Onset of η-nuclear binding scenarios

Hadrons in Nuclei, JU Krakow, June 2017

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η nuclear quasibound states

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

A. Cieplý plus FGM, NPA 925 (2014) 126

Review: A. Gal et al., Acta Phys. Polon. B 45 (2014) 673

Onset of η nuclear binding

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

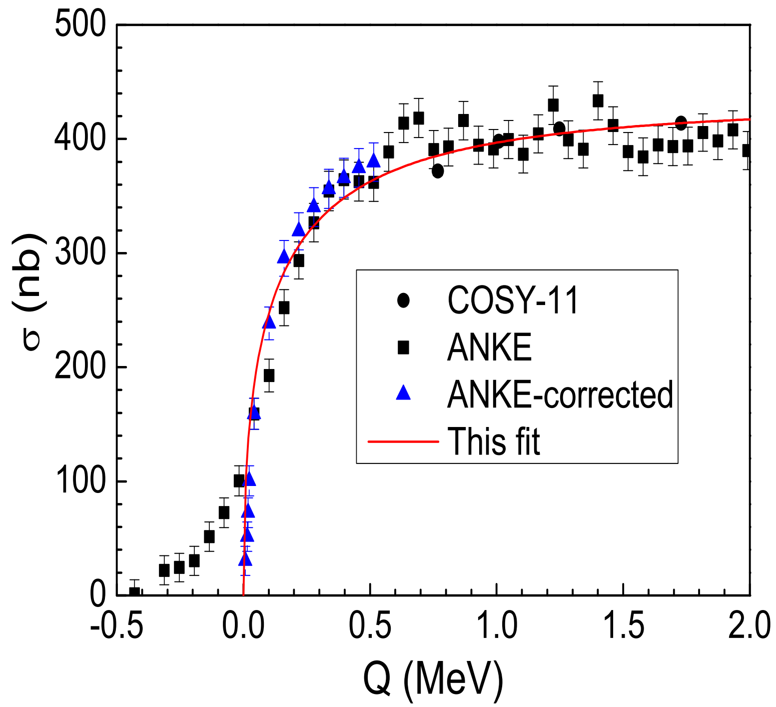
B. Bazak plus BFG, PLB (2017), arXiv:1703.02861

N. Barnea, E. Friedman, A. Gal, to be submitted

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. Re the onset of binding, Krusche & Wilkin (2015) state:
"The most straightforward (but not unique) interpretation of the data is that the $\eta\,$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.

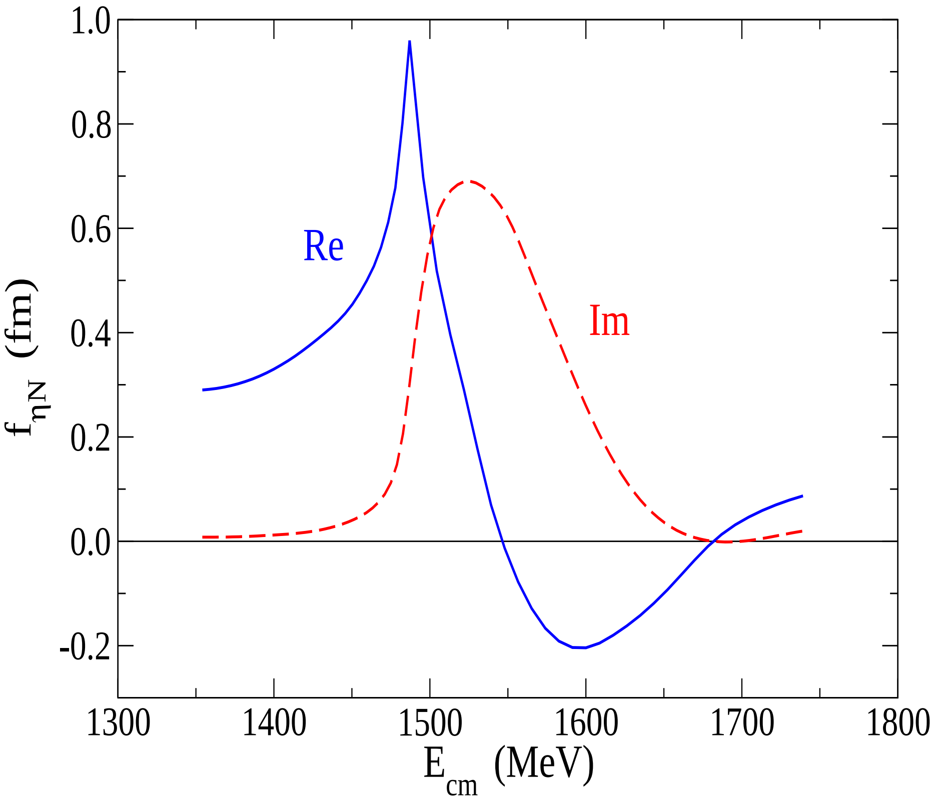
Xie-Liang-Oset-Moskal-Skurzok-Wilkin, PRC 95 (2017) 015202

$$a(\eta\,^3\text{He}) = [-(2.23\pm1.29)+i(4.89\pm0.57)]\ \text{fm}$$

- **Would $\eta\,^4$He be bound? Fix & Kolesnikov (arXiv:1703.06591) argue: NO, since the denser ^{4}He medium leads to a stronger subthreshold suppression.**

η nuclear quasibound states

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



$a_{\eta N}$ (fm) model dependence

a	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, NPA 919 (2013) 46

- Re $a_{\eta N}$ varies from 0.2 to 1.0 fm, Im $a_{\eta N}$: 0.2–0.3 fm.
- M1, M2, GW free-space models; GR, CS in-medium.
- Strong subthreshold fall-off in both Re $f_{\eta N}$ and Im $f_{\eta N}$.
- In-medium: E dependence, Pauli blocking, self energies.

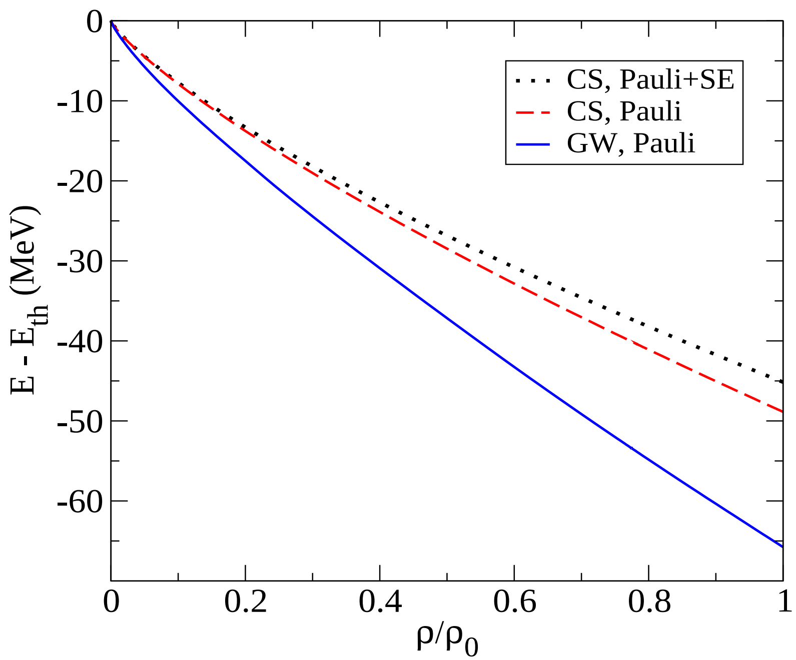
Self-consistency in mesic-atom & nuclear calculations

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

$$s = (\sqrt{s_{\rm th}} - B_\eta - B_N)^2 - (\vec{p}_\eta + \vec{p}_N)^2 < s_{\rm th}$$

$$\sqrt{s_{\eta N}} \to E_{\rm th} - B_N - B_\eta - \xi_N \frac{p_N^2}{2m_N} - \xi_\eta \frac{p_\eta^2}{2m_\eta}$$

$$\xi_{N(\eta)} = \frac{m_{N(\eta)}}{(m_N+m_\eta)} \qquad \frac{p_\eta^2}{2m_\eta} \sim -V_\eta - B_\eta$$



η is not at rest!

$E_{\eta N}$ subthreshold shift vs. nuclear density in $1s_\eta$ ^{40}Ca.

A dominant in-medium effect.

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

In-medium ηN amplitudes

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

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

- KG equation and self-energies:

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

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

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

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

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

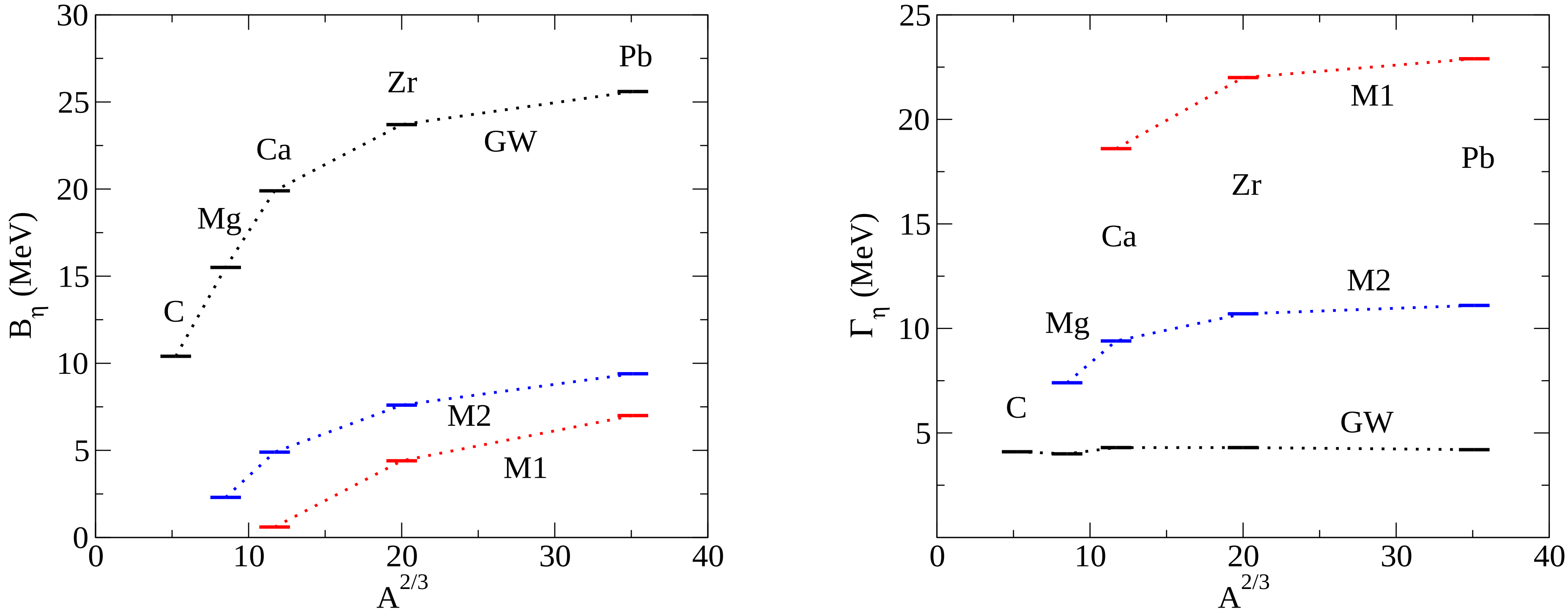
- $N^*(1535) \Rightarrow$ energy dependent $f_{\eta N}(\sqrt{s})$.

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

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

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

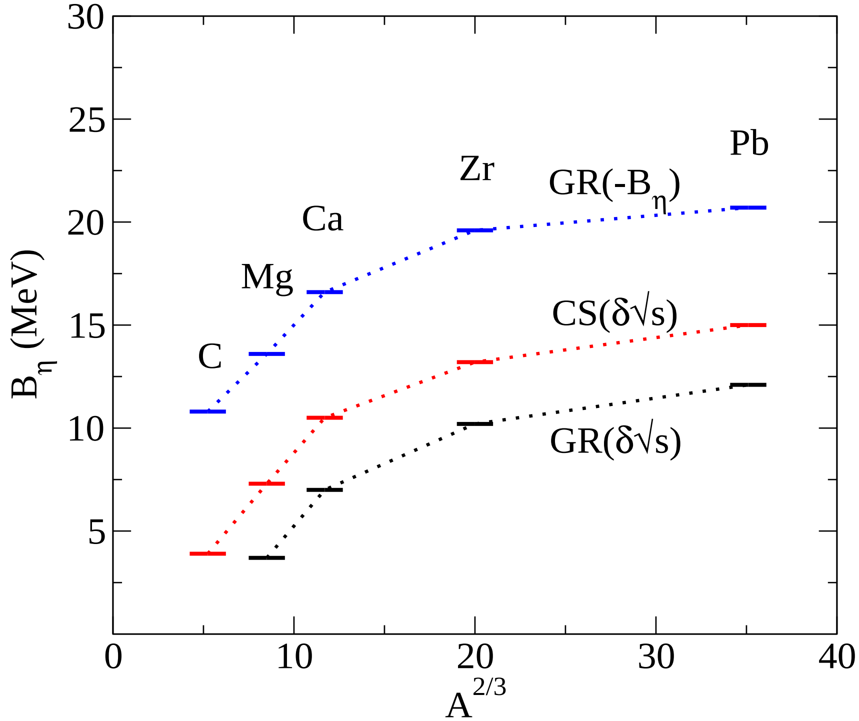
Model dependence I

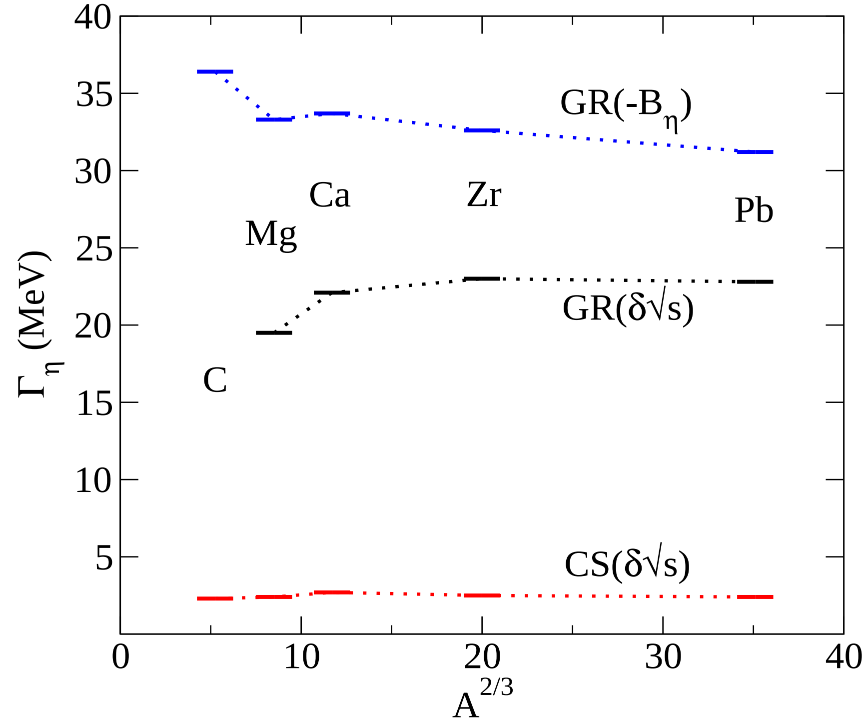


$1s_\eta$ B & Γ using WRW Pauli-blocked $f_{\eta N}$

- **E dependence treated self consistently.**
  - **Larger Re $a_{\eta N} \Rightarrow$ larger B_η.**
  - **Widths are unrelated to Im $a_{\eta N}$.**

Model dependence II



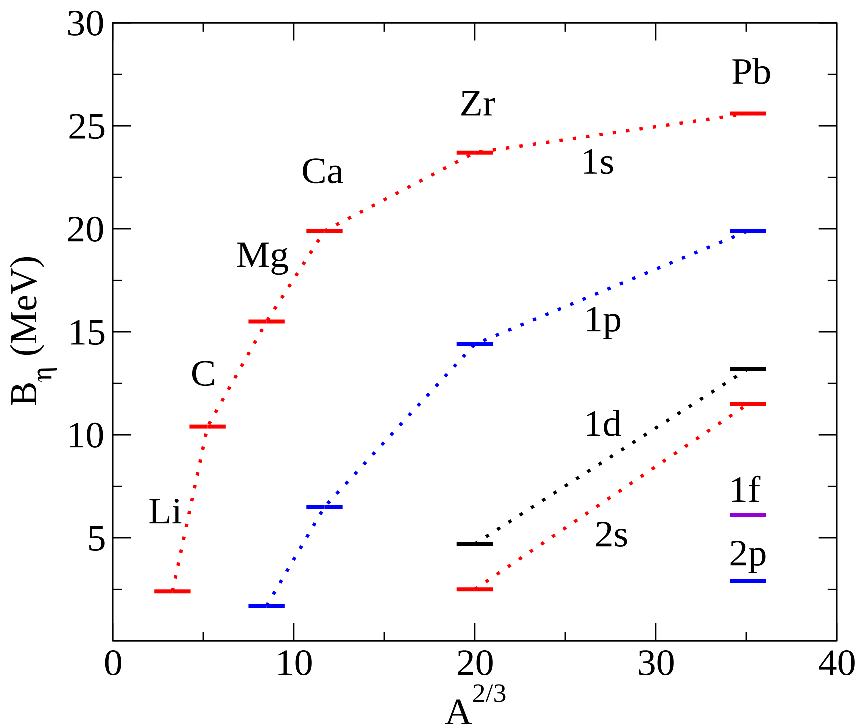


Sensitivity of calc. B_{1s_η} **&** Γ_{1s_η} **to self-consistency version**

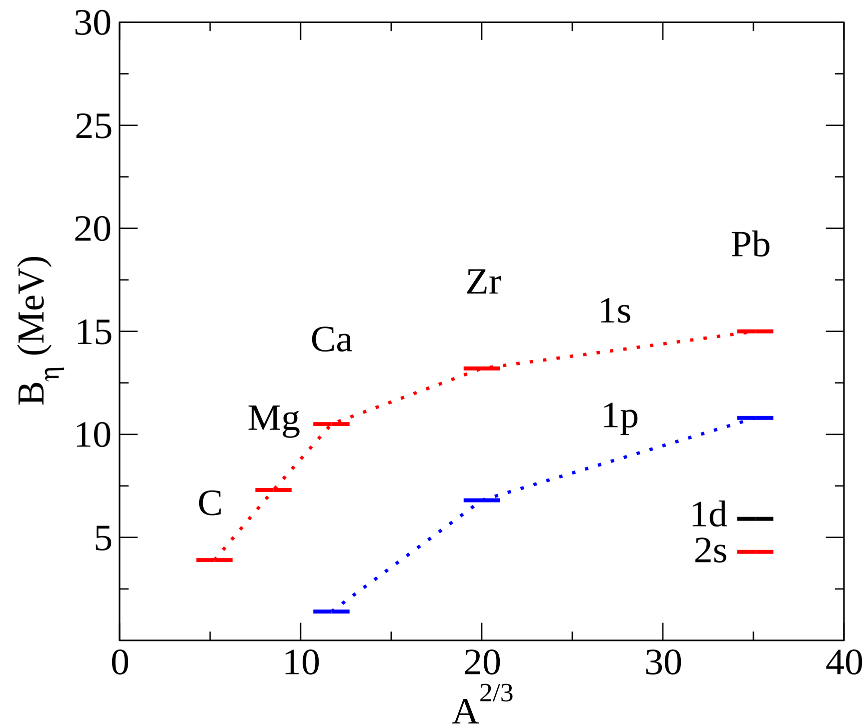
- $\langle \delta\sqrt{s} \rangle$ **goes deeper into subthreshold, thereby reducing further** B_{1s_η} **&** Γ_{1s_η}**.**
- **GR's widths are too large to resolve** η **bound states.**

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

Model predictions for small widths



GW model

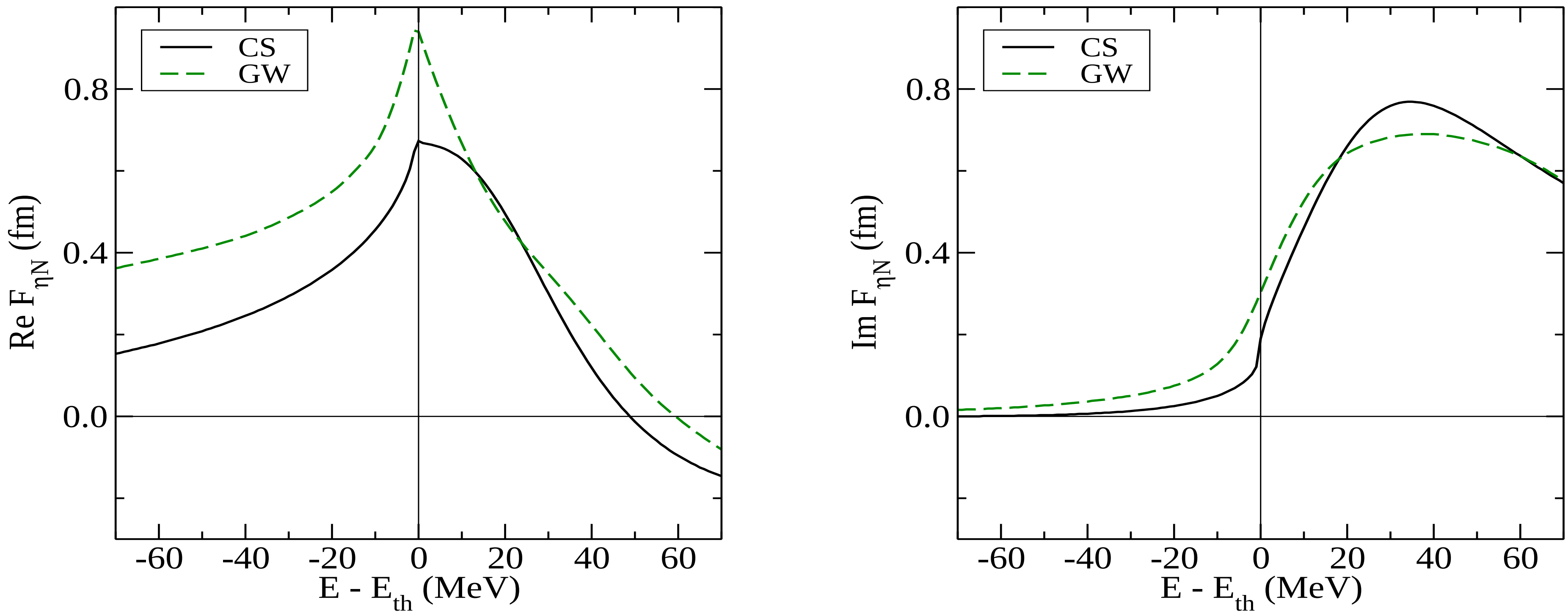


CS model

- **Widths of only a few MeV in each of these models.**
- **What makes the subthreshold values of Im $f_{\eta N}$ sufficiently small to generate small widths?**

Onset of η nuclear binding

ηN model input

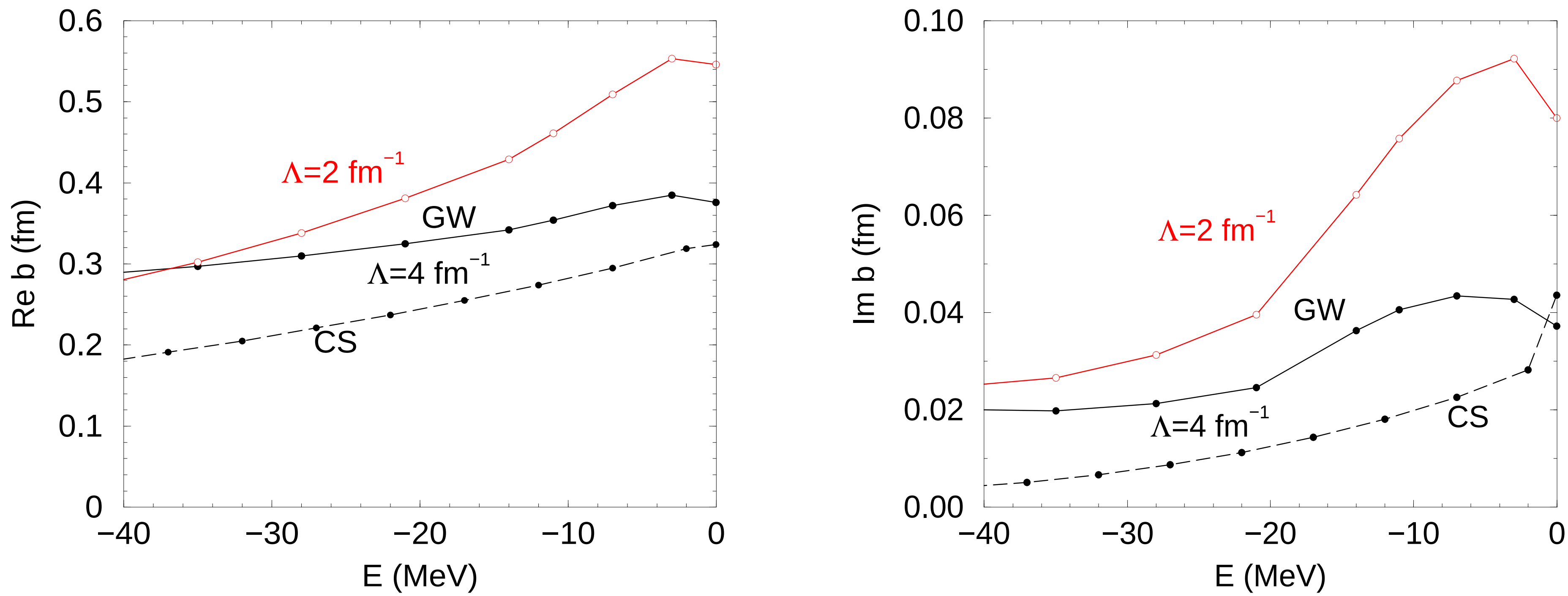


CM s-wave scattering amplitude $F_{\eta N}(E)$ in two meson-baryon coupled-channel $N^*(1535)$ models.

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

- **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 $E < 0$

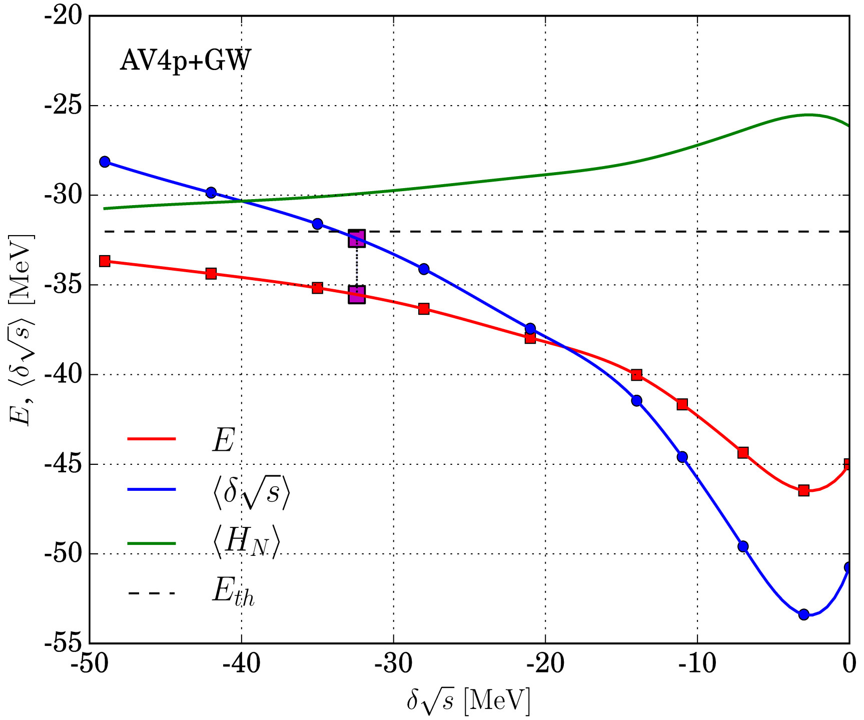
$$\mathbf{v}_{\eta N}\mathbf{(E;r)} = -\frac{4\pi}{2\mu_{\eta N}}\ \mathbf{b(E)} \left(\frac{\Lambda}{2\sqrt{\pi}}\right)^3 \exp\left(-\frac{\Lambda^2 r^2}{4}\right)$$

- **Scale Λ is inversely proportional to the range of $\mathbf{v}_{\eta N}$.**
- **In pionless EFT, vector-meson exchange requires $\Lambda \leq 4\ \mathrm{fm}^{-1}$.**

Energy dependence in η nuclear few-body systems

- $N^*(1535)$ **induces strong energy dependence of the scattering amplitudes** $f_{\eta N}(\sqrt{s})$ **and the effective input potentials** $v_{\eta N}(\sqrt{s})$.
- $s = (\sqrt{s_{\rm th}} - B_\eta - B_N)^2 - (\vec{p}_\eta + \vec{p}_N)^2 < s_{\rm th}$
- **Expanding nonrelativistically near** $\sqrt{s_{\rm th}}$**:**
$\langle \delta\sqrt{s} \rangle = -\frac{B}{A} + \frac{A-1}{A}E_\eta - \xi_N \frac{1}{A}\langle T_N \rangle - \xi_\eta \left(\frac{A-1}{A}\right)^2 \langle T_\eta \rangle$,
$\delta\sqrt{s} \equiv \sqrt{s} - \sqrt{s_{\rm th}}, \;\; E_\eta = \langle H - H_N \rangle, \;\; \xi_{N(\eta)} \equiv \frac{m_{N(\eta)}}{(m_N + m_\eta)}$.
- **Self-consistency:**
output $\langle \sqrt{s} \rangle =$ **input** $\sqrt{s}$**.**

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

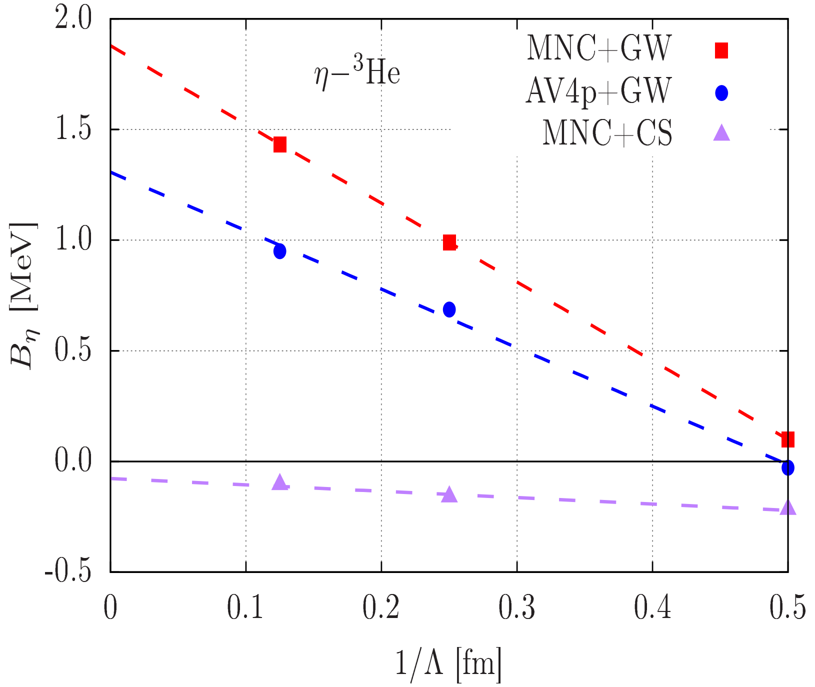


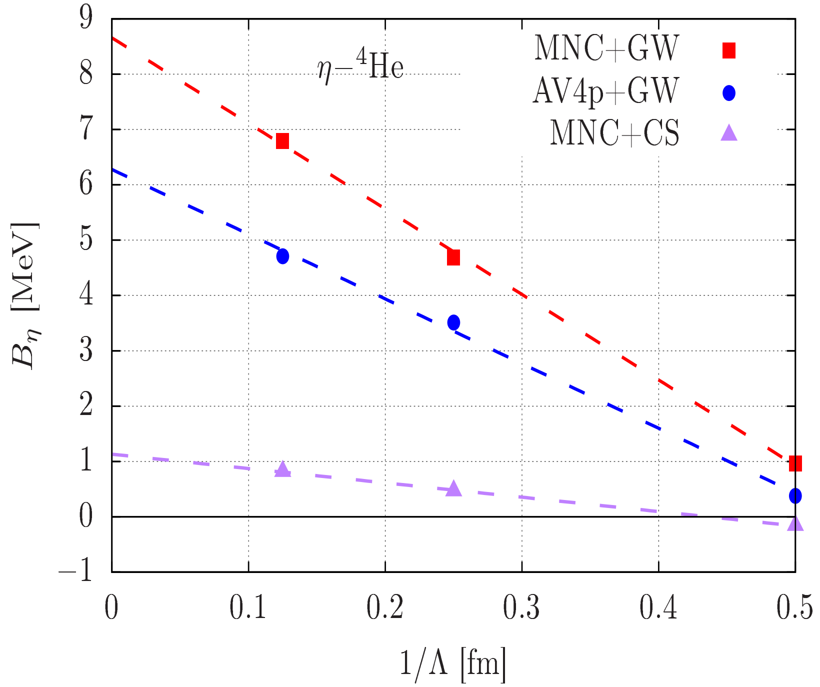
Self consistency plot

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

- **Stochastic Variational Method calculations with correlated Gaussian trial wavefunctions.**
- **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

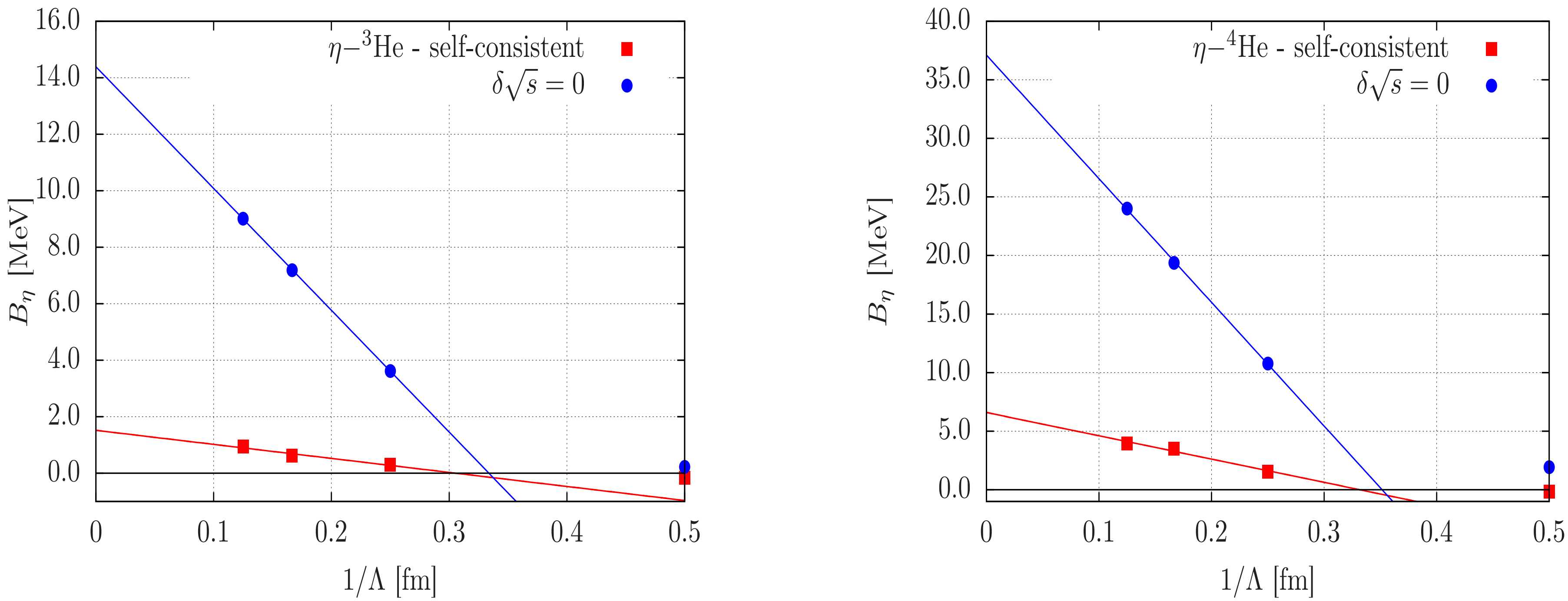




B_η as a function of $1/\Lambda$

- These bindings will decrease by $\leq$0.3 MeV when Im v is treated nonperturbatively.
- AV4' is more realistic for NN than Minnesota (MNC).
- CS does not bind $\eta\,^3$He & unlikely to bind $\eta\,^4$He.

Scale dependence; pionless EFT



B_η as a function of $1/\Lambda$

- **Two NN & one NNN contact terms at LO.**
  Add one ηN contact term ($\sim$ b(E)).
- **No ηNN contact term needed to avert collapse.**
- **Crucial role of self consistency in reducing η binding.**

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.**
- **The onset of binding $\eta\,^3$He requires a minimal value of Re $a_{\eta N}$ close to 1 fm, yielding then a few MeV η binding in $\eta\,^4$He. The onset of binding $\eta\,^4$He requires a lower value of Re $a_{\eta N}$, roughly exceeding 0.7 fm.**

Thanks to my collaborators N. Barnea, B. Bazak, A. Cieplý, E. Friedman, J. Mareš