Evgeny Epelbaum, RUB

The Extreme Matter Physics of Nuclei, GSI Darmstadt 11.5.12

RUB

Probing light nuclei with external sources

Outline

- Introduction
- Exchange currents from chiral EFT
- Some applications
- Reactions involving pions
  - Pion-deuteron scattering
  - Pion production in NN collisions
  - Pion production & CSB
- Summary & outlook

From QCD to nuclear physics

The roadmap: QCD $\longrightarrow$ Chiral Perturbation Theory $\longrightarrow$ hadron dynamics

NN interaction is strong, resummations/nonperturbative methods needed...

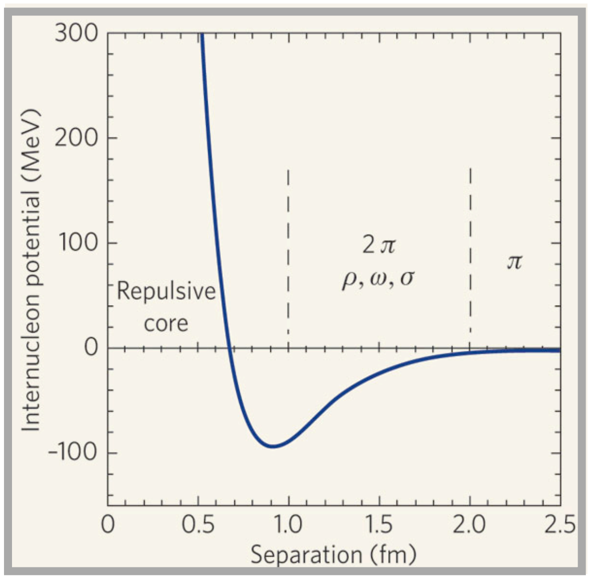
Simplification: nonrelativistic problem ($|\vec{p}_i| \sim M_\pi \ll m_N$) $\longrightarrow$ **the QM A-body problem** Weinberg '91

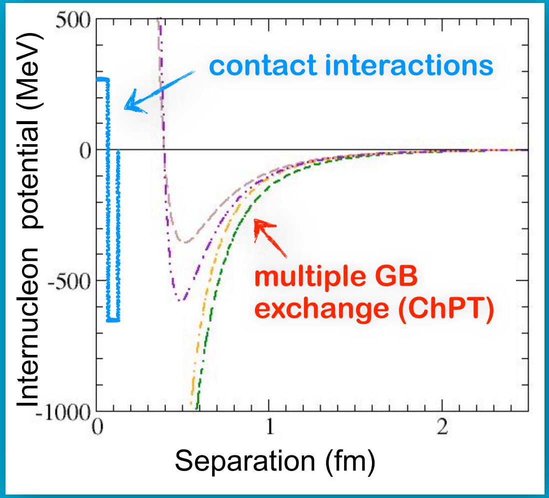
$$\left[\left(\sum_{i=1}^{A}\frac{-\vec{\nabla}_i^2}{2m_N}+\mathcal{O}(m_N^{-3})\right)+\underbrace{V_{2N}+V_{3N}+V_{4N}+\ldots}_{\text{derived within in ChPT}}\right]|\Psi\rangle = E|\Psi\rangle$$

$\rightarrow$ talk by Hermann Krebs

can be solved on a lattice

$\rightarrow$ talk by Ulf-G. Meißner

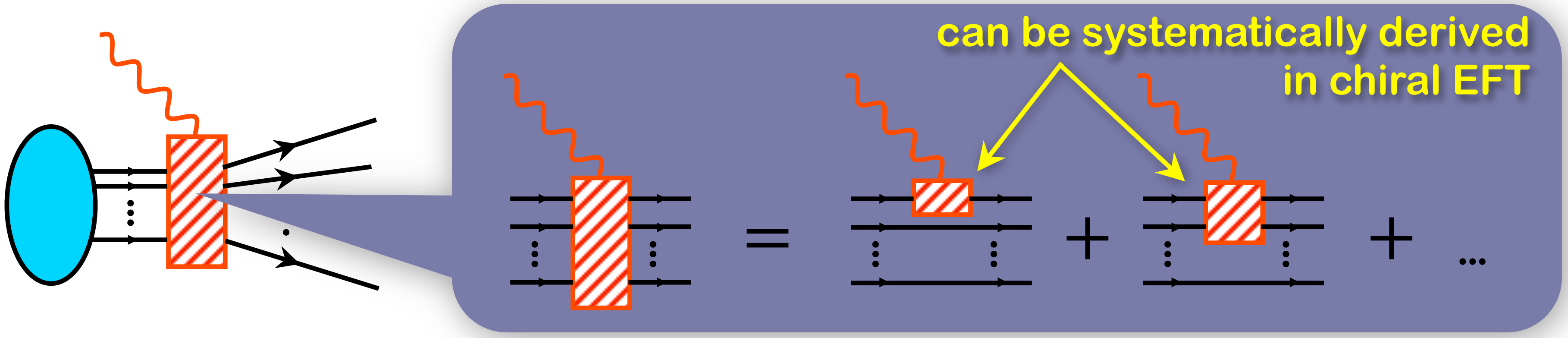




- **unified description of $\pi\pi$, πN and NN**
- **consistent many-body forces and currents**
- **systematically improvable**
- **bridging different reactions (electroweak, π-prod., ...)**
- **precision physics with/from light nuclei**

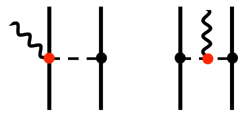
Electromagnetic currents

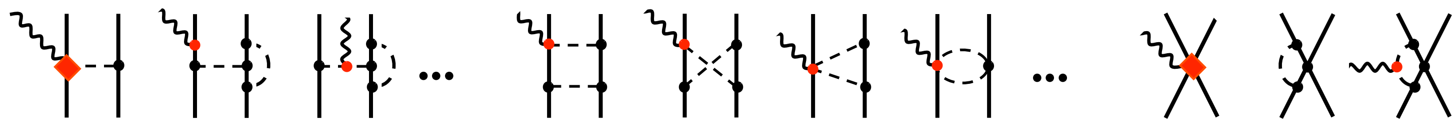
(one-photon exchange approximation)



For Compton scattering, see: Grießhammer, McGovern, Phillips, Feldman, arXiv:1203.6834 [nucl-th]

Electromagnetic exchange currents

Order eQ^{-1} :  well known since decades Chemtob, Rho, Friar, Riska, Adam, …

Order eQ : 

- **Threshold kinematics** $\omega \sim |\vec{q}\,| \sim M_\pi^2/m$

  Park, Min, Rho '95; Park, Kubodera, Min, Rho; Song, Lazauskas, Park, Min, ...

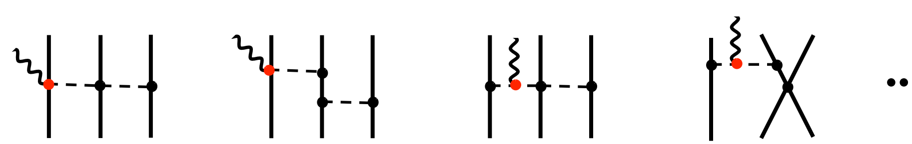
  Application to $np \to d\gamma$ at threshold: $\sigma_{1N} = 306.6 \text{ mb} \quad \longrightarrow \quad \boxed{\sigma_{1N+2N} = 334 \pm 3 \text{ mb}}$

  to be compared with $\sigma_{\rm exp} = 334.2 \pm 0.5 \text{ mb}$

- **General kinematics** $\omega \sim M_\pi^2/m, \quad |\vec{q}\,| \sim M_\pi$

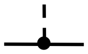
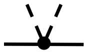
  Pastore, Schiavilla, Girlanda, Viviani; Kölling, Krebs, EE, Meißner

Notice: 3N diagrams do not yield currents at this order...



From L_{eff} to nuclear forces/currents

Method of unitary transformation (Taketani, Mashida, Ohnuma, Okubo, EE, Glöckle, Meißner, Krebs, Kölling)

- Canonical transformation & quantization: $\mathcal{L}_{\pi \mathrm{N}} \longrightarrow \mathcal{H}_{\pi \mathrm{N}} =$  +  + ...

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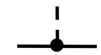
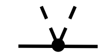
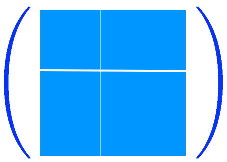
- Canonical transformation & quantization: $\mathcal{L}_{\pi N} \longrightarrow \mathcal{H}_{\pi N} =$  +  + ...

- **Nuclear forces via UT (Fock space):** $H \to \tilde{H} = U^\dagger$  $U = \begin{pmatrix} \tilde{H}_{\text{nucl}} & 0 \\ 0 & \tilde{H}_{\text{rest}} \end{pmatrix}$

  - „Minimal" UT computed perturbatively $H = \sum_{\kappa=1}^{\infty} (1/\Lambda)^\kappa H^{(\kappa)}$
  - Only $\tilde{H}_{\text{nucl}}$ is needed below the pion production threshold
  - We employ all additional UTs possible at a given order in the expansion
  - Renormalizability $\longrightarrow$ unambigous results for 4NF & (static) 3NF upto N^3LO

    EE '06,'07; Bernard, EE, Krebs, Meißner '08

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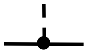
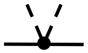
- Canonical transformation & quantization: $\mathcal{L}_{\pi N} \longrightarrow \mathcal{H}_{\pi N} =$  +  + ...

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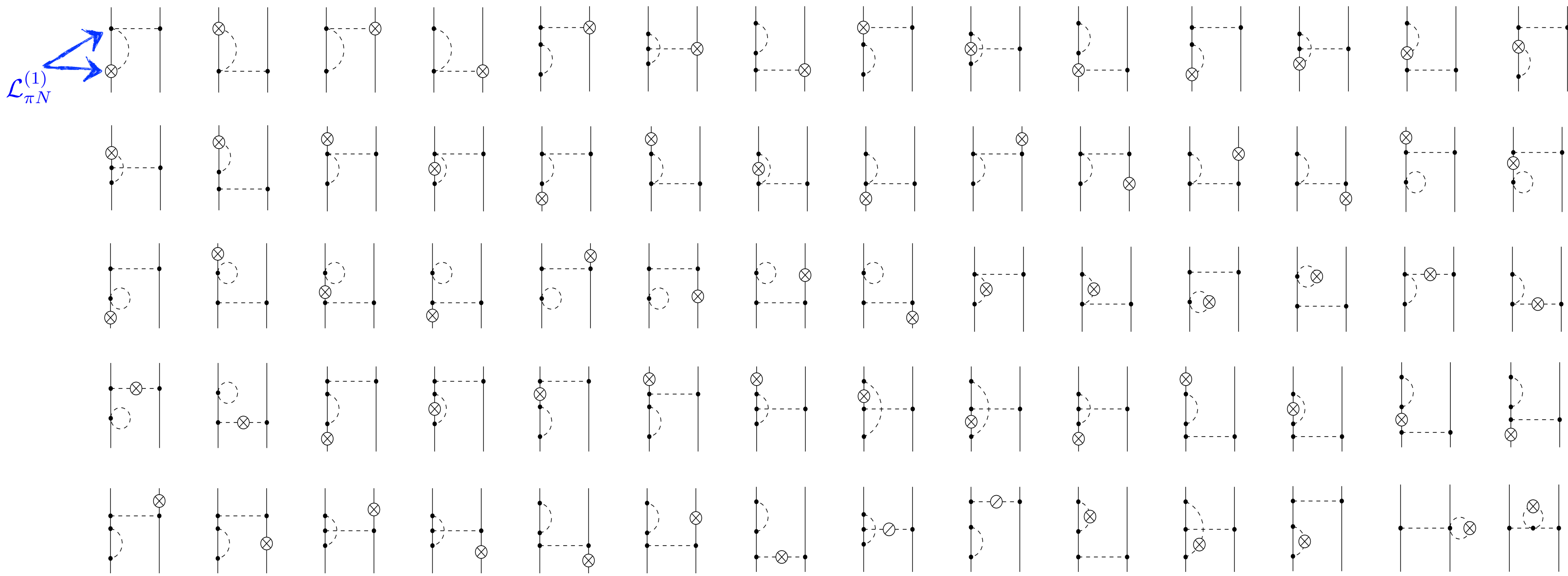
Effective current operator

- „Bare" current $J^\mu(x) = \partial_\nu \frac{\partial \mathcal{L}_{\pi N \gamma}}{\partial(\partial_\nu \mathcal{A}_\mu)} - \frac{\partial \mathcal{L}_{\pi N \gamma}}{\partial \mathcal{A}_\mu}$
- Effective hadronic current $J_\mu \to \tilde{J}_\mu = U^\dagger \begin{pmatrix} \; & \; \\ \; & \; \end{pmatrix} U = \begin{pmatrix} \tilde{J}_\mu^{\text{nucl}} & \; \\ \; & \; \end{pmatrix}$
- Need additional, $\mathcal{A}_\mu$-dependent UTs $\eta U' \eta \Big|_{\mathcal{A}_\mu = 0} = 1_\eta$ to enforce renormalizability

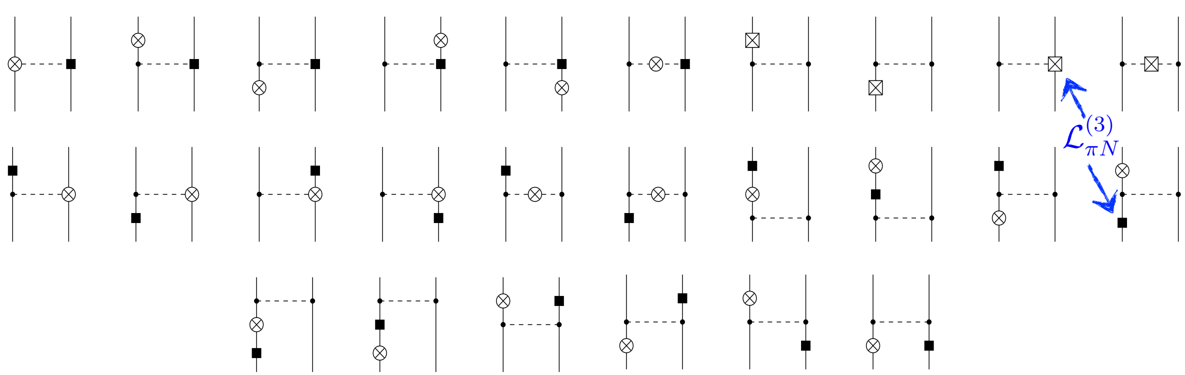
One-pion exchange current

Kölling, EE, Krebs, Meißner ’11

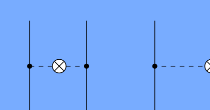
Loop diagrams with $\mathcal{L}_{\pi N}^{(1)}$-vertices



Tree-level diagrams with 1 insertion from $\mathcal{L}_{\pi N}^{(3)}$



All UV divergences must be absorbed in d_i‘s and renormalization of the LO current (F_π, M_π)



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Current density

$$\vec{J}_{1\pi} = \frac{\vec{\sigma}_2 \cdot \vec{q}_2}{q_2^2 + M_\pi^2} [\vec{q}_1 \times \vec{q}_2] \Big[\tau_2^3 \, f_1(k) + \vec{\tau}_1 \cdot \vec{\tau}_2 \, f_2(k) \Big] + [\vec{\tau}_1 \times \vec{\tau}_2]^3 \, \frac{\vec{\sigma}_2 \cdot \vec{q}_2}{q_2^2 + M_\pi^2} \Big\{ \vec{k} \times [\vec{q}_2 \times \vec{\sigma}_1] \, f_3(k) + \vec{k} \times [\vec{q}_1 \times \vec{\sigma}_1] \, f_4(k) + \vec{\sigma}_1 \cdot \vec{q}_1 \left(\frac{\vec{k}}{k^2} - \frac{\vec{q}_1}{q_1^2 + M_\pi^2} \right) f_5(k) + \left[\frac{\vec{\sigma}_1 \cdot \vec{q}_1}{q_1^2 + M_\pi^2} \vec{q}_1 - \vec{\sigma}_1 \right] f_6(k) \Big\}$$

$$f_1(k) = 2ie \frac{g_A}{F_\pi^2} \, \bar{d}_8 \, , \quad f_2(k) = 2ie \frac{g_A}{F_\pi^2} \, \bar{d}_9 \, , \quad f_3(k) = -ie \frac{g_A}{64 F_\pi^4 \pi^2} \left[g_A^3 \, (2L(k) - 1) + 32 F_\pi^2 \pi^2 \bar{d}_{21} \right] ,$$

$$f_4(k) = -ie \frac{g_A}{4F_\pi^2} \, \bar{d}_{22} \, , \quad f_5(k) = -ie \frac{g_A^2}{384 F_\pi^4 \pi^2} \left[2(4M_\pi^2 + k^2) L(k) + \left(6 \, \bar{l}_6 - \frac{5}{3} \right) k^2 - 8 M_\pi^2 \right] ,$$

$$f_6(k) = -ie \frac{g_A}{F_\pi^2} M_\pi^2 \, \bar{d}_{18} \, ,$$

Charge density

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$$f_7(k) = e \frac{g_A^4}{64 F_\pi^4 \pi} \left[A(k) + \frac{M_\pi - 4M_\pi^2 \, A(k)}{k^2} \right]$$

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One-pion exchange current

Kölling, EE, Krebs, Meißner ’11

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$$

$$
f_6(k) \;=\; -ie \frac{g_A}{F_\pi^2} M_\pi^2 \bar{d}_{18}
$$

Low-energy constants: $\bar{l}_6, \; \bar{d}_{18}$ (fairly) well known; $\bar{d}_8, \; \bar{d}_9, \; \bar{d}_{21}, \; \bar{d}_{22}$ - less well known (can, in principle, be fit to π-photoproduction data...)

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Comparison with Pastore et al., PRC 80 (09) 034004: **agree,**

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$$\begin{aligned} \vec{J}_{1\pi} \;=\; & \frac{\vec{\sigma}_2 \cdot \vec{q}_2}{q_2^2 + M_\pi^2} [\vec{q}_1 \times \vec{q}_2] \left[\tau_2^3 \, f_1(k) + \vec{\tau}_1 \cdot \vec{\tau}_2 \, f_2(k) \right] + [\vec{\tau}_1 \times \vec{\tau}_2]^3 \, \frac{\vec{\sigma}_2 \cdot \vec{q}_2}{q_2^2 + M_\pi^2} \Big\{ \vec{k} \times [\vec{q}_2 \times \vec{\sigma}_1] \, f_3(k) \\ + \; & \vec{k} \times [\vec{q}_1 \times \vec{\sigma}_1] \, f_4(k) + \vec{\sigma}_1 \cdot \vec{q}_1 \left(\frac{\vec{k}}{k^2} - \frac{\vec{q}_1}{q_1^2 + M_\pi^2} \right) f_5(k) + \left[\frac{\vec{\sigma}_1 \cdot \vec{q}_1}{q_1^2 + M_\pi^2} \vec{q}_1 - \vec{\sigma}_1 \right] f_6(k) \Big\} \end{aligned}$$

$$f_1(k) \;=\; 2ie \frac{g_A}{F_\pi^2} \, \bar{d}_8 \qquad f_2(k) = 2ie \frac{g_A}{F_\pi^2} \, \bar{d}_9 \,, \qquad f_3(k) = -ie \frac{g_A}{64 F_\pi^4 \pi^2} \left[g_A^3 \, (2L(k) - 1) + 32 F_\pi^2 \pi^2 \bar{d}_{21} \right] ,$$

$$f_4(k) \;=\; -ie \frac{g_A}{4F_\pi^2} \, \bar{d}_{22} \qquad f_5(k) = -ie \frac{g_A^2}{384 F_\pi^4 \pi^2} \left[2(4M_\pi^2 + k^2) L(k) + \left(6 \, \bar{l}_6 - \frac{5}{3} \right) k^2 - 8 M_\pi^2 \right] ,$$

$$f_6(k) \;=\; -ie \frac{g_A}{F_\pi^2} M_\pi^2 \, \bar{d}_{18} \,,$$

Comparison with Pastore et al., PRC 80 (09) 034004:

agree, **„slightly“ disagree,**

Charge density

$$\rho_{1\pi} = \frac{\vec{\sigma}_2 \cdot \vec{q}_2}{q_2^2 + M_\pi^2} \tau_2^3 \left[\vec{\sigma}_1 \cdot \vec{k} \, \vec{q}_2 \cdot \vec{k} \, f_7(k) \, + \, \vec{\sigma}_1 \cdot \vec{q}_2 \, f_8(k) \right] \, + 1/m_N\text{-corrections (tree level)}$$

$$\begin{aligned} f_7(k) \;&=\; e \frac{g_A^4}{64 F_\pi^4 \pi} \left[A(k) + \frac{M_\pi - 4M_\pi^2 \, A(k)}{k^2} \right] \\ f_8(k) \;&=\; e \frac{g_A^4}{64 F_\pi^4 \pi} \left[(4M_\pi^2 + k^2) A(k) - M_\pi \right] \end{aligned}$$

One-pion exchange current

Kölling, EE, Krebs, Meißner '11

Notation: $\langle \vec{p}_1{}' \, \vec{p}_2{}' | J^\mu_{\rm complete} \, | \vec{p}_1 \, \vec{p}_2 \rangle = \delta(\vec{p}_1{}' + \vec{p}_2{}' - \vec{p}_1 - \vec{p}_2 - \vec{k}) \; [J^\mu \; + \; (1 \leftrightarrow 2)]$

Current density

$$\begin{aligned}\vec{J}_{1\pi} \; &= \; \frac{\vec{\sigma}_2 \cdot \vec{q}_2}{q_2^2 + M_\pi^2} \, [\vec{q}_1 \times \vec{q}_2] \left[\tau_2^3 \, f_1(k) + \vec{\tau}_1 \cdot \vec{\tau}_2 \, f_2(k) \right] + [\vec{\tau}_1 \times \vec{\tau}_2]^3 \, \frac{\vec{\sigma}_2 \cdot \vec{q}_2}{q_2^2 + M_\pi^2} \Big\{ \vec{k} \times [\vec{q}_2 \times \vec{\sigma}_1] \, f_3(k) \\ &+ \; \vec{k} \times [\vec{q}_1 \times \vec{\sigma}_1] \, f_4(k) + \vec{\sigma}_1 \cdot \vec{q}_1 \left(\frac{\vec{k}}{k^2} - \frac{\vec{q}_1}{q_1^2 + M_\pi^2} \right) f_5(k) + \left[\frac{\vec{\sigma}_1 \cdot \vec{q}_1}{q_1^2 + M_\pi^2} \vec{q}_1 - \vec{\sigma}_1 \right] f_6(k) \Big\}\end{aligned}$$

$$f_1(k) \; = \; 2ie \frac{g_A}{F_\pi^2} \, \bar{d}_8 \qquad f_2(k) = 2ie \frac{g_A}{F_\pi^2} \, \bar{d}_9 \, , \qquad f_3(k) = -ie \frac{g_A}{64 F_\pi^4 \pi^2} \left[g_A^3 \, (2L(k) - 1) + 32 F_\pi^2 \pi^2 \bar{d}_{21} \right] ,$$

$$f_4(k) \; = \; -ie \frac{g_A}{4F_\pi^2} \, \bar{d}_{22} \qquad f_5(k) = -ie \frac{g_A^2}{384 F_\pi^4 \pi^2} \left[2(4M_\pi^2 + k^2) L(k) + \left(6 \, \bar{l}_6 - \frac{5}{3} \right) k^2 + 8 M_\pi^2 \right] ,$$

$$f_6(k) \; = \; -ie \frac{g_A}{F_\pi^2} M_\pi^2 \, \bar{d}_{18} \, ,$$

Comparison with Pastore et al., PRC 80 (09) 034004:

agree, „slightly" disagree, completely disagree

Charge density

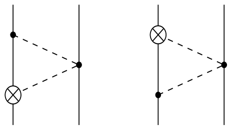
$$\rho_{1\pi} \; = \; \frac{\vec{\sigma}_2 \cdot \vec{q}_2}{q_2^2 + M_\pi^2} \tau_2^3 \left[\vec{\sigma}_1 \cdot \vec{k} \; \vec{q}_2 \cdot \vec{k} \, f_7(k) \; + \; \vec{\sigma}_1 \cdot \vec{q}_2 \, f_8(k) \right] \; + 1/m_N\text{-corrections (tree level)}$$

$$\begin{aligned} f_7(k) \; &= \; e \frac{g_A^4}{64 F_\pi^4 \pi} \left[A(k) + \frac{M_\pi - 4M_\pi^2 \, A(k)}{k^2} \right] \\ f_8(k) \; &= \; e \frac{g_A^4}{64 F_\pi^4 \pi} \left[(4M_\pi^2 + k^2) A(k) - M_\pi \right] \end{aligned}$$

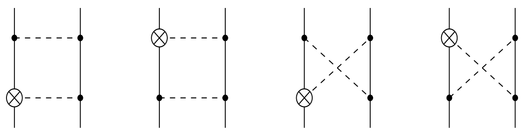
completely missing in
Pastore et al., PRC 80 (09) 034004

Two-pion exchange current density

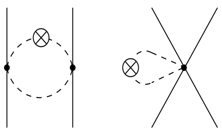
Kölling, EE, Krebs, Meißner ’09



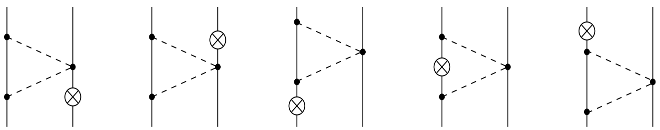
$$\vec J = e\,\frac{g_A^2 M_\pi^7}{128\pi^3 F_\pi^4}\left[\vec\nabla_{10}\,[\vec\tau_1\times\vec\tau_2]^3 + 2\left[\vec\nabla_{10}\times\vec\sigma_2\right]\tau_1^3\right]\,\delta(\vec x_{20})\,\frac{K_1(2x_{10})}{x_{10}^2}$$



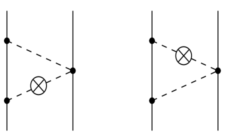
$$\vec J = -\,e\,\frac{g_A^4 M_\pi^7}{256\pi^3 F_\pi^4}\left(3\nabla_{10}^2-8\right)\left[\vec\nabla_{10}\,[\vec\tau_1\times\vec\tau_2]^3 + 2\left[\vec\nabla_{10}\times\vec\sigma_2\right]\tau_1^3\right]\delta(\vec x_{20})\,\frac{K_0(2x_{10})}{x_{10}} + e\,\frac{g_A^4 M_\pi^7}{32\pi^3 F_\pi^4}\left[\vec\nabla_{10}\times\vec\sigma_1\right]\tau_2^3\,\delta(\vec x_{20})\,\frac{K_1(2x_{10})}{x_{10}^2}\,,$$



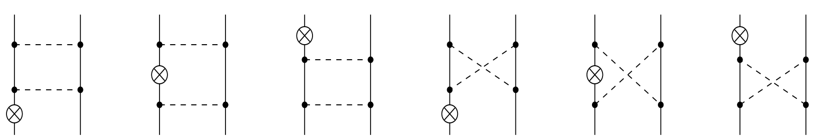
$$\vec J = -\,e\,\frac{M_\pi^7}{512\pi^4 F_\pi^4}\,[\vec\tau_1\times\vec\tau_2]^3\,(\vec\nabla_{10}-\vec\nabla_{20})\,\frac{K_2(x_{10}+x_{20}+x_{12})}{(x_{10}\,x_{20}\,x_{12})(x_{10}+x_{20}+x_{12})}$$



$$\vec J = 0$$

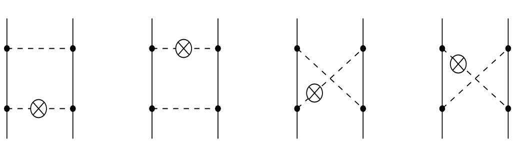


$$\vec J = -\,e\,\frac{g_A^2 M_\pi^7}{256\pi^4 F_\pi^4}\left(\vec\nabla_{10}-\vec\nabla_{20}\right)\left[[\vec\tau_1\times\vec\tau_2]^3\,\vec\nabla_{12}\cdot\vec\nabla_{20} - 2\tau_1^3\vec\sigma_2\cdot\left[\vec\nabla_{12}\times\vec\nabla_{20}\right]\right] \times \frac{K_1(x_{10}+x_{20}+x_{12})}{(x_{10}\,x_{20}\,x_{12})}\,,$$



$$\vec J = 0$$

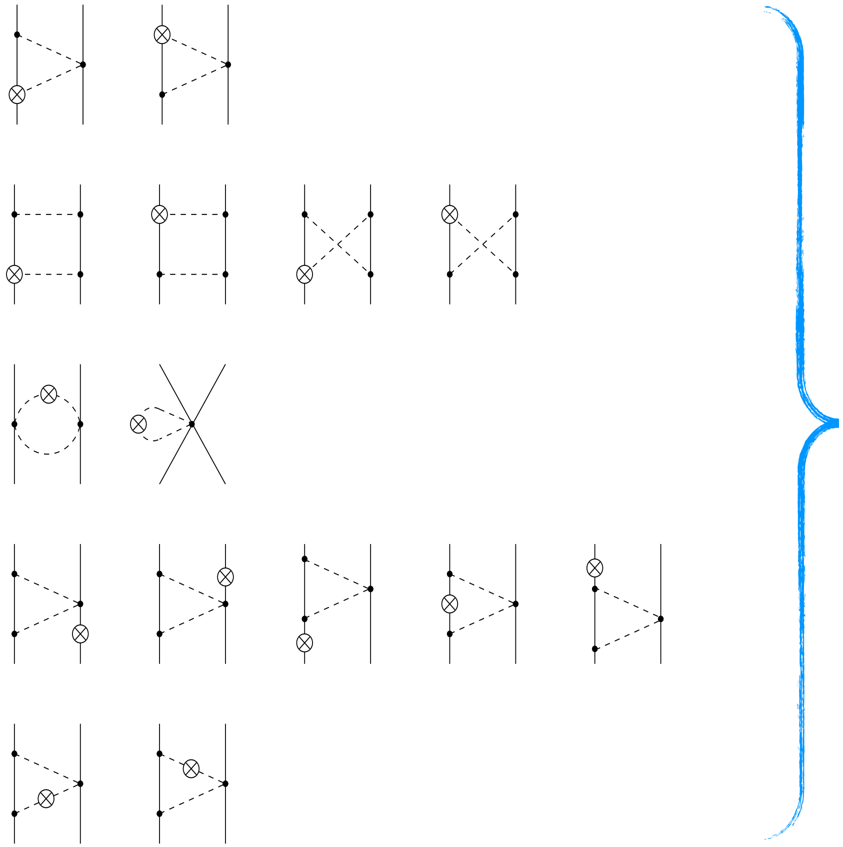
- ✓ parameter-free results,
- ✓ (almost) complete agreement with Pastore et al.



$$\vec J = e\,\frac{g_A^4 M_\pi^7}{512\pi^4 F_\pi^4}\left(\vec\nabla_{10}-\vec\nabla_{20}\right)\left[[\vec\tau_1\times\vec\tau_2]^3\,\vec\nabla_{12}\cdot\vec\nabla_{10}\,\vec\nabla_{12}\cdot\vec\nabla_{20} + 4\tau_2^3\vec\sigma_1\cdot\left[\vec\nabla_{12}\times\vec\nabla_{10}\right]\vec\nabla_{12}\cdot\vec\nabla_{20}\right] \times \frac{x_{10}+x_{20}+x_{12}}{x_{10}\,x_{20}\,x_{12}}\,K_0(x_{10}+x_{20}+x_{12})\,,$$

Two-pion exchange charge density

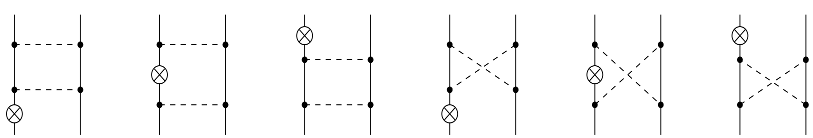
Kölling, EE, Krebs, Meißner ’09

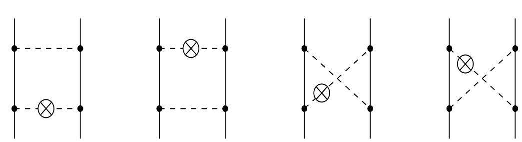


$$\rho = 0$$

- ✓ parameter-free results
- ✓ nonvanishing 2-body density even in the static limit (!)
- ✓ results agree with Pastore et al.

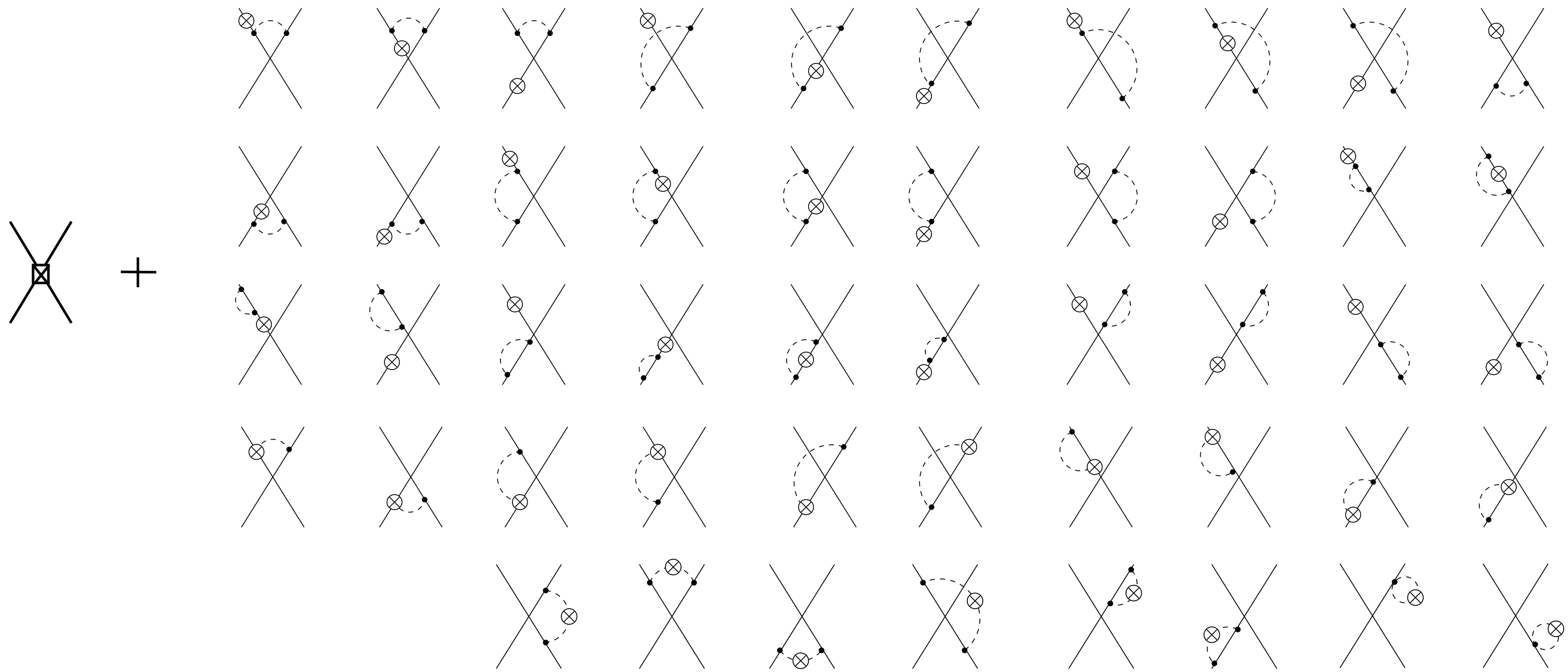
$$\rho = -\,e\,\frac{g_A^4\,M_\pi^7}{256\pi^2 F_\pi^4}\,\delta(\vec{x}_{20})\left[\tau_1^3\left(2\nabla_{10}^2-4\right) - \tau_2^3\vec{\sigma}_1\cdot\vec{\sigma}_2\right]\frac{e^{-2x_{10}}}{x_{10}^2} + \tau_2^3\,\vec{\sigma}_1\cdot\vec{\nabla}_{10}\,\vec{\sigma}_2\cdot\vec{\nabla}_{10}$$
$$-\,e\,\frac{g_A^4\,M_\pi^7}{128\pi^2 F_\pi^4}\,\delta(\vec{x}_{20})\,\tau_1^3\,\left(3\nabla_{10}^2-11\right)\,\frac{e^{-2x_{10}}}{x_{10}}$$





$$\rho = -\,e\,\frac{g_A^4\,M_\pi^7}{512\pi^3 F_\pi^4}\Big[(\tau_1^3+\tau_2^3)\Big(\vec{\nabla}_{12}\cdot\vec{\nabla}_{10}\vec{\nabla}_{12}\cdot\vec{\nabla}_{20} + \vec{\nabla}_{12}\cdot\big[\vec{\nabla}_{10}\times\vec{\sigma}_1\big]\,\vec{\nabla}_{12}\cdot\big[\vec{\nabla}_{20}\times\vec{\sigma}_2\big]\Big)$$
$$+\,[\vec{\tau}_1\times\vec{\tau}_2]^3\,\vec{\nabla}_{12}\cdot\vec{\nabla}_{10}\,\vec{\nabla}_{12}\cdot\big[\vec{\nabla}_{20}\times\vec{\sigma}_2\big]\Big]\,\frac{e^{-x_{10}}}{x_{10}}\,\frac{e^{-x_{20}}}{x_{20}}\,\frac{e^{-x_{12}}}{x_{12}}\,.$$

Short-range currents



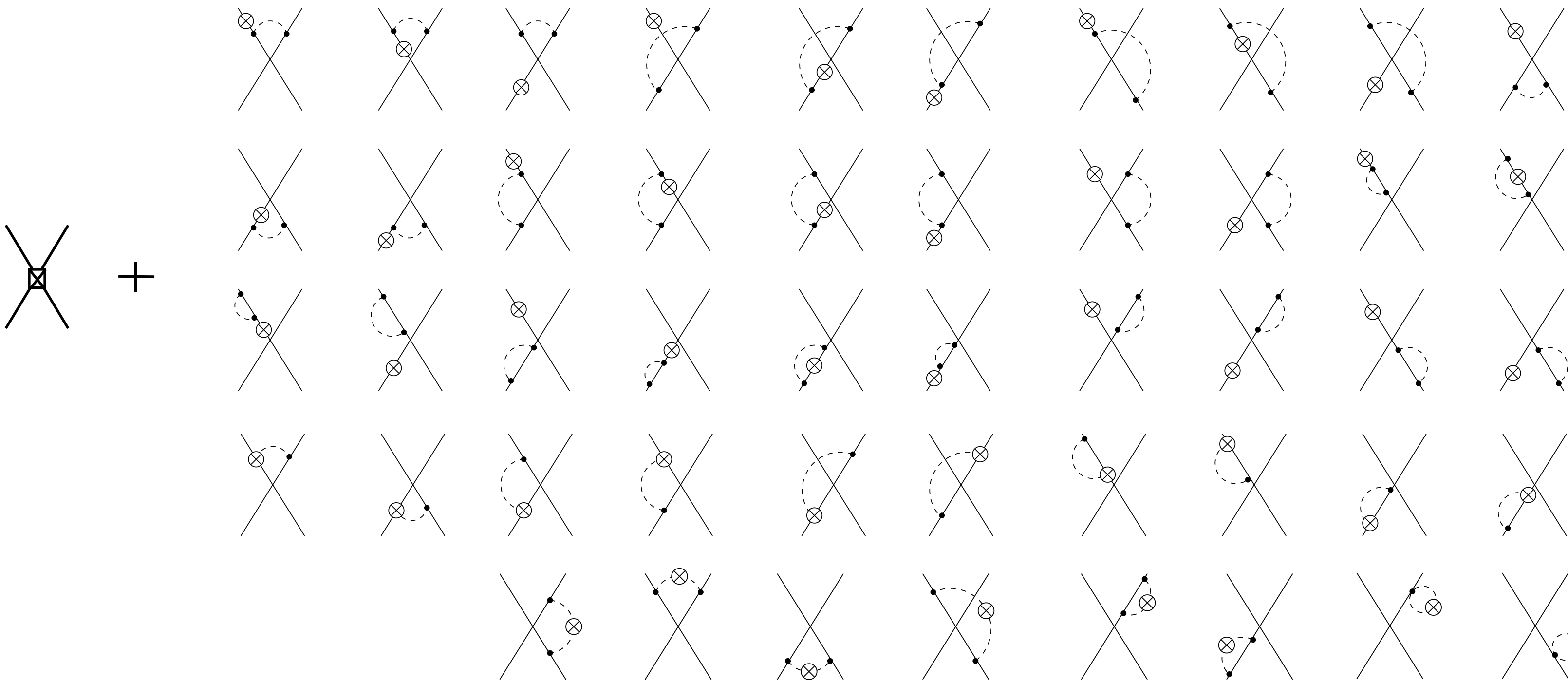
Current density

$$\vec{J}_{\rm contact} = e\,\frac{i}{16}\,[\vec{\tau}_1\times\vec{\tau}_2]^3\,\Big[(C_2+3C_4+C_7)\,\vec{q}_1-(-C_2+C_4+C_7)\,\,(\vec{\sigma}_1\cdot\vec{\sigma}_2)\,\,\vec{q}_1+C_7\,(\vec{\sigma}_2\cdot\vec{q}_1\,\vec{\sigma}_1+\,\vec{\sigma}_1\cdot\vec{q}_1\,\vec{\sigma}_2)\Big]$$
$$-\;e\,\frac{C_5\,i}{16}\,\tau_1^3\,\,[(\vec{\sigma}_1+\vec{\sigma}_2)\times\vec{q}_1]+ieL_1\,\tau_1^3\,\Big[(\vec{\sigma}_1-\vec{\sigma}_2)\times\vec{k}\Big]+ieL_2\,\,[(\vec{\sigma}_1+\vec{\sigma}_2)\times\vec{q}_1]$$

Charge density $\rho_{\rm contact}=C_T\,\tau_1^3\,\Big[\vec{\sigma}_1\cdot\vec{k}\,\vec{\sigma}_2\cdot\vec{k}\,f_9(k)+\vec{\sigma}_1\cdot\vec{\sigma}_2\,f_{10}(k)\Big]$

with $f_9(k)=e\frac{g_A^2}{32F_\pi^2\pi}\left(A(k)+\frac{M_\pi-4M_\pi^2\,A(k)}{k^2}\right)\,,\qquad f_{10}(k)=e\frac{g_A^2}{32F_\pi^2\pi}\,\left(M_\pi-(4M_\pi^2+3k^2)\,A(k)\right)$

Short-range currents



Current density

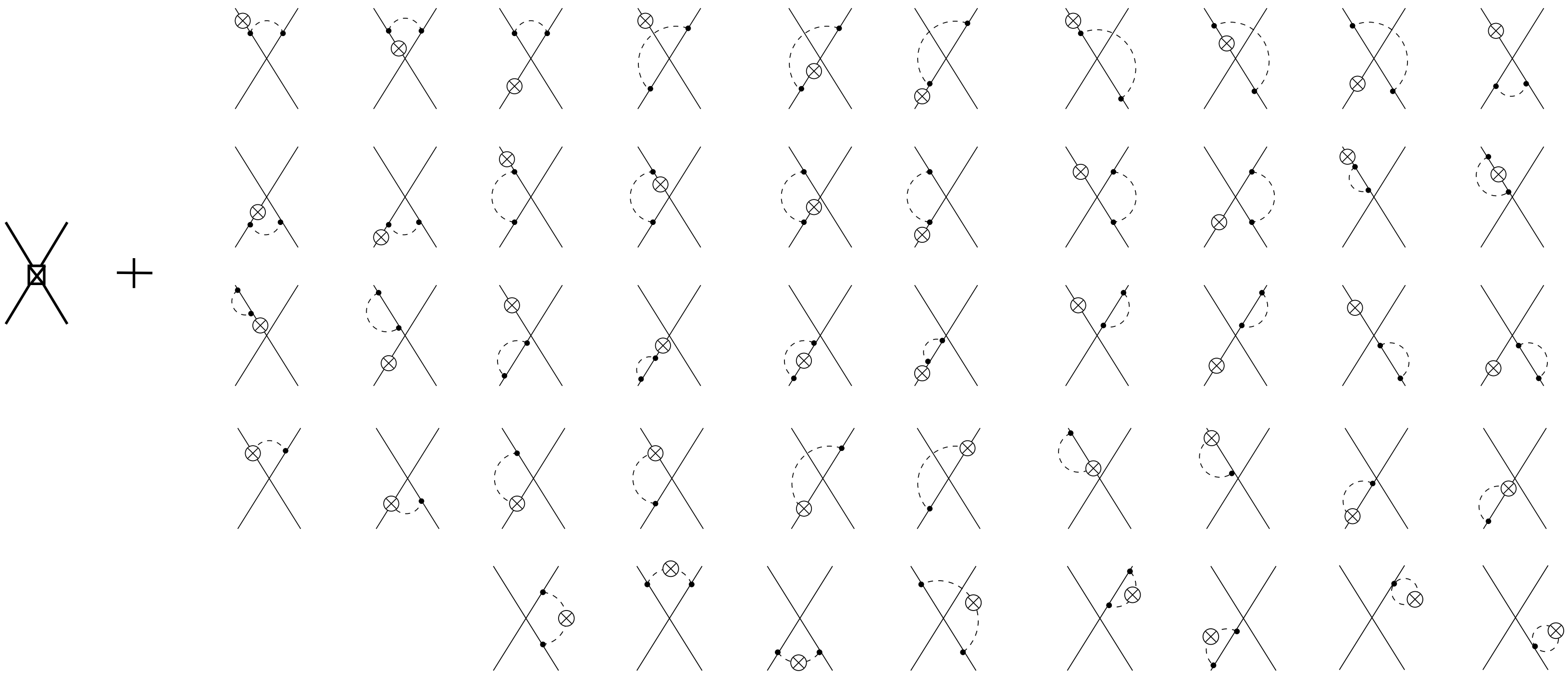
$$
\begin{aligned}
\vec{J}_{\rm contact} \;=\;& e\,\frac{i}{16}\,[\vec{\tau}_1\times\vec{\tau}_2]^3\,\Big[(C_2+3C_4+C_7)\;\vec{q}_1-(-C_2+C_4+C_7)\;(\vec{\sigma}_1\cdot\vec{\sigma}_2)\;\vec{q}_1+C_7\;(\vec{\sigma}_2\cdot\vec{q}_1\,\vec{\sigma}_1+\,\vec{\sigma}_1\cdot\vec{q}_1\,\vec{\sigma}_2)\Big]\\
&-\;e\,\frac{C_5\,i}{16}\,\tau_1^3\;[(\vec{\sigma}_1+\vec{\sigma}_2)\times\vec{q}_1]+i\,e\,L_1\,\tau_1^3\;\Big[(\vec{\sigma}_1-\vec{\sigma}_2)\times\vec{k}\Big]+i\,e\,L_2\,[(\vec{\sigma}_1+\vec{\sigma}_2)\times\vec{q}_1]
\end{aligned}
$$

Two new LECs $L_{1,2}$ (C_i's are the same as in the potential)

Charge density $\rho_{\rm contact}=C_T\,\tau_1^3\,\Big[\vec{\sigma}_1\cdot\vec{k}\,\vec{\sigma}_2\cdot\vec{k}\,f_9(k)+\vec{\sigma}_1\cdot\vec{\sigma}_2\,f_{10}(k)\Big]$

with $f_9(k)=e\dfrac{g_A^2}{32F_\pi^2\pi}\left(A(k)+\dfrac{M_\pi-4M_\pi^2\,A(k)}{k^2}\right)$, $\qquad f_{10}(k)=e\dfrac{g_A^2}{32F_\pi^2\pi}\,\big(M_\pi-(4M_\pi^2+3k^2)\,A(k)\big)$

Short-range currents



Current density

$$\vec{J}_{\rm contact} = e\,\frac{i}{16}\,[\vec{\tau}_1\times\vec{\tau}_2]^3\Big[(C_2+3C_4+C_7)\,\vec{q}_1-(-C_2+C_4+C_7)\,(\vec{\sigma}_1\cdot\vec{\sigma}_2)\,\vec{q}_1+C_7\,(\vec{\sigma}_2\cdot\vec{q}_1\,\vec{\sigma}_1+\vec{\sigma}_1\cdot\vec{q}_1\,\vec{\sigma}_2)\Big]$$
$$-\; e\,\frac{C_5\,i}{16}\,\tau_1^3\,[(\vec{\sigma}_1+\vec{\sigma}_2)\times\vec{q}_1]+i\,eL_1\,\tau_1^3\,\Big[(\vec{\sigma}_1-\vec{\sigma}_2)\times\vec{k}\Big]+i\,eL_2\,[(\vec{\sigma}_1+\vec{\sigma}_2)\times\vec{q}_1]$$

Two new LECs $L_{1,2}$ (C_i's are the same as in the potential)

Pion loop contributions differ from the ones by Pastore et al.

Charge density

$$\rho_{\rm contact}=C_T\,\tau_1^3\,\Big[\vec{\sigma}_1\cdot\vec{k}\,\vec{\sigma}_2\cdot\vec{k}\,f_9(k)+\vec{\sigma}_1\cdot\vec{\sigma}_2\,f_{10}(k)\Big]$$

with $f_9(k)=e\frac{g_A^2}{32F_\pi^2\pi}\left(A(k)+\frac{M_\pi-4M_\pi^2\,A(k)}{k^2}\right)$, $\quad f_{10}(k)=e\frac{g_A^2}{32F_\pi^2\pi}\left(M_\pi-(4M_\pi^2+3k^2)\,A(k)\right)$

Em currents & the deuteron elastic FFs

Meißner, Walzl, Phillips, …

- FFs of the deuteron:

$$G_M = -\frac{1}{\sqrt{2\eta}|e|}\langle 1|J^+|0\rangle, \qquad G_Q = \frac{1}{2\eta|e|m_d^2}\Big(\langle 0|\rho|0\rangle - \langle 1|\rho|1\rangle\Big), \qquad G_C = \frac{1}{3|e|}\Big(\langle 1|\rho|1\rangle + \langle 0|\rho|0\rangle + \langle -1|\rho|-1\rangle\Big)$$

- Using exp. data for 1N FFs as input allows to probe nuclear structure effects Phillips '03

- Most of the exchange current/charge operators are isovectors. The only relevant isoscalar pieces are:

$$\vec{J}_{1\pi} = 2ie\frac{g_A}{F_\pi^2}\,\bar{d}_9\,\vec{\tau}_1\cdot\vec{\tau}_2\,\frac{\vec{\sigma}_2\cdot\vec{q}_2\;\vec{q}_1\times\vec{q}_2}{q_2^2+M_\pi^2}$$

$$\rho_{1\pi} = \frac{eg_A^2}{16F_\pi^2 m_N}\,\vec{\tau}_1\cdot\vec{\tau}_2\left[(1-2\bar{\beta}_9)\,\frac{\vec{\sigma}_1\cdot\vec{k}\;\vec{\sigma}_2\cdot\vec{q}_2}{q_2^2+M_\pi^2} + \left(2\bar{\beta}_8-1\right)\frac{\vec{\sigma}_1\cdot\vec{q}_2\,\vec{\sigma}_2\cdot\vec{q}_2}{(q_2^2+M_\pi^2)^2}\,\vec{q}_2\cdot\vec{k}_1\right]$$

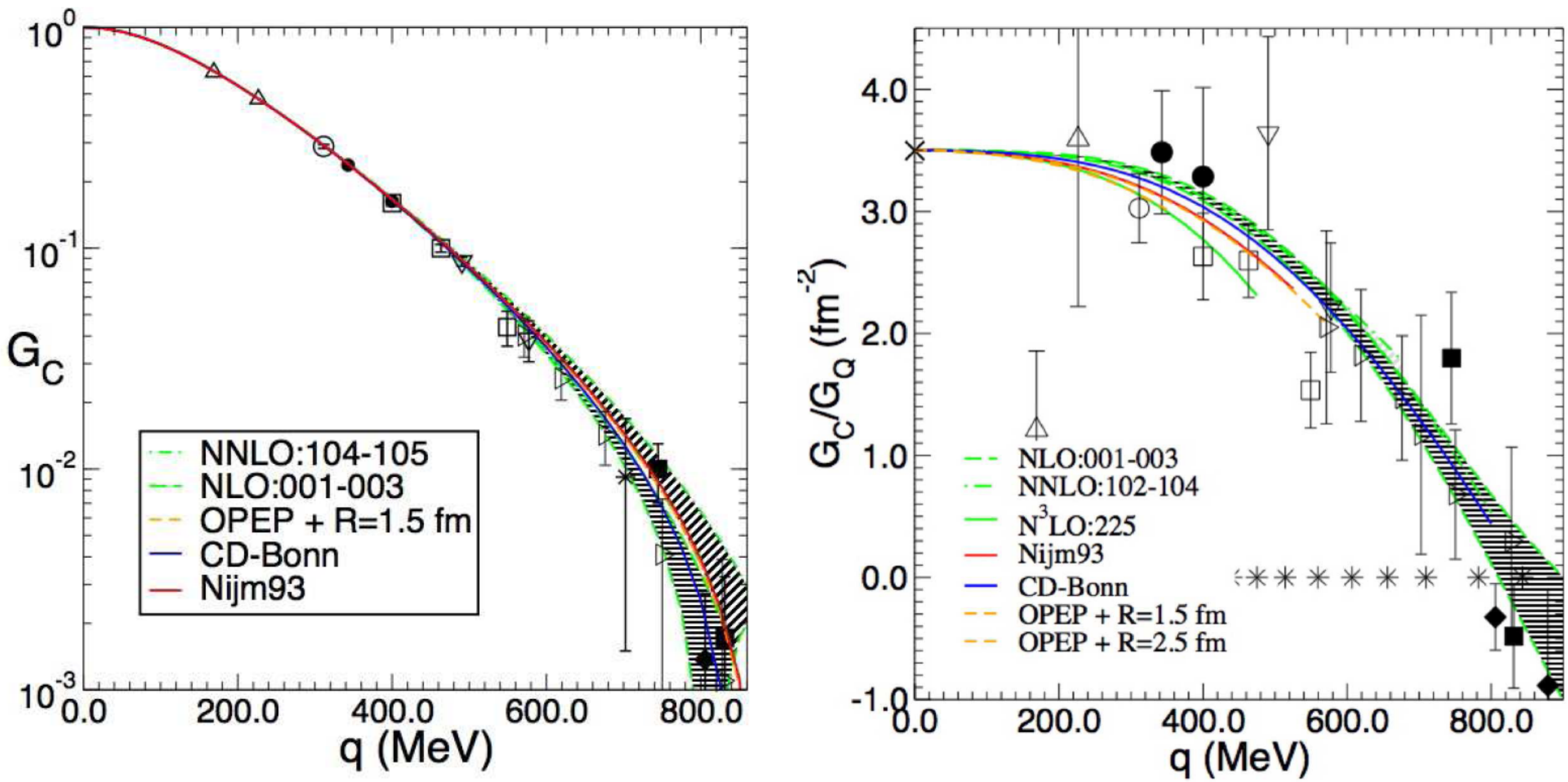
$$\vec{J}_{\rm contact} = ieL_2\,\left[(\vec{\sigma}_1+\vec{\sigma}_2)\times\vec{q}_1\right]$$

- The constants $\bar{\beta}_{8,9}$ parametrize the unitary ambiguity & have to be chosen consistently with the potential Friar '80, Adam, Goller, Arenhövel '93, EE, Glöckle, Meißner '04

- The LECs $\bar{d}_9,\; L_2$ contribute to the magnetic FF

Em currents & the deuteron elastic FFs

Phillips '07



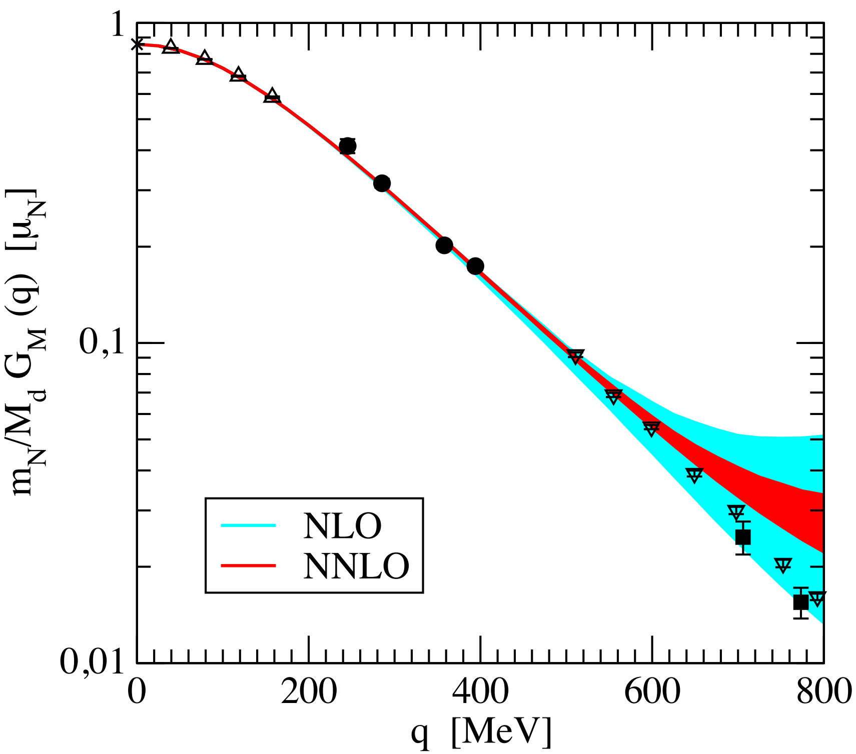
(from Phillips, J. Phys. G 34 (2007) 365)

- G_C: parameter-free prediction; G_C/G_Q: 1 short-range term fitted to the quadrupole moment;
- In both cases 1N FFs used as input…

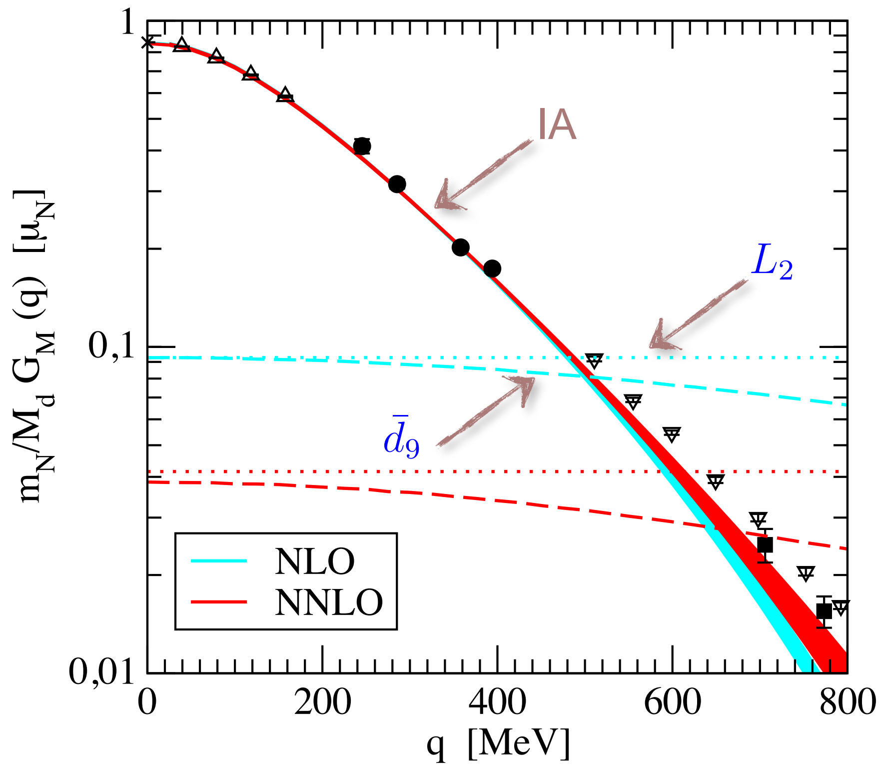
Em currents & the deuteron elastic FFs

Kölling, EE, Phillips, in preparation

Deuteron magnetic form factor



IA and exchange current contributions



- 1N form factors from Belushkin, Hammer, Meißner '07
- $\bar{d}_9, \; L_2$ fitted to the deuteron magnetic moment and FF for q < 400 MeV:

$\bar{d}_9 = -0.01 \ldots 0.01 \text{ GeV}^{-2} \quad L_2 = 0.28 \ldots 0.48 \text{ GeV}^{-4}$ (NNLO WF)

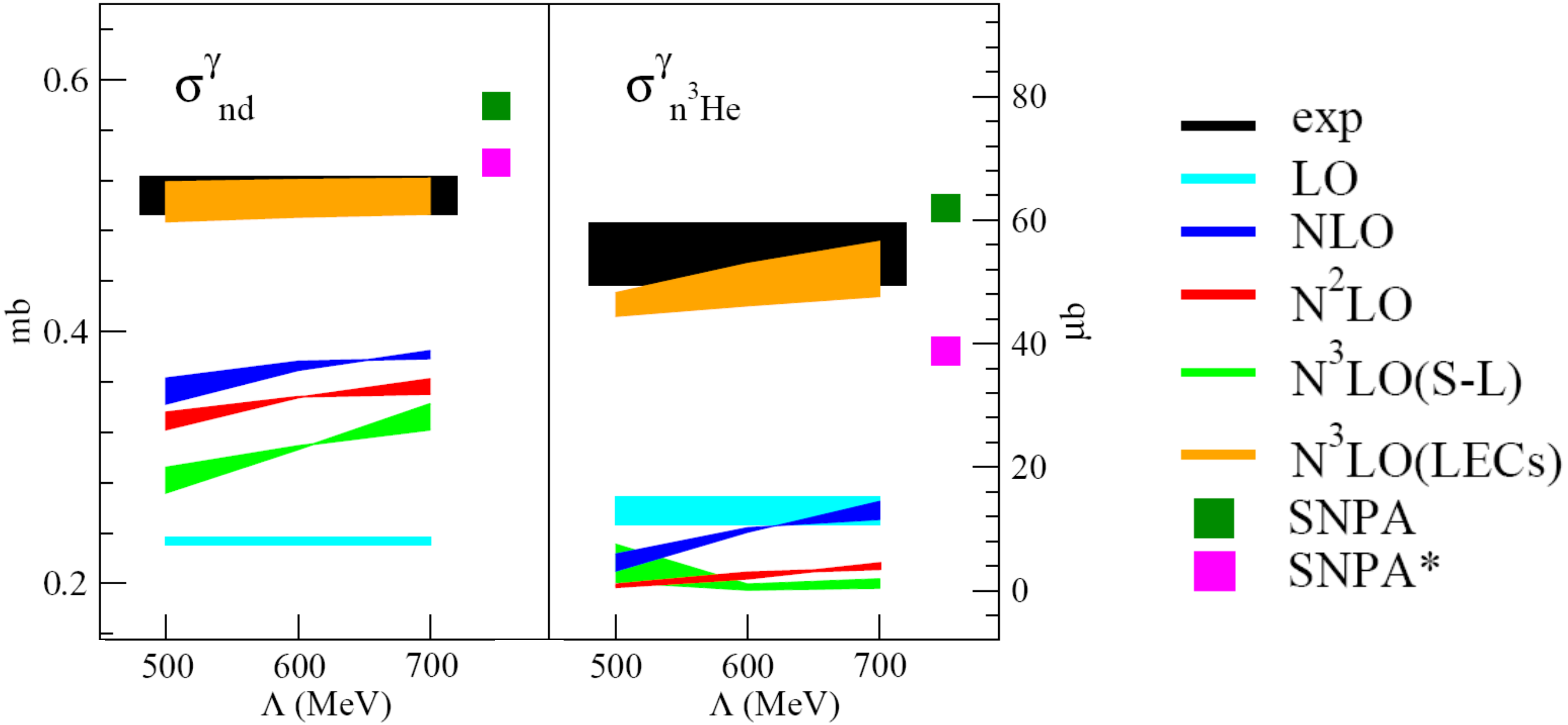
Pion photoproduction: $\bar{d}_9 = -0.06 \text{ GeV}^{-2}$ Gasparyan, Lutz '10

Em currents & rad. neutron capture

Girlanda, Kievsky, Marcucci, Pastori , Schiavilla, Viviani, PRL 105 (10) 232502

LECs „determined“ assuming Δ-dominance + magnetic moments of ^{2}H, ^{3}H, ^{3}He + σ_{np}^{γ}

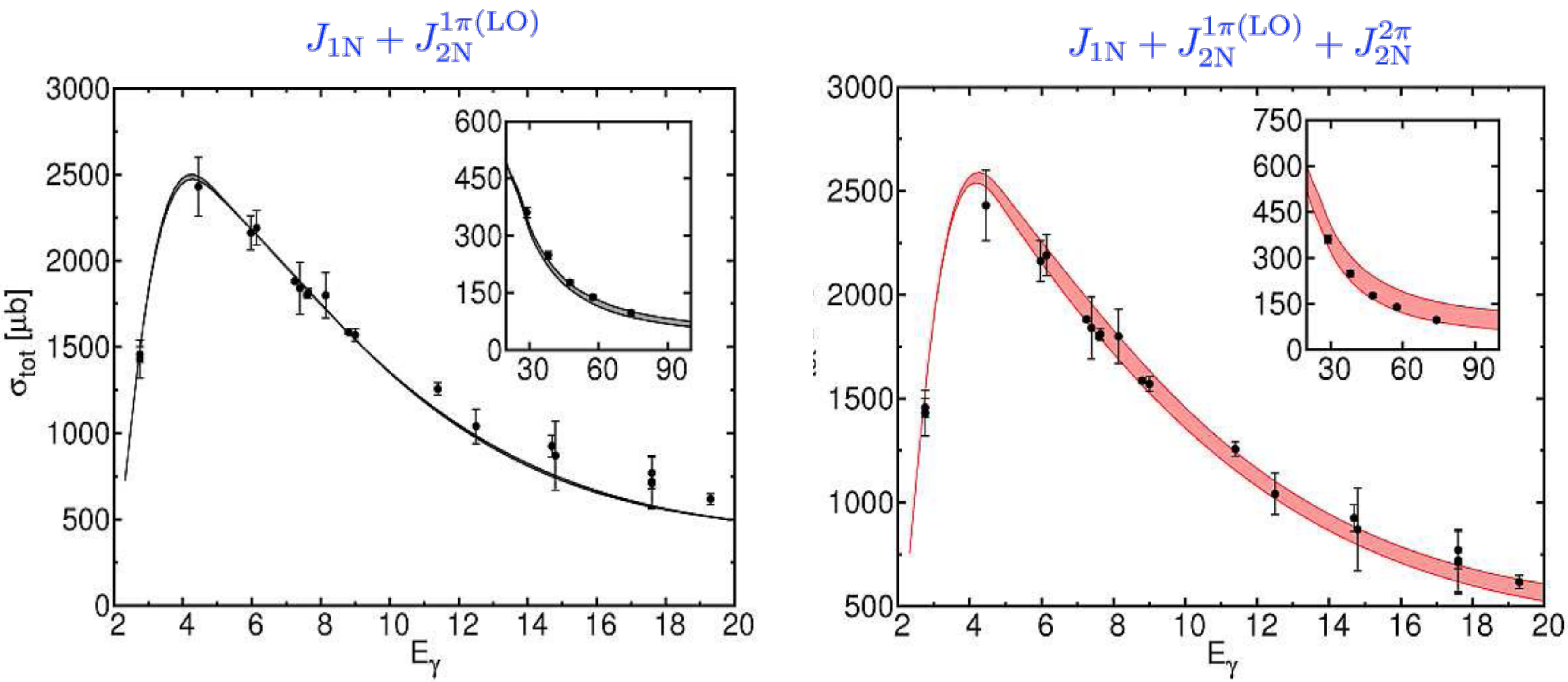
➡ predictions for nd, n^{3}He radiative capture reactions for thermal neutrons (MEC dominated)



related recent work: Lazauskas, Song, Park ‘09

Deuteron photodisintegration

Rozpedzik, Golak, Kölling, EE, Skibinski, Witala, Nogga ’11

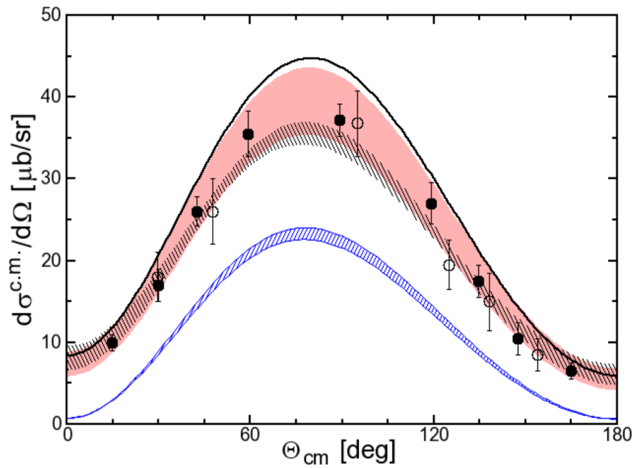


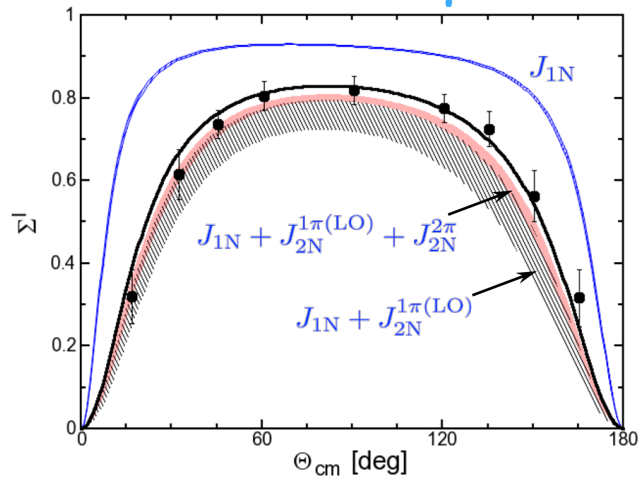
short-range & (subleading)1π-exchange terms still to be included

Deuteron photodisintegration

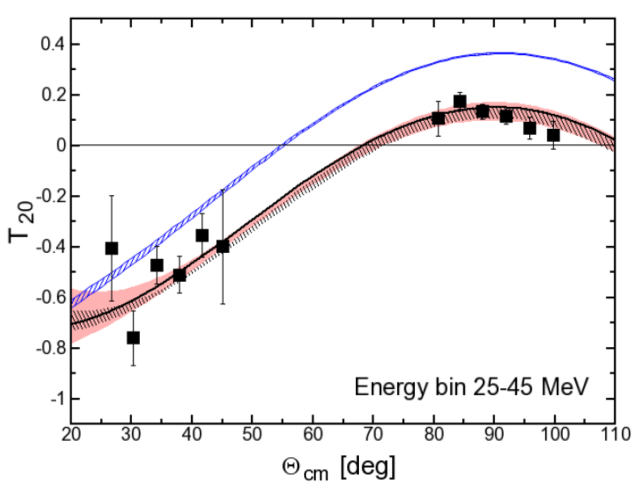
Rozpedzik, Golak, Kölling, EE, Skibinski, Witala, Krebs ’11

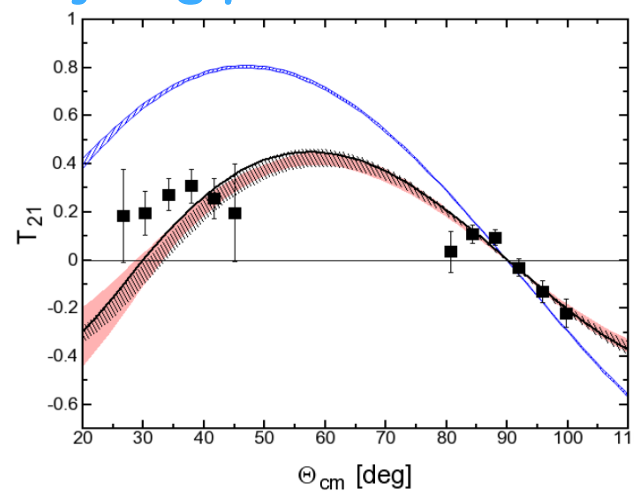
Cross section and photon analyzing power at E_γ =30 MeV





Deuteron tensor analyzing powers



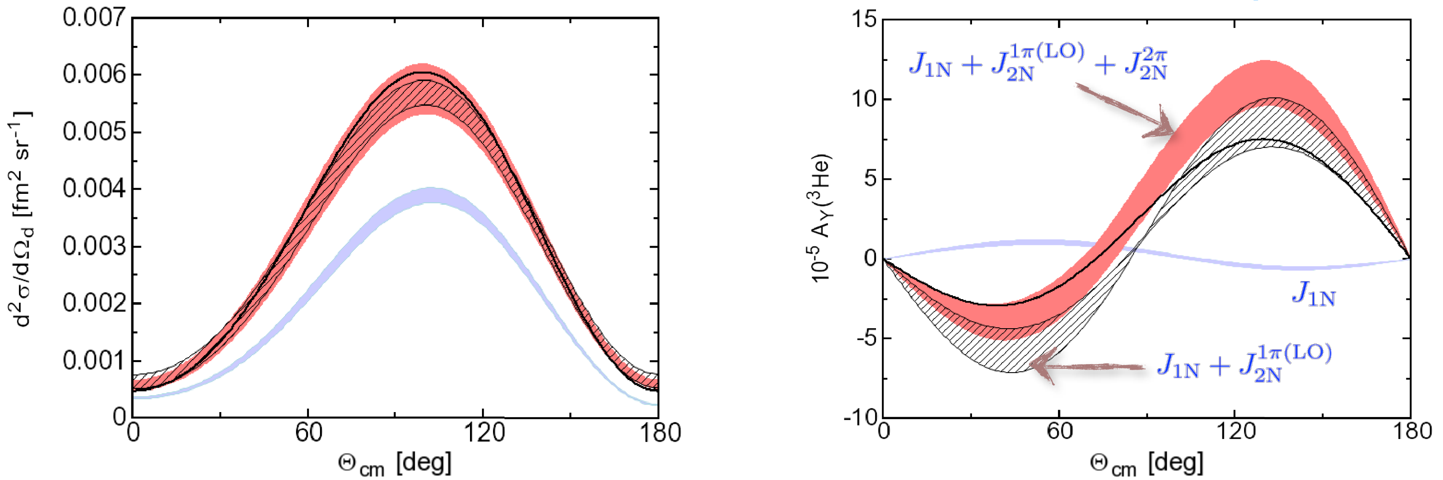


large sensitivity to MEC; short-range & 1π-exchange terms still to be included

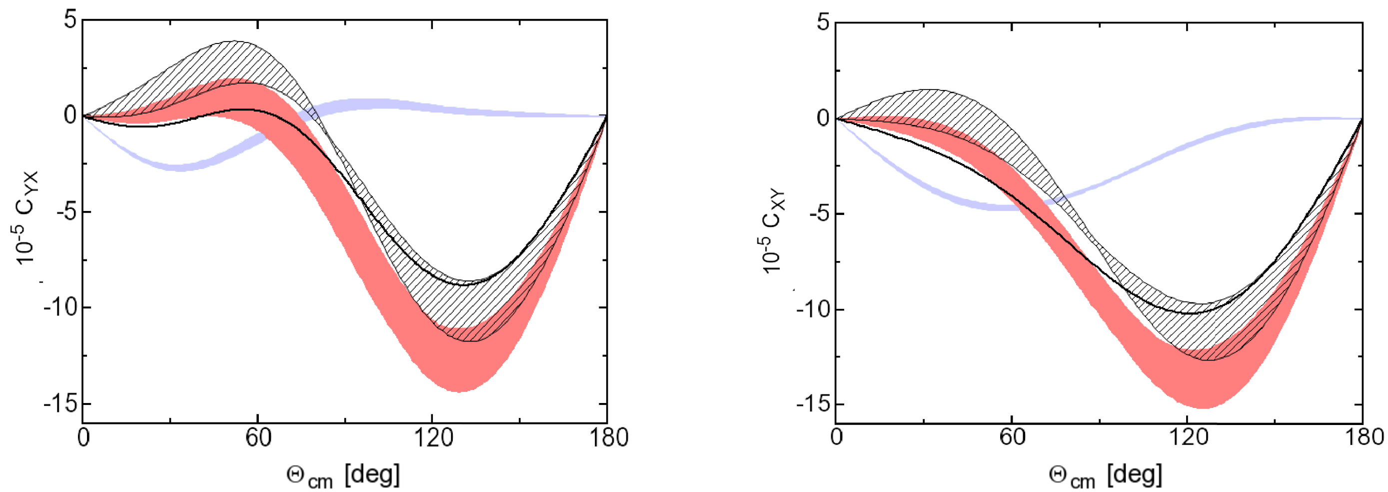
^{3}He 2-body photodisintegration

Rozpedzik, Golak, Kölling, EE, Skibinski, Witala, Krebs ’11

Cross section and photon analyzing power at E_γ =20 MeV



Spin correlation coefficients



large sensitivity to MEC; short-range & 1π-exchange terms still to be included

Reactions involving pions

- **Pion-deuteron scattering and pion-nucleon scattering lengths**
  Weinberg'92, Beane et al.'93, Baru et al.'04,'11, Liebig'10
- **Pion production in NN collisions**
  Cohen et al.'96; Dmitrasinovic et al.'99; da Rocha et al.'00; Hanhart et al.'01,'02, Baru et al.'09, Filin et al. '12
- **$np \to d\pi^0$ and the strong nucleon mass shift**
  Niskanen '99; van Kolck et al. '00; Bolton, Miller '09; Filin, Baru, E.E., Haidenbauer, Hanhart, Kudryavtsev, Meißner '09
- **Pion photo/electroproduction off light nuclei**
  Beane, Bernard, Lee, Meißner, van Kolck, Krebs, Lenkewitz EE, Hammer
- **$\gamma d \to \pi^+ nn$ and nn scattering length**
  Lensky, Baru, EE, Hanhart, Haidenbauer, Kudryavtsev, Meißner '07

Pion-deuteron scattering

Pion-nucleon amplitude at threshold (in the isospin limit): $T^{ba}_{\pi N} \propto \left[\delta^{ab}\boldsymbol{a}^{+} + i\epsilon^{bac}\tau^{c}\boldsymbol{a}^{-}\right]$

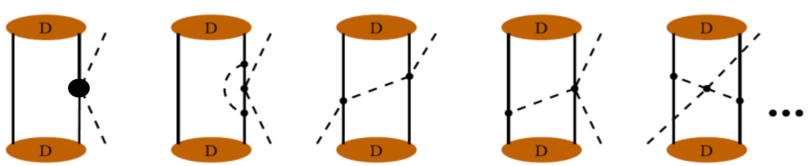
Recent data on hadronic atoms:

πH: $\epsilon_{1s} = (-7.120 \pm 0.012)\,\mathrm{eV}, \quad \Gamma_{1s} = (0.823 \pm 0.019)\,\mathrm{eV}$ Gotta et al., Lect. Notes. Phys. 745 (08) 165

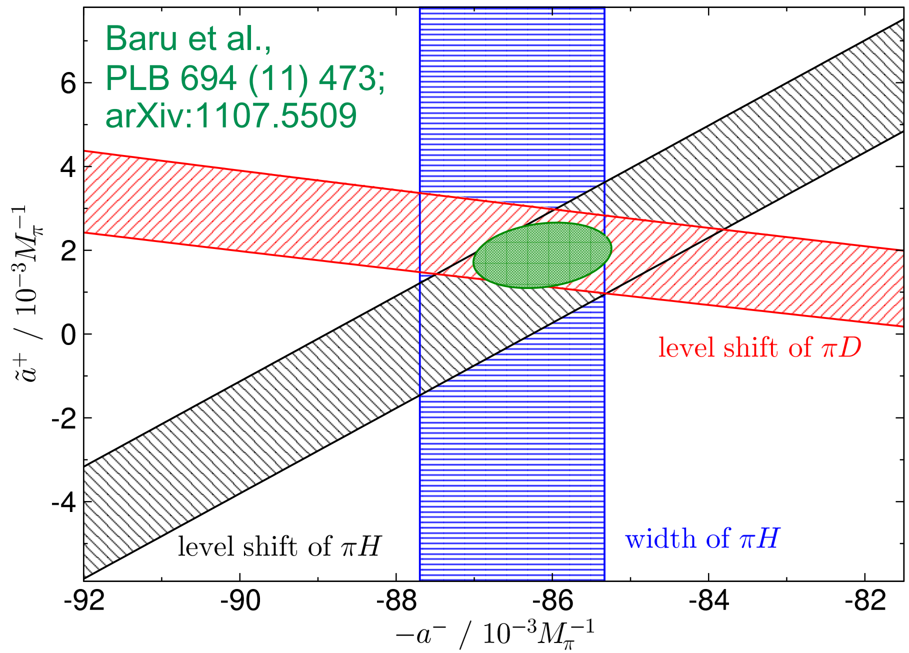
πD: $\epsilon^{D}_{1s} = (2.356 \pm 0.031)\,\mathrm{eV}$ Strauch et al., Eur. Phys. J A47 (11) 88

Use chiral EFT to extract information on a^{+} and a^{-} from $a_{\pi d}$:

Weinberg '92; Beane et al.'98,'03; Liebig et al.'11; Meißner et al. '06; Baru et al. '04-'11;...

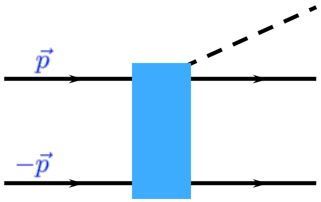


- careful analysis of IB effects
- radiative corrections included
- the scale $\sqrt{M_\pi m_N}$ must be taken into account (3-body singularity, dispersive corrections)



Pion production in NN collisions

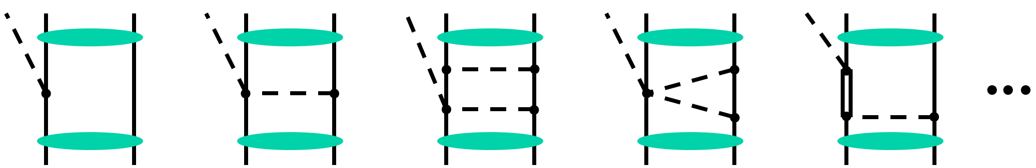
Considerably more challenging due to the appearance of a new „soft“ scale $|\vec{p}| \gtrsim \sqrt{M_\pi m_N} \sim 350 \text{ MeV}$



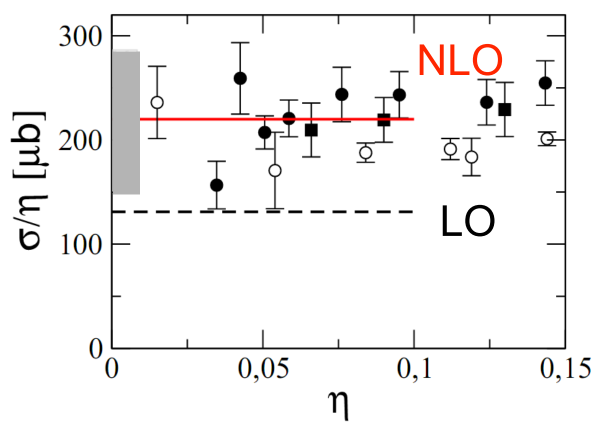
→ slower convergence of the chiral expansion (expansion parameter $\sqrt{M_\pi m_N}/\Lambda_\chi$ vs M_π/Λ_χ)

State-of-the-art

- hybrid approach (EFT description of the 2N system for $|\vec{p}| \sim \sqrt{M_\pi m_N}$ not yet available)
- Δ(1232) isobar plays an important role → must be included as an explicit DOF
- s-wave pion production worked out up to NLO
  Cohen et al.’96; Dmitrasinovic et al.’99; da Rocha et al.’00; Hanhart et al.’01,’02



results for pp → dπ$^+$



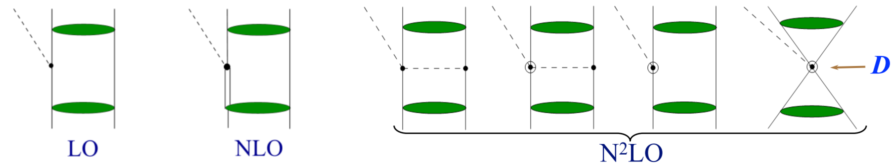
$\sigma = \alpha\eta + \mathcal{O}(\eta^3), \quad \eta \equiv k_\pi/M_\pi$

- proper separation of irred. contributions crucial!
  Lensky et al. ’01
- NNLO contributions (no Δ) worked out recently
  Filin et al. ’12

p-wave π-production and the D-term

Hanhart, van Kolck, Miller '00; Baru, EE, Haidenbauer, Hanhart, Kudryavtsev, Lensky, Meißner '09

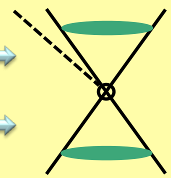
- Loops start to contribute at N^{3}LO
- Up to N^{2}LO, D is the only unknown LEC
- Simultaneous description of



$pn \to pp\pi^-$, $pp \to pn\pi^+$ and $pp \to d\pi^+$ → nontrivial consistency check of chiral EFT

$|\vec{p}\,'| \sim M_\pi$ ⇒

$|\vec{p}| \sim \sqrt{M_\pi m_N}$ ⇒

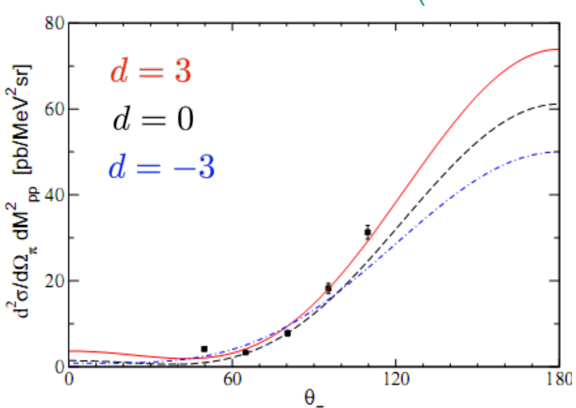


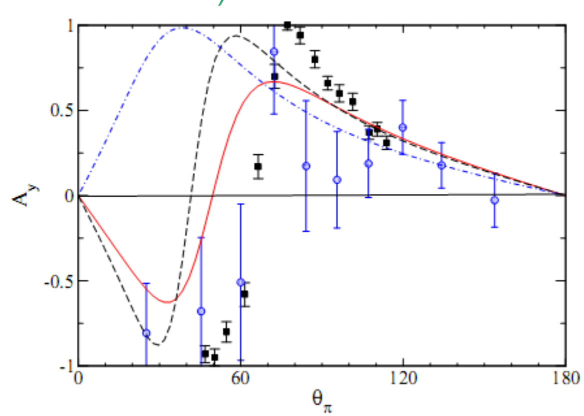
⇐ $^1S_0$ for $pp \to pn\pi^+$, $pp \to d\pi^+$; $^3S_1$ for $pn \to pp\pi^-$

⇐ $^3S_1$ for $pp \to pn\pi^+$, $pp \to d\pi^+$; $^1S_0$ for $pn \to pp\pi^-$

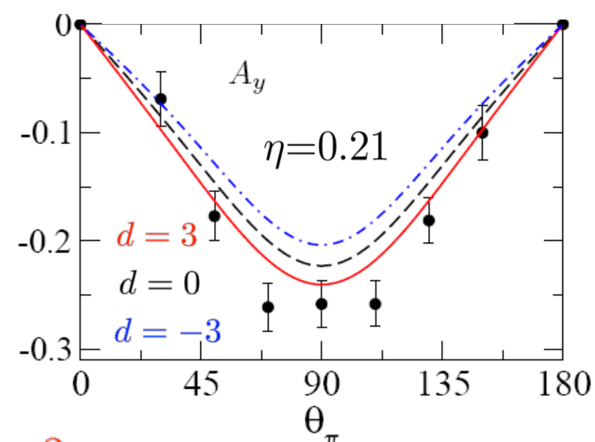
Reaction pn → ppπ^-

(data from TRIUMF and PSI)





Reaction pp → dπ^+



→ overall best description for $d = 3$

Isospin breaking & few-N systems

Origins of isospin breaking in the Standard Model: $m_u \neq m_d$, photons

Isospin breaking & few-N systems

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- Manifestation in the hadron spectrum: mass splittings

$$M_{\pi^\pm} = 139.57 \text{ MeV}, \quad M_{\pi^0} = 134.98 \text{ MeV}$$ ← mainly of electromagnetic origin

$$m_p = 938.27 \text{ MeV}, \quad m_n = 939.57 \text{ MeV}$$ ← both strong and electromagnetic

$$\delta m_N^{\text{str}} \equiv (m_n - m_p)^{\text{str}} = 2.05 \pm 0.3 \text{ MeV}$$ Gasser, Leutwyler '82 (Cottingham sum rule)

$$\delta m_N^{\text{em}} \equiv (m_n - m_p)^{\text{em}} = -0.76 \pm 0.3 \text{ MeV}$$

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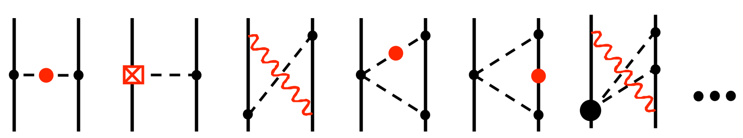
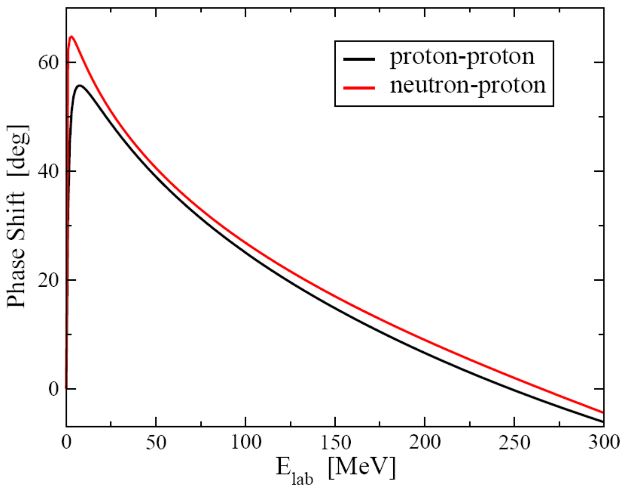
- Different (strong) forces between nn, np and pp

van Kolck, Friar, Niskanen, Kaiser, EE, Meißner, …





Manifestations

– differences in NN phase shifts,

– BE differences in mirror nuclei (CSB)

$E_{^3He} - E_{^3H}$:

Coulomb	Breit	K.E.	Two-Body	Three-body	Theory	Experiment
648	28	14	65(22)	5	760(22)	764

Friar et al. PRC 71 (2005) 024003

Isospin breaking & few-N systems

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- $dd \rightarrow \alpha\pi^0$ cross section measurement at IUCF @ 228.5 / 231.8 MeV
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$$\sigma = 12.7 \pm 2.2 \,/\, 15.1 \pm 3.1 \text{ pb}$$

Theoretical analysis challenging; first estimations yield the right order of magnitude.
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- forward-backward asymetry in $np \to d\pi^0$ @ 279.5 MeV (TRIUMF)
  Opper et al. '03

$$A_{\rm fb} = \frac{\int [d\sigma/d\Omega(\theta) - d\sigma/d\Omega(\pi-\theta)]\, d[cos\theta]}{\int [d\sigma/d\Omega(\theta) + d\sigma/d\Omega(\pi-\theta)]\, d[cos\theta]} = \Big[17.2 \pm 8(\text{stat}) \pm 5.5(\text{sys})\Big] \times 10^{-4}$$

np → dπ⁰ & the np mass difference

Bolton, Miller '09; Filin, Baru, E.E., Haidenbauer, Hanhart, Kudryavtsev, Meißner '09

$$\frac{d\sigma}{d\Omega} = A_0 + \underbrace{A_1\, P_1(\cos\theta_\pi)} + A_2\, P_2(\cos\theta_\pi) + \ldots \longrightarrow A_{fb} \simeq \frac{A_1}{2A_0}$$

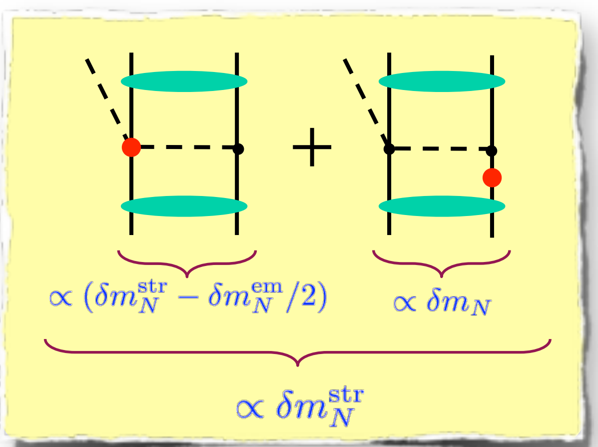
gives rise to A_{fb}, nonzero only for $pn \to d\pi^0$ due to interference of IB and IC amplitudes

- A_0 can be determined from the pionic deuterium lifetime measurement @ PSI:

$$\sigma(np \to d\pi^0) = \frac{1}{2}\sigma(nn \to d\pi^-) = \frac{1}{2} \times 252^{+5}_{-11}\, \eta\ [\mu\text{b}] \longrightarrow A_0 = 10.0^{+0.2}_{-0.4}\, \eta\ [\mu\text{b}]$$

- A_1 at LO: $A_1 = \frac{1}{128\pi^2}\frac{\eta M_\pi}{p(M_\pi + m_d)^2}\Re\Big[\underbrace{\Big(M_{^1S_0\to{}^3S_1,\,p} + \frac{2}{3}M_{^1D_2\to{}^3S_1,\,p}\Big)}\, M^*_{^1P_1\to{}^3S_1,\,s}\Big]$

IC amplitudes calculated at NLO Baru et al.'09



Our result: $A_{\rm fb}^{\rm LO} = (11.5 \pm 3.5) \times 10^{-4}\ \delta m_N^{\rm str}/\text{MeV}$

$$\longrightarrow \boxed{\delta m_N^{\rm str} = 1.5 \pm 0.8\,(\text{exp.}) \pm 0.5\,(\text{th.})\ \text{MeV}}$$

Lattice: $\delta m_N^{\rm str} = 2.26 \pm 0.57 \pm 0.42 \pm 0.10\ \text{MeV}$ Beane et al.'07

Cottingham SR: $\delta m_N^{\rm str} = 2.05 \pm 0.3\ \text{MeV}$ Gasser, Leutwyler '82

Summary & outlook

Electromagnetic currents

- worked out at leading loop order (ready-to-use expressions available)
- can be tested e.g. in $^2H/^3He$ photodisintegration

To be done: determination of LECs, already converged? (higher-orders/Δ), complete calculations including short-range terms, ...

Reactions involving pions

- precision calculation of pion-deuteron scattering
- pioneering studies of pion production in NN collisions
- great success of a theory: strong nucleon mass shift from A_{fb}

To be done: pion reactions with heavier nuclei, higher orders in pion production and extension of nuclear chiral EFT beyond the pion production threshold, ...

Also good progress on topics not covered (Compton scatt., axial currents, ...)