Studies of mesic atoms and nuclei

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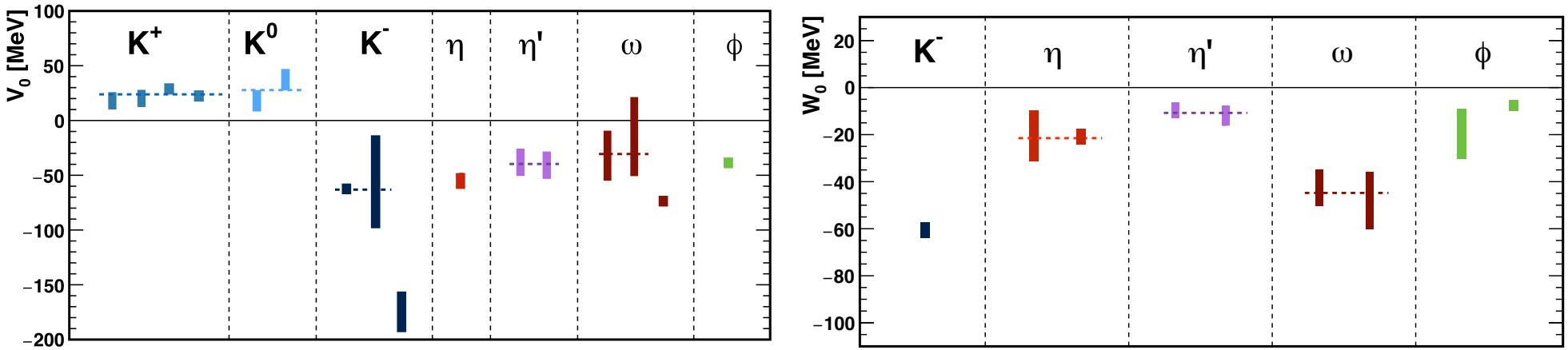
Motivation: application of meson-baryon chiral phenomenology to mesic atoms and to **mesic nuclei**

- Partial restoration of chiral symmetry from π^- atoms. Update in NPA 928 (2014) 128.
- $\bar{K}$-nucleus potentials from K^- atoms; 1N vs. 2N absorption: NPA 959 (2017) 66.
- Search for $\bar{K}$, η, η', ϕ nuclear states; review by Metag-Nanova-Paryev, PPNP (in press). See also Barnea et al. (2017) **Onset of η nuclear binding.**



Experimentally determined meson-nucleus potential $V_0 + \mathrm{i}W_0$

Metag-Nanova-Paryev, PPNP (in press)

Hadronic (h) atom scenarios

h	Re $V_{\rm opt}$	Im $V_{\rm opt}$	comments
π^-	vol. repulsion	moderate	excellent data
	surf. attraction		well underst.
Σ^-	vol. repulsion	moderate	limited data
	tail attraction		poorly underst.
K^-	attractive	absorptive	good data
	how deep ?	1N vs. 2N	open problems
$\bar{p}$	??	absorptive	excellent data

Optical model analyses of hadronic atom data

- **Handle large data sets across periodic table.**
- **Identify characteristic entities, thereby linking microscopic approaches to experiments.**

Tools of the trade: optical potential variants

- **Make $V_{\rm opt}$ functional of the nuclear density ρ.**
- **Respect the low-density limit $V_{\rm opt}(\rho) \to t_{hN} * \rho$.**
- **For pions, consider $\rho_n - \rho_p$ dependence of b_1 using $r_n - r_p \approx \gamma \frac{N-Z}{A} + \delta$ with $\gamma \approx 1.0 \pm 0.1$ fm.**
- **Introduce self consistently medium effects, particularly subthreshold hN kinematics.**

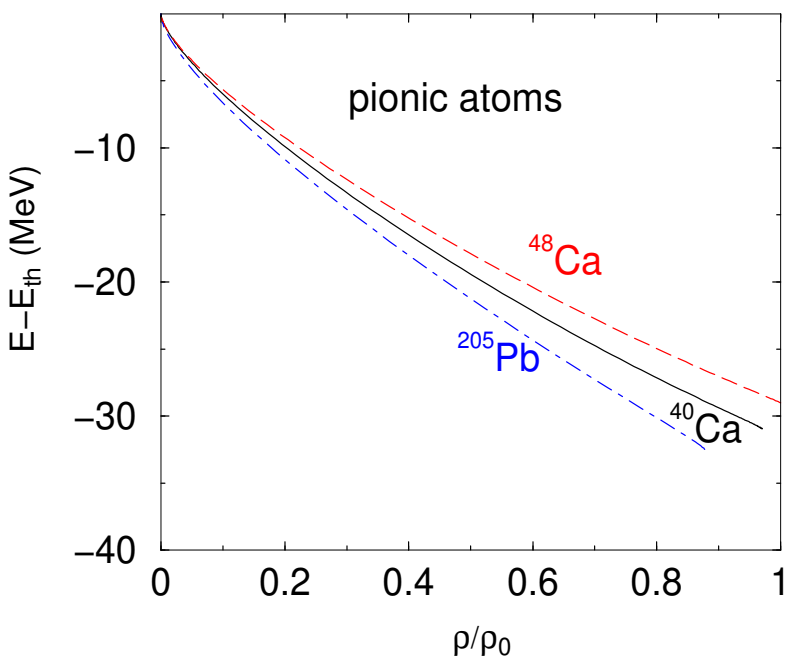
Self-consistency in mesic-atom & nuclear calculations

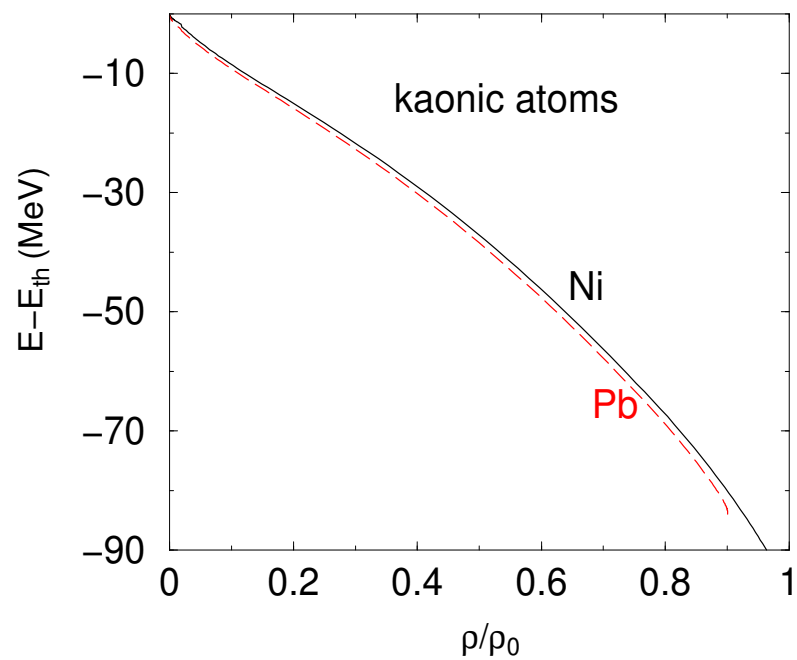
Cieplý-Friedman-Gal-Gazda-Mareš, PLB 702 (2011) 402

$$s_{hN} = (\sqrt{s_{\rm th}} - B_h - B_N)^2 - (\vec{p}_h + \vec{p}_N)^2 < s_{\rm th}$$

$$\sqrt{s_{hN}} \to E_{\rm th} - B_N - B_h - \xi_N \frac{p_N^2}{2m_N} - \xi_h \frac{p_h^2}{2m_h}$$

$$\xi_{N(h)} = \frac{m_{N(h)}}{(m_N + m_h)} \qquad \frac{p_h^2}{2m_h} \sim -V_h - B_h$$





in-medium π^- energy shift **in-medium K^- energy shift**

In-medium hN amplitudes

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

Cieplý-Friedman-Gal-Mareš, NPA 925 (2014) 126

- KG equation and self-energies:

  $[\,\nabla^2 + \tilde{\omega}_h^2 - m_h^2 - \Pi_h(\omega_h, \rho)\,]\,\psi = 0$

  $\tilde{\omega}_h = \omega_h - \mathrm{i}\Gamma_h/2, \quad \omega_h = m_h - B_h$

  $\Pi_h(\omega_h, \rho) \equiv 2\omega_h V_h = -4\pi \frac{\sqrt{s}}{m_N} f_{hN}(\sqrt{s}, \rho)\rho$

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

  $f_{hN}^{\mathrm{WRW}}(\sqrt{s}, \rho) = \frac{f_{hN}(\sqrt{s})}{1+\xi(\rho)(\sqrt{s}/m_N) f_{hN}(\sqrt{s})\rho}, \quad \xi(\rho) = \frac{9\pi}{4p_F^2} I(\tilde{\omega}_h)$

- $\sqrt{s}$: $\Lambda^*(1405) \Rightarrow f_{K^-N}(\sqrt{s})$, $N^*(1535) \Rightarrow f_{\eta N}(\sqrt{s})$.

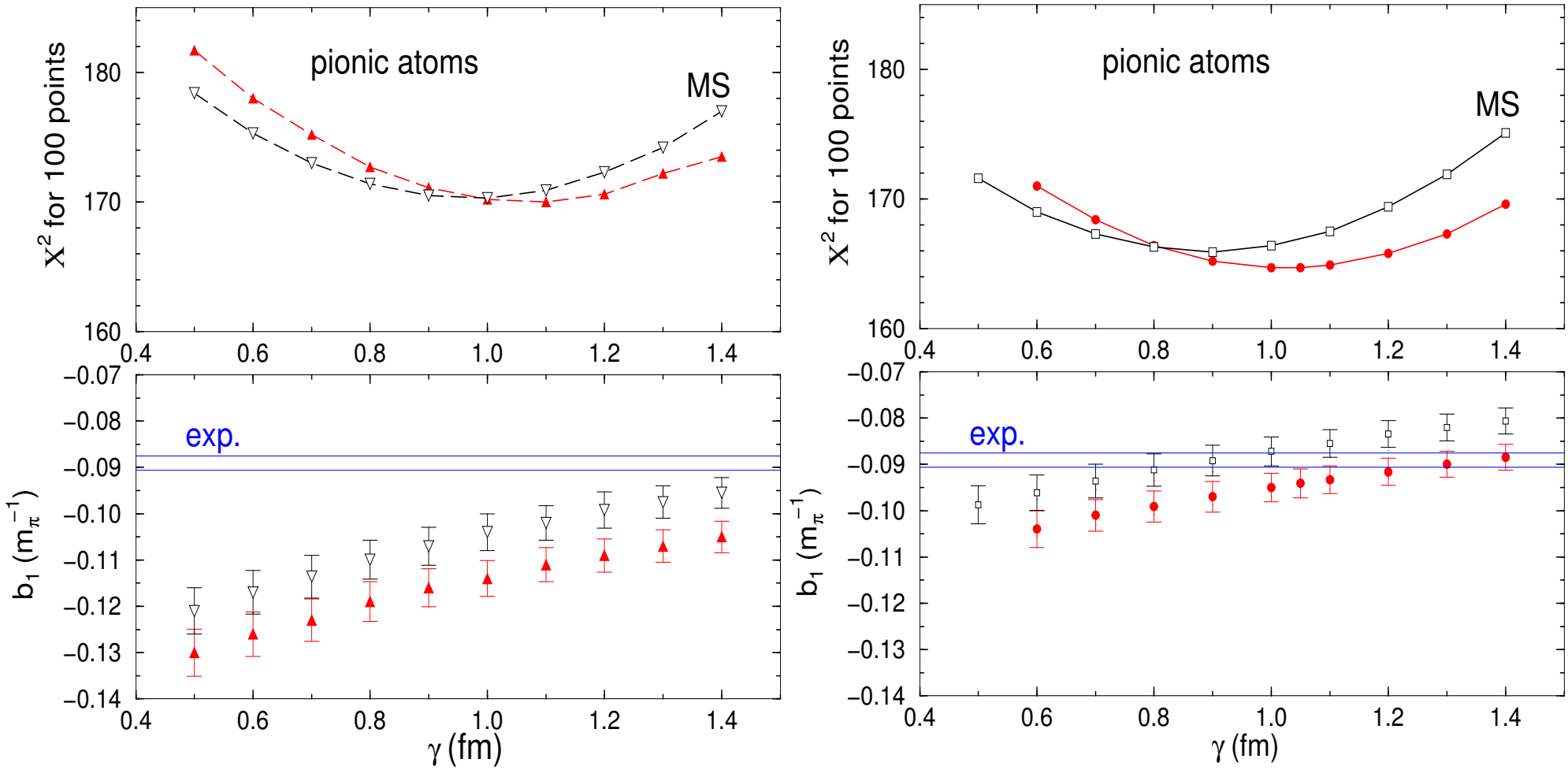
  In medium $\Rightarrow$ go subthreshold: $\quad \delta\sqrt{s} = \sqrt{s} - \sqrt{s_{\mathrm{th}}}$

  $\delta\sqrt{s} \approx -B_N \frac{\rho}{\bar{\rho}} - \xi_N B_h \frac{\rho}{\rho_0} - \xi_N T_N (\frac{\rho}{\bar{\rho}})^{2/3} + \xi_h \mathrm{Re}\, V_h(\sqrt{s}, \rho)$

- **A self-consistency cycle in $\delta\sqrt{s}$ for given ρ.**

Partial restoration of chiral symmetry in/from pionic atoms

Update: Friedman-Gal, NPA 928 (2014) 128



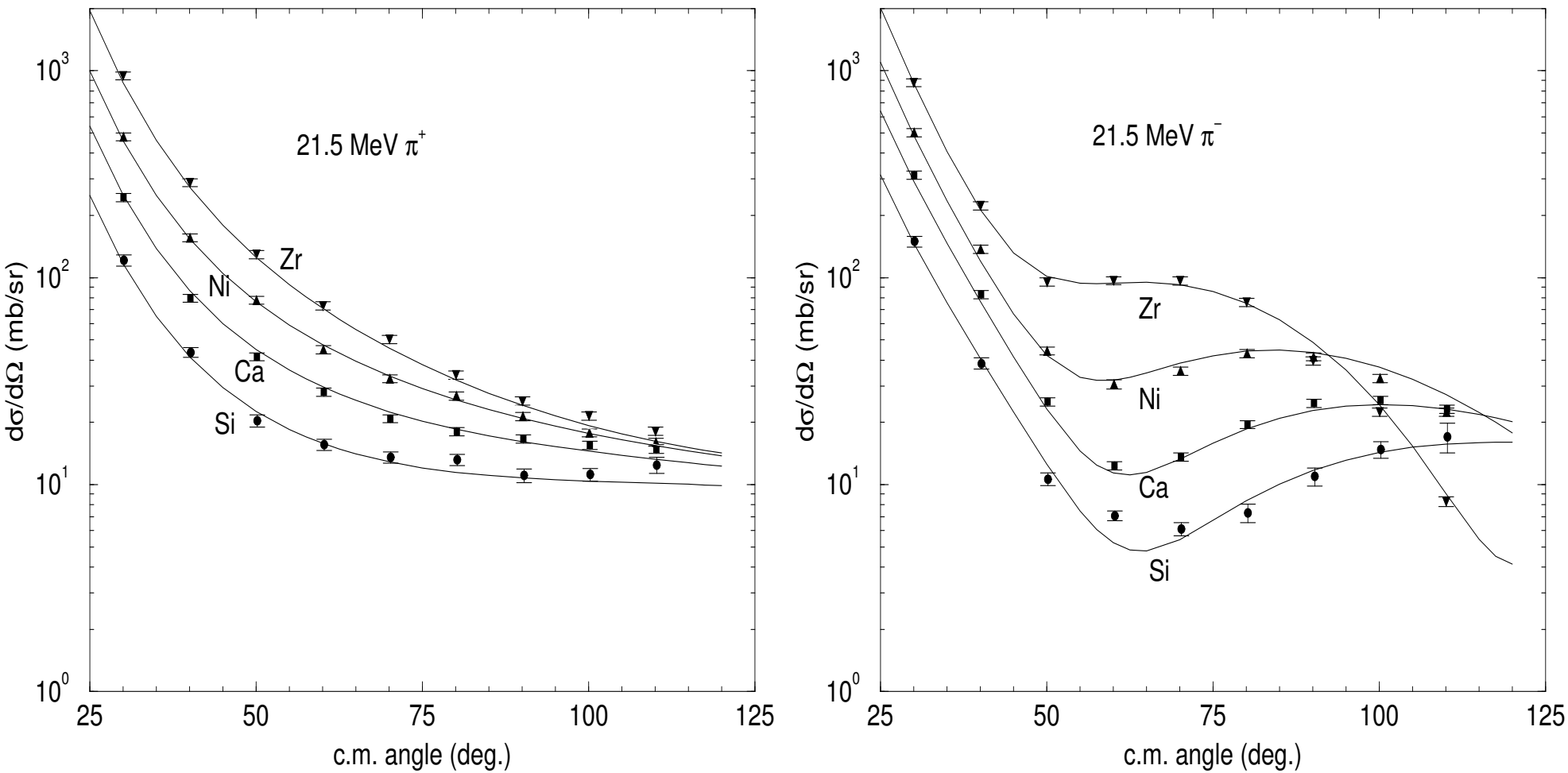
empirical $b_0(E)$ using b_1 independent of ρ

empirical $b_0(E)$ using $b_1(\rho)$ with πN σ term

γ dependence of fits to 100 data points, Ne to U

More precise determination of b_1 than thru DBS

E. Friedman, A. Gal, NPA 928 (2014) 128



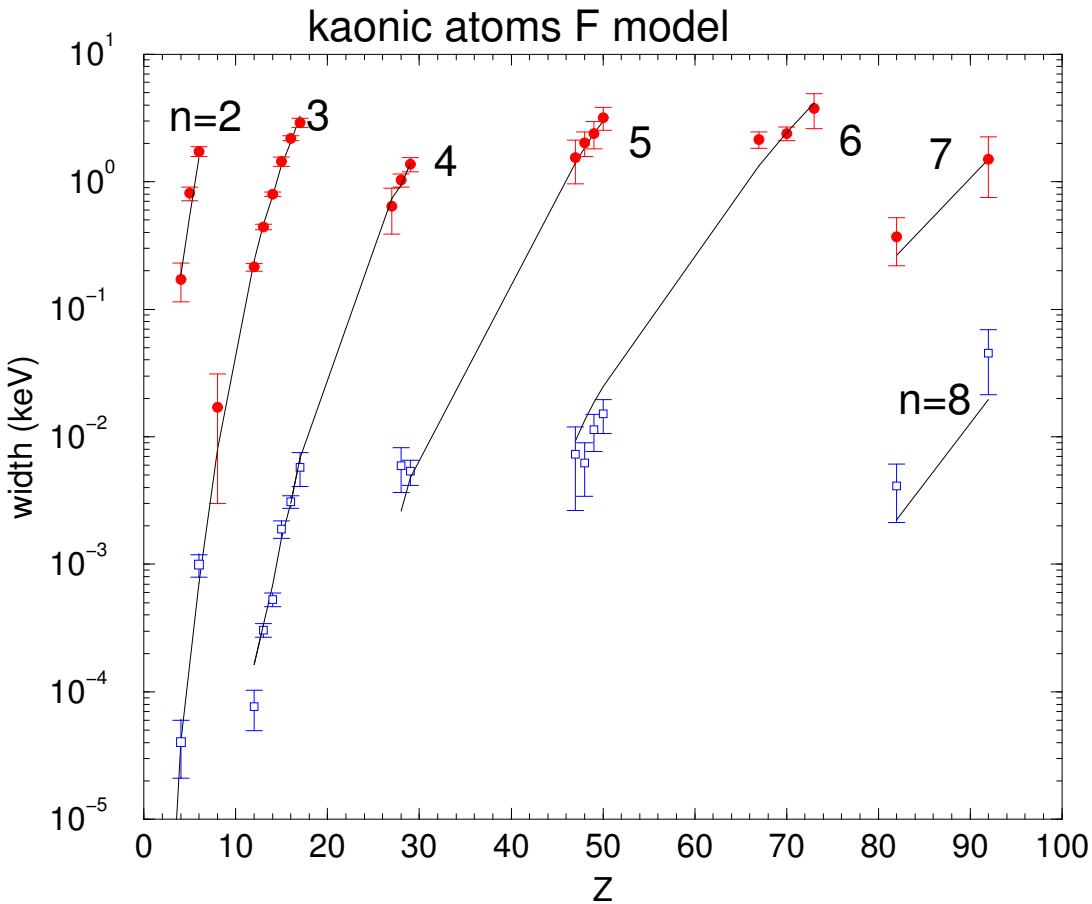
E. Friedman et al., PRL 93 (2004) 122302, PRC 72 (2005) 034609

PSI results reproduced with $b_1(\rho)$ ansatz (Weise, 2000)

$$b_1(\rho) = -\frac{\mu_{\pi N}}{8\pi f_\pi^2(\rho)}, \qquad \frac{f_\pi^2(\rho)}{f_\pi^2} = \frac{<\bar{q}q>_\rho}{<\bar{q}q>_0} \simeq 1 - \frac{\sigma\rho}{m_\pi^2 f_\pi^2}$$

Consistency between π^- atoms & $\pi^\pm$ scattering deductions.

What do K^- atoms tell us?



K^-_{atom} widths from Li to U

Lowest χ^2, 84 per 65 data points,
in phenomenological potential model F (deep)

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

Latest kaonic atoms study

E. Friedman - A. Gal, NPA 959 (2017) 66

including capture-at-rest fractions from bubble-chamber experiments

H. Davis et al., NC 53 (1968) 313

J.W. Moulder et al., NPB 35 (1971) 332

C. Vander Velde-Wilquet et al., NC 39A (1977) 538

Single vs. multi-nucleon absorption

Multinucleon fraction from 3 bubble-chamber experiments:

0.26±0.03 (C, F, Br) 0.28±0.03 (Ne) 0.19±0.03 (C)

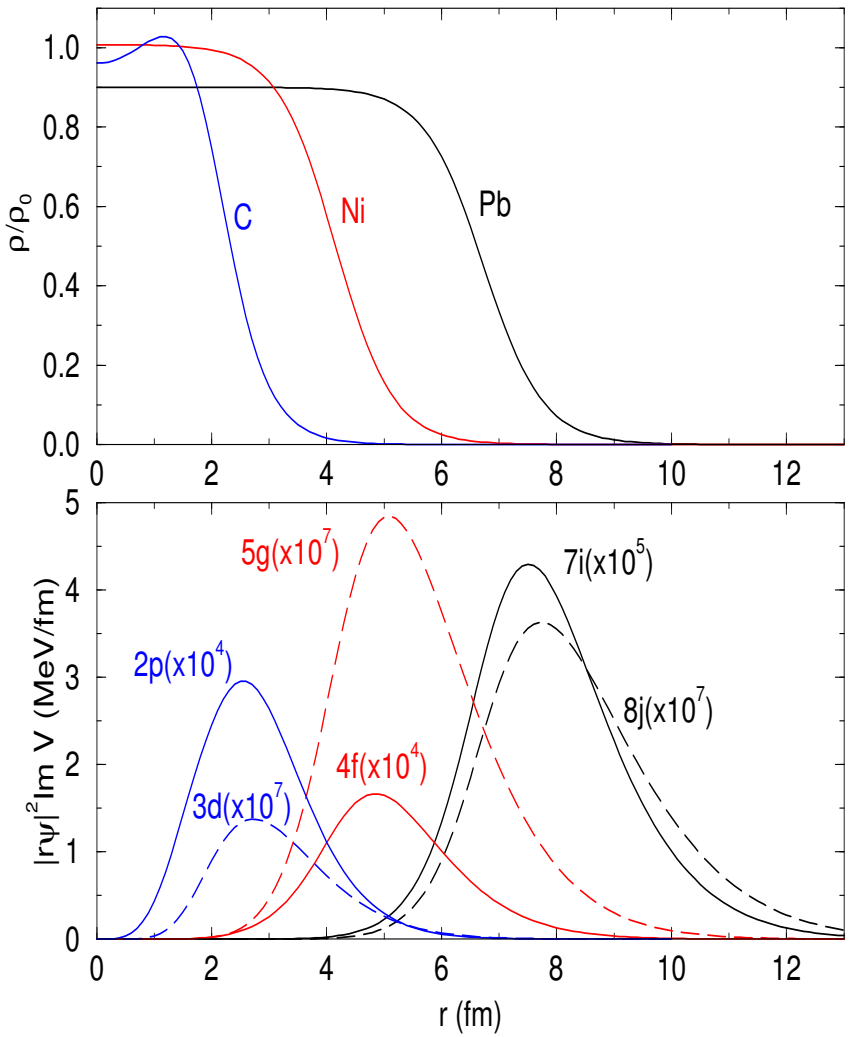
Larger uncertainties from nuclear emulsions

Accept 0.25±0.05 for C & heavier nuclei, hence single-nucleon fraction 0.75±0.05, to constrain K^- atomic data fits, using

$$\Gamma \sim \int |r\psi|^2 \, \mathrm{Im} V_{K^-} \, dr \text{ with } V_{K^-} = V_{K^-}^{\mathrm{1N}} + V_{K^-}^{\mathrm{mN}}$$

to separate mN from 1N absorption.

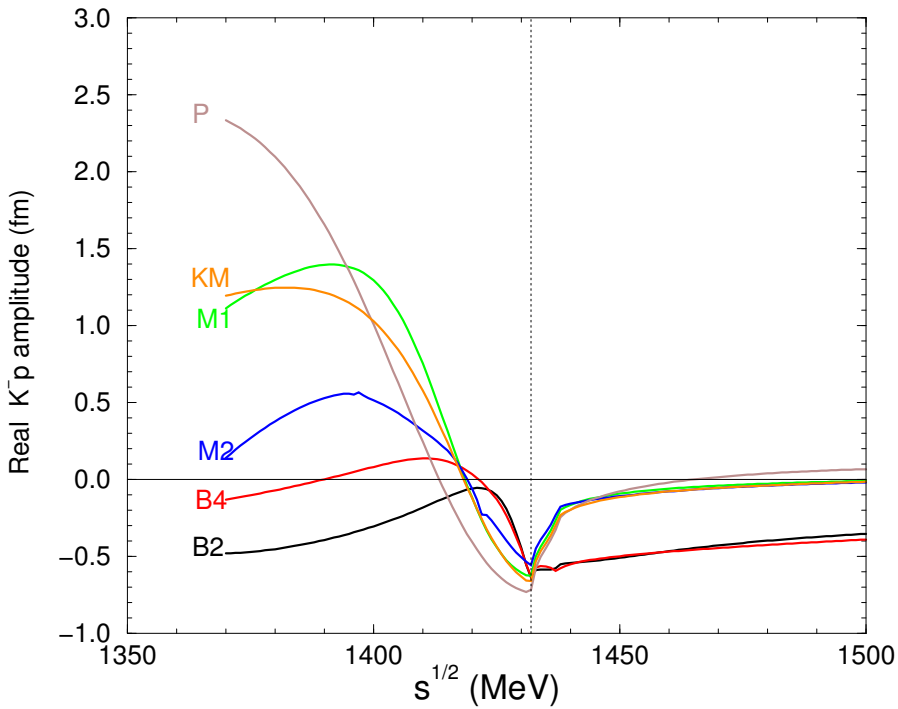
Where does absorption take place?

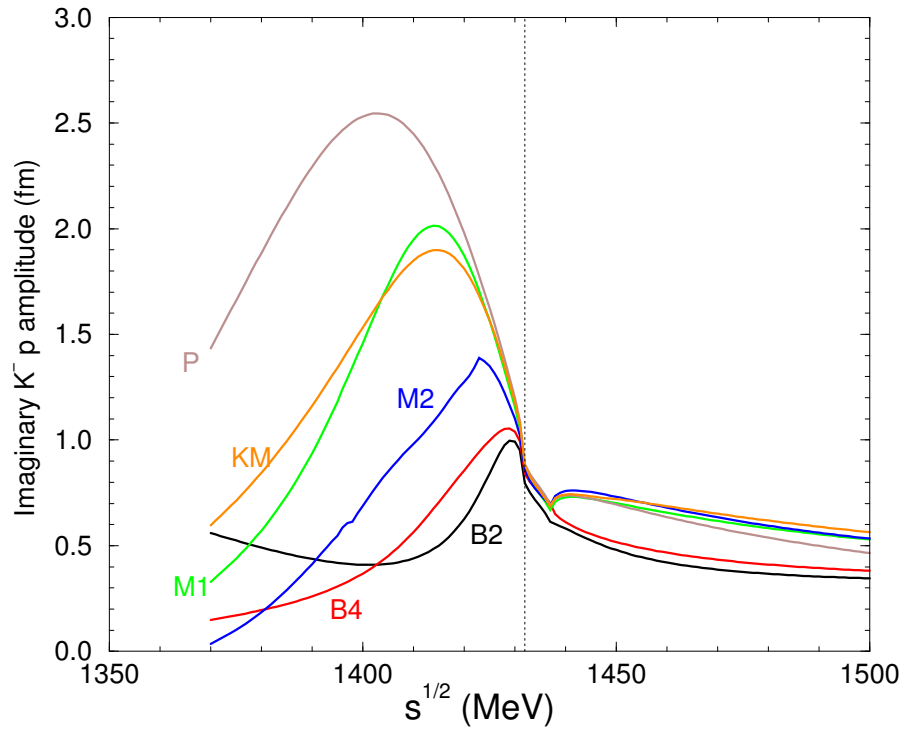


Lower: $|r\psi|^2 \, \mathrm{Im}\, V_{K^-}^{\mathrm{phenom.}}$
Upper: nuclear density profile

- **Overlap peaks at 15-20% ρ_0 (10-15% ρ_0) for lower (upper) state; little higher in C.**
- **Consistent with BC experiments that yield multinucleon absorption fraction of 0.25±0.05 from carbon on.**
- **Use it to constrain K^- atom optical potential fits.**

Six K^-p scattering amplitudes from NLO χSU(3) CC dynamics



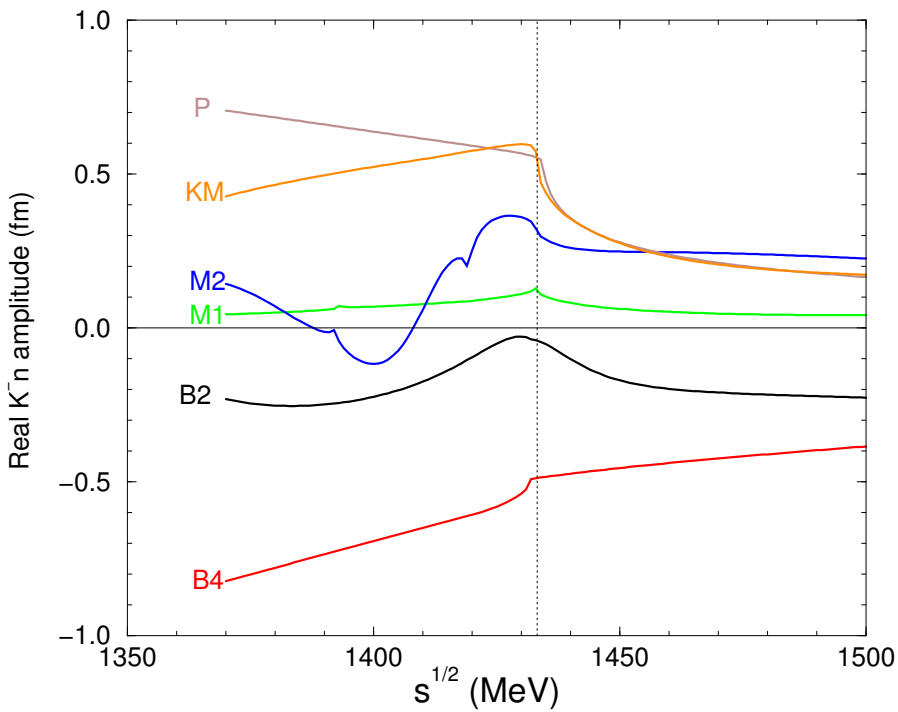


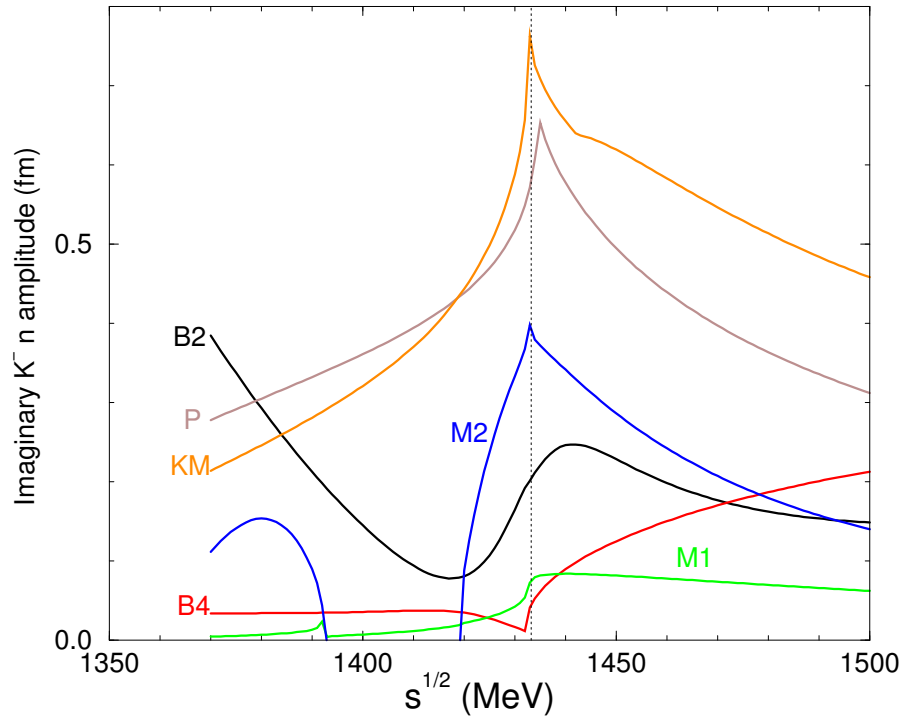
KM=IHW, P=Prague, M1,M2=GO, B1,B2=Bonn

Distinctly different at subthreshold energies

From Cieply,Mai,Meißner,Smejkal, NPA 954 (2016) 17

Six K^-n scattering amplitudes from NLO χSU(3) CC dynamics



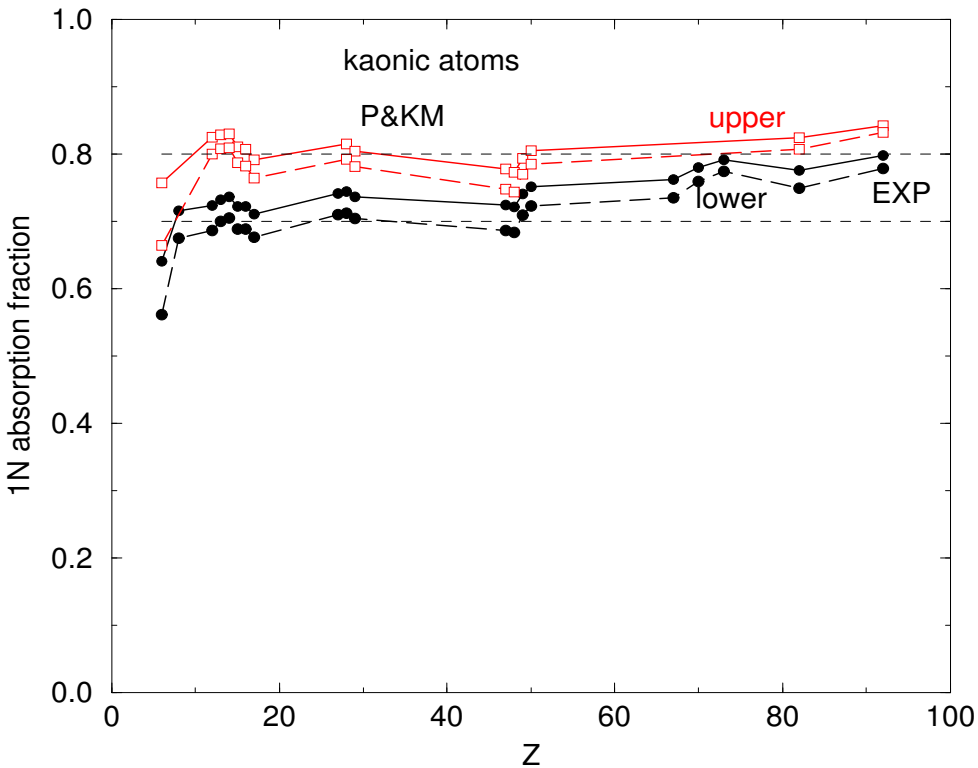


KM=IHW, P=Prague, M1,M2=GO, B1,B2=Bonn

Distinctly different at ALL energies

From Cieply,Mai,Meißner,Smejkal, NPA 954 (2016) 17

Models P & KM 1N absorption fractions

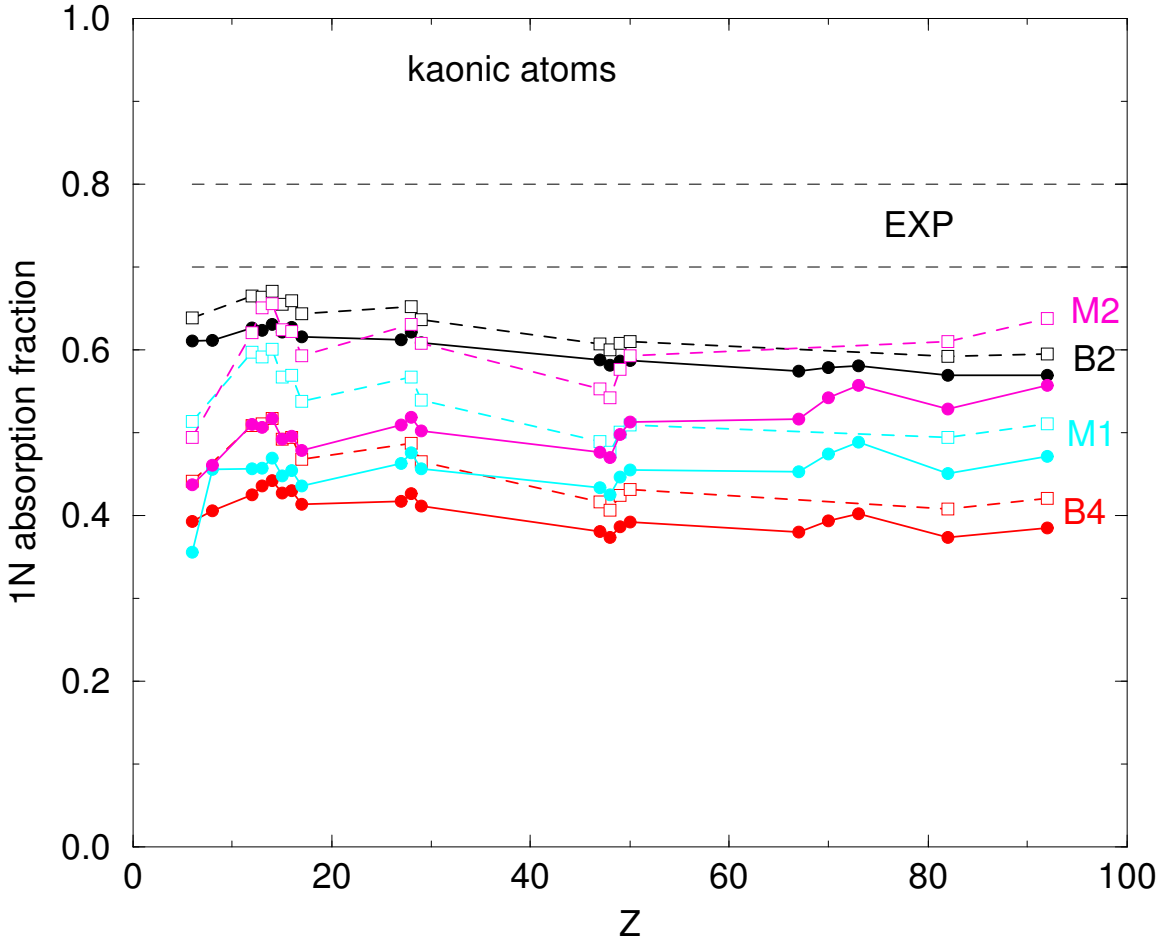


exp. 1N fraction 0.75±0.05

- circles: lower states
  squares: upper states
  solid curves: α=1
  dashed curves: α=2
- $V_{K^-}^{\mathrm{mN}} = -\frac{4\pi}{2\mu_K} B (\frac{\rho}{\rho_0})^\alpha \rho$
  with B & α fitted.
- α_{P}=1.4±1.2, χ^2=125
  α_{KM}=1.8±0.8, χ^2=122
  per 65 data points.

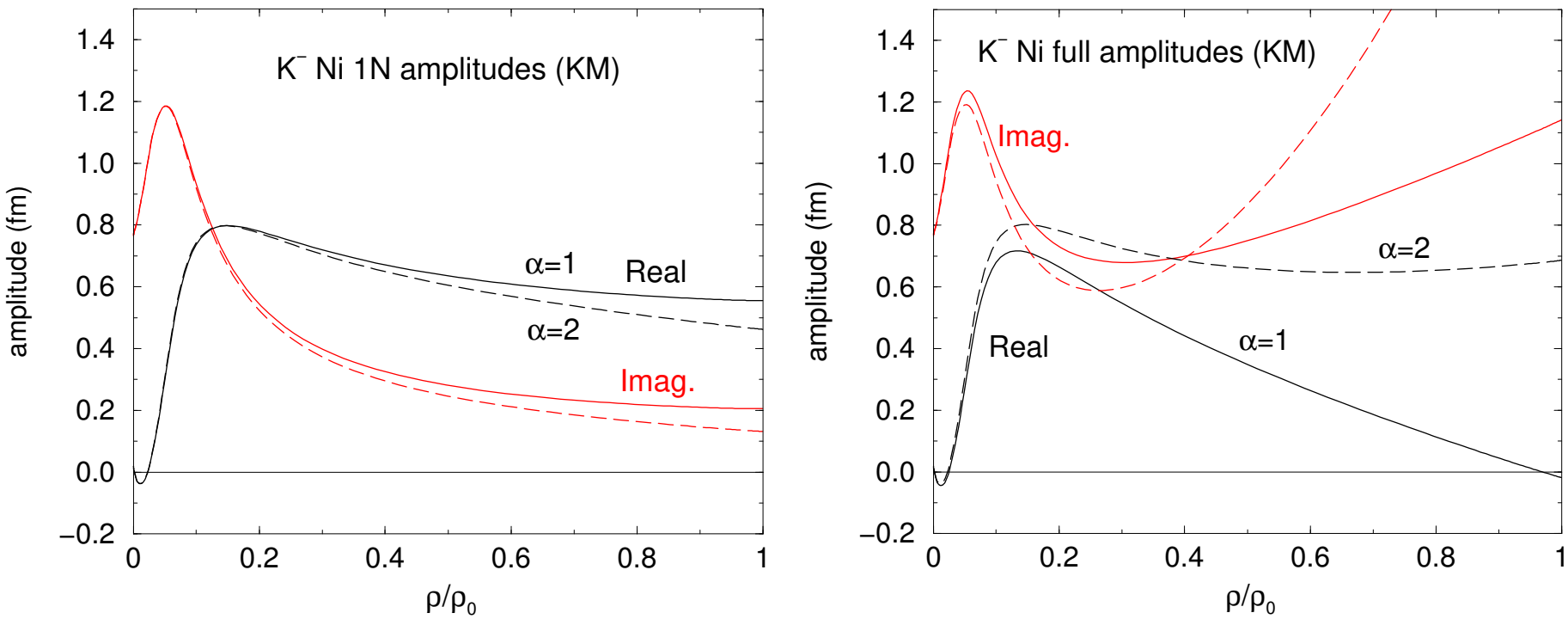
P & KM
indistinguishable as far as absorption fractions are concerned.

1N absorption fractions in other models



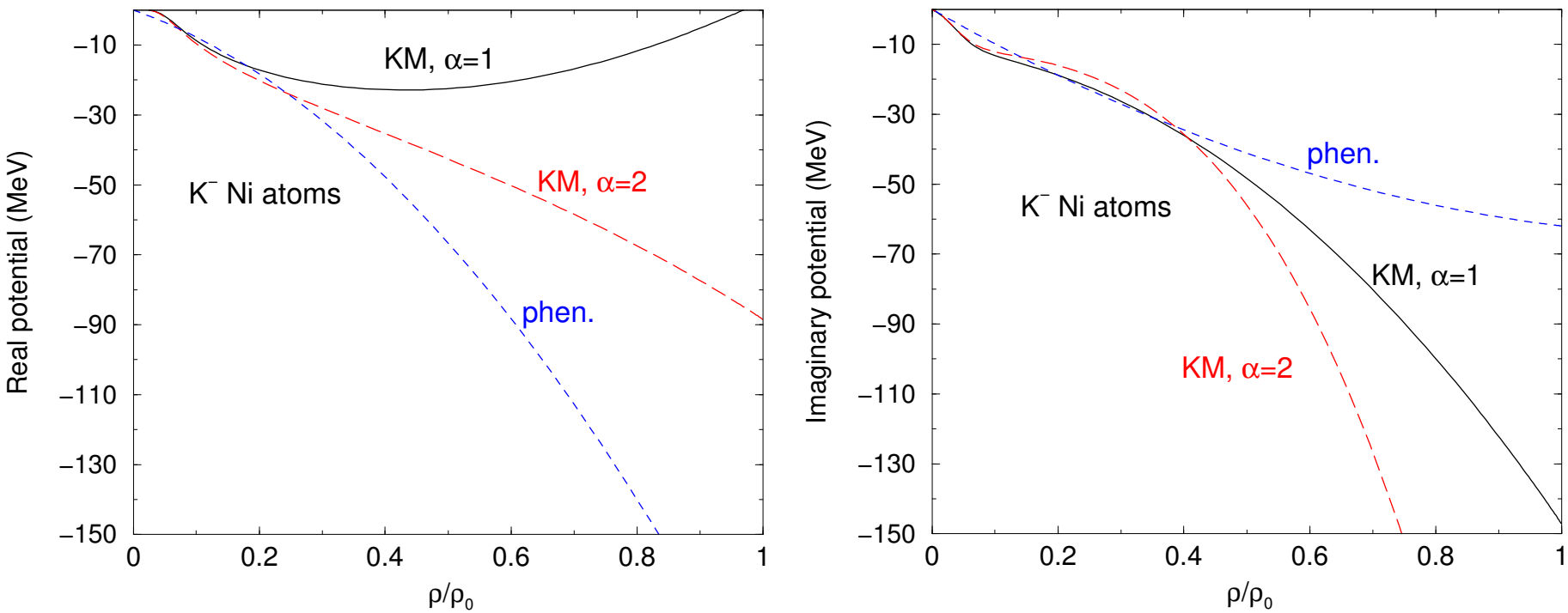
The other models do not make it up.

K^- Ni best-fit in-medium 1N & full amplitudes in model KM

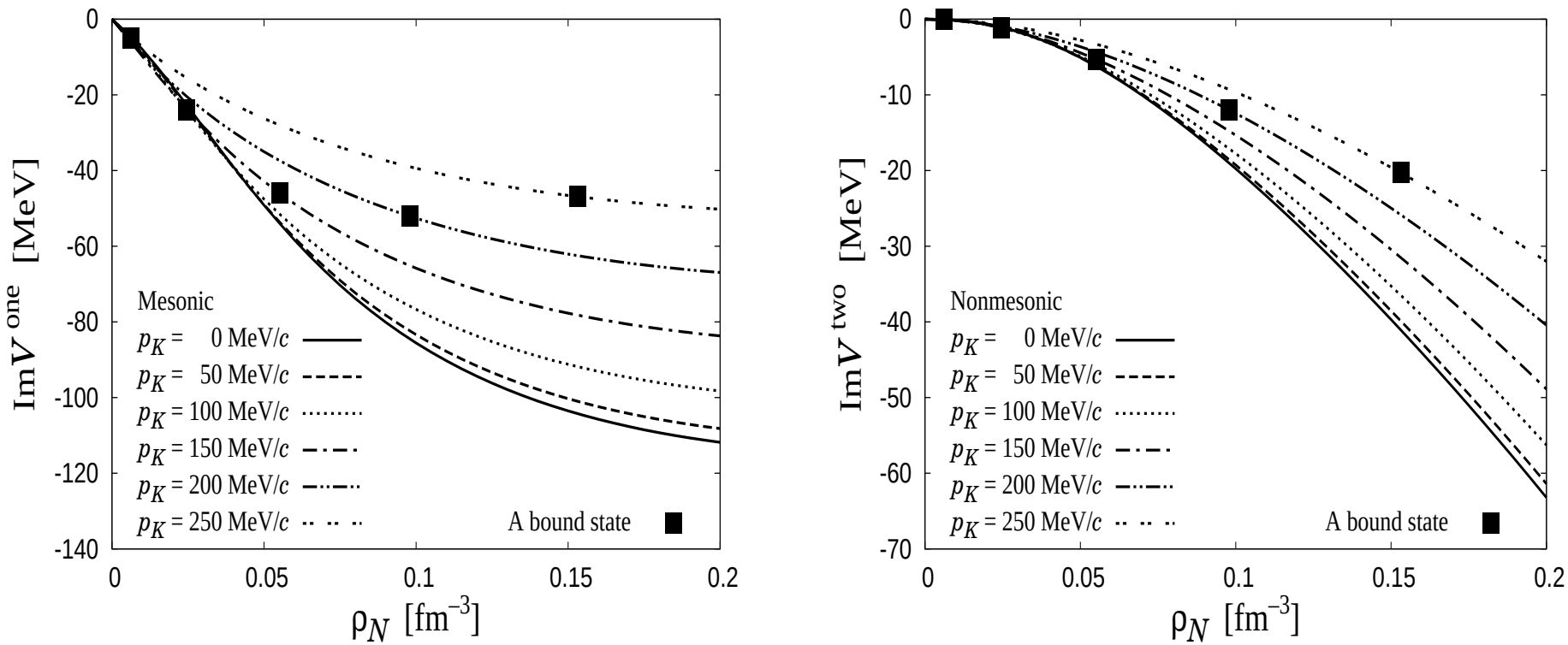


- **1N in-medium amplitude depends little on α.**
- **However, both real and imaginary parts of the FULL amplitude depend strongly on α at $\rho \geq 0.5\,\rho_0$.**

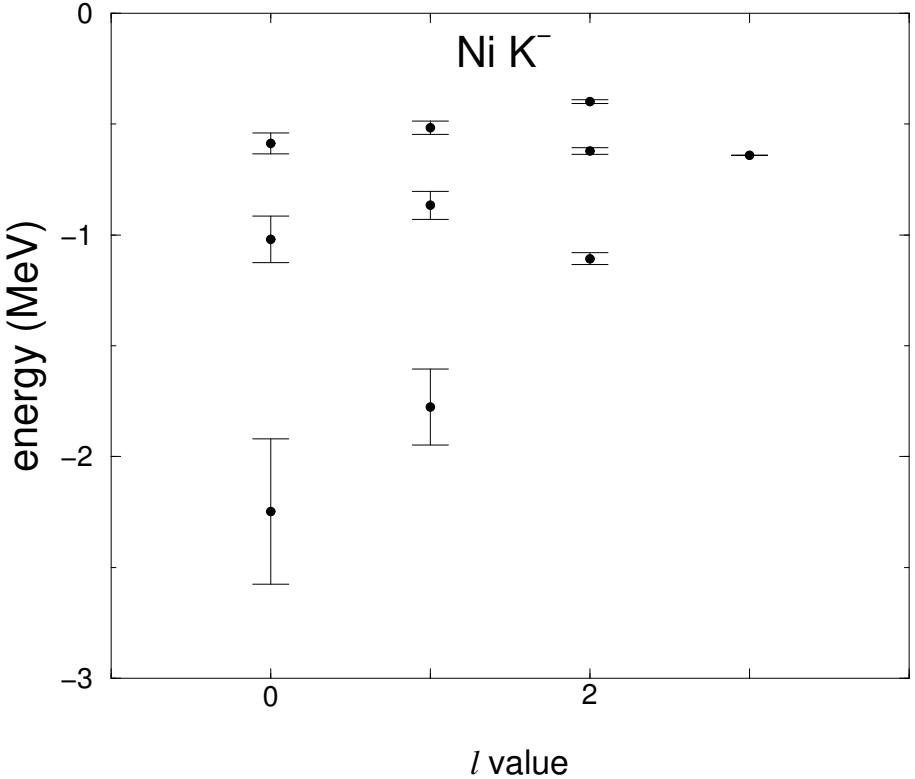
K^- Ni best-fit optical potentials in Model KM plus mN term, α=1&2

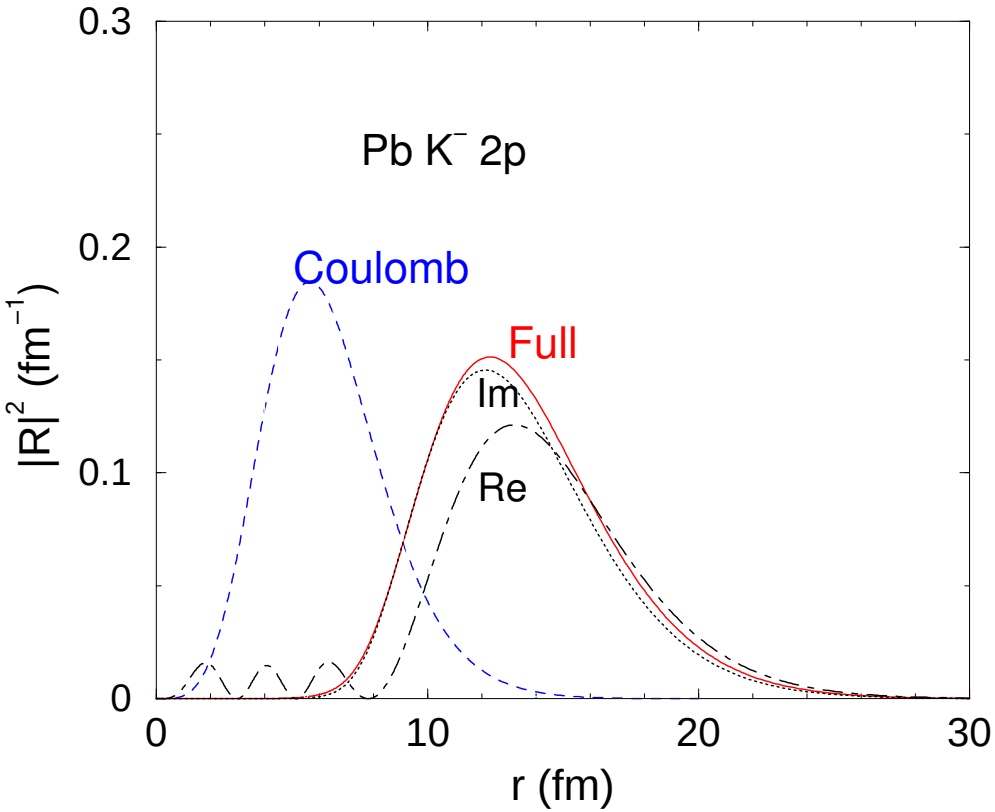


- **Re V_{K^-} is undetermined at $\rho \geq 0.25\,\rho_0$. Extrapolation to ρ_0 gives shallower potentials than best-fit phen. potentials.**
- **Im V_{K^-} is undetermined at $\rho \geq 0.5\,\rho_0$. Extrapolation to ρ_0 gives deeper potentials than best-fit phenom. potentials.**



K^- nuclear 1N (left) and 2N (right) absorptive potentials, calculated in a chiral unitary model [PRC 86 (2012) 065205] by Sekihara, Yamagata-Sekihara, Jido, Kanada-En'yo. Empirical 2N:1N $\approx$ 1:3 BR is reached at too high density.





Deeply bound atomic states **Narrow thru repulsion**

Saturation of absorption at work

Spectrum is insensitive to Re V

Friedman-Gal (1999), PLB 459 43, NPA 658 345

Summary

- **Absorption fractions exhibit little dependence on nuclear species and atomic state.**
- **Absorption fractions favor models P and KM.**
- **Re V_{K^-} determined only up to 25% ρ_0.**
- **Im V_{K^-} determined up to 50% ρ_0.**
- **Subthreshold energies down to -30 MeV reached; no phase-space correction made.**
- **Good mN interaction models badly needed.**
- **Are there any narrow K^- nuclear states?**
  Hrtánková-Mareš (2017)
  PLB 770, 342; PRC 96, 015205

Onset of η nuclear binding

N. Barnea, E. Friedman, A. Gal, PLB 747 (2015) 345

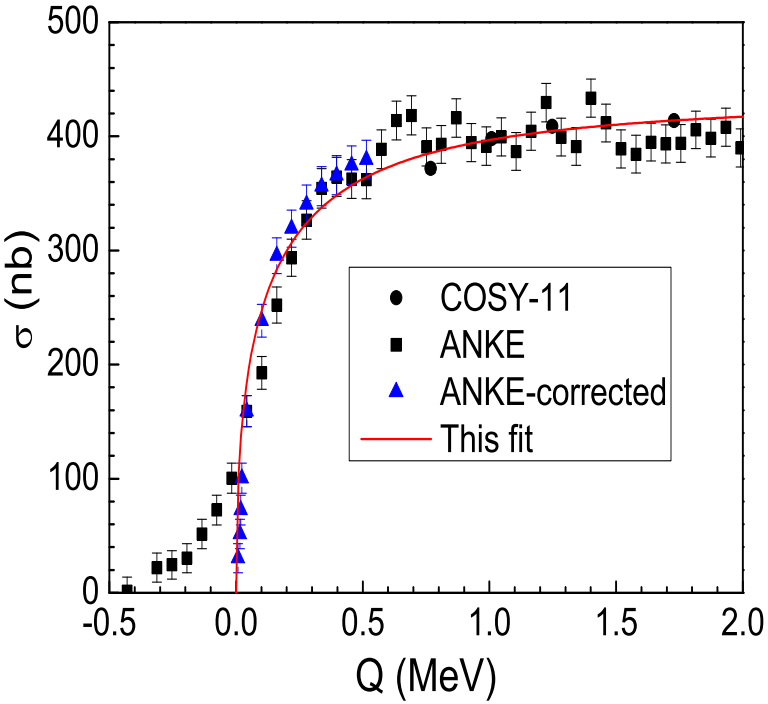
N.Barnea, B.Bazak, E.Friedman, A.Gal, PLB 771 (2017) 297

N. Barnea, E. Friedman, A. Gal, NPA 968 (2017) 35

Background & Motivation

- **The ηN s-wave interaction below N*(1535) is attractive in a $\pi N - \eta N$ model [Bhalelao–Liu (1985)]. Bound states of η(548) in A$\geq$12 nuclei could exist [Haider–Liu (1986)].**
- **Chiral N*(1535) meson-nucleon coupled channel models were introduced by Kaiser, Weise et al (1995-1997) and subsequently by Oset et al (2002). These & other models have been used to calculate η–nuclear quasibound states.**
- **Exp. searches for such states with proton, pion or photon induced η production reactions are inconclusive.**
  For the onset of binding, Krusche & Wilkin (2015) state:
  "The most straightforward (but not unique) interpretation of the data is that the η d system is unbound, the $\eta\,^4$He is bound, but that the $\eta\,^3$He case is ambiguous."

Hints from $\eta\,^3$He production



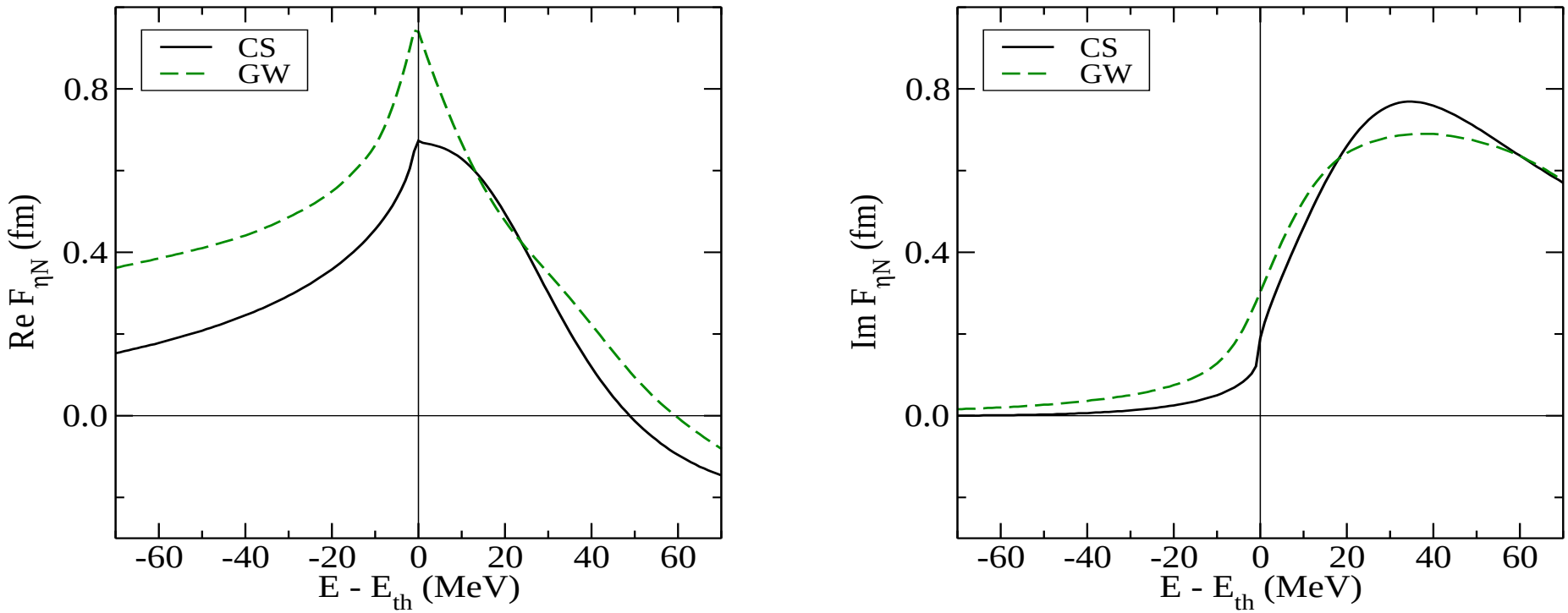
Fitted dp→ $\eta\,^3$He x-sections below 2 MeV vs. experiment. Remarkable energy dependence, suggesting a nearby S-matrix pole could be in action. Deduced a($\eta\,^3$He) excludes a quasibound state pole.

Xie-Liang-Oset-Moskal-Skurzok-Wilkin, PRC 95 (2017) 015202

a($\eta\,^3$He) = [−(2.23±1.29)+i(4.89±0.57)] fm

- **Would $\eta\,^4$He be bound? NOT seen in dd→ ^{3}He+N+π [WASA-at-COSY NPA 959 (2017) 102]. Argued to be more UNBOUND than $\eta\,^3$He [Fix-Kolesnikov, PLB 772 (2017) 663] owing to a stronger subthreshold suppression in ^{4}He.**

ηN model input

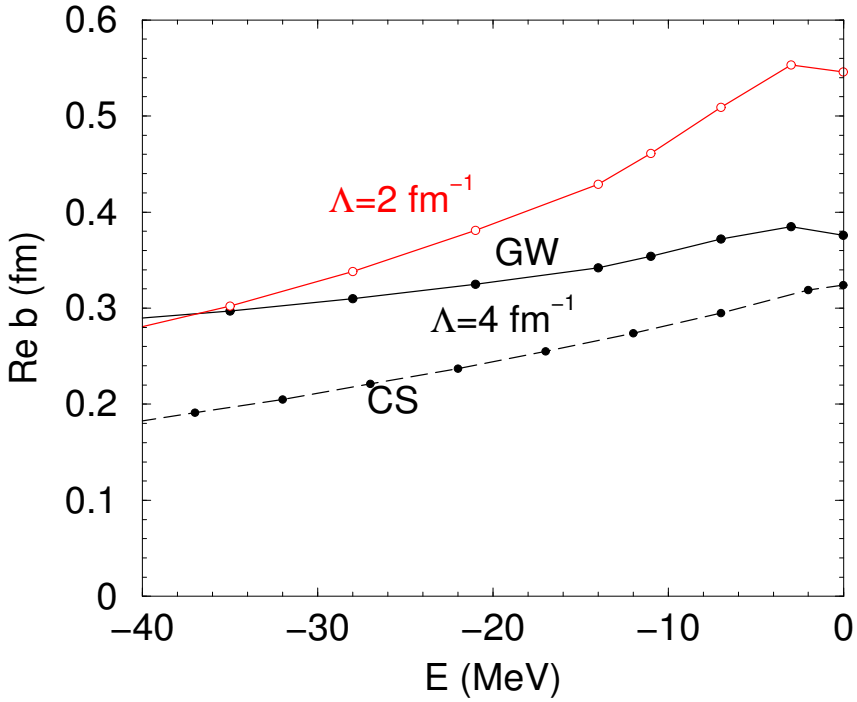


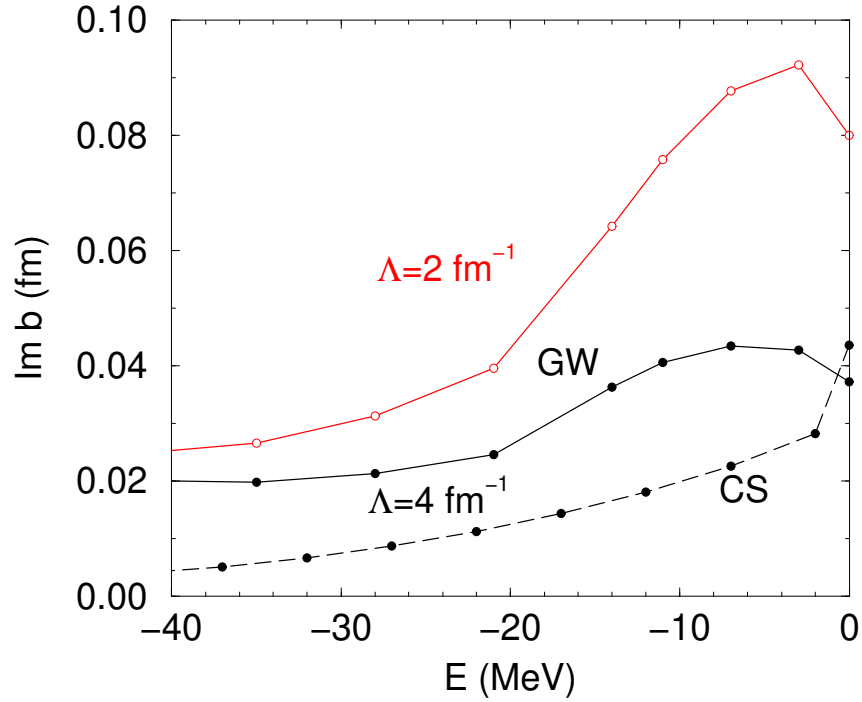
CM s-wave scattering amplitude $F_{\eta N}(E)$ in two meson-baryon coupled-channel $N^*(1535)$ models.

$$a_{\eta N}^{GW}=0.96+i0.26 \text{ fm}, \qquad a_{\eta N}^{CS}=0.67+i0.20 \text{ fm}$$

- **Derive local, energy dependent potentials $v_{\eta N}(E;r)$ that reproduce $F_{\eta N}(E)$ below threshold, for use in solving the ηNN, ηNNN, ηNNNN few-body Schroedinger equations.**

$\mathbf{F}_{\eta N}(\mathbf{E}) \Rightarrow \mathbf{v}_{\eta N}(\mathbf{E})$ in models GW & CS





Strength b(E) of effective potential $\mathbf{v}_{\eta N}(\mathbf{E})$ at $E < 0$

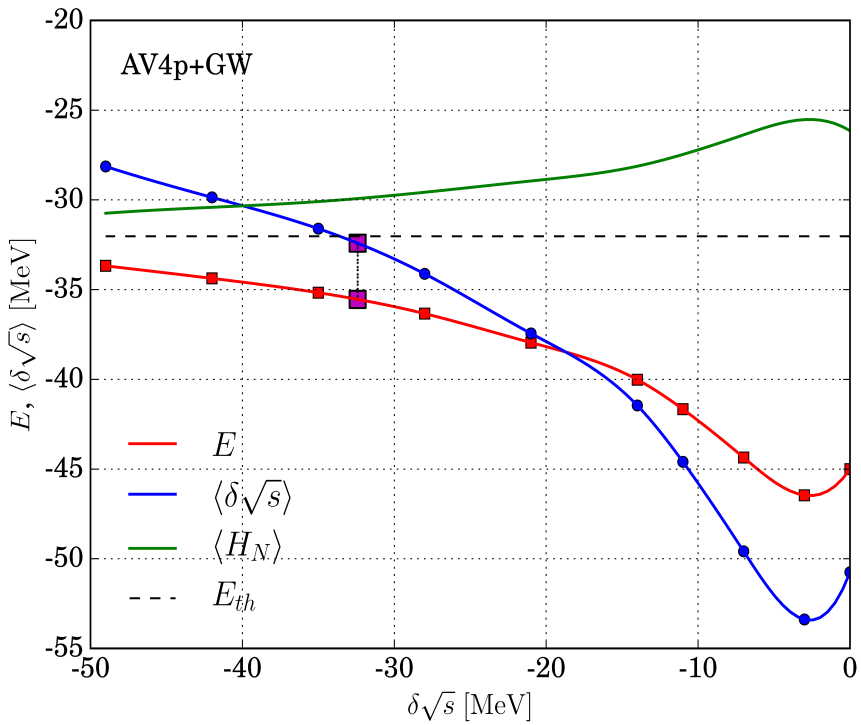
$$\mathbf{v}_{\eta N}(\mathbf{E};\mathbf{r}) = -\frac{4\pi}{2\mu_{\eta N}}\ \mathbf{b}(\mathbf{E}) \left(\frac{\Lambda}{2\sqrt{\pi}}\right)^3 \exp\left(-\frac{\Lambda^2 r^2}{4}\right)$$

- **Scale Λ is inversely proportional to the range of $\mathbf{v}_{\eta N}$.**
- **$\mathbf{v}_{\eta N}$ is a regulated contact term in π-less EFT which for $\Lambda \leq m_\rho \approx 4$ fm^{-1} replaces vector-meson exchange.**

Energy dependence in η nuclear few-body systems

- $N^*(1535)$ **makes near-threshold** $f_{\eta N}(\sqrt{s})$ **& input potential** $v_{\eta N}(\sqrt{s})$ **strongly energy dependent.**
  $s = (\sqrt{s_{\rm th}} - B_\eta - B_N)^2 - (\vec{p}_\eta + \vec{p}_N)^2 < s_{\rm th}$
- **Expanding NR near** $\sqrt{s_{\rm th}}$ **& evaluating** $\langle \delta\sqrt{s} \rangle$**:**
  $\langle \delta\sqrt{s} \rangle = -\frac{B}{A} + \frac{A-1}{A} E_\eta - \xi_N \frac{1}{A} \langle T_A \rangle - \xi_\eta \left(\frac{A-1}{A}\right)^2 \langle T_\eta \rangle,$
  $\delta\sqrt{s} \equiv \sqrt{s} - \sqrt{s_{\rm th}}, \;\; E_\eta = \langle H - H_A \rangle, \;\; \xi_{N(\eta)} \equiv \frac{m_{N(\eta)}}{(m_N + m_\eta)}.$
  Agrees to O(1/A) with optical-model limit.
- **Self-consistency: output** $\langle \sqrt{s} \rangle$ **= input** $\sqrt{s}$**.**
- **Near threshold** E_η **&** $\langle T_\eta \rangle \to 0$**, yet** $\langle \delta\sqrt{s} \rangle_{\rm th} \neq 0$**.**
  Similarly, $\langle \delta\sqrt{s} \rangle_{\rm th} \neq 0$ **in kaonic atoms, starting with** $K^- d$**:** $\langle \delta\sqrt{s} \rangle_{\rm th} = -\frac{B_d}{2} - \frac{0.655}{2} \langle T_d \rangle = -4.9$ **MeV.**

Recent SVM results for $\eta\,^{3,4}$He

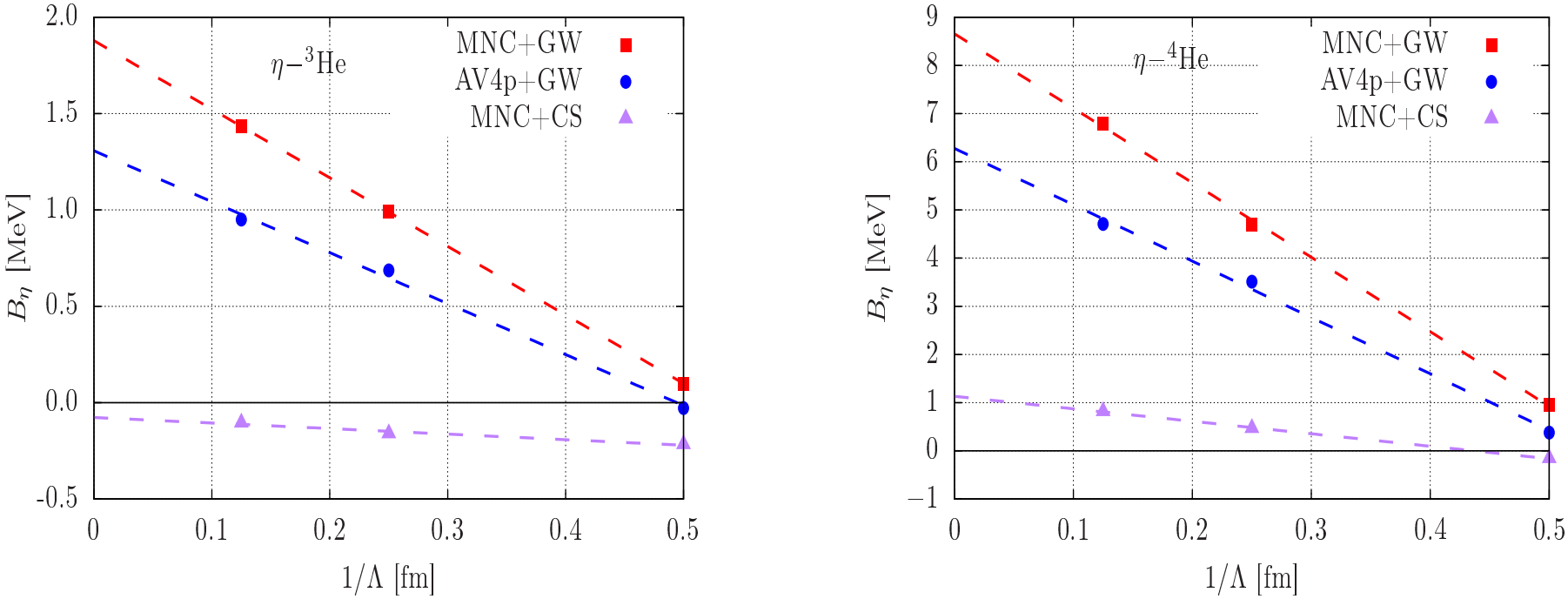


Self consistency plot

$\eta\,^4$He bound-state energy E, $\langle\delta\sqrt{s}\rangle$ & $\langle H_N = H_A\rangle$, for AV4' v_{NN} & GW $v_{\eta N}$(E) with scale Λ=4 fm^{-1}.

- Stochastic Variational Method calculations with correlated Gaussian trial wavefunctions, resulting in:
- ηd is definitely unbound in both GW and CS (2015).
- $\eta\,^3$He is nearly or just bound in GW & unbound in CS.
- $\eta\,^4$He is bound in GW and just or nearly bound in CS.

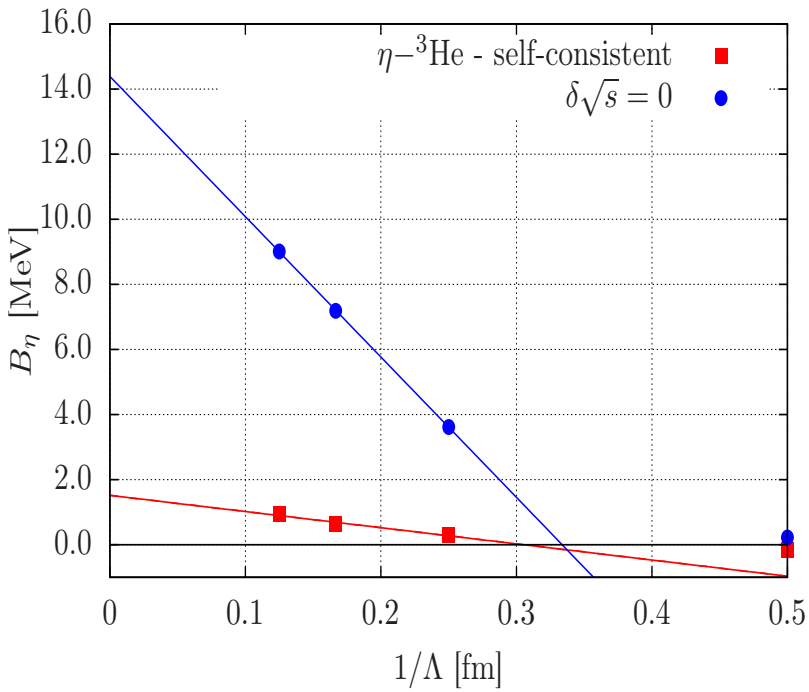
Scale dependence; semi-realistic NN

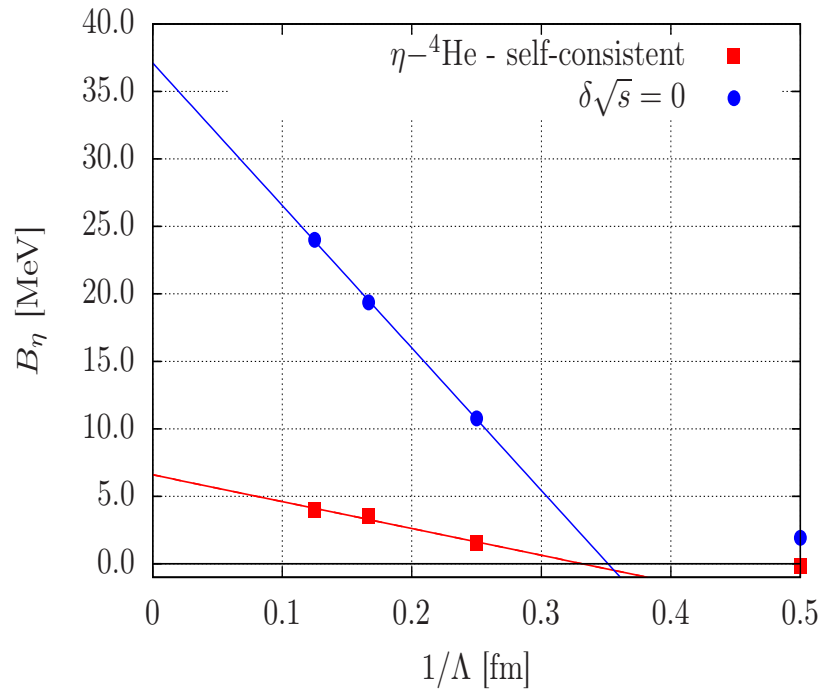


B_η as a function of $1/\Lambda$

- **These bindings will decrease by $\leq$0.3 MeV when Im v is added. GW just binds $\eta\,^3$He, & definitely binds $\eta\,^4$He.**
- **AV4p (Argonne) more realistic than MNC (Minnesota).**
- **CS does not bind $\eta\,^3$He & is unlikely to bind $\eta\,^4$He.**

Scale dependence; pionless EFT at LO

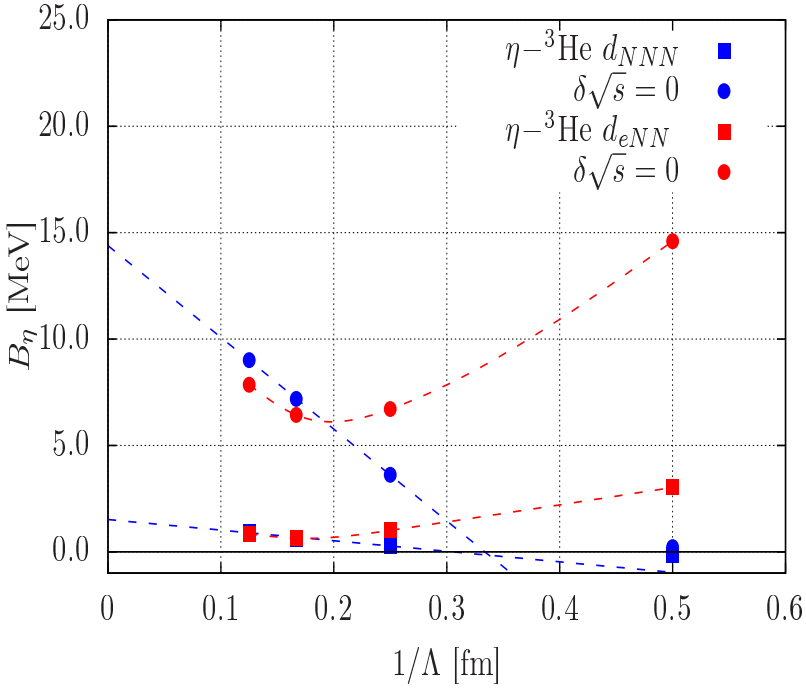


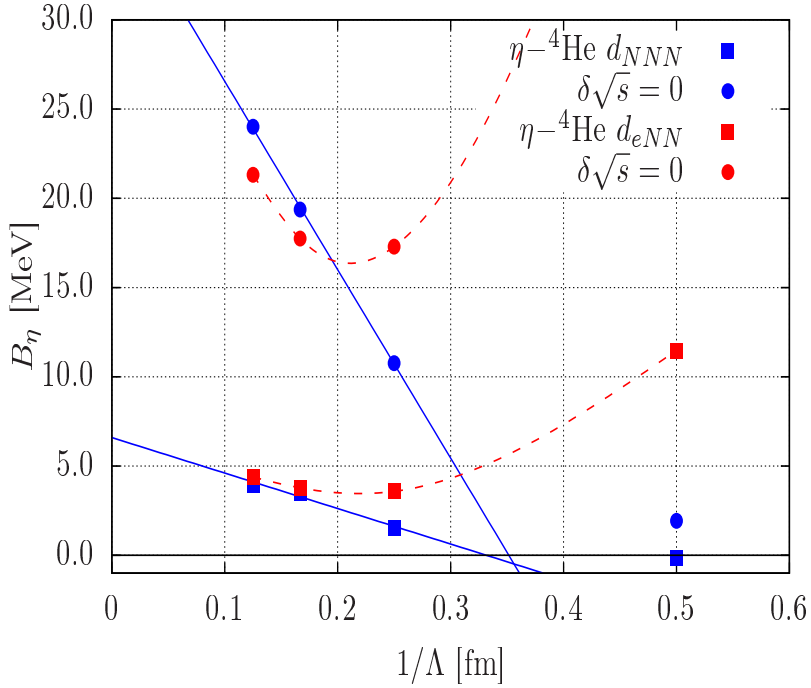


$B_\eta(\Lambda)$ using $v_{\eta N}^{GW}(E)$: with & w/o self consistency

- **Nuclear dynamics generated from two NN & one NNN contact terms (CT). NNN CT averts ^{3}He collapse.**
- **Add one ηN & one ηNN CT; given no ηNN datum, use CT(ηNN)=CT(NNN) to start with.**

Pionless EFT at LO; ηNN CT





Dependence of $B_\eta(\Lambda)$ on choice of ηNN CT
from Erratum to PLB 771 (2017) 297

- **ηNN=NNN CTs vs. fitting to assumed $B_\eta(\eta NN)$=0.**
- **Appreciable model dependence for $\Lambda \leq m_\rho \approx 4$ fm^{-1}.**
  Need data beyond ηN modeling.

Summary

- **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 (i.e. widths), and (iii) which nuclear targets and reactions to try.**

- **Binding $\eta\,^3$He requires a minimum value of Re $a_{\eta N}$ close to 1 fm, yielding then a few MeV $B_\eta(\eta\,^4$He). Binding $\eta\,^4$He requires a lower value of Re $a_{\eta N}$, roughly exceeding 0.7 fm. Calculated widths of near-threshold atates are a few MeV.**

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