Light hypernuclei based on chiral interactions at next-to-leading order

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- Motivation
- Numerical technique
- Light Hypernuclei
  - separation energies based on chiral interactions
  - CSB of four-body hypernuclei
- Conclusions & Outlook

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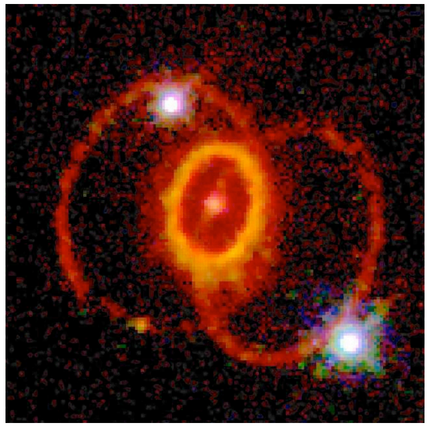
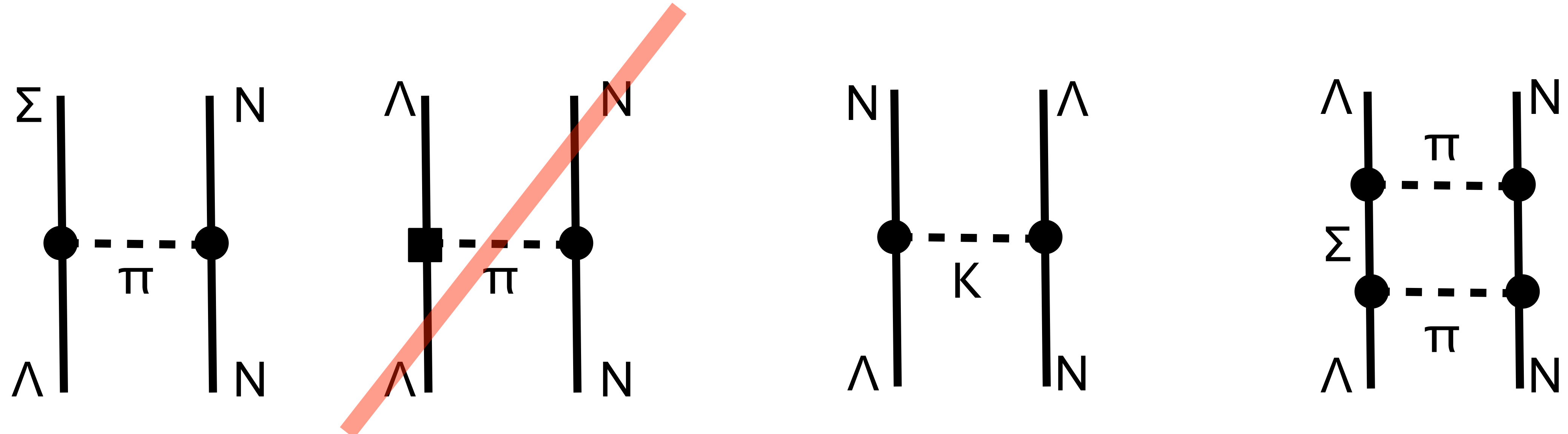
Hypernuclear interactions

Why is understanding hypernuclear interactions interesting?



(SN1987a)

- „phenomenologically“
  - *hyperon contribution to the EOS, neutron stars, supernovae*
  - *Λ as probe to nuclear structure*
- conceptually
  - ***Λ-Σ** conversion process*
  - *experimental access to explicit chiral symmetry breaking*



suppressed by
isospin symmetry

$m_K \approx 500\ \mathrm{MeV}$

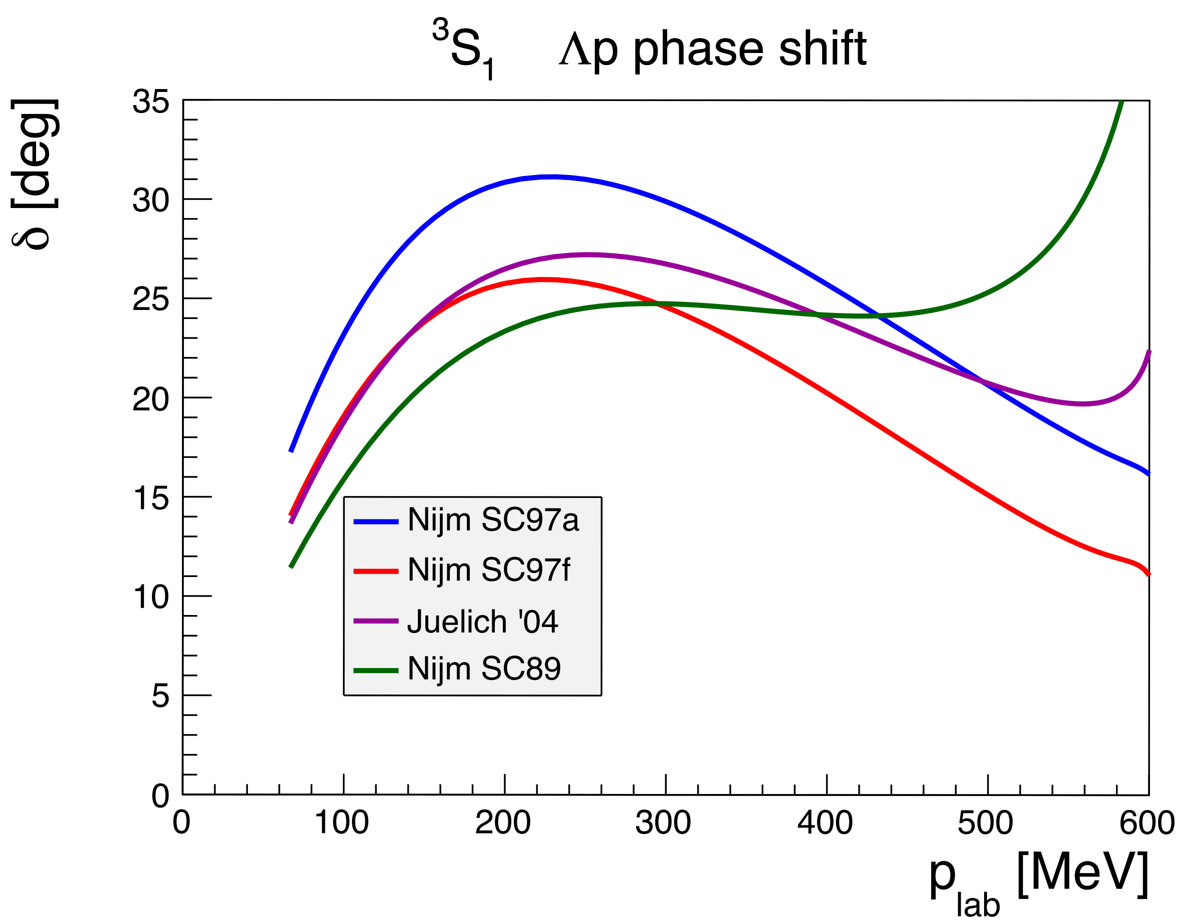
Hypernuclear interactions

35 YN data, no YN bound state, large uncertainties

→ no partial wave analysis possible

YN interaction models (Jülich 89/04, Nijmegen 89/97a-f, ...)

describe all data **more than perfectly**, but are not phase equivalent



	$^1a(\Lambda p)$ [fm]	$^3a(\Lambda p)$ [fm]
SC97a	-0.7	-2.15
SC97b	-0.9	-2.11
SC97c	-1.2	-2.06
SC97d	-1.7	-1.93
SC97e	-2.1	-1.83
SC97f	-2.5	-1.73
SC89	-2.6	-1.38
Jülich ´04	-2.6	-1.73

How to further constrain the YN interactions?

Hypernuclei

- *ΛN interaction generally weaker than the NN interaction*
  - *naively:* ***core nucleus + hyperons***
  - ***„separation energies“*** *are almost 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***
- *size of YNN interactions?*
- ***non-trivial constraints*** *on the YN interaction even from lightest ones*

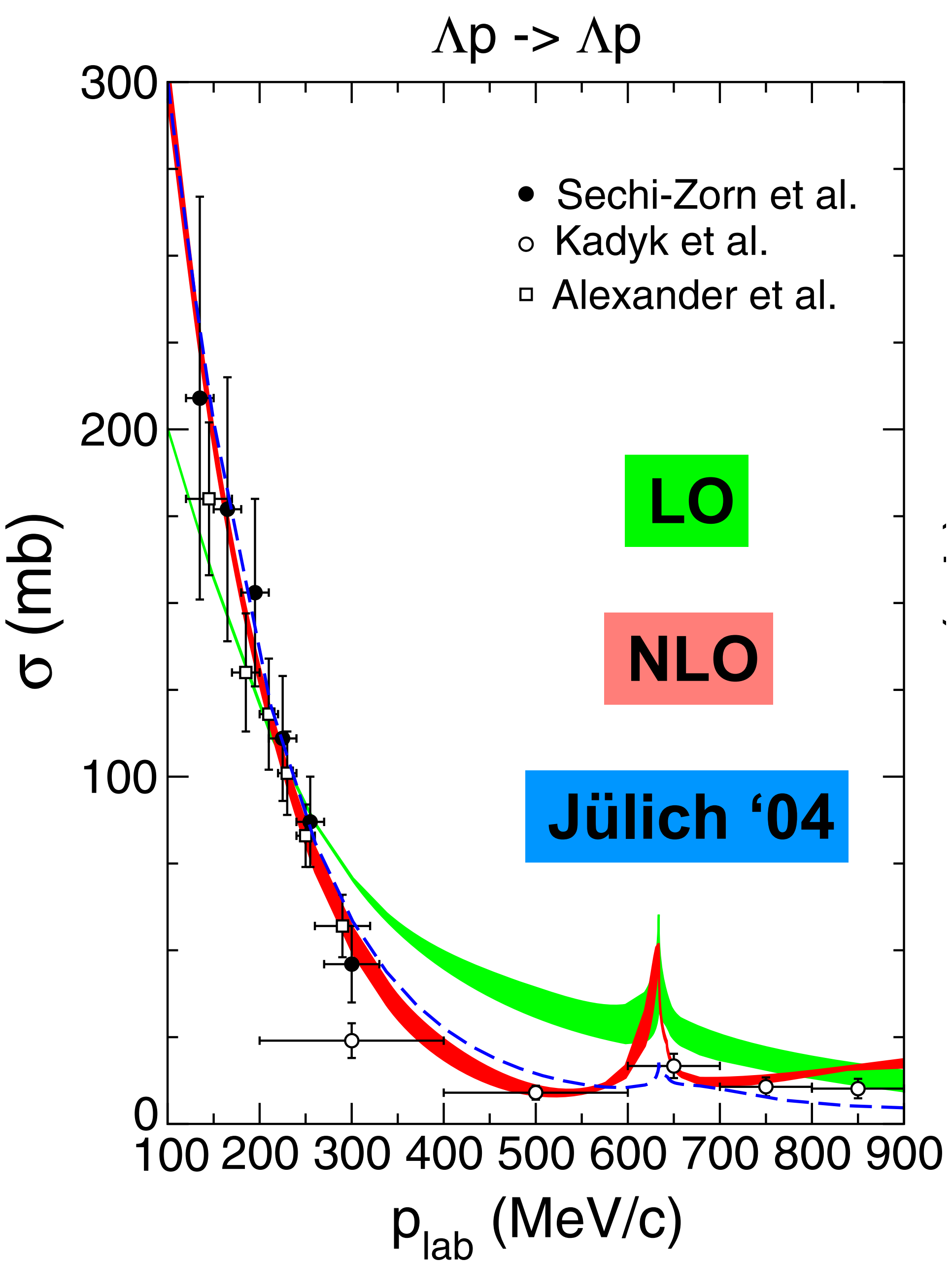
$$^{3}_{\Lambda}\mathrm{H}\left(\frac{1}{2}^{+}\right)$$

$$^{4}_{\Lambda}\mathrm{H}\left(0^{+}\right) - ^{4}_{\Lambda}\mathrm{He}\left(0^{+}\right)$$

$$^{4}_{\Lambda}\mathrm{H}\left(1^{+}\right) - ^{4}_{\Lambda}\mathrm{He}\left(1^{+}\right)$$

(from Panda@FAIR web page)

Chiral interactions at LO, NLO



	$^1a(\Lambda p)$ [fm]	$^3a(\Lambda p)$ [fm]
LO	-1.9	-1.2
NLO	-2.9	-1.5 ... -1.7
Jülich ´04	-2.6	-1.7

(Polinder et al., NPA 779, 244 (2006),
Haidenbauer et al. , NPA 915, 24 (2013)
see Johann Haidenbauer's talk)

- hypertriton binding energy provides constraint on spin dependence of the YN interaction
- better description of the energy dependence in NLO
- significantly increased scattering lenghts in NLO compared to LO

Numerical technique

non-rel. Schrödinger equation $\Psi = G_0 V \Psi$ $G_0 = \frac{1}{E - H_0}$

→ decomposition in five **Yakubovsky components**

$$\Psi = (1+P)(\psi_{1A} + \psi_{1B} + \psi_{2A} + \psi_{2B}) + (1 - P_{12})(1+P)\psi_{1C}$$

solution of the **Yakubovsky equations**

$$\psi_{1A} = G_0 t_{12} P(\psi_{1A} + \psi_{1B} + \psi_{2A}) + (1 + G_0 t_{12}) G_0 V_{123}^{(3)} \Psi$$

$$\psi_{1B} = G_0 t_{12}((1 - P_{12})(1 - P_{23})\psi_{1B} + P\psi_{2B})$$

$$\psi_{1C} = G_0 t_{14}(\psi_{1A} + \psi_{1B} + \psi_{2A} - P_{12}\psi_{1C} + P_{12}P_{23}\psi_{1C} + P_{13}P_{23}\psi_{2B})$$

$$\psi_{2A} = G_0 t_{12}((P_{12} - 1)P_{13}\psi_{1C} + \psi_{2B})$$

$$\psi_{2B} = G_0 t_{34}(\psi_{1A} + \psi_{1B} + \psi_{2A})$$

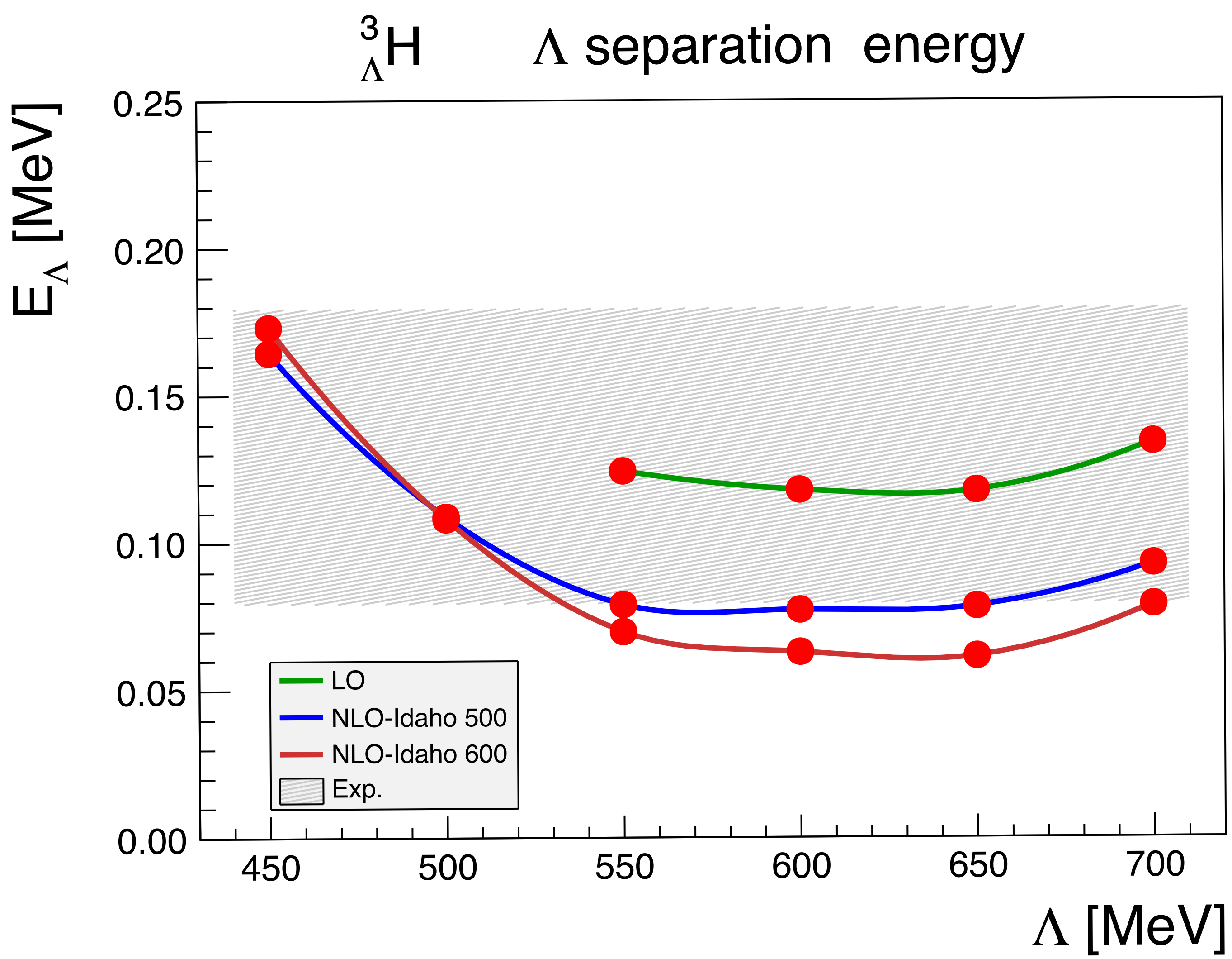
$$(P = P_{12}P_{23} + P_{13}P_{23})$$

→ improved convergence in terms of partial waves

carefully check convergence with respect to partial waves,
stability with respect to mesh points, ...

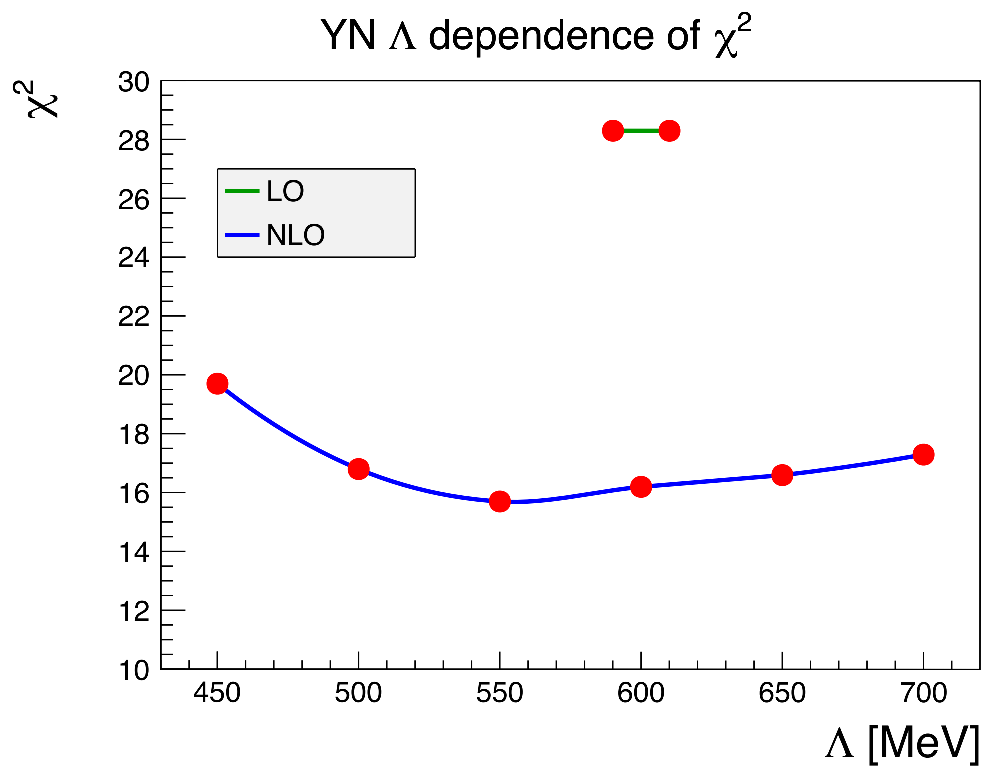
(see Nogga et. al., PRL 88,172501 (2002))

Hypertriton separation energies



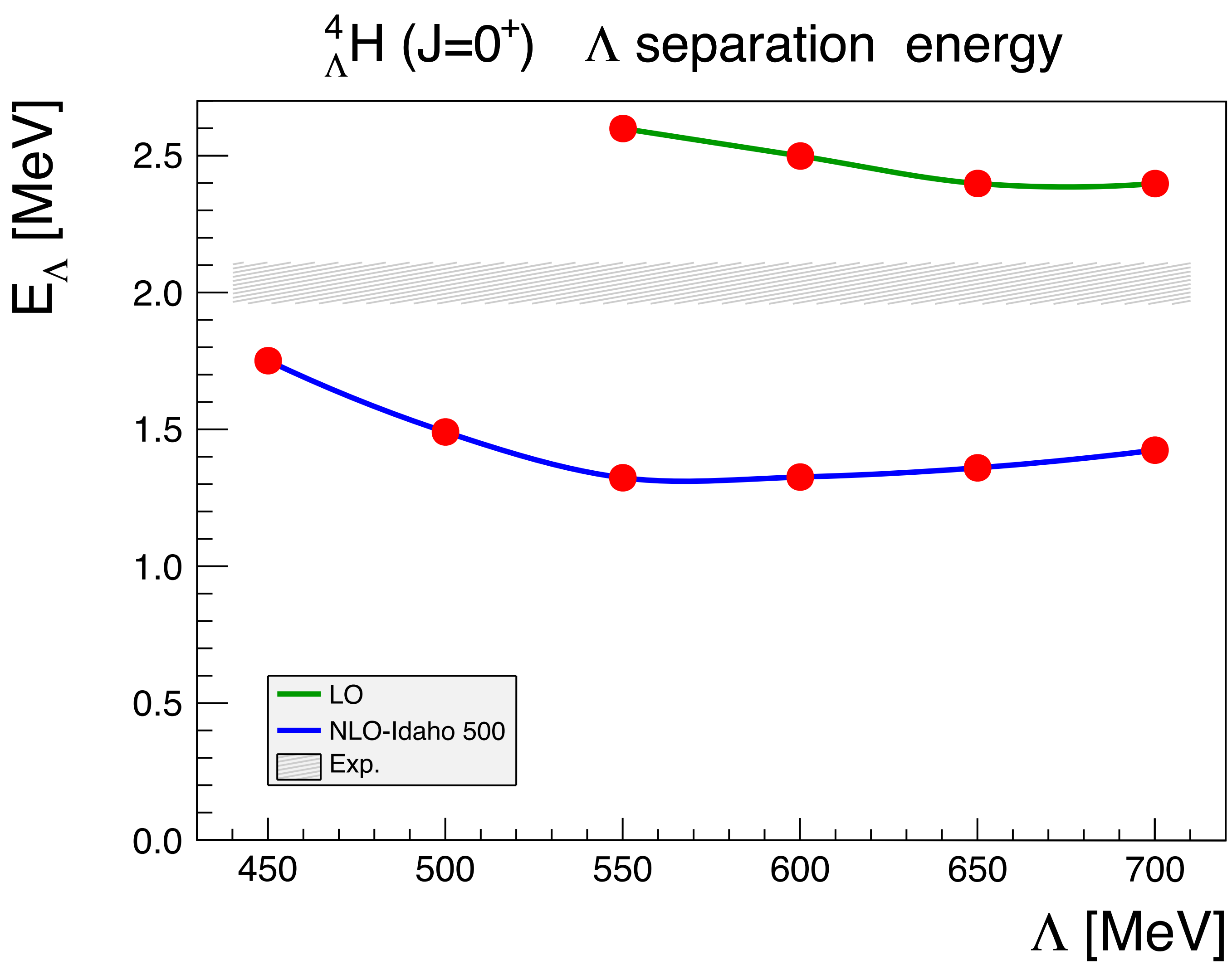
separation energies:

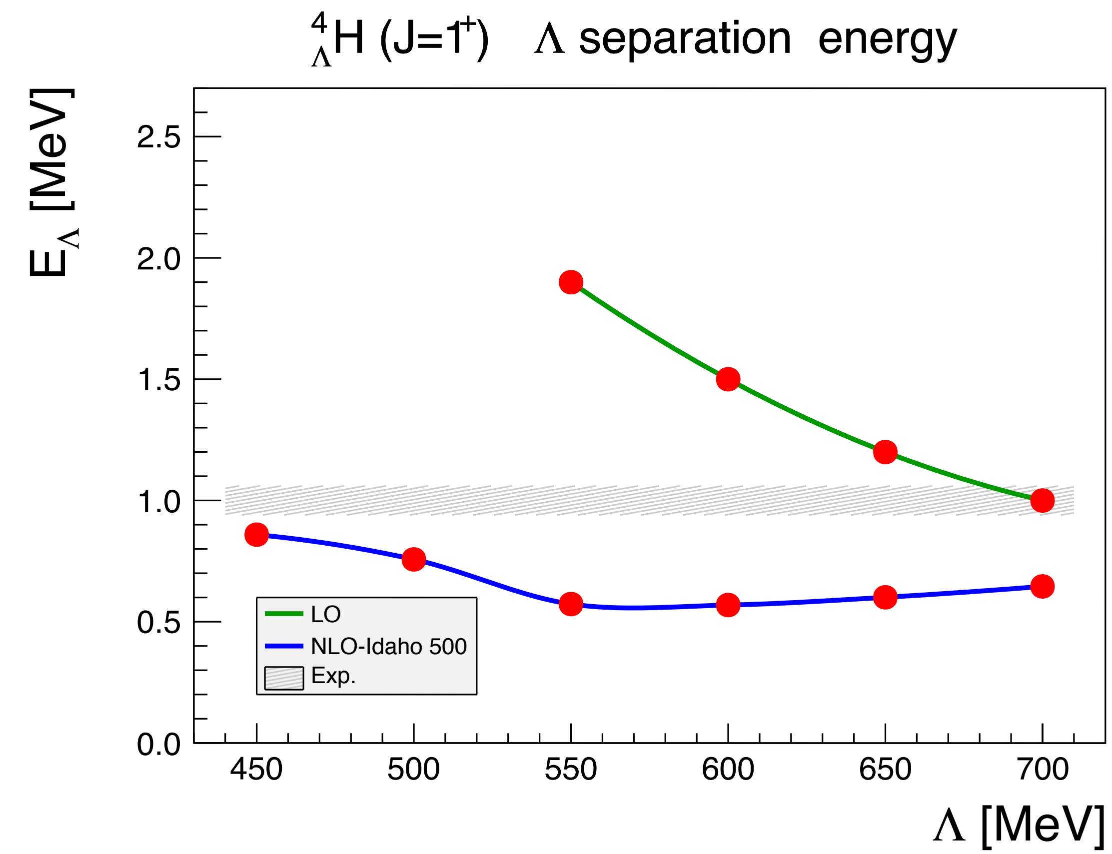
$$E_\Lambda = E(core) - E(hypernucleus)$$



- singlet scattering length for one cutoff chosen so that hypertriton binding energy is OK
- cutoff variation
  - is **lower bound** for magnitude of higher order contributions
  - correlation with χ^2 of YN interaction ?
- long range 3BFs need to be explicitly estimated

Separation energies for $^{4}_{\Lambda}\mathrm{H}$





- LO/NLO results: LO uncertainty in 0^{+} is underestimated by cutoff variation
- NLO results in line with model results, implies underbinding
- long range 3BFs need to be explicitly estimated

- **but:** for this version of NLO, results are **inconsistent** with experiment
  - note: this NLO does not allow for SU(3) breaking in contact part of YN
  - ad-hoc p-waves

CSB at NLO & for model interactions

Contributions to the difference of ${}^4_\Lambda\mathrm{H}\,(0^+) - {}^4_\Lambda\,\mathrm{He}\,(0^+)$ separation energies

Λ [MeV]	450	500	550	600	650	700	Jülich 04	Nijm SC97	Nijm SC89	Expt.
ΔT [keV]	44	50	52	51	46	40	0	47	132	-
ΔV_{NN} [keV]	-3	-2	5	5	3	0	-31	-9	-9	-
ΔV_{YN} [keV]	-11	-11	-11	-10	-8	-7	2	37	228	-
tot [keV]	30	37	46	46	41	33	-29	75	351	350
P_{Σ^-}	1.0%	1.1%	1.2%	1.2%	1.1%	0.9%	0.3%	1.0%	2.7%	-
P_{Σ^0}	0.6%	0.6%	0.7%	0.7%	0.6%	0.5%	0.3%	0.5%	1.4%	-
P_{Σ^+}	0.1%	0.1%	0.2%	0.2%	0.2%	0.1%	0.3%	0.0%	0.1%	-

- **kinetic energy contribution is driven by Σ component**
- NN force contribution due to small deviation of Coulomb
- YN force contribution:
  - *SC89 CSB is strong*
  - *NLO CSB is zero, only Coulomb acts (Σ component)*

Conclusions & Outlook

- YN interactions are interesting
  - *Λ-Σ conversion, explicit chiral symmetry breaking*
- YN interactions are not well understood
  - *well known: YN models fail*
  - *NLO of chiral interactions: still freedom to adjust YN forces*
  - *further estimates of three-baryon interactions are required*
- hypernuclei are an essential source of information on YN
  - *it is not trivial to describe the simplest systems consistently*
  - *experiments for **very light** hypernuclei are important!*
- CSB for four-body hypernuclei is a puzzle
  - *related to Λ-Σ conversion*
  - *experiments for **very light** hypernuclei are important!*
- extension of complete calculations to larger systems **(access more data)**
  (see also Petr Navratil's and Robert Roth's talk)