Onset of η-meson binding

Exotic Atoms & Related Topics (EXA2017), Vienna

Avraham Gal

Racah Institute of Physics, Hebrew University, Jerusalem

η nuclear quasibound states

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

A.Cieplý, E.Friedman, A.Gal, J. Mareš, NPA 925 (2014) 126

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

Onset of η nuclear binding in He

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

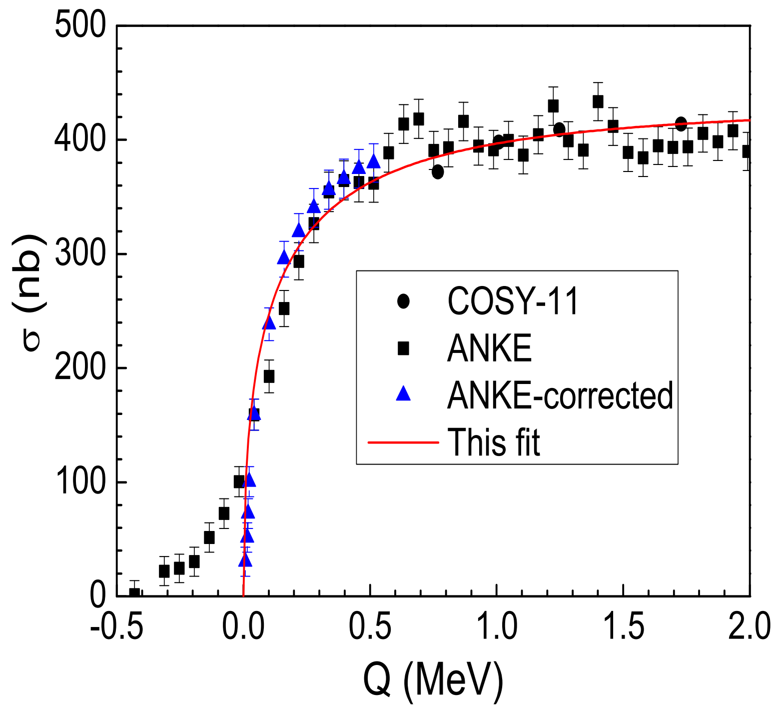
N.Barnea, B.Bazak, E.Friedman, A.Gal, PLB 771 (2017) 297

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≥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.

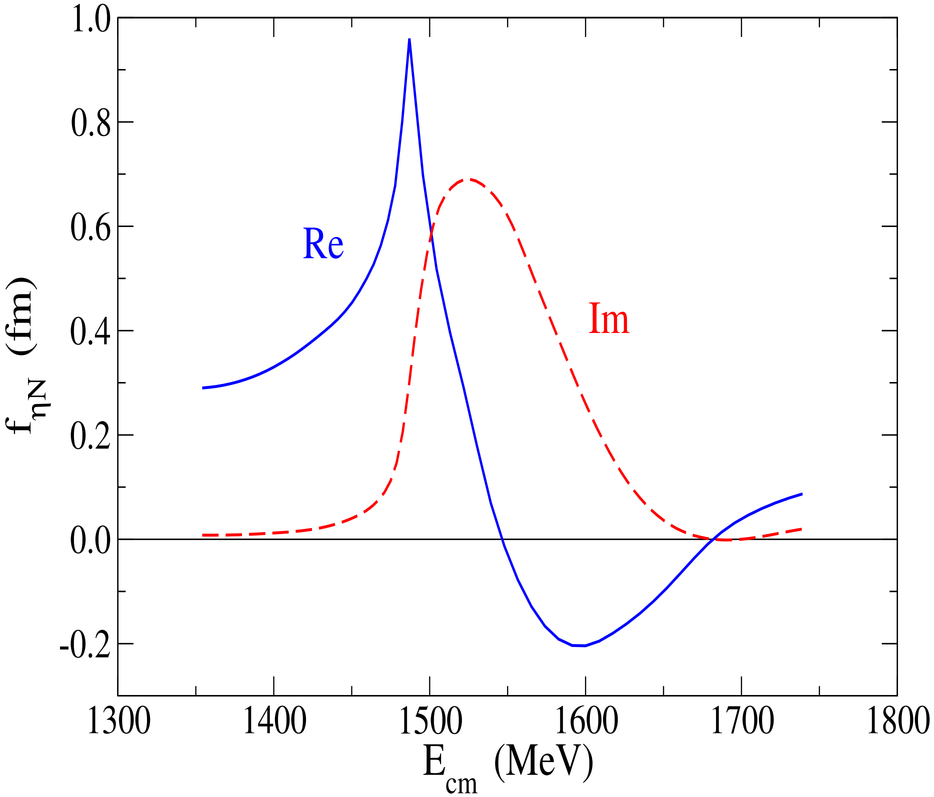
Xie-Liang-Oset-Moskal-Skurzok-Wilkin, PRC 95 (2017) 015202

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

- 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.

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.

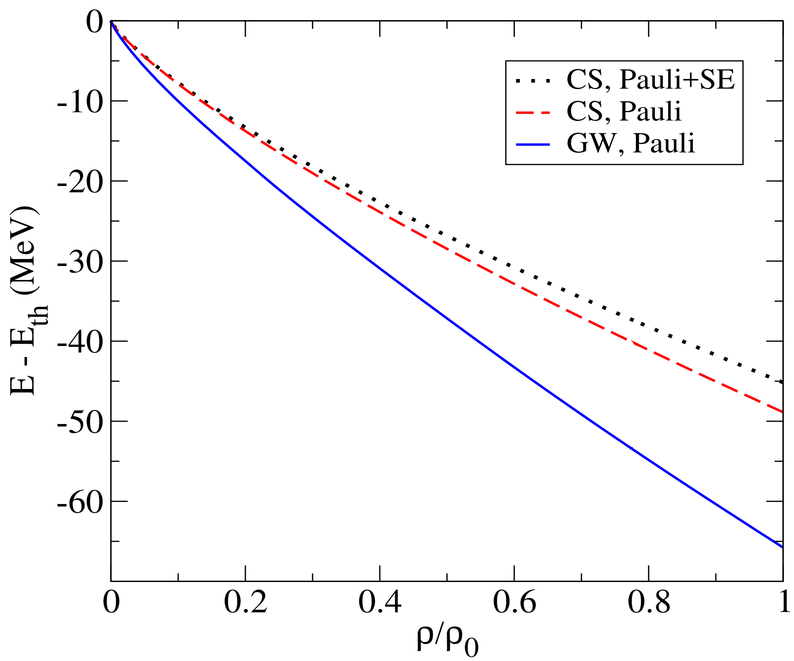
Self-consistency in mesic-atom & nuclear calculations

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

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

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

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



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

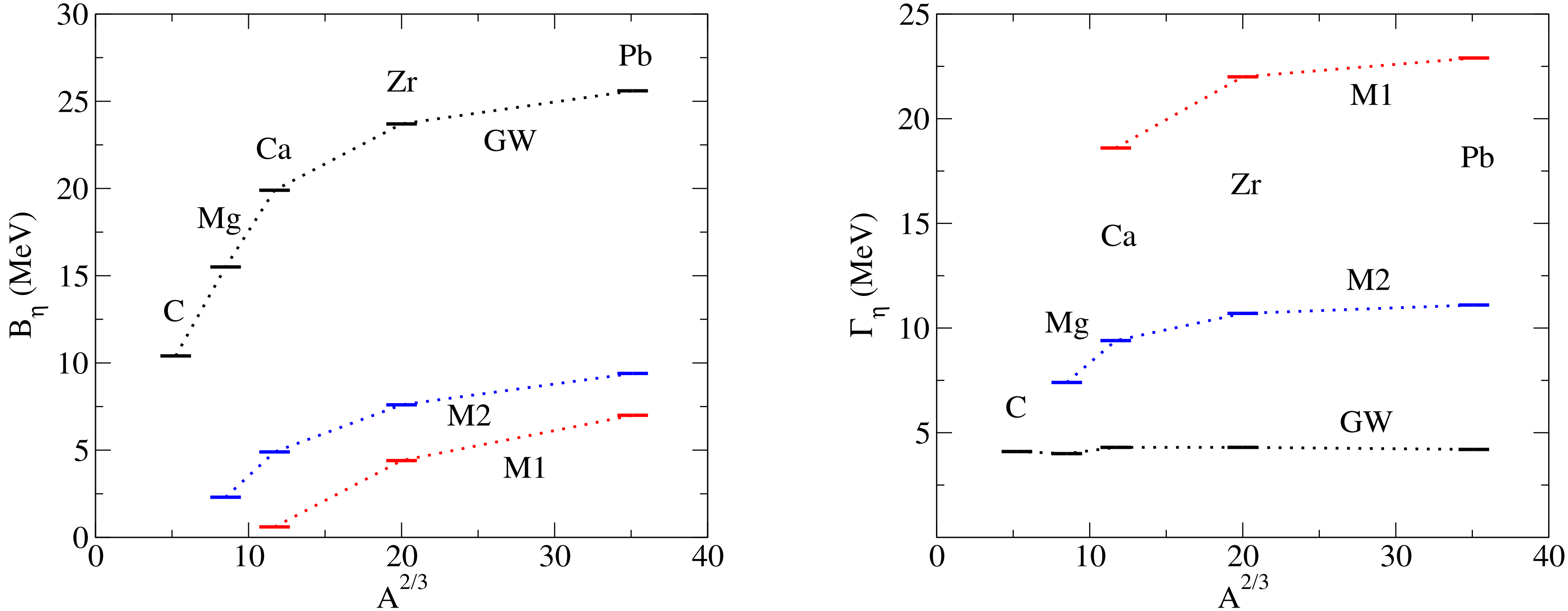
In-medium ηN amplitudes

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):
  $f_{\eta N}^{\mathrm{WRW}}(\sqrt{s}, \rho) = \frac{f_{\eta N}(\sqrt{s})}{1+\xi(\rho)(\sqrt{s}/m_N)f_{\eta N}(\sqrt{s})\rho}, \quad \xi(\rho) = \frac{9\pi}{4p_F^2} I(\tilde{\omega}_\eta)$
- $N^*(1535) \Rightarrow$ energy dependent $f_{\eta N}(\sqrt{s})$.
  In medium $\Rightarrow$ go subthreshold: $\quad \delta\sqrt{s} = \sqrt{s} - \sqrt{s_{\mathrm{th}}}$
  $\delta\sqrt{s} \approx -B_N \frac{\rho}{\bar{\rho}} - \xi_N B_\eta \frac{\rho}{\rho_0} - \xi_N T_N (\frac{\rho}{\bar{\rho}})^{2/3} + \xi_\eta \mathrm{Re}\, V_\eta(\sqrt{s}, \rho)$
- **A self-consistency cycle in $\delta\sqrt{s}$ for given ρ.**

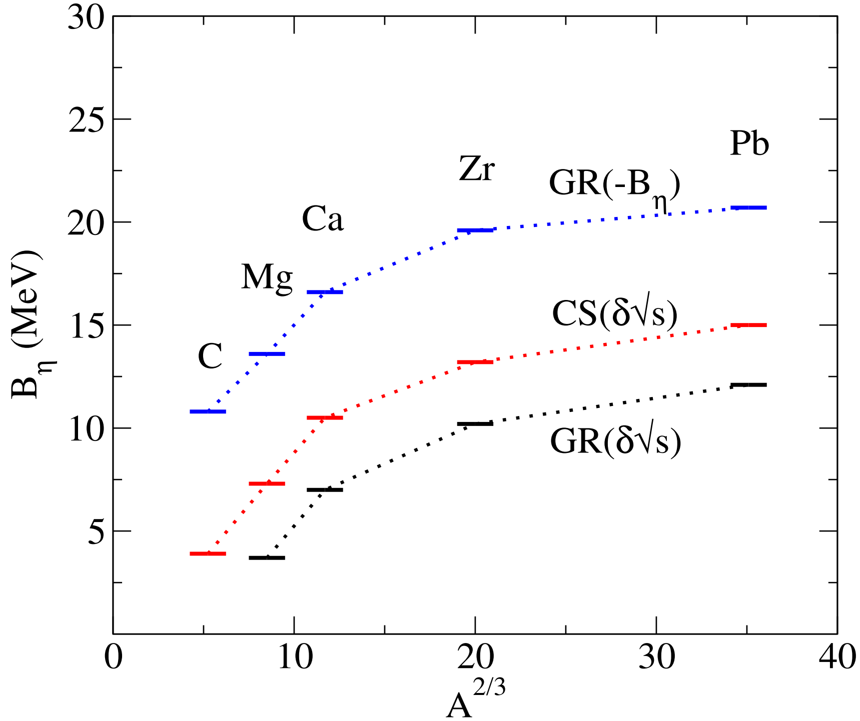
Model dependence I

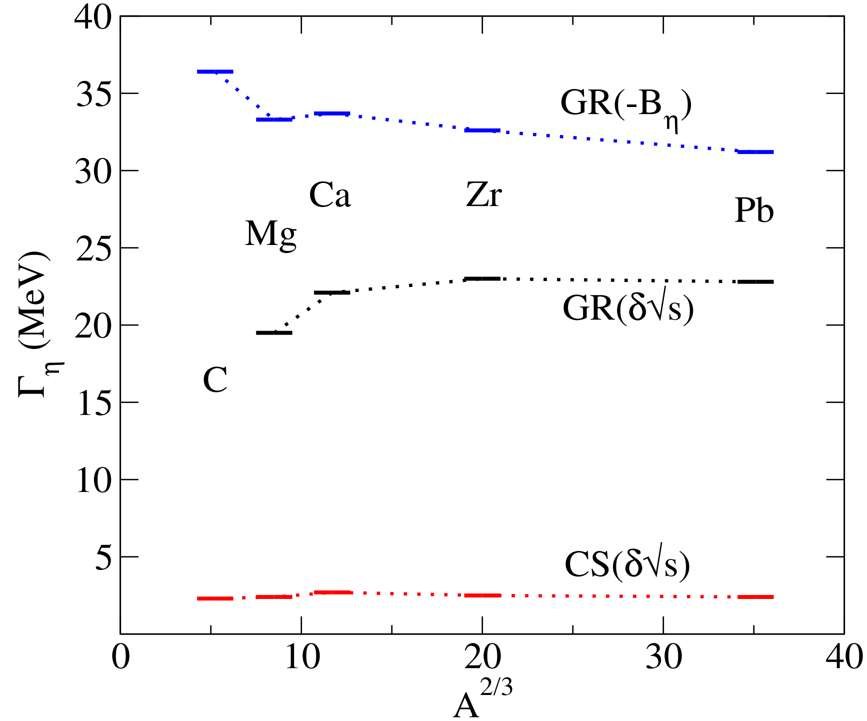


$1s_\eta$ B & Γ using WRW Pauli-blocked $f_{\eta N}$

- **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



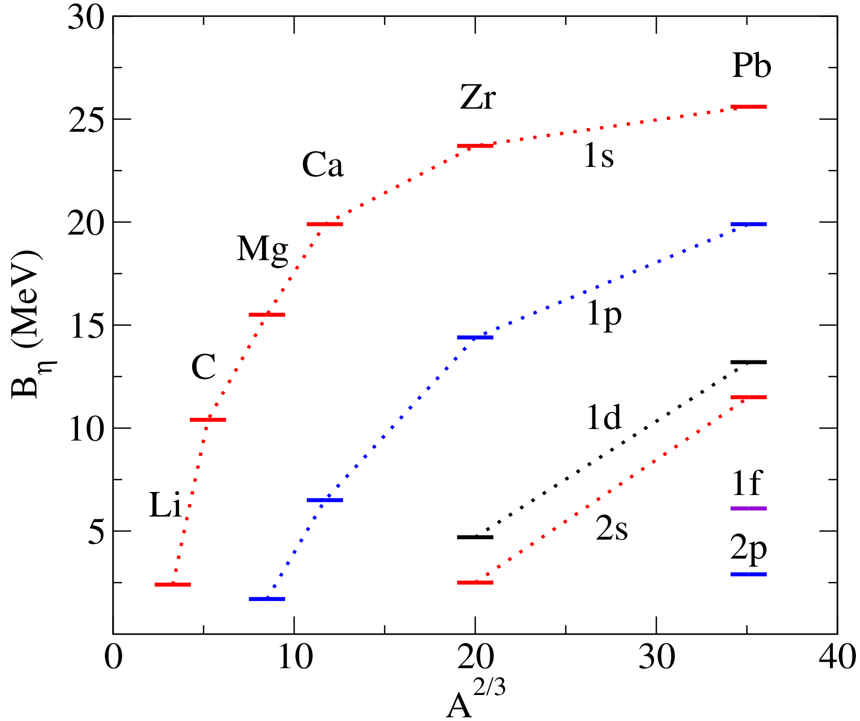


Sensitivity of calc. B_{1s_η} **&** Γ_{1s_η} **to self-consistency version**

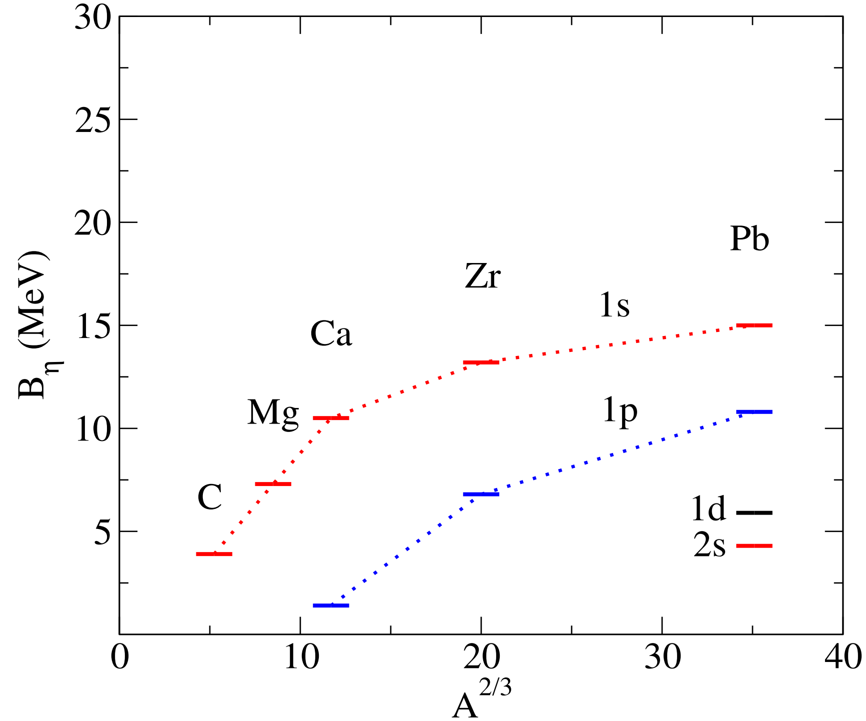
- $\langle\delta\sqrt{s}\rangle$ **goes deeper into subthreshold, thereby reducing further** B_{1s_η} **&** Γ_{1s_η}**.**
- **GR's widths are too large to resolve** η **bound states.**

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?

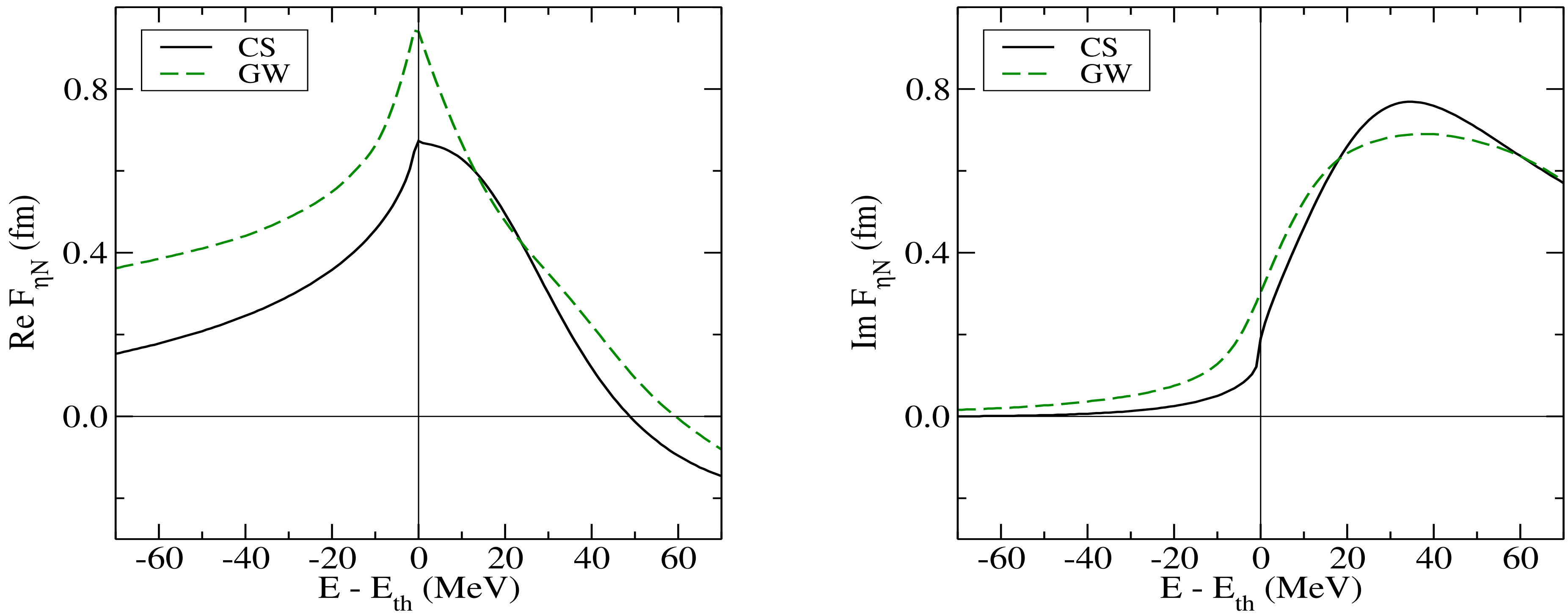
Onset of η nuclear binding

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

ηN model input

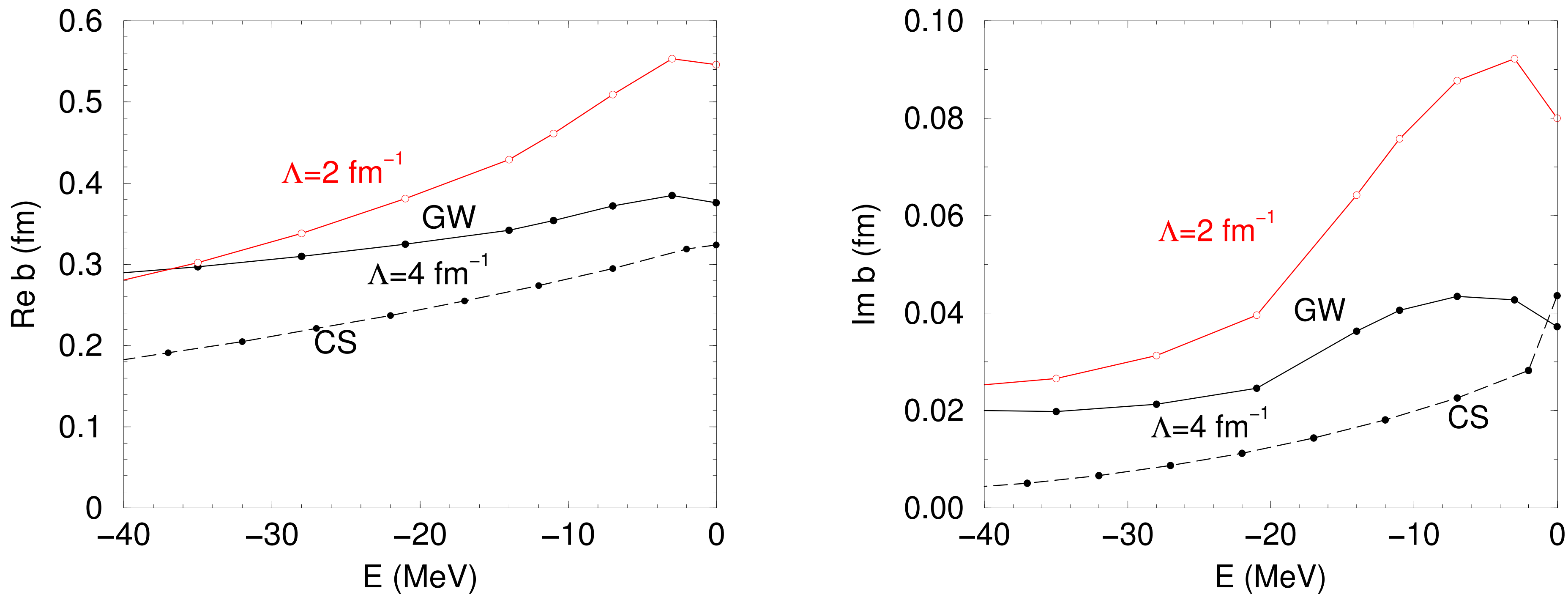


CM s-wave scattering amplitude $F_{\eta N}$(E) in two meson-baryon coupled-channel N^*(1535) models.

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

- **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 $E<0$

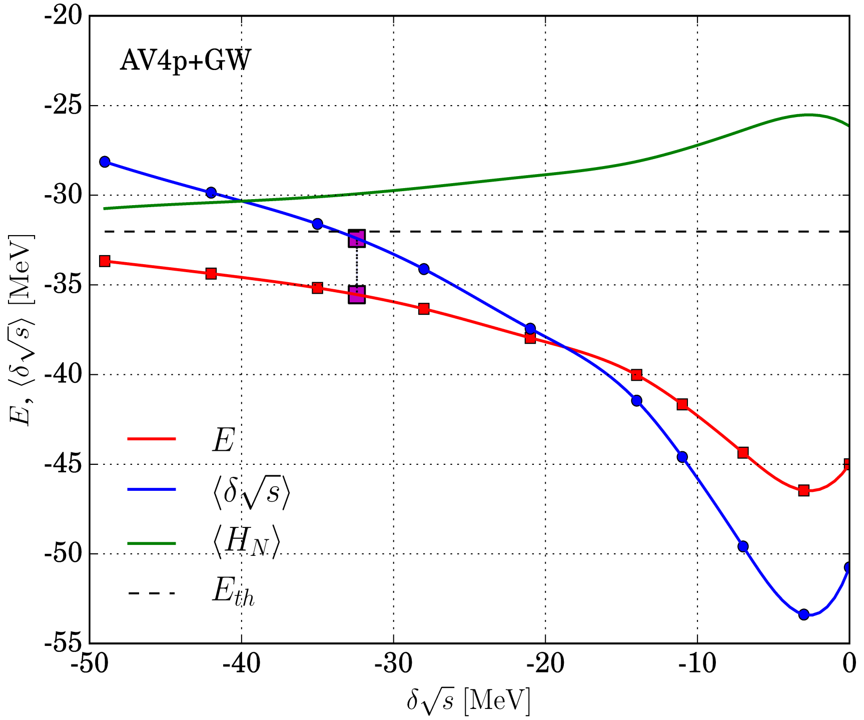
$$\mathbf{v}_{\eta N}(\mathbf{E;r}) = -\frac{4\pi}{2\mu_{\eta N}}\ \mathbf{b(E)} \left(\frac{\Lambda}{2\sqrt{\pi}}\right)^3 \exp\left(-\frac{\Lambda^2 r^2}{4}\right)$$

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

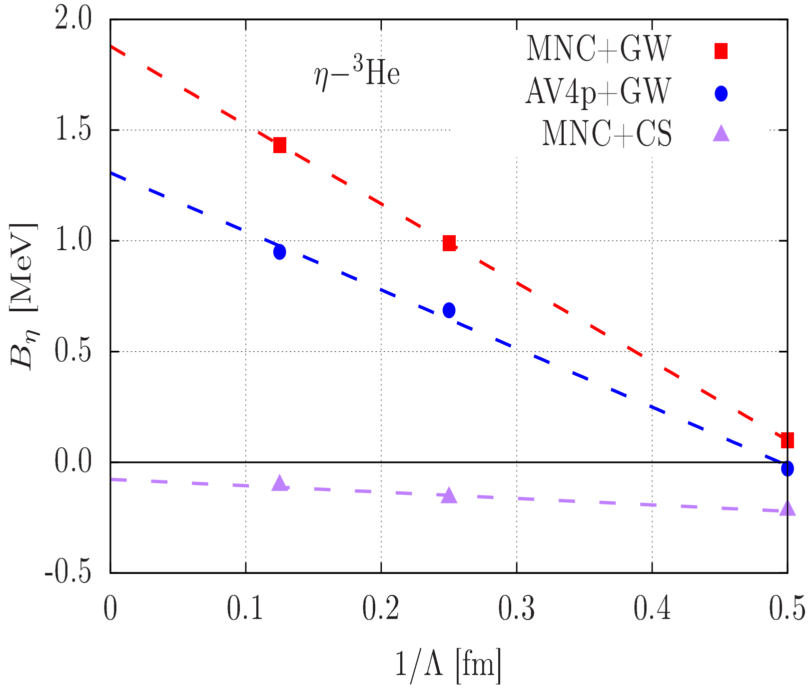


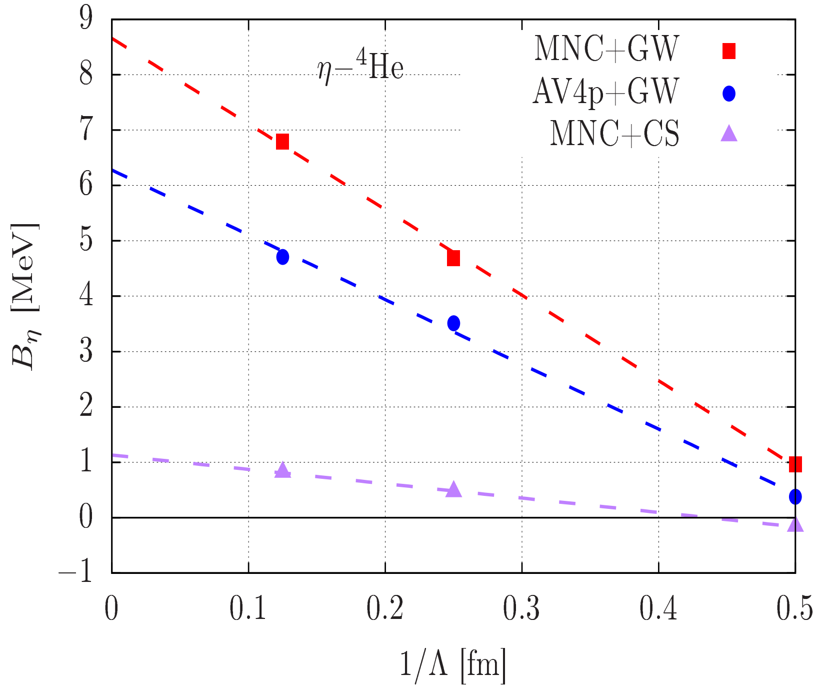
Self consistency plot

$\eta\,^4$He bound-state energy $\mathbf{E}$, $\langle\delta\sqrt{s}\rangle$ & $\langle H_N = H_A\rangle$, for AV4' v_{NN} & GW $\mathrm{v}_{\eta N}$(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

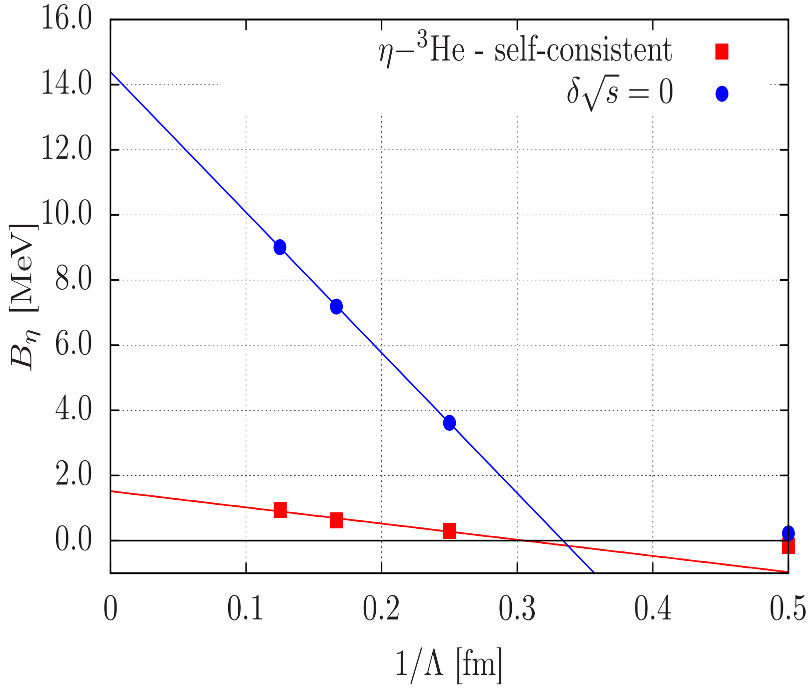


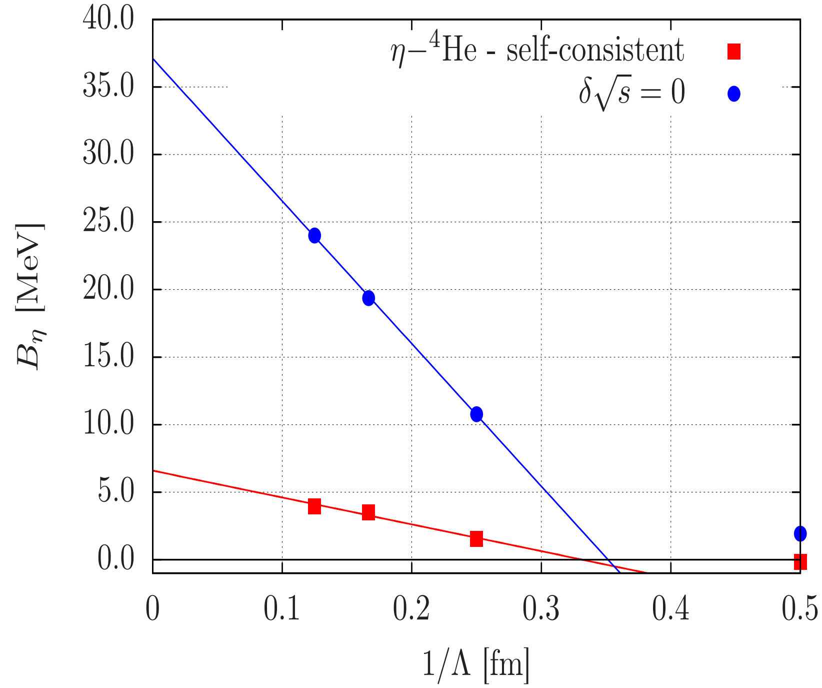


B_η as a function of $1/\Lambda$

- **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

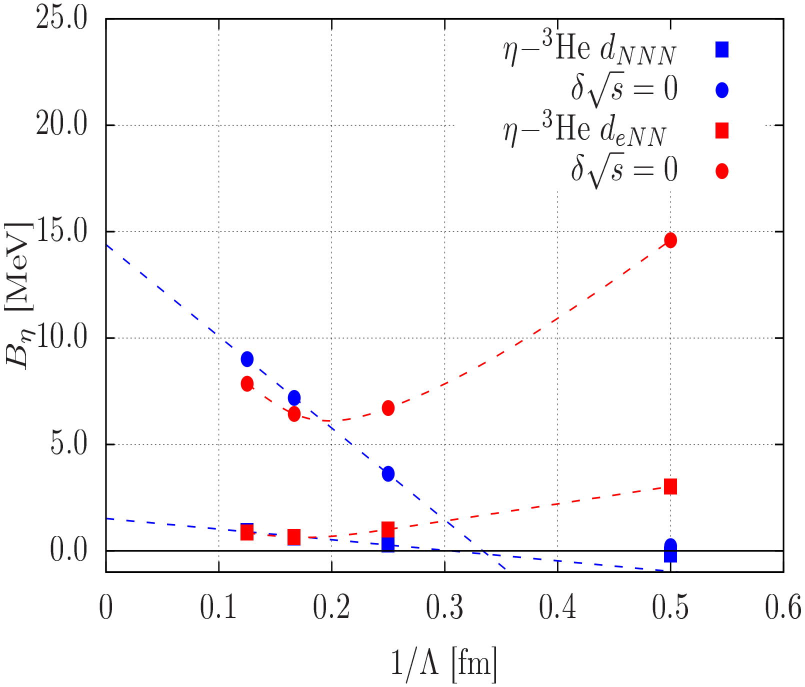


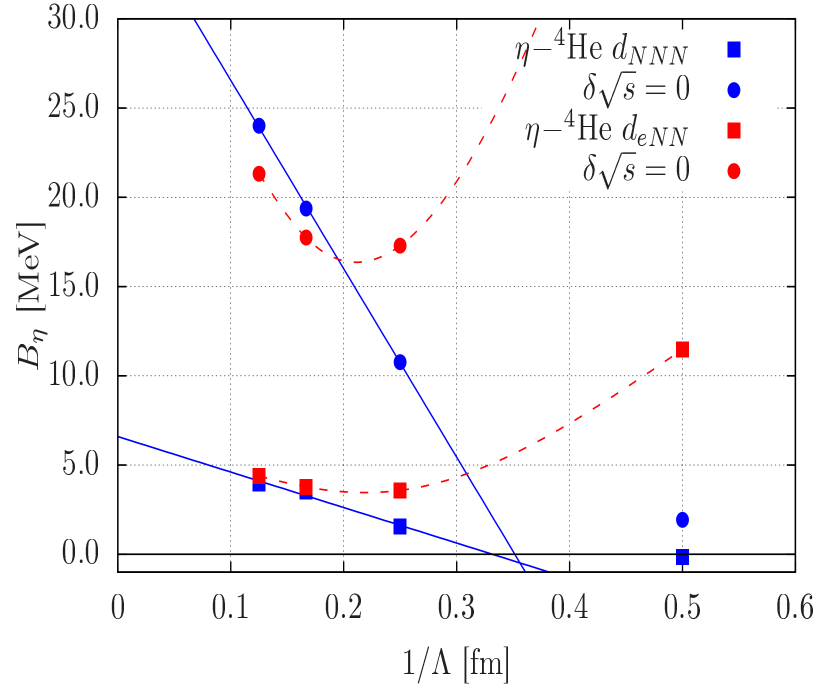


$B_\eta(\Lambda)$ using $v^{GW}_{\eta N}(E)$: with & w/o self consistency

- **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.**

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