Baryon-baryon interaction in chiral effective field theory

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Outline

Chiral Effective Field Theory

- Starting point: Chiral Lagrangian
  $\mathcal{L}_{QCD} \rightarrow \mathcal{L}_{EFT} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \ldots$
- Spontaneous chiral symmetry breaking of QCD
  $\rightarrow$ pions are Goldstone bosons
- Separation of scales, Power counting

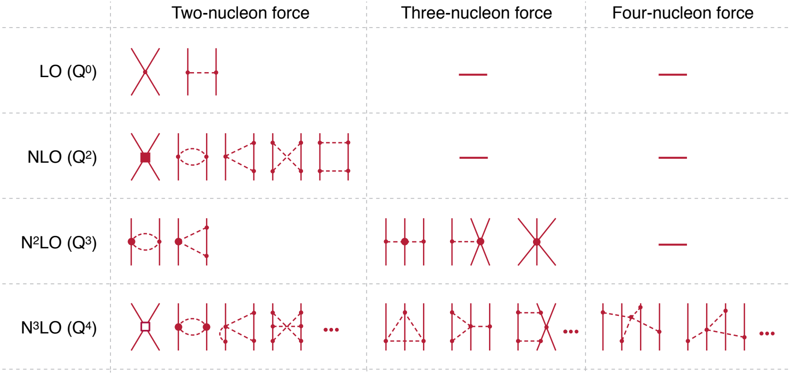
  light dof (pions) $\ll \Lambda_\chi \leq$ heavy dof (ρ, ω, ...)

  Systematic expansion in powers of Q/Λ_χ & m_π/Λ_χ ($\Lambda_\chi \approx$ 1 GeV)

  at low momenta Q short-distance dynamics remains unresolved
  $\rightarrow$ heavy dof are represented by contact terms (low-energy constants)
- pion-pion and pion-nucleon sectors are perturbative in Q
  $\rightarrow$ chiral perturbation theory
- NN interaction requires non-perturbative resummation
  (bound states, large scattering lengths)
  $\rightarrow$ chirally expand V_{NN}
  use in a regularized Lippmann-Schwinger equation

  (Weinberg (1991), van Kolck, Epelbaum/Meißner, Entem/Machleidt, ...)

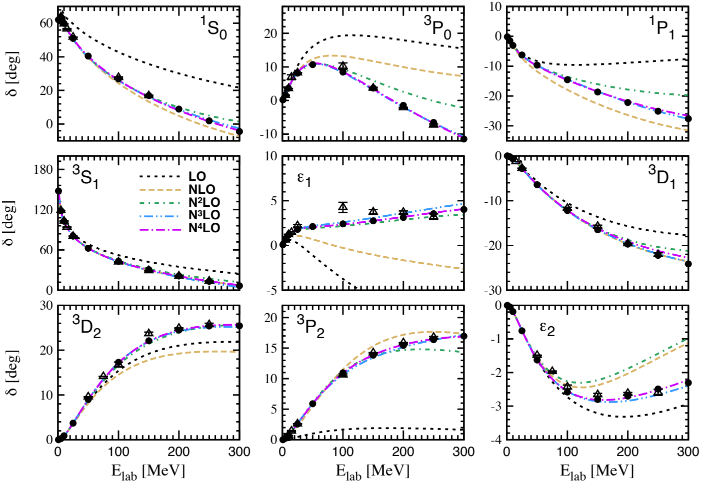
NN forces in chiral effective field theory (E. Epelbaum)



salient features:

- Power counting
  systematic improvement by going to higher order
  theoretical uncertainty can be estimated
- two- and three-baryon forces, etc., can be derived in a consistent way

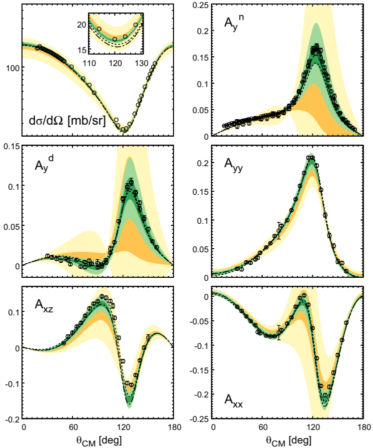
NN forces in chiral EFT

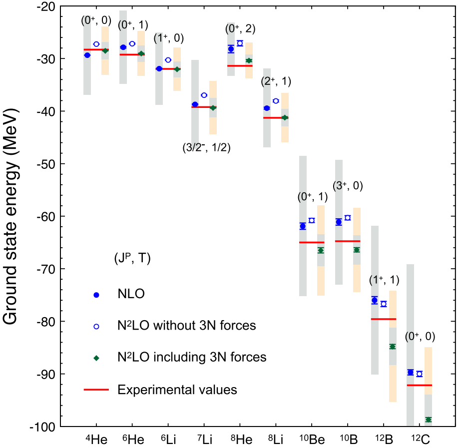


P. Reinert et al., EPJA 54 (2018) 86 [up to N^{4}LO !!]

(see also Entem, Machleidt, Nosyk, Front.in Phys. 8 (2020) 57)

Nd scattering and light nuclei





E. Epelbaum et al., EPJA 56 (2020) 92

P. Maris et al., PRC 103 (2021) 054001

nucleon-deuteron scattering, $A \leq 4$ nuclei: Faddeev-Yakubovsky calculations

$A > 4$ nuclei: “ab initio” approaches like No-Core Shell Model, No-Core Configuration Interaction

BB interaction in chiral effective field theory

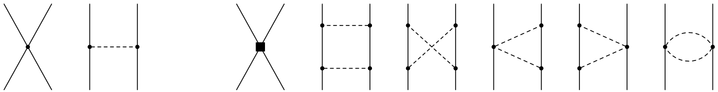
Follow the scheme of S. Weinberg
in complete analogy to the chiral EFT study of the *NN* interaction by
E. Epelbaum, W. Glöckle, U.-G. Meißner (NPA 671 (2000) 295)

Obstacle: *YN* and *YY* data base is rather poor

- contact terms (LECs) need to be fixed from data!
- only about 40 data points
- constraints from hypernuclei (${}^{3}_{\Lambda}$H binding energy)
- no polarization data $\Rightarrow$ no phase shift analysis

$\rightarrow$ impose $SU(3)_f$ constraints: SU(3) χEFT

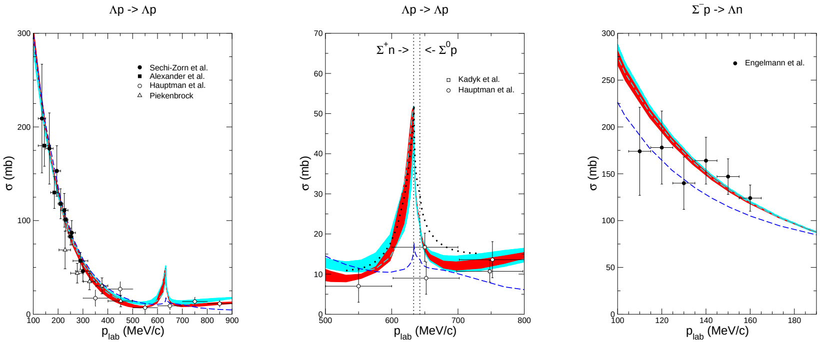
Dof: octet baryons (N, Λ, Σ, Ξ), pseudoscalar mesons (π, K, η)



LO: H. Polinder, J.H., U.-G. Meißner, NPA 779 (2006) 244

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

YN integrated cross sections



NLO13 ... all (10) S-wave LECs are fixed from a fit directly to available *YN* data
NLO19 ... 2 of those are fixed from the *NN* sector within (broken) SU(3) symmetry
... (10) P-wave LECs are fixed from the *NN* sector (4) + educated guess
(bands represent regulator dependence – cutoff $\Lambda = 500 - 650$ MeV)

NLO13: J.H., S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W. Weise, NPA 915 (2013) 24

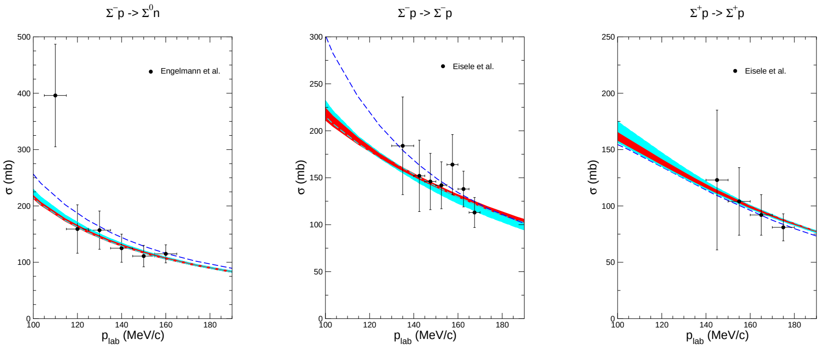
NLO19: J.H., U.-G. Meißner, A. Nogga, EPJA 56 (2020) 91

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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NLO19: J.H., U.-G. Meißner, A. Nogga, EPJA 56 (2020) 91

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

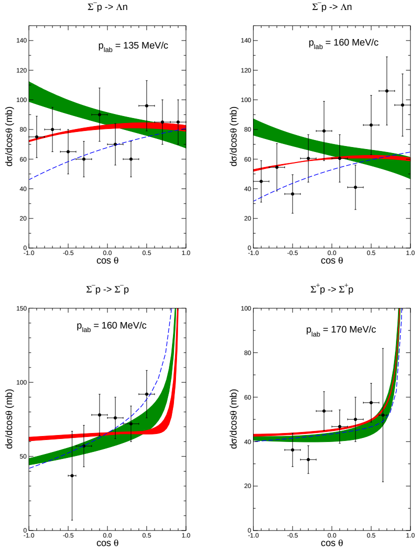
quality of the fit – total χ^2 (36 data points):

NLO13: 15.7 $\cdots$ 16.8   NLO19: 16.0 $\cdots$ 18.1   Jülich '04: $\approx$ 22

YN differential cross sections

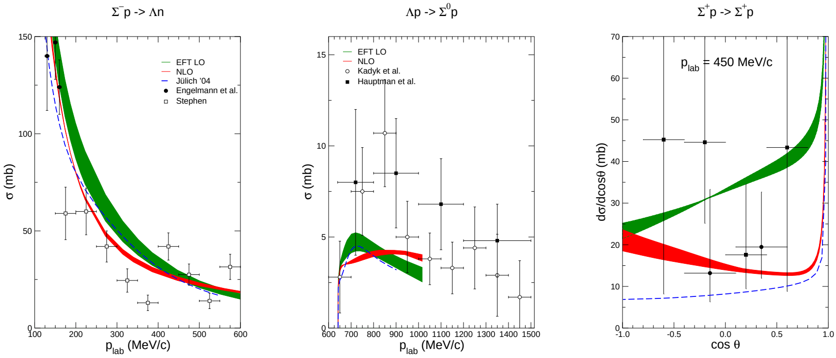
R. Engelmann et al.,
PL 21 (1966) 587
$100 \le p_{\Sigma^-} \le 170$ MeV
$150 \le p_{\Sigma^-} \le 170$ MeV

F. Eisele et al.,
PL 37B (1971) 204
$150 \le p_{\Sigma^-} \le 170$ MeV
$160 \le p_{\Sigma^+} \le 180$ MeV



LO: H. Polinder, J.H., U.-G. Meißner, NPA 779 (2006) 244
NLO13: J.H., S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W. Weise, NPA 915 (2013) 24

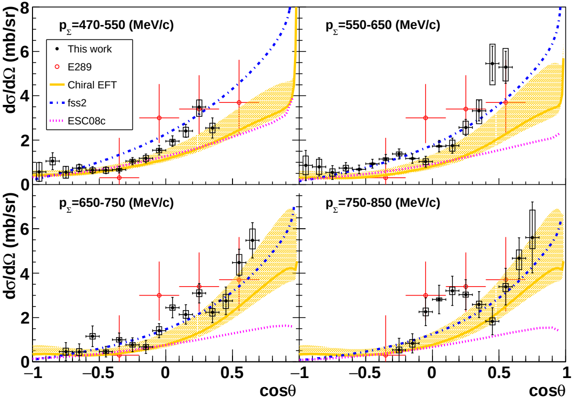
YN cross sections - higher energies



inconsistencies: $T_{\Lambda p \to \Sigma^0 p} \approx \frac{1}{\sqrt{2}} \; T_{\Sigma^- p \to \Lambda n}$!!

large uncertainties

Differential cross sections for $\Sigma^- p$ from J-PARC



J-PARC E40 Collaboration (K. Miwa et al.), arXiv:2104.13608

Results for $\Sigma^- p \to \Lambda n$ and $\Sigma^+ p$ are on the way (APFB 2020, March 2021)

predictions of chiral EFT: agreement for $\Sigma^- p \to \Lambda n$
some discrepancies for $\Sigma^+ p$

$\Rightarrow$ determination of P-wave LECs from YN data should be feasible

YN scattering lengths, Hypernuclei binding energies

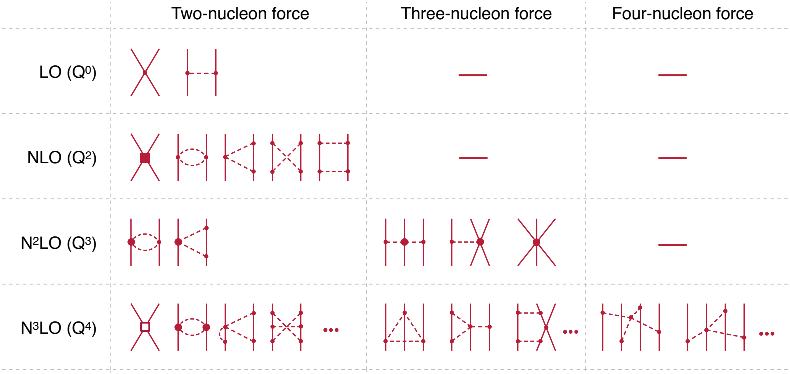
	NLO13	NLO19	Jülich '04	NSC97f	experiment
Λ [MeV]	$500 \cdots 650$	$500 \cdots 650$			
$a_s^{\Lambda p}$	$-2.91 \cdots -2.90$	$-2.91 \cdots -2.90$	-2.56	-2.51	$-1.8^{+2.3}_{-4.2}$
$a_t^{\Lambda p}$	$-1.61 \cdots -1.51$	$-1.52 \cdots -1.40$	-1.66	-1.75	$-1.6^{+1.1}_{-0.8}$
$a_s^{\Sigma^+ p}$	$-3.60 \cdots -3.46$	$-3.90 \cdots -3.43$	-4.71	-4.35	
$a_t^{\Sigma^+ p}$	$0.49 \cdots 0.48$	$0.48 \cdots 0.42$	0.29	-0.25	
χ^2	$15.7 \cdots 16.8$	$16.0 \cdots 18.1$	≈ 22	16.7	
$E(^3_\Lambda\mathrm{H})$	$0.135 \cdots 0.087$	$0.100 \cdots 0.091$	0.046	0.099	$0.13(5)$
$E(^4_\Lambda\mathrm{He})$					
(0^+)	$1.705 \cdots 1.477$	$1.643 \cdots 1.462$	1.704	1.832	$2.39(3)$
(1^+)	$0.790 \cdots 0.580$	$1.226 \cdots 0.916$	2.312	0.575	$0.98(3)$

Binding (separation) energies from solving coupled-channel (ΛN-ΣN) Faddeev-Yakubovsky equations
(a, r in fm; E ... separation energy in MeV, e.g. $E(^3_\Lambda\mathrm{H}) = B(^3_\Lambda\mathrm{H}) - \mathrm{B_d}$)

- $E(^3_\Lambda\mathrm{H})$ 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
- $^4_\Lambda\mathrm{He}(0^+)$ ... underpredicted by chiral YN potentials as well as by meson-exchange models!

  $\Rightarrow$ clear evidence for missing three-body forces

Next step: go up to N^{2}LO



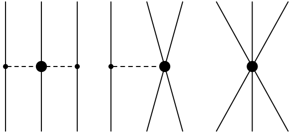
N^{2}LO: no new (additional) *BB* LECs in the two-body sector

leading-order three-body forces

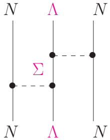
Three-body forces

- SU(3) χEFT 3BFs at N^{2}LO (S. Petschauer et al., PRC 93 (2016) 014001)
- however, 5 LECs for ΛNN 3BF alone! (only 2 LECs for NNN)

SU(3) χEFT :

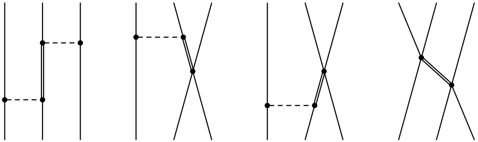


(at LO!) :



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

- 3BFs with inclusion of decuplet baryons (S. Petschauer et al., NPA 957 (2017) 347)



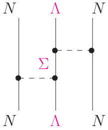
estimate ΛNN 3BF based on the $\Sigma^*(1385)$ excitation (appear at NLO!)

- only 1 LEC for ΛNN (2 LECs for YNN in general)

Estimation of 3BFs based on NLO results

- ${}^{3}_{\Lambda}\mathrm{H}$
  (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 similar/smaller ΔE_Λ from $\Sigma^*(1385)$ excitation



  (c) ${}^{3}\mathrm{H}$: 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)
  ${}^{3}_{\Lambda}\mathrm{H}$: $|\langle V_{\Lambda N}\rangle|_{{}^{3}_{\Lambda}\mathrm{H}} \sim$ 3 MeV $\rightarrow \Delta E_\Lambda$ (3BF) $\approx Q^3\,|\langle V_{\Lambda N}\rangle|_{{}^{3}_{\Lambda}\mathrm{H}} \simeq$ 40 keV

- ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$
  (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^+)

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

Hypernuclei with $A > 4$

ab initio no-core shell model (NCSM)

Basic idea: use harmonic oscillator states and soft interactions

- m-scheme uses single particle states (center-of-mass motion not separated)
- antisymmetrization for nucleons easily performed (Slater determinant)
- larger dimensions (applications to *p*-shell hypernuclei by Wirth & Roth)

Jacobi-NCSM

- uses relative (Jacobi) coordinates (Hoai Le et al., EPJA 56 (2020) 301)
- explicit separation of center-of-mass motion possible
- antisymmetrization for nucleons difficult but feasible for $A \leq 9$
- small dimensions

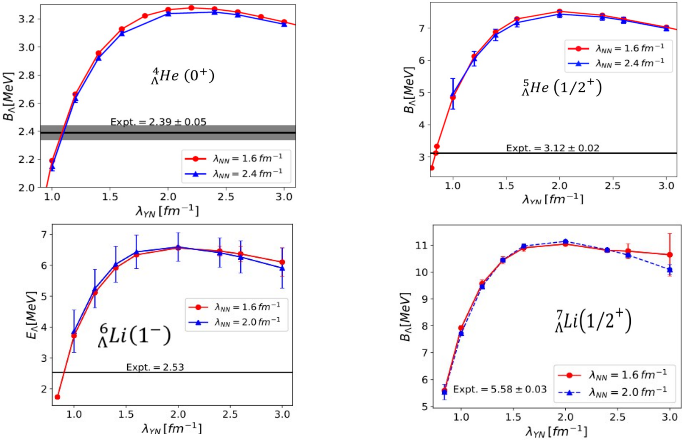
Soft interactions: Similarity renormalization group (SRG) (unitary transformation)

$$\frac{dH(s)}{ds} = [[T, H(s)], H(s)] \qquad H(s) = T + V(s) \qquad V(s) : V^{NN}(s), V^{YN}(s)$$

- Flow equations are solved in momentum space
- parameter (cutoff) $\lambda = \left(4\mu_{BN}^2/s\right)^{1/4}$ is a measure of the width of the interaction in momentum space
- $V(s)$ is phase equivalent to original interaction
- transformation leads to induced 3BFs, 4BFs, ...
  (induced 3BFs included in the calculations by Wirth & Roth)
  (so far omitted in our studies)

NCSM results for light hypernuclei (by Hoai Le)

- Dependence of binding energies on SRG cutoff λ_{YN} (YN: NLO19 (600))



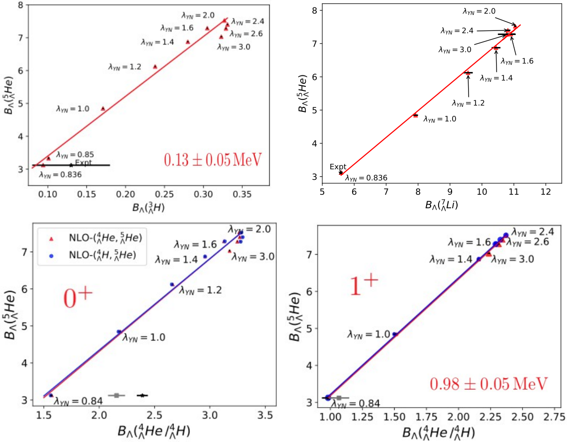
SRG-induced 3BFs are rather large (Wirth & Roth)
→ have to be included before including chiral 3BFs

Are SRG-induced 3BFs > chiral (explicit) 3BFs?

Are 3BFs generally more important for hypernuclei than for nuclei?

NCSM results for light hypernuclei (by Hoai Le)

- Dependence of binding energies on SRG cutoff λ_{YN} (YN: NLO19 (600))



B_Λ for different $\lambda_{\Lambda N}$ are strongly (linearly) correlated!

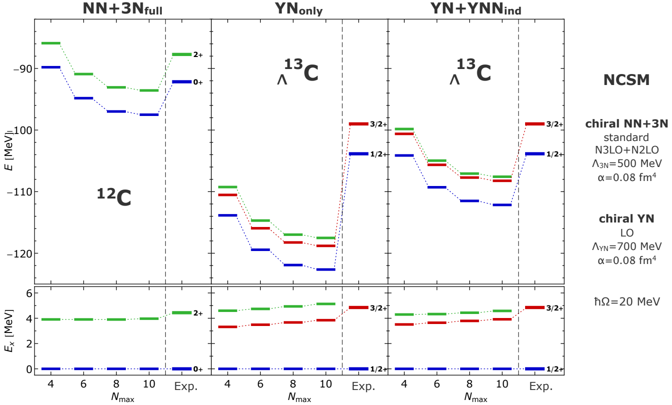
omitted SRG-induced 3BF may depend on a single parameter $\Rightarrow$

minimize effect of SRG-induced 3BF by tuning λ_{YN} to a particular hypernucleus (${}^5_\Lambda$He)

(in practice encodes SRG-induced + explicit 3BFs)

NCSM results by Wirth & Roth (LO)

R. Wirth, R. Roth, PRL 117 (2016) 182501

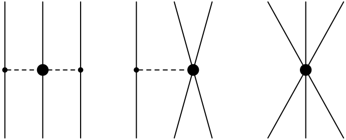


SRG-evolved YN forces only: strong overbinding

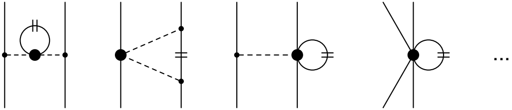
SRG-induced YNN forces lead to sizable corrections (are repulsive!)

density dependent effective YN interaction

three-body force:



density dependent effective YN interaction:

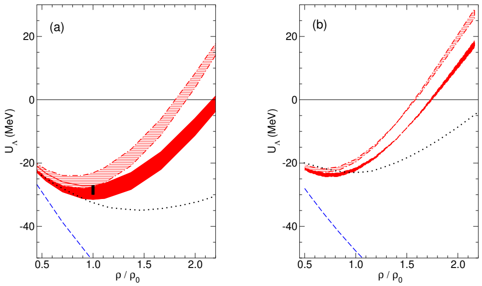


close two baryon lines by sum over occupied states within the Fermi sea
arising 3BF LECs can be constrained by resonance saturation (via decuplet baryons)
($\rightarrow$ 1 for ΛNN; 2 for YNN, $Y = \Lambda, \Sigma, \Xi$)

J.W. Holt, N. Kaiser, W. Weise, PRC 81 (2010) 064009 (for NNN)
S. Petschauer et al., NPA 957 (2017) 347 (for ΛNN)
D. Gerstung et al., EPJA 56 (2020) 175 (ΛNN, ΣNN)

Results for Λ single-particle potential (NLO13)

symmetric nuclear matter　　　　neutron matter



—— χEFT at NLO
– · – χEFT at NLO + density-dependent ΛN interaction derived from chiral ΛNN 3BF
– – Jülich '04; · · · Nijmegen NSC97f

$\Rightarrow$ NLO13: less attractive or even repulsive for $\rho > \rho_0$
neutron stars: hyperons appear at higher density

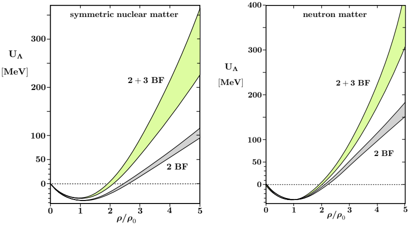
3BF LECs are treated as free parameters
can ΛNN 3BF be constrained by binding energies of (light) hypernuclei?
has not been explored so far!!

Implications for neutron stars (incl. chiral 3BF)

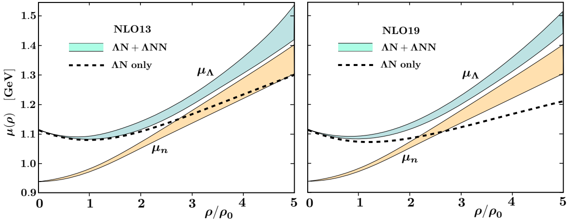
D. Gerstung et al.,
EPJA 56 (2020) 175
(NLO13 & NLO19; ΛNN, ΣNN)

U_Λ ... Λ single-particle potential

$(U_\Lambda(\rho_0 = 0.17\,\mathrm{fm}^{-3}) \approx -28 \cdots - 30$ MeV)



Chemical potentials of the Λ hyperon (μ_Λ) and the neutron (μ_n)



$\mu_\Lambda(\rho) \leq \mu_n(\rho) \Rightarrow$ energetically favorable to replace n by Λ $\quad (\mu_\Lambda(\rho) = M_\Lambda + U_\Lambda(\rho))$

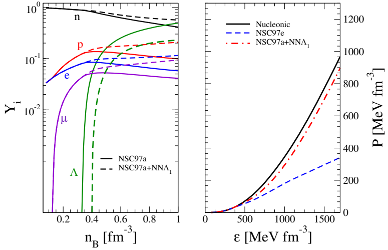
Equation-of-state becomes too soft to support $2\,M_\odot$ neutron stars ("hyperon puzzle")

Implications for neutron stars (incl. chiral 3BF)

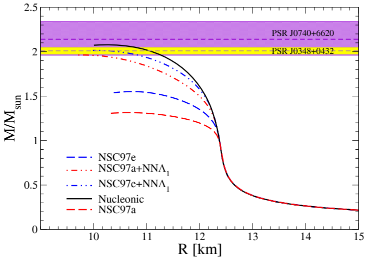
Logoteta, Vidaña, Bombaci,
EPJA 55 (2019) 207
(Nijmegen NSC97 potentials)

Composition and EoS
of neutron star matter

($n_B \equiv \rho$)



Mass-radius relation without and with chiral ΛNN force

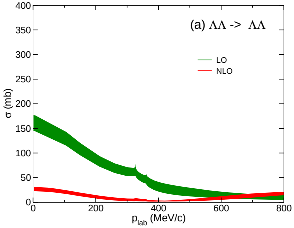


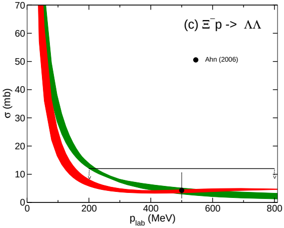
	$M_{max}(M_\odot)$	R (km)	n_c (fm^{-3})
Nucleonic	2.08	10.26	1.15
NSC97a	1.31	10.60	1.40
NSC97a+NNΛ_1	1.96	9.80	1.30
NSC97a+NNΛ_2	1.97	9.87	1.28
NSC97e	1.54	10.81	1.18
NSC97e+NNΛ_1	2.01	10.10	1.20
NSC97e+NNΛ_2	2.02	10.15	1.19

Selected results for $S = -2$

constraints: $\Lambda\Lambda$, ΞN data + ΛN, ΣN interaction / (broken) SU(3) flavor symmetry

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





$\Lambda\Lambda$ effective range parameters

Λ	NLO 500	NLO 550	NLO 600	NLO 650	LO 550	LO 600	LO 650	LO 700
$a_{^1S0}$	-0.62	-0.61	-0.66	-0.70	-1.52	-1.52	-1.54	-1.67
$r_{^1S0}$	7.00	6.06	5.05	4.56	0.82	0.59	0.31	0.34

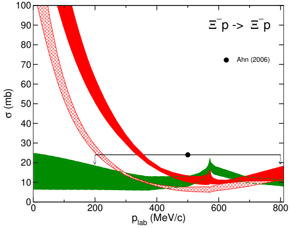
empirical: $a_{\Lambda\Lambda}$ = -1.2 $\pm$ 0.6 fm (Gasparyan et al.)

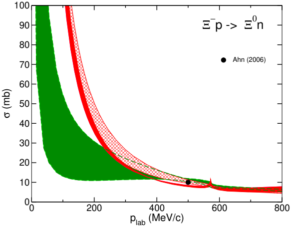
$-1.92 < a_{\Lambda\Lambda} < -0.50$ fm (A. Ohnishi et al.)

^{12}C(K^-, $K^+\Lambda\Lambda X$) (C.-J. Yoon et al.)

$\Lambda\Lambda$ correlations in heavy-ion collisions (STAR)

Selected results for $S = -2$





filled band: J.H., U.-G. Meißner, EPJA 55 (2019) 23

hatched band: NLO interaction from NPA 954 (2016)

single-particle potential of Ξ in nucleonic matter, $U_\Xi(0)$:

		EFT NLO (2019)	EFT NLO (2016)	ESC08c	HAL QCD
	Λ [MeV]	$500 \cdots 650$	$500 \cdots 650$		
$U_\Xi(0)$	S; $I = 0$	$-7.5 \cdots -5.9$	$-7.5 \cdots -5.9$	-6.6	-8.9
	S; $I = 1$	$0.9 \cdots 5.0$	$20.5 \cdots 27.0$	0.4	5.3
	total	$-5.5 \cdots -3.8$	$22.4 \cdots 27.7$	-7.0	-3.6

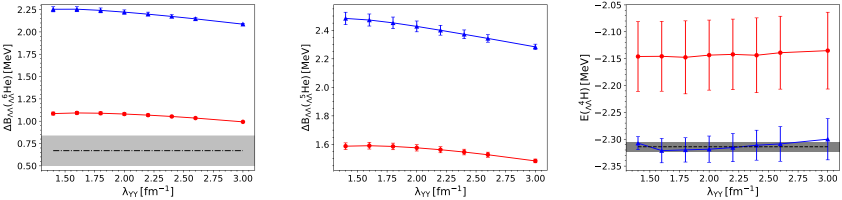
S ... ${}^1S_0$, ${}^3S_1$-${}^3D_1$ $I = 1$: NLO (2016) - both repulsive; NLO (2019) - ${}^3S_1$-${}^3D_1$ attractive

ESC08c: M.M Nagels et al., arXiv:1504:02634; HAL QCD: T. Inoue, AIP Conf.Proc. 2130 (2019) 020002

"Canonical" value: $U_\Xi(0) \approx -15$ MeV

Results for $\Lambda\Lambda$ hypernuclei from NCSM

Hoai Le et al., arXiv:2103.08395; EPJA, in print



—— LO(600) —— NLO(600)

Nagara event:

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda}(^{6}_{\Lambda\Lambda}\mathrm{He}) - 2B_{\Lambda}(^{5}_{\Lambda}\mathrm{He}) = 0.67 \pm 0.17 \text{ MeV}$$

(K. Nakazawa, Nucl. Phys. A 835 (2010) 207)

(H. Takahashi et al., Phys. Rev. Lett. 87 (2001) 212502: $\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.20^{+0.18}_{-0.11}$ MeV)

$^{5}_{\Lambda\Lambda}\mathrm{He}$ ... most likely bound $^{4}_{\Lambda\Lambda}\mathrm{H}$ ... presumably unbound

- a study of Ξ hypernuclei is under way

Summary

Baryon-baryon interaction constructed within chiral EFT

- Approach is based on a modified Weinberg power counting, analogous to the *NN* case
- The potential (contact terms, pseudoscalar-meson exchanges) is derived imposing $SU(3)_f$ constraints
- YN: Excellent results at next-to-leading order (NLO)
  low-energy data are reproduced with a quality comparable to phenomenological models
- $S = -2$: $\Lambda\Lambda$, ΞN results are in agreement with empirical constraints
  SU(3) symmetry breaking when going from NN to YN to YY!
- SU(3) symmetry provides a useful guiding line (fulfilled within 10 to 30 %)
  however, one should not follow SU(3) symmetry too strictly

Outlook and prospects

- YN: Extension to next-to-next-to-leading order (N^2LO)
- YN: detailed study of differential scattering observables
  $\rightarrow$ determination of P-wave amplitudes
- ${}^3_\Lambda\mathrm{H}$, ${}^4_\Lambda\mathrm{H}$, ${}^4_\Lambda\mathrm{He}$ ... inclusion of three-body forces, quantification of their effects

  (can be done on the basis of assuming decuplet saturation)
- study of $A > 4$ hypernuclei using "ab initio" approaches like the NCSM (including SRG-induced 3BF + chiral 3BF)

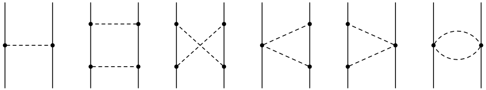
  (feasible up to $A \approx 12 - 14$)
- main (eternal) challenge: How to connect few- and many-body calculations in a reliable and controlled way!

backup slides

BB interaction in chiral effective field theory

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

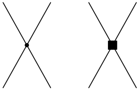
- degrees of freedom: octet baryons (N, Λ, Σ, Ξ), pseudoscalar mesons (π, K, η)
- pseudoscalar-meson exchanges – similar to meson-exchange potentials



- 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) [for NN, ΛN, ΣN, $\Lambda\Lambda$, ΞN, ..., $\Xi\Xi$]

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

$SU(3)$ 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	$V_{\beta\rightarrow\alpha}$
$S = 0$	$NN \rightarrow NN$	0	–	$C_\beta^{10^*}$	–
	$NN \rightarrow NN$	1	C_α^{27}	–	–
$S = -1$	$\Lambda N \rightarrow \Lambda N$	$\frac{1}{2}$	$\frac{1}{10}\left(9C_\alpha^{27} + C_\alpha^{8_s}\right)$	$\frac{1}{2}\left(C_\beta^{8_a} + C_\beta^{10^*}\right)$	$-C^{8_{sa}}$
	$\Lambda N \rightarrow \Sigma N$	$\frac{1}{2}$	$\frac{3}{10}\left(-C_\alpha^{27} + C_\alpha^{8_s}\right)$	$\frac{1}{2}\left(-C_\beta^{8_a} + C_\beta^{10^*}\right)$	$-3C^{8_{sa}}$
					$C^{8_{sa}}$
	$\Sigma N \rightarrow \Sigma N$	$\frac{1}{2}$	$\frac{1}{10}\left(C_\alpha^{27} + 9C_\alpha^{8_s}\right)$	$\frac{1}{2}\left(C_\beta^{8_a} + C_\beta^{10^*}\right)$	$3C^{8_{sa}}$
	$\Sigma N \rightarrow \Sigma N$	$\frac{3}{2}$	C_α^{27}	C_β^{10}	–

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

No. of contact terms: LO: 2 (NN) + 3 (YN) + 1 (YY)
NLO: 7 (NN) + 11 (YN) + 4 (YY)

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

Contact terms for YN – partial-wave projected

spin-momentum structure up to NLO

$$
\begin{aligned}
V(^1S_0) &= \tilde{C}_{^1S_0} + C_{^1S_0}(p^2 + p'^2) \\
V(^3S_1) &= \tilde{C}_{^3S_1} + C_{^3S_1}(p^2 + p'^2) \\
V(\alpha) &= C_\alpha \, p \, p' \qquad \alpha \,\hat{=}\, {}^1P_1,\ {}^3P_0,\ {}^3P_1,\ {}^3P_2 \\
V(^3D_1 - {}^3S_1) &= C_{^3S_1 - {}^3D_1} \, p'^2
\end{aligned}
$$

$$
\begin{aligned}
V(^1P_1 - {}^3P_1) &= C_{^1P_1 - {}^3P_1} \, p \, p' \\
V(^3P_1 - {}^1P_1) &= C_{^3P_1 - {}^1P_1} \, p \, p'
\end{aligned}
$$

(antisymmetric spin-orbit force: $(\vec{\sigma}_1 - \vec{\sigma}_2) \cdot (\vec{q} \times \vec{k})$)

- $\tilde{C}_\alpha$, C_α ... low-energy constants (LECs)
- need to be fixed by a fit to (NN, YN, ...) data

Coupled channels Lippmann-Schwinger Equation

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

ρ', $\rho = \Lambda N$, ΣN ($\Lambda\Lambda$, ΞN, $\Lambda\Sigma$, $\Sigma\Sigma$)

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:

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

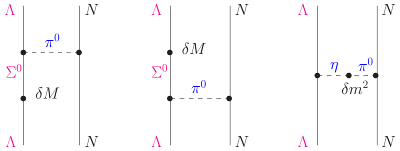
consider values $\Lambda = 500$ - 650 MeV [guided by NN, achieved χ^2]

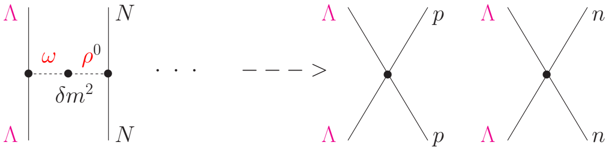
ideally the regulator (Λ) dependence should be absorbed completely by the LECs

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

Charge symmetry breaking - in chiral EFT





Σ^0-Λ mixing + π^0-η mixing + CSB contact terms

Electromagnetic mass matrix:

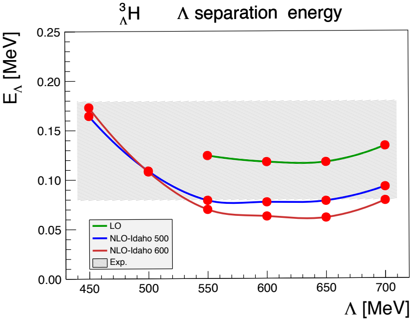
$\langle\Sigma^0|\delta M|\Lambda\rangle = [M_{\Sigma^0} - M_{\Sigma^+} + M_p - M_n]/\sqrt{3}$,
$\langle\pi^0|\delta m^2|\eta\rangle = [m^2_{\pi^0} - m^2_{\pi^+} + m^2_{K^+} - m^2_{K^0}]/\sqrt{3}$, etc.

(R.H. Dalitz & F. von Hippel, PL 10 (1964) 153)

⇒ J.H., U.-G. Meißner, A. Nogga, arXiv:2107.01134

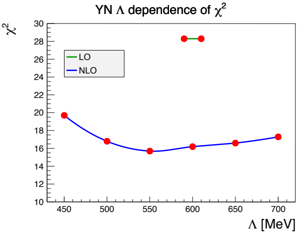
(different approach to Gal & Gazda (2016) !!)

Hypertriton (Faddeev calculation by A. Nogga)



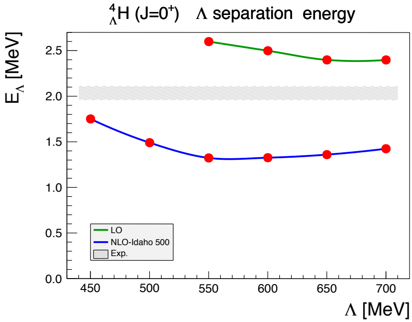
separation energies:

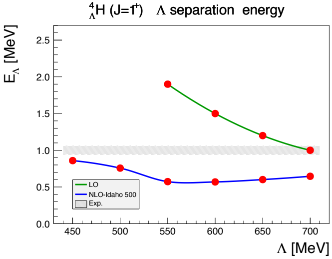
$$E_\Lambda = E(core) - E(hypernucleus)$$



- Λp $^1S_0$ / $^3S_1$ scattering lengths are chosen so that $^3_\Lambda$H is bound
- however, effect of three-body forces needs to be explicitly estimated
- cutoff variation:
  - * $NNN \rightarrow$ is lower bound for magnitude of higher order contributions
  - * ΛNN - correlation with χ^2 of YN interaction?

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





- LO: unexpected small cutoff dependence in 0^+ result
- NLO: underbinding $\rightarrow$ comparable to what is observed in calculations with phenomenological potentials (Jülich '04, NSC97f)
- possible effects of long range three-body forces?
- open problem: charge symmetry breaking ${}^4_\Lambda\mathrm{H} \leftrightarrow {}^4_\Lambda\mathrm{He}$