Light hypernuclei based on chiral BB and 3B forces

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- Motivation
- YN interactions
- J-NCSM & SRG evolution of (hyper-)nuclear interactions
- Uncertainty of Λ separation energies & chiral YNN interactions
- Chiral YNN forces
- Application of YNN forces to light hypernuclei
- Conclusions & Outlook

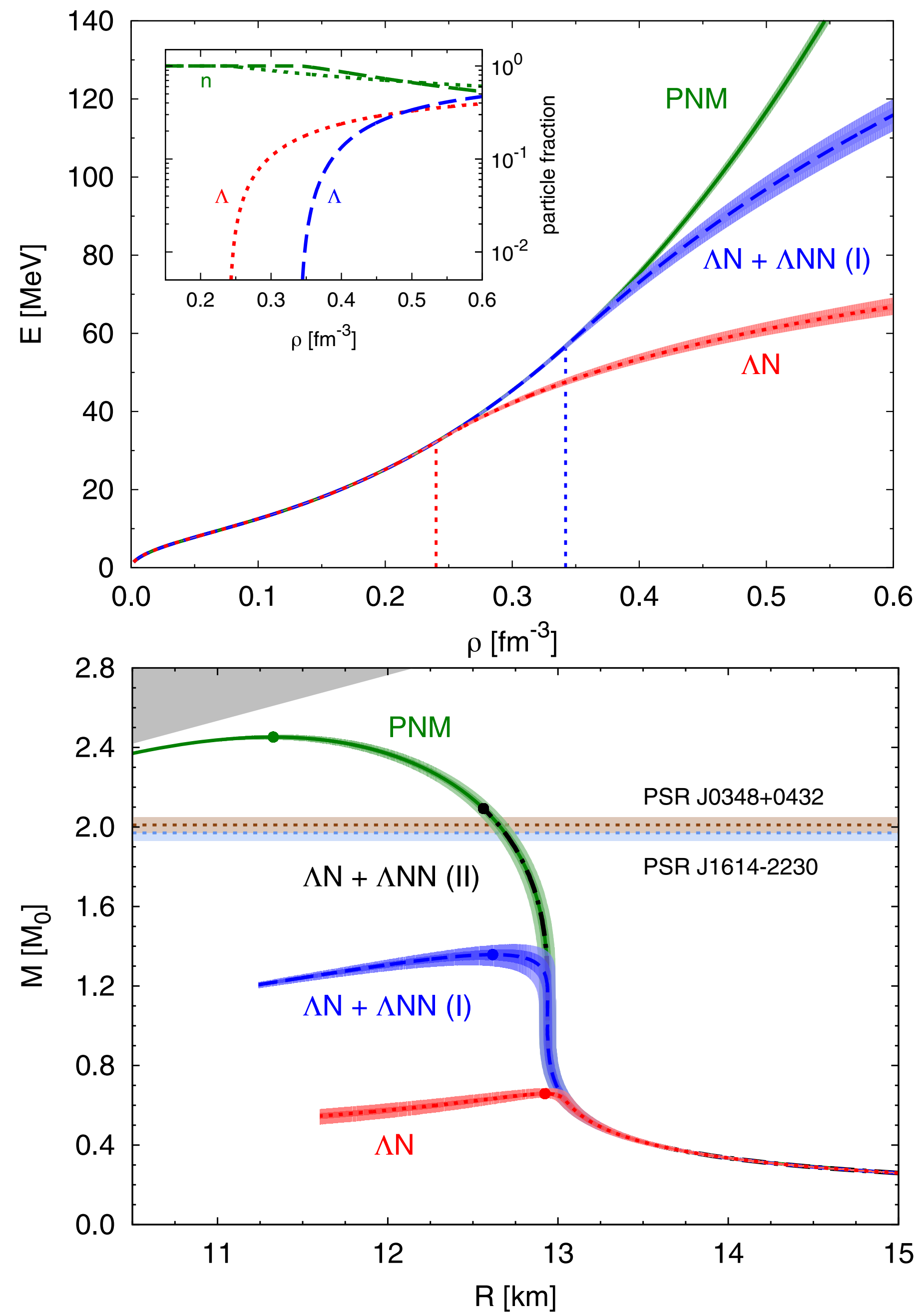
in collaboration with Johann Haidenbauer, Hoai Le, Ulf Meißner

Feburary 24th, 2026

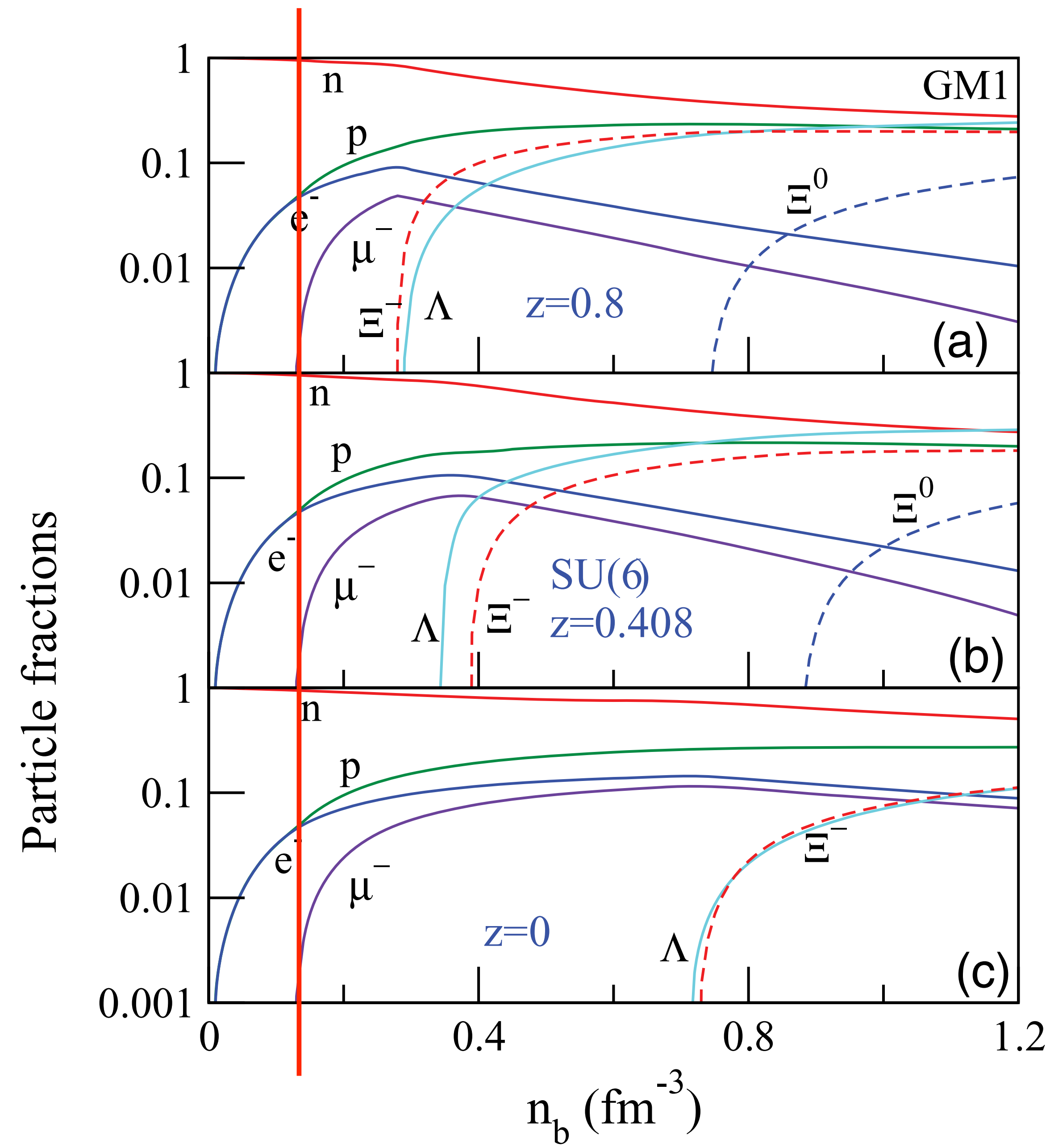
Hypernuclear interactions

Why is understanding hypernuclear interactions interesting?

- *hyperon contribution to the EOS, neutron stars, supernovae*
- *"hyperon puzzle"*
- *Λ as probe to nuclear structure*
- ***flavor dependence of baryon-baryon interactions***



(Lonardoni et al. (2015))

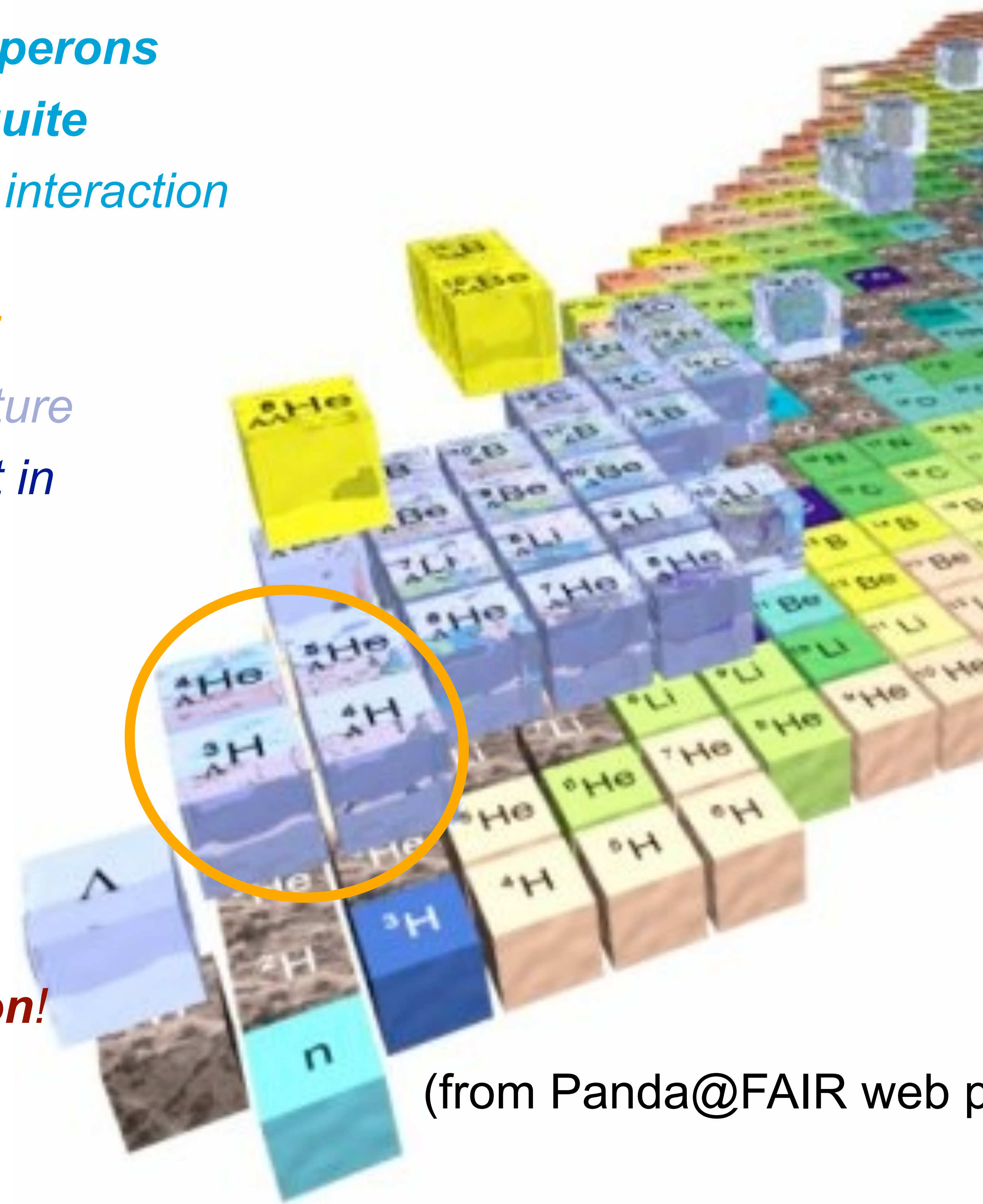


(Weissenborn et al. 2012)

Hypernuclei

Only few YN data. Hypernuclear data provides additional constraints.

- *ΛN interactions are generally weaker than the NN interaction*
  - *naively:* ***core nucleus + hyperons***
  - *„separation energies" are* ***quite*** *independent from NN(+3N) interaction*
- *no Pauli blocking of Λ in nuclei*
  - *good to study nuclear structure*
  - *even light hypernuclei exist in* ***several spin states***
- ***non-trivial constraints*** *on the YN interaction even from lightest ones*
- *size of* ***YNN*** *interactions? need to include* ***Λ-Σ conversion****!*



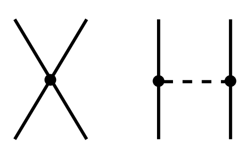
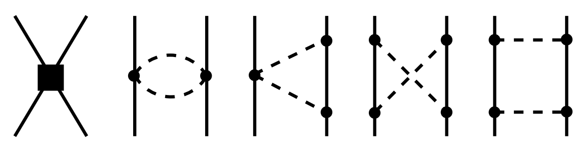
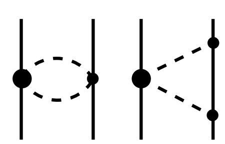
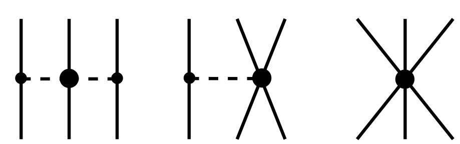
(from Panda@FAIR web page)

Chiral NN & YN interactions

EFT based approaches

Chiral EFT implements **chiral symmetry of QCD**

- symmetries constrain exchanges of Goldstone bosons
- relations of two- and three- and more-baryon interactions
- breakdown scale $\approx 600 - 700\,\mathrm{MeV}$
- Semi-local momentum regularization (SMS) up to N²LO (for YN)

	BB force	3B force	4B force	
LO		—	—	**5 NN/YN** short range parameters
NLO		—	—	**23 NN/YN** short range parameters
N^2LO			—	no additional contact terms in NN/YN

(adapted from Epelbaum, 2008)

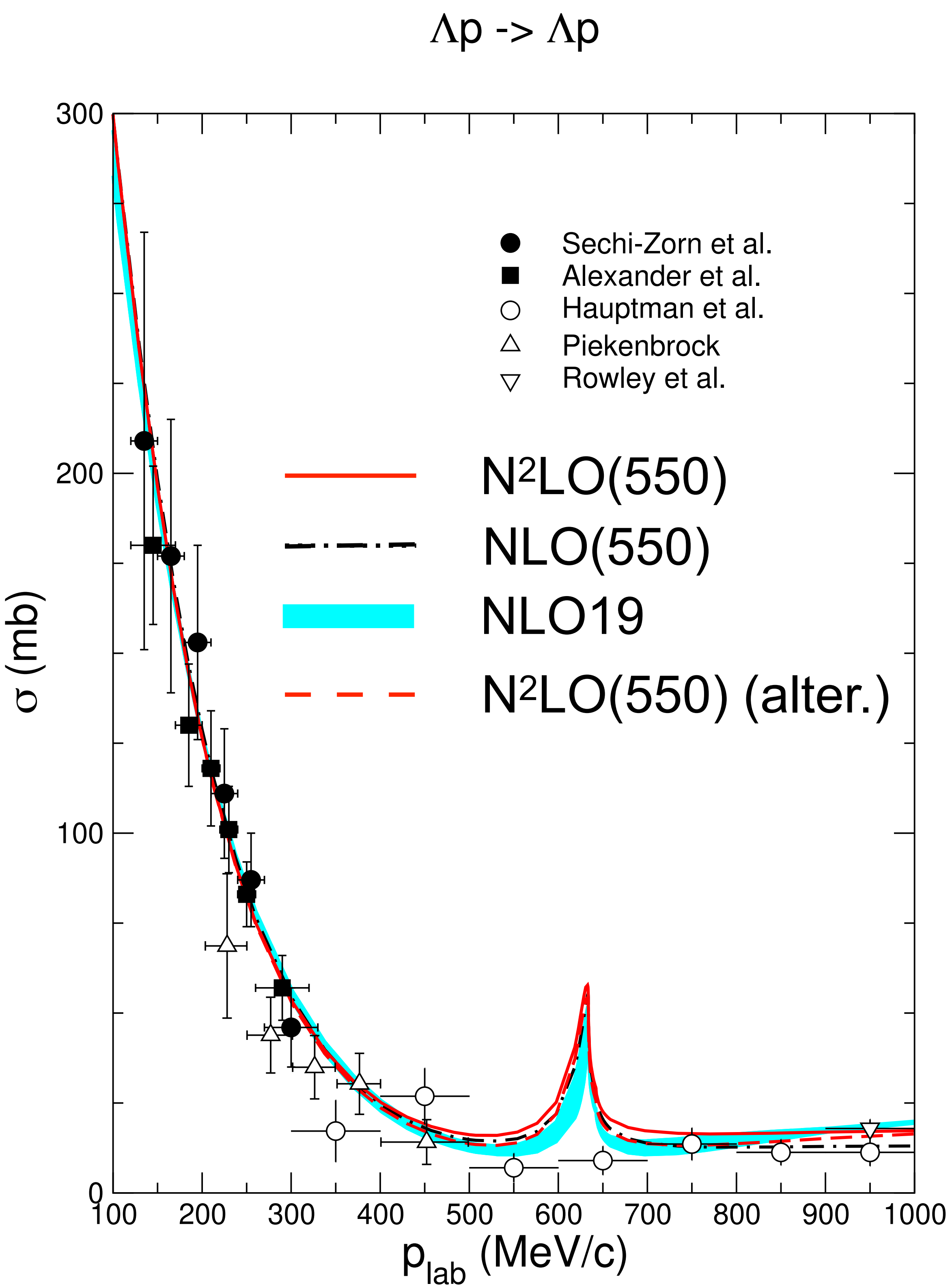
Retain flexibility to adjust to data due to counter terms

Regulator required — cutoff/different orders often used to estimate uncertainty

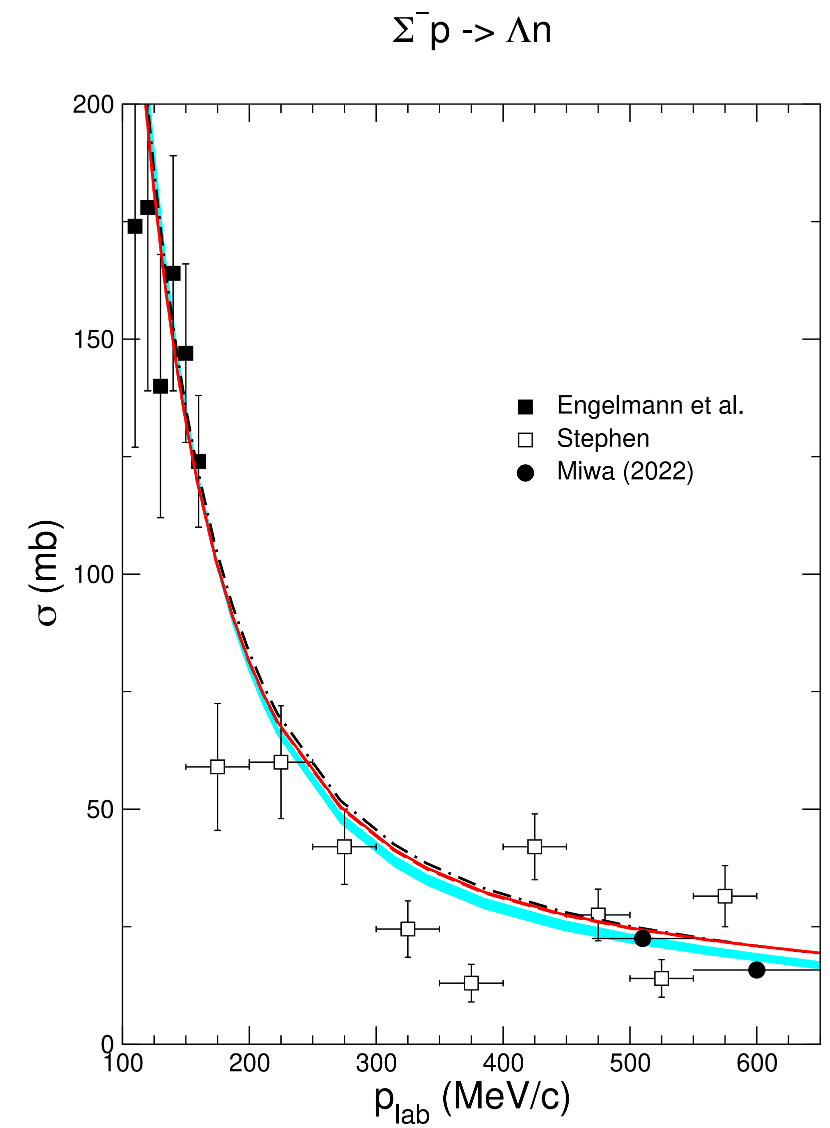
$\Lambda - \Sigma$ **conversion** is explicitly included (3BFs starting from N²LO)

SMS NLO/N²LO interaction

Selected results (show $\Lambda = 550\,\mathrm{MeV}$, others are very similar in quality)



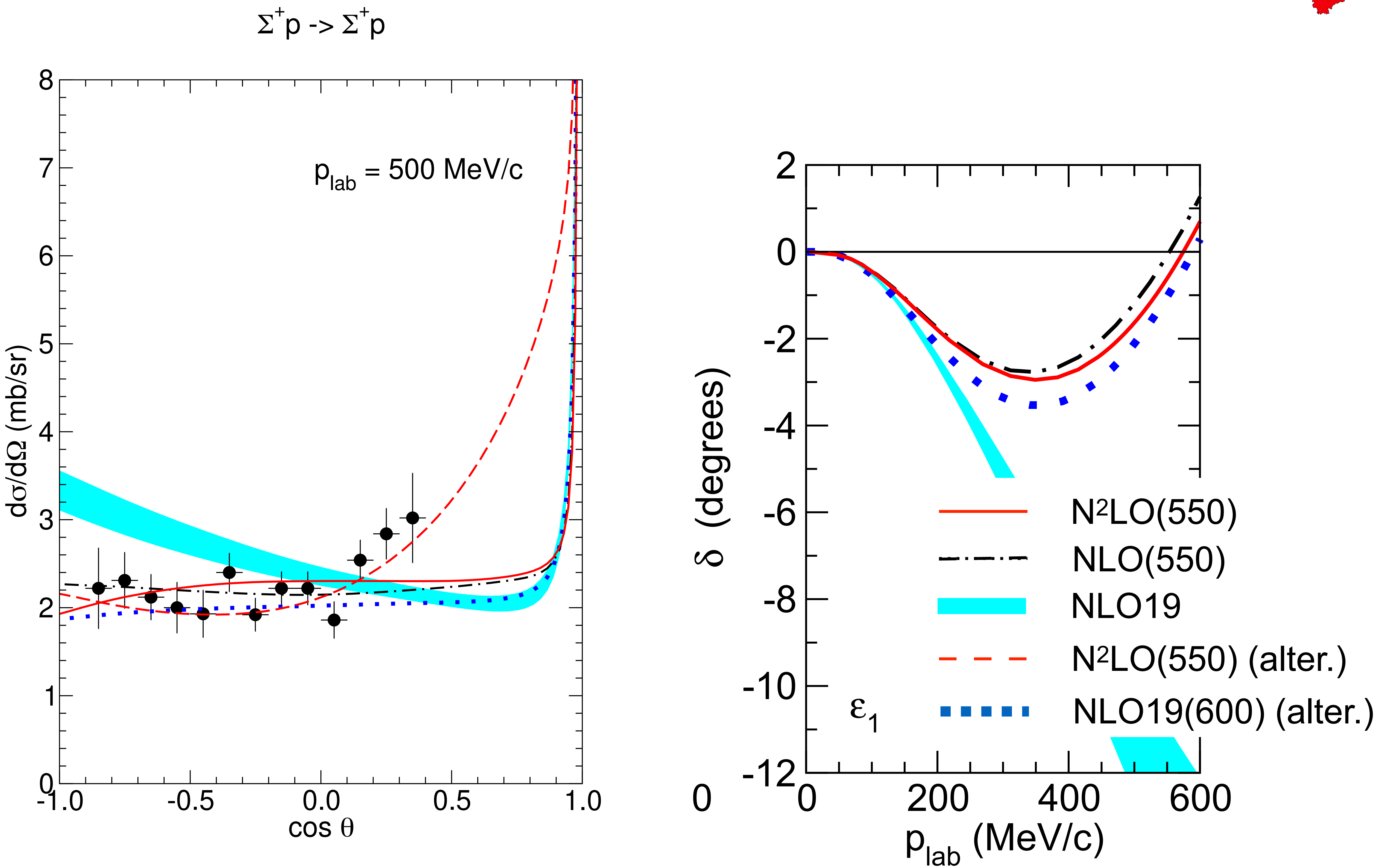
- most relevant cross sections very similar in NLO and N²LO
- similar to NLO19
- alternative fit (see later)



J. Haidenbauer et al. EPJ A 59, 63 (2023)

SMS NLO/N²LO interaction

new data (Miwa(2022)) at higher energies provides **new constraints**!



J. Haidenbauer et al. EPJ A 59, 63 (2023)

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"

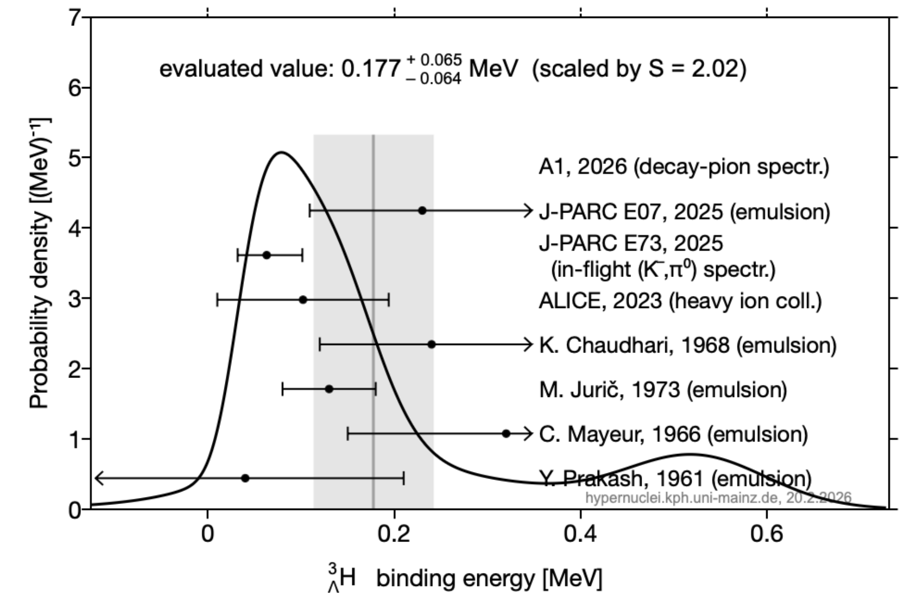
(Bogner et al. PRC 75,061001 (2007))

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

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**
- Evolution can be restricted to **2-,3-, … body level** (approximation)
- $\lambda = \left(\frac{4\mu_{BN}^2}{s}\right)^{1/4}$ is a measure of the width of the interaction in momentum space
- **dependence** of results on λ or s is a measure for **missing terms**

Induced 3BF & $^{3}_{\Lambda}\mathrm{H}$

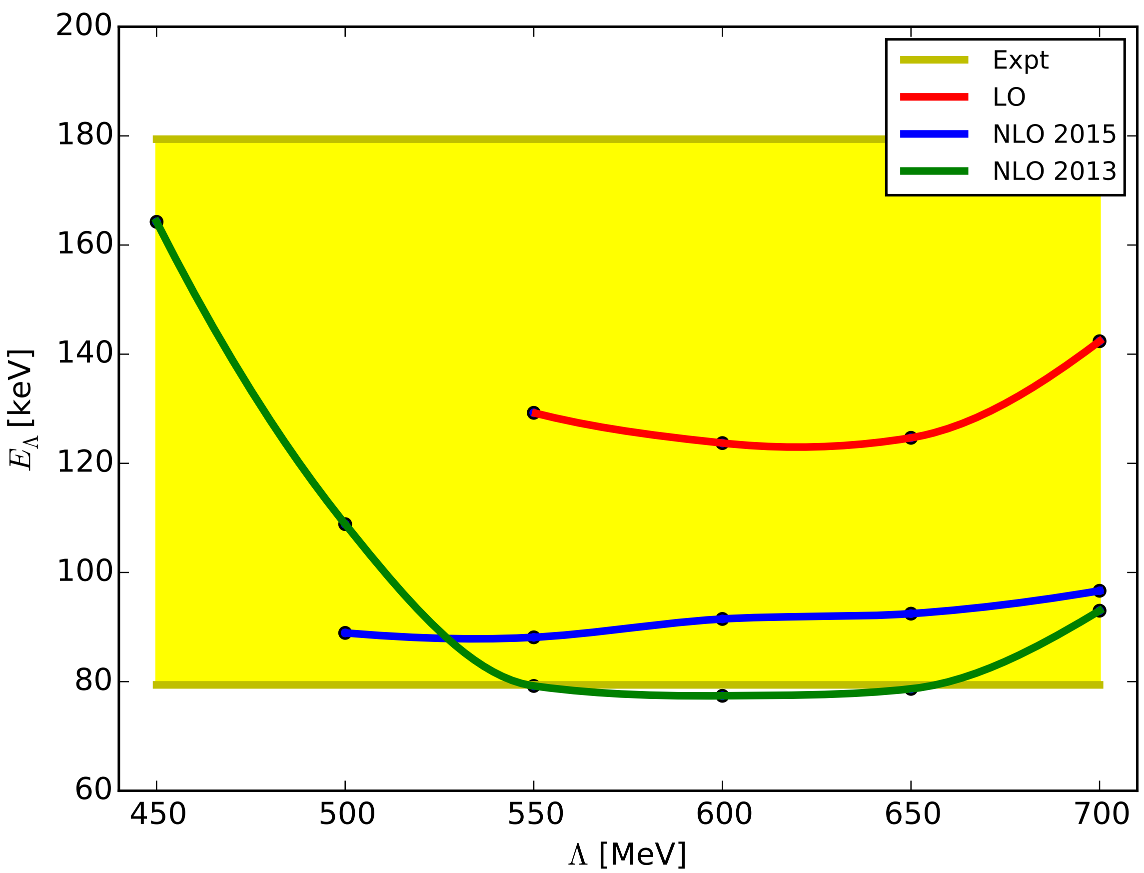


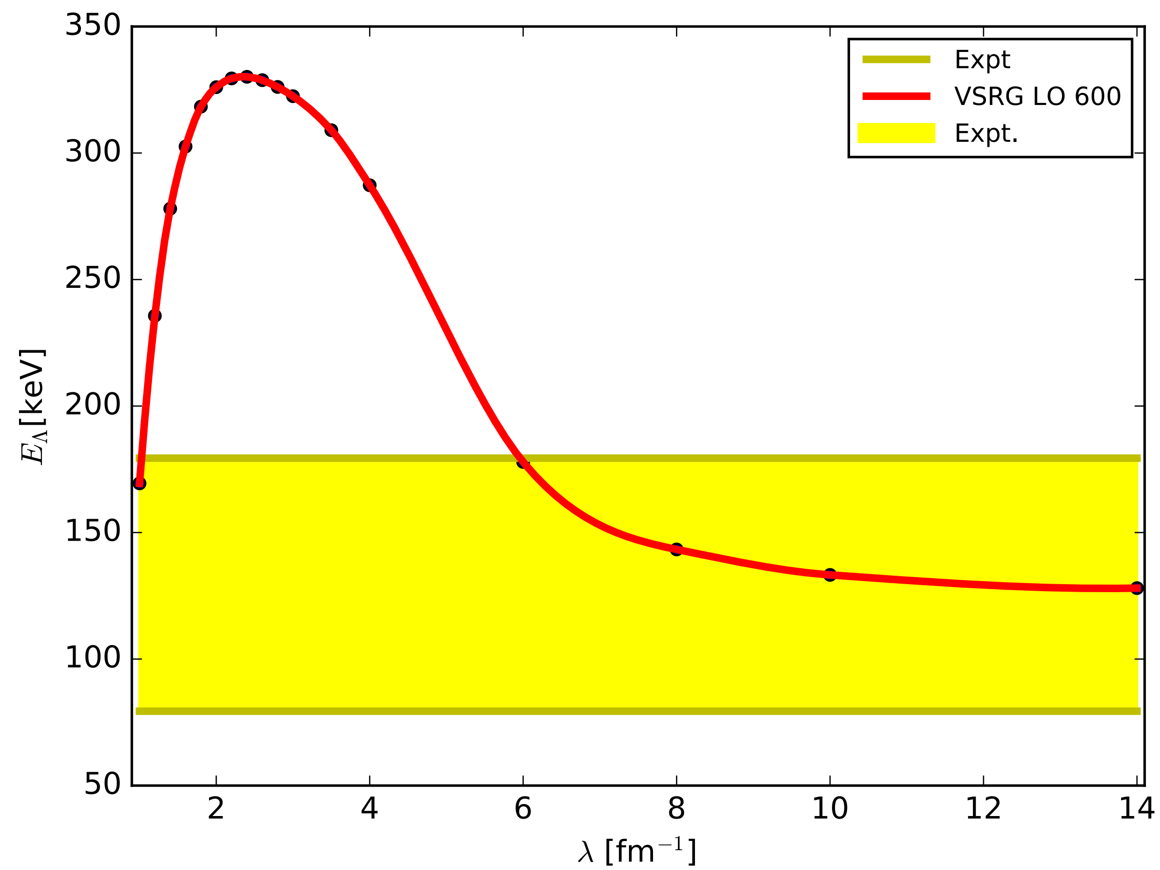
https://hypernuclei.kph.uni-mainz.de

- $^{3}_{\Lambda}\mathrm{H}$ experiments are … confusing
- $^{3}_{\Lambda}\mathrm{H}$ used to determine spin dependence of YN

and: SRG parameter dependence is significant when NN and YN interactions are evolved

→ induced YNN interactions are important

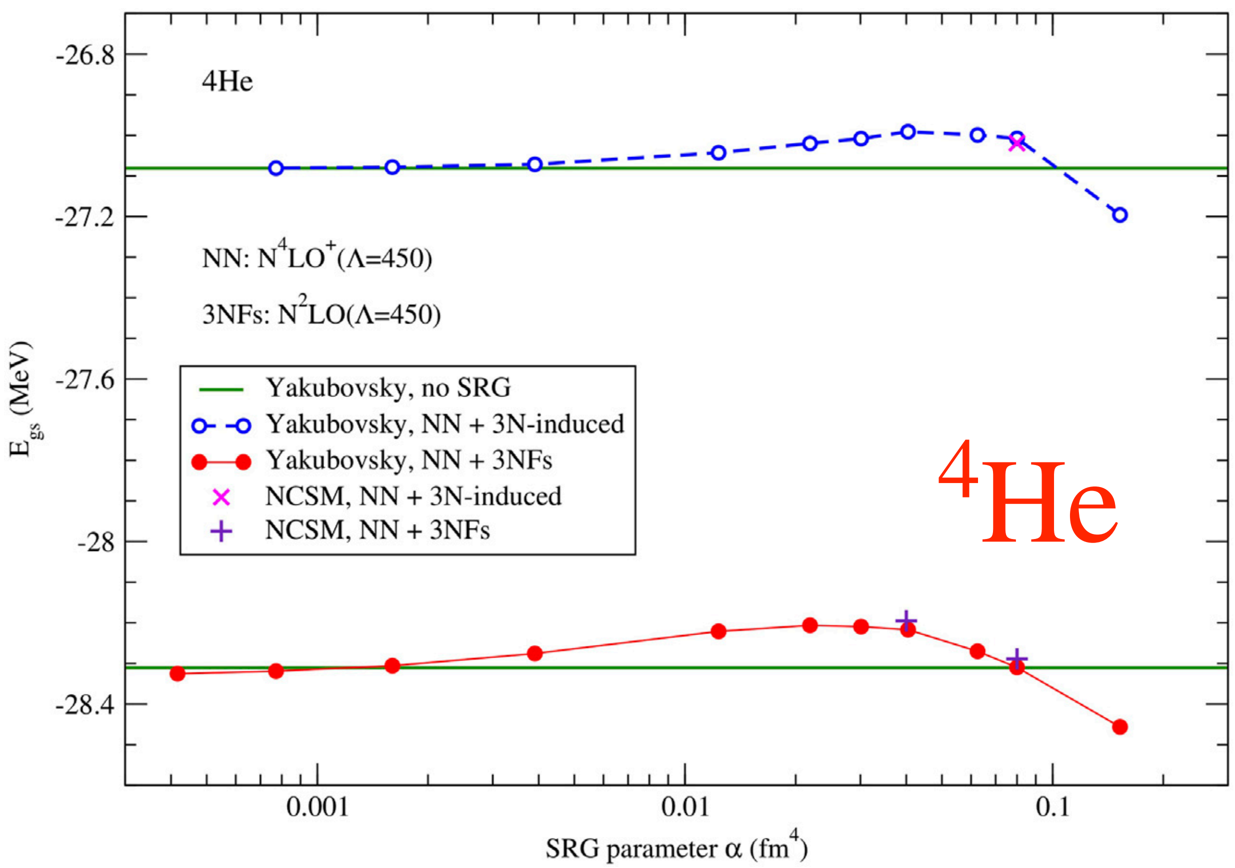




Hypertriton energy used to determine relative strength of singlet and triplet YN force

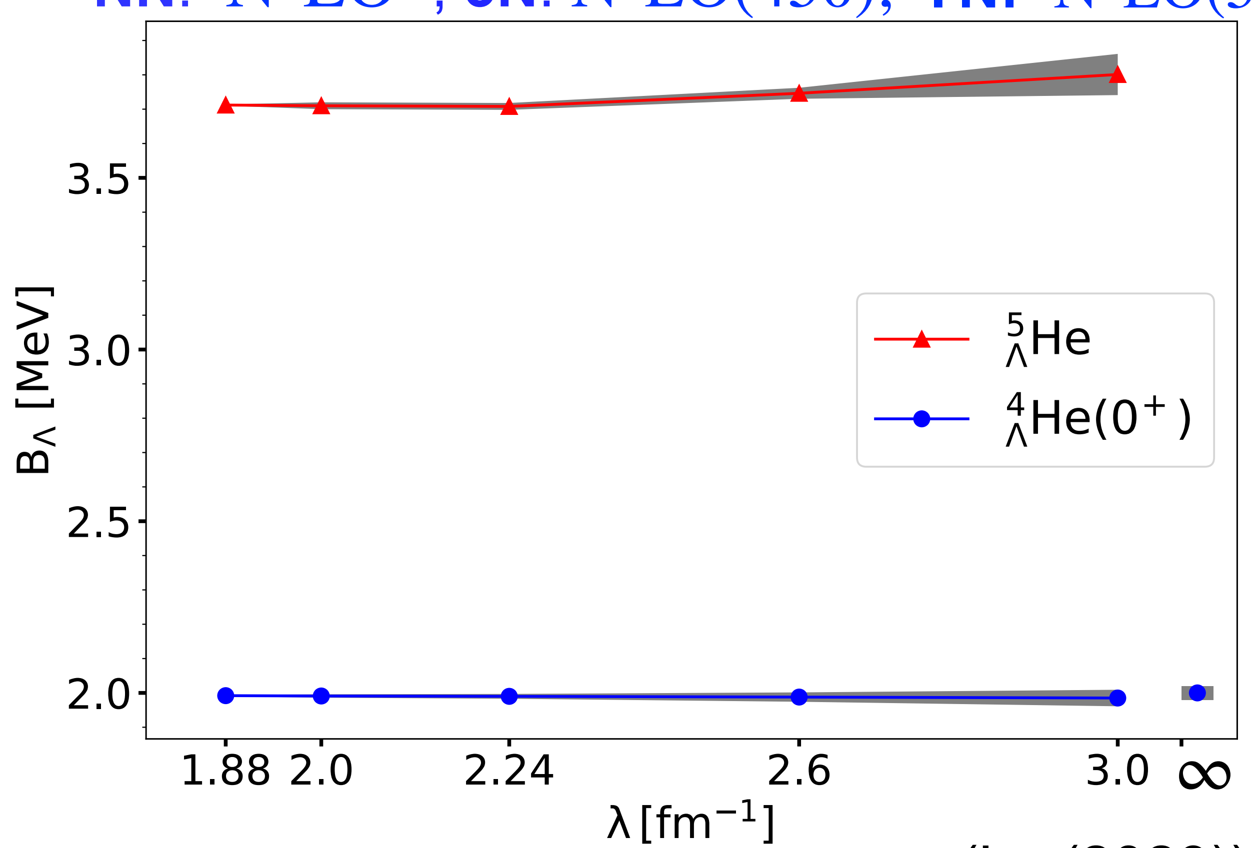
SRG dependence of results

- SRG-induced 3N and YNN interactions
- ^{4}He binding energies varies by $\approx 100 - 200$ keV (relevant in the future?)
- separation energies are even less dependent (YNNN forces small)



(Maris, Le, Nogga, Roth, Vary (2023))

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



(Le (2023))

For **hypernuclei**, calculations based on SRG induced BB and 3B interactions are sufficiently accurate!

Uncertainty analysis to $A = 3$ to 5

Order N^2LO requires combination of chiral NN, YN, 3N and YNN interaction

Results for **different orders** enable uncertainty estimate:

Ansatz for the order by order convergence:

$$X_K = X_{ref} \sum_{k=0}^{K} c_k \, Q^k \quad \text{where} \quad Q = M_\pi^{eff} / \Lambda_b \quad (X_{ref} \text{ LO, exp., max, …})$$

Bayesian analysis of the uncertainty following Melendez et al. 2017,2019

Extracting c_k for $k \leq K$ **from calculations**

→ **probability distributions** for c_k

→ $$\delta X_K = X_{ref} \sum_{k=K+1}^{\infty} c_k \, Q^k$$

Uncertainty due to missing higher orders is more relevant than numerical uncertainty! (for light nuclei)

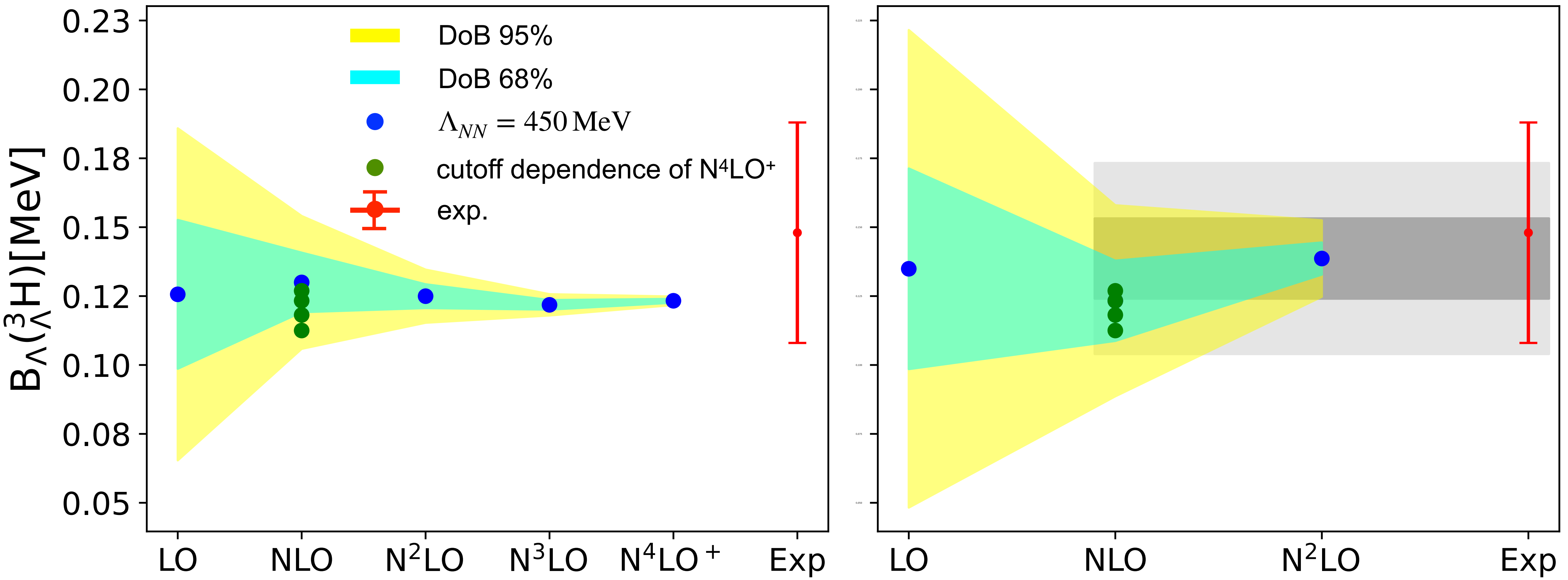
Application to ${}^{3}_{\Lambda}\mathrm{H}$

- Q, ν_0 and τ_0 are chosen using all available data (NN and YN convergence)
- uncertainties are extracted using c_k for NN or YN convergence
- use c_k of individual hypernuclei

→ individual uncertainties for NN and YN convergence for each separation energy

consistent with experimental data

cutoff dependence always at least NLO (YNN missing!)

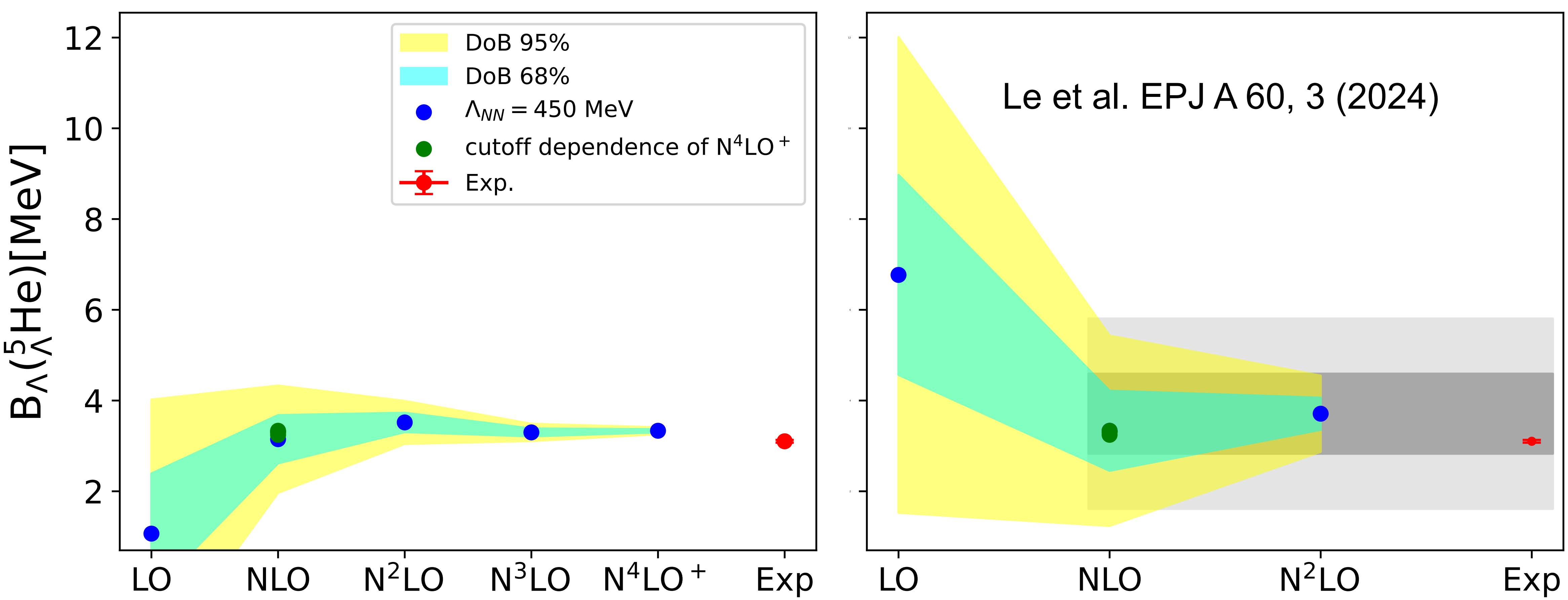


Application to ${}^{5}_{\Lambda}\mathrm{He}$ and summary

- **without YNN**: sizable uncertainties at $A = 4$ and 5
- $A = 3$ sufficiently accurate
- NN/YN dependence small at least for $A = 3$

nucleus	$\Delta_{68}(NN)$	$\Delta_{68}(YN)$
${}^{3}_{\Lambda}\mathrm{H}$	0.011	0.015
${}^{4}_{\Lambda}\mathrm{He}\,(0^+)$	0.157	0.239
${}^{4}_{\Lambda}\mathrm{He}\,(1^+)$	0.114	0.214
${}^{5}_{\Lambda}\mathrm{He}$	0.529	0.881

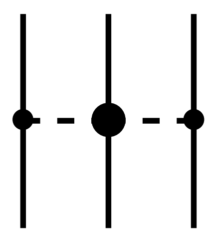
→ at the same time: estimate of YNN !



YNN (ΛNN) interactions

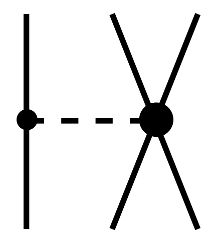
Leading 3BF with the usual topologies (Petschauer et al. PRC 93, 014001 (2016))

ChPT → all octet mesons contribute → **only take π** explicitly into account



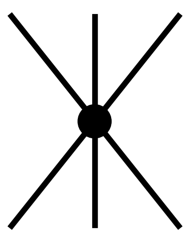
2 LECs in ΛNN

(up to 10)



2 LECs in ΛNN

(up to 14)



3 LECs in ΛNN

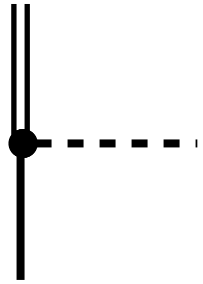
5 LECs in ΣNN + 1 Λ-Σ transition

only few data → need to keep the **# of LECs** small

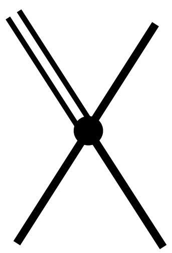
Decuplet baryons ($\Sigma^* \ldots$) might enhance YNN partly to NLO

(Petschauer et al., NPA 957, 347 (2017))

By decuplet saturation all LECs can be related to the following leading octet-decuplet transitions (Petschauer et al. Front. Phys. 8,12 (2020))



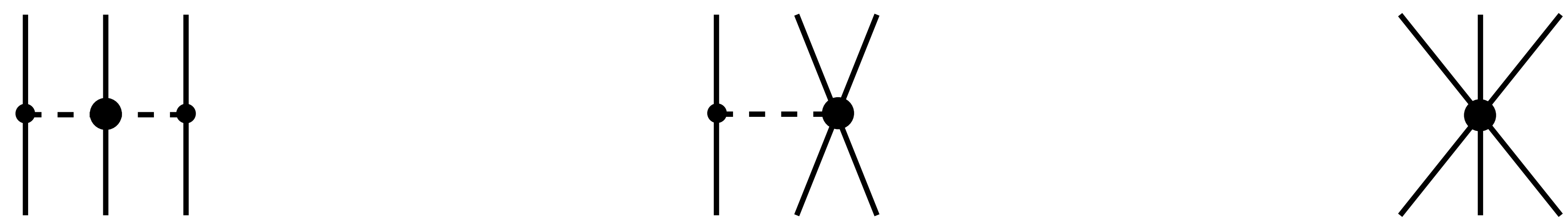
$\propto C = \frac{3}{4} g_A$



$\propto G_1, G_2$ → **reduction to 2 LECs**

YNN (ΛNN) interactions

Decuplet saturation relates all LECs to G_1 and G_2



	$\propto C^2$	$\propto CG_1, CG_2$	$\propto (G_1)^2, (G_2)^2, G_1G_2$
For ΛNN:	$\propto C^2$	$\propto C(G_1 + 3G_2)$	$\propto (G_1 + 3G_2)^2$ 1 LEC

→ density dependent BB interactions (Petschauer et al., NPA 957, 347 (2017))

→ application to nuclear matter (Haidenbauer et al., EPJ A 53, 121 (2017))

neutron stars (Logoteta et al., EJA 55, 207 (2019))

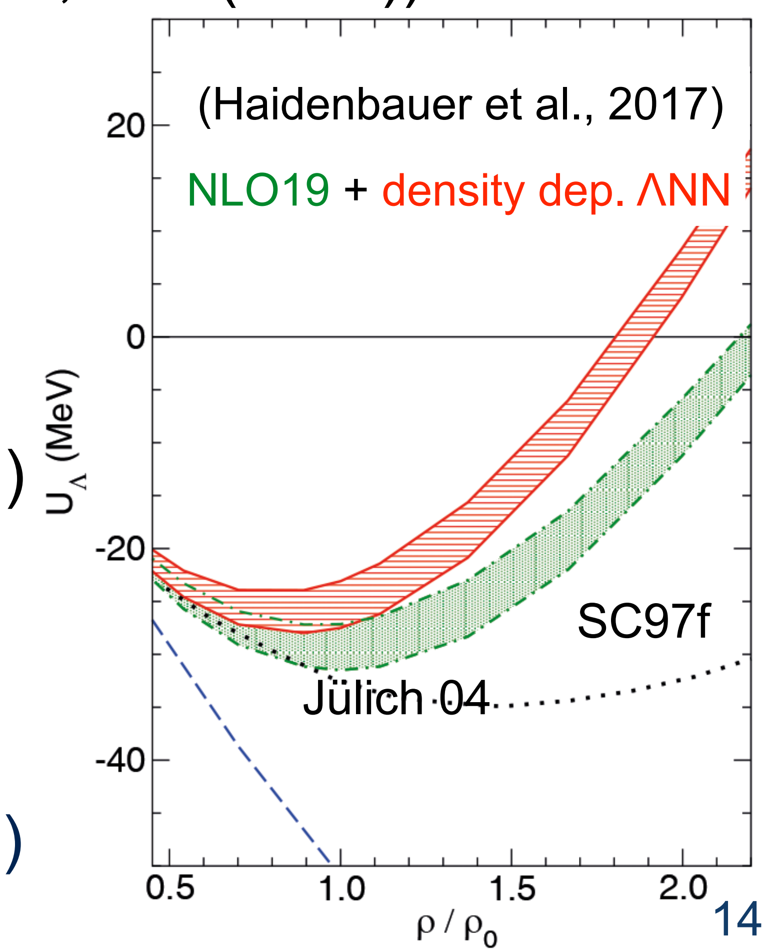
- contribution on the single particle potentials can be large
- realistic results seem to require partly cancelations of 2π and 1π exchange

(fixes sign of $G_1 + 3G_2$!)

Recently: successful benchmark of matrix elements (Hoai Le et al. EPJ A 61,21 (2025))

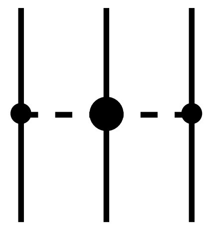
and first direct application to light hypernuclei including Σ's

(Hoai Le et al. PRL 134, 072502 (2025))

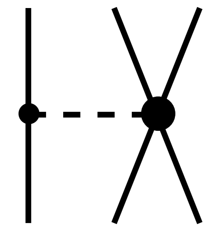


YNN (ΛNN) interactions in practice

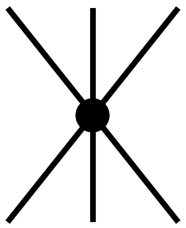
Decuplet approximation in YNN



$\propto C^2$



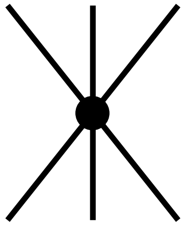
$\propto CG_1, CG_2$



$\propto (G_1)^2, (G_2)^2, G_1 G_2$

is **not** sufficient to fix spin dependence

→ + ΛNN contact terms **without decuplet constraints**



ΛNN $\propto C_1', C_2', C_3'$

***ad hoc* choice:** alter C_2:

$$C_1' = C_3' = \frac{(G_1 + 3G_2)^2}{72\Delta}$$

$$C_2' = 0$$

→

$$V_{\Lambda NN} = C_2{}' \, \vec{\sigma}_1 \cdot \left(\vec{\sigma}_2 + \vec{\sigma}_3\right) \left(1 - \vec{\tau}_2 \cdot \vec{\tau}_3\right)$$

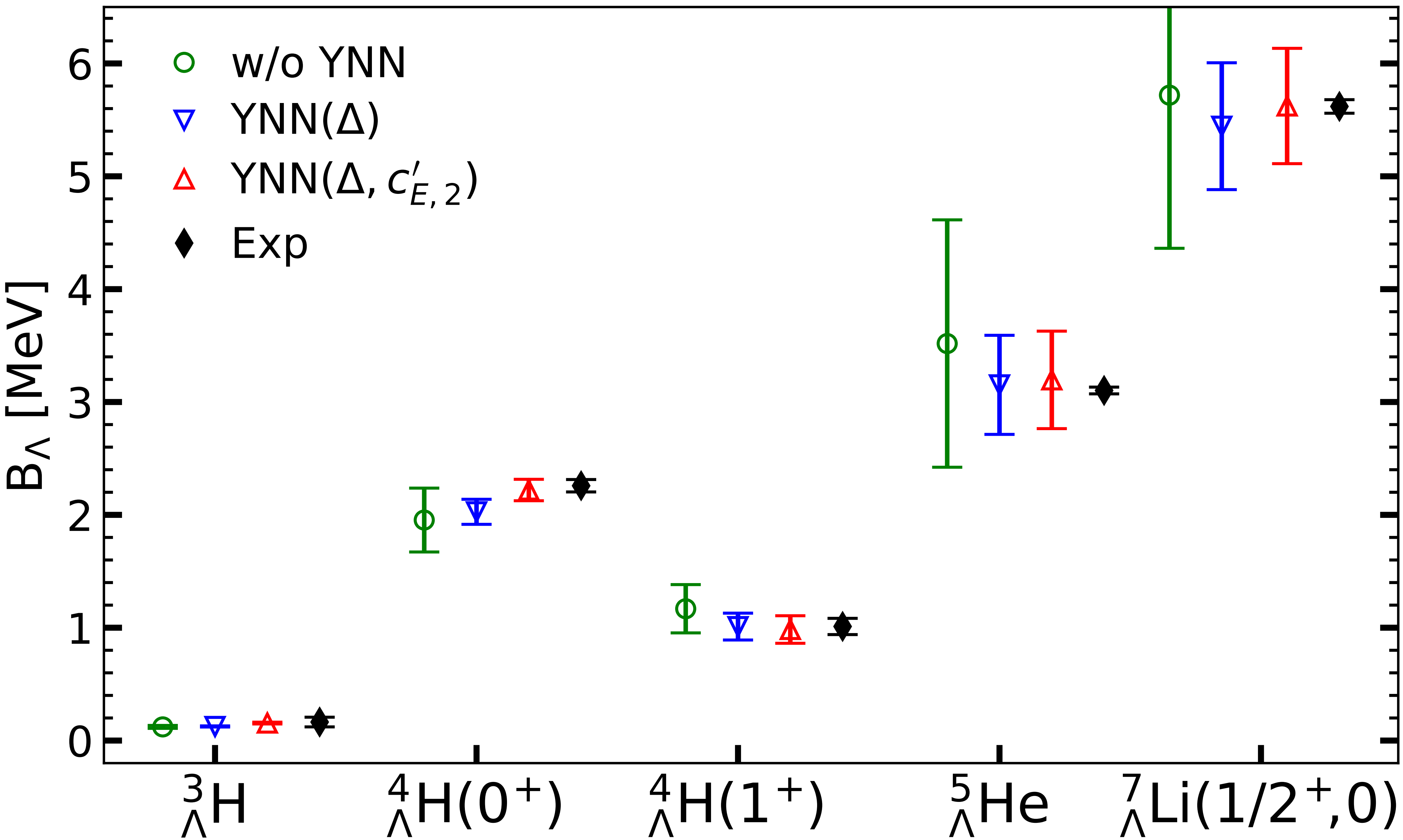
$$C_2' = G_3$$

C_2' introduces a spin dependent interaction in the most relevant particle channel

(see also Hildenbrand et al. arXiv:2406.17638)

YNN fit

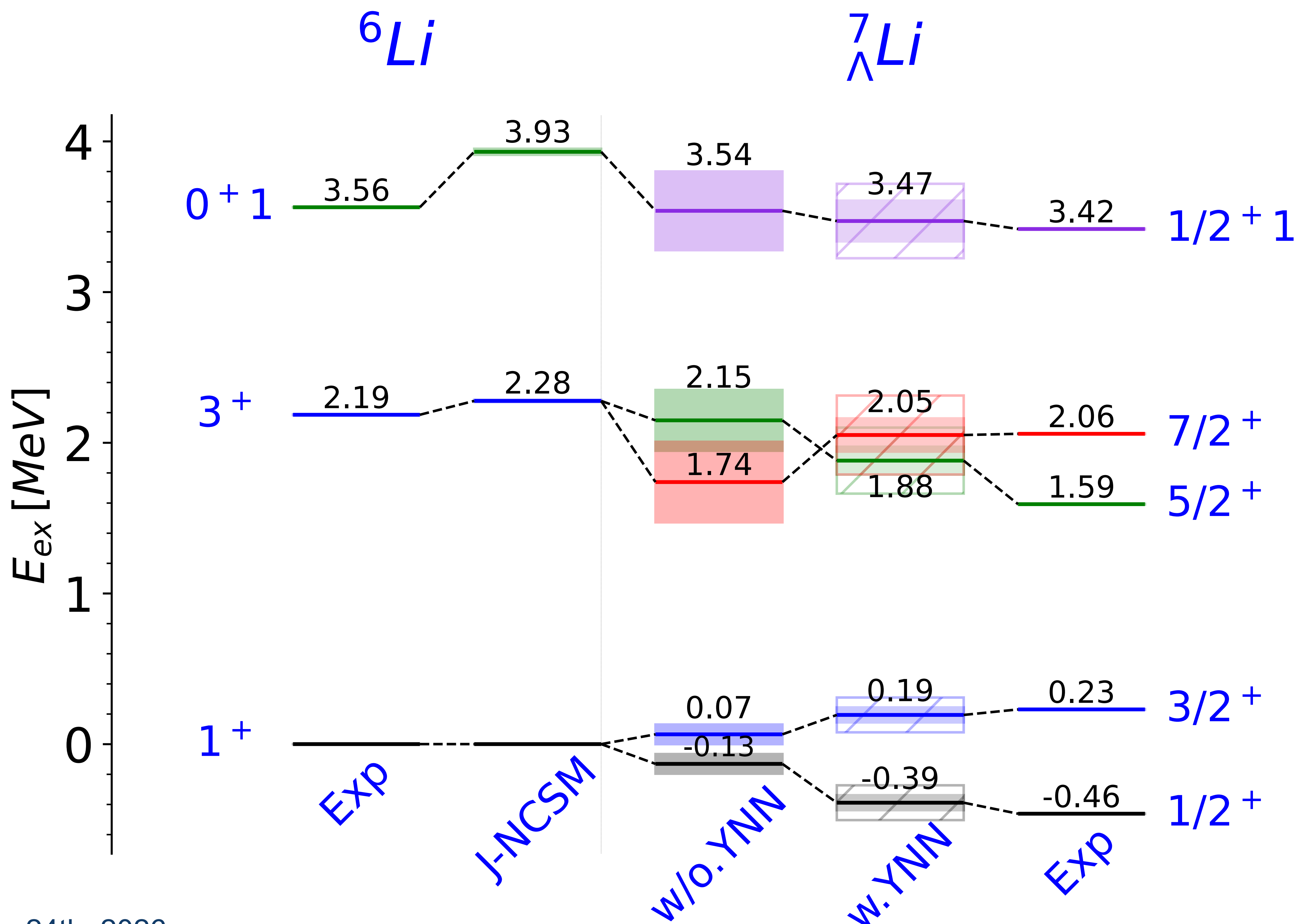
- Fit to 0^+ and 1^+ state of ${}^4_\Lambda\mathrm{He}$ and/or ${}^5_\Lambda\mathrm{He}$
- spin-dependence in A=4 not well explained by decuplet saturation
- C_2' term improves 0^+ of ${}^4_\Lambda\mathrm{He}$ and $1/2^+$ of ${}^7_\Lambda\mathrm{Li}$
- agreement generally much better than $\mathrm{N^2LO}$ uncertainty



YNN prediction for $^{7}_{\Lambda}\mathrm{Li}$

JÜLICH Forschungszentrum

- good agreement
- C_2' term included, but not very important (not shown)
- higher states have significant uncertainty



Conclusions & Outlook

- **YN interactions not well understood**
  - *scarce YN data*
  - *more information necessary to solve "hyperon puzzle"*
- **Hypernuclei provide important constraints**
  - $^1S_0$ ΛN *scattering length &* ${}^{3}_{\Lambda}\mathrm{H}$
  - CSB of ΛN scattering & ${}^{4}_{\Lambda}\mathrm{He}$ / ${}^{4}_{\Lambda}\mathrm{H}$
- **SMS YN interactions up to $\mathrm{N^2LO}$**
  - *order LO, NLO and N^2LO allow uncertainty quantification*
  - *have a **non-unique** determination of contact interactions (more data necessary)*
- **Chiral 3BF**
  - *decuplet saturation alone does not improve spin dependence*
  - *spin-dependent $\Lambda\mathrm{NN}$ leads to further improvement*

  - *study cutoff dependence / application to more p-shell hypernuclei*
  - *extension to Λd scattering: probably more insight for higher densities*
  - *extension Λd/Λpp correlations: info on different spin/isospin states*