Mitglied der Helmholtz-Gemeinschaft

Using light hypernuclei to constrain hypernuclear interactions

Andreas Nogga, Forschungszentrum Jülich

10th International Conference on Quarks and Nuclear Physics (QNP2024),
Universitat de Barcelona, Barcelona, Spain, July 8-12, 2024

- Motivation
- YN interactions
- Uncertainty of Λ separation energies and size of chiral 3BF contributions
- Chiral YNN interactions
- Conclusions & Outlook

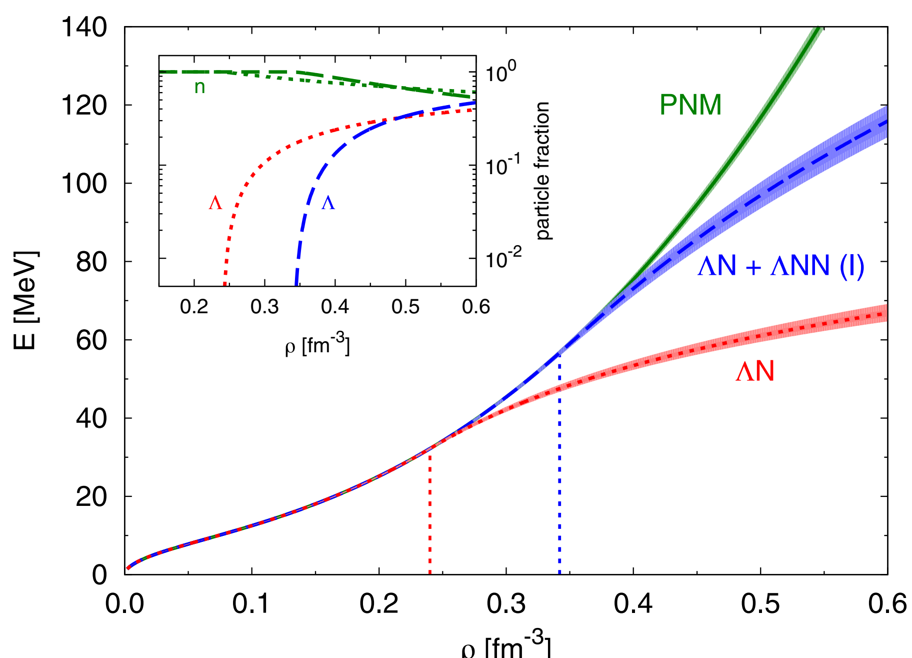
in collaboration with Johann Haidenbauer, **Hoai Le**, Ulf Meißner

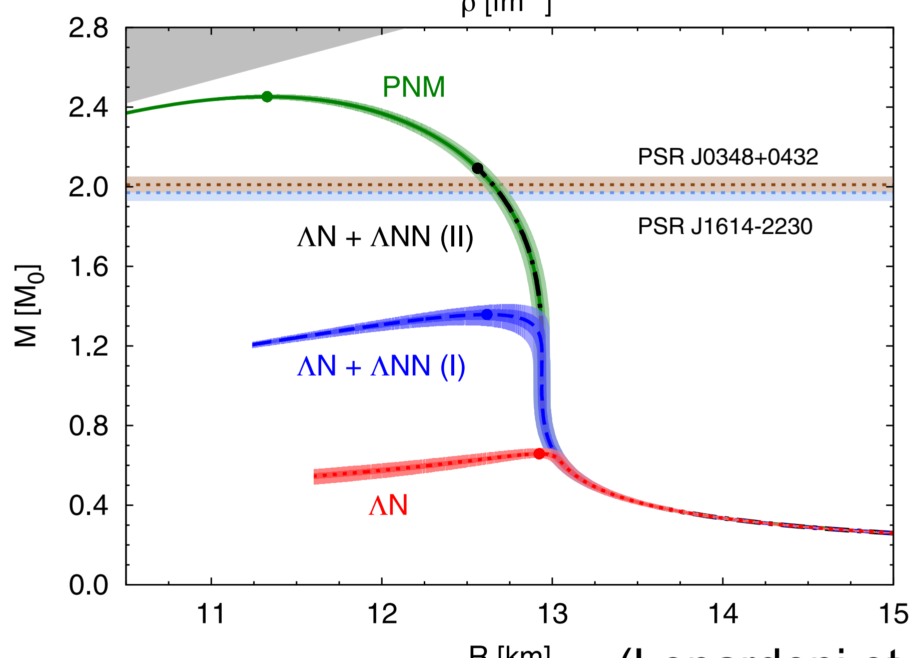
July 10th, 2024

Hypernuclear interactions

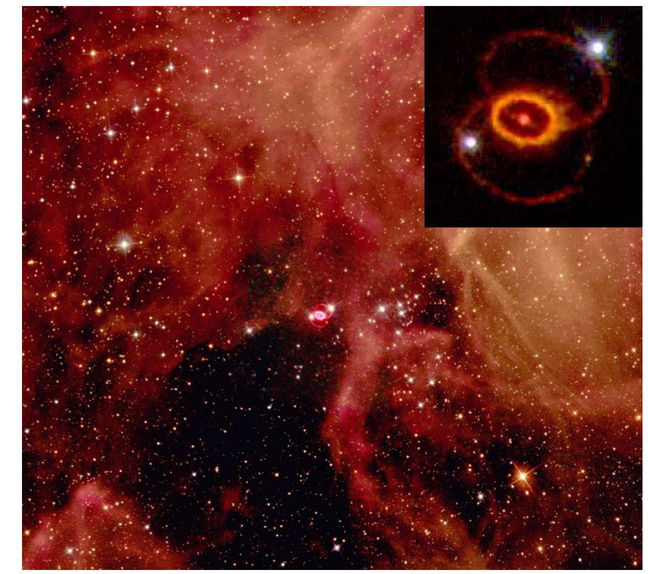
Why is understanding hypernuclear interactions interesting?

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

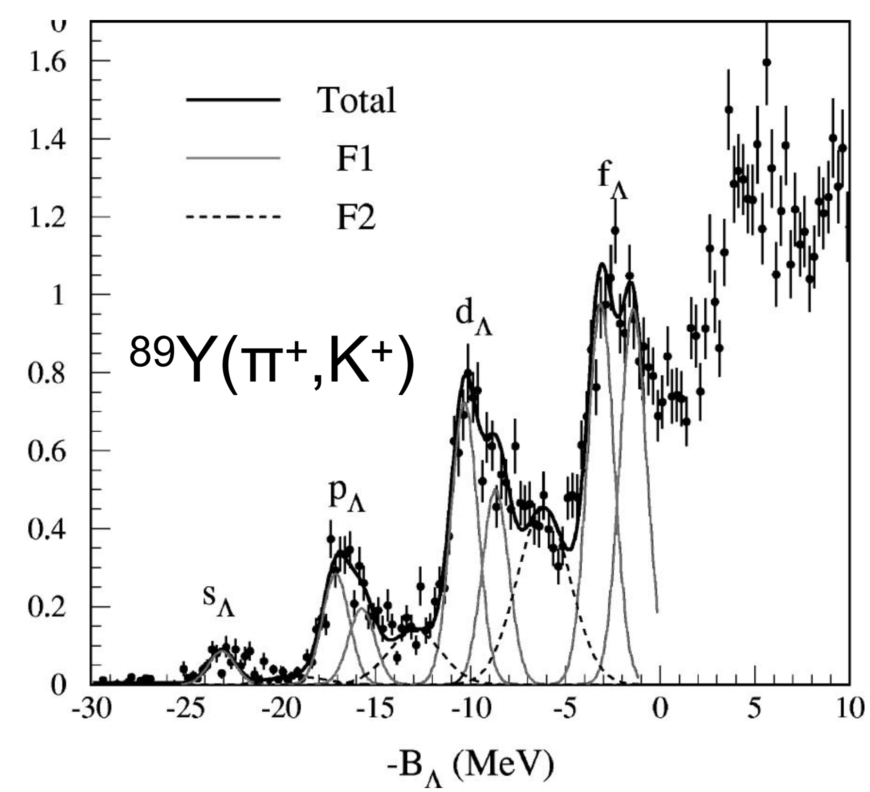




(Lonardoni et al. (2015))



(SN1987a, Wikipedia)



(Hotchi et al. (2001))

Hypernuclei

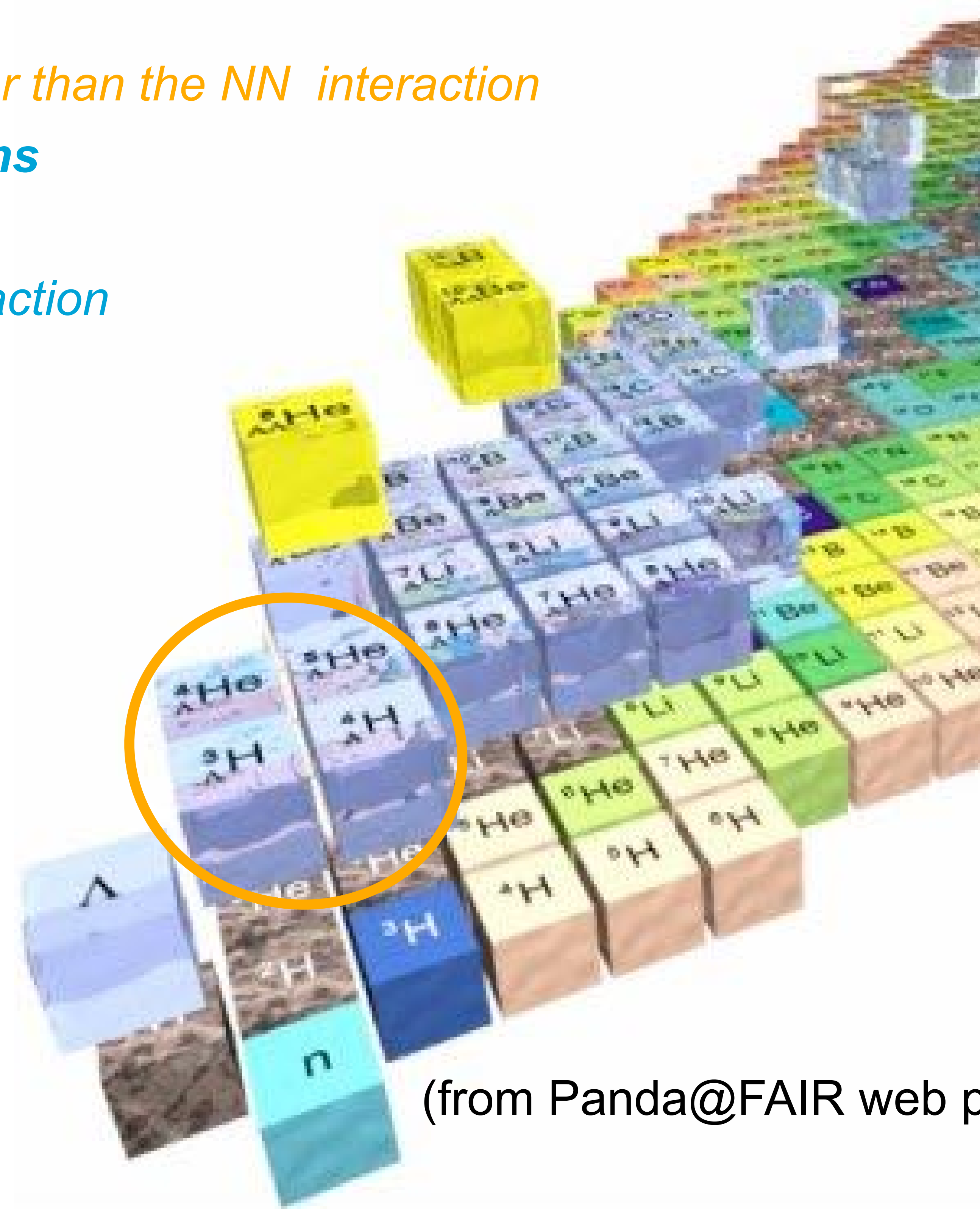
Only few YN data. Hypernuclear data provides additional constraints.

- *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*

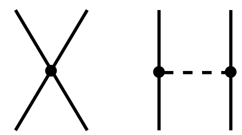
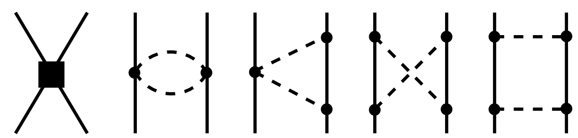
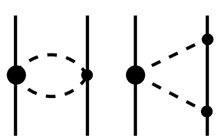
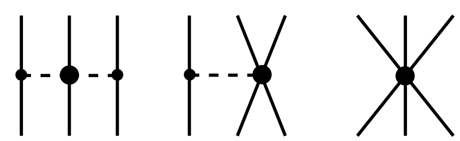
- *size of* ***YNN*** *interactions? need to include* ***Λ-Σ conversion****!*



(from Panda@FAIR web page)

Chiral NN & YN interactions

EFT based approaches

	BB force	3B force	4B force
LO		—	—
NLO		—	—
N^2LO			—

5 NN/YN short range parameters

23 NN/YN short range parameters

no additional contact terms in NN/YN

Chiral EFT implements **chiral symmetry of QCD** (adapted from Epelbaum, 2008)

- 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 N^2LO

Retain flexibility to adjust to data due to counter terms

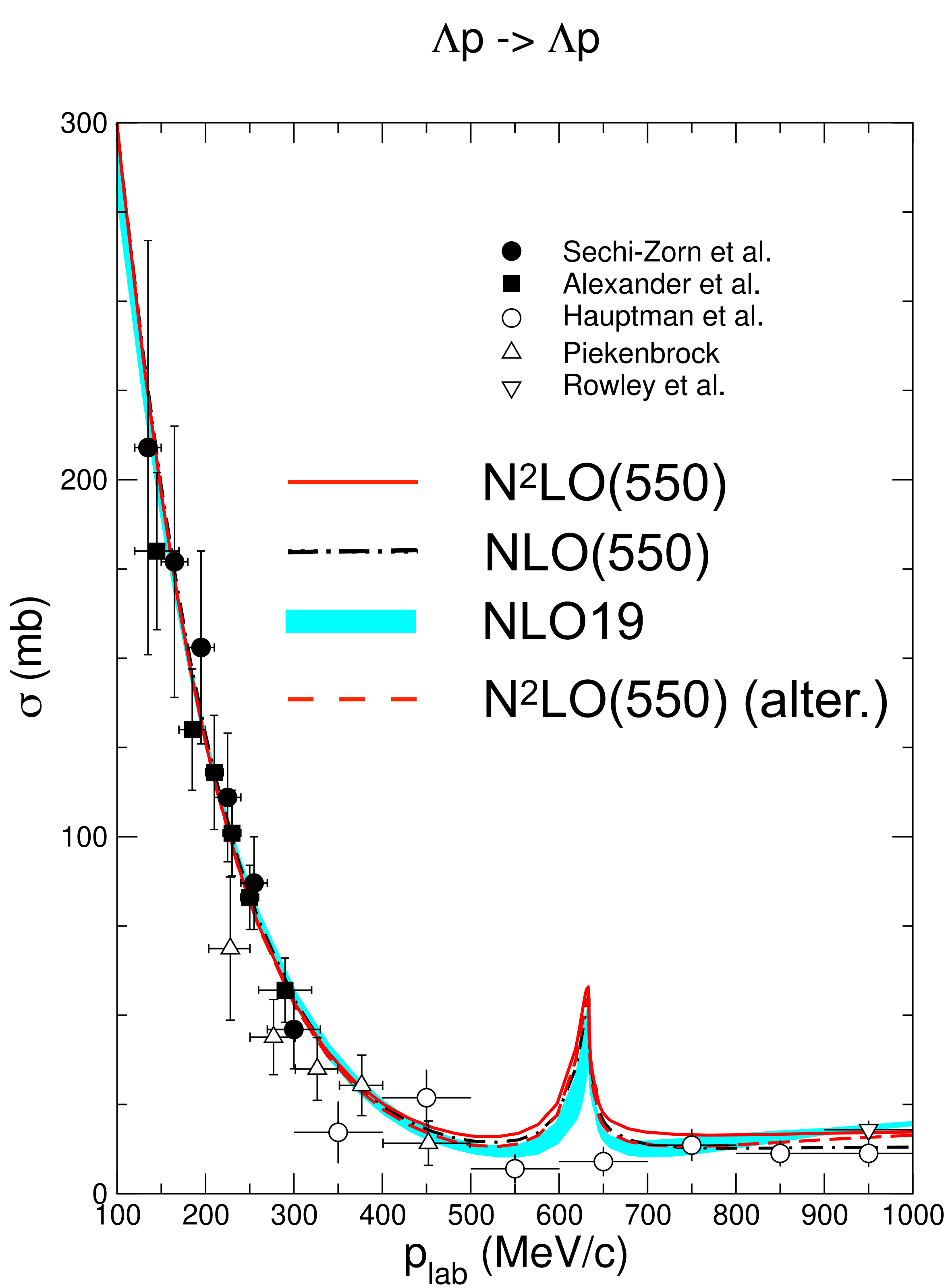
Regulator required — cutoff/different orders often used to estimate uncertainty

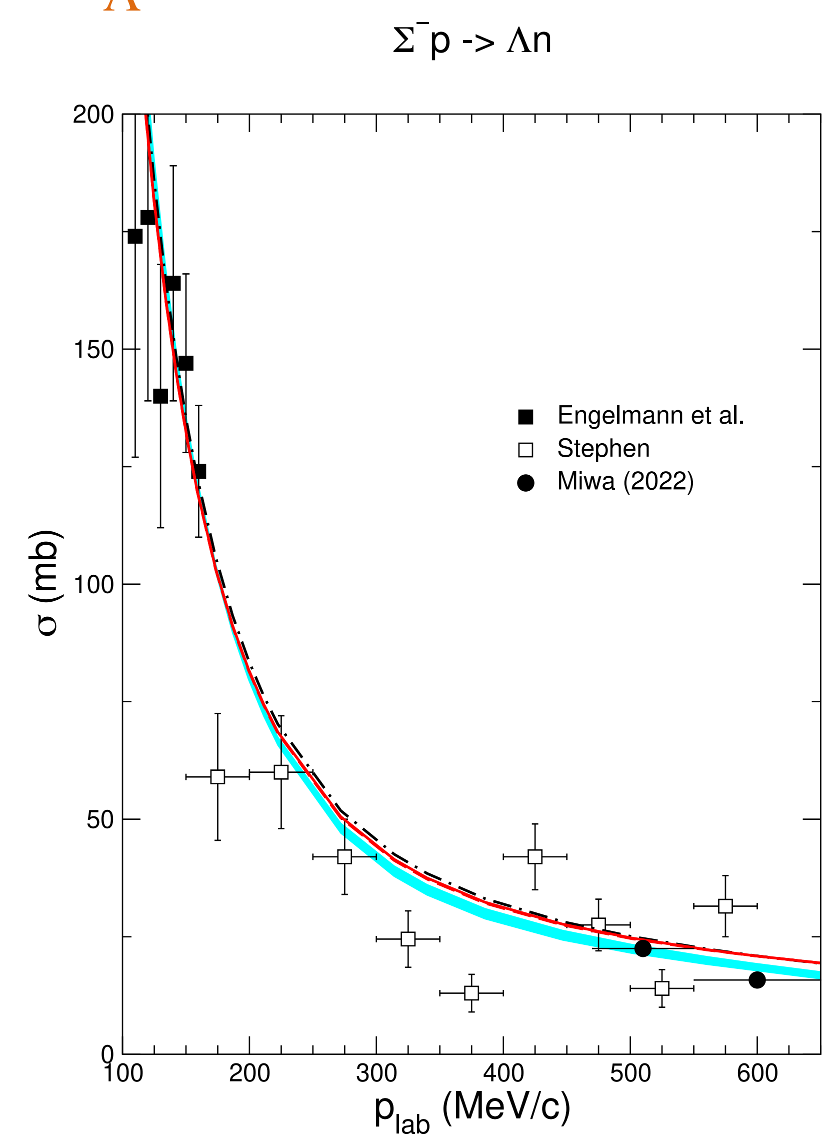
$\Lambda-\Sigma$ **conversion** is explicitly included (3BFs appear only in $\mathbf{N^2LO}$)

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 (non-local regulator)
- alternative fit (see later)
- uses ${}^{3}_{\Lambda}\mathrm{H}$ to determine spin dependence

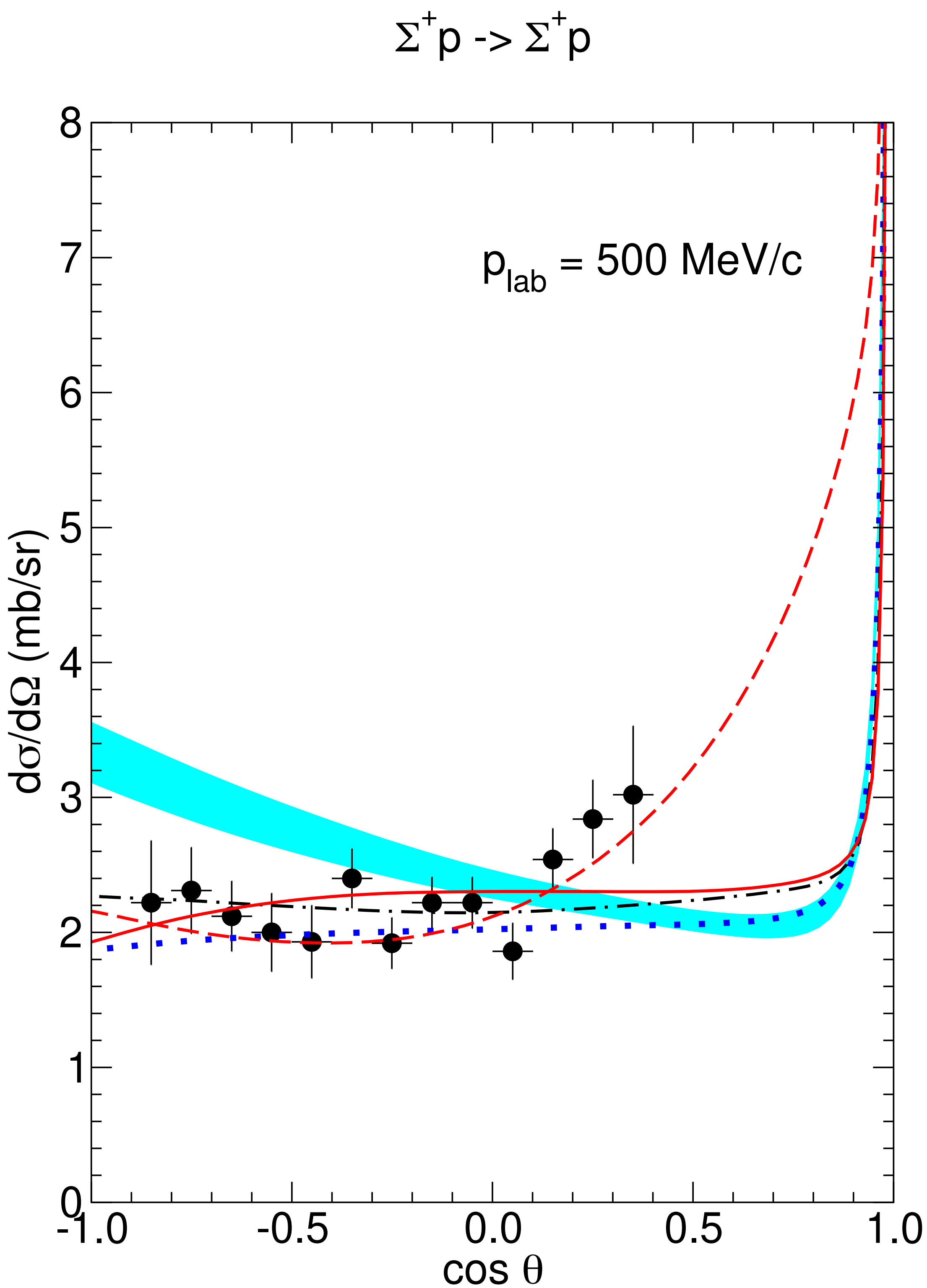


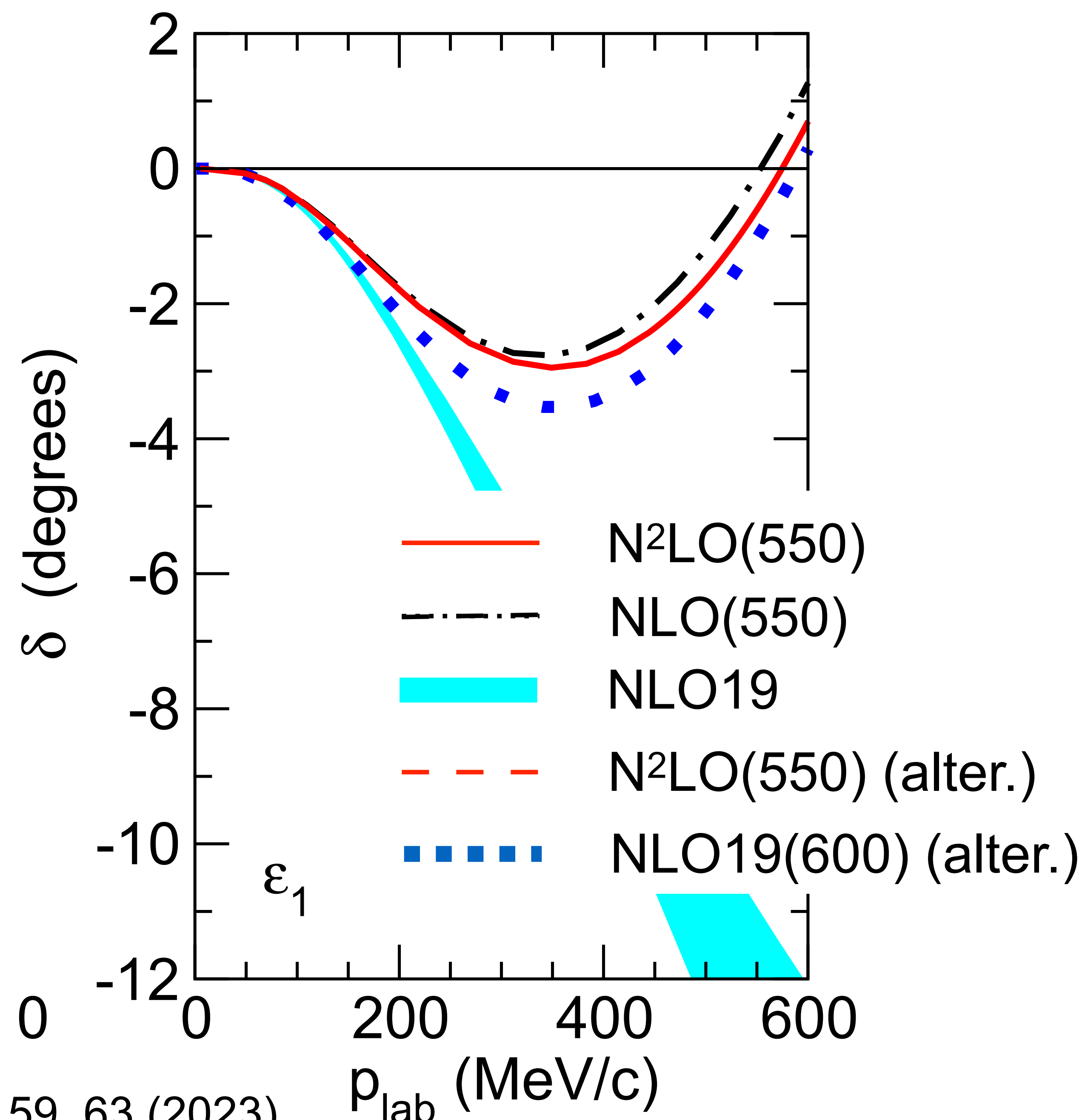


J. Haidenbauer et al. EPJ A 59, 63 (2023).

SMS NLO/N^{2}LO interaction

new data (Miwa(2022), see talk on Friday) at higher energies provides **new constraints**!





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

Uncertainty analysis to $A=3$ to 5

Order N²LO 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

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

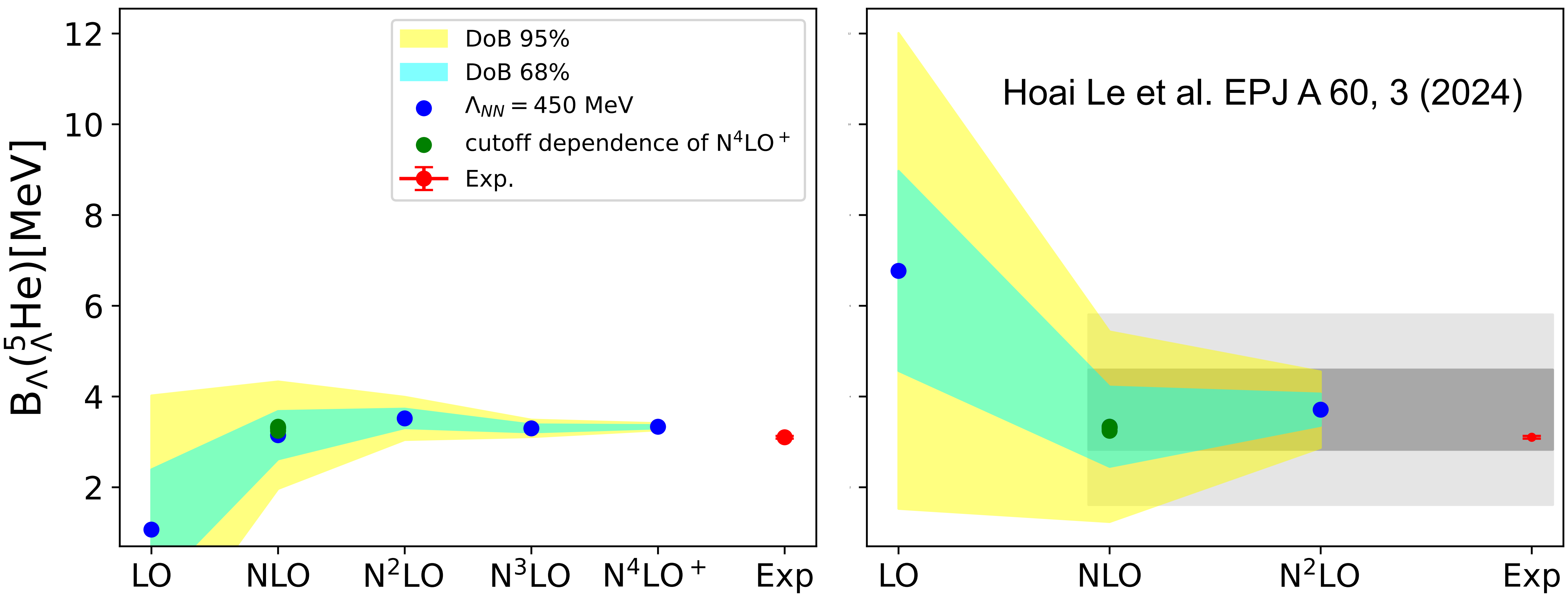
Uncertainty due to missing higher orders is more relevant than numerical uncertainty! (for light nuclei)

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

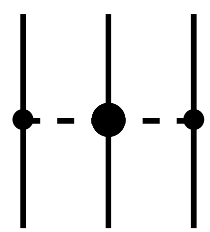
→ at the same time: estimate of YNN !



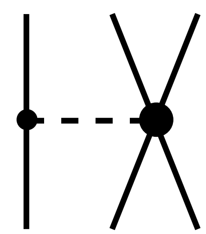
YNN (ΛNN) interactions

Leading 3BF with the usual topologies (see Petschauer et al., 2016 & 2017)

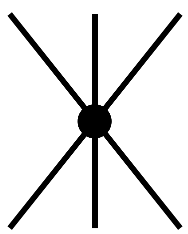
ChPT → all octet mesons contribute → **only take π** explicitly into account



2 LECs in ΛNN
(up to 10)



2 LECs in ΛNN
(up to 14)

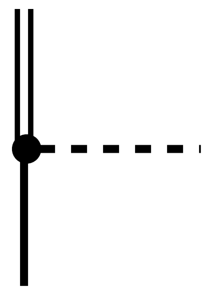


3 LECs in ΛNN
5 LECs in ΣNN + 1 Λ-Σ transition

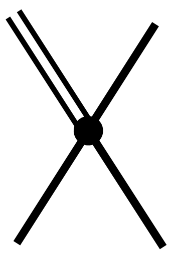
only few data → need to keep the **# of LECs** small

Decuplet baryons ($\Sigma^* \ldots$) might enhance YNN partly to NLO (see Petschauer et al., 2017)

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



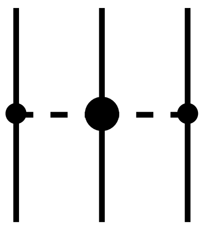
$\propto C = \frac{3}{4} g_A$

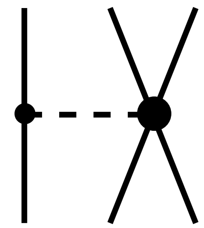


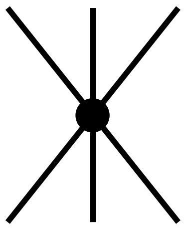
$\propto G_1, G_2$ → **reduction to 2 LECs**

YNN (ΛNN) interactions

Decuplet saturation relates all LECs to G_1 and G_2





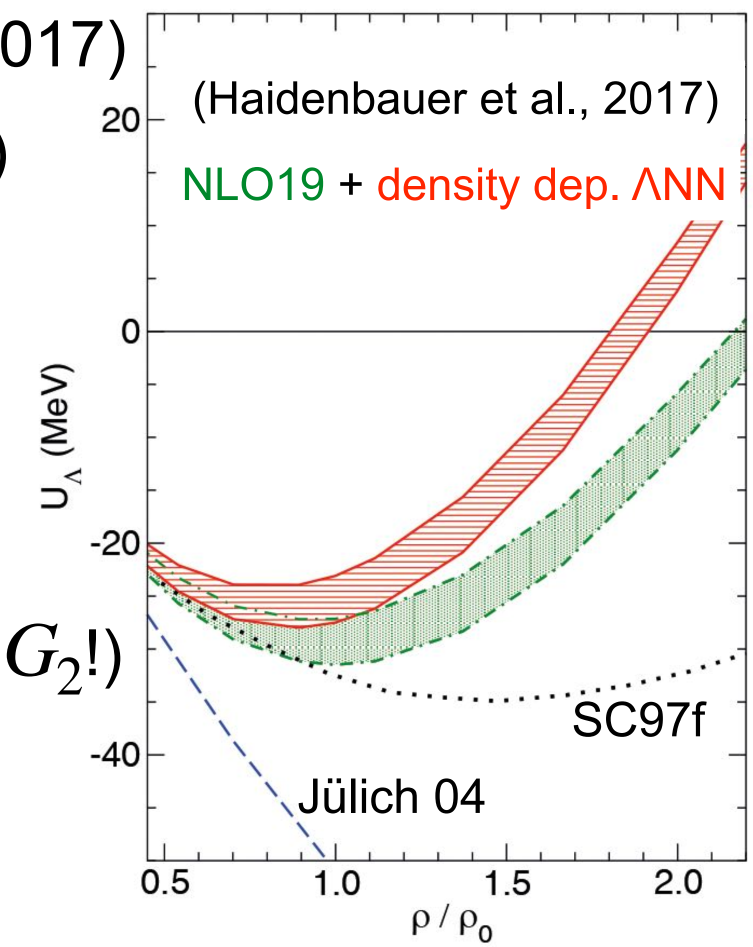


	$\propto C^2$	$\propto CG_1, CG_2$	$\propto (G_1)^2, (G_2)^2, G_1G_2$
For ΛNN:	$\propto C^2$	$\propto C(G_1 + 3G_2)$	$\propto (G_1 + 3G_2)^2$ 1 LEC

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

→ application to nuclear matter (Haidenbauer et al., 2017)

neutron stars (Logoteta et al., 2019)

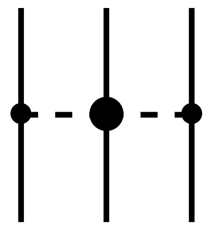


- contribution on the single particle potentials can be large
- realistic results seem to require partly cancelations of 2π and 1π exchange (fixes sign of $G_1 + 3G_2$!)

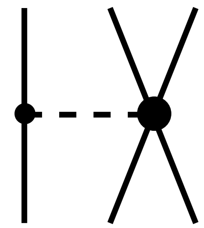
Recently: successful benchmark of matrix elements:
Hoai Le et al. arXiv:2407.02064v1

YNN (ΛNN) interactions in practice

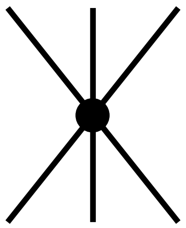
Decuplet approximation in YNN



$\propto C^2$



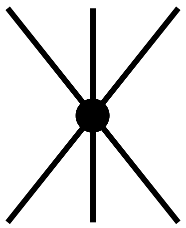
$\propto CG_1, CG_2$



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

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:

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

$$C_2' = 0$$

→

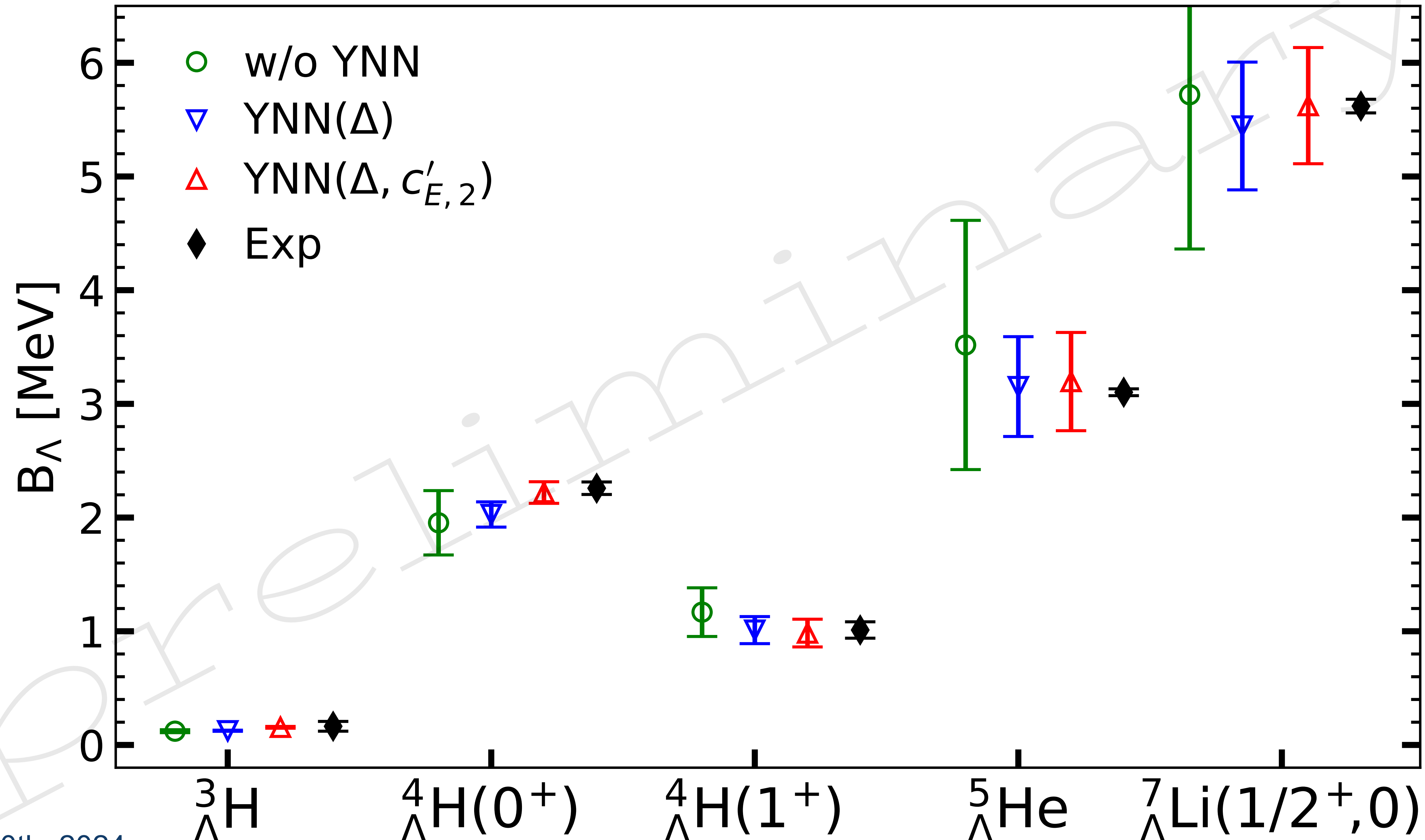
$$V_{\Lambda NN} = C_2{}' \, \vec{\sigma}_1 \cdot \left(\vec{\sigma}_2 + \vec{\sigma}_3\right) \left(1 - \vec{\tau}_2 \cdot \vec{\tau}_3\right)$$

$$C_2' = G_3$$

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

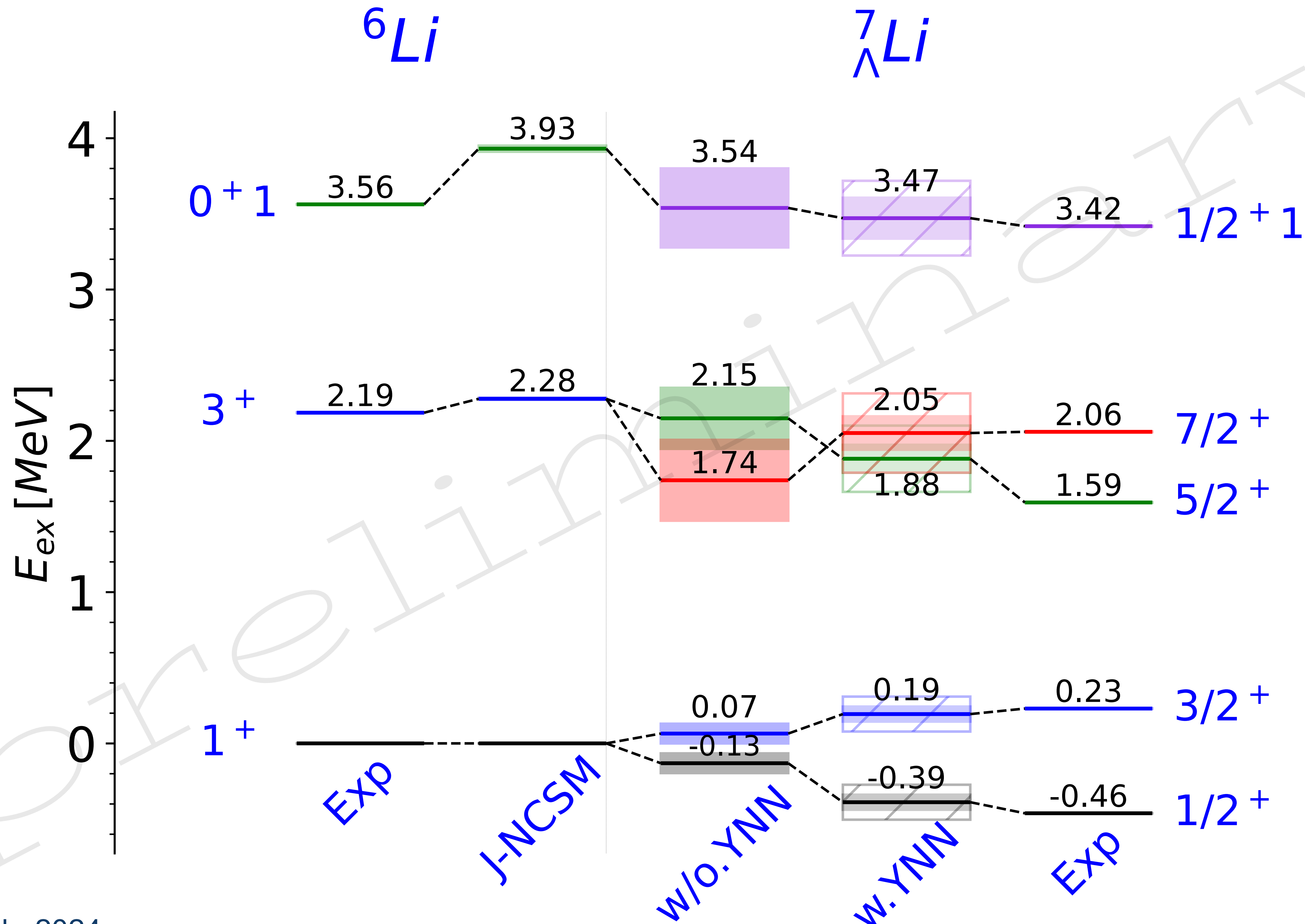
YNN fit

- 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 $^{7}_{\Lambda}\mathrm{Li}$

- 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"*
- **New SMS YN interactions**
  - *give an accurate description low energy YN data*
  - *order LO, NLO and N^2LO allow uncertainty quantification*
  - *have a **non-unique** determination of contact interactions (data necessary)*
- **Chiral 3BF** need to be included
  - *NLO uncertainty is sizable in $A = 4$ and beyond*
  - *chiral 3BFs are now available — non-local and SMS regularization*
  - *fitting to ${}^{4}_{\Lambda}\mathrm{He}$ and/or ${}^{5}_{\Lambda}\mathrm{He}$ possible — results agree with previous estimates*
  - *but: decuplet saturation alone does not improve spin dependence*
  - *spin-dependent $\Lambda\mathrm{NN}$ leads to further improvement*

  - *however: uncertainty estimate in N^2LO of incomplete N^2LO YNN force?*
  - *study cutoff dependence*
  - *application to more p-shell hypernuclei*

Conclusions & Outlook

- **YN interactions not well understood**
  - *scarce YN data*
  - *more information necessary to solve "hyperon puzzle"*
- **New SMS YN interactions**
  - *give an accurate description low energy YN data*
  - *order LO, NLO and N^2LO allow uncertainty quantification*
  - *have a **non-unique** determination of contact interactions (data necessary)*
- **Chiral 3BF** need to be included
  - *NLO uncertainty is sizable in $A = 4$ and beyond*
  - *chiral 3BFs are now available — non-local and SMS regularization*
  - *fitting to ${}^{4}_{\Lambda}\mathrm{He}$ and/or ${}^{5}_{\Lambda}\mathrm{He}$ possible — results agree with previous estimates*
  - *but: decuplet saturation alone does not improve spin dependence*
  - *spin-dependent $\Lambda\mathrm{NN}$ leads to further improvement*

  - *however: uncertainty estimate in N^2LO of incomplete N^2LO YNN force?*
  - *study cutoff dependence*
  - *application to more p-shell hypernuclei*

Thank you!