# $\bar{K}$ nuclear interactions and dynamics

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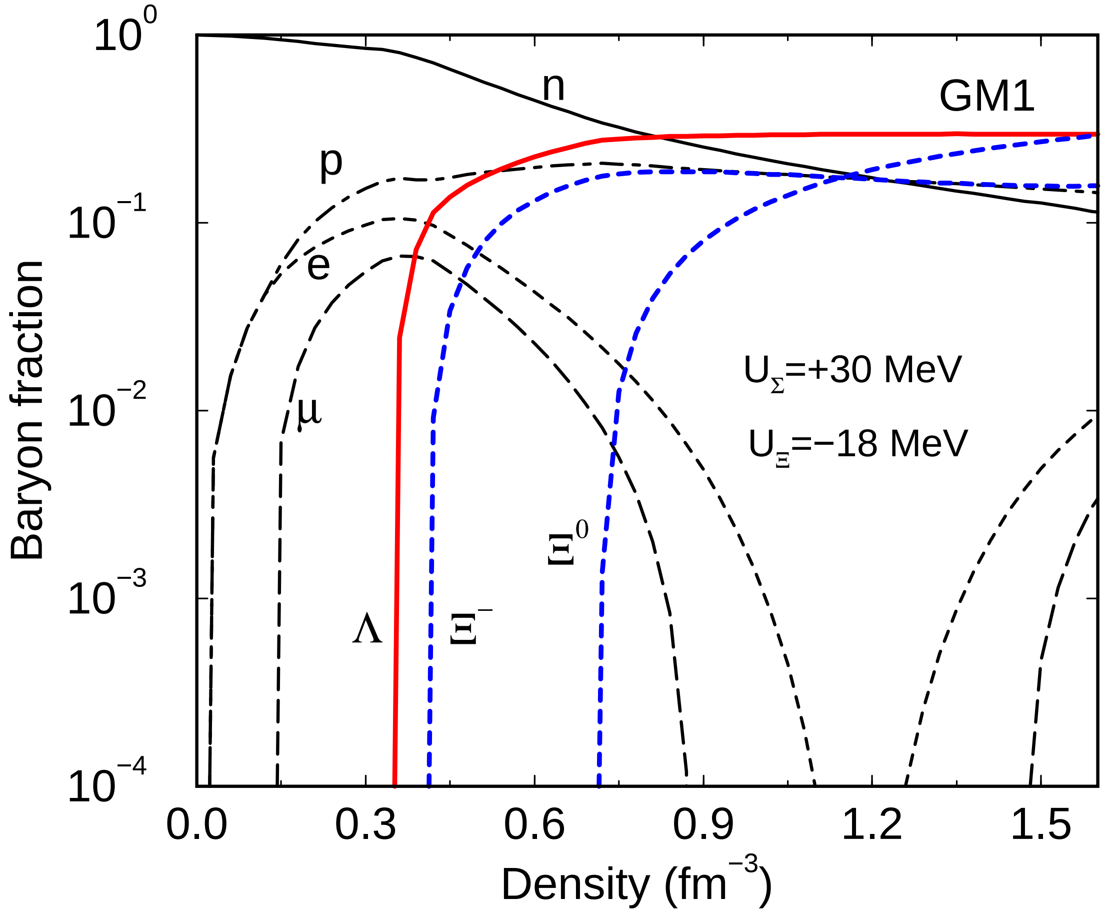
- $\bar{K}N - \pi Y$ dynamics and studies of $K^-pp$
- $\bar{K}$-nucleus potentials from $K^-$ atoms (see Friedman's talk)
- Narrow $\bar{K}$ nuclear quasibound states?
- $\bar{K}$ in multistrange matter; $\bar{K}$ condensation?

**NPA 804 (2008)     NPA 835 (2010) [HYP-X]**

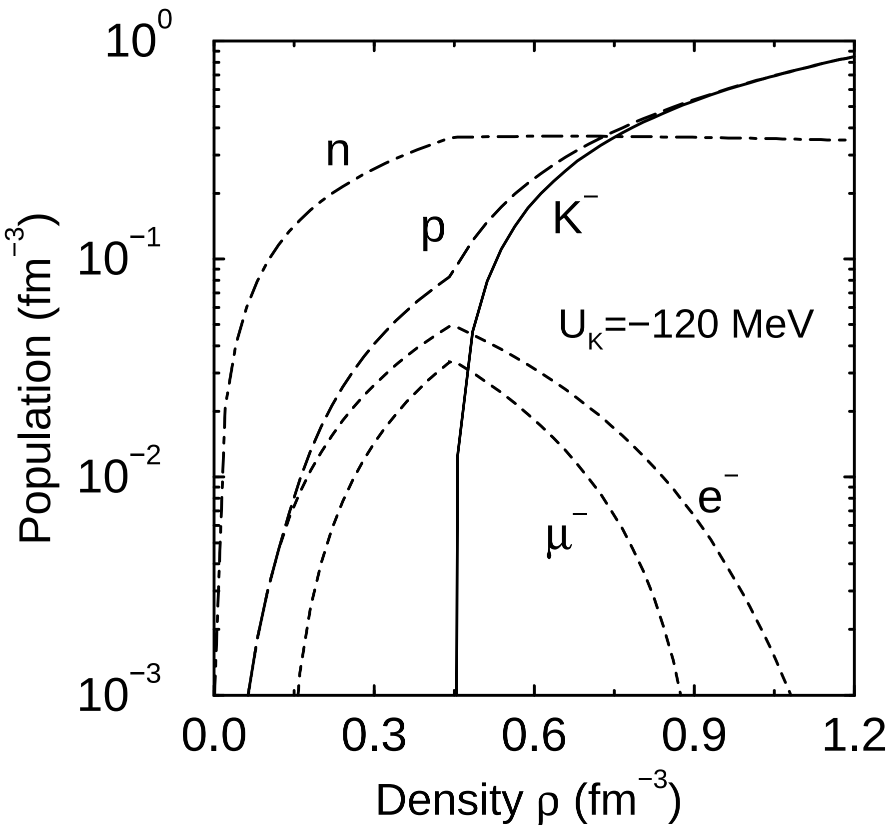
and many other reports in MESON 2010




J. Schaffner-Bielich, NPA 804 (2008) 309

RMF calculation of baryon & lepton fractions in neutron star matter

Strangeness acts for densities $\geq 2.5\rho_0$; why not $\Lambda \rightarrow p + K^-$?




N.K. Glendenning, J. Schaffner-Bielich, PRC 60 (1999) 025803

Lepton depletion $\ell^- \to K^- + \nu_\ell$ occurs for $\rho \geq 3\rho_0$

However, hyperons abort $K^-$ condensation in neutron-star matter

# $\bar{K}N - \pi Y$ dynamics and studies of $K^{-}pp$

# Weinberg-Tomozawa leading chiral SU(3) effective ps meson - baryon potential

Zero-range limit of F-type SU(3) vector-meson exchange;
introduce form factors fitted to low-energy data

$$V_{ij}(\sqrt{s}) = -\frac{C_{ij}}{4f^2}(2\sqrt{s} - M_i - M_j)\sqrt{\frac{E_i + M_i}{2M_i}}\sqrt{\frac{E_j + M_j}{2M_j}}$$

$C^{I=0}_{\bar{K}N-\pi\Sigma}$ diagonal $= 3,\ 4,$ and off-diagonal $= -\sqrt{3/2}$

$C^{I=1}_{\bar{K}N-\pi\Sigma-\pi\Lambda}$ diagonal $= 1,\ 2,\ 0,$ and $\bar{K}N$ off-diagonal $= -1\ -\sqrt{3/2}$

$$V_{ij} \to T_{ij}: \qquad T_{ij}(\sqrt{s}) = V_{ij}(\sqrt{s}) + V_{il}(\sqrt{s})\,G_l(\sqrt{s})\,T_{lj}(\sqrt{s})$$

$T_{\bar{K}N-\bar{K}N} * \rho$: $\bar{K}$-nuclear energy dependent potential

Extend to NLO

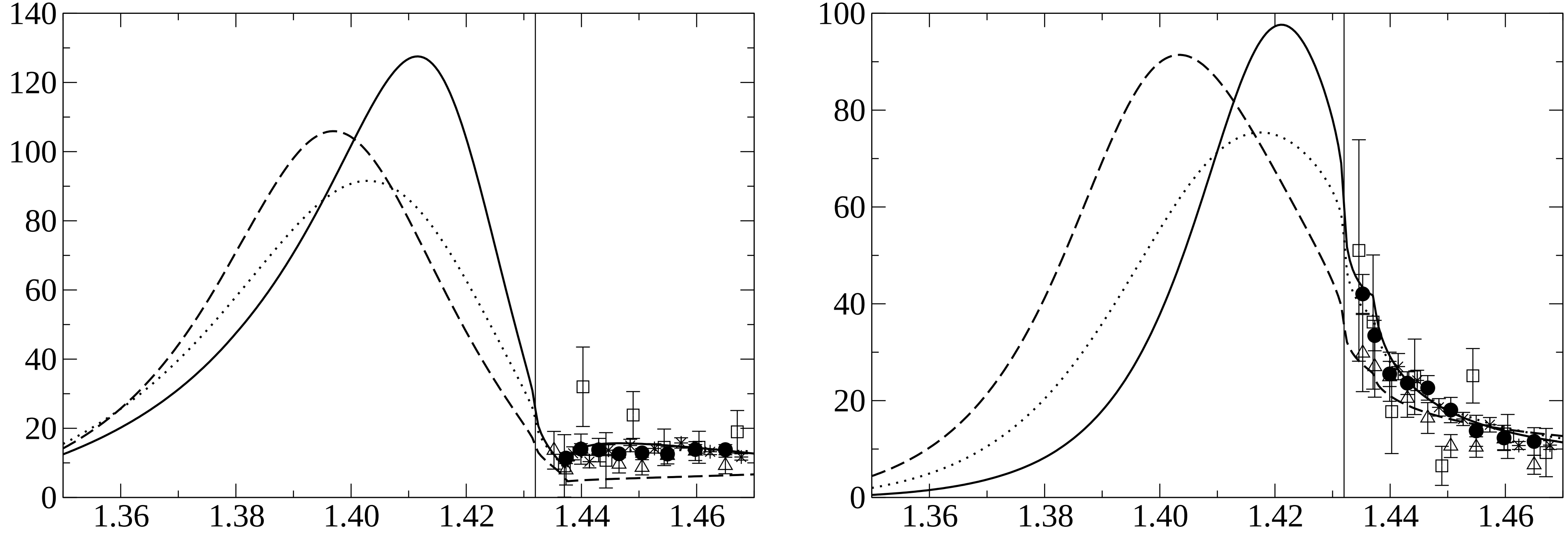
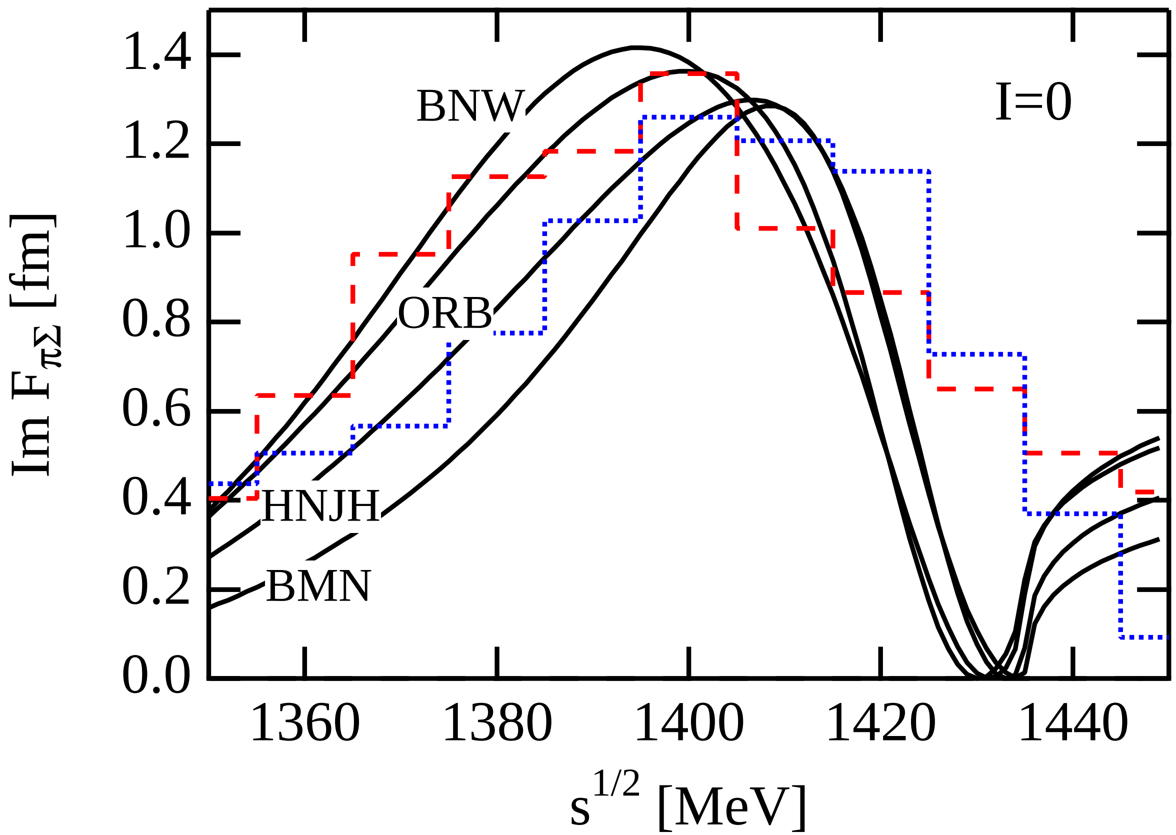



Figure 1: Calculated cross sections for $K^-p \to \pi^\mp\Sigma^\pm$ multiplied by $4|\mathbf{q}_{cm}^{K^-p}|\sqrt{s}$ and continued below the $K^-p$ threshold (vertical line), for three chiral coupled-channel fits to the $K^-p$ low-energy data. The fit shown by the solid (dashed) lines excludes (includes) the DEAR value for $a_{K^-p}$.

From B. Borasoy, R. Nißler, W. Weise, EPJA 25 (2005) 79.

Extrapolation below threshold $\rightarrow \pi\Sigma$ resonance $\Lambda(1405)$

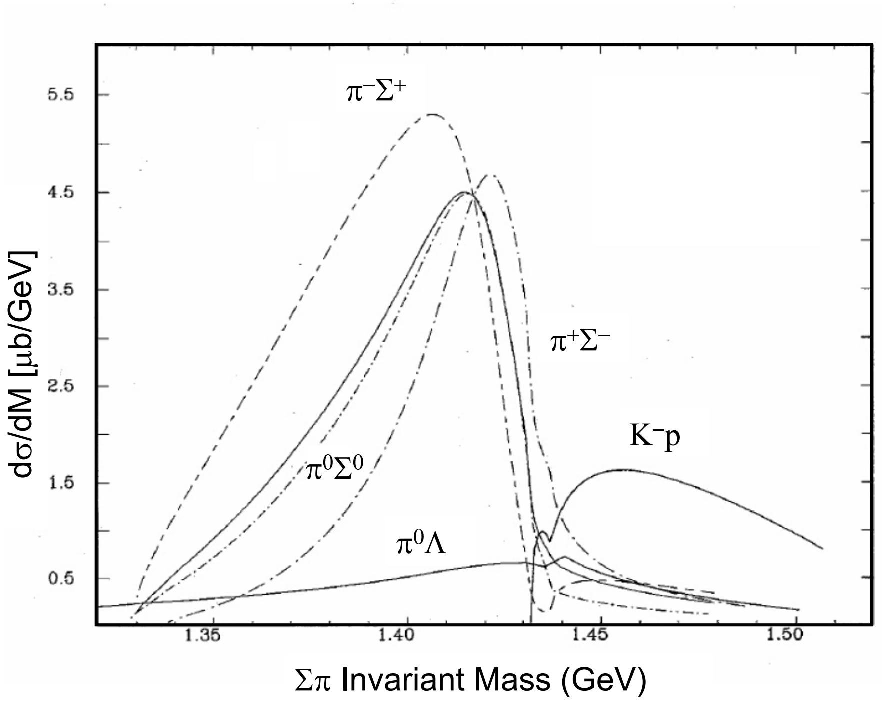
$$\gamma = \frac{\Gamma(K^-p\to\pi^+\Sigma^-)}{\Gamma(K^-p\to\pi^-\Sigma^+)} = 2.36 \pm 0.04 \implies \quad \text{isospin dependence}$$

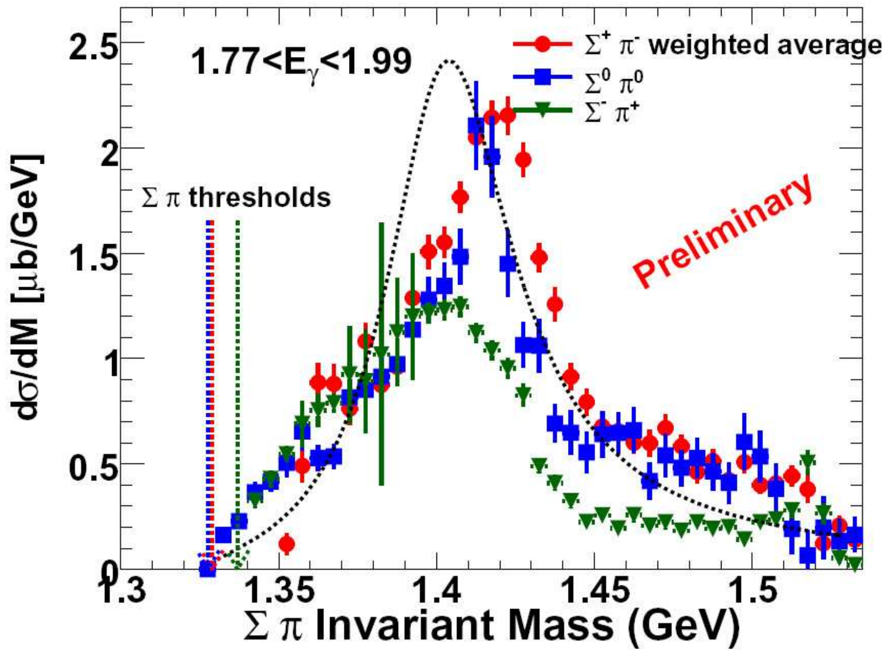



T. Hyodo, W. Weise, PRC 77 (2008) 035204 (— $\pi^-\Sigma^+$, ... sum of $\pi^\pm\Sigma^\mp$)

$\Lambda(1405)$ shape in $\pi - \Sigma$ spectrum, calculated in chiral models

Do chiral models work well? Experimentally, need a $\pi^0\Sigma^0$ spectrum



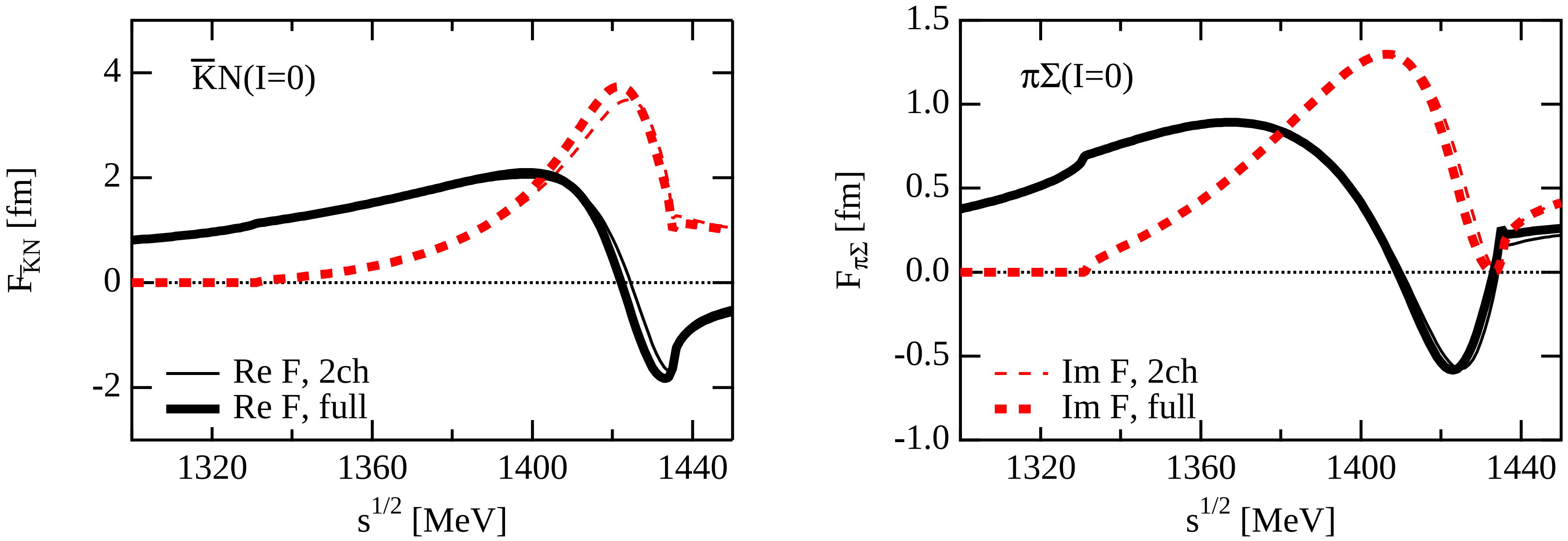




R. Schumacher (for the CLAS Collab.) NPA 835 (2010) 231

Line shapes of Λ(1405) predicted in a chiral model (left) and presented by CLAS in HYP-X (right)

Related, weaker statistics data from LEPS and COSY-ANKE

$I = 0 \leftrightarrow I = 1$ interferences split $\Sigma^{\pm}\pi^{\mp}$ spectra

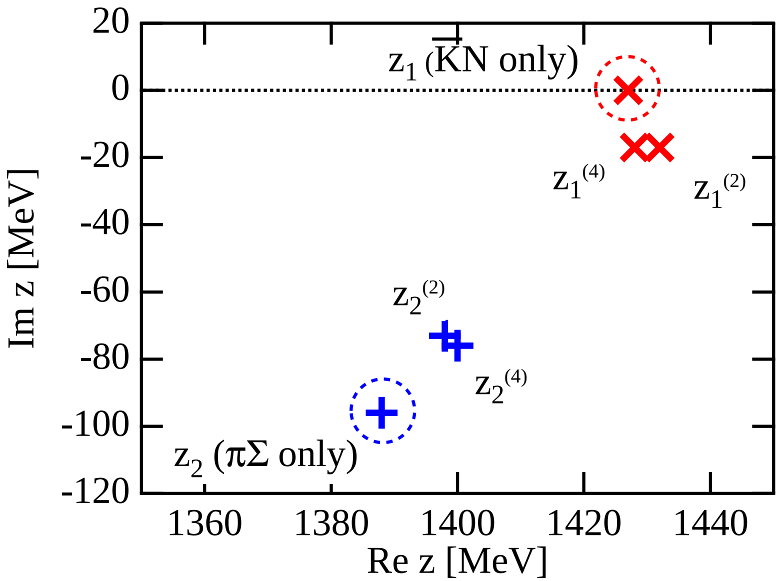


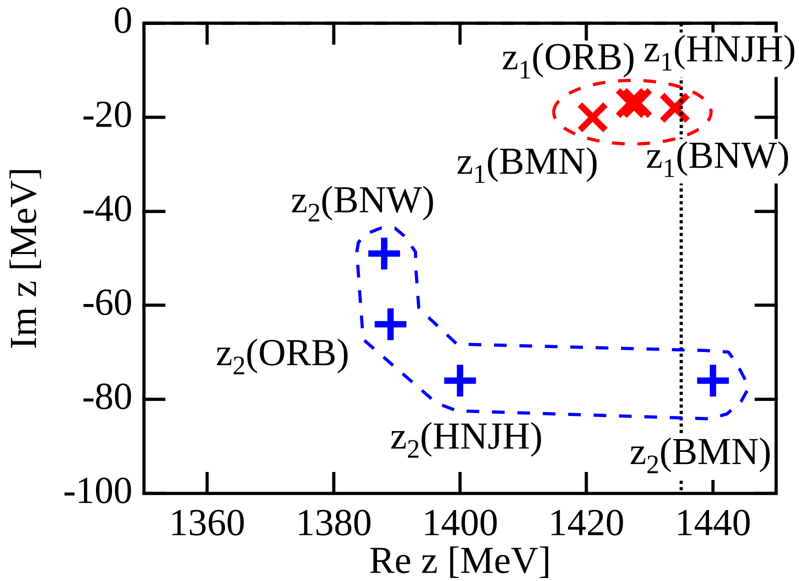

T. Hyodo, W. Weise, PRC 77 (2008) 035204

$I = 0$ coupled-channel amplitudes

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

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



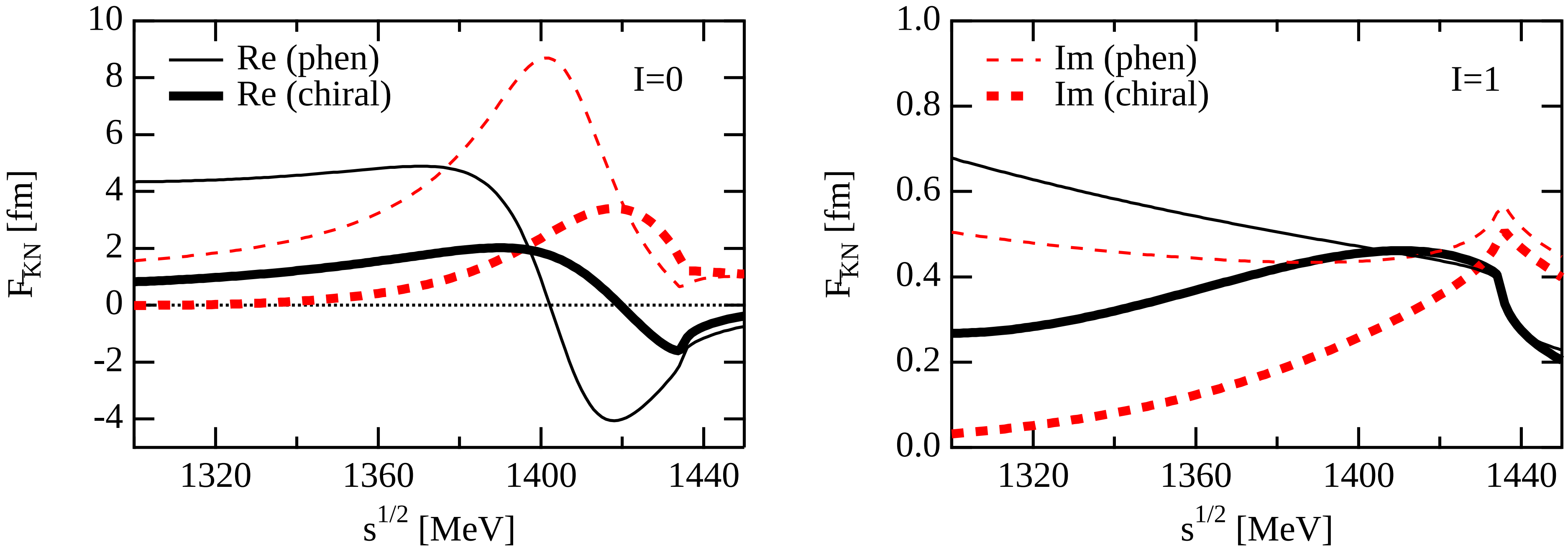

T. Hyodo, W. Weise, PRC 77 (2008) 035204

Two-pole structure in chiral coupled-channel calculations

Sizable model dependence for $\pi\Sigma$ resonance pole

$\bar{K}N$ QuasiBound State (QBS) at $\approx$ 1426 MeV

Single-pole calculations: $\bar{K}N$ QBS at $\approx$ 1405, bound by 27 MeV



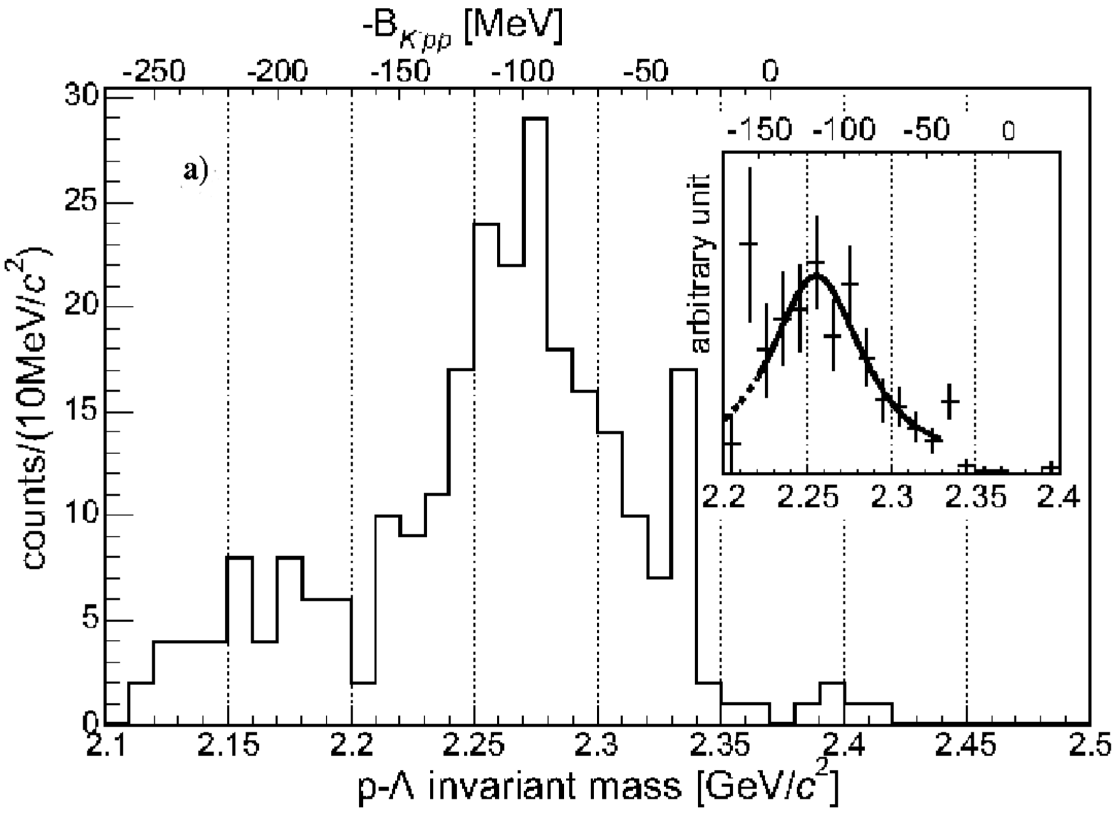

T. Hyodo, W. Weise, PRC 77 (2008) 035204

Critique of single-pole phenomenological $\bar{K}N$ potential

*phen*: T. Yamazaki, Y. Akaishi, PRC 76 (2007) 045201

$\bar{K}N$ QBS: at 1405 MeV (phen) or at 1420 MeV (chiral)?

Different starting points in $\bar{K}$-nuclear cluster calculations

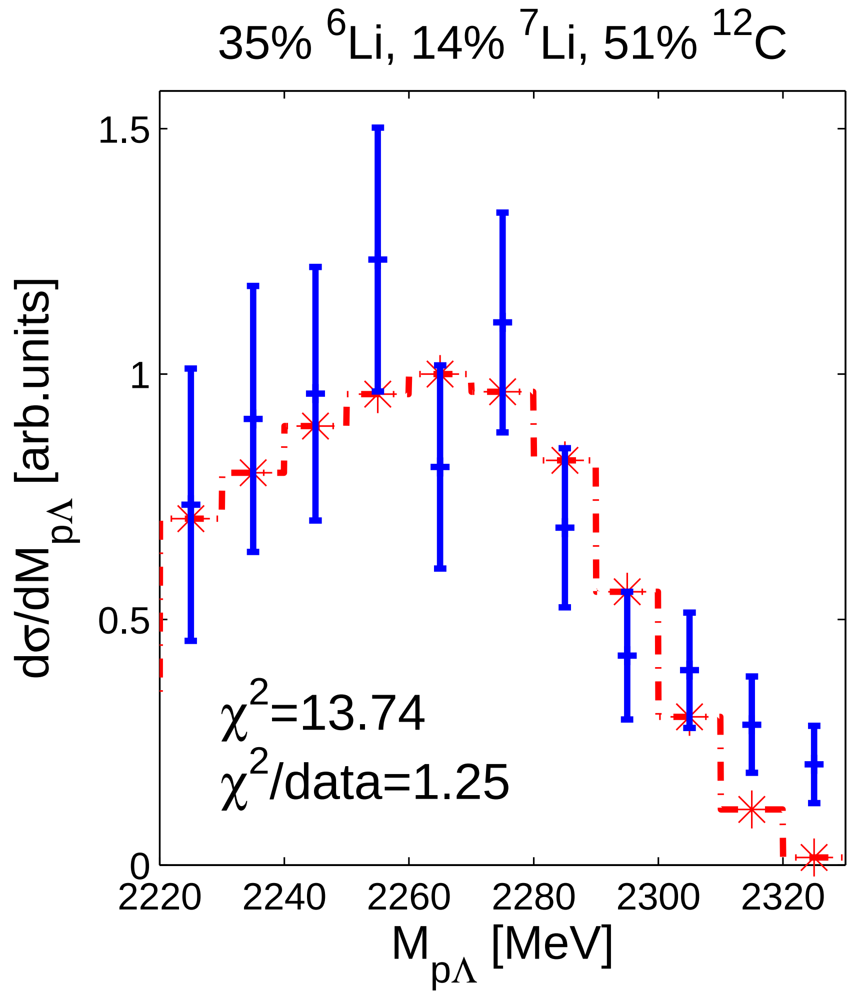



M. Agnello et al. (FINUDA collab.), PRL 94 (2005) 212303

$\Lambda p$ spectrum from $K^-$ absorption in Li and C

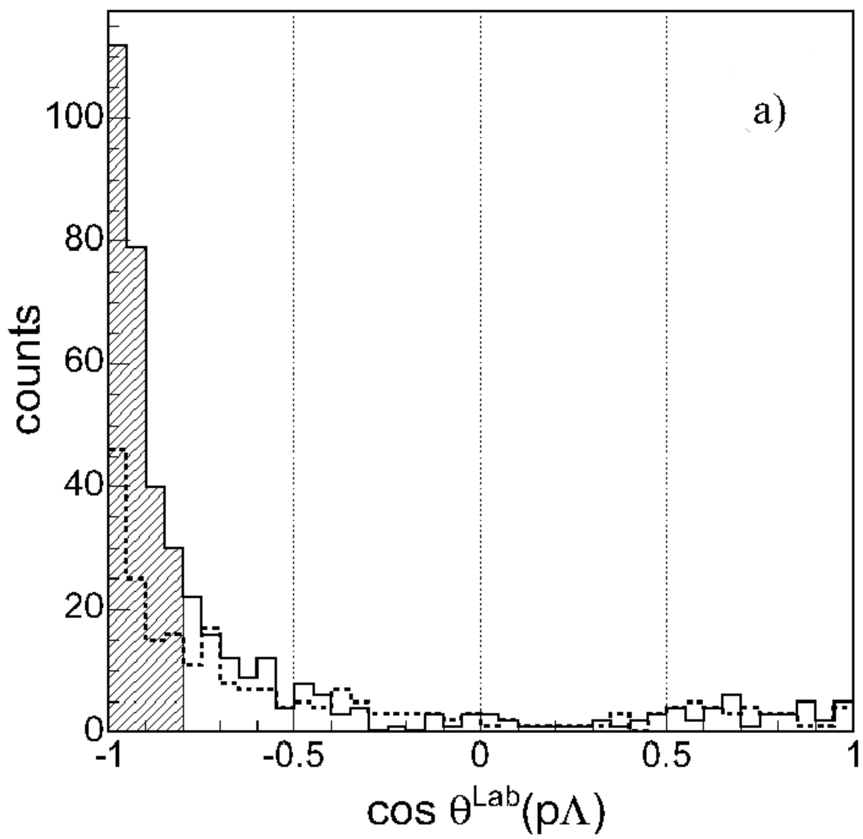
Evidence for a $K^-pp$ quasibound state? no production constraint

Contested by Magas, Oset, Ramos, Toki, PRC 74 (2006) 025206




V.K. Magas, presented at PANIC08

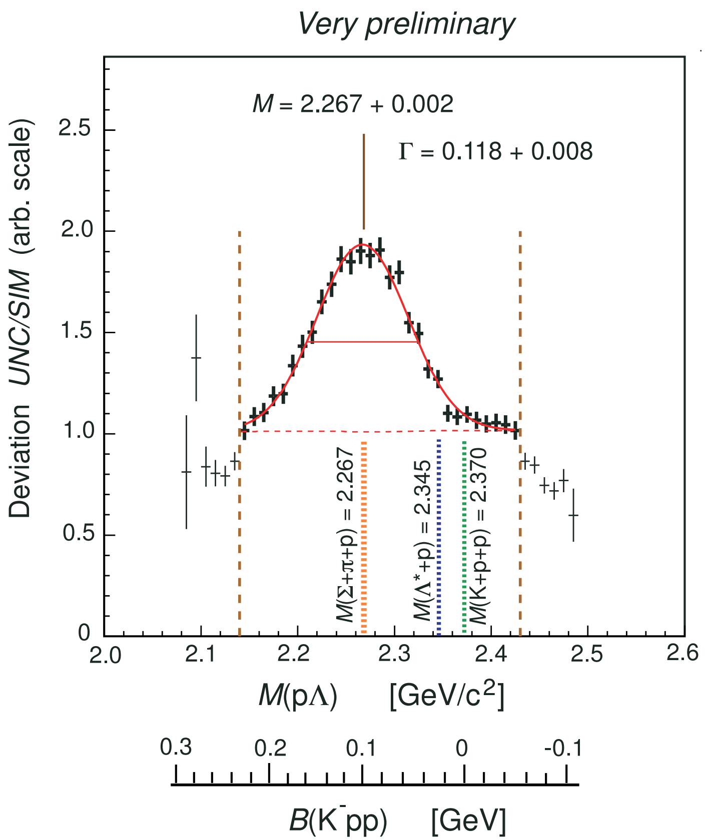
$\Lambda p$ spectrum from quasi-free simulation of $K^-$ absorption

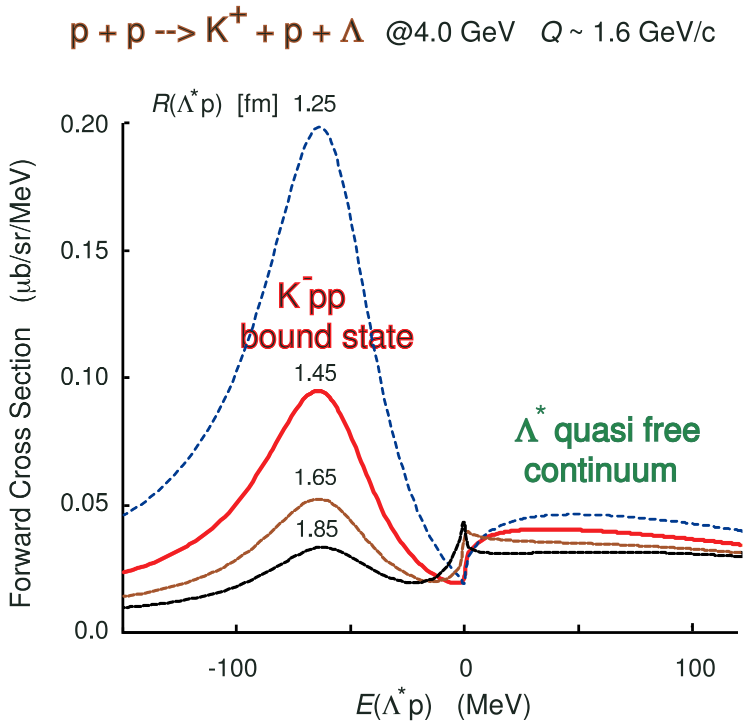



M. Agnello et al. (FINUDA collab.), PRL 94 (2005) 212303

$\Lambda p$ angular correlation; supporting a $K^- pp$ quasibound state?

Sharper correlation than produced by quasi-free processes




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

Broad $K^-pp$ structure at $\pi N \Sigma$ threshold?

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

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

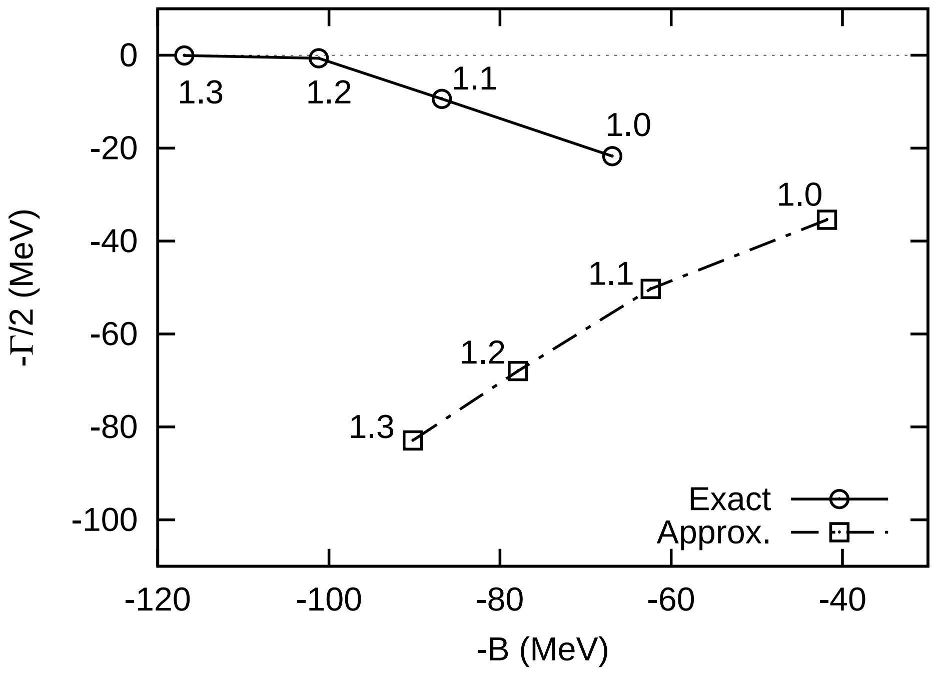
# Exotic $\bar{K}$ structures, with unbound nuclear cores

onset of binding: $K^- pp$ and $\overline{K}^0 nn$, in particular $I_{NN} = 1, I_{\text{tot}} = 1/2$

| | $\bar{K}N$ channel | | | coupled channels | | |
|---|---|---|---|---|---|---|
| (MeV) | var. [1] | var. [2] | Faddeev [3] | Faddeev [4] | Faddeev [5] | var. [6] |
| $B$ | 48 | 17–23 | 50–70 | 60–95 | 9-16, 67-89 | 40–80 |
| $\Gamma$ | 61 | 40–70 | 90–110 | 45–80 | 34-46, 244-320 | 40–85 |


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. Y. Ikeda, H. Kamano, T. Sato, arXiv:1004.4877 [nucl-th]
6. S. Wycech, A.M. Green, PRC **79** (2009) 014001 (including $p$ waves)


Robust binding, but large widths and a broad range for $B$ and $\Gamma$




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

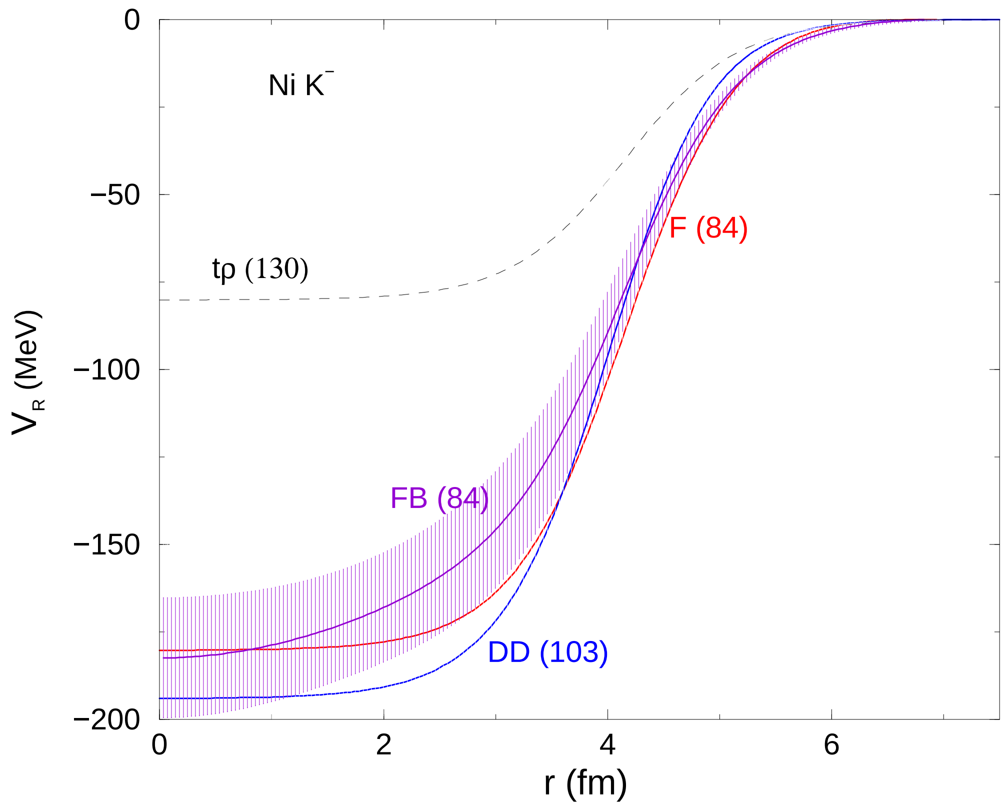
Faddeev calculations of $K^-pp$ with $\bar{K}N - \pi Y$ input

Exact: coupled $\bar{K}NN - \pi YN$. Approx: effective $\bar{K}NN$ single channel

Explicit coupled channels produce 25 MeV extra binding

QBS pole behaves more physically for 'Exact' than for 'Approx'

# $\bar{K}$-nucleus potentials from $K^-$ atoms

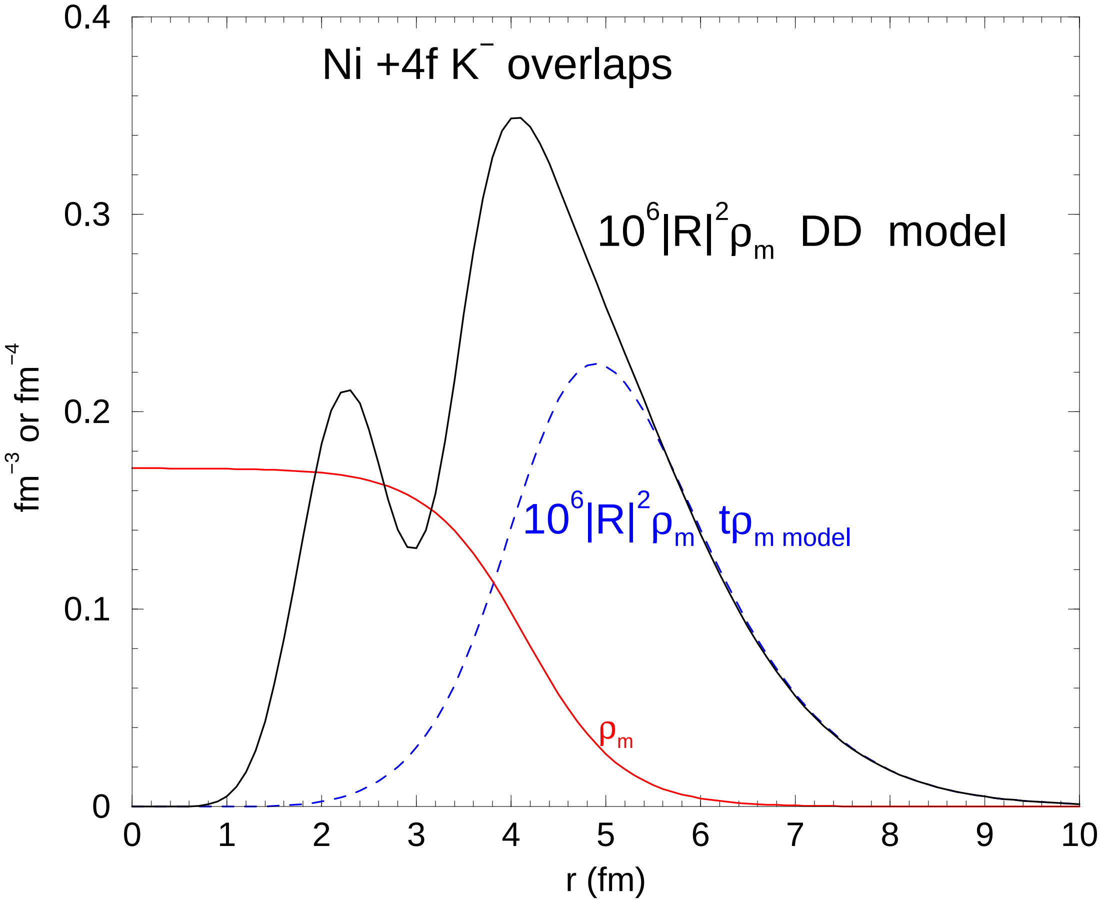



J. Mareš, E. Friedman, A. Gal, NPA 770 (2006) 84

$K^-$-Ni best-fit (real) potentials with respect to 65 data points

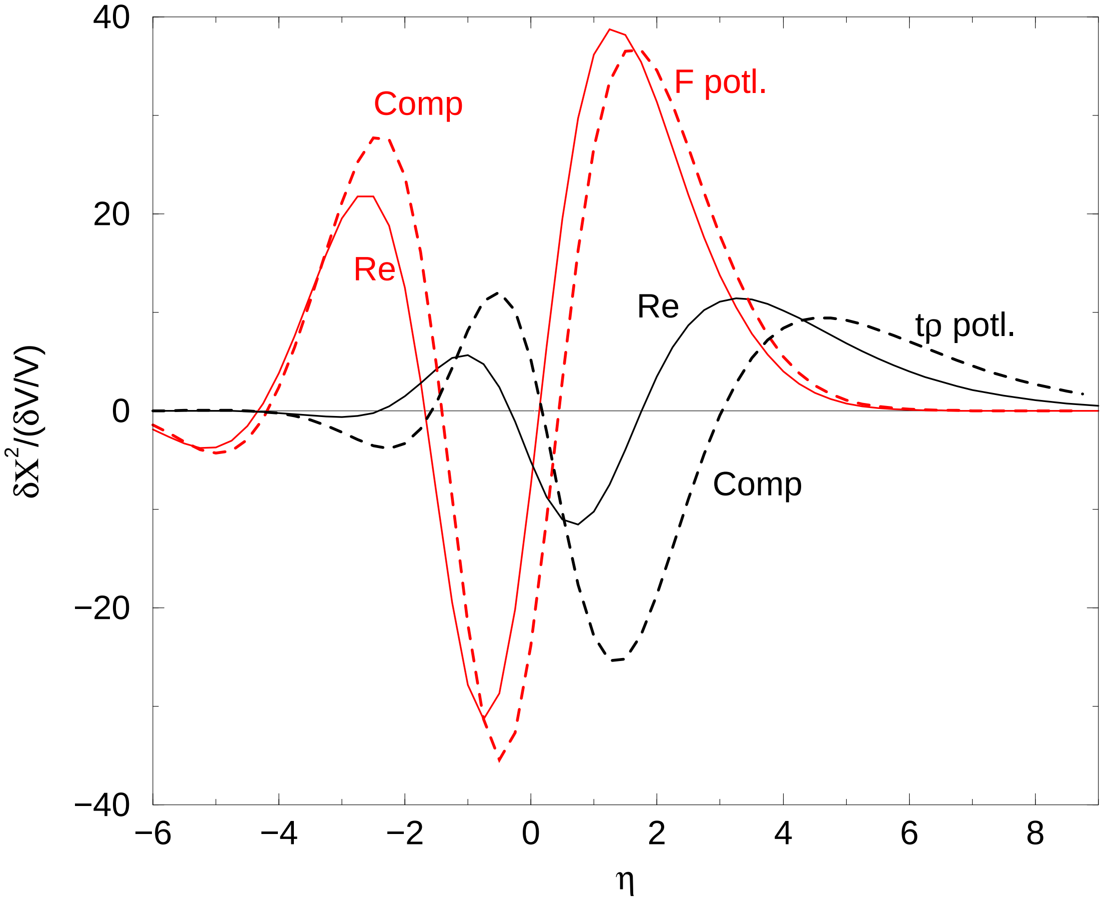
Lowest $\chi^2 = 84$: Fourier-Bessel (FB) model-independent analysis

Density dependent models DD and F offer improvement over $t\rho$




E. Friedman (2009); see also E. Friedman, A. Gal, Phys. Rep. 452 (2007) 89

$K^-$ atomic wavefunction $R$ for deep DD potential penetrates, whereas for the shallower $t\rho$ it does not penetrate the nucleus

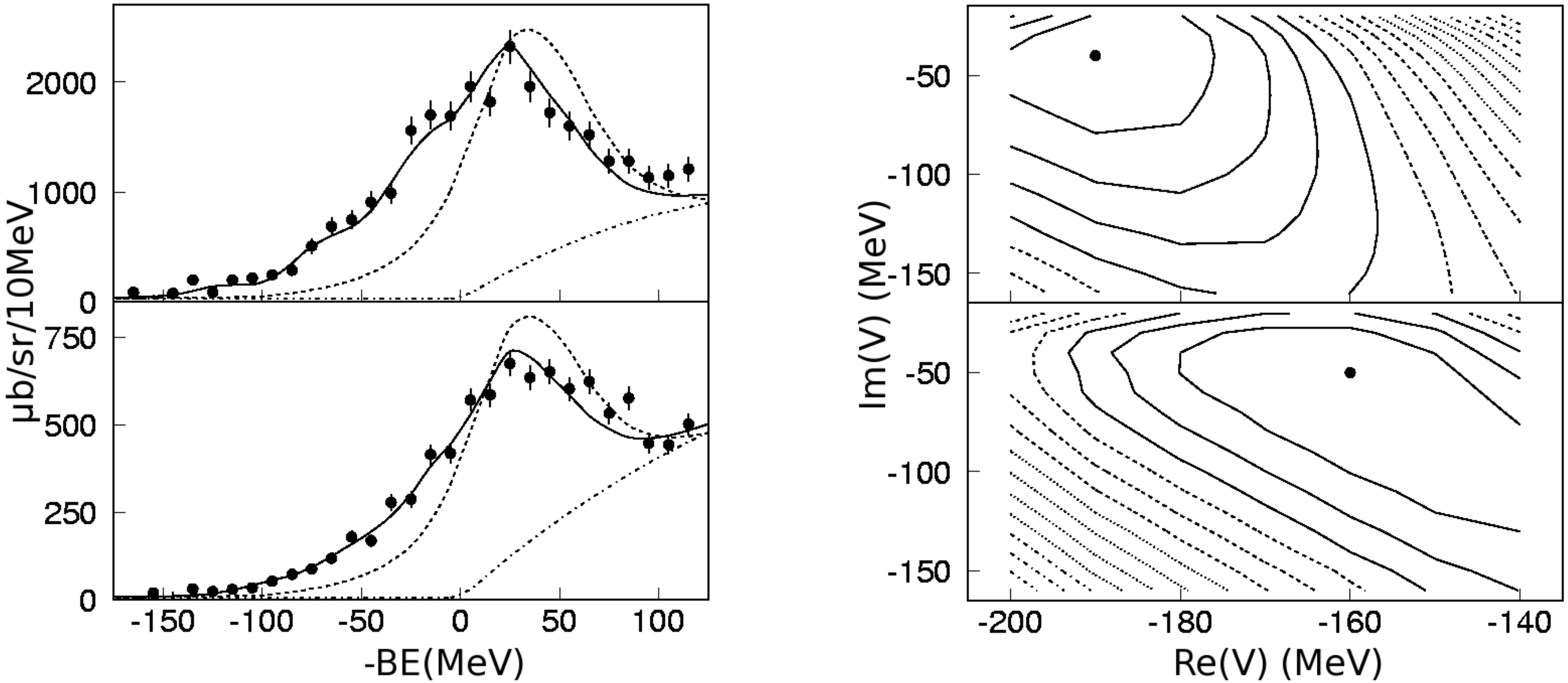



N. Barnea, E. Friedman, PRC 75 (2007) 022202

Functional Derivative analysis $[\eta = (r - R)/a]$

Deep potential (F) is determined inside the nucleus

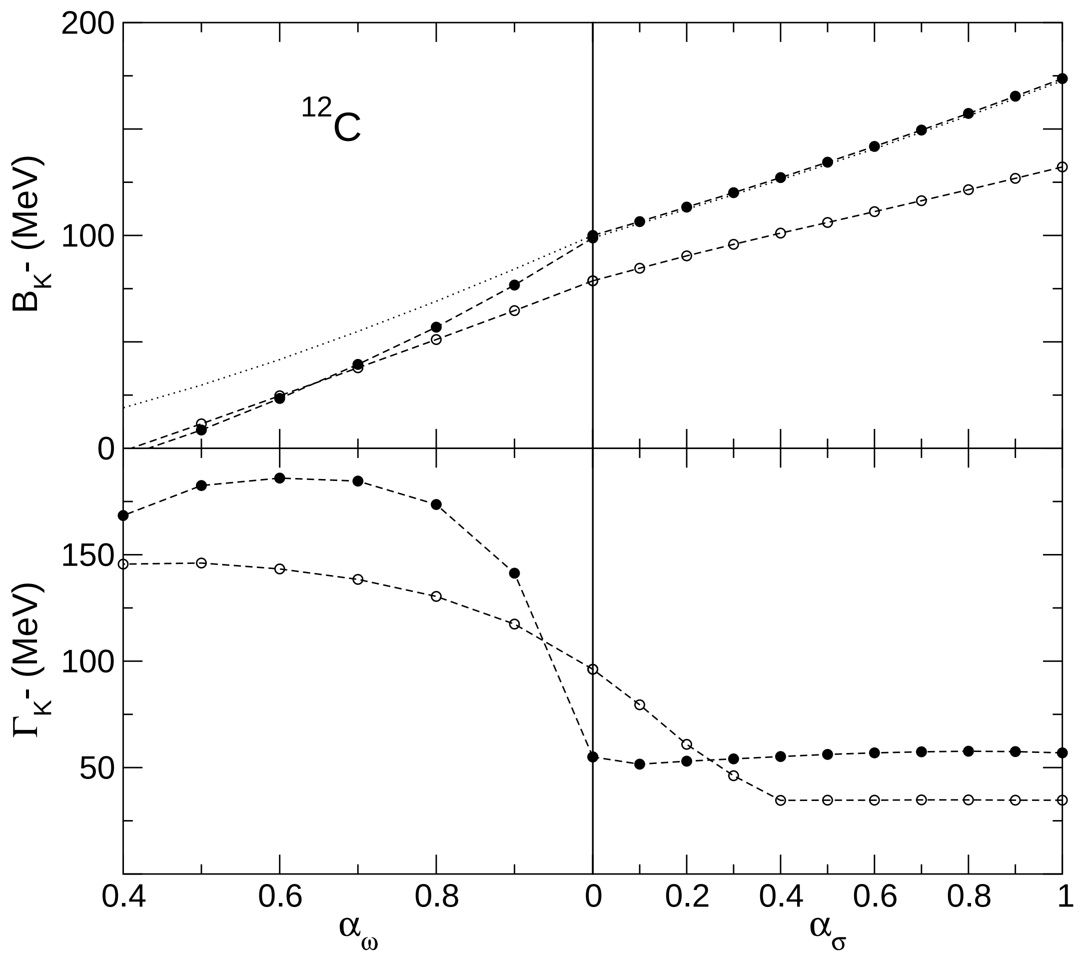
# Narrow $\bar{K}$ nuclear quasibound states?




T. Kishimoto et al., PTP 118 (2007) 181

KEK-PS E548 missing mass spectra (left) and $\chi^2$ contour plots (right) for $(K^-, n)$ (upper) & $(K^-, p)$ (lower) at $p_{\rm inc} = 1$ GeV/c on $^{12}$C

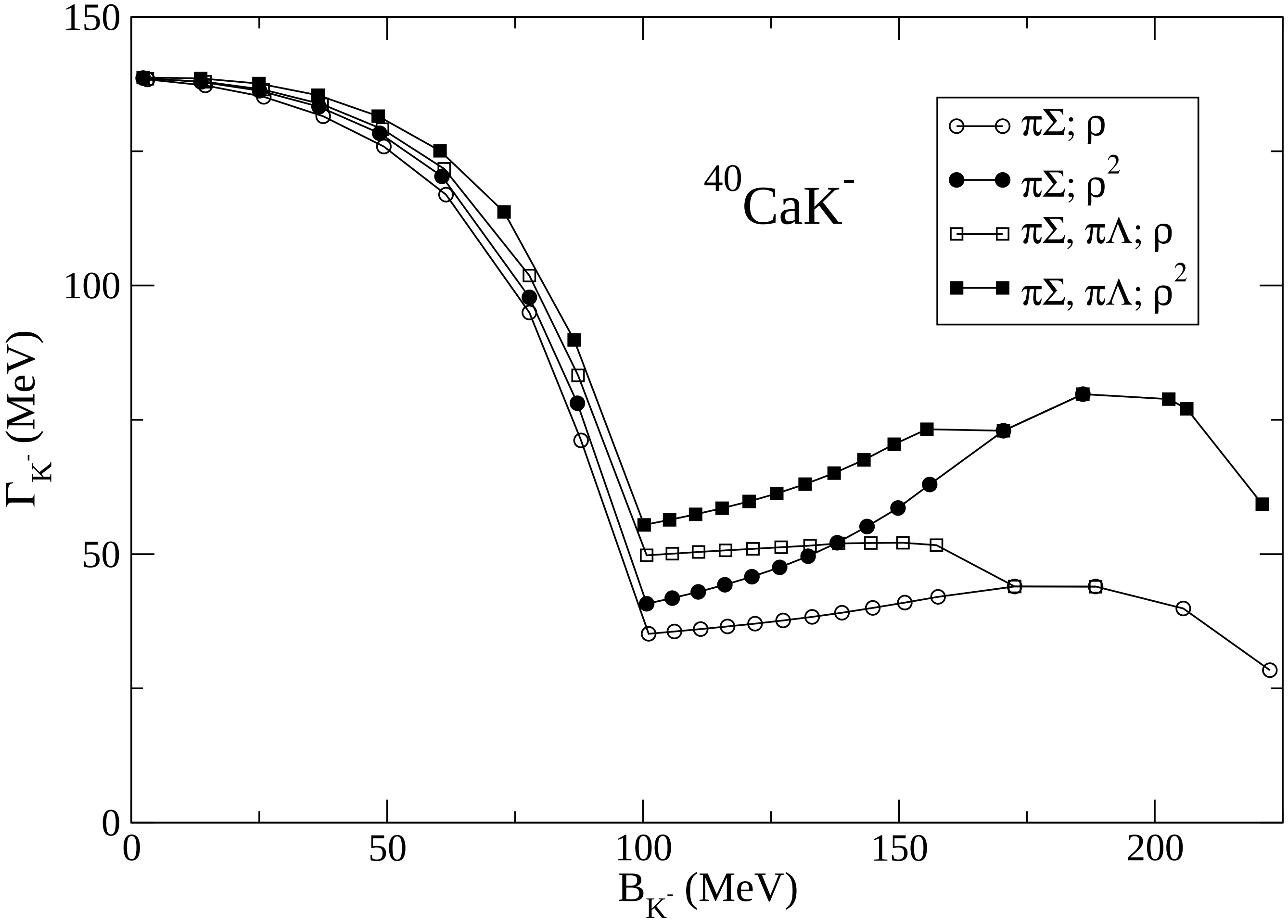
Deep potential conclusion challenged by Magas et al. PRC 81 (2010) 024609




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

$B_{K^-}$ and $\Gamma_{K^-}$ in RMF calculations: static - empty, dynamical - solid

Re $V_{K^-}$ depends on $\omega$ & $\sigma$ couplings; Im $V_{K^-}$ from $K^-$ atoms with energy dependence reflecting $\bar{K}N \to \pi Y$ & $\bar{K}NN \to YN$



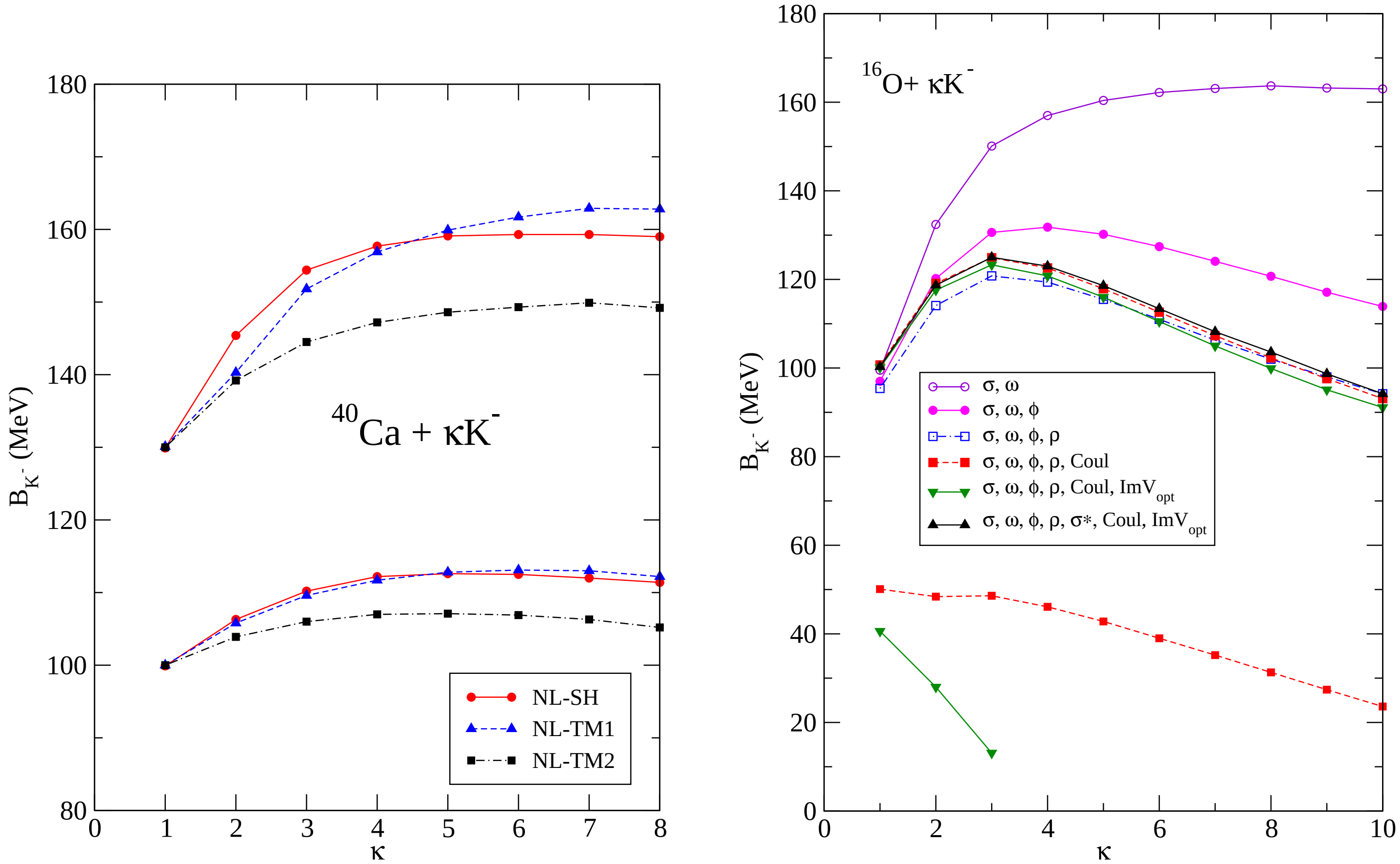

D. Gazda, E. Friedman, A. Gal, J. Mareš, PRC 76 (2007) 055204

$\Gamma_{K^-}$ as a function of $B_{K^-}$ in RMF calculations

Very large widths above $\pi\Sigma$ threshold at $B_{K^-} \approx 100$ MeV

$\Gamma_{\bar{K}} > 50$ MeV for deeply bound states

# $\bar{K}$ in multistrange matter; $\bar{K}$ condensation?

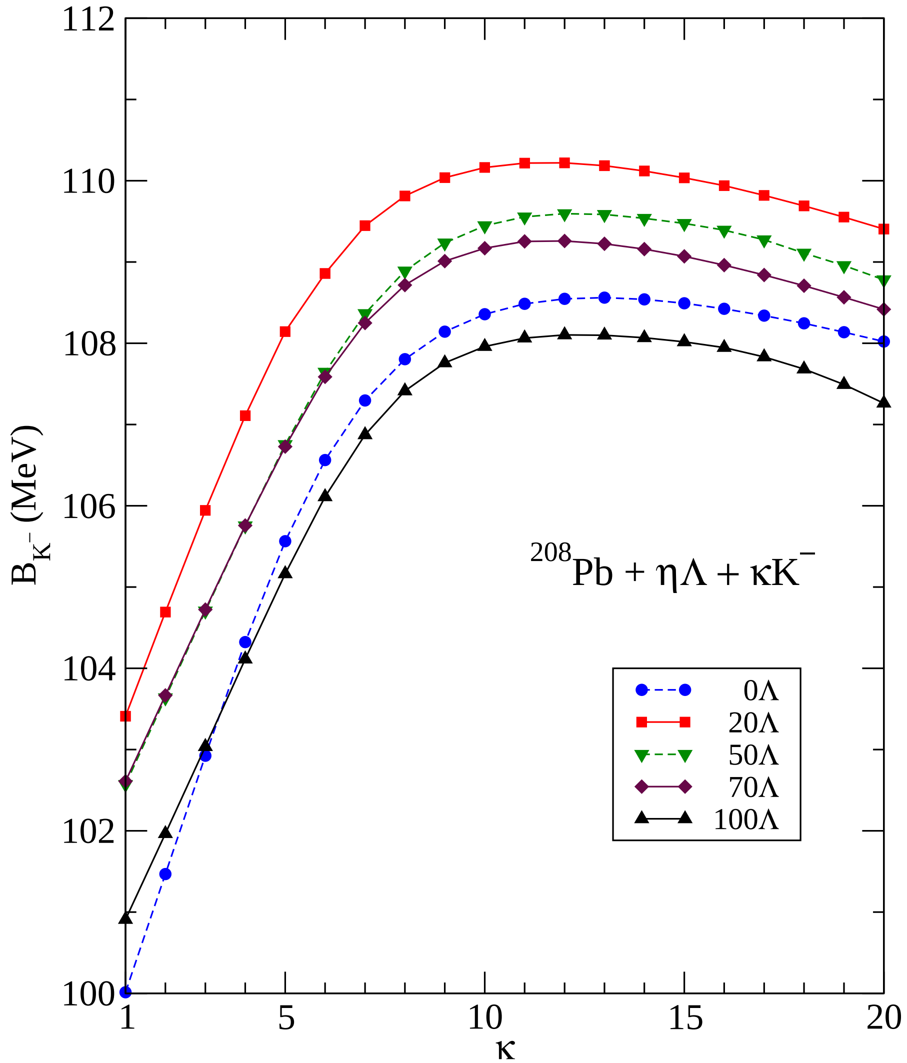



D. Gazda, E. Friedman, A. Gal, J. Mareš, PRC 77 (2008) 045206

Saturation of $B_{\bar{K}}(\kappa)$ in multi $K^-$ nuclei

$B_{\bar{K}}(\kappa \to \infty) << (m_K + M_N - M_\Lambda) \approx 320$ MeV

How robust is the saturation observed for $B_{\bar{K}}(\kappa)$?




D. Gazda, E. Friedman, A. Gal, J. Mareš, PRC 80 (2009) 035205

Saturation of $B_{\bar{K}}(\kappa)$ in $^{208}\mathrm{Pb} + \eta\Lambda + \kappa K^-$ far from $\bar{K}$ condensation

# 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

- $\overline{K}$ separation energy saturates in multi-$\overline{K}$ nuclei, and also in multi-$\overline{K}$ hypernuclei. $\overline{K}$ condensation is unlikely in self-bound matter on Earth

- $\overline{K}$ condensation in neutron stars is uncertain, but the more robust hyperon degrees of freedom will surely void or delay it