Pion reaction with few-N systems

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$NN \to NN\pi$. Motivation

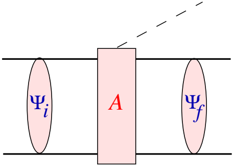
π production in *NN* collisions

- test of ChPT in the process with large momentum transfer [This talk]
- determination of LECs ($(N\bar{N})^2\pi$ contact term) [This talk]
- direct connection to few-body forces, weak processes, pion photoproduction,...
- key to dispersive corrections to πd scattering: $\pi d \to NN \to \pi d$ (our work 2007)
- accurate data are available due to *COSY; IUCF; TRIUMF, Uppsala*
- necessary for studying isospin violation (IV) – direct access to QCD parameters
  $pn \to d\pi^0$ [This talk],Opper et al. (2003), v.Kolck et al (2000), Bolton and Miller (2 days ago)
  $dd \to \alpha\pi^0$ —Stephenson et al. (2003), Gårdestig et al. (2004); Nogga et al.(2006), Fonseca et al.(3 days ago)

Power Counting

ChPT treatment (Weinberg 1992)

- expand the transition operator:
- convolute with the (non-perturbative) wave functions



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

Relevant scales in the production operator A

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

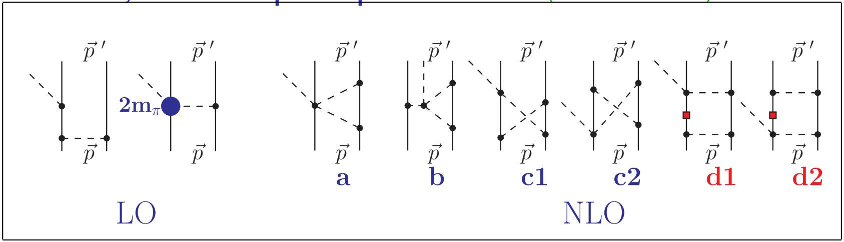
s-wave pion: Cohen et al. (1996); Hanhart et al. (2000)

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

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

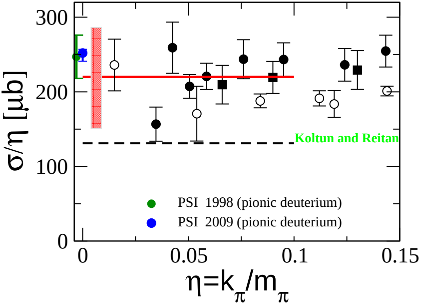
$$\chi \sim \frac{k_\pi}{p} \sim \frac{p}{M_N} \sim \sqrt{\frac{m_\pi}{M_N}}$$

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



NLO contribution

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

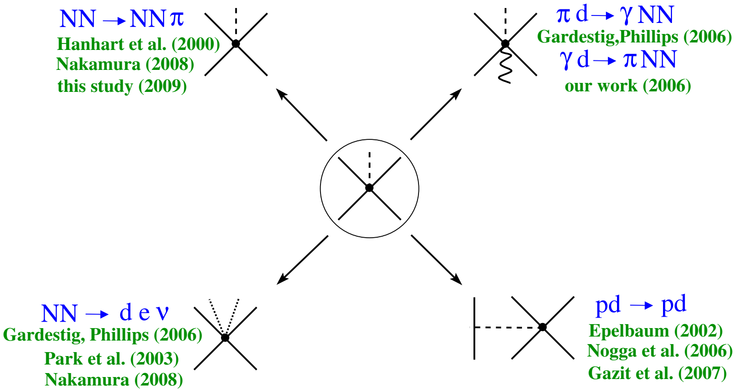


Theoretical uncertainty is $\mathcal{O}(\frac{m_\pi}{M_N}) \sim 25-30\%$.

$\to$ N^2LO calculation is necessary to reduce the uncertainty – important for IV.

$\to$ N^2LO $pp \to pp\pi^0$

$(N\bar{N})^2\pi$ LEC

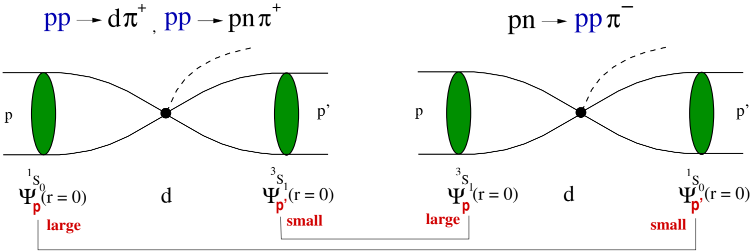


Low-momentum transfer: $NN \to de\nu, \pi d \to \gamma NN, \gamma d \to \pi NN, pd \to pd, \ldots$
Large-momentum transfer: $NN \to NN\pi$

Nakamura (2008): $pp \to de^+\nu, pp \to pn\pi^+$

Conclusion: failure of simultaneous description

$(N\bar{N})^2\pi$ LEC d in $NN \to NN\pi$



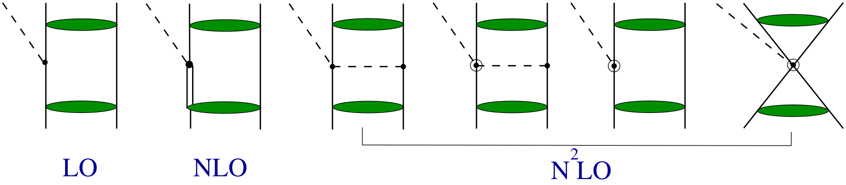
Description with the same LEC d – non–trivial test of consistency

Why do we expect this to work?

$$\Psi_q(r=0) = \left(1 + M_N \int_0^\infty d^3p \frac{T(p,q,q)}{q^2 - p^2 + i0}\right) = \mathrm{C}\exp\left\{\frac{1}{\pi}\int_{4m_N^2}^{\infty} ds' \frac{\delta_{NN}(s')}{s' - s(q) + i0}\right\}$$

- energy dependence of $\Psi_q(0)$ – model independent
- C –model dependent
- $C_{^1S_0}$ and $C_{^3S_1}$ are absorbed in d

p-wave pion production mechanism



d: ${}^1S_0 \to {}^3S_1 p$ in $pp \to pn\pi^+/d\pi^+$
d: ${}^3S_1 \to {}^1S_0 p$ in $pn \to pp\pi^-$

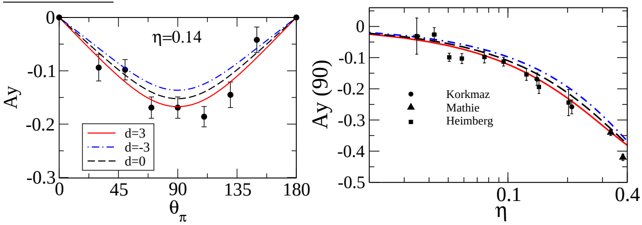
- d=d(Λ) – depends on the regularization scheme and type of NN interaction
- d absorbs the short-range part of the production operator

$$A_{c_i} \sim \left(\frac{c_3}{2} + c_4 + \frac{1}{4M_N}\right) \frac{(\vec{p}-\vec{p}\,')^2}{(\vec{p}-\vec{p}\,')^2 + m_\pi^2} \to const + O(N^4LO)$$

LEC d avsorbs A_{c_i}

$NN \rightarrow NN\pi$, Results

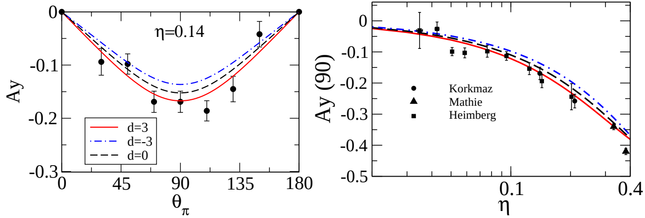
$pp \rightarrow d\pi^+$



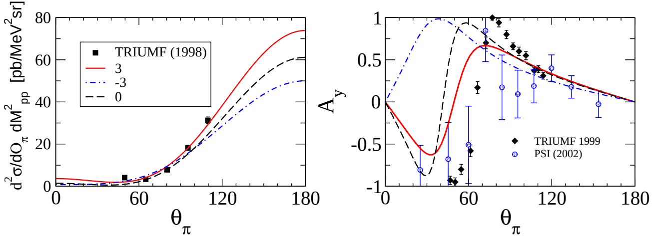
Positive $d \simeq 3$ is clearly preferred

$NN \rightarrow NN\pi$, Results

$pp \rightarrow d\pi^+$



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



New measurement of $pn \rightarrow pp\pi^-$ at low energies (ANKE at COSY 2009)

Positive $d \simeq 3$ is clearly preferred

$pp \to pn\pi^+$, Results

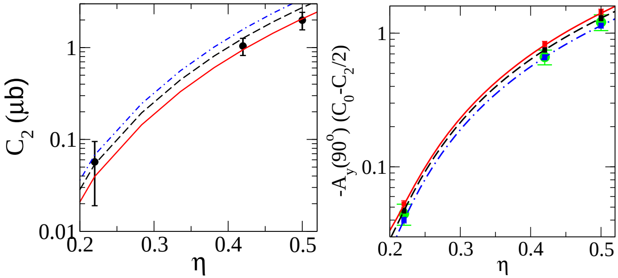
$a0: {}^1S_0 \to {}^3S_1 p$
$a2: {}^1D_2 \to {}^3S_1 p$
$a1: {}^3P_1 \to {}^3S_1 s$
IUCF, Flammang et al. (1998)

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

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

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

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



- Again positive $d \simeq 3$ is preferred
- influence of Pp states needs to be understood

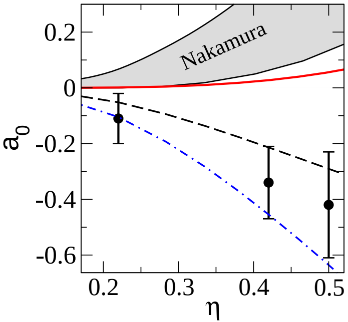
$pp \to pn\pi^+$, Partial wave analysis Flammang et al (1998)

Drawbacks of PWA

- old $pp \to pp\pi^0$ data were used to extract $C_0^{I=1}$. New data (COSY 2003) are 50% larger!
- $C_0^{I=1}$ is not corrected for the difference between pp and pn interactions at low energies: $a_{pp} \simeq 7.8$ fm $\ll a_{pn} \simeq 23.7$ fm
  Integrated ratio of the Jost functions:

$$R = \frac{\int d\tau_3 |F_{pn}(p)|^2}{\int d\tau_3 |F_{pp}(p)|^2} \simeq 1.5 \qquad \text{for } \eta = 0.22$$

- No Pp states



Nakamura's result: failure of bridging programm between pp fusion and $NN\pi$

Conclusion is based on wrong PWA!

$NN \to NN\pi$, Isospin Conserving part. Conclusion

s-wave production.

- NLO calculation gets a bulk of data
- N^2LO is needed to reduce the uncertainty in $pp \to d\pi^+$ and understand $pp \to pp\pi^0$ (Myhrer et al. (2008))

p-wave production, N^2LO calculation

- stydying different channels of $NN\pi$ simultaneousely – non-trivial test for LEC $(N\bar{N})^2\pi$ in different kinematical regimes
- consistent description of all channels with the same LEC is possible!
- we think all reactions with different kinematics connected by $(N\bar{N})^2\pi$ counter term can be described consistently

Future plans

$NN \to NN\pi + pp \to de^+\nu + \cdots$ within the same framework

CSB effects in $pn \to d\pi^0$

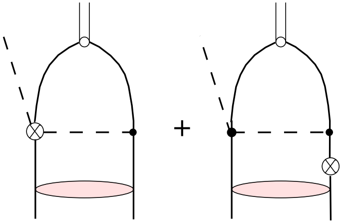
$$\frac{d\sigma}{d\Omega}(\theta) = C_0 + C_1 P_1(\cos\theta) + C_2 P_2(\cos\theta) + \ldots \qquad \frac{d\sigma}{d\Omega}(\theta) \neq \frac{d\sigma}{d\Omega}(\pi - \theta)$$

experiment: $A_{fb} = (17.2 \pm 8 \pm 5.5)10^{-4}$ (Opper, TRIUMF (2003))

theory: (v.Kolck et al. (2000), Bolton, Miller (2009))

- not complete LO calculation
- strong overestimation of the data: $A_{fb} = (50 \pm 10)10^{-4}$ (Miller et al (2006))

our study: (Filin et al., (2009)) – complete LO (not complete N^{2}LO calculation).



$$+ \quad \sim \left(\delta M_{qm} - \frac{\delta M_{em}}{2}\right) + \frac{\delta M_{qm} + \delta M_{em}}{2} \to \delta M_{qm}$$ can be extracted!

$A_{fb} = (19 \pm 10)10^{-4}$ (current study), but still complete N^{2}LO is nesessary