Meson-baryon interactions and baryon resonances

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"Nanoscience and Quantum Physics"

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Contents

- $\Lambda(1405)$ in meson-baryon scattering

  T. Hyodo, D. Jido, arXiv:1104.4474, submitted to Prog. Part. Nucl. Phys.

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

- Toward realistic meson-baryon interaction

  - Constraint by accurate $\bar{K}N$ data

    Y. Ikeda, T. Hyodo, W. Weise, in preparation

  - Information of $\pi\Sigma$ channel

    Y. Ikeda, T. Hyodo, D. Jido, H. Kamano, T. Sato, K. Yazaki, arXiv:1101.5190 [nucl-th], to appear in Prog. Theor. Phys.,
    T. Hyodo, M. Oka, arXiv:1105.5494 [nucl-th]

- Summary

Chiral symmetry breaking in hadron physics

Chiral symmetry: QCD with massless quarks

Consequence of chiral symmetry breaking in hadron physics

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- **appearance of the Nambu-Goldstone (NG) boson**

  $m_\pi \sim 140 \text{ MeV}$

- **dynamical generation of hadron masses**

  $M_p \sim 1 \text{ GeV} \sim 3M_q, \quad M_q \sim 300 \text{ MeV} \quad v.s. \quad 3 - 7 \text{ MeV}$

- **constraints on the NG-boson--hadron interaction**
  low energy theorems <-- current algebra
  systematic low energy ($m, p/4\pi f_\pi$) expansion: ChPT

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Chiral symmetry and its breaking

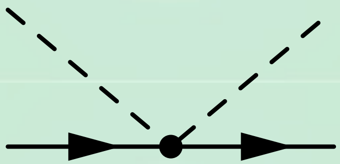
$$SU(3)_R \otimes SU(3)_L \to SU(3)_V$$

Underlying QCD <==> observed hadron phenomena

s-wave low energy interaction in ChPT

Leading order term for the meson-baryon scattering

$$\mathcal{L}^{\mathrm{WT}} = \frac{1}{4f^2}\mathrm{Tr}\left(\bar{B}i\gamma^{\mu}[\Phi\partial_{\mu}\Phi - (\partial_{\mu}\Phi)\Phi, B]\right)$$



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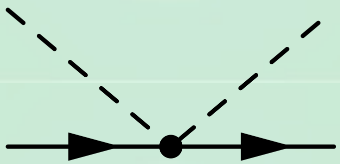

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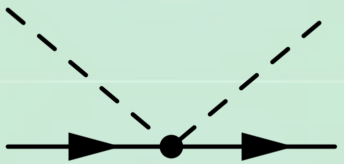

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$$Y = Y_{\bar{i}} + Y_i = Y_{\bar{j}} + Y_j, \quad I = I_{\bar{i}} + I_i = I_{\bar{j}} + I_j,$$

- Flavor SU(3) symmetry --> sign and strength

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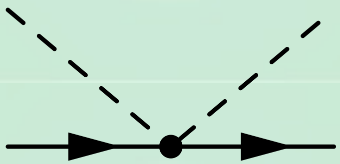

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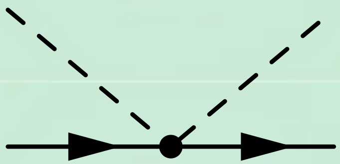

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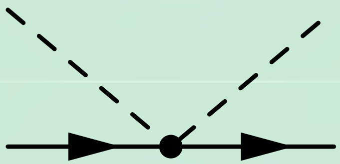

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If the interaction is strong, resummation is mandatory.

Scattering amplitude and unitarity

Unitarity of S-matrix: Optical theorem

$$\mathrm{Im}[T^{-1}(s)] = \frac{\rho(s)}{2}$$

phase space of two-body state

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General amplitude by dispersion relation

$$T^{-1}(\sqrt{s}) = \boxed{\sum_i \frac{R_i}{\sqrt{s}-W_i} + \tilde{a}(s_0)} + \frac{s-s_0}{2\pi}\int_{s^+}^{\infty} ds' \frac{\rho(s')}{(s'-s)(s'-s_0)}$$

R_i, W_i, a: to be determined by chiral interaction

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Identify dispersion integral = loop function G, the rest = V^{-1}

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Scattering amplitude

The function V is determined by the matching with ChPT

$$T^{(1)} = V^{(1)}, \quad T^{(2)} = V^{(2)}, \quad T^{(3)} = V^{(3)} - V^{(1)}GV^{(1)}, \quad \dots$$

Amplitude T: consistent with chiral symmetry + unitarity

Chiral unitary approach

Meson-baryon scattering amplitude

- Interaction <-- chiral symmetry

Y. Tomozawa, Nuovo Cim. 46A, 707 (1966); S. Weinberg, Phys. Rev. Lett. 17, 616 (1966)

- Amplitude <-- unitarity in coupled channels

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

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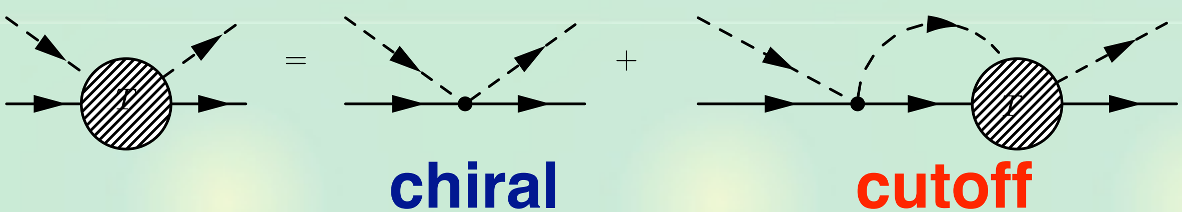
$$T = \frac{1}{1 - VG} V$$



N. Kaiser, P. B. Siegel, W. Weise, Nucl. Phys. A594, 325 (1995),
E. Oset, A. Ramos, Nucl. Phys. A635, 99 (1998),
J. A. Oller, U. G. Meissner, Phys. Lett. B500, 263 (2001),
M.F.M. Lutz, E. E. Kolomeitsev, Nucl. Phys. A700, 193 (2002), ... many others

It successfully reproduces the scattering observables as well as the dynamically generated resonances.

The Λ(1405) resonance

$$\Lambda(1405) : J^P = 1/2^-, I = 0$$

(PDG)

mass : 1406.5 ± 4.0 MeV, width : 50 ± 2 MeV

decay mode: $\Lambda(1405) \to (\pi\Sigma)_{I=0}$ **100%**

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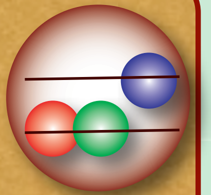
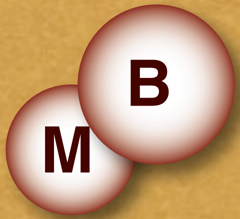
"naive" quark model
: p-wave ~1600 MeV?



N. Isgur, G. Karl, PRD18, 4187 (1978)



Coupled channel
multi-scattering

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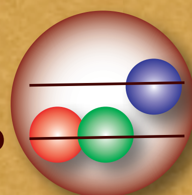

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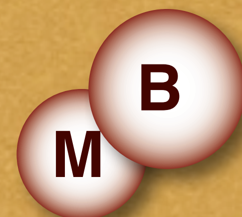

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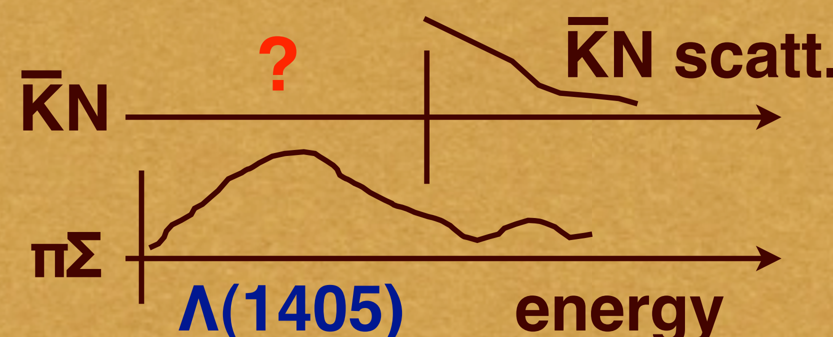
$\bar{K}N$ interaction below threshold

T. Hyodo, W. Weise, PRC 77, 035204 (2008)

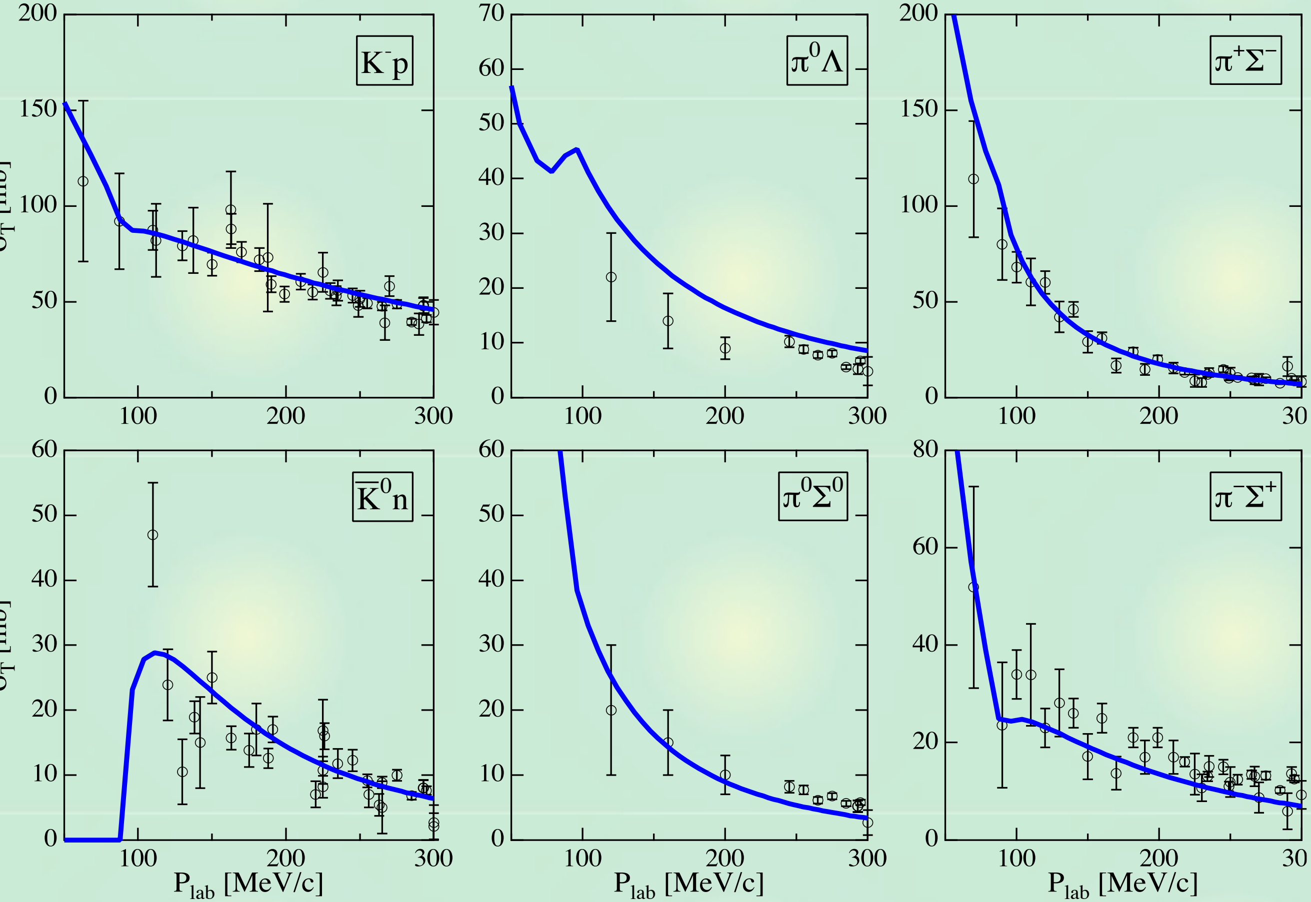
--> $\bar{K}N$ potential, kaonic nuclei

A. Dote, T. Hyodo, W. Weise,
NPA804, 197 (2008); PRC 79, 014003 (2009)



A simple model (1 parameter) v.s. experimental data

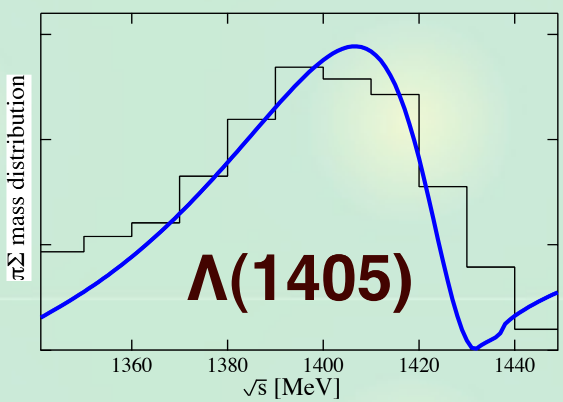
Total cross section of K-p scattering



Branching ratio

	γ	R_c	R_n
exp.	2.36	0.664	0.189
theo.	1.80	0.624	0.225

πΣ spectrum



T. Hyodo, S.I. Nam, D. Jido, A. Hosaka, PRC68, 018201 (2003); PTP 112, 73 (2004)

Good agreement with data above, at, and below $\bar{K}N$ threshold

more quantitatively --> fine tuning, higher order terms,...

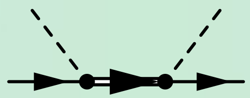
Pole structure in the complex energy plane

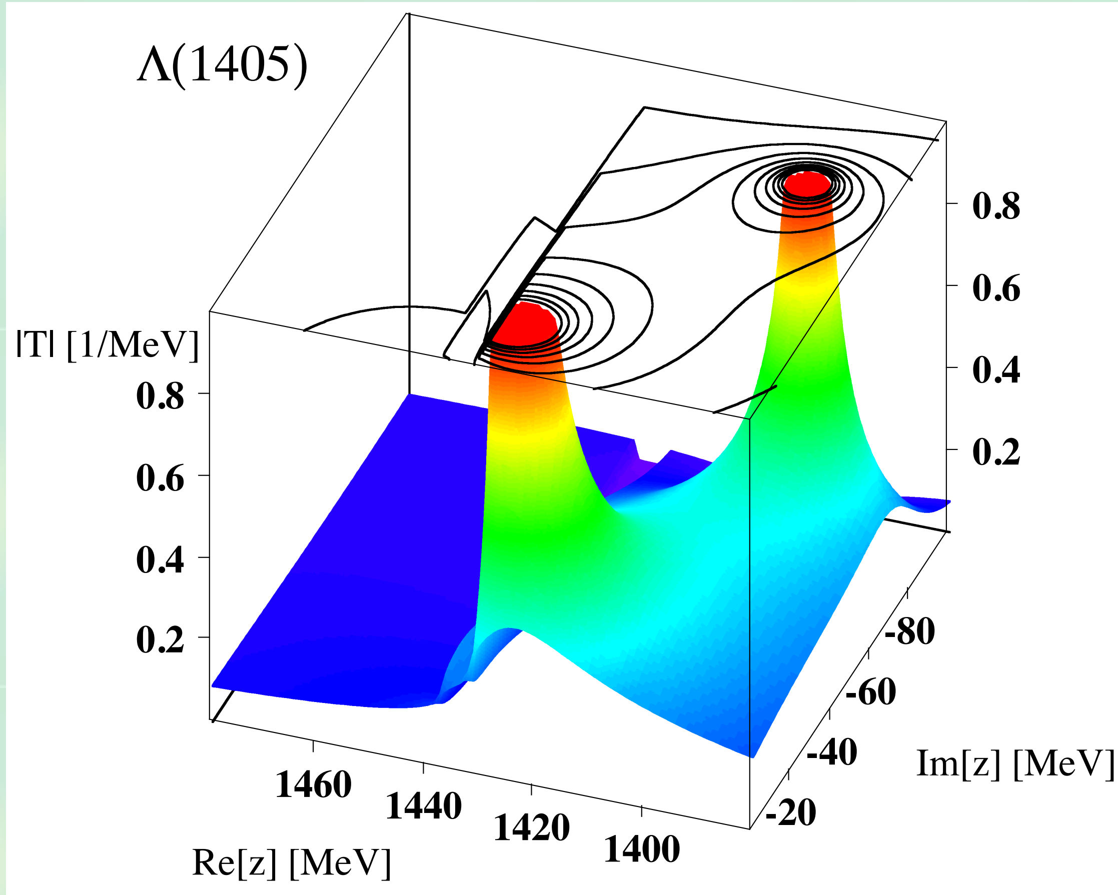
Resonance state ~ pole of the scattering amplitude

D. Jido, J.A. Oller, E. Oset, A. Ramos, U.G. Meissner, Nucl. Phys. A 723, 205 (2003)

$$T_{ij}(\sqrt{s}) \sim \frac{g_i g_j}{\sqrt{s} - M_R + i\Gamma_R/2}$$

$\sim$





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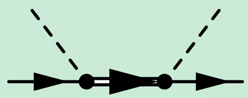
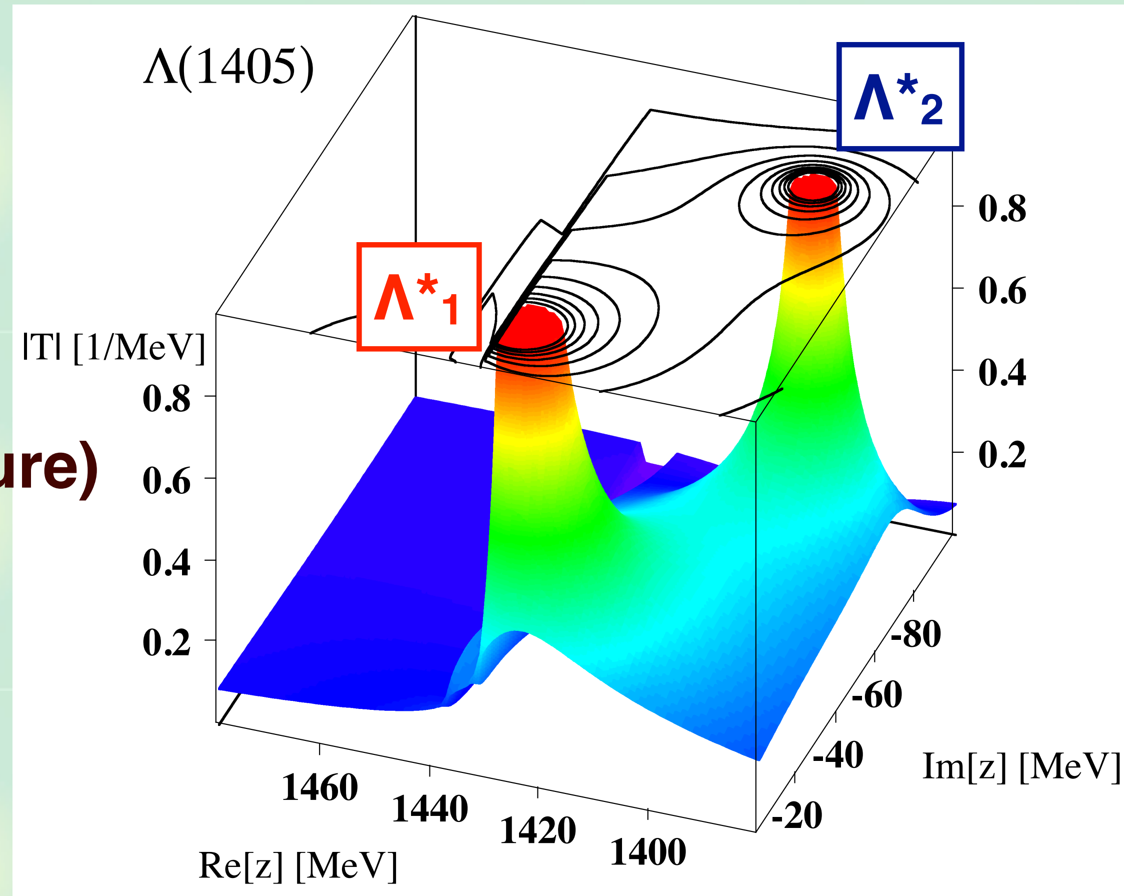
$\sim$ 



Two poles for one resonance (bump structure)

--> Superposition of two states ?

--> different πΣ spectra?

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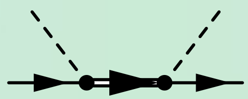
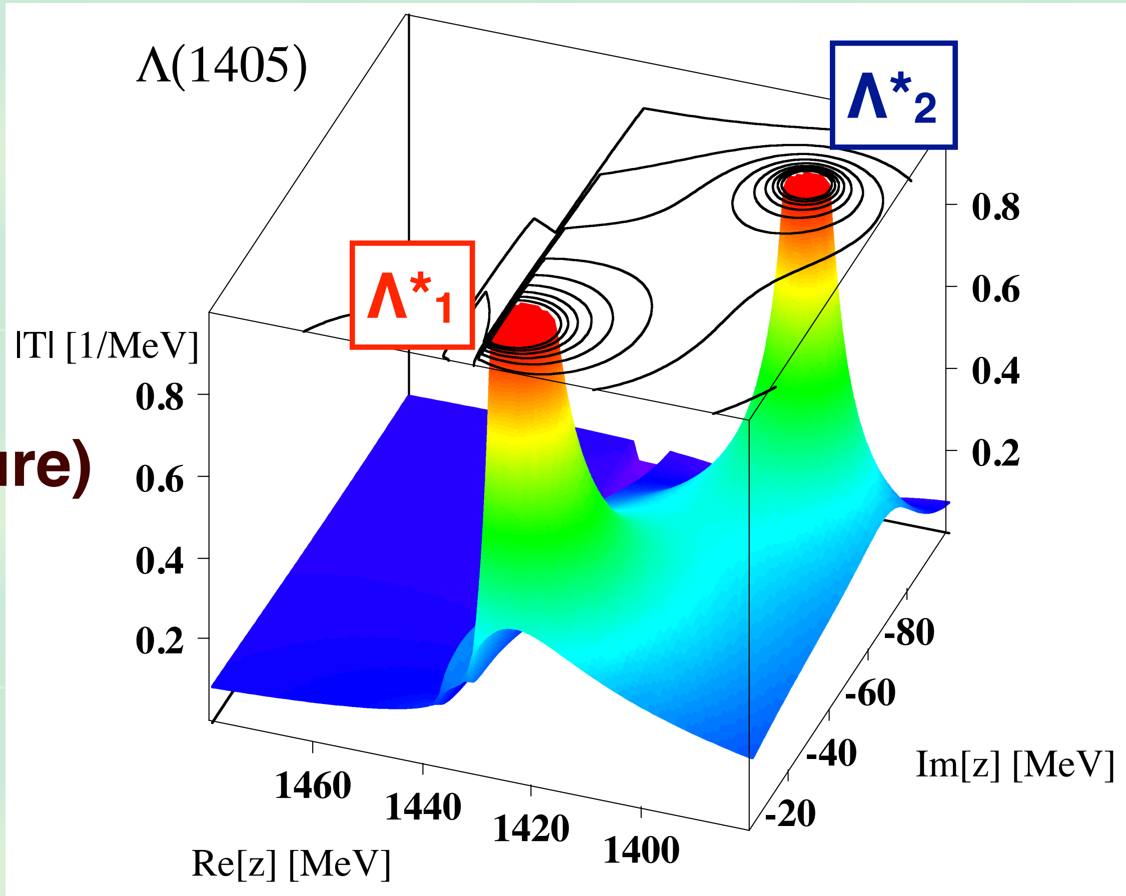
$\sim$ 



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What is the origin of this structure?

Origin of the two-pole structure

Leading order chiral interaction for K̄N-πΣ channel

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

$$V_{ij} = -C_{ij}\frac{\omega_i + \omega_j}{4f^2}$$

$$\begin{array}{cc} & \begin{array}{cc} \bar{K}N & \pi\Sigma \end{array} \\ C_{ij} = & \begin{pmatrix} 3 & -\sqrt{\frac{3}{2}} \\ -\sqrt{\frac{3}{2}} & 4 \end{pmatrix} \end{array}$$

at threshold

$$\omega_i \sim m_i, \quad 3.3 m_\pi \sim m_K$$

$$\Rightarrow V_{\bar{K}N} \sim 2.5 V_{\pi\Sigma}$$

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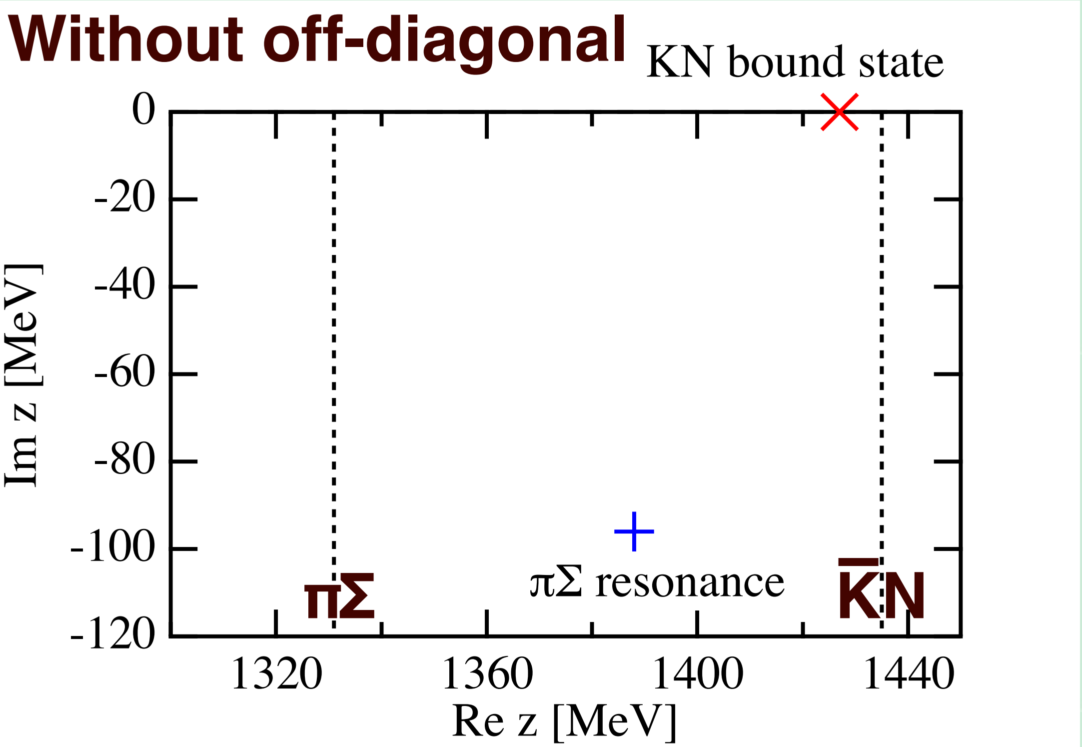

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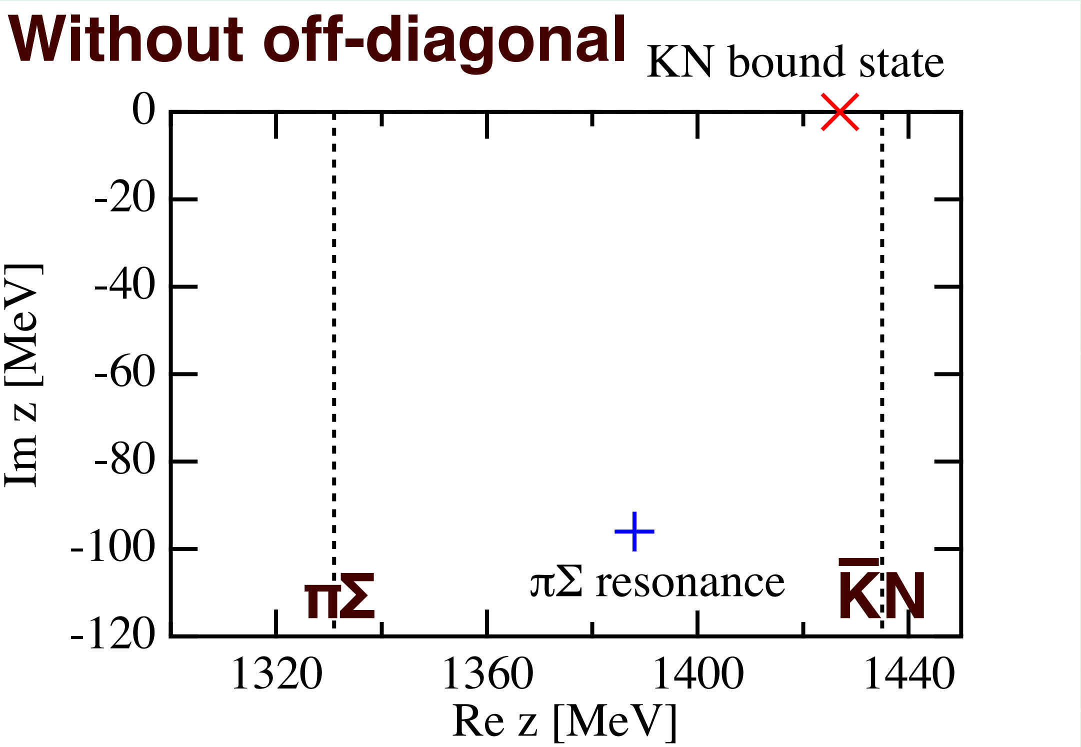

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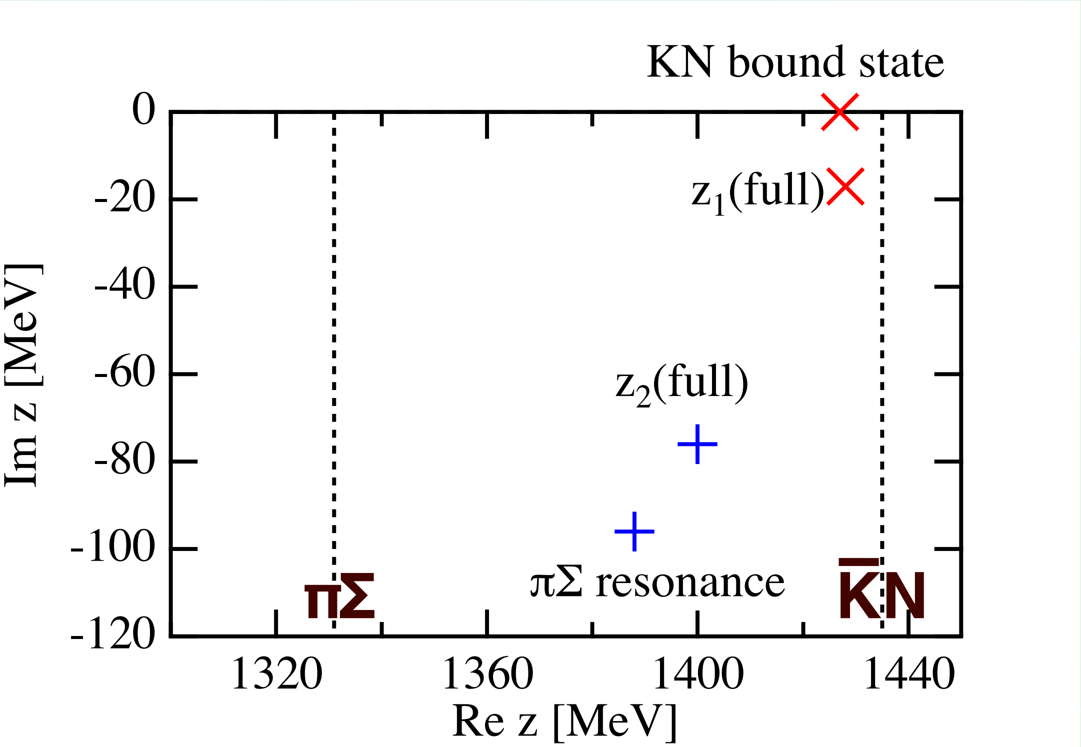


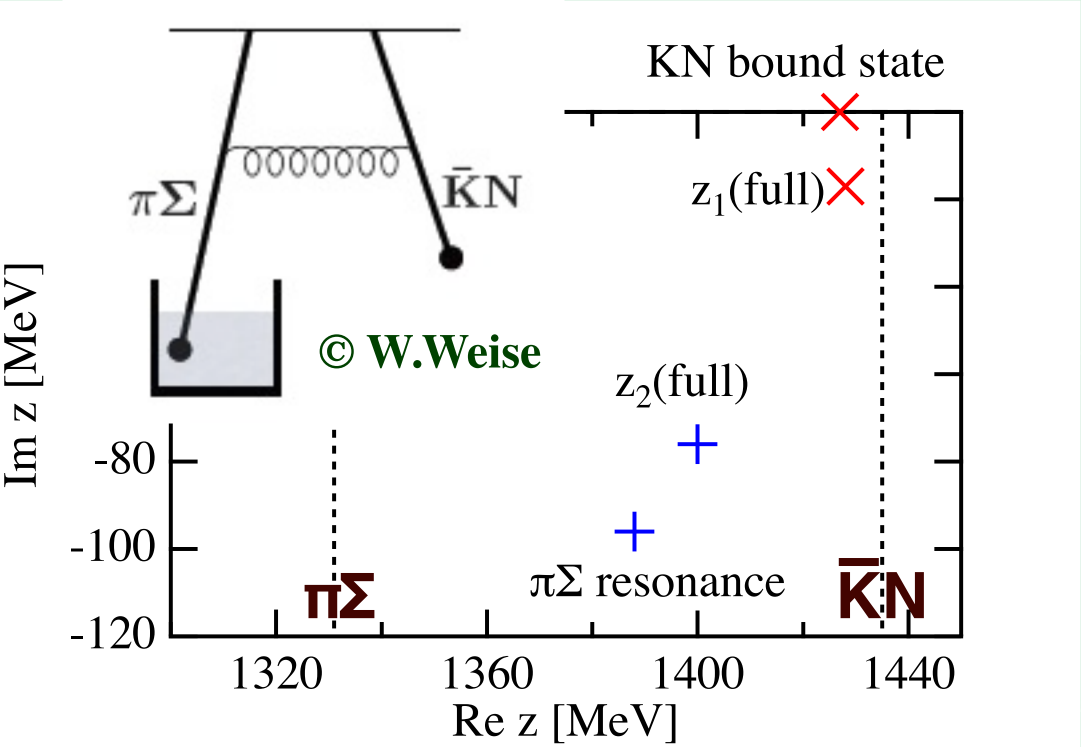
Origin of the two-pole structure

Leading order chiral interaction for K̄N-πΣ channel

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

$$V_{ij} = -C_{ij}\frac{\omega_i+\omega_j}{4f^2}$$

$$\begin{array}{ccc} & \bar{K}N & \pi\Sigma \\ C_{ij} = & \multicolumn{2}{c}{\begin{pmatrix} 3 & -\sqrt{\frac{3}{2}} \\ -\sqrt{\frac{3}{2}} & 4 \end{pmatrix}} \end{array}$$



at threshold

$$\omega_i \sim m_i, \quad 3.3m_\pi \sim m_K$$

$$\Rightarrow V_{\bar{K}N} \sim 2.5V_{\pi\Sigma}$$

Very strong attraction in K̄N (higher energy) --> bound state
Strong attraction in πΣ (lower energy) --> resonance

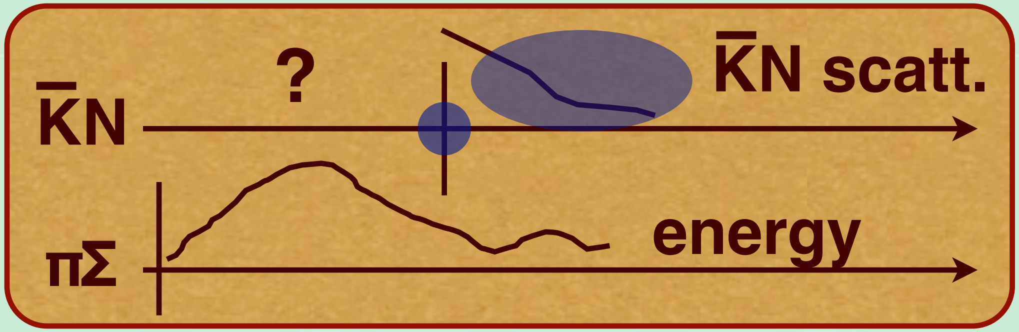
Model dependence? Effects from higher order terms?

Experimental constraints for S=-1 MB scattering

K-p total cross sections (bubble chamber, large errors)

$\bar{K}N$ threshold observables

- threshold branching ratios (old but accurate)
- K-p scattering length



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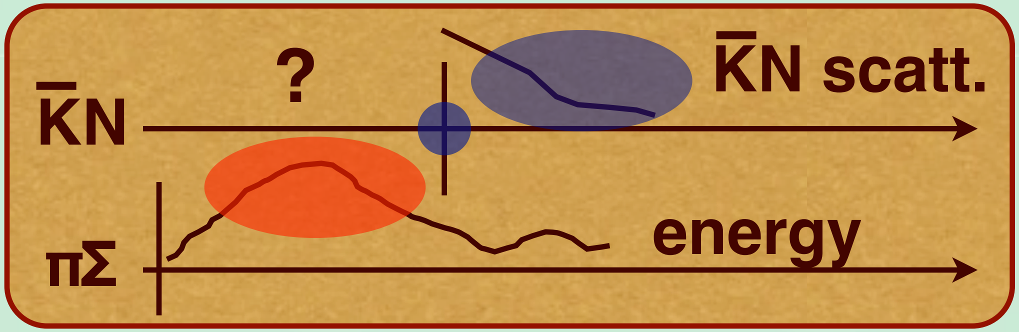

πΣ mass spectra

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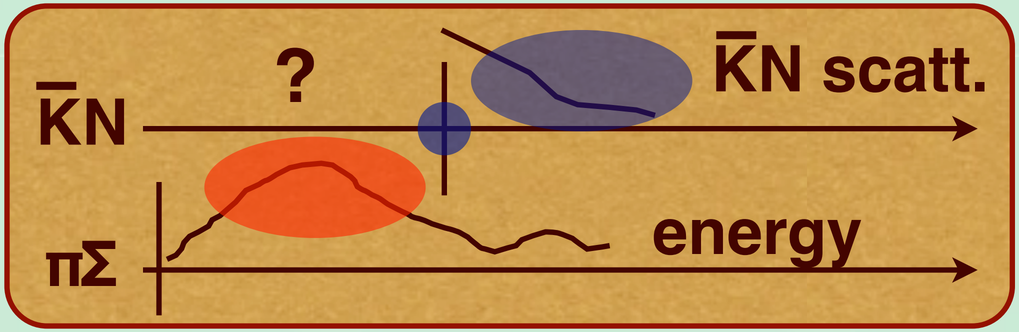

πΣ mass spectra

- new data is becoming available (LEPS, CLAS, HADES,...)
- normalization, reaction dependence,... <-- to be predicted?

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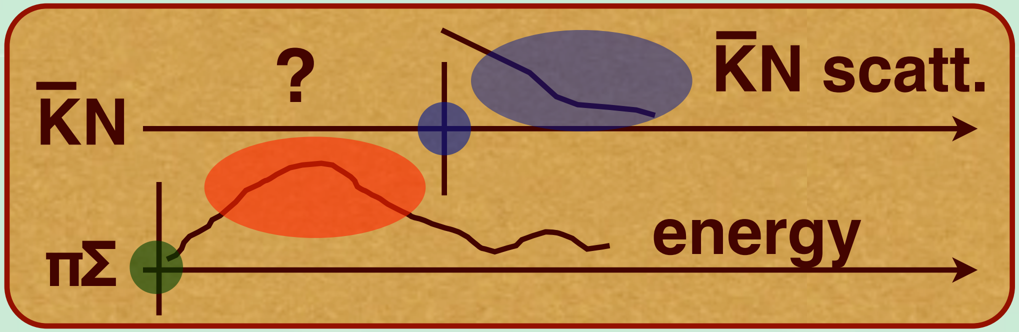


πΣ mass spectra

- new data is becoming available (LEPS, CLAS, HADES,...)
- normalization, reaction dependence,... <-- to be predicted?

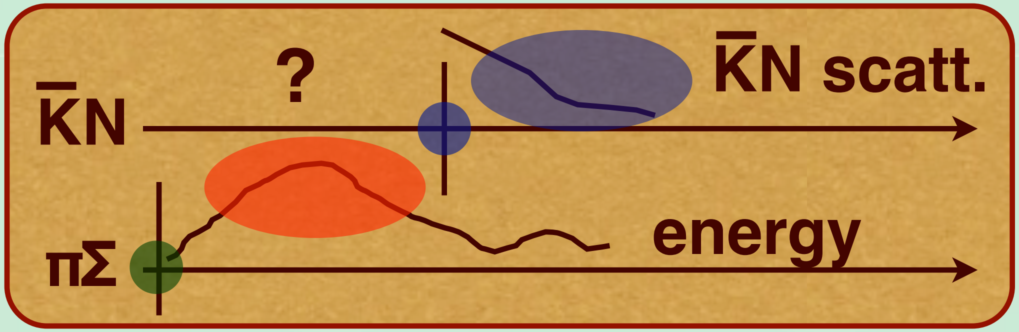
πΣ threshold observables (so far no data)

Experimental constraints for S=-1 MB scattering

K-p total cross sections (bubble chamber, large errors)

$\bar{K}N$ threshold observables

- threshold branching ratios (old but accurate)
- K-p scattering length <-- SIDDHARTA exp.



$\pi\Sigma$ mass spectra

- new data is becoming available (LEPS, CLAS, HADES,...)
- normalization, reaction dependence,... <-- to be predicted?

$\pi\Sigma$ threshold observables (so far no data)

Constraints from $\overline{\mathrm{K}}$N data

- K-p total cross sections

$$K^- p \to (K^- p, \bar{K}^0 n, \pi^0 \Lambda, \pi^0 \Sigma^0, \pi^+ \Sigma^-, \pi^- \Sigma^+)$$

Constraints from $\bar{\mathrm{K}}$N data

- K-p total cross sections

$$K^- p \to (K^- p, \bar{K}^0 n, \pi^0\Lambda, \pi^0\Sigma^0, \pi^+\Sigma^-, \pi^-\Sigma^+)$$

- Threshold branching ratios

$$\gamma = \frac{\Gamma(K^- p \to \pi^+\Sigma^-)}{\Gamma(K^- p \to \pi^-\Sigma^+)} = 2.36 \pm 0.04$$

$$R_c = \frac{\Gamma(K^- p \to \pi^+\Sigma^-, \pi^-\Sigma^+)}{\Gamma(K^- p \to \text{all inelastic channels})} = 0.664 \pm 0.011$$

$$R_n = \frac{\Gamma(K^- p \to \pi^0\Lambda)}{\Gamma(K^- p \to \text{neutral states})} = 0.189 \pm 0.015$$

R.J. Nowak, *et al.*, Nucl. Phys. B139, 61 (1978); D.N. Tovee, *et al.*, *ibid*, B33, 493 (1971)

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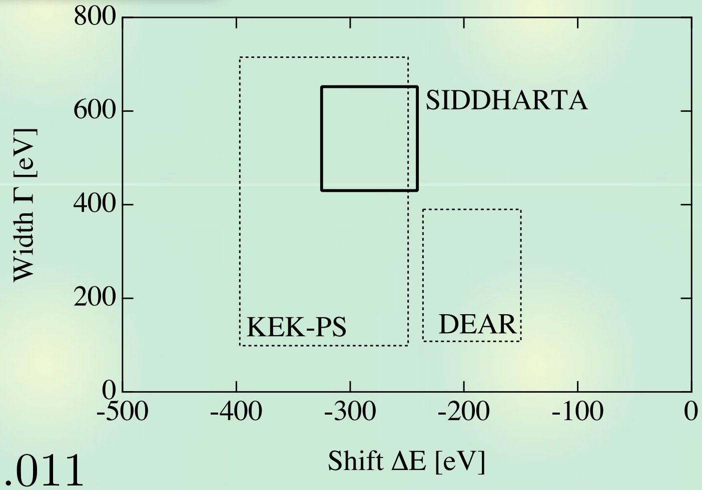

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- Shift and width of 1s level of kaonic hydrogen (SIDDHARTA)

$$\Delta E = -283 \pm 36 \pm 6 \text{ eV}, \quad \Gamma = 541 \pm 89 \pm 22 \text{ eV}$$

Bazzi, *et al.*, arXiv:1105.3090 [nucl-ex]

$$\Delta E - \frac{i}{2}\Gamma = -2\alpha^3\mu_c^2 a_{K^-p}[1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p}]$$ **<-- scattering length**

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

Construction of the realistic amplitude

Systematic χ2 fitting with SIDDHARTA data

Y. Ikeda, T. Hyodo, W. Weise, in preparation

Interaction kernel: NLO ChPT

B. Borasoy, R. Nissler, W. Weise, Eur. Phys. J. A25, 79-96 (2005);
B. Borasoy, U.G. Meissner, R. Nissler, Phys. Rev. C74, 055201 (2006)

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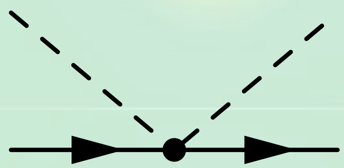
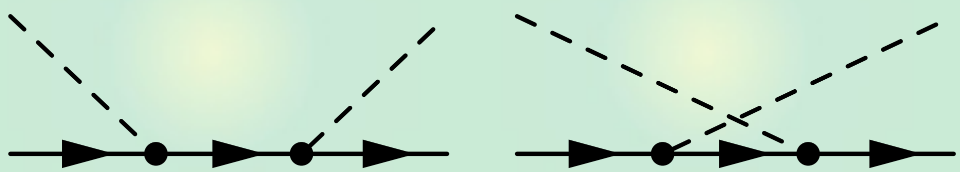


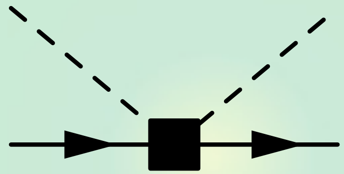
$\mathcal{O}(p)$

2) Born terms



$\mathcal{O}(p)$

3) NLO terms



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

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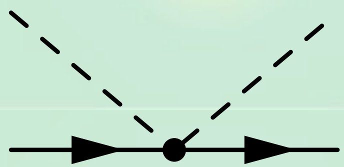
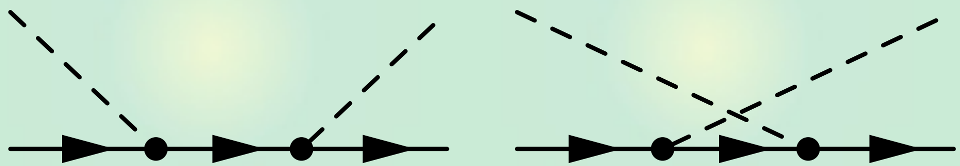


$\mathcal{O}(p)$

WT model

2) Born terms



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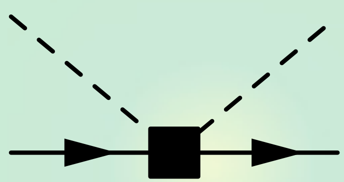

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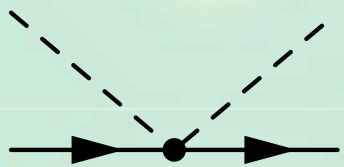
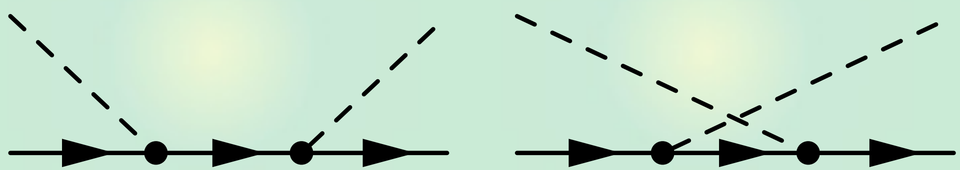


$\mathcal{O}(p)$

WT model

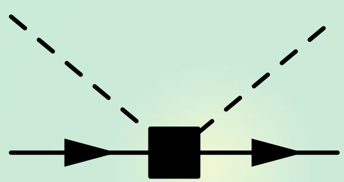
2) Born terms



$\mathcal{O}(p)$

WTB model

3) NLO terms



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

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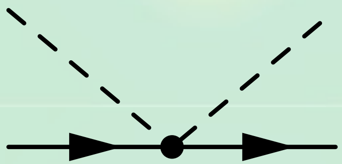
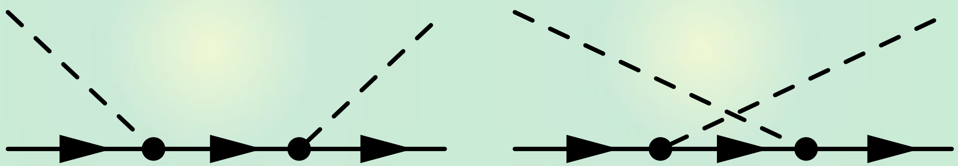


$\mathcal{O}(p)$

WT model

2) Born terms



$\mathcal{O}(p)$

WTB model

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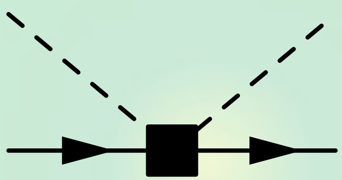

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NLO model

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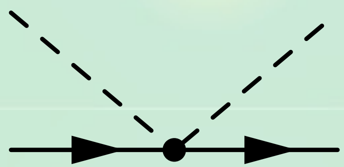

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WT model

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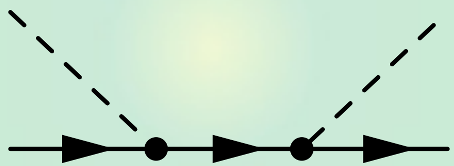

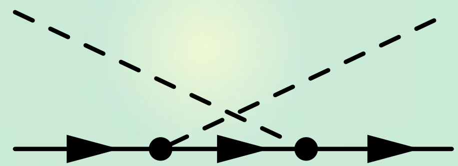

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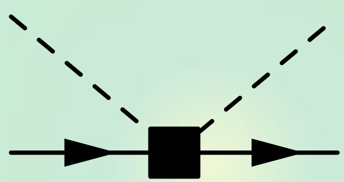


$\mathcal{O}(p^2)$

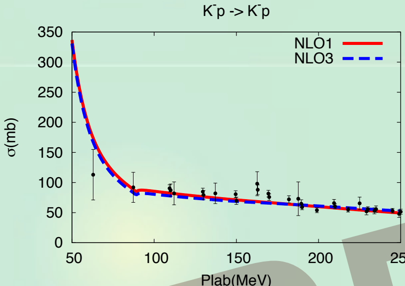
NLO model

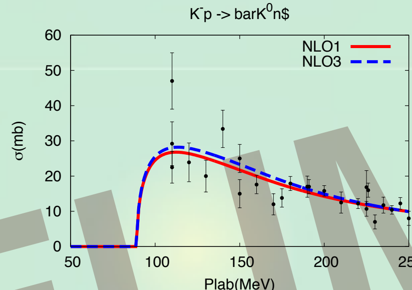
Parameters: 6 cutoffs (+ 7 low energy constants in NLO)

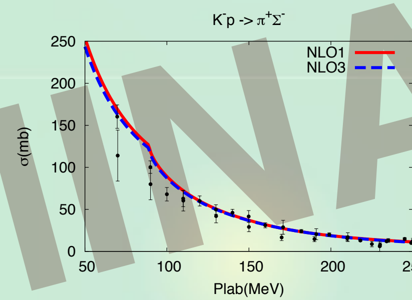
Result by NLO model

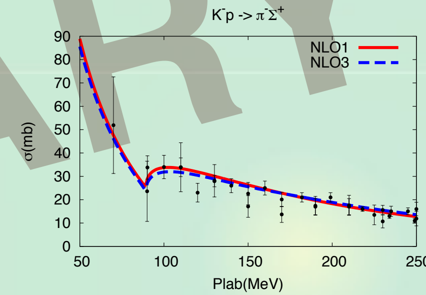
Observables	Theory	Experiment
ΔE (eV)	306	283 ± 42
Γ (eV)	591	541 ± 111
γ	2.36	2.36 ± 0.04
R_c	0.659	0.664 ± 0.011
R_n	0.192	0.189 ± 0.015
a_{K^-p} (fm)	$-0.81 + i0.87$	
Poles of the $\Lambda(1405)$ (MeV)	$1424.2 - i26.3,\ 1380.7 - i81.3$	

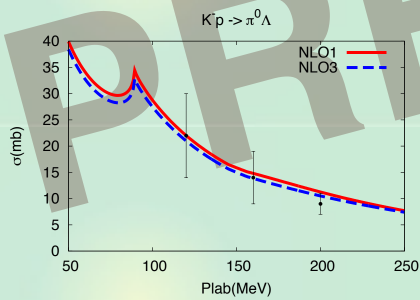
PRELIMINARY

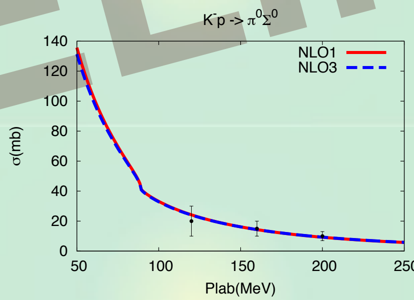


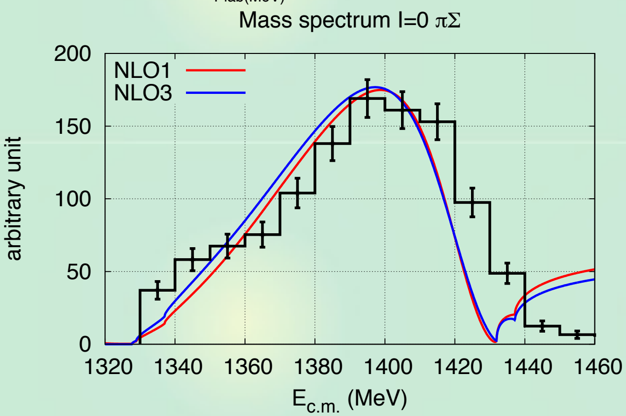












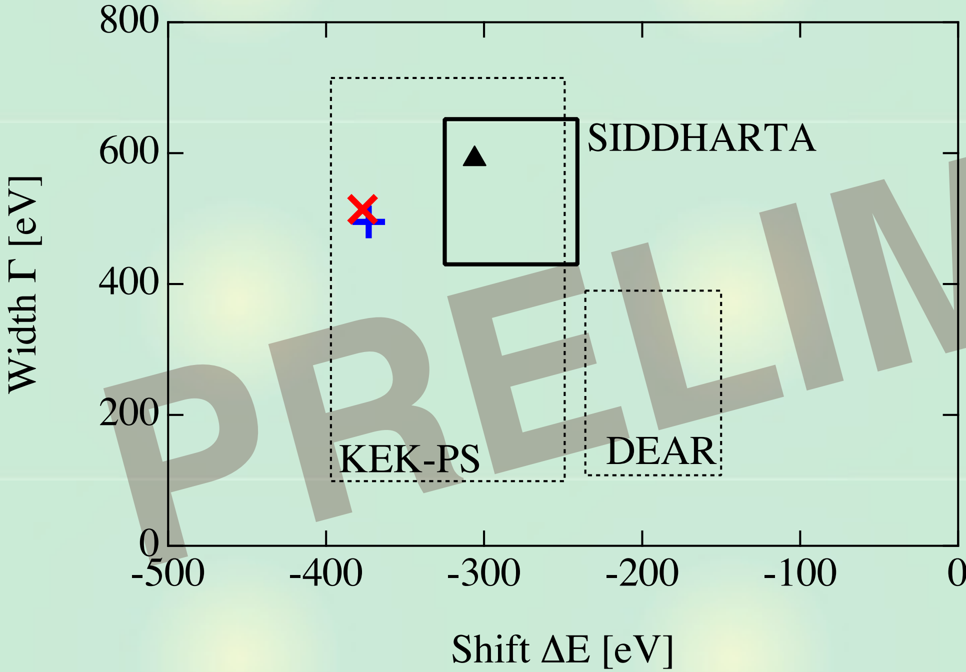
Good description of data (χ2/dof ~ 1)

Summary of results

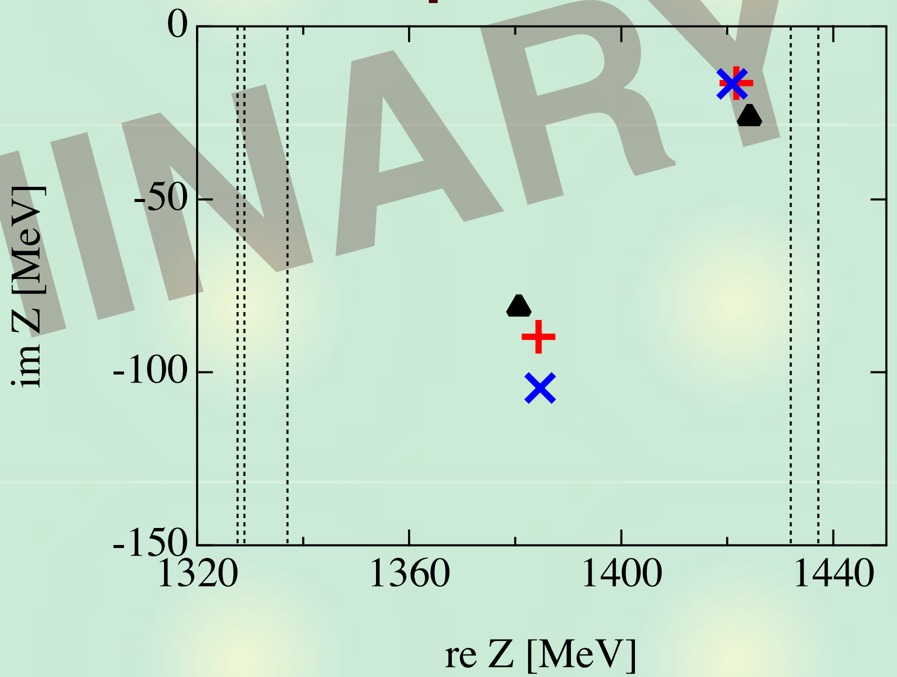
Results from three models

	WT	WTB	NLO
χ2/dof	1.12	1.15	0.957

Shift and width



Pole positions



Error analysis is now underway

Y. Ikeda, T. Hyodo, W. Weise, in preparation

πΣ threshold behavior

Effect of the πΣ threshold data for $\bar{K}$N-πΣ amplitude

Y. Ikeda, T. Hyodo, D. Jido, H. Kamano, T. Sato, K. Yazaki,
arXiv:1101.5190 [nucl-th], to appear in Prog. Theor. Phys.

Extrapolations with a given $\bar{K}$N(I=0) scattering length
--> uncertainty in subthreshold

Model	A1	A2	B E-dep	B E-indep
parameter ($\pi\Sigma$)	$d_{\pi\Sigma} = -1.67$	$d_{\pi\Sigma} = -2.85$	$\Lambda_{\pi\Sigma} = 1005$ MeV	$\Lambda_{\pi\Sigma} = 1465$ MeV
parameter ($\bar{K}N$)	$d_{\bar{K}N} = -1.79$	$d_{\bar{K}N} = -2.05$	$\Lambda_{\bar{K}N} = 1188$ MeV	$\Lambda_{\bar{K}N} = 1086$ MeV
pole 1 [MeV]	$1422 - 16i$	$1425 - 11i$	$1422 - 22i$	$1423 - 29i$
pole 2 [MeV]	$1375 - 72i$ (R)	1321 (B)	$1349 - 54i$ (R)	1325 (V)
$a_{\pi\Sigma}$ [fm]	0.934	-2.30	1.44	5.50
r_e [fm]	5.02	5.89	3.96	0.458
$a_{\bar{K}N}$ [fm] (input)	$-1.70 + 0.68i$	$-1.70 + 0.68i$	$-1.70 + 0.68i$	$-1.70 + 0.68i$

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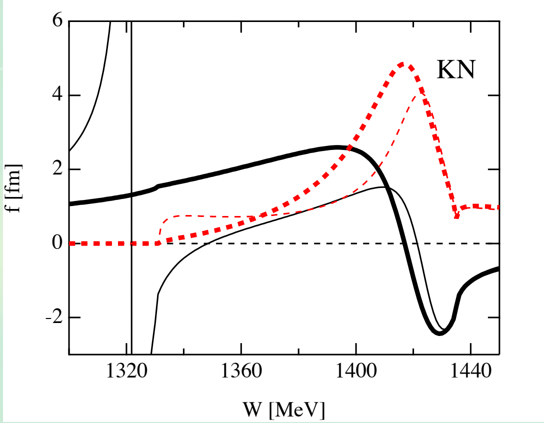
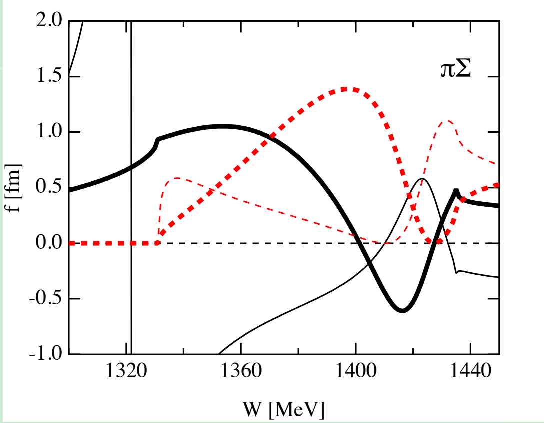
subthreshold behavior

<-- πΣ scattering length, effective range





Determination of the $\pi\Sigma$ scattering length

$\pi\,\pi$ scattering length from K --> $\pi\,\pi\,\pi$ decay

N. Cabibbo, Phys. Rev. Lett. 93, 121801 (2004);
NA48/2, J.R. Batley, *et al.*, Phys. Lett. B686, 101 (2010)

Determination of the πΣ scattering length

π π scattering length from K --> π π π decay

N. Cabibbo, Phys. Rev. Lett. 93, 121801 (2004);
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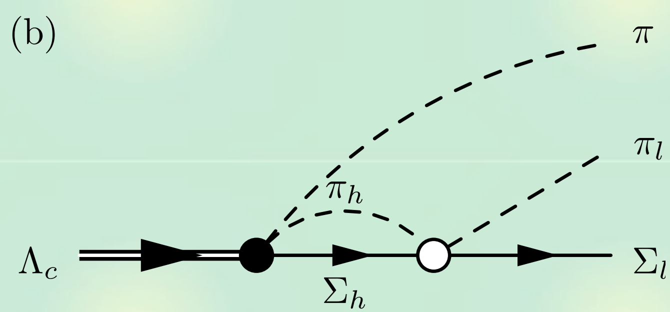
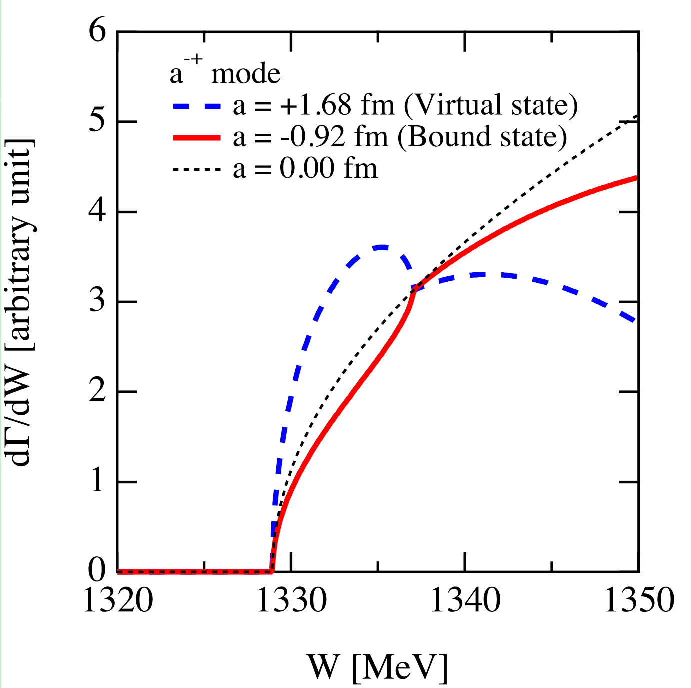
Analogy: πΣ scattering lengths from Λc --> π π Σ decays

T. Hyodo, M. Oka, arXiv:1105.5494 [nucl-th]

isospin violation
+ threshold cusp
+ amplitude interference





Expansion of the spectrum around cusp --> scattering length

Summary 1

We study the $\bar{K}N$-$\pi\Sigma$ interaction and $\Lambda(1405)$ based on chiral SU(3) symmetry and unitarity

- **Chiral symmetry constrains the NG boson dynamics with hadrons.**

- **Unitarity should be taken into account for a strongly interacting system.**

- **Two poles for $\Lambda(1405)$**

  <-- attractive $\bar{K}N$ and $\pi\Sigma$ interactions

T. Hyodo, D. Jido, arXiv:1104.4474, submitted to Prog. Part. Nucl. Phys.

Summary 2

Recent developments to construct a realistic meson-baryon interaction

- **New $\bar{K}N$ threshold data by SIDDAHRTA**
  - systematic χ2 analysis with NLO terms

    Y. Ikeda, T. Hyodo, W. Weise, in preparation

- **Threshold information of πΣ channel**
  - importance of πΣ threshold behavior

    Y. Ikeda, T. Hyodo, D. Jido, H. Kamano, T. Sato, K. Yazaki, arXiv:1101.5190 [nucl-th], to appear in Prog. Theor. Phys.

  - scattering length from Λc decay

    T. Hyodo, M. Oka, arXiv:1105.5494 [nucl-th]