RUHR UNIVERSITÄT BOCHUM RUB

Role of Spin in NN→NNπ

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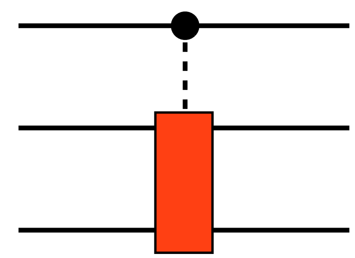
in collaboration with
E. Epelbaum, A. Filin, C. Hanhart, H. Krebs, A. Kudryavtsev, V. Lensky,
U.-G. Meißner, F. Myhrer

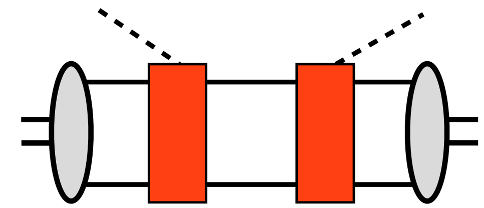
recent review article Int. Jour. Mod. Phys. (2014)

$NN \to NN\pi$. Introduction

- Direct Connection to other low-energy reactions



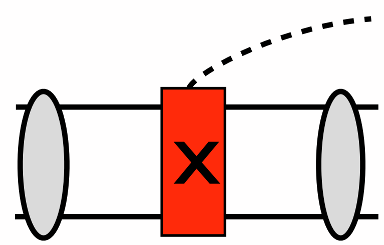
3N Forces



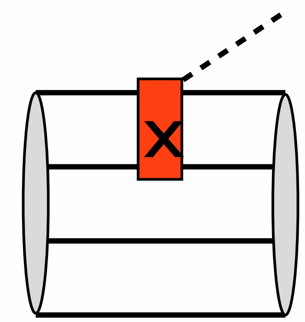
+ ...

Pionic Deuterium
$\pi d \to NN \to \pi d$

- Study of isospin violation in NN reactions



$pn \to d\pi^0$



$dd \to \alpha\pi^0$

Exp. Data:

TRIUMF (2003), IUCF (2004), COSY (2014)

- Non-trivial production mechanism: Channels with drastically different Cross Sections

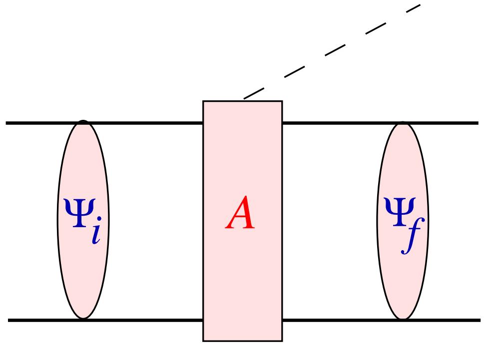
For example: $pp \to d\pi^+$ and $pp \to pp\pi^0$

- Appropriate Framework - Chiral EFT: successfully applied to πN and NN interactions - main ingredients of $NN \to NN\pi$

Weinberg, Gasser, Meißner, Epelbaum, ...

$NN \to NN\pi$ within ~~hybrid~~ chiral EFT.

Weinberg (1992)



- Chiral expansion of the production operator A at low energies
  - New scale in $NN \to NN\pi$: $p \simeq \sqrt{m_\pi m_N}$ — initial NN momentum in cms
  - $\boxed{\chi \sim \frac{p}{\Lambda_\chi} \sim \sqrt{\frac{m_\pi}{m_N}}}$ — expansion parameter in $NN \to NN\pi$

    Cohen et al. (1996); Hanhart et al. (2000)
  - Explicit $\Delta(1232)$-resonance: $m_\Delta - m_N \sim p$
  - long-range operators (OPE, π-loops) $\longrightarrow$ explicitly
  - short-range mechanisms $\to$ local contact operators(LECs)

Investigate convergence by explicit treatment of higher-order terms

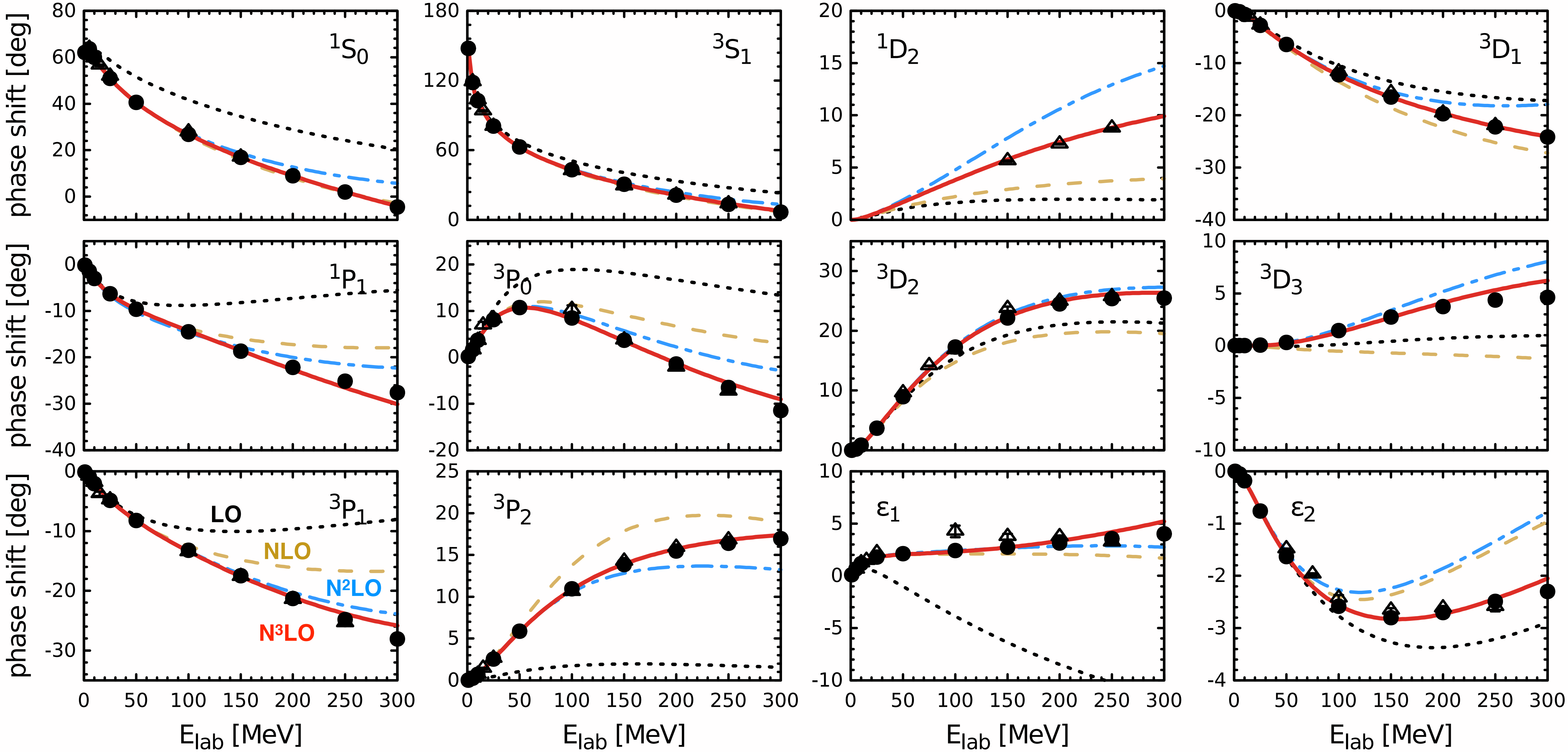
- Convolution with the NN wave functions: CD-Bonn, CCF, AV18, ...

  and <u>**Chiral EFT**</u>

NN phase shifts in Chiral EFT

Convergence order by order: LO, NLO, N^2LO, N^3LO

Epelbaum et al. (2014)

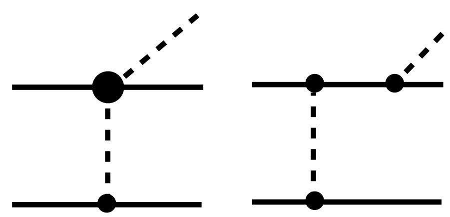
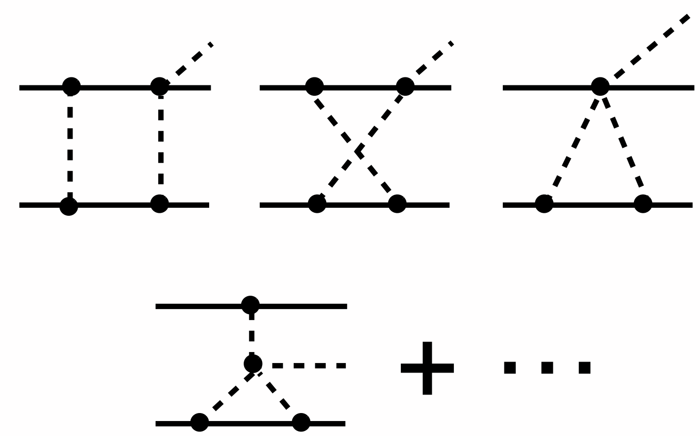
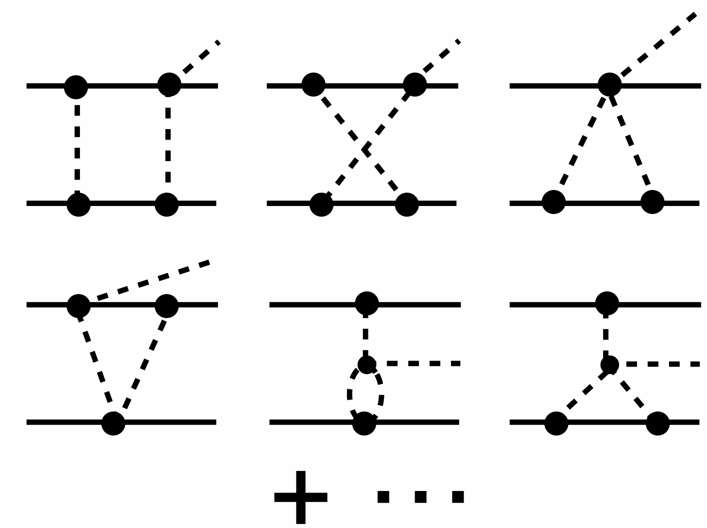


N^3LO: Almost perfect description of Phase Shifts even above pion threshold: $E_{lab} \simeq 279$ MeV

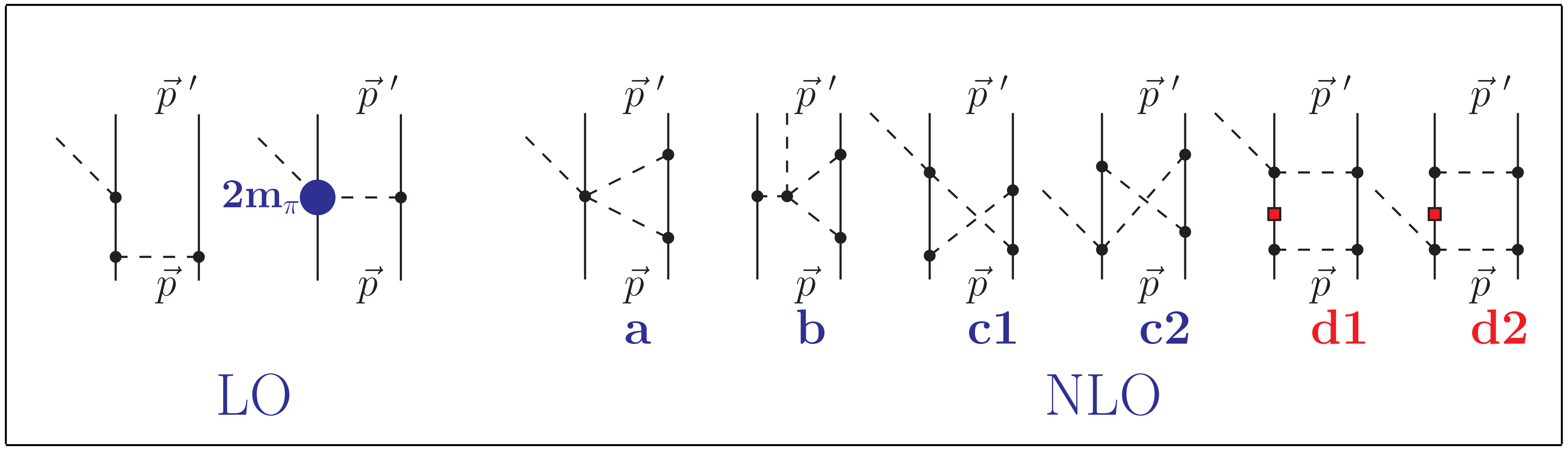
Calculation of $NN \rightarrow NN\pi$ with Chiral wave functions becomes possible

From S-wave pion production to isospin violation in NN reactions

s-wave pion production operators

$\chi_{\text{MCS}} \sim \sqrt{\frac{m_\pi}{m_N}}$	LO	NLO	NNLO
			
$pp \to d\pi^+$	big contribution Koltun et al. (1966)	0 Lensky et al. (2006)	small, correction to LO
$pp \to pp\pi^0$	almost negligible Cohen et al. (1996), Park et al. (1996)	0 Hanhart and Kaiser (2005)	small, but main contribution (!)

S-wave pion production: Theory vs. Experiment

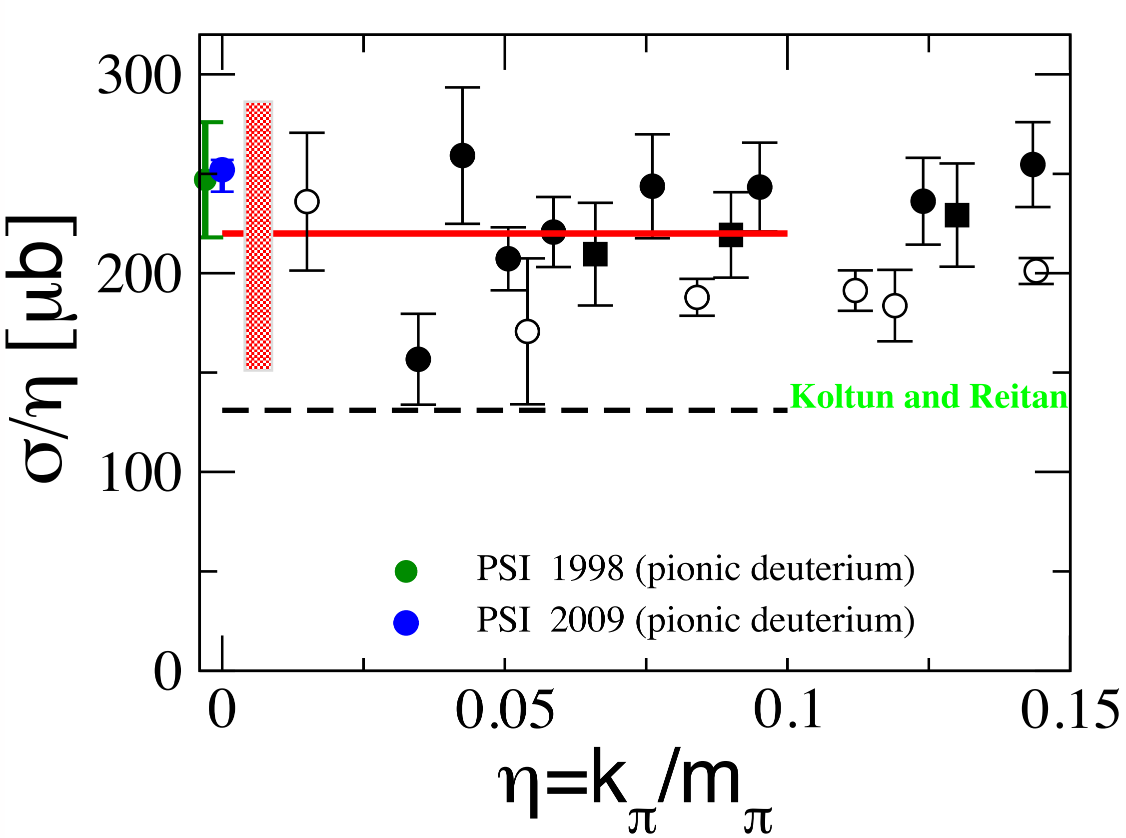


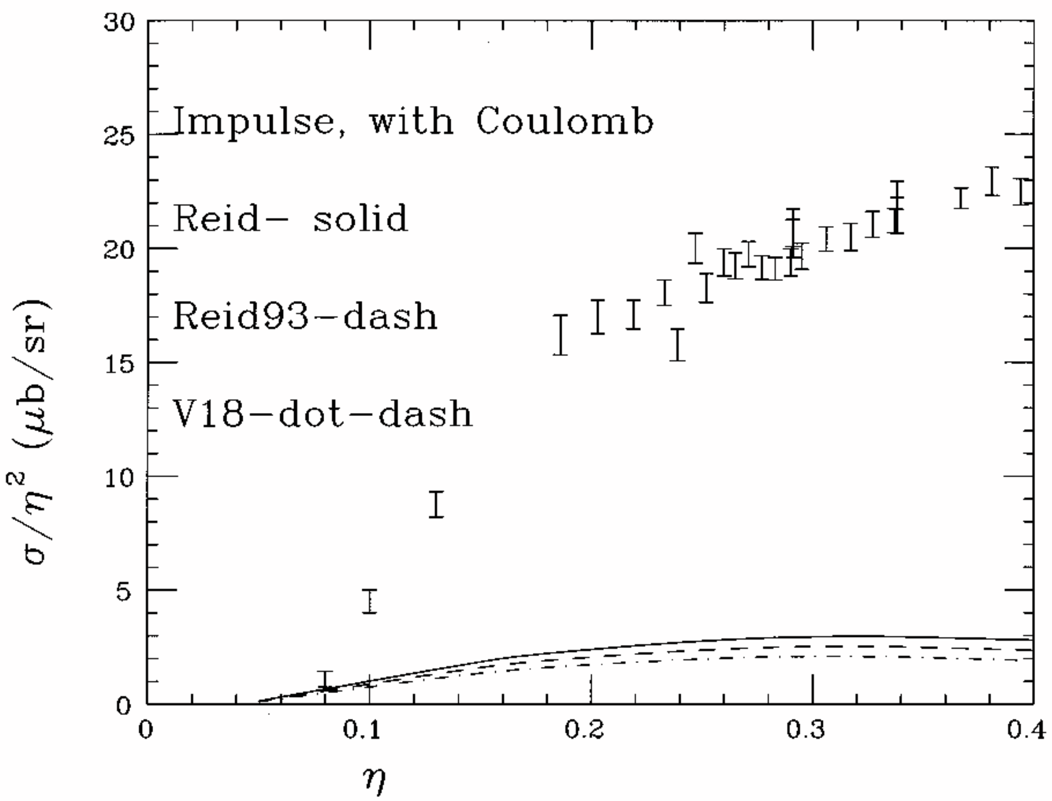
pp → dπ$^+$

pp → ppπ^0

Theory band — from Lensky et al. (2006)

Picture and Theory curves: from Cohen et al. (1996)
Similar conclusions: Park et al. (1996)





Quantitative description

Underestimation of data by an order of magnitude

s-wave pion production operators

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	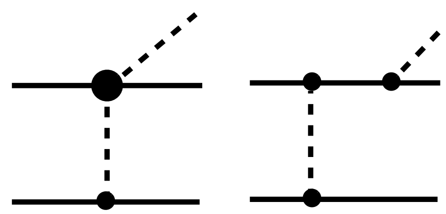	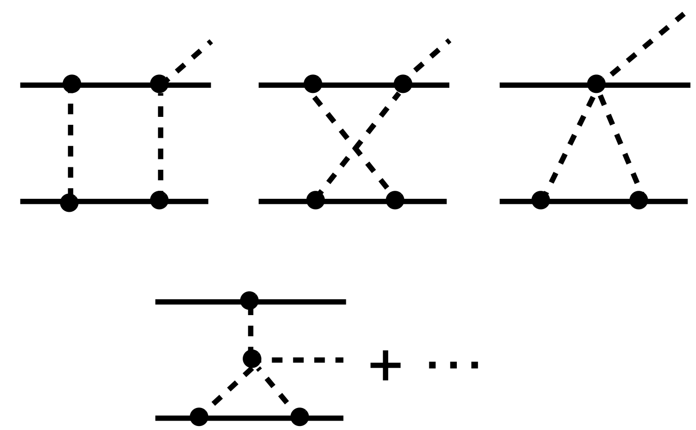	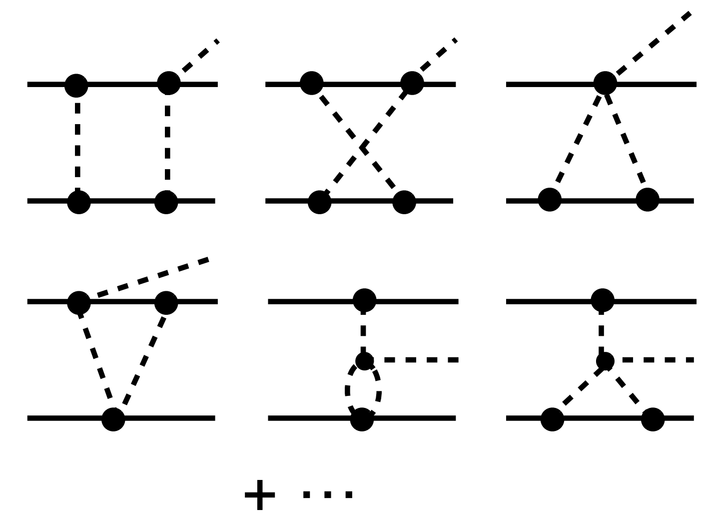
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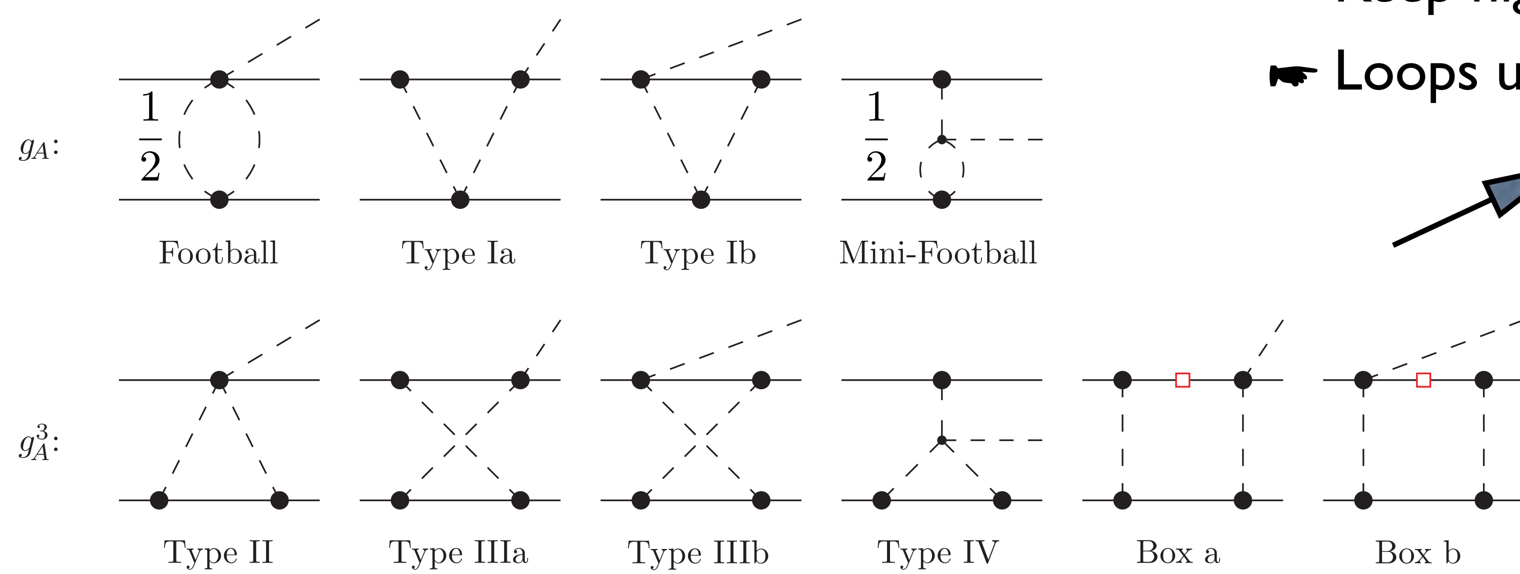
For $pp \to pp\pi^0$ LO rescattering contribution is forbidden, NLO is zero

$\Rightarrow$ effects of NNLO loops are very important

NNLO loop-diagrams

- Topologies of NNLO diagrams:



☛ Keep higher-order vertices from $\mathcal{L}_{\pi N}^{(2)}$

☛ Loops undergo significant cancellations

- Compact analytic result: Filin, V.B., Epelbaum, Hanhart, Krebs, Kudryavtsev, Myhrer (2012)

$$iM_{nucl}^{\text{Sym.}} = \frac{g_A^3}{f_\pi^5} v \cdot q\, \tau_+^a \left(i\varepsilon^{\alpha\mu\nu\beta} v_\alpha k_{1\mu} S_{1\nu} S_{2\beta} \right) \left(-2 I_{\pi\pi} \right)$$

→ $pp \to pp\pi^0$

$$+ \frac{g_A^3}{f_\pi^5} v \cdot q\, \tau_\times^a (S_1 + S_2) \cdot k_1 \left(-\frac{19}{24} I_{\pi\pi} + \frac{5}{9} \frac{1}{(4\pi)^2} \right)$$

$$+ \frac{g_A}{f_\pi^5} v \cdot q\, \tau_\times^a (S_1 + S_2) \cdot k_1 \left(\frac{1}{6} I_{\pi\pi} - \frac{1}{18} \frac{1}{(4\pi)^2} \right)$$

→ $pp \to d\pi^+$

with only one basic integral: $I_{\pi\pi} = \frac{\mu^\epsilon}{i} \int \frac{d^{4-\epsilon} l}{(2\pi)^{4-\epsilon}} \frac{1}{(l^2 - m_\pi^2 + i0)((l+k_1)^2 - m_\pi^2 + i0)}$

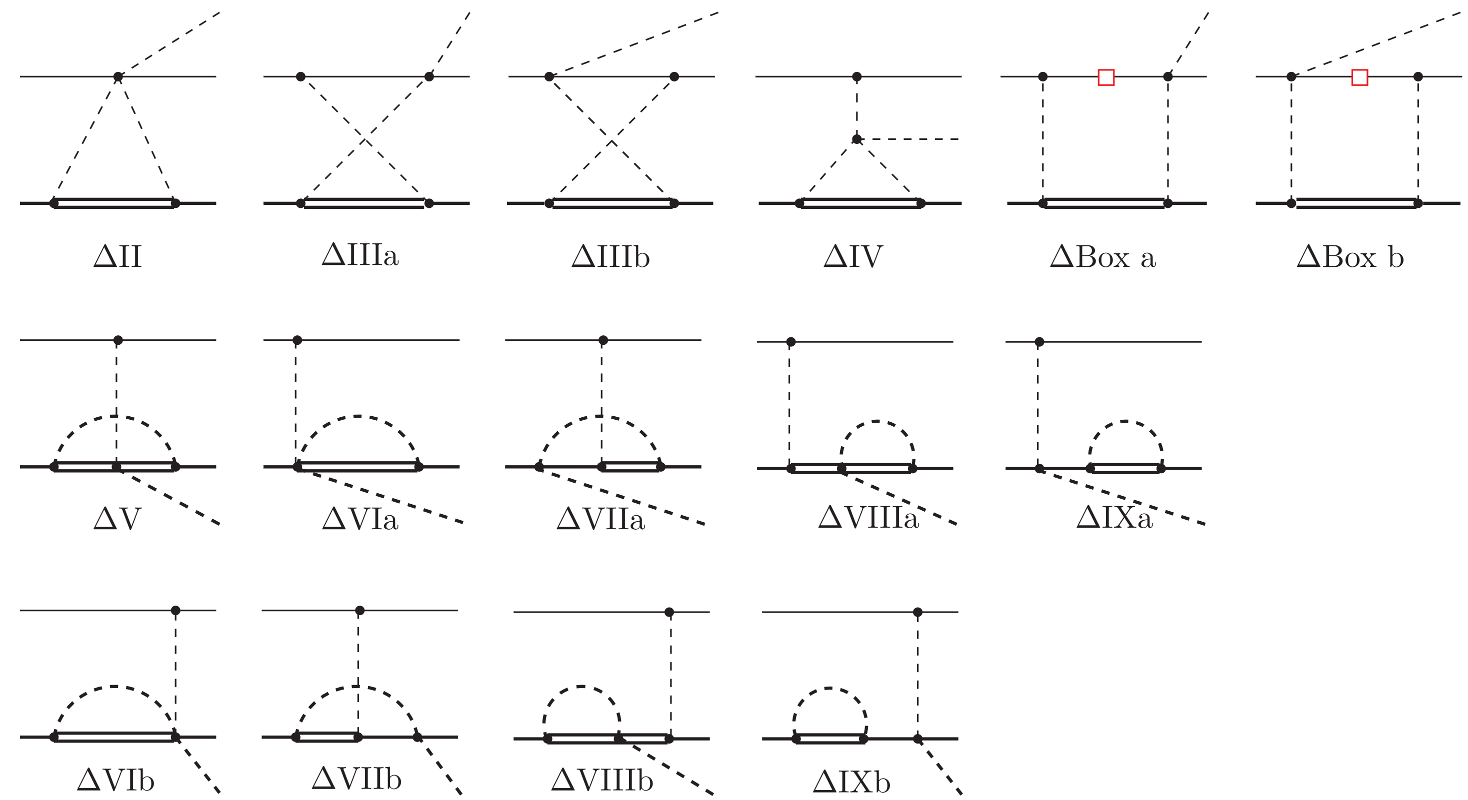
Explicit Delta: More NNLO Loops

- Delta-nucleon mass difference

  m_Δ-m_N≃280 MeV → same order as p

  ⇒ dynamical degree of freedom

Filin, V.B., Epelbaum, Hanhart, Krebs, Kudryavtsev, Myhrer (2013)



Result:

$$
\begin{aligned}
iM^{\rm NNLO}_{\Delta\text{-loops}} &= \frac{g_A g^2_{\pi N\Delta}}{f_\pi^5} v\cdot q\, \tau^a_+ \left(i\varepsilon^{\alpha\mu\nu\beta} v_\alpha k_{1\mu} S_{1\nu} S_{2\beta}\right) \\
&\times\left\{\frac{2}{9}\left(I_{\pi\pi}+\frac{1}{2}\frac{J_{\pi\Delta}}{\Delta}+\Delta J_{\pi\pi\Delta}+\frac{2}{(4\pi)^2}\right)+\frac{1}{18}k_1^2 J_{\pi\pi N\Delta}\right\} \\
&+ \frac{g_A g^2_{\pi N\Delta}}{f_\pi^5} v\cdot q\, \tau_\times (S_1+S_2)\cdot k_1 \\
&\times\left\{\frac{5}{9}\left(I_{\pi\pi}+\frac{1}{2}\frac{J_{\pi\Delta}}{\Delta}+\Delta J_{\pi\pi\Delta}+\frac{2}{(4\pi)^2}\right)+\frac{1}{18}k_1^2 J_{\pi\pi N\Delta}\right. \\
&\left.+\frac{8}{9}\frac{\delta^2}{k_1^2}\left(I_{\pi\pi}+\frac{1}{2}\frac{J_{\pi\Delta}}{\Delta}+\Delta J_{\pi\pi\Delta}+\frac{2}{(4\pi)^2}\right)-\frac{2}{27}\left(I_{\pi\pi}+\frac{1}{2}\frac{J_{\pi\Delta}}{\Delta}+\frac{1}{3}\frac{2}{(4\pi)^2}\right)\right\}.
\end{aligned}
$$

→ $pp\to pp\pi^0$

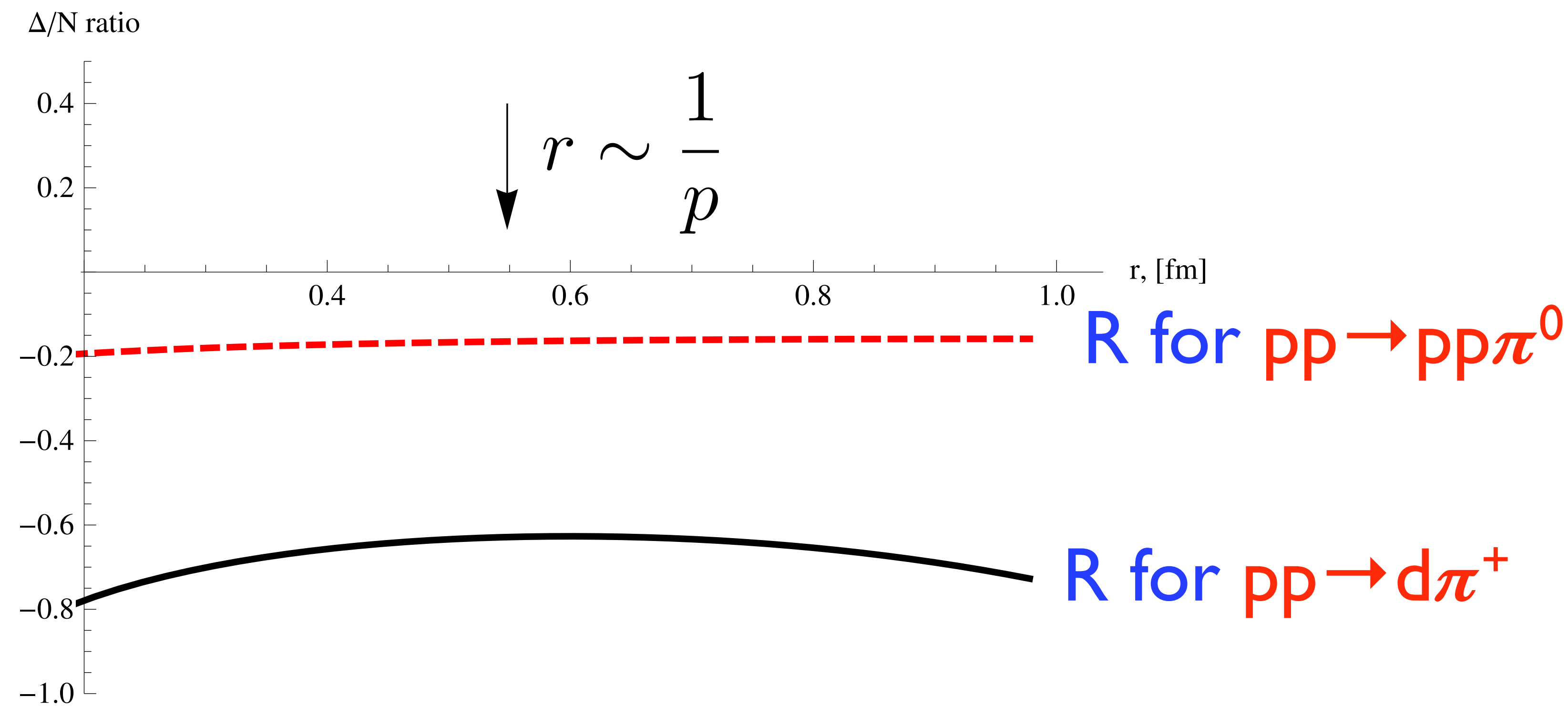
→ $pp\to d\pi^+$

Correct analytic behavior: If $m_\Delta\to\infty$ the contribution of Delta vanishes (decoupling)

The Role of Long-range parts of Loops

Ratio of model-independent long-range loop contributions:

R= Delta Loops/Nucleon Loops



- Nucleon and Delta loops are of similar size: Proves power counting
- Net effect of long-range loops looks consistent with what is needed from Data

$pp \to d\pi^+$: ☛ net result is small due to cancellations
☛ good description of data already at NLO

$pp \to pp\pi^0$: ☛ net result is of sizable
☛ we probe NNLO contributions directly (LO + NLO $\approx$ 0)

Explicit calculation: in progress...

Charge symmetry breaking

Charge symmetry – invariance under interchange of u- and d-quarks

- Approximate symmetry of QCD
- Explicitly broken due to quark-mass difference and electromagnetic effects
- On the level of hadrons → invariance under interchange of p and n

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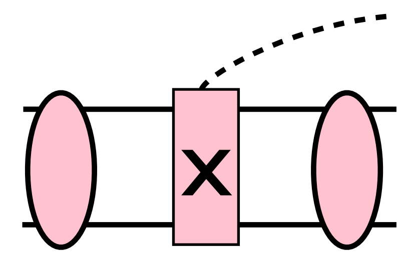
Charge symmetry breaking in $pn \to d\pi^0$:

Opper et al. (2003), v.Kolck et al (2000), Bolton and Miller (2009), Filin et al.(2009)



- Interchange of p and n changes differential cross section
- Forward-Backward Assymetry $$A_{\rm fb} \propto \frac{\frac{d\sigma}{d\Omega}(\theta) - \frac{d\sigma}{d\Omega}(\pi-\theta)}{\frac{d\sigma}{d\Omega}(\theta) + \frac{d\sigma}{d\Omega}(\pi-\theta)}$$ TRIUMF (2003)
- Theory: $$A_{\rm fb} \propto \frac{\mathrm{Re}(M^{\rm CSB}_{\text{s-wave}} M^{\rm CS*}_{\text{p-wave}})}{|M^{\rm CS}_{\text{s-wave}}|^2} \propto (m_p - m_n)^{\rm str}$$ due to $m_u - m_d$

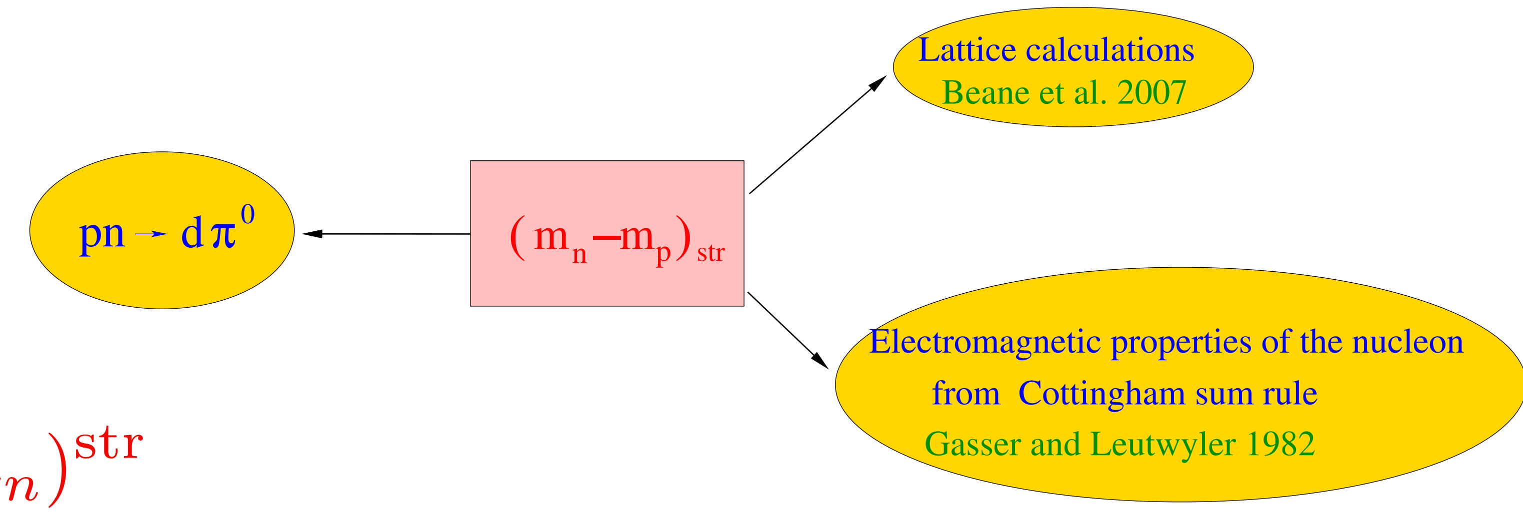
Charge symmetry breaking in $pn \to d\pi^0$

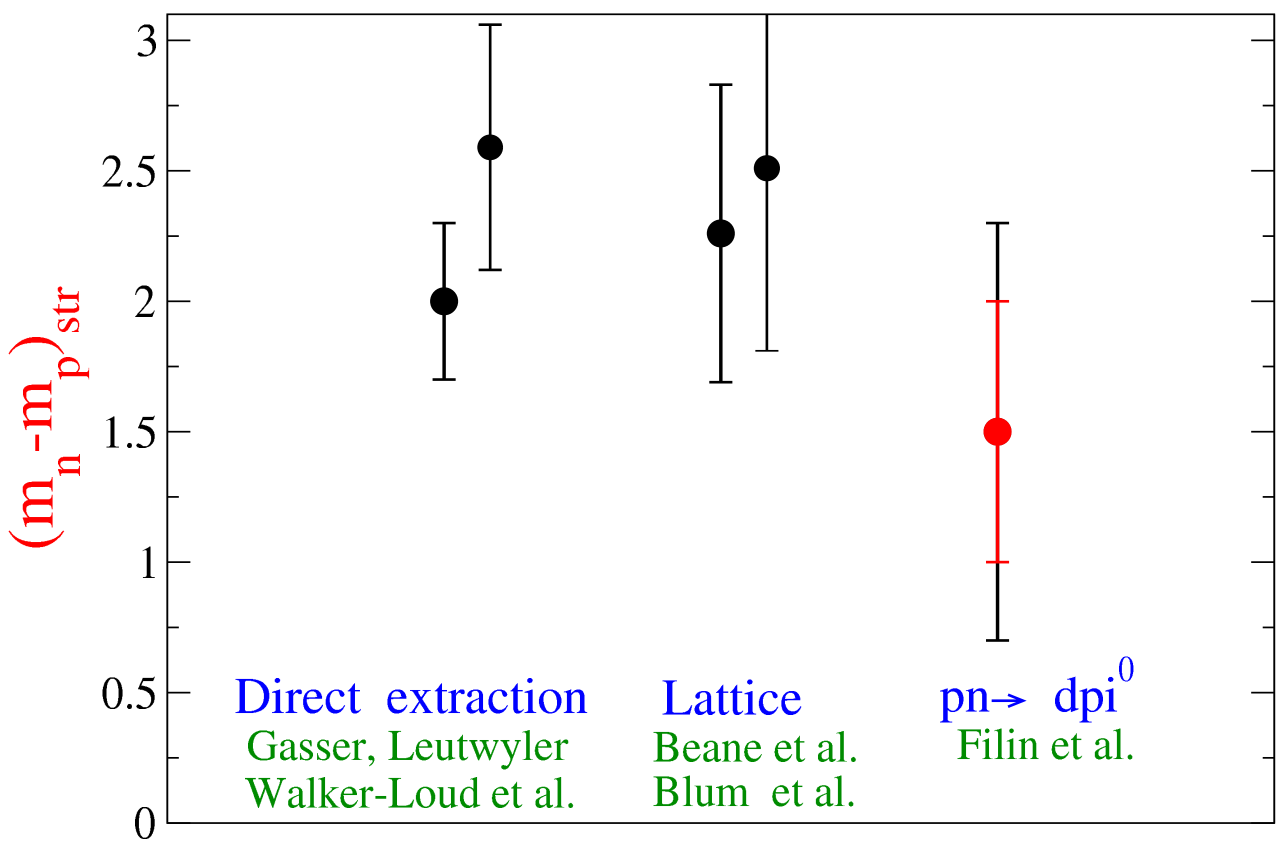
Experiment

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

Our LO result:

$$A_{fb} = (11.5 \pm 3.5) \cdot 10^{-4}\ (m_p - m_n)^{\mathrm{str}}$$





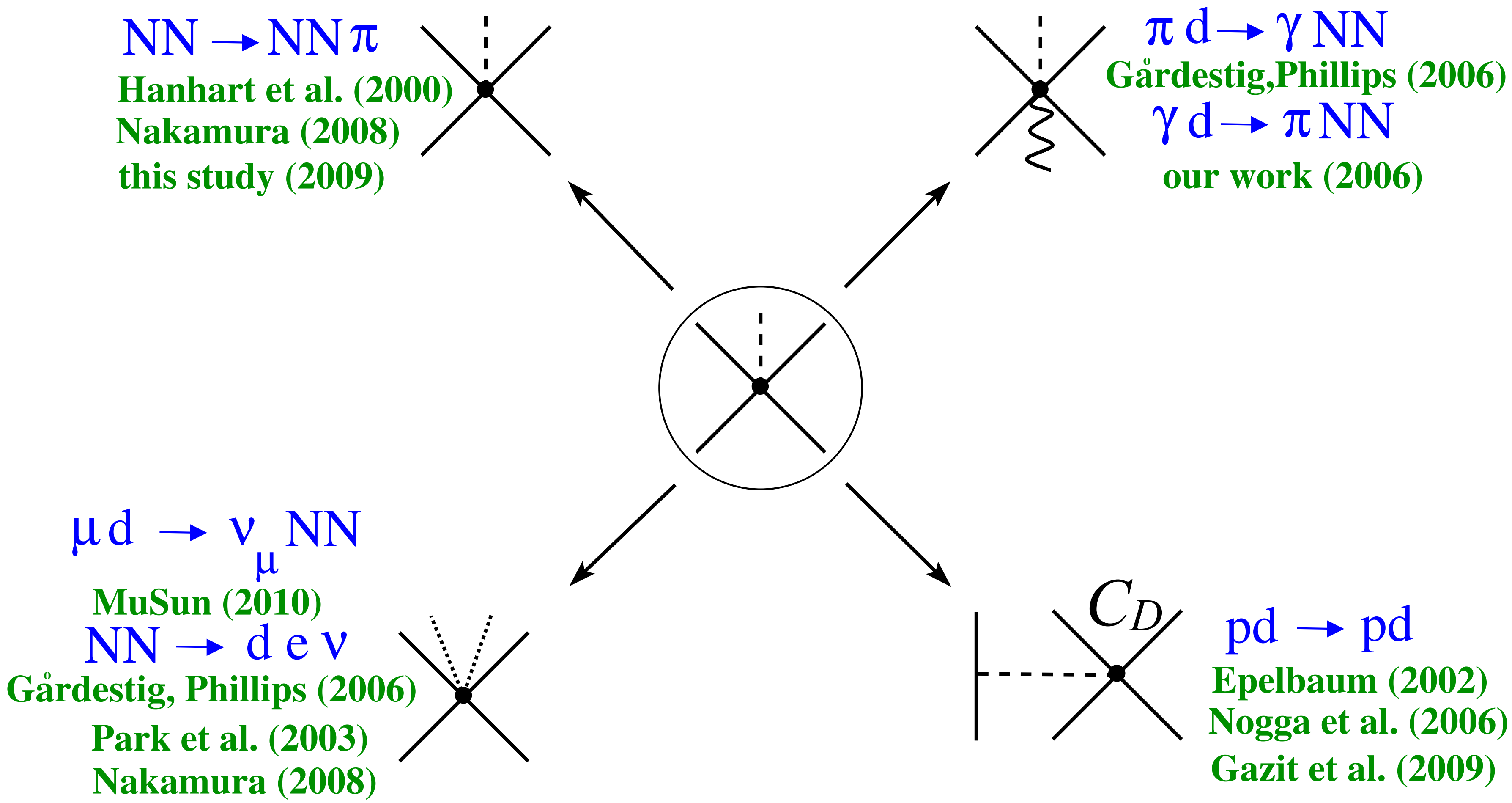
Further Improvements require:

- CSB Chiral Loops at NNLO
- Combined analysis together with $dd \to \alpha\pi^0$

First studies: Nogga et al. (2004,2006)

From NN$\rightarrow$NNπ to weak few-nucleon reactions, 3N-force, ...

p-wave pion production and $(N^\dagger N)^2 \pi$ LEC



$$\mathcal{L} = -2d \, \left(N^\dagger \, S \cdot u \, N\right) N^\dagger N$$

$$f_\pi u_\mu = -\boldsymbol{\tau}\partial_\mu \boldsymbol{\pi} - \varepsilon_{3ab} V_\mu \pi_a \tau_b + f_\pi A_\mu + \cdots$$

NN→NN*π*: Best channel to extract LEC *d* is pn→ppπ^- V.B. et al (2009)

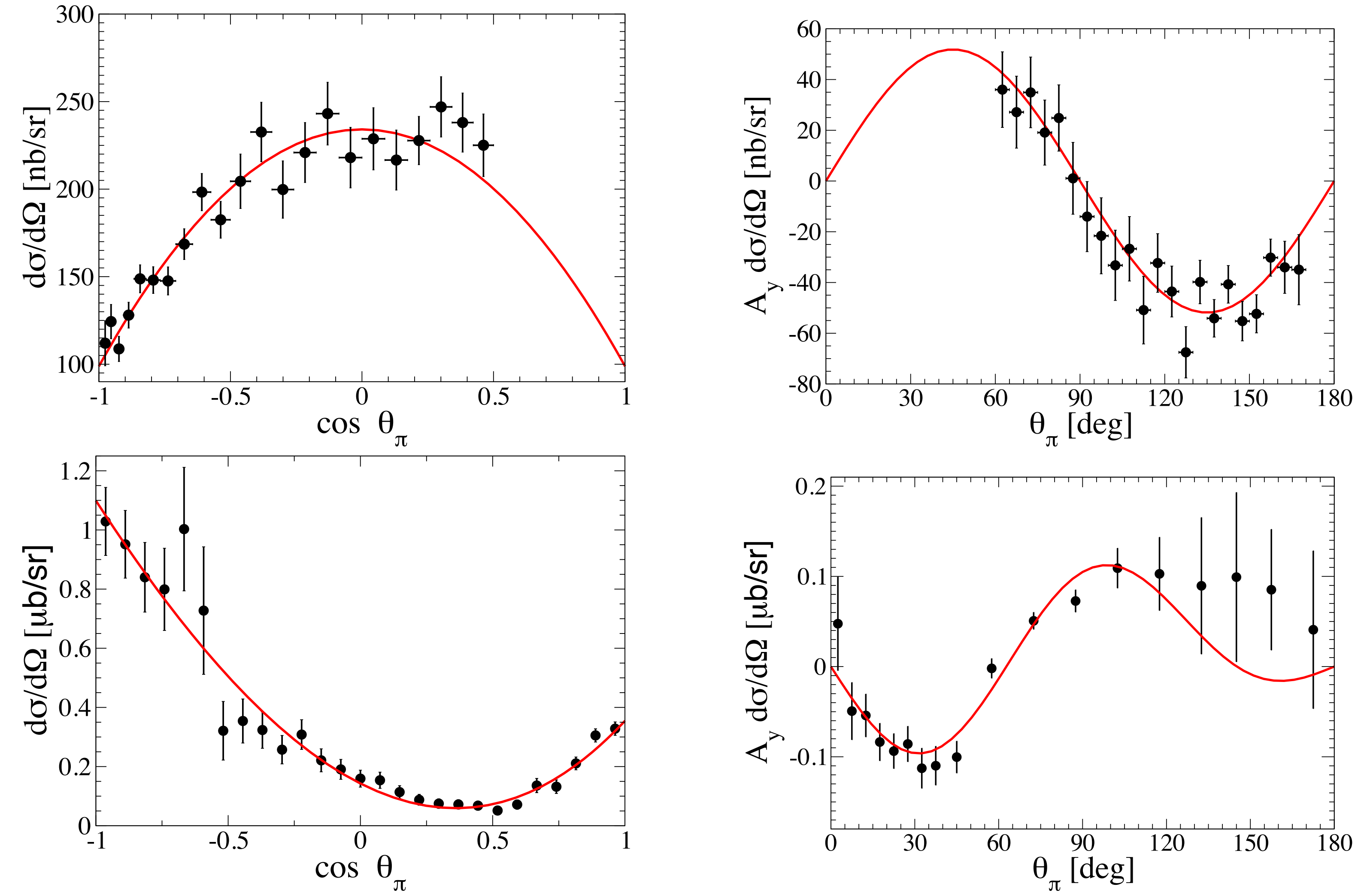
Relevant Transition: ${}^3S_1 \rightarrow {}^1S_0 p$ ⇒ proposal to measure at COSY

$pp \to (pp)_S\pi^0$ and $pn \to (pp)_S\pi^-$ at COSY and amplitude anaylsis (ANKE 2012)

$T_{lab} = 353$ MeV , $E_{pp} < 3$ MeV $\Longrightarrow$ S-wave pp state: $(pp)_S$

$pp \to (pp)_S\pi^0$

$pn \to (pp)_S\pi^-$



- confirmed older TRIUMF data and extended them to the whole angular domain
- no signal of $\cos^4\theta_\pi$ (and higher power) terms $\Longrightarrow$ partial waves higher than **(pion)** $d-$waves are irrelevant
- 5 partial waves: $M^{^3P_0}_{\text{s-wave}}$, $M^{^3S_1}_{\text{p-wave}}$, $M^{^3D_1}_{\text{p-wave}}$, $M^{^3P_2}_{\text{d-wave}}$ and $M^{^3F_2}_{\text{d-wave}}$ to be fitted to data
- impose the phase information from NN interaction $M = |M|e^{i\delta_{ISI}}e^{i\delta_{FSI}}$ – Watson theorem for uncoupled or weakly coupled partial waves

Results of PWA

- Direct fit to data on $pp \to (pp)_S\pi^0$ yields for s- and d-wave amplitudes

$$
\begin{aligned}
M^{^3P_0}_{\mathrm{s-wave}} &= (55.3 \pm 0.4) - (14.7 \pm 0.1)i \sqrt{\mathrm{nb/sr}} \\
M^{^3P_2}_{\mathrm{d-wave}} &= -(26.6 \pm 1.1) - (8.6 \pm 0.4)i \sqrt{\mathrm{nb/sr}} \\
M^{^3F_2}_{\mathrm{d-wave}} &= (5.3 \pm 2.3) \sqrt{\mathrm{nb/sr}}
\end{aligned}
$$

- robust results confirmed by global fit to $pp \to (pp)_S\pi^0$ and $pn \to (pp)_S\pi^-$
- pion d-waves are quite large even near threshold
- comparison of χEFT* with data on the amplitude level is possible

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$$M_{\mathrm{s-wave}}^{^3P_0} = (55.3 \pm 0.4) - (14.7 \pm 0.1)i \sqrt{\mathrm{nb/sr}}$$

$$M_{\mathrm{d-wave}}^{^3P_2} = -(26.6 \pm 1.1) - (8.6 \pm 0.4)i \sqrt{\mathrm{nb/sr}}$$

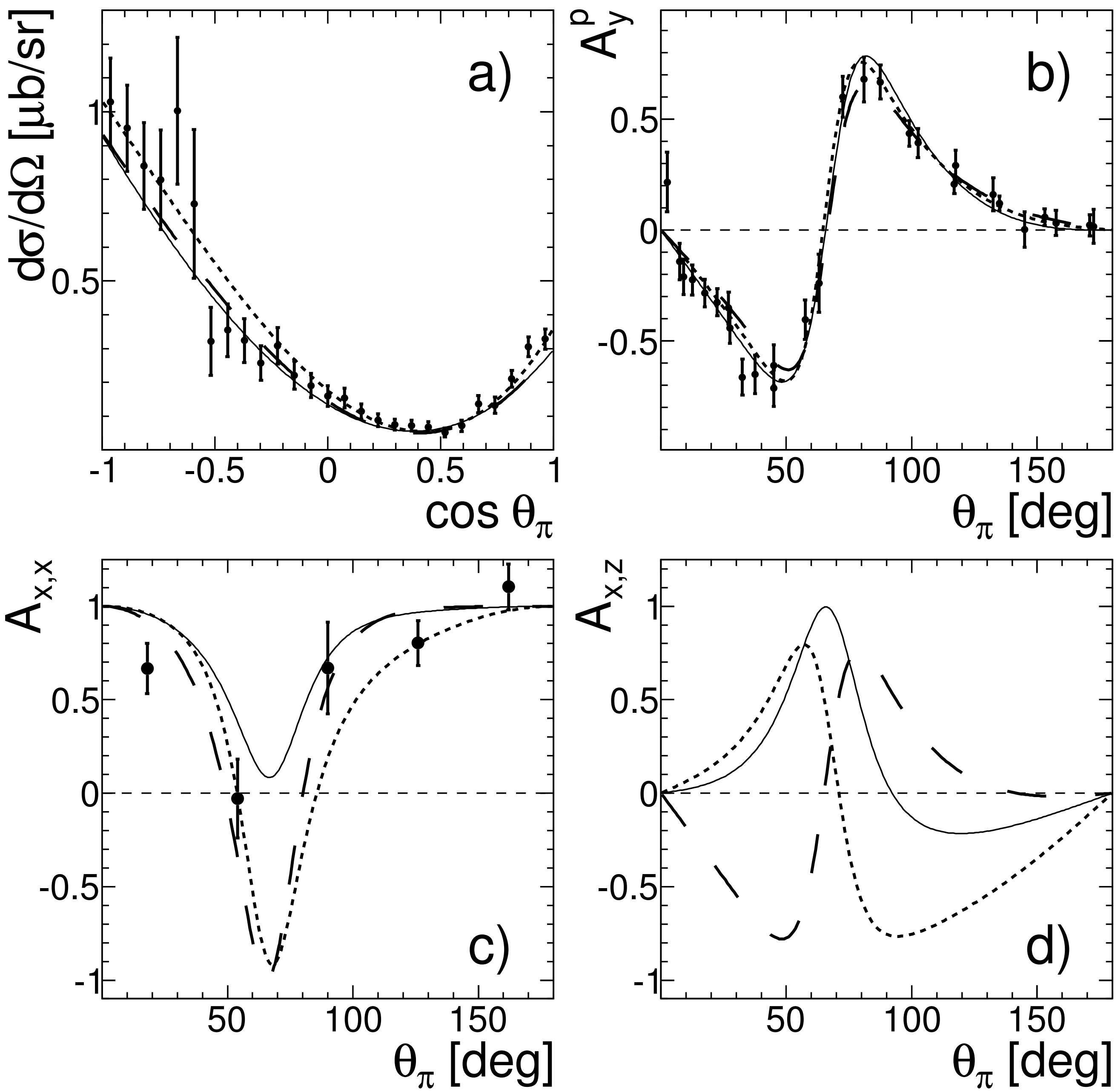
$$M_{\mathrm{d-wave}}^{^3F_2} = (5.3 \pm 2.3) \sqrt{\mathrm{nb/sr}}$$

- robust results confirmed by global fit to $pp \to (pp)_S\pi^0$ and $pn \to (pp)_S\pi^-$
- pion d-waves are quite large even near threshold
- comparison of χEFT* with data on the amplitude level is possible
- But there is NO definite conclusion for p-wave amplitudes

PWA has 3 minima with almost the same χ^2 but with different p-wave amplitudes!

Results of PWA

Amplitude	Real	Imaginary	Im/Re
Solution 1: $\chi^2/ndf = 101/82$ solid line			
$^3S_1 \rightarrow {}^1S_0p$	-37.5 ± 1.7	16.5 ± 1.9	-0.44 ± 0.06
$^3D_1 \rightarrow {}^1S_0p$	-93.1 ± 6.5	122.7 ± 4.4	-1.32 ± 0.11
Solution 2: $\chi^2/ndf = 103/82$ dashed line			
$^3S_1 \rightarrow {}^1S_0p$	-63.7 ± 2.5	-1.3 ± 1.6	0.02 ± 0.03
$^3D_1 \rightarrow {}^1S_0p$	-109.9 ± 4.2	52.9 ± 3.2	-0.48 ± 0.03
Solution 3: $\chi^2/ndf = 106/82$ dotted line			
$^3S_1 \rightarrow {}^1S_0p$	-25.4 ± 1.9	-7.3 ± 1.5	0.20 ± 0.07
$^3D_1 \rightarrow {}^1S_0p$	-172.2 ± 5.6	92.0 ± 6.2	-0.53 ± 0.04



– All solutions describe $d\sigma/d\Omega$ and A_y

– $A_{x,x}$ could be useful but high precision needed

– $A_{x,x}$ at COSY (2013): not enough statistics

– $A_{x,z}$ is most promising

Results of PWA. Theory Insights

Amplitude	Real	Imaginary	tan(δ)= Im/Re
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- Phases should not be far from those predicted by the Watson theorem: $\tan\delta_{^3S_1} = 0.03$ and $\tan\delta_{^3D_1} = -0.46$ (SAID, Arndt et al.(2000))
- Preference against solution 1 and possibly in favour of solution 2.
- For the relevant $^3S_1 \to ^1S_0 p$ amplitude our N^{2}LO χEFT* calculation (2009) gave -53.7 - 2.6 I $\Longrightarrow$ indication in favour of solution 2

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  (tan δ =0.05)

Summary

We investigate chiral dynamics in the reaction NN-NNπ at low energies

Non-trivial production mechanism

- ➔ pp-dπ^+ is dominated by the Weinberg-Tomosawa mechanism while pp-ppπ^0 probes higher-order (NNLO) contributions
- ➔ Chiral Loops at NNLO are derived: big potential to understand data in both channels

Charge symmetry breaking in NN-NNπ

- ➔ Access to the quark-mass induced contribution to the proton-neutron mass difference
- ➔ NLO calculation of pn-dπ^0 in agreement with lattice and dispersive results

Connection to other low-energy reactions: LEC d

- ➔ Can be extracted from NN-NNπ: pn-ppπ^- measured at COSY
- ➔ PWA of data: no unique solution for the relevant $^3S_1$- $^1S_0$p amplitude
- ➔ PWA + theory constraints: probably the unique solution