Onset of binding ΛΛ Hypernuclei

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- **Introduction to ΛΛ hypernuclei**

Clearly identified species: ${}^{6}_{\Lambda\Lambda}$He, ${}^{10}_{\Lambda\Lambda}$Be, ${}^{13}_{\Lambda\Lambda}$B.

Lighter ΛΛ hypernuclei?

- **$\not\pi$EFT of light ΛΛ hypernuclei**

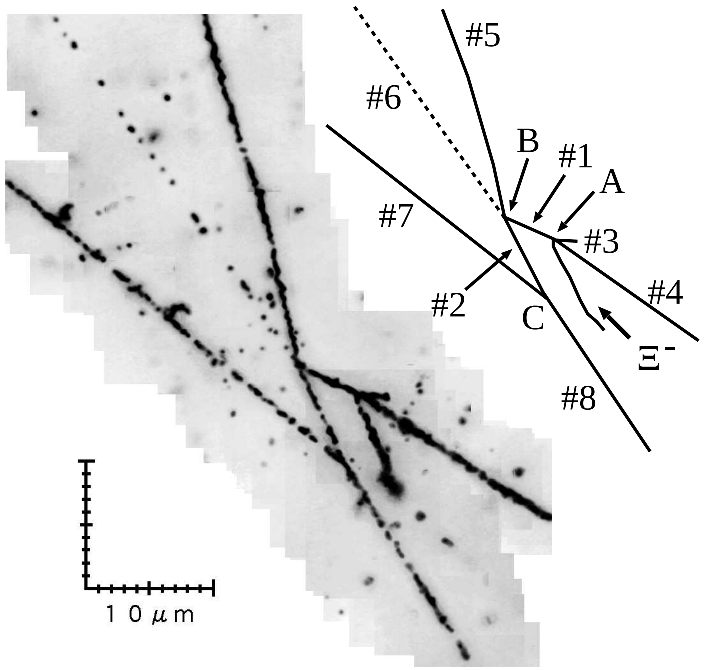
s-shell hypernuclei: overbinding of ${}^{5}_{\Lambda}$He

Contessi-Barnea-Gal, PRL 121 (2018) 102502.

The onset of ΛΛ hypernuclear binding

+ Schäfer & Mareš, PLB 797 (2019) 134893.

Introduction to $\Lambda\Lambda$ Hypernuclei



Nagara event, $_{\Lambda\Lambda}{}^{6}\mathrm{He}$, (KEK-E373) PRL 87 (2001) 212502

$B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^{6}\mathrm{He}_{\mathrm{g.s.}})$**=6.91±0.16 MeV, unambiguously determined.**

- **A:** Ξ^- **capture** $\Xi^- + {}^{12}\mathrm{C} \to {}_{\Lambda\Lambda}{}^{6}\mathrm{He} + t + \alpha$
- **B: weak decay** ${}_{\Lambda\Lambda}{}^{6}\mathrm{He} \to {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-$ **(no** ${}_{\Lambda\Lambda}{}^{6}\mathrm{He} \to {}^{4}\mathrm{He} + H$**)**
- **C:** ${}^{5}_{\Lambda}\mathrm{He}$ **nonmesic weak decay to 2** Z**=1 recoils + n.**

The elusive H dibaryon

Jaffe's H(uuddss) [PRL 38 (1977) 195] predicted stable

$$\mathbf{H} \sim \mathcal{A}[\sqrt{\mathbf{1/8}}\ \Lambda\Lambda + \sqrt{\mathbf{1/2}}\ N\Xi - \sqrt{\mathbf{3/8}}\ \Sigma\Sigma,]_{I=S=0}$$

- **To forbid ${}^{6}_{\Lambda\Lambda}$He$\to$H+^{4}He, impose B(H)$\leq$7 MeV. A bound H most likely overbinds ${}^{6}_{\Lambda\Lambda}$He [Gal, PRL 110 (2013) 179201].**

- **LQCD: a weakly bound H becomes unbound. SU(3)$_{\rm f}$ breaking pushes it to $\approx N\Xi$ threshold, $\approx$26 MeV in $\Lambda\Lambda$ continuum [HALQCD, NPA 881 (2012) 28; Haidenbauer & Meißner, ibid. 44].**

- **Search for m(H)$\leq$2.05 GeV by BaBar in Υ(2S,3S)$\to$H$\bar{\Lambda}\bar{\Lambda}$ is negative [PRL 122 (2019) 072002].**

Binding energy consistency of $\Lambda\Lambda$ hypernuclei

event	${}^{A}_{\Lambda\Lambda}Z$	$B^{\rm exp}_{\Lambda\Lambda}$	$B^{\rm CM}_{\Lambda\Lambda}$ †	$B^{\rm SM}_{\Lambda\Lambda}$ ††
E373-Nagara	${}^{6}_{\Lambda\Lambda}$He	6.91 ± 0.16	6.91 ± 0.16	6.91 ± 0.16
E373-DemYan	${}^{10}_{\Lambda\Lambda}$Be	14.94 ± 0.13 ‡	14.74 ± 0.16	14.97 ± 0.22
E373-Hida	${}^{11}_{\Lambda\Lambda}$Be	20.83 ± 1.27	18.23 ± 0.16	18.40 ± 0.28
E373-Hida	${}^{12}_{\Lambda\Lambda}$Be	22.48 ± 1.21	–	20.72 ± 0.20
E176	${}^{13}_{\Lambda\Lambda}$B	23.4 ± 0.7 *	–	23.21 ± 0.21

† **E. Hiyama et al., PRL 104 (2010) 212502, & refs. therein.**

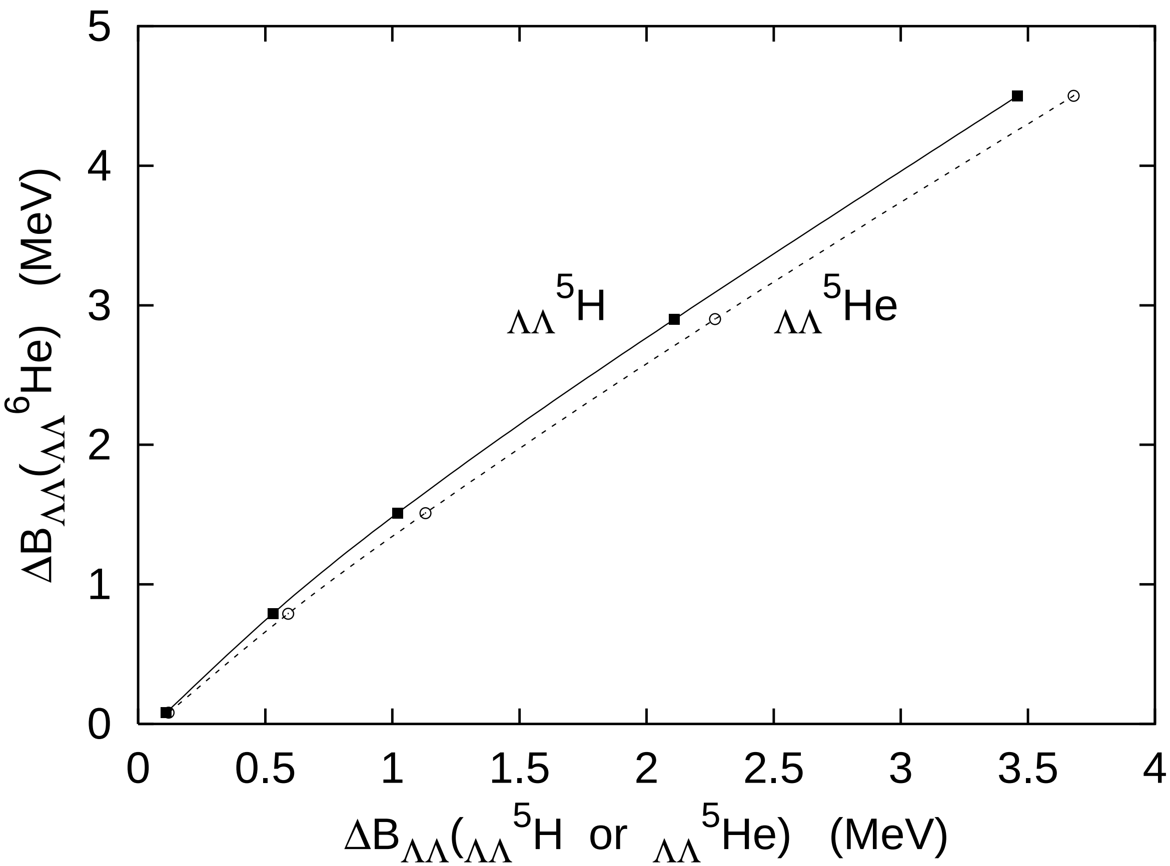
†† **A. Gal, D.J. Millener, PLB 701 (2011) 342, assuming that**

$< V_{\Lambda\Lambda} > \approx \Delta B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{6}\mathrm{He})$**=0.67±0.16 MeV.**

‡ **Assuming production in** ${}^{10}_{\Lambda\Lambda}$Be **non g.s.** $2^+(3.04$ MeV$)$.

* **Assuming** ${}^{13}_{\Lambda\Lambda}\mathrm{B}_{\rm g.s.}$ **decay to** ${}^{13}_{\Lambda}\mathrm{C}^*(5/2^+, 3/2^+; 4.8\ \mathrm{MeV}) + \pi^-$.

- **Unassigned events: Hida [PTPS 185 (2010) 335] & Mino [PTEP 2019 (2019) 021D02].**
- **Search for lighter $\Lambda\Lambda$ hypernuclei.**



Faddeev calc. by I.N. Filikhin, A. Gal, NPA 707 (2002) 491

$\Delta B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{6}\mathrm{He}) \equiv B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{6}\mathrm{He}) - 2B_{\Lambda}({}_{\Lambda}^{5}\mathrm{He}) \approx 0.7$ **MeV**

implying that $_{\Lambda\Lambda}{}^5$H & $_{\Lambda\Lambda}{}^5$He are also bound.

With $_{\Lambda\Lambda}{}^4$H likely unbound, $\Lambda\Lambda$ binding onset is $_{\Lambda\Lambda}{}^5$H & $_{\Lambda\Lambda}{}^5$He.

$\not\pi$EFT of Light Hypernuclei

Overbinding problem in s-shell

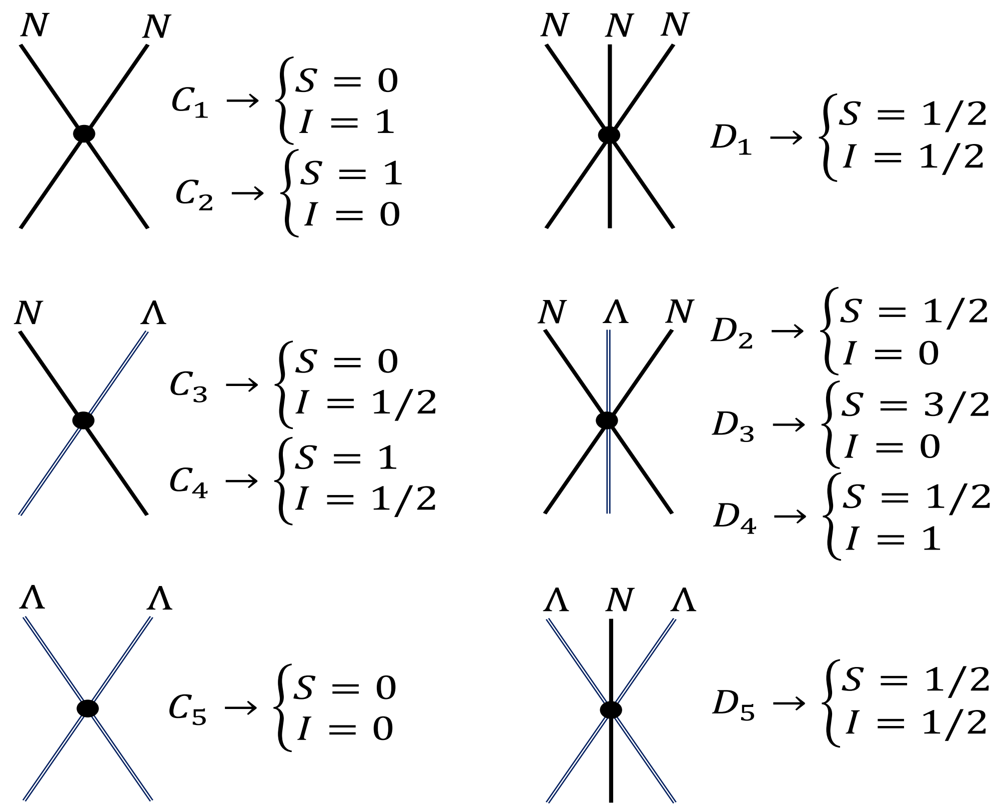
(MeV)	$B_\Lambda(^3_\Lambda\mathrm{H})$	$B_\Lambda(^4_\Lambda\mathrm{He}_{\mathrm{g.s.}})$	$E_x(^4_\Lambda\mathrm{He}_{\mathrm{exc.}})$	$B_\Lambda(^5_\Lambda\mathrm{He})$
Exp.	0.13(5)	2.39(3)	1.406(3)	3.12(2)
Dalitz	0.10	–	–	≥5.16
MC(I)	–	2.13(8)	–	5.1(1)
MC(II)	−1.2(2)	1.22(9)	–	3.22(14)
χLO(600)	0.11(1)	2.444	1.278	5.82(2)
χLO(700)	–	2.423	1.941	4.43(2)
χNLO13(500)	0.135	1.705	0.915	–
χNLO19(650)	0.095	1.530	0.614	–

- All models use ΛNN terms to some extent.
- LO cutoff dependent; NLO worse than LO.
- $^3_\Lambda$H: (I,S)=$(0,\frac{1}{2})$; $(0,\frac{3}{2})$ & $(1,\frac{1}{2})$ unbound.

2-body & 3-body diagrams in $\not\pi$EFT

L. Contessi, M. Schafer, N. Barnea, A. Gal, J. Mareš

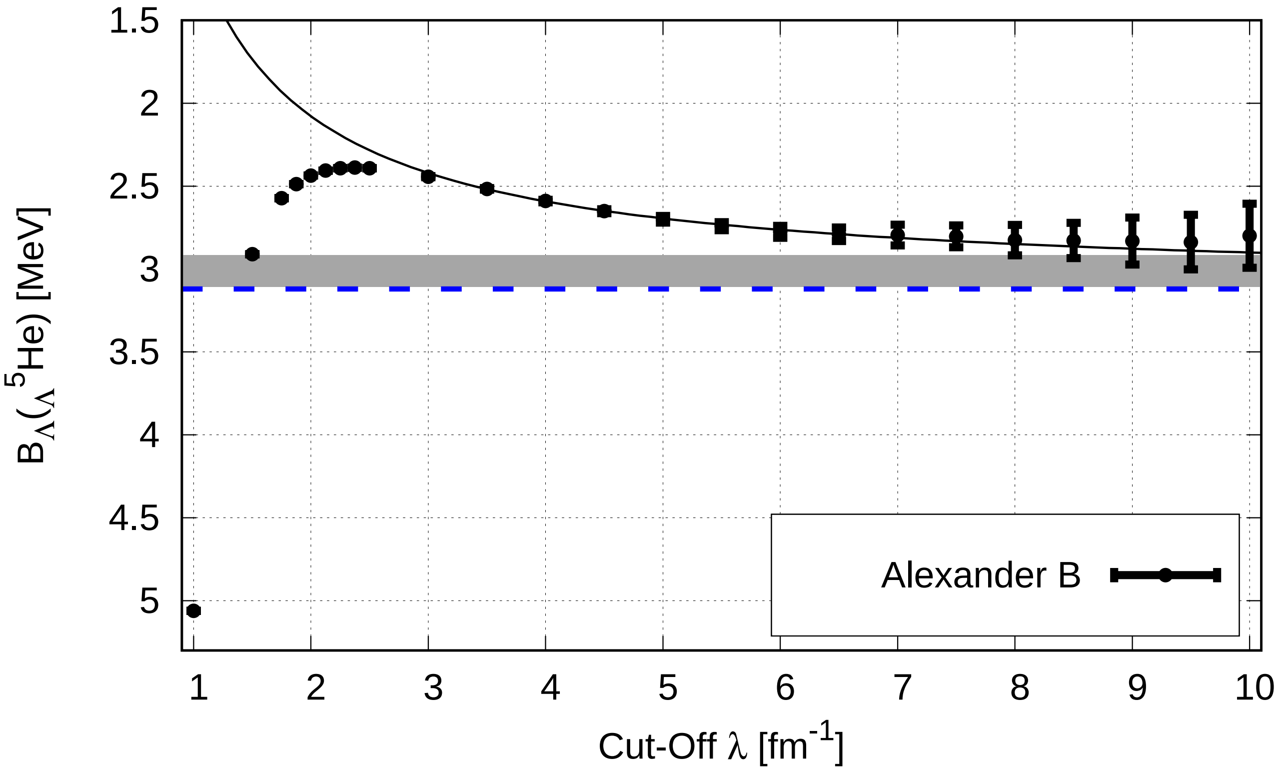
PLB 797 (2019) 134893



Nuclei: C_1, C_2 from NN scattering lengths, fit D_1 to B(^{3}H), then 'predict' B(^{4}He).

How to proceed in Λ & $\Lambda\Lambda$ hypernuclei?

s-shell Λ hypernuclei in $\not\pi$EFT



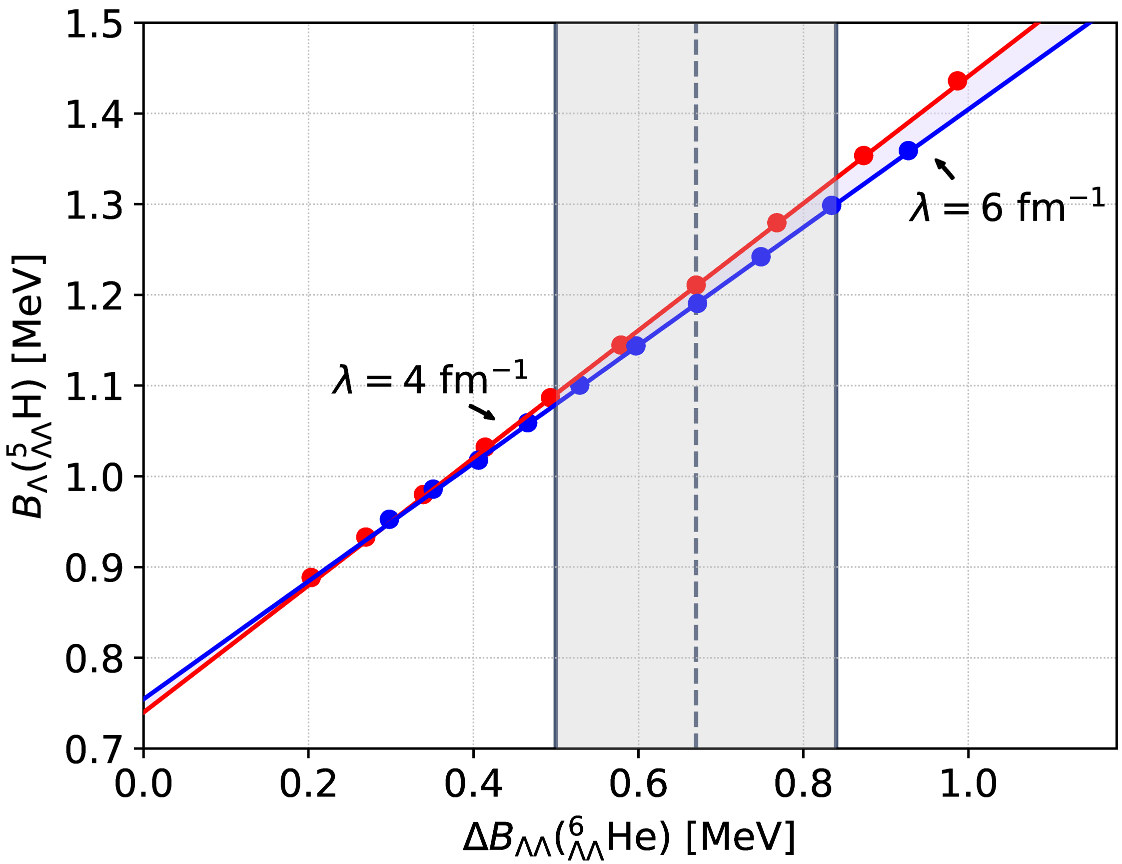
L.Contessi N.Barnea A.Gal, PRL 121 (2018) 102502

Fit 2 ΛN LECs to ΛN scattering lengths.

Fit 3 ΛNN LECs to the three known A=3,4 levels.

$B_\Lambda({}^5_\Lambda\text{He})$ vs. cut-off λ in LO $\not\pi$EFT SVM

Contessi et al. s-shell ΛΛ hyp. in $\not\pi$EFT

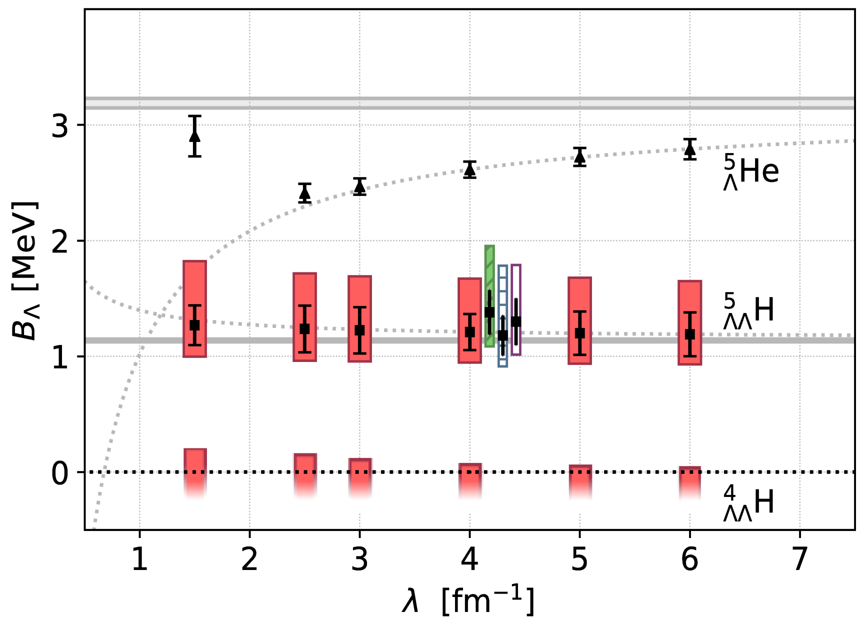


A Tjon-line correlation similar to that in FG 2002.

Weak dependence on the ΛΛ LEC related to $a_{\Lambda\Lambda}$.

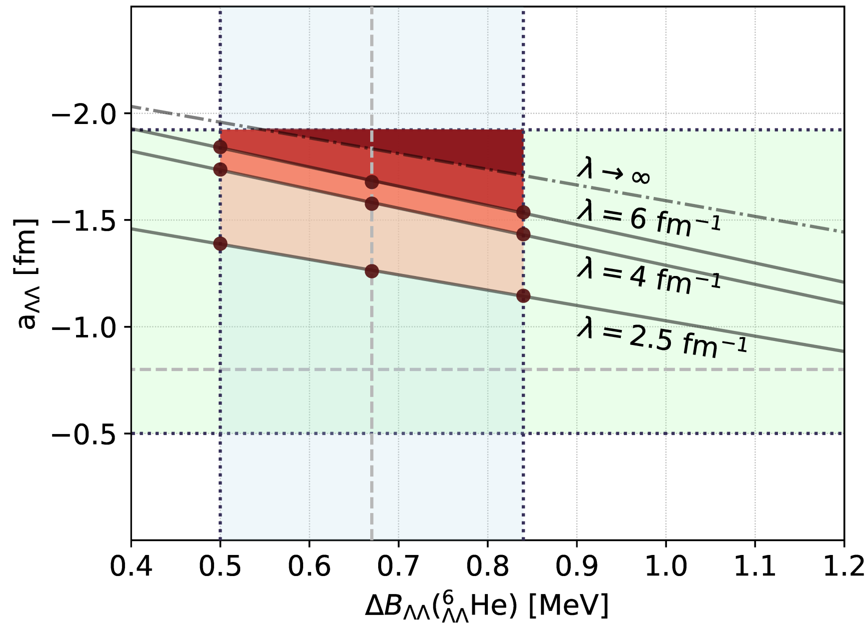
The ΛΛN LEC is fitted to $\Delta B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^{6}\mathrm{He})$

Recent $\not{\pi}$EFT $\Lambda\Lambda$ calculations



B_Λ vs. $\not{\pi}$EFT cutoff λ

$_{\Lambda\Lambda}{}^5$H bound, $_{\Lambda\Lambda}{}^4$H unlikely



minimum $|a_{\Lambda\Lambda}|$ to bind $_{\Lambda\Lambda}{}^4$H

is over 1.5 fm, too large!

- Contessi-Schafer-Barnea-Gal-Mareš, PLB 797 (2019) 134893.
- Neutral systems $\Lambda\Lambda$n & $\Lambda\Lambda$nn safely unbound.
- Argue that $\Lambda\Lambda$–ΞN coupling effect is minor.

Summary & Outlook

- ${}^{5}_{\Lambda}$**He overbinding problem resolved.**
- **Role of** ΛNN **forces in** ${}^{A}_{\Lambda}Z$ **& neutron stars?**
- ${}^{3}_{\Lambda}$**n (Λnn) is unbound.**
- **Onset of ΛΛ binding:** ${}_{\Lambda\Lambda}{}^{4}$**H or** ${}_{\Lambda\Lambda}{}^{5}$**Z? (E07, P75).**
- ${}_{\Lambda\Lambda}{}^{3}$**n (ΛΛn) and** ${}_{\Lambda\Lambda}{}^{4}$**n (ΛΛnn) are unbound.**
- **Shell model works well for g.s. beyond** ${}_{\Lambda\Lambda}{}^{6}$**He.**
- **Study excited states by slowing down** Ξ^- **from** $\bar{p}p \to \Xi^-\bar{\Xi}^+$ **in FAIR (PANDA).**

Thanks for your attention!