Evgeny Epelbaum, RUB

Electroweak properties of light nuclei, INT Seattle, 5-9.11.12

RUB

Electromagnetic currents in chiral effective field theory

Outline

- Introduction
- Exchange currents at leading-loop order
- Exchange currents and the deuteron form factors
- Exchange currents and deuteron photodisintegration
- Pion photoproduction off light nuclei
- Summary & outlook

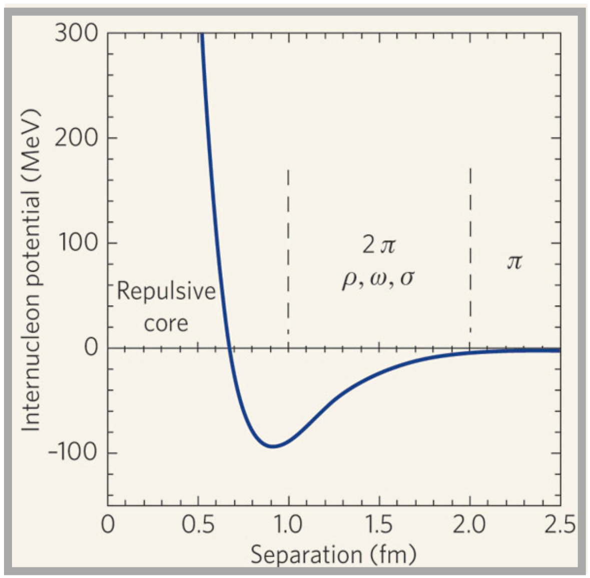
Introduction

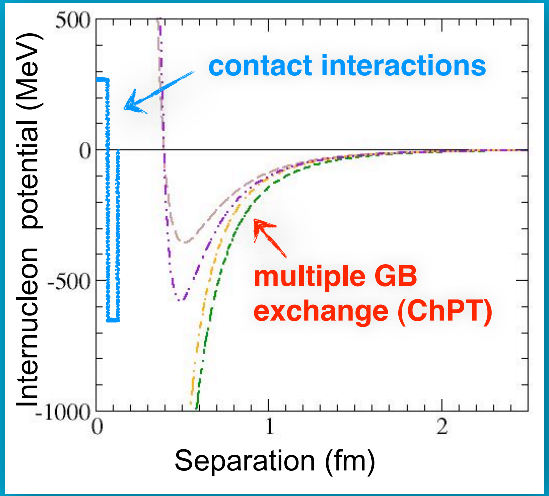
The roadmap: QCD ⟶ Chiral Perturbation Theory ⟶ hadron dynamics

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

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

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

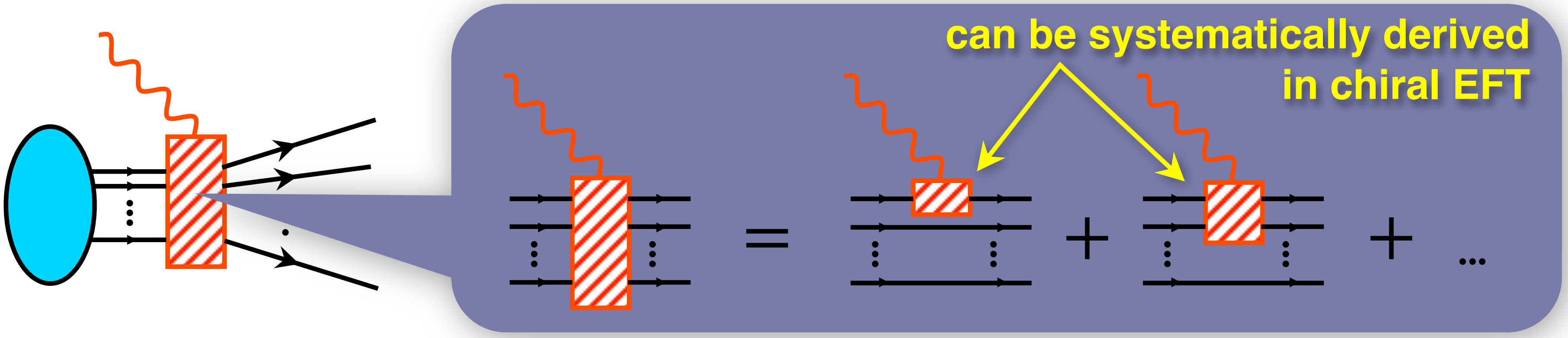




- **unified description of $\pi\pi$, πN and NN**
- **consistent many-body forces and currents**
- **systematically improvable**
- **bridging different reactions (electroweak, π-prod., ...)**
- **precision physics with/from light nuclei**

Electromagnetic currents

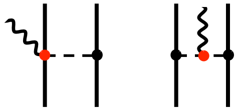
(one-photon exchange approximation)



for Compton scattering see talks by Harald Grießhammer and Winfried Leidemann

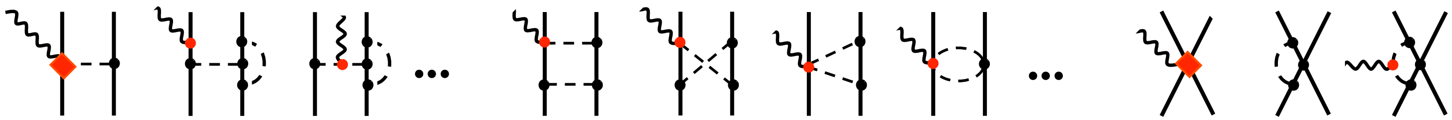
Electromagnetic exchange currents

Order eQ^{-1} :



well known since decades   Chemtob, Rho, Friar, Riska, Adam, …

Order eQ :



- **First ChPT calculations**

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

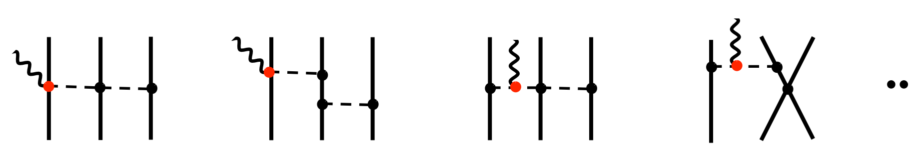
  Application to $np \to d\gamma$ at threshold: $\sigma_{1N} = 306.6 \text{ mb} \longrightarrow \sigma_{1N+2N} = 334 \pm 3 \text{ mb}$

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

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

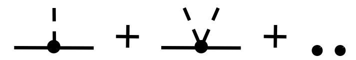
  TOPT: Pastore, Schiavilla, Girlanda, Viviani; UT: Kölling, Krebs, EE, Meißner

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: $\mathcal{L}_{\pi \mathrm{N}} \longrightarrow \mathcal{H}_{\pi \mathrm{N}} =$ 

From $L_{\rm eff}$ to nuclear forces/currents

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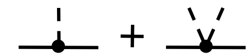
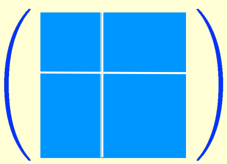
- Canonical transformation & quantization: $\mathcal{L}_{\pi N} \longrightarrow \mathcal{H}_{\pi N} =$  $+ \ldots$

- **Nuclear forces via UT (Fock space):** $H \to \tilde{H} = U^\dagger$  $U = \begin{pmatrix} \tilde{H}_{\rm nucl} & 0 \\ 0 & \tilde{H}_{\rm rest} \end{pmatrix}$
  - „Minimal" UT computed perturbatively $H = \sum_{\kappa=1}^{\infty} (1/\Lambda)^\kappa H^{(\kappa)}$
  - Only $\tilde{H}_{\rm nucl}$ is needed below the pion production threshold
  - We employ all additional UTs possible at a given order in the expansion
  - Renormalizability ⟶ unambigous results for 4NF & (static) 3NF upto N³LO

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

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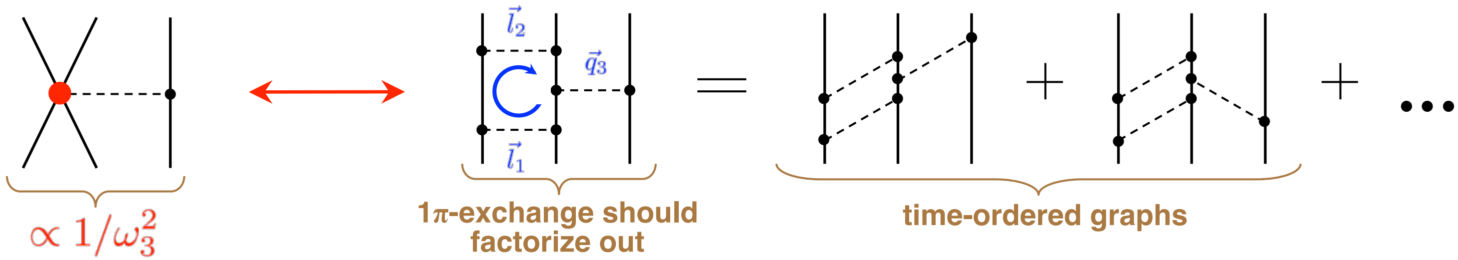

$$V = \ldots = \int d^3 l_1 \, d^3 l_2 \, \delta(\vec{l}_1 - \vec{l}_2 - \vec{q}_1) \Big[\ldots \Big]$$

$$\times \left[2 \frac{\omega_1^2 + \omega_2^2}{\omega_1^4 \, \omega_2^4 \, \omega_3^2} + \frac{8}{\omega_1^2 \, \omega_2^2 \, \omega_3^4} - \frac{\omega_1 + \omega_2}{\omega_1^3 \, \omega_2^3 \, \omega_3^3} - \frac{2}{\omega_1^4 \, \omega_2^2 \, \omega_3 \, (\omega_1 + \omega_3)} - \frac{2}{\omega_1^2 \, \omega_2^4 \, \omega_3 \, (\omega_2 + \omega_3)} \right]$$

$\omega_{1,2} = \sqrt{\vec{l}_{1,2}^{\,2} + M_\pi^2}$

⇒ cannot renormalize the potential !

Solution (E.E.'06)

Nuclear potentials are not uniquely defined. Employing additional UTs in Fock space, it was (so far) always possible to maintain renormalizability at the level of the nuclear Hamiltonian. Same problem emerges for the current operators…

From L_{eff} to nuclear forces/currents

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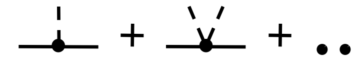
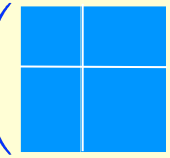
- Canonical transformation & quantization: $\mathcal{L}_{\pi N} \longrightarrow \mathcal{H}_{\pi N} =$ 

- **Nuclear forces via UT (Fock space):** $H \rightarrow \tilde{H} = U^\dagger \Big($  $\Big) U = \begin{pmatrix} \tilde{H}_{\text{nucl}} & 0 \\ 0 & \tilde{H}_{\text{rest}} \end{pmatrix}$
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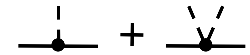
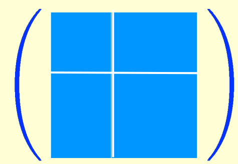
- Canonical transformation & quantization: $\mathcal{L}_{\pi \rm N} \longrightarrow \mathcal{H}_{\pi \rm N} =$  + ...

Nuclear forces via UT (Fock space):

$H \to \tilde{H} = U^\dagger$  $U = \begin{pmatrix} \tilde{H}_{\rm nucl} & 0 \\ 0 & \tilde{H}_{\rm rest} \end{pmatrix}$

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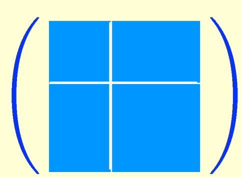
EE '06,'07; Bernard, EE, Krebs, Meißner '08

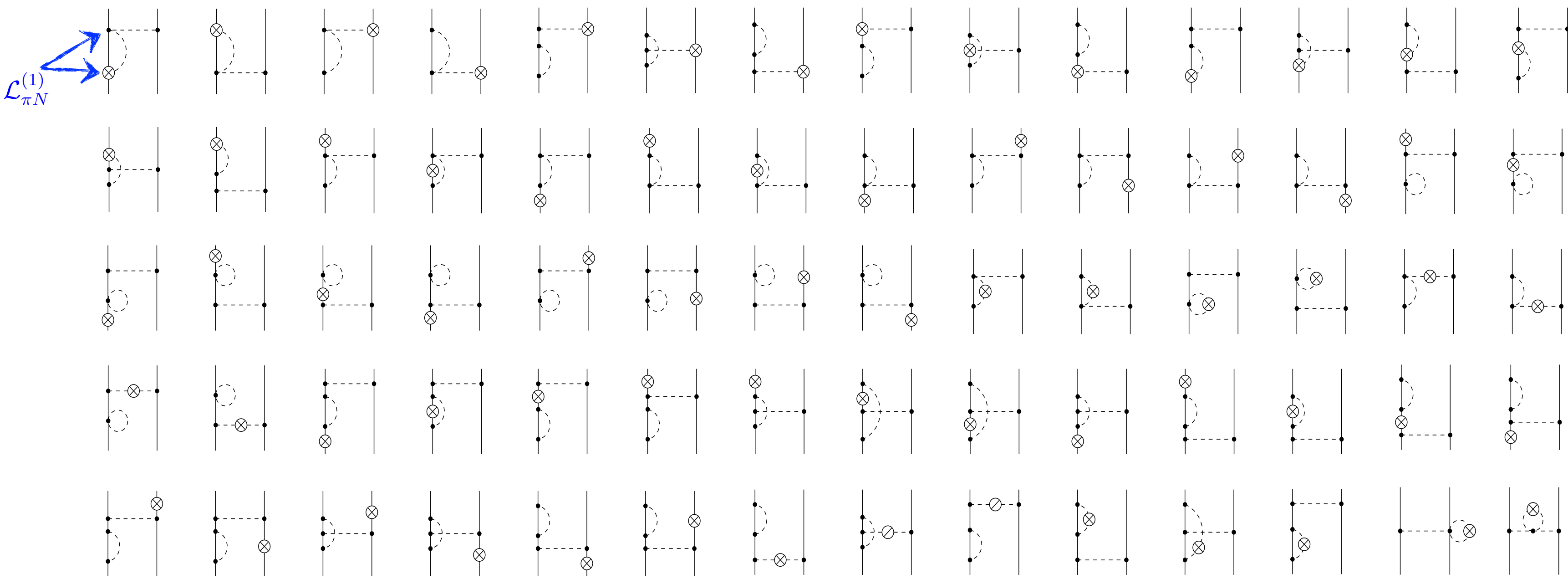
Effective current operator

- „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 $J_\mu \to \tilde{J}_\mu = U^\dagger$  $U = \begin{pmatrix} \tilde{J}_\mu^{\rm nucl} & \\ & \end{pmatrix}$
- Need additional, $\mathcal{A}_\mu$-dependent UTs $\eta U' \eta \big|_{\mathcal{A}_\mu = 0} = 1_\eta$ to enforce renormalizability

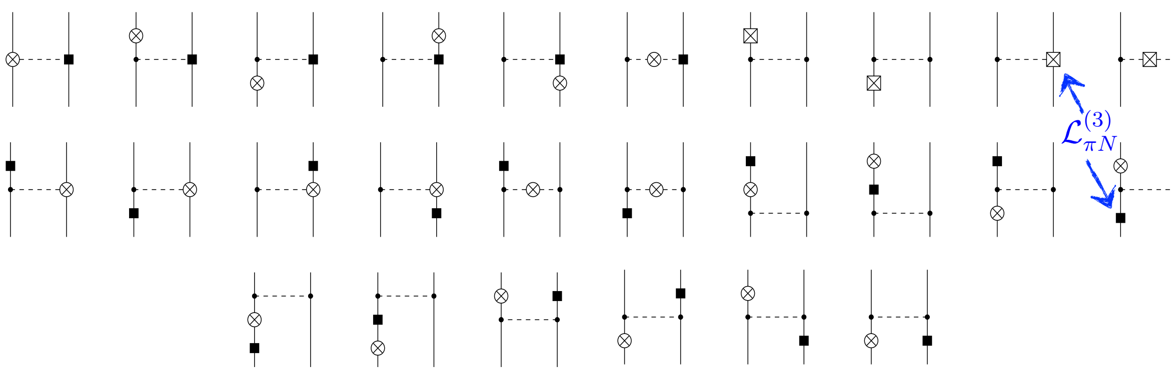
One-pion exchange current

Kölling, EE, Krebs, Meißner ’11

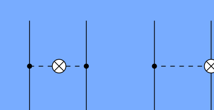
Loop diagrams with $\mathcal{L}_{\pi N}^{(1)}$ -vertices



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)



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

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

$$
\begin{aligned}
f_1(k) \;\; &= \;\; 2ie \frac{g_A}{F_\pi^2} \, \bar{d}_8 \, , \quad f_2(k) = 2ie \frac{g_A}{F_\pi^2} \, \bar{d}_9 \, , \quad f_3(k) = -ie \frac{g_A}{64 F_\pi^4 \pi^2} \left[g_A^3 \, (2L(k) - 1) + 32 F_\pi^2 \pi^2 \bar{d}_{21} \right] , \\
f_4(k) \;\; &= \;\; -ie \frac{g_A}{4F_\pi^2} \, \bar{d}_{22} \, , \quad f_5(k) = -ie \frac{g_A^2}{384 F_\pi^4 \pi^2} \left[2(4M_\pi^2 + k^2) L(k) + \left(6 \, \bar{l}_6 - \frac{5}{3} \right) k^2 - 8M_\pi^2 \right] , \\
f_6(k) \;\; &= \;\; -ie \frac{g_A}{F_\pi^2} M_\pi^2 \, \bar{d}_{18} \, ,
\end{aligned}
$$

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

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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...)

Charge density

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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...)

Low-energy constants:

$\bar{l}_6 = 16.5(1.1)$ (pion charge radius) Gasser, Leutryler '84

$\bar{d}_{18} = 0.4 \; {\rm GeV}^{-2}$ (Goldberger-Treiman discrepancy)

The LECs $\bar{d}_8$, $\bar{d}_9$, and $2\bar{d}_{21} - \bar{d}_{22}$ can be determined from pion photoproduction

Fearing, Hemmert, Lewis, Unkmeir '00, Gasparyan, Lutz '10

$\bar{d}_8$ GeV^2	$\bar{d}_9$ GeV^2	$\bar{d}_{20}$ GeV^2	$(2\,\bar{d}_{21} - \bar{d}_{22})$ GeV^2
3.35	−0.06	0.61	0.05

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Charge density

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

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

$$f_8(k) = e \frac{g_A^4}{64 F_\pi^4 \pi} \left[(4M_\pi^2 + k^2) A(k) - M_\pi \right]$$

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

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

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

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

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

Charge density

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

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

$$f_8(k) = e\frac{g_A^4}{64 F_\pi^4 \pi}\left[(4M_\pi^2 + k^2) A(k) - M_\pi \right]$$

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

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

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

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

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

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

Charge density

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

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

$$f_8(k) = e \frac{g_A^4}{64 F_\pi^4 \pi} \left[(4M_\pi^2 + k^2) A(k) - M_\pi \right]$$

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

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

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

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

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

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

agree, „slightly" disagree,

Charge density

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

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

$$
f_8(k) = e \frac{g_A^4}{64 F_\pi^4 \pi} \left[(4 M_\pi^2 + k^2) A(k) - M_\pi \right]
$$

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

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

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

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

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

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

agree, **„slightly" disagree**, **completely disagree**

Charge density

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

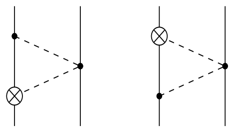
$$f_7(k) = e \frac{g_A^4}{64 F_\pi^4 \pi} \left[A(k) + \frac{M_\pi - 4M_\pi^2 \, A(k)}{k^2} \right]$$

$$f_8(k) = e \frac{g_A^4}{64 F_\pi^4 \pi} \left[(4M_\pi^2 + k^2) A(k) - M_\pi \right]$$

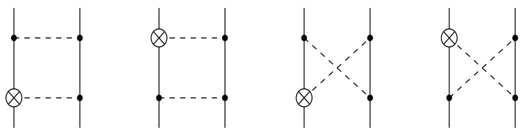
← absent in Pastore et al., PRC 80 (09) 034004

Two-pion exchange current density

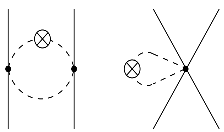
Kölling, EE, Krebs, Meißner ’09



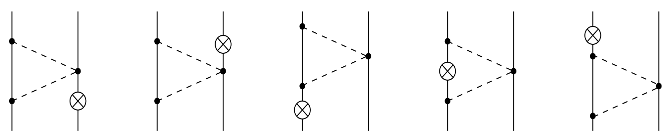
$$\vec J = e \frac{g_A^2 M_\pi^7}{128\pi^3 F_\pi^4}\left[\vec\nabla_{10}\,[\vec\tau_1\times\vec\tau_2]^3 + 2\left[\vec\nabla_{10}\times\vec\sigma_2\right]\tau_1^3\right]\,\delta(\vec x_{20})\,\frac{K_1(2x_{10})}{x_{10}^2}$$



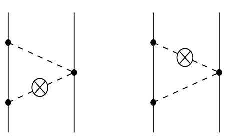
$$\vec J = -\,e\,\frac{g_A^4 M_\pi^7}{256\pi^3 F_\pi^4}\left(3\nabla_{10}^2-8\right)\left[\vec\nabla_{10}\,[\vec\tau_1\times\vec\tau_2]^3 + 2\left[\vec\nabla_{10}\times\vec\sigma_2\right]\tau_1^3\right]\delta(\vec x_{20})\,\frac{K_0(2x_{10})}{x_{10}} + e\,\frac{g_A^4 M_\pi^7}{32\pi^3 F_\pi^4}\left[\vec\nabla_{10}\times\vec\sigma_1\right]\tau_2^3\,\delta(\vec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



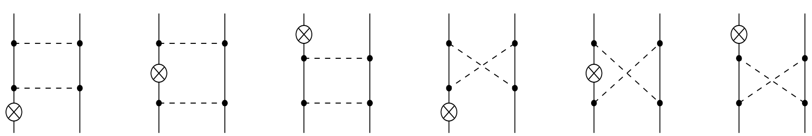
$$\vec J = -\,e\,\frac{M_\pi^7}{512\pi^4 F_\pi^4}\,[\vec\tau_1\times\vec\tau_2]^3\,(\vec\nabla_{10}-\vec\nabla_{20})\,\frac{K_2(x_{10}+x_{20}+x_{12})}{(x_{10}\,x_{20}\,x_{12})(x_{10}+x_{20}+x_{12})}$$



$$\vec J = 0$$

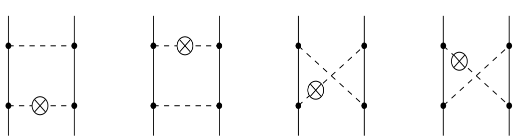


$$\vec J = -\,e\,\frac{g_A^2 M_\pi^7}{256\pi^4 F_\pi^4}\left(\vec\nabla_{10}-\vec\nabla_{20}\right)\left[[\vec\tau_1\times\vec\tau_2]^3\,\vec\nabla_{12}\cdot\vec\nabla_{20} - 2\tau_1^3\vec\sigma_2\cdot\left[\vec\nabla_{12}\times\vec\nabla_{20}\right]\right] \times\frac{K_1(x_{10}+x_{20}+x_{12})}{(x_{10}\,x_{20}\,x_{12})}\,,$$



$$\vec J = 0$$

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

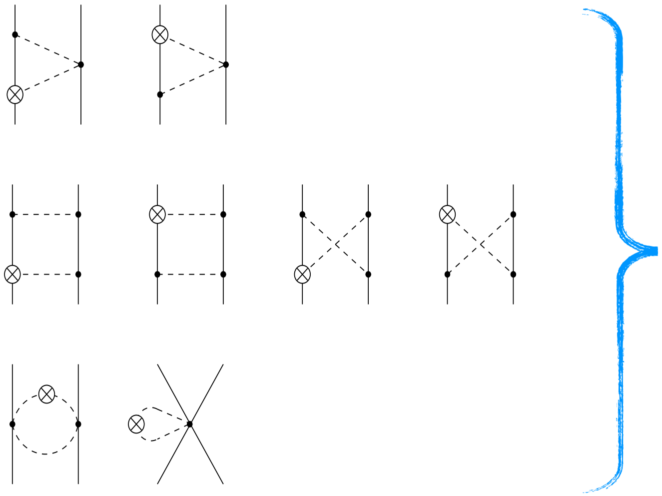


$$\vec J = e\,\frac{g_A^4 M_\pi^7}{512\pi^4 F_\pi^4}\left(\vec\nabla_{10}-\vec\nabla_{20}\right)\left[[\vec\tau_1\times\vec\tau_2]^3\,\vec\nabla_{12}\cdot\vec\nabla_{10}\,\vec\nabla_{12}\cdot\vec\nabla_{20} + 4\tau_2^3\vec\sigma_1\cdot\left[\vec\nabla_{12}\times\vec\nabla_{10}\right]\,\vec\nabla_{12}\cdot\vec\nabla_{20}\right]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

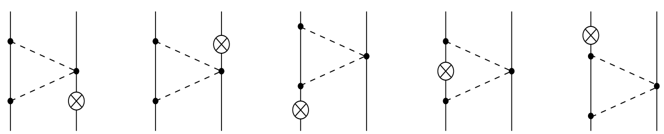
Two-pion exchange charge density

Kölling, EE, Krebs, Meißner '09

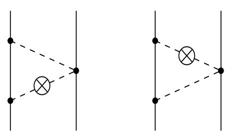
- ✓ parameter-free
- ✓ nonvanishing 2-body density even in the static limit (!)
- ✓ results agree with Pastore et al.



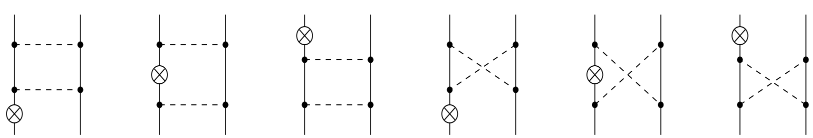
$$\rho \;=\; 0$$



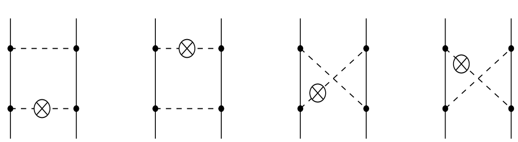
$$\rho = e\frac{g_A^2 M_\pi^7}{256\pi^2 F_\pi^4}\,\tau_1^3\,\delta(\vec{x}_{20})\,(\nabla_{10}^2 - 2)\,\frac{e^{-2x_{10}}}{x_{10}^2}$$



$$\rho = e\frac{g_A^2 M_\pi^7}{256\pi^2 F_\pi^4}\,\tau_2^3\,\delta(\vec{x}_{20})\,(\nabla_{10}^2 - 2)\,\frac{e^{-2x_{10}}}{x_{10}^2}$$



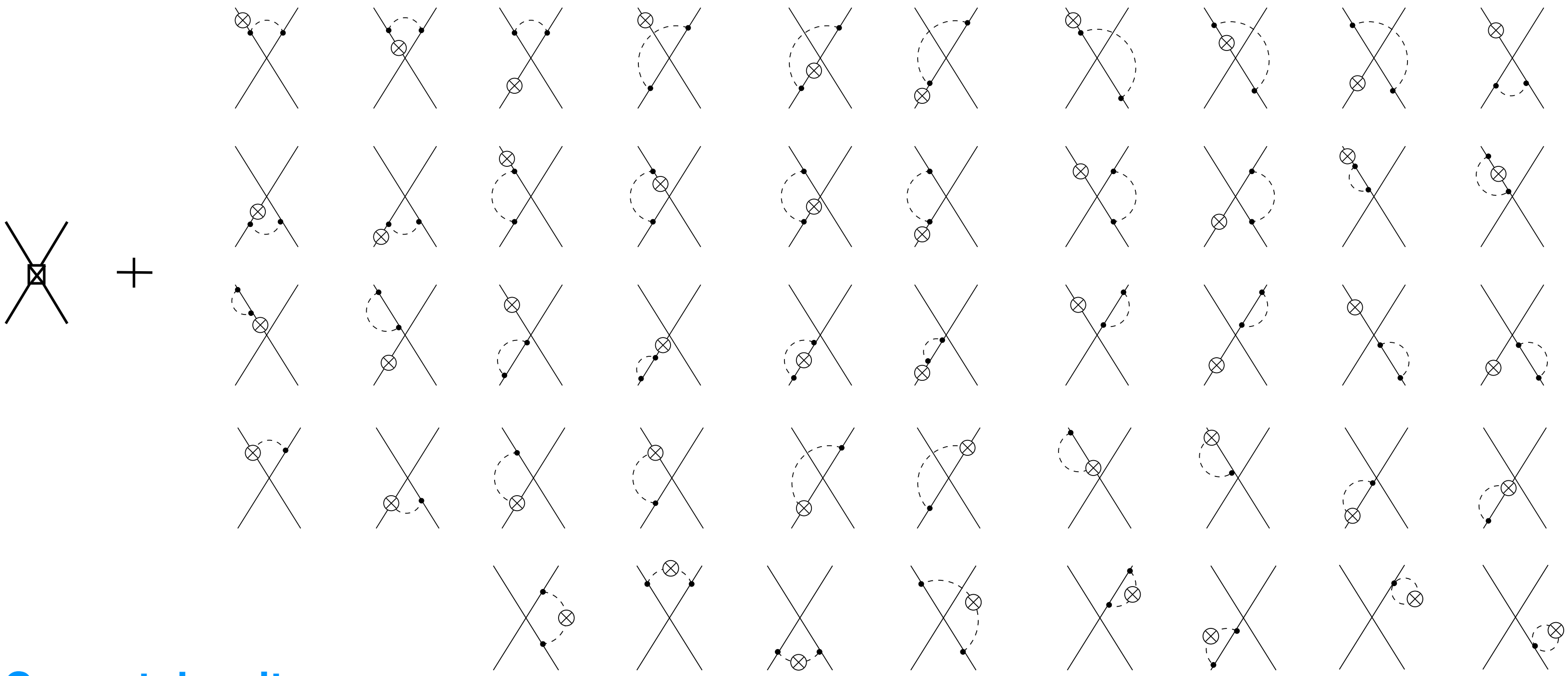
$$\begin{aligned}\rho \;=\; & -e\frac{g_A^4 M_\pi^7}{256\pi^2 F_\pi^4}\,\delta(\vec{x}_{20})\Big[\tau_1^3\left(2\nabla_{10}^2 - 4\right) \\ & + \tau_2^3\,\vec{\sigma}_1\cdot\vec{\nabla}_{10}\,\vec{\sigma}_2\cdot\vec{\nabla}_{10} \;-\; \tau_2^3\vec{\sigma}_1\cdot\vec{\sigma}_2\Big]\frac{e^{-2x_{10}}}{x_{10}^2}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



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

Short-range currents

Kölling, EE, Krebs, Meißner '11



Current density

$$\vec{J}_{\rm contact} = e\frac{i}{16}[\vec{\tau}_1\times\vec{\tau}_2]^3\Big[(C_2+3C_4+C_7)\,\vec{q}_1-(-C_2+C_4+C_7)\,(\vec{\sigma}_1\cdot\vec{\sigma}_2)\,\vec{q}_1+C_7\,(\vec{\sigma}_2\cdot\vec{q}_1\,\vec{\sigma}_1+\vec{\sigma}_1\cdot\vec{q}_1\,\vec{\sigma}_2)\Big]$$
$$-e\frac{C_5 i}{16}(\tau_1^3-\tau_2^3)\,(\vec{\sigma}_1+\vec{\sigma}_2)\times\vec{q}_1+ieL_1\,\tau_1^3\,(\vec{\sigma}_1-\vec{\sigma}_2)\times\vec{k}+ieL_2\,(\vec{\sigma}_1-\vec{\sigma}_2)\times\vec{q}_1$$

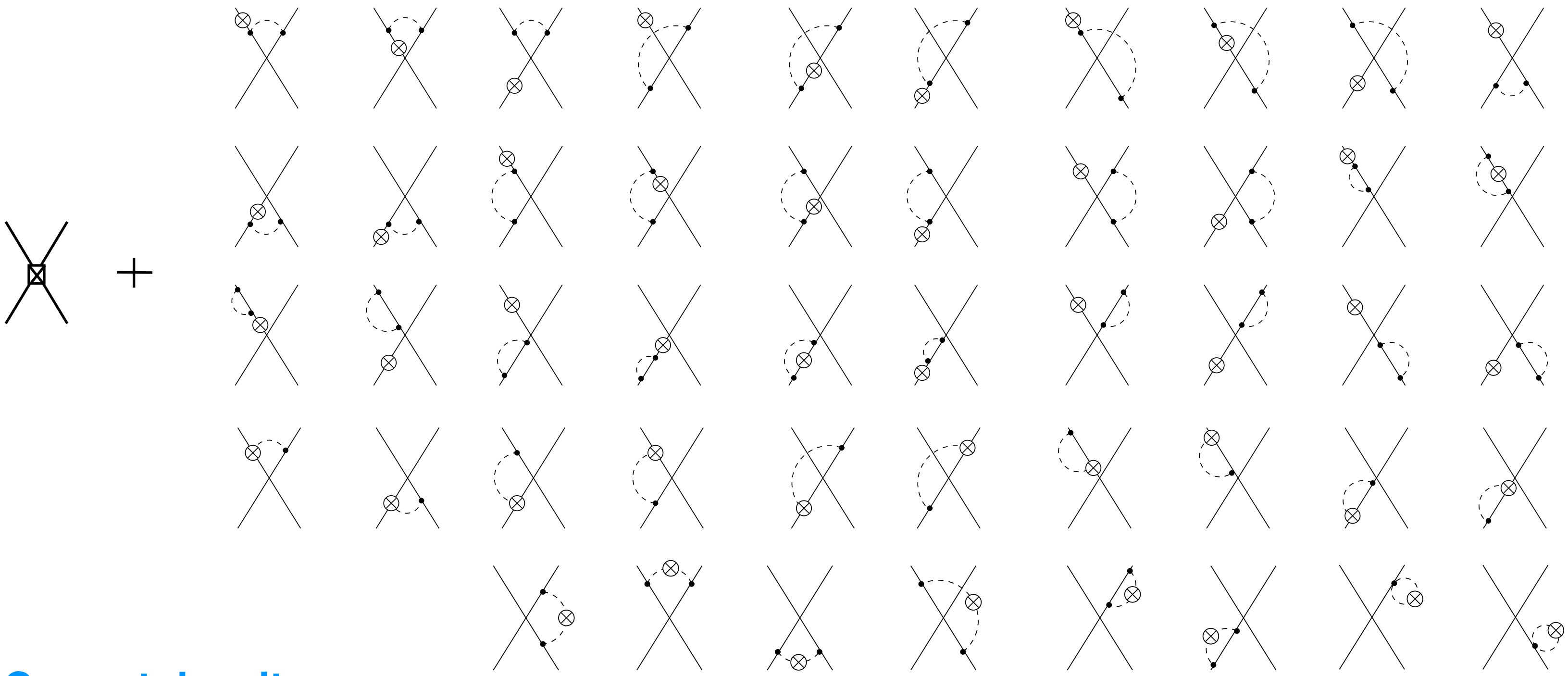
Charge density

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

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

Kölling, EE, Krebs, Meißner '11



Current density

$$\vec{J}_{\rm contact} = e\frac{i}{16}[\vec{\tau}_1 \times \vec{\tau}_2]^3 \Big[(C_2 + 3C_4 + C_7)\,\vec{q}_1 - (-C_2 + C_4 + C_7)\,(\vec{\sigma}_1 \cdot \vec{\sigma}_2)\,\vec{q}_1 + C_7\,(\vec{\sigma}_2 \cdot \vec{q}_1\,\vec{\sigma}_1 + \vec{\sigma}_1 \cdot \vec{q}_1\,\vec{\sigma}_2)\Big]$$
$$- e\frac{C_5 i}{16}(\tau_1^3 - \tau_2^3)(\vec{\sigma}_1 + \vec{\sigma}_2) \times \vec{q}_1 + ieL_1\tau_1^3(\vec{\sigma}_1 - \vec{\sigma}_2) \times \vec{k} + ieL_2(\vec{\sigma}_1 - \vec{\sigma}_2) \times \vec{q}_1$$

Two new LECs ***L***

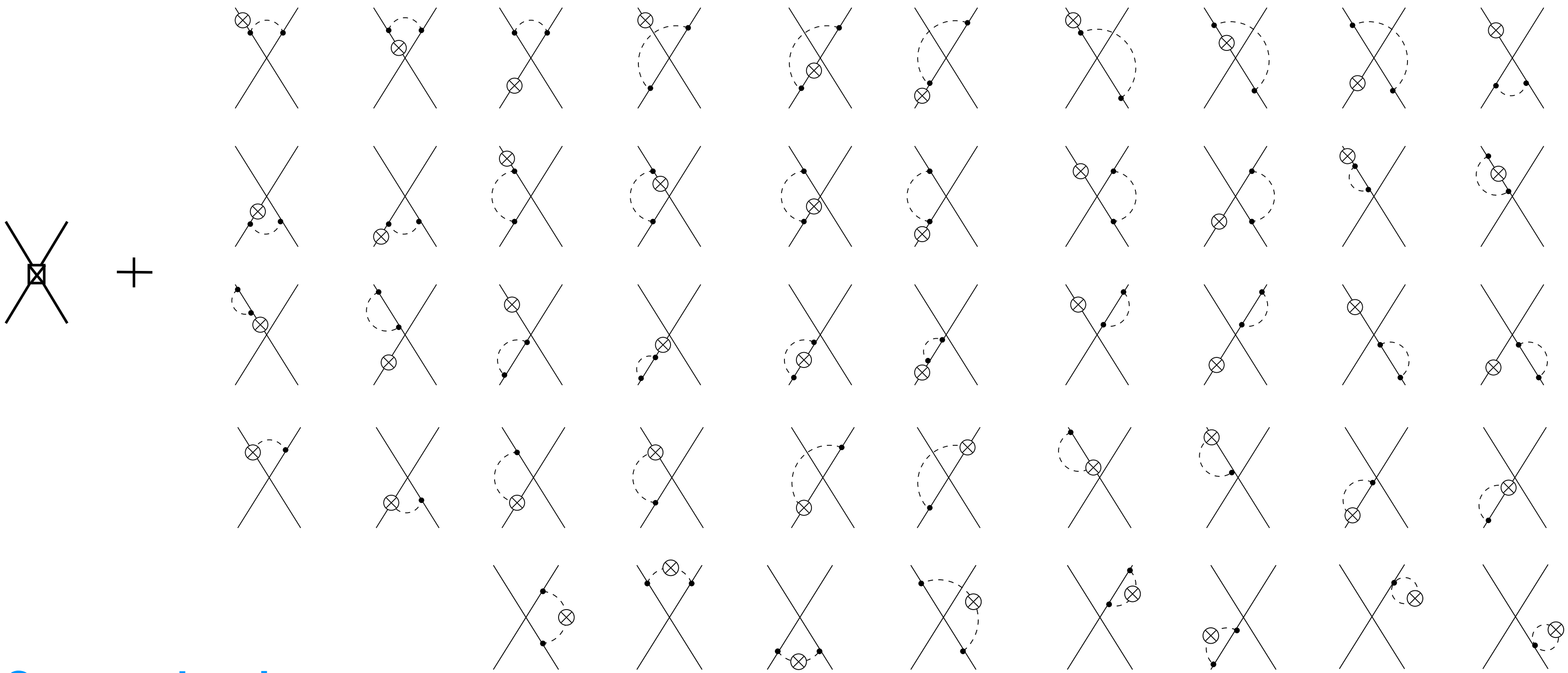
Charge density

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

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

Kölling, EE, Krebs, Meißner '11



Current density

$$\vec{J}_{\rm contact} = e\,\frac{i}{16}\,[\vec{\tau}_1 \times \vec{\tau}_2]^3 \Big[(C_2 + 3C_4 + C_7)\,\vec{q}_1 - (-C_2 + C_4 + C_7)\,(\vec{\sigma}_1 \cdot \vec{\sigma}_2)\,\vec{q}_1 + C_7\,(\vec{\sigma}_2 \cdot \vec{q}_1\,\vec{\sigma}_1 + \vec{\sigma}_1 \cdot \vec{q}_1\,\vec{\sigma}_2)\Big] - e\frac{C_5 i}{16}\,(\tau_1^3 - \tau_2^3)\,(\vec{\sigma}_1 + \vec{\sigma}_2) \times \vec{q}_1 + ieL_1\,\tau_1^3\,(\vec{\sigma}_1 - \vec{\sigma}_2) \times \vec{k} + ieL_2\,(\vec{\sigma}_1 - \vec{\sigma}_2) \times \vec{q}_1$$

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

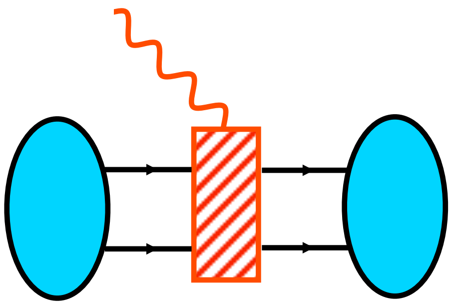
Pion loop contributions differ from the ones by Pastore et al.

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

Exchange currents
and the deuteron form factors



for more applications see talks by Sonia Bacca, Tae-Sun Park and Saori Pastore

Em currents and the deuteron form factors

Meißner, Walzl, Phillips, Kölling, EE, ...

- 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:

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

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

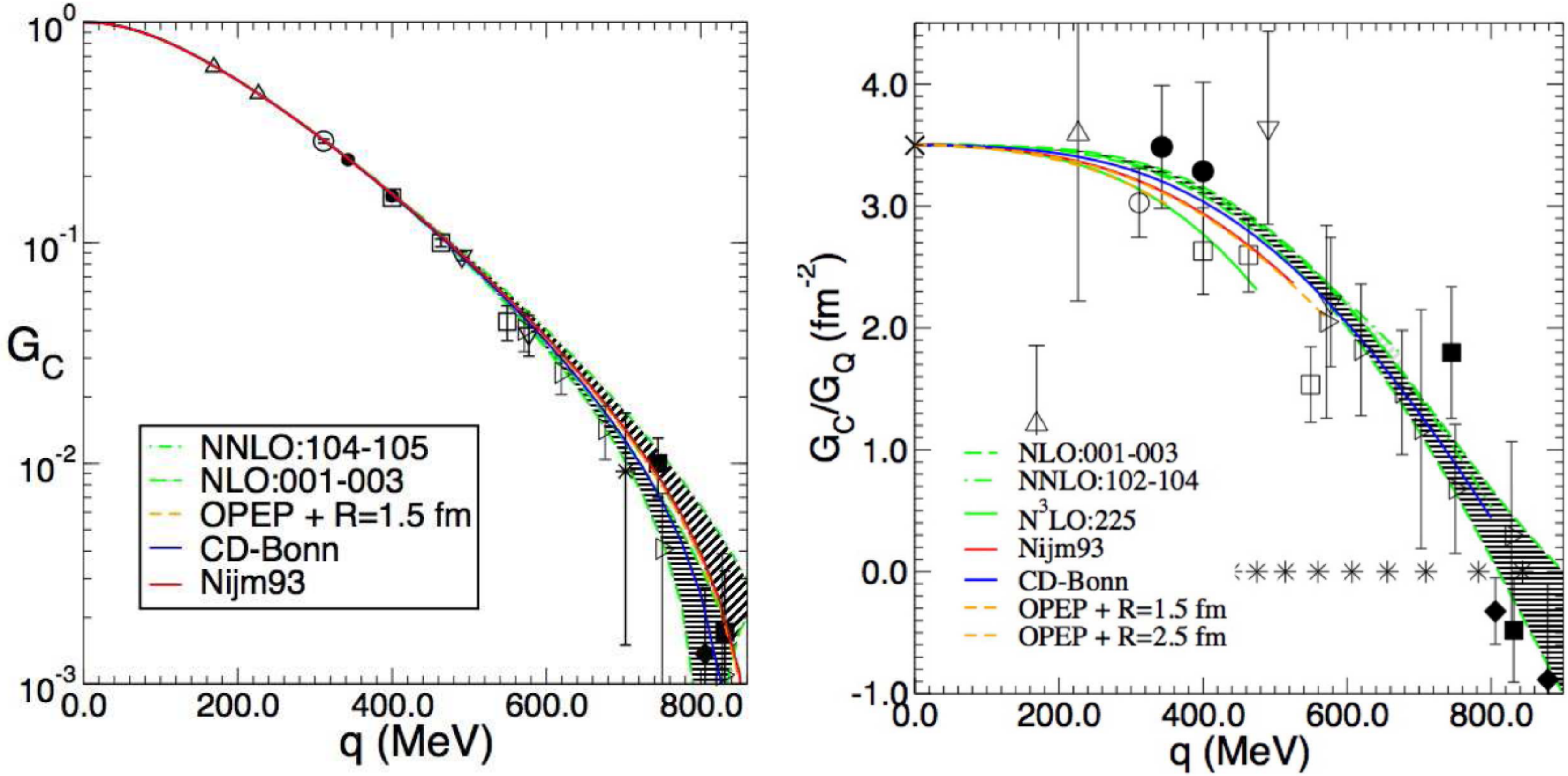
$$\vec{J}_{\rm contact} = ieL_2\,\left[(\vec{\sigma}_1+\vec{\sigma}_2)\times\vec{q}_1\right]$$

- 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 and the deuteron form factors

Phillips '07



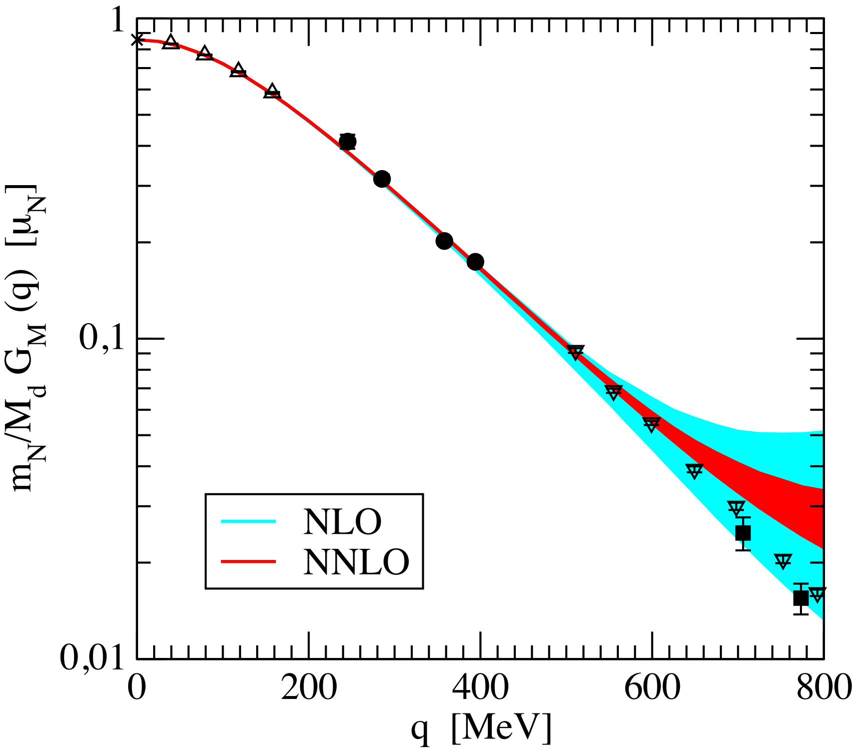
(from Phillips, J. Phys. G 34 (2007) 365)

- 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…

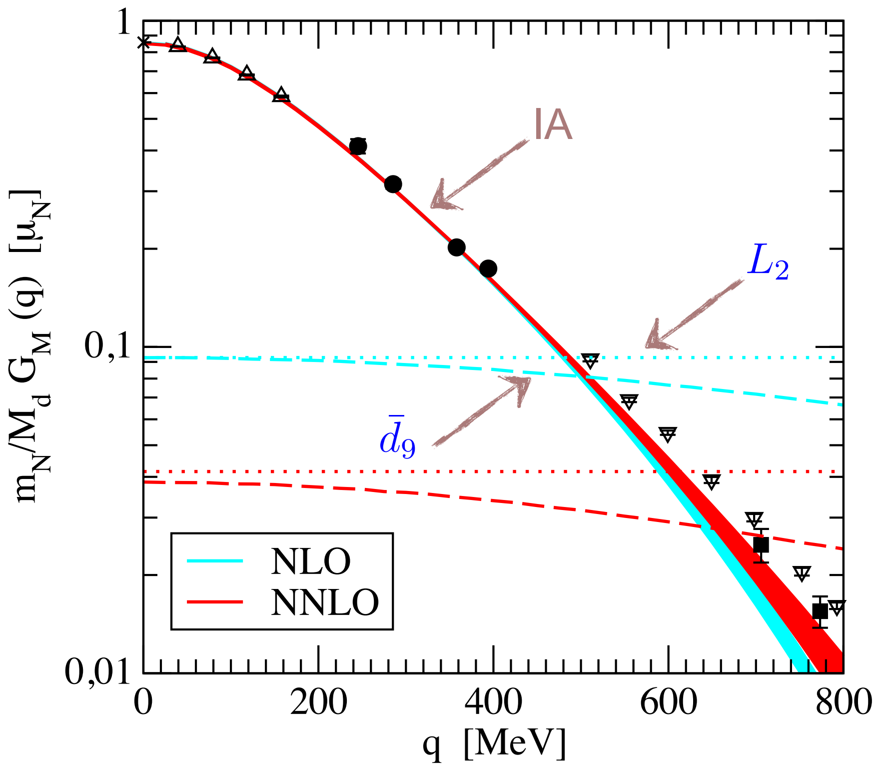
Em currents and the deuteron form factors

Kölling, EE, Phillips ’12

Deuteron magnetic form factor



IA and exchange current contributions



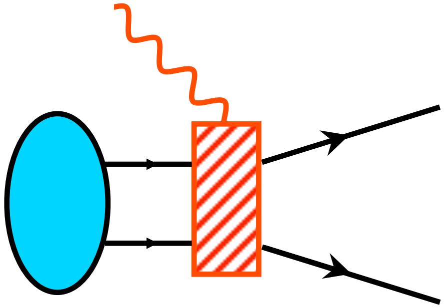
- 1N form factors from Belushkin, Hammer, Meißner ’07
- $\bar{d}_9,\ L_2$ fitted to the deuteron magnetic moment and FF for q < 400 MeV:

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

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

2π-exchange current

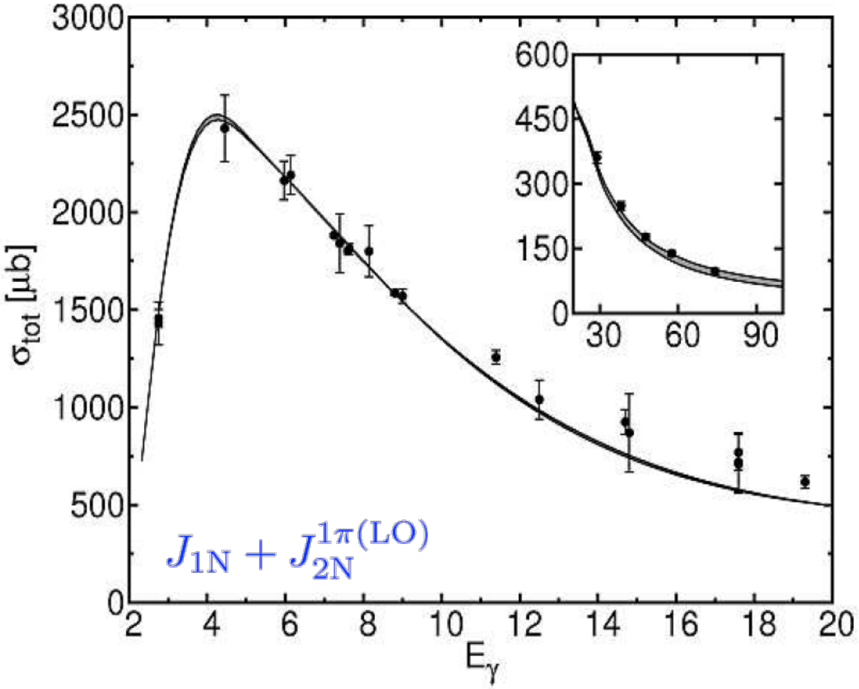
and ^{2}H / ^{3}He photodisintegration

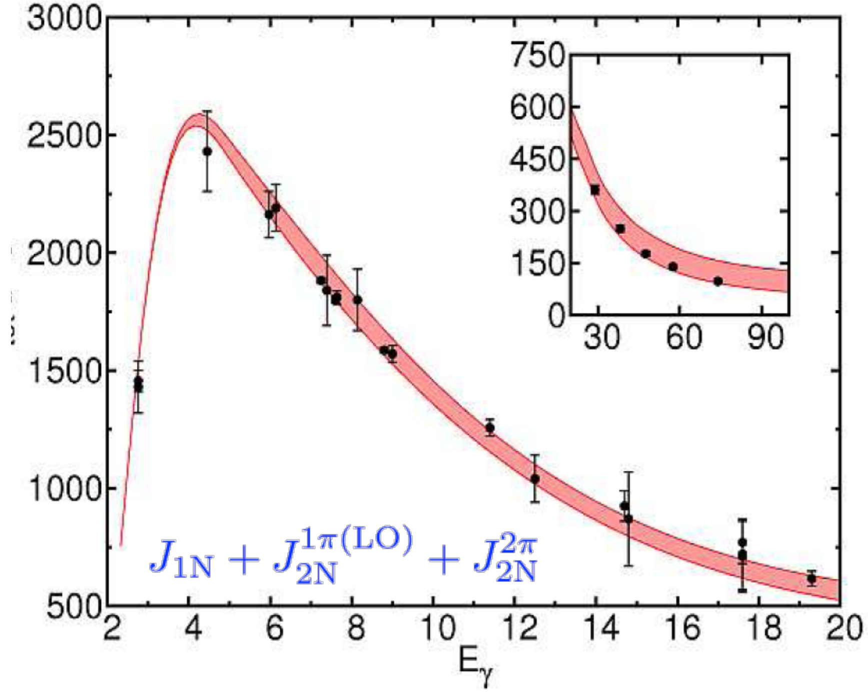


Deuteron photodisintegration

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

Sensitivity of the total cross section to the 2π-exchange current



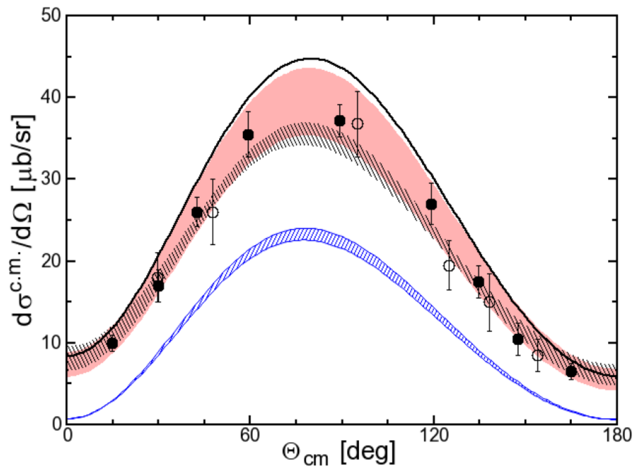


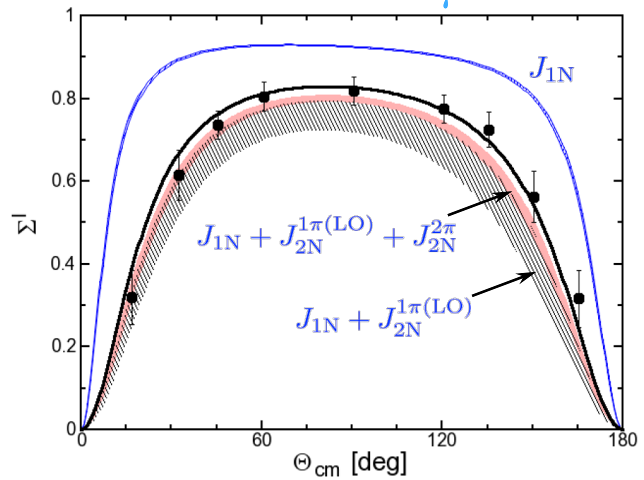
short-range & (subleading)1π-exchange terms still to be included

Deuteron photodisintegration

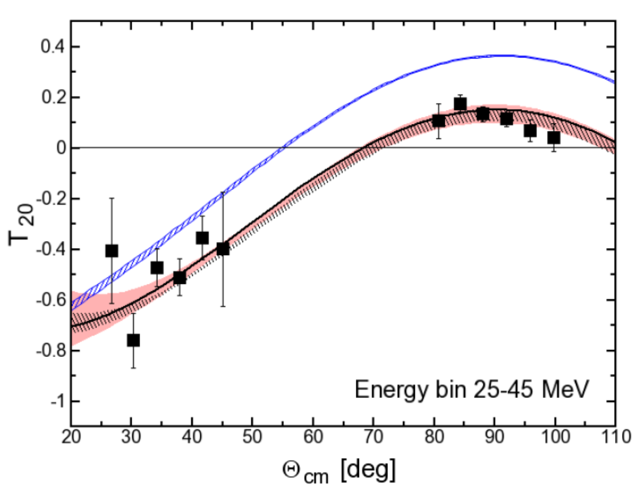
Rozpedzik, Golak, Kölling, EE, Skibinski, Witala, Nogga '11

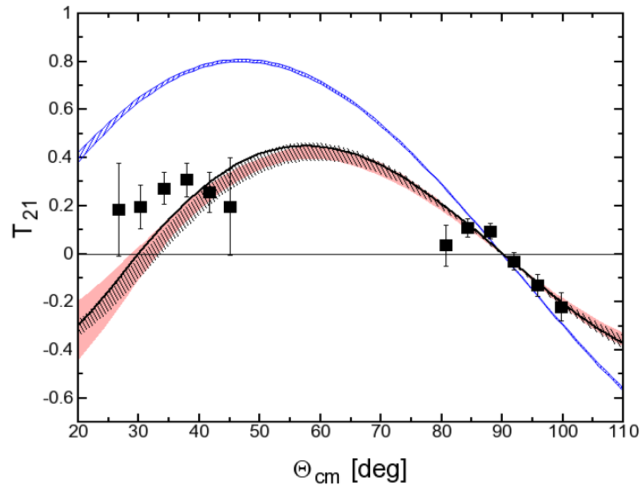
Cross section and photon analyzing power at E_γ =30 MeV





Deuteron tensor analyzing powers



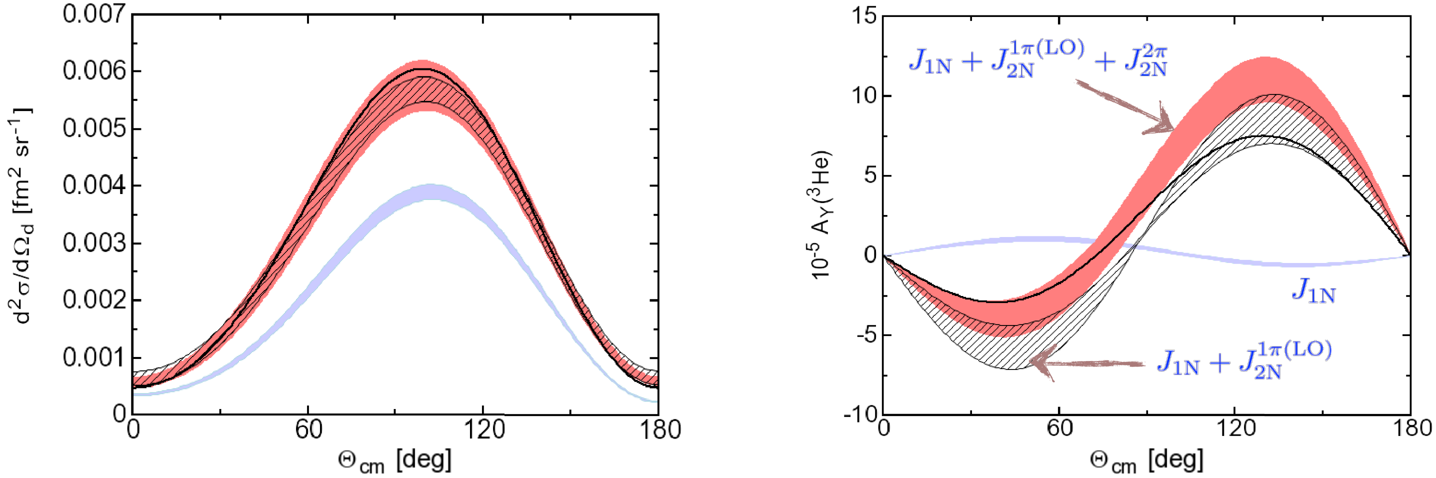


large sensitivity to MEC; short-range & 1π-exchange terms still to be included

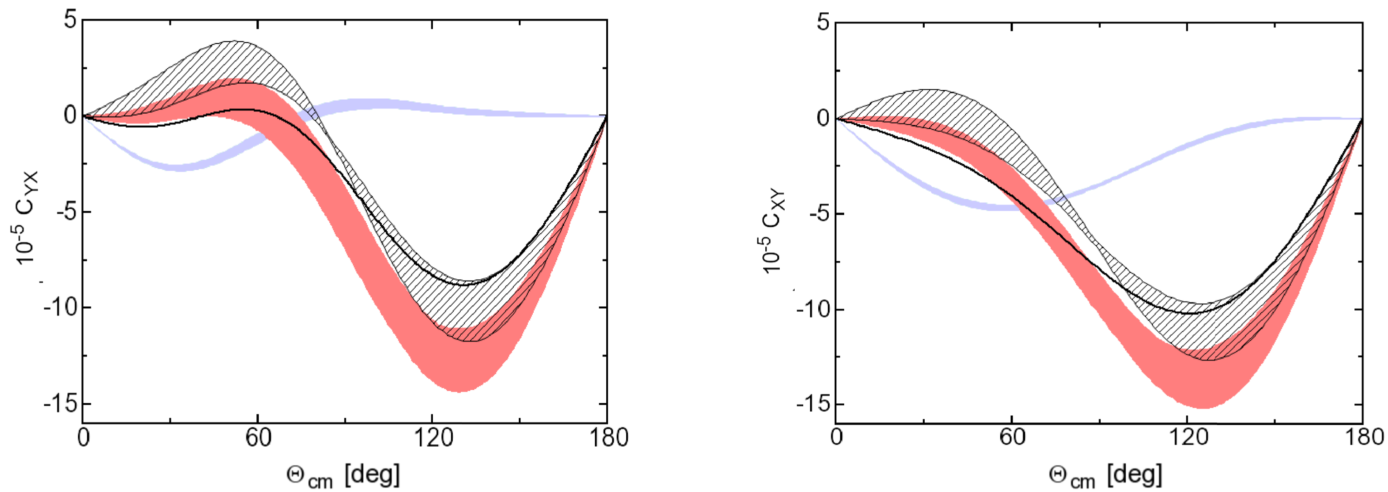
^{3}He 2-body photodisintegration

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

Cross section and photon analyzing power at E_γ =20 MeV



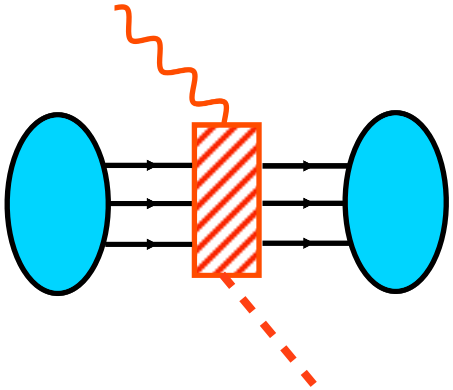
Spin correlation coefficients



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

Coherent pion photoproduction off ^3He

Lenkewitz, EE, Hammer, Meißner ’11,’12



Neutral pion photoproduction off ^{3}He

Motivation

- Testing chiral EFT (2NF + 3NF + currents)
- Use reactions $\pi^- d \to nn\gamma$ and $d\gamma \to nn\pi^+$ to extract nn scattering length
  Gardestig, Phillips '06; Lensky, Baru, EE, Hanhart, Haidenbauer, Kudryavtsev, Meißner '07
- Pion production off light nuclei and the neutron amplitude.

Pion electroproduction amplitude off a spin-1/2 particle at threshold:

$$\mathcal{M}_\lambda = 2i\, E_{0+}\, (\vec{\epsilon}_{\lambda,T} \cdot \vec{S}) + 2i\, L_{0+}\, (\vec{\epsilon}_{\lambda,L} \cdot \vec{S})$$

ChPT predictions at q⁴ (in units of $10^{-3}\, M_{\pi^+}^{-1}$):

$$E_{0+}^{\pi^0 p} = -1.16\,, \quad E_{0+}^{\pi^0 n} = +2.13$$
$$L_{0+}^{\pi^0 p} = -1.35\,, \quad L_{0+}^{\pi^0 n} = -2.41$$

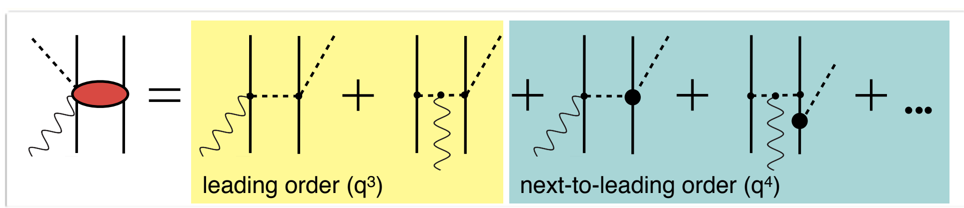
Bernard, Kaiser, Meißner '96,'01

Pion photo- and electroproduction off ^{2}H explored theoretically and experimentally
Theory: Beane, Bernard, Lee, Meißner, van Kolck '97, Krebs, Bernard, Meißner '04; Experiment: Saclay, Saskatoon

^{3}He as an effective neutron target: order-q⁴ calculation

Lenkewitz, EE, Hammer, Meißner '11, '12

- No 3N currents at order q⁴
- 2N currents purely long-range and parameter free



- Use Monte-Carlo integration to compute convolution integrals with the chiral ^{3}He WF

Neutral pion photoproduction off ^{3}He

Individual contributions to the three-nucleon multipoles

^{3}He	1N (q^4)	2N (q^3)	1N-boost	2N-static (q^4)	2N-recoil (q^4)	total
E_{0+} $[10^{-3}/M_{\pi^+}]$	$+1.71(4)(9)$	$-3.95(3)$	$-0.23(1)$	$-0.02(0)(1)$	$+0.01(2)(1)$	$-2.48(11)$
L_{0+} $[10^{-3}/M_{\pi^+}]$	$-1.89(4)(9)$	$-3.09(2)$	$-0.00(0)$	$-0.07(1)(1)$	$+0.07(7)(0)$	$-4.98(12)$
^{3}H	1N (q^4)	2N (q^3)	1N-boost	2N-static (q^4)	2N-recoil (q^4)	total
E_{0+} $[10^{-3}/M_{\pi^+}]$	$-0.93(3)(5)$	$-4.01(3)$	$-0.35(1)$	$-0.02(1)(1)$	$+0.01(2)(0)$	$-5.28(7)$
L_{0+} $[10^{-3}/M_{\pi^+}]$	$-0.99(4)(5)$	$-3.13(1)$	$-0.02(0)$	$-0.07(0)(1)$	$+0.07(7)(0)$	$-4.14(10)$

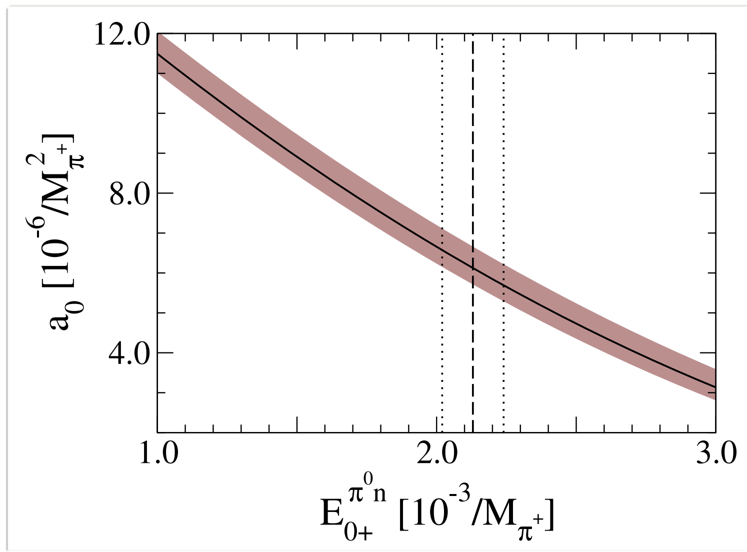
- small q^4 2N terms, reliable nuclear corrections
- a large sensitivity of the S-wave threshold photoproduction cross section

$$a_0 = \frac{|\vec{k}\,|}{|\vec{q}\,|}\frac{d\sigma}{d\Omega}\bigg|_{q=0} = |E_{0+}^{\pi^0\,^3\mathrm{He}}|^2$$

to the elementary multipole $E_{0+}^{\pi^0 n}$

- Our prediction $E_{0+}^{\pi^0\,3\mathrm{He}} = -2.48(11)$ versus (model-dependent) extraction from the Saclay measurement $E_{0+}^{\pi^0\,3\mathrm{He}} = -2.8 \pm 0.2$

Argan et al. '80, '88



Summary and outlook

E.m. exchange current & charge density

- worked out at leading loop order (ready-to-use expressions available)
- 1π-exchange terms depend on a few LECs (some of which are poorly known), 2π-exchange terms parameter-free, short-range currents depend on $L_{1,2}$

Converged? To be done: subleading 1-loop contributions and/or chiral EFT with Δ

Elastic form factors of the deuteron

- good agreement with the data (provided 1N FFs are used as input)
- the extracted value of d_9 consistent with other determinations

To be done: extension to the 3N and 4N systems (to probe isovector currents)

$^2H/^3He$ photodisintegration

- the best place to test the currents, seems to be sensitive to individual terms

To be done: complete analysis including 1π and short-range contributions

Neutral pion photoproduction off ^3He

- large sensitivity to the neutron multipole, nuclear corrections well under control
- prediction for ^3He, experiments called for!

To be done: extensions beyond threshold, check of convergence, heavier nuclei, ...