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Constraints on the Λn interaction from CSB of A=4 hypernuclei

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- Motivation
- Chiral YN interactions
- Estimates of 3BF contributions for ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ / ${}^{4}_{\Lambda}\mathrm{He}$
- CSB of the YN interaction
- Determination of CSB contact interactions and Λn scattering length
- Conclusions & Outlook

in collaboration with Johann Haidenbauer and Ulf Meißner

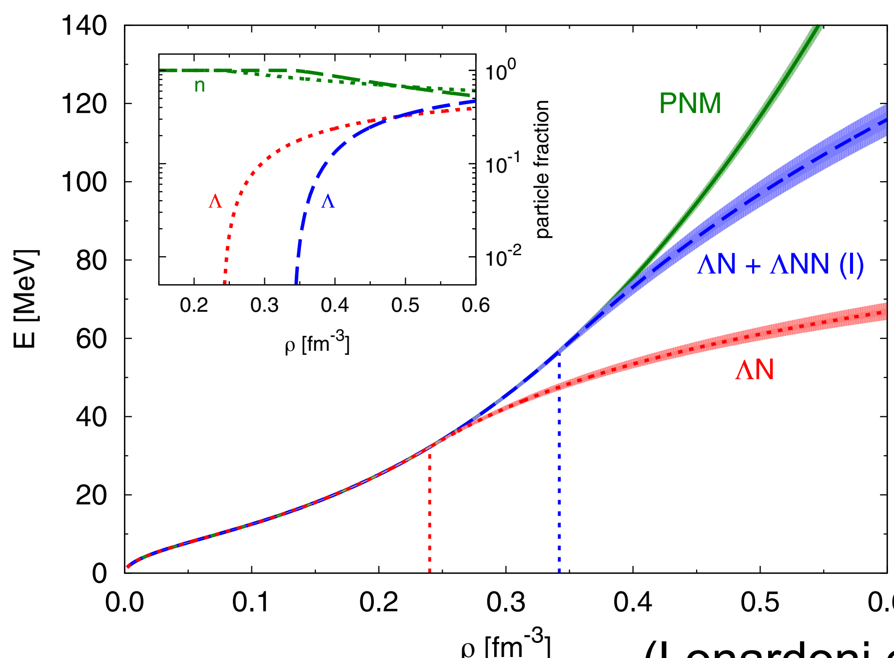
J. Haidenbauer et al. FBS 62, 105 (2021).

November 16th, 2021

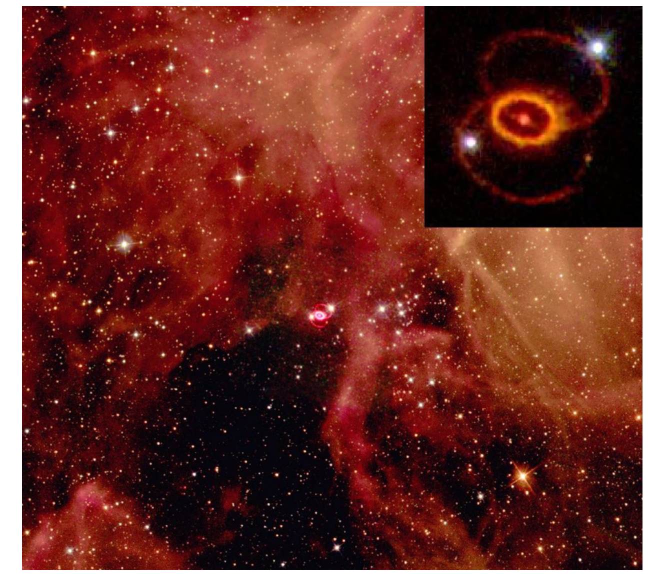
Hypernuclear interactions

Why is understanding hypernuclear interactions interesting?

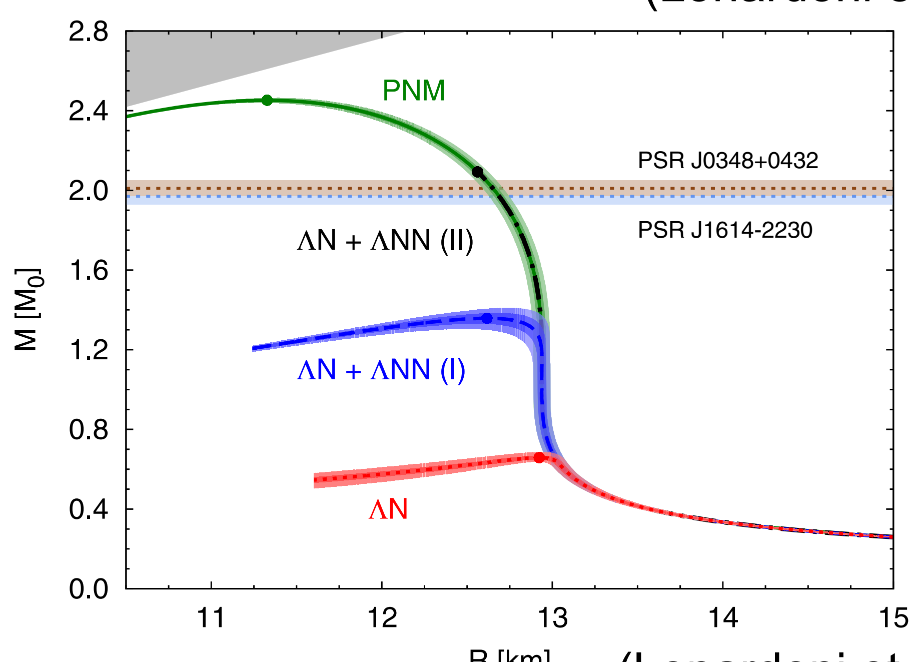
- *hyperon contribution to the EOS, neutron stars, supernovae*
- *Λ as probe to nuclear structure*
- *direct access to explicit chiral symmetry breaking*



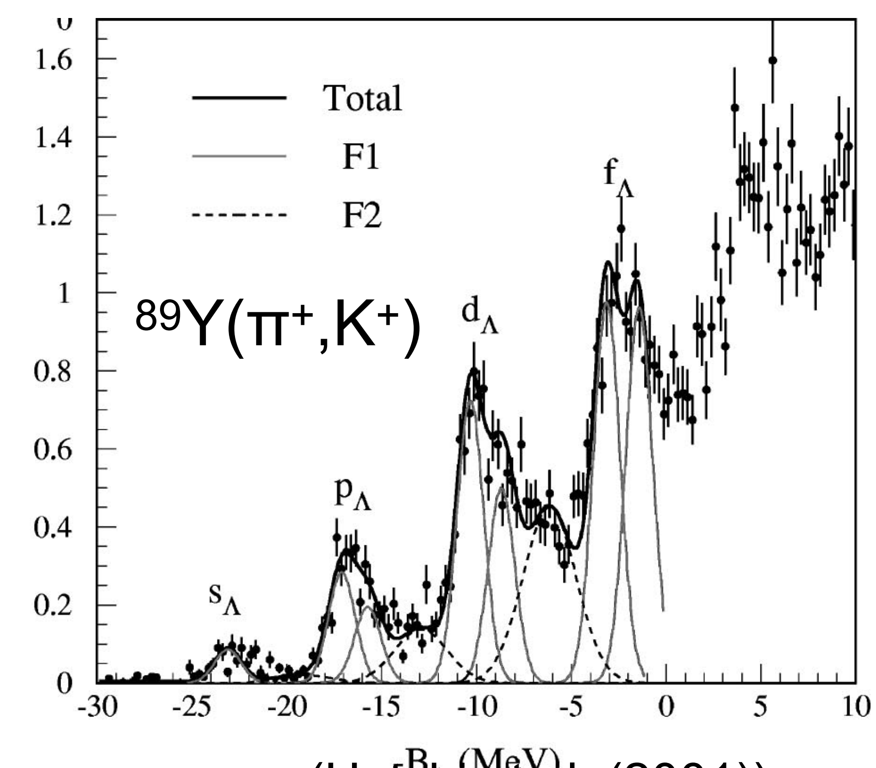
(Lonardoni et al. (2015))



(SN1987a, Wikipedia)



(Lonardoni et al. (2015))

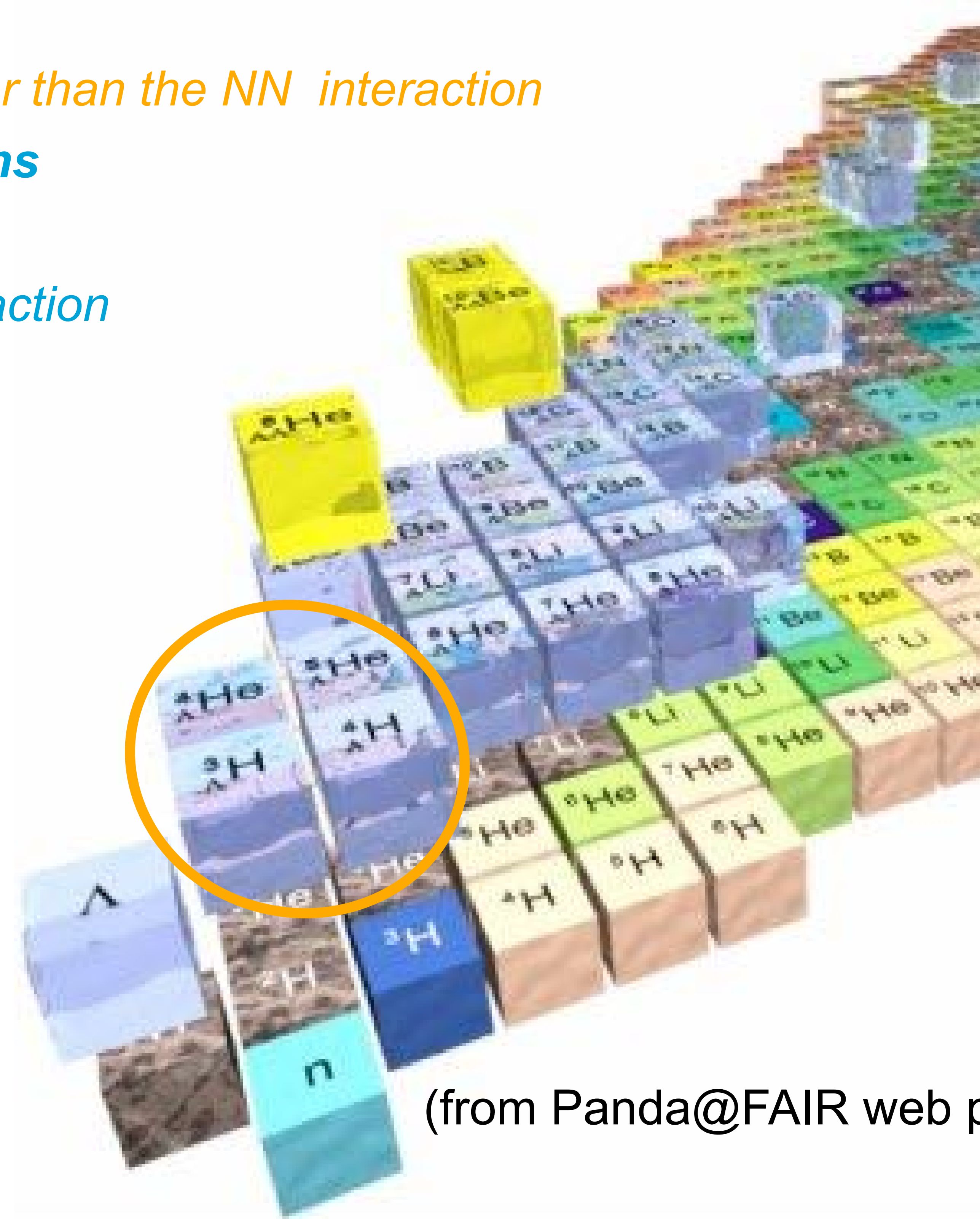


(Hotchi et al. (2001))

Hypernuclei

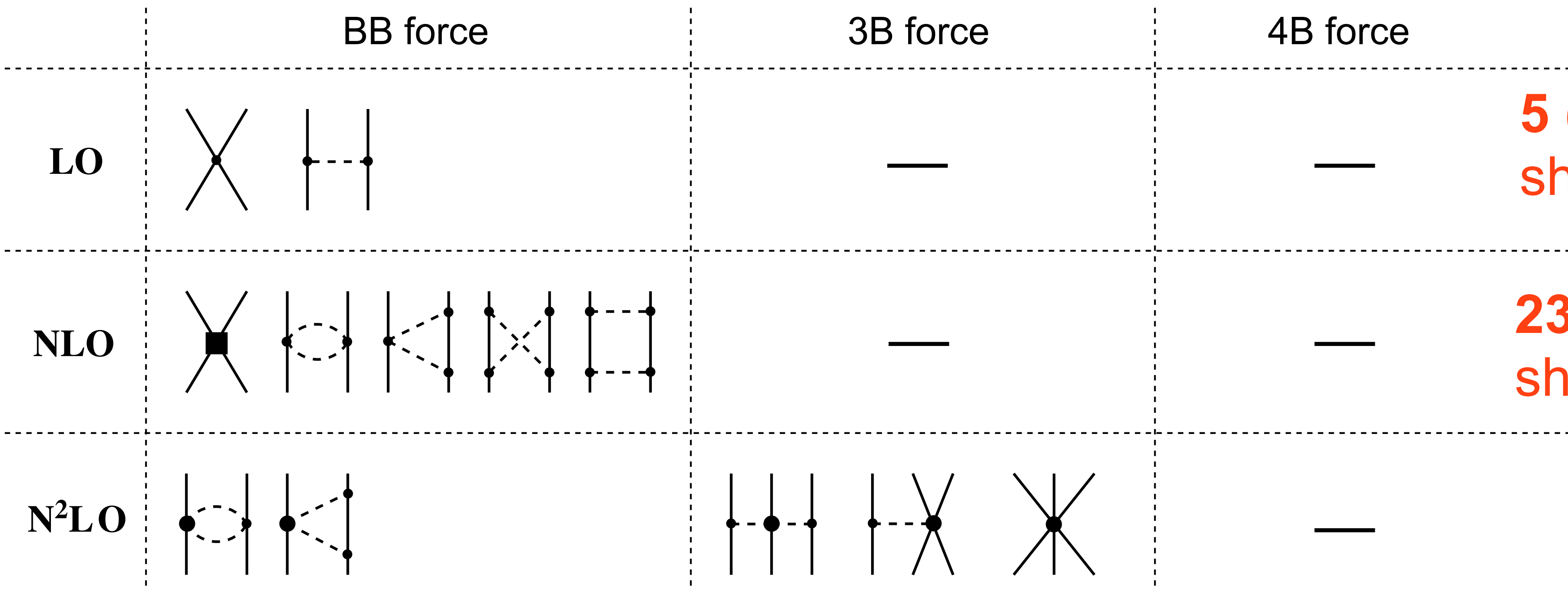
Hyperons can bind to nuclei. The binding energies are known experimentally.

- *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



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

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

(adapted from Epelbaum, 2008)

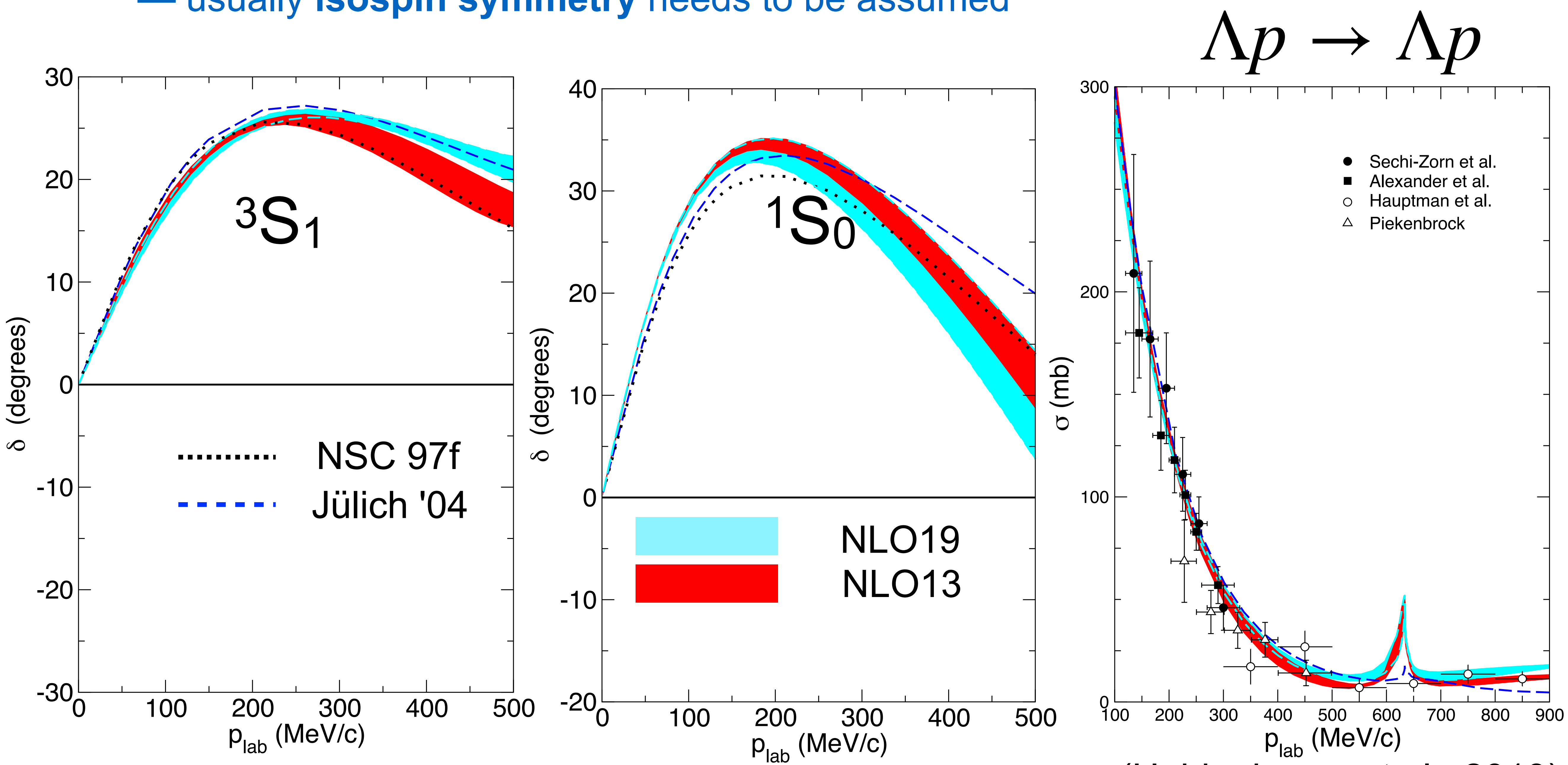
additional constraints required (e.g. for YN only 35 data, but 23 parameters at NLO)
data too scarce to uniquely determine the short range LECs!

→ **Two** realization for the YN interaction at NLO: NLO13 & NLO19
with different assumptions on the LECs
(J. Haidenbauer et al., 2013 & 2019)

Chiral interactions include symmetries of QCD & retain flexibility to adjust to data
Regulator required — cutoff is also used to estimate uncertainty and 3BF size
Λ-Σ conversion is explicitly included (size of 3BFs expected to be N^2LO)

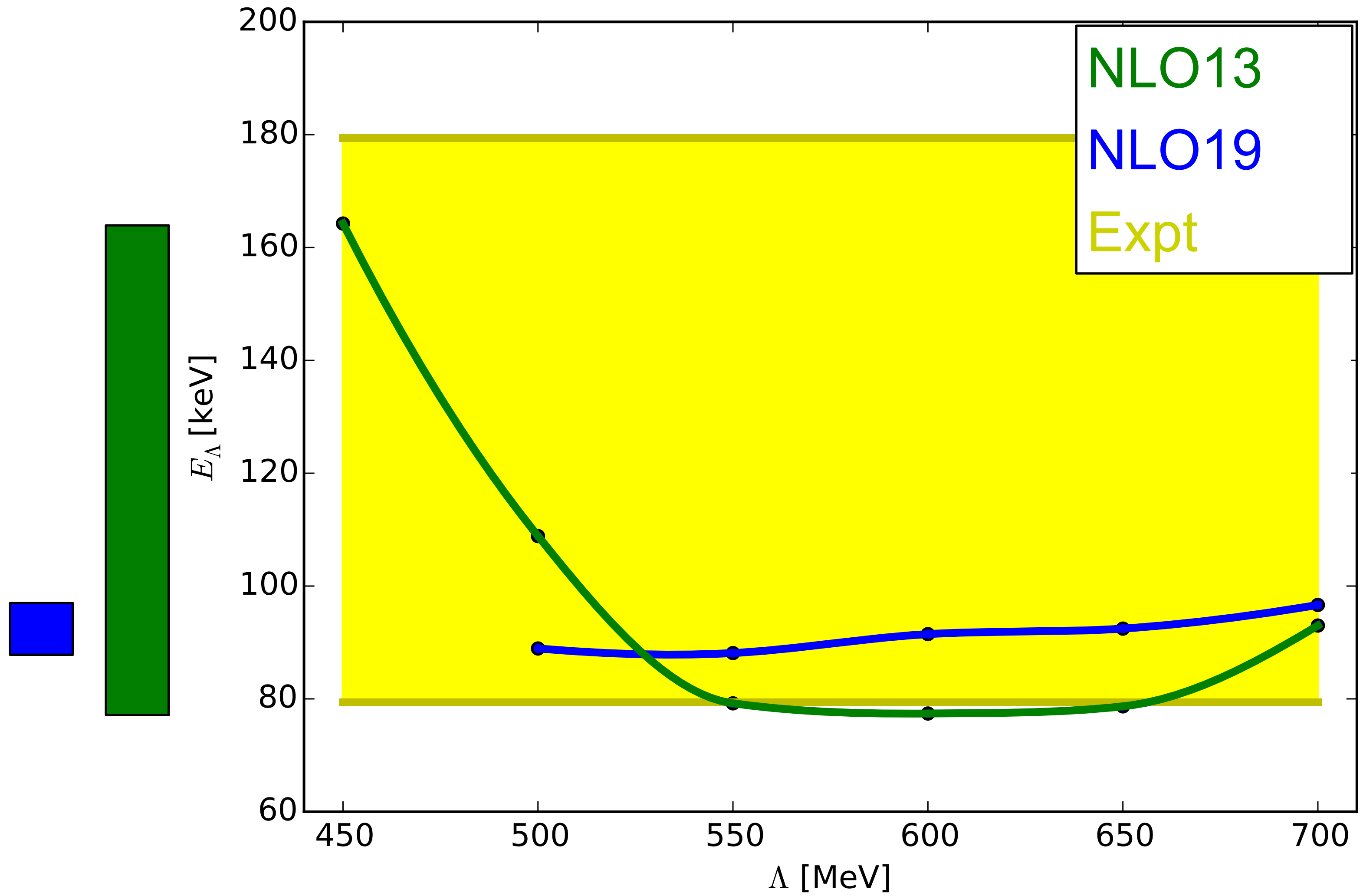
NLO13 / NLO19 - tool to estimate 3BF

- Regularization required
  - — Dependence on cutoff **indicates** uncertainty
- NLO13 and NLO19 interactions largely phase shift equivalent
  - — differences shown later indicate size of three-baryon interactions
- Note that there is no Λn data
  - — usually **isospin symmetry** needs to be assumed



(Haidenbauer at al., 2019)

Hypertriton separation energies



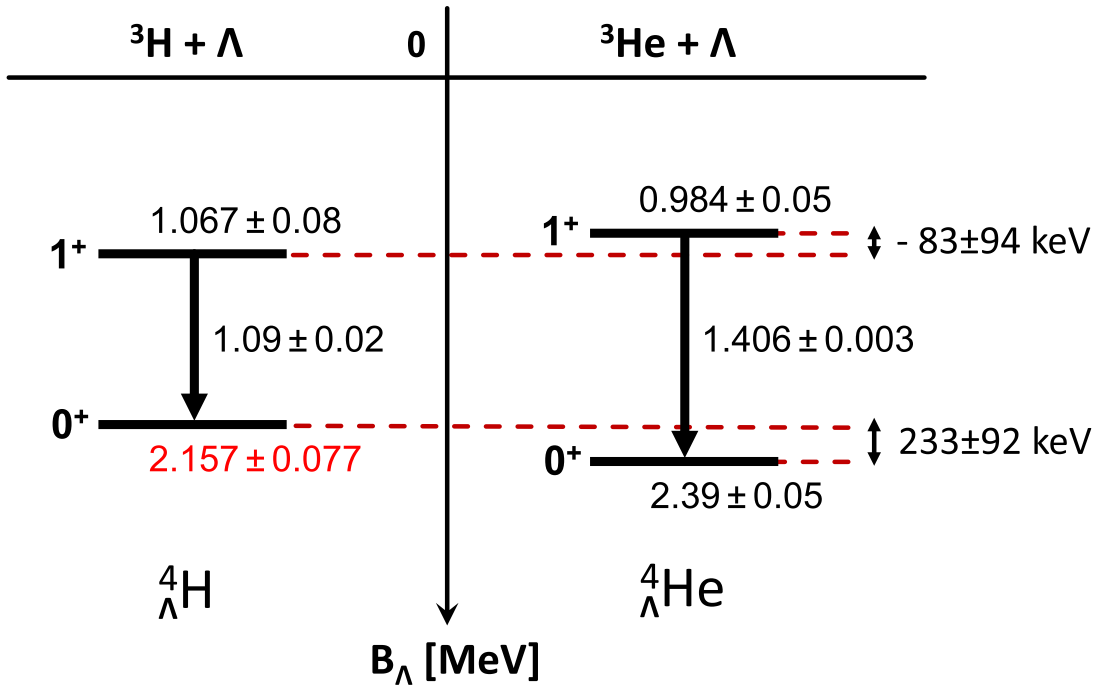
Separation energies for A=3 not well known:

$$E_\Lambda({}^3_\Lambda\mathrm{H}) = (0.13 \pm 0.05)\ \mathrm{MeV}$$

- separation energies almost independent of NN interactions ($E_\Lambda = E({}^2\mathrm{H}) - E({}^3_\Lambda\mathrm{H})$)
- ${}^1S_0$ scattering length for **one** cutoff chosen so that hypertriton binding energy is OK
- **3BFs** seem to be smaller than experimental uncertainty
  (but further insight into **(long range) 3BFs** is needed)

→ YN spin dependence can be constrained by ${}^3_\Lambda\mathrm{H}$

Separation energies for A=4



(from Schulz et al., 2016
also uses data from
Yamamoto et al., 2015; Juric et al, 1973
and Bedjidian et al. 1976,1979)

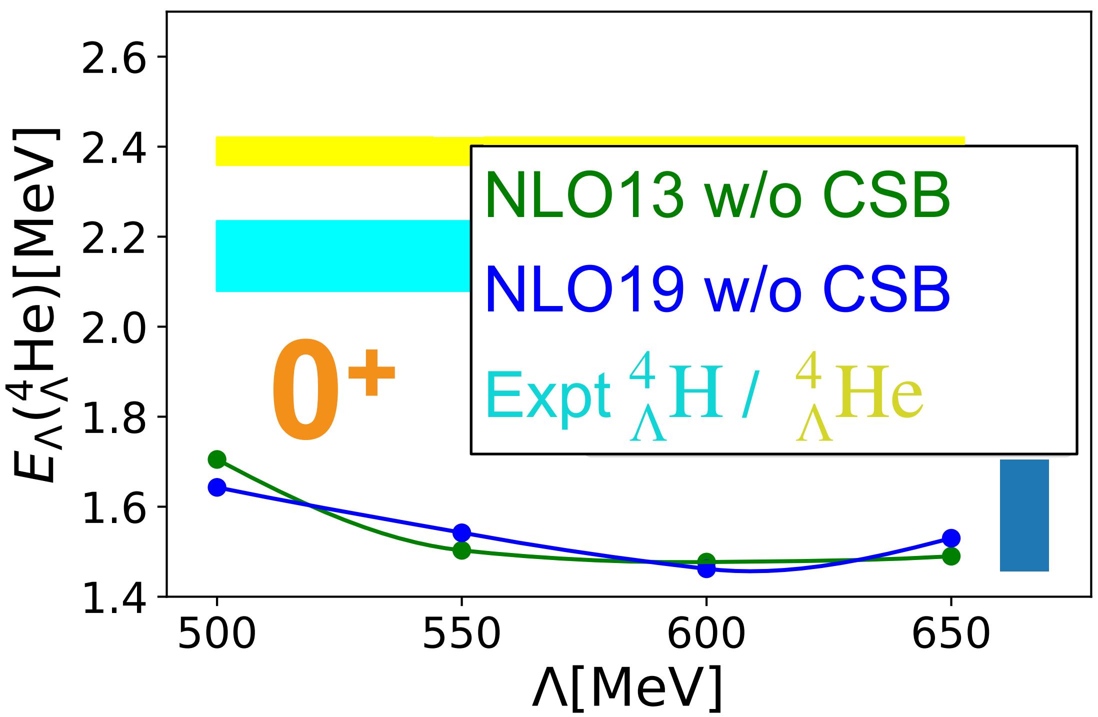
- data available for **all four** separation energies
- few and difficult experiments (new experiments planned!)
- recent remeasurement at J-PARC **changed 0^+ - 1^+ splitting** for $^4_\Lambda\mathrm{He}$

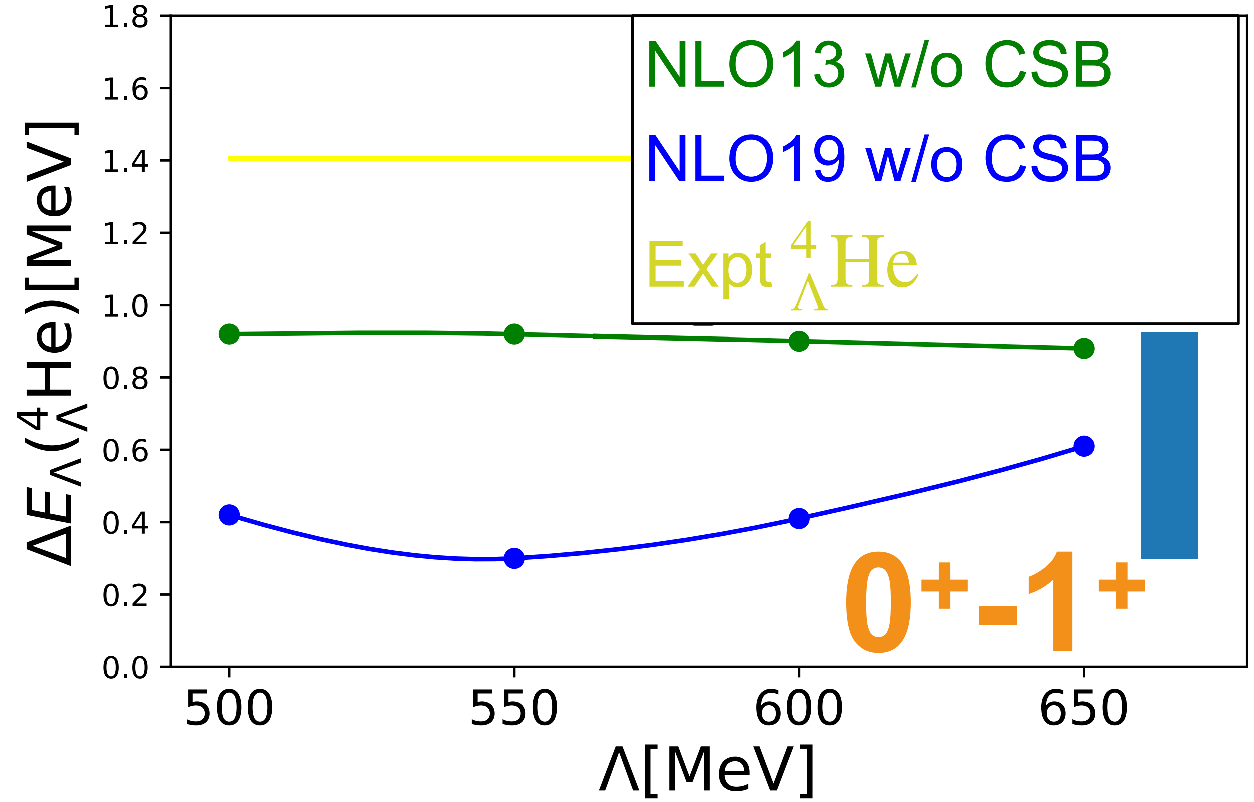
- interestingly: current data indicates strong **CSB** for **0^+** but small **CSB** for **1^+** state
- previous calculations have shown that CSB is almost entirely due to strong interaction
  Coulomb contribution almost cancels in separation energies (Bodmer et al., 1985)

➡ Λp and Λn interactions are different! Can we quantify this difference?

Estimate of 3BFs for ${}^{4}_{\Lambda}\mathrm{H}$ / ${}^{4}_{\Lambda}\mathrm{He}$

(here: NN = chiral SMS, Reinert et al. 2018)





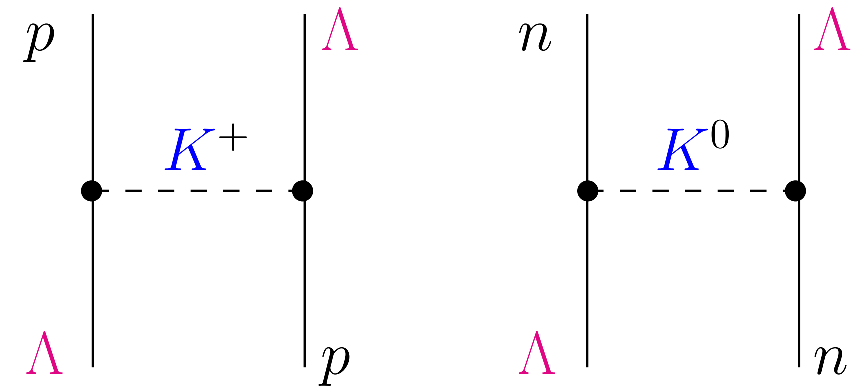
- ${}^{4}_{\Lambda}\mathrm{H}$ / ${}^{4}_{\Lambda}\mathrm{He}$ is **not** well described even at NLO interactions (same any model)
- NLO13/19 are similar for the 0^+ state (less similar for 1^+)

→ **indication for significant 3BF** contributions to the ground state energy and the splitting

For the following, we assume that CSB 3BFs are insignificant and that predictions for CSB are not significantly affected by missing higher order interactions!

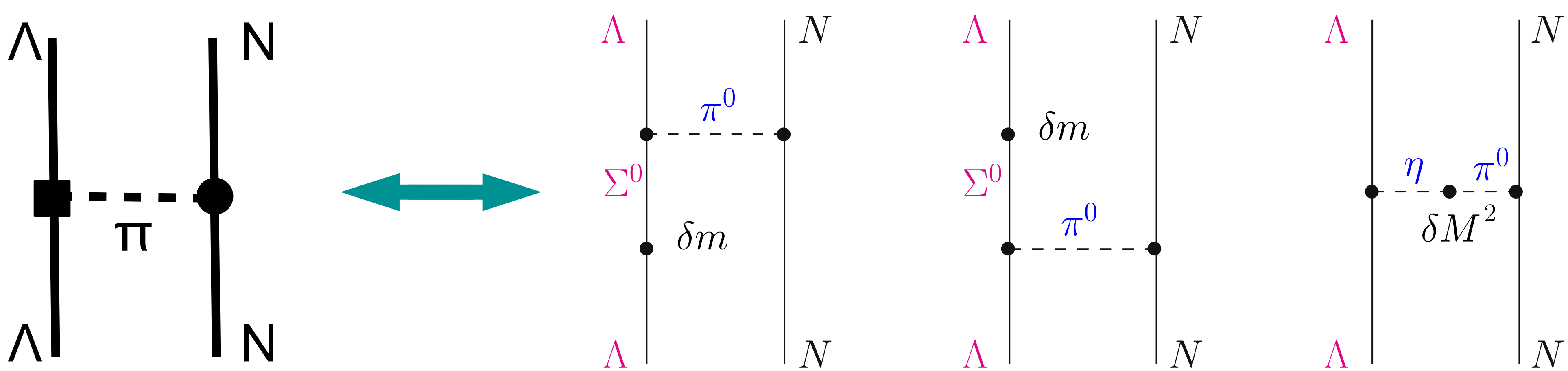
CSB contributions to YN interactions

- **formally leading** contributions:
  Goldstone boson mass difference
  — very small due to the small relative difference of kaon masses

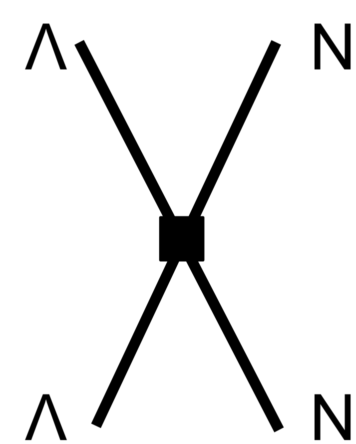


- **subleading but most important**
  — effective CSB ΛΛπ coupling constant (Dalitz, van Hippel, 1964)

$$f_{\Lambda\Lambda\pi} = \left[-2 \frac{\langle \Sigma^0 | \delta m | \Lambda \rangle}{m_{\Sigma^0} - m_\Lambda} + \frac{\langle \pi^0 | \delta M^2 | \eta \rangle}{M_\eta^2 - M_{\pi^0}^2} \right] f_{\Lambda\Sigma\pi} \approx (-0.0297 - 0.0106)\, f_{\Lambda\Sigma\pi}$$



- **so far less considered, but equally important**
  — CSB contact interactions (for singlet and triplet)



Aim: use A=4 hypernuclei to determine the two unknown CSB LECs and predict Λn scattering

Fit of contact interactions

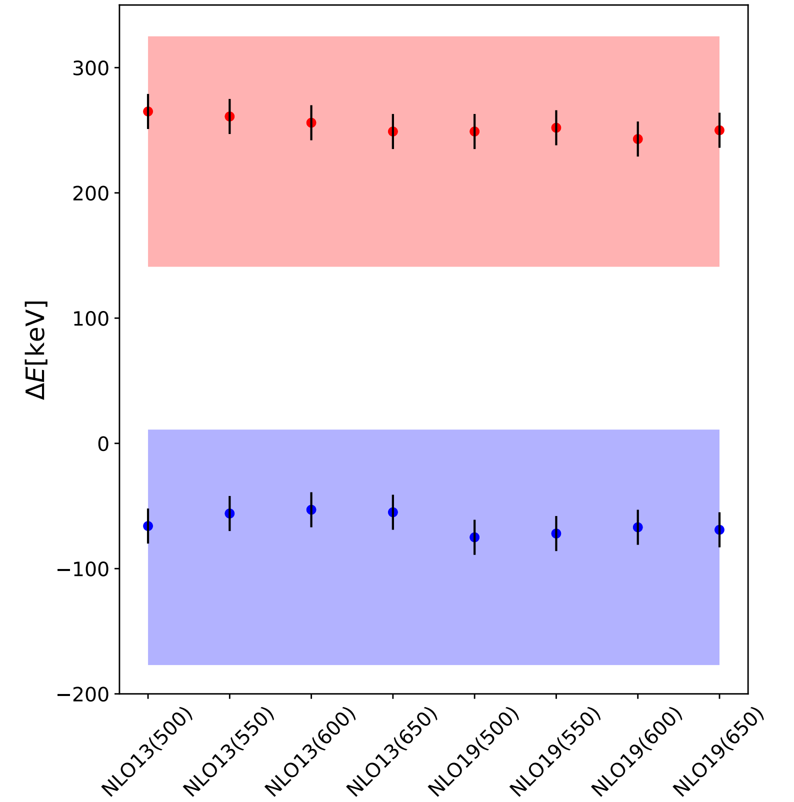
- Adjust the two CSB contact interactions to one main scenario (**CSB1**, shown here) and two more for testing (**CSB2**,**CSB3**) sensitivities
- Size of LECs as expected by power counting

$$\frac{m_d - m_u}{m_u + m_d}\left(\frac{M_\pi}{\Lambda}\right)^2 C_{S,T} \approx 0.3 \cdot 0.04 \cdot 0.5 \cdot 10^4\,\mathrm{GeV} \propto 6 \cdot 10^{-3} \cdot 10^4\,\mathrm{GeV}$$

Λ	NLO13		NLO19	
	C_s^{CSB}	C_t^{CSB}	C_s^{CSB}	C_t^{CSB}
500	4.691×10^{-3}	-9.294×10^{-4}	5.590×10^{-3}	-9.505×10^{-4}
550	6.724×10^{-3}	-8.625×10^{-4}	6.863×10^{-3}	-1.260×10^{-3}
600	9.960×10^{-3}	-9.870×10^{-4}	9.217×10^{-3}	-1.305×10^{-3}
650	1.500×10^{-2}	-1.142×10^{-3}	1.240×10^{-2}	-1.395×10^{-3}

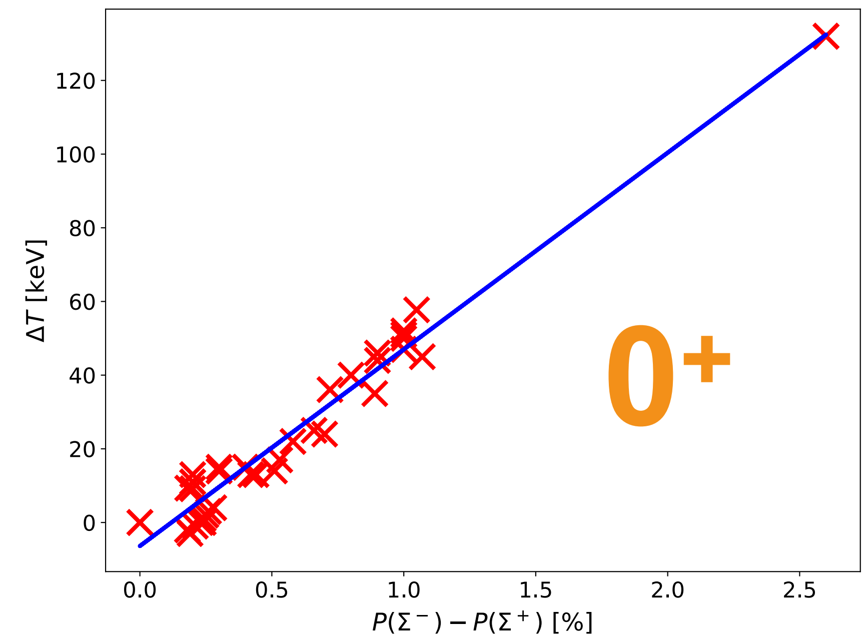
The values of the LECs are in 10^4 GeV^{-2}

- Problem: large experimental uncertainty of experiment
- here only fit to central values to test theoretical uncertainties



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

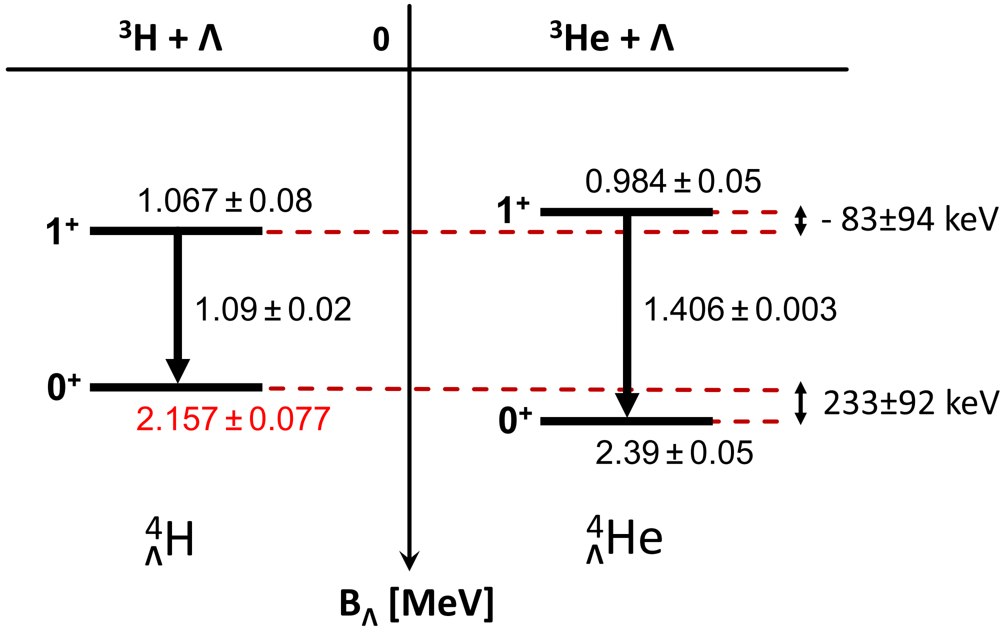


0+

interaction	$\langle T\rangle_{CSB}$	$\langle V_{YN}\rangle_{CSB}$	V_{NN}^{CSB}	ΔE_Λ^{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

1+

interaction	$\langle T\rangle_{CSB}$	$\langle V_{YN}\rangle_{CSB}$	V_{NN}^{CSB}	ΔE_Λ^{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



(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 ${}^4_\Lambda\mathrm{H}$ / ${}^4_\Lambda\mathrm{He}$
- **without** CSB: $a_s^{\Lambda n} \approx 2.9\ fm$ **with** CSB1: $a_s^{\Lambda n} \approx 3.3\ fm$
- improved description of Λp data
- almost independent of cutoff & NLO variant
- CSB of triplet is smaller than of singlet

for "CSB1": currently best experimental values

	$a_s^{\Lambda p}$	$a_t^{\Lambda p}$	$a_s^{\Lambda n}$	$a_t^{\Lambda n}$	$\chi^2(\Lambda p)$	$\chi^2(\Sigma N)$	$\chi^2(\text{total})$
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

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

Fitting to older values 350/240 keV splitting (**CSB2**) results in significantly different scattering length: $a_s^{\Lambda n} < a_s^{\Lambda p} \approx 3.8 \pm 0.2\ fm$ (refit necessary!)

Conclusions & Outlook

- **YN interactions not well understood**
  - *scarce YN data*
  - *more information necessary to solve "hyperon puzzle"*
- **Hypernuclei provide important constraints**
  - *here: CSB of ΛN scattering &* $^{4}_{\Lambda}\mathrm{He}$ / $^{4}_{\Lambda}\mathrm{H}$
  - *new experiments planned at J-PARC, J-Lab, MAMI, PANDA,…*
- **Chiral 3BF** need to be included
  - *YN interactions do not describe the A=4 hypernuclei well*
  - *explicit chiral 3BFs are formulated and currently implemented*

    (Petschauer et al., (2016))
- ***J-NCSM*** *(see talk of Hoai Le later today!)*
  - *reliable predictions are possible for* $S = -1$ *and* -2 for $A > 4$

    (see talk of Hoai Le later today)
  - *study CSB of p-shell hypernuclei*