Status of the hyperon-nucleon interaction in chiral effective field theory

Johann Haidenbauer

IAS, Forschungszentrum Jülich, Germany

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(Hoai Le, Ulf-G. Meißner, Andreas Nogga)

Outline

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)

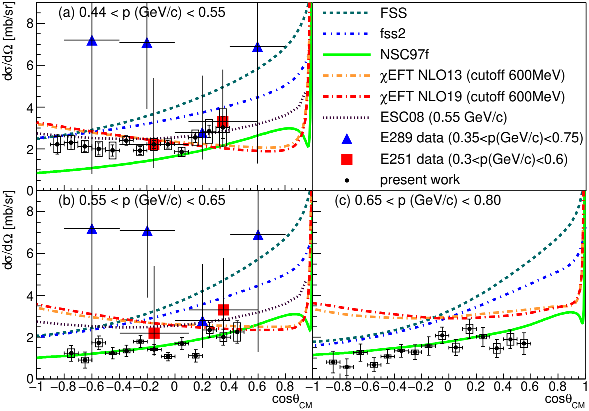
- pseudoscalar-meson exchanges
- contact terms – represent unresolved short-distance dynamics
  involve low-energy constants (LECs) that need to be fixed
  by a fit to data

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

(*BB* systems with strangeness $S = -1$ to -6)

New ΣN data from E40 Collaboration at J-PARC

$\Sigma^+ p$: T. Nanamura et al., arXiv:2203:08393



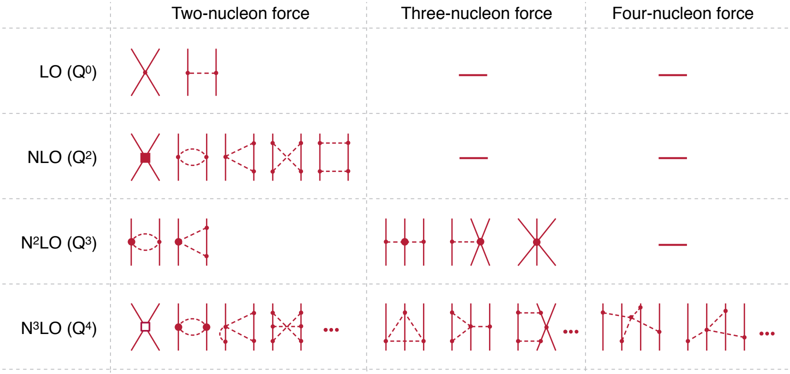
($\Sigma^- p$: K. Miwa et al., PRC 104 (2021) 045204; $\Sigma^- p \to \Lambda n$: K. Miwa et al., PRL 128 (2021) 072501)

$p_{lab} = 500$ MeV/c ($E_{lab} = 100.7$ MeV); $p_{lab} = 600$ MeV/c ($E_{lab} = 142.8$ MeV)

beyond of validity of NLO interaction?; role of higher partial waves?
($\Lambda p \pi^+$ threshold is at $p_{lab} \approx 600$ MeV/c)

Extension of chiral EFT interaction up to NNLO

(Nucleon-nucleon forces in chiral EFT (E. Epelbaum))

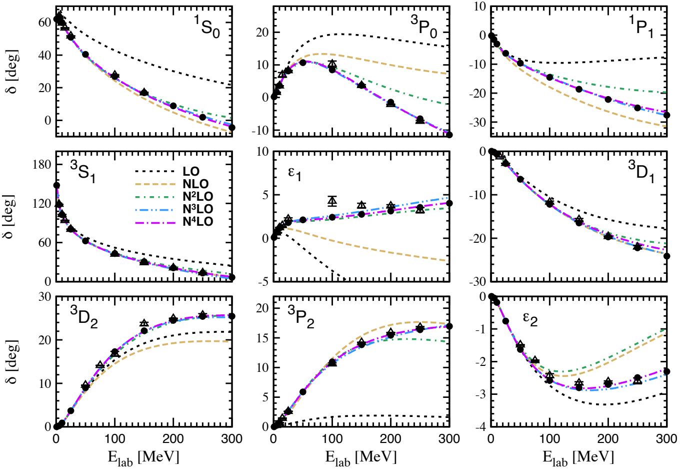


N^{2}LO: no new (additional) LECs in the two-body sector

leading-order three-body forces (3BFs)

NN interaction in chiral EFT

Semilocal momentum-space (SMS) regularized chiral *NN* potential



(Reinert, Krebs, Epelbaum, EPJA 54 (2018) 86) [up to N^{4}LO (N^{4}LO$^+$) !!]

LO to NLO: drastic change in all partial waves

NLO to N^{2}LO: changes mostly in *P*-waves and higher partial waves

chiral YN potential up to NNLO

adopt the framework of Reinert, Krebs, Epelbaum, EPJA 54 (2018) 86:

“Semilocal momentum-space regularized (SMS) chiral NN potentials”

- employ a regulator that minimizes artifacts from cutoff Λ

nonlocal cutoff $(\vec{q} = \vec{p}\,' - \vec{p})$

$$V_{1\pi}^{\mathrm{reg}} \propto \frac{e^{-\frac{p'^4+p^4}{\Lambda^4}}}{\vec{q}^{\,2}+m_\pi^2} \to \frac{1}{\vec{q}^{\,2}+m_\pi^2}\left[1 - \frac{p'^4+p^4}{\Lambda^4} + \mathcal{O}(\Lambda^{-8})\right]$$

local cutoff:

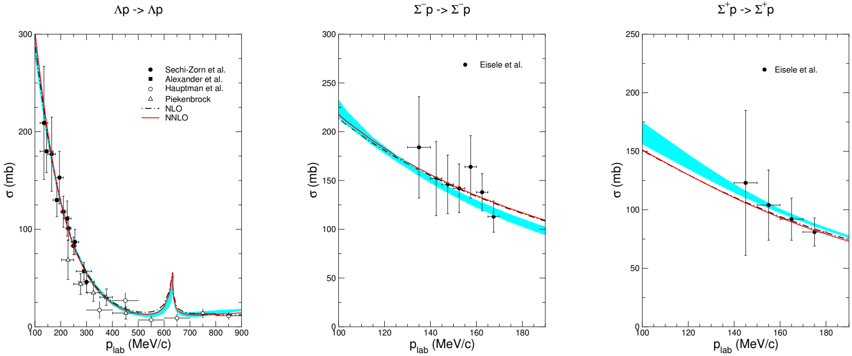
$$V_{1\pi}^{\mathrm{reg}} \propto \frac{e^{-\frac{\vec{q}^{\,2}+m_\pi^2}{\Lambda^2}}}{\vec{q}^{\,2}+m_\pi^2} \to \frac{1}{\vec{q}^{\,2}+m_\pi^2} - \frac{1}{\Lambda^2} + \frac{\vec{q}^{\,2}+m_\pi^2}{\Lambda^4} + \ldots$$

does not affect long-range physics at any order in the $1/\Lambda^2$ expansion

applicable to 2π exchange too:

$$V_{2\pi} = \frac{2}{\pi}\int_{2m_\pi}^{\infty} \mu d\mu \frac{\rho(\mu)}{\vec{q}^{\,2}+\mu^2} \to V_{2\pi}^{\mathrm{reg}} = e^{-\frac{\vec{q}^{\,2}}{2\Lambda^2}} \frac{2}{\pi}\int_{2m_\pi}^{\infty} \mu d\mu \frac{\rho(\mu)}{\vec{q}^{\,2}+\mu^2} e^{-\frac{\mu^2}{2\Lambda^2}} \quad + \ldots$$

Preliminary results for SMS chiral YN interactions

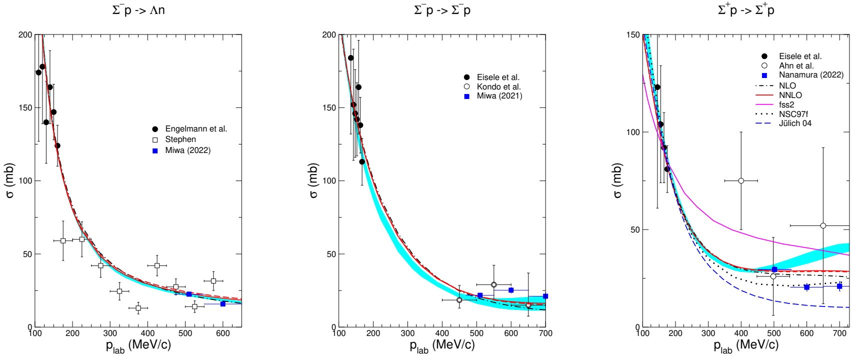


SMS YN potentials up to NLO, NNLO (with $\Lambda = 550$ MeV)
NLO19: J.H., U.-G. Meißner, A. Nogga, EPJA 56 (2020) 91

quality of the fit – total χ^2 (36 data points):
NLO19(600): 16.0 SMS NLO: 15.2 SMS NNLO: 15.6

cross sections dominated by S-waves (are already well described at NLO)
→ (as expected) practically no change when going to NNLO

Preliminary results for SMS YN interactions



integrated cross sections at higher energies not included in the fitting process!

$\Sigma^+ p \to \Sigma^+ p$ and $\Sigma^- p \to \Sigma^- p$ cross sections:

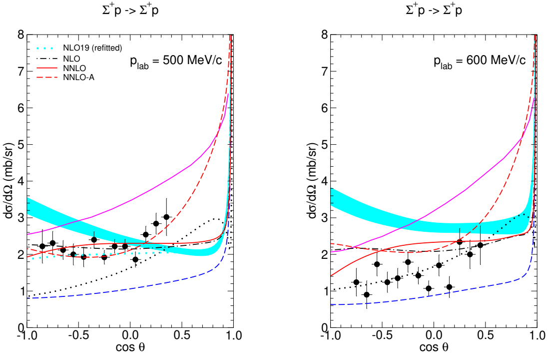
$$\sigma = \frac{2}{\cos\theta_{\max} - \cos\theta_{\min}} \int_{\cos\theta_{\min}}^{\cos\theta_{\max}} \frac{d\sigma(\theta)}{d\cos\theta} d\cos\theta$$

$\cos\theta_{\min} = -0.5;\ \cos\theta_{\max} = 0.5$

fss2 ... Fujiwara et al. (constitutent quark model) Jülich 04, Nijmegen NSC97f ... meson-exchange potentials

Preliminary results for SMS YN interactions

$\Sigma^+ p$ (T. Nanamura et al., arXiv:2203:08393)



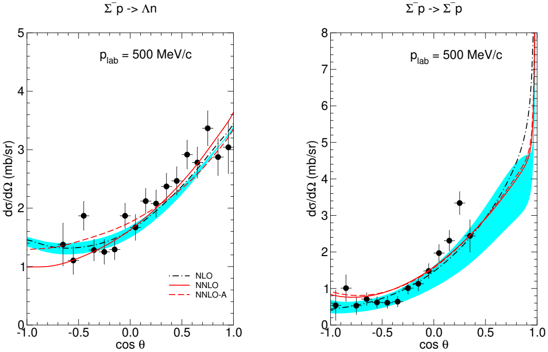
LECs in the ${}^1S_0$, ${}^3S_1$-${}^3D_1$ fixed from low-energy cross sections

SMS NLO: LECs in ${}^3P$-waves taken over from NN fit (RKE)
(strict SU(3) symmetry: $V_{NN} \equiv V_{\Sigma^+p}$ in the ${}^1S_0$, ${}^3P_{0,1,2}$ partial waves!)

SMS NNLO: LECs in P-waves fitted to the E40 data (two examples)!

data for $(550 \le p \le 650)$ MeV/c are overestimated (influence of $\Lambda p \pi^+$ threshold?)

Preliminary results for SMS YN interactions

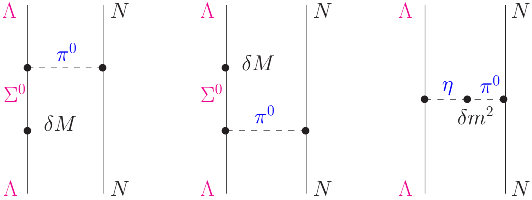


$\Sigma^- p \to \Lambda n$: quite well reproduced by NLO19 (NLO13) and SMS YN potentials
$\Sigma^- p \to \Sigma^- p$: behavior at forward angles remains unclear

$\Sigma^- p$ and $\Sigma^- p \to \Lambda n$ data for $(550 \le p \le 650)$ MeV/c are reproduced with comparable quality

- no unique determination of all P-wave LECs possible
- one needs data from additional channels (Λp, $\Sigma^- p \to \Sigma^0 n$, ...)
- one needs additional differential observables (polarizations, ...)

Charge symmetry breaking in the ΛN interaction



CSB due to $\Lambda - \Sigma^0$ mixing leads to a long-ranged contribution to the ΛN interaction

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

Strength can be estimated from the electromagnetic mass matrix:

$$\langle\Sigma^0|\delta M|\Lambda\rangle = [M_{\Sigma^0} - M_{\Sigma^+} + M_p - M_n]/\sqrt{3}$$

$$\langle\pi^0|\delta m^2|\eta\rangle = [m^2_{\pi^0} - m^2_{\pi^+} + m^2_{K^+} - m^2_{K^0}]/\sqrt{3}$$

$$f_{\Lambda\Lambda\pi} = [-2\frac{\langle\Sigma^0|\delta M|\Lambda\rangle}{M_{\Sigma^0}-M_\Lambda} + \frac{\langle\pi^0|\delta m^2|\eta\rangle}{m^2_\eta - m^2_{\pi^0}}]\, f_{\Lambda\Sigma\pi}$$

latest PDG mass values ⇒

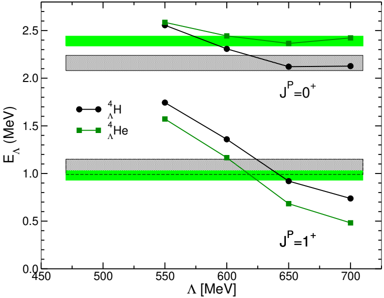
$$f_{\Lambda\Lambda\pi} \approx (-0.0297 - 0.0106)\, f_{\Lambda\Sigma\pi} \approx -0.0403\, f_{\Lambda\Sigma\pi}$$

CSB in $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He by Gazda and Gal

D. Gazda and A. Gal, NPA 954 (2016) 161: assume that

$$V^{CSB}{}_{\Lambda N\to\Lambda N} = -2\frac{\langle\Sigma^0|\delta M|\Lambda\rangle}{M_{\Sigma^0}-M_\Lambda}\tau_{N_z}\frac{1}{\sqrt{3}}\,V_{\Lambda N\to\Sigma N} \qquad \tau_{N_z} = 1(\mathrm{p});\ -1(\mathrm{n})$$

use our LO YN interaction (calculations in the no-core shell model)



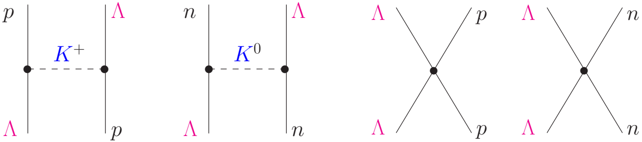
- splitting for the 1^+ state somewhat too large
- fairly strong cutoff dependence

⇒ EFT: the latter signals that something is missing!

CSB in chiral EFT

CSB (CIB) in χEFT: worked out for *pp*, *nn* (and *np*) scattering

Walzl, Meißner, Epelbaum, NPA 693 (2001) 663; Epelbaum, Glöckle, Meißner, NPA 747 (2005) 362
J. Friar et al., PRC 68 (2003) 024003
LO: Coulomb interaction, m_{π^0}-$m_{\pi^\pm}$ in OPE   NLO: isospin breaking in $f_{NN\pi}$, leading-order contact terms



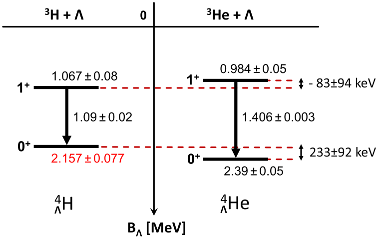
Gazda/Gal results: short-distance dynamics is relevant
→ one has to account for that by appropriate contact terms
(in line with the power counting)

NN $^1S_0$: $a_{pp} - a_{nn} \approx 1.5$ fm
mostly due to short-range forces (ρ^0-ω mixing, a_1^0-f_1 mixing)

Faddeev-Yakubovsky calculation for NLO13 and NLO19 interactions
with CSB forces including contact terms:
(J.H., U.-G. Meißner, A. Nogga, FBS 62 (2021) 105)

Charge symmetry breaking in $^4_\Lambda$H-$^4_\Lambda$He

- $\Delta E(0^+) = E^{0^+}_\Lambda(^4_\Lambda\mathrm{He}) - E^{0^+}_\Lambda(^4_\Lambda\mathrm{H})$ $= 233 \pm 92$ keV
- $\Delta E(1^+) = E^{1^+}_\Lambda(^4_\Lambda\mathrm{He}) - E^{1^+}_\Lambda(^4_\Lambda\mathrm{H})$ $= -83 \pm 94$ keV



adjust CSB contact terms to ΔE's

(Schulz et al., 2016; Yamamoto et al., 2015)

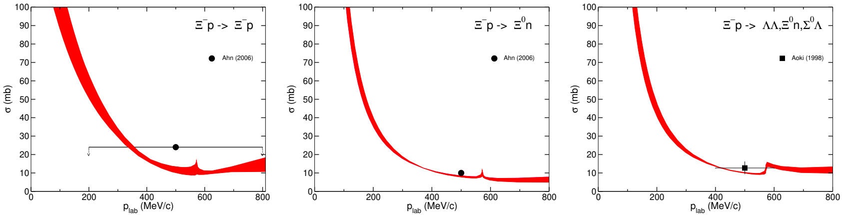
(fm // keV)	$a_s^{\Lambda p}$	$a_s^{\Lambda n}$	$a_t^{\Lambda p}$	$a_t^{\Lambda n}$	$\Delta E(0^+)$	$\Delta E(1^+)$
NLO19(500)	-2.649	-3.202	-1.580	-1.467	249	-75
NLO19(550)	-2.640	-3.205	-1.524	-1.407	252	-72
NLO19(600)	-2.632	-3.227	-1.473	-1.362	243	-67
NLO19(650)	-2.620	-3.225	-1.464	-1.365	250	-69

CSB in singlet ($^1S_0$) much larger than in triplet ($^3S_1$)
practically independent of cutoff; same results for NLO13
without CSB: $a_s^{\Lambda p} \approx a_s^{\Lambda n} \approx -2.9$ fm

- CSB in $A = 7, 8$ Λ-hypernuclei, see talk of Hoai Le

Selected results for the ΞN system

(J.K. Ahn et al., PLB 633 (2006) 214; S. Aoki et al., NPA 644 (1998) 365)



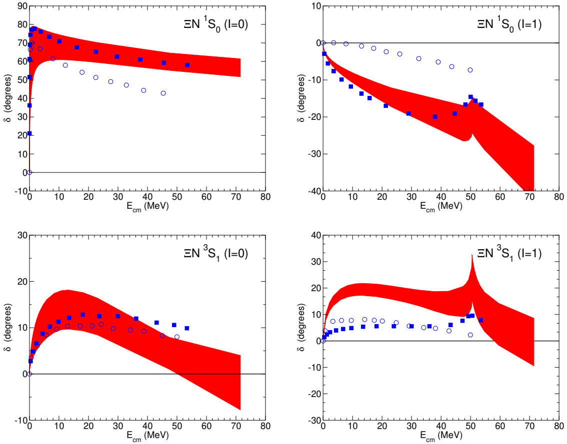
ΞN scattering lengths [in fm]:

	$I = 0,\ ^1S_0$	$I = 1,\ ^1S_0$		$I = 0,\ ^3S_1$		$I = 1,\ ^3S_1$	
potential	a_s	a_s	r_s	a_t	r_t	a_t	r_t
NLO (500)	-7.71- i 2.03	0.37	-4.80	-0.33	-6.86	-1.17	3.44
NLO (550)	-7.24- i 20.79	0.39	-4.95	-0.39	-1.77	-1.15	3.80
NLO (600)	-10.89- i 14.91	0.34	-7.20	-0.62	1.00	-1.13	3.95
NLO (650)	-8.14- i 2.43	0.31	-9.16	-0.85	1.42	-0.90	4.27

- scattering lengths $|a| \lesssim 1$ fm, except for $I = 0,\ ^1S_0$
- ΞN interaction is fairly weak

J.H., U.-G. Meißner, EPJA 58 (2019) 23

ΞN: Comparison with HAL QCD results



HAL QCD Collaboration (almost at physical point, $m_\pi \approx 145$ MeV):
open circles from E. Hiyama et al., PRL 124 (2020) 092501 (no $\Lambda\Sigma$, $\Sigma\Sigma$)
filled squares from M. Kohno & K. Miyagawa, PTEP 2021 (2021) 103D04

Nuclear matter properties

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

potential	I	$^1S_0$	$^3S_1$	S-waves	P-waves	total
NLO (500)	0	-2.6	-3.3			
	1	12.7	-11.8	-5.0	-0.4	-5.5
NLO (550)	0	-2.9	-3.1			
	1	12.4	-9.5	-3.1	-0.7	-3.8
NLO (550)*	0	-3.15	-3.24			
	1	9.64	-11.0	-7.7	-1.1	-8.8
HAL QCD	0	-3.15	-5.36			
	1	7.12	-2.41	-4.11	-	-4.11
Ehime	0	-0.80	0.47			
(1.82)	1	-1.5	-8.6	-10.43	-11.4	-21.8

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

E. Friedman & A. Gal (optical potential, PLB 820 (2021) 136555): $U_\Xi \leq -20$ MeV

Y. Tanimura et al. (relativistic mean field, PRC 105 (2022) 044324): $U_\Xi \approx -12$ MeV

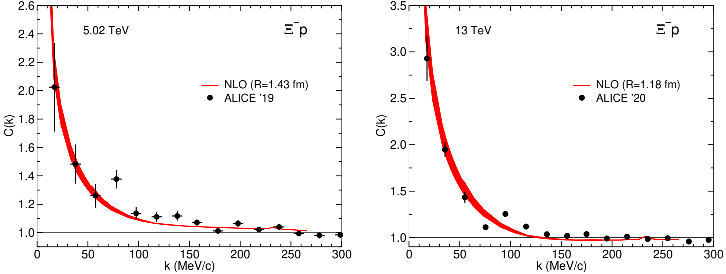
(from analyzing $^{15}_{\Xi}$C and $^{12}_{\Xi}$Be events)

NLO (550)*: M. Kohno, PRC 100 (2019) 024313 (continuous prescription)

HAL QCD: T. Inoue, AIP Conf. Proc. 2130 (2019) 020002

Ehime: M. Yamaguchi et al., PTP 105 (2001) 627

ΞN: two-particle momentum correlation functions



$$C_{\rm th}(k) = \frac{1}{4} C_{{}^1S_0}(k) + \frac{3}{4} C_{{}^3S_1}(k); \qquad C_\alpha(k) \simeq 1 + \int_0^\infty 4\pi r^2\, dr\, S_{12}(\mathbf{r}) \left[|\psi(k,r)|^2 - |j_0(kr)|^2\right]$$

$$C(k) = (a + b\,k)\,(1 + \lambda\,(C_{\rm th}(k) - 1)); \qquad S_{12}(\mathbf{r}) = \exp(-r^2/4R^2)/(2\sqrt{\pi}R)^3$$

a, b, λ, R ... additional parameters that need to be determined (→ talk of Yuki Kamiya)

ALICE Collaboration: *p*-Pb at 5.02 TeV (PRL 123 (2019) 112002) *pp* at 13 TeV (Nature 588 (2020) 232)

$R = 1.427$ fm; $\lambda = 0.513$ $R = 1.02$ fm; $\lambda = 1$

we adopt $R = 1.427$ fm & 1.18 fm, respectively
(same source radii as found in corresponding fits to *pp* correlation functions)

(J.H., U.-G. Meißner, arXiv:2201.08238)

Y. Kamiya et al., PRC 105 (2022) 014915, using HAL QCD potential: $R = 1.27$ fm & 1.05 fm
Z.-W. Liu et al., arXiv:2201.04997, cov. χEFT mimicking the HAL QCD potential: $R = 1.427$ fm & 1.182 fm

Summary

Hyperon-nucleon interaction within chiral EFT

- ΛN-ΣN interaction within semilocal momentum-space regularized chiral EFT
  confirm our previous YN results (up to NLO) based on a nonlocal regulator
  successful extension to NNLO
  new $\Sigma^{\pm}p$ differential cross sections around $p_{lab} \approx 500$ MeV/c can be described
  unique determination of the P-waves is not yet possible
- Charge symmetry breaking within chiral EFT
  regulator independent results require pertinent contact terms
  CSB splittings in ${}^{4}_{\Lambda}\mathrm{He}$-${}^{4}_{\Lambda}\mathrm{H}$ ($\Delta E(0^{+}) = 233 \pm 92$ keV; $\Delta E(1^{+}) = -83 \pm 94$ keV)
  imply $a_{\Lambda p} - a_{\Lambda n} = 0.62 \pm 0.08$ fm for ${}^{1}S_{0}$ state
  however, `hypernuclei.kph.uni-mainz.de`: 178 ± 55 keV; -139 ± 58 keV
  Elena Botta, HYP2018: 140 ± 120 keV
- ΞN interaction should be fairly weak as suggested by
  the few existing experimental constraints on the ΞN cross sections
  measurements of ΞN two-particle momentum correlations
  lattice QCD simulations close to the physical point
  light Ξ-hypernuclei ($A \geq 4$) could still exist → see talk of Hoai Le
- next step: calculate ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$, ${}^{4}_{\Lambda}\mathrm{H}$, ... with inclusion of three-body forces