Status of $\Lambda(1405)$ in chiral dynamics

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- **Pole structure of the $\Lambda(1405)$ region**
  - **Chiral SU(3) dynamics**

    Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012);
    M. Tanabashi, *et al.* (Particle Data Group), PRD 98, 030001 (2018)
- **Some comments from recent studies**
  - **$K^{-}p$ correlation function** —> Talk by Y. Kamiya (Friday)

    ALICE collaboration, arXiv:1905.13470 [nucl-ex];
    Y. Kamiya. T. Hyodo, K Morita, A. Ohnishi, in preparation
  - **Pole and finite volume spectrum**

    Y. Tsuchida, T. Hyodo, Phys. Rev. C97, 0552113 (2018)

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

Two aspects of $K/\bar{K}$ meson

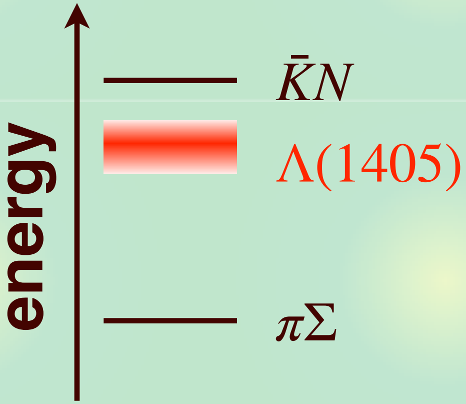
- **NG boson** of chiral $\mathrm{SU(3)_R \otimes SU(3)_L \to SU(3)_V}$
- **Massive** due to strange quark: $m_K \sim 496\ \mathrm{MeV}$

—> **Spontaneous**/**explicit** symmetry breaking

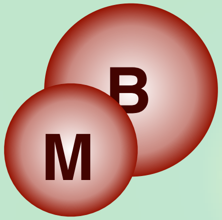
$\bar{K}N$ interaction ...

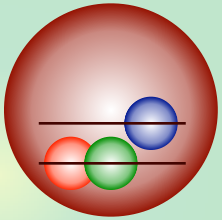
T. Hyodo, D. Jido, PPNP 67, 55 (2012)

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



molecule





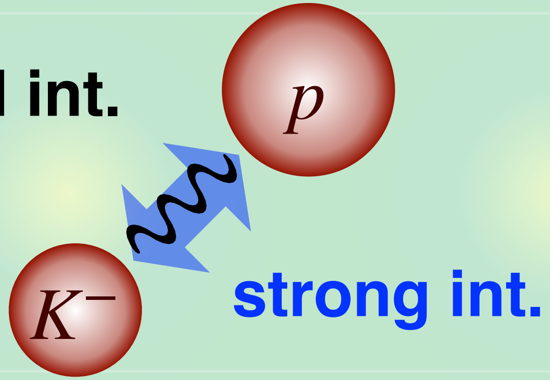
three-quark

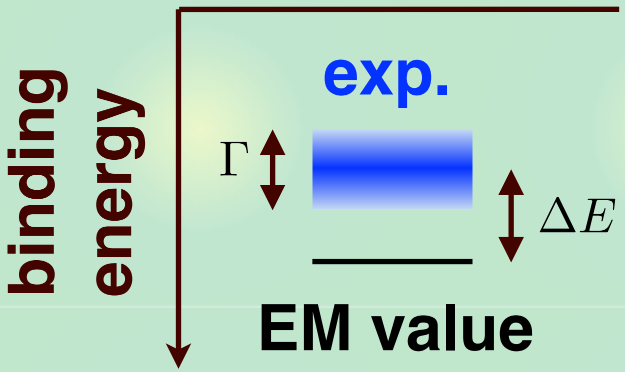
- is fundamental building block for $\bar{K}$-nuclei, $\bar{K}$ in medium, ...

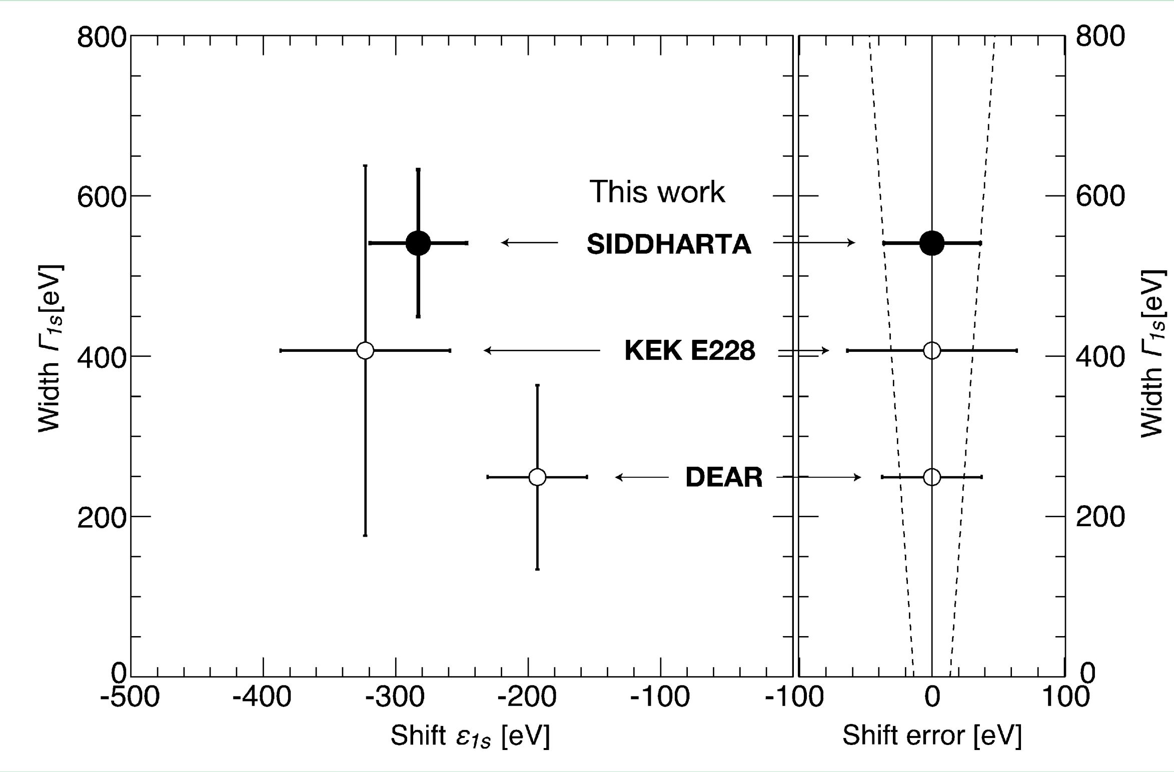
SIDDHARTA measurement

Precise measurement of the kaonic hydrogen X-rays

M. Bazzi, *et al.*, PLB 704, 113 (2011); NPA 881, 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)

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

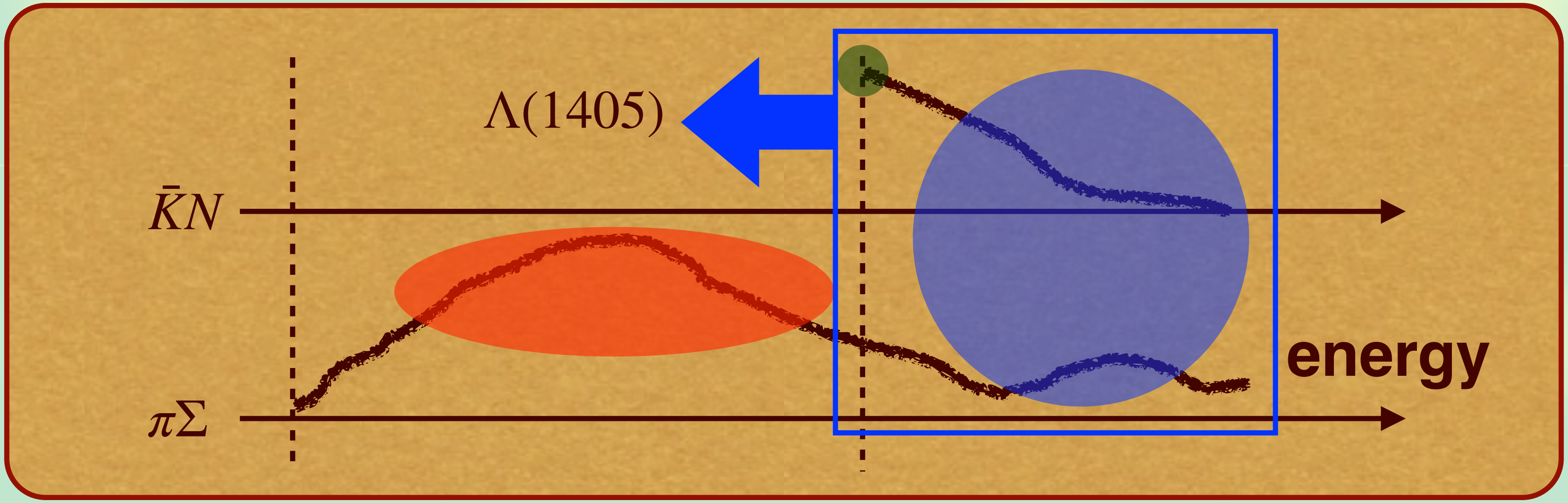
Strategy for $\bar{K}N$ interaction

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

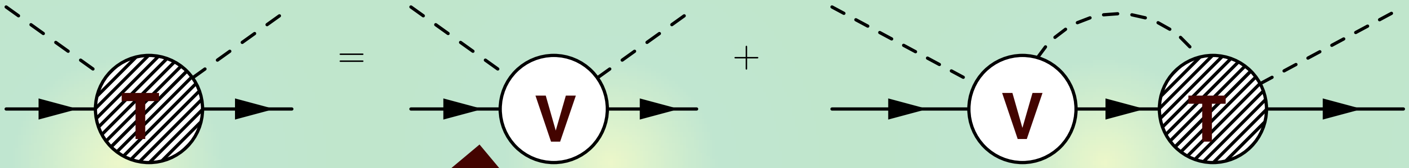
- $\pi\Sigma$ **mass spectra** (new data: LEPS, CLAS, HADES,…)



Construction of the realistic amplitude

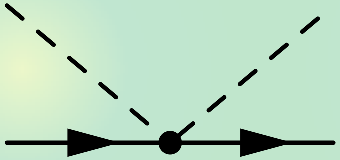
Chiral SU(3) coupled-channels $(\bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, \eta\Sigma, K\Xi)$ approach

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



Chiral perturbation theory

1) TW term

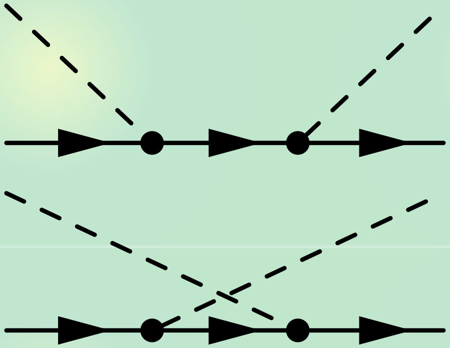


$\mathcal{O}(p)$

6 cutoffs

TW model

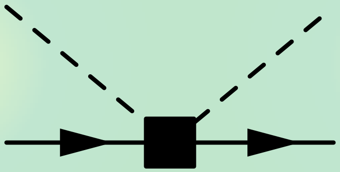
2) Born terms



$\mathcal{O}(p)$

TWB model

3) NLO terms



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

7 LECs

NLO model

Best-fit results

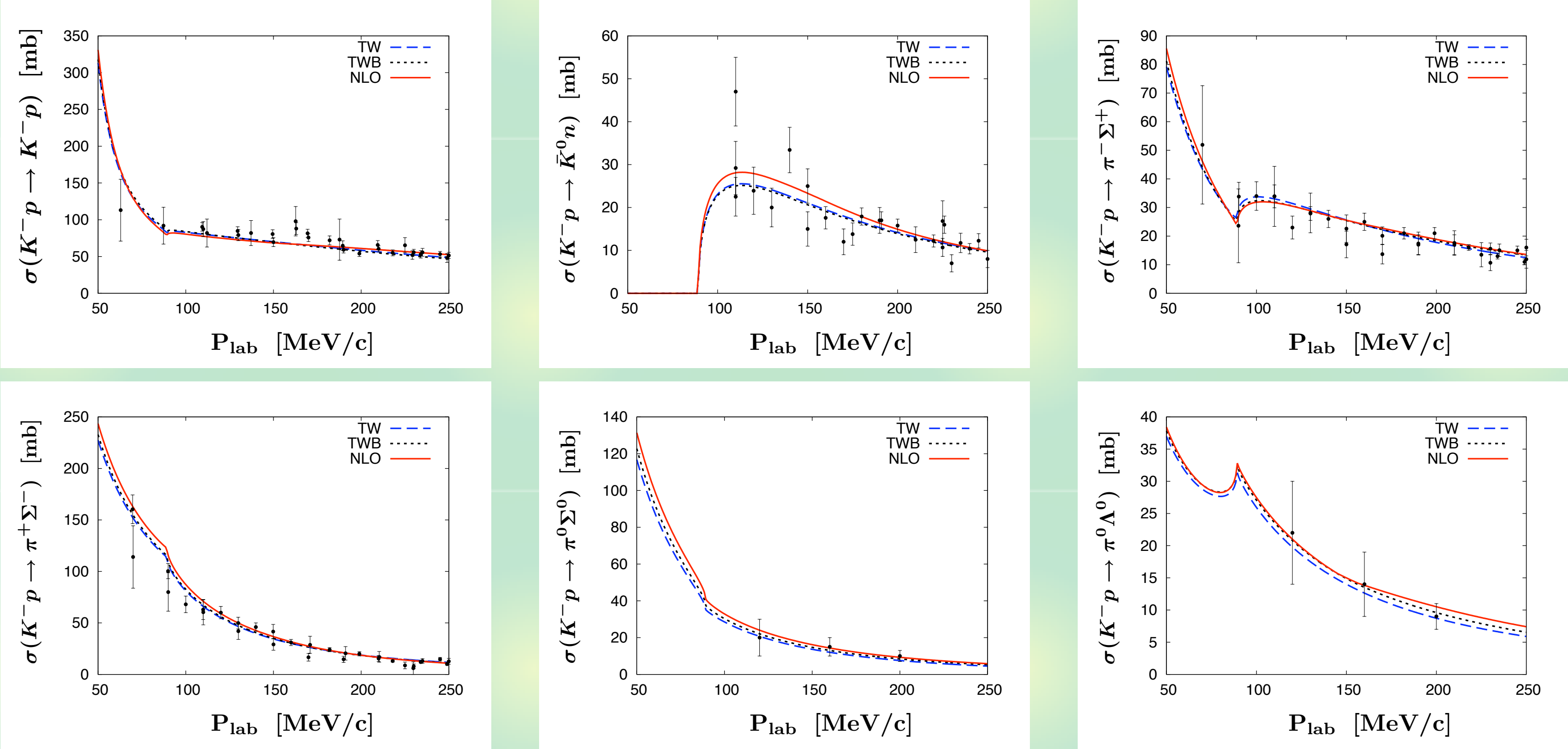
K at rest

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

SIDDHARTA

Branching ratios

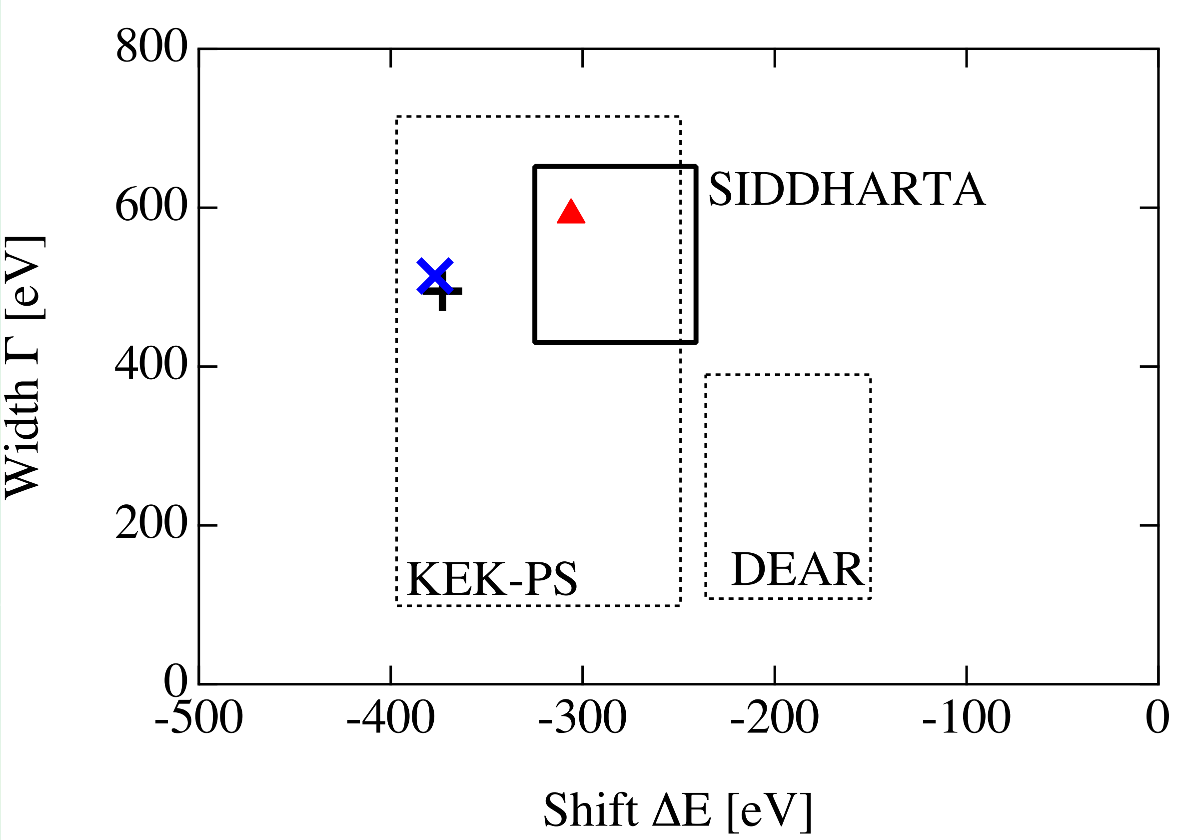
K^-p cross sections



Accurate description of all existing data ($\chi^2/\mathrm{d.o.f} \sim 1$)

Comparison with SIDDHARTA

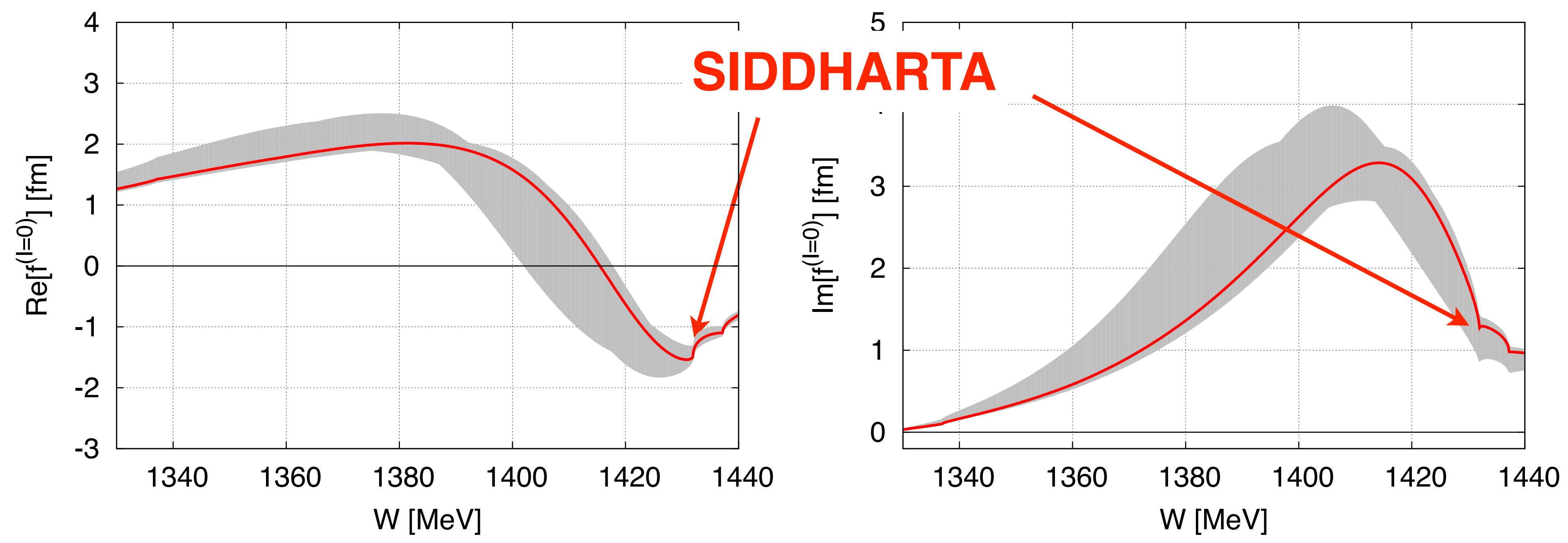
	TW	TWB	NLO
χ^2/d.o.f.	1.12	1.15	0.957



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

Subthreshold extrapolation

Uncertainty of $\bar{K}N \to \bar{K}N(I=0)$ amplitude below threshold

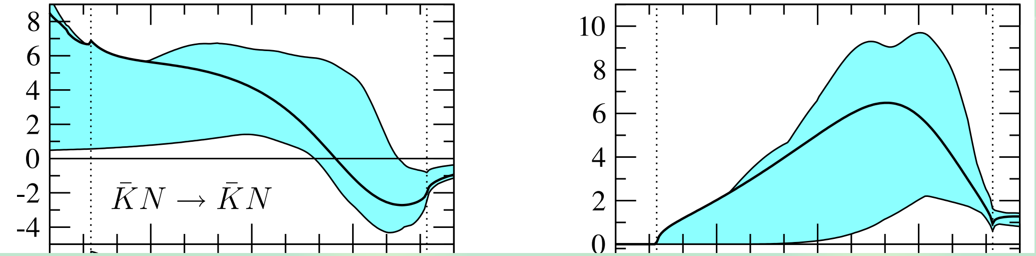


SIDDHARTA

Y. Kamiya, K. Miyahara, S. Ohnishi, Y. Ikeda, T. Hyodo, E. Oset, W. Weise, NPA 954, 41 (2016)

- c.f. without SIDDHARTA

R. Nissler, Doctoral Thesis (2007)



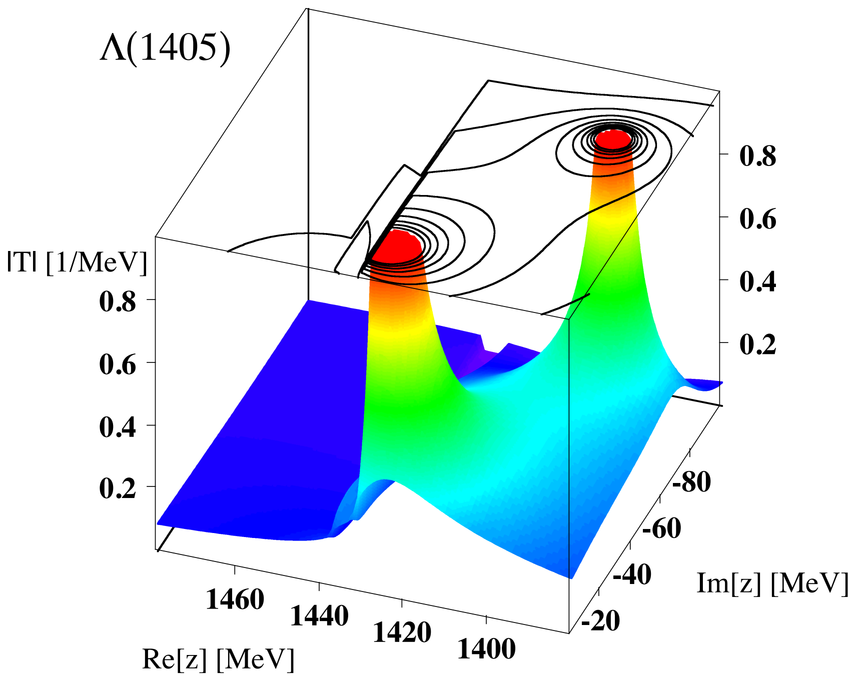
SIDDHARTA is essential for subthreshold extrapolation.

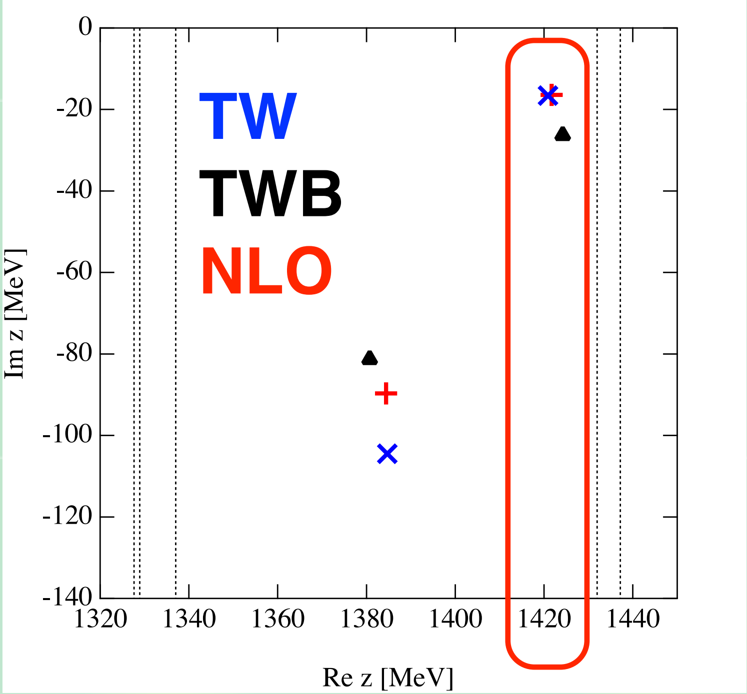
Extrapolation to complex energy: two poles

Two poles: superposition of two states

J.A. Oller, U.G. Meissner, PLB 500, 263 (2001);
D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, NPA 723, 205 (2003);
T. Hyodo, W. Weise, PRC 77, 035204 (2008)

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



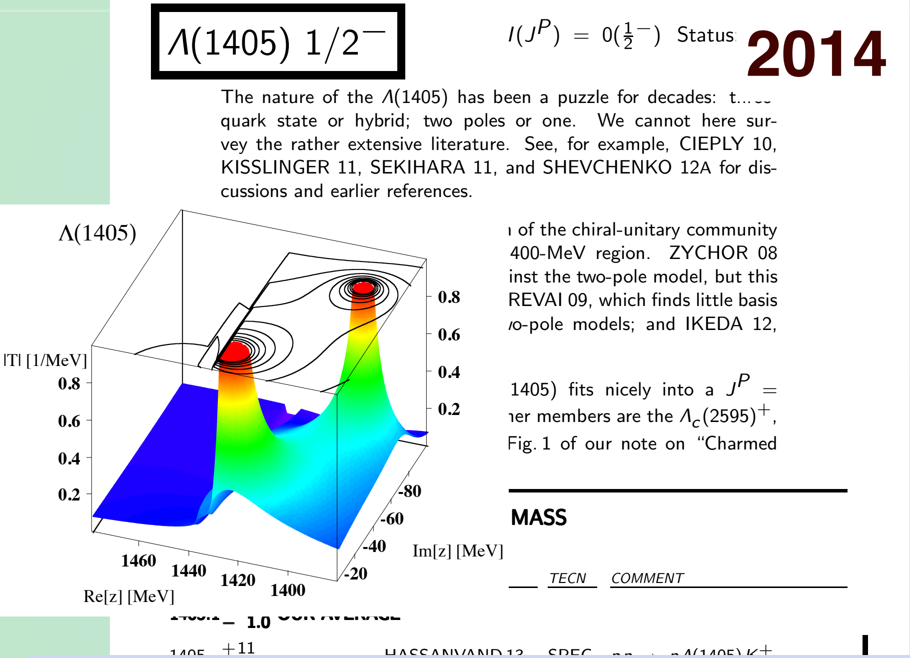


NLO analysis confirms the two-pole structure.

PDG changes

PDG particle listing of $\Lambda(1405)$

M. Tanabashi, *et al.*, PRD 98, 030001 (2018), `http://pdg.lbl.gov/`



2014

$\Lambda(1405)\ 1/2^-$ $I(J^P) = 0(\frac{1}{2}^-)$ Status

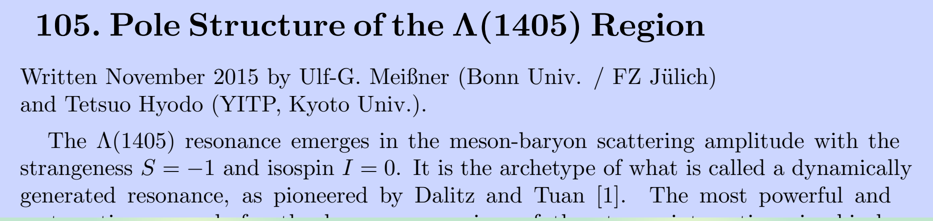
The nature of the $\Lambda(1405)$ has been a puzzle for decades: t... quark state or hybrid; two poles or one. We cannot here survey the rather extensive literature. See, for example, CIEPLY 10, KISSLINGER 11, SEKIHARA 11, and SHEVCHENKO 12A for discussions and earlier references.

of the chiral-unitary community 400-MeV region. ZYCHOR 08 inst the two-pole model, but this REVAI 09, which finds little basis o-pole models; and IKEDA 12,

1405) fits nicely into a $J^P =$ ner members are the $\Lambda_c(2595)^+$, Fig. 1 of our note on "Charmed

MASS

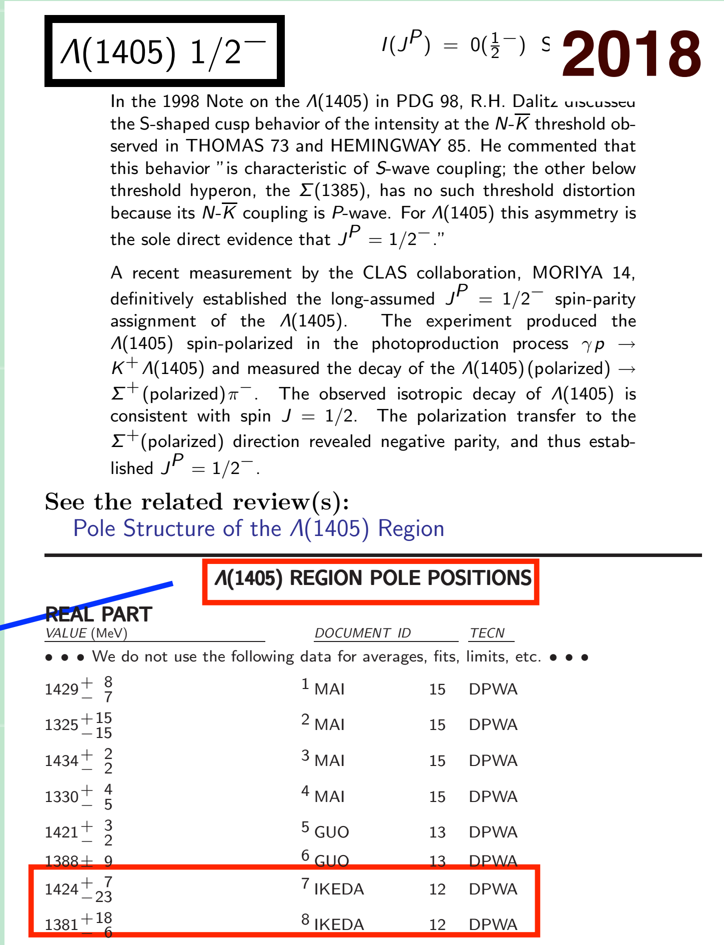
TECN COMMENT



105. Pole Structure of the $\Lambda(1405)$ Region

Written November 2015 by Ulf-G. Meißner (Bonn Univ. / FZ Jülich) and Tetsuo Hyodo (YITP, Kyoto Univ.).

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 what is called a dynamically generated resonance, as pioneered by Dalitz and Tuan [1]. The most powerful and



2018

$\Lambda(1405)\ 1/2^-$ $I(J^P) = 0(\frac{1}{2}^-)$ S

In the 1998 Note on the $\Lambda(1405)$ in PDG 98, R.H. Dalitz discussed the S-shaped cusp behavior of the intensity at the N-$\overline{K}$ threshold observed in THOMAS 73 and HEMINGWAY 85. He commented that this behavior "is characteristic of S-wave coupling; the other below threshold hyperon, the $\Sigma(1385)$, has no such threshold distortion because its N-$\overline{K}$ coupling is P-wave. For $\Lambda(1405)$ this asymmetry is the sole direct evidence that $J^P = 1/2^-$."

A recent measurement by the CLAS collaboration, MORIYA 14, definitively established the long-assumed $J^P = 1/2^-$ spin-parity assignment of the $\Lambda(1405)$. The experiment produced the $\Lambda(1405)$ spin-polarized in the photoproduction process $\gamma p \to K^+ \Lambda(1405)$ and measured the decay of the $\Lambda(1405)$(polarized) $\to \Sigma^+$(polarized)π^-. The observed isotropic decay of $\Lambda(1405)$ is consistent with spin $J = 1/2$. The polarization transfer to the Σ^+(polarized) direction revealed negative parity, and thus established $J^P = 1/2^-$.

See the related review(s):
Pole Structure of the $\Lambda(1405)$ Region

$\Lambda(1405)$ REGION POLE POSITIONS

REAL PART

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE (MeV)	*DOCUMENT ID*		*TECN*
1429^{+8}_{-7}	[1] MAI	15	DPWA
1325^{+15}_{-15}	[2] MAI	15	DPWA
1434^{+2}_{-2}	[3] MAI	15	DPWA
1330^{+4}_{-5}	[4] MAI	15	DPWA
1421^{+3}_{-2}	[5] GUO	13	DPWA
1388 ± 9	[6] GUO	13	DPWA
1424^{+7}_{-23}	[7] IKEDA	12	DPWA
1381^{+18}_{-6}	[8] IKEDA	12	DPWA

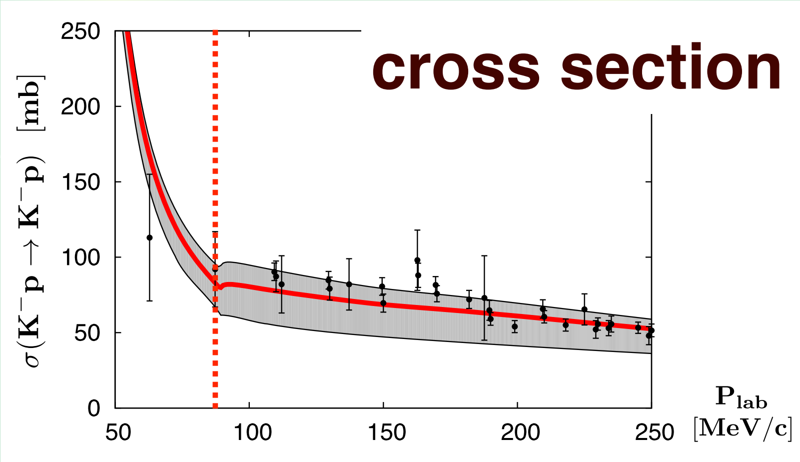
- **Our analysis** (+ 2 other groups)
- **Pole positions** are now tabulated, prior to mass/width.

Correlation function

K^-p total cross sections

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011)

- Old bubble chamber data



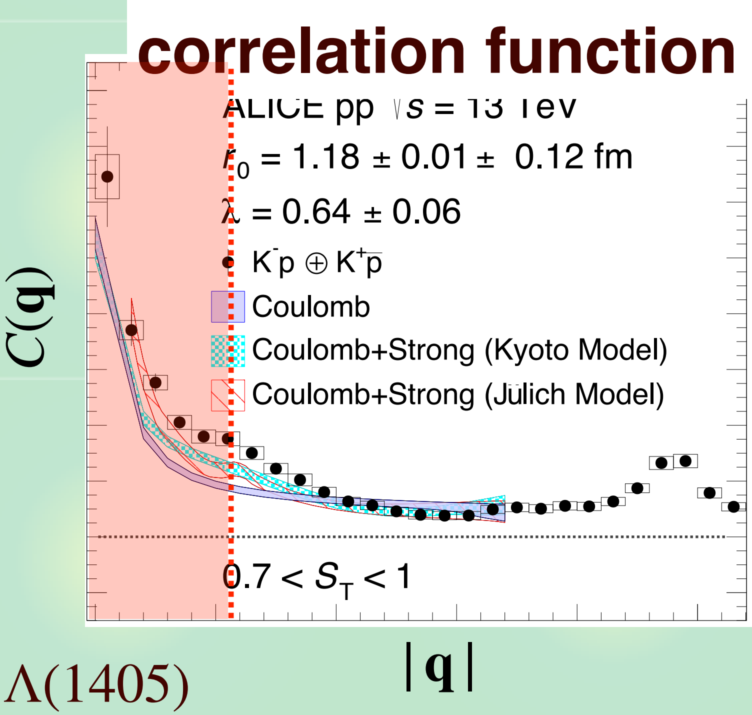
K^-p correlation function

ALICE collaboration, arXiv:1905.13470 [nucl-ex]

$$C(\mathbf{q}) = \frac{N_{K^-p}(\mathbf{p}_{K^-}, \mathbf{p}_p)}{N_{K^-}(\mathbf{p}_{K^-})N_p(\mathbf{p}_p)}$$

- Excellent precision ($\bar{K}^0 n$ cusp)
- Low-energy data below $\bar{K}^0 n$

$$C(\mathbf{q}) \simeq \int d^3\mathbf{r}\, S(\mathbf{r})\,|\,\Psi_{\mathbf{q}}^{(-)}(\mathbf{r})\,|^2$$



—> Important constraint on $\bar{K}N$ and $\Lambda(1405)$

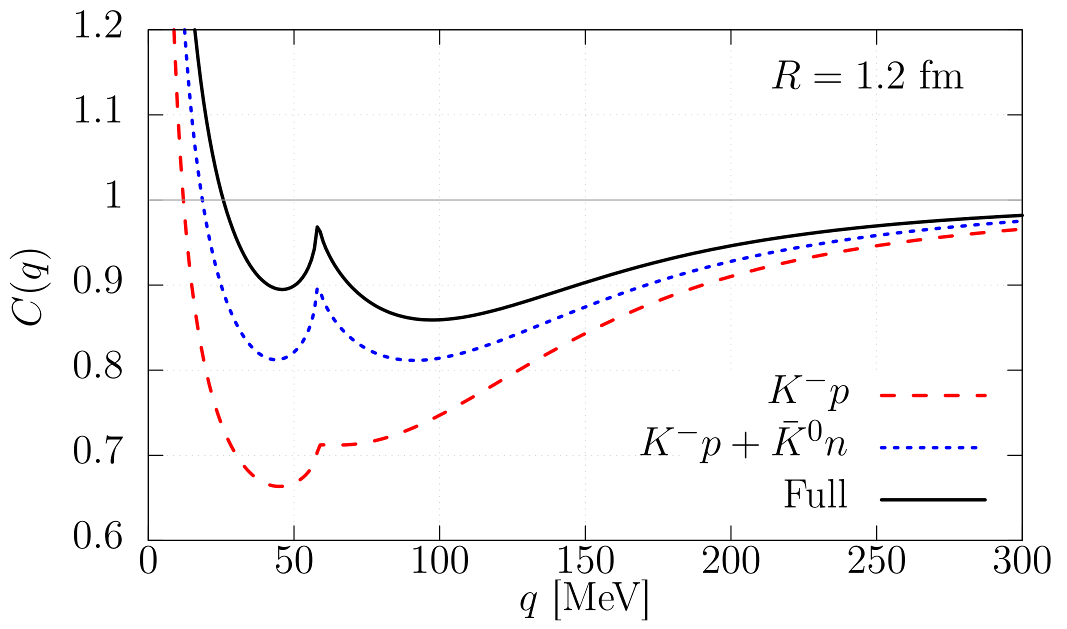
Results

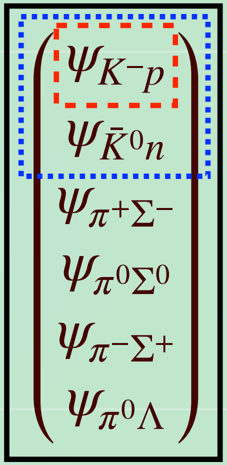
Developing theoretical framework to calculate $C(q)$ with

- **interaction: coupled-channel $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential**

K. Miyahara. T. Hyodo, W. Weise, PRC98, 025201 (2018)

- **static spherical source $S(\mathbf{r})$, weight $\omega_i = 1$**





$$\begin{pmatrix} \psi_{K^{-}p} \\ \psi_{\bar{K}^{0}n} \\ \psi_{\pi^{+}\Sigma^{-}} \\ \psi_{\pi^{0}\Sigma^{0}} \\ \psi_{\pi^{-}\Sigma^{+}} \\ \psi_{\pi^{0}\Lambda} \end{pmatrix}$$

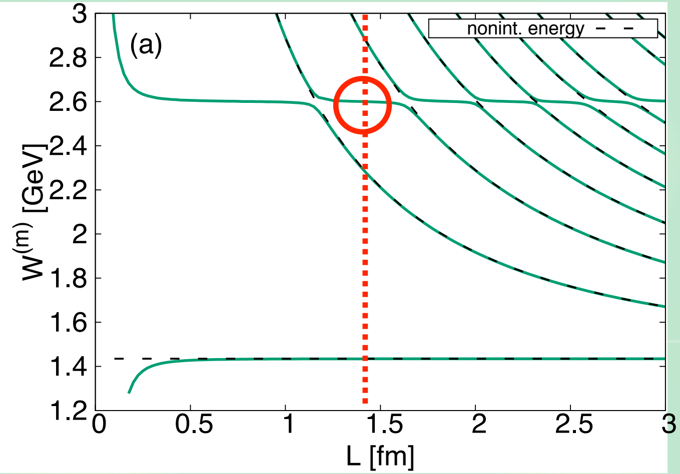
- **$\bar{K}^{0}n$ cusp is prominent with inclusion of $\psi_{\bar{K}^{0}n}$**
- **Coupled channels enhance $K^{-}p$ correlation**

Resonance and finite volume spectrum

Sharp resonance and finite volume spectrum (toy model)

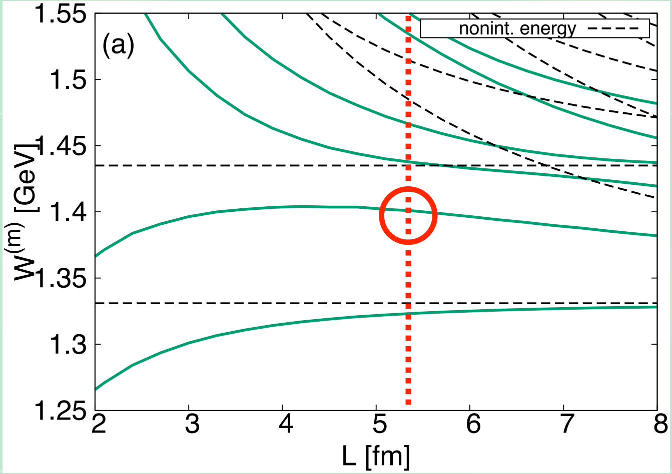
Y. Tsuchida, T. Hyodo, Phys. Rev. C97, 0552113 (2018)

- dashed: free eigenenergy
- solid: with interaction
- additional energy level



$\Lambda(1405)$ case (amplitude with two poles)

- Only one additional level
- # of additional energy levels
  $=$ # of $\pi/2$ crossings of phase shift
  $\neq$ # of poles



Summary

- **Pole structure of the $\Lambda(1405)$ region is now well constrained by the experimental data. Nominal $\Lambda(1405)$ can be a superposition of two states.**

  Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012);
  M. Tanabashi, *et al.* (Particle Data Group), PRD 98, 030001 (2018)

- **$K^- p$ correlation function will be a new accurate constraint on the $\Lambda(1405)$**

  ALICE collaboration, arXiv:1905.13470 [nucl-ex];
  Y. Kamiya. T. Hyodo, K Morita, A. Ohnishi, in preparation

- **Finite volume spectrum does not directly indicate the pole structure.**

  Y. Tsuchida, T. Hyodo, Phys. Rev. C97, 0552113 (2018)