Light Λ hypernuclei within χEFT and theoretical uncertainties

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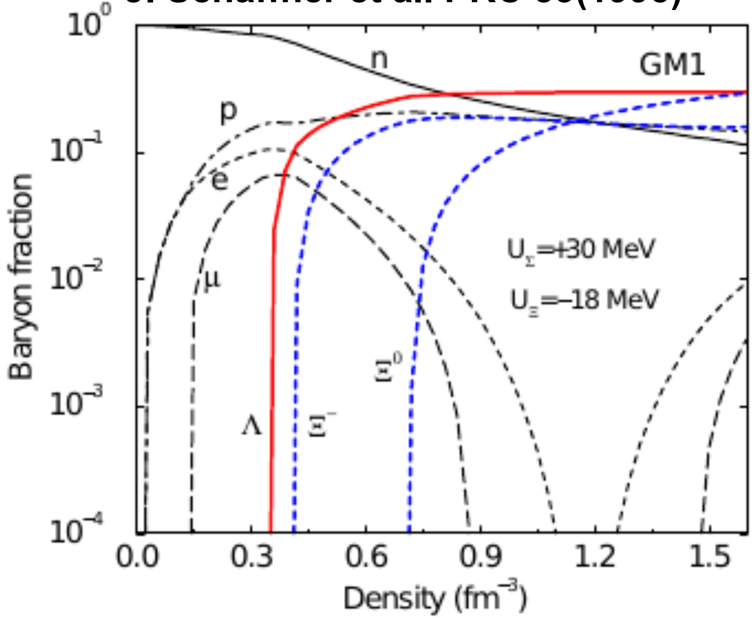
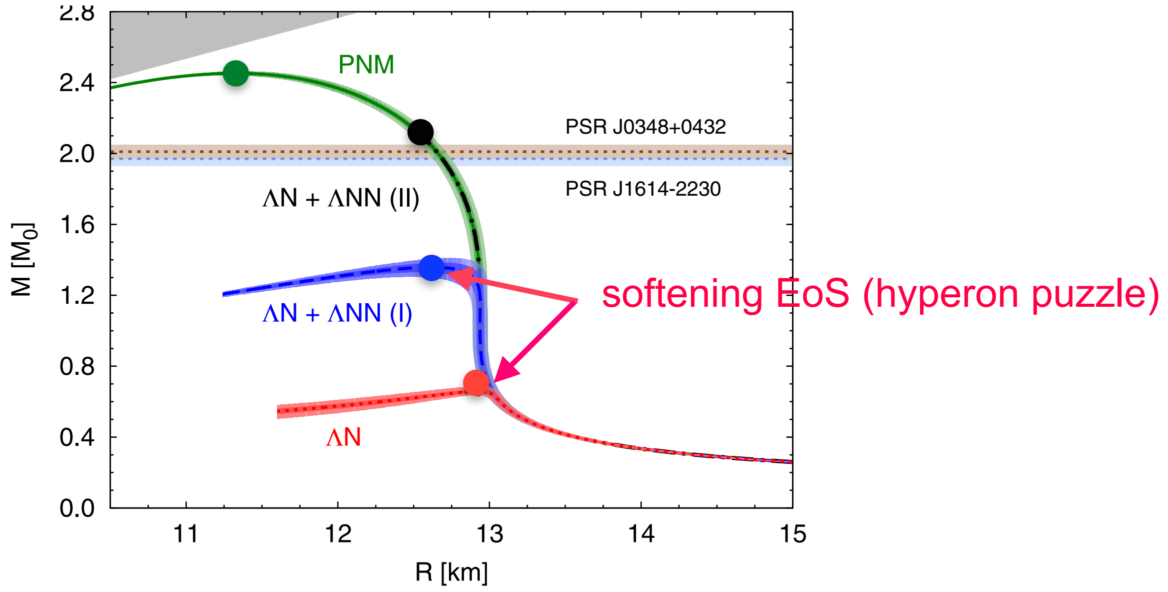
Why is hypernuclear physics interesting?

J. Schaffner et al. PRC 53(1995)



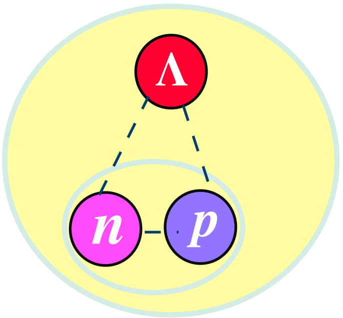
- contribute to NS at $\rho = 2 - 3\rho_0$

D. Lonardoni et al. PRL 114(2015)

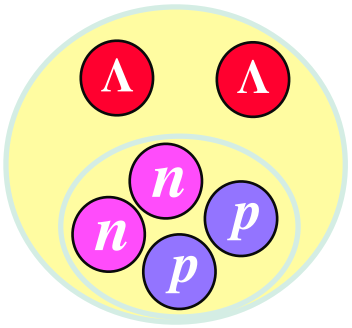


- can 3BFs resolve the puzzle?

$^{3}_{\Lambda}$H



$^{6}_{\Lambda\Lambda}$He



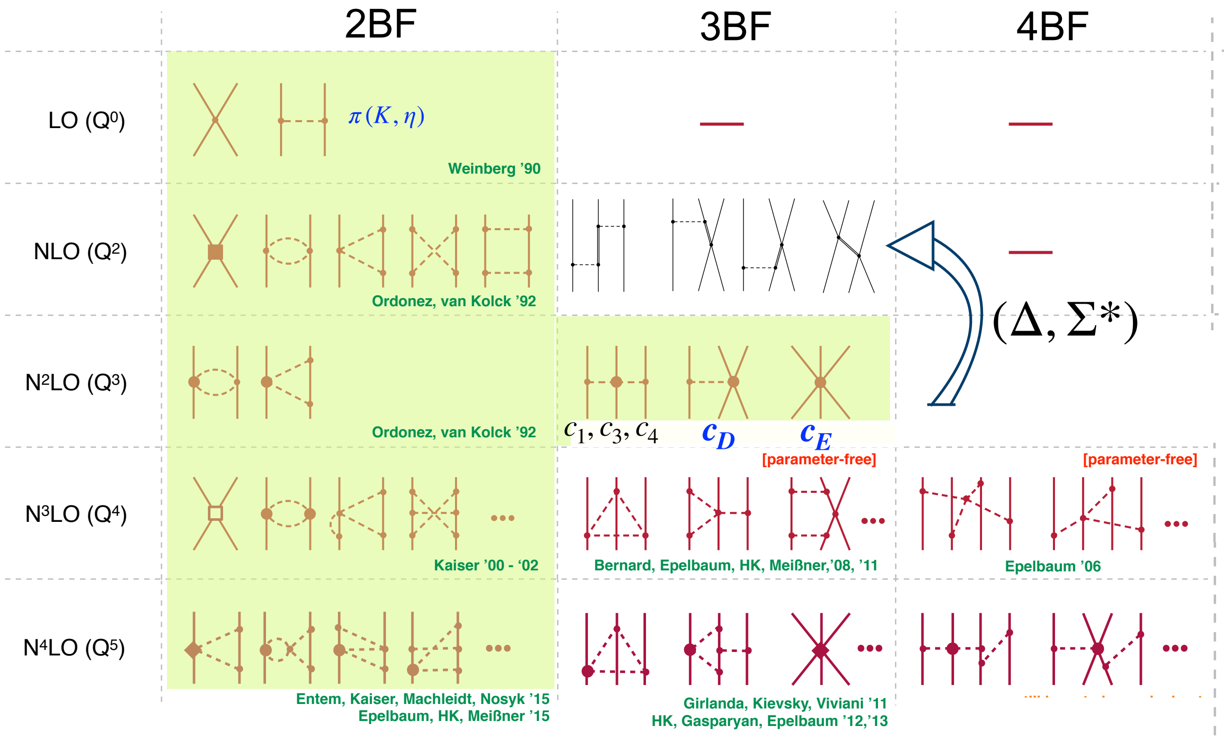
~ 40 Λ-hypernuclei
$^{3}_{\Lambda}\mathrm{H}, {}^{4}_{\Lambda}\mathrm{He}, \cdots, {}^{208}_{\Lambda}\mathrm{Pb}$

ΛΛ (Ξ)-hypernuclei
$^{6}_{\Lambda\Lambda}\mathrm{He}, {}^{10}_{\Lambda\Lambda}\mathrm{Be}, {}^{11}_{\Lambda\Lambda}\mathrm{Be}; {}^{15}_{\Xi}\mathrm{C}$

- scarce hyperon-nucleon (YN) scattering data
  → difficult to constrain free-space YN interactions
- hypernuclei → laboratory to explore **YN (BB) interactions / test SU(3) symmetry of QCD**
- **ab initio (NCSM)** treatment of hypernuclei → **connect underlying interactions & hypernuclear observables**

BB interactions in χEFT

S. Weinberg PLB 251(1990), NPB 363(1991); E. Epelbaum, H.-W. Hammer, U.-G. Meißner RMP 81(2009)



2NN / 5YN LECs (short range parameters)

+7NN / 18YN LECs

no additional LECs for 2BFs

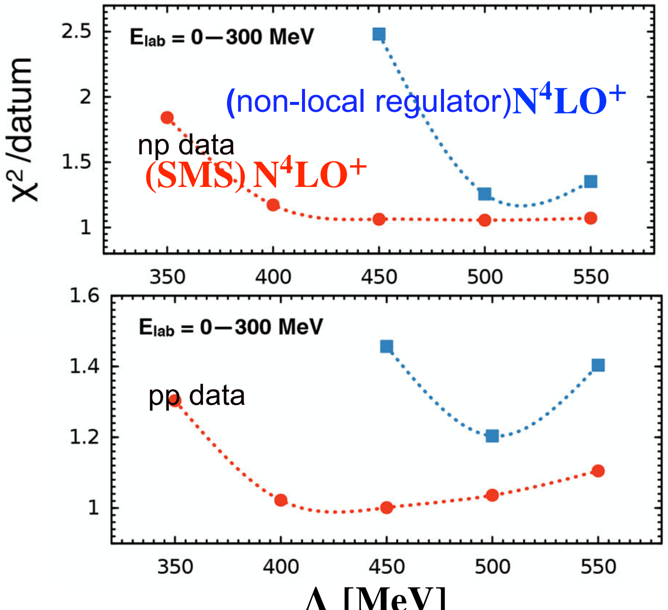
+**2NNN** / 5ΛNN LECs

+15NN LECs

+5NN LECs

(adapted from H. Krebs CD workshop 2021)

P. Reinert et al. EPJA (2018)



- **~5000** NN + **Nd** scattering data + ^{2}H, ^{3}H/^{3}He

→ **SMS** NN forces up to N^4LO^+ $(\chi^2 \sim 1)$, 3NF up to N^2LO

P. Reinert et al. EPJA (2018), LENPIC(2021,2022), talk by Epelbaum (03.08)

- semi-local momentum space regularization (**SMS**):
  - local regulator for pion exchange interactions

→ **maintain long-range parts + reduce cutoff artefacts**

YN interactions up to N^{2}LO

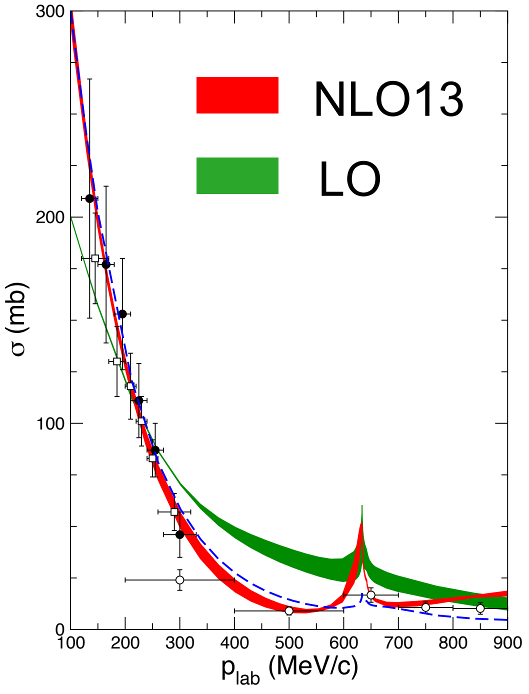
LO: **H. Polinder, J. Haidenbauer, U.-G. Meißner NPA 779(2006)**

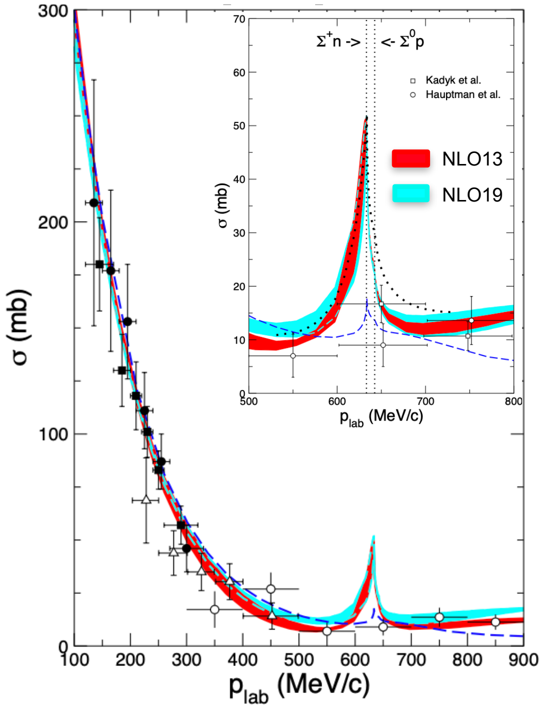
NLO13: **J. Haidenbauer et al NPA 915(2013);** NLO19: **J. Haidenbauer, U.-G. Meißner, A. Nogga EPJA 56(2020)**

SMS NLO, N^{2}LO: **J. Haidenbauer, U.-G. Meißner, A. Nogga, HL EPJA 59(2023)**

- most of s-wave LECs are fitted to 36 data points ($\Lambda p \to \Lambda p,\ \Sigma N \to \Sigma N,\ \Sigma N \to \Lambda N$) + $B_\Lambda({}^3_\Lambda\mathrm{H})$
- at **NLO:** two realisations **NLO13** & **NLO19** **(phase equivalent; NLO13 leads to a larger** $V_{\Lambda N \leftrightarrow \Sigma N}$ **)**

  → tool to **assess effect of YNN forces** in many-body systems
- **SMS** NLO, N^{2}LO: employ a novel regularization scheme as in NN





	χ^2	$B_\Lambda({}^3_\Lambda\mathrm{H})$
LO(600)	28.3	0.135
NLO13(600)	16.8	0.09
NLO19(600)	16.3	0.091
SMS NLO(550)	15.7	0.123
SMS N^{2}LO	15.6	0.139

→
- **LO** describes YN data poorly. Significant improvement at NLO

  (**LO** results are useful for truncation error estimation)
- **SMS** interactions lead to a slightly more attractive ΛN potential

Jacobi-NCSM approach

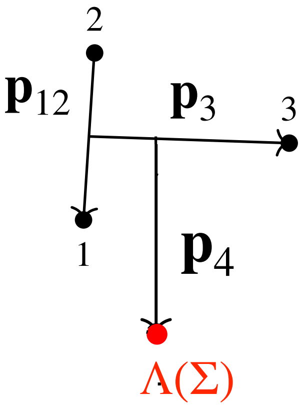
S. Liebig, U.-G. Meißner, A. Nogga, EPJA 52(2016); HL, J. Haidenbauer, U.-G. Meißner, A. Nogga EPJA 56 (2020)

- **Idea:** represent the A-body translationally invariant hypernuclear Hamiltonian:

$$H = T_{rel} + V^{NN} + V^{YN} + V^{NNN} + V^{YNN} + \Delta M + \cdots$$

$\Lambda N \leftrightarrow \Sigma N$

in a basis constructed from HO functions



- Jacobi basis: **depends on relative Jacobi coordinates of all particles**

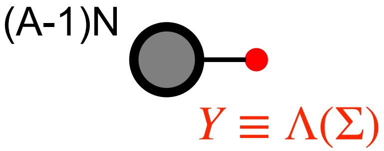
(A-1)N

$$| \bullet\!-\!\bullet \rangle = |\mathcal{N} J T, \underbrace{\mathcal{N}_{A-1} J_{A-1} T_{A-1},}_{antisym.(A-1)N} \underbrace{n_Y l_Y I_Y\, t_Y;}_{\Lambda(\Sigma)\ state} (J_{A-1}(l_Y s_Y) I_Y)\, J, (T_{A-1} t_Y) T \rangle$$

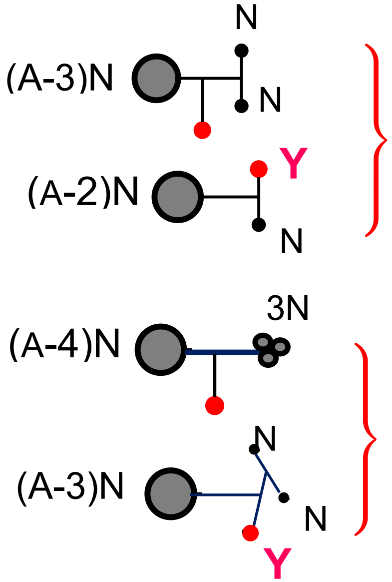
$\Lambda(\Sigma)$

(independent of ω)

- intermediate bases for evaluating Hamiltonian:



trans. coefficients $\longrightarrow$ **independent of ω**



$\rightarrow$ for NN, YN forces

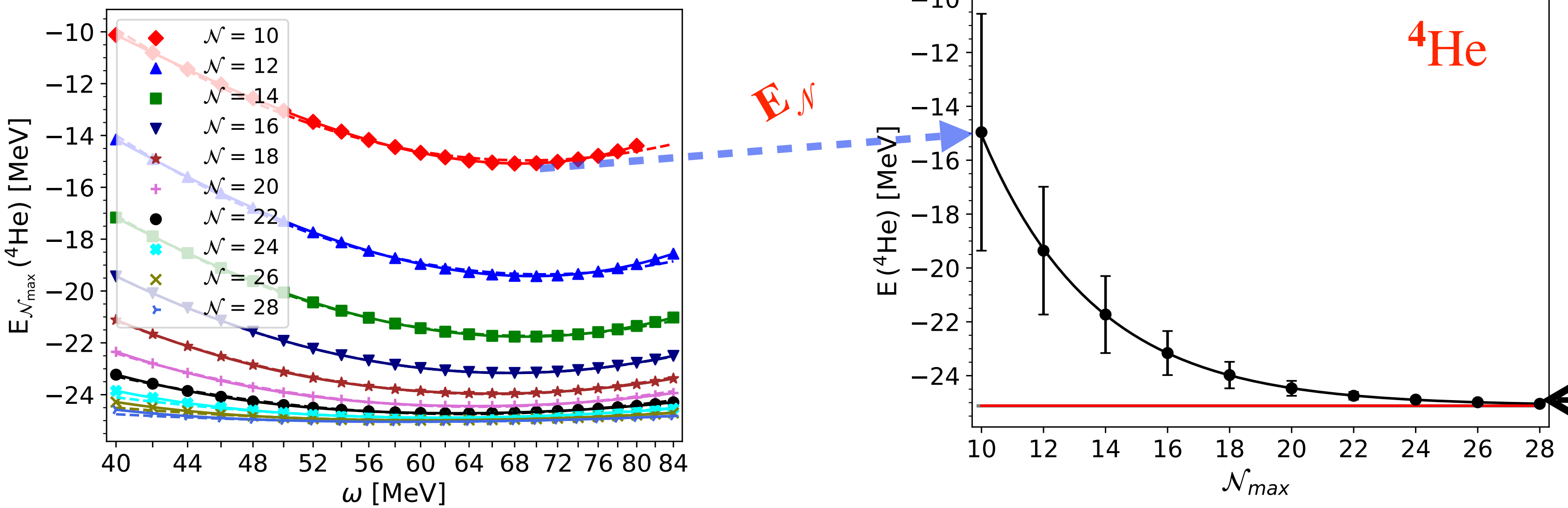
$\rightarrow$ for 3N, YNN forces

- basis truncation: $\mathcal{N} = \mathcal{N}_{A-1} + 2n_\lambda + \lambda \leq \mathcal{N}_{max} \Rightarrow E_b = E_b(\omega, \mathcal{N}_{max})$ $\xrightarrow{\text{extrapolation}}$ $E_{b,\infty}$

Extrapolation in ω & $\mathcal{N}$ spaces

S. Liebig, U.-G. Meißner, A. Nogga, EPJA 52(2016); HL, J. Haidenbauer, U.-G. Meißner, A. Nogga EPJA 56 (2020)

- $\mathbf{E_b}(\omega, \mathcal{N}) = \mathbf{E}_{\mathcal{N}} + \kappa(\log(\omega) - \log(\omega_{\mathbf{opt}}))^2$
- $\mathbf{E}_{\mathcal{N}} = \mathbf{E}_\infty + \mathbf{A}e^{-\mathbf{b}\mathcal{N}}$



NN: SMS N^{2}LO(550)

$\mathbf{E}(^4\mathrm{He}, \mathbf{NCSM}) = -\mathbf{25.14} \pm \mathbf{0.06}$

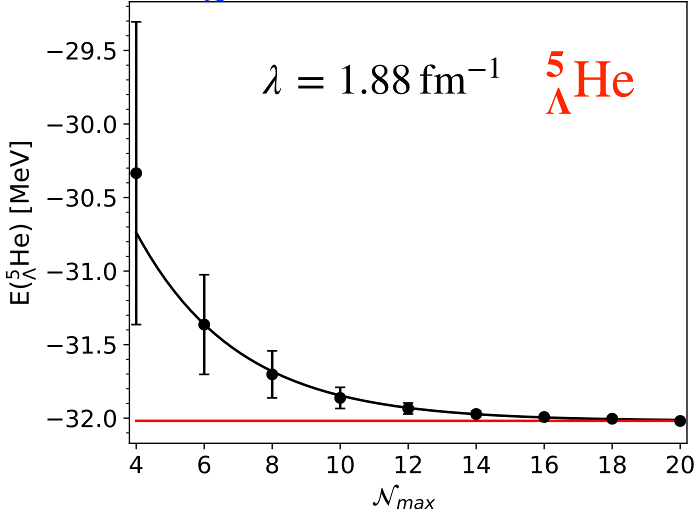
$\mathbf{E}(^4\mathrm{He}, \mathbf{FY}) = -\mathbf{25.15} \pm \mathbf{0.02}$

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

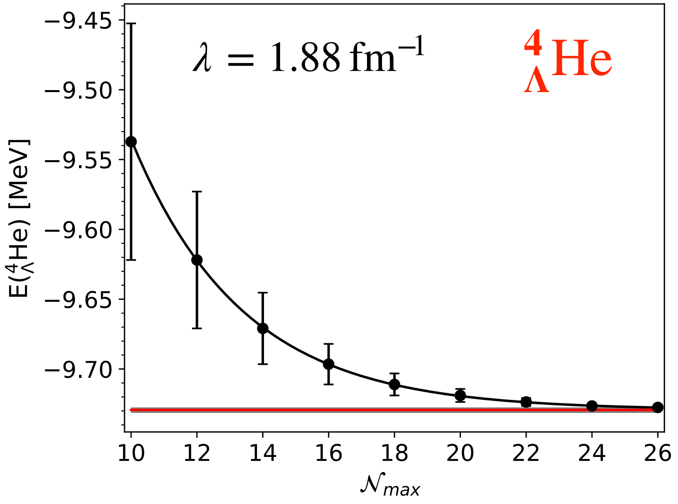
Numerical uncertainties

- NCSM calculations for hypernuclei with **bare SMS** NN (3N) and YN interactions **converge poorly**
- NCSM uncertainties for **SRG-evolved** potentials:
  - ~ several keV for $\mathbf{A} \leq \mathbf{5}$
  - ~ hundred(s) keV for $\mathbf{A} = \mathbf{7}\,(\mathbf{8})$
- FY uncertainties: ~ **1 (20)** keV for ${}^3_\Lambda\mathrm{H}$ (${}^4_\Lambda\mathrm{He}$)

$\mathbf{E}({}^5_\Lambda\mathrm{He}) = -\mathbf{32.018} \pm \mathbf{0.001}$



$\mathbf{E}({}^4_\Lambda\mathrm{He}) = -\mathbf{9.729} \pm \mathbf{0.002}$



Similarity Renormalization Group (SRG)

Idea: **continuously apply unitary transformation to H to suppress off-diagonal matrix elements**

→ speed up the convergence of NCSM calculations (observables e.g. energies are conserved)

F.J. Wegner NPB 90 (2000). S.K. Bogner, R.J. Furnstahl, R.J. Perry PRC 75 (2007)

$$\frac{dV(s)}{ds} = [[T_{rel}, V(s)], H(s)], \qquad H(s) = T_{rel} + V(s) + \Delta M$$

$$s = 0 \to \infty \qquad V(s) = V_{12}(s) + V_{13}(s) + V_{23}(s) + V_{123}(s), \quad V_{123,s=0} \equiv V^{bare}_{NNN}; \quad (V^{bare}_{YNN} = 0)$$

- separate SRG flow equations for 2-body and 3-body interactions:

S.K. Bogner et al PRC75 (2007), K. Hebeler PRC85 (2012)

$$\frac{dV^{NN}(s)}{ds} = [[T^{NN}, V^{NN}], T^{NN} + V^{NN}]$$

$$\frac{dV^{YN}(s)}{ds} = [[T^{YN}, V^{YN}], T^{YN} + V^{YN} + \Delta M]$$

$$\frac{dV_{123}}{ds} = [[T_{12}, V_{12}], V_{31} + V_{23} + V_{123}] + [[T_{31}, V_{31}], V_{12} + V_{23} + V_{123}] + [[T_{23}, V_{23}], V_{12} + V_{31} + V_{123}] + [[T_{rel}, V_{123}], H_s]$$

→ **SRG-induced YNNs are generated even if** $V^{bare}_{YNN} = 0$

- SRG-induced beyond 3BFs are not included. **Estimate size of omitted 4BFs by varying** $\lambda = (4\mu^2/s)^{1/4}$ **[fm^{-1}]**

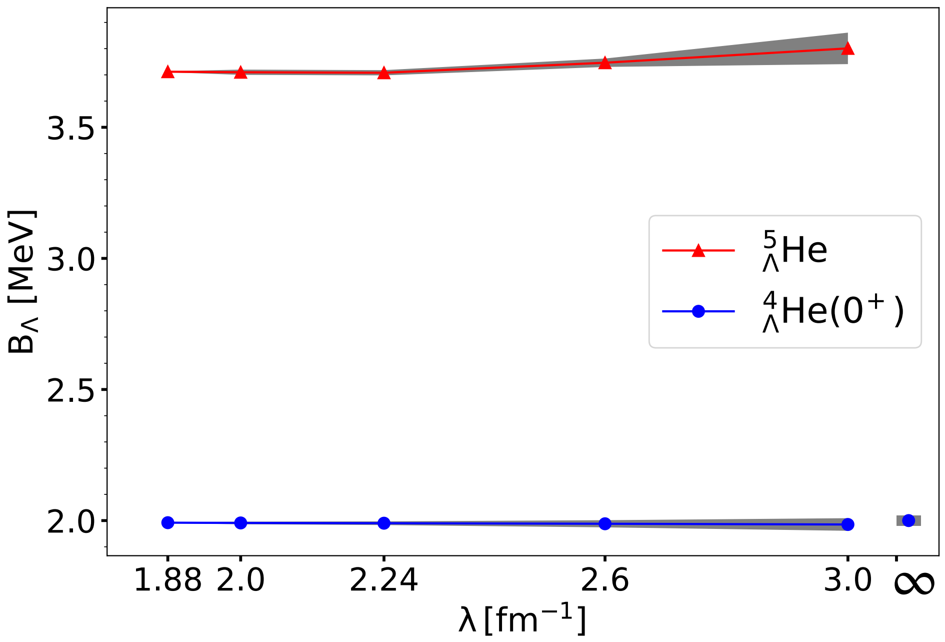
Effect of SRG-induced 4BFs in A=4,5

HL, J. Haidenbauer, U.-G. Meißner, A. Nogga (in preparation)

- **Estimate size of omitted 4BFs by varying λ**

λ [fm^{-1}]	$B_\Lambda({}^4_\Lambda\text{He}, 0^+)$	$B_\Lambda({}^5_\Lambda\text{He})$
1.88	1.992 ± 0.002	3.712 ±0.001
2.00	1.991 ± 0.005	3.705± 0.005
2.236	1.990 ± 0.007	3.708 ± 0.006
2.60	1.989 ± 0.014	3.744 ± 0.008
3.00	1.985 ± 0.024	3.806 ± 0.030
∞	2.01 ± 0.02	

NN: N^{4}LO$^+$, **3N**: N^{2}LO(450); **YN**: N^{2}LO(550)



$\lambda = \infty$: FY calculation using **bare NN + 3N + YN interactions**

- Variation of B_Λ for $1.88 \leq \lambda \leq 3.0$ **fm^{-1}**:

$$\Delta B_\Lambda({}^4_\Lambda\text{He}) = 10 \pm 25 \text{ KeV}$$

$$\Delta B_\Lambda({}^5_\Lambda\text{He}) = 90 \pm 30 \text{ KeV}$$

→ **contributions of induced 4BFs to $B_\Lambda({}^4_\Lambda\text{He}, {}^5_\Lambda\text{He})$ are negligible**

Results for A=3-8 hypernuclei

NN: **SMS** **$N^4LO^+(450)$** 3N: **$N^2LO(450)$**

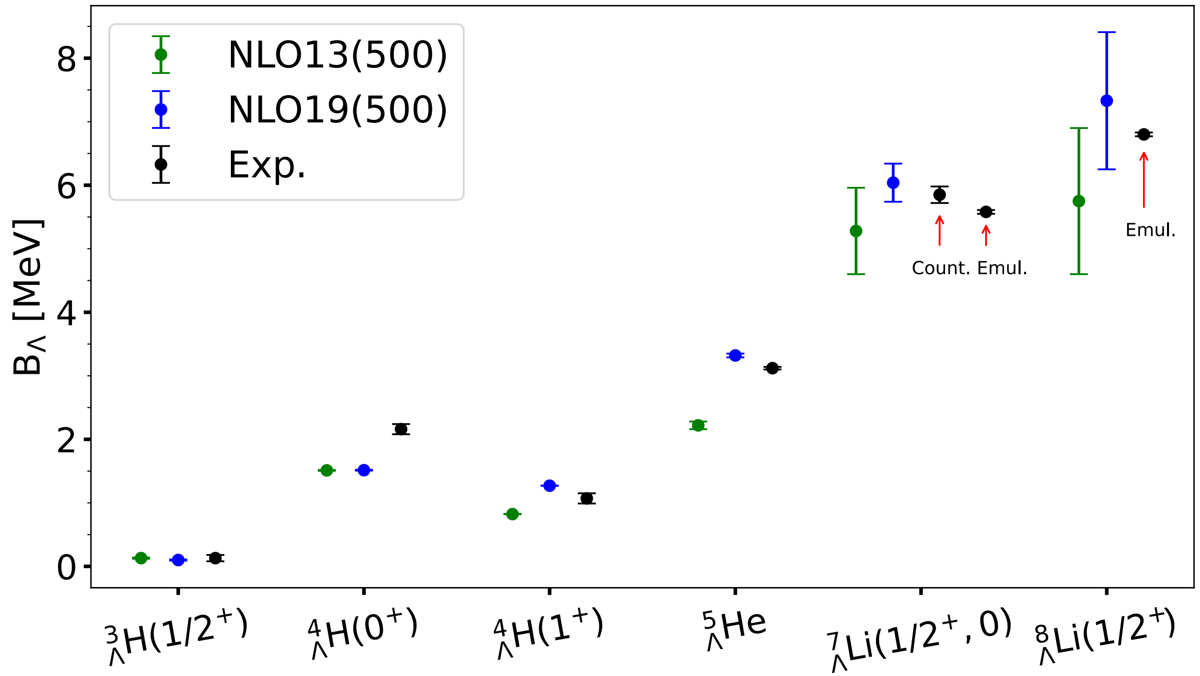
YN: **NLO13**, **NLO19**(500); **SMS** **NLO, $N^2LO(550)$**

Predictions for $B_\Lambda(A \leq 8)$ with NLO13 & NLO19

HL, J. Haidenbauer, U.-G. Meißner, A. Nogga PRC 107(2023)

- **NLO13** & **NLO19** build on non-local regulator; **phase equivalent in 2-body sector**
- **NLO13** characterised by a stronger $\Lambda N - \Sigma N$ transition potential $({}^3S_1 - {}^3D_1)$

→ **manifest in higher-body observables** **(J. Haidenbauer U.-G. Meißner, A. Nogga EPJA 56(2020))**



NN:SMS N^4LO^+(450)

+3N: N^2LO(450)

+YN: NLO13,19(CSB)

+SRG-induced YNN

Experiment:

M. Agnello et al. PLB 681(2009)

M. Juric NPB 52(1973)

- ${}^4_\Lambda$H(1^+), ${}^5_\Lambda$He, ${}^7_\Lambda$Li, ${}^8_\Lambda$Li are **fairly well described** by **NLO19**; **NLO13** underestimates these B_Λ

→ • **signal for missing chiral YNN forces:** ~ 50 **KeV to** $B_\Lambda({}^3_\Lambda\mathrm{H})$, $\sim 200 - 300$ **KeV to** $B_\Lambda({}^4_\Lambda\mathrm{He})$

$\sim 0.7 - 1$ **MeV to** $B_\Lambda({}^5_\Lambda\mathrm{He})$ **(J. Haidenbauer et al EPJA 56(2020))**

Predictions for $B_\Lambda(A \leq 5)$ with SMS NLO, $\mathrm{N^2LO}$

HL, J. Haidenbauer, U.-G. Meißner, A. Nogga (in preparation)

- NLO13 & NLO19 build on non-local regulator;
- SMS NLO, $\mathrm{N^2LO}$ use local regulator for long-range interactions (**milden cutoff artifacts**)

→ **SMS** potentials lead to **a more attractive** ΛN **(J. Haidenbauer, U.-G. Meißner, A. Nogga, HL EPJA 59(2023))**

	${}^3_\Lambda\mathrm{H}$	${}^4_\Lambda\mathrm{He}(0^+)$	${}^4_\Lambda\mathrm{He}(1^+)$	${}^5_\Lambda\mathrm{He}$
NLO13	0.090	1.48 ± 0.02	0.58 ± 0.02	2.22 ± 0.06
NLO19	0.091	1.46 ± 0.02	1.06 ± 0.02	3.32 ± 0.03
NLO	0.124	2.061 ± 0.001	1.087 ± 0.009	3.334 ± 0.008
$\mathrm{N^2LO}$	0.139	1.992 ± 0.002	1.23 ± 0.009	3.710 ± 0.007
Exp*	0.148 ± 0.040	2.169 ± 0.042 (${}^4_\Lambda\mathrm{H}$) 2.347 ± 0.036 (${}^4_\Lambda\mathrm{He}$)	1.081 ± 0.046 (${}^4_\Lambda\mathrm{H}$) 0.942 ± 0.036 (${}^4_\Lambda\mathrm{He}$)	3.102 ± 0.030

NN:SMS $\mathrm{N^4LO^+}$(450)

+3N: $\mathrm{N^2LO}$(450)

+SRG-induced YNN

* **https://hypernuclei.kph.uni-mainz.de/**

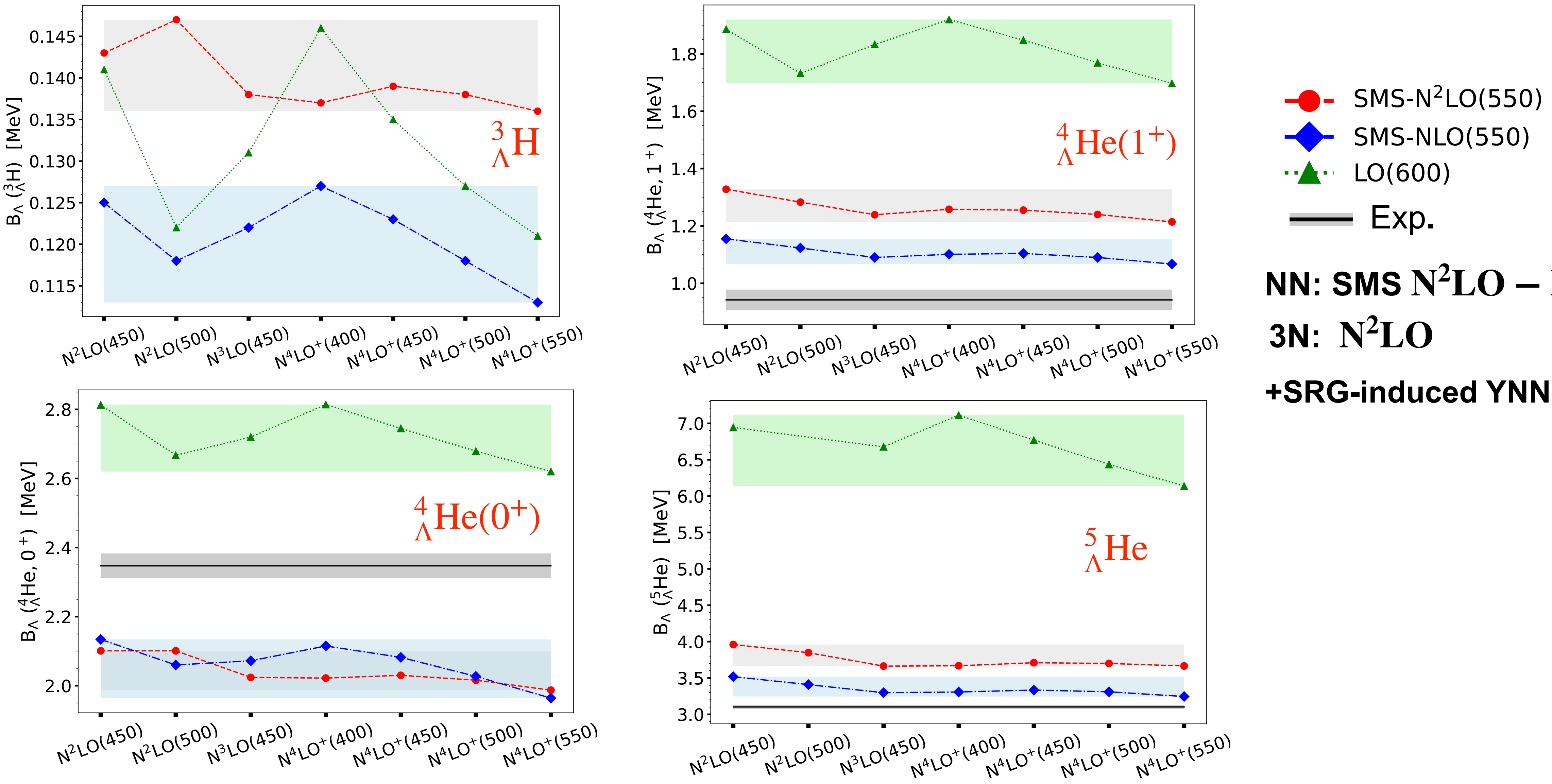
→ • all s-shell states are fairly well described with **SMS NLO & $\mathrm{N^2LO}$**

- **chiral YNN forces** contribute at $\mathrm{N^2LO}$ (5 **LECs** for ΛNN) → not possible to fix

  with decuplet saturation at NLO: 2 LECs (1 ΛNN+ 1 ΣNN) → fit to $B_\Lambda({}^4_\Lambda\mathrm{He}(0^+,1^+))$ **or** $B_\Lambda(\mathrm{He}(0^+), {}^5_\Lambda\mathrm{He}(1/2^+))$

  (work in progress)

Variation due to NN & YN interactions



NN: SMS $N^2LO - N^4LO^+$

3N: N^2LO

+SRG-induced YNN

→ **variations due to NN potentials < variations due to YN & differences to experiment;**

Variation due to NN interactions

NN: $N^2LO(450-500), N^3LO(450), N^4LO^+(400-550)$; 3N: N^2LO

considered NN + YN potentials	$B_\Lambda(^3_\Lambda H)$	$B_\Lambda(^4_\Lambda He, 0^+)$	$B_\Lambda(^4_\Lambda He, 1^+)$	$B_\Lambda(^5_\Lambda He)$
$N^4LO^+(400-550) + N^2LO(550)$	3	43	44	44
$N^4LO^+(400-550) + NLO(550)$	14	110	25	90
$(N^2LO, N^3LO, N^4LO^+) + N^2LO(550)$	11	114	114	295
$(N^2LO, N^3LO, N^4LO^+) + NLO(550)$	14	147	88	273
$N^4LO^+(400-550) + LO(600)$	25	194	223	970
Gazda* variation with cutoff	50	270	240	1150
Gazda* variance σ_{model}	20	100	100	400

*D. Gazda et al PRC 106(2022): based on **LO YN** + 42 **non-local** regularized NN(3N) N^2LO_{sim}

$\sigma_{\mathrm{model}} \equiv [\sigma^2(N^2LO_{sim})]^{1/2}$ (talk by Gazda)

→ • for YN **NLO, N^2LO: NN variations are "small", especially when SMS N^4LO^+ are employed**

• NN variations are expected to be counterbalanced by chiral YNN forces

Truncation error estimation

- NN &YN interactions are truncated at certain orders → higher-order contributions?
- **Epelbaum, Krebs and Meißner:**
  - cutoff variations → no **reliable estimate for truncation errors**
  - estimate truncation error at each order via **expected + actual size of higher-order corrections:**

E. Epelbaum, H. Krebs, U.-G. Meißner EPJA 51(2015)

$$X^{(k)} = X^{(0)} + \sum_{i=2}^{k} \Delta X^{(i)};$$

$$\delta X^{(0)} = Q^2 \, | X^{\mathrm{LO}} | ;$$

$$\delta X^{(\mathrm{i})} = \max_{2 \le j \le i} \left(Q^{i+1} | X^{(0)} | , Q^{i+1-j} | X^{(\mathrm{j})} - X^{(\mathrm{j}-1)} | \right); \qquad Q = M_\pi^{eff} / \Lambda_b$$

(Q: expansion parameter)

- **Furnstahl, Klco, Phillips, Melendez, Weslowski :**

R. J. Furnstahl et al PRC 92(2015)
J. A. Melendez et al PRC 96 (2017), 100(2019)

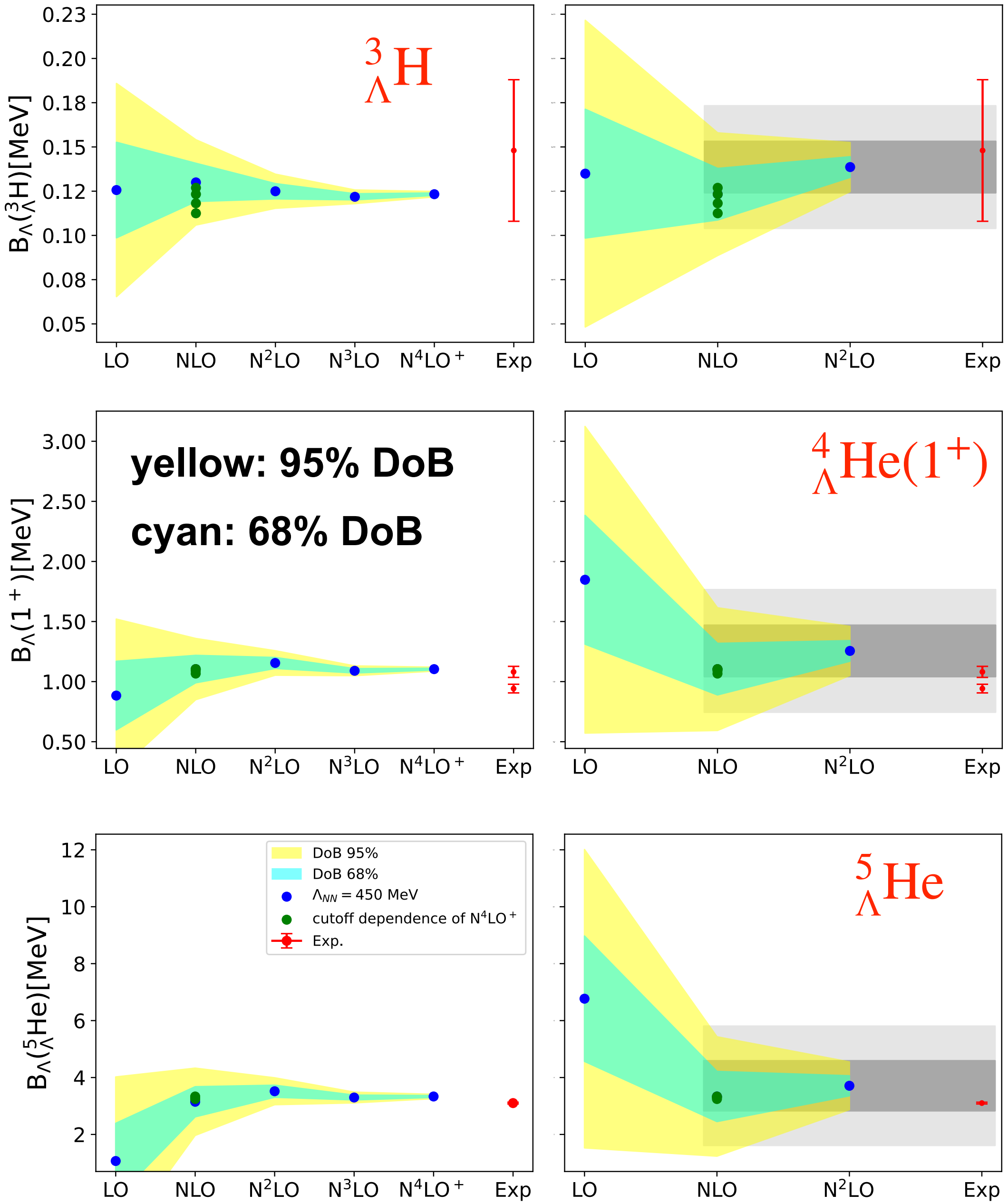
$$X^{(k)} = X^{(0)} + \sum_{i=2}^{k} \Delta X^{(i)} =: X_{ref} \left(c_0 + c_2 Q^2 + c_3 Q^3 + \cdots \right)$$

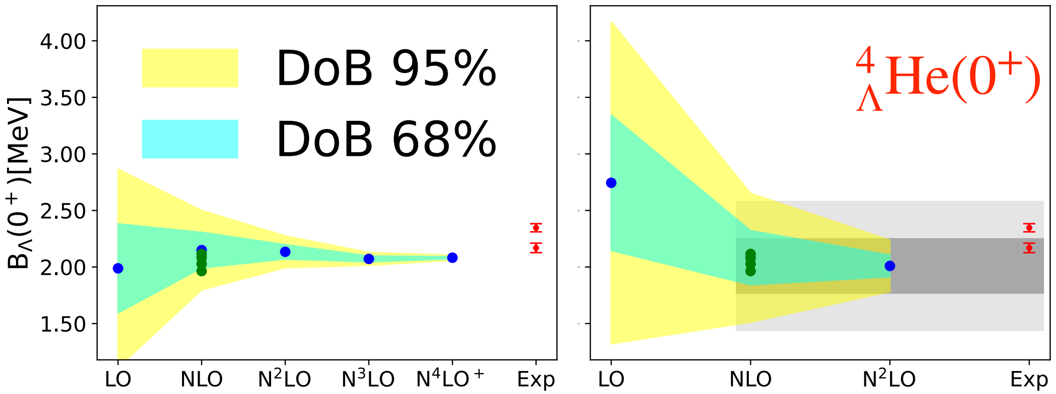
$$\delta X^{(k)} = X_{ref} \Big(\sum_{n=k+1}^{\infty} c_n Q^n \Big); \qquad c_n \sim \mathcal{O}(1); \qquad c_n | \bar{c}^2 \overset{\text{iid}}{\sim} \mathcal{N}(0, \bar{c}^2); \qquad \bar{c}^2 \sim \chi^{-2}(\nu_0, \tau_0^2)$$

(pointwise model)

$Q, \bar{c}^2$: learn from **order-by-order calculations together with prior expectations + consistency plots**

Truncation error estimation



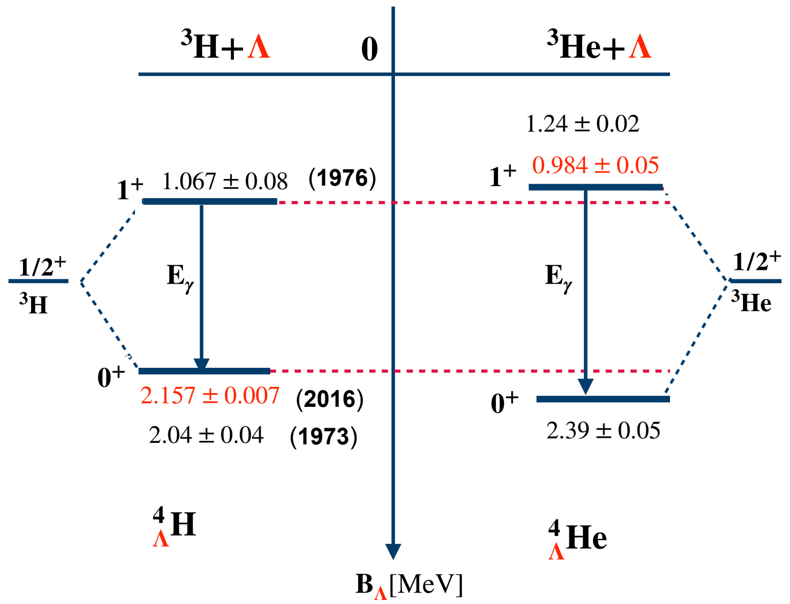


→
- NN convergence is **“faster”** than YN
- uncertainty due to YN truncation is dominant
- YNN contribution (half of 68%DoB interval at NLO):

$\sim$ **0.15, 0.24, 900 KeV for $^3_\Lambda$H, $^3_\Lambda$He, $^5_\Lambda$He**

→ **consistent** with estimates using **NLO13** & **NLO19**

Charge symmetry breaking (CSB) in A=4



Schulz et al (2016); Yamamoto et al (2015); Juric et al (1973); Bedjidian et al (1976,1979)

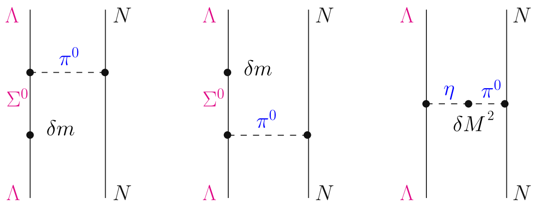
$$\Delta E(1^+) = B_\Lambda({}^4_\Lambda\mathrm{He}, 1^+) - B_\Lambda({}^4_\Lambda\mathrm{H}, 1^+) = -83 \pm 94 \text{ keV}$$

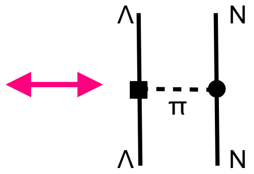
$$\Delta E(0^+) = B_\Lambda({}^4_\Lambda\mathrm{He}, 0^+) - B_\Lambda({}^4_\Lambda\mathrm{H}, 0^+) = 233 \pm 92 \text{ keV}$$

$$\Delta E({}^3\mathrm{H}, {}^3\mathrm{He}) \sim \underbrace{683}_{\text{Coulomb}} + \underbrace{81}_{\Delta M(p,n)} \text{ keV}$$ **(R. Brandenburg et al NPA 294(1978))**

CSB YN interactions at NLO **(J. Haidenbauer, U.-G. Meißner, A. Nogga FBS 62(2021))**

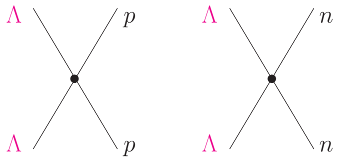
- sub-leading contributions are dominant:





$$f_{\Lambda\Lambda\pi} = \left[-2\frac{\langle\Sigma^0|\delta m|\Lambda\rangle}{m_{\Sigma^0} - m_\Lambda} + \frac{\langle\pi^0|\delta M^2|\eta\rangle}{M_\eta^2 - M_{\pi^0}^2}\right] f_{\Lambda\Sigma\pi}$$

(Dalitz, von Hippel, 1964)



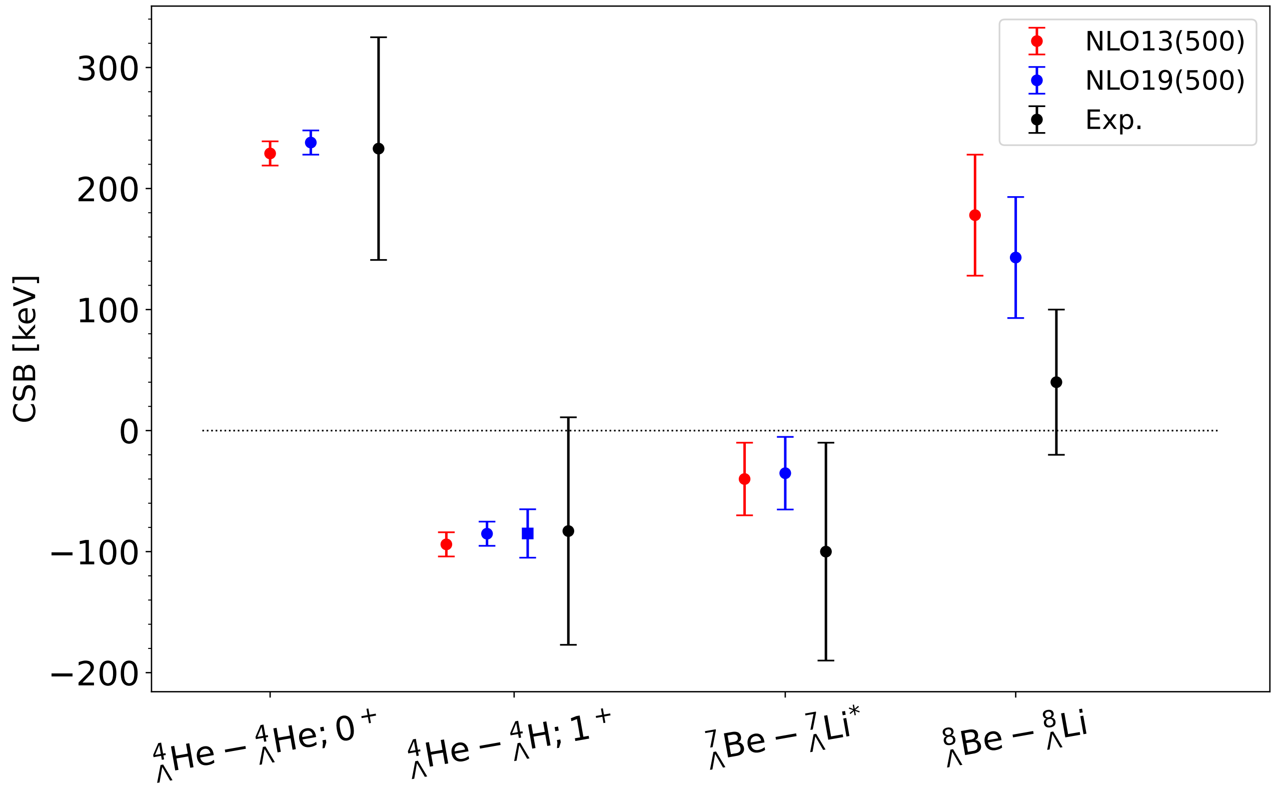
C_S^{CSB}, C_t^{CSB} adjusted to $\Delta E(0^+, 1^+)$

(fm//keV)	$a_s^{\Lambda p}$	$a_s^{\Lambda n}$	δa_s	$a_t^{\Lambda p}$	$a_t^{\Lambda n}$	δa_t
NLO19(**500**) no CSB	**-2.91**	**-2.91**	**0**	**-1.42**	**-1.41**	**-0.01**
CSB(**500**)	**-2.65**	**-3.20**	**0.55**	**-1.58**	**-1.47**	**-0.11**
CSB(550)	-2.64	-3.21	0.57	-1.52	-1.41	-0.11
CSB(600)	-2.63	-3.23	0.6	-1.47	-1.36	-0.09
CSB(650)	-2.62	-3.23	0.61	-1.46	-1.37	-0.09

→ **cutoff (and YN) independent prediction for $a(\Lambda n)$**

CSB results in A=4-8

HL, J. Haidenbauer, U.-G. Meißner, A. Nogga PRC 107(2023)



NN:SMS N^4LO+(450)

+3N: N^2LO(450)

+YN: NLO13,19(CSB)

+SRG-induced YNN

- CSB predictions for A=7 **are comparable to experiment.**
- both potentials predict a somewhat **larger CSB in A=8 doublet as compared to experiment**

→ ‣ experimental CSB splitting for A=8 **larger than 40 ± 60 keV**?

‣ CSB estimated for A=4: **too large? different spin-dependence**?

Fitting LECs to new Star measurement

Recent STAR measurement suggests somewhat different CSB in A=4:

$$\Delta E(1^+) = B_\Lambda({}^4_\Lambda\mathrm{He}, 1^+) - B_\Lambda({}^4_\Lambda\mathrm{H}, 1^+)$$

$$= -83 \pm 94\ \mathrm{keV} \quad \Rightarrow \text{(CSB)}$$

$$= \mathbf{-160 \pm 140 \pm 100}\ \mathrm{keV} \quad \Rightarrow \text{(CSB*)}$$

$$\Delta E(0^+) = B_\Lambda({}^4_\Lambda\mathrm{He}, 0^+) - B_\Lambda({}^4_\Lambda\mathrm{H}, 0^+)$$

$$= 233 \pm 92\ \mathrm{keV} \quad \Rightarrow \text{(CSB)}$$

$$= \mathbf{160 \pm 140 \pm 100}\ \mathrm{keV} \quad \Rightarrow \text{(CSB*)}$$

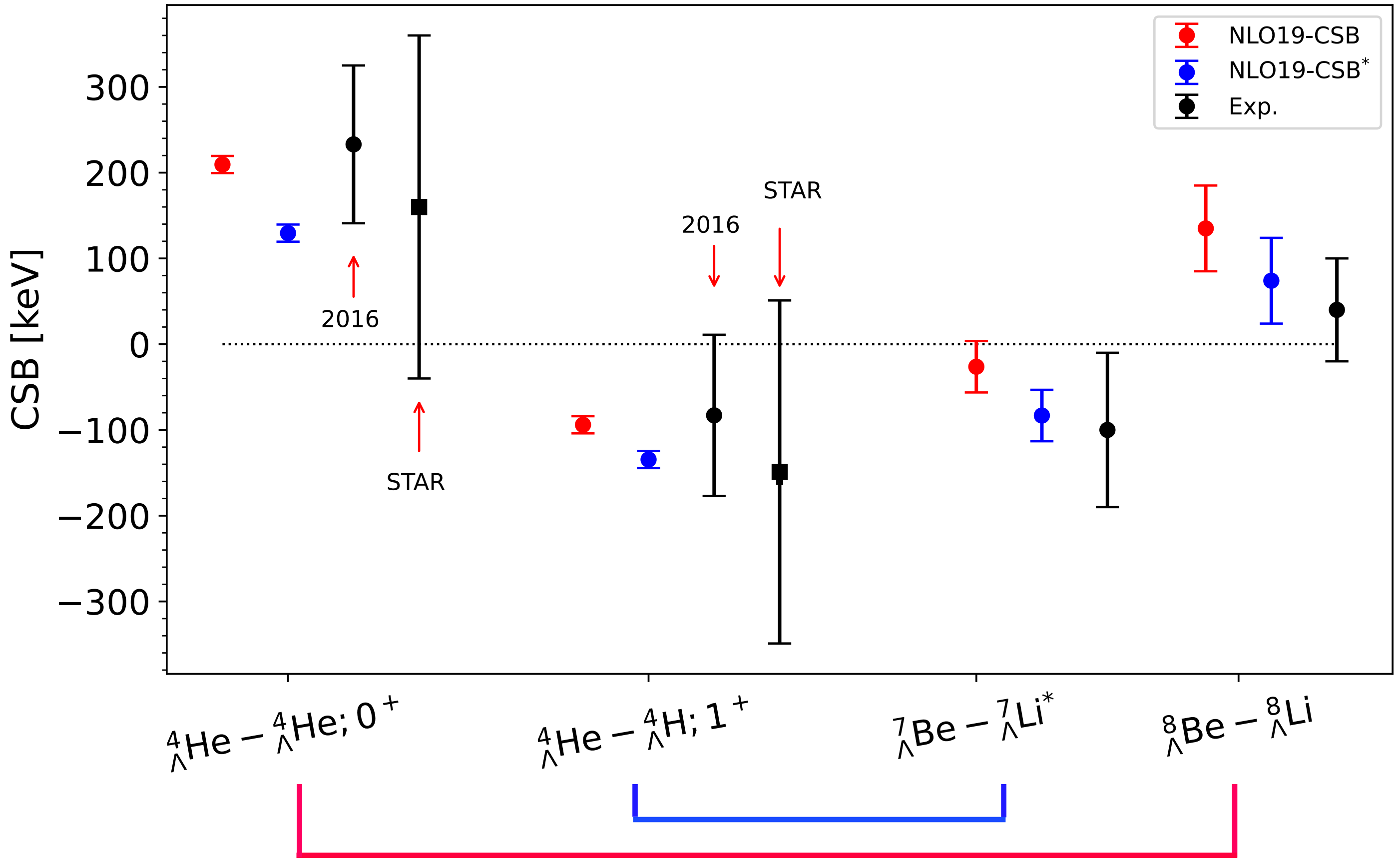
* STAR Collaboration PLB 834 (2022)

	NLO19(500)	CSB	CSB*
$a_s^{\Lambda p}$	-2.91	-2.65	-2.58
$a_s^{\Lambda n}$	-2.91	-3.20	-3.29
$\boldsymbol{\delta a_s}$	**0**	**0.55**	**0.71**
$a_t^{\Lambda p}$	-1.42	-1.57	-1.52
$a_t^{\Lambda n}$	-1.41	-1.45	-1.49
$\boldsymbol{\delta a_t}$	**-0.01**	**-0.12**	**-0.03**

→ $\delta a({}^1\mathbf{S}_0)$ **increases** while $\delta a({}^3\mathbf{S}_1)$ **decreases**

→ **How does the STAR measurement affect the predictions of CSB in A=7,8 multiplets ?**

Impact of Star measurement on CSB in A=7,8



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

+YN: NLO13,19(CSB)

$$\lambda_{NN} = 1.6\,\mathrm{fm}^{-1}$$

$$\lambda_{YN}^{opt} = 0.823\,\mathrm{fm}^{-1}$$

$$B_\Lambda(^5_\Lambda\mathbf{He}, \lambda_{YN}^{opt}) = B_\Lambda(^5_\Lambda\mathbf{He}, \mathrm{3BFs})$$

- **CSB* fit predicts reasonable CSB in both A=7 and A=8 systems**
- CSB in A=4($\mathbf{0^+}$) and A=8, and in A=4($\mathbf{1^+}$) and A=7 are correlated

→ accurate CSB in A=7 & 8 may allow for an independent check of A=4 CSB

Summary

- At our disposal we have 3 tools to tackle light (hyper)nuclear systems:
  - s-shell (hyper)nuclei: Faddeev-Yakubovsky, NLEFT (**D. Frame et al EPJA 56(2020)**)
  - s-shell & light p-shell: Jacobi NCSM approach; numerical uncertainties (s-shell) ~ few keV

  → **establish a direct link between chiral YN interactions and observables ($A \leq 9$)**

- YN at **NLO & $\mathbf{N^2LO}$** yields **reasonable $\mathbf{B_\Lambda}$ in** $A = \mathbf{3-8}$ hypernuclei.
  NLO13 & NLO19 results show a clear signal of missing chiral YNN forces

- study convergence w.r. to NN & YN orders in $A = 3 - 5$ hypernuclei

- **CSB NLO** interactions **reproduce** experimental CSB for $\boldsymbol{A = 4, 7}$ multiplets,
  $\boldsymbol{A = 8}$ CSB prediction **is larger** than experiment

Thank you for the attention!