

Baryon-baryon interaction from Effective Field Theory

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- 1 Introduction
- 2 YN , YY , ΞY , $\Xi\Xi$ in chiral effective field theory
- 3 LO Results
- 4 NLO Results
- 5 Summary

- seminal work

S. Weinberg, PLB 251 (1990) 288; NPB 363 (1991) 3

- first application to the NN interaction

C. Ordoñez, L. Ray, and U. van Kolck, PRC 53 (1996) 2086

- further investigations

J.L. Friar, S.A. Coon

C.A. da Rocha, R. Higa, M.R. Robilotta

N. Kaiser, R. Brockmann, S. Gerstendörfer, W. Weise

D.B. Kaplan, M.J. Savage, M.B. Wise

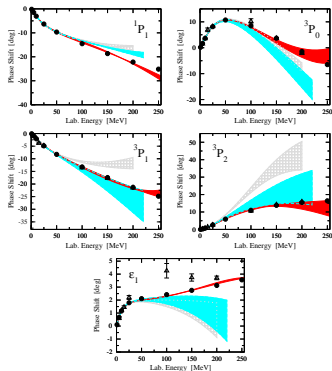
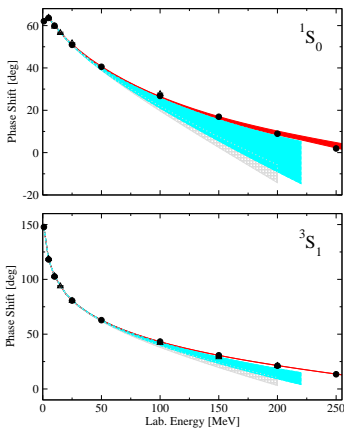
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- most advanced results (N^3LO)

D.R. Entem and R. Machleidt, PRC 68 (2003) 041001

E. Epelbaum, W. Glöckle, Ulf-G. Meißner, NPA747 (2005) 362

Chiral Effective Field Theory for the NN interaction



NLO , N^2LO , N^3LO

(E. Epelbaum, W. Glöckle, Ulf-G. Meißner, NPA747 (2005) 362)

Chiral Effective Field Theory for the NN interaction

	Two-nucleon force	Three-nucleon force	Four-nucleon force
LO		—	—
NLO		—	—
N ² LO			—
N ³ LO			

YN , YY , ΞY , $\Xi\Xi$ in chiral effective field theory

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

Obstacle: YN data base is rather poor
practically no information on YY
(\rightarrow impose $SU(3)_f$ constraints)

few investigations so far (for YN only):

- C.K. Korpa et al., PRC 65 (2001) 015208
- S.R. Beane et al., NPA747 (2005) 55

pion-less theory; Kaplan-Savage-Wise resummation scheme

We follow the scheme of E. Epelbaum et al.

(E. Epelbaum, W. Glöckle, Ulf-G. Meißner, NPA747 (2005) 362)

YN data [$S = -1$]

- about 35 data points, all from the 1960s
- 10 new data points, from the KEK-PS E251 collaboration (from ≈ 2000)
(cf. > 4000 NN data for $E_{lab} < 350$ MeV!)

YY data [$S = -2$]

- a few rough estimations of ΞN cross sections from the 1970s
- “more precise” cross sections (for $\Xi^- p$ and $\Xi^- p \rightarrow \Lambda\Lambda$) published in 2006

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

$$V_{\text{eff}} \equiv V_{\text{eff}}(Q, g, \mu) = \sum_{\nu} (Q/\Lambda)^{\nu} \mathcal{V}_{\nu}(Q/\mu, g)$$

- Q ... soft scale (baryon three-momentum, Goldstone boson four-momentum, Goldstone boson mass)
- Λ ... hard scale
- g ... pertinent low-energy constants
- μ ... regularization scale
- \mathcal{V}_{ν} ... function of order one
- $\nu \geq 0$... chiral power

Lowest order (LO): $\nu = 0$

- a) non-derivative four-baryon contact terms
- b) one-meson (Goldstone boson) exchange diagrams

Leading order (LO) contact term for NN

The LO contact term for the NN interaction:

$$\mathcal{L} = C_i (\bar{N}\Gamma_i N) (\bar{N}\Gamma_i N)$$

$$\Gamma_1 = 1, \Gamma_2 = \gamma^\mu, \Gamma_3 = \sigma^{\mu\nu}, \Gamma_4 = \gamma^\mu \gamma_5, \Gamma_5 = \gamma_5$$

Considering the large components of the nucleon spinors only, the LO contact term becomes

$$\mathcal{L} = -\frac{1}{2} C_S (\varphi_N^\dagger \varphi_N) (\varphi_N^\dagger \varphi_N) - \frac{1}{2} C_T (\varphi_N^\dagger \boldsymbol{\sigma} \varphi_N) (\varphi_N^\dagger \boldsymbol{\sigma} \varphi_N)$$

The LO contact term potential resulting from the interaction Lagrangian:

$$V^{NN \rightarrow NN} = C_S + C_T \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$

C_S and C_T ... low-energy constants; to be determined in a fit to the experimental data.

Leading order contact terms for YN and YY

spin-momentum structure of the LO contact term potential resulting from the BB interaction Lagrangian:

$$V^{BB \rightarrow BB} = C_S^{BB \rightarrow BB} + C_T^{BB \rightarrow BB} \sigma_1 \cdot \sigma_2$$

$SU(3)$ structure for scattering of two octet baryons:
direct product:

$$8 \otimes 8 = 1 \oplus 8_a \oplus 8_s \oplus 10^* \oplus 10 \oplus 27$$

There are only 6 independent low-energy constants for the BB interaction!

(8 independent spin-isospin channels in YN alone!)

C_S^i, C_T^i can be expressed by the coefficients corresponding to the $SU(3)_f$ irreducible representations:

$$C^1, C^{8_a}, C^{8_s}, C^{10^*}, C^{10}, C^{27}$$

BB contact interactions in terms of $SU(3)_f$ irreducible representations

	Channel	Isospin	V_{3S1}
$S = 0$	$NN \rightarrow NN$	0	C^{10^*}
$S = -1$	$\Lambda N \rightarrow \Lambda N$	$\frac{1}{2}$	$\frac{1}{2} (C^{8_a} + C^{10^*})$
	$\Lambda N \rightarrow \Sigma N$	$\frac{1}{2}$	$\frac{1}{2} (-C^{8_a} + C^{10^*})$
	$\Sigma N \rightarrow \Sigma N$	$\frac{1}{2}$	$\frac{1}{2} (C^{8_a} + C^{10^*})$
	$\Sigma N \rightarrow \Sigma N$	$\frac{3}{2}$	C^{10}
$S = -2$	$\Xi N \rightarrow \Xi N$	0	C^{8_a}
	$\Xi N \rightarrow \Xi N$	1	$\frac{1}{3} (C^{10} + C^{10^*} + C^{8_a})$
	$\Xi N \rightarrow \Sigma \Lambda$	1	$\frac{\sqrt{6}}{6} (C^{10} - C^{10^*})$
	$\Xi N \rightarrow \Sigma \Sigma$	1	$\frac{\sqrt{2}}{6} (C^{10} + C^{10^*} - 2C^{8_a})$
	$\Sigma \Lambda \rightarrow \Sigma \Lambda$	1	$\frac{1}{2} (C^{10} + C^{10^*})$
	$\Sigma \Lambda \rightarrow \Sigma \Sigma$	1	$\frac{\sqrt{3}}{6} (C^{10} - C^{10^*})$
	$\Sigma \Sigma \rightarrow \Sigma \Sigma$	1	$\frac{1}{6} (C^{10} + C^{10^*} + 4C^{8_a})$

	Channel	Isospin	V_{1S0}
$S = 0$	$NN \rightarrow NN$	1	C^{27}
$S = -1$	$\Lambda N \rightarrow \Lambda N$	$\frac{1}{2}$	$\frac{1}{10} (9C^{27} + C^{8_s})$
	$\Lambda N \rightarrow \Sigma N$	$\frac{1}{2}$	$\frac{3}{10} (-C^{27} + C^{8_s})$
	$\Sigma N \rightarrow \Sigma N$	$\frac{1}{2}$	$\frac{1}{10} (C^{27} + 9C^{8_s})$
	$\Sigma N \rightarrow \Sigma N$	$\frac{1}{2}$	C^{27}
$S = -2$	$\Lambda\Lambda \rightarrow \Lambda\Lambda$	0	$\frac{1}{40} (27C^{27} + 8C^{8_s} + 5C^1)$
	$\Lambda\Lambda \rightarrow \Xi N$	0	$\frac{-1}{40} (18C^{27} - 8C^{8_s} - 10C^1)$
	$\Lambda\Lambda \rightarrow \Sigma\Sigma$	0	$\frac{\sqrt{3}}{40} (-3C^{27} + 8C^{8_s} - 5C^1)$
	$\Xi N \rightarrow \Xi N$	0	$\frac{1}{40} (12C^{27} + 8C^{8_s} + 20C^1)$
	$\Xi N \rightarrow \Sigma\Sigma$	0	$\frac{\sqrt{3}}{40} (2C^{27} + 8C^{8_s} - 10C^1)$
	$\Sigma\Sigma \rightarrow \Sigma\Sigma$	0	$\frac{1}{40} (C^{27} + 24C^{8_s} + 15C^1)$
	$\Xi N \rightarrow \Xi N$	1	$\frac{1}{5} (2C^{27} + 3C^{8_s})$
	$\Xi N \rightarrow \Sigma\Lambda$	1	$\frac{\sqrt{6}}{5} (C^{27} - C^{8_s})$
	$\Sigma\Lambda \rightarrow \Sigma\Lambda$	1	$\frac{1}{5} (3C^{27} + 2C^{8_s})$
	$\Sigma\Sigma \rightarrow \Sigma\Sigma$	2	C^{27}

five contact terms for the $S = -1$ channels

one additional contact term (C^1) for the $l = 0$, $S = -2$ channels

One pseudoscalar-meson exchange

LO $SU(3)_f$ -invariant pseudoscalar-meson-baryon interaction
Lagrangian:

$$\mathcal{L} = - \left\langle \frac{g_A(1-\alpha)}{\sqrt{2}F_\pi} \bar{B} \gamma^\mu \gamma_5 \{ \partial_\mu P, B \} + \frac{g_A \alpha}{\sqrt{2}F_\pi} \bar{B} \gamma^\mu \gamma_5 [\partial_\mu P, B] \right\rangle$$

g_A is the axial-vector strength: $g_A \simeq 1.26$

F_π is the weak pion decay constant: $F_\pi = 92.4 \text{ MeV}$

$\alpha = F/(F + D)$ and $g_A = F + D$

$$P = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & \frac{-\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ -K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}$$

One pseudoscalar-meson exchange

$$\begin{aligned}
 \mathcal{L} = & -f_{NN\pi} \bar{N} \gamma^\mu \gamma_5 \boldsymbol{\tau} N \cdot \partial_\mu \boldsymbol{\pi} + i f_{\Sigma\Sigma\pi} \bar{\Sigma} \gamma^\mu \gamma_5 \boldsymbol{\Sigma} \times \boldsymbol{\Sigma} \cdot \partial_\mu \boldsymbol{\pi} \\
 & - f_{\Lambda\Sigma\pi} [\bar{\Lambda} \gamma^\mu \gamma_5 \boldsymbol{\Sigma} + \bar{\Sigma} \gamma^\mu \gamma_5 \boldsymbol{\Lambda}] \cdot \partial_\mu \boldsymbol{\pi} - f_{\Xi\Xi\pi} \bar{\Xi} \gamma^\mu \gamma_5 \boldsymbol{\tau} \Xi \cdot \partial_\mu \boldsymbol{\pi} \\
 & - f_{\Lambda NK} [\bar{N} \gamma^\mu \gamma_5 \boldsymbol{\Lambda} \partial_\mu K + \bar{\Lambda} \gamma^\mu \gamma_5 N \partial_\mu K^\dagger] \\
 & - f_{\Xi\Lambda K} [\bar{\Xi} \gamma^\mu \gamma_5 \boldsymbol{\Lambda} \partial_\mu K_c + \bar{\Lambda} \gamma^\mu \gamma_5 \Xi \partial_\mu K_c^\dagger] \\
 & - f_{\Sigma NK} [\bar{\Sigma} \cdot \gamma^\mu \gamma_5 \partial_\mu K^\dagger \boldsymbol{\tau} N + \bar{N} \gamma^\mu \gamma_5 \boldsymbol{\tau} \partial_\mu K \cdot \boldsymbol{\Sigma}] \\
 & - f_{\Sigma\Xi K} [\bar{\Sigma} \cdot \gamma^\mu \gamma_5 \partial_\mu K_c^\dagger \boldsymbol{\tau} \Xi + \bar{\Xi} \gamma^\mu \gamma_5 \boldsymbol{\tau} \partial_\mu K_c \cdot \boldsymbol{\Sigma}] - f_{NN\eta_8} \bar{N} \gamma^\mu \gamma_5 N \partial_\mu \eta \\
 & - f_{\Lambda\Lambda\eta_8} \bar{\Lambda} \gamma^\mu \gamma_5 \boldsymbol{\Lambda} \partial_\mu \eta - f_{\Sigma\Sigma\eta_8} \bar{\Sigma} \cdot \gamma^\mu \gamma_5 \boldsymbol{\Sigma} \partial_\mu \eta - f_{\Xi\Xi\eta_8} \bar{\Xi} \gamma^\mu \gamma_5 \Xi \partial_\mu \eta
 \end{aligned}$$

$$\begin{aligned}
 f_{NN\pi} &= f & f_{NN\eta_8} &= \frac{1}{\sqrt{3}}(4\alpha - 1)f & f_{\Lambda NK} &= -\frac{1}{\sqrt{3}}(1 + 2\alpha)f \\
 f_{\Xi\Xi\pi} &= -(1 - 2\alpha)f & f_{\Xi\Xi\eta_8} &= -\frac{1}{\sqrt{3}}(1 + 2\alpha)f & f_{\Xi\Lambda K} &= \frac{1}{\sqrt{3}}(4\alpha - 1)f \\
 f_{\Lambda\Sigma\pi} &= \frac{2}{\sqrt{3}}(1 - \alpha)f & f_{\Sigma\Sigma\eta_8} &= \frac{2}{\sqrt{3}}(1 - \alpha)f & f_{\Sigma NK} &= (1 - 2\alpha)f \\
 f_{\Sigma\Sigma\pi} &= 2\alpha f & f_{\Lambda\Lambda\eta_8} &= -\frac{2}{\sqrt{3}}(1 - \alpha)f & f_{\Xi\Sigma K} &= -f
 \end{aligned}$$

One pseudoscalar-meson exchange

$$V^{B_1 B_2 \rightarrow B'_1 B'_2} = -f_{B_1 B'_1 P} f_{B_2 B'_2 P} \frac{(\boldsymbol{\sigma}_1 \cdot \mathbf{k})(\boldsymbol{\sigma}_2 \cdot \mathbf{k})}{\mathbf{k}^2 + m_P^2}$$

$f_{B_1 B'_1 P}$... coupling constants;

m_P ... mass of the exchanged pseudoscalar meson.

- **SU(3) breaking** due to **the mass splitting** of the **ps** mesons ($m_\pi = 138.0$ MeV, $m_K = 495.7$ MeV, $m_\eta = 547.3$ MeV) is **taken into account**.

Details:

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

(H. Polinder, J.H., U.-G. Meißner, PLB 653 (2007) 29)

Coupled channels Lippmann-Schwinger Equation

$$T_{\rho' \rho}^{\nu' \nu, J}(p', p) = V_{\rho' \rho}^{\nu' \nu, J}(p', p) + \sum_{\rho'', \nu''} \int_0^\infty \frac{dp'' p''^2}{(2\pi)^3} V_{\rho' \rho''}^{\nu' \nu'', J}(p', p'') \frac{2\mu_{\nu''}}{p^2 - p''^2 + i\eta} T_{\rho'' \rho}^{\nu'' \nu, J}(p'', p)$$

$$\begin{aligned} \rho', \rho &= \Lambda N, \Sigma N \\ &= \Lambda \Lambda, \Sigma \Sigma, \Xi N, \Sigma \Lambda \\ &= \Xi \Lambda, \Xi \Sigma \end{aligned}$$

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

Coulomb interaction is included via the **Vincent-Phatak method**

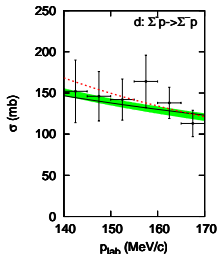
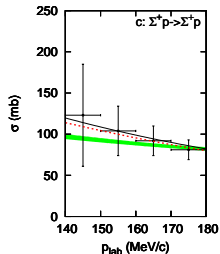
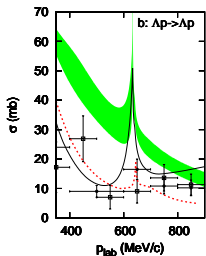
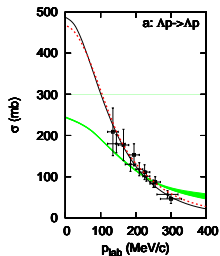
The potential in the **LS** equation is cut off with the **regulator function**:

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

consider values $\Lambda = 550 - 700$ MeV

(**No $SU(3)$ constraints** from the NN sector **are imposed!**)

γN integrated cross sections



— EFT LO
(NPA 779 (2006) 244)

— Jülich '04
(PRC 72 (2005) 044005)

— Nijmegen NSC97f
(PRC 59 (1999) 21)

ΛN effective range parameters [fm]

	EFT LO				Jülich '04	NSC97f	experiment
Λ [MeV]	550	600	650	700			
$a_s^{\Lambda p}$	-1.90	-1.91	-1.91	-1.91	-2.56	-2.51	$-1.8^{+2.3}_{-4.2}$
$r_s^{\Lambda p}$	1.44	1.40	1.36	1.35	2.75	3.03	
$a_t^{\Lambda p}$	-1.22	-1.23	-1.23	-1.23	-1.66	-1.75	$-1.6^{+1.1}_{-0.8}$
$r_t^{\Lambda p}$	2.05	2.13	2.20	2.27	2.93	3.32	
$a_s^{\Sigma^+ p}$	-2.24	-2.32	-2.36	-2.29	-4.71	-4.35	
$r_s^{\Sigma^+ p}$	3.74	3.60	3.53	3.63	3.31	3.14	
$a_t^{\Sigma^+ p}$	0.70	0.65	0.60	0.56	0.29	-0.25	
$r_t^{\Sigma^+ p}$	-2.14	-2.78	-3.55	-4.36	-11.54	-25.35	
$({}^3_\Lambda\text{H}) E_B$	-2.35	-2.34	-2.34	-2.36	-2.27	-2.30	-2.354(50)

${}^4_{\Lambda}\text{He}$ and ${}^4_{\Lambda}\text{H}$ results

Λ separation energies for ${}^4_{\Lambda}\text{H}$:

(Andreas Nogga, arXiv:nucl-th/0611081)

	EFT LO				Jülich '04	NSC97f	expt.
Λ [MeV]	550	600	650	700			
$E_{sep}(0^+)$ [MeV]	2.63	2.46	2.36	2.38	1.87	1.60	2.04
$E_{sep}(1^+)$ [MeV]	1.85	1.51	1.23	1.04	2.34	0.54	1.00
ΔE_{sep} [MeV]	0.78	0.95	1.13	1.34	-0.48	0.99	1.05
CSB- 0^+ [MeV]	0.01	0.02	0.02	0.03	-0.01	0.12	0.35
CSB- 1^+ [MeV]	-0.01	-0.01	-0.01	-0.01	—	-0.01	0.24

(CSB: $E_{sep}({}^4_{\Lambda}\text{He}) - E_{sep}({}^4_{\Lambda}\text{H})$)

\Rightarrow LO YN EFT yields a qualitative description of four-body hypernuclei

Strangeness $S=-2$ channels in the **particle** basis:

$$Q = +2: \Sigma^+\Sigma^+$$

$$Q = +1: \Xi^0 p, \Sigma^+\Lambda, \Sigma^0\Sigma^+$$

$$Q = 0: \Lambda\Lambda, \Xi^0 n, \Xi^- p, \Sigma^0\Lambda, \Sigma^0\Sigma^0, \Sigma^-\Sigma^+$$

$$Q = -1: \Xi^- n, \Sigma^-\Lambda, \Sigma^-\Sigma^0$$

$$Q = -2: \Sigma^-\Sigma^-$$

There is some **experimental information** on the $Q = 0$ channel:

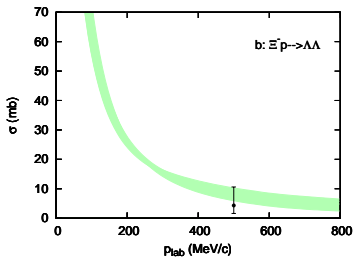
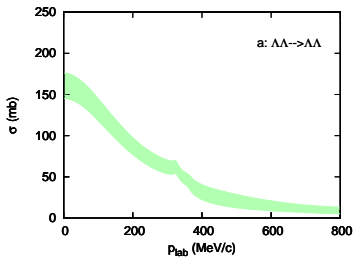
- $\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda}({}^6_{\Lambda\Lambda}\text{He}) - 2B_{\Lambda}({}^5_{\Lambda}\text{He}) = 1.01 \pm 0.20^{+0.18}_{-0.11}$ MeV

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

- $\Xi^- p$ scattering **cross section** at $p_{lab} = 500$ MeV/c

(J.K. Ahn et al., Phys. Lett. B 633 (2006) 214)

$\Upsilon\Upsilon$ integrated cross sections



cut off $\Lambda = 600$ MeV

$a_{1S_0}^\Lambda$; $r_{1S_0}^\Lambda$ [in fm]

-1.52; 0.59 EFT

(PLB 653 (2007) 29)

-1.32; 4.40 ESC04d (Rijken)

(PRC 73 (2006) 044008)

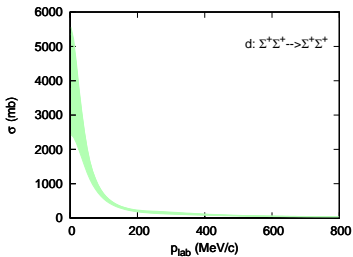
-0.81; 3.80 fss2 (Fujiwara)

(Prog. Part. Nucl. Phys. 58 (2007) 439)

$\sigma_{exp} = 4.3^{+6.3}_{-2.7}$ mb
at $p_{lab} = 500$ MeV/c

J.K. Ahn et al., 2006

$\Upsilon\Upsilon$ integrated cross sections

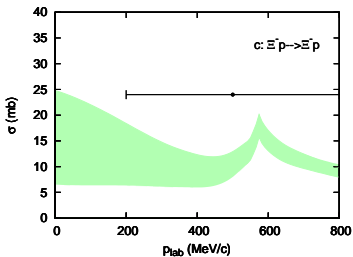


cut off $\Lambda = 600$ MeV

$a_{1S_0}^{\Sigma^+ \Sigma^+}; r_{1S_0}^{\Sigma^+ \Sigma^+}$ [in fm]

-7.76; 2.00 EFT

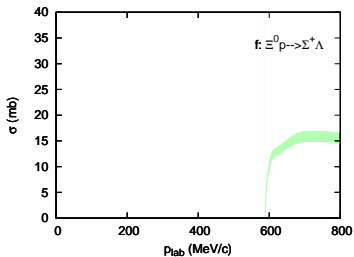
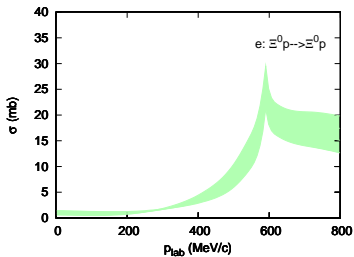
-63.7; 2.37 fss2 (Fujiwara)



$\sigma^{\text{exp}} \leq 24$ mb

J.K. Ahn et al., 2006

$\Upsilon\Upsilon$ integrated cross sections



cut off $\Lambda = 600$ MeV

$a_{1S_0}^{\Xi^0 p}; r_{1S_0}^{\Xi^0 p}$ [in fm]

0.19; -37.7 EFT

0.14; 4.67 ESC04d (Rijken)

0.33; -9.19 fss2 (Fujiwara)

$a_{3S_1}^{\Xi^0 p}; r_{3S_1}^{\Xi^0 p}$ [in fm]

-0.003; - EFT

-0.203; 27.5 fss2 (Fujiwara)

$S = -3, -4$ sector

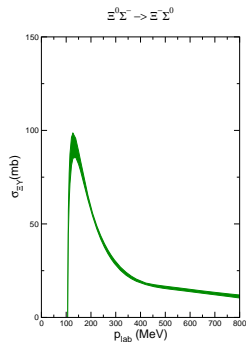
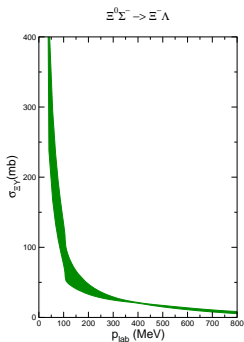
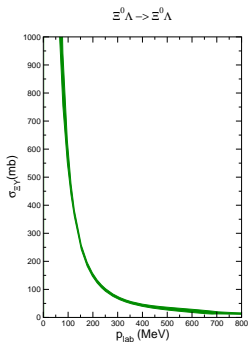
BB contact interactions in terms of $SU(3)_f$ irreducible representations

	Channel	Isospin	V_{3S1}
$S = 0$	$NN \rightarrow NN$	0	C^{10^*}
$S = -1$	$\Lambda N \rightarrow \Lambda N$	$\frac{1}{2}$	$\frac{1}{2} (C^{8_a} + C^{10^*})$
	$\Lambda N \rightarrow \Sigma N$	$\frac{1}{2}$	$\frac{1}{2} (-C^{8_a} + C^{10^*})$
	$\Sigma N \rightarrow \Sigma N$	$\frac{1}{2}$	$\frac{1}{2} (C^{8_a} + C^{10^*})$
	$\Sigma N \rightarrow \Sigma N$	$\frac{3}{2}$	C^{10}
$S = -3$	$\Xi\Lambda \rightarrow \Xi\Lambda$	$\frac{1}{2}$	$\frac{1}{2} (C^{8_a} + C^{10})$
	$\Xi\Lambda \rightarrow \Xi\Sigma$	$\frac{1}{2}$	$\frac{1}{2} (-C^{8_a} + C^{10})$
	$\Xi\Sigma \rightarrow \Xi\Sigma$	$\frac{1}{2}$	$\frac{1}{2} (C^{8_a} + C^{10})$
	$\Xi\Sigma \rightarrow \Xi\Sigma$	$\frac{3}{2}$	C^{10^*}
$S = -4$	$\Xi\Xi \rightarrow \Xi\Xi$	0	C^{10}

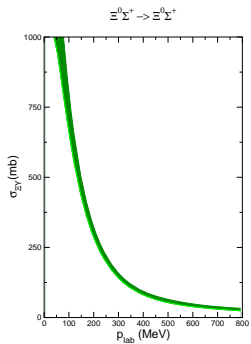
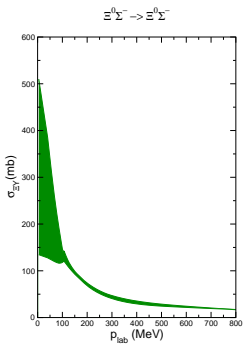
10 and 10* representations interchange their roles when going from the $S = 0, -1$ to the $S = -3, -4$ channels

$S = -3, -4$ sector

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



J.H., U.-G. Meißner, arXiv:0907.1395 [nucl-th]



$\sigma_{\Xi Y}$ [mb] at $p_{lab} = 150$ MeV/c

	EFT LO				NSC97a	NSC97f	fss2
Λ (MeV)	550	600	650	700			
$\Xi^0 \Lambda \rightarrow \Xi^0 \Lambda$	254	269	268	262	38.5	66.7	29.0
$\Xi^0 \Sigma^- \rightarrow \Xi^- \Lambda$	66.4	58.8	49.5	40.9			
$\Xi^0 \Sigma^- \rightarrow \Xi^- \Sigma^0$	82.0	83.0	85.2	89.0			
$\Xi^0 \Sigma^- \rightarrow \Xi^0 \Sigma^-$	92.8	99.0	99.0	96.8			
$\Xi^0 \Sigma^+ \rightarrow \Xi^0 \Sigma^+$	430	469	484	492	725	357	400

Note: NSC97b $\rightarrow \sigma_{\Xi^0 \Lambda \rightarrow \Xi^0 \Lambda} \approx 250$ mb

(Nijmegen: Stoks & Rijken, PRC 59 (1999) 3009)

(fss2: Fujiwara, Suzuki & Nakamoto, Prog. Part. Nucl. Phys. 58 (2007) 439)

ΞY effective range parameters [fm]

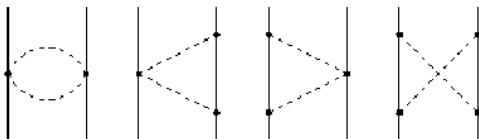
	EFT LO				NSC97a	NSC97f	fss2
Λ [MeV]	550	600	650	700			
$a_s^{\Xi\Lambda}$	-33.5	35.4	12.7	9.07	-0.80	-2.11	-1.08
$r_s^{\Xi\Lambda}$	1.00	0.93	0.87	0.84	4.71	3.21	3.55
$a_t^{\Xi\Lambda}$	0.33	0.33	0.32	0.31	0.54	0.33	0.26
$r_t^{\Xi\Lambda}$	-0.36	-0.30	-0.29	-0.27	-0.47	2.79	2.15
$a_s^{\Xi^0\Sigma^+}$	4.28	3.45	2.97	2.74	4.13	2.32	-4.63
$r_s^{\Xi^0\Sigma^+}$	0.96	0.90	0.84	0.81	1.46	1.17	2.39
$a_t^{\Xi^0\Sigma^+}$	-2.45	-3.11	-3.57	-3.89	3.21	1.71	-3.48
$r_t^{\Xi^0\Sigma^+}$	1.84	1.72	1.70	1.70	1.28	0.96	2.52

effective range parameters [fm]

	EFT LO				NSC97a	NSC97f	fss2
Λ [MeV]	550	600	650	700			
$a_s^{\Xi\Xi}$	3.92	3.16	2.71	2.47	17.81	2.38	-1.43
$r_s^{\Xi\Xi}$	0.92	0.85	0.79	0.75	1.85	1.29	3.20
$a_t^{\Xi\Xi}$	0.63	0.59	0.55	0.52	0.40	0.48	3.20
$r_t^{\Xi\Xi}$	1.04	1.05	1.08	1.11	3.45	2.80	0.22

γN interaction in NLO

- Two-pseudoscalar-meson exchange diagrams (V_{NLO}^{TBEP})
- BB contact terms with two derivatives ($V^{(2)}$)



$$\begin{aligned} V^{(2)} &= C_1 \vec{q}^2 + C_2 \vec{k}^2 + (C_3 \vec{q}^2 + C_4 \vec{k}^2)(\sigma_1 \cdot \sigma_2) \\ &+ iC_5(\sigma_1 + \sigma_2) \cdot (\vec{q} \times \vec{k}) + C_6(\vec{q} \cdot \sigma_1)(\vec{q} \cdot \sigma_2) + C_7(\vec{k} \cdot \sigma_1)(\vec{k} \cdot \sigma_2) \\ &+ iC_8(\sigma_1 - \sigma_2) \cdot (\vec{q} \times \vec{k}) \end{aligned}$$

$$V_{NLO} = V^{(2)} + V_{NLO}^{TBEP}$$

$$\vec{q} = \vec{p}' - \vec{p}; \quad \vec{k} = (\vec{p}' + \vec{p})/2$$

SU(3) symmetry

	Channel	I	$V_{1S0}, V_{3P0,3P1,3P2}$	$V_{3S1}, V_{3S1-3D1}, V_{1P1}$	$V_{1P1-3P1}$
$S = 0$	$NN \rightarrow NN$	1	C^{27}	C^{10^*}	–
$S = -1$	$\Lambda N \rightarrow \Lambda N$	$\frac{1}{2}$	$\frac{1}{10} (9C^{27} + C^{8_s})$	$\frac{1}{2} (C^{8_a} + C^{10^*})$	$\frac{-1}{\sqrt{20}} C^{8_s 8_a}$
	$\Lambda N \rightarrow \Sigma N$	$\frac{1}{2}$	$\frac{3}{10} (-C^{27} + C^{8_s})$	$\frac{1}{2} (-C^{8_a} + C^{10^*})$	$\frac{3}{\sqrt{20}} C^{8_s 8_a}$
	$\Sigma N \rightarrow \Sigma N$	$\frac{1}{2}$	$\frac{1}{10} (C^{27} + 9C^{8_s})$	$\frac{1}{2} (C^{8_a} + C^{10^*})$	$\frac{-1}{\sqrt{20}} C^{8_s 8_a}$
	$\Sigma N \rightarrow \Sigma N$	$\frac{3}{2}$	C^{27}	C^{10}	–

Number of contact terms

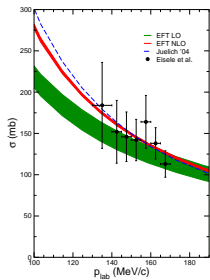
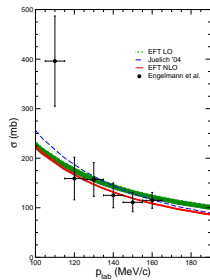
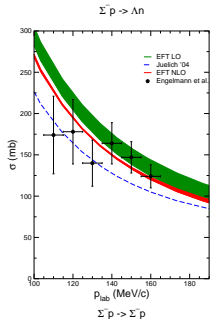
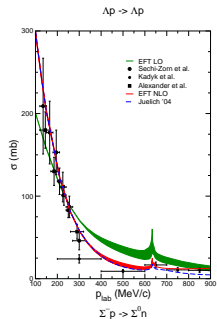
	LO		NLO	
	NN	YN	NN	YN
1S_0	1	1 + 1	1	1 + 1
3P_0	0	0	1	1 + 1
3P_1	0	0	1	1 + 1
3P_2	0	0	1	1 + 1
3S_1	1	1 + 2	1	1 + 2
$^3S_1 - ^3D_1$	0	0	1	1 + 2
1P_1	0	0	1	1 + 2
$^1P_1 - ^3P_1$	0	0	0	1
Σ	2	2 + 3	7	7 + 11

Preliminary (incomplete) NLO results

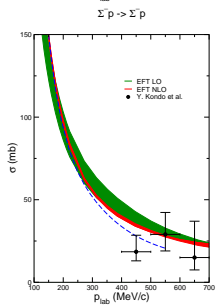
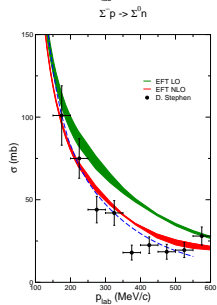
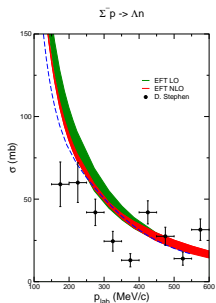
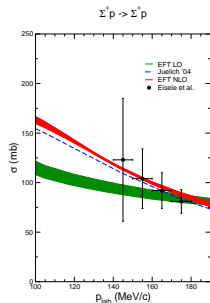
- Additional contact terms in S-waves are taken into account
 - Contact terms in P-waves are not yet included
 - Two-pseudoscalar-meson exchange diagrams are missing

 - no SU(3) constraints from the NN sector are imposed (SU(3) symmetry is used to relate ΛN and ΣN !)
 - leading order SU(3) breaking in the one-boson exchange diagrams (coupling constants) is ignored
- ⇒ S. Kazmierowski, diploma thesis

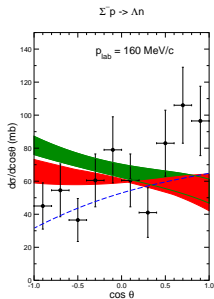
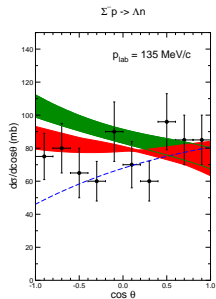
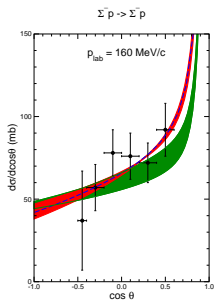
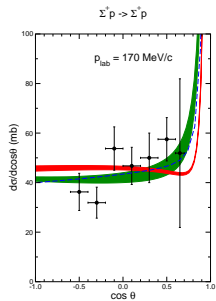
ΥN integrated cross sections



ΥN integrated cross sections



ΥN differential cross sections



ΛN effective range parameters [fm]

	EFT NLO				EFT LO	NSC97f	experiment
Λ [MeV]	550	600	650	700	550		
$a_s^{\Lambda p}$	-2.61	-2.61	-2.59	-2.63	-1.90	-2.51	$-1.8^{+2.3}_{-4.2}$
$r_s^{\Lambda p}$	2.67	2.56	2.37	2.36	1.44	3.03	
$a_t^{\Lambda p}$	-1.64	1.63	-1.62	-1.63	-1.22	-1.75	$-1.6^{+1.1}_{-0.8}$
$r_t^{\Lambda p}$	2.72	2.79	2.95	2.95	2.05	3.32	
$a_s^{\Sigma^+ p}$	-4.13	-4.11	-3.99	-3.97	-2.24	-4.35	
$r_s^{\Sigma^+ p}$	3.08	3.04	2.99	3.02	3.74	3.14	
$a_t^{\Sigma^+ p}$	-0.01	0.01	0.01	0.01	0.70	-0.25	
$r_t^{\Sigma^+ p}$	-	-	-	-	-2.14	-25.35	
χ^2	16.8	16.7	16.5	16.9	29.6	16.7	
$({}^3_\Lambda\text{H}) E_B$	-2.34	-2.34	-2.39	-2.38	-2.35	-2.30	-2.354(50)

YN , YY , ΞY , $\Xi\Xi$ interactions based on *EFT*

- approach is based on a modified **Weinberg power counting**, analogous to the NN case
- **LO** potential (**contact terms**, **one-pseudoscalar-meson exchange**) is derived imposing **$SU(3)_f$** constraints
- **Good description** of the empirical YN data was achieved (with only **5 free parameters!**)
- **Results compatible** with the sparse empirical information on the YY interaction (**1 free parameter**)

- Preliminary (incomplete) YN results in next-to-leading order (NLO) look very promising

Next tasks:

- A combined study of the NN and YN systems in chiral EFT, based on a complete NLO calculation
- A more thorough exploration of the interrelation between the elementary YN interaction and the properties of light hypernuclei
 - calculate the $YNNN$ bound states
 - consider YNN three-body forces