Pion production in nucleon-nucleon collisions at low energies: status and perspectives

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

$NN \to NN\pi$. Motivation

Study of π production in *NN* collisions:

- test of ChPT in the process with large momentum transfer
- allows for determination of LECs ($(N\bar{N})^2\pi$ contact term)
  $\Longrightarrow$ direct connection to other low-energy processes
- key to dispersive corrections to πd scattering: $\pi d \to NN \to \pi d$ (our work 2007)
  $\Longrightarrow$ extraction of s-wave πN scattering lengths from data on $\pi^- p$ and $\pi^- d$ atoms (V.B., C.Hanhart, M.Hoferichter, B.Kubis, A.Nogga, D.Phillips (2010))
- accurate data are available due to *COSY; IUCF; TRIUMF, Uppsala*

Isospin Conserving π-production: necessary for studying isospin violation (IV)

$pn \to d\pi^0$: 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)

CSB effects and neutron-proton mass difference

$$\delta m_N = m_n - m_p = \delta m_N^{str} + \delta m_N^{em} = 1.29 \text{ MeV}$$

δm_N^{str} and δm_N^{em} contribute to different low-energy reactions

Possibilities to determine δm_N^{str} and δm_N^{em} :

- Cottingham sum rule – provides an electromagnetic contribution to the nucleon self mass: $\delta m_N^{em} = (-0.7 \pm 0.3)$ MeV $\Longrightarrow$ $\delta m_N^{str} = (2.0 \pm 0.3)$ MeV (Gasser, Leutwyler (1982))
- Weinberg's idea (1977): large CSB effects in π^0 processes, e.g., $a_{\pi^0 p} - a_{\pi^0 n}$

$$a_{\pi^0 p} - a_{\pi^0 n} = -\frac{1}{4\pi(1 + M_\pi/m_N)f_\pi^2}\delta m_N^{str} + O(q^4)$$ (Meißner, Steininger (1998))

  However, experimentally very difficult, if possible!

- Forward-backward assymetry in $pn \to d\pi^0$ can serve to pin down δm_N^{str} and δm_N^{em} (v.Kolck, Miller, Niskanen (2000))
- $dd \to \alpha\pi^0$ (Stephenson et al., Gårdestig et al.; Nogga et al., Fonseca et al.)
- lattice calculations (Beane et al. (2007))

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

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

$$A_{fb} = \frac{\int_0^{\pi/2} \left(\frac{d\sigma}{d\Omega}(\theta) - \frac{d\sigma}{d\Omega}(\pi-\theta)\right) \sin\theta d\theta}{\int_0^{\pi/2} \left(\frac{d\sigma}{d\Omega}(\theta) + \frac{d\sigma}{d\Omega}(\pi-\theta)\right) \sin\theta d\theta} = \frac{C_1}{2C_0}$$

experiment: (Opper et al., TRIUMF (2003))

measurement at $T_{lab} = 279.5$ MeV (threshold $T_{lab} = 275.1$ MeV), $\eta = k_\pi / M_\pi = 0.17$

$$A_{fb} = (17.2 \pm 8 \pm 5.5)10^{-4}$$

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

$$A_{fb} = \frac{C_1}{2C_0}$$

Near threshold regime ($\eta = 0.17$) $\Longrightarrow$ s- and p-wave pion productions only:

IC	IV
$^3P_1 \to {}^3S_1 s$	$^1P_1 \to {}^3S_1 s$
$^1S_0 \to {}^3S_1 p$	$^3S_1 \to {}^3S_1 p$
$^1D_2 \to {}^3S_1 p$	$^3D_1 \to {}^3S_1 p$
	$^3D_2 \to {}^3S_1 p$

$$\mathcal{M}_{pn \to d\pi^0} = M^{\mathrm{IC,s}}[\vec{S} \times \vec{n}]\vec{\varepsilon}_d + M^{\mathrm{IC,p}}_{^1S_0}(\hat{k}_\pi \vec{\varepsilon}_d) + M^{\mathrm{IC,p}}_{^1D_2}\left[(\vec{n}\hat{k}_\pi)(\vec{n}\vec{\varepsilon}_d) - \frac{1}{3}(\hat{k}_\pi \vec{\varepsilon}_d)\right] + M^{\mathrm{IV}}_s(\vec{n}\vec{\varepsilon}_d) + \cdots$$

theory:

$$C_1 \sim \mathrm{Re}\, \mathrm{M}^{\mathrm{IV}}_{\mathrm{s-wave}} \mathrm{M}^{*\mathrm{IC}}_{\mathrm{p-wave}} + \mathrm{Re}\, \mathrm{M}^{\mathrm{IV}}_{\mathrm{p-wave}} \mathrm{M}^{*\mathrm{IC}}_{\mathrm{s-wave}}$$

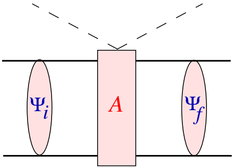
LO... N^{2}LO...

C_0 – total cross section, basically $^3P_1 \to {}^3S_1 s$

Pion reactions on few-nucleon systems

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

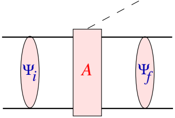


A is perturbative
$\Psi_{i/f}$ are treated non–perturbatively

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

$\pi d \to \pi d$	Weinberg, Gasser et al, Beane et al, Meißner et al, our works
$\pi^3He \to \pi^3He$, $\pi^4He \to \pi^4He$	our works
$\gamma d \to \pi NN$	our works
$\pi d \to \gamma NN$	Gårdestig and Phillips
$\gamma d \to \pi^0 d$	Beane et al, Krebs et al.

Power Counting, $NN \to NN\pi$



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

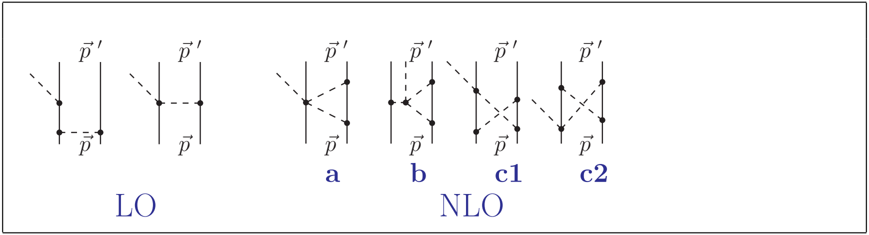
s-wave pion:

$$\chi \sim \frac{p}{m_N} \sim \sqrt{\frac{M_\pi}{m_N}}$$

p-wave pion: $k_\pi \le M_\pi$

$$\chi \sim \frac{k_\pi}{p} \sim \frac{p}{m_N} \sim \sqrt{\frac{M_\pi}{m_N}}$$

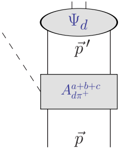
s-wave pion production up to NLO



NLO contribution Hanhart, Kaiser (2002)

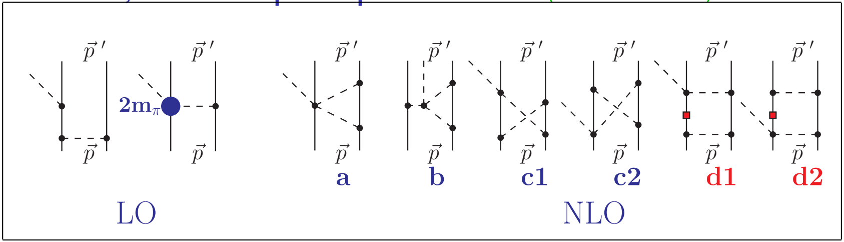
$$pp \to d\pi^+: \qquad A^{\mathrm{a+b+c}}_{d\pi^+} = \frac{g_A^3|\vec{q}|}{256 f_\pi^5}(\vec{\sigma}_1 + \vec{\sigma}_2)\cdot\frac{\vec{q}}{2}, \qquad \vec{q} = \vec{p} - \vec{p}'$$

$$pp \to pp\pi^0: \qquad A^{\mathrm{a+b+c}}_{pp\pi^0} = 0$$



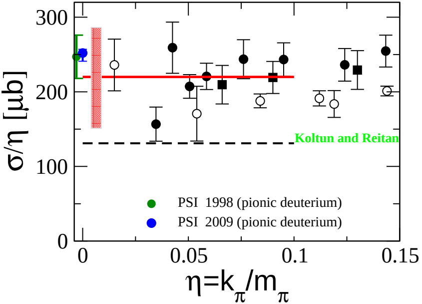
growing operator $\Longrightarrow$ large sensitivity to the *NN* w. f.
Gårdestig, Phillips, Elster (2005)

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



NLO contribution

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

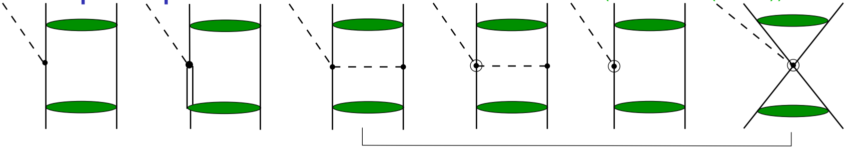


Theoretical uncertainty is $\mathcal{O}(\frac{m_\pi}{m_N}) \sim 30\%$.

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

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

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



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

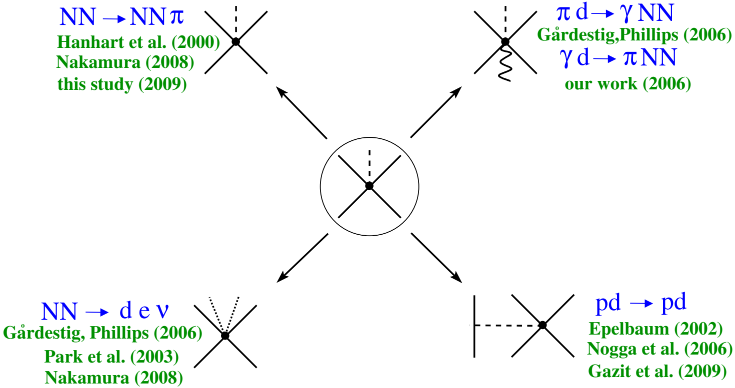
Our goals: to study different channels: $pp \to d\pi^+$, $pp \to pn\pi^+$ and $pn \to pp\pi^-$

- to see if it is possible to describe them simultaneousely with only one unknown $(N\bar{N})^2\pi$ LEC d
- to investigate convergence of the chiral expansion
- to obtain accurate p-wave amplitudes necessary for CSB studies

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

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

p-wave pion production and $(N\bar{N})^2\pi$ LEC

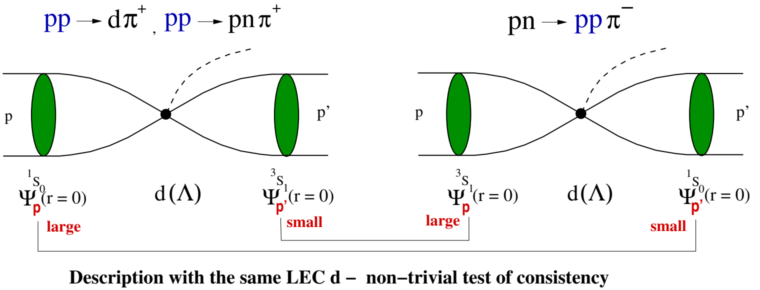


Low-momentum transfer: $NN \to de\nu, \mu d \to \nu_\mu NN, \pi d \to \gamma NN, \gamma d \to \pi NN, pd \to pd, \ldots$
Large-momentum transfer: $NN \to NN\pi$

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

Conclusion: failure of simultaneous description

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

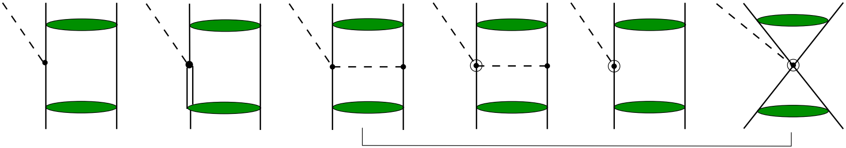


Why do we expect this to work?

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

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

p-wave pion production mechanism



d: ${}^1S_0 \rightarrow {}^3S_1 p$ in $pp \rightarrow pn\pi^+/d\pi^+$
d: $({}^3D_1 - {}^3S_1) \rightarrow {}^1S_0 p$ in $pn \rightarrow pp\pi^-$

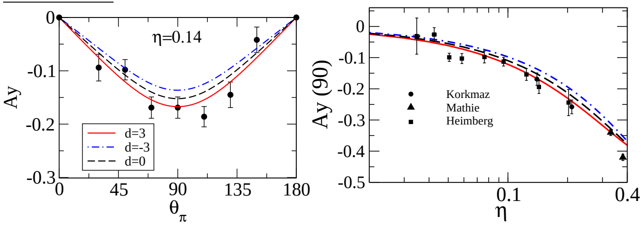
- d=d(Λ) – depends on the regularization scheme and type of NN interaction
- d absorbs the short-range part of the production operator

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

LEC d absorbs A_{c_i}

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

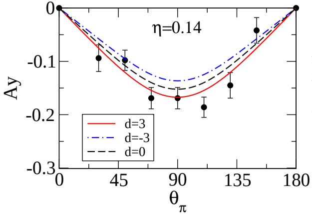
$pp \to d\pi^+$

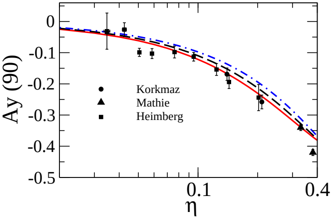


Positive $d \simeq 3$ is clearly preferred

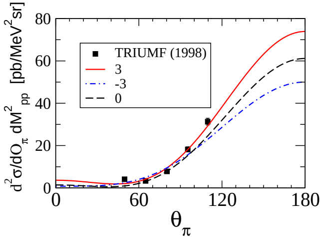
$NN \to NN\pi$, Results (our work (2009))

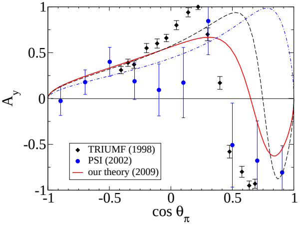
$pp \to d\pi^+$





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



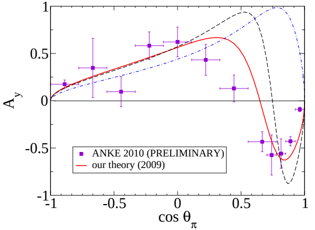


New measurement of $pn \to pp\pi^-$ at different energies (ANKE at COSY 2010) IMPORTANT!

Positive $d \simeq 3$ is clearly preferred

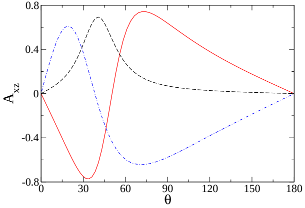
$pn \to pp\pi^-$, Measurement at COSY

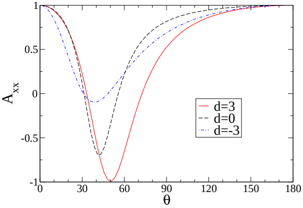
Analyzing power at Tlab $\sim$ 340-380 MeV (ANKE (2010), S.Dymov et al.: PRELIMINARY)



Positive $d \simeq 3$ is clearly preferred

Prediction for double polarization observables





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)

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

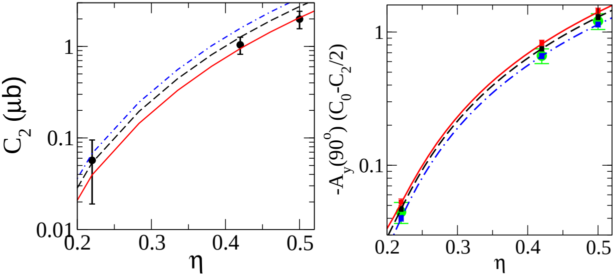
$a0: {}^1S_0 \rightarrow {}^3S_1 p$
$a2: {}^1D_2 \rightarrow {}^3S_1 p$
$a1: {}^3P_1 \rightarrow {}^3S_1 s$
IUCF, Flammang et al. (1998)

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

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

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

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



- influence of Pp states needs to be understood

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

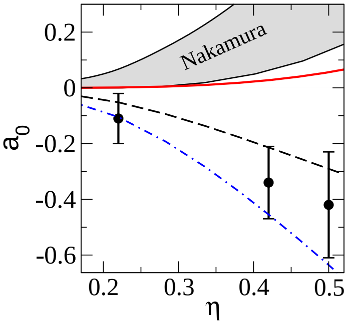
$pp \to pn\pi^+$, Partial wave analysis Flammang et al (1998)

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 program between pp fusion and $NN\pi$

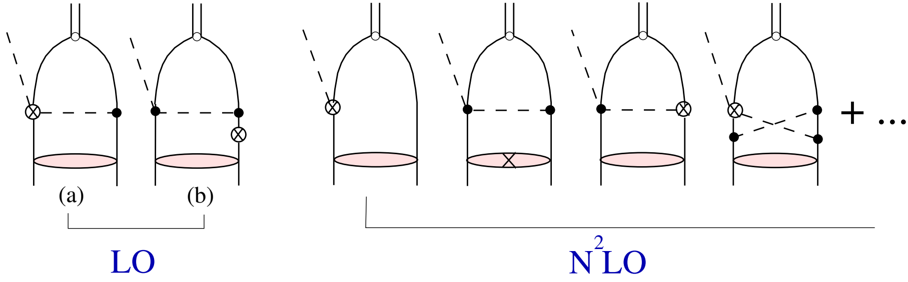
Conclusion is based on wrong PWA!

s- and p-wave isospin conserving pion production is under control.

Next goal: Charge Symmetry Breaking effects

CSB effects in $pn \to d\pi^0$. Power counting

CSB operators for s-wave pion up to N^2LO



$$\mathcal{L}_{\rm IC}^{(0)} = N^\dagger \left[\frac{1}{4F_\pi^2} \boldsymbol{\tau} \cdot (\dot{\boldsymbol{\pi}} \times \boldsymbol{\pi}) + \frac{g_A}{2F_\pi} \boldsymbol{\tau} \cdot \vec{\sigma} \cdot \vec{\nabla} \boldsymbol{\pi} \right] N + \cdots \quad ,$$

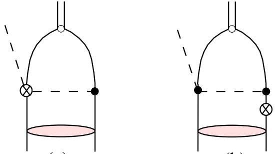
$$\mathcal{L}_{\rm IV}^{(0)} = \frac{\delta m_N}{2} N^\dagger \tau_3 N - \frac{\delta m_N^{\rm str}}{4F_\pi^2} N^\dagger \boldsymbol{\tau} \cdot \boldsymbol{\pi} \pi_3 N - \frac{\delta m_N^{\rm em}}{4F_\pi^2} N^\dagger (\tau_3 \boldsymbol{\pi}^2 - \boldsymbol{\tau} \cdot \boldsymbol{\pi} \pi_3) N + \ldots$$

No terms at NLO $\Longrightarrow$ theoretical uncertainty of LO calculation is $\sim \chi^2 \simeq \frac{M_\pi}{m_N} \sim 15\%$

IV p-wave pion starts from N^2LO.

CSB effects in $pn \to d\pi^0$. Additional IV operator at LO.

New contribution from diagram (b) at LO (our work (2009))



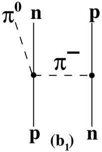
(a) (b)

πN Lagrangians relevant at LO:

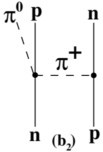
$$\mathcal{L}_{\rm iv}^{(0)} = -\frac{\delta M_N^{\rm str}}{4F_\pi^2} N^\dagger \boldsymbol{\tau}\cdot\boldsymbol{\pi}\pi_3 N - \frac{\delta M_N^{\rm em}}{4F_\pi^2} N^\dagger(\tau_3\boldsymbol{\pi}^2 - \boldsymbol{\tau}\cdot\boldsymbol{\pi}\pi_3)N$$

$$\mathcal{L}_{WT}^{(0)} = \frac{1}{4F_\pi^2} N^\dagger \boldsymbol{\tau}\cdot(\dot{\boldsymbol{\pi}}\times\boldsymbol{\pi})N$$

WT Lagrangian is time-dependent $\Longrightarrow$ vertex $\sim q_0 + M_\pi$ depends on δm_N through q_0



$$V_{WT} = \frac{i\sqrt{2}}{4f_\pi^2}\left(\frac{-3m_\pi}{2} - \delta m_N\right)$$



$$V_{WT} = \frac{i\sqrt{2}}{4f_\pi^2}\left(\frac{3m_\pi}{2} - \delta m_N\right)$$

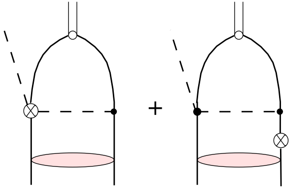
Terms $\sim \delta m_N$ add up!

CSB effects in $pn \to d\pi^0$. Our results

Filin et al. (2009) Strategy:

To minimize the theoretical uncertainty of IC amplitudes as much as possible using data!

- IC p-wave (N^{2}LO) calculation – very good description of data
- take C_0 directly from data on pionic deuterium atom
  $\sigma(nn \to d\pi^-) = 252^{+5}_{-11} \cdot \eta\ [\mu b]$
- perform complete LO calculation of CSB amplitudes



$$\sim \left(\delta M_N^{str} - \frac{\delta m_N^{em}}{2}\right) + \frac{\delta m_N^{str} + \delta m_N^{em}}{2} \to \frac{3}{2}\delta m_N^{str}$$

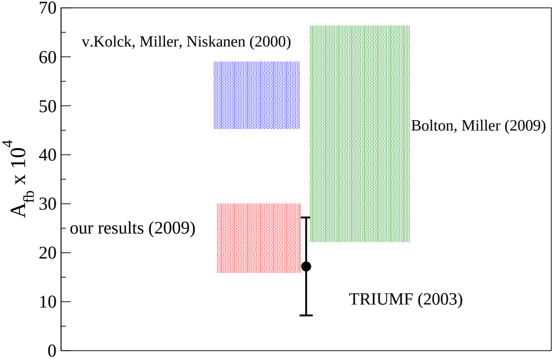
Our LO result: $A_{fb} = (11.5 \pm 3.5)10^{-4}\delta M_N^{str}$

$$\delta m_N^{\rm str} = (1.5 \pm 0.8\ (\rm exp.) \pm 0.5\ (\rm th.))\ \rm MeV \qquad pn \to d\pi^0 \text{ at LO}$$

$$\delta m_N^{\rm str} = (2.0 \pm 0.3)\ \rm MeV \qquad \text{Gasser and Leutwyler}$$

$$\delta m_N^{\rm str} = (2.26 \pm 0.57 \pm 0.42 \pm 0.10)\ \rm MeV \qquad \text{lattice data Beane et al.(2007)}$$

CSB effects in $pn \to d\pi^0$. Comparison to other works



δm_N^{str}=2.0 MeV

CSB at LO (Bolton and Miller): main origins of discrepancies with our results

- s- and p-wave IC amplitudes are calculated at NLO
  $\Longrightarrow$ 30% +15% uncertainties in A_{fb}
- Δ-isobar contribution at NLO to the p-wave amplitudes is too large $\Longrightarrow$ phenom. formfactors with $\Lambda \approx$ 400 MeV are introduced.
  Still A_y in $pp \to d\pi^+$ is overestimated by about 30%.

$NN \to NN\pi$. Summary and Outlook

s-wave production, NLO calculation

- quantitative understanding of $pp \to d\pi^+$ with 15% uncertainty in the amplitude

p-wave production, N^2LO calculation

- studying different channels of $NN\pi$ simultaneously – good test for LEC $(N\bar{N})^2\pi$ in different kinematic regimes
- good overall description of all channels with the same LEC!
- chiral expansion indeed converges in accordance to power counting

CSB effects in $pn \to d\pi^0$, LO calculation

- unique opportunity to extract $\delta m_N^{\mathrm{str}}$ from a dynamical process: $\delta m_N^{\mathrm{str}} = (1.5 \pm 0.8\ (\mathrm{exp.}) \pm 0.5\ (\mathrm{th.}))$ MeV
- Non-trivial consistency with the Cottingham sum rule and lattice results

$NN \to NN\pi$. Outlook

We are on the way to control pion dynamics in $NN \to NN\pi$

Further steps and future plans

- $pp \to pp\pi^0$ still needs to be understood. N^{2}LO is in progress (Kim et al. (2008), our group)
- N^{2}LO calculation for $pp \to d\pi^+$ (in progress) and CSB effects for $pn \to d\pi^0$ together with $dd \to \alpha\pi^0$
- $NN \to NN\pi + pp \to de^+\nu + \cdots$ within the same framework is interesting!
- results from ANKE are highly awaited
  - $pn \to pp\pi^-$ at low energies is the best chance to fix $4N\pi$ CT in $NN \to NN\pi$
  - planned measurements of spin-correlation coefficients, A_y and $d\sigma/d\Omega$ for $pn \to pp\pi^-$ and $pp \to pp\pi^0$ would allow for a partial wave analysis
- extension of ChPT NN interaction above pion threshold