$A = 4 - 7 \; \Xi$ Hypernuclei Based on Interactions from Chiral EFT

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HL, J. Haidenbauer, U.-G. Meißner, A. Nogga
(arXiv:2109.06648 [nucl-th] (2021))

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Outline

- Introduction

  ‣ Baryon-Baryon interactions in chiral effective field theory (χEFT)

  ‣ Empirical constraints from S=-2 sector

- Numerical approach:

  ‣ Jacobi no-core shell model (J-NCSM) for S=-2

  ‣ Extrapolation of the results

- Results & discussion for $NNN\Xi$, $^{5}_{\Xi^-}H$, and $^{7}_{\Xi^-}H$

- Summary

Baryon-Baryon interactions in χEFT

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LO: H. Polinder et al., NPA 779 (2006). **NLO**: J. Haidenbauer et al., NPA 915 (2013)

- degrees of freedom: octet baryons $(N, \Lambda, \Sigma, \Xi)$, pseudoscalar mesons (π, K, η)
- based on Weinberg power counting as in the NN case

LO:

π, K, η

unresolved short-distance dynamics
is absorbed into contact terms (LECs)

NLO:
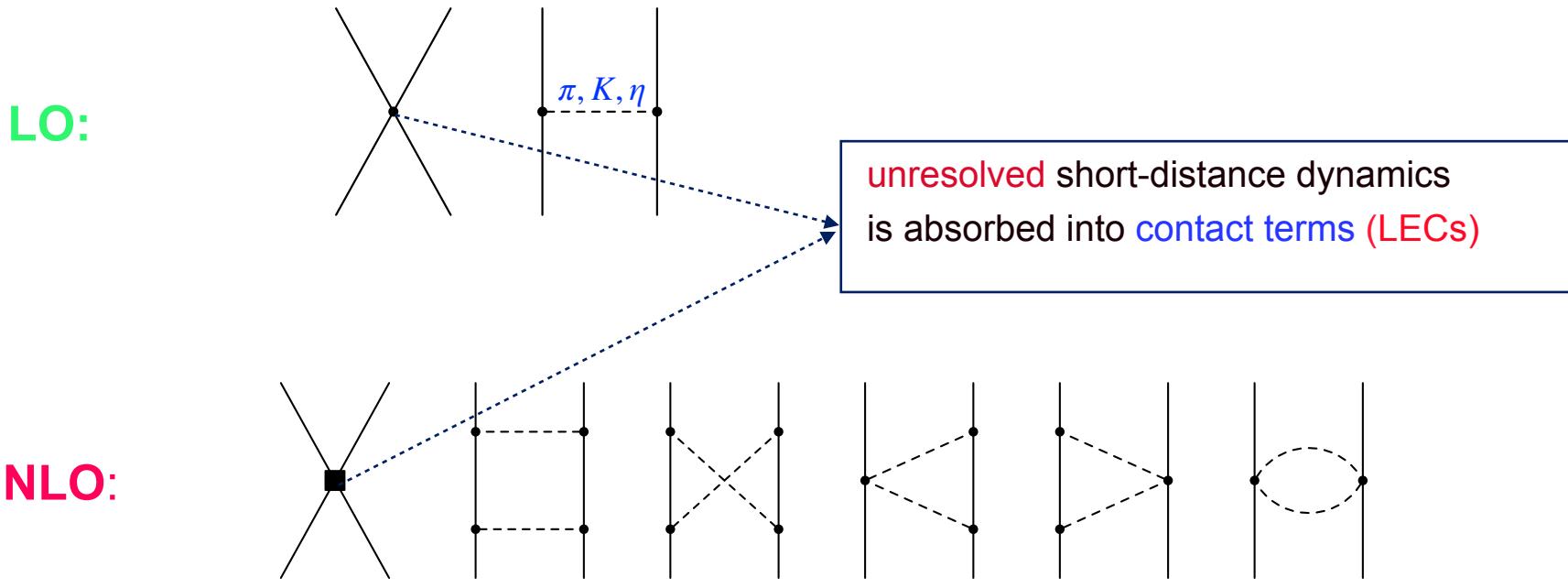
- exploit $SU(3)_f$ to fix BBM couplings and relate various LECs, allow $SU(3)_f$ breaking where it seems appropriate

→ number of contact terms:

NN:	2 (LO)	7 (NLO)
YN:	+ 3 (LO)	+ 11 (NLO)
YY:	+ 1 (LO)	+ 4 (NLO)

⇒ 28 LECs for S=-2 at NLO

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Constraints from S=-2 sector: ΞN

- some data/ limits for ΞN (in)elastic cross sections $(200 < P_\Xi < 800$ MeV/c)

$$\sigma_{\Xi^- p \to \Lambda\Lambda} = 4.3^{+6.3}_{-2.7} \text{ mb, \quad at } p_\Xi = 500 \text{ MeV/c}$$

(J.K. Ahn et al, PLB 633 (2006) 214)

$$\sigma_{\Xi^- p \to \Xi^- p} < 24 \text{ mb;} \qquad \sigma_{\Xi^- p \to \Lambda\Lambda} < 12 \text{ mb}$$

- in-medium inelastic cross section: $\sigma_{\Xi^- N} = 12.7^{+3.5}_{-3.1}$ mb $(400 < p_\Xi < 600$ MeV/c) (S. Aoki et al., NPA 644 (1998))

$\longrightarrow$ ΞN interaction can not be very strong

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- events support Ξ-bound states:

$\Xi^- - {}^{14}N({}^{15}_{\Xi^-}C):$ $B_\Xi = 3.87(1.03) \pm 0.21(0.18)$ MeV   (KISO)   K. Nakazawa et al., PTEP 033D02 (2015)

$\qquad\qquad\qquad = 4.96 \pm 0.77$ MeV   (KINKA)   M. Yoshimoto et al., PTEP 073D02 (2021)

$\qquad\qquad\qquad = 1.27 \pm 0.21$ MeV   (IBUKI)   S.H. Hayakawa et al., PRL 126 (2021)

$\qquad\qquad\qquad$ → Ξ^- is captured in nuclear 1p state   (see also E. Friedman, A. Gal PLB 820(2021)

$\qquad\qquad B_\Xi = 8.00 \pm 0.77$ (KINKA), 6.27 ± 0.27 (IRRAWADDY)   (M.Yoshimoto et al., PTEP (2021))

$\qquad\qquad\qquad$ → s-shell $\Xi-$ nuclear state

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${}^{12}C(K^-, K^+)^{12}_{\Xi^-}Be$:   T. Fukuda et al. PRC 58 (1998), P. Khaustov PRC 61 (2000)

$\longrightarrow$ Ξ single particle potential $U_\Xi \approx -14$ MeV $(U_\Lambda \approx -30$ MeV$)$

T. Nagae et al., PoS (INPC2016) 038, AIP Conf. Proc 2130 (2019), $B_\Xi \approx 9$ MeV (and 2 MeV)

Constraints from S=-2 sector: $\Lambda\Lambda$

- $\Lambda\Lambda$ hypernuclei: $^{6}_{\Lambda\Lambda}$He (Nagara), $^{10}_{\Lambda\Lambda}$Be (Demachi-Yanagi), $^{11}_{\Lambda\Lambda}$Be (Hida)

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda}(^{6}_{\Lambda\Lambda}\text{He}) - 2B_{\Lambda}(^{5}_{\Lambda}\text{He}) = 1.01 \pm 0.2 \,\text{MeV}$$

(H. Takahashi et al., PRL 87 (2001)

$$= 0.67 \pm 0.17 \,\text{MeV}$$

(K. Nakazawa et al., NPA 835 (2010))

$\longrightarrow \quad -1.32 < a_{\Lambda\Lambda} < -0.73 \,\text{fm}$ $\qquad ^{6}_{\Lambda\Lambda}$He calculations based on 2001 value (Filikhin, Fujiwara, Rijken, …)

$a_{\Lambda\Lambda} = -1.2 \pm 0.6 \,\text{fm}$ $\qquad$ deduced from $\Lambda\Lambda$ invariant mass spectrum of $^{12}C(K^-, K^+)\Lambda\Lambda$

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YY interaction at NLO J. Haidenbauer et al., NPA 954 (2016) 273, EPJA 55 (2019) 23

- exploit $SU(3)_f$ symmetry to relate LECs in S=-2 sector to LECs in S=-1,0 sectors

⟶ 5 unknown LECs (2 in s-wave, 3 in p-wave) at NLO

	$a_{\Lambda\Lambda}$	$a_{\Xi^0 n}(^1S_0)$	$U_{\Xi}(p_{=0})$
NLO(500)	-0.62	-1.30 - i0.07	-5.5
NLO(550)	-0.61	-2.05 - i0.27	-3.8
NLO(600)	-0.66	-1.95 - i0.25	-4.3
NLO(650)	-0.70	-1.41 - i0.09	-4.1
HAL QCD*	-0.78(0.22)	-2.07(0.39) - i0.14(0.06)	-4(2)

(* Y. Kamiya et al., arXiv:2108.09644

T. Inoue, AIP Conf. Proc. 2130(2019))

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- study $^{6}_{\Lambda\Lambda}$He, $^{5}_{\Lambda\Lambda}$He and $^{4}_{\Lambda\Lambda}$H using LO and NLO

(HL et al., EPJA 57 (2021) 217)

→ $^{6}_{\Lambda\Lambda}$He is fairly well described with NLO; $^{5}_{\Lambda\Lambda}$He is predicted to be bound

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- Kohno et al., use Ξ s.p. potential obtained with NLO to study finite systems: $\Xi^- - ^{14}N$, $\Xi^- - ^{12}C$

(M. Kohno PRC 100 (2019), M. Kohno, K. Miyagawa., arXiv:2107.03784)

→ reasonable agreement with experiment can be obtained

Possible lightest Ξ hypernucleus?

variational Gaussian expansion method using ESC08c and HAL QCD

E. Hiyama et al., PRL 124 (2020) 092501

- $\Xi N - \Lambda\Sigma - \Sigma\Sigma$, $\Lambda\Lambda - \Xi N$ coupling effects are renormalized into $V_{\Xi N - \Xi N}$

→ - Nijmegen ESC08c leads to $NN\Xi(J^\pi, T) = (3/2^+, 1/2)$; $NNN\Xi(1^+, 0), (0^+, 1)(1^+, 1)$ bound states

- HAL QCD predicts a loosely bound $(1^+, 0)$ state in $NNN\Xi$

Faddeev equation for $NN\Xi$ with modern ΞN potentials

K. Miyagawa and M. Kohno FBS 65 (2021)

- original ΞN potentials are employed to obtain $T_{\Xi N, \Xi N}$

→ - no bound states are obtained with chiral NLO or HAL QCD

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## Faddeev equation for $NN\Xi$ with modern ΞN potentials

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Our aim:

- **study predictions of chiral interactions for $A = 4 - 7$ Ξ systems using Jacobi NCSM**
  - ▸ input Hamiltonian: chiral NN ($N^4LO^+(450)$) and S=-2 NLO potentials
  - ▸ $\Xi N - \Lambda\Sigma - \Sigma\Sigma$ transition in S=-2 is explicitly considered
  - ▸ $\Lambda\Lambda - \Xi N (^{11}S_0)$ coupling is effectively incorporated by re-adjusting the strength of $V_{\Xi N - \Xi N}$

NLO(500)

ΞN phase shifts predicted by modern interactions

NLO(500) & HAL QCD*

(* E. Hiyama et al. PRL 124, 092501 (2020))

Nijmegen ESC08c*
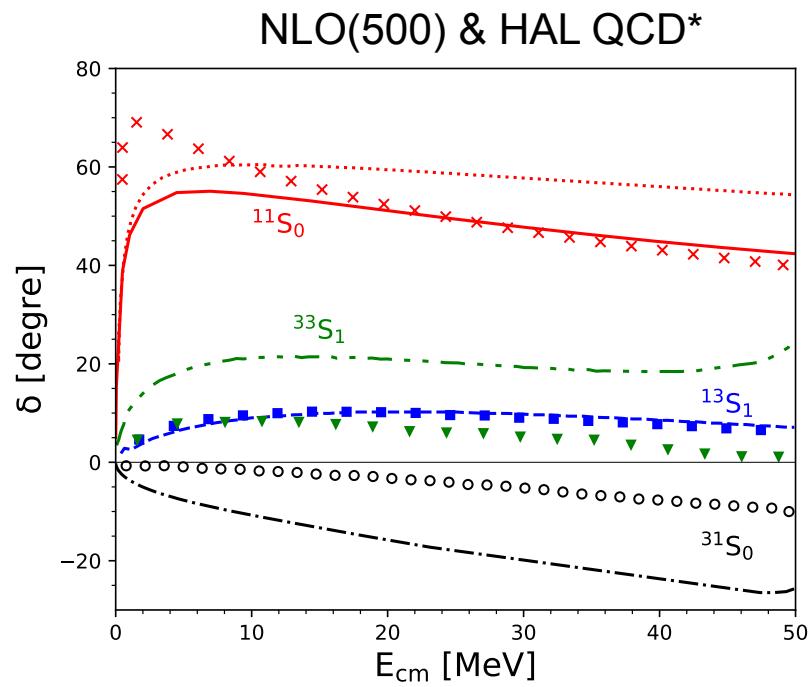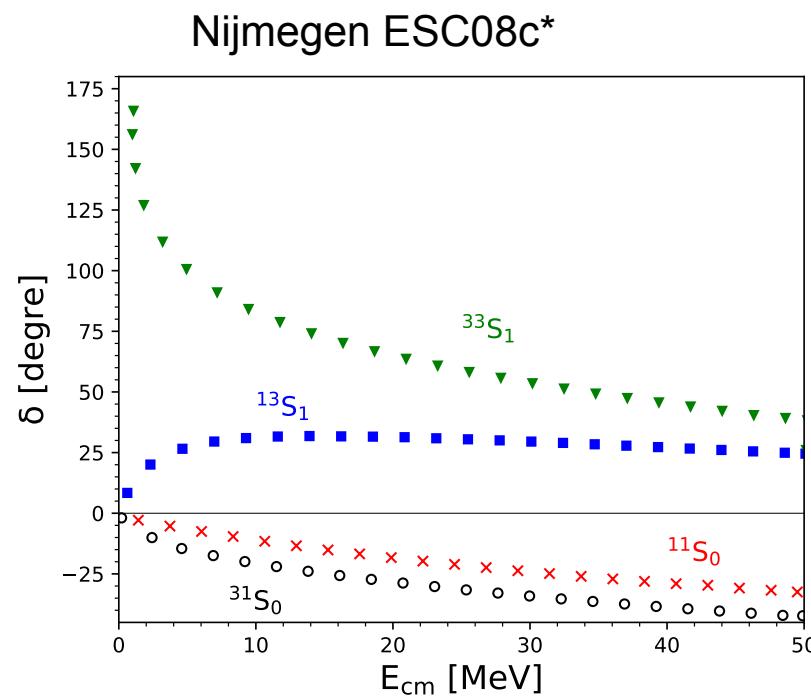
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- $^{11}S_0$ is rather attractive in NLO and HAL QCD, but repulsive in ESC08c

- $^{33}S_1$ is strongly attractive in ESC08c (lead to a ΞN bound state),
  it is only moderately (weakly) attractive in NLO (HAL QCD)

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6

Jacobi No-Core Shell Model (J-NCSM)

- an expansion of the wavefunction in a many-body HO basis depending on Jacobi coordinates

$$\mathbf{p}_{12} = \frac{m_2}{m_1 + m_2}\mathbf{k}_1 - \frac{m_1}{m_1 + m_2}\mathbf{k}_2$$

$$\mathbf{p}_3 = \frac{m_2 + m_1}{m_1 + m_2 + m_3}\mathbf{k}_3 - \frac{m_3}{m_1 + m_2 + m_3}(\mathbf{k}_2 + \mathbf{k}_2)$$

$$\vdots$$

$$\mathbf{p}_A = \frac{\sum_{i=1}^{A-1} m_i}{\sum_{i=1}^{A} m_i}\mathbf{k}_A - \frac{m_A}{\sum_{i=1}^{A} m_i}\sum_{i=1}^{A-1}\mathbf{k}_i$$
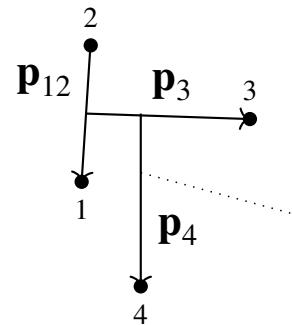
- ▸ explicit removal of c.m. motion

- ▸ all particles are active (no inert core) ⟶ employ microscopic BB interactions

- ▸ converge slowly ⟶ require soft interactions (use techniques e.g., Vlow_k, SRG)

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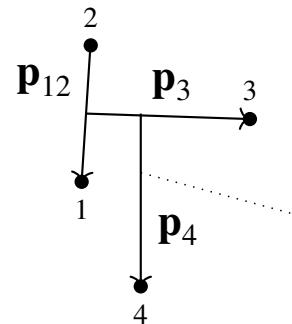
- ▸ explicit removal of c.m. motion
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- basis functions are split into two orthogonal sets:

$$\left| \genfrac{}{}{0pt}{}{Y_1}{Y_2}{\bullet}{\bigcirc} \right\rangle = |\,\mathcal{N}JT, \alpha_{A-2}\, \underbrace{\alpha_{Y_1Y_2}}_{|\Lambda\Sigma\rangle,|\Sigma\Sigma\rangle}\, n_\lambda\lambda; ((l_{Y_1Y_2}S_{Y_1Y_2})J_{Y_1Y_2}(\lambda J_{A-2})I_\lambda)J, ((t_{Y_1}t_{Y_2})T_{Y_1Y_2}T_{A-2})T\,\rangle \equiv |\,\alpha^{*(Y_1Y_2)}\rangle \qquad (\textit{JJ}\text{-coupling})$$

$$\left| \bigcirc\!\!-\!\!\overset{\Xi}{\bullet} \right\rangle = |\,\mathcal{N}JT, \alpha_{A-1}\, n_\Xi\, l_\Xi\, t_\Xi; (J_{A-1}(l_\Xi s)I_\Xi)J, (T_{A-1}t_\Xi)T\,\rangle \equiv |\,\alpha^{*(\Xi)}\rangle$$

⇒ hypernuclear wavefunction

$$|\Psi(\pi, J, T)\rangle = \sum_{\alpha^{*(Y_1Y_2)}} C_{\alpha^{*(Y_1Y_2)}} |\,\alpha^{*(Y_1Y_2)}(\mathcal{N}JT)\rangle + \sum_{\alpha^{*(\Xi)}} C_{\alpha^{*(\Xi)}} |\,\alpha^{*(\Xi)}(\mathcal{N}JT)\rangle$$

- basis truncation:

$$\mathcal{N} = \mathcal{N}_{A-2} + N_{Y_1Y_2} + 2n_\lambda + \lambda = \mathcal{N}_{A-1} + 2n_\Xi + \lambda_\Xi \leq \mathcal{N}_{max} \Rightarrow E_b = E_b(\omega, \mathcal{N}_{max})$$

⟶ require $\mathcal{N}_{max} \to \infty$ extrapolation

- extract converged binding energy

$$\mathscr{N} = \mathscr{N}_{A-2} + N_{Y_1Y_2} + 2n_\lambda + \lambda = \mathscr{N}_{A-1} + 2n_\Xi + \lambda_\Xi \le \mathscr{N}_{max} \quad \Rightarrow E_b = E_b(\omega, \mathscr{N}_{max})$$

$$E_b(\omega, \mathscr{N}) = E_{\mathscr{N}} + \kappa(\log(\omega) - \log(\omega_{opt}))^2$$

$$E_{\mathscr{N}} = E_\infty + Ae^{-b\mathscr{N}}$$

$E_{\mathscr{N}+2} - E_{\mathscr{N}}$

$E_{\mathscr{N}}$

$\delta E = E_\infty - E_{\mathscr{N}_{max}}$

(a) $E_{\mathscr{N}}(^4_\Xi \mathrm{H}(1^+,0))$ as a function of ω.

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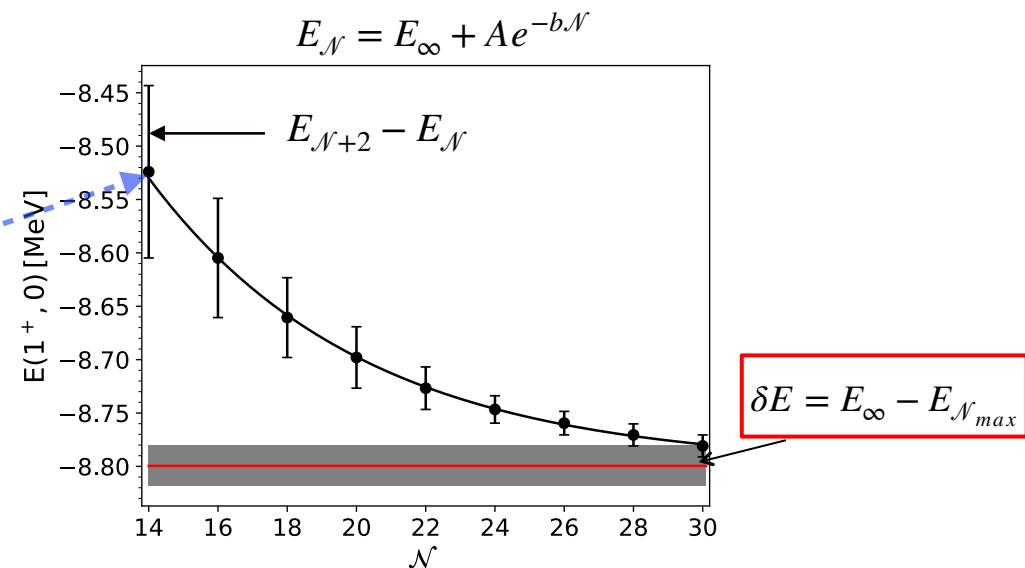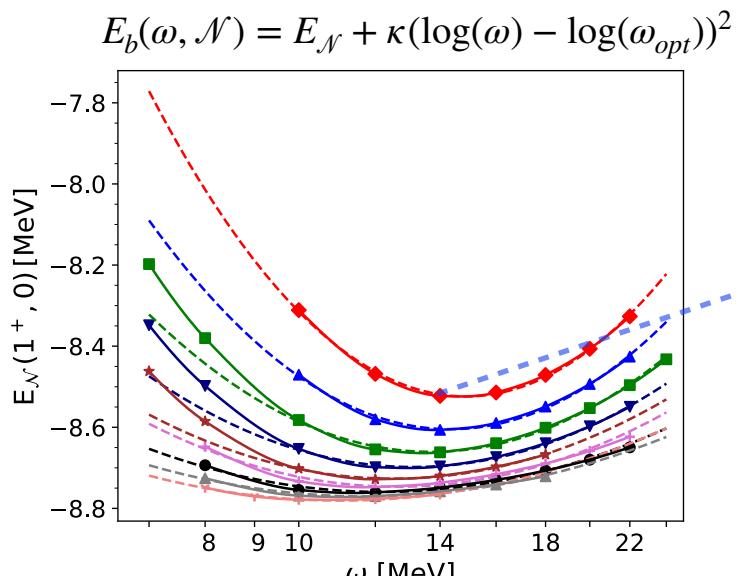
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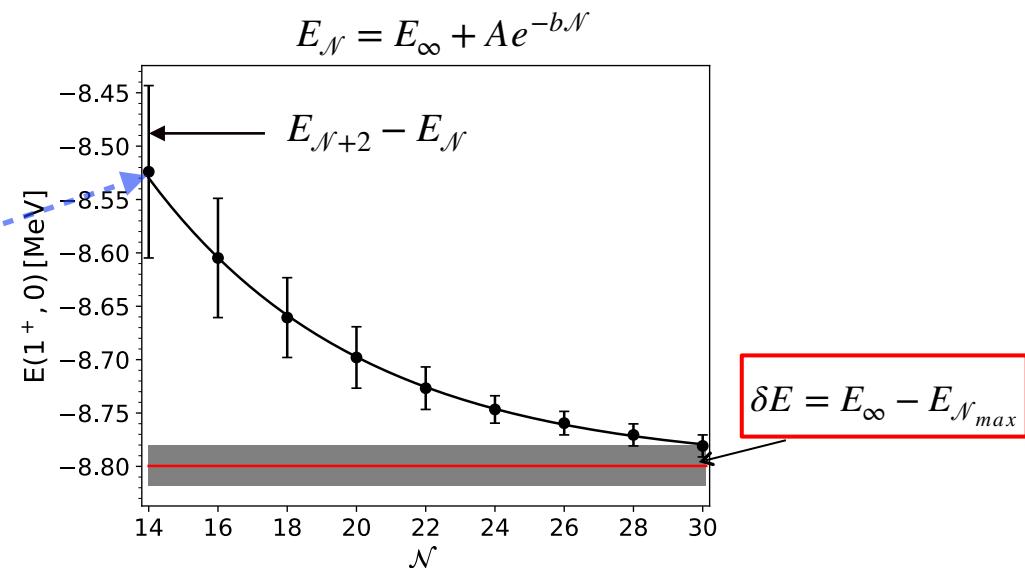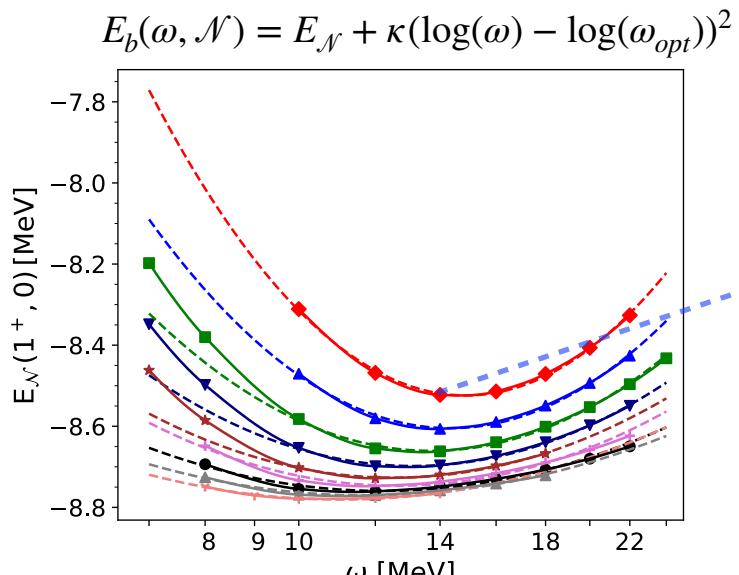
- extract converged separation energy B_Ξ:

$$B_{\Xi,\mathcal{N}} = E_{\mathcal{N}}(^3H) - E_{\mathcal{N}}(^4_\Xi H), \quad \mathcal{N} = 14, \cdots, 30$$

- $\mathcal{N}_{max}(^5_\Xi H) = 16, \quad \mathcal{N}_{max}(^7_\Xi H) = 12$
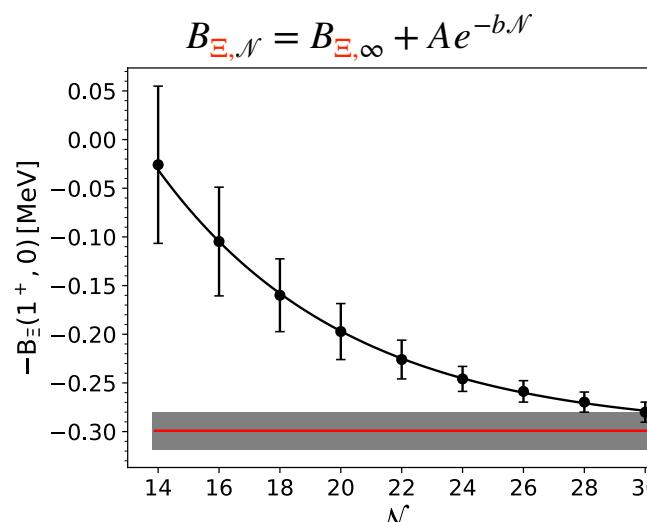
$$B_{\Xi,\mathcal{N}} = B_{\Xi,\infty} + Ae^{-b\mathcal{N}}$$

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Dependence of energies on SRG

- apply SRG evolution to $N^4LO^+(450)$ and S=-2 NLO(500) to speed up convergence:

$$\lambda_{NN} = 1.6\,\text{fm}^{-1}, \quad 1.4 \leq \lambda_{YY} \leq 3.0\,\text{fm}^{-1}$$

    → estimate effect of SRG-induced 3-body forces

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$^4_\Xi\text{H}(1^+,0)$
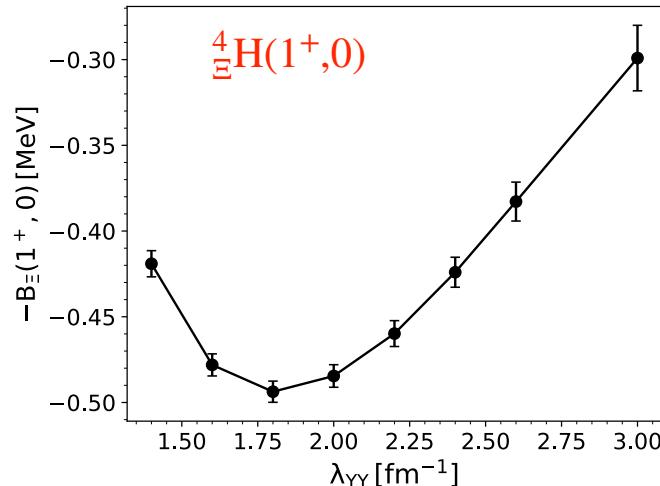
	ΔB^{SRG}_{Ξ} [keV]	$\Delta B^{SRG}_{\Lambda\Lambda}$ [keV]	ΔB^{SRG}_{Λ} [keV]
A=4	190 ± 30	-	740 ± 2
A=5	460 ± 140	80 ± 40	1501 ± 20
A=6	-	100 ± 17	-

- effect of SRG evolution on B_Ξ is moderately large, however, $\Delta B^{SRG}_\Xi \ll B_\Xi$

→ SRG dependence will not affect conclusions on the existence of bound states
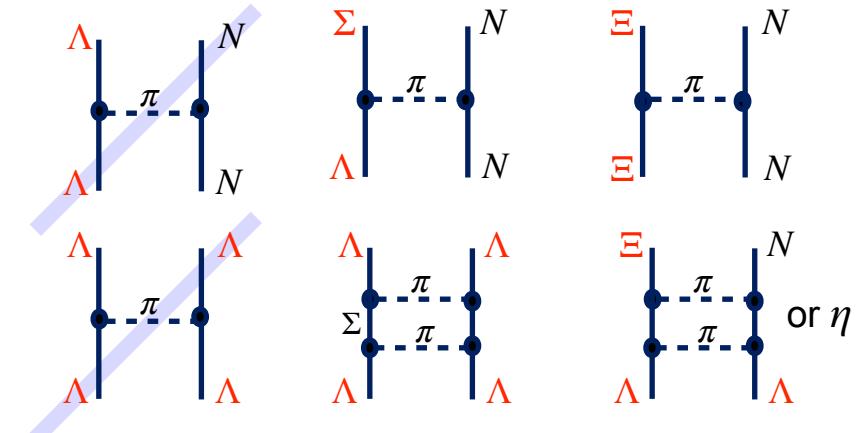
suppressed by isospin symmetry

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Results for $NNN\Xi,\ {}^{5}_{\Xi^-}\text{H}(1/2^+,1/2),\ {}^{7}_{\Xi^-}\text{H}(1/2^+,3/2)$

- $\lambda_{NN} = \lambda_{YY} = 1.6\ \text{fm}^{-1}$

- neglect mass difference between Ξ^- and Ξ^0: $m_\Xi = (m_{\Xi^-} + m_{\Xi^0})/2$

- assume isospin symmetry, states are labelled by the isospin T (and mT)

Results for A=4-7

	NLO(500)		others	
	B_Ξ [MeV]	Γ [MeV]	B_Ξ [MeV]	Γ [MeV]
$^4_\Xi\mathrm{H}(1^+,0)$	0.48 ± 0.01	0.74	$0.36(16)(26)^{(1)}$	$0.06^{(1)}$
			$10.20^{(2)}$	$0.89^{(2)}$
$^4_\Xi\mathrm{n}(0^+,1)$	0.71 ± 0.08	0.2	$3.55^{(2)}$	$0.43^{(2)}$
$^4_\Xi\mathrm{n}(1^+,1)$	0.64 ± 0.11	0.01	$10.11^{(2)}$	$0.03^{(2)}$
$^4_\Xi\mathrm{H}(0^+,0)$	-	-	-	-
$^5_\Xi\mathrm{H}(\frac{1}{2}^+,\frac{1}{2})$	2.16 ± 0.10	0.19	$1.7^{(3)}$	$0.2^{(3)}$
			$2.0^{(4)}$	$0.45^{(4)}$
$^7_\Xi\mathrm{H}(\frac{1}{2}^+,\frac{3}{2})$	3.50 ± 0.39	0.2	$3.15^{(5)}$	$0.02^{(5)}$
			$1.8^{(6)}$	$2.64^{(6)}$

(1) HAL QCD (t/a=12)

(2) Nijmegen ESC08c

    E.Hiyama et al., PRL 124 (2020)

(3) K. Myint, Y. Akaishi PTPS 117 (1994)

(4) E. Friedman, A. Gal PLB 820(2021)

(5) HAL QCD (t/a=11)

(6) Nijmegen ESC04d

    H. Fujioko APFB2021, March (2021)

$$\Gamma \simeq -2\,\mathrm{Im}\,\langle \Psi_{B_\Xi} | T_{\Xi N - \Xi N} | \Psi_{B_\Xi} \rangle$$

- $\Xi^- p$ Coulomb interaction contributes roughly 200, 600 and 400 keV to $NNN\Xi$, $^5_\Xi\mathrm{H}$ and $^7_\Xi\mathrm{H}$

	$\langle V^{S=-2} \rangle$ [MeV]					E [MeV]
	$^{11}S_0$	$^{31}S_0$	$^{13}S_1$	$^{33}S_1$	total	
$^4_\Xi$H$(1^+,0)$	-1.95	0.02	-0.7	-2.31	-5.21	-8.97
$^4_\Xi$n$(0^+,1)$	-0.6	0.25	-0.004	-0.74	-1.37	-9.07
$^4_\Xi$n$(1^+,1)$	-0.02	0.16	-0.13	-1.14	-1.30	-9.0
$^4_\Xi$H$(0^+,0)$	-0.002	0.08	-0.01	-0.006	-0.11	-6.94
$^5_\Xi$H$(1/2^+,1/2)$	-0.96	0.94	-0.58	-3.63	-4.88	-31.43
$^7_\Xi$H$(1/2^+,3/2)$	-1.23	1.79	-0.79	-6.74	-8.04	-33.22
$U_\Xi(p_\Xi = 0)^*$	-3.15	9.64	-3.24	-11	-8.8	

* M. Kohno PRC 100(2019) (based on NLO(550))

→ the attraction in $^{33}S_1$ is essential for the binding of A=4-7 Ξ-hypernuclei

Results for A=4-7

	$|\Xi N\rangle$					
	$|^{11}S_0\rangle$	$|^{31}S_0\rangle$	$|^{13}S_1\rangle$	$|^{33}S_1\rangle$	$J \geq 2$	total
$^4_\Xi\mathrm{H}(1^+,0)$	12.88	0.18	25.91	35.72	24.80	99.49
$^4_\Xi\mathrm{n}(0^+,1)$	8.24	13.32	0.23	23.29	54.73	99.81
$^4_\Xi\mathrm{n}(1^+,1)$	0.14	9.22	9.83	33.08	47.56	99.83
$^4_\Xi\mathrm{H}(0^+,0)$	0.02	11.87	14.65	0.11	73.33	99.98
$^5_\Xi\mathrm{H}(1/2^+,1/2)$	4.82	12.18	14.37	35.53	32.59	99.49
$^7_\Xi\mathrm{H}(1/2^+,3/2)$	3.71	12.92	11.11	38.36	32.94	99.04

Probabilities (%) of finding a pair $|\Xi N\rangle$ in different partial-wave states

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- **Assumption:**
  - ‣ no particle conversion contributing
  - ‣ clear core-Ξ structure, both core nucleons and Ξ are in s-wave states

- **A=3 system:**

$$_{\Xi}^{3}H(\tfrac{1}{2}^{+}, \tfrac{1}{2}) : \quad \tilde{V}_{\Xi N} \approx \frac{3}{16}V_{\Xi N}^{11S_0} + \frac{9}{16}V_{\Xi N}^{31S_0} + \frac{1}{16}V_{\Xi N}^{13S_1} + \frac{3}{16}V_{\Xi N}^{33S_1}$$

$$_{\Xi}^{3}H(\tfrac{3}{2}^{+}, \tfrac{1}{2}) : \quad \tilde{V}_{\Xi N} \approx \frac{1}{4}V_{\Xi N}^{13S_1} + \frac{3}{4}V_{\Xi N}^{33S_1}$$

- **A=4 system:**

$$_{\Xi}^{4}H(1^{+},0) : \quad \tilde{V}_{\Xi N} \approx \frac{1}{6}V_{\Xi N}^{11S_0} + \frac{1}{3}V_{\Xi N}^{13S_1} + \frac{1}{2}V_{\Xi N}^{33S_1}$$

$$_{\Xi}^{4}H(0^{+},1) : \quad \tilde{V}_{\Xi N} \approx \frac{1}{6}V_{\Xi N}^{11S_0} + \frac{1}{3}V_{\Xi N}^{31S_0} + \frac{1}{2}V_{\Xi N}^{33S_1}$$

$$_{\Xi}^{4}H(1^{+},1) : \quad \tilde{V}_{\Xi N} \approx \frac{1}{6}V_{\Xi N}^{31S_0} + \frac{1}{6}V_{\Xi N}^{13S_1} + \frac{2}{3}V_{\Xi N}^{33S_1}$$

$$_{\Xi}^{4}H(0^{+},0) : \quad \tilde{V}_{\Xi N} \approx \frac{1}{2}V_{\Xi N}^{31S_0} + \frac{1}{2}V_{\Xi N}^{13S_1}$$

- **A=5 system:**

$$_{\Xi}^{5}H(\tfrac{1}{2}^{+}, \tfrac{1}{2}) : \quad \tilde{V}_{\Xi N} \approx \frac{1}{16}V_{\Xi N}^{11S_0} + \frac{3}{16}V_{\Xi N}^{31S_0} + \frac{3}{16}V_{\Xi N}^{13S_1} + \frac{9}{16}V_{\Xi N}^{33S_1}$$

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Estimate partial-wave contributions

- **Assumption:**
  - ‣ no particle conversion contributing
  - ‣ clear core-Ξ structure, both core nucleons and Ξ are in s-wave states

$(J_{core}, T_{core}, m_\Xi^t)$	$^4_\Xi H(1^+, 0)$	$^4_\Xi n(0^+, 1)$	$^4_\Xi n(1^+, 1)$	$^4_\Xi H(0^+, 0)$
$(\frac{1}{2}, \frac{1}{2}, -\frac{1}{2})$	49.66	97.48	97.44	49.98
$(\frac{1}{2}, \frac{1}{2}, \frac{1}{2})$	49.66	–	–	49.98
$(\frac{1}{2}, \frac{3}{2}, \frac{1}{2})$	–	0.54	0.55	–
$(\frac{1}{2}, \frac{3}{2}, -\frac{1}{2})$	–	1.6	1.6	–
others	0.16	0.17	0.22	0.02

$(J_{core}, T_{core}, m_\Xi^t)$	$^5_\Xi H(\frac{1}{2}^+, \frac{1}{2})$
$(0, 0, -\frac{1}{2})$	96.03
$(0, 0, \frac{1}{2})$	1.1
$(0, 1, \frac{1}{2})$	2.1
others	0.3

$(J_{core}, T_{core}, m_\Xi^t)$	$^7_\Xi H(\frac{1}{2}^+, \frac{3}{2})$
$(0, 1, -\frac{1}{2})$	94.44
$(0, 2, -\frac{1}{2})$	0.7
$(0, 2, \frac{1}{2})$	2.8
others	1.13

Probabilities (%) of finding nucleons with certain (J_{core}, T_{core}) and a Ξ (m_Ξ^t) in the A=4-7 wavefunctions

Summary

we studied A=4-7 Ξ hypernuclei using J-NCSM and NLO(500) ΞN potential

- $\Lambda\Sigma - \Xi N - \Sigma\Sigma$ conversions is fully included; $\Lambda\Lambda - \Xi N$ coupling is incorporated into the strength of $V_{\Xi N - \Xi N}$

- effect of SRG evolution on B_Ξ is moderate, larger than in $\Lambda\Lambda$ systems but much smaller than in Λ hypernuclei

- found 3 loosely bound states $(1^+, 0)$, $(0^+, 1)$, $(1^+, 1)$ in $NNN\Xi$
  $^5_\Xi\text{H}(1/2^+, 1/2)$, $^7_\Xi\text{H}(1/2^+, 3/2)$ are more tightly bound

  ‣ these bindings are predominantly due to the attraction of ΞN potential in $^{33}S_1$ channel
  ‣ all bound states are predicted to have very small decay widths

future works: study dependence of B_Ξ on chiral cutoff. Include SRG-induced 3BF

experimental confirmation?

- $NNN\Xi$ could be produced in heavy ion collisions or in $^4\text{He}(K^-, K^+)$ reaction
- $^7_\Xi\text{H}$ is expected to be produced and studied in $^7\text{Li}(K^-, K^+)$ reaction at J-PARC **(H. Fujioka et al., FBS 69(2021))**

- production of $^5_\Xi\text{H}$?
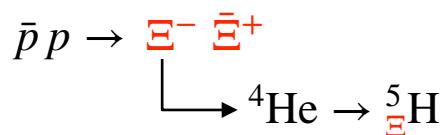
  $\bar{p}\, p \rightarrow \Xi^- \bar{\Xi}^+$ PANDA **(J.I. Pütz PhD Thesis (2020))**
  $\quad\quad\quad\quad \llcorner\!\rightarrow {}^4\text{He} \rightarrow {}^5_\Xi\text{H}$

  $\rightarrow \bar{\Xi}^+ \Xi^*(1530)$, then $\Xi^*(1530) \rightarrow \Xi^- + \pi^+$
  $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \llcorner\!\rightarrow {}^4\text{He} \rightarrow {}^5_\Xi\text{H}$

Thank you!