Current status of $\Lambda(1405)$ and its structure

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2015, Oct. 26th

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    Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)
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    Y. Kamiya, T. Hyodo, arXiv:1509.00146 [hep-ph]

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

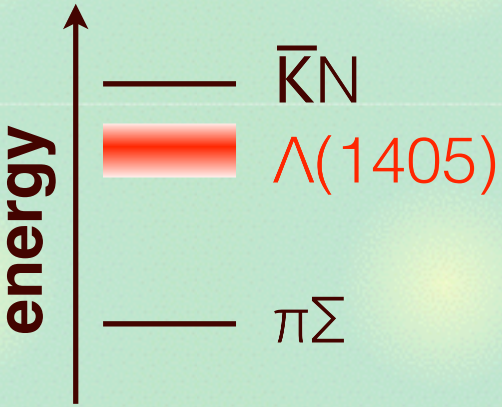
Two aspects of $K(\bar{K})$ meson

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

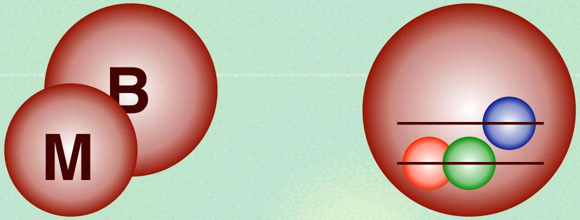
—> **spontaneous**/**explicit** symmetry breaking

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

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



- is coupled with πΣ channel
- generates Λ(1405) below threshold



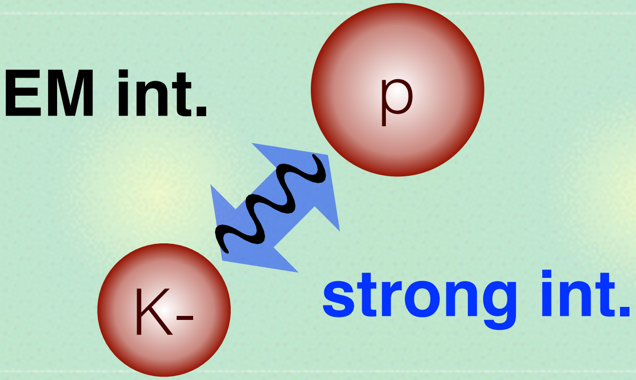
molecule three-quark

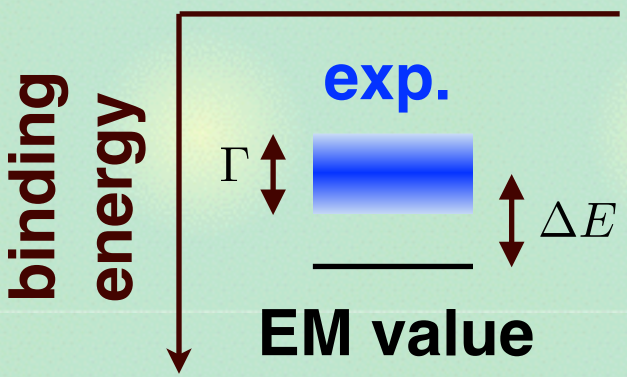
- is fundamental building block for $\bar{K}$-nuclei, $\bar{K}$ in medium, ...

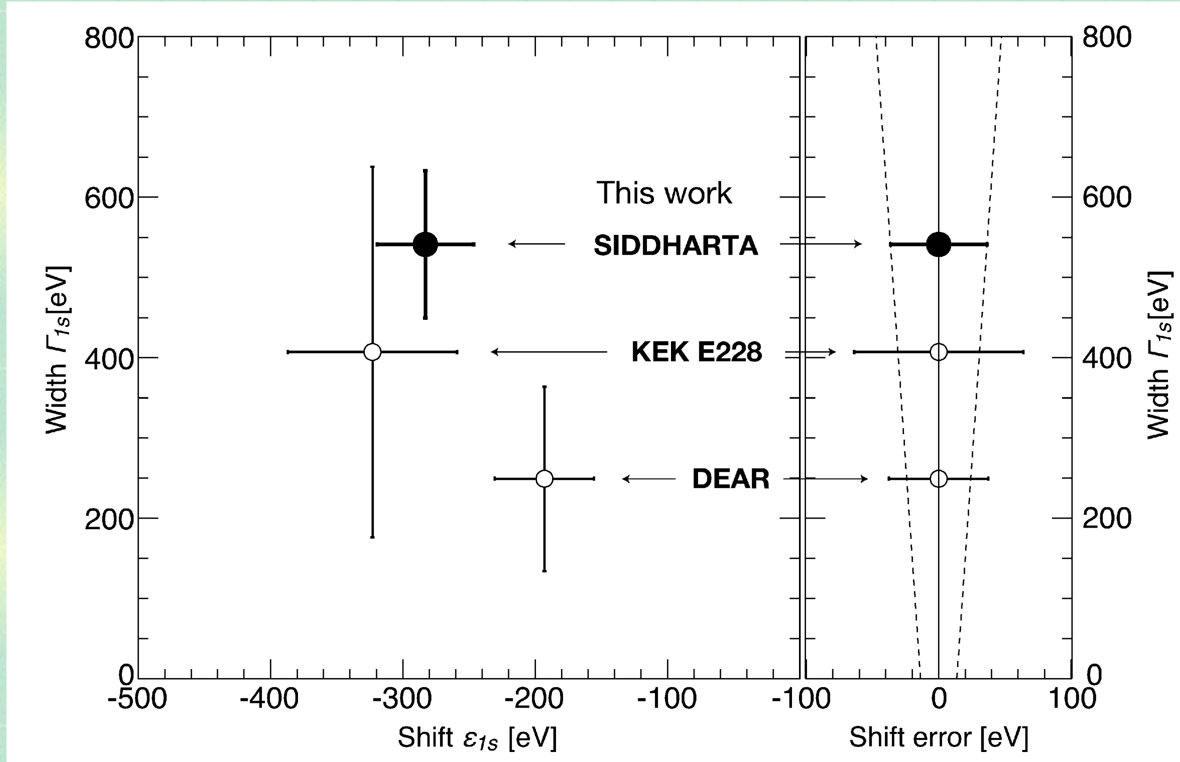
SIDDHARTA measurement

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

πΣ invarint mass spectra

πΣ spectrum before 2008: single mode, no absolute values

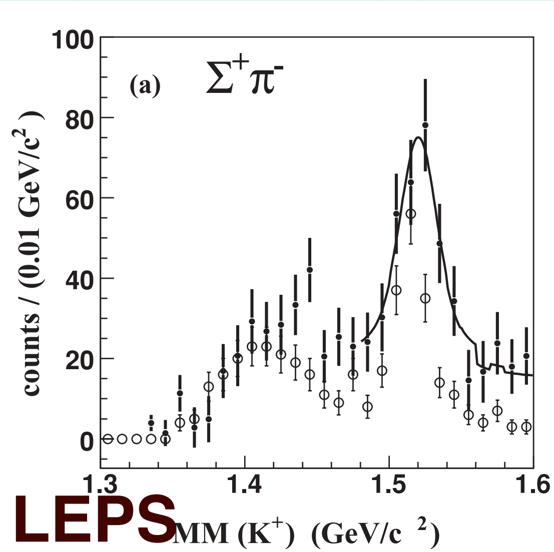
R.J. Hemingway, Nucl. Phys. B253, 742 (1985)

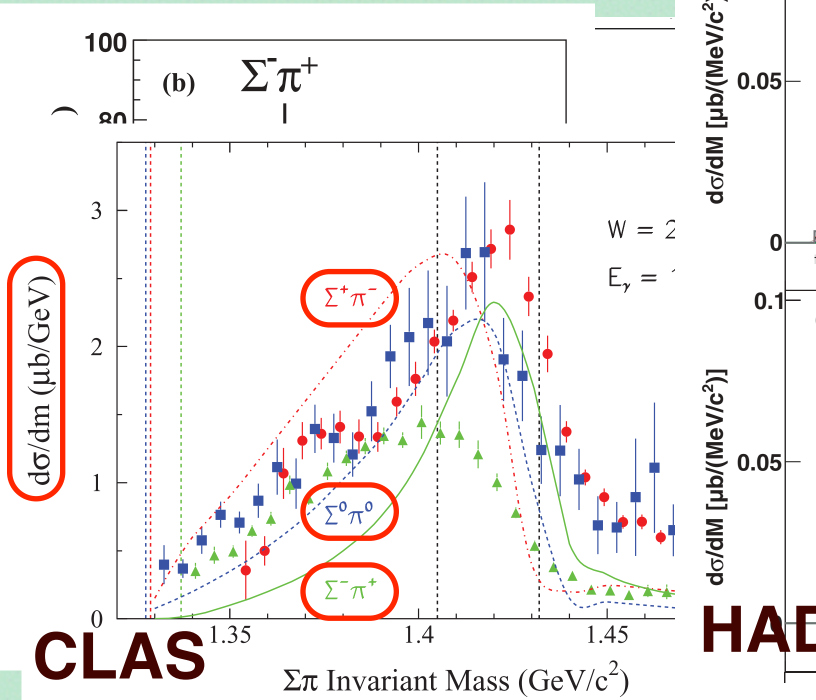
After 2008: γp -> $K^+(\pi\Sigma)^0$ LEPS, CLAS, pp -> $K^+p(\pi\Sigma)^0$ HADES

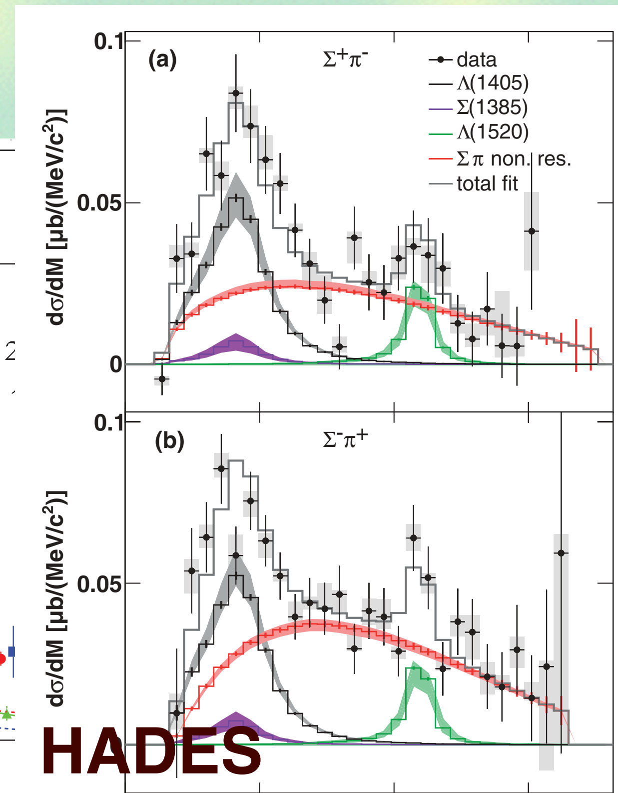
M. Niiyama, *et al.*, Phys. Rev. C78, 035202 (2008);

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.

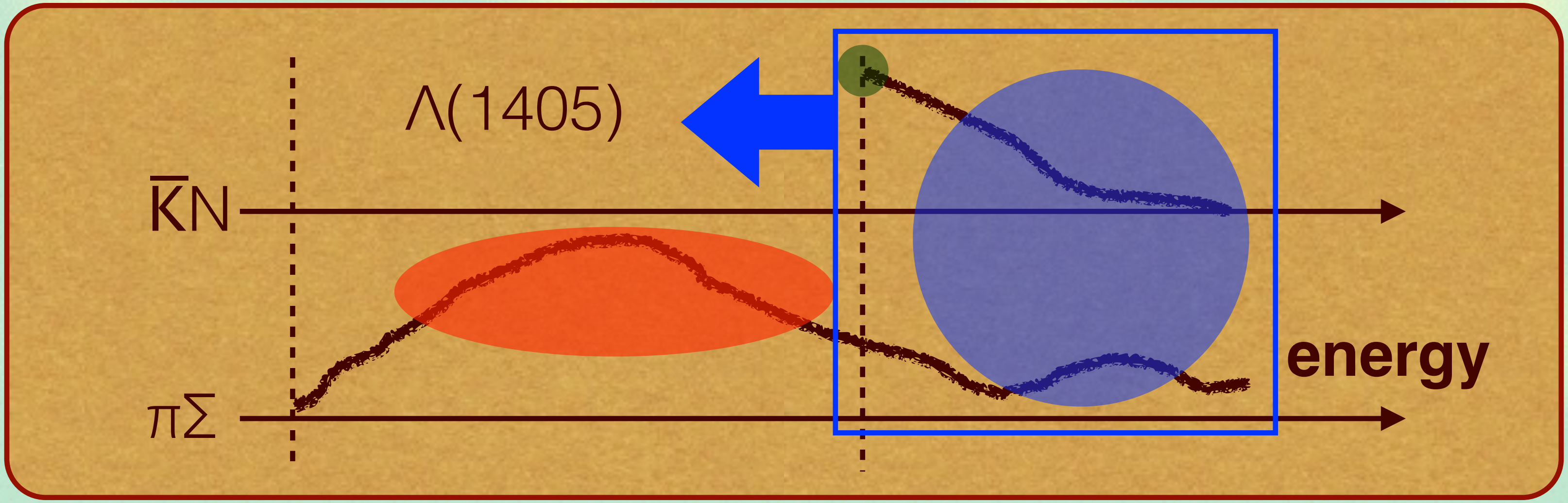
Strategy for $\bar{K}N$ interaction

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

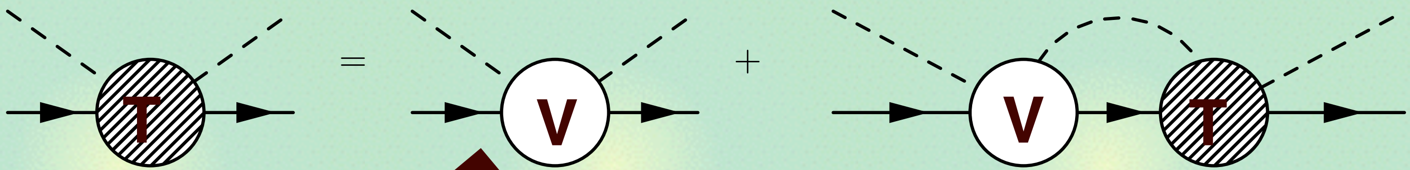
- πΣ **mass spectra** **(new data: LEPS, CLAS, HADES,…)**



Construction of the realistic amplitude

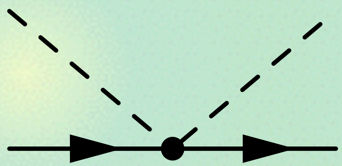
Chiral coupled-channel approach with systematic χ^2 fitting

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



Chiral perturbation theory

1) TW term

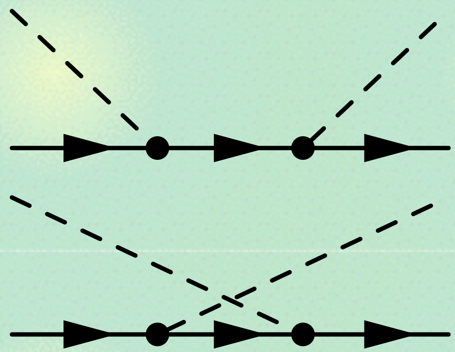


$\mathcal{O}(p)$

6 cutoffs

TW model

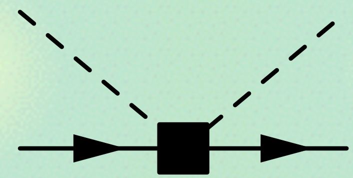
2) Born terms



$\mathcal{O}(p)$

TWB model

3) NLO terms



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

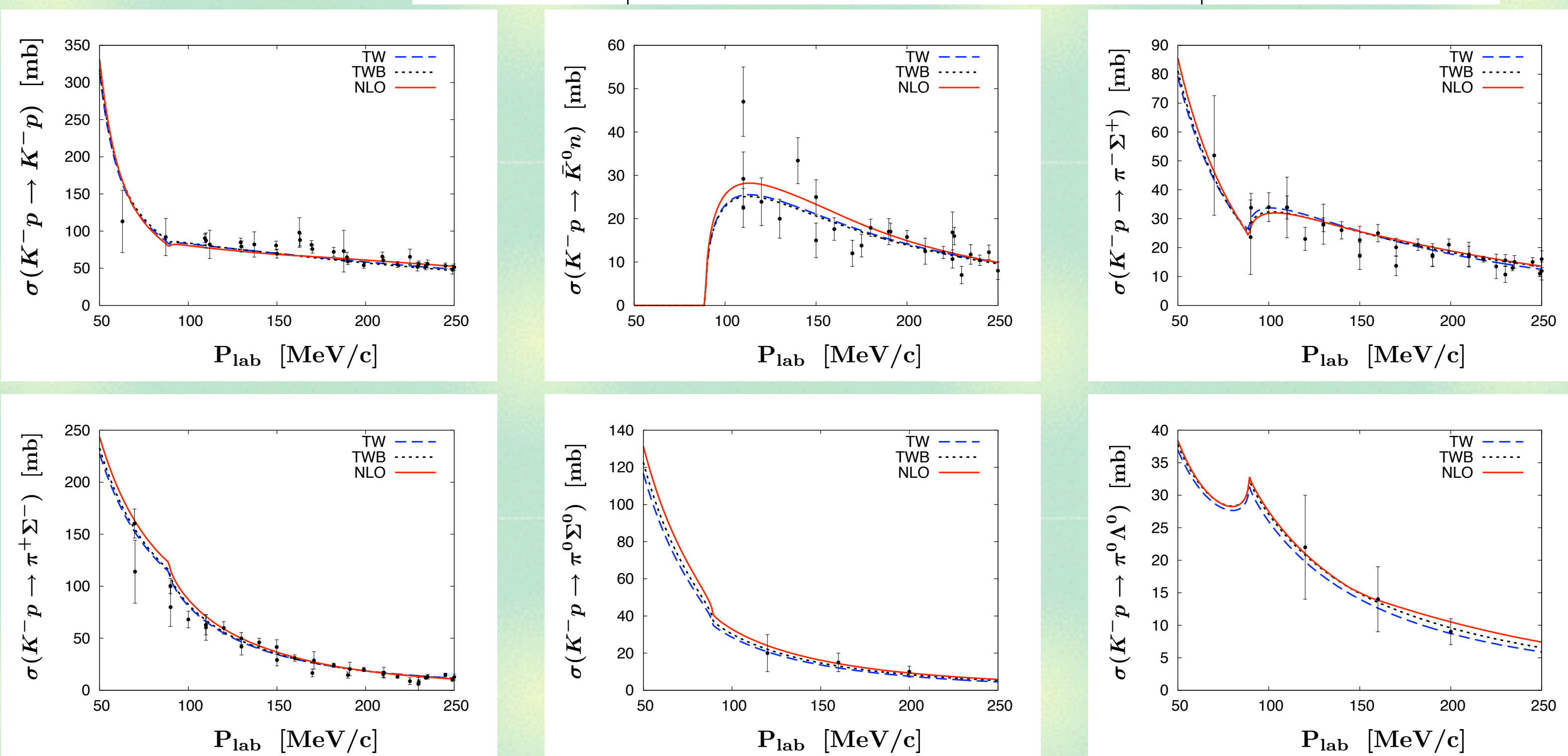
7 LECs

NLO model

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		

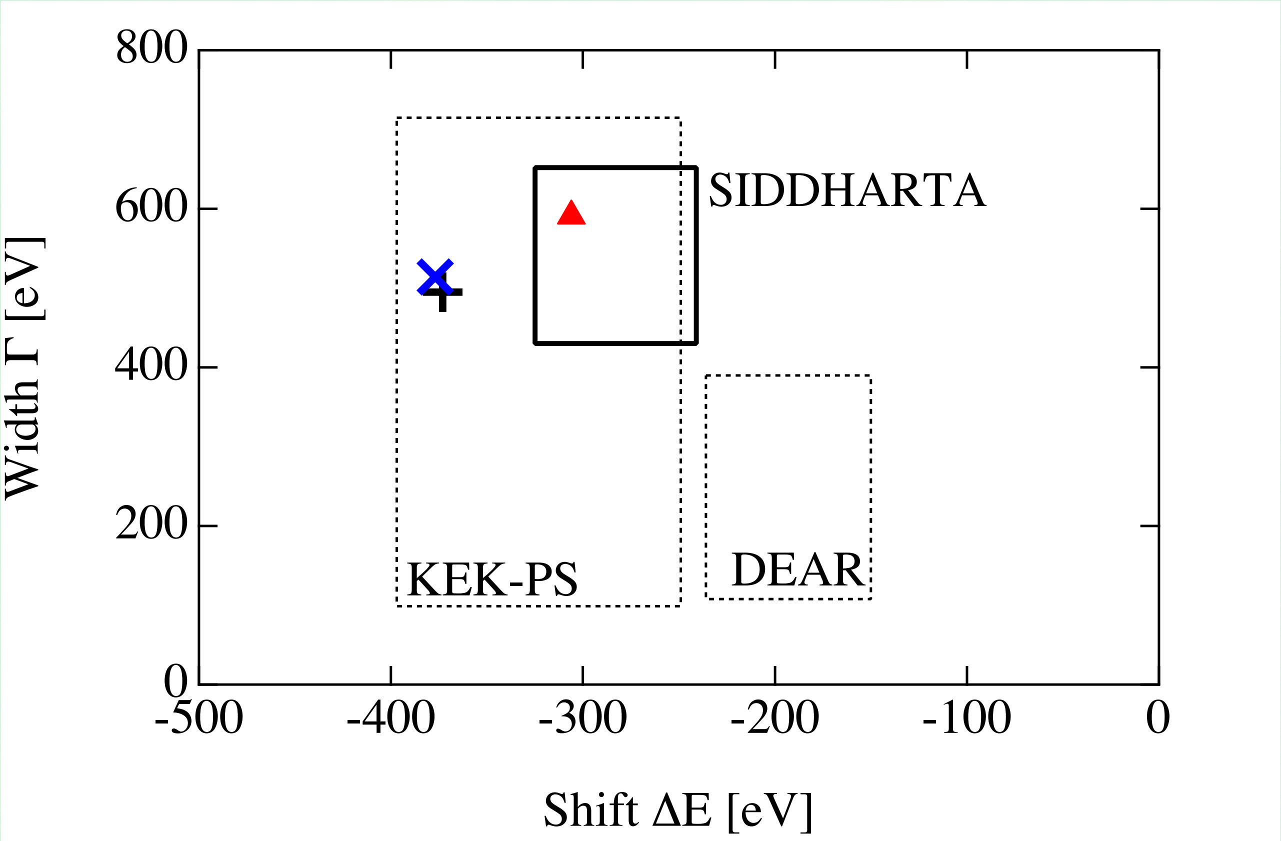
cross sections



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

Comparison with SIDDHARTA

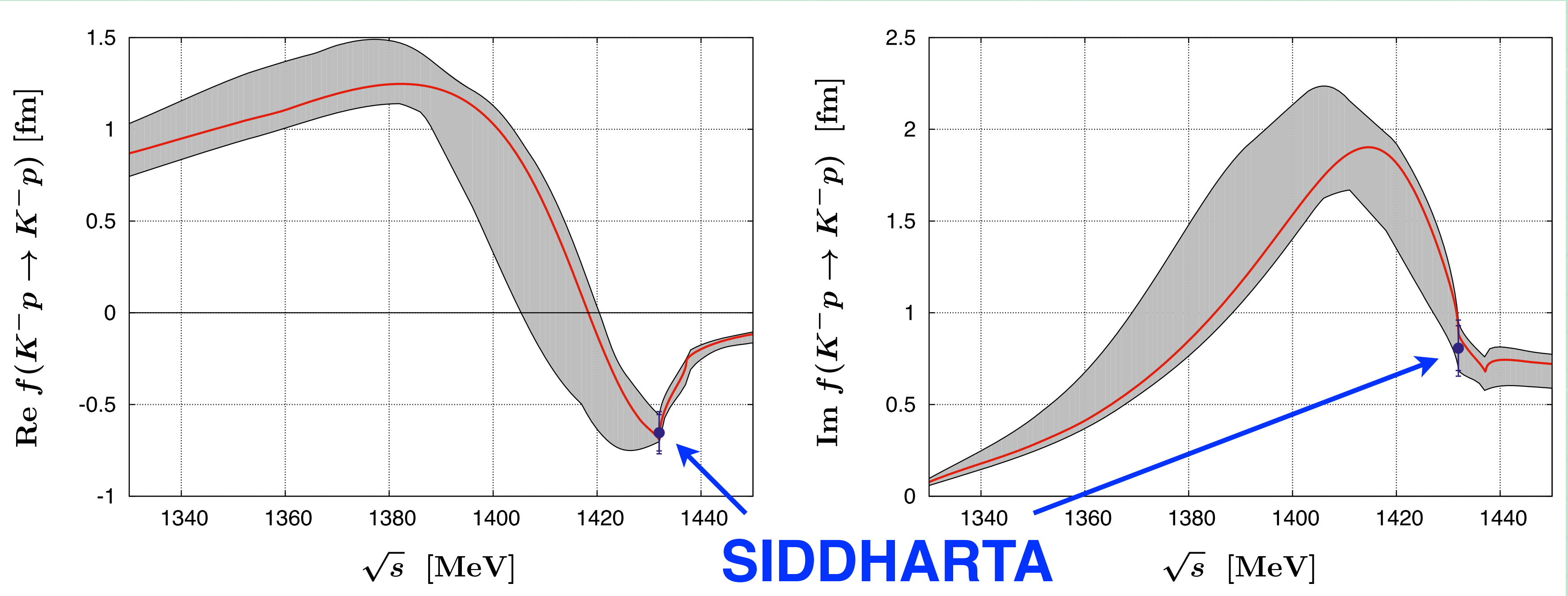
	TW	TWB	NLO
χ^2/d.o.f.	1.12	1.15	0.957



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

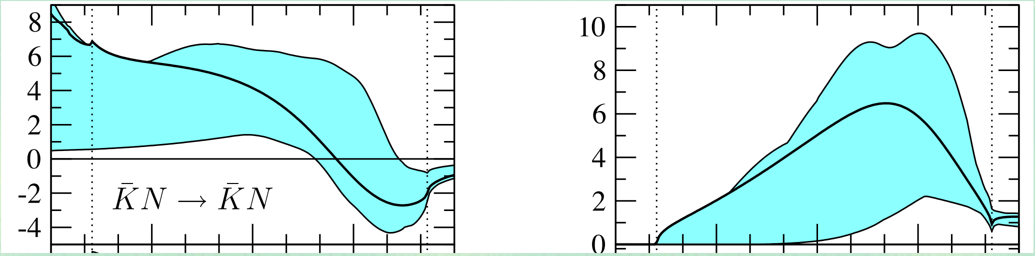
Subthreshold extrapolation

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)



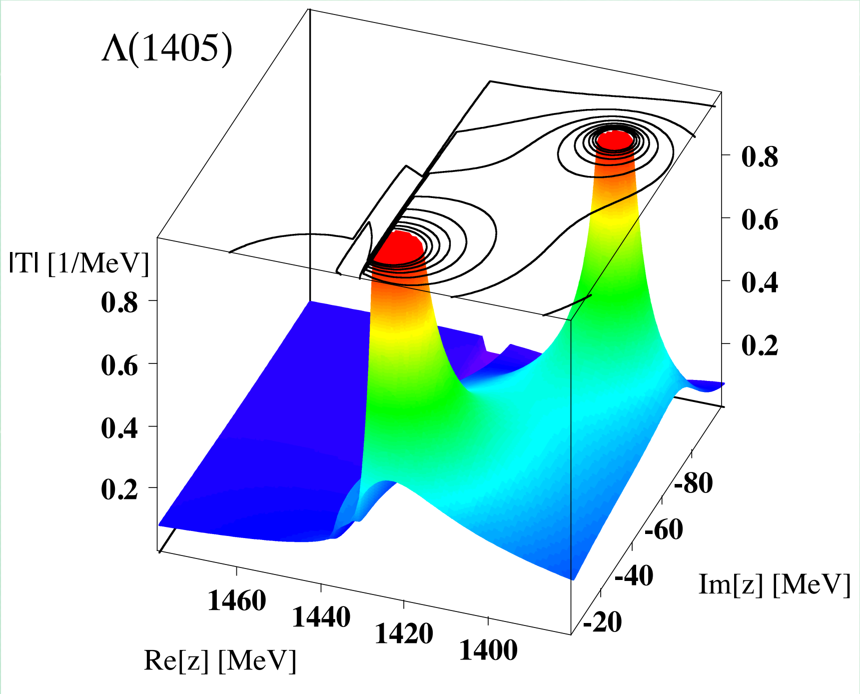
Subthreshold extrapolation is better controlled.

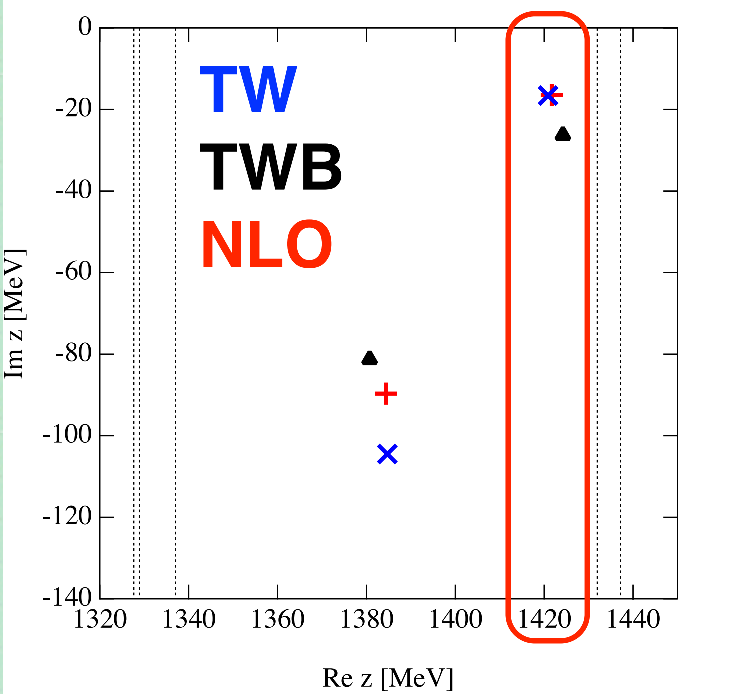
Extrapolation to complex energy: two poles

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 TW in 1 and 8 ($\bar{K}N$ and $\pi\Sigma$) channels





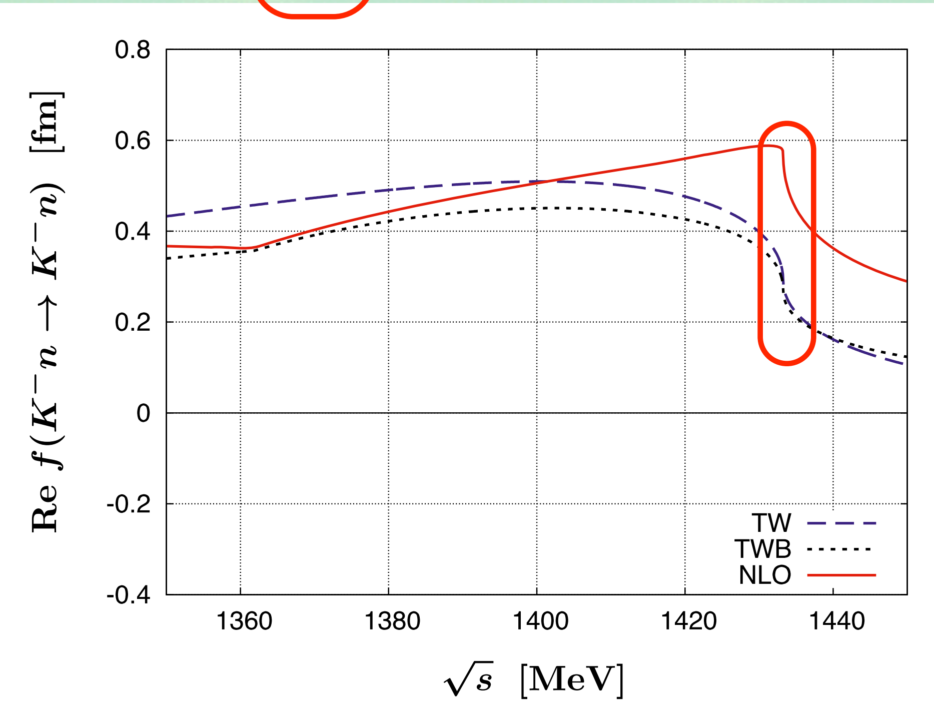
NLO analysis confirms the two-pole structure.

Remaining ambiguity

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

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

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



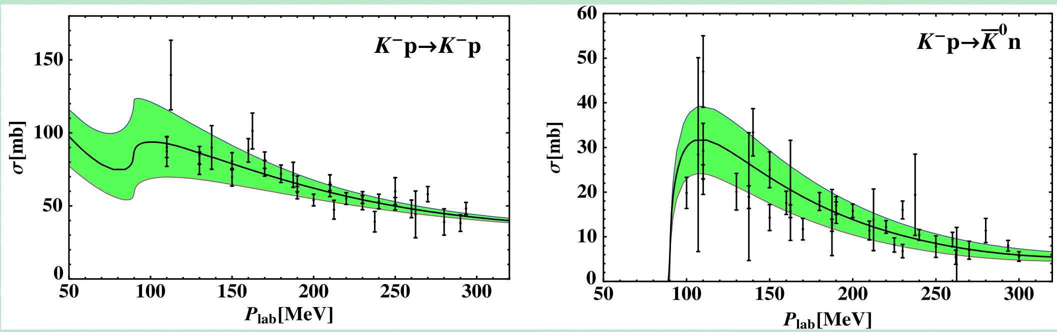
Some deviation: constraint on I=1 (<— kaonic deuterium)

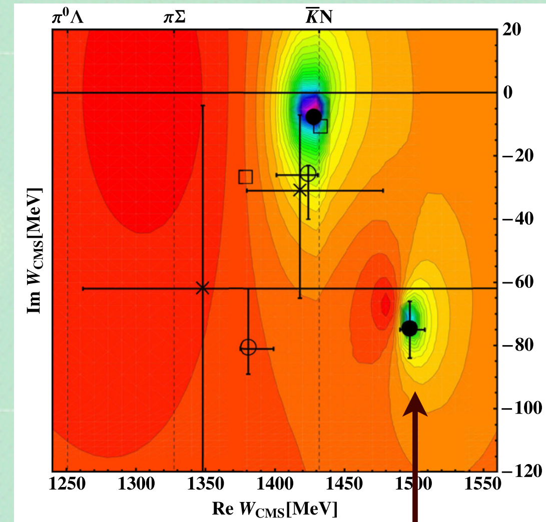
Analyses by other groups

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

- Bonn group

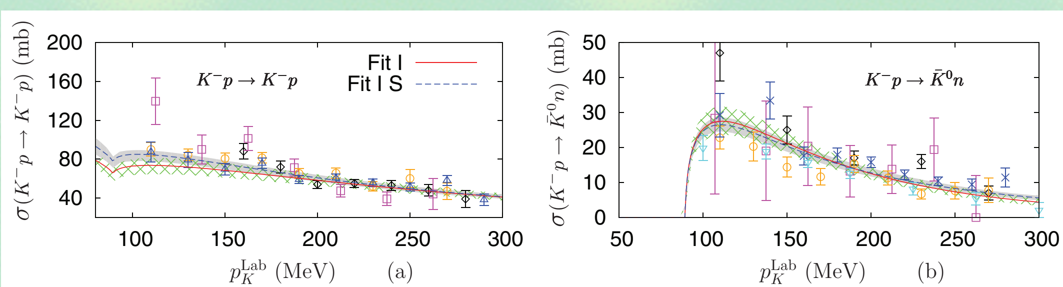
M. Mai, U.-G. Meissner, Nucl. Phys. A900, 51 (2013)





- Murcia group

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



large number of parameters —> several local minima

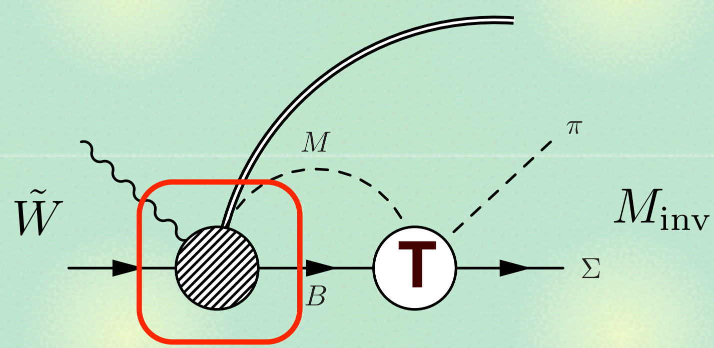
"exotic" solution by Bonn group (second pole above $\bar{K}N$)?

Constraints from the πΣ spectrum

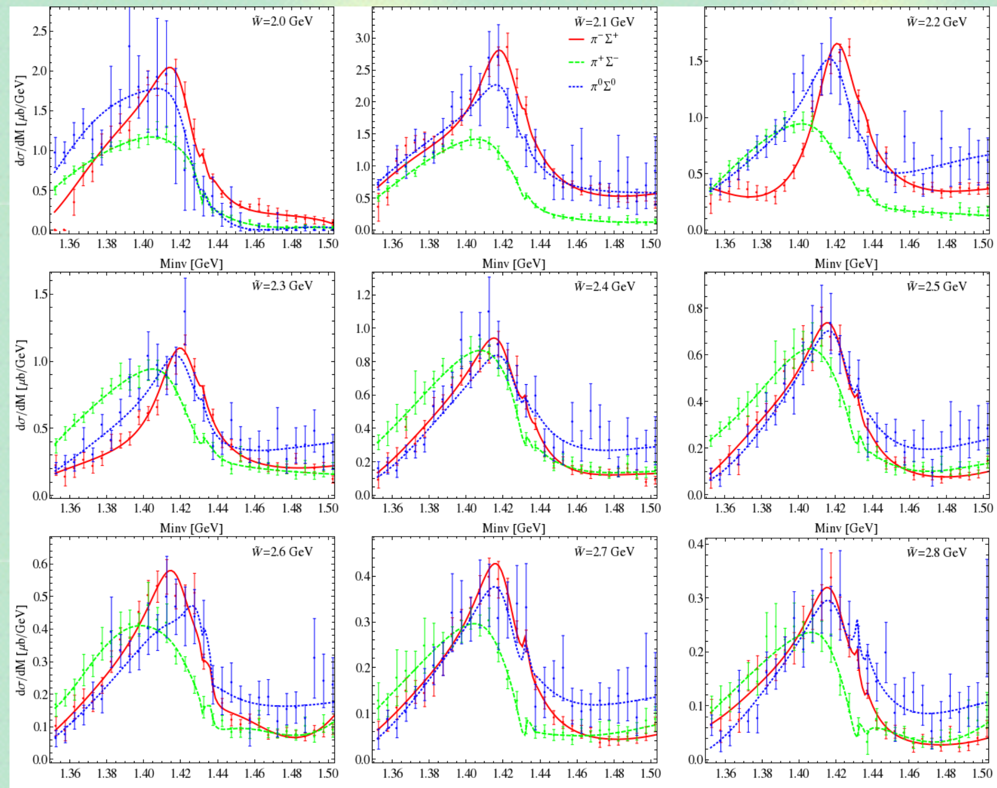
Combined analysis of scattering data + πΣ spectrum

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 πΣ 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 $\Lambda(1405)$

Mini-review prepared for PDG

Pole structure of the $\Lambda(1405)$

Ulf-G. Meißner, Tetsuo Hyodo

February 4, 2015

The $\Lambda(1405)$ 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)

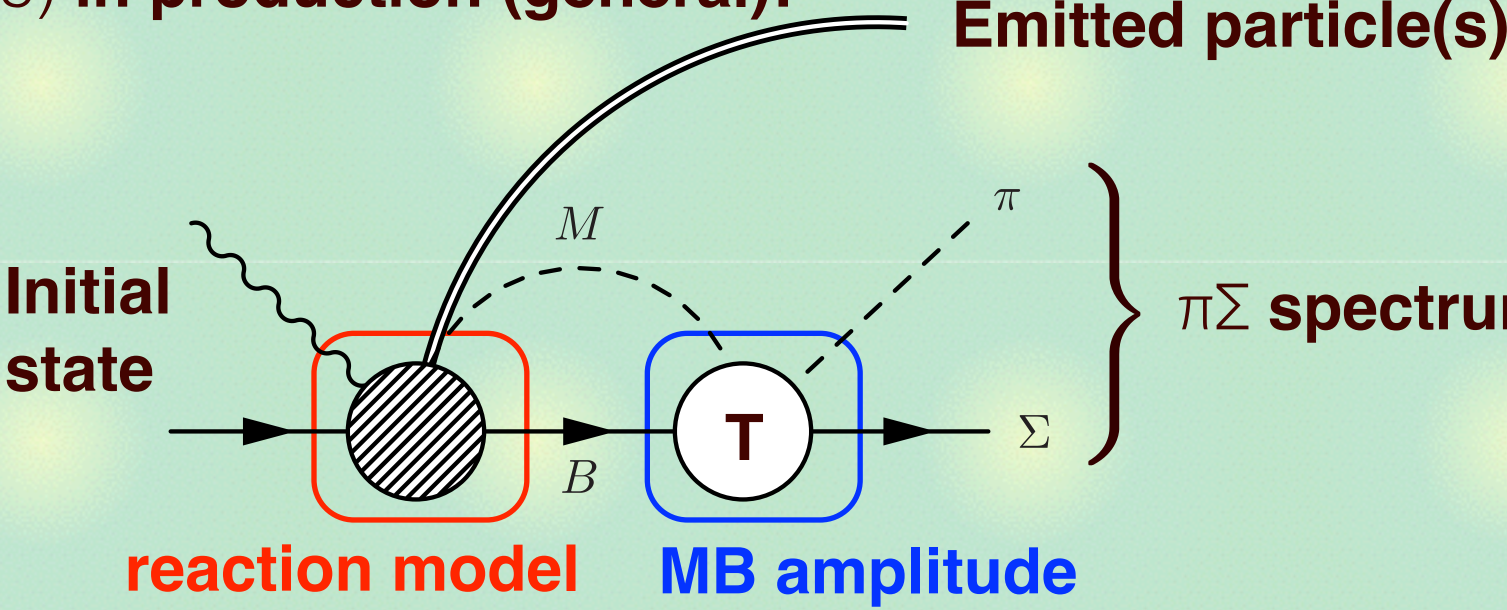
L. Roca, E. Oset, Phys. Rev. C 87, 055201 (2013); C 88, 055206 (2013)

πΣ spectra and $\bar{K}N$ interaction

Can πΣ spectra constrain the MB amplitude?

- Yes, but not directly.

Λ(1405) in production (general):

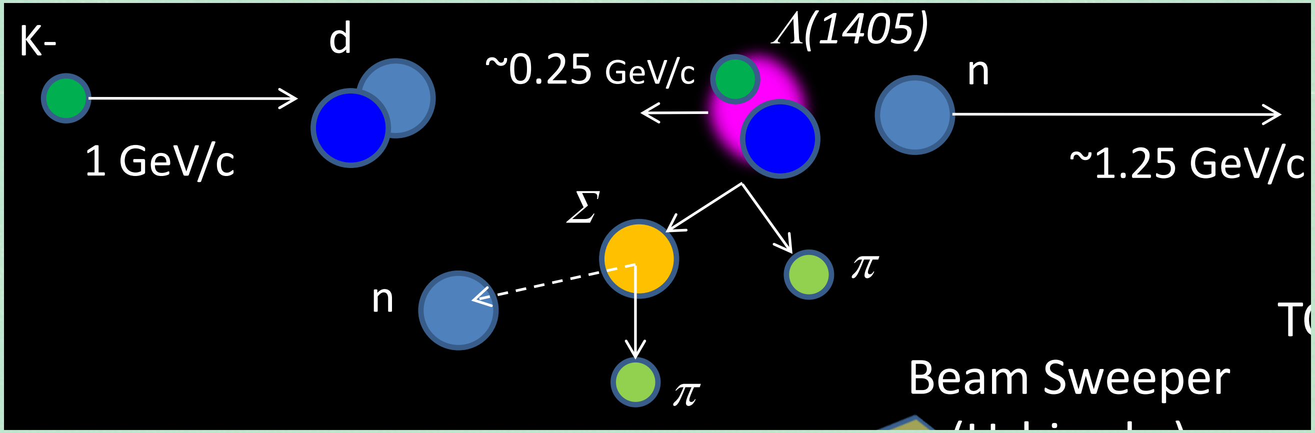


- **πΣ spectra depend on the reaction (ratio of $\bar{K}N$/πΣ in the intermediate state, interference with I=1,...).**

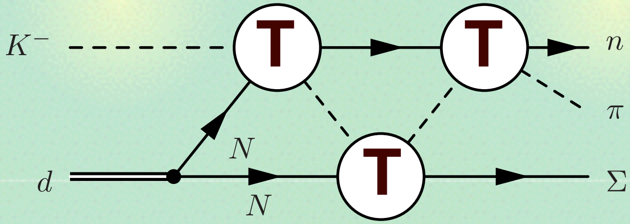
—> Detailed model analysis for each reaction

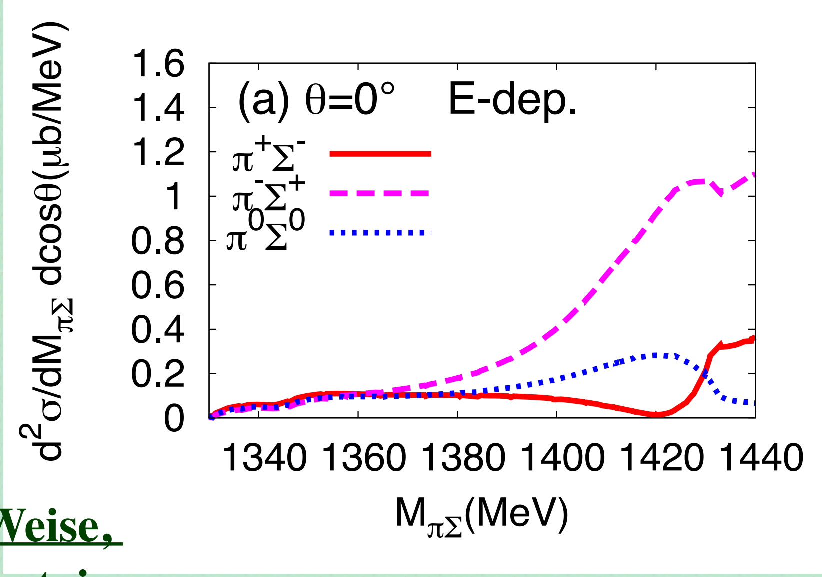
K-d **reaction**

J-PARC E31 experiment: K-d -> n$(\pi\Sigma)^0$ @P_{K-} = 1 **GeV**



Full Faddeev(AGS) calculation for initial state process





+ infinitely many diagrams

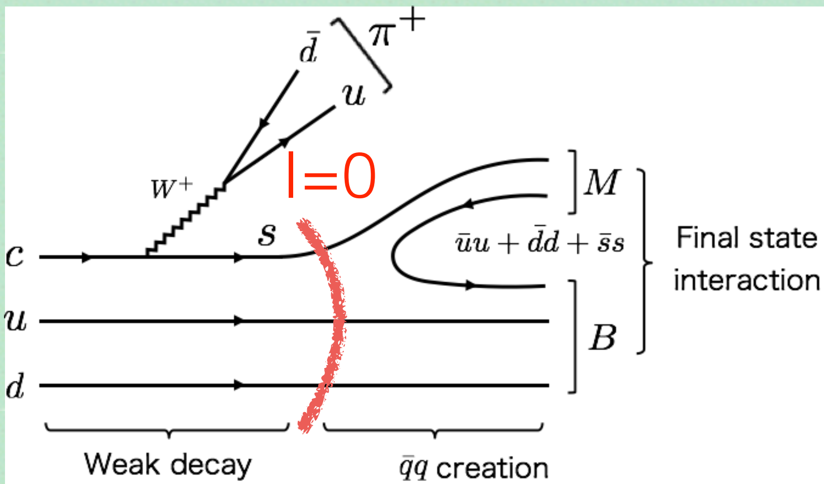
S. Ohnishi, Y. Ikeda, T. Hyodo, E. Hiyama, W. Weise,
J. Phys. Conf. Ser. 569, 012077 (2014) + in preprataion

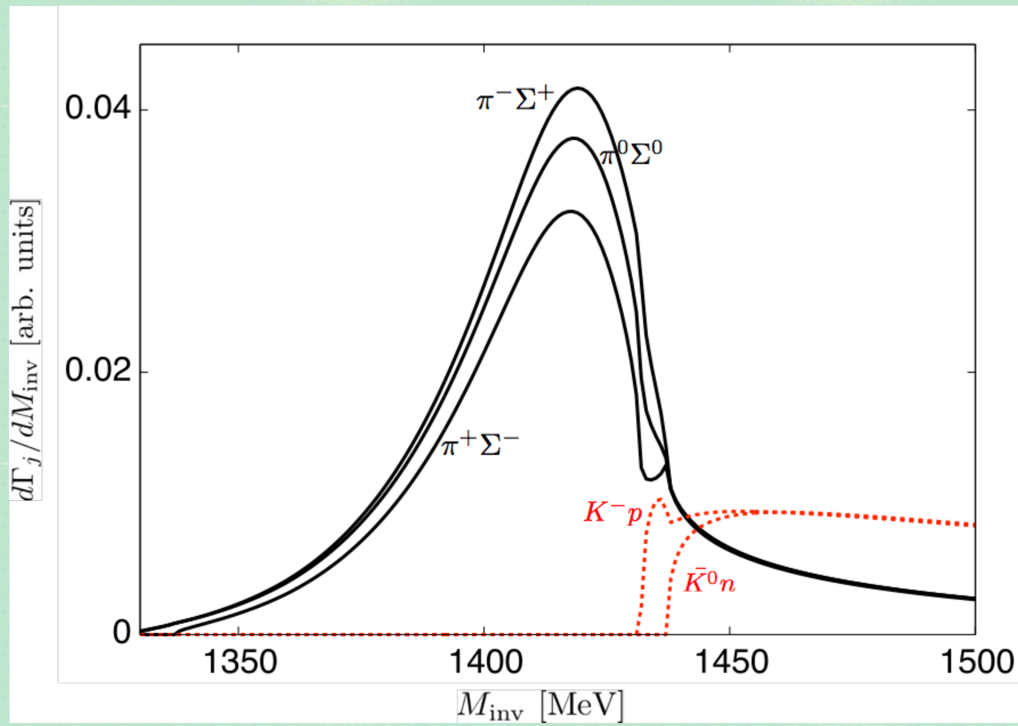
Λ_c weak decay

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

K. Miyahara, T. Hyodo, E. Oset, arXiv:1508.04882 [nucl-th], to appear in Phys. Rev. C

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

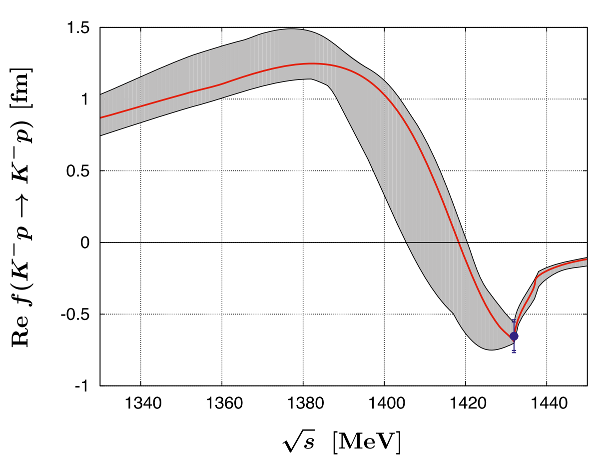


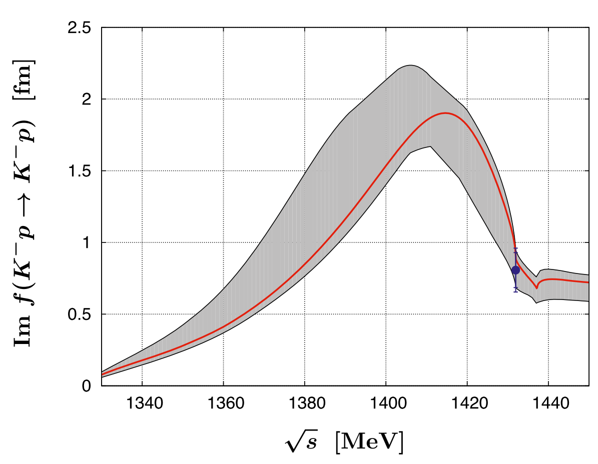


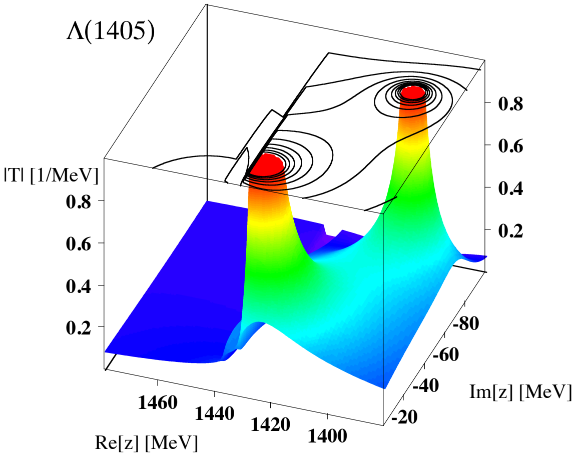
Clean Λ(1405) signal can be found in the charged $\pi\Sigma$ modes.

Summary: Λ(1405) and $\bar{K}N$ interaction

- **The Λ(1405) in $\bar{K}N$ scattering is well understood by NLO chiral coupled-channel approach with accurate K^-p scattering length.**
- **Two poles are associated with the Λ(1405).**
- **Reliable reaction model will be important to analyze precise πΣ mass spectra.**





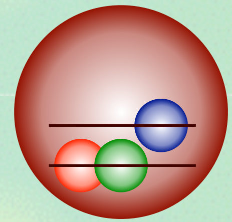


$\bar{K}$N molecule?

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

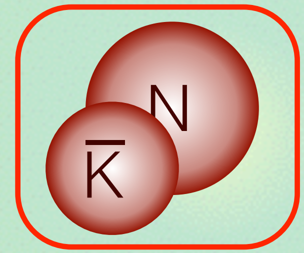
- constituent quark model: too light?

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



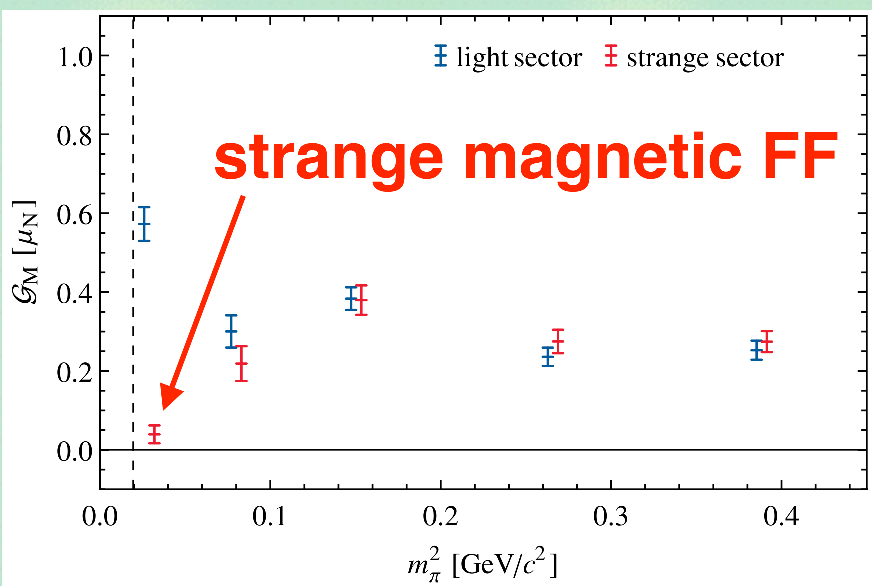
- vector meson exchange model

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

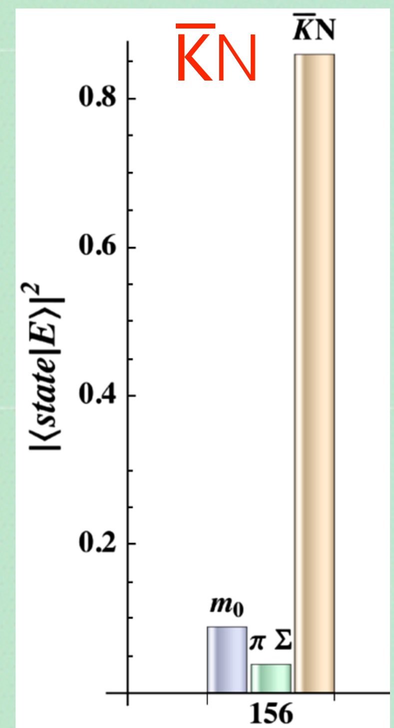


Recent lattice QCD study

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



overlaps in Hamiltonian model



$\bar{K}N$ potential and wave function

Local $\bar{K}N$ potential —> coupled-channel amplitude

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

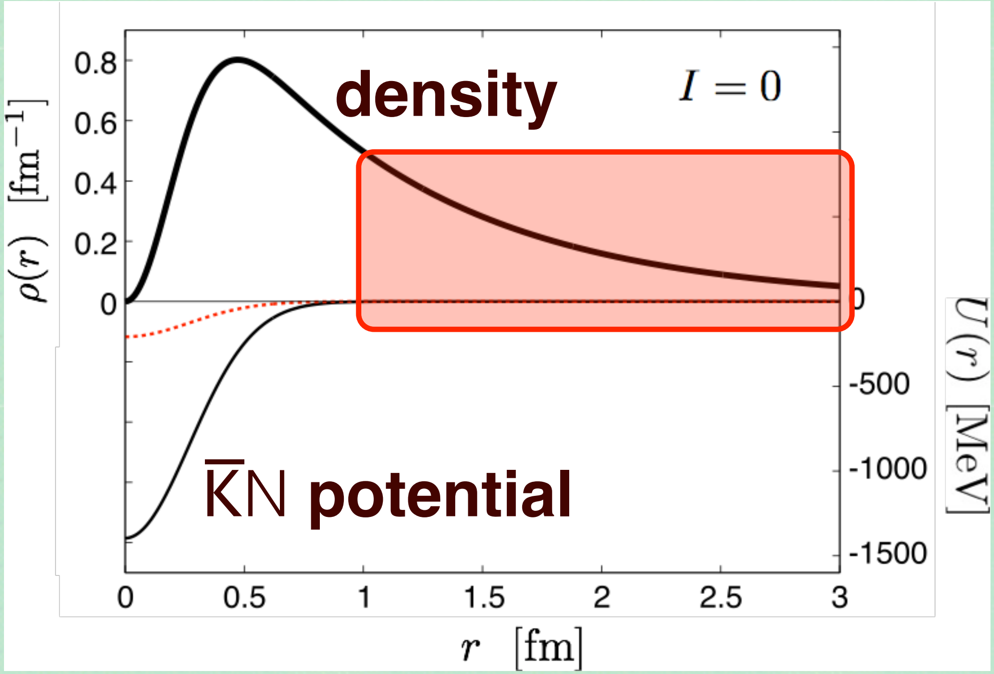
- Equivalent amplitude on the real axis
- Single-channel, complex, energy-dependent potential

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: strategy

- **Model-independent determination of structure**

  S. Weinberg, Phys. Rev. 137, B672 (1965)

"elementary" Z	or	composite X
- uududd		- NN(s-wave)
- ΔΔ - πNN - ...		

<— experimentally observable quantities

- **Valid for stable state near s-wave threshold**
  - **Deuteron only!**
- **Application to Λ(1405)**
  - **Generalization to unstable state**

Weak binding relation for bound state

Compositeness X **of weakly-bound** (R ≫ R_{typ}) **s-wave state**

S. Weinberg, Phys. Rev. 137, B672 (1965);
T. Hyodo, Int. J. Mod. Phys. A 28, 1330045 (2013)

$$a_0 = R\left\{\frac{2X}{1+X} + \mathcal{O}\left(\frac{R_{\rm typ}}{R}\right)\right\}, \quad r_e = R\left\{\frac{X-1}{X} + \mathcal{O}\left(\frac{R_{\rm typ}}{R}\right)\right\}$$

a **: scattering length,** r_e **: effective range**
R = $(2\mu B)^{-1/2}$ **: radius <— binding energy**
R_{typ} **: typical length scale of the interaction**

- **Deuteron is** NN **composite** (a_0~R≫r_e) **<— observables, without referring to the nuclear force/wave function.**

EFT formulation for the weak binding relation

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

- **Clear foundation of the setup and the correction term**
- **Generalizable to quasi-bound state case**

Effective field theory

Low-energy description of bound + continuum system

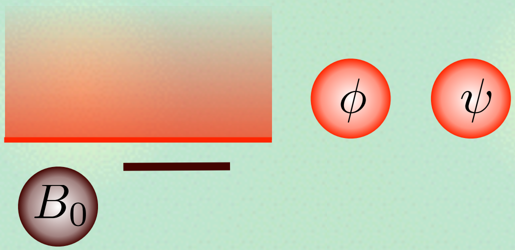
- **nonrelativistic QFT with contact interaction**

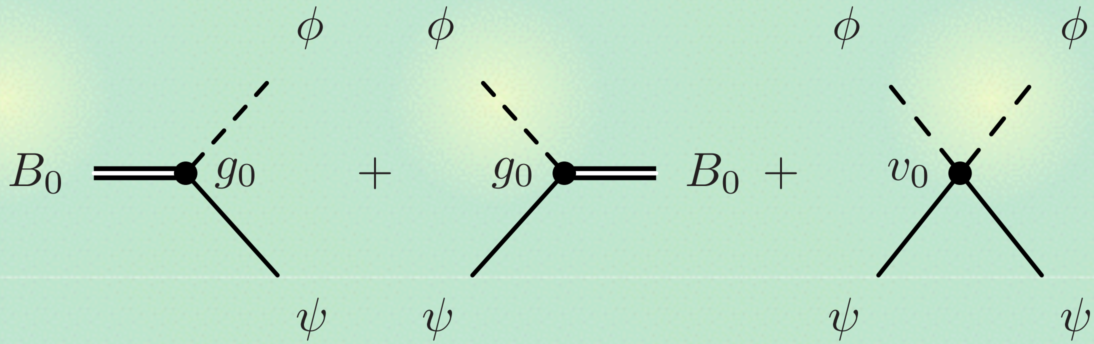
D.B. Kaplan, Nucl. Phys. B494, 471 (1997)

E. Braaten, M. Kusunoki, D. Zhang, Annals Phys. 323, 1770 (2008)

$$H_{\text{free}} = \int d\boldsymbol{r}\left[\frac{1}{2M}\nabla\psi^{\dagger}\cdot\nabla\psi + \frac{1}{2m}\nabla\phi^{\dagger}\cdot\nabla\phi + \frac{1}{2M_0}\nabla B_0^{\dagger}\cdot\nabla B_0 + \nu_0 B_0^{\dagger}B_0\right],$$

$$H_{\text{int}} = \int d\boldsymbol{r}\left[g_0\left(B_0^{\dagger}\phi\psi + \psi^{\dagger}\phi^{\dagger}B_0\right) + v_0\psi^{\dagger}\phi^{\dagger}\phi\psi\right]$$





- **cutoff:** $\Lambda \sim 1/R_{\text{typ}}$ **(typical length scale of the interaction)**
- **low-energy:** $p \ll \Lambda$ **(wavelength is too large to resolve the short range structure of the interaction)**

Compositeness and elementariness

Eigenstate in $n_\phi+n_{B0}=n_\psi+n_{B0}=1$ sector: $(H_{\rm free}+H_{\rm int})|\,\Psi\,\rangle = E|\,\Psi\,\rangle$

$$|\,\Psi\,\rangle = c|\,B_0\,\rangle + \int \frac{d\boldsymbol{p}}{(2\pi)^3}\chi(\boldsymbol{p})|\,\boldsymbol{p}\,\rangle, \quad |\,B_0\,\rangle = \frac{\tilde{B}_0^\dagger(\boldsymbol{0})}{\sqrt{\mathcal{V}}}|\,0\,\rangle, \quad |\,\boldsymbol{p}\,\rangle = \frac{\tilde{\psi}^\dagger(\boldsymbol{p})\tilde{\phi}^\dagger(-\boldsymbol{p})}{\sqrt{\mathcal{V}}}|\,0\,\rangle$$

- Normalization of bound state |B> + completeness relation

$$\langle\,B\,|\,B\,\rangle = 1, \quad 1 = |\,B_0\,\rangle\langle\,B_0\,| + \int \frac{d\boldsymbol{p}}{(2\pi)^3}|\,\boldsymbol{p}\,\rangle\langle\,\boldsymbol{p}\,|$$

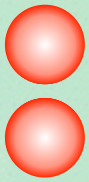
- Decomposition of unity

$$1 = Z + X$$

$$Z \equiv |\langle\,B_0\,|\,B\,\rangle|^2 = |c|^2, \quad X \equiv \int \frac{d\boldsymbol{p}}{(2\pi)^3}|\langle\,\boldsymbol{p}\,|\,B\,\rangle|^2 = \int \frac{d\boldsymbol{p}}{(2\pi)^3}|\chi(\boldsymbol{p})|^2$$

elementariness

compositeness

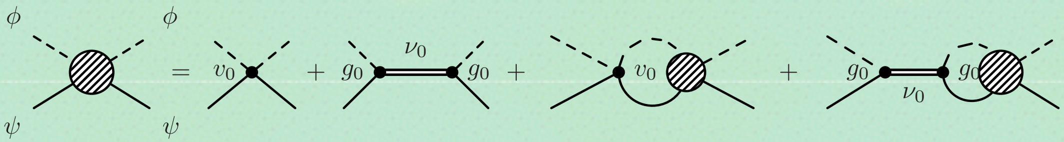


Z, X**: real and nonnegative —> probabilistic interpretation**

Weak binding relation in EFT

Scattering amplitude of ΨΦ system (analytic, exact!)

$$f(E) = -\frac{\mu}{2\pi}\frac{1}{[v(E)]^{-1} - G(E)}$$



$$v(E) = v_0 + \frac{g_0^2}{E - \nu_0}, \quad G(E) = \frac{1}{2\pi^2}\int_0^{\Lambda} dp \frac{p^2}{E - p^2/(2\mu) + i0^+}$$

Compositeness X is in general cutoff (model) dependent.

T. Sekihara, T. Hyodo, D. Jido, PTEP2015, 063D04 (2015)

$$X = \{1 + G^2(-B)v'(-B)\,[G'(-B)]^{-1}\}^{-1}$$

Expansion of scattering length by 1/R

cutoff dependent

$$a_0 = -f(E=0) = c_1 R + c_2 R^0 + \cdots = R\left\{\frac{2X}{1+X} + \mathcal{O}\left(\frac{R_{\rm typ}}{R}\right)\right\}, \quad R = \frac{1}{\sqrt{2\mu B}}$$

cutoff independent

- **Leading order term is expressed by X!**

X <— (B, a_0) if R is much larger than $R_{\rm typ}$.

Generalization to quasi-bound state

Introduce additional channel (decay channel)

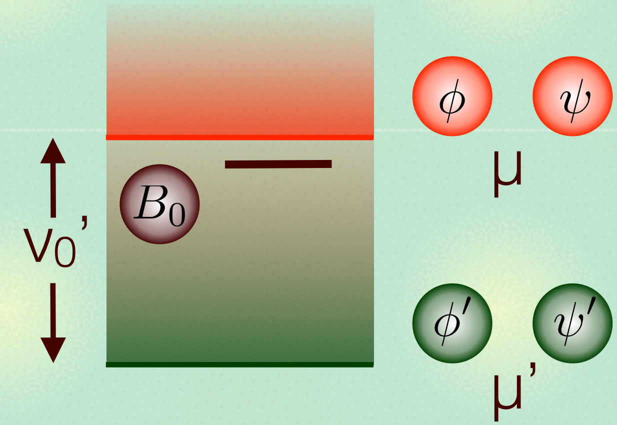
$$H'_{\text{free}} = \int d\boldsymbol{r}\left[\frac{1}{2M'}\nabla\psi'^{\dagger}\cdot\nabla\psi' - \nu_{\psi}\psi'^{\dagger}\psi' + \frac{1}{2m'}\nabla\phi'^{\dagger}\cdot\nabla\phi' - \nu_{\phi}\phi'^{\dagger}\phi'\right],$$

$$H'_{\text{int}} = \int d\boldsymbol{r}\left[g'_0\left(B_0^{\dagger}\phi'\psi' + \psi'^{\dagger}\phi'^{\dagger}B_0\right) + v'_0\psi'^{\dagger}\phi'^{\dagger}\phi'\psi' + v_0^t(\psi^{\dagger}\phi^{\dagger}\phi'\psi' + \psi'^{\dagger}\phi'^{\dagger}\phi\psi)\right],$$

Quasi-bound state

$$H = H_{\text{free}} + H'_{\text{free}} + H_{\text{int}} + H'_{\text{int}}$$

$$H|QB\rangle = E_{QB}|QB\rangle, \quad E_{QB}\in\mathbb{C}$$



Scattering amplitude

$$v(E) = v_0 + \frac{g_0^2}{E-\nu_0} + \frac{\left(v_0^t + \frac{g_0 g'_0}{E-\nu_0}\right)^2}{[\bar{G}(E)]^{-1} - (v'_0 + \frac{g_0'^2}{E-\nu_0})}$$

Generalized relation: $X_{\psi\phi}$ **<— (**E_{QB}**,** a_0**) if |R| is larger than** R_{typ}**, l**

$$a_0 = R\left\{\frac{2X}{1+X} + \mathcal{O}\left(\left|\frac{R_{\text{typ}}}{R}\right|\right) + \sqrt{\frac{\mu'^3}{\mu^3}}\mathcal{O}\left(\left|\frac{l}{R}\right|^3\right)\right\}, \quad R = \frac{1}{\sqrt{-2\mu E_{QB}}}, \quad l \equiv \frac{1}{\sqrt{2\mu\nu'_0}}$$

Application

Generalized relation of compositeness X <— (E_{QB}, a_0)

$$a_0 = R\left\{\frac{2X}{1+X} + \mathcal{O}\left(\left|\frac{R_{\rm typ}}{R}\right|\right) + \sqrt{\frac{\mu'^3}{\mu^3}}\mathcal{O}\left(\left|\frac{l}{R}\right|^3\right)\right\}, \quad R = \frac{1}{\sqrt{-2\mu E_{QB}}}, \quad l \equiv \frac{1}{\sqrt{2\mu\nu'_0}}$$

- |R| ~ 2 fm **-> Error terms** ($R_{\rm typ}$ **by vector meson exchange)**

$$\left|\frac{R_{\rm typ}}{R}\right| \lesssim 0.12, \quad \left|\frac{l}{R}\right|^3 \lesssim 0.16$$

- **NLO Analyses of** Λ(1405) **with SIDDHARTA**

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: structure of Λ(1405)

- **Composite nature of the weakly binding state can be determined only from observables.**
- **EFT formulation provides clear basis of the weak binding relation and enables us to generalize the relation to quasi-bound states.**

$$a_0 = R\left\{ \frac{2X}{1+X} + \mathcal{O}\left(\left|\frac{R_{\rm typ}}{R}\right|\right) + \sqrt{\frac{\mu'^3}{\mu^3}}\,\mathcal{O}\left(\left|\frac{l}{R}\right|^3\right) \right\}, \quad R = \frac{1}{\sqrt{-2\mu E_{QB}}}, \quad l \equiv \frac{1}{\sqrt{2\mu\nu_0'}}$$

- **Recent determinations of the scattering length and the pole position indicate that the Λ(1405) is a $\bar{K}$N molecule.**

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