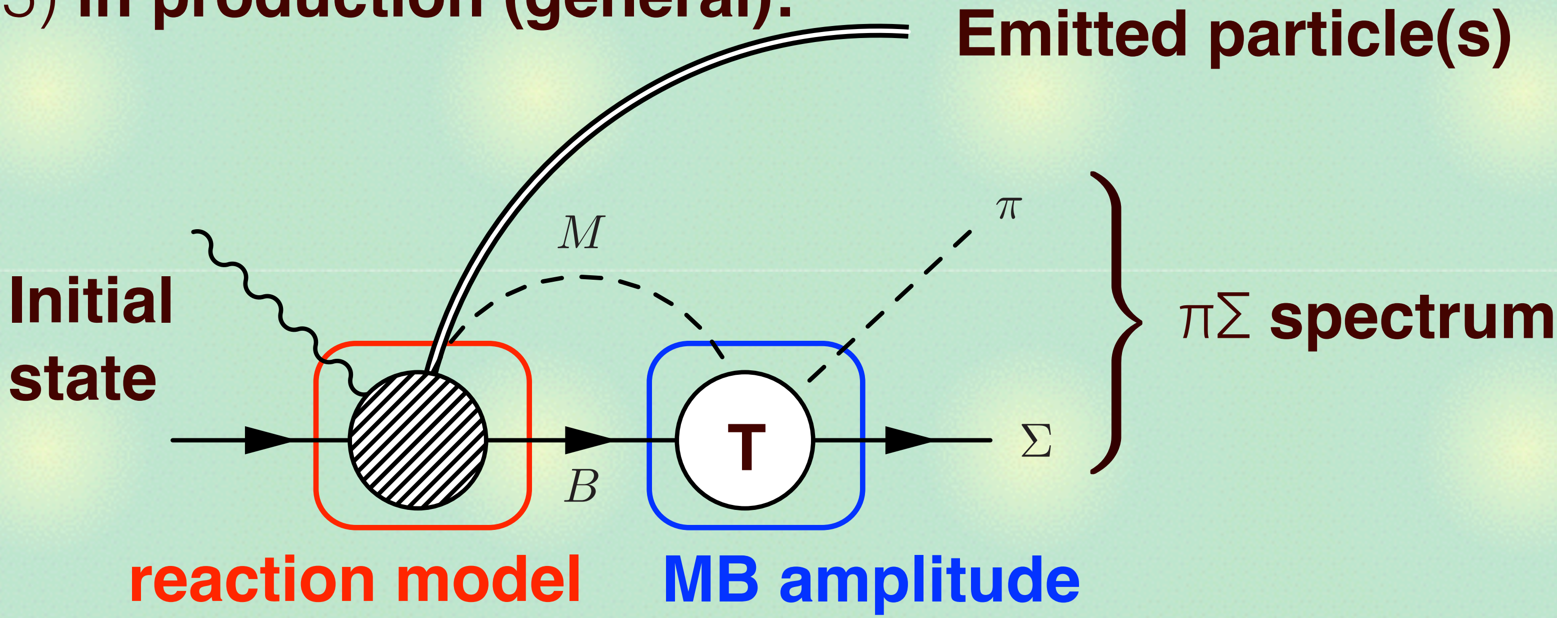
L. Roca, E. Oset, Phys. Rev. C 87, 055201 (2013); C 88, 055206 (2013)

πΣ spectra and $\bar{K}N$ interaction

Can πΣ spectra constrain the MB amplitude?

- Yes, but not directly.

Λ(1405) in production (general):



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

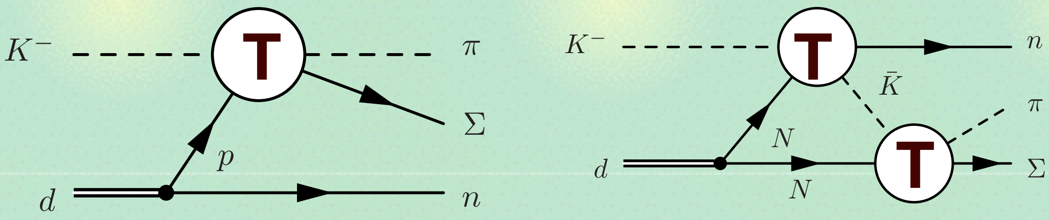
—> Detailed model analysis for each reaction

K-d reaction

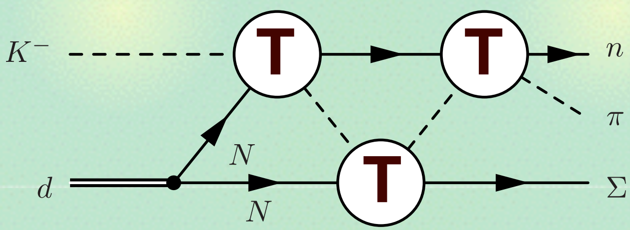
J-PARC E31 experiment: K-d -> n(πΣ)^0 @P_{K-} = 1 GeV

- two-step approaches

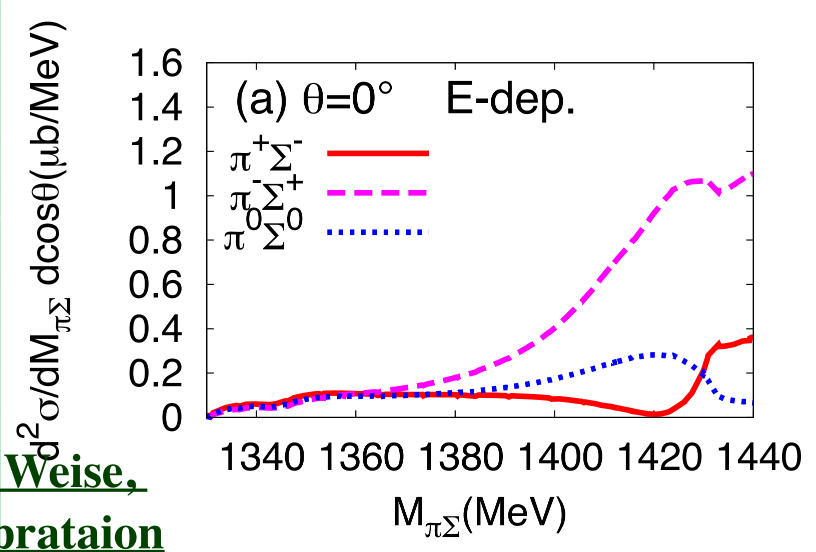
D. Jido, E. Oset, T. Sekihara, Eur. Phys. J. A42, 257 (2009); A47, 42 (2011);
K. Miyagawa, J. Haidenbauer, Phys. Rev. C85, 065201 (2012);
J. Yamagata-Sekihara, T. Sekihara, D. Jido, PTEP 043D02 (2013)



Full Faddeev(AGS) calculation with relativistic kinematics



+ infinitely many diagrams



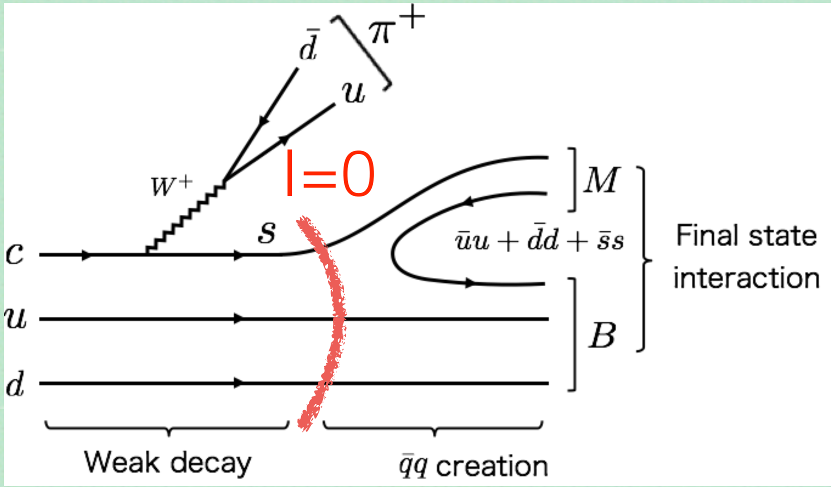
S. Ohnishi, Y. Ikeda, T. Hyodo, E. Hiyama, W. Weise,
J. Phys. Conf. Ser. 569, 012077 (2014) + in prepratiaon

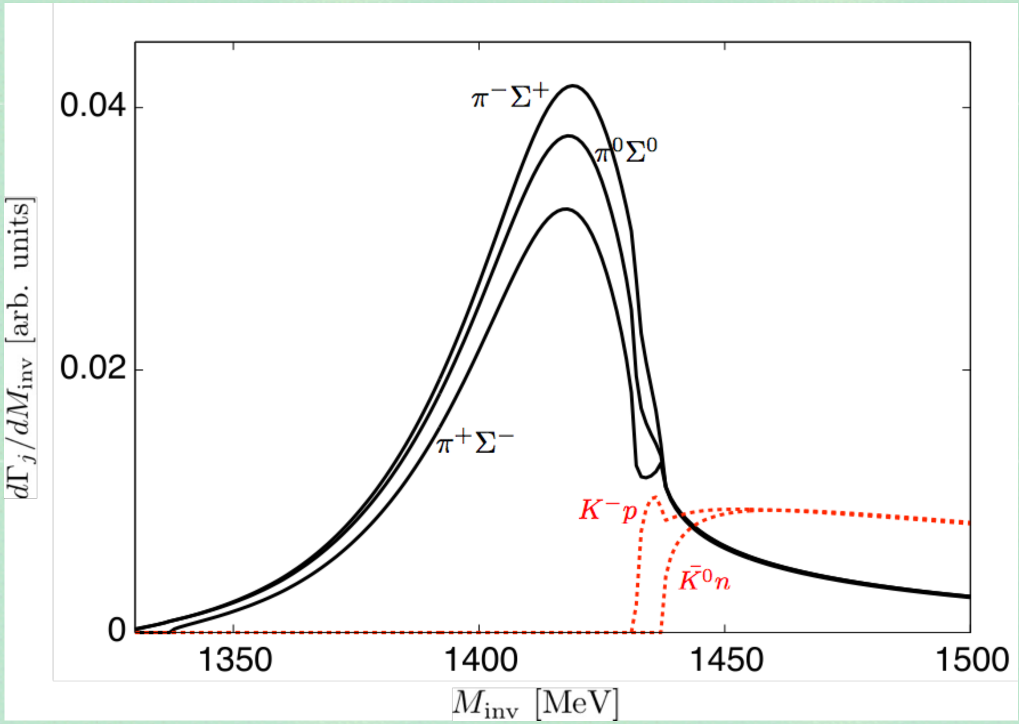
Λ_c decay

Weak decay of Λ_c —> π^+MB (MB=$\pi\Sigma$, $\bar{K}$N)

K. Miyahara, T. Hyodo, E. Oset, arXiv:1508.04882 [nucl-th]

- **final state interaction of MB generates Λ(1405)**
- **dominant process (CKM, N_c counting, diquark correlation) filters the MB pair in I=0.**





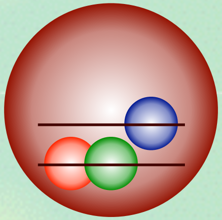
Clean Λ(1405) signal can be found in the charged πΣ modes.

$\bar{K}N$ molecule

Structure of Λ(1405): three-quark or meson-baryon?

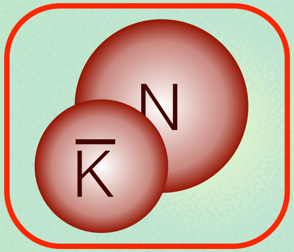
- constituent quark model: too light?

  N. Isgur, G. Karl, Phys. Rev. D 18, 4187 (1978)



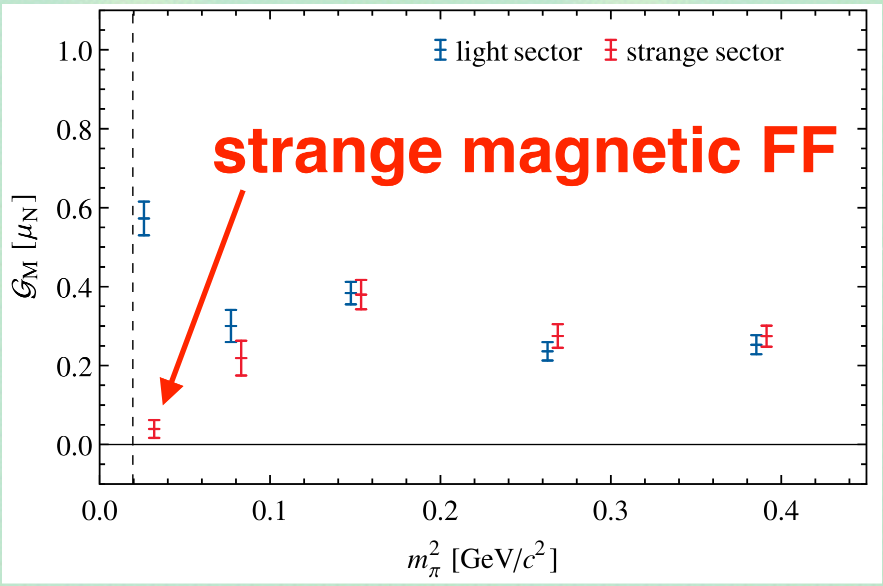
- vector meson exchange: well reproduce

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

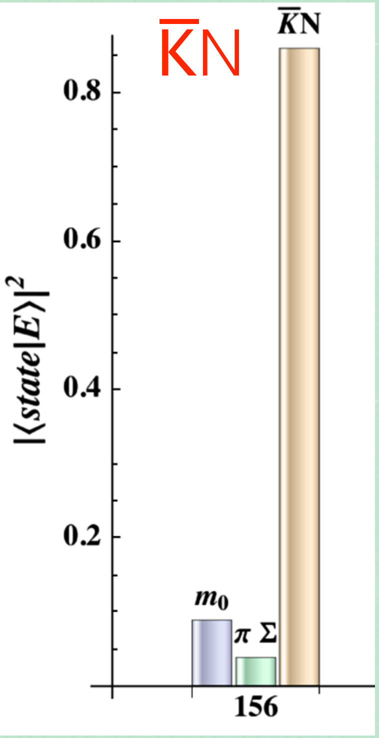


Recent lattice QCD study

J. Hall, *et al.*, Phys. Rev. Lett. 114, 132002 (2015)



overlaps in Hamiltonian model



$\bar{K}N$ potential

Local $\bar{K}N$ potential —> wave function

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

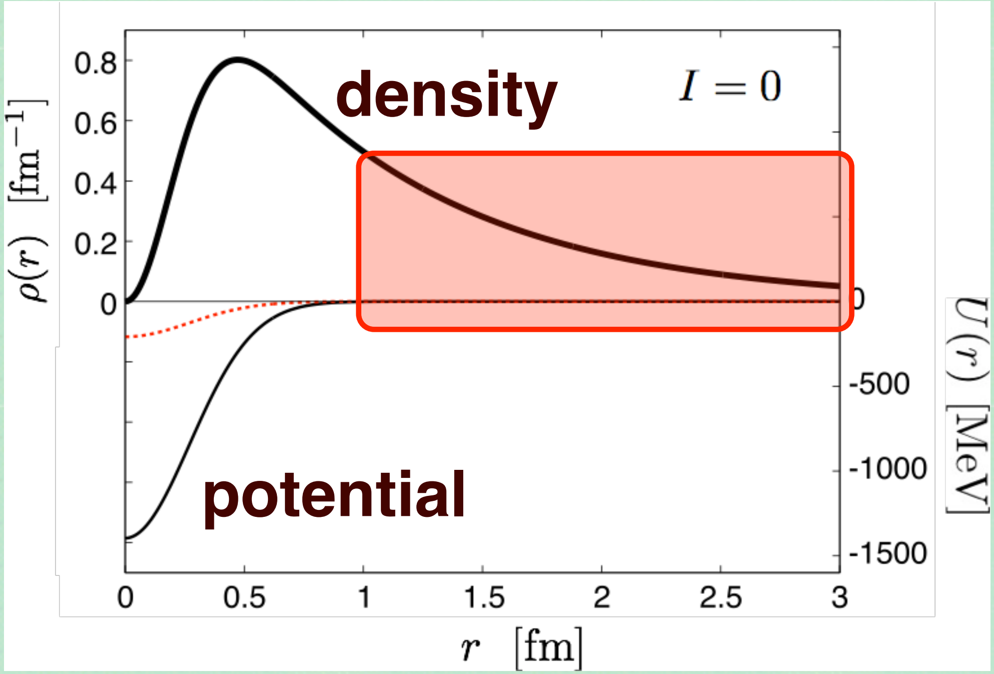
- Equivalent amplitude on the real axis
- Single-channel, complex, energy-dependent

Realistic $\bar{K}N$ potential for NLO with SIDDHARTA (χ^2/dof ~ 1)

K. Miyahara, T. Hyodo, arXiv:1506.05724 [nucl-th]

- Substantial distribution at r > 1 fm
- root mean squared radius

$$\sqrt{\langle r^2 \rangle} = 1.44 \text{ fm}$$



The size of Λ(1405) is much larger than ordinary hadrons.

Compositeness

Model-independent relation of compositeness X <— (B, a_0)

S. Weinberg, Phys. Rev. 137, B672 (1965); V. Baru, *et al.*, Phys. Lett. B 586, 53 (2004)

- Generalization to quasi-bound states

Talk by Kamiya 2B2

Y. Kamiya, T. Hyodo, arXiv:1509.00146 [hep-ph]

$$a_0 = R\left\{\frac{2X}{1+X} + \mathcal{O}\left(\left|\frac{R_{\rm typ}}{R}\right|\right) + \sqrt{\frac{\mu'^3}{\mu^3}}\mathcal{O}\left(\left|\frac{l}{R}\right|^3\right)\right\}, \quad R = 1/\sqrt{2\mu E_{QB}}$$

- NLO Analyses of Λ(1405) with SIDDHARTA (χ^2/d.o.f. ~ 1)

Ref.	E_{QB} (MeV)	a_0 (fm)	$X_{\bar{K}N}$	$\tilde{X}_{\bar{K}N}$	U	$\lvert r_e/a_0\rvert$
[43]	$-10-i26$	$1.39-i0.85$	$1.2+i0.1$	1.0	0.5	0.2
[44]	$-4-i8$	$1.81-i0.92$	$0.6+i0.1$	0.6	0.0	0.7
[45]	$-13-i20$	$1.30-i0.85$	$0.9-i0.2$	0.9	0.1	0.2
[46]	$2-i10$	$1.21-i1.47$	$0.6+i0.0$	0.6	0.0	0.7
[46]	$-3-i12$	$1.52-i1.85$	$1.0+i0.5$	0.8	0.6	0.4

[43] Ikeda-Hyodo-Weise, [44,46] Mai-Meissner, [45] Guo-Oller

Λ(1405) is a $\bar{K}N$ molecule. <— observable quantities

Summary: Λ(1405)

- **The** Λ(1405) **in** K̄N **scattering is well understood by NLO chiral coupled-channel approach with accurate** K-p **scattering length.**
- **Reliable reaction model will be important to analyze precise** πΣ **mass spectra.**
- **Various analyses (lattice, realistic potential, compositeness relation) consistently indicate that the** Λ(1405) **is a** K̄N **molecule.**