S-shell Λ & $\Lambda\Lambda$ hypernuclei based on chiral interactions

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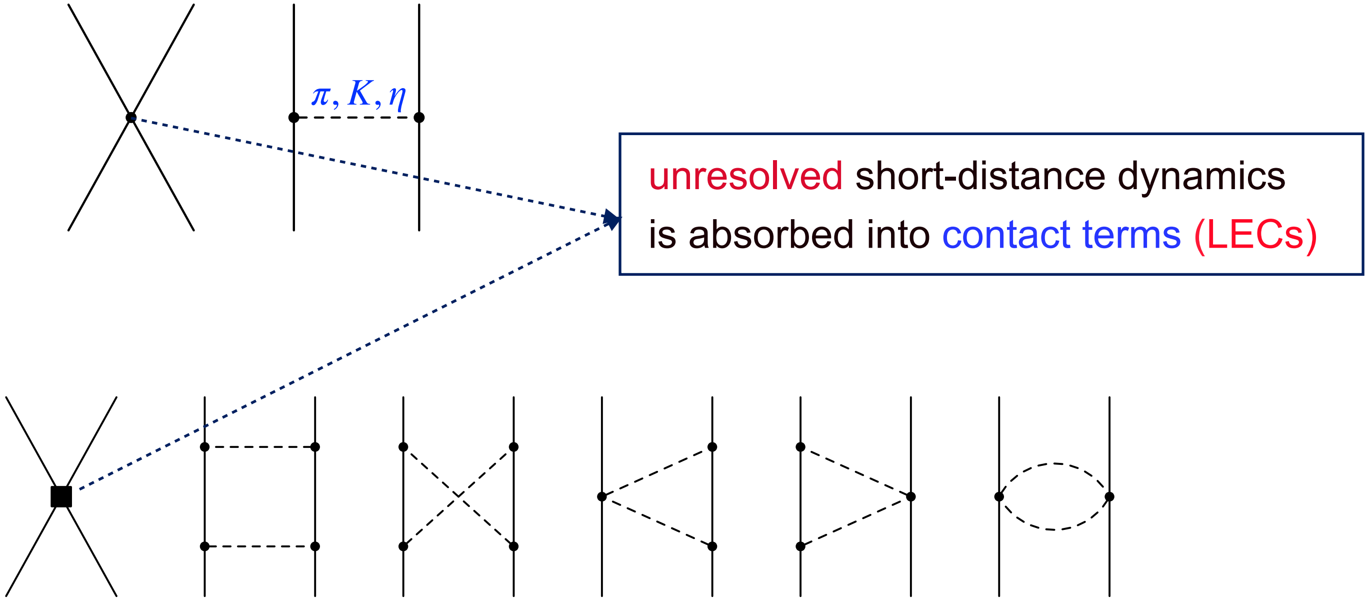
Baryon-Baryon interactions in χEFT

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:

NLO:



- LECs are determined via a fit to experimental data:
  - NN: > 5000 data + deuteron ⟶ sophisticated NN potentials up to $\mathrm{N^4LO+}$
    (P. Reinert et al. EPJA 54 (2018), D. R. Entem et al PRC 68 (2003))
  - YN: ~ 37 data, no two-body YN bound state
  - YY: no direct YY scattering data, no YY bound state

  } ⟶ YN and YY potentials up to NLO

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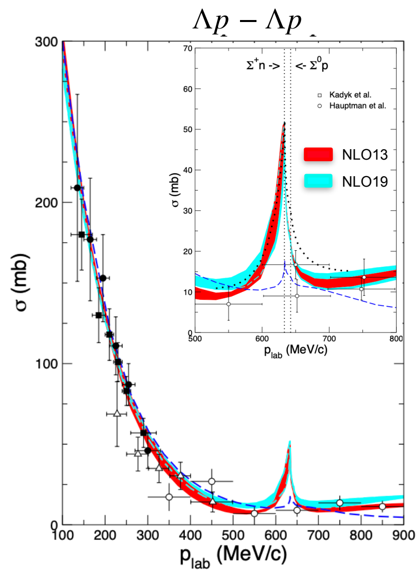
YN interactions at NLO

NLO13: J. Haidenbauer et al., NPA 915 (2013), NLO19: EPJ A 56 (2019) 91

- two realisations at NLO: NLO13 and NLO19
  - almost phase equivalent
  - NLO13 leads to a larger transition potential $\underbrace{\text{larger transition potential } V_{\Lambda N-\Sigma N}}_{\text{not an observable}}$

→ NLO13 and NLO19 as a tool to estimate effect of YNN forces

(Haidenbauer EPJA (2019))



$\Lambda_{YN} = 500,..,650$ MeV

→ estimate theoretical uncertainty

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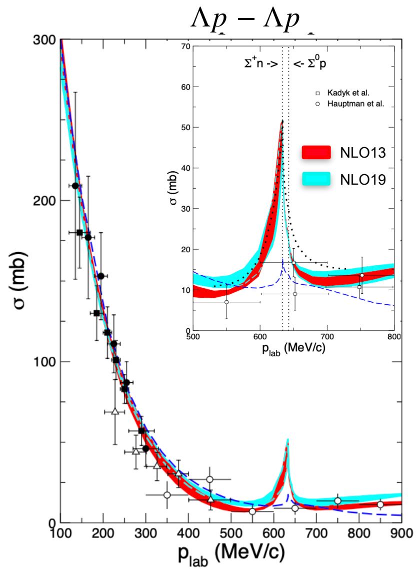

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YY interactions up to NLO

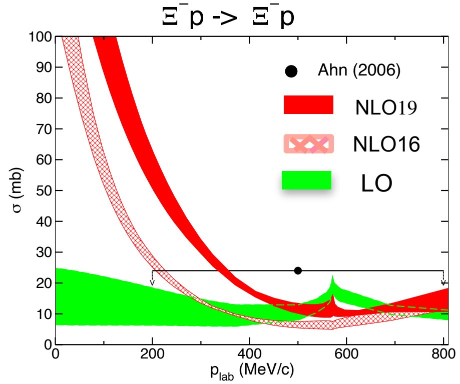
NLO: J. Haidenbauer et al., NPA 954 (2016) 273, EPJA 55 (2019) 23
LO: H. Polinder et al., PLB 653 (2007) 29.

- some data for ΞN (in)elastic cross sections $(200 < P_\Xi < 800$ MeV/c)
- $\Lambda\Lambda$ hypernuclei: $^{6}_{\Lambda\Lambda}$He (Nagara), $^{10}_{\Lambda\Lambda}$Be, $^{11}_{\Lambda\Lambda}$Be

$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda}(^{6}_{\Lambda\Lambda}\text{He}) - 2B_\Lambda(^{5}_{\Lambda}\text{He}) = 0.67 \pm 0.17$ MeV (K. Nakazawa NPA 835 (2010))

→ use $SU(3)_f$ to relate LECs in S=-2 sector to LECs in S=-1 sector

→ additional constraints on YN, YY interactions are expected from studying $\Lambda, \Lambda\Lambda$ hypernuclei



(Haidenbauer (2019))

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Our aim:

- develop Jacobi NCSM for S=-1,-2 hypernuclei
  - based on realistic chiral NN, YN and YY interactions
  - $\Lambda N - \Sigma N$, $YY - \Xi N$ conversions are explicitly taken into account

→ study predictions of chiral YN and YY potentials for A=4-7 Λ, $\Lambda\Lambda$ hypernuclei

→ provide useful constraints to improve YY, YN interactions

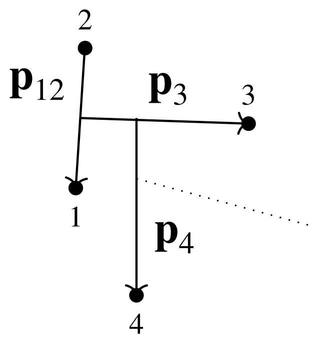
Jacobi no-core shell model (J-NCSM)

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

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

$$\mathbf{p}_3 = \frac{m_1 + m_2}{m_1 + m_2 + m_3}\mathbf{k}_3 - \frac{m_3}{m_1 + m_2 + m_3}(\mathbf{k}_1 + \mathbf{k}_2)$$

$$\ldots$$



  - explicit removal of c.m. motion
  - antisymmetrization of basis states is demanding $(A \leq 9)$

- all particles are active (no inert core) → employ microscopic BB interactions
- converge slowly → require soft interactions (use techniques like, e.g., Vlow_k, SRG)

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Similarity Renormalization Group (SRG)

- BB interactions contain short-range and tensor correlations that couple low- and high-momentum states → NCSM calculations converge slowly

- pre-diagonalize the Hamiltonian via SRG

  F.J. Wegner NPB 90 (2000). S.K. Bogner et al., PRC 75 (2007)

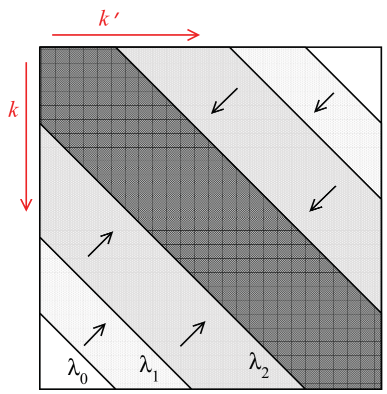
$$\frac{dV_s}{ds} = \left[\left[\sum \frac{p^2}{2\mu}, V_s\right], H_s\right], \qquad H_s = T_{rel} + V_s = T_{rel} + V_s^{NN} + V_s^{YN} + V_s^{YY}$$

- restrict to 2-body space → $V_s^{NN}, V_s^{YN}, V_s^{YY}$ can be evolved separately

- $\lambda = (4\mu^2/s)^{1/4}$, $[\lambda] = [p]$: a measure of the width of V in p-space

  (S.K. Bogner et al. PRC 75 (2007))

  (R.J. Furnstahl et al. NPBP 228 (2012))



- omit SRG-induced 3B, 4B… forces ⇒ $E_b = E_b(\lambda)$

  → estimate contribution of SRG-induced 3BF

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Results for $A = 4 - 7\ \Lambda$ hypernuclei

(H. Le, J. Haidenbauer, U.-G. Meißner, A. Nogga PLB (2020), EPJA 8 (2020))

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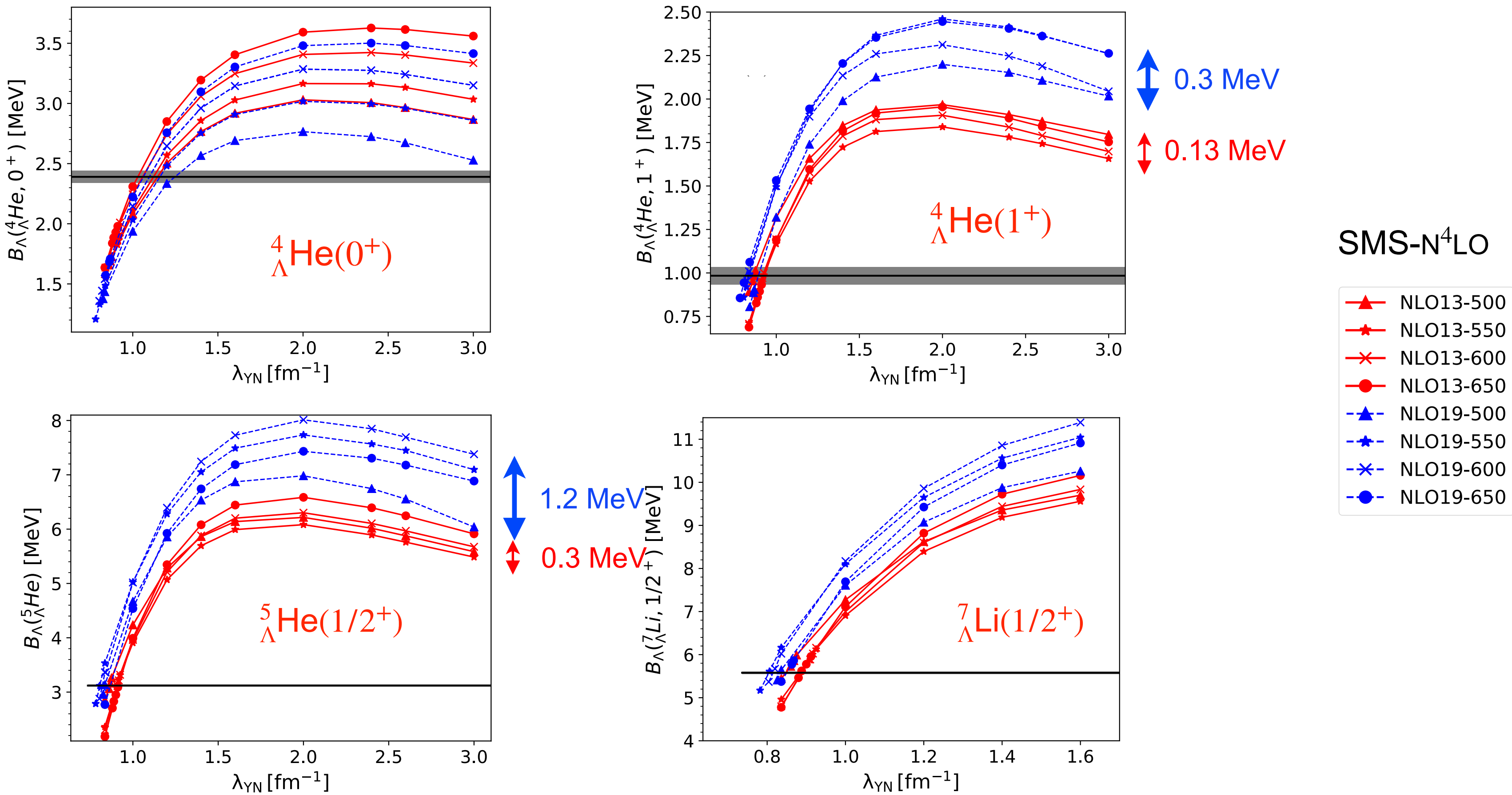
Impact of YN interactions on B_Λ

- NLO13 and NLO19 are almost phase equivalent
- NLO13 leads to a stronger $\Lambda N - \Sigma N$ transition → manifest in higher-body observables



- cutoff dependence is larger for NLO19 → less freedom to absorb cutoff artifacts into LECs
- B_Λ(NLO19) > B_Λ(NLO13) → possible contribution of chiral YNN force

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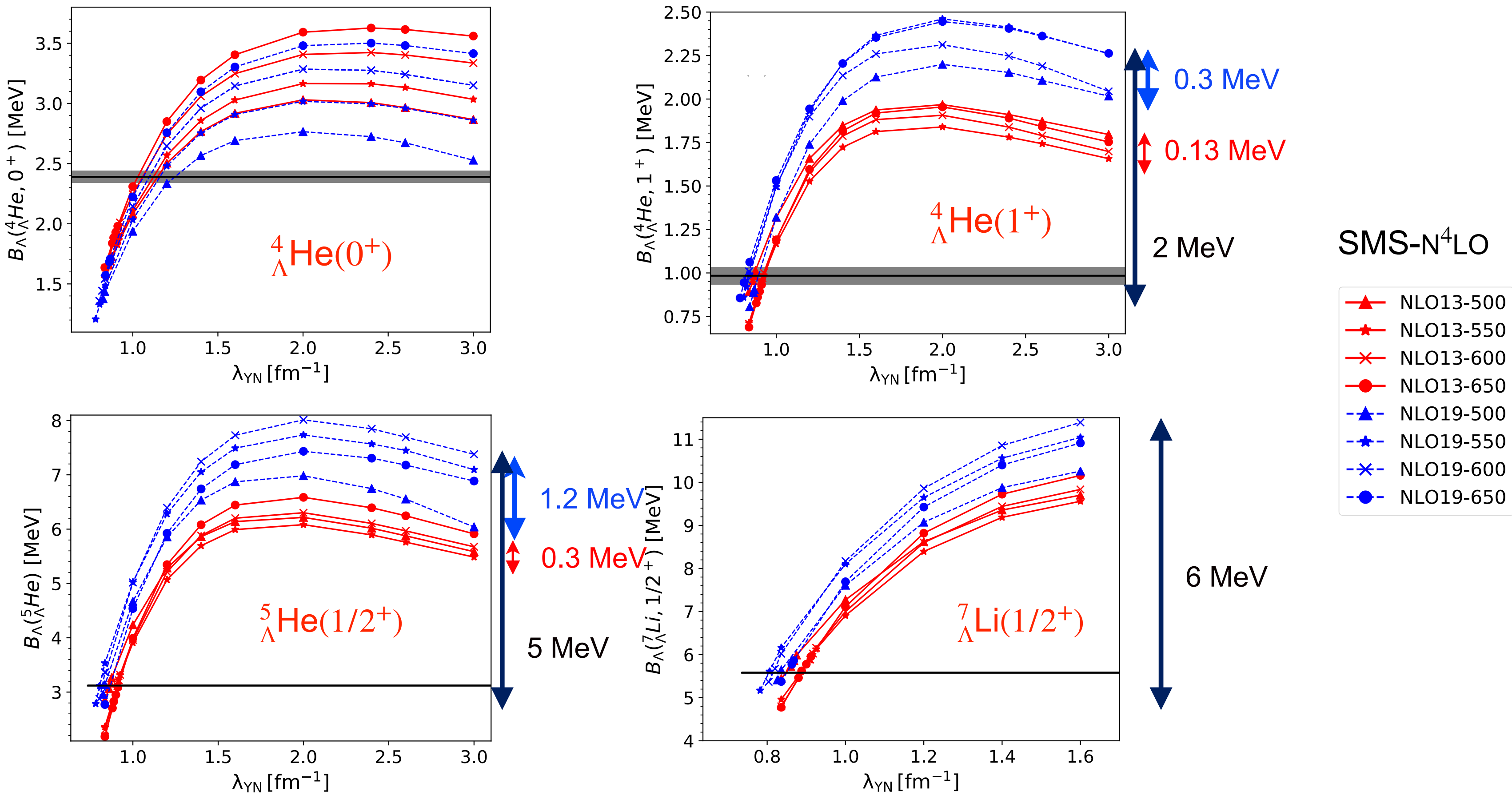

- cutoff dependence is larger for NLO19 → less freedom to absorb cutoff artifacts into LECs
- $B_\Lambda(\mathrm{NLO19}) > B_\Lambda(\mathrm{NLO13})$ → possible contribution of chiral YNN force
- strong dependence of B_Λ on λ_{YN} → contribution of SRG-induced YNN force is significant

(R. Wirth et al PRL (2014,2016), PRC(2018))

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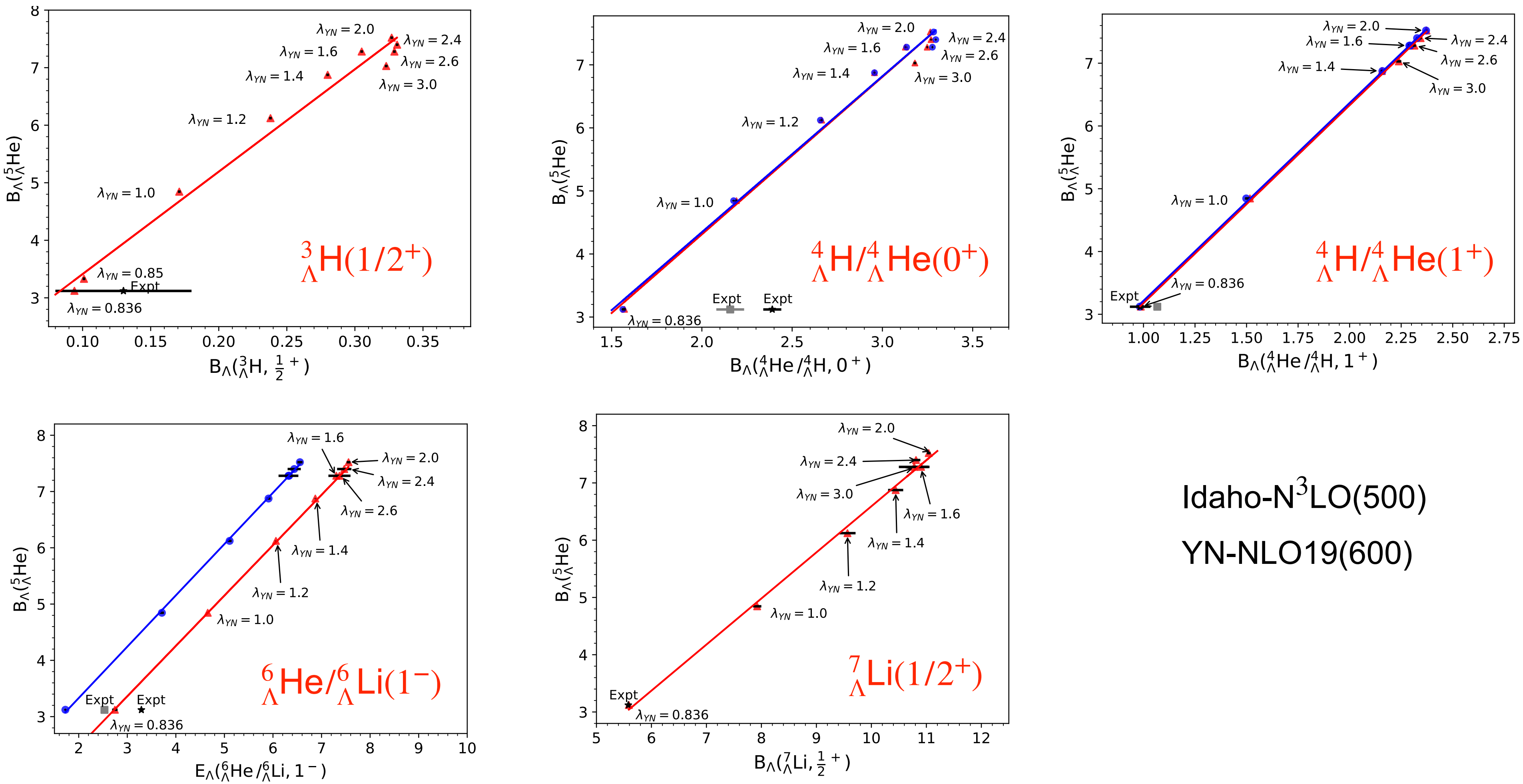
Correlation of the Λ-separation energies

- B_Λ of different hypernuclei computed for a same range of λ_{YN} are strongly correlated



Idaho-N^{3}LO(500)

YN-NLO19(600)

- B_Λ of ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}(1^+)$, ${}^{5}_{\Lambda}\mathrm{He}$ and ${}^{7}_{\Lambda}\mathrm{Li}$ are well reproduced at $\lambda_{YN} = 0.84\ \mathrm{fm}^{-1}$

→ minimize effect of (SRG-induced) YNN forces by tuning λ_{YN} so that a particular hypernucleus (${}^{5}_{\Lambda}\mathrm{He}$) is described properly

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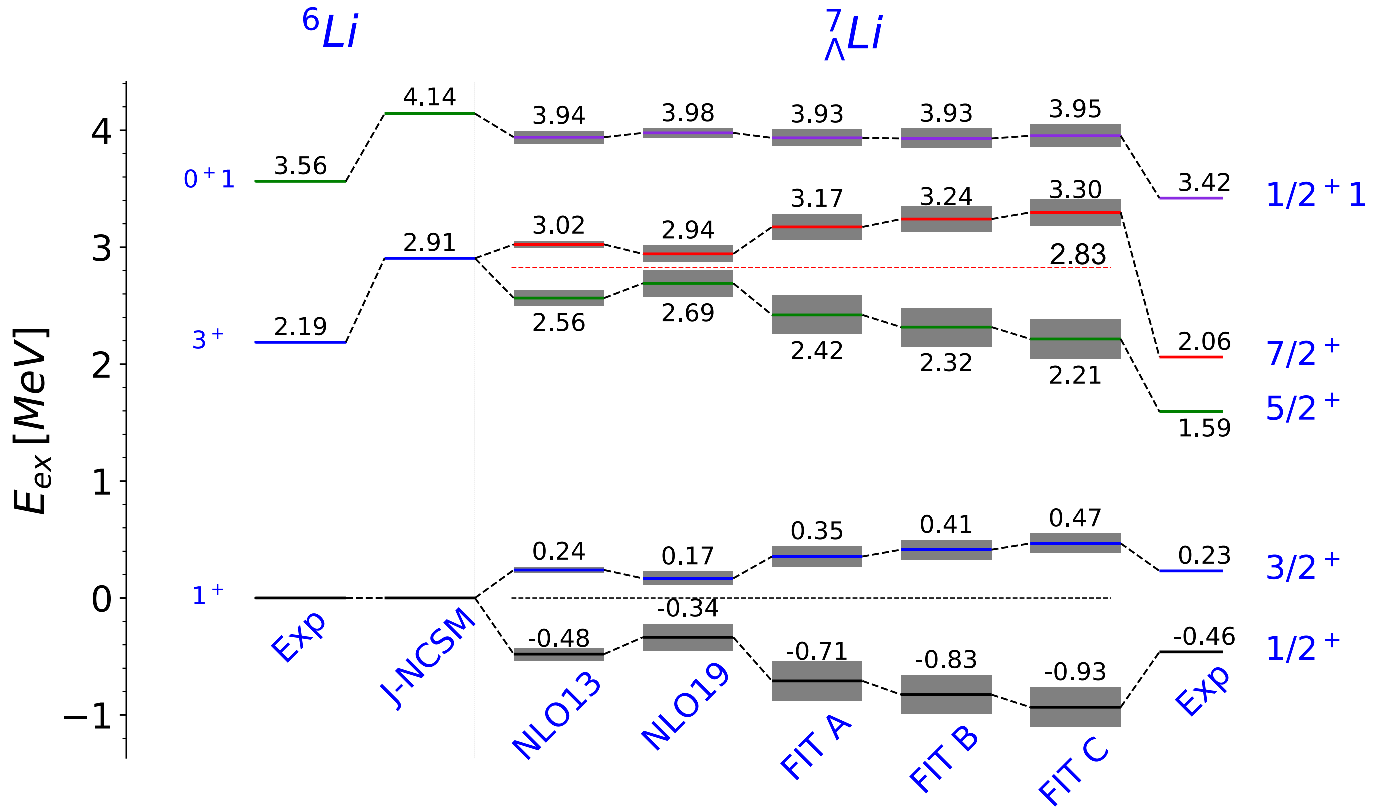
Impact of an increased $B_\Lambda(^3_\Lambda\mathrm{H})$ on $^7_\Lambda$Li spectrum

- Choose λ_{YN} to reproduce: $B_\Lambda(^5_\Lambda\mathrm{He}) = 3.12 \pm 0.02$ MeV

$B_\Lambda(^3_\Lambda\mathrm{H}) = 0.13 \pm 0.05$ MeV (up to 2019: NLO13, NLO19)

$= 0.41 \pm 0.12$ MeV (STAR 2019: FITA, FITB, FITC)



NN: SMS-N^{4}LO+(450)

→ overall effect of an increased $B_\Lambda(^3_\Lambda\mathrm{H})$ on $^7_\Lambda$Li spectrum is small

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Results for ${}^{6}_{\Lambda\Lambda}$He, ${}^{5}_{\Lambda\Lambda}$He, ${}^{4}_{\Lambda\Lambda}$H

(H. Le, J. Haidenbauer, U.-G. Meißner, A. Nogga EPJA 57 (2021))

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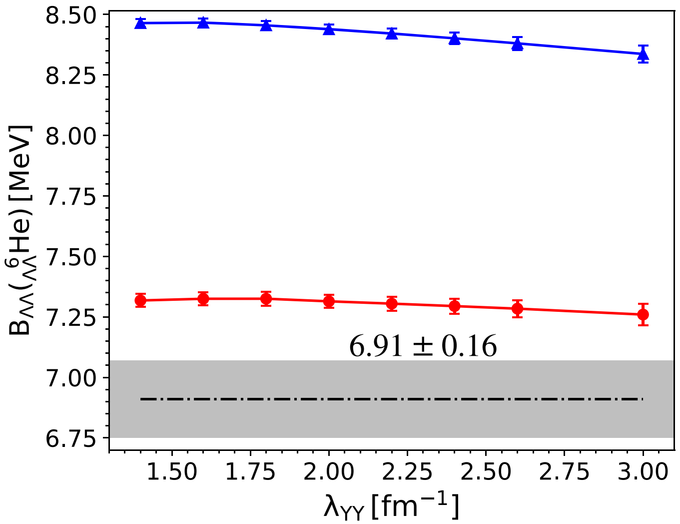
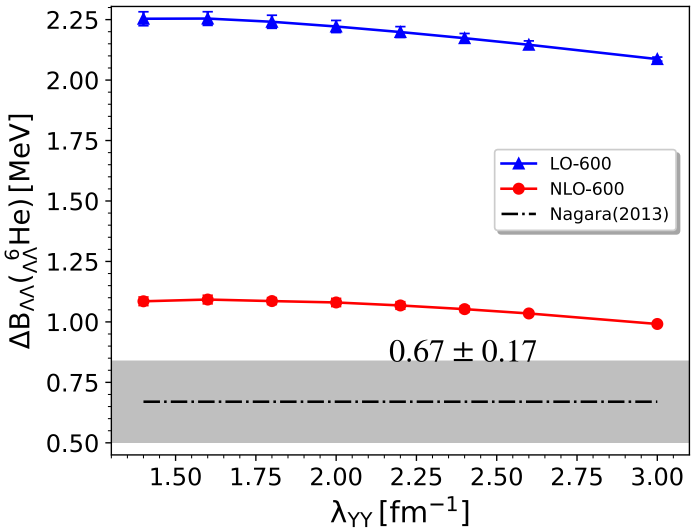
${}^{6}_{\Lambda\Lambda}$He$(0^{+},0)$

NN : N^{4}LO + (450), $\lambda_{NN} = 1.6\,\text{fm}^{-1}$, YN : NLO19(650), $\lambda_{YN} = 0.87\,\text{fm}^{-1}$

→ reproduce separation energies of ${}^{4}_{\Lambda}$He(1^{+}), ${}^{5}_{\Lambda}$He, ${}^{7}_{\Lambda}$Li, but slightly underbind ${}^{4}_{\Lambda}$He(0^{+})





λ_{YY} fm^{-1}	NLO(600)			LO(600)		
	$P_{\Lambda\Sigma}$	$P_{\Sigma\Sigma}$	P_{Ξ}	$P_{\Lambda\Sigma}$	$P_{\Sigma\Sigma}$	P_{Ξ}
1.4	0.13	0.11	0.02	0.17	0.04	0.5
2.0	0.13	0.11	0.07	0.17	0.05	0.84
3.0	0.12	0.13	0.12	0.18	0.08	1.08

$P_{\Sigma}({}^{5}_{\Lambda}\text{He, YN-NLO19}) = 0.07\,\%$

Probabilities (%) of finding $\Sigma, \Sigma\Sigma, \Xi$ in ${}^{6}_{\Lambda\Lambda}$He

- Effect of SRG-induced YYN forces is negligible
- NLO results are comparable to the Nagara, LO overbinds the system
- $P_{\Lambda\Sigma}, P_{\Sigma\Sigma} \approx P_{\Sigma}({}^{5}_{\Lambda}\text{He})$ are less sensitive to SRG-YY

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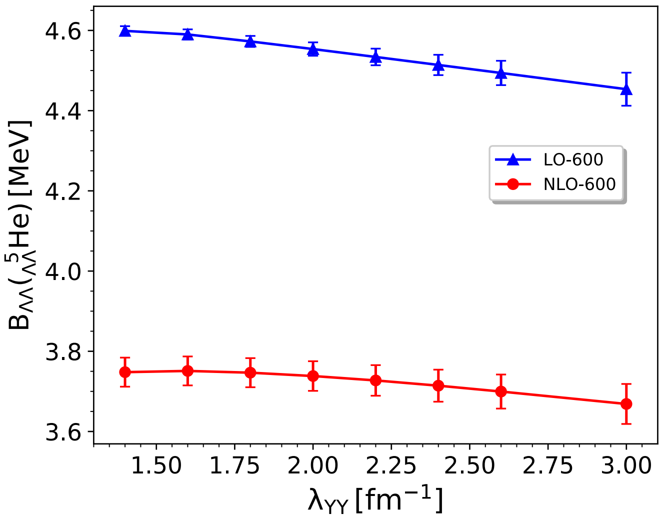
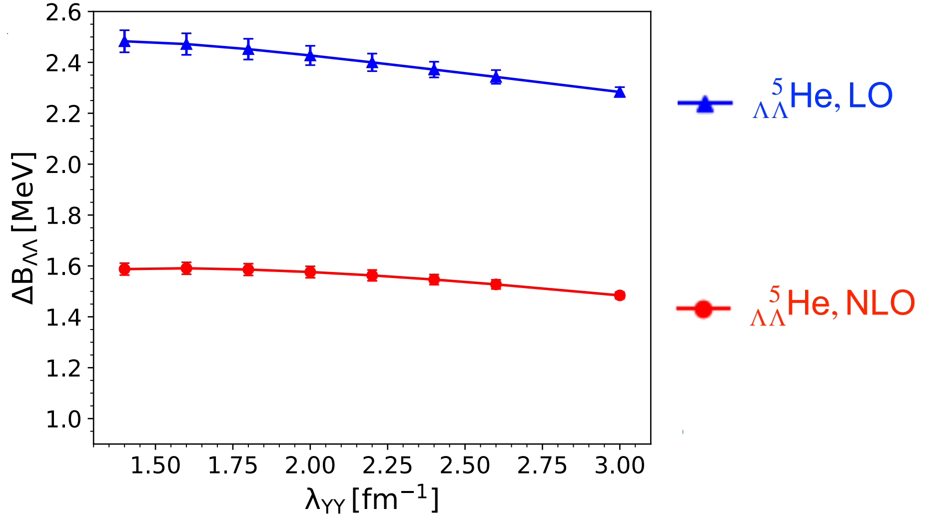
$^{5}_{\Lambda\Lambda}$He$(\frac{1}{2}^+,\frac{1}{2})$





- effect of SRG-induced YYN force on $\Delta B_{\Lambda\Lambda}, B_{\Lambda\Lambda}$ is minor

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$^{5}_{\Lambda\Lambda}\mathrm{He}(\frac{1}{2}^{+},\frac{1}{2})$

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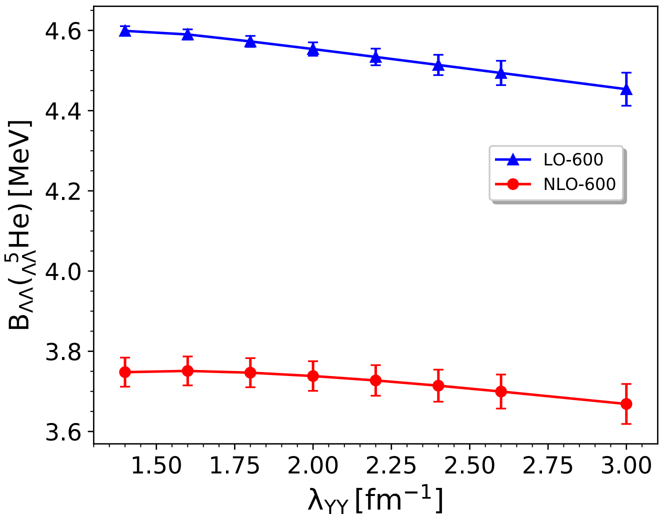

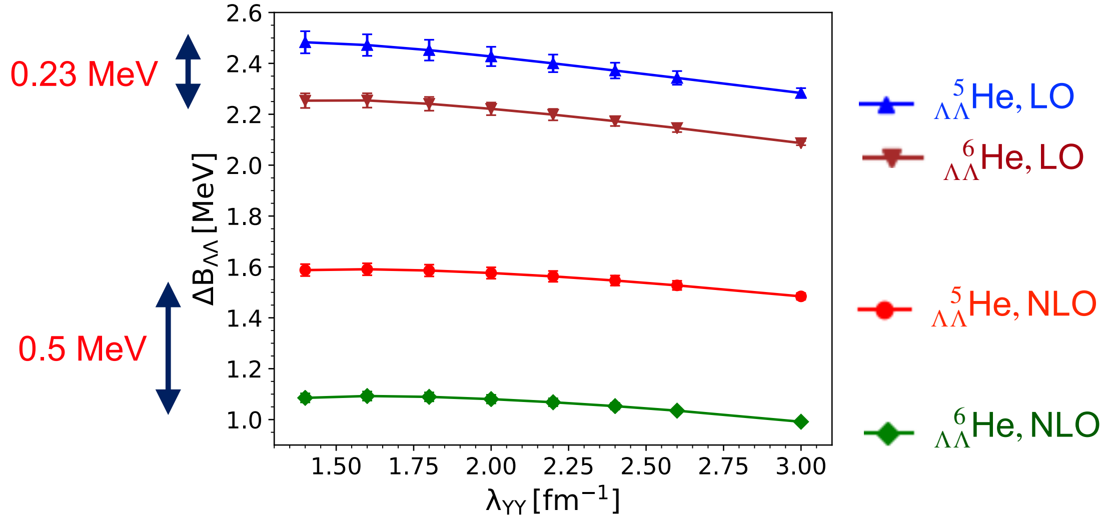

- effect of SRG-induced YYN force on $\Delta B_{\Lambda\Lambda}, B_{\Lambda\Lambda}$ is minor
- Large difference between $\Delta B_{\Lambda\Lambda}$: $\Delta B_{\Lambda\Lambda}(^{5}_{\Lambda\Lambda}\mathrm{He}) > \Delta B_{\Lambda\Lambda}(^{6}_{\Lambda\Lambda}\mathrm{He})$ (K. S. Myint et al EPJ (2003))

  FY calculations: $\Delta B_{\Lambda\Lambda}(^{5}_{\Lambda\Lambda}\mathrm{He}) < \Delta B_{\Lambda\Lambda}(^{6}_{\Lambda\Lambda}\mathrm{He})$ (I. Filikhin, A. Gal NPA 707 (2002))

- $P_{\Xi}(^{6}_{\Lambda\Lambda}\mathrm{He}) < P_{\Xi}(^{5}_{\Lambda\Lambda}\mathrm{He})$

  $\Rightarrow \Lambda\Lambda - \Xi N$ transition is suppressed in $^{6}_{\Lambda\Lambda}\mathrm{He}$

  B. F. Gibson PTPS 117, 339 (1994)

  E. Hiyama et al. PPNP (2009)

	$^{5}_{\Lambda\Lambda}\mathrm{He}$		$^{6}_{\Lambda\Lambda}\mathrm{He}$	
	P_{Ξ}	$B_{\Lambda\Lambda}$	P_{Ξ}	$B_{\Lambda\Lambda}$
NLO($\lambda_{YY}=2$)	0.38	3.67 ± 0.03	0.07	7.62 ± 0.02
LO($\lambda_{YY}=2$)	1.36	4.53 ± 0.01	0.84	8.40 ± 0.02

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${}^{5}_{\Lambda\Lambda}\text{He}(\frac{1}{2}^+, \frac{1}{2})$

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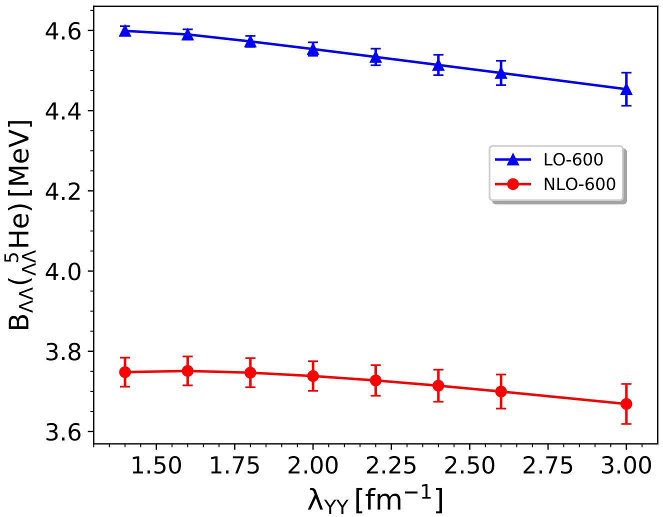

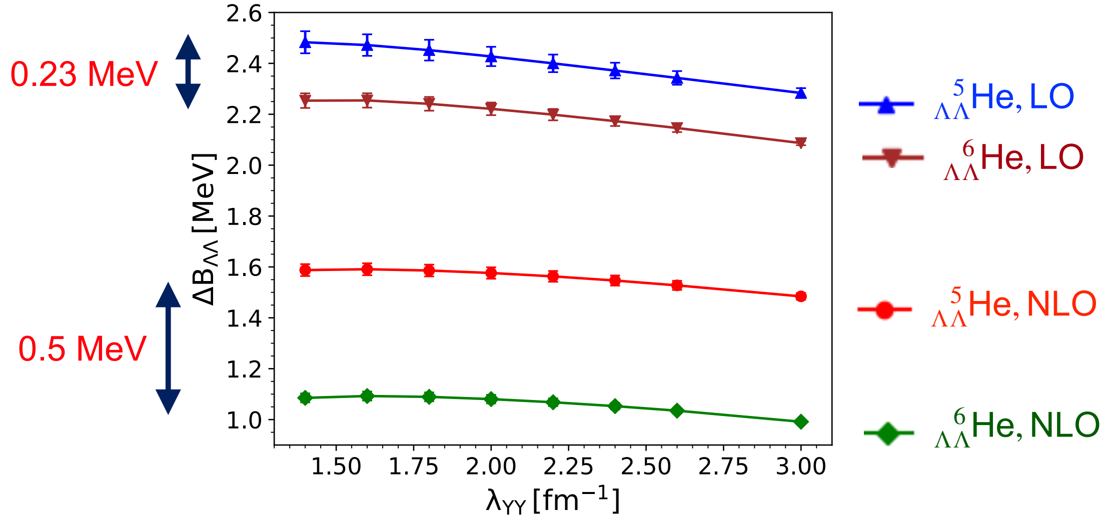

- effect of SRG-induced YYN force on $\Delta B_{\Lambda\Lambda}, B_{\Lambda\Lambda}$ is minor
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- $P_{\Xi}({}^{6}_{\Lambda\Lambda}\text{He}) < P_{\Xi}({}^{5}_{\Lambda\Lambda}\text{He})$

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mNDs*		3.66	0.28	7.54

* H. Nemura et al., PRL 94 (2005)

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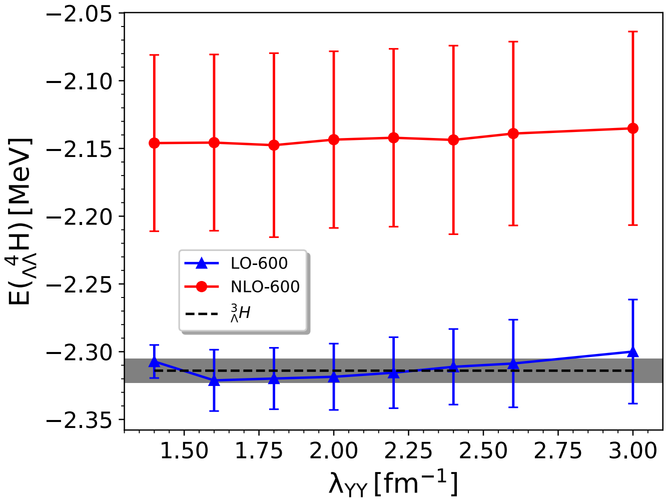
Is ${}^{4}_{\Lambda\Lambda}$H$(1^+,0)$ stable against the breakup to ${}^{3}_{\Lambda}$H $+\ \Lambda$?



→ NLO leads to a particle unstable ${}^{4}_{\Lambda\Lambda}$H. Existence of $A = 4\ \Lambda\Lambda$ hypernucleus is unlikely

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Summary

- develop J-NCSM for Λ & $\Lambda\Lambda$ hypernuclei up to p-shell
- study the predictions of YN NLO13 & NLO19 for hypernuclear observables

  → the difference in NLO13 & NLO19 predictions are attributed to YNN force
- SRG-YN evolutions strongly affect Λ-separation energies
  - B_Λ of different systems are strongly correlated
  - overall impact of an increased $B_\Lambda({}^3_\Lambda\mathrm{H})$ on spectrum of ${}^7_\Lambda$Li is small
- investigate ${}^{6}_{\Lambda\Lambda}$He, ${}^{5}_{\Lambda\Lambda}$He, ${}^{4}_{\Lambda\Lambda}$H using chiral YY LO & NLO interactions
  - SRG YY evolution has minor effects on $\Delta B_{\Lambda\Lambda}$ and $P_{\Lambda\Sigma}, P_{\Sigma\Sigma}$
  - LO overbinds ${}^{6}_{\Lambda\Lambda}$He; NLO results are comparable to experiment
  - both interactions result in $\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) < \Delta B_{\Lambda\Lambda}({}^{5}_{\Lambda\Lambda}\mathrm{He})$, ${}^{4}_{\Lambda\Lambda}$H is unstable
- inclusion of χEFT and SRG-induced 3N forces, SRG-induced YNN forces is in progress
- investigate the existence of s-shell Ξ hypernuclei using YY NLO (in print)

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Thank you for your attention!

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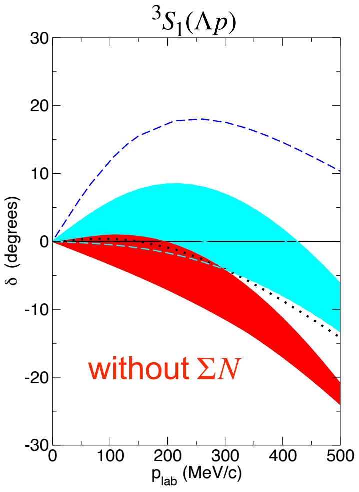

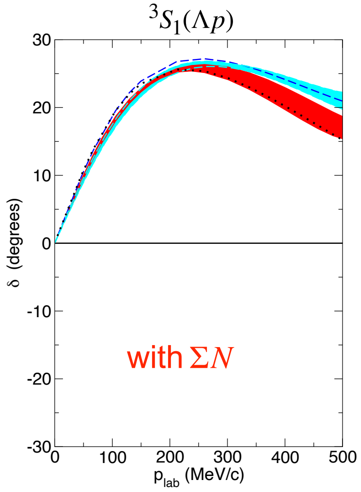

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Correlation of the Λ-separation energies

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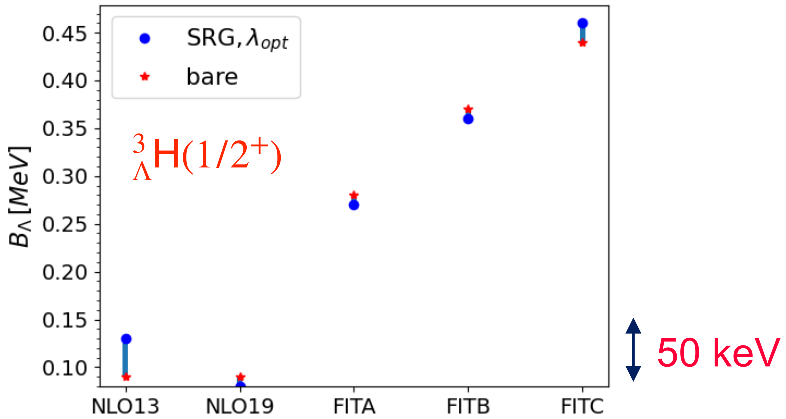
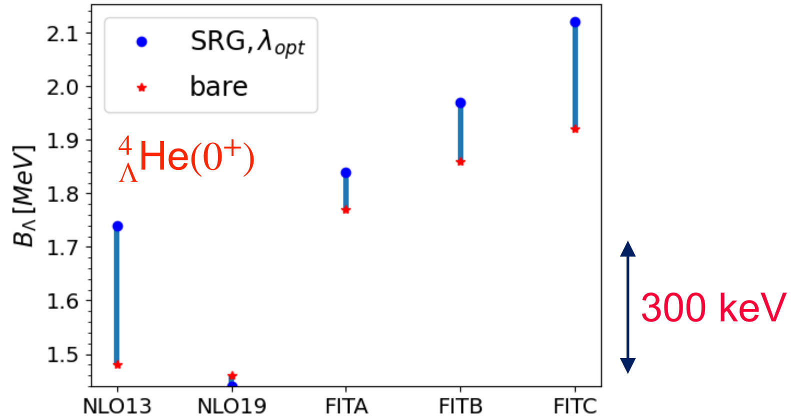
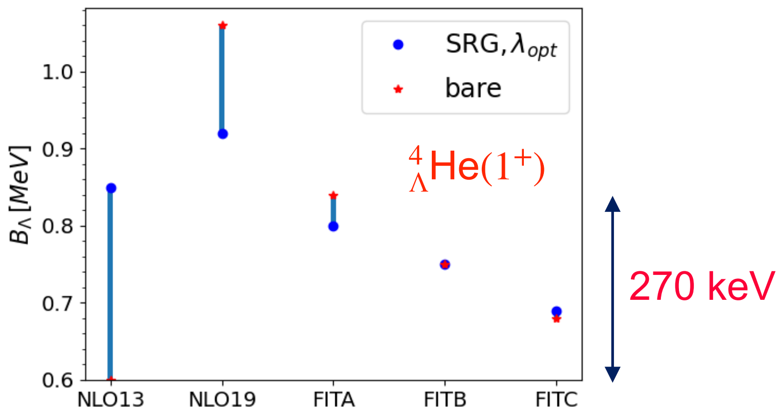
$$B_\Lambda(^3_\Lambda\text{H}) = 0.13 \pm 0.05 \text{ MeV} \quad \text{(before 2019: NLO13, NLO19)}$$

$$= 0.41 \pm 0.12 \text{ MeV} \quad \text{(STAR 2019: FITA, FITB, FITC)}$$







→ $B_\Lambda(^3_\Lambda\text{H}, ^4_\Lambda\text{He})$ agree with the bare values within theoretical uncertainties

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