Hypernuclei based on chiral interactions

JÜLICH Forschungszentrum

Andreas Nogga, Forschungszentrum Jülich

19th International Conference on Hadron Spectroscopy and Structure
in memoriam Simon Eidelman (HADRON 2021), Mexico City

- Motivation
- Chiral YN interactions and estimates of 3BF contributions
- SRG evolution of (hyper-)nuclear interactions
- Impact of an increased $E_\Lambda({}^3_\Lambda H)$ on hypernuclear binding
- Light $S = -2$ hypernuclei
- Determination of CSB contact interactions and Λn scattering length
- Conclusions & Outlook

in collaboration with Johann Haidenbauer, **Hoai Le**, Ulf Meißner

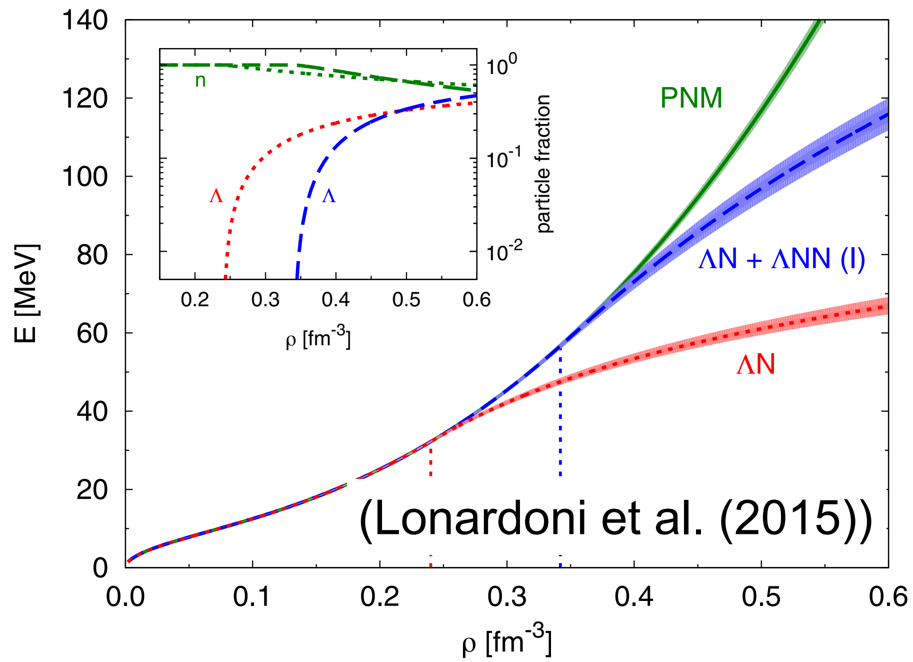
J. Haidenbauer et al. [arXiv:2107.01134 [nucl-th]].
H. Le et al., Eur. Phys. J. A 57 (2021), 217 [arXiv:2103.08395 [nucl-th]].
H. Le et al., Eur. Phys. J. A 56 (2020) 301 [arXiv:2008.11565 [nucl-th]].
H. Le et al., Phys. Lett. B 801 (2020), 135189[arXiv:1909.02882 [nucl-th]].

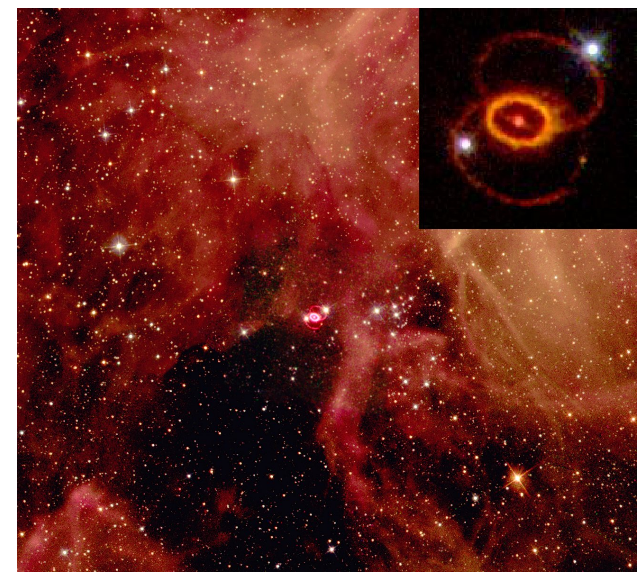
Juli 29th, 2021

Hypernuclear interactions

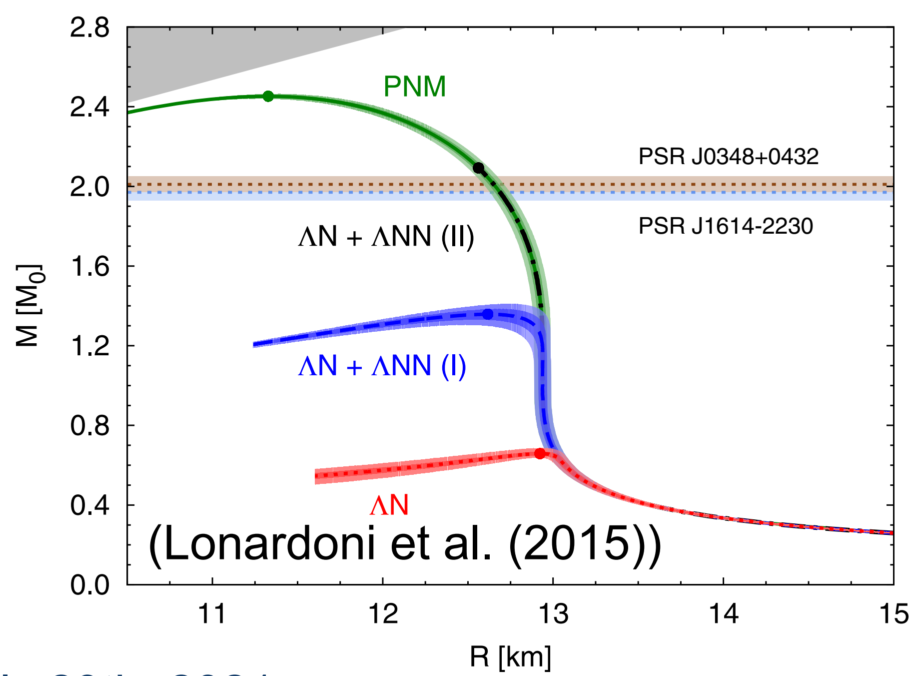
Why is understanding hypernuclear interactions interesting?

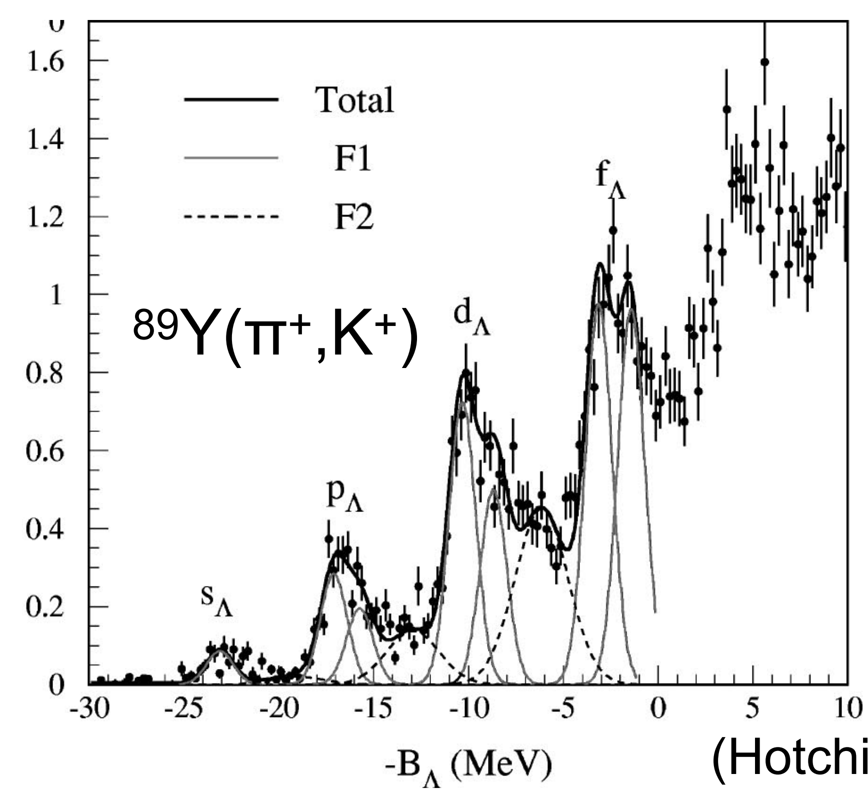
- „phenomenologically“
  - *hyperon contribution to the EOS, neutron stars, supernovae*
  - *Λ as probe to nuclear structure*





(SN1987a, Wikipedia)





(Hotchi et al. (2001))

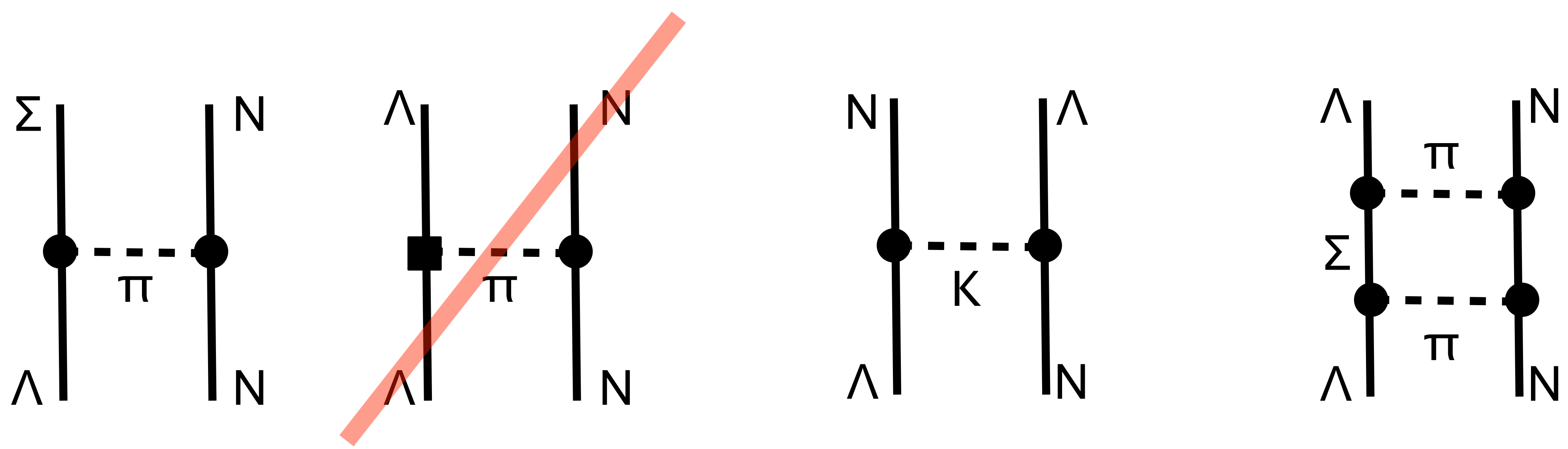
Hypernuclear interactions

Why is understanding hypernuclear interactions interesting?

- Hypernuclear interactions have interesting properties

For example

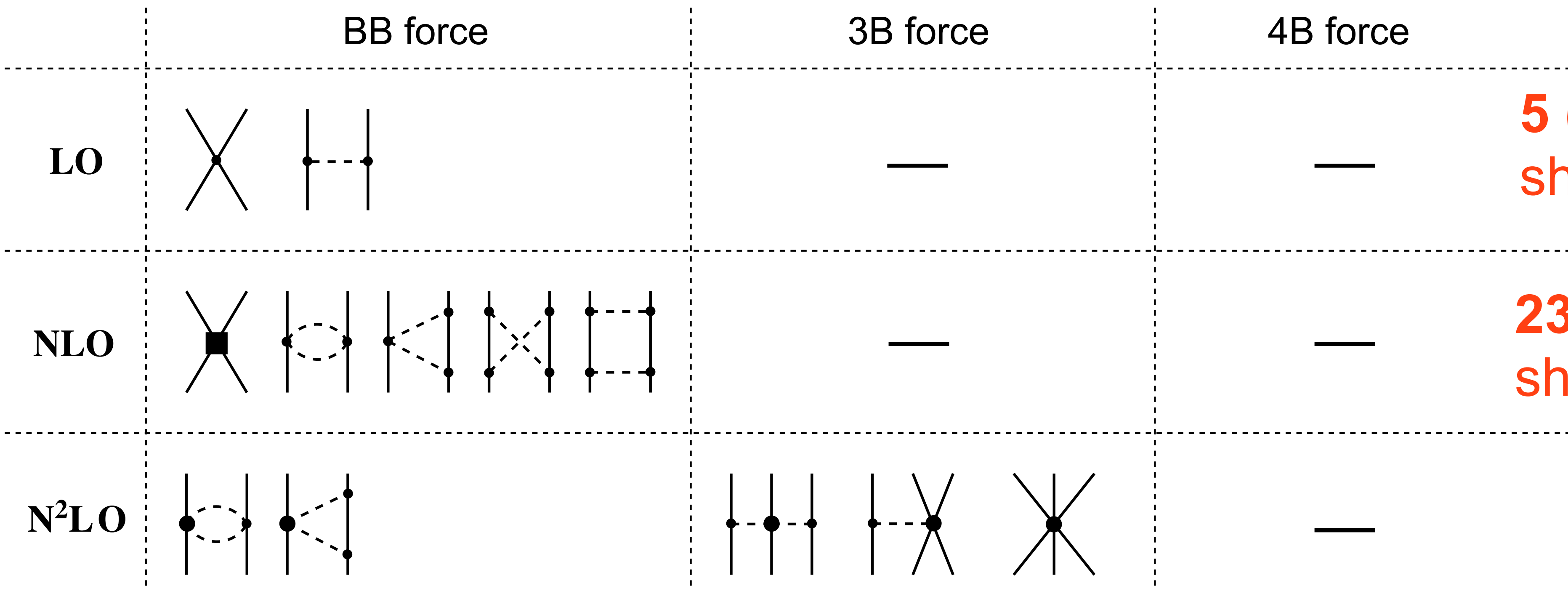
- *Particle conversion process is sometimes long-range part of the interaction*
- *experimental access to explicit chiral symmetry breaking*



suppressed by
isospin symmetry (CSB!)

$m_K \approx 500 \text{ MeV}$

Chiral NN & YN & YY interactions



5 (+1) NN/YN (YY)
short range parameters

23(+5) NN/YN (YY)
short range parameters

(adapted from Epelbaum, 2008)

additional constraints required (e.g. for YN only 35 data, but 23 parameters at NLO)

data too scarce to uniquely determine the short range LECs!

→ **Two** realization for the YN interaction at NLO: NLO13 & NLO19
with different assumptions on the LECs

(J. Haidenbauer et al., 2013 & 2019)

YY interaction at NLO

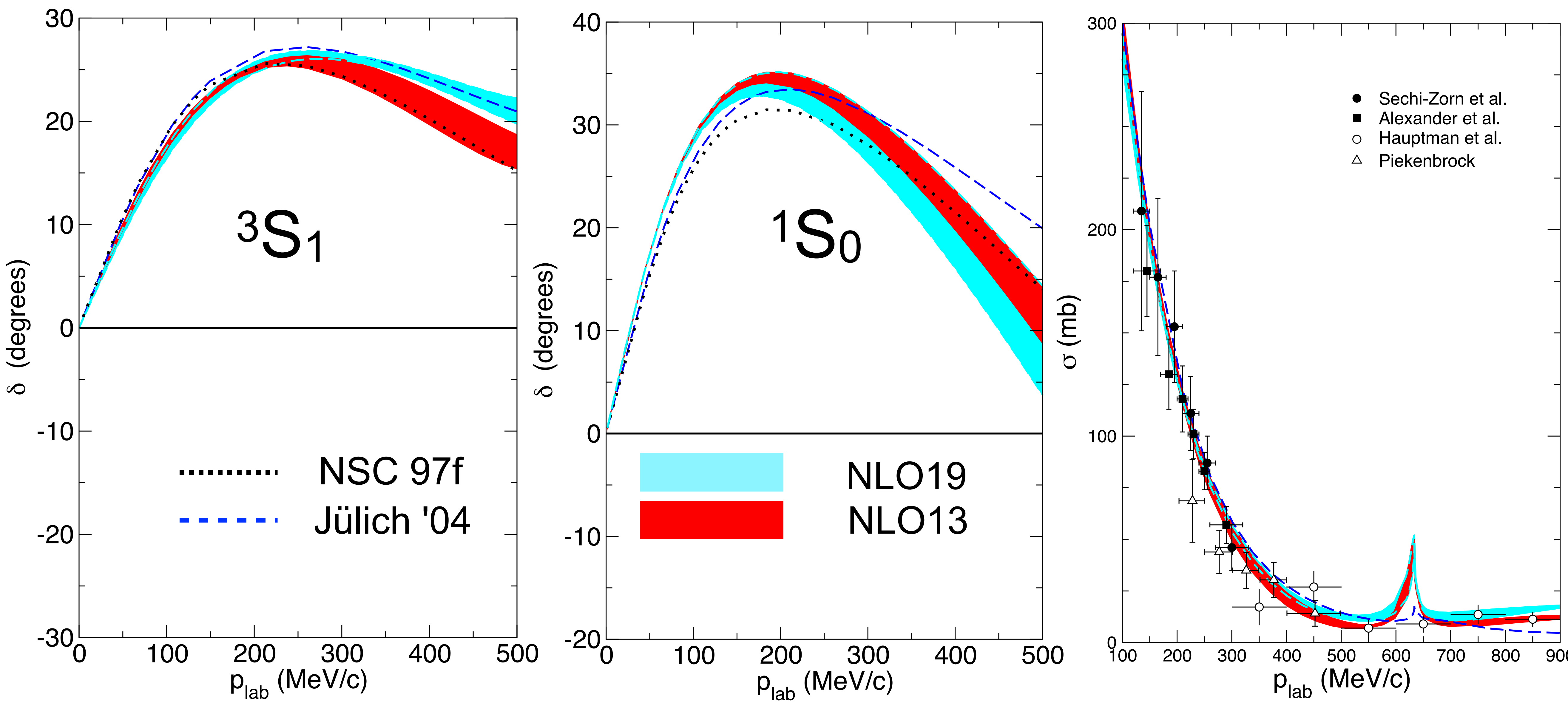
(J. Haidenbauer et al., 2016 & 2019)

Chiral interactions include symmetries of QCD & retain flexibility to adjust to data

Regulator required — cutoff is also used to estimate uncertainty

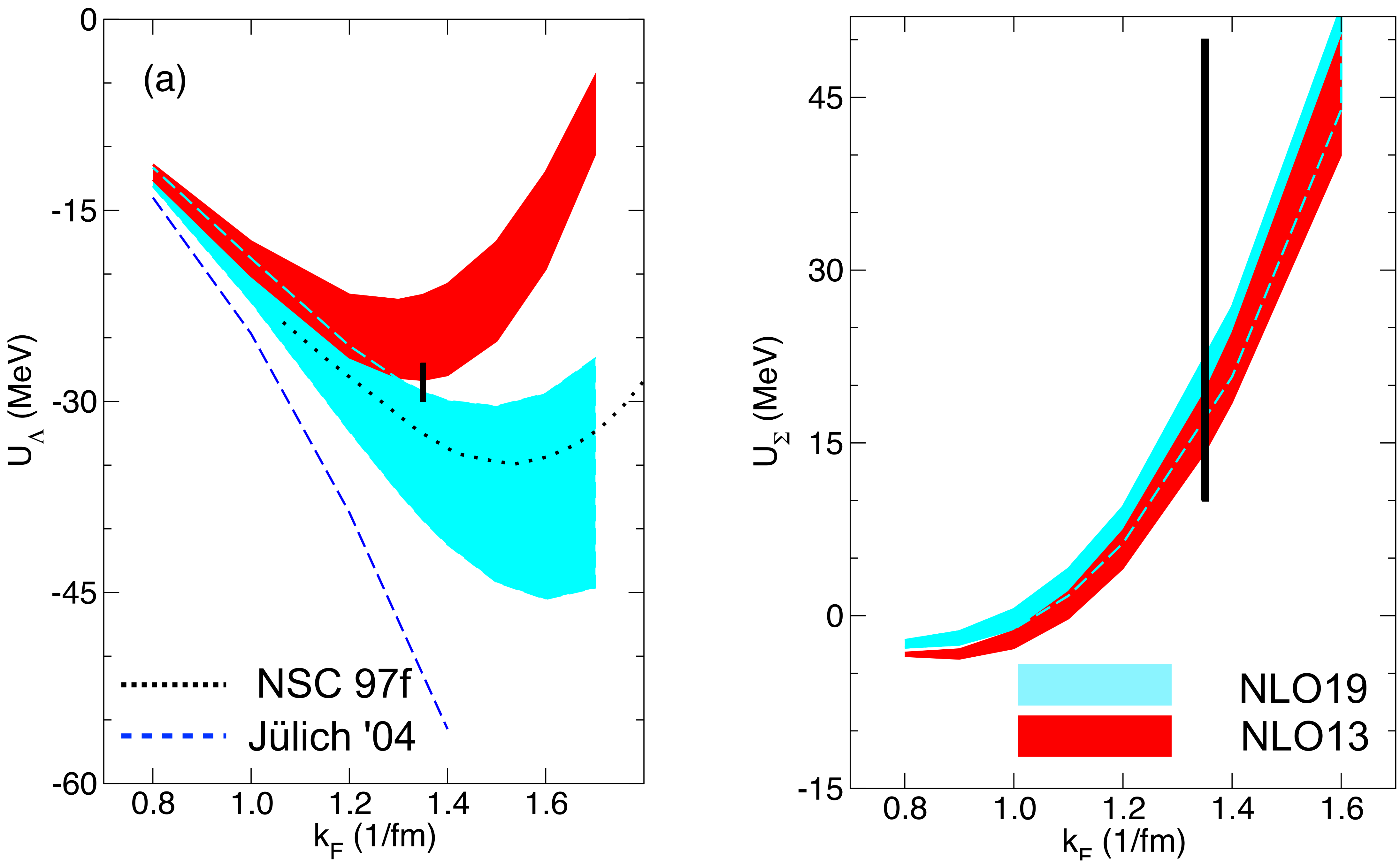
NLO13 / NLO19 - tool to estimate 3BF

- Regularization required
  — Dependence on cutoff **indicates** uncertainty
- NLO13 and NLO19 interactions largely phase shift equivalent
  — differences indicate size of three-baryon interactions



(Haidenbauer at al., 2019)

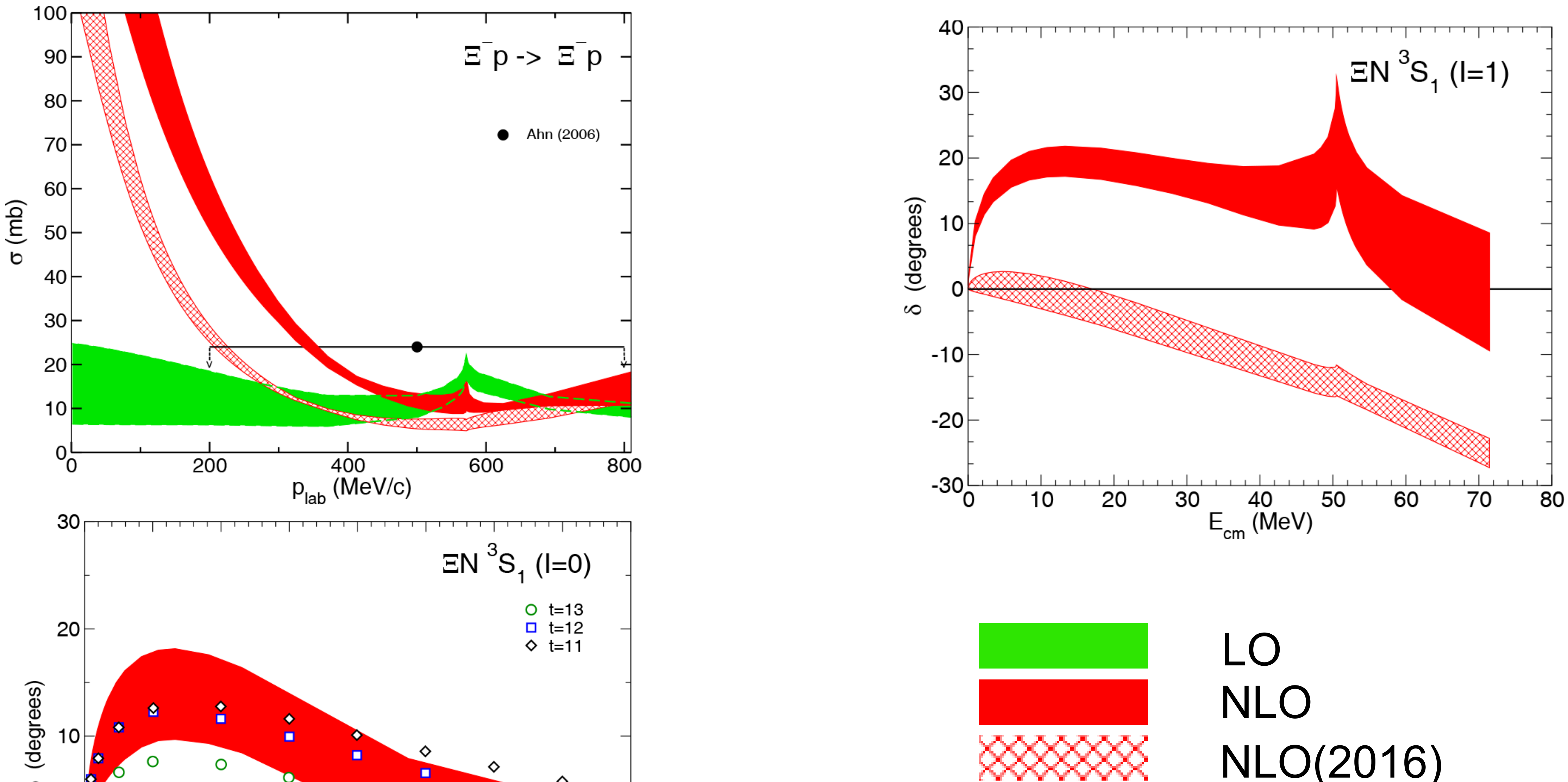
3BF contribution in nuclear matter ?



(Haidenbauer at al., 2019)

→ Indication that 3BF contribution is significant at saturation density
Probably less important for light hypernuclei

YY interaction



(Haidenbauer at al., 2019)

→ adjusted to data & LQCD (HAL QCD)

updated version consistent with Ξ-nuclei (only change in $\Xi N\ {}^3S_1$)

SRG interactions

Similarity renormalization group is by now a **standard tool** to obtain soft effective interactions for various many-body approaches (NCSM, coupled-cluster, MBPT, …)

Idea: perform a unitary transformation of the NN (and YN interaction) using a cleverly defined "generator"

$$\frac{dH_s}{ds} = [\underbrace{[T, H(s)]}_{\equiv\eta(s)}, H(s)] \qquad H(s) = T + V(s)$$

this choice of generator drives *V(s)* into a diagonal form in momentum space

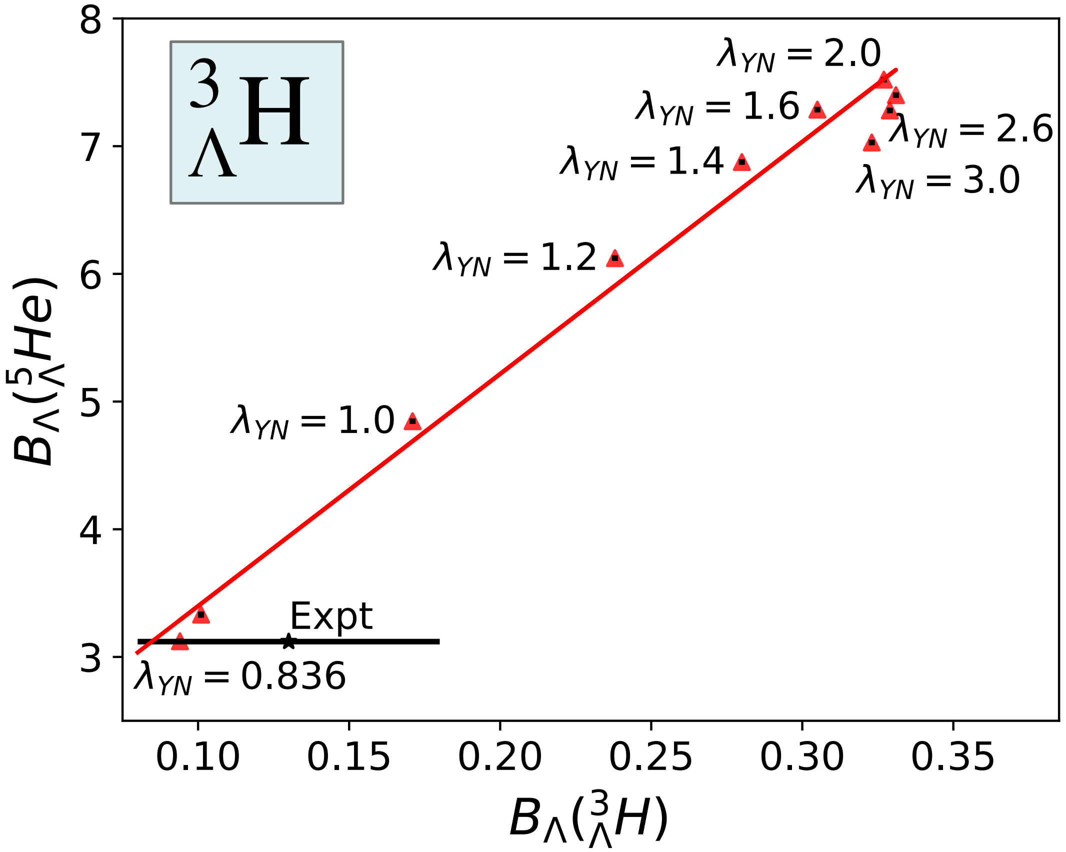
- *V(s)* will be phase equivalent to original interaction
- short range *V(s)* will change towards softer interactions
- 3BF, 4BF, … can in principle be generated but are omitted here
- $\lambda = \left(\frac{4\mu_{BN}^2}{s}\right)^{1/4}$ is a measure of the width of the interaction in momentum space

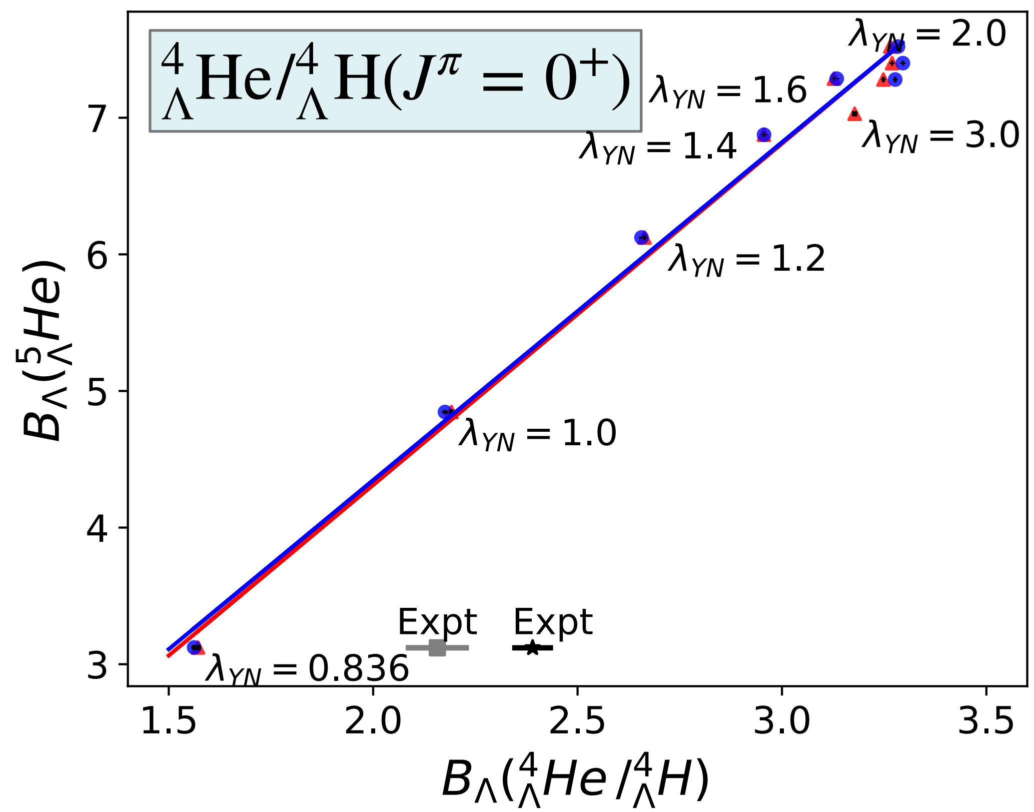
(Bogner et al., 2007)

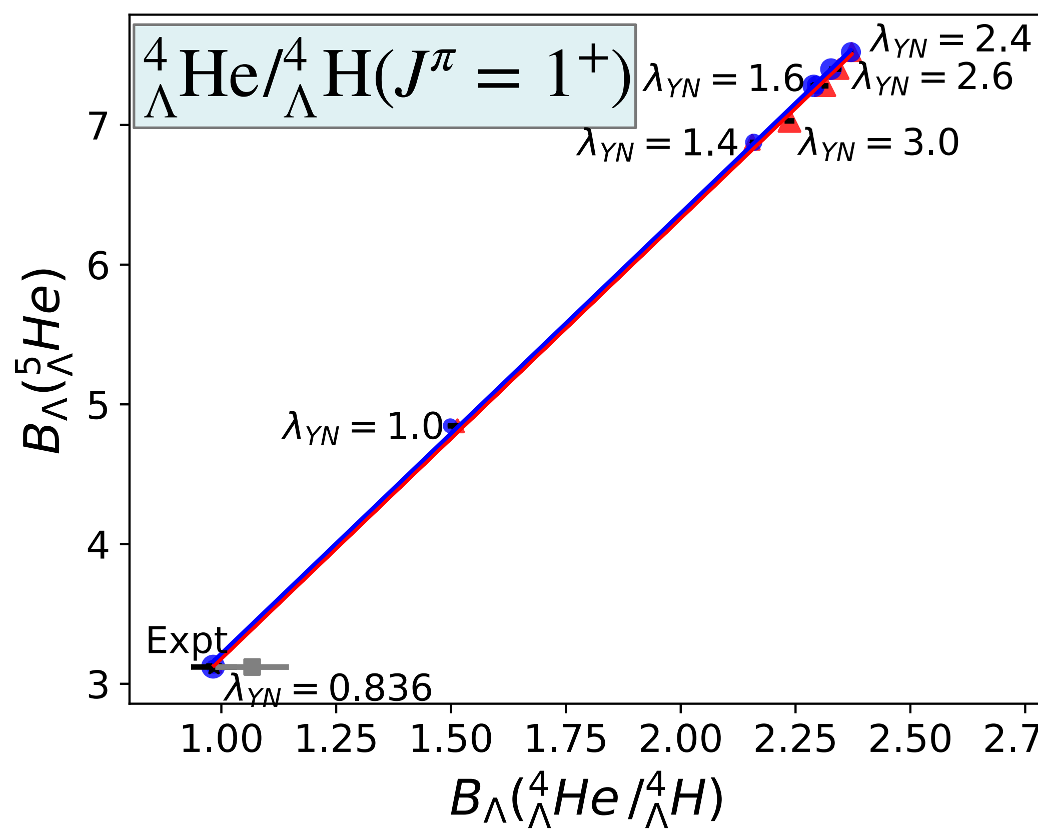
Unfortunately: ΛNN SRG induced-3BFs are large, probably much larger than chiral ones! (see also Wirth et al. (2016))

Correlation of separation energies

Separation energies of s-shell hypernuclei are strongly correlated (to $^{5}_{\Lambda}\mathrm{He}$)



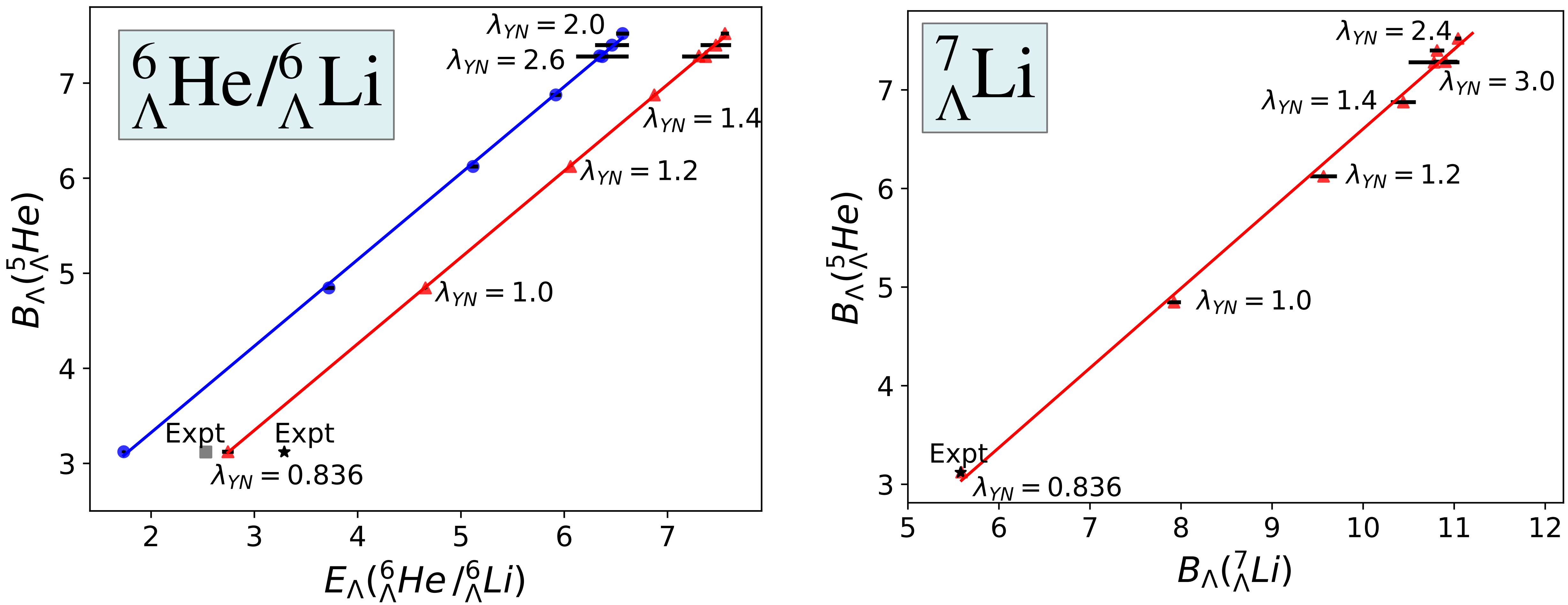




- YN interaction: **NLO 600 (2015)**
- no CSB in YN and masses added here (yet)
- strong overbinding for $\lambda \gtrsim 1.0\ \mathrm{fm}^{-1}$
- but A=3 and A=5 consistently predicted for $\lambda \approx 0.836\ \mathrm{fm}^{-1}$

p-shell hypernuclei

Separation energies of p-shell hypernuclei are also correlated (to $^{5}_{\Lambda}\mathrm{He}$)

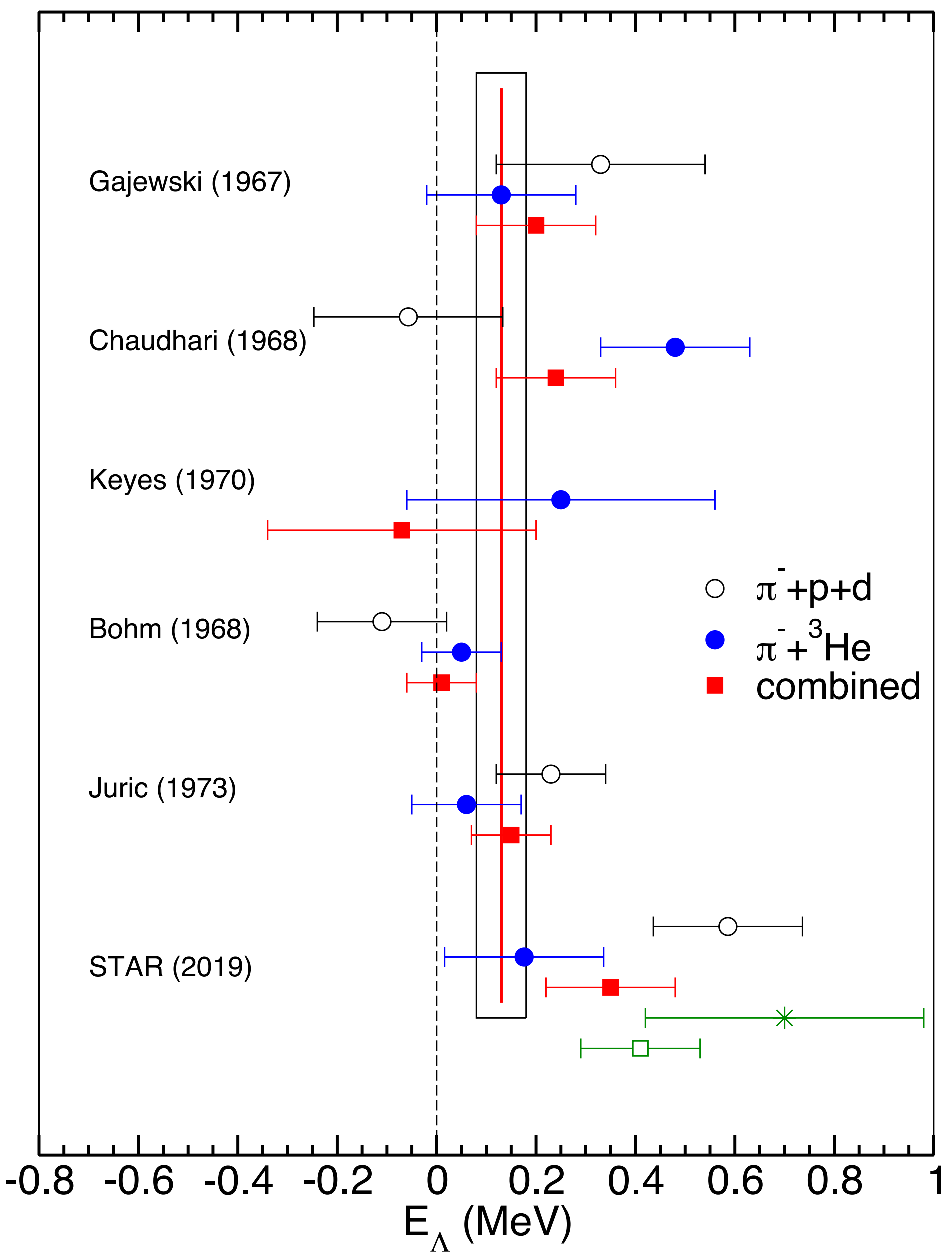


- YN interaction: **NLO19(600)**
- $^{7}_{\Lambda}\mathrm{Li}$ astonishingly well reproduced at "magic" $\lambda \approx 0.836 \ \mathrm{fm}^{-1}$
- A=6 in our calculations not particle stable
- NCSM works for narrow resonances
- Coulomb contribution in $A = 6$ ($^{4}\mathrm{He}$ is used as baseline)

Increased binding of ${}^{3}_{\Lambda}\mathrm{H}$

- ${}^{3}_{\Lambda}\mathrm{H}$ is used to determine relative strength of ${}^{3}S_{1}$/ ${}^{1}S_{0}$ interactions or relative size of $a_3^{\Lambda N}$ and $a_1^{\Lambda N}$
- Jurič et al. (**1973!**) $E_\Lambda\left({}^{3}_{\Lambda}\mathrm{H}\right) = (130 \pm 50)\ \mathrm{keV}$

  new: Adam et al. (2019) $E_\Lambda\left({}^{3}_{\Lambda}\mathrm{H}\right) = (410 \pm 120)\ \mathrm{keV}$



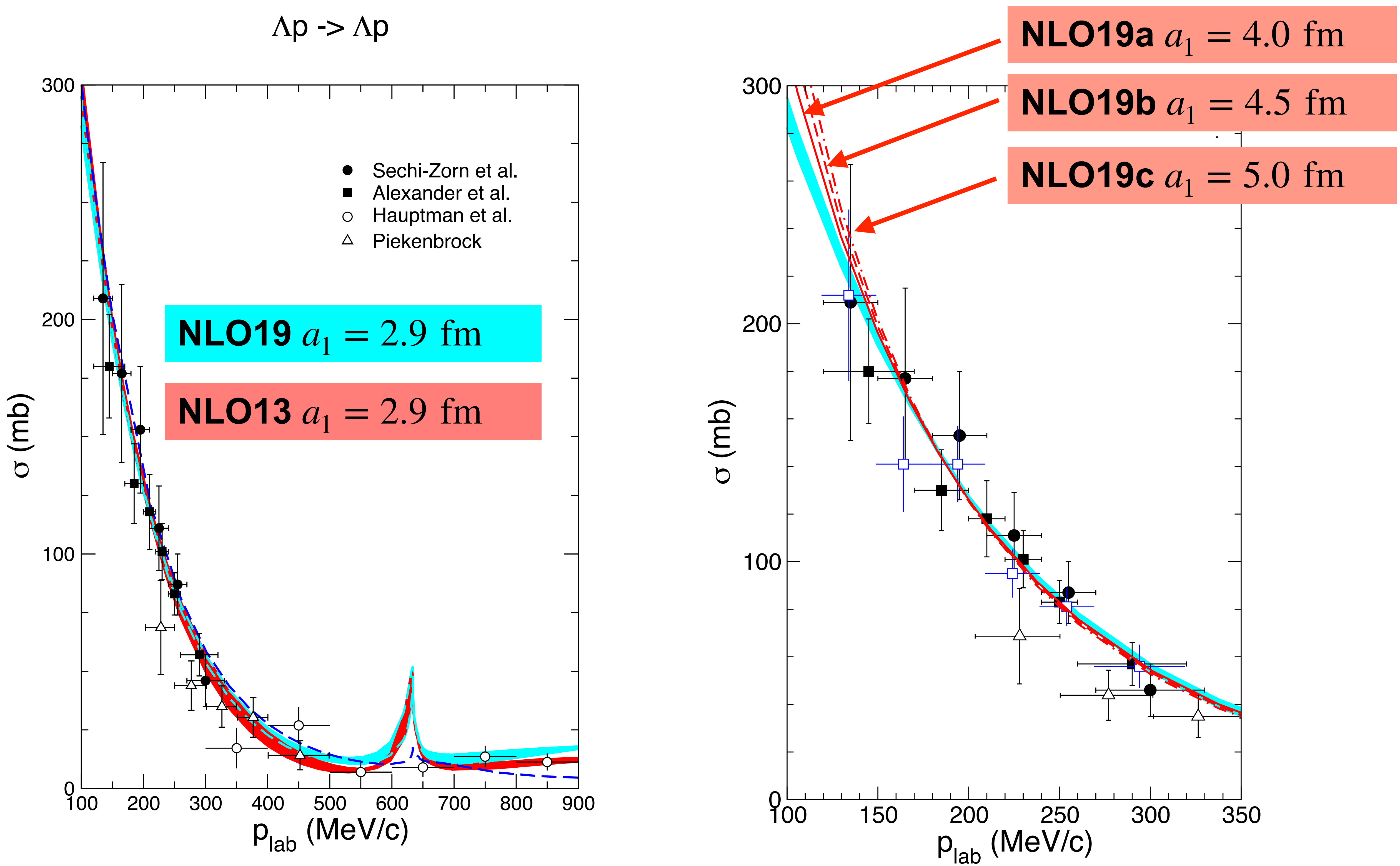
- separation energies of light hypernuclei have often been obtained many years ago from emulsion data
- systematic uncertainties?
- different experiments contradict each other

What would be the impact on hypernuclear binding in general if ${}^{3}_{\Lambda}\mathrm{H}$ the binding increases?

Equivalent to: What happens if $a_1^{\Lambda N}$ increases?

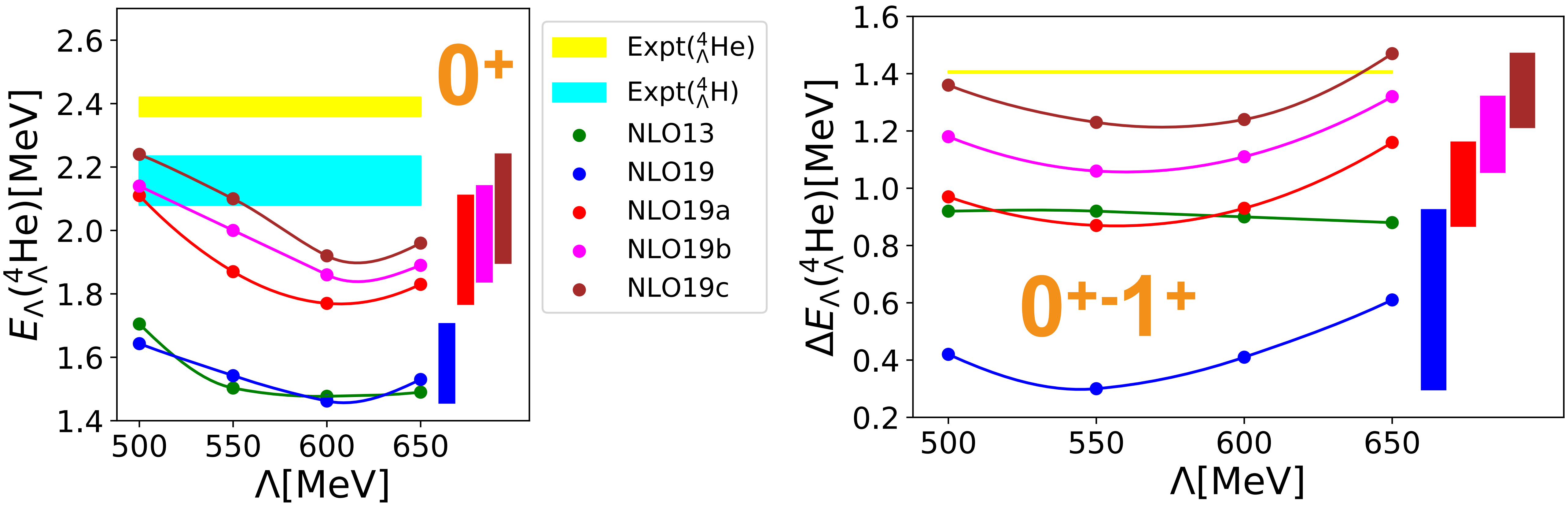
(Le et al., 2020)

Increasing $a_1^{\Lambda N}$ ….



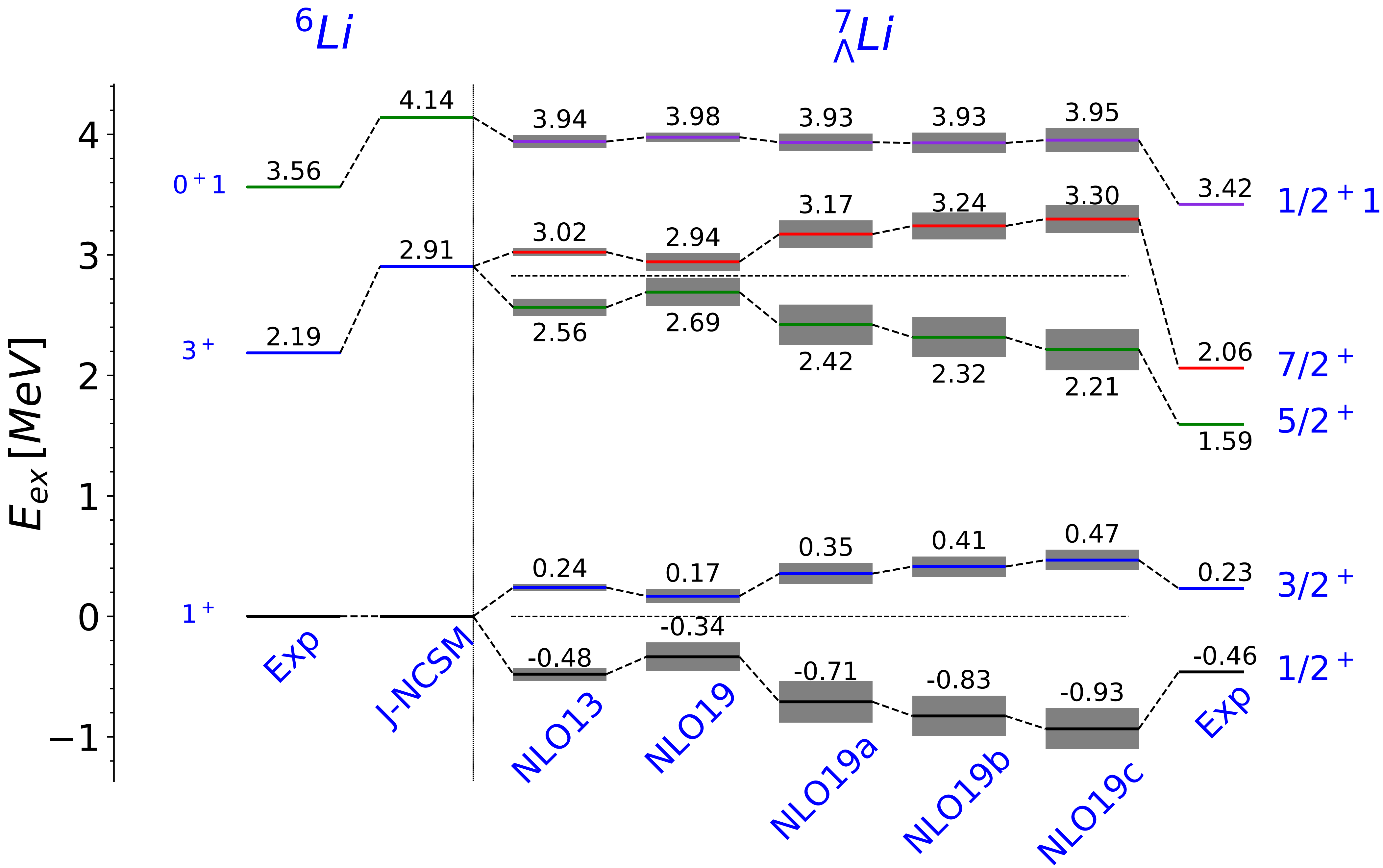
… can be done without changing the nice description of available YN data ✔

Increasing $a_1^{\Lambda N}$ ....



… improves the description of $^4_\Lambda\mathrm{He}$ ✔

Increasing $a_1^{\Lambda N}$ ….



… does not distort the description of $^7_\Lambda$Li ✔

In summary: an increase of the hypertriton binding energy is not excluded by binding energies of other light hypernuclei!

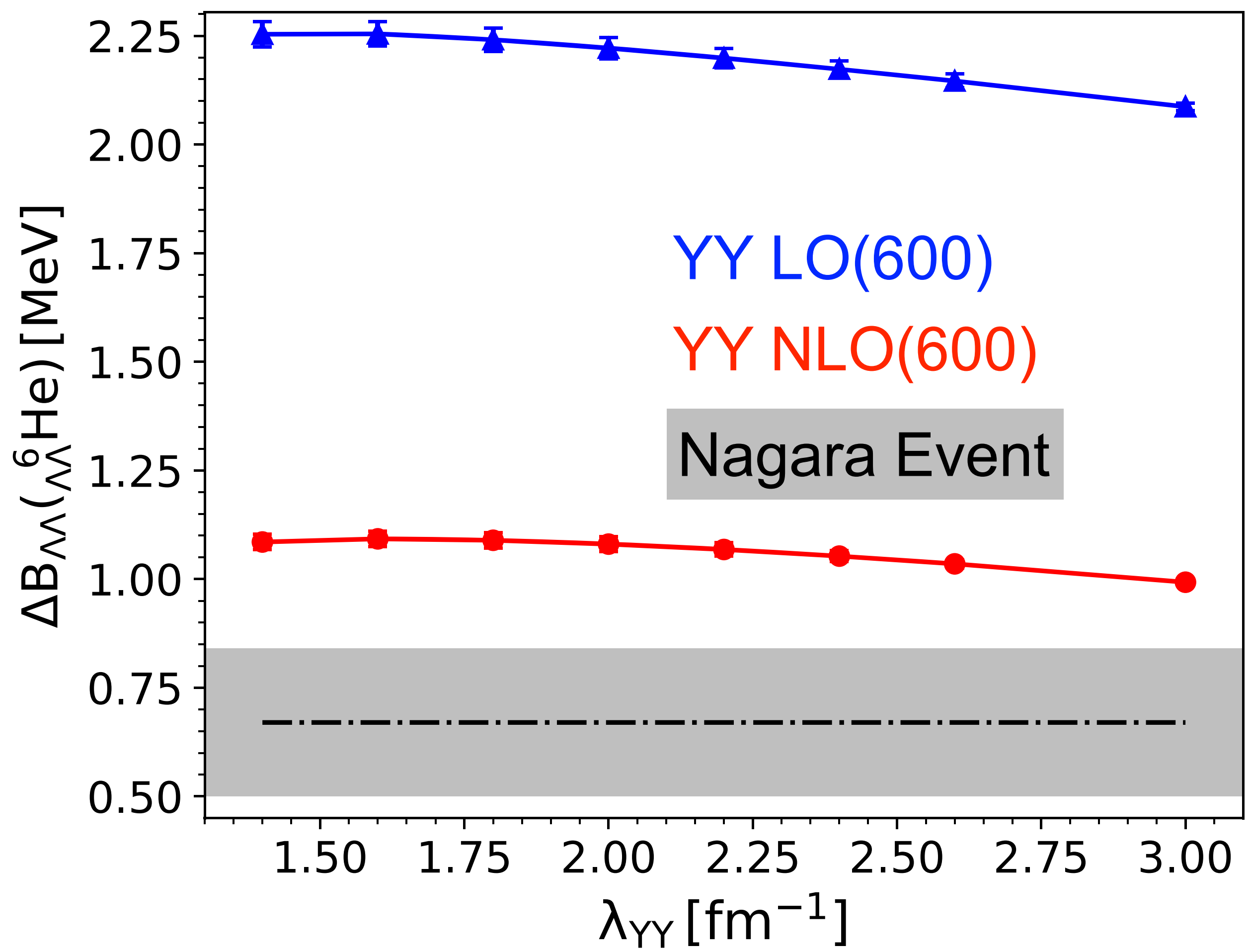
$S = -2$ hypernuclei — ${}^{6}_{\Lambda\Lambda}\mathrm{He}$

(Le et al., 2021)

- $\Lambda\Lambda$ excess binding energy

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_{\Lambda}$$
$$= 2E\left({}^{A-1}_{\Lambda}X\right) - E\left({}^{A}_{\Lambda\Lambda}X\right) - E\left({}^{A-2}X\right)$$

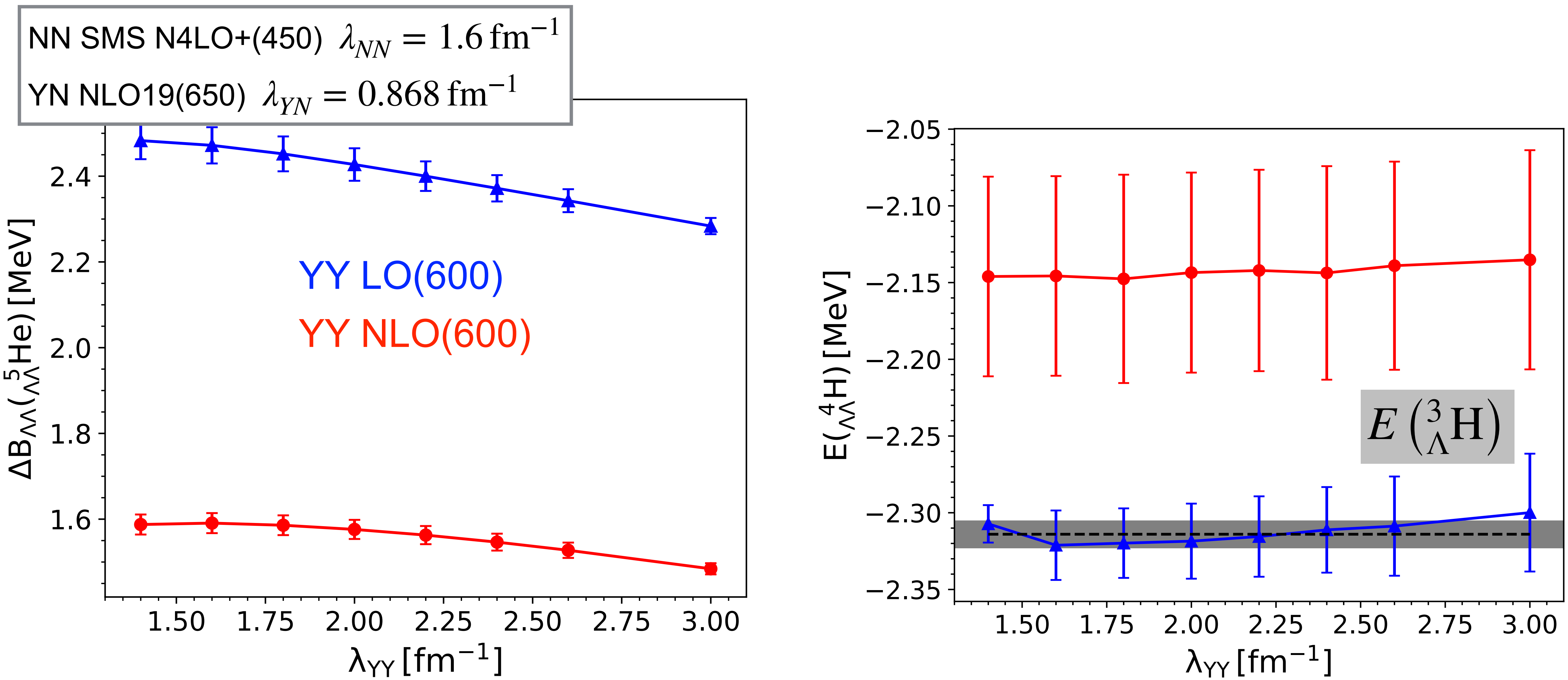
- NN, YN and YY interactions contribute
- use NN and YN that describe nuclei and single Λ hypernuclei
- small λ_{YY} dependence
- LO overbinds YY
- NLO predicts binding fairly well



NN SMS N4LO+(450) $\lambda_{NN} = 1.6\,\mathrm{fm}^{-1}$
YN NLO19(650) $\lambda_{YN} = 0.868\,\mathrm{fm}^{-1}$

Can an $S = -2$ bound state for $A = 4,5$ be expected?

$S = -2$ hypernuclei — ${}^{5}_{\Lambda\Lambda}\mathrm{He}$ & ${}^{4}_{\Lambda\Lambda}\mathrm{H}$



- $A = 5$: $\Lambda\Lambda$ excess binding energy & $A = 4$: binding energy
- $A = 5$: LO & NLO predicts bound state
- $A = 4$: NLO unbound, LO at threshold to binding (see also Contessi et al., 2019)
- excess energy larger for $A = 5$ than for $A = 6$ (in contrast to Filikhin et al., 2002!)

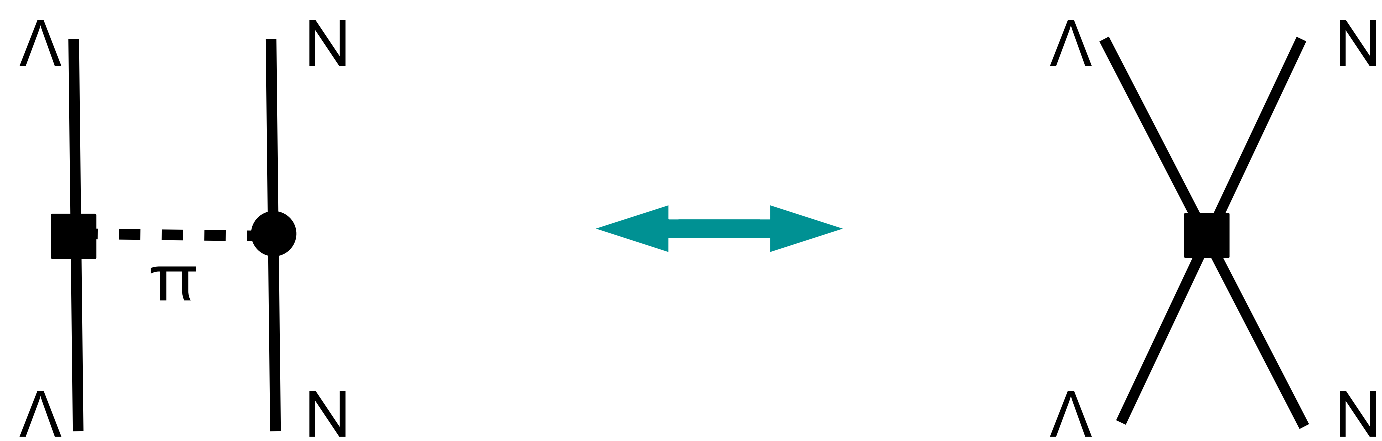
$S = -2$ bound state for $A = 5$ can be expected,

for $A = 4$ less likely but not ruled out!

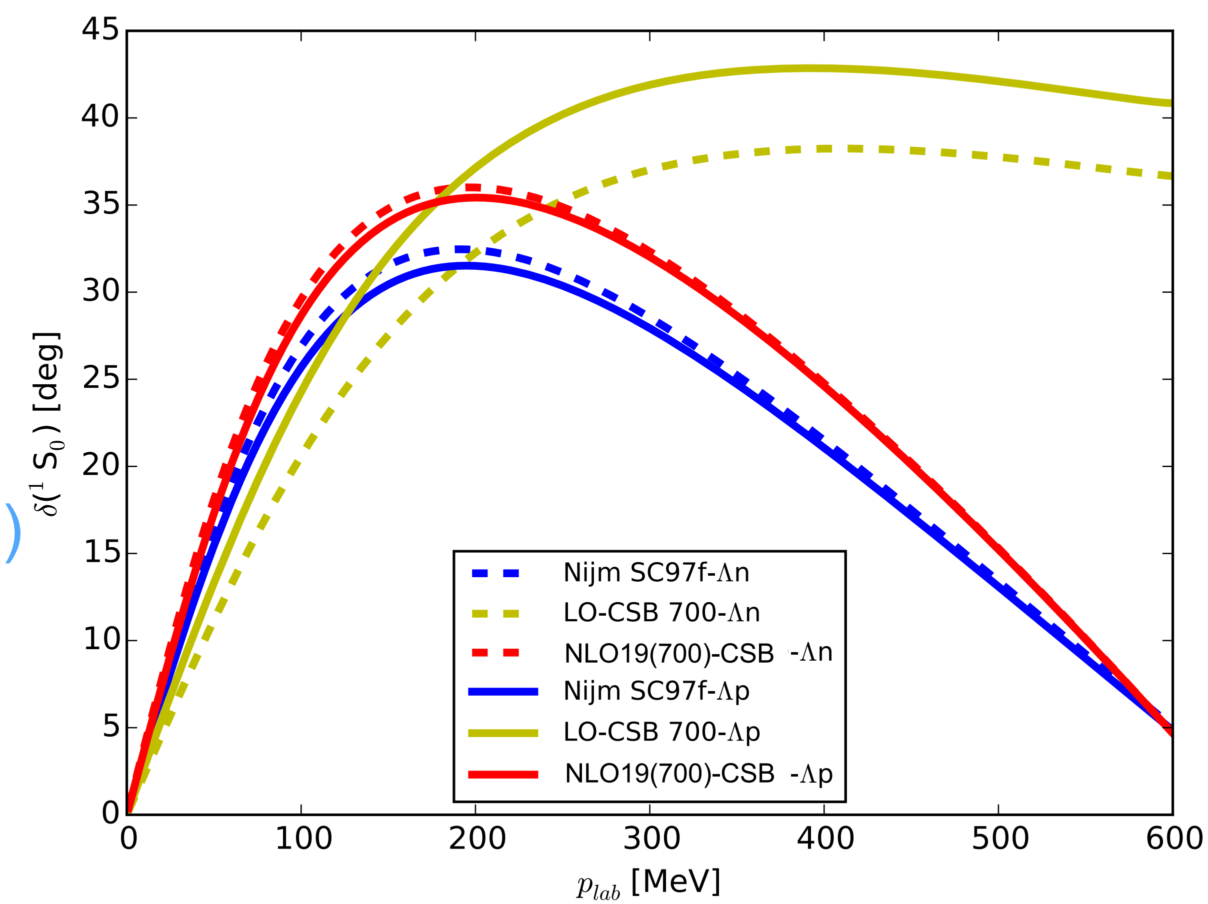
Standard approach to CSB in YN

add ΛΛπ coupling using Σ^0-Λ mixing and π^0-η mixing

other short ranged mechanisms are usually neglected → **model dependence**



- CSB leads to new long-ranged contribution to the YN interaction
- possibly large CSB contributions
- CSB for LO larger than for SC97 and NLO
- seems to be supported by experiment (e.g. approximately 230 keV CSB in A=4)
- Gazda & Gal (2016) relate it to ΣN-ΛN matrix elements to include long- and short range interactions



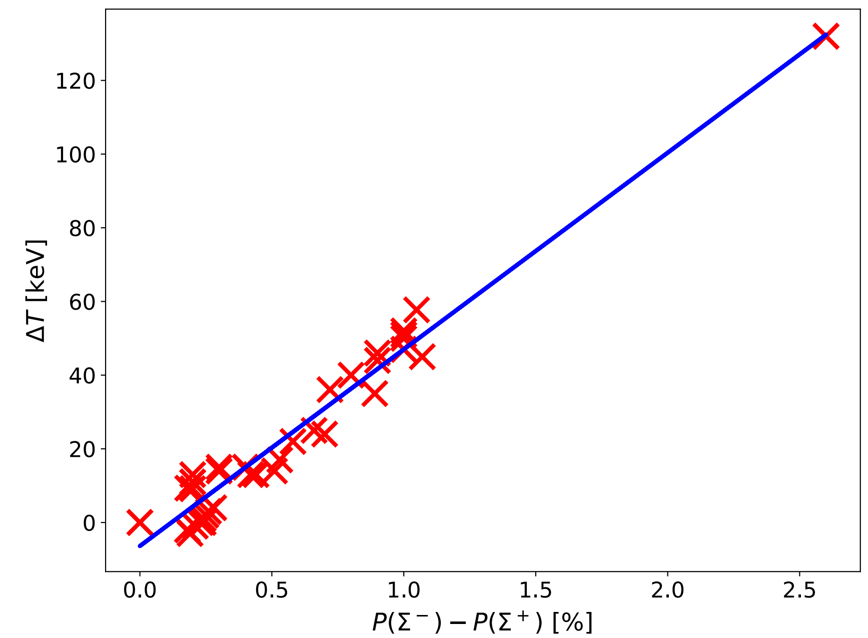
CSB contributions in ${}^{4}_{\Lambda}\mathrm{He}$

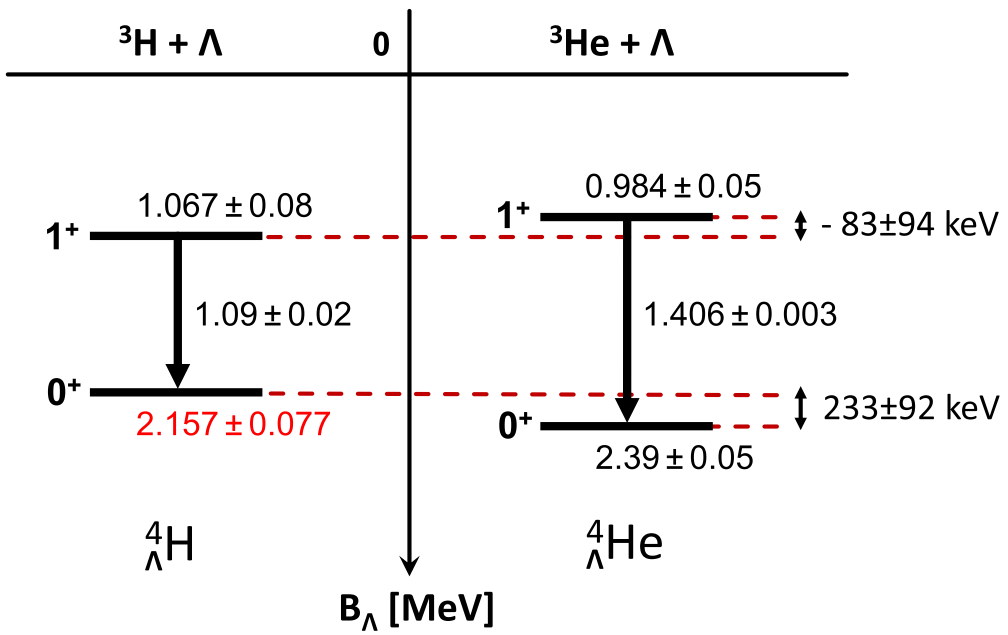
- perturbative calculations of CSB
- breakdown in kinetic energy, YN and NN interaction
- kinetic energy less important for chiral interactions

interaction	$\langle T\rangle_{CSB}$	$\langle V_{YN}\rangle_{CSB}$	V_{NN}^{CSB}	$\Delta E_{\Lambda}^{pert}$	ΔE_{Λ}
NLO13(500)	44	200	16	261	265
NLO13(550)	46	191	20	257	261
NLO13(600)	44	187	20	252	256
NLO13(650)	38	189	18	245	249
NLO19(500)	14	224	5	243	249
NLO19(550)	14	226	7	247	252
NLO19(600)	22	204	12	238	243
NLO19(650)	26	207	12	245	250

interaction	$\langle T\rangle_{CSB}$	$\langle V_{YN}\rangle_{CSB}$	V_{NN}^{CSB}	$\Delta E_{\Lambda}^{pert}$	ΔE_{Λ}
NLO13(500)	5	-90	15	-71	-66
NLO13(550)	5	-86	18	-63	-56
NLO13(600)	4	-83	19	-59	-53
NLO13(650)	3	-80	17	-59	-55
NLO19(500)	1	-84	3	-80	-75
NLO19(550)	2	-81	2	-77	-72
NLO19(600)	4	-82	6	-71	-67
NLO19(650)	4	-79	9	-66	-69

(Haidenbauer et al., 2021)





(Schulz et al.,2016; Yamamoto, 2015)

How model-dependent are predictions for the Λn scattering length?

Prediction for Λn scattering

- assuming the current experimental situation for ${}^4_\Lambda\mathrm{He}$ / ${}^4_\Lambda\mathrm{He}$
- **without** CSB: $a_s^{\Lambda n} \approx 2.9\ fm$ **with** CSB: $a_s^{\Lambda n} \approx 3.3\ fm$
- improved description of Λp data
- almost independent of cutoff & NLO variant
- CSB of $a_t^{\Lambda n}$ is smaller

	$a_s^{\Lambda p}$	$a_t^{\Lambda p}$	$a_s^{\Lambda n}$	$a_t^{\Lambda n}$	$\chi^2(\Lambda p)$	$\chi^2(\Sigma N)$	$\chi^2(\text{total})$
NLO13(500)	-2.604	-1.647	-3.267	-1.561	4.47	12.13	16.60
NLO13(550)	-2.586	-1.551	-3.291	-1.469	3.46	12.03	15.49
NLO13(600)	-2.588	-1.573	-3.291	-1.487	3.43	12.38	15.81
NLO13(650)	-2.592	-1.538	-3.271	-1.452	3.70	12.57	16.27
NLO19(500)	-2.649	-1.580	-3.202	-1.467	3.51	14.69	18.20
NLO19(550)	-2.640	-1.524	-3.205	-1.407	3.23	14.19	17.42
NLO19(600)	-2.632	-1.473	-3.227	-1.362	3.45	12.68	16.13
NLO19(650)	-2.620	-1.464	-3.225	-1.365	3.28	12.76	16.04

(Haidenbauer et al., 2021)

An accurate prediction for the Λn interaction is possible using hypernuclei!

Conclusions & Outlook

- **YN & YY interactions are interesting**
  - *EOS and hyperon puzzle*
  - *access to explicit chiral symmetry breaking*
- **YN & YY interactions not well understood**
  - *conversion processes often drive long range part of interaction*
  - *scarce YN, almost no YY data*
- **Hypernuclei provide important constraints**
  - $^1S_0$ ΛN *scattering length &* ${}^{3}_{\Lambda}\mathrm{H}$ *& impact on other hypernuclei*
  - $^1S_0$ $\Lambda\Lambda$ *scattering length &* ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ *& predictions for A=4,5*
  - *CSB of* ΛN *scattering &* ${}^{4}_{\Lambda}\mathrm{He}$ / ${}^{4}_{\Lambda}\mathrm{H}$
- ***J-NCSM***
  - *reliable predictions are possible for ranges of interactions for* $S=-1$ *and* -2
  - ***need SRG induced 3BFs** to validate choice of* λ_{YN} *(see also Wirth et al. (2016))*
  - *estimates of **chiral 3BFs** are needed (implementing Petschauer et al., (2016))*
  - *study sensitivity to p-wave interaction*
  - *study CSB of p-shell hypernuclei*