πNN system at low energies

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in collaboration with E. Epelbaum, A. Filin, J. Haidenbauer, C. Hanhart, A. Kudryavtsev, V. Lensky and U.-G. Meißner

Related works: EPJA **27**, 37 (2006); PRC **80**, (2009) 044003; Phys. Lett. B **681**, (2009) 423; Phys. Lett. B **648**, 46 (2007)

Pion reactions on few nucleon systems.

- non-trivial tests of ChPT
  - * $\pi \mathrm{A} \to \pi \mathrm{A}, \gamma d \to \pi NN, \pi d \to \gamma NN, \cdots$ low-momentum transfer
  - * $NN \to NN\pi$ large-momentum transfer
- Low-energy reactions are connected by chiral symmetry

  Examples:
  - * $NN \to NN\pi$ allows for determination of LEC $(N\bar{N})^2\pi$

    $\Longrightarrow$ contributes also to

    few-body forces, weak reactions, pion photoproduction,...
  - * $NN \to NN\pi$: key to dispersive corrections to πd scattering:

    $\pi d \to NN \to \pi d$

Pion reactions on few-nucleon systems.

Tests of isospin symmetry. Extraction of fundamental two-body parameters

- πH and πd data $\Longrightarrow$ the s-wave πN scattering lengths a^+ and a^-

  V.B., C.Hanhart, M.Hoferichter, B.Kubis, A.Nogga, D.Phillips (2010)

  * High accuracy calculation of πd scattering: theoretical uncertainty $\sim$ 5%

  * Reliable only if isospin violation in πN and πNN is included!
    Martin Hoferichter talk

- CSB in $pn \to d\pi^0$ $\Longrightarrow$ strong contribution to $(m_n - m_p)^{str}$ Arseniy Filin talk

  A. Filin, V.B., E. Epelbaum, J. Haidenbauer, C. Hanhart, A. Kudryavtsev, U.-G. Meißner (2009)

Forward-backward assymetry of $\frac{d\sigma}{d\Omega}(\theta)$ in $pn \to d\pi^0$: $\quad A_{fb} \sim \frac{\mathrm{Re}\, M^{IV}_{s-wave} M^{*IC}_{p-wave}}{|M^{IC}_{s-wave}|^2}$

$M^{IV}_{s-wave} \sim (m_n - m_p)^{str}$ — $(m_d - m_u)$-induced term

CSB study is feasible only if IC $NN \to NN\pi$ is under control this talk

$pn \to d\pi^0$: Opper et al. (2003), v.Kolck et al (2000), Bolton and Miller (2009), A. Filin et al.(2009)
$dd \to \alpha\pi^0$: Stephenson et al.(2003), Gårdestig et al.(2004); Nogga et al.(2006), Fonseca et al. (2009)

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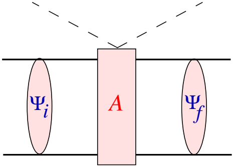
πNN system within EFT: Power counting

ChPT treatment (Weinberg 1992)

- expand the transition operator using ChPT. Include irreducible graphs only.
  - ChPT natural expansion parameter $\chi \sim \frac{q}{\Lambda_{\rm ChPT}} \sim \frac{M_\pi}{m_N}$;
  - each graph gets its chiral order according to the counting rules;
  - $A = C_0 + C_1\chi + C_2\chi^2 + \cdots +$ non-analytic terms
- convolute with the (non-perturbative) wave functions

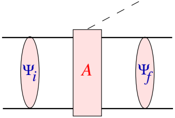


A is perturbative
$\Psi_{i/f}$ are treated non–perturbatively

– successful application to many low-momentum transfer reactions, for instance:

$\pi d \to \pi d$	many studies, see Martin Hoferichter talk
$\pi^3He \to \pi^3He$, $\pi^4He \to \pi^4He$	our works
$\gamma d \to \pi NN$	our works
$\pi d \to \gamma NN$	Gårdestig et al.
$\gamma d \to \pi^0 d$	Beane et al, Krebs et al.

$NN \to NN\pi$: Power Counting



Naive application of the Weinbergs's P.C. (with $q \sim M_\pi$) to $NN\pi \Longrightarrow$ disaster!
(Park et al. (1996), Hanhart et al. (1998))

- NLO corrections increase discrepancy with the data
- N^2LO terms are larger than those at NLO.

Modified power counting Cohen et al. (1996); Hanhart et al. (2000)

new small scale in the production operator: $p \simeq \sqrt{m_\pi M_N}$ — initial NN momentum in c.m.s

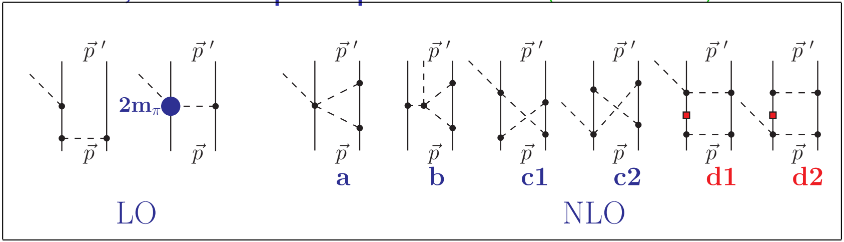
s-wave pion:

$$\chi \sim \frac{p}{M_N} \sim \sqrt{\frac{m_\pi}{M_N}}$$

p-wave pion: $k_\pi \leq m_\pi$

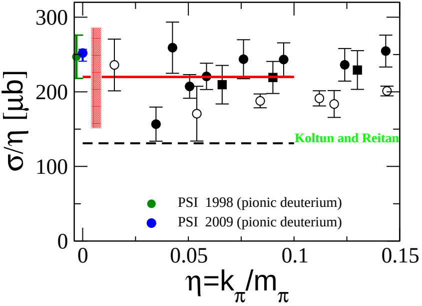
$$\chi \sim \frac{k_\pi}{p} \sim \frac{p}{M_N} \sim \sqrt{\frac{m_\pi}{M_N}}$$

$pp \to d\pi^+$, s-wave pion production (our work 2006)



NLO contribution

$$A_{d\pi^+}^{a+b+c+d1(irr)+d2(irr)} = \frac{g_A^3|\vec{q}|}{256 f_\pi^5}(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\frac{\vec{q}}{2}\left(-2+3+0-\frac{1}{4}-\frac{3}{4}\right) = 0$$

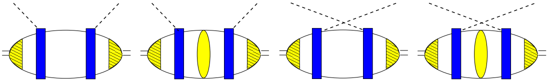


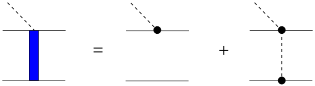
Theoretical uncertainty is $\mathcal{O}(\frac{m_\pi}{M_N}) \sim 30\%$.

$\to$ N^{2}LO calculation is necessary to reduce the uncertainty

$\to$ N^{2}LO $pp \to pp\pi^0$ in progress (our group, Kim et. al (2009))

From $NN \to NN\pi$ to dispersive corrections to $\pi d \to \pi d$





Faddeev calculations: Afnan, Thomas (1974), Koltun, Mizutani (1977)

$\longrightarrow$ only "direct" pions are included; $a_{\pi d} = -(5.6 \pm 1.4) \cdot 10^{-3} M_\pi^{-1}$

ChPT calculation: V. Lensky, V.B., J. Haidenbauer, C. Hanhart, A. Kudryavtsev, and U.-G. Meißner (2007)

$\longrightarrow$ "Direct" terms are in rough agreement with Faddeev calculations

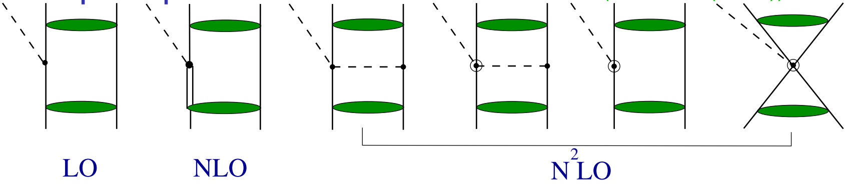
$\longrightarrow$ "crossed" terms are of similar size

$\longrightarrow$ Large cancellation of direct and crossed terms

$$a_{\pi d}^{disp} = -(2.9 \pm 1.4) \times 10^{-3}\, m_\pi^{-1} \Longrightarrow a_{\pi d}^{disp} / \mathrm{Re}\, (a_{\pi d}^{exp}) \sim 10\%$$

Important correction to achieve a 5% accuracy for πd scattering!

p-wave pion production in $NN \to NN\pi$ (our work (2009))



first calculation: $pp \to pn\pi^+$ channel Hanhart, Miller, v.Kolck (2000)

This study: different channels – $pp \to d\pi^+$, $pp \to pn\pi^+$ and $pn \to pp\pi^-$ – with the goals:

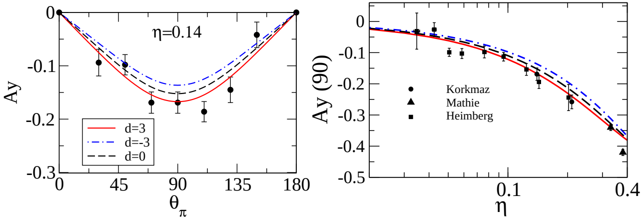
- simultaneous description with only one unknown $(N\bar{N})^2\pi$ LEC d?
- convergence of the chiral expansion?
- accurate p-wave amplitudes for CSB studies

$$\mathcal{L}^{(0)} = N^\dagger \left[\frac{g_A}{2f_\pi} \boldsymbol{\tau} \cdot \vec{\sigma} \cdot \vec{\nabla} \boldsymbol{\pi} \right] N + \frac{h_A}{2f_\pi} \left[N^\dagger (\mathrm{T} \cdot \vec{S} \cdot \vec{\nabla} \boldsymbol{\pi}) \Psi_\Delta + h.c. \right] + \cdots ,$$

$$\begin{aligned} \mathcal{L}^{(1)} &= \frac{1}{8 m_N f_\pi^2} (i N^\dagger \boldsymbol{\tau} \cdot (\boldsymbol{\pi} \times \vec{\nabla} \boldsymbol{\pi}) \cdot \vec{\nabla} N + h.c.) - \frac{1}{f_\pi^2} N^\dagger \Big[c_3 (\vec{\nabla} \boldsymbol{\pi})^2 \\ &+ \frac{1}{2} \left(c_4 + \frac{1}{4 M_N} \right) \varepsilon_{ijk} \varepsilon_{abc} \sigma_k \tau_c \partial_i \pi_a \partial_j \pi_b \Big] N - \frac{d}{f_\pi} N^\dagger (\boldsymbol{\tau} \cdot \vec{\sigma} \cdot \vec{\nabla} \boldsymbol{\pi}) N \, N^\dagger N + \cdots . \end{aligned}$$

$NN \to NN\pi$, Results (our work (2009))

$pp \to d\pi^+$



Positive $d \simeq 3$ is preferred

$NN \to NN\pi$, Results (our work (2009))

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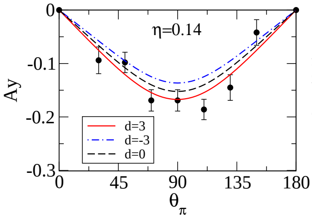
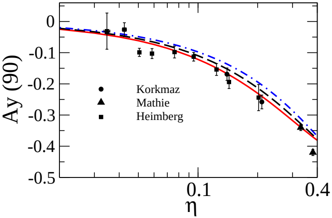
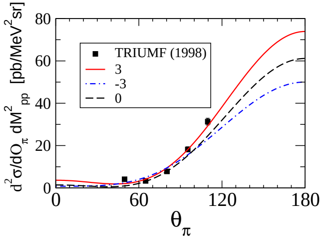
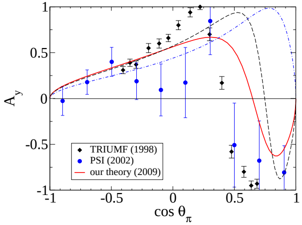




$pn \to pp\pi^-$: $T_{lab} = 353$ MeV ($\eta = 0.6$), $M_{pp} \leq 1.5$ MeV ($^3S_1$-$^3D_1$)$\to$ $^1S_0 p$



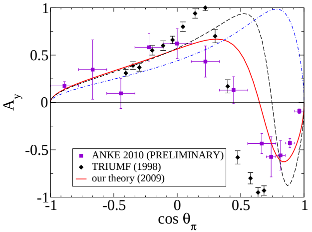


- Impact of pion d-waves needs to be understood!

Positive $d \simeq 3$ is preferred

$pn \to pp\pi^-$, Measurement at COSY

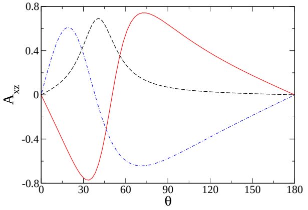
Analyzing power at Tlab $\sim$ 340-380 MeV (ANKE (2010), S.Dymov et al.: PRELIMINARY)

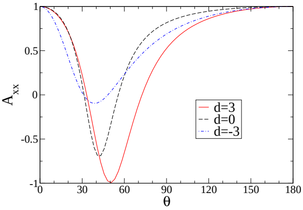


Positive $d \simeq 3$ is clearly preferred

impact of pion d-waves needs to be understood!

Double polarization observables are important to single out the relevant p-wave amplitudes





Measurement: $d\sigma/d\Omega(1 - A_{xx}) \sim |C_1 - C_2/3|^2 * \sin^2(\theta)$ – direct access to p-wave amplitudes $C_1(d)$ and $C_2(d)$. (V.B., S.Dymov, C. Hanhart, A. Kacharava, Yu. Uzikov, C. Wilkin)

$pp \to pn\pi^+$, Results (our work (2009))

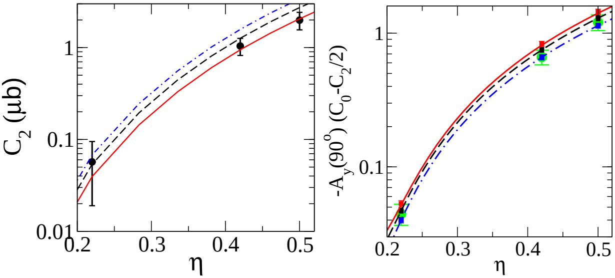
$$\frac{d\sigma}{d\Omega} = C_0 + C_2 P_2(\cos\theta) + \ldots$$

$a0$: ${}^1S_0 \to {}^3S_1 p$
$a2$: ${}^1D_2 \to {}^3S_1 p$
$a1$: ${}^3P_1 \to {}^3S_1 s$
IUCF, Flammang et al. (1998)

$$C_0 = \frac{|a_0|^2 + |a_1|^2 + |a_2|^2}{4} + C_0^{I=1},$$

$$C_2 = \frac{|a_2|^2}{4} - \frac{1}{\sqrt{2}}\mathrm{Re}[a_0 a_2^*],$$

$$A_y(90^\circ)\left(C_0 - \frac{C_2}{2}\right) = \frac{1}{4}(\sqrt{2}\mathrm{Im}[a_1 a_0^*] + \mathrm{Im}[a_1 a_2^*]).$$



- influence of Pp states needs to be understood

We can describe all channels of $NN \to NN\pi$ with the same LEC d!

Summary and Outlook

We studied different pion reactions on few nucleon systems

— $NN \to NN\pi$: s- and p-wave IC pion production is under control $\Longrightarrow$ access to

- CSB in $pn \to d\pi^0$ ($dd \to \alpha\pi^0$) and thus to the quark-mass induced neutron-proton mass difference δm^{str} Arseniy Filin talk
- dispersive corrections to $\pi d \to \pi d$.

— $\pi H \to \pi H$, $\pi d \to \pi d$, $\pi^3\mathrm{He} \to \pi^3\mathrm{He}$, ... $\Longrightarrow$ access to s-wave πN scattering: $\{a^+, a^-\}$
Inclusion of isospin violation is mandatory Martin Hoferichter talk

— $\pi^- d \to \gamma nn$ A. Gardestig and D. R. Phillips (2006)
$\gamma d \to \pi^+ nn$ V. Lensky, V. Baru, E. Epelbaum, C. Hanhart, J. Haidenbauer, A. Kudryavtsev and U.-G.Meißner (2005,2007)
$\Longrightarrow$ access to the nn scattering length and thus to CSB in NN sector

πNN system is very important to deepen our understanding of low-energy QCD