Baryon-baryon interaction from chiral effective field theory

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Outline

Experimental status

NN [$S = 0$]

- > 5000 NN data for $E_{lab} < 350$ MeV!

ΛN, ΣN [$S = -1$]

- about 35 data points, all from the 1960s
- 10 new data points, from the KEK-PS E251 collaboration (from ≈ 2000)

YY [$S = -2$]

- a few rough estimates of ΞN cross sections from the 1970s
- a few more cross sections (for $\Xi^- p$ and $\Xi^- p \to \Lambda\Lambda$) published in 2006

$S = -3, -4$: uncharted territory

role of SU(3) flavor symmetry

meson-exchange approach:

use NN and YN data + SU(3) 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

$\Rightarrow$ the derived/employed YN interaction is too attractive
... presumably likewise those for $\Lambda\Lambda$, ΞN, ..., $\Xi\Xi$

conspiracy between

- the assumed SU(3) symmetry for the baryon-baryon (BB) potentials
- increasing masses of the baryons with strangeness

role of SU(3) flavor symmetry

Schrödinger equation:

$$-\frac{d^2 u}{dr^2} + 2\mu_{B\,B'} V_{B\,B'}\, u = k^2\, u, \qquad \mu_{B\,B'} \text{...reduced mass}$$

${}^1S_0$: $V_{NN}^{I=1} \approx V_{\Sigma N}^{I=3/2} \approx V_{\Xi\Sigma}^{I=3/2} \approx V_{\Xi\Xi}^{I=1}$ (according to SU(3))

$\mu_{\Sigma N}/\mu_{NN} \approx 1.12$
$\mu_{\Xi\Xi}/\mu_{NN} \approx 1.40$

→ increase in the strength of the effective interaction
→ drastic effect for attractive potentials ($V_{B\,B'} < 0$)

	$S=0$		$S=-1$		$S=-2$	...
strict SU(3):	$2\mu_{B\,B'} V_{B\,B'}$	$>$	$2\mu_{B\,B'} V_{B\,B'}$	$>$	$2\mu_{B\,B'} V_{B\,B'}$	...
empirically:	$2\mu_{B\,B'} V_{B\,B'}$	$\lesssim$	$2\mu_{B\,B'} V_{B\,B'}$	$\lesssim$	$2\mu_{B\,B'} V_{B\,B'}$	

⇒ employ SU(3) chiral effective field theory (χEFT)
allows to implement SU(3) flavor symmetry
but also SU(3) symmetry breaking
in a consistent way

BB interaction in chiral effective field theory

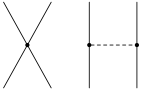
Baryon-baryon interaction in SU(3) χEFT à la Weinberg (1990)

Advantages:

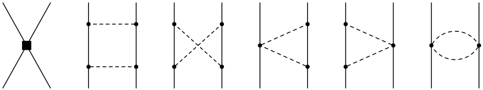
- Power counting
  systematic improvement by going to higher order
- Possibility to derive two- and three-baryon forces and external current operators in a consistent way

- degrees of freedom: octet baryons (N, Λ, Σ, Ξ), pseudoscalar mesons (π, K, η)
- pseudoscalar-meson exchanges
- contact terms – represent unresolved short-distance dynamics

LO :



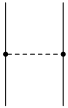
NLO :



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

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

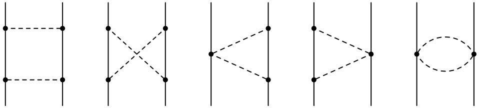
pseudoscalar-meson exchange diagrams



$$V^{OBE}_{B_1 B_2 \to B_1' B_2'} = -f_{B_1 B_1' P} f_{B_2 B_2' P} \frac{(\vec{\sigma}_1 \cdot \vec{q})\,(\vec{\sigma}_2 \cdot \vec{q})}{\vec{q}^{\,2} + m_P^2}$$

$f_{B_1 B_1' P}$ ... coupling constants fulfil standard SU(3) relations
m_P ... mass of the exchanged pseudoscalar meson

$SU(3)$ symmetry breaking due to the mass splitting of the ps mesons (m_π = 138.0 MeV, m_K = 495.7 MeV, m_η = 547.3 MeV) taken into account already at LO!



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

Contact terms for YN – partial-wave projected

spin-momentum structure up to NLO

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

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

(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

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

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

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)

Breaking of SU(3) symmetry

S. Petschauer, N. Kaiser, NPA 916 (2013) 1:

example: $^1S_0$ partial wave for pure $\{27\}$ states

$$
\begin{aligned}
V^{I=1}_{NN} &= \tilde{C}^{27} + C^{27}(p^2+p'^2) + \frac{1}{2}C_1^{\chi}(m_K^2 - m_\pi^2) \\
V^{I=3/2}_{\Sigma N} &= \tilde{C}^{27} + C^{27}(p^2+p'^2) + \frac{1}{4}C_1^{\chi}(m_K^2 - m_\pi^2) \\
V^{I=2}_{\Sigma\Sigma} &= \tilde{C}^{27} + C^{27}(p^2+p'^2) \\
V^{I=3/2}_{\Xi\Sigma} &= \tilde{C}^{27} + C^{27}(p^2+p'^2) + \frac{1}{4}C_2^{\chi}(m_K^2 - m_\pi^2) \\
V^{I=1}_{\Xi\Xi} &= \tilde{C}^{27} + C^{27}(p^2+p'^2) + \frac{1}{2}C_2^{\chi}(m_K^2 - m_\pi^2)
\end{aligned}
$$

C_1^{χ}, C_2^{χ}, LECs that break SU(3) symmetry of LO contact terms

BB scattering for $S=0$ to $S=-4$: 6 LECs for $^1S_0$ and 6 LECs for $^3S_1$
$\rightarrow$ cannot be determined from presently available data

impose SU(3) symmetry for BB systems with equal S: $\{\Lambda N, \Sigma N\}$ or $\{\Lambda\Lambda, \Sigma\Sigma, \Xi N, \Lambda\Sigma\}$
allow for SU(3) symmetry breaking between NN and $\{\Lambda N, \Sigma N\}$, $\{\Lambda N, \Sigma N\}$ and
$\{\Lambda\Lambda, \Sigma\Sigma, \Xi N, \Lambda\Sigma\}$, etc.

Coupled channels Lippmann-Schwinger Equation

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

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

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

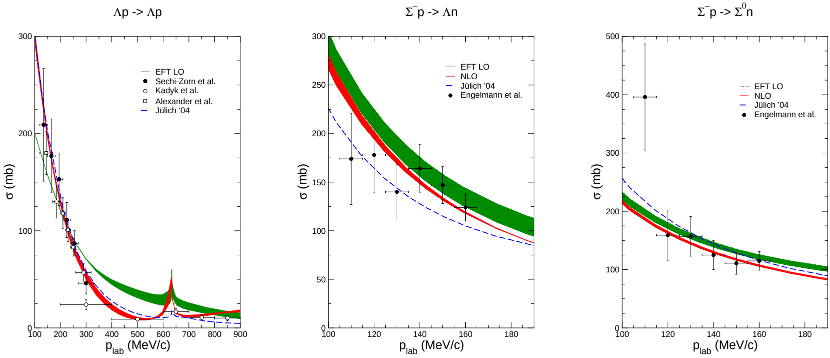
Coulomb interaction is included via the Vincent-Phatak method

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 $\Lambda =$ 550 - 700 MeV [LO]
500 - 650 MeV [NLO]

YN integrated cross sections

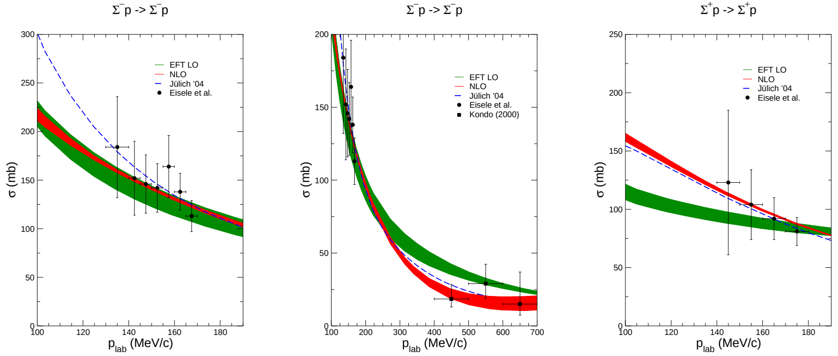


LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244

NLO: J.H., N. Kaiser, et al., NPA 915 (2013) 24

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

YN integrated cross sections



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

Brueckner reaction-matrix formalism

conventional non-relativistic lowest order Brueckner theory:

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

Q ... Pauli projection operator

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

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

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

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

⇒ J.H, U.-G. Meißner, NPA 936 (2015) 29
S. Petschauer, et al., EPJA 52 (2016) 15

Nuclear matter properties

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

	EFT LO	EFT NLO	Jülich '04	Jülich '94
Λ [MeV]	$550 \cdots 700$	$500 \cdots 650$		
$U_\Lambda(0)$	$-38.0 \cdots -34.4$	$-28.2 \cdots -22.4$	-51.2	-29.8
$U_\Sigma(0)$	$28.0 \cdots 11.1$	$17.3 \cdots 11.9$	-22.2	-71.4

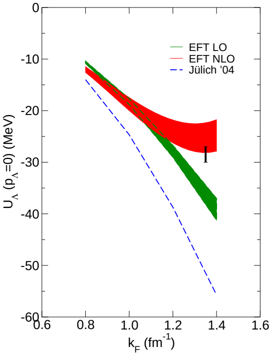
"Empirical" value for the Λ binding energy in nuclear matter: $\approx 27 - 30$ MeV

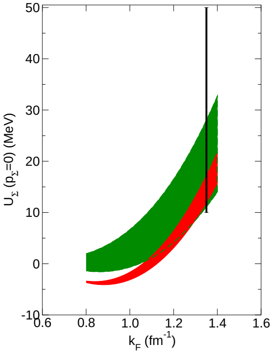
ΣN (I=3/2): ${}^3S_1$–${}^3D_1$: decisive for Σ properties in nuclear matter

- A description of YN data is possible with an attractive as well as a repulsive ${}^3S_1$–${}^3D_1$ interaction
- adopt the repulsive solution in accordance with evidence from
  - level shifts and widths of Σ^- atoms
  - (π^-, K^+) inclusive spectra related to Σ^- formation in heavy nuclei
- Lattice QCD calculations support also a repulsive ${}^3S_1$–${}^3D_1$!
  S. Beane et al., PRL 109 (2012) 172001; H. Nemura, Lattice2017, (Granada, June 2017)

Jülich '94: A. Reuber, K. Holinde, J. Speth, NPA 570 (1994) 543

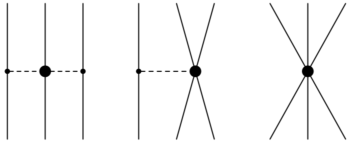
k_F dependence of s.p. potentials



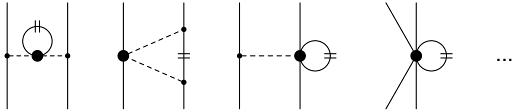


density dependent effective YN interaction

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



density dependent effective YN interaction:

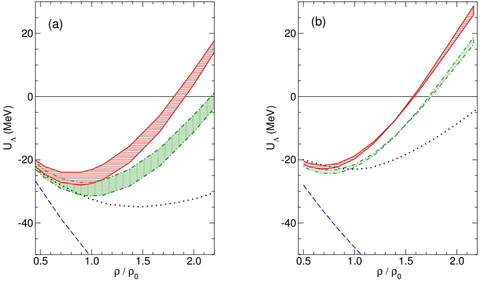


close two baryon lines by sum over occupied states within the Fermi sea
arising 3BF LECs can be constrained by resonance saturation (via decuplet baryons)

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

Results for Λ at larger density ρ

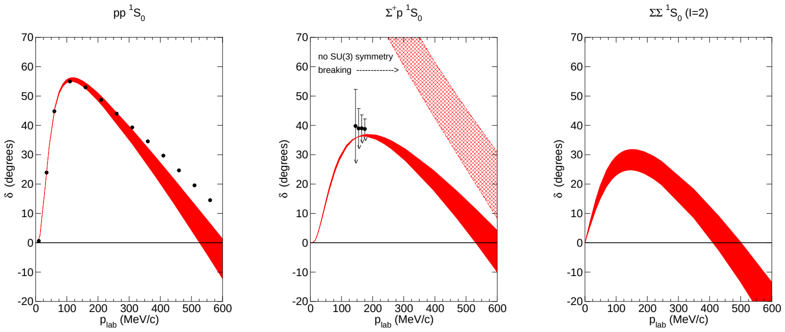
symmetric nuclear matter / neutron matter



— · — χEFT at NLO
—— χEFT at NLO + density-dependent Λ*N* interaction derived from chiral Λ*NN* 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

Breaking of SU(3) symmetry



$$V_{pp} = \tilde{C}^{27} + C^{27}(p^2 + p'^2) + \frac{1}{4}C_1^{\chi}(m_K^2 - m_\pi^2) + V^{OBE} + V^{TBE}$$

$$V_{\Sigma^+p} = \tilde{C}^{27} + C^{27}(p^2 + p'^2) + V^{OBE} + V^{TBE}$$

$$V_{\Sigma^+\Sigma^+} = \tilde{C}^{27} + C^{27}(p^2 + p'^2) - \frac{1}{4}C_1^{\chi}(m_K^2 - m_\pi^2) + V^{OBE} + V^{TBE}$$

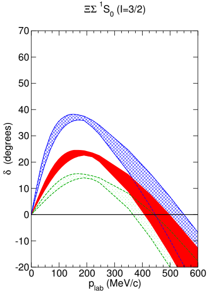
J.H., U.-G. Meißner, S. Petschauer, EPJA 51 (2015) 17:

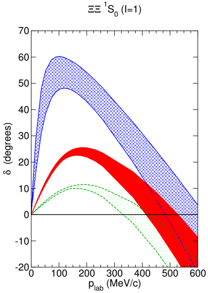
determine $\tilde{C}^{27}$, C^{27}, C_1^{χ} from a combined fit to pp and Σ^+p

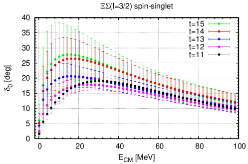
$C_1^{\chi} < 0 \Rightarrow$ increasing repulsion for $S = 0 \rightarrow S = -1 \rightarrow S = -2$

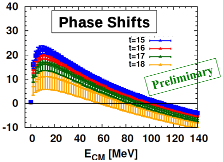
Breaking of SU(3) symmetry: S=-3,-4

(i) blue: $V^{CT}_{\Sigma\Sigma} = V^{CT}_{\Xi\Sigma} = V^{CT}_{\Xi\Xi}$; (ii) green: SU(3) breaking as for $NN \to \Sigma N \to \Sigma\Sigma$; (iii) red: "(i + ii)/2"









HAL QCD lattice results ($m_\pi = 146$ MeV): N. Ishii ($\Xi\Sigma$), T. Doi ($\Xi\Xi$) Lattice2017 (Granada, June 2017)

- cf. also $^3S_1$ results for $\Xi\Sigma$ ($I = 3/2$) and $\Xi\Xi$ ($I = 0$)

Information on $S = -2$ systems

Constraints on the $\Lambda\Lambda$ scattering length:

- $\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) - 2B_{\Lambda}({}^{5}_{\Lambda}\mathrm{He}) = 1.01 \pm 0.20^{+0.18}_{-0.11}$ MeV

  (H. Takahashi et al., Phys. Rev. Lett. 87 (2001) 212502)

  0.67 ± 0.17 MeV

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

  ${}^{6}_{\Lambda\Lambda}$He calculations (Filikhin; Fujiwara; Rijken; ...)

  $\Rightarrow -1.32 < a_{\Lambda\Lambda} < -0.73$ fm [based on 2001 value!]

- $a_{\Lambda\Lambda}$ = -1.2 $\pm$ 0.6 fm

  (A. Gasparyan et al., Phys. Rev. C 85 (2012) 0152047)

  deduced from $\Lambda\Lambda$ invariant mass spectrum of the reaction ${}^{12}C(K^-, K^+\Lambda\Lambda X)$

- $-1.25 < a_{\Lambda\Lambda} < -0.56$ fm

  (K. Morita et al., Phys. Rev. C 91 (2015) 024916)

  deduced from analyzing $\Lambda\Lambda$ correlations in relativistic heavy-ion collisions

Information on $S = -2$ systems

Constraints on the ΞN interaction:

- data/limits for the range $200 < p_\Xi < 800$ MeV/c

  $\sigma_{\Xi^- p \to \Lambda\Lambda} < 12$ mb, at 90% confidence level
  $\sigma_{\Xi^- p \to \Xi^- p} < 24$ mb, at 90% confidence level
  $\sigma_{\Xi^- p \to \Lambda\Lambda} = 4.3^{+6.3}_{-2.7}$ mb, at $p_\Xi = 500$ MeV/c

  (J.K. Ahn et al., PLB 633 (2006) 214)

- in-medium cross sections:

  inelastic $\sigma_{\Xi^- N} = 12.7^{+3.5}_{-3.1}$ mb (400 $< p_\Xi <$ 600 MeV/c)

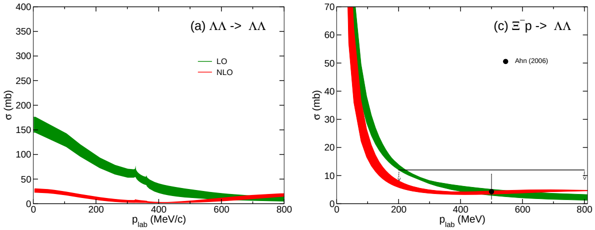
  (S. Aoki et al., NPA 644 (1998) 365)

- older data at higher energies (Charlton, 1970; Muller, 1972):

  $\sigma_{\Xi^- p \to \Xi^- p} = 13 \pm 6$ mb ($p_\Xi = 1 - 4$ GeV/c)
  $\sigma_{\Xi^0 p \to \Xi^0 p} = 19 \pm 10$ mb ($p_\Xi = 1 - 4$ GeV/c)

  $\sigma_{\Xi^0 p \to \Xi^0 p} = 8$ mb
  $\sigma_{\Xi^0 p \to \Sigma^+ \Lambda} = 24$ mb ($p_\Xi \approx 2$ GeV/c)

$\Rightarrow$ ΞN cross sections are small $\to$
ΞN interaction cannot be very strong !

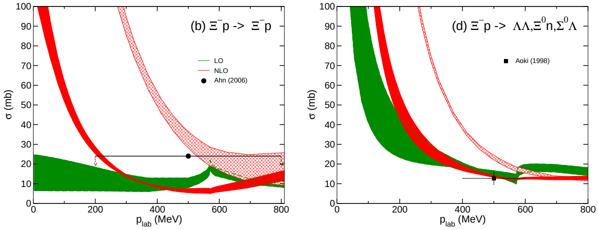


$\Lambda\Lambda$ effective range parameters

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

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

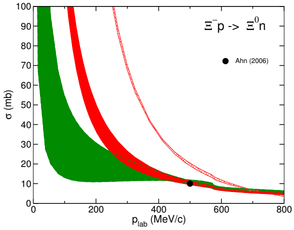


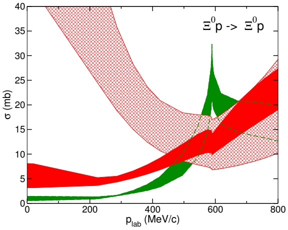
hatched band: use $\tilde{C}^{i}_{^3S1}$ as fixed in YN (SU(3))

filled band: $\tilde{C}^{8a}_{^3S1}$ readjusted

		NLO				LO			
Λ		500	550	600	650	550	600	650	700
$\Xi^0 n$	$a_{^3S1}$	−0.25	−0.20	−0.26	−0.34	−0.34	−0.25	−0.20	−0.15
	(SU(3))	11.39	5.15	4.78	4.74				
$\Xi^0 p$	$a_{^1S0}$	0.37	0.39	0.34	0.31	0.21	0.19	0.17	0.13
	$a_{^3S1}$	−0.20	−0.04	0.02	0.04	0.02	0.00	0.02	0.03
	(SU(3))	−1.01	−0.85	−0.72	−0.66				
$\Sigma^+\Sigma^+$	$a_{^1S0}$	−2.19	−1.94	−1.83	−1.82	−6.23	−7.76	−9.42	−9.27

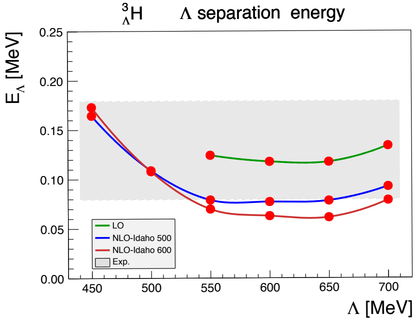
Results for $S = -2$





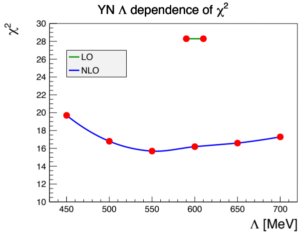
hatched band: use $\tilde{C}^{i}_{3S1}$ as fixed in YN (SU(3)) filled band: $\tilde{C}^{8a}_{3S1}$ readjusted

Hypertriton results (from Faddeev calculation)



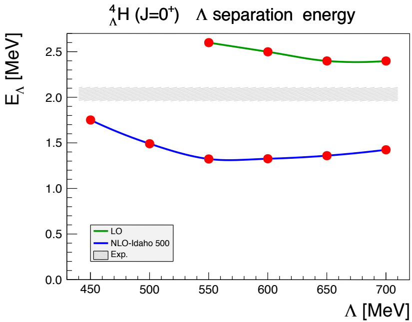
separation energies:

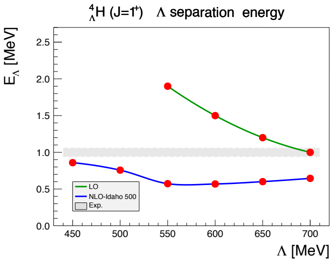
$$E_\Lambda = E(core) - E(hypernucleus)$$



- Λp $^1S_0$ / $^3S_1$ scattering lengths are chosen so that $^3_\Lambda$H is bound
- long range 3BFs need to be explicitly estimated
- cutoff variation:
  - * $NNN \to$ is lower bound for magnitude of higher order contributions
  - * ΛNN - correlation with χ^2 of YN interaction?

${}^{4}_{\Lambda}$H results (from Faddeev-Yakubovsky calculation)





- LO: unexpected small cutoff dependence in 0^{+} result
- NLO: underbinding $\rightarrow$ comparable to what is observed in calculations with phenomenological potentials (Jülich '04, NSC97f)
- long range 3BFs need to be explicitly estimated

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
- Λ and Σ in nuclear matter:
  Λ single-particle potential at nuclear matter saturation density is in line with "empirical" value
  a repulsive Σ single-particle potential is achieved
  a weak Λ-nuclear spin-orbit potential is achieved
- $S = -2$: $\Lambda\Lambda$, 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

Backup slides

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

	Channel	Isospin	V_{3S1}	Isospin	V_{1S0}
$S = 0$	$NN \to NN$	0	C^{10^*}	1	C^{27}
$S = -1$	$\Lambda N \to \Lambda N$	$\frac{1}{2}$	$\frac{1}{2}\left(C^{8_a} + C^{10^*}\right)$	$\frac{1}{2}$	$\frac{1}{10}\left(9C^{27} + C^{8_s}\right)$
	$\Lambda N \to \Sigma N$	$\frac{1}{2}$	$\frac{1}{2}\left(-C^{8_a} + C^{10^*}\right)$	$\frac{1}{2}$	$\frac{3}{10}\left(-C^{27} + C^{8_s}\right)$
	$\Sigma N \to \Sigma N$	$\frac{1}{2}$	$\frac{1}{2}\left(C^{8_a} + C^{10^*}\right)$	$\frac{1}{2}$	$\frac{1}{10}\left(C^{27} + 9C^{8_s}\right)$
	$\Sigma N \to \Sigma N$	$\frac{3}{2}$	C^{10}	$\frac{3}{2}$	C^{27}
$S = -3$	$\Xi\Lambda \to \Xi\Lambda$	$\frac{1}{2}$	$\frac{1}{2}\left(C^{8_a} + C^{10}\right)$	$\frac{1}{2}$	$\frac{1}{10}\left(9C^{27} + C^{8_s}\right)$
	$\Xi\Lambda \to \Xi\Sigma$	$\frac{1}{2}$	$\frac{1}{2}\left(-C^{8_a} + C^{10}\right)$	$\frac{1}{2}$	$\frac{3}{10}\left(-C^{27} + C^{8_s}\right)$
	$\Xi\Sigma \to \Xi\Sigma$	$\frac{1}{2}$	$\frac{1}{2}\left(C^{8_a} + C^{10}\right)$	$\frac{1}{2}$	$\frac{1}{10}\left(C^{27} + 9C^{8_s}\right)$
	$\Xi\Sigma \to \Xi\Sigma$	$\frac{3}{2}$	C^{10^*}	$\frac{3}{2}$	C^{27}
$S = -4$	$\Xi\Xi \to \Xi\Xi$	0	C^{10}	1	C^{27}

10 and 10^* representations interchange their roles when going from the $S = 0, -1$ to the $S = -3, -4$ channels

NLO calculation for ΛN, ΣN scattering

Pseudoscalar-meson exchange

- All one- and two-pseudoscalar-meson exchange diagrams are included
- $SU(3)$ symmetry is broken by using the physical m_π, m_K, and m_η
- $SU(3)$ breaking in the coupling constants is ignored
  $f_\pi = f_K = f_\eta = f_0 = 93$ MeV; $\alpha = F/(F+D) = 0.4$; $F + D = g_A = 1.26$
- Correction to V^{OBE} due to baryon mass differences are ignored

Contact terms

- $SU(3)$ symmetry is assumed
  (at NLO $SU(3)$ breaking corrections to the LO contact terms arise!)
- 10 contact terms in S-waves
  fixed from fit to ΛN and ΣN data
  no SU(3) constraints from the NN sector are imposed!
- 12 contact terms in P-waves and in ${}^3S_1 - {}^3D_1$
  SU(3) constraints from the NN sector are imposed!
- 1 contact term in ${}^1P_1 - {}^3P_1$ (singlet-triplet mixing)
  is fixed from considering Λ-nuclear spin-orbit force in medium