Hyperon-nucleon interaction in few- and many body systems

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Outline

1. Introduction
2. Hyperon-nucleon interaction in chiral effective field theory
3. Hyperon properties in infinite nuclear matter
4. Three- and four-body systems
5. Is the hypertriton more strongly bound?
6. Summary

Interaction of strange baryons

- ΛN and ΣN scattering

  $\rightarrow$ Role of SU(3) flavor symmetry

- H dibaryon
  - Jaffe (1977) $\rightarrow$ deeply bound 6-quark state with $I = 0$, $J = 0$, $S = -2$
  - many experimental searches but no convincing signal
  - Lattice QCD (2010) $\rightarrow$ evidence for a bound H dibaryon ($\Lambda\Lambda$)

- Few-body systems with hyperons: ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$, ...

  $\rightarrow$ Role of three-body forces

  large charge symmetry breaking ${}^{4}_{\Lambda}\mathrm{H} \leftrightarrow {}^{4}_{\Lambda}\mathrm{He}$

- (Λ, Σ) hypernuclei and hyperons in nuclear matter

  $\rightarrow$ very small spin-orbit splitting: weak spin-orbit force

  existence of Ξ hypernuclei

  repulsive Σ nuclear potential

- implications for astrophysics

  $\rightarrow$ hyperon stars

  stability/size of neutron stars

  softening of equation of state (hyperon puzzle)

role of SU(3) flavor symmetry

meson-exchange approach:

use NN and YN data + SU(3) flavor symmetry to fix all parameters
$\rightarrow$ make predictions for $\Lambda\Lambda$, ΞN, ..., $\Xi\Xi$

NN: strongly fine-tuned system
(shallow bound states, large scattering length)

strict application of SU(3) symmetry leads to deficiencies/artifacts in the YN sector

- resonances (Jülich YN model, 1989)
- deeply bound ΛN states (Jülich 2004, several Nijmegen potentials)
- ΣN interaction with isospin $I = 3/2$ is attractive, while empirically the Σ-nuclear interaction is found to be repulsive

$\Rightarrow$ YN potentials too attractive, need short-range phenomenology

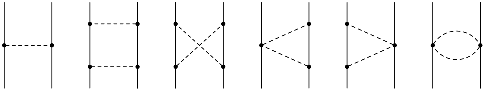
SU(3) chiral effective field theory (χEFT):

- power counting (systematic improvement by going to higher order)
- two- and three-baryon forces can be derived in a consistent way
- SU(3) symmetry + SU(3) symmetry breaking emerge in a consistent way

BB interaction in chiral effective field theory

Baryon-baryon interaction in SU(3) χEFT à la Weinberg (1990) [up to NLO]

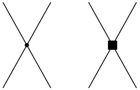
- degrees of freedom: octet baryons (N, Λ, Σ, Ξ), pseudoscalar mesons (π, K, η)
- pseudoscalar-meson exchanges – similar to meson-exchange potentials



- short-distance dynamics remains unresolved – represented by contact terms (involve low-energy constants (LECs) that need to be fixed from data)
  (in meson-exchange: ρ, ω, K^*, $f_0(500)$, $f_0(980)$, $a_0(980)$, κ, Pomeron, Odderon, ...)

$$V^{CT}_{B_1 B_2 \to B_1' B_2'} = \tilde{C}_\alpha + C_\alpha(p'^2 + p^2) \quad (C_\beta p'^2,\; C_\gamma p' p)$$

$\alpha = {}^1S_0, {}^3S_1$; $\beta = {}^3S_1 - {}^3D_1$; $\gamma = {}^3P_0, {}^1P_1, {}^3P_1, {}^3P_2$



No. of LECs is limited by SU(3) flavor symmetry:

6 at LO + 22 at NLO (in total)

5 at LO + 5 at NLO (for S-waves; dominant for ΛN and ΣN scattering at low energies)

BB interaction in chiral effective field theory

- NLO interaction from 2013

  J.H., S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W. Weise, NPA 915 (2013) 24

  fix all *S*-wave LECs from a fit directly to available low-energy Λp and ΣN scattering data ($\approx$ 36 data points)
  no recourse to information on *NN* interaction

  only for *P*-waves information for *NN* scattering is used

  $\Rightarrow$ excellent description of data is achieved ($\chi^2 \approx 16 - 17$)

  However, the LECs of the *YN* potential could not be determined uniquely

  correlations between the LO and NLO LECs are observed

- NLO interaction from 2019

  J.H., U.-G. Meißner, A. Nogga, arXiv:1906.11681

  explore those correlations between the LO and NLO LECs

  explore consequences for the *YN* interaction, for light hypernuclei, and for in-medium properties of the Λ and Σ hyperons

  reduce correlations by taking over 2 (NLO) LECs from the *NN* sector, fixed from the $^1S_0$ and $^3S_1$ *NN* phase shifts

  decision is somewhat arbitrary - but in line with the power counting up to NLO:
  SU(3) symmetry in the NLO LECs
  SU(3) symmetry breaking in the LO LECs due to $m_\pi - m_K$ mass difference

Coupled channels Lippmann-Schwinger Equation

$$T^{\nu'\nu,J}_{\rho'\rho}(p',p) = V^{\nu'\nu,J}_{\rho'\rho}(p',p) + \sum_{\rho'',\nu''} \int_0^\infty \frac{dp'' p''^2}{(2\pi)^3} V^{\nu'\nu'',J}_{\rho'\rho''}(p',p'') \frac{2\mu_{\rho''}}{p^2 - p''^2 + i\eta} T^{\nu''\nu,J}_{\rho''\rho}(p'',p)$$

$\rho', \ \rho = \Lambda N, \ \Sigma N \quad (\Lambda\Lambda, \ \Xi N, \ \Lambda\Sigma, \ \Sigma\Sigma)$

LS equation is solved for particle channels (in momentum space)

Coulomb interaction is included via the Vincent-Phatak method

The potential in the LS equation is cut off with the regulator function:

$$V^{\nu'\nu,J}_{\rho'\rho}(p',p) \to f^\Lambda(p') V^{\nu'\nu,J}_{\rho'\rho}(p',p) f^\Lambda(p); \quad f^\Lambda(p) = e^{-(p/\Lambda)^4}$$

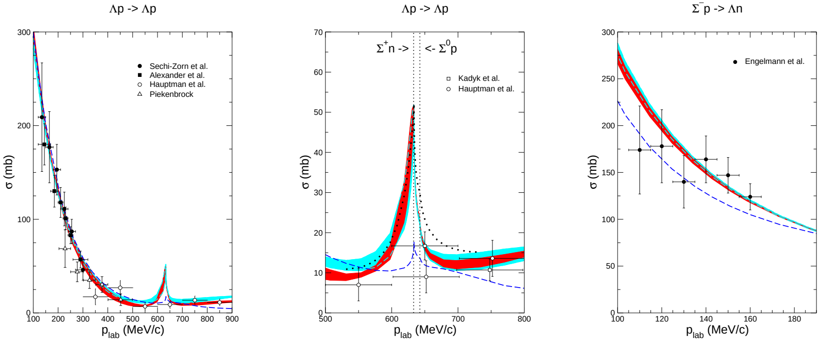
consider values $\Lambda = 500$ - 650 MeV [guided by *NN*, achieved χ^2]

ideally the regulator (Λ) dependence should be absorbed completely by the LECs

in practice there is a residual regulator dependence (shown by bands below)

- tells us something about the convergence
- tells us something about the size of higher-order contributions

YN integrated cross sections



NLO13: J.H., S. Petschauer, et al., NPA 915 (2013) 24

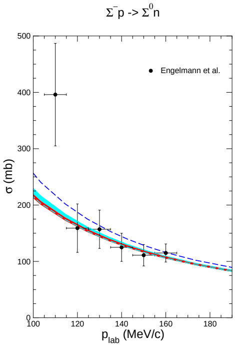
NLO19: J.H., U.-G. Meißner, A. Nogga, arXiv:1906.11681

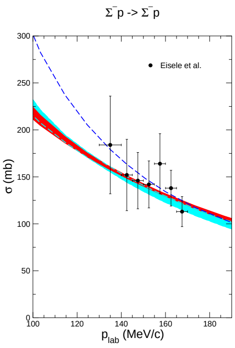
Jülich '04: J.H., U.-G. Meißner, PRC 72 (2005) 044005

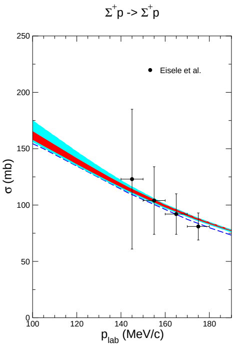
Nijmegen NSC97f: T.A. Rijken et al., PRC 59 (1999) 21

data points included in the fit are represented by filled symbols!

YN integrated cross sections







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YN scattering lengths [fm]

	NLO13	NLO19	Jülich '04	NSC97f	experiment*
Λ [MeV]	500 ··· 650	500 ··· 650			
$a_s^{\Lambda p}$	−2.91 ··· −2.90	−2.91 ··· −2.90	−2.56	−2.51	$-1.8^{+2.3}_{-4.2}$
$a_t^{\Lambda p}$	−1.61 ··· −1.51	−1.52 ··· −1.40	−1.66	−1.75	$-1.6^{+1.1}_{-0.8}$
$a_s^{\Sigma^+ p}$	−3.60 ··· −3.46	−3.90 ··· −3.43	−4.71	−4.35	
$a_t^{\Sigma^+ p}$	0.49 ··· 0.48	0.48 ··· 0.42	0.29	−0.25	
χ^2	15.7 ··· 16.8	16.0 ··· 18.1	$\approx$ 22	16.7	
$({}^3_\Lambda\mathrm{H})\ E_B$	−2.30 ··· −2.33	−2.32 ··· −2.32	−2.27	−2.30	−2.354(50)

*G. Alexander et al., PR 173 (1968) 1452

Note: $({}^3_\Lambda\mathrm{H})\ E_B$ is used as additional constraint in EFT and Jülich '04

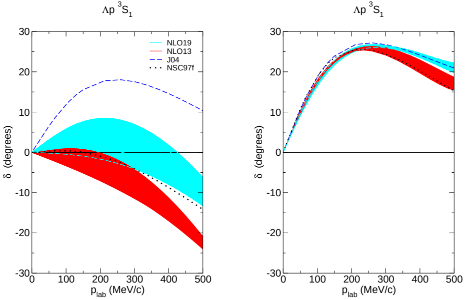
Λp data alone do not allow to disentangle ${}^1S_0$ (s) and ${}^3S_1$ (t) contributions

Is there a difference between NLO13 and NLO19?

yes!

$\Rightarrow$ Coupling strength between the ΛN and ΣN channels ($V_{\Lambda N \leftrightarrow \Sigma N}$) is different

can be best seen by switching off the channel coupling:



ΛN–ΣN coupling switched off full result

but ... recall ... the potential is not an observable!

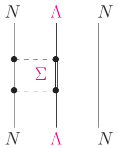
$V_{\Lambda N}$ (NLO13) $\neq V_{\Lambda N}$ (NLO19), $V_{\Lambda N \leftrightarrow \Sigma N}$ (NLO13) $\neq V_{\Lambda N \leftrightarrow \Sigma N}$ (NLO19), ...

$\sigma_{\Lambda p}$ (NLO13) $\cong \sigma_{\Lambda p}$ (NLO19), $\sigma_{\Sigma^- p \to \Lambda n}$ (NLO13) $\cong \sigma_{\Sigma^- p \to \Lambda n}$ (NLO19), ...

Consequences?

consequences for in-medium properties:
ΛN–ΣN coupling is suppressed
for increasing no. of nucleons
(dispersive effects; Pauli blocking effects)

$V^{eff}_{\Lambda N}(E) = V_{\Lambda N} + V_{\Lambda N \to \Sigma N}\,(E - H_0)^{-1}\, V_{\Sigma N \to \Lambda N}$



EFT: in consistent few- and many-body calculations, differences in the two-body potential are to be compensated by many-body forces

Similarity renormalization group (SRG) transformation:

- Many-body approaches like the no-core shell model require soft effective interactions as input
- unitary transformation that preserves two-body observables
  (S.K. Bogner, R.J. Furnstahl, R.J. Perry, PRC 75 (2007) 061001)
- diagonalization of the *NN* interaction leads to induced 3- and many-body forces
- *YN*: diagonalization includes ΛN–ΣN decoupling
  $\Rightarrow$ sizable induced *YNN* forces (R. Wirth, R. Roth, PRC 100 (2019) 044313)

Λ and Σ in infinite nuclear matter

non-relativistic lowest order Brueckner theory (Bethe-Goldstone equation):

$$\langle YN|G_{YN}(\zeta)|YN\rangle = \langle YN|V|YN\rangle + \sum_{Y'N} \langle YN|V|Y'N\rangle \, \langle Y'N|\frac{Q}{\zeta - H_0}|Y'N\rangle \, \langle Y'N|G_{YN}(\zeta)|YN\rangle$$

Q ... Pauli projection operator

$$\zeta = E_Y(p_Y) + E_N(p_N)$$

$$E_\alpha(p_\alpha) = M_\alpha + \frac{p_\alpha^2}{2M_\alpha} + U_\alpha(p_\alpha), \qquad \alpha = \Lambda, \Sigma, \; N$$

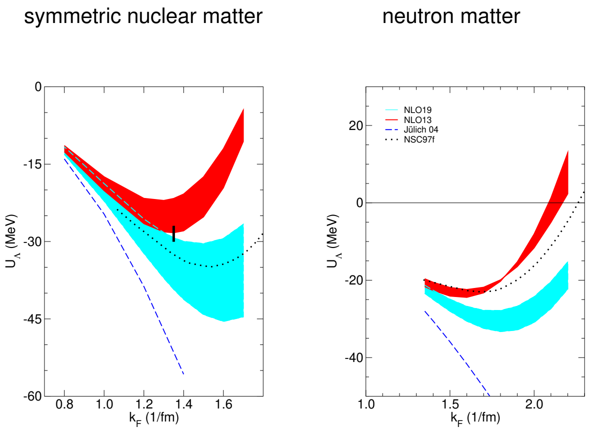
U_α ... single-particle potential

$$U_Y(p_Y) = \int_{p_N \le k_F} d^3p_N \, \langle YN|G_{YN}(\zeta(U_Y))|YN\rangle$$

$B_Y(\infty) = -U_Y(p_Y = 0)$ - evaluated at saturation point of nuclear matter

$\Rightarrow$ J.H., U.-G. Meißner, NPA 936 (2015) 29; S. Petschauer, et al., EPJA 52 (2016) 15
J.H., U.-G. Meißner, A. Nogga, arXiv:1906.11681

k_F dependence of $U_\Lambda(p_\Lambda = 0)$



- Bethe-Goldstone equation for coupled channels: only dispersive effects are included
- contributions from three-body forces are missing

(S. Petschauer et al., NPA 957 (2017) 347): ΛNN force $\rightarrow$ density-dependend effective ΛN interaction

Nuclear matter properties

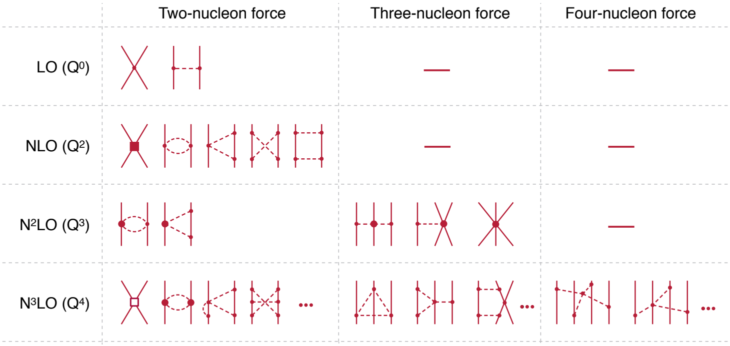
$U_Y(p_Y = 0)$ [in MeV] at saturation density, $k_F = 1.35\ \mathrm{fm}^{-1}$ ($\rho_0 = 0.166\ \mathrm{fm}^{-3}$)

	NLO13	NLO19	Jülich '04	NSC97f
Λ [MeV]	500 ··· 650	500 ··· 650		
		$U_\Lambda(0)$		
$^1S_0$	$-15.3 \cdots -11.3$	$-12.5 \cdots -11.1$	-10.2	-14.6
$^3S_1$-$^3D_1$	$-14.6 \cdots -12.5$	$-28.0 \cdots -19.7$	-36.3	-23.1
total	$-28.3 \cdots -21.6$	$-39.3 \cdots -29.2$	-51.2	-32.4
		$U_\Sigma(0)$		
$^3S_1$-$^3D_1$ (3/2)	$44.8 \cdots 40.0$	$41.0 \cdots 38.0$	11.7	-6.4
total	$19.4 \cdots 14.1$	$21.6 \cdots 14.1$	-22.2	-16.1

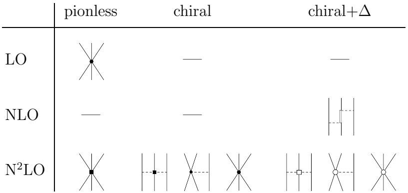
"Empirical" value for the $U_\Lambda(0)$ in nuclear matter: $\approx -27 \ldots - 30$ MeV
for the Σ: $\approx +30 \pm 20$ MeV

ΣN (I=3/2): $^3S_1$–$^3D_1$: decisive for Σ properties in nuclear matter

3- and many-body forces in chiral EFT (E. Epelbaum)

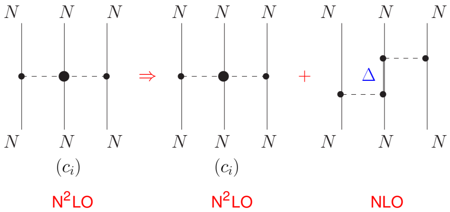


different hierarchy of 3BFs
for other counting schemes
(Hammer, Nogga, Schwenk,
Rev. Mod. Phys. 85 (2013) 197)



Three-nucleon forces: Explicit inclusion of the Δ(1232)

- Explicit treatment of the Δ (Krebs, Gasparyan, Epelbaum, PRC 98 (2018) 014003):



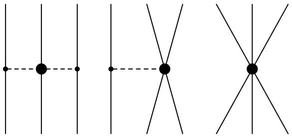
LECs (from πN)	c_1	c_2	c_3	c_4
Δ-less approach	-0.75	3.49	-4.77	3.34
Δ-full approach	-0.75	1.90	-1.78	1.50
Δ contribution	0	2.81	-2.81	1.40

- more natural size of LECs
- better convergence of EFT expansion (3NF from Δ(1232) appears at NLO!)
- applicability at higher energies

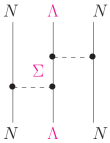
Three-body forces

- SU(3) χEFT 3BFs nominally at N^{2}LO (S. Petschauer et al., PRC 93 (2016) 014001)

SU(3) χEFT :

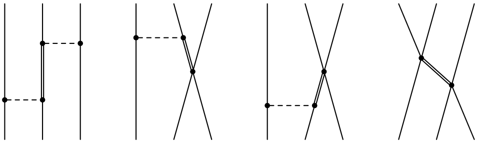


(at LO!) :



solve coupled channel (ΛN-ΣN) Faddeev-Yakubovsky equations:
$\Rightarrow$ ΛNN "3BF" from Σ coupling is automatically included
remaining 3BF expected to be small

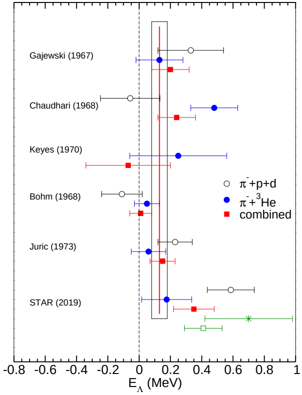
- ΛNN 3BF via Σ^* excitation in SU(3) χEFT with $\{10\}$ baryons (NLO)



estimate ΛNN 3BF based on the $\Sigma^*(1385)$ excitation (S. Petschauer et al., NPA 957 (2017) 347)

Status - hypertriton

$$^{3}_{\Lambda}\mathrm{H} \to \pi^- + p + d, \; \to \pi^- + {}^{3}\mathrm{He}$$

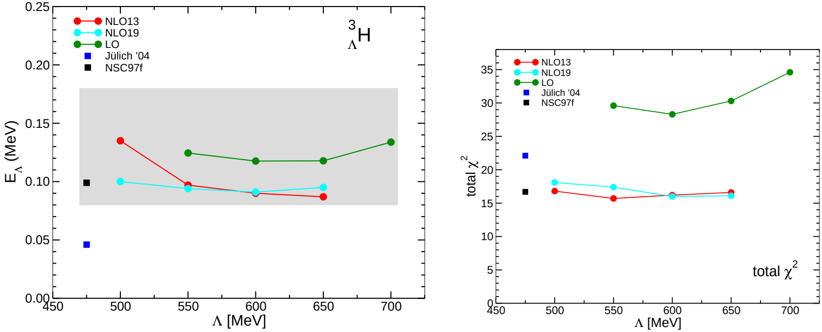


benchmark: (M. Jurič et al., 1973): 0.13 $\pm$ 0.05 MeV

STAR (J. Adam et al., arXiv:1904.10520) ($^{3}_{\Lambda}\mathrm{H}+^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}$): 0.41 $\pm$ 0.12 $\pm$ 0.11 MeV

(separation energy $E_\Lambda = B_\Lambda - B_d$)

Hypertriton (Faddeev calculation by A. Nogga)

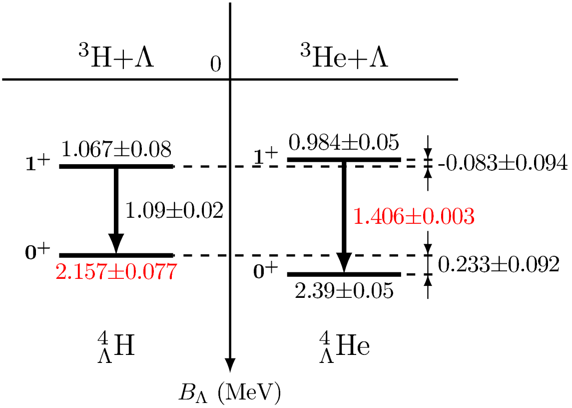


- Λp $^1S_0$ / $^3S_1$ scattering lengths are chosen so that $^3_\Lambda$H is bound
- cutoff variation:

  * *NNN* $\rightarrow$ is lower bound for magnitude of higher order contributions
  * Λ*NN* - correlation with χ^2 of *YN* interaction

  $\Rightarrow$ effect of three-body forces small?

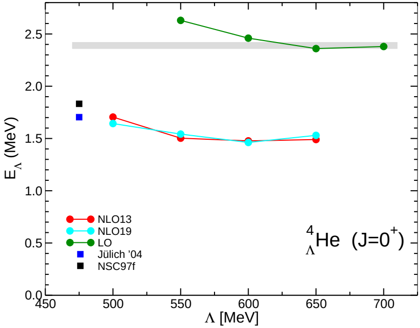
Status - ${}^4_\Lambda$H, ${}^4_\Lambda$He

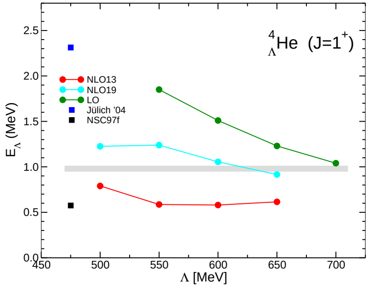


large CSB in 0^+, small CSB in 1^+

F. Schulz et al. [A1 Collaboration] (2016), T.O. Yamamoto et al. [J-PARC E13 Collaboration] (2015)

${}^{4}_{\Lambda}$He results (Faddeev-Yakubovsky – by A. Nogga)





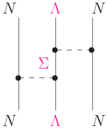
- LO: unexpected small cutoff dependence in 0^{+} result
- NLO: underbinding in χEFT and for phenomenological potentials
- possible effects of long ranged three-body forces?
- open problem: charge symmetry breaking ${}^{4}_{\Lambda}\mathrm{H} \leftrightarrow {}^{4}_{\Lambda}\mathrm{He}$
  (experiment $\approx$ 230 keV theory $\approx$ 100 keV)

(see, however, D. Gazda, A. Gal, NPA 954 (2016) 161; $\langle \Lambda N | V_{CSB} | \Lambda N \rangle \propto \langle \Lambda N | V | \Sigma N \rangle$)

Estimation of 3BFs based on NLO results

- $^{3}_{\Lambda}$H
  (a) cutoff variation: ΔE_Λ (3BF) $\leq$ 50 keV
  (b) "3BF" from ΛN-ΣN coupling:

  switch off ΛN-ΣN coupling
  in Faddeev-Yakubovsky equations:
  ΔE_Λ (3BF) $\approx$ 10 keV
  expect smaller ΔE_Λ from $\Sigma^*(1385)$ excitation



  (c) ^{3}H: 3NF $\sim Q^3 \, |\langle V_{NN}\rangle|_{^3\mathrm{H}} \sim$ 650 keV
  ($|\langle V_{NN}\rangle|_{^3\mathrm{H}} \sim$ 50 MeV; $Q \sim m_\pi/\Lambda_b$; $\Lambda_b \simeq 600$ MeV)
  $^{3}_{\Lambda}$H: $|\langle V_{\Lambda N}\rangle|_{^3_\Lambda\mathrm{H}} \sim$ 3 MeV $\rightarrow \Delta E_\Lambda$ (3BF) $\approx Q^3 \, |\langle V_{\Lambda N}\rangle|_{^3_\Lambda\mathrm{H}} \simeq$ 40 keV

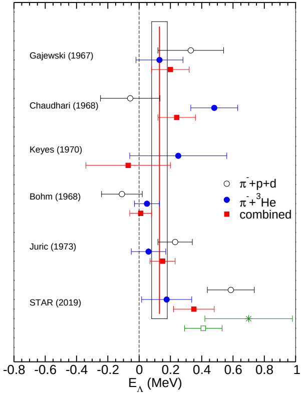
  Note: root-mean-square radius of $^{3}_{\Lambda}$H: $\sqrt{\langle r^2\rangle} \approx 5$ fm
  (deuteron: $\sqrt{\langle r^2\rangle} \approx 2$ fm)
  $\Rightarrow$ most of the time Λ and two Ns are outside of the range of a standard 3BF!

- $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He
  (a) cutoff variation: ΔE_Λ (3BF) $\approx$ 200 keV (0^+) and $\approx$ 300 keV (1^+)
  (b) "3BF" from ΛN-ΣN coupling:
  ΔE_Λ (3BF) $\approx$ 230 – 340 keV (0^+), $\approx$ 150 – 180 keV (1^+)

$^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H(He) calculations with explicit inclusion of 3BFs are planned for the future

Status - hypertriton

$$^3_\Lambda\mathrm{H} \to \pi^- + p + d, \to \pi^- + {}^3\mathrm{He}$$



benchmark: (M. Jurič et al., 1973): 0.13 $\pm$ 0.05 MeV

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(separation energy $E_\Lambda = B_\Lambda - B_d$)

Binding energy of the hypertriton

spin dependence of Λp cross section

$$\sigma_{\Lambda p} \propto \frac{1}{4}|T^{s}_{\Lambda p}|^2 + \frac{3}{4}|T^{t}_{\Lambda p}|^2 \quad \left(\propto \frac{1}{4}\frac{a_s^2}{1+a_s^2 k^2} + \frac{3}{4}\frac{a_t^2}{1+a_t^2 k^2}\right)$$

relevant spin-dependence for s-shell hypernuclei (Herndon & Tang, PR 153 (1967) 1091)

$$^{3}_{\Lambda}\mathrm{H}: \quad \tilde{V}_{\Lambda N} \approx \frac{3}{4} V^{s}_{\Lambda N} + \frac{1}{4} V^{t}_{\Lambda N}$$

to retain $\sigma_{\Lambda p}$ and increase $^{3}_{\Lambda}\mathrm{H}$ binding:

⇒ increase Λp interaction in the $^1S_0$ state and reduce the one in $^3S_1$

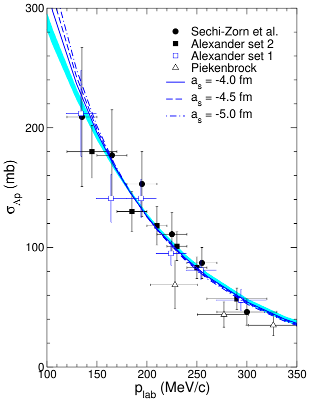
can this be achieved? what happens for the other light hypernuclei?

what happens for the in-medium properties of the Λ and Σ?

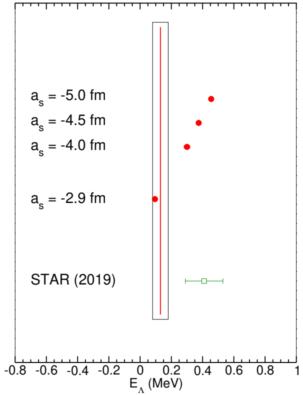
⇒ Hoai Le et al., arXiv:1909.02882

Correlation between a_s and ${}^3_\Lambda$H separation energy

Λp cross section



hypertriton



$\Rightarrow$ Hoai Le et al., arXiv:1909.02882

(requires SU(3) symmetry breaking in the LO LECs for ΛN, ΣN!)

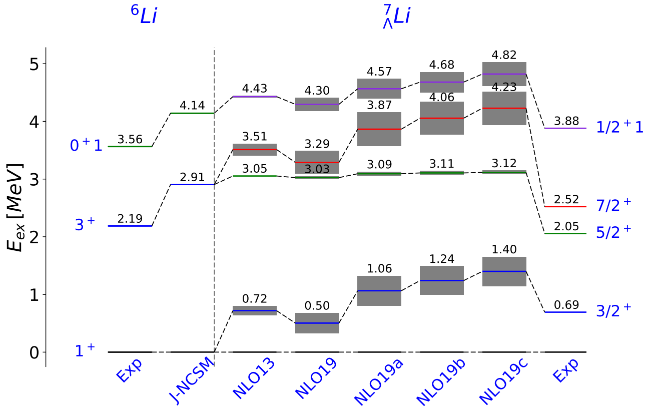
(otherwise $\Sigma^+ p$ channel is no longer satisfactorily described)

Binding energy of the hypertriton

YN interaction	NLO19	Fit A	Fit B	Fit C	experiment
a_s [fm]	-2.91	-4.00	-4.50	-5.00	$-1.8^{+2.3}_{-4.2}$
a_t [fm]	-1.41	-1.22	-1.15	-1.09	$-1.6^{+1.1}_{-0.8}$
χ^2 (total)	16.01	16.44	16.93	17.61	
χ^2 (Λp only)	3.31	3.94	4.46	5.10	
$U_\Lambda(0)$ [MeV]	-32.6	-31.7	-31.3	-30.8	-27 $\cdots$ -30
E_Λ ($^3_\Lambda\mathrm{H}$) [MeV]	0.10	0.28	0.37	0.44	0.13 ± 0.05
					0.41 ± 0.12
E_Λ ($^4_\Lambda\mathrm{He}(0^+)$) [MeV]	1.46	1.77	1.86	1.92	2.39 ± 0.03
E_Λ ($^4_\Lambda\mathrm{He}(1^+)$) [MeV]	1.06	0.84	0.75	0.68	0.98 ± 0.03
ΔE_Λ ($^4_\Lambda\mathrm{He}$) [MeV]	0.41	0.93	1.11	1.24	1.406 ± 0.002

(NLO19 (600) is used as starting point)

calculation within the no-core shell model (Hoai Le et al., arXiv:1909.02882)



- excitation spectrum of the ^{6}Li core is not reproduced (3NFs missing!)
- qualitative agreement with experiment for all YN potentials
- none of the YN potentials agrees quantitatively

⇒ for $^{7}_{\Lambda}$Li three-body forces are non-negligible

Summary

Hyperon-nucleon interaction constructed within chiral EFT

- Approach is based on a modified Weinberg power counting, analogous to applications for *NN* scattering
- The potential (contact terms, pseudoscalar-meson exchanges) is derived imposing $SU(3)_f$ constraints
- $S = -1$: Excellent results at next-to-leading order (NLO)
  Λp, ΣN low-energy data are reproduced with a quality comparable to phenomenological models
- Strength of the ΛN-ΣN transition potential (Λ-Σ conversion) is not an observable
  Λ-Σ conversion and 3BFs are interrelated in few- and many body applications
- ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$ ... effects of three-body forces should be small
  needs to be quantified/confirmed by explicit inclusion of 3BFs
- nothing speaks against a somewhat larger binding energy of ${}^{3}_{\Lambda}\mathrm{H}$!

Backup slides

$SU(3)$ structure of contact terms for BB

$SU(3)$ structure for scattering of two octet baryons $\rightarrow$
$8 \otimes 8 = 1 \oplus 8_a \oplus 8_s \oplus 10^* \oplus 10 \oplus 27$

BB interaction can be given in terms of LECs corresponding to the $SU(3)_f$ irreducible representations: C^1, C^{8a}, C^{8s}, C^{10^*}, C^{10}, C^{27}

	Channel	I	V_α	V_β	$V_{\beta\to\alpha}$
$S = 0$	$NN \to NN$	0	–	$C^{10^*}_\beta$	–
	$NN \to NN$	1	C^{27}_α	–	–
$S = -1$	$\Lambda N \to \Lambda N$	$\frac{1}{2}$	$\frac{1}{10}\left(9C^{27}_\alpha + C^{8s}_\alpha\right)$	$\frac{1}{2}\left(C^{8a}_\beta + C^{10^*}_\beta\right)$	$-C^{8sa}$
	$\Lambda N \to \Sigma N$	$\frac{1}{2}$	$\frac{3}{10}\left(-C^{27}_\alpha + C^{8s}_\alpha\right)$	$\frac{1}{2}\left(-C^{8a}_\beta + C^{10^*}_\beta\right)$	$-3C^{8sa}$
					C^{8sa}
	$\Sigma N \to \Sigma N$	$\frac{1}{2}$	$\frac{1}{10}\left(C^{27}_\alpha + 9C^{8s}_\alpha\right)$	$\frac{1}{2}\left(C^{8a}_\beta + C^{10^*}_\beta\right)$	$3C^{8sa}$
	$\Sigma N \to \Sigma N$	$\frac{3}{2}$	C^{27}_α	C^{10}_β	–

$\alpha = {}^1S_0, {}^3P_0, {}^3P_1, {}^3P_2$, $\quad \beta = {}^3S_1, {}^3S_1 - {}^3D_1, {}^1P_1$

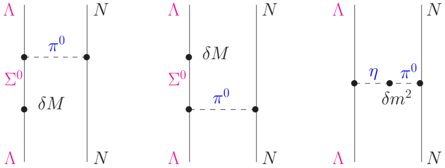
No. of contact terms (LECs): limited by SU(3) symmetry

LO : 6 [2 (NN, $\Xi\Xi$) + 3 (YN, ΞY) + 1 (YY)]
NLO: 22 [7 (NN, $\Xi\Xi$) + 11 (YN, ΞY) + 4 (YY)]

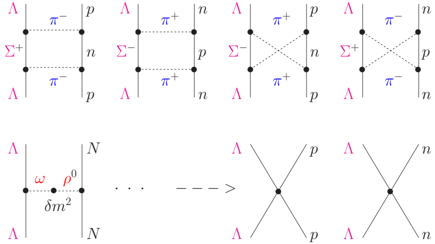
(No. of spin-isospin channels in NN+YN: 10 $\quad S = -2, -3, -4$: 27)

Charge symmetry breakinig in ΛN

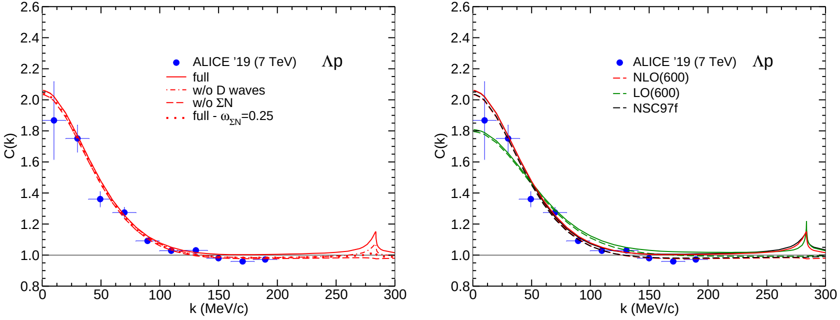
Dalitz, von Hippel (1964)



short range contributions



Correlation function for Λp



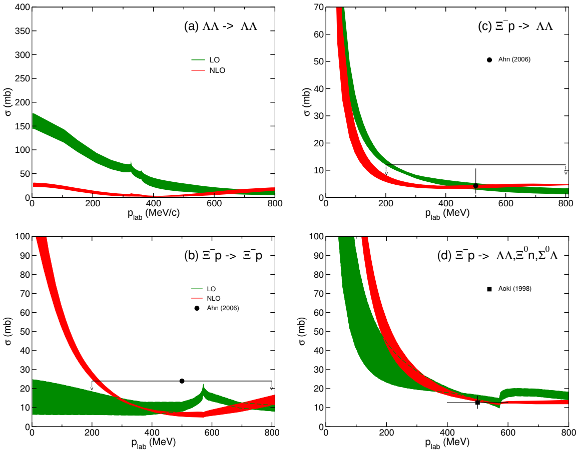
ALICE Collaboration (S. Acharya al., PRC 99 (2019) 024001): pp at $\sqrt{s} = 7$ TeV
$R = 1.125 \pm 0.018$ fm, $\lambda = 0.4713$ $[C(k) \to 1 + \lambda(C(k) - 1)]$

spin average: $|\psi(k,r)|^2 = \frac{1}{4}|\psi_{(^1S_0)}(k,r)|^2 + \frac{3}{4}|\psi_{(^3S_1)}(k,r)|^2$

cusp at the ΣN threshold comes from $\psi_{\Sigma N - \Lambda p}$ $^3S_1 \to {}^3S_1$ and/or $^3D_1 \to {}^3S_1$ components of the wave function

their weights ω_β are free parameters!

Selected results for $S = -2$

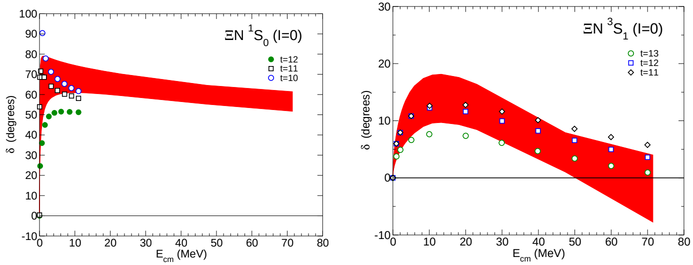


ΛΛ $^1S_0$ scattering length (NLO):

$a_{\Lambda\Lambda} = -0.61 \cdots -0.70$ fm   empirical: $a_{\Lambda\Lambda}$ = -1.2 $\pm$ 0.6 fm

J.H., U.-G. Meißner, S. Petschauer, NPA 954 (2016) 273

ΞN: Comparison with HAL QCD results



HAL QCD Collaboration, from K. Sasaki's talk at *Lattice2017*, Granada, Spain

results are for different sink-source time-separations *t*

Nuclear matter properties

$U_{\Xi}(p_{\Xi} = 0)$ [in MeV] at saturation density, $k_F = 1.35\ \mathrm{fm}^{-1}$ ($\rho_0 = 0.166\ \mathrm{fm}^{-3}$)

	EFT NLO (2019)	EFT NLO (2016)	ESC08c	fss2
Λ [MeV]	500 ··· 650	500 ··· 650		
$U_{\Xi}(0)$	−5.5 ··· −3.8	22.4 ··· 27.7	−7.0	−1.5

"Canonical" value for the depth of the Ξ single-particle potential: ≈ -15 MeV

Nijmegen ESC08c: M.M Nagels, T.A. Rijken, Y. Yamamoto, arXiv:1504:02634

Quark model fss2: Y. Fujiwara, Y. Suzuki, C. Nakamoto, Prog. Part. Nucl. Phys. 58 (2007) 439
(U_{Ξ} results from M. Kohno, S. Hashimoto, Prog. Theor. Phys. 123 (2010) 157)

Spin dependence

Shell model: role of the spin-dependence of the ΛN potential for the binding energies of s-shell hypernuclei

$$
\begin{aligned}
{}^{3}_{\Lambda}\mathrm{H}: &\quad \tilde{V}_{\Lambda N} \approx \frac{3}{4} V^{s}_{\Lambda N} + \frac{1}{4} V^{t}_{\Lambda N} \\
{}^{4}_{\Lambda}\mathrm{He}\ (0^{+}): &\quad \tilde{V}_{\Lambda N} \approx \frac{1}{2} V^{s}_{\Lambda N} + \frac{1}{2} V^{t}_{\Lambda N} \\
{}^{4}_{\Lambda}\mathrm{He}\ (1^{+}): &\quad \tilde{V}_{\Lambda N} \approx \frac{1}{6} V^{s}_{\Lambda N} + \frac{5}{6} V^{t}_{\Lambda N} \\
{}^{5}_{\Lambda}\mathrm{He}: &\quad \tilde{V}_{\Lambda N} \approx \frac{1}{4} V^{s}_{\Lambda N} + \frac{3}{4} V^{t}_{\Lambda N}
\end{aligned}
$$

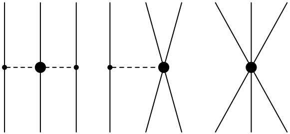
$$
\sigma_{\Lambda p} = \frac{1}{4}|f^{s}_{\Lambda p}|^2 + \frac{3}{4}|f^{t}_{\Lambda p}|^2
$$

recall: we use different spin-dependence of $\sigma_{\Lambda p}$ and $B({}^{3}_{\Lambda}\mathrm{H})$ to fix the relative strength of the ${}^{1}S_{0}$ and ${}^{3}S_{1}$ ΛN interactions

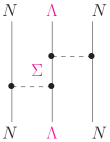
Three-body forces

SU(3) χEFT 3BFs nominally at N^{2}LO (S. Petschauer et al., PRC 93 (2016) 014001)

SU(3) χEFT :

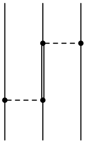


(at LO!) :



3BF-type contributions in YNN systems:

- ΛNN "3BF" via Σ coupling in standard SU(3) χEFT at LO
- ΛNN 3BF via Σ^* excitation in SU(3) χEFT with $\{10\}$ baryons (NLO)

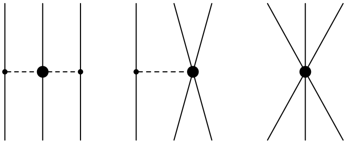


solve coupled channel (ΛN-ΣN) Faddeev-Yakubovsky equations:
$\Rightarrow$ ΛNN "3BF" from Σ coupling is automatically included
remaining 3BF much smaller than in $\not\pi$EFT

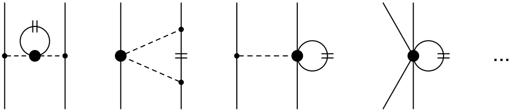
estimate ΛNN 3BF based on the $\Sigma^*(1385)$ excitation (S. Petschauer et al., NPA 957 (2017) 347)

density dependent effective YN interaction

three-body force (nominally at N^2LO):



density dependent effective YN interaction:

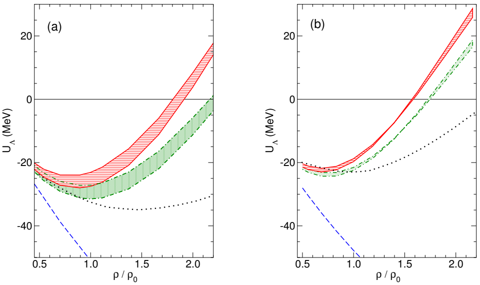


close two baryon lines by sum over occupied states within the Fermi sea
arising 3BF LECs can be constrained by resonance saturation (via decuplet baryons)

J.W. Holt, N. Kaiser, W. Weise, PRC 81 (2010) 064009 (for *NNN*)
S. Petschauer et al., NPA 957 (2017) 347 (for ΛNN)

Results for Λ at larger density ρ

symmetric nuclear matter　　　　neutron matter



— · —　χEFT at NLO

———　χEFT at NLO + density-dependent ΛN interaction derived from chiral ΛNN 3BFs

— —　Jülich '04;　· · ·　Nijmegen NSC97f

$\Rightarrow$ χEFT: less attractive or even repulsive for $\rho > \rho_0$
neutron stars: hyperons appear at higher density
impact on the so-called hyperon puzzle