In-medium $\bar{K}$ & η mesons

Mesic Nuclei, JU Krakow, Sept. 2013
Hadrons in Nuclei, YITP Kyoto, Oct. 2013

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- $\bar{K}N - \pi Y$ **chiral dynamics and its consequences**
- $\bar{K}$ **nuclear few-body systems**
- $\bar{K}$**-nucleus potentials from** K^- **atoms**

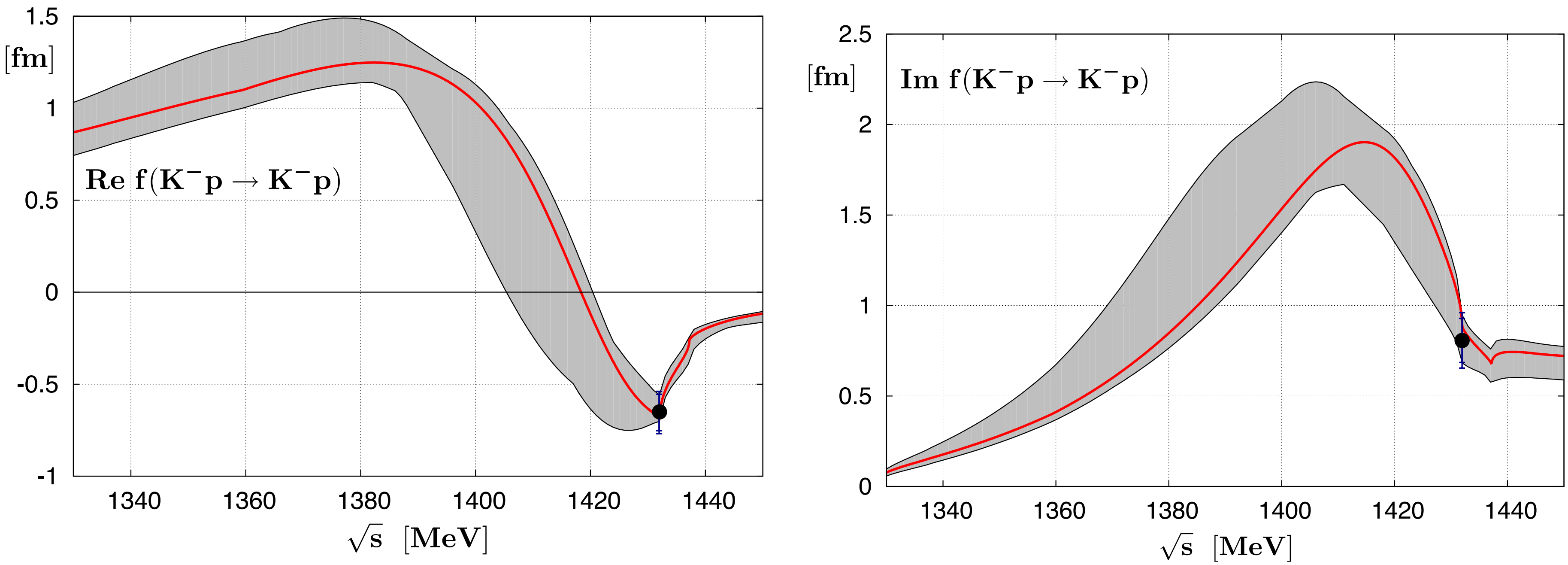
  A.Gal in HYP2012 Proc., NPA 914 (2013) 270

- **Quest for** η **nuclear quasibound states**

  E.Friedman, A.Gal, J.Mareš, PLB 725 (2013) 334

$\bar{K}N - \pi Y$ Chiral Dynamics

$K^- p$ scattering amplitude from NLO chiral SU(3) dynamics



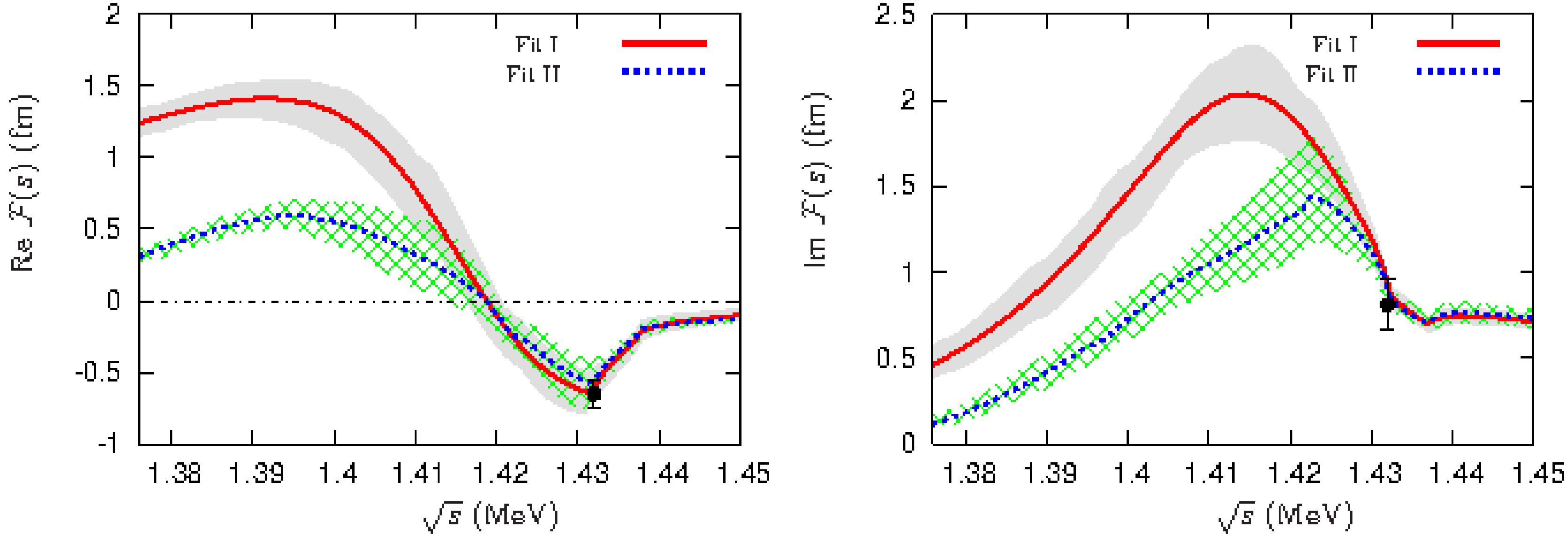
Y. Ikeda, T. Hyodo, W. Weise (IHW), PLB **706** (2011) 63; NPA **881** (2012) 98

Strong subthreshold $K^- p$ attraction; $\Lambda(1405)$ physics

Consequences for kaonic atoms and K^- nuclear quasibound states

K^- absorption might be governed by out-of-model $K^- NN \to YN$

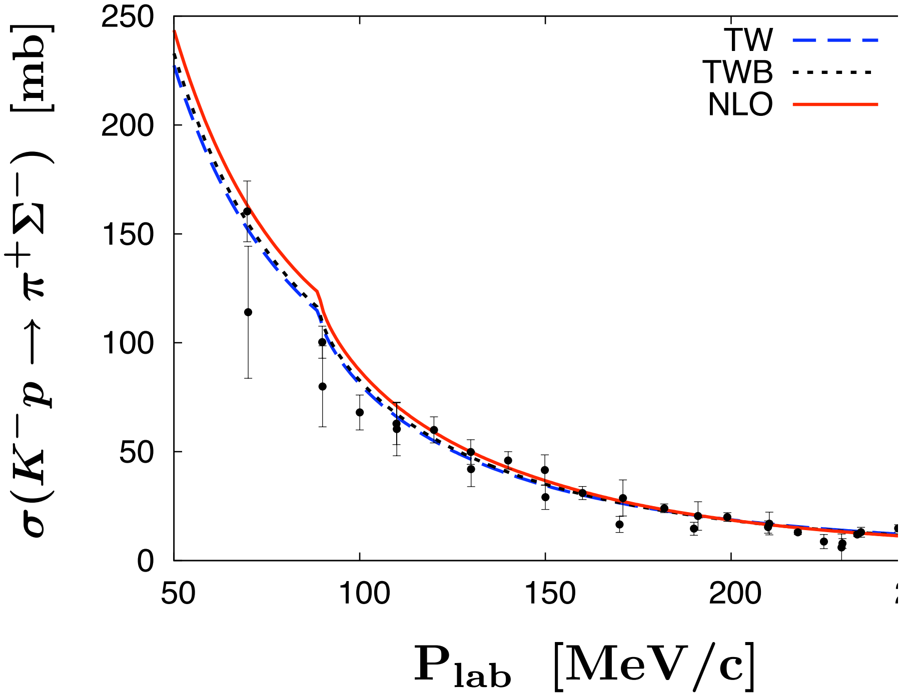
$K^- p$ subthreshold ambiguity

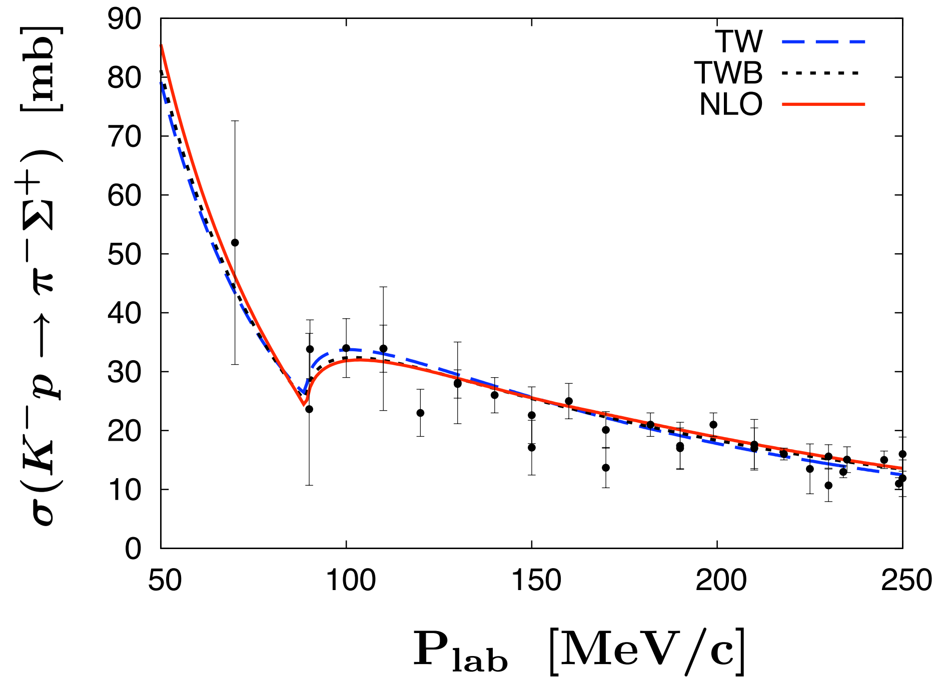


Two NLO chiral-model fits by Guo-Oller, PRC 87 (2013) 035202

- Fit I: one value of meson weak-decay constant $f = 125.7 \pm 1.1$ MeV.
- Fit II: separate fixed values for $f_\pi, \ f_K, \ f_\eta$.

  Fit II will create problems when confronted with kaonic-atom data.

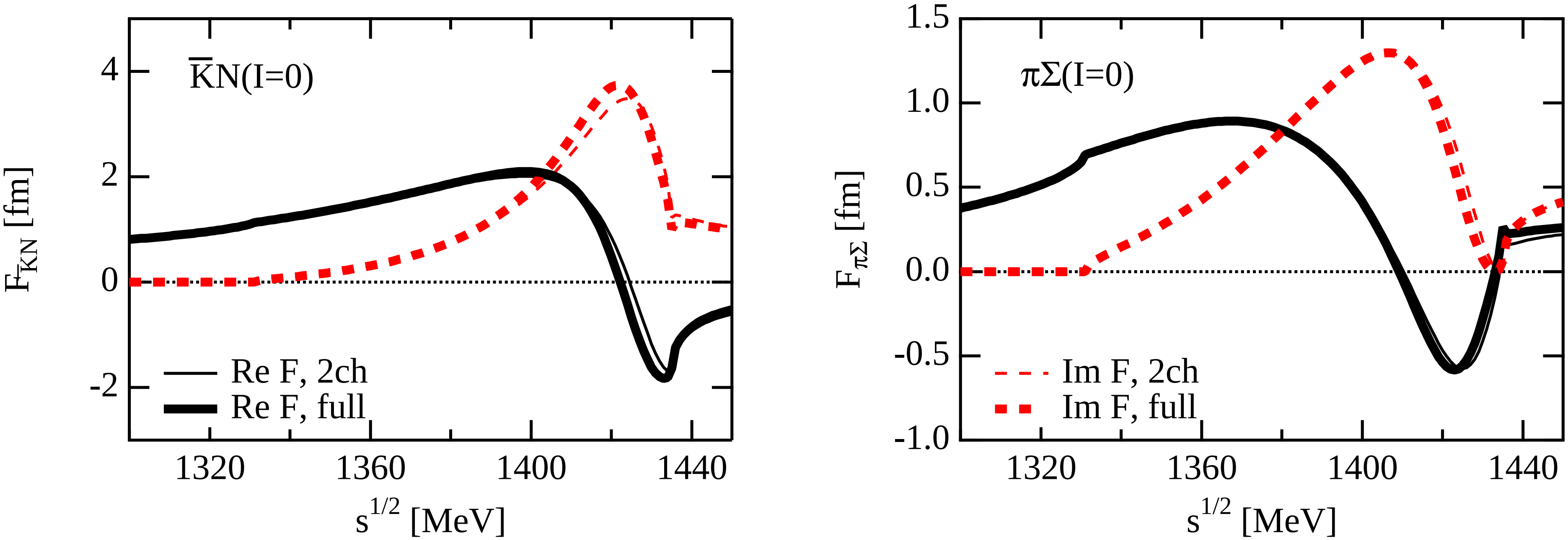




$K^- p \to \pi^\pm \Sigma^\mp$ reaction data fitted by LEC of NLO scheme for $\bar{K}N - \pi Y$ coupled channels $(Y = \Lambda, \Sigma)$

Y. Ikeda, T. Hyodo, W. Weise, NPA 881 (2012) 98

Large difference in cross sections $\Rightarrow$ Strong isospin dependence



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

$I = 0$ coupled-channel amplitudes

Location of 'resonances': $\bar{K}N \approx 1420$ MeV, $\pi\Sigma \approx 1405$ MeV

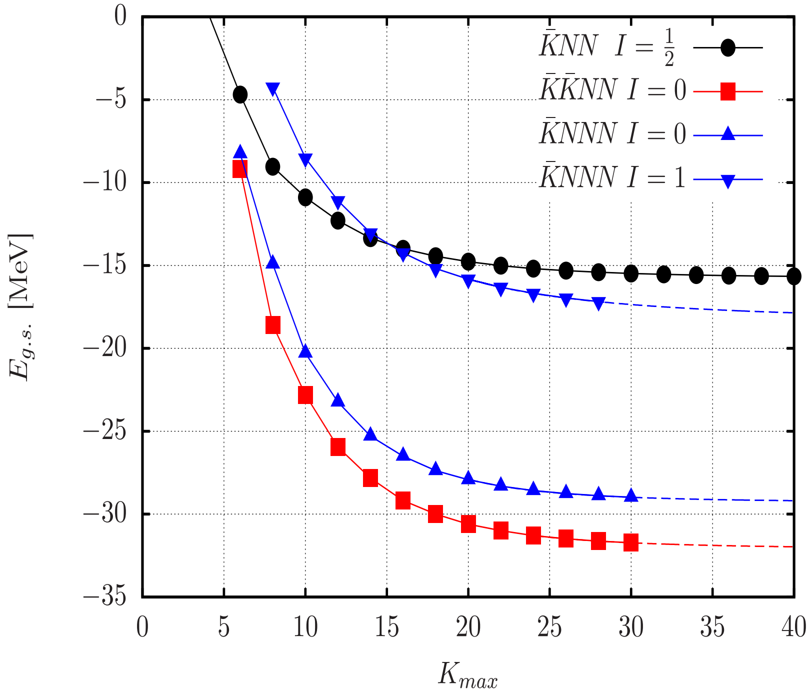
Are there two distinct '$\Lambda(1405)$' resonances?

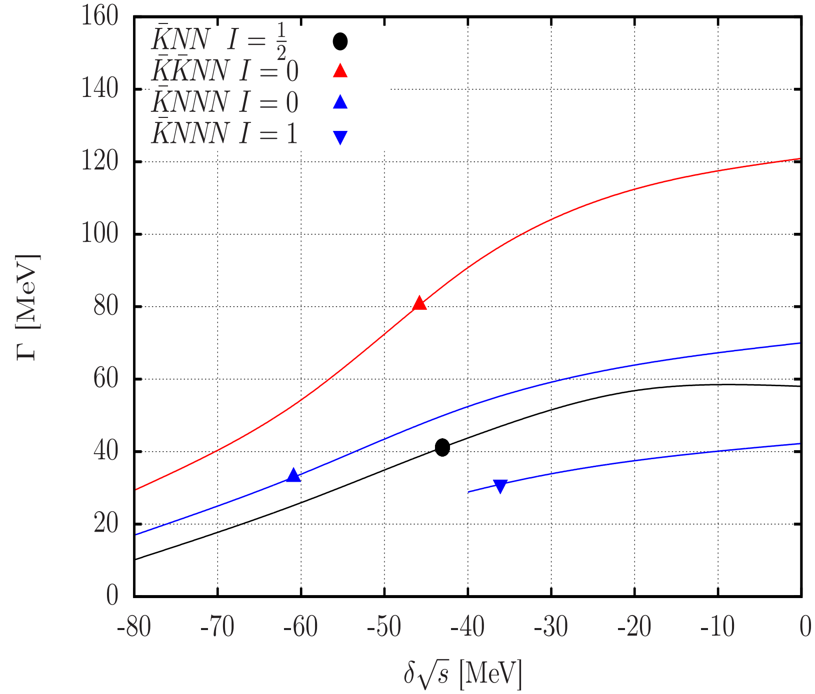
$\overline{K}$ nuclear few-body systems

Energy dependence in $\bar{K}$ nuclear few-body systems

- $\Lambda(1405)$ induces strong energy dependence of the scattering amplitudes $f_{\bar{K}N}(\sqrt{s})$ and the underlying effective single-channel input potentials $v_{\bar{K}N}(\sqrt{s})$.
- $s = (\sqrt{s_{\rm th}} - B_K - B_N)^2 - (\vec{p}_K + \vec{p}_N)^2 \leq s_{\rm th}$
- Expanding nonrelativistically near $\sqrt{s_{\rm th}} \equiv m_K + m_N$:
$\delta\sqrt{s} = -\frac{B}{A} - \frac{A-1}{A} B_K - \xi_N \frac{A-1}{A} \langle T_{N:N} \rangle - \xi_K \left(\frac{A-1}{A}\right)^2 \langle T_K \rangle$,
$\delta\sqrt{s} \equiv \sqrt{s} - \sqrt{s_{\rm th}},\ \ B_K = -E_K,\ \ \xi_{N(K)} \equiv \frac{m_{N(K)}}{(m_N + m_K)}$.
- Self-consistency: output $\sqrt{s}$ from solving the Schroedinger equation identical with input $\sqrt{s}$.

3– & 4–body B & Γ calculated self-consistently





N. Barnea, A. Gal, E.Z. Liverts, PLB **712** (2012)

- Variational calculation in hyperspherical basis controlled by $K_{\max}$
- $\bar{K}N$ energy dependence [Hyodo–Weise, PRC 77 (2008) 035204] restrains B & Γ by treating $\delta\sqrt{s_{\bar{K}N}}$ self-consistently
- B(4-body) small w.r.t. non-chiral estimates of over 100 MeV

- $\bar{K}NN$: is there an excited $I = 1/2$ quasibound state ($\bar{K}d$, dominantly $I_{NN} = 0$) on top of "K^-pp" g.s. ?

- Bayar & Oset [NPA **881** (2012) 127]: **YES**, bound by about 9 MeV, from a peak in $|T_{\bar{K}NN}|^2$ calculated in a fixed-scatterer approximation to Faddeev equations.

- Shevchenko [NPA **890-1** (2012) 50]: **UNLIKELY**, judging from the K^-d scattering length and effective range deduced from a $\bar{K}NN$ Faddeev calculation.

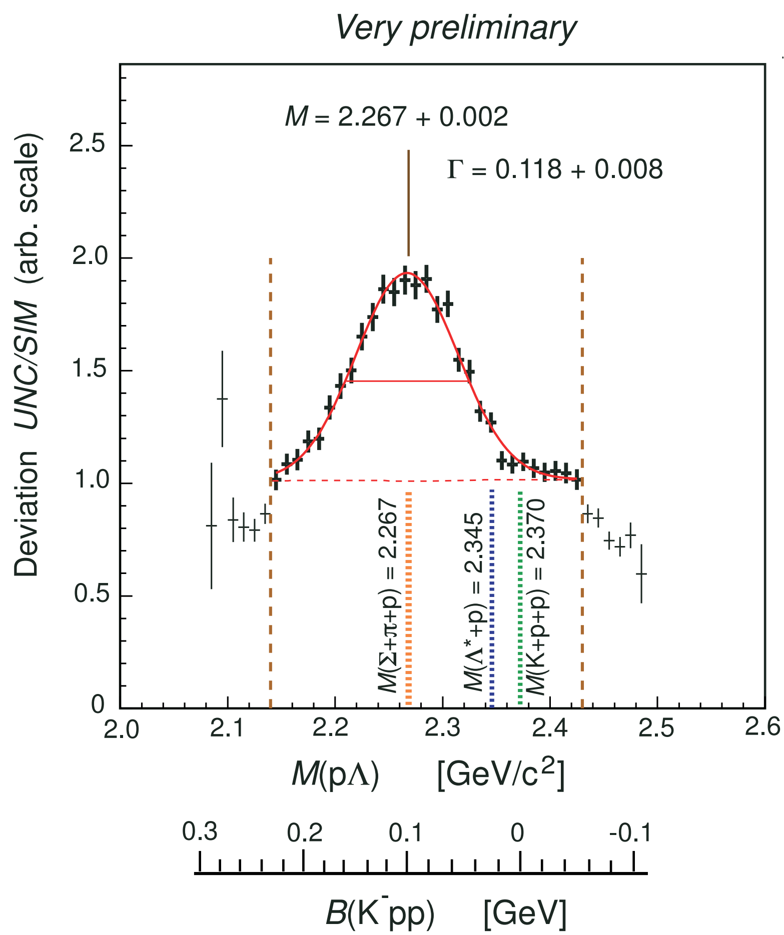
- Barnea, Gal & Liverts do not find such a bound state below the Λ^*N threshold at $B = 11.4$ MeV.

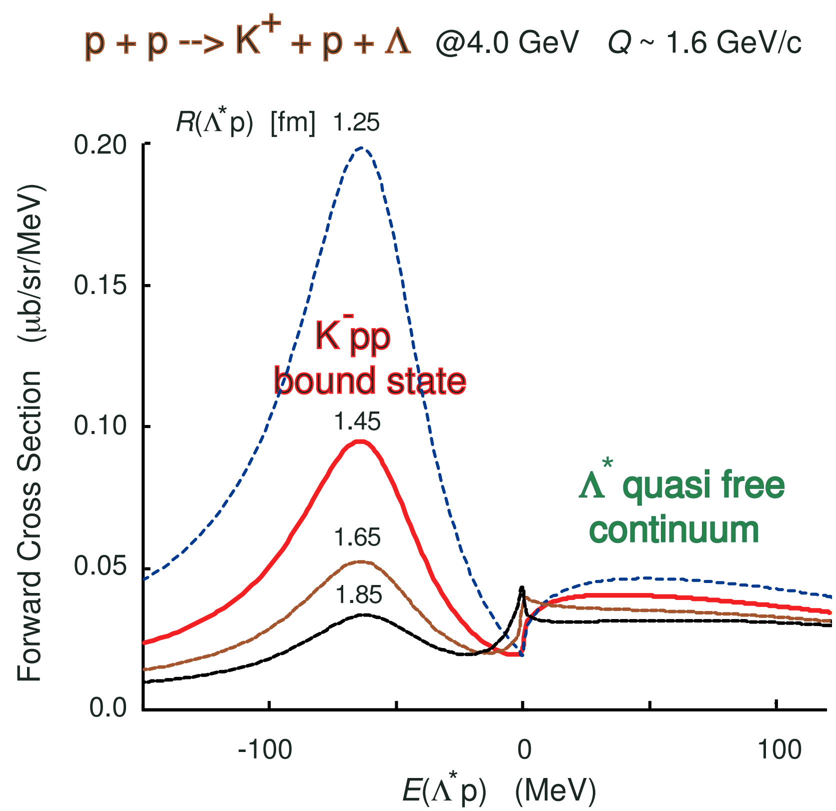
$K^- pp$ calculated binding energies & widths (in MeV)

	chiral, energy dependent			non-chiral, static calculations			
	var. [1]	var. [2]	Fad. [3]	var. [4]	Fad. [5]	Fad. [6]	var. [7]
B	16	17–23	9–16	48	50–70	60–95	40–80
Γ	41	40–70	34–46	61	90–110	45–80	40–85

1. N. Barnea, A. Gal, E.Z. Liverts, PLB **712** (2012)
2. A. Doté, T. Hyodo, W. Weise, NPA **804** (2008) 197, PRC **79** (2009) 014003
3. Y. Ikeda, H. Kamano, T. Sato, PTP **124** (2010) 533
4. T. Yamazaki, Y. Akaishi, PLB **535** (2002) 70
5. N.V. Shevchenko, A. Gal, J. Mareš, PRL **98** (2007) 082301
6. Y. Ikeda, T. Sato, PRC **76** (2007) 035203, PRC **79** (2009) 035201
7. S. Wycech, A.M. Green, PRC **79** (2009) 014001 (including p waves)

Robust binding & large widths; chiral models give weak binding





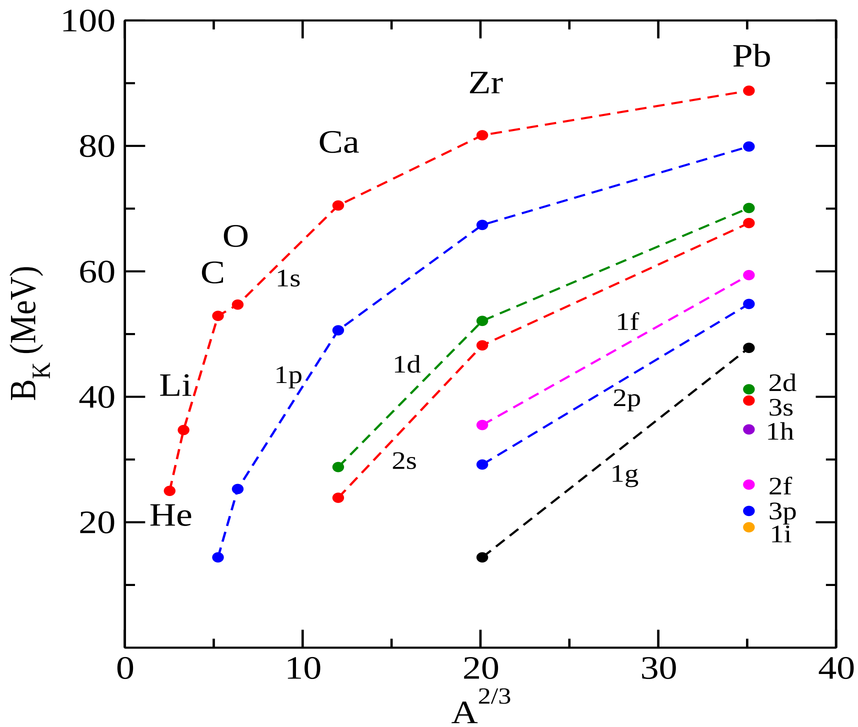
Yamazaki et al. PRL 104 (2010) 132502, DISTO data reanalysis at 2.85 GeV

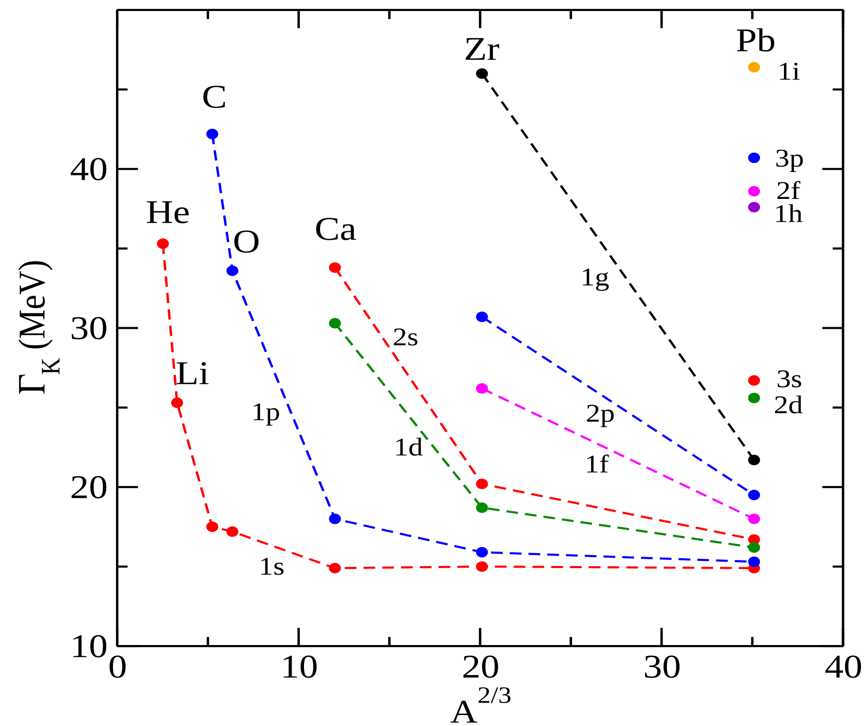
Broad K^-pp structure in $pp \to \Lambda p K^+$ at $\pi N \Sigma$ threshold

Forthcoming experiments: $pp \to (K^-pp) + K^+$ at GSI

K^{-3}He $\to (K^-pp) + n$ (E15) & $\pi^+ d \to (K^-pp) + K^+$ (E27) at J-PARC

RMF quasibound spectra calculated self-consistently (NLO30 '+ SE')

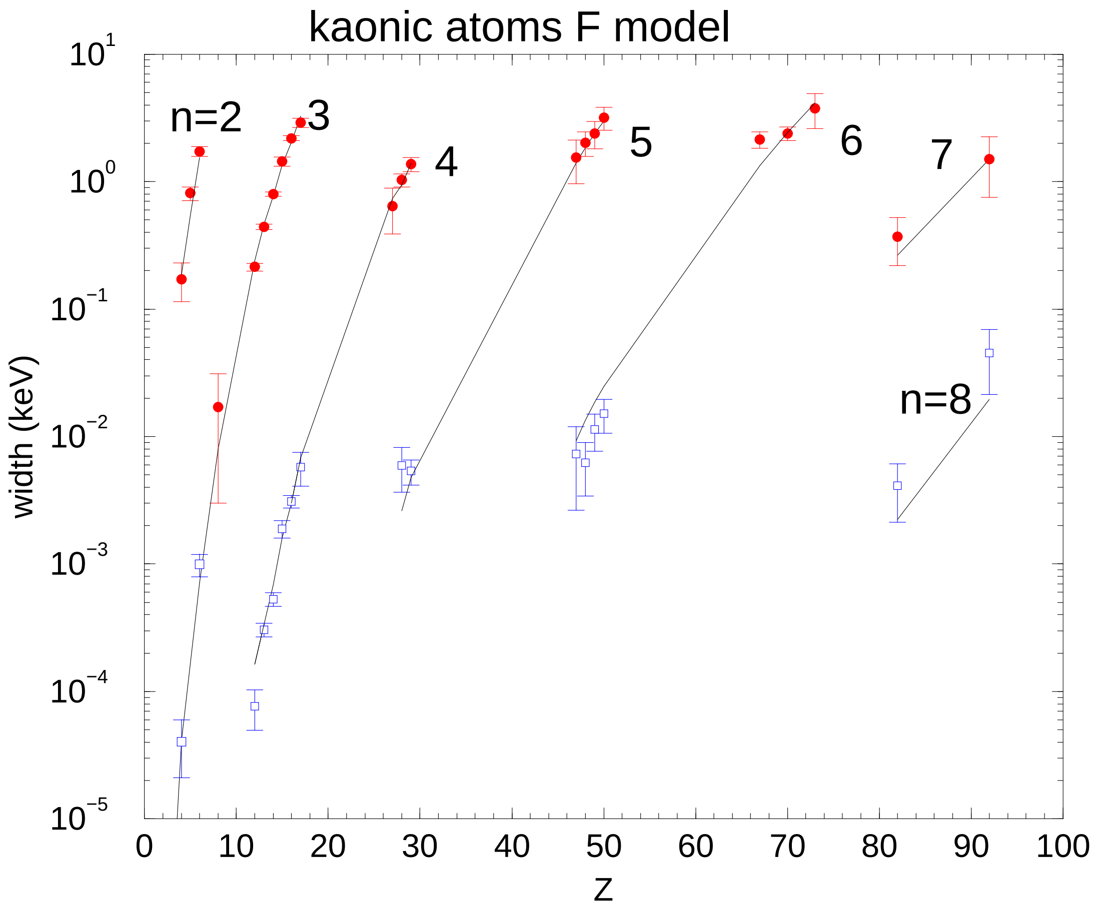




D. Gazda, J. Mareš, NPA 881 (2012) 159

- NLO30 is a chirally motivated coupled channel separable model with in-medium versions [A. Cieplý, J. Smejkal, NPA 881 (2012) 115]
- Γ_K due only to $K^- N \to \pi Y$ (no $K^- NN \to YN$) decay modes
- Self consistency: deep K^- levels are narrower than shallow ones

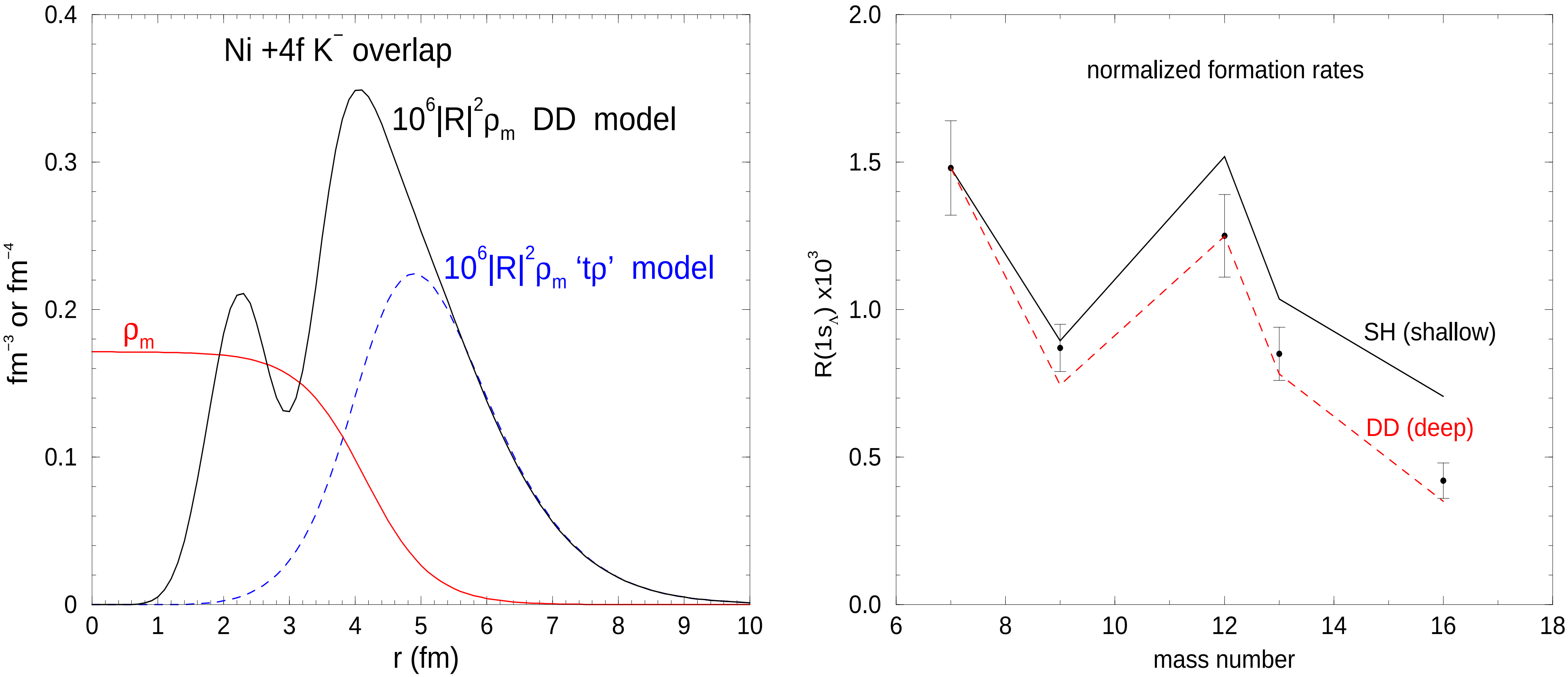
What do K^- atoms tell us?



$K^-_{\rm atom}$ widths across the periodic table in model F (deep pot.)

Lowest χ^2 phenom. model, $\chi^2 = 84$ per 65 data points,

J. Mareš, E. Friedman, A. Gal, NPA 770 (2006) 84.



Left: K^--Ni 4f atomic wavefunction overlap with nuclear density for deep potential, revealing a nuclear $\ell = 3$ quasibound state.

Right: FINUDA $1s_\Lambda$ formation rates in $K^-_{\rm stop}$ capture in nuclei [Cieplý-Friedman-Gal-Krejčiřík, PLB 698 (2011) 226].

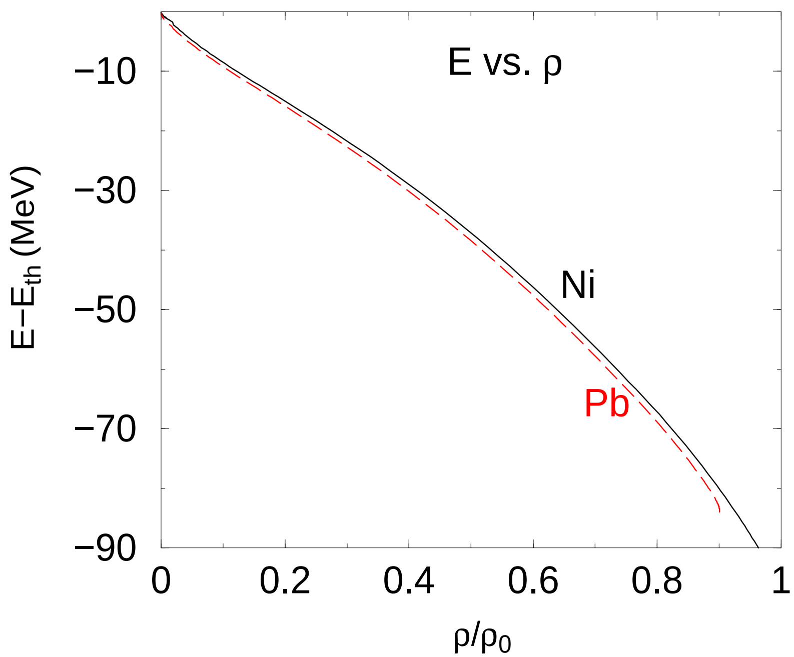
Deep K^- nuclear potential is favored.

Self-consistency requirement imposed in recent K^- atom calculations

[Cieplý-Friedman-Gal-Gazda-Mareš, PLB 702 (2011) 402]:

$$\sqrt{s_{K^-N}} \to E_{\rm th} - B_N - B_K - \xi_N \frac{p_N^2}{2m_N} - \xi_K \frac{p_K^2}{2m_K}$$

$$\xi_{N(K)} = \frac{m_{N(K)}}{(m_N + m_K)} \qquad \frac{p_K^2}{2m_K} \sim -V_{K^-} \approx 100 \text{ MeV}$$

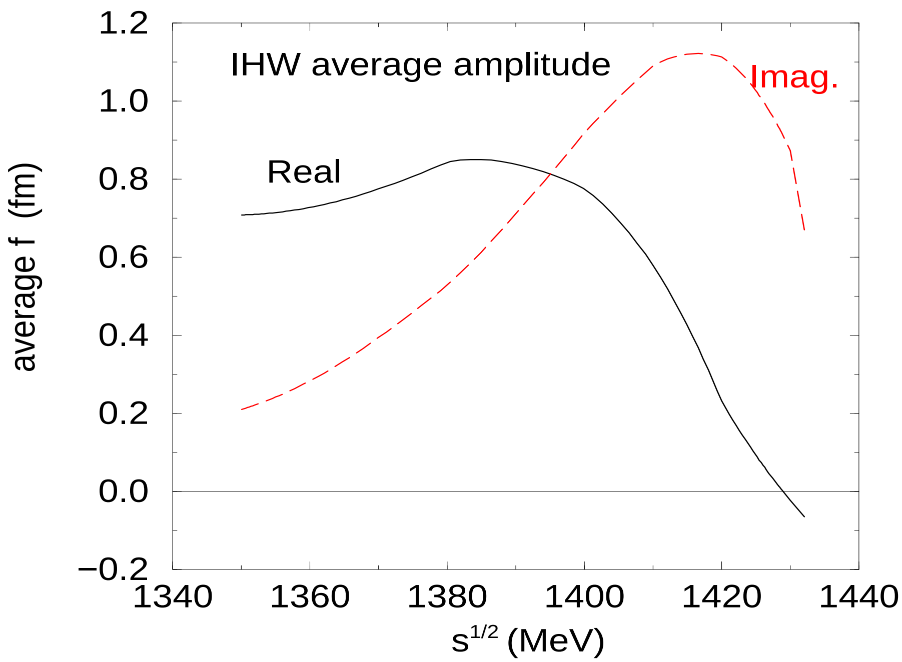


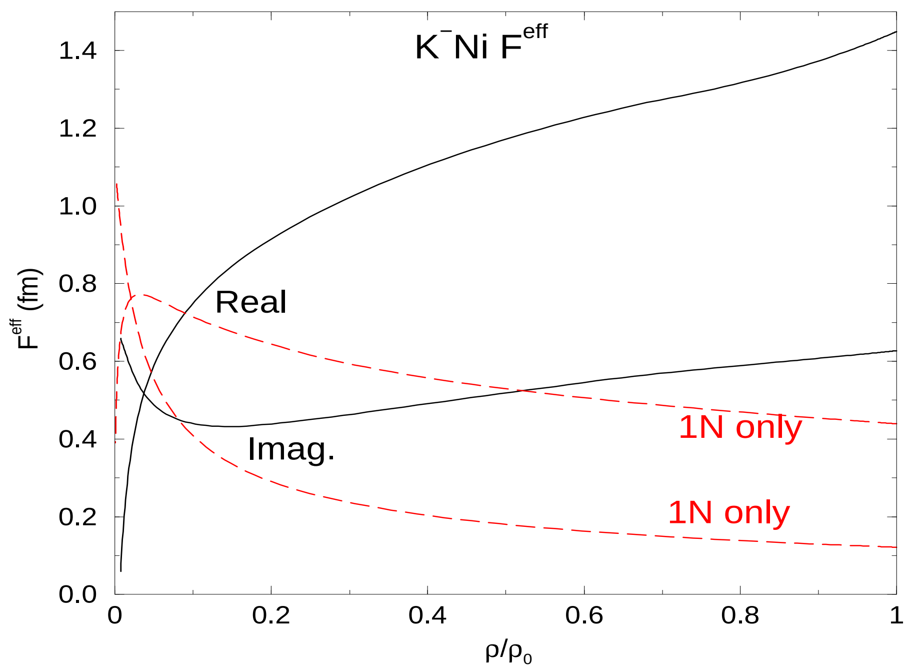
K^- is not at rest!

Friedman-Gal, NPA 899 (2013) 60

K^-N subthreshold energy *vs* nuclear density in K^- atoms.

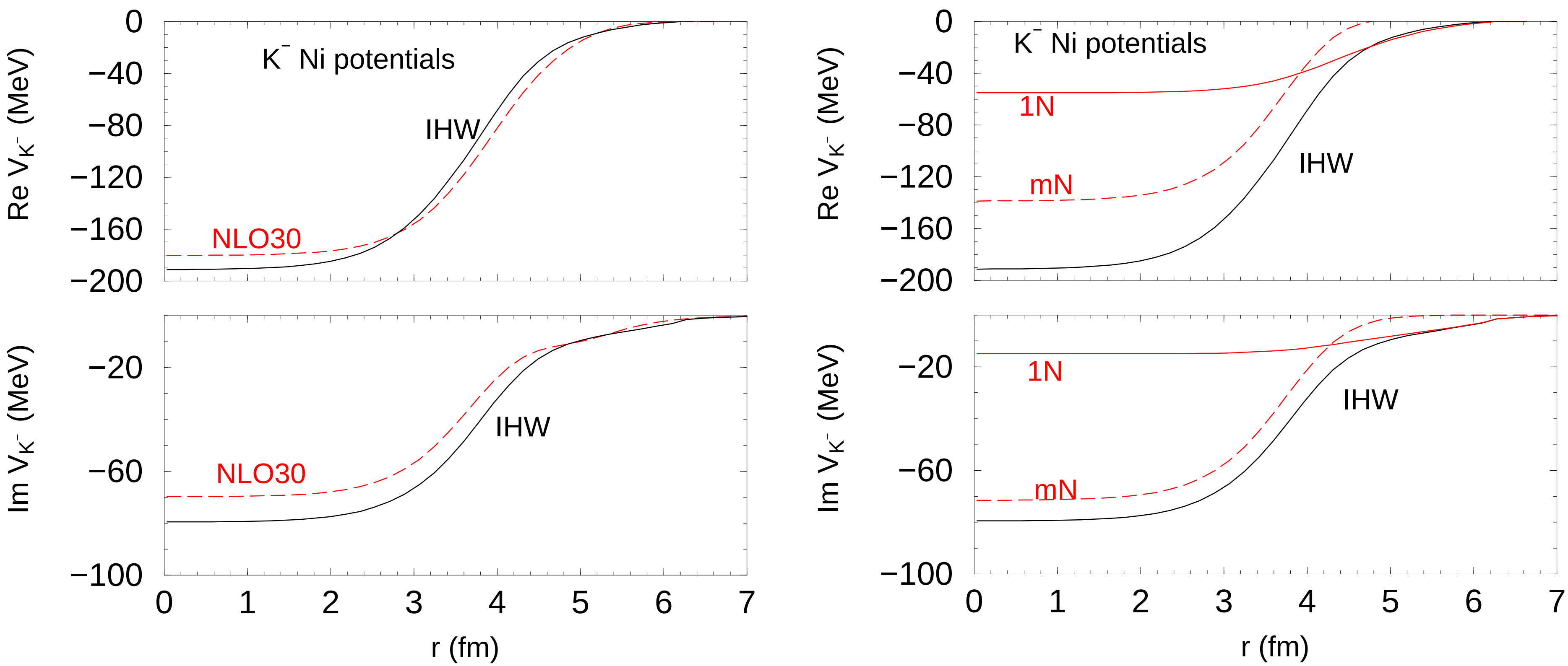
A dominant in-medium effect





Left: IHW free-space input f_{K^-N} Right: atomic-fit output $\mathcal{F}^{\rm eff}_{\rm tot}$

- Subthreshold energy shift is applied self consistently to in-medium 1N amplitude plus (2+...)N phenomenological amplitude.
- Multiple-scattering inclusion of in-medium correlations.
- K^--atom best-fit: $\chi^2/{\rm N}_{\rm data} = 118/65$ [Friedman-Gal, NPA 899 (2013) 60].

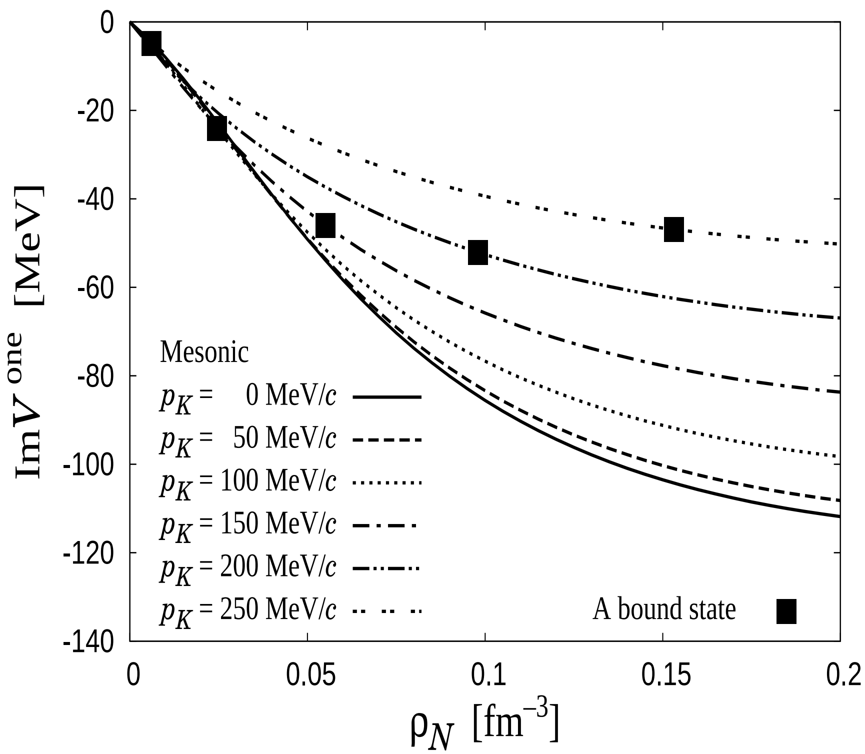


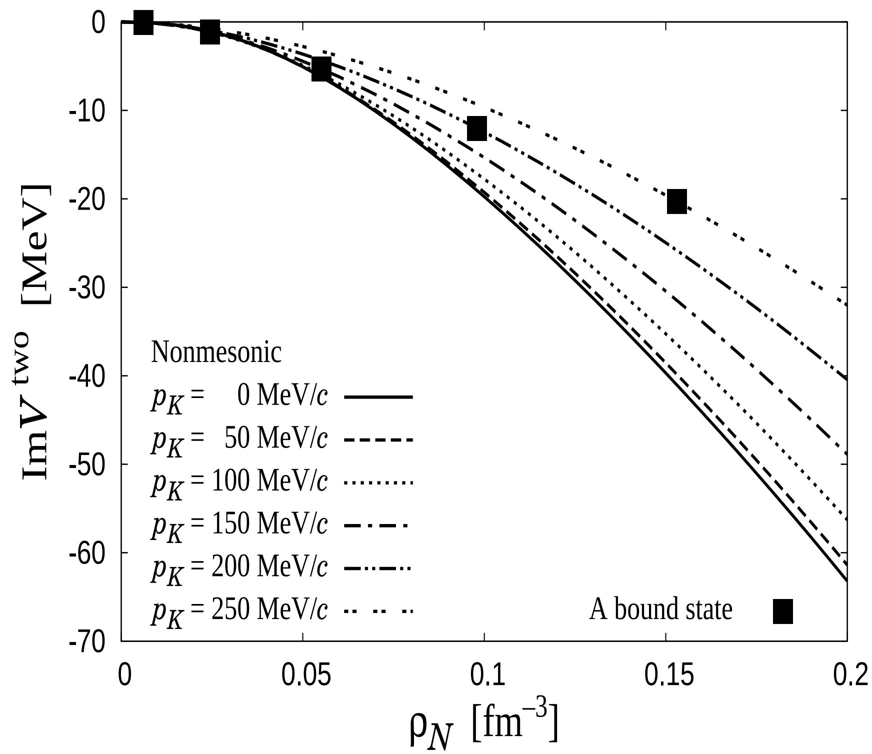
Kaonic-atom best-fit V_{K^-} for Ni & its non-additive breakdown into in-medium 1N and phenomenological m(any)N contributions.

NLO30: A. Cieply, J. Smejkal, NPA **881** (2012) 115 (in-medium).

IHW: Y. Ikeda, T. Hyodo, W. Weise, NPA **881** (2012) 98.

Figures taken from Friedman-Gal, NPA 899 (2013) 60.



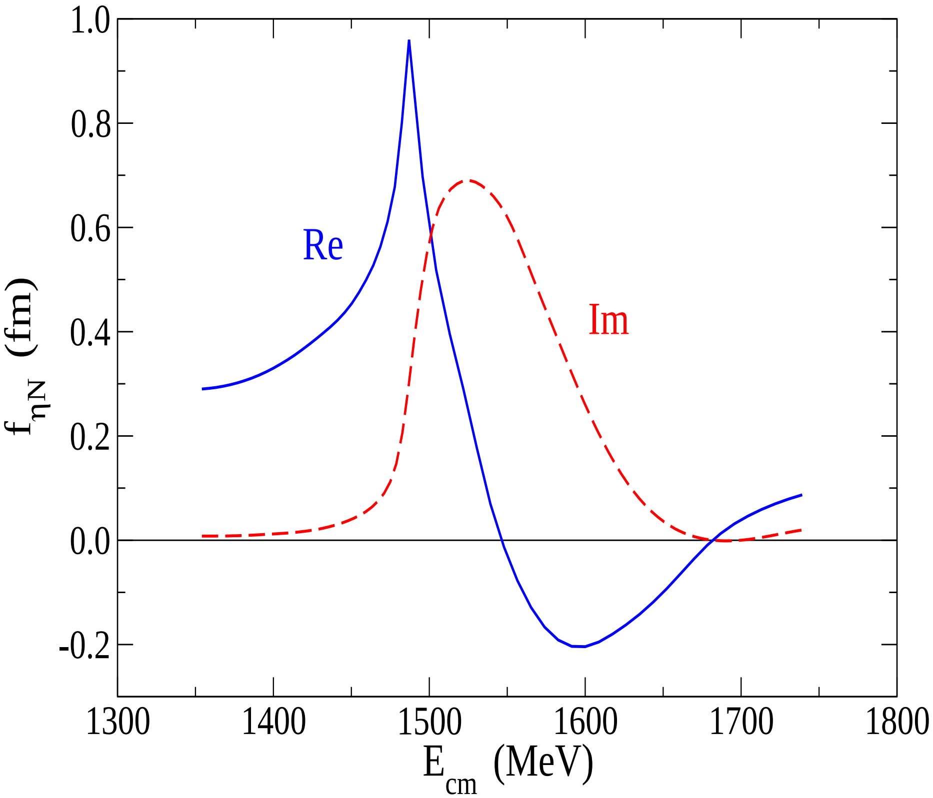


K^- nuclear 1N (left) and 2N (right) absorptive potentials, both calculated in a chiral unitary approach [PRC 86 (2012) 065205] by Sekihara, Yamagata-Sekihara, Jido, Kanada-En'yo.

Note: empirical 25% 2N:1N BR is reached at too high density.

η nuclear quasibound states

$f_{\eta N}(\sqrt{s})$ from K-matrix & $N^*(1535)$ chiral models



$a_{\eta N}$ model dependence

a(fm)	M1	M2	GW	GR	CS
Re	0.22	0.38	0.96	0.26	0.67
Im	0.24	0.20	0.26	0.24	0.20

Mai et al. PRD 86 (2012) 094033
Green-Wycech PRC 71 (2005) 014001
Garcia-Recio et al. PLB 550 (2002) 47
Cieply-Smejkal arXiv:1308.4300, NPA

- Re a varies between 0.2 to 1.0 fm; Im a stable 0.2–0.3 fm.
- M1, M2, GW free-space models; GR, CS in-medium.
- In-medium: energy dependence, Pauli blocking, self-energies.

In-medium ηN amplitudes

Friedman-Gal-Mareš, PLB 725 (2013) 334

Cieplý-Friedman-Gal-Mareš, in preparation

- KG equation and self-energies:

  $[\,\nabla^2 + \tilde{\omega}_\eta^2 - m_\eta^2 - \Pi_\eta(\omega_\eta, \rho)\,]\,\psi = 0$

  $\tilde{\omega}_\eta = \omega_\eta - \mathrm{i}\Gamma_\eta/2, \quad \omega_\eta = m_\eta - B_\eta$

  $\Pi_\eta(\omega_\eta, \rho) \equiv 2\omega_\eta V_\eta = -4\pi \frac{\sqrt{s}}{m_N} f_{\eta N}(\sqrt{s}, \rho)\rho$

- Pauli blocking (Waas-Rho-Weise NPA 617 (1997) 449):

  $f_{\eta N}^{\mathrm{WRW}}(\sqrt{s}, \rho) = \frac{f_{\eta N}(\sqrt{s})}{1+\xi(\rho)(\sqrt{s}/m_N) f_{\eta N}(\sqrt{s})\rho}, \qquad \xi(\rho) = \frac{9\pi}{4p_F^2}$

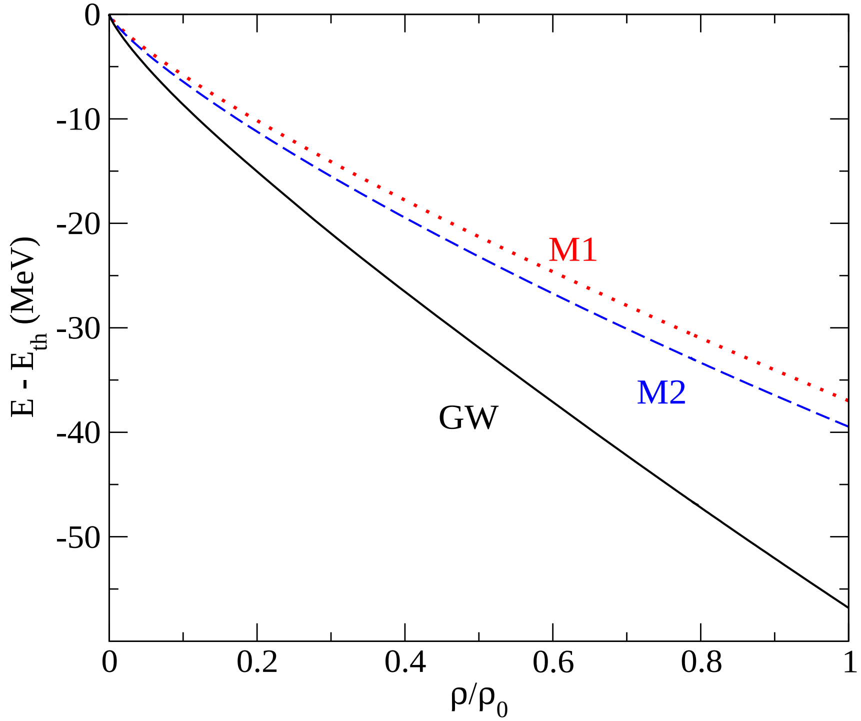
- $N^*(1535) \Rightarrow$ energy dependent $f_{\eta N}(\sqrt{s})$.

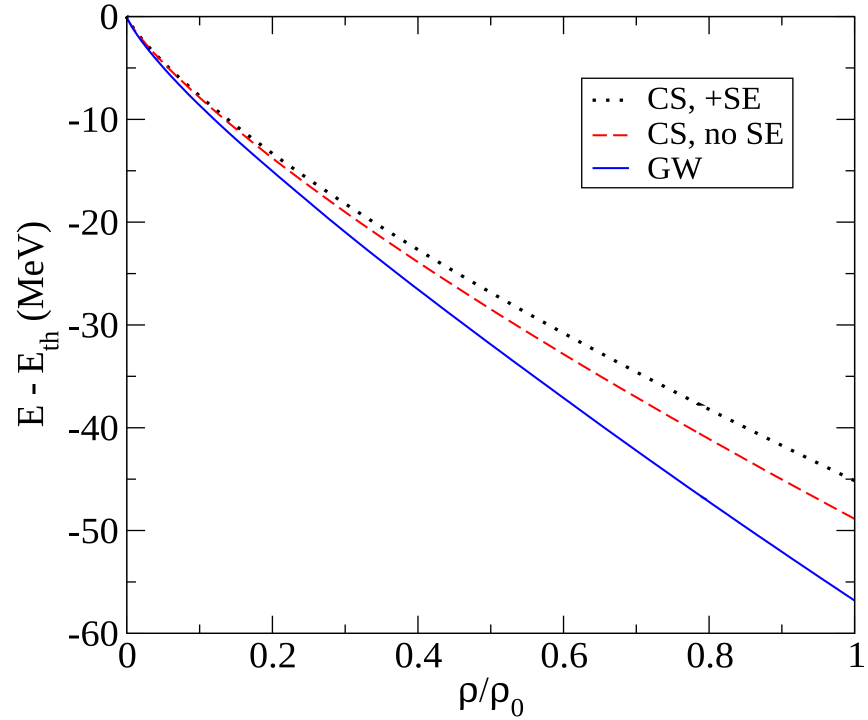
  In medium $\Rightarrow$ go subthreshold: $\quad \delta\sqrt{s} = \sqrt{s} - \sqrt{s_{\mathrm{th}}}$

  $\delta\sqrt{s} \approx -B_N \frac{\rho}{\bar{\rho}} - \xi_N B_\eta \frac{\rho}{\rho_0} - \xi_N T_N \left(\frac{\rho}{\rho_0}\right)^{2/3} + \xi_\eta \mathrm{Re}\, V_\eta(\sqrt{s}, \rho)$

  Self-consistency relationship between $\delta\sqrt{s}$ & ρ

Self-consistency relationship

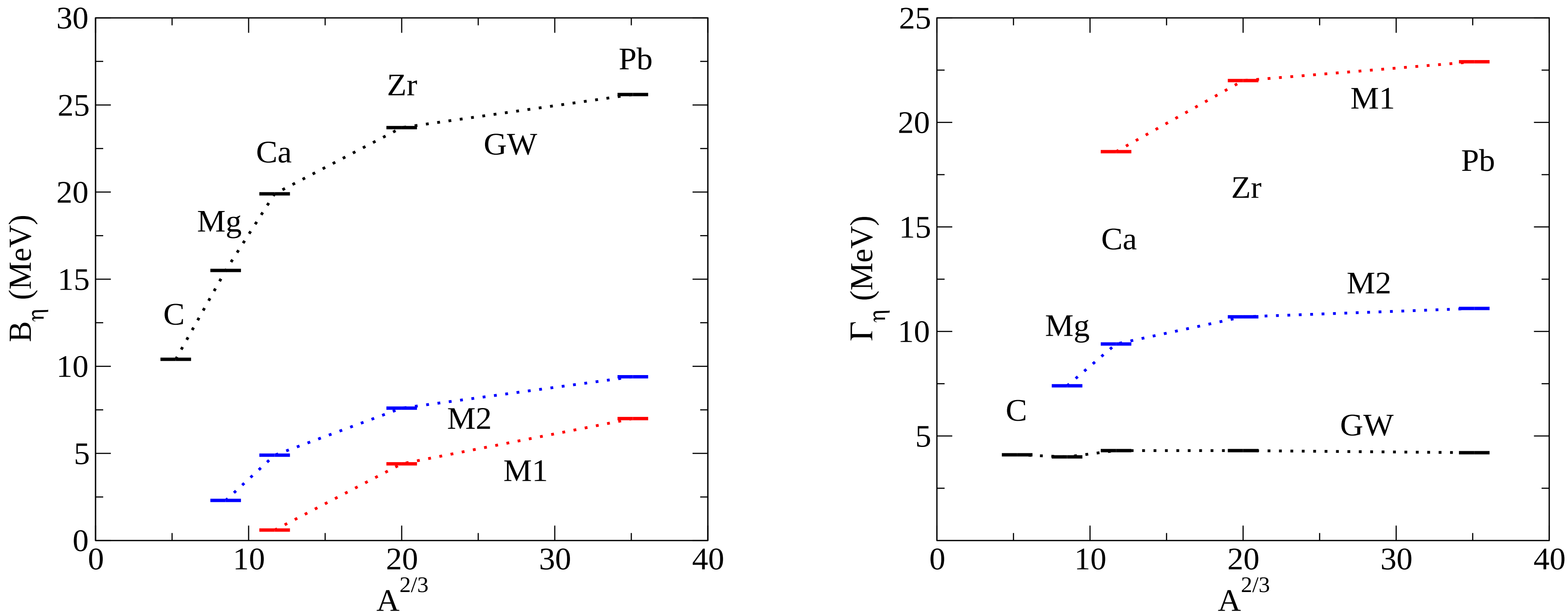




$\delta\sqrt{s}$ vs. ρ for $1s_\eta$ bound state in Ca using in-medium $f_{\eta N}$

- 40–60 MeV subthreshold energy shifts at nuclear matter density ρ_0, larger than shifting down by B_η (GR) or by 30 MeV (Haider-Liu)
- Larger Re $a_{\eta N} \Rightarrow$ larger $\delta\sqrt{s} = E - E_{\rm th}$

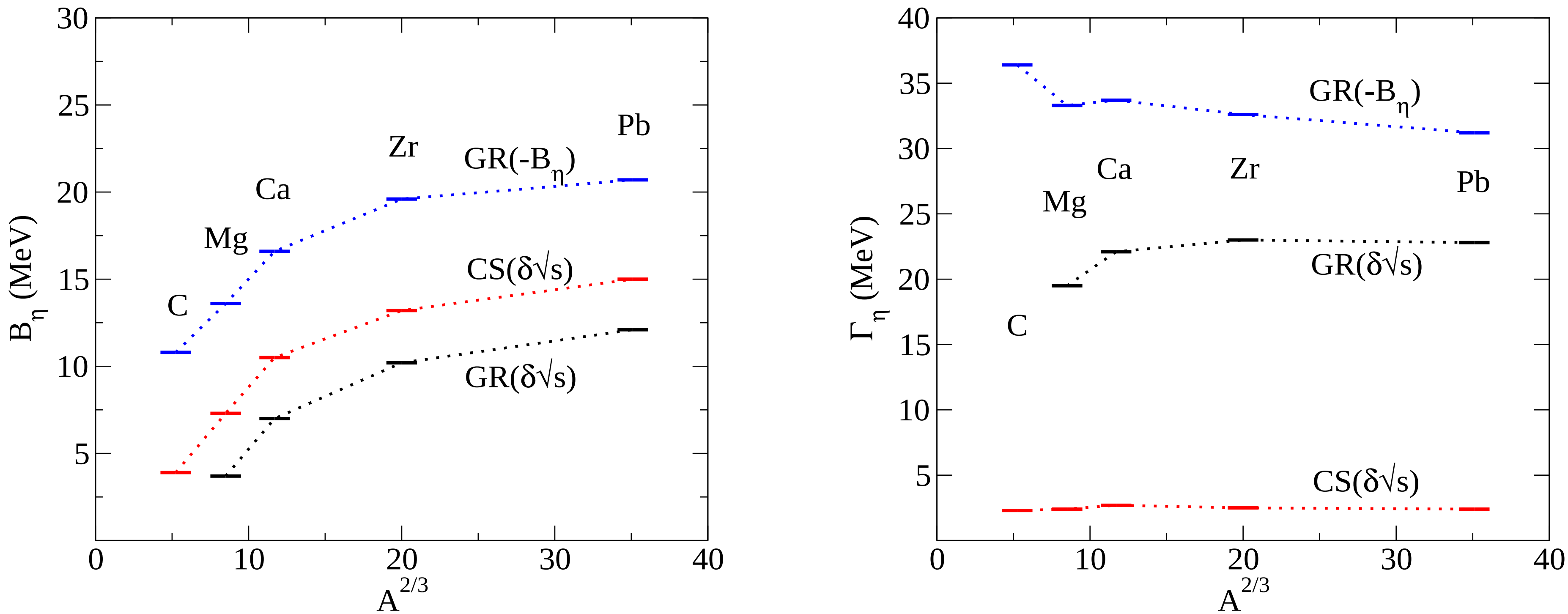
Model dependence I



Binding energy and width of $1s_\eta$ bound states across the periodic table using WRW Pauli-blocked $f_{\eta N}$

- Larger Re $a_{\eta N} \Rightarrow$ larger B_η
- Widths are unrelated to Im $a_{\eta N}$

Model dependence II

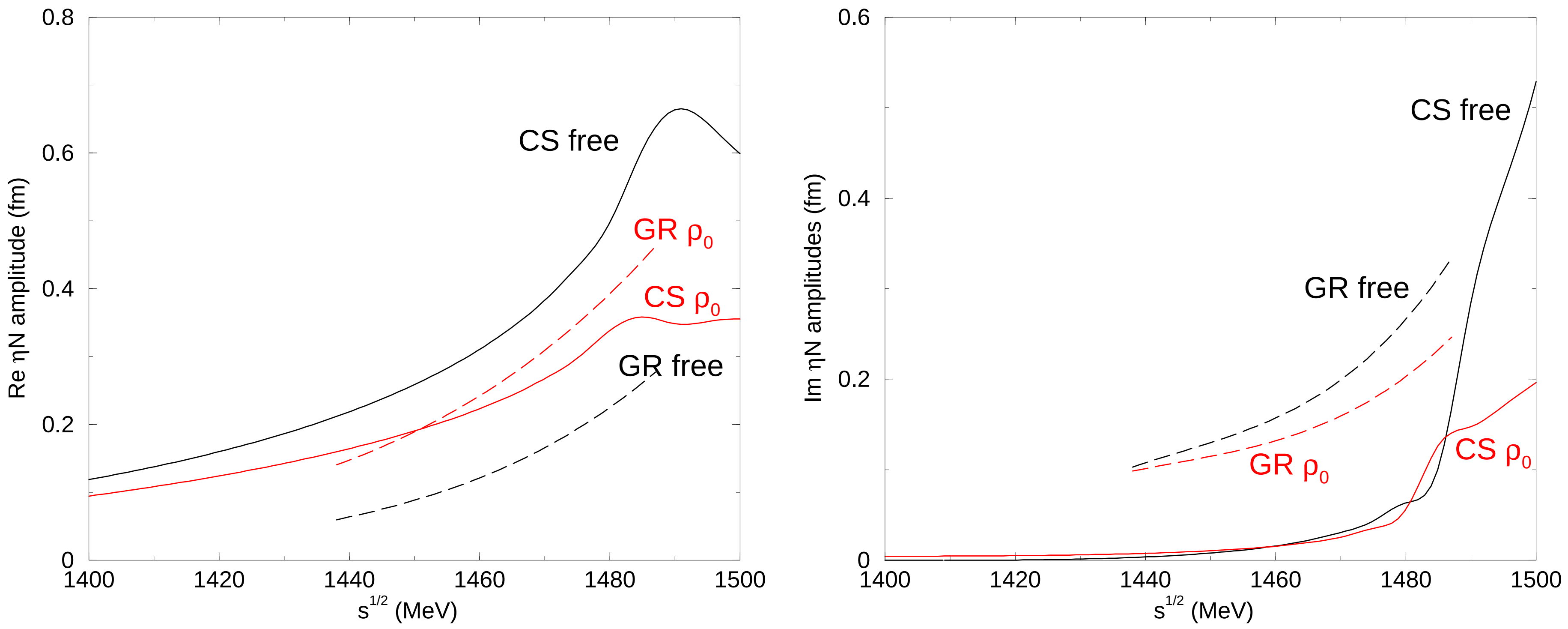


Sensitivity of calculated B_{1s_η} and Γ_{1s_η} to version of self-consistency

- $\delta\sqrt{s}$ recipe reduces both B_{1s_η} and Γ_{1s_η} w.r.t. $-B_{1s_\eta}$ recipe
- GR's widths are too large to resolve η bound states

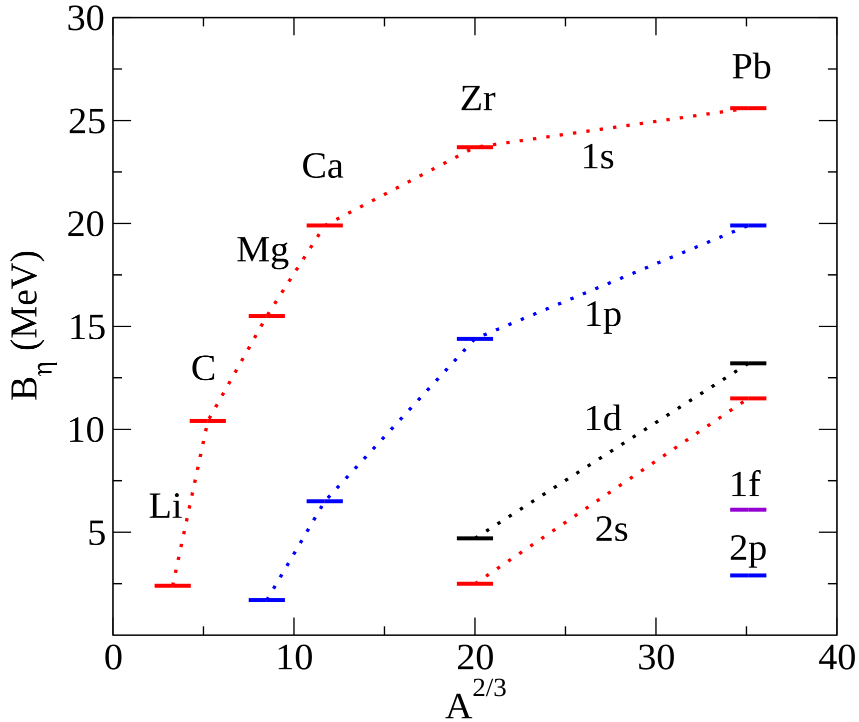
  Why $\Gamma_\eta(\mathrm{GR}) \gg \Gamma_\eta(\mathrm{CS})$ for similar Im $a_{\eta N}$?

Energy dependence of free-space & in-medium amplitudes

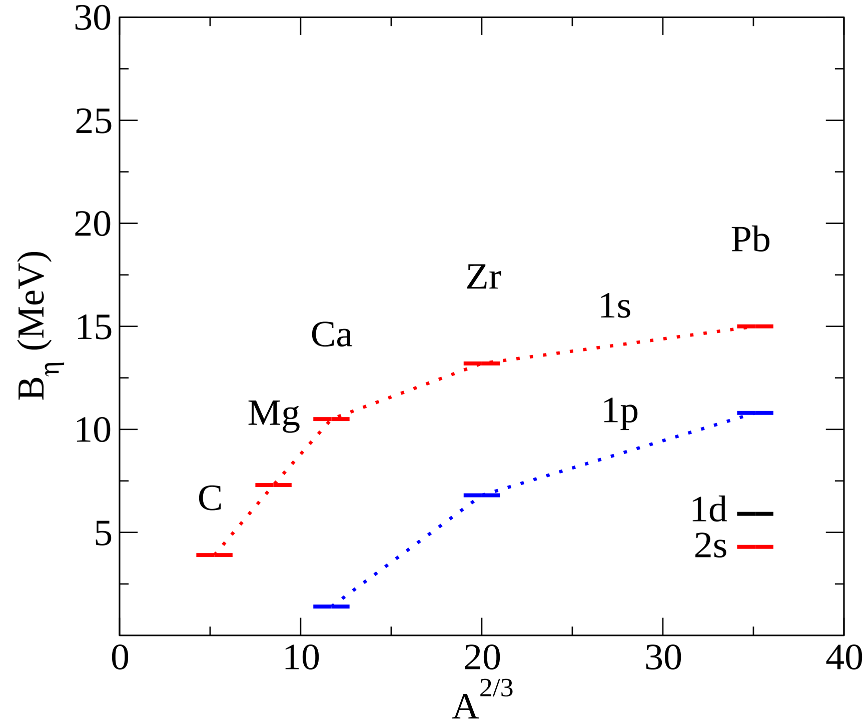


- Subthreshold Re $f_{\eta N}$ similar in both in-medium models in spite of large free-space difference at threshold
- Subthreshold Im $f_{\eta N}$ differ widely, which explains the huge difference between Γ_η(GR) and Γ_η(CS)

Model predictions for small widths



GW model



CS model

- more theoretical work is needed to figure out what makes subthreshold values of Im $f_{\eta N}$ sufficiently small to generate small widths.

Summary

- Large widths, $\Gamma_{\overline{K}} > 50$ MeV, expected for single-$\overline{K}$ quasibound nuclear states. Focus on light systems. Searches for $K^- pp$ are underway in GSI and J-PARC.

- Major issues: (i) how deep is $\overline{K}$ nuclear spectrum? (ii) how big is $\Gamma(\overline{K}NN \to YN)$ w.r.t. $\Gamma(\overline{K}N \to \pi Y)$?

- **Subthreshold behavior of $f_{\eta N}$ is crucial in studies of η-nuclear bound states to decide whether (i) such states exist, (ii) can they be resolved (widths?), and (iii) which nuclear targets and reactions to try?**

Thanks to my collaborators N. Barnea, A. Cieplý, E. Friedman, D. Gazda, J. Mareš