Antikaon-Nuclear Interactions

Wolfram Weise
Technische Universität München

- Brief History:
  Antikaons in Matter, Kaon Condensation and all that
- Low-Energy QCD with Strange Quarks
  - Chiral SU(3) Dynamics and Coupled Channels
  - $\bar{\mathrm{K}}$-Nucleon Effective Interaction
- Antikaon-Nuclear Quasibound States ?
  - Prototype Systems: $\mathbf{K^-pp}$ and $\mathbf{K^-Nuclei}$

Brief History, Part I

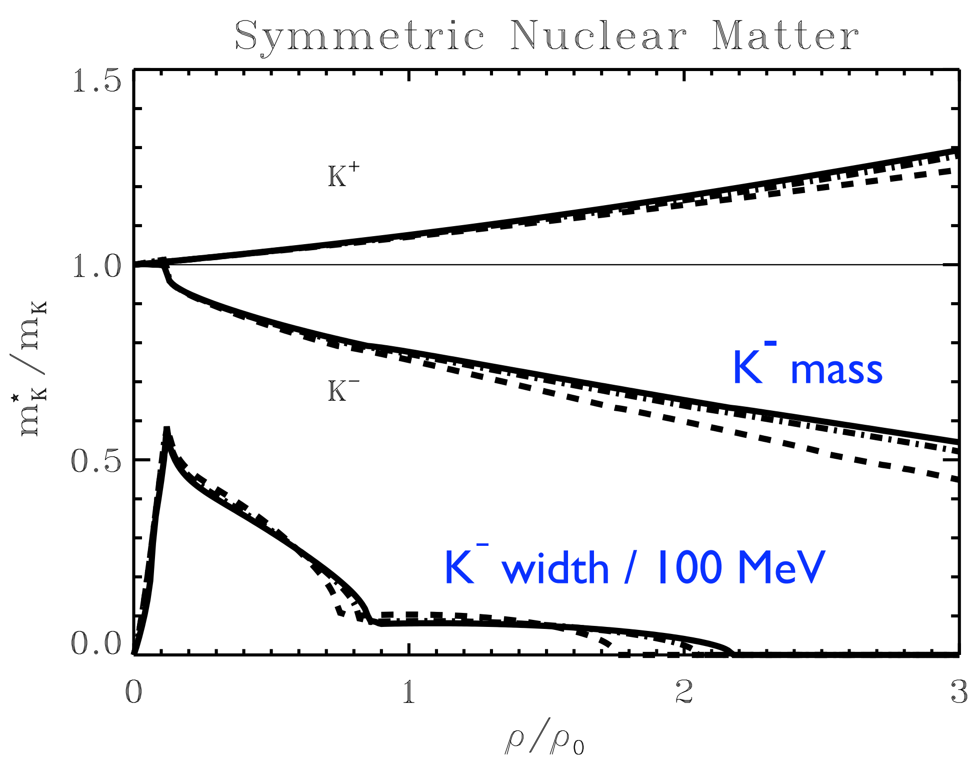
Kaons and Antikaons in Nuclear Matter

In-medium Chiral SU(3) Dynamics with Coupled Channels

- **Kaon spectrum in matter** determined by:

$$\omega^2 - \vec{q}^2 - m_K^2 - \Pi_K(\omega, \vec{q}; \rho) = 0$$

$$\Pi_{K^-} = 2\omega U_{K^-} = -4\pi \left[f_{K^-p}\, \rho_p + f_{K^-n}\, \rho_n \right] + \ldots + $$ **Pauli blocking, Fermi motion, 2N correlations**



T. Waas, N. Kaiser, W.W.: Phys. Lett. B 379 (1996) 34

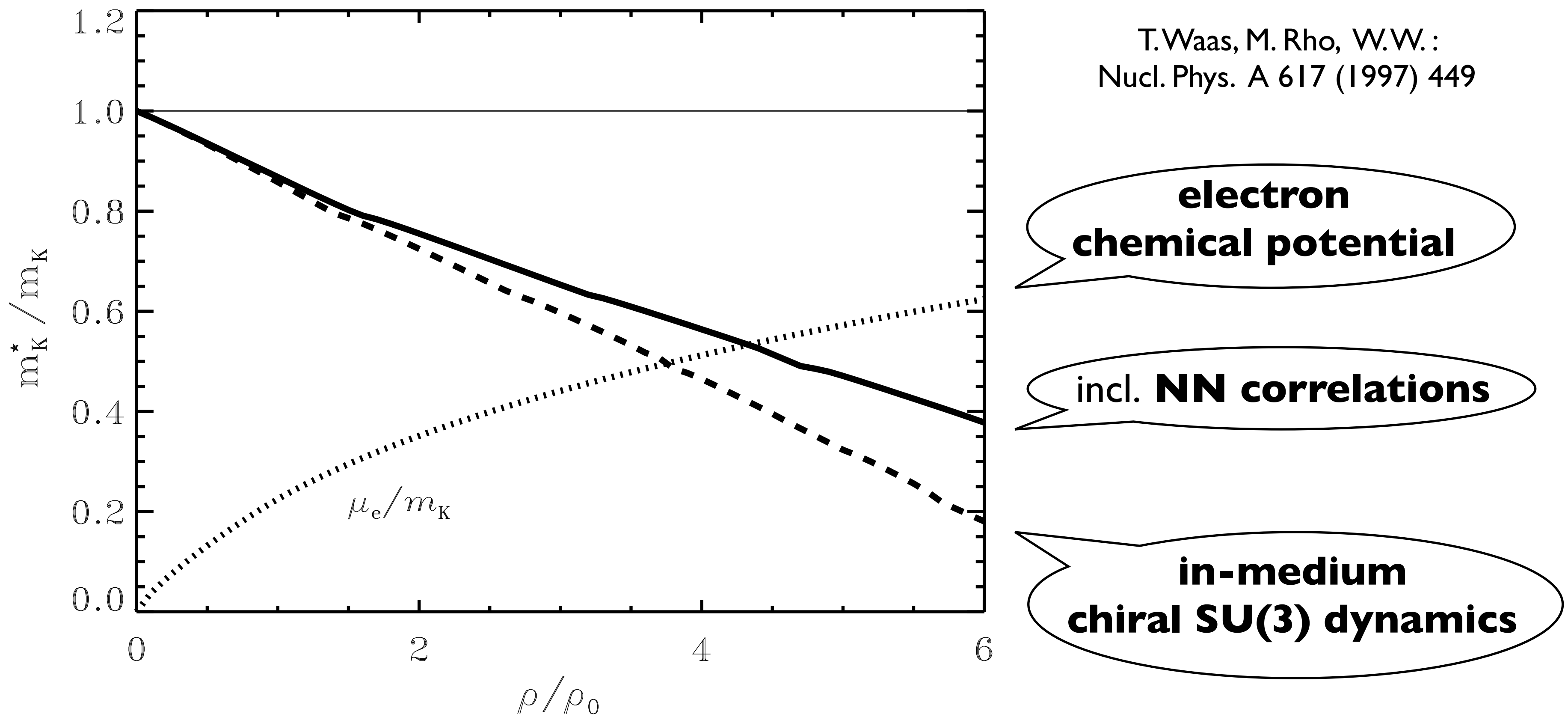
T. Waas, W.W.: Nucl. Phys. A 625 (1997) 287

- Note: In-medium $\bar{K}$ width drops when mass falls below $\pi\Sigma$ threshold

Brief History, Part II

Kaon Condensation in Neutron Matter

- first suggested by D. Kaplan, A. Nelson (1985) on the basis of **attractive K^-N Weinberg-Tomozawa term**
- at high density, energetically favourable to condense K^-



T. Waas, M. Rho, W.W.: Nucl. Phys. A 617 (1997) 449

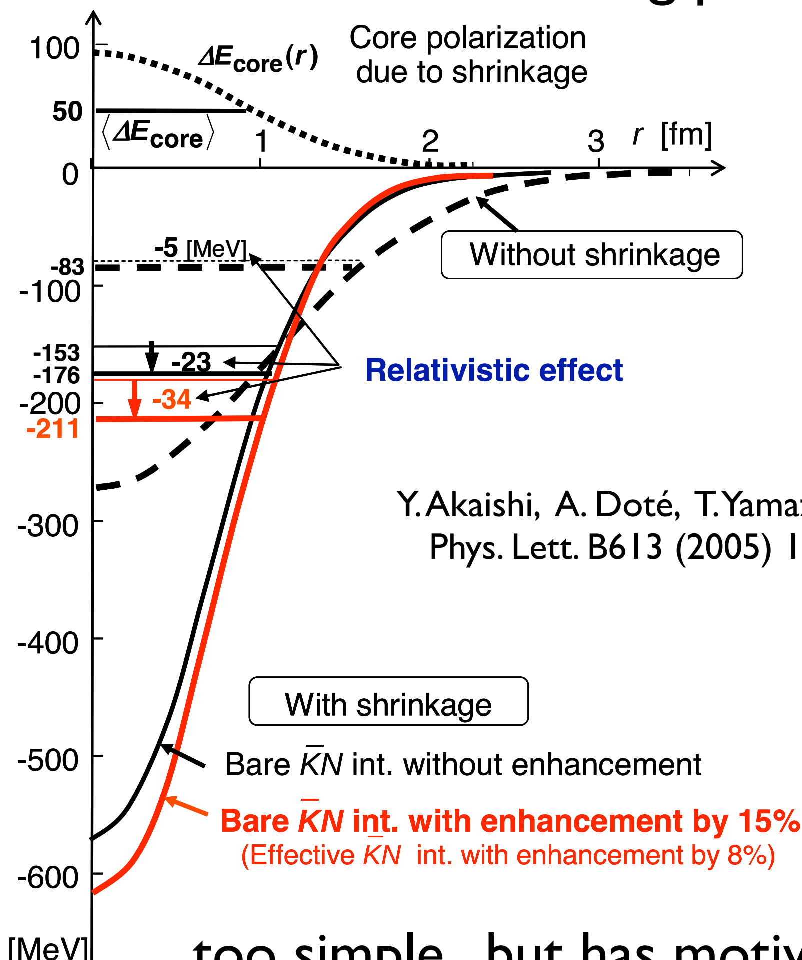
- conversion to hyperons via $K^-NN \rightarrow YN$?

Brief History, Part III

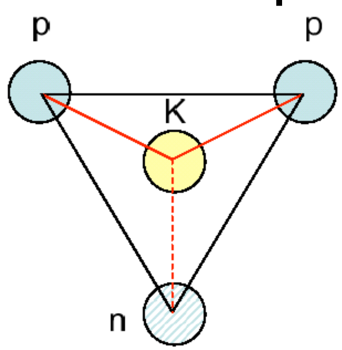
Deeply Bound Antikaon-Nuclear Clusters ?

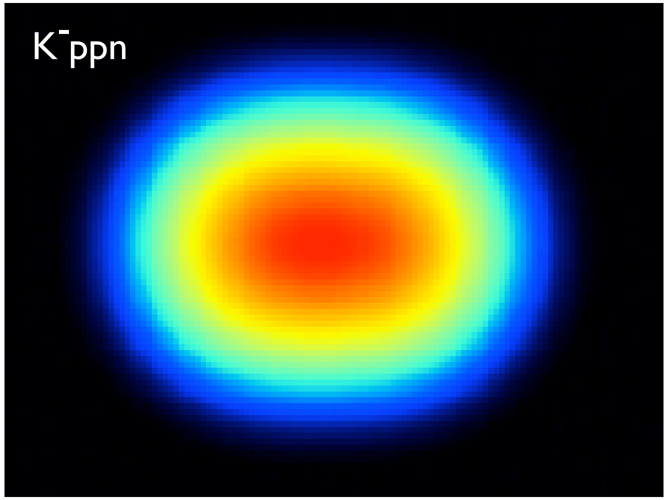
Y. Akaishi, T. Yamazaki, Phys. Rev. C65 (2002) 044005

- Calculation of deeply bound K^-ppn system using phenomenological $\bar{K}$N and NN potentials



Y. Akaishi, A. Doté, T. Yamazaki, Phys. Lett. B613 (2005) 140





... too simple, but has motivated a great amount of recent activities

1.

Framework: Low-Energy QCD with Strange Quarks

Chiral SU(3) Dynamics

- Non-perturbative (coupled-channels) approach to
  antikaon-nucleon interaction

- Important constraints:
  - $\bar{\mathrm{K}}\mathrm{N}$ threshold physics
  - $\pi\Sigma$ mass spectra

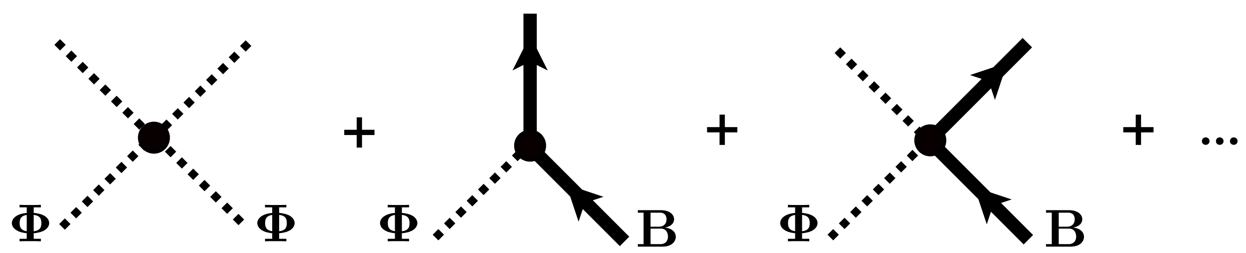
- Nature and properties of $\Lambda(1405)$ as
  $\bar{\mathrm{K}}\mathrm{N}$ quasibound state embedded in the $\pi\Sigma$ continuum

CHIRAL SU(3) EFFECTIVE FIELD THEORY

- Interacting systems of **NAMBU-GOLDSTONE BOSONS** (**pions**, **kaons**) coupled to **BARYONS**

$$\mathcal{L}_{eff} = \mathcal{L}_{mesons}(\Phi) + \mathcal{L}_B(\Phi, \Psi_B)$$

- Leading **DERIVATIVE** couplings (involving $\partial^\mu \Phi$) determined by spontaneously broken **CHIRAL SYMMETRY**



higher orders
with additional
low-energy constants

- Low-Energy Expansion: **CHIRAL PERTURBATION THEORY**

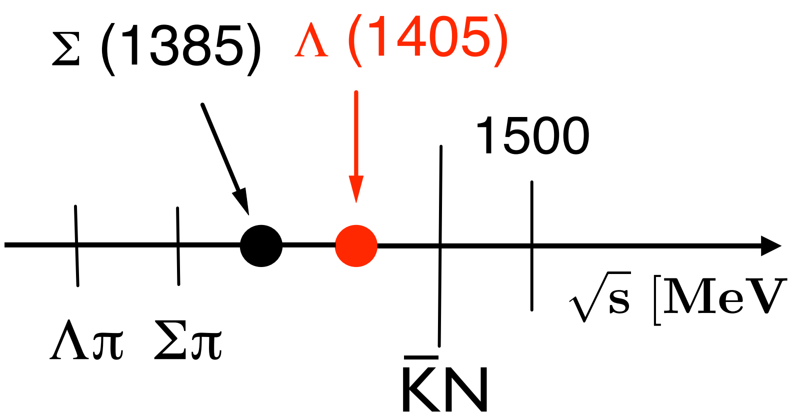
"small parameter": $\dfrac{p}{4\pi f_\pi} \sim \dfrac{\text{energy / momentum}}{1\ \text{GeV}}$

- works well for low-energy **pion-pion** and **pion-nucleon** interactions

► ... but **NOT** for systems with **strangeness** $S = -1$ ($\bar{K}N,\ \pi\Sigma,\ \dots$)

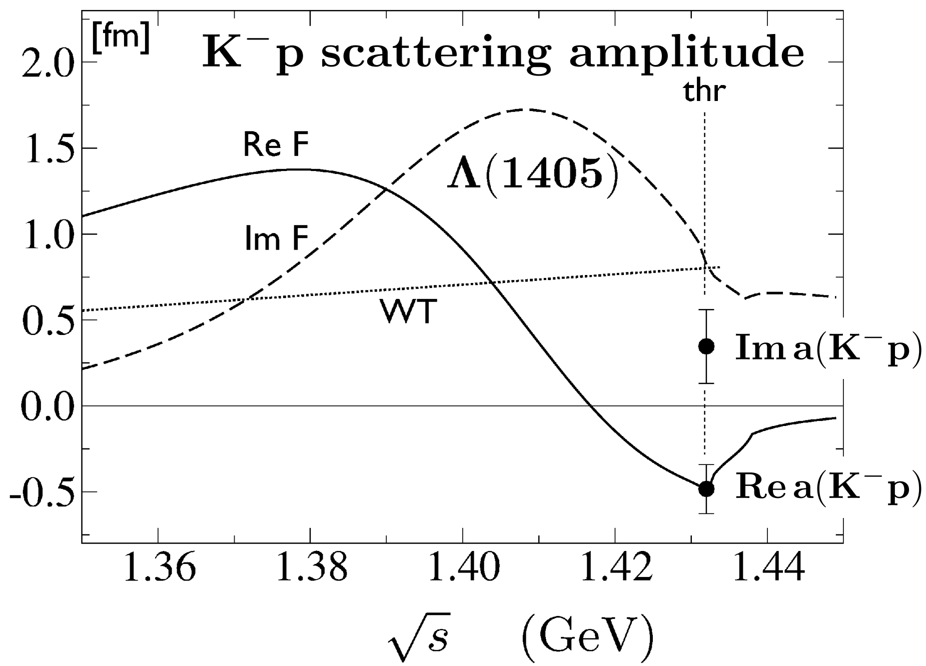
Low-Energy $\bar{K}N$ Interactions

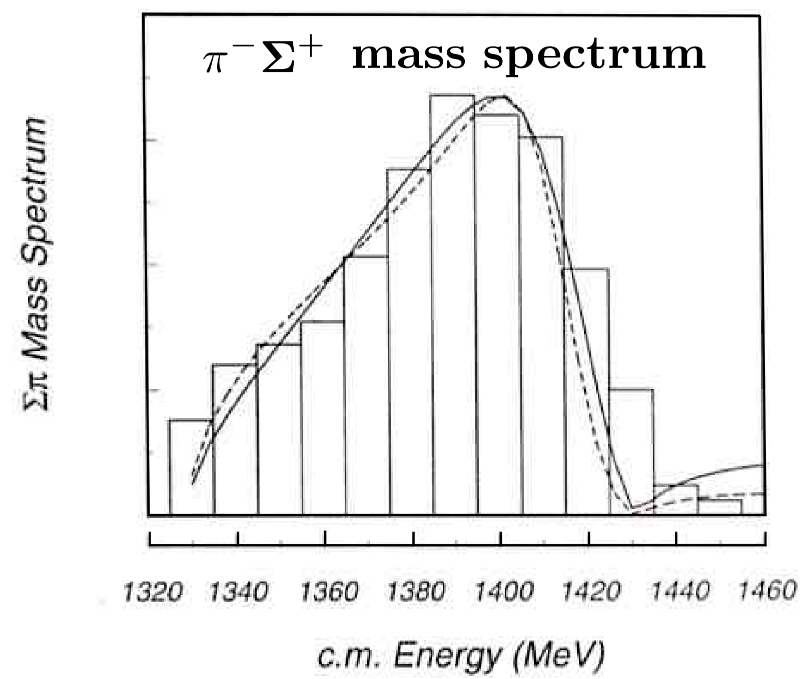
- Chiral Perturbation Theory **NOT** applicable: $\Lambda(1405)$ just below K^-p threshold



Non-perturbative
Coupled Channels
approach based on
Chiral SU(3) Dynamics

N. Kaiser, P. Siegel, W.W. (1995)
E. Oset, A. Ramos (1998)



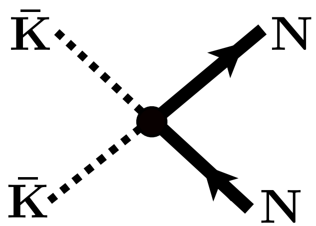


CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

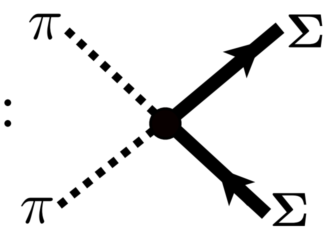
$$\mathbf{T_{ij} = K_{ij} + \sum_n K_{in}\, G_n\, T_{nj}}$$

- Leading s-wave I = 0 meson-baryon interactions (Weinberg-Tomozawa)

ch. 1 :



ch. 2 :

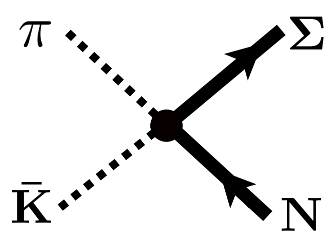


$$\mathbf{K_{11} = \frac{3}{2f^2}(\sqrt{s} - M_N)} \qquad \mathbf{K_{22} = \frac{2}{f^2}(\sqrt{s} - M_\Sigma)}$$

strong enough to produce
- $\bar{\mathrm{K}}\mathrm{N}$ **bound state**
- $\pi\Sigma$ **resonance**

- Channel coupling

  $\mathbf{12 \leftrightarrow 21}$:



$$\mathbf{K_{12} = \frac{-1}{2f^2}\sqrt{\frac{3}{2}}\left(\sqrt{s} - \frac{M_N + M_\Sigma}{2}\right)}$$

- Dynamical generation of $\Lambda(1405)$ as **quasi-bound KN (I = 0) state**

early history: R.H. Dalitz et al. (1967)

The TWO POLES scenario

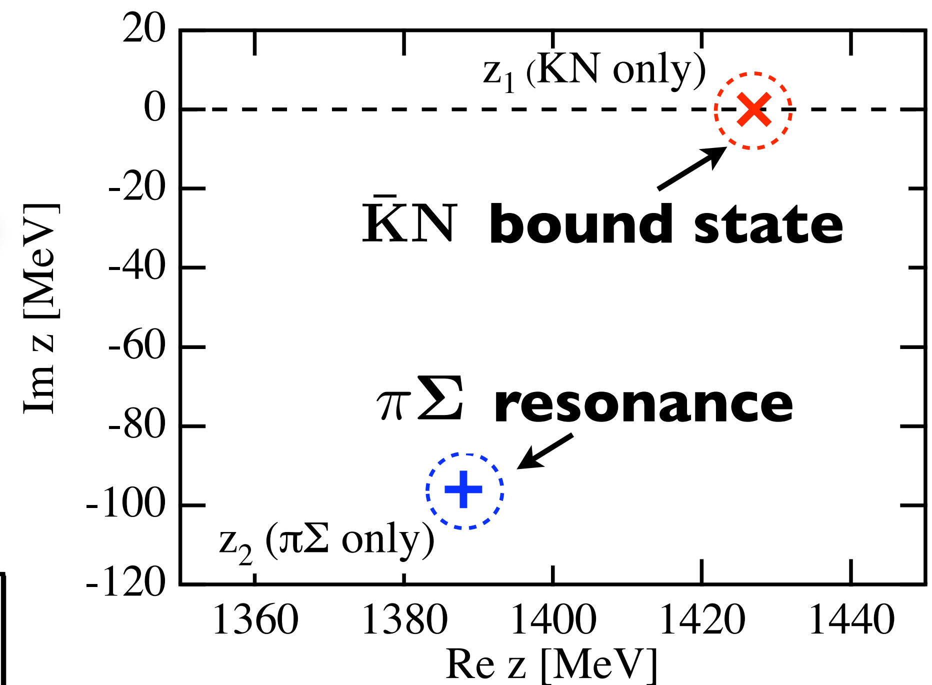
D. Jido et al., Nucl. Phys. A725 (2003) 181

- Singularities of $\bar{K}N$ amplitude in the complex energy plane

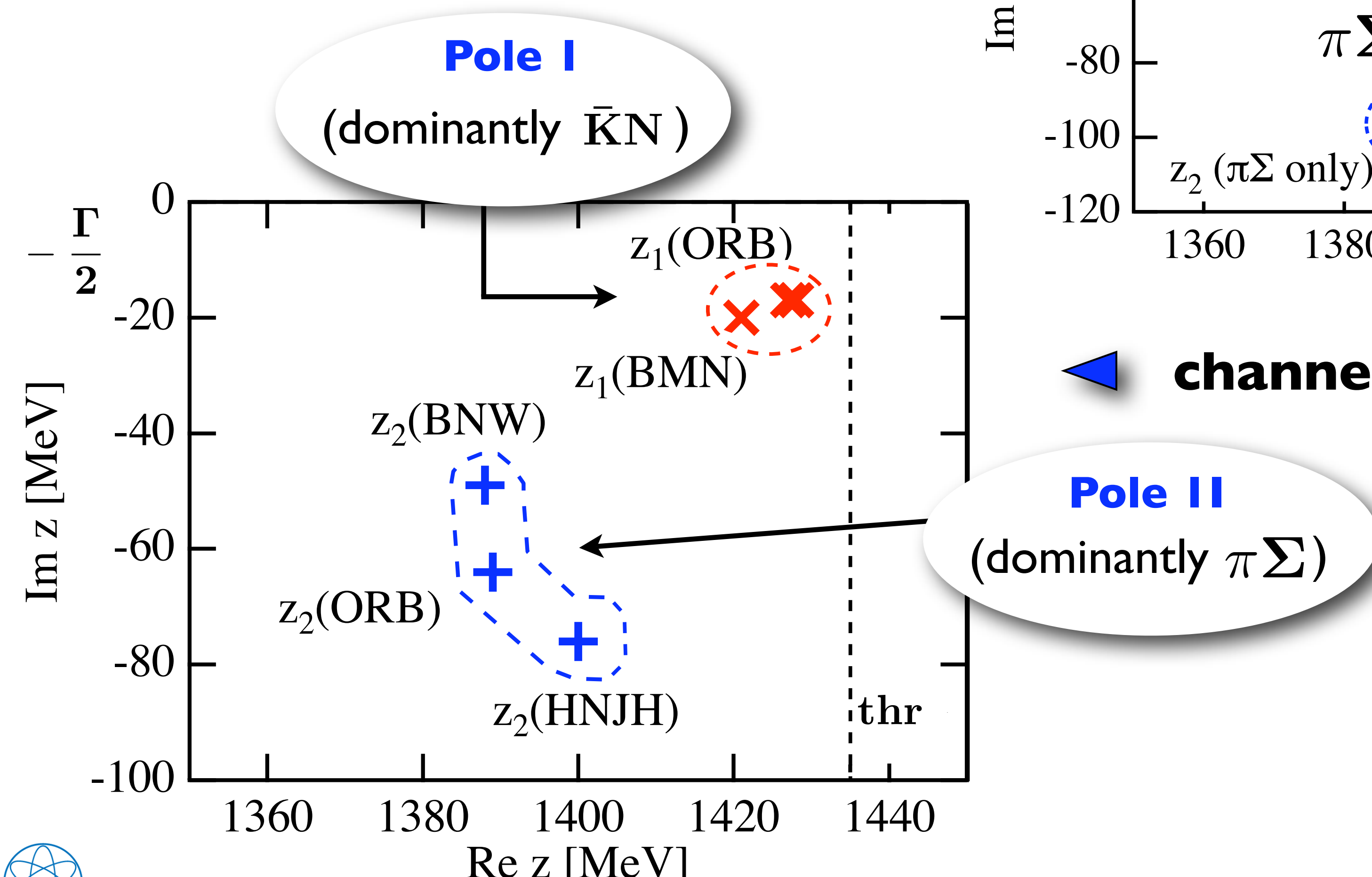
starting point:

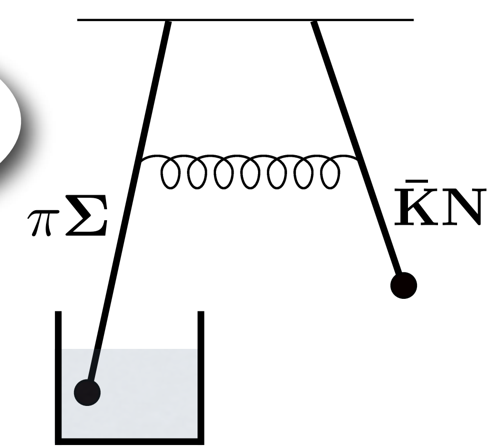
no channel coupling ▶

T. Hyodo, W.W., Phys. Rev. C77 (2008) 03524



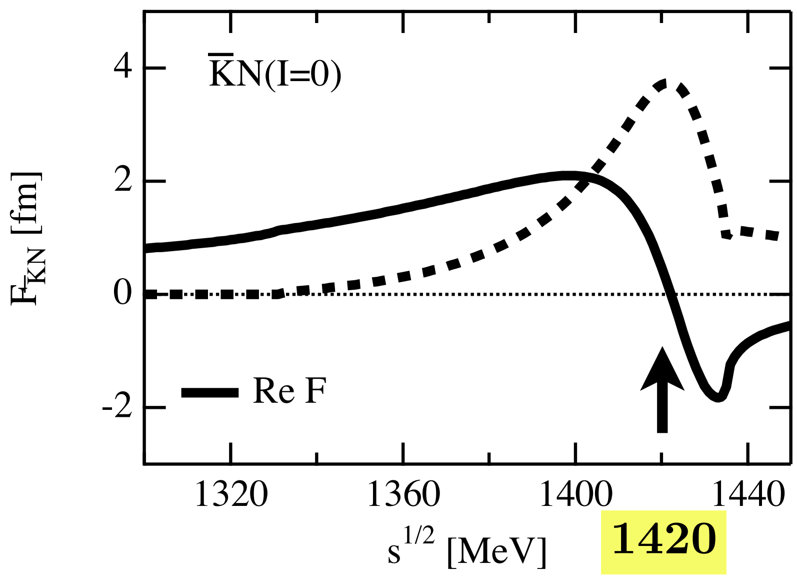
◀ **channel coupling** at work

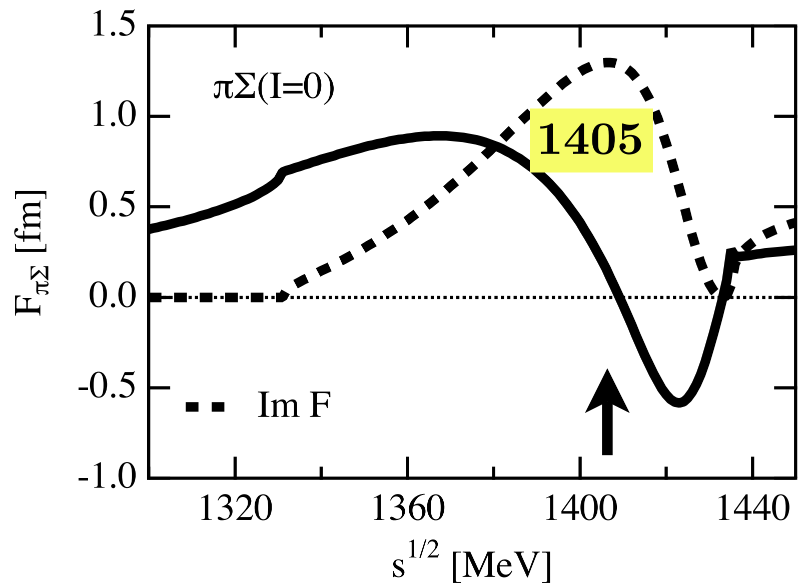




The TWO POLES scenario (contd.)

- $\bar{K}N$ and $\pi\Sigma$ amplitudes: T. Hyodo, W.W. : Phys. Rev. C77 (2008) 03524



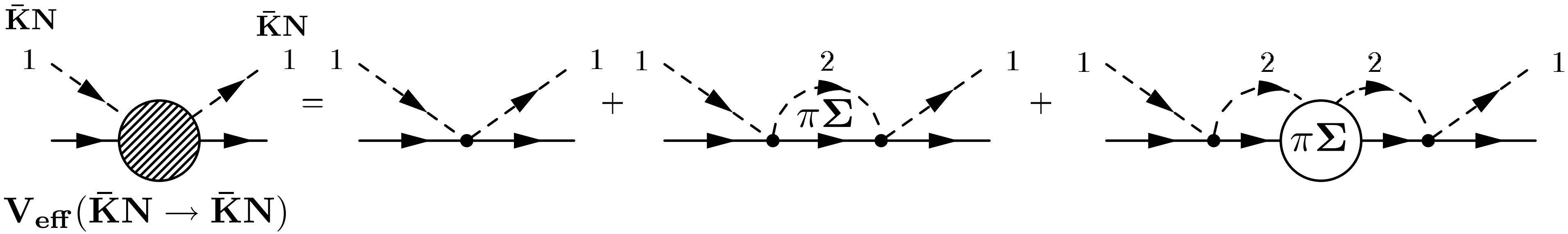


- **Note difference** in pole positions and spectra of $\bar{K}N$ and $\pi\Sigma$
  D. Jido et al., NP A725 (2003) 263

- Equivalent $\bar{K}N$ **effective interaction** should produce quasibound state at **1420** MeV (**not** 1405 MeV)

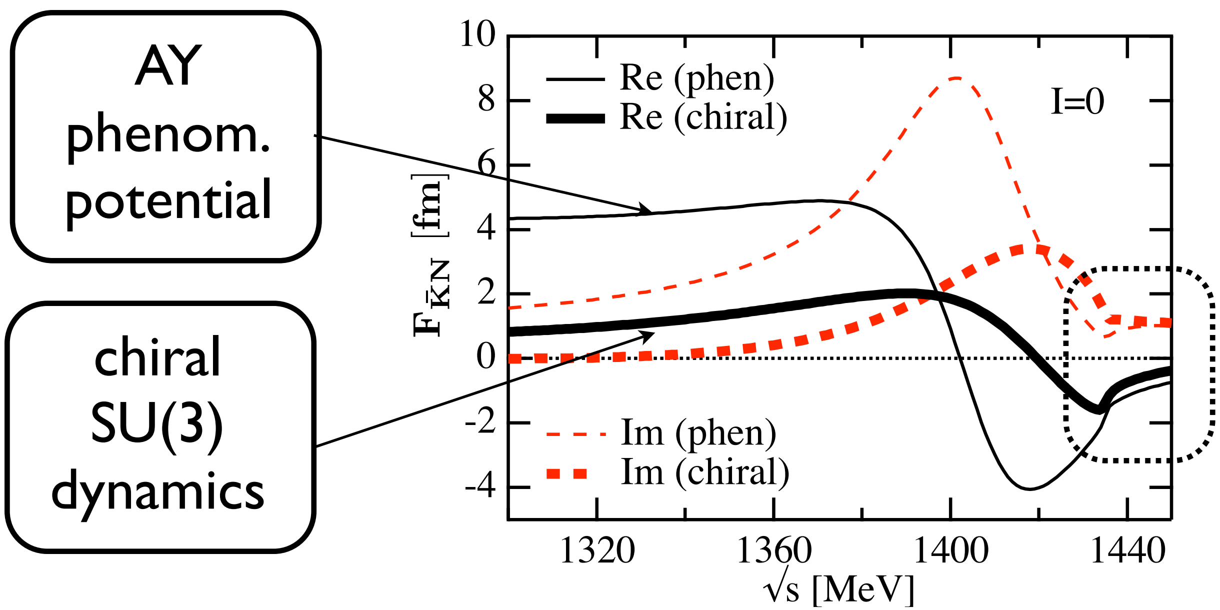
I = 0 $\bar{K}N$ Effective Interaction

T. Hyodo, W.W.: Phys. Rev. C 77 (2008) 03524



$V_{eff}(\bar{K}N \to \bar{K}N)$ is:

- **complex**
- **energy dependent**
- **non-local**



large differences in **subthreshold** extrapolations

- **Chiral dynamics** predicts significantly **weaker attraction** than AY (local, energy independent) potential in **far-subthreshold** region

2.

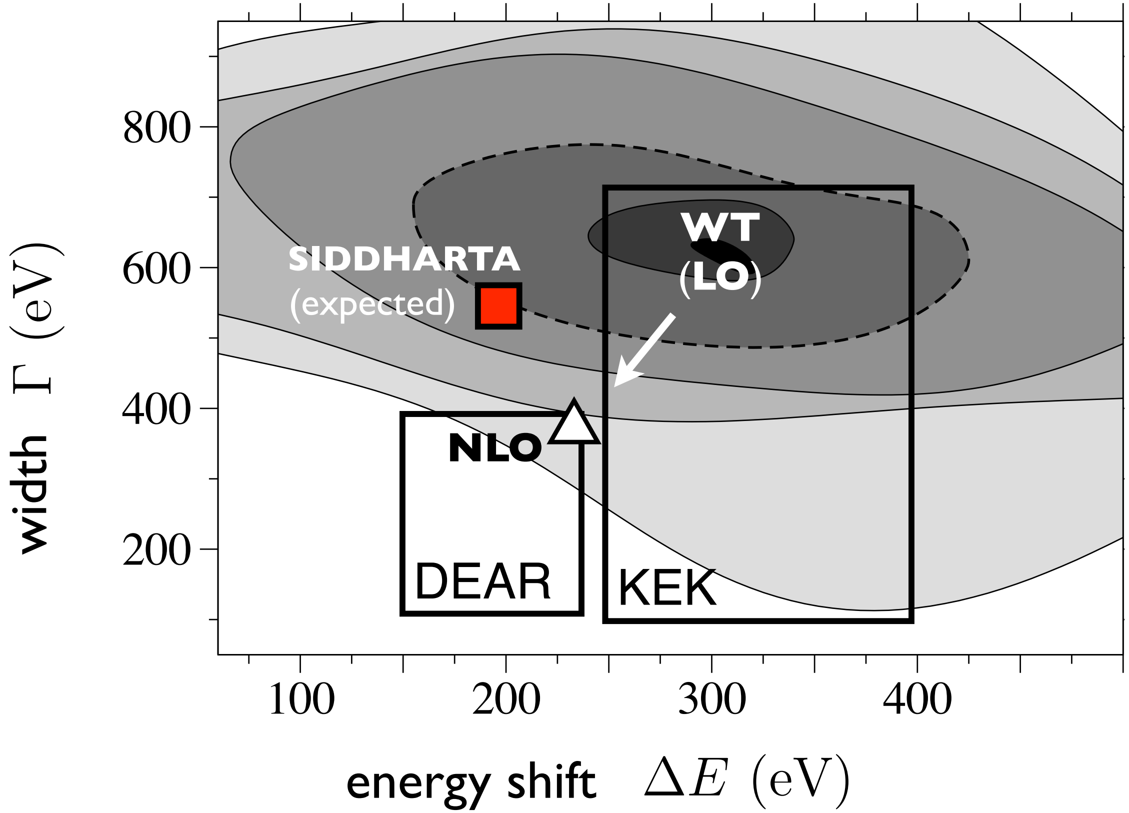
Results
Constraints
Extrapolations

- Kaonic hydrogen and antikaon-nucleon scattering length
- Low-energy antikaon-nucleon scattering
- Subthreshold extrapolations

. . .

$\bar{K}N$ Threshold Physics

- Precision measurements of **kaonic hydrogen**:



from **DEAR** to **SIDDHARTA**

- important constraints for **Chiral SU(3) Dynamics**

B. Borasoy et al.
Eur. Phys. J. A25 (2005) 79
Phys. Rev. C74 (2006) 055201

Deser-Trueman formula
+ corrections (Rusetsky et al.)

scattering length

a(K^-p) (**DEAR / LNF**)

- 0.47 (±0.10) + i **0.30** (±0.17) [fm]

(G. Beer et al., Phys. Rev. Lett. 94 (2005) 212302)

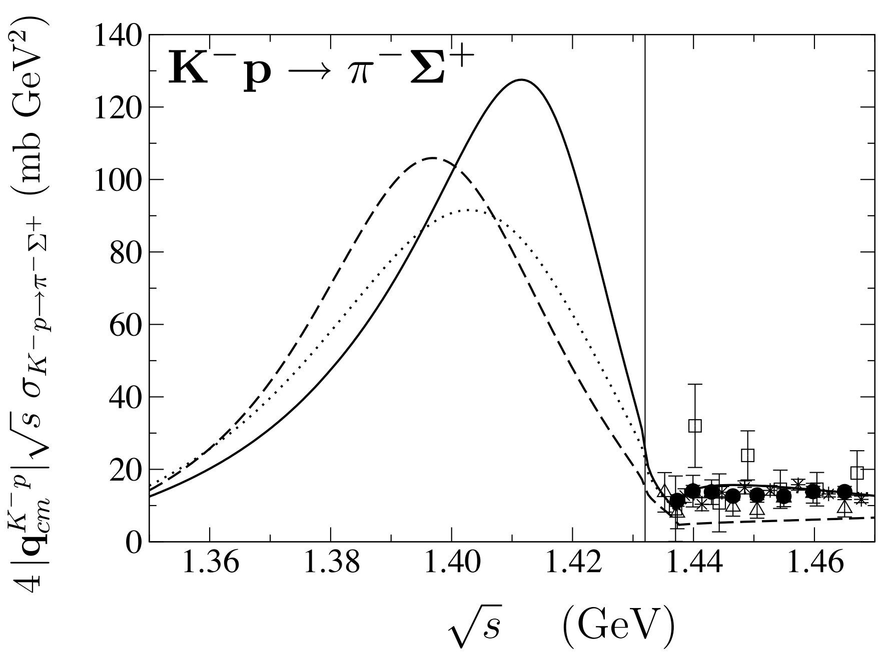
a(K^-p) (**KEK**)

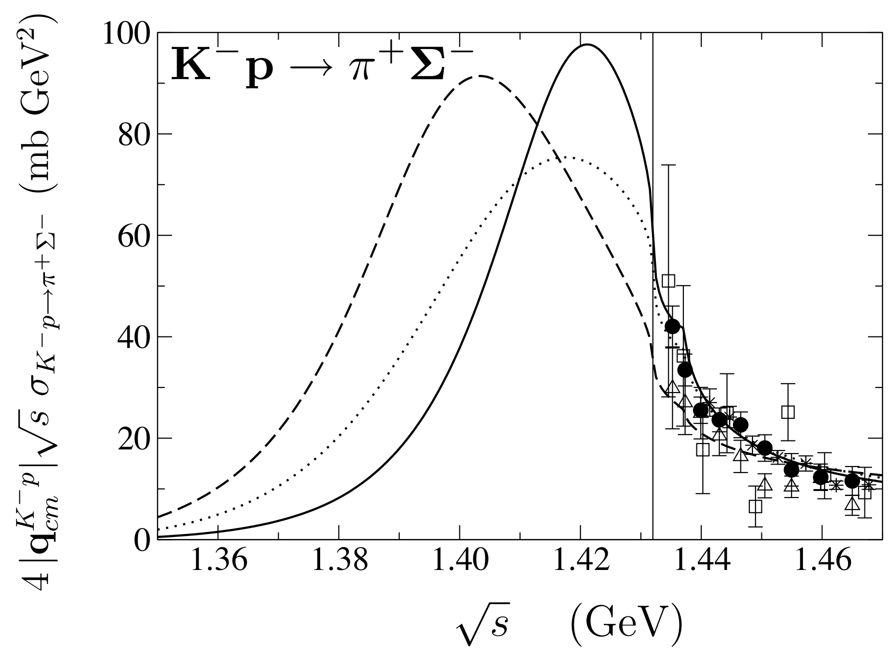
- 0.78 (±0.18) + i **0.49** (±0.37) [fm]

(M. Iwasaki et al., Phys. Rev. Lett. 78 (1997) 3067)

CONSTRAINTS for SUBTHRESHOLD EXTRAPOLATIONS

B. Borasoy, R. Nissler, W.W.: Eur. Phys. J. A25 (2005) 79





- - - - - - - with
———— without
kaonic hydrogen (DEAR) constraints

- Sensitivity of $\pi\Sigma$ mass spectrum to $K^- p$ threshold conditions
  - ► looking forward to **SIDDHARTA** data
  - ► need accurate $\pi\Sigma$ mass distributions

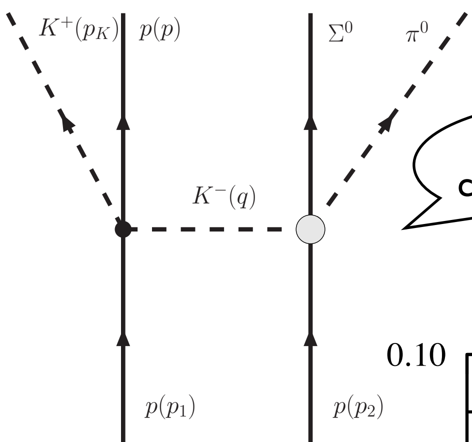
... in order to have reasonable predictive power for subthreshold extrapolations

$\pi\Sigma$ MASS SPECTRA

- New ANKE data: $\mathbf{p\,p \rightarrow p\,K^+\,\{\Sigma^0\pi^0\}}$

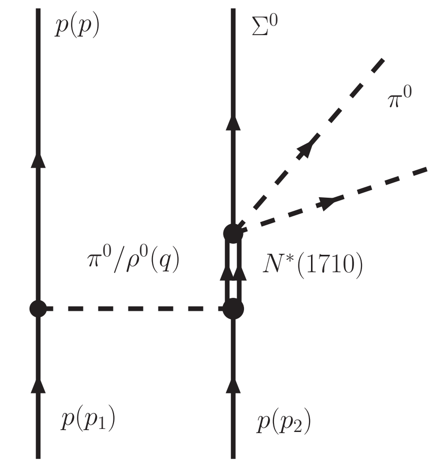
I. Zychor et al.
Phys. Lett. B660 (2008) 167

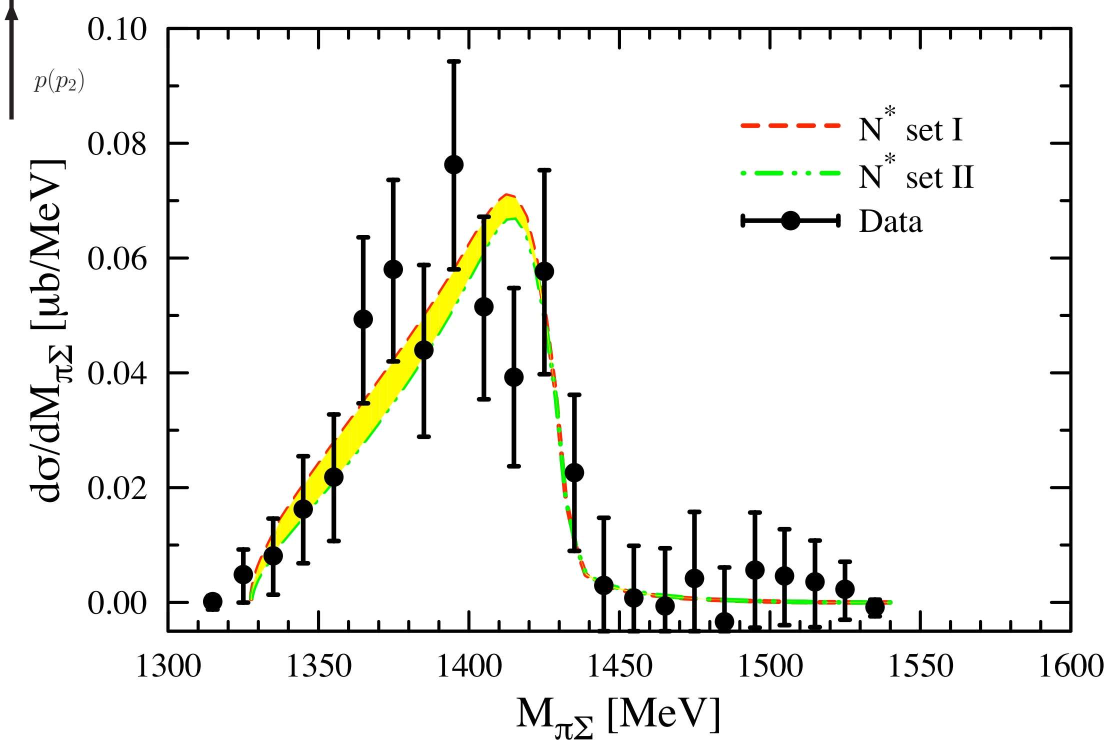
... in comparison with theory:



Chiral SU(3) coupled channels

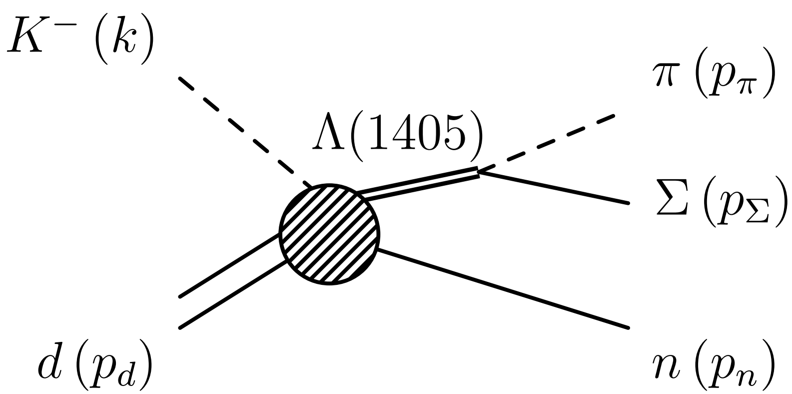
S. Geng, E. Oset
Eur. Phys. J A34 (2007) 405

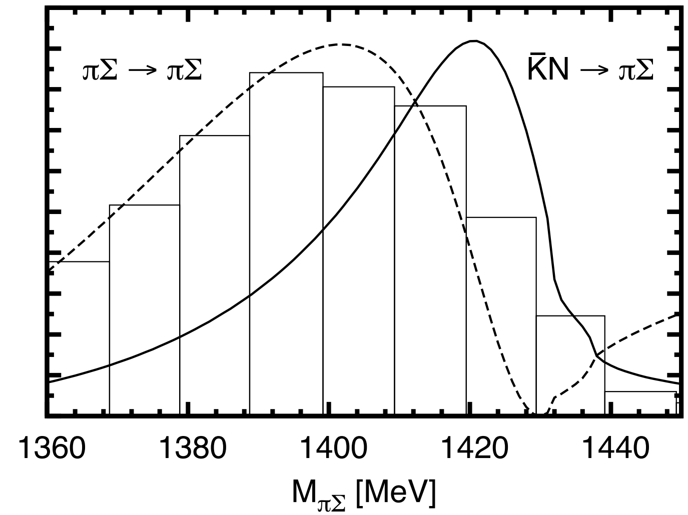




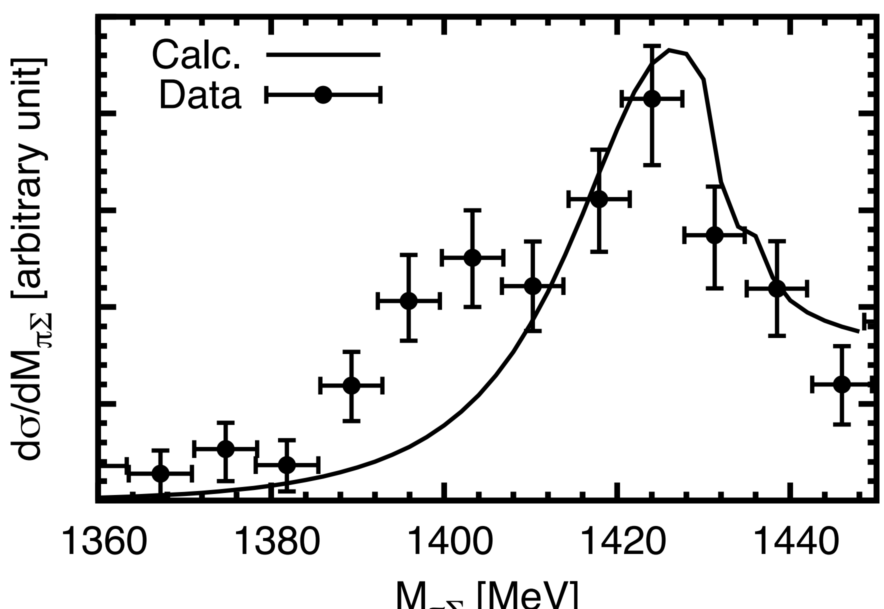
$\pi\Sigma$ MASS SPECTRA (contd.)

- Kaonic production of $\Lambda(1405)$ from deuterium





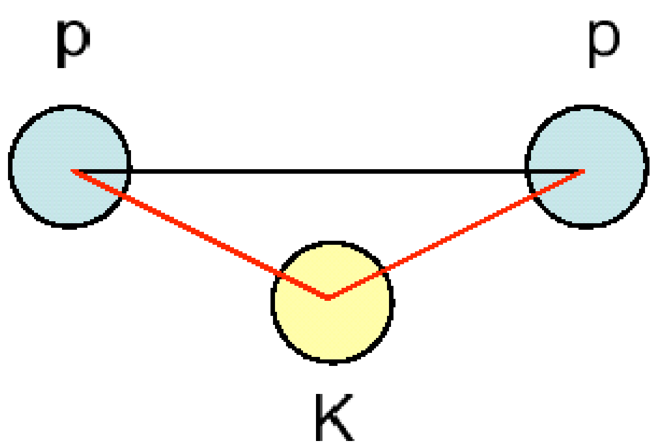
Two-Pole scenario

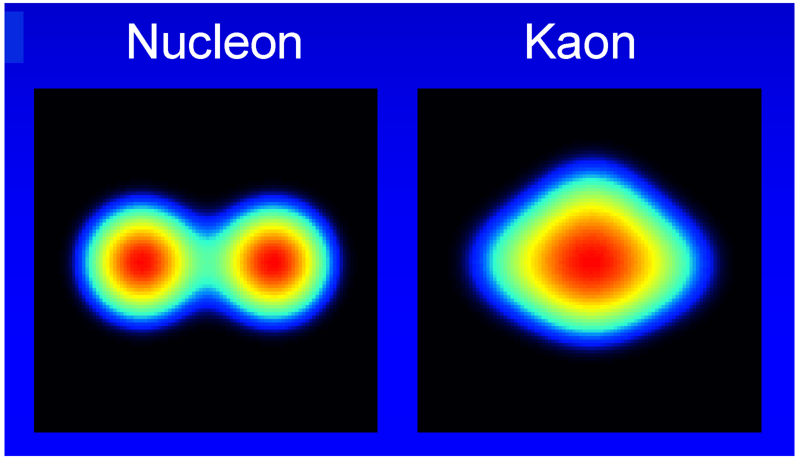


D. Jido, E. Oset, T. Sekihara
arXiv 0904.3410 [nucl-th]

exp. data:
O. Braun et al.
Nucl. Phys. B129 (1977) 1

3.
Prototype Antikaon-Nuclear Few-Body System: K^-pp





- **3-Body (Faddeev) Calculations**
- **Variational Calculations**

- **Limited predictive power** in both approaches
(subthreshold / off shell extrapolations, necessary approximations, . . .)

OVERVIEW

- Binding energies and widths of quasibound $\{\bar{\mathbf{K}}[\mathbf{NN}]_{\mathbf{T=1}}\}_{\mathbf{I=1/2}}$

variational AY phenomenol. potential	variational chiral SU(3) dynamics	3-body coupled channels separable potentials	variational coupled channels phenom. input

	ATMS [1]	AMD [2]	Faddeev [3]	Faddeev [4]	variational [5]
B	48	17–23	50–70	60–95	40–80
Γ	61	40–70	90–110	45–80	40–85

(compilation: Avraham Gal)

1. T. Yamazaki, Y. Akaishi, PLB **535** (2002) 70
2. A. Doté, T. Hyodo, W. Weise, NPA **804** (2008) 197, PRC **79** (2009) 014003
3. N.V. Shevchenko, A. Gal, J. Mareš, PRL **98** (2007) 082301
4. Y. Ikeda, T. Sato, PRC **76** (2007) 035203, PRC **79** (2009) 035201
5. S. Wycech, A.M. Green, PRC **79** (2009) 014001 (including p waves)

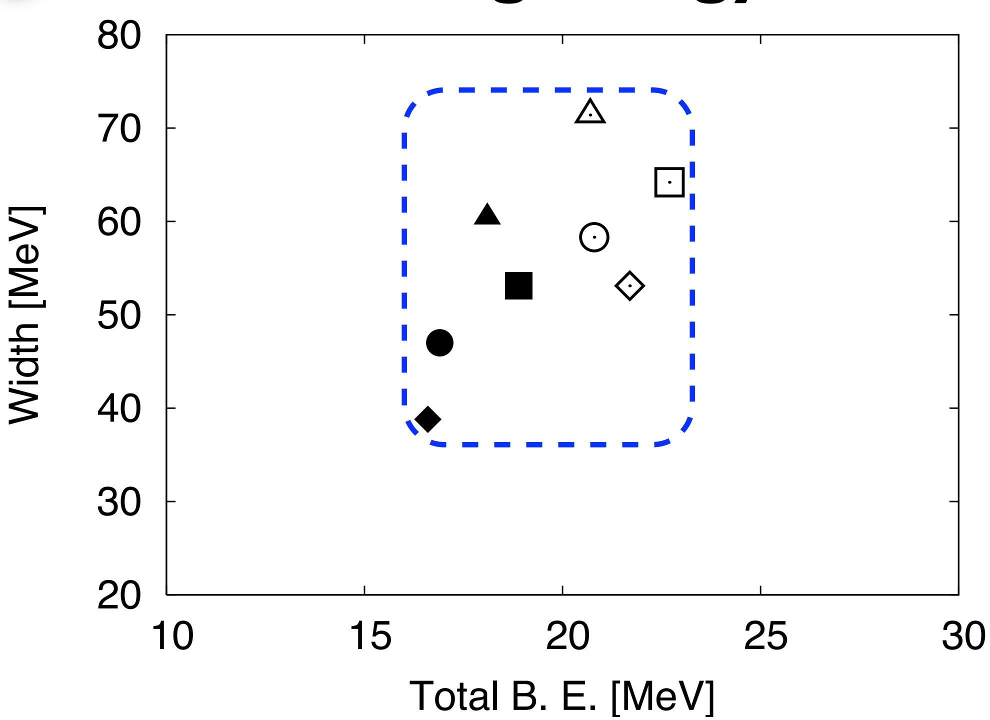
- note: width includes only $\bar{K}NN \to \pi\Sigma N$, not $\bar{K}NN \to YN$

Results: Variational Calculations

A. Doté, T. Hyodo, W.W.: Nucl. Phys. A 804 (2008) 197, Phys. Rev. C 79 (2009) 014003

- Input: **realistic NN interaction** (Argonne v18)
  $\bar{\mathrm{K}}\mathrm{N}$ **effective interaction** from **Chiral SU(3) Dynamics**

- $\mathrm{K}^-\mathrm{pp}$ **binding energy** and **width** using a variety of **chiral models**



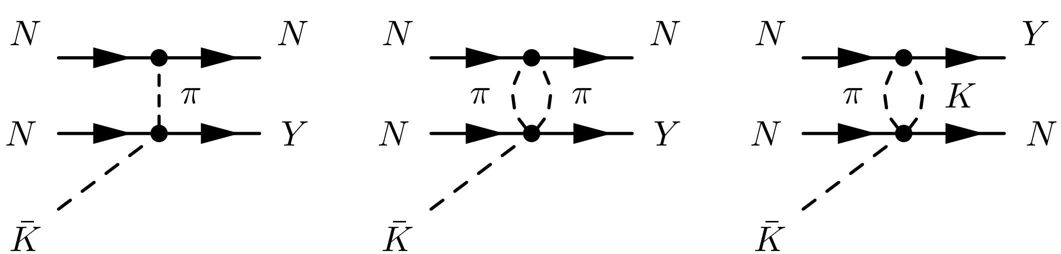
- Result: **weak** binding

$$\mathbf{B(K^-pp) = 19 \pm 3\,MeV}$$
$$\mathbf{\Gamma = 40 - 70\,MeV}$$

- but: $\bar{\mathrm{K}}\mathrm{NN} \leftrightarrow \pi\Sigma\mathrm{N}$
  3-body dynamics incomplete

- additional increase of width by $\bar{\mathrm{K}}\mathrm{NN} \to \mathrm{YN}$ **absorption**

$$\mathbf{\delta\Gamma_{abs} \simeq 10\ MeV}$$



K^-pp System:
Coupled-Channels Faddeev Approach

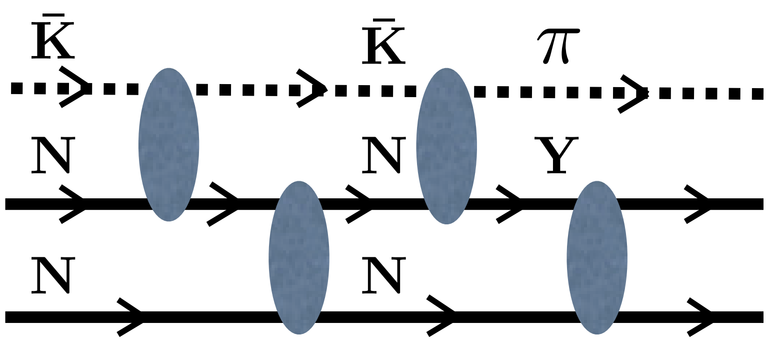
N.V. Shevchenko, J. Mares, A. Gal, PRL 98 (2007) 082301
N.V. Shevchenko, et al., PRC 76 (2007) 044004

Y. Ikeda, T. Sato, PRC 76 (2007) 035203
Y. Ikeda, T. Sato, PRC 79 (2009) 035201

- **Separable** approximation for (s-wave) two-body potentials

  $\mathbf{K^-p \leftrightarrow K^-p}$ $\mathbf{K^-p \leftrightarrow \pi\Sigma}$ $\mathbf{NN,\ \Sigma N}$

- Constrained by measured cross sections and scattering lengths



spectator
dynamics
is important

- Results:

$\mathbf{B \sim 50 - 70\,MeV}$
$\mathbf{\Gamma \sim 90 - 110\,MeV}$
(Shevchenko et al.)

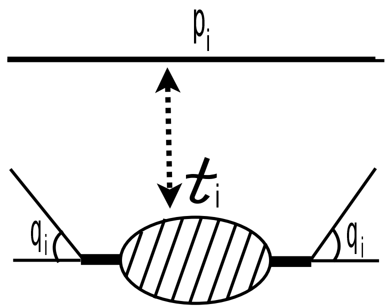
$\mathbf{B \sim 60 - 95\,MeV}$
$\mathbf{\Gamma \sim 45 - 80\,MeV}$
(Ikeda & Sato)

► effect of separable approximation on subthreshold behaviour ?

K⁻pp System: Coupled-Channels Faddeev Approach

(contd.)

- Importance of full **3-body** coupled-channels dynamics



Y. Ikeda, T. Sato, PRC 79 (2009) 035201

$$t_{\alpha,\beta}(W) \;=\; v_{\alpha,\beta} + \sum_{\gamma} v_{\alpha,\gamma} G_0^{\gamma N}(W) t_{\gamma,\beta}(W)$$

$$G_0^{\alpha N}(W) \;=\; \frac{1}{W - E_N(\vec{p}_N) - \sqrt{(E_{M_\alpha}(\vec{q}) + E_{B_\alpha}(\vec{q}))^2 + \vec{p}_N^{\,2}} + i\epsilon}$$

- ... tends to increase binding as compared to variational approaches (with effective single-channel interactions)
- but:
  separable approximation and strong cutoff (off-shell) dependence in extrapolations to far-subthreshold region

4.

Antikaon-Nuclear Systems

- mostly theoretical excursions to heavier antikaon-nuclear systems

► Klein-Gordon eqn. calculations using chiral SU(3) interaction plus NN correlations

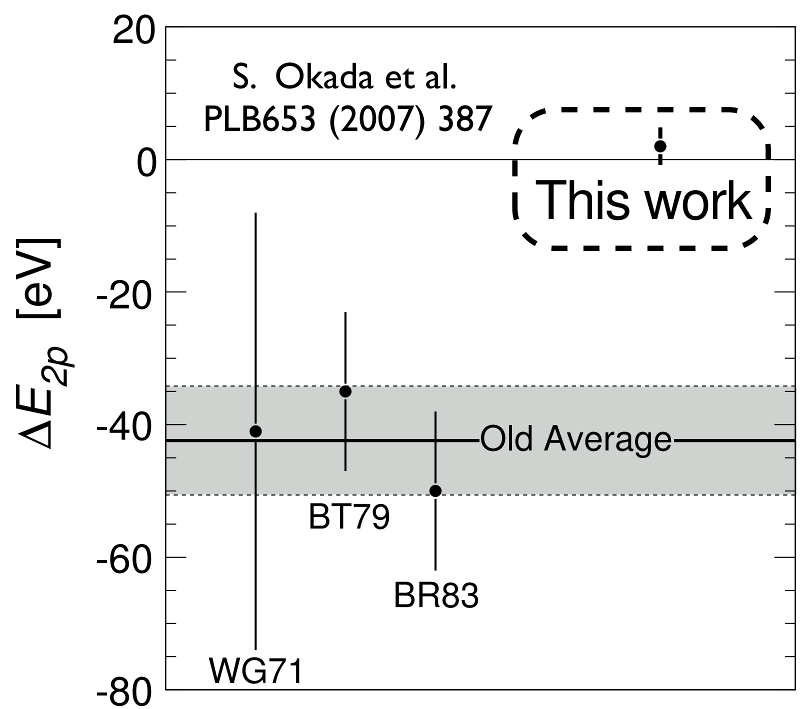
► Improved calculation of $\bar{K}NN \rightarrow YN$ width

► Relativistic mean-field approach to multi-$\bar{\mathrm{K}}$-nuclear systems

News from Kaonic Atoms

- Precision measurement of **kaonic** ^{4}He (3d→2p)

energy shift



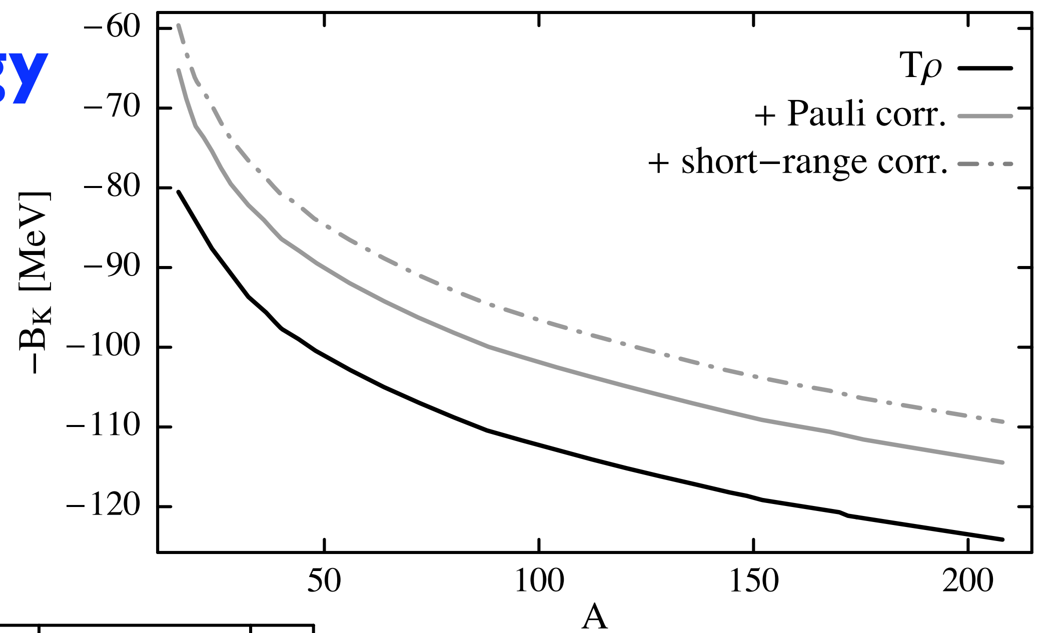
- rules out "super strong" kaon-nuclear interaction
- consistent with systematics of kaonic atoms analysis

E. Friedman, A. Gal: Phys. Rept. 452 (2007) 89

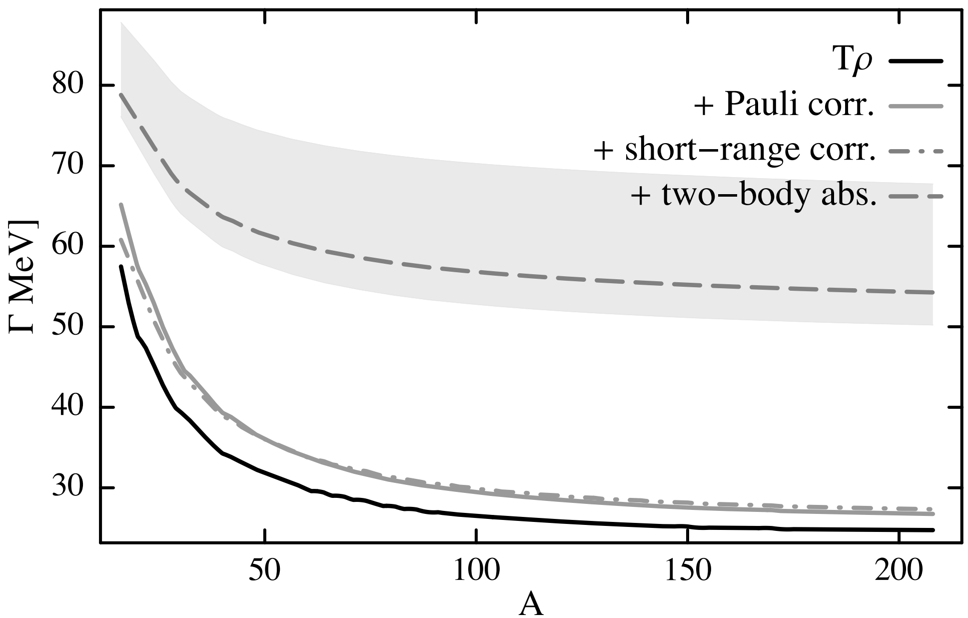
Antikaon - Nuclear Quasibound States

$$\left[\omega^2 + \vec{\nabla}^2 - m_K^2 - \Pi(\omega;\, \vec{r})\right] \phi_K(\vec{r}) = 0$$

binding energy



Systematics
as function of
nuclear mass number



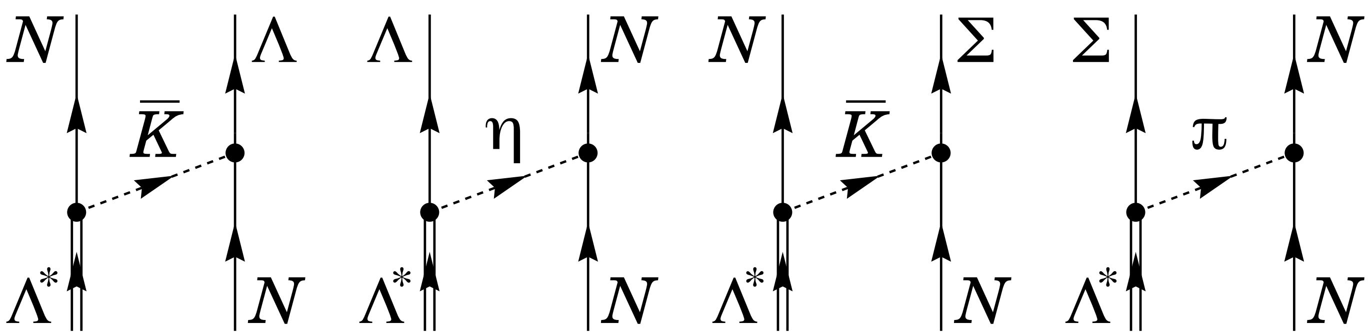
decay width

R. Härtle, W.W.
Nucl. Phys. A 804 (2008) 173

Antikaon Absorption on Nucleon Pairs

T. Sekihara, D. Jido, Y. Kahada-En´yo   Phys. Rev. C79 (2009) 062201

- Basic process: $\mathbf{K^- N N \rightarrow \Lambda(1405)\, N \rightarrow Y\, N}$



- Result:
non-mesonic decay width

$$\mathbf{\Gamma(\Lambda^* N \rightarrow Y\, N) \simeq 22\, MeV}$$

at normal nuclear matter density

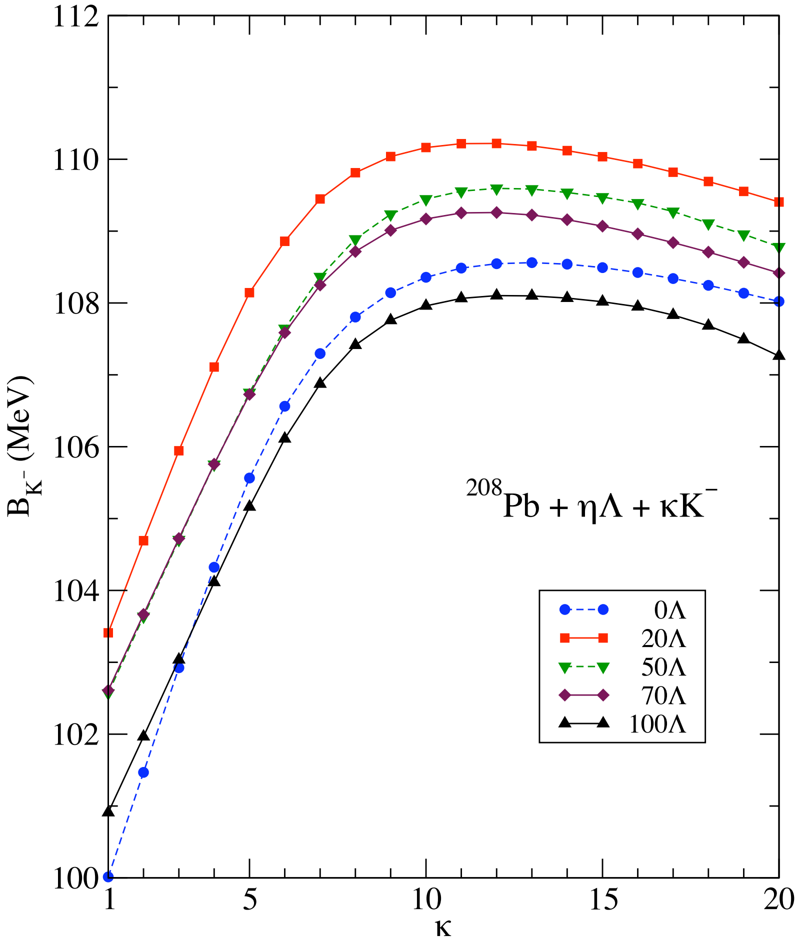
Multi K^--Nuclear Systems

D. Gazda, E. Friedman, A. Gal, J. Mares Phys. Rev. C77 (2008) 045206 & arXiv: 0906.5344 [nucl-th]

- Relativistic mean-field model for antikaons, nucleons and hyperons

  - Repulsion between antikaons

  - Saturation of antikaon binding energy



  - ... prevents kaon condensation in this scenario

(⟶ see talk by J. Mares)

Summary & Conclusions

- Low-energy QCD with strange quarks $\leftrightarrow$ **Chiral SU(3) Dynamics**
- Strongly **attractive** I = 0 antikaon-nucleon interaction $\rightarrow$
  coupled channels (two poles), dynamically generated $\Lambda(1405)$
- Extrapolations to **far-subthreshold** region uncertain $\rightarrow$

  constraints needed:
  - high-precision $\bar{\mathrm{K}}\mathrm{N}$ **threshold data**
  - much improved $\pi\Sigma$ **mass spectra**
- $\bar{\mathrm{K}}\mathrm{NN}$ **quasibound** system?

  all calculations (Faddeev, variational) give binding

  $\mathrm{B} \sim 20 - 80\,\mathrm{MeV}$ ... but large width $\Gamma \sim 40 - 100\,\mathrm{MeV}$
- Stronger binding in heavier nuclei expected, but still large widths

  $$\mathrm{K^-NN} \rightarrow \Lambda(1405)\,\mathrm{N} \rightarrow \mathrm{Y\,N}$$
- Answers in sight? ▶ SIDDHARTA, J-PARC, AMADEUS, GSI