Hyperon-nucleon interaction in few- and many-body systems

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Outline

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
  $\rightarrow$ stability/size of neutron stars
  softening of equation of state (hyperon puzzle)
  hyperon stars

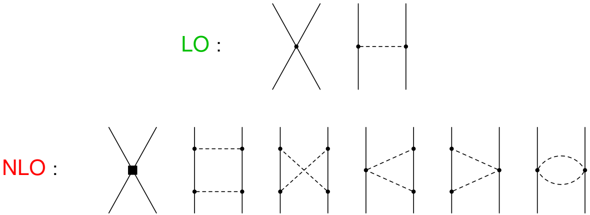
BB interaction in chiral effective field theory

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

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 (V^{OBE}, V^{TBE})
- contact terms – represent unresolved short-distance dynamics (V^{CT})



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

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

BB interaction up to NLO

Pseudoscalar-meson exchange

$$V^{OBE}_{B_1B_2\to B'_1B'_2} = -f_{B_1B'_1P}f_{B_2B'_2P}\frac{(\vec\sigma_1\cdot\vec q)(\vec\sigma_2\cdot\vec q)}{\vec q^{\,2}+m_P^2}, \quad \vec q=\vec p\,'-\vec p$$

$$V^{TBE}_{B_1B_2\to B'_1B'_2} = \ldots$$

$f_{B_1B'_1P}$ ... 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)

Contact interaction V^{CT} - partial-wave projected

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

$\tilde C$'s, C's ... low-energy constants (LECs) ... to be fixed from fit to 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^{8_a}, C^{8_s}, C^{10^*}, C^{10}, C^{27}

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

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

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

NB: ΛN, $\Sigma N \to$ 10 LECs in S waves relevant at low energies

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:

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

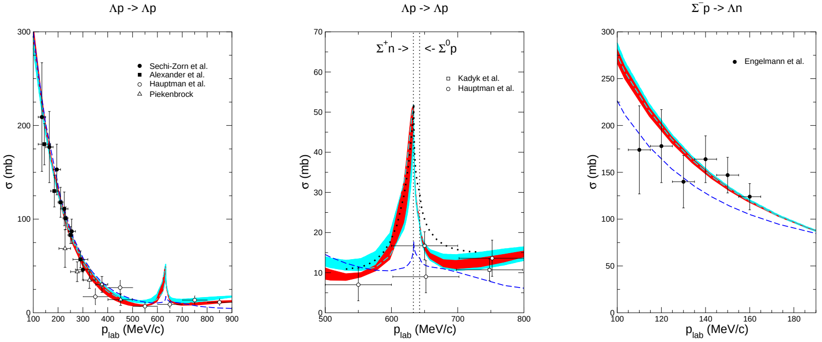
consider values $\Lambda = 500$ - 650 MeV [guided by *NN*, achieved χ^2]

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 ... all S-wave LECs are fixed from a fit directly to available YN data
NLO19 ... consider constraints from the NN interaction within (broken) SU(3) symmetry

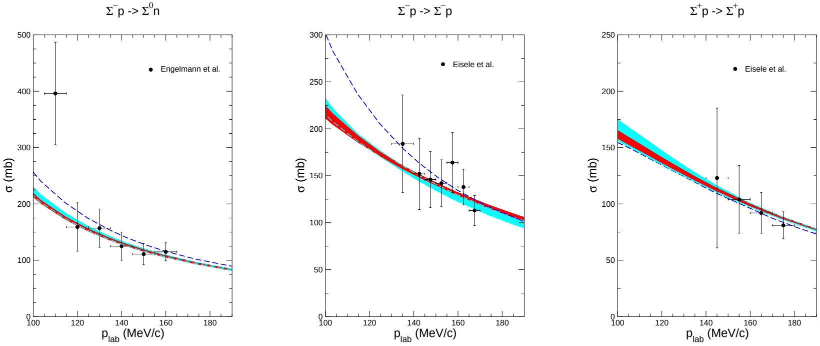
NLO13: J.H., S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W. Weise, NPA 915 (2013) 24

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!



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

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

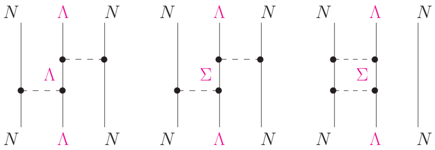
NLO13: 15.7 $\cdots$ 16.8 NLO19: 16.0 $\cdots$ 18.1 Jülich '04: $\approx$ 22

Difference between NLO13 and NLO19

Different coupling strength between the ΛN and ΣN channels ($V_{\Lambda N \leftrightarrow \Sigma N}$)

consequences for in-medium properties:
ΛN–ΣN coupling is suppressed for increasing number of nucleons

dispersive effects in few-body systems:



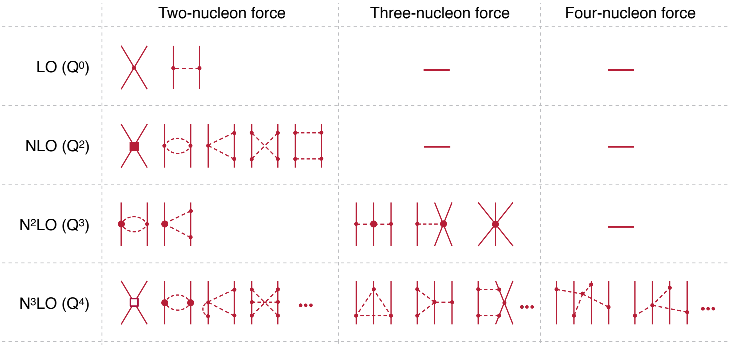
$V^{eff}_{\Lambda N}(E) \approx V_{\Lambda N} + V_{\Lambda N \to \Sigma N} \frac{1}{E - H_0} V_{\Sigma N \to \Lambda N}$
(propagator includes the energy of the spectator nucleons!)

Pauli blocking effects in nuclear matter:
$V^{eff}_{\Lambda N}(\epsilon) \approx V_{\Lambda N} + V_{\Lambda N \to \Sigma N} \frac{Q}{\epsilon - H_0} V_{\Sigma N \to \Lambda N}$

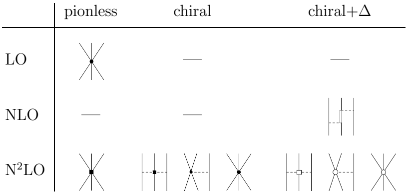
EFT: in consistent few- and many-body calculations, differences in the two-body potential (in the ΛN–ΣN coupling) are to be compensated by many-body forces

$\rightarrow$ tool for estimating effects from three-body forces!

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



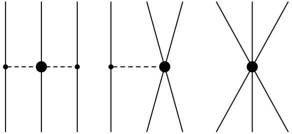
different hierarchy of 3BFs
for other counting schemes
(Hammer, Nogga, Schwenk,
Rev. Mod. Phys. 85 (2013) 197)



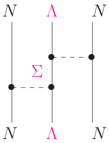
Three-body forces

- SU(3) χEFT 3BFs nominally at N^{2}LO (S. Petschauer et al., PRC 93 (2016) 014001)
- not included in present (NLO) calculation!

SU(3) χEFT :

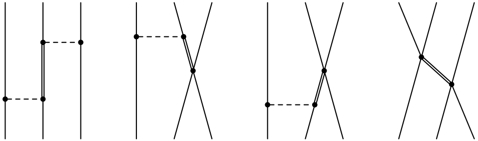


(at LO!) :



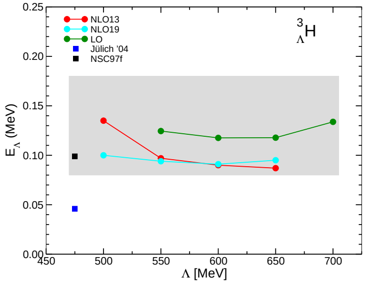
solve coupled channel (ΛN-ΣN) Faddeev-Yakubovsky equations:
$\Rightarrow$ ΛNN "3BF" from Σ coupling is automatically included
remaining 3BF expected to be moderate

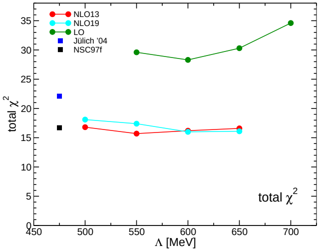
- ΛNN 3BF via Σ^* excitation in SU(3) χEFT with $\{10\}$ baryons (NLO)



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

Hypertriton (Faddeev calculation by A. Nogga)





(separation energy $E_\Lambda = B_\Lambda - B_d$ = 0.13 $\pm$ 0.05 MeV (M. Jurič et al., 1973))

- $B(^3_\Lambda\mathrm{H})$ 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
- cutoff variation:

* *NNN* $\to$ is lower bound for magnitude of higher order contributions

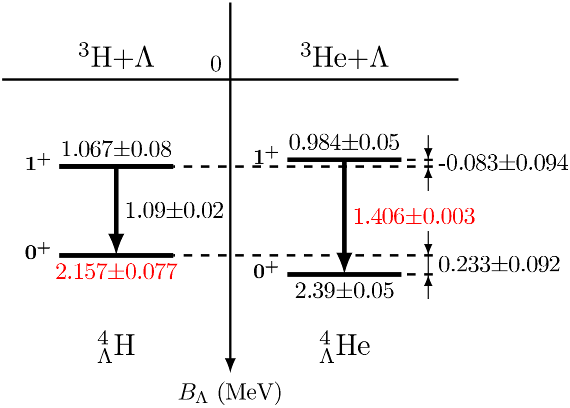
* ΛNN - correlation with χ^2 of YN interaction

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

♦ STAR (J. Adam et al., Nature Phys. 16 (2020) 409) ($^3_\Lambda\mathrm{H}$+$^3_{\bar\Lambda}\bar{\mathrm{H}}$): 0.41 $\pm$ 0.12 $\pm$ 0.11 MeV !?

(*NN* potential: SMS N^{4}LO+ (450) (P. Reinert et al., EPJA 54 (2018) 86))

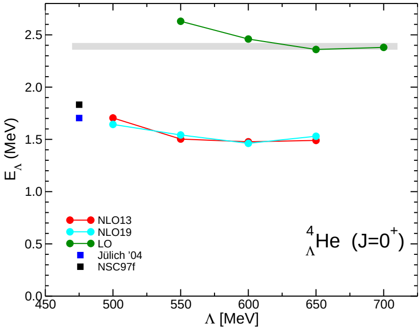
Status - $^4_\Lambda$H, $^4_\Lambda$He

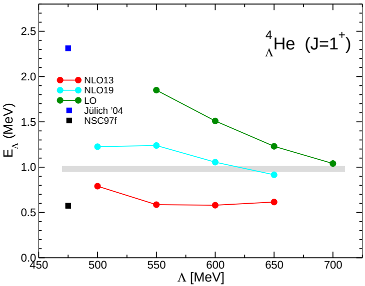


large CSB in 0^+ ($\Delta \approx 233$ keV), small CSB in 1^+ ($\Delta \approx -83$ keV)

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)





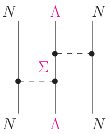
- LO: unexpected small cutoff dependence in 0^+ result
- NLO: underbinding in χEFT and for phenomenological potentials
- possible effects of long ranged three-body forces?

(no CSB in χEFT YN potentials!)

Estimation of 3BFs based on NLO results

- ${}^3_\Lambda$H
  (a) cutoff variation: ΔE_Λ (3BF) $\lesssim$ 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}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

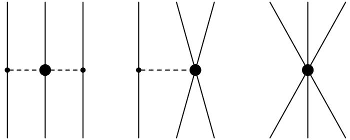
- ${}^4_\Lambda$H, ${}^4_\Lambda$He
  (a) cutoff variation: ΔE_Λ (3BF) $\approx$ 200 keV (0^+) and $\approx$ 300 keV (1^+)
  (b) "3BF" from ΛN-ΣN coupling:
  ΔE_Λ (3BF) $\approx$ 230 – 340 keV (0^+), $\approx$ 150 – 180 keV (1^+)

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

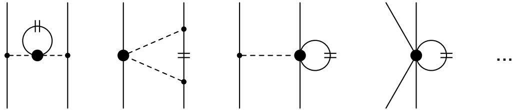
density dependent effective YN interaction

(for application to heavy hypernuclei and hyperons in infinite nuclear matter)

three-body force:



$\Rightarrow$ 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 ΣNN, ΞNN, ...)

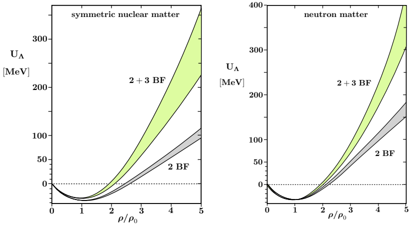
J.W. Holt, N. Kaiser, W. Weise, PRC 81 (2010) 064009 (for NNN)
S. Petschauer et al., NPA 957 (2017) 347 (for ΛNN)
D. Gerstung et al., EPJA 56 (2020) 175 (ΛNN, ΣNN)

Implications for neutron stars (incl. chiral 3BF)

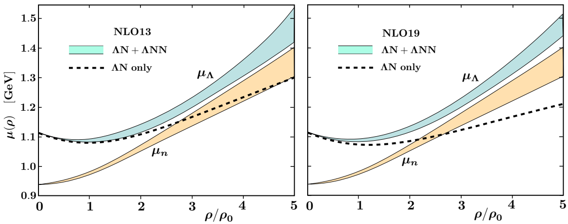
D. Gerstung et al.,
EPJA 56 (2020) 175
(NLO13 & NLO19; ΛNN, ΣNN)

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 $\quad (\mu_\Lambda(\rho) = M_\Lambda + U_\Lambda(\rho))$

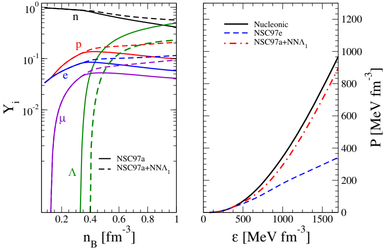
Equation-of-state becomes too soft to support $2\,M_\odot$ neutron stars ("hyperon puzzle")

Implications for neutron stars (incl. chiral 3BF)

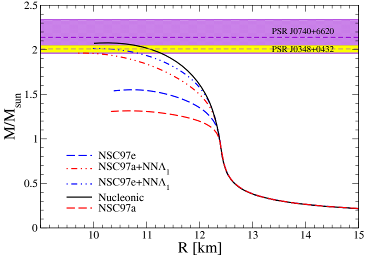
Logoteta, Vidaña, Bombaci,
EPJA 55 (2019) 207
(Nijmegen NSC97 potentials)

Composition and EoS
of neutron star matter

($n_B \equiv \rho$)

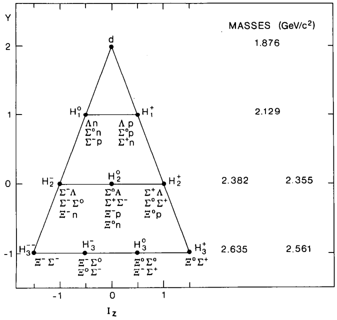


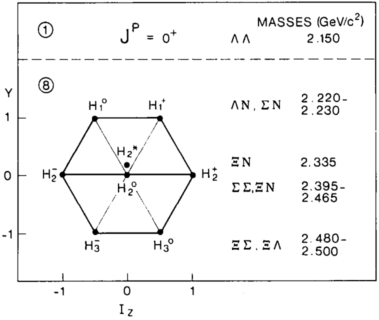
Mass-radius relation without and with chiral ΛNN force



	$M_{max}(M_\odot)$	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

Strange dibaryons





R.J. Oakes, PR 131 (1963) 2239

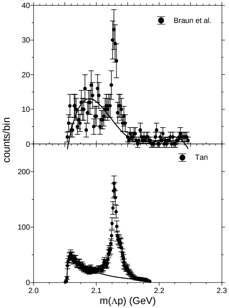
SU(3) flavor symmetry $\{10^*\}$
strange partners of the deuteron

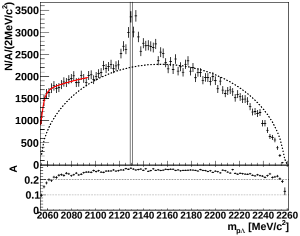
R.L. Jaffe, PRL 38 (1977) 195

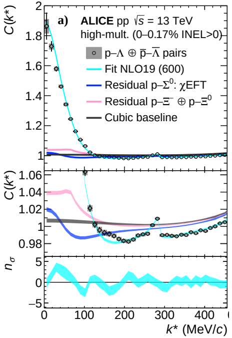
MIT quark bag model

Experimental evidence for threshold structure

$M_{\Sigma^+} + M_n = 2128.97$ MeV $M_{\Sigma^0} + M_p = 2130.87$ MeV







$K^- d \to \pi^- \Lambda p$ $pp \to K^+ \Lambda p$ Λp corr. in pp coll.

T.T. Tan, PRL 7 (1969) 395
O. Braun et al., NPB 124 (1977) 45

M. Röder et al., EPJA 49 (2013) 157

S. Acharya [ALICE Coll.], arXiv:2104.04427

"ordinary" threshold effect? bound state? virtual state (np $^1S_0$) ?

χ^2 for $\Sigma^- p$ and $\Sigma^+ p$ data

ΛN result near ΣN threshold is primarily constrained by near-threshold (20) $\Sigma^- p$ data

reaction	NLO13				NLO19				Jülich '04	NSC97f (ND)
	500	550	600	650	500	550	600	650		
$\Sigma^- p \to \Lambda n$	3.7	3.9	4.1	4.4	4.7	4.7	4.0	4.4	8.3	3.9 (4.3)
$\Sigma^- p \to \Sigma^0 n$	6.1	5.8	5.8	5.7	5.5	5.5	6.0	5.7	6.4	6.0 (5.5)
$\Sigma^- p \to \Sigma^- p$	2.0	1.8	1.9	1.9	3.0	2.9	2.2	1.9	1.6	2.3 (3.6)
$\Sigma^+ p \to \Sigma^+ p$	0.3	0.4	0.5	0.3	0.3	0.4	0.4	0.3	0.1	0.2 (0.1)
r_R	0.1	0.2	0.1	0.2	1.1	0.7	0.1	0.5	53.6	0.0 (0.9)
total χ^2	12.2	12.0	12.3	12.5	14.6	14.2	12.7	12.8	70 [16.4]	12.4 (14.4)

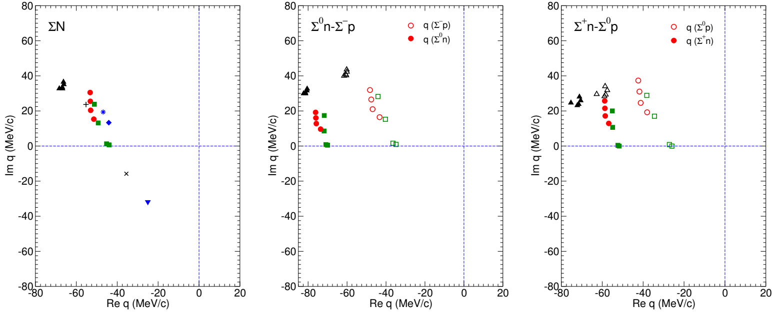
$$\left(r_R = \frac{1}{4}\,\frac{\sigma_s(\Sigma^- p \to \Sigma^0 n)}{\sigma_s(\Sigma^- p \to \Lambda n) + \sigma_s(\Sigma^- p \to \Sigma^0 n)} + \frac{3}{4}\,\frac{\sigma_t(\Sigma^- p \to \Sigma^0 n)}{\sigma_t(\Sigma^- p \to \Lambda n) + \sigma_t(\Sigma^- p \to \Sigma^0 n)} \right)$$

best description of near-threshold ΣN data: NLO13, NLO19 (600,650), NSC97a-f
$\Rightarrow \chi^2 = 12 - 13$

J.H., U.-G. Meißner, arXiv:2105.00836 $\Rightarrow$ search for ΣN poles in complex plane

Poles in the complex $q_{\Sigma N}$ plane

- 2nd quadrant (sheet II, bt): unstable bound state
- 3rd quadrant (sheet IV, tb): inelastic virtual state



● NLO13 ■ NLO19 ▲ Nijmegen NSC97b-f ▼ Jülich '04 × Nijmegen ND (1977)

NLO13: E = 2131.90 − i1.39 · · · 2131.25 − i3.01 MeV
NLO19: E = 2131.73 − i1.11 · · · 2131.35 − i0.00 MeV
NSC97: E = 2133.04 − i3.80 · · · 2133.79 − i3.53 MeV

Thresholds: $\Sigma^+ n$ (2128.97) $\Sigma^0 p$ (2130.87)

$\Rightarrow$ bound state (dibaryon) – but above threshold!

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
- $S = -1$ dibaryon: strong evidence for its existence
  – but not as ideal textbook (Breit-Wigner type) resonance

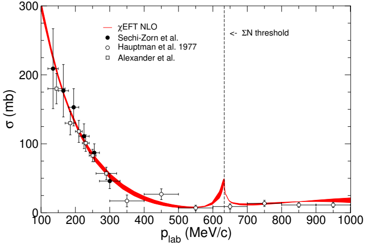
Hypernuclei

- for very light hypernuclei three-body forces should be small (${}^{3}_{\Lambda}\mathrm{H}$) or moderate (${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$)
  needs to be quantified/confirmed by explicit inclusion of 3BFs
- ${}^{5}_{\Lambda}\mathrm{He}$, etc. ... effects of three-body forces could be more significant
- Study of charge-symmetry breaking in ${}^{4}_{\Lambda}\mathrm{H} - {}^{4}_{\Lambda}\mathrm{He}$ is under way
- Λ hypernuclei - data with higher precision are needed to quantify 3BFs

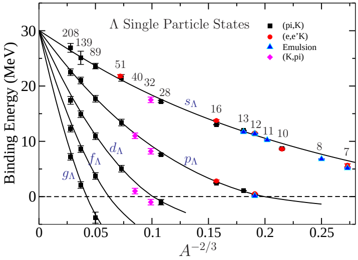
Backup slides

ΛN interaction: bulk properties are known

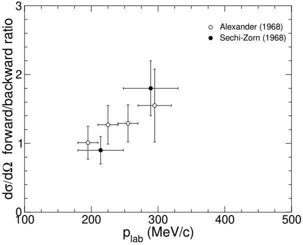
Λp cross section



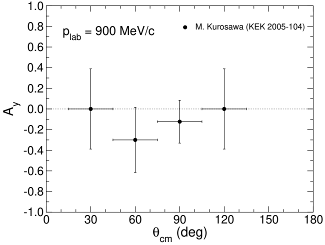
Λ hypernuclei



Λp -> Λp



Λp -> Λp



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	≈ 22	16.7	
$B(^3_\Lambda\mathrm{H})$	−2.30 ⋯ −2.33	−2.32 ⋯ −2.32	−2.27	−2.30	−2.354(50)

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

Note: $B(^3_\Lambda\mathrm{H})$ 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

(a, r in fm; B in MeV)

Λ and Σ in infinite nuclear matter

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

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

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

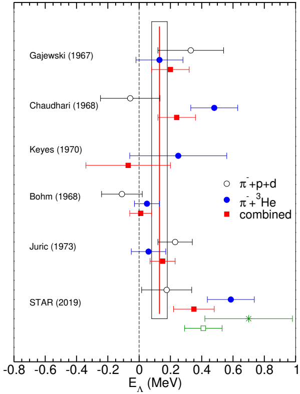
$$U_Y(p_Y) = \int_{p_N \le k_F} d^3 p_N \, \langle YN|G_{YN}(\zeta(U_Y))|YN\rangle$$

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

⇒ J.H., U.-G. Meißner, NPA 936 (2015) 29; S. Petschauer, et al., EPJA 52 (2016) 15
J.H., U.-G. Meißner, A. Nogga, EPJA 56 (2020) 91

Status - hypertriton

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



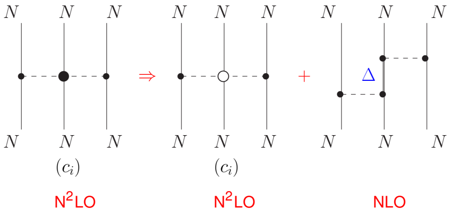
benchmark: (M. Jurič et al., 1973): 0.13 $\pm$ 0.05 MeV

STAR (J. Adam et al., Nature Phys. 16 (2020) 409) ($^3_\Lambda\mathrm{H}$+$^3_\Lambda\bar{\mathrm{H}}$): 0.41 $\pm$ 0.12 $\pm$ 0.11 MeV

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

Three-nucleon forces: Explicit inclusion of the $\Delta(1232)$

- 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 $\Delta(1232)$ appears at NLO!)
- applicability at higher energies