STATUS OF CHAPTER 4

June 22, 2025 | Christoph Hanhart | IKP/IAS Forschungszentrum Jülich

NRW-FAIR

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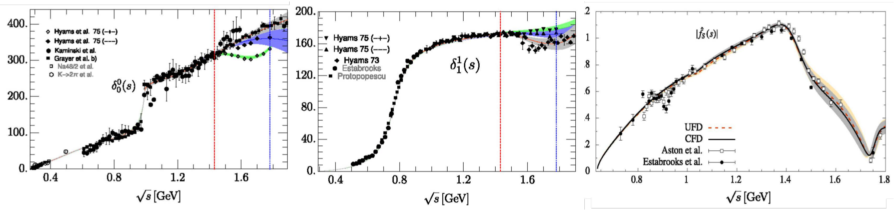
MOTIVATION - GOAL OF THE CHAPTER

- For various hadron-hadron interactions
  - present the current level of understanding
  - and why they are of interest
- Show how we get important additional insights from FAIR through
  - pion induced reactions (especially inelastic)
  - hypernuclei
  - *pp* induced production reactions in different kinematics using either
    - dispersion theory
    - femtoscopy

$\pi\pi$, πK, $\bar{K}K$ SCATTERING

R. Pelaez et al., Phys. Rept., 969(2022); EPJC79(2019)1008

$\pi\pi \to \pi\pi$ S0-wave $\quad$ $\pi\pi \to \pi\pi$ P-wave $\quad$ $K\pi \to K\pi$ $|f_S| = \left|f_0^{1/2} + f_0^{3/2}/2\right|$



- appear in the final state of many decays
- very well known for $\sqrt{s} \leq 1.4$ GeV (very sophisticated theory!+data)
- can be included systematically
- can be used to benchmark extraction strategies

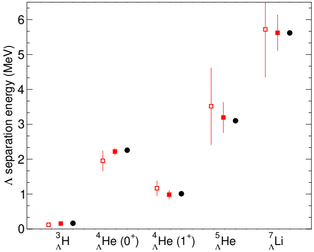
note: challenging, since scattering lengths are small

REACTIONS WITH HYPERONS

Hyperon-nucleon and hyperon-hyperon interactions needed

- to understand SU(3) in hadron-hadron dynamics
- get a deeper understanding of hypernuclei (and vice versa)
- for the structure of neutron starts (hyperon puzzle)

chiral NLO and NNLO vs. exp.

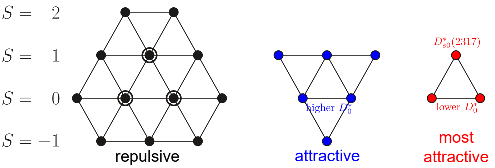


H.Le at al., PRL134 (2025) 7, 072502

$\Longrightarrow$ Hyperon-nucleon interaction dominated by $^3S_1$
$\Longrightarrow$ Hypertriton dominated by $^1S_0$
$\Longrightarrow$ Three-body forces (@NNLO, effect. 2 para) improve agreement
$\Longrightarrow$ Higher partial waves not well constrained
$\Longrightarrow$ Indication for repulsion of 3B forces for large A
$\Longrightarrow$ Hyperon-hyperon interaction largely unconstrained

REACTIONS WITH CHARM

- π, K, η D meson scattering shows intriguing SU(3) structure (e.g. two poles in πD) similar to Λ(1405)



- Various non-trivial states predicted for *DN* system (e.g. $\Lambda_c(2595)$ and the $\pi\Sigma_c$ channel)

  $\Longrightarrow$ $\pi\Sigma_c$ and *DN* scattering lengths?

- Phenomenological calculations give attractive $\Lambda_c N$ interaction with bound state formation expected— HALQCD gives repulsion

To be clarified:

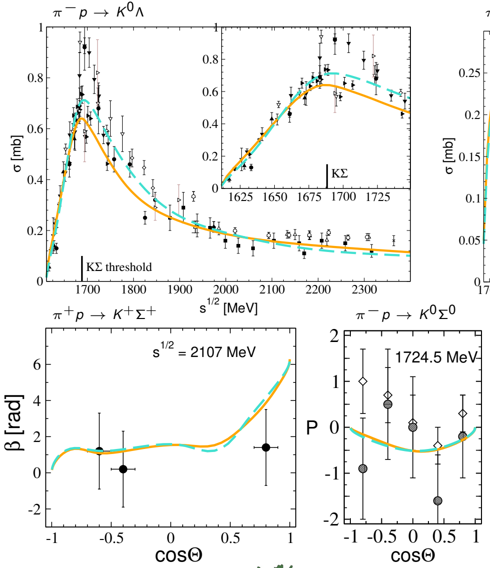
$\Longrightarrow$ How much charm physics can be done at FAIR in the near future?

$\Longrightarrow$ For which systems can we expect non-trivial result?

$\Longrightarrow$ In which chapter shall the above be discussed (in what depth)?

ON PION INDUCED REACTIONS

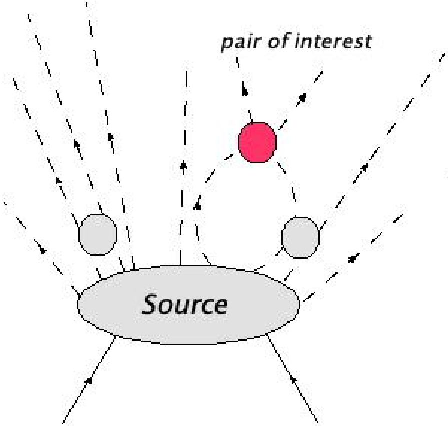
D.Rönchen et al., Eur.Phys.J.A 49 (2013) 44

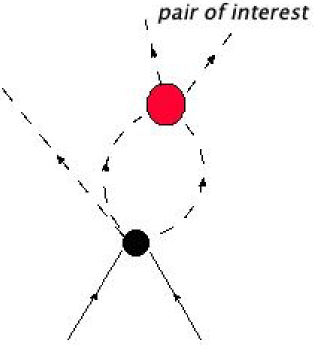


- data often inconsistent
- often no systematic uncertainties
- polarisation data scarce

$\Longrightarrow$ no unique analysis

SCATTERING PARAMETERS FROM FSI





High energies $\Longrightarrow$
high multiplicities
(near) elastic scattering

Near Threshold $\Longrightarrow$
low multiplicities
production from point source

DIFFERENT OPTIONS

Production from	
small momentum transfer (femtoscopy)	large momentum transfer (this talk)
e.g. heavy ion or *pp* collisions	e.g. meson production in *pp* coll.
weak dependence from production	sizeable dep. from production
uncertainty difficult to quantify	controllable uncertainties
spin states with known weights	admixture of spin states unknown

In any case: Two methods with very different systematics

DISPERSION INTEGRAL

For large momentum transfer reactions we find

$$A(s,t,m^2) = \exp\left[\frac{1}{\pi}\int_{m_0^2}^{\infty}\frac{\delta(m'^{\,2})}{m'^{\,2}-m^2-i0}dm'^{\,2}\right]\Phi(s,t,m^2),$$

- large momentum transfer → Φ is at most weakly m^2 dependent.

  $\Longrightarrow$ included into uncertainty estimate

- The FSI effect in terms of the (elastic) scattering phaseshift.

  $\Longrightarrow$ large m' region into uncertainty estimate

- Equation can be inverted

$$\delta_S(m^2) = -\frac{1}{2\pi}\int_{m_0^2}^{m_{max}^2}\frac{dm'^{\,2}}{m'^{\,2}-m^2}\sqrt{\frac{(m_{max}^2-m^2)(m^2-m_0^2)}{(m_{max}^2-m'^{\,2})(m'^{\,2}-m_0^2)}}\log\left\{\frac{1}{p'}\left(\frac{d^2\sigma_S}{dm'^{\,2}dt}\right)\right\}$$

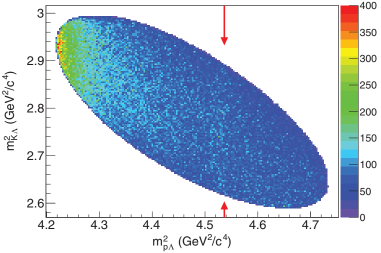
$a_{\Lambda p}$ FROM $pp \to pK\Lambda$

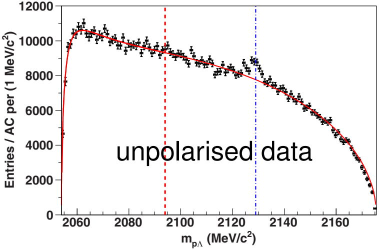
F. Hauenstein et al. [COSY-TOF], PRC95(2017)034001

S=1 and S=0 possible in final state with unknown relative weight

Unpolarised data give access only to effective scattering length $a_{\rm eff}$

Gasparyan, Haidenbauer, CH PRC72(2005)034006





Procedure: Fit $m_{p\Lambda}$ spectrum with $\exp\{C_0 + C_1/(m^2_{p\Lambda} - C_2)\}$, then

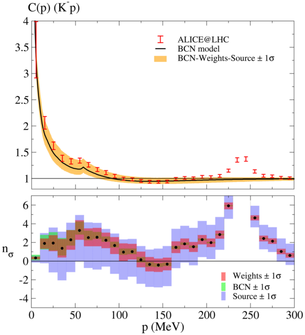
$$a_{\rm eff} = \frac{C_1}{2}\sqrt{\frac{m_0^2(m^2_{max} - m_0^2)}{m_p m_\Lambda (m^2_{max} - C_2)(m_0^2 - C_2)^3}} \Longrightarrow -1.38^{+0.04}_{-0.05\,{\rm stat.}} \pm 0.22_{\rm syst.} \pm 0.3_{\rm theo.}\ {\rm fm}$$

FEMTOSCOPY

Object studied: Pair-correlation functions (CF):

$$CF(q) = 1 + \underbrace{\int S(\vec{r})\ \left(|\Psi(q,\vec{r})|^2 - |j_0(q,r)|^2\right)\, dr^3}_{\text{theory: Koonin-Pratt-formula}} = \underbrace{\frac{Same(q)}{Mixed(q)}}_{\text{experiment}}$$

- Strong final state interactions leave significant imprints in CFs
- Many corrections need to be applied to data to access relevant piece
- Data for various systems with various sources
- Accuracy of extracted scattering parameters difficult to quantify



P. Encarnación et al., PRD111(2025) 114013

ACCURACY?

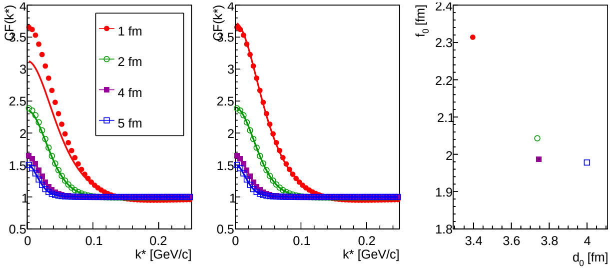
- Source function universal?
- Sensitivity to short range wave function? (strong model dependence)

E. Epelbaum, et al., arXiv:2504.08631

Lednicky-Lyuboshitz formula may address the issue

$$CF(q) = 1 + \frac{|f(q)|^2}{2R^2} F_0(d_0) + \frac{2\mathrm{Re}(f(q))}{\sqrt{\pi}R} F_1(2qR) - \frac{\mathrm{Im}(f(q))}{R} F_2(2qR) + \ldots$$

Comparison Usmani pot. vs. LL formula: $\Delta a \gtrsim 0.3$ fm??, Δd_0 unclear



Moreover: Relativistic treatment and different isospins may be necessary

For πK: M. Albaladejo, et al., PLB866(2025)139552

SUMMARY: STATUS CHAPTER 4

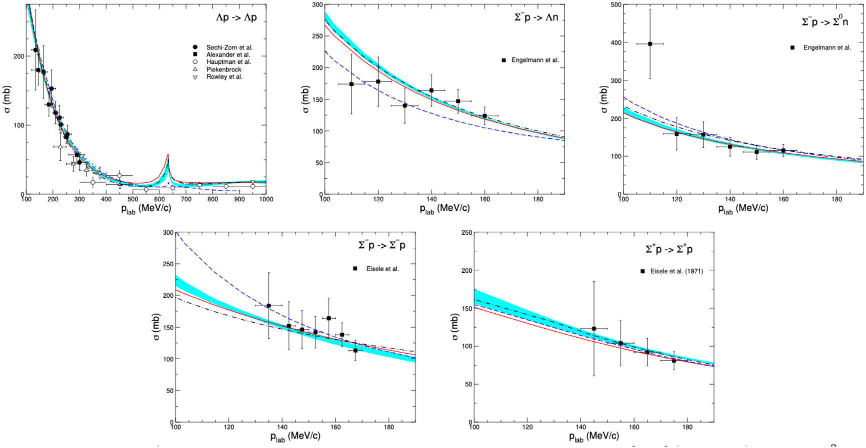
Overall: Chapter 4 is in a good shape! $\Longrightarrow$ Thanks a lot to all contributors!

- Still a lot to be learned esp. about hyperons and their interactions
- Need to discuss what can be done for charmed systems
- Pion induced reactions will help to refine e.g. hyperon-kaon interactions and the N^*/Δ^* spectrum
- Dispersive method for FSI extraction needs to be exploited further (e.g. $\Sigma^+\Sigma^+$ channel)
- Femtoscopy: Here the most still needs to be done for chapter 4
  - What is the accuracy of the extraction?
  - Can we control it parametrically?
  - Is the source really universal? πK from pp : $R = 0.4 - 0.7$ fm

    M. Albaladejo, et al., PLB866(2025)139552
  - What should be discussed in the whitepaper?

Back-up slides

HYPERON-NUCLEON INTERACTION



M.Döring et al., arxiv:2505.02745

πK FROM *pp*

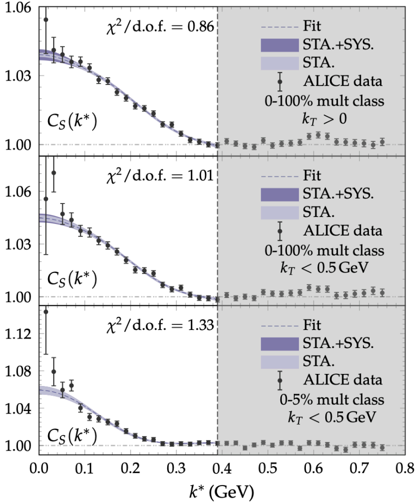


Table 1: Parameters and χ^2/d.o.f. of the fits in Fig. 1.

	0-100% m. cl. $k_T > 0$	0-100% m. cl. $k_T < 0.5$ GeV	0-5% m. cl. $k_T < 0.5$ GeV
χ^2/d.o.f.	0.86	1.01	1.33
R (fm)	0.36(3)(3)	0.41(3)(3)	0.68(5)(3)
λ	0.19(2)(4)	0.29(4)(5)	0.80(14)(13)
$(N-1)\times10^2$	0.80(8)(7)	0.85(8)(6)	0.97(6)(4)

- ALICE analysis gave different $K^*(700)$ masses per setting
- These fits consistent with πK scattering data
- Relativistic corrections sizeable
- Both isospin 1/2 and 3/2 important

For πK: M. Albaladejo, et al., PLB866(2025)139552

THREE STRATEGIES

Three different strategies to proceed:

1. Assume that phaseshifts are given by effective range expansion;
   $p' \operatorname{ctg}(\delta(m^2)) = 1/a + (1/2) r p'^{\,2}$ (sign!) $\Rightarrow$

$$A(m^2) = \frac{(p'^{\,2} + \alpha^2) r/2}{1/a + (r/2) p'^{\,2} - i p'} \Phi(m^2) \,,$$

   $\alpha = 1/r(1 + \sqrt{1 + 2r/a})$ (*Jost–function method*)

   Sibirtsev et al. (1996, 2004), Shyam et al. (2001), ...

2. Ignore numerator (*Watson method*) — Goldberger, Watson 1964

3. Invert the equation and express phaseshifts through observables — Geshkenbein (1969)
   and restrict integration range! (*Integral*) — Gasparyan et al. (2004)ff

This is the most systematic approach in line with goal

SCATTERING LENGTH

It is possible to invert the Omnes-function: Geshkenbein (1969), Gasparyan et al. (2004)

$$\delta_S(m^2) = -\frac{1}{2\pi}\int_{m_0^2}^{m_{max}^2} \frac{dm'^{\,2}}{m'^{\,2}-m^2}\sqrt{\frac{(m_{max}^2-m^2)(m^2-m_0^2)}{(m_{max}^2-m'^{\,2})(m'^{\,2}-m_0^2)}}\log\left\{\frac{1}{p'}\left(\frac{d^2\sigma_S}{dm'^{\,2}dt}\right)\right\}$$

with $\lim_{m^2\to m_0^2}\delta_S(s) = a_S p(s)$ and S denoting a specified spin state

we chose: $\epsilon_{max} = m_{max} - m_0 \simeq 1/(2\mu a^2) \approx 40$ MeV for $a \sim 1$ fm

Estimates for uncertainties: $\delta a^{(th)} = \delta a^{(lhc)} + \delta a^{m_{max}} \sim 0.3$ fm since

$$|\delta a^{m_{max}}| = \frac{2}{\pi p'_{max}}\left|\int_0^\infty \frac{\delta(y)dy}{(1+y^2)^{(3/2)}}\right| \leq \frac{2}{\pi p'_{max}}|\delta_{max}| \sim 0.2 \text{ fm}$$

$$\delta a^{(lhc)} \sim (p'_{max}/p^2) \sim 0.05 \text{ fm}$$

using $\delta_{max} = 0.4$ rad (for ΛN - see next pages) and $p' \sim 1/a$

TESTING THE METHOD

Gasparyan, Haidenbauer, CH PRC72(2005)034006

We want to test the dispersive method

$\Longrightarrow$ Can only be done if we know true parameters

Our strategy:

- Generate pseudo data for $d\sigma/dm^2$ for various models for ΛN (and NN)
- Extract scattering length.
- Compare to exact value.

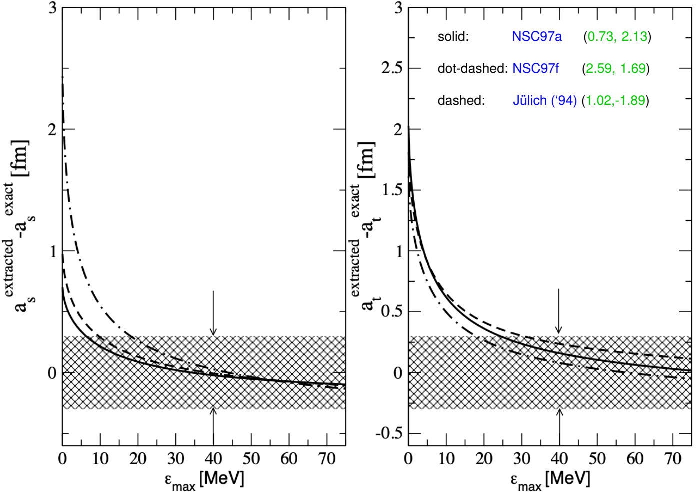
Note: any working method should work for any realistic model

We use $S = 0$ & $S = 1$ for YN from (where in green: scattering lengths in fm)

NSC97a (0.73,2.13), NSC97f (2.59,1.69), Jülich ('94) (1.02,-1.89)

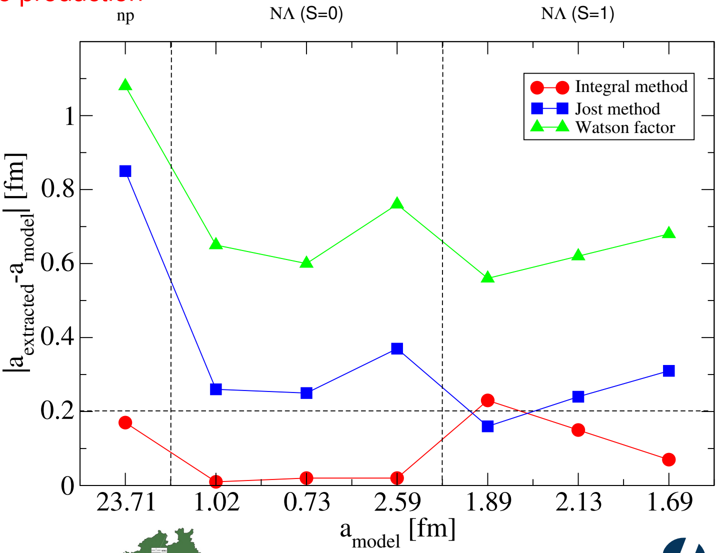
TESTING THE DISPERSIVE METHOD

Calculations for production operator with π and K exchange!



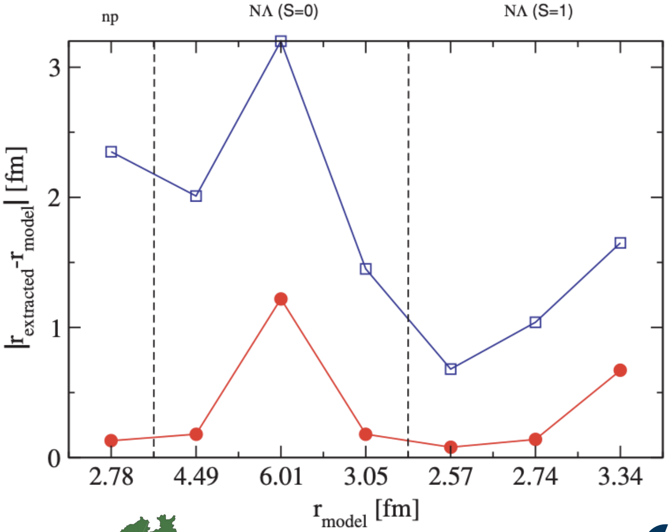
COMPARISON OF METHODS

Pointlike production



EFFECTIVE RANGE

$\Longrightarrow$ enters as $a^2((2/3)a - r_e)$

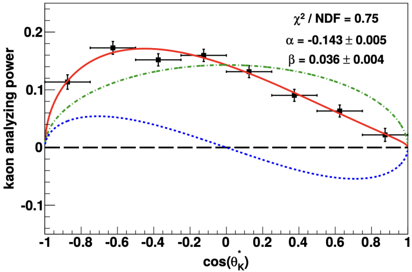


SPIN TRIPLET $a_{\Lambda p}$ FROM $\vec{p}p \to pK\Lambda$

F. Hauenstein et al. [COSY-TOF], PRC95(2017)034001

Gasparyan, Haidenbauer, CH PRC72(2005)034006

Spin=1 can be isolated from analysing power



$$A_{0y}\sigma_0 = -\frac{1}{4}k^2\beta\sin(2\theta)\cos(\phi) + \sin(\theta)\cos(\phi)(\text{spin triplet only}) ,$$

Needs for each $m_{p\Lambda}$ bin angular dist.

Procedure: Fit $m_{p\Lambda}$ spectrum with $\exp\{C_0 + C_1/(m_{p\Lambda}^2 - C_2)\}$, then

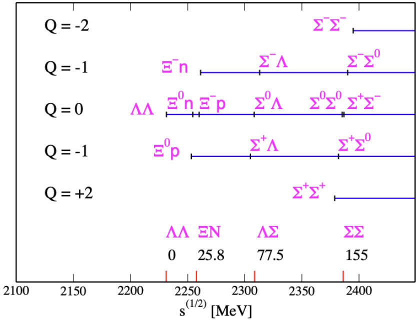
$$a_t = \frac{C_1}{2}\sqrt{\frac{m_0^2(m_{max}^2 - m_0^2)}{m_p m_\Lambda (m_{max}^2 - C_2)(m_0^2 - C_2)^3}} \Longrightarrow -2.55^{+0.72}_{-1.39}\,{}_{\mathrm{stat.}} \pm 0.6_{\mathrm{syst.}} \pm 0.3_{\mathrm{theo.}}\ \mathrm{fm}$$

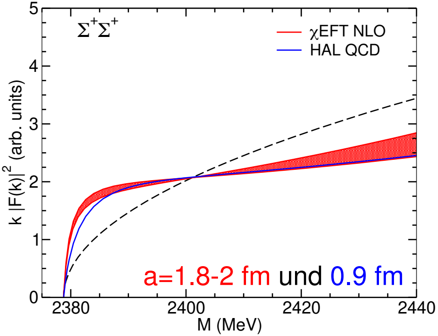
Combined analysis of femtoscopy and scattering: $-1.4 \pm 0.2 \pm 0.?_{\mathrm{theo.}}$ fm

see Mihaylov, Haidenbauer, Sarti PLB850(2024)138550

THE $S = -2$ SYSTEMS

Moving to $S = -2$





J.Haidenbauer, private communication

- Needs high statistics and high resolution
- $\Sigma^{\pm}\Sigma^{\pm}$ and $\Lambda\Lambda$ are identical fermions $\Longrightarrow$ S-wave must be spin zero

  Note: repulsive Coulomb interaction can be accounted for

  Gasparyan, CH, Haidenbauer, Phys.Rev.C 72 (2005) 034006
- Threshold difference $\Lambda\Lambda$-ΞN rather small

OPPORTUNITIES WITH PROTONS AT SIS100

The high initial energy ($\sqrt{s_{\max}} = 7.5$ GeV) promises access to

- $pp \to ppJ/\psi$ and the pJ/ψ interaction $\sqrt{s} > 5$ GeV

  $\Longrightarrow$ discovery channel of $\bar{c}c$ pentaquarks & role of $\Lambda_c D^{(*)}$ channels

- $pp \to p\Sigma_c^{(*)}\bar{D}^{(*)}$ and the $\Sigma_c^{(*)}\bar{D}^{(*)}$ interaction $\sqrt{s} > 5.6$ GeV

  $\Longrightarrow$ formation of $\bar{c}c$ pentaquarks

- $pp \to \bar{K}^0\bar{K}^0\Sigma^+\Sigma^+$ and the $\Sigma^+\Sigma^+$ interaction (S=0 only!) $\sqrt{s} > 3.4$ GeV

  $\Longrightarrow$ closely SU(3) related to pp scattering

- .... certainly many more

Note: Measurements need to be well above threshold, but not too high ...

Challenge: Needs high resolution for small relative momenta and
high statistics