Electromagnetic currents from the method of unitary transformation

Stefan Kölling

Forschungszentrum Jülich,
& HISKP (Theorie) Bonn

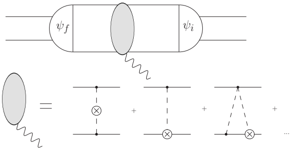
e-mail: s.koelling@fz-juelich.de

in collaboration with: D. Rozpedzik, J. Golak, E. Epelbaum, H. Krebs and U.-G. Meißner

Workshop Electron-Nucleus Scattering XI, Elba, 22.06.2010

Motivation

- Following Weinberg['90,'91,'92] successful application of ChPT to calculate nuclear forces.
- Calculate only irreducible kernel and iterate.
  $\longrightarrow$ Method of unitary transformation[Epelbaum et al. '98].
- Consistent derivation of electromagnetic-current J^{μ}



- $\vec{\nabla} \cdot \vec{J} = -i\,[H, \rho]$
- Treat em-interaction as perturbation
- Convolute between wave-functions.

- Define effective current with unitary transformation

$$\eta V_{\text{eff}} \eta = \eta U'^{\dagger} \eta U^{\dagger} H U \eta U' \eta - H_0, \quad U = \begin{pmatrix} \eta \left(1 + A^{\dagger} A\right)^{-\frac{1}{2}} & -A^{\dagger} \left(1 + A A^{\dagger}\right)^{-\frac{1}{2}} \\ A \left(1 + A^{\dagger} A\right)^{-\frac{1}{2}} & \lambda \left(1 + A A^{\dagger}\right)^{-\frac{1}{2}} \end{pmatrix},$$

$$\eta J^{\mu}_{\text{eff}} \eta = \eta U'^{\dagger} \eta U^{\dagger} J^{\mu} U \eta U' \eta,$$

with projectors η (λ) on the purely nucleonic (rest) subspace.

Lagrangian we use

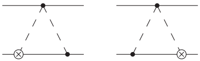
$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}^{(2)}_{\pi\pi} + \mathcal{L}^{(4)}_{\pi\pi} + \mathcal{L}^{(1)}_{\pi N} + \mathcal{L}^{(3)}_{\pi N} + \mathcal{L}^{(0)}_{NN} + \mathcal{L}^{(2)}_{NN} + \mathcal{L}^{(2)}_{NN\gamma} \,, \\
\mathcal{L}^{(2)}_{\pi\pi} &= \frac{F_\pi^2}{4} \langle D_\mu U D^\mu U^\dagger + \chi_+ \rangle \,, \\
\mathcal{L}^{(4)}_{\pi\pi} &= \frac{l_3}{16} \langle \chi_+ \rangle^2 + \frac{l_4}{16} \Big(2 \langle D_\mu U D^\mu U^\dagger \rangle \langle \chi_+ \rangle + 2 \langle \chi^\dagger U \chi^\dagger U + \chi U^\dagger \chi U^\dagger \rangle - 4 \langle \chi^\dagger \chi \rangle \Big) \\
&\quad + i \frac{l_6}{2} \langle f^R_{\mu\nu} D^\mu U D^\nu U^\dagger + f^L_{\mu\nu} (D^\mu U)^\dagger D^\nu U \rangle \,, \\
\mathcal{L}^{(1)}_{\pi N} &= \bar{N} \left[i (v \cdot D) + \mathring{g}_A (S \cdot u) \right] N \,, \\
\mathcal{L}^{(3)}_{\pi N} &= \bar{N} \Big[d_{16} S \cdot u \langle \chi_+ \rangle + i d_{18} S^\mu \left[D_\mu, \chi_- \right] \\
&\quad + d_6 v^\nu \left[D^\mu, \tilde{f}^+_{\mu\nu} \right] + d_7 v^\nu \left[D^\mu, \langle f^+_{\mu\nu} \rangle \right] + d_8 \epsilon^{\mu\nu\alpha\beta} v_\beta \langle \tilde{f}^+_{\mu\nu} u_\alpha \rangle + d_9 \epsilon^{\mu\nu\alpha\beta} v_\beta \langle f^+_{\mu\nu} \rangle u_\alpha \\
&\qquad + d_{20} i S^\mu v^\nu \left[\tilde{f}^+_{\mu\nu}, v \cdot u \right] + d_{21} i S^\mu \left[\tilde{f}^+_{\mu\nu}, u^\nu \right] + d_{22} S^\mu \left[D^\nu, f^-_{\mu\nu} \right] \Big] N \,, \\
\mathcal{L}^{(0)}_{NN} &= -\frac{1}{2} C_S \bar{N} N \, \bar{N} N + 2 C_T \bar{N} S_\mu N \, \bar{N} S^\mu N \,, \\
\mathcal{L}^{(2)}_{NN\gamma} &= e \, \epsilon_{\mu\nu\rho\sigma} v^\mu f^{\nu\rho} \left[\tilde{C}_1 \bar{N}_v S^\sigma N_v \bar{N}_v N_v + \tilde{C}_2 \left(\bar{N}_v S^\sigma \tau^3 N_v \bar{N}_v N_v - \bar{N}_v S^\sigma N_v \bar{N}_v \tau^3 N_v \right) \right] \,,
\end{aligned}
$$

with the β-functions (Gasser et al. '02)

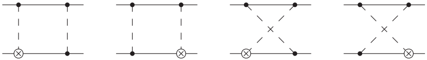
$$
\begin{aligned}
d_i &= d_i^r(\mu) + \frac{\beta_i}{F_\pi^2} L \,, \quad l_i = l_i^r(\mu) + \gamma_i L \\
\beta_7 &= \beta_8 = \beta_9 = \beta_{18} = \beta_{22} = 0, \;\; \beta_6 = -\frac{1}{6} - \frac{5}{6} g_A^2, \;\; \beta_{16} = \frac{1}{2} g_A + g_A^3, \;\; \beta_{21} = -g_A^3, \;\; \gamma_4 = 2, \;\; \gamma_6 = -\frac{1}{3} \,.
\end{aligned}
$$

Two-Pion exchange currents

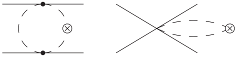
Class 1:



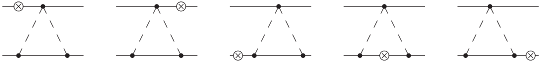
Class 2:



Class 3:

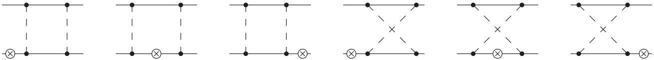


Class 4:



Class 5:

Class 6:



Class 7:

Two-Pion exchange currents in configuration-space

$$\vec{J}_{c1}(\vec{r}_{10},\vec{r}_{20}) = e\,\frac{g_A^2 M_\pi^7}{128\pi^3 F_\pi^4}\left[\vec{\nabla}_{10}[\vec{\tau}_1\times\vec{\tau}_2]^3 + 2\left[\vec{\nabla}_{10}\times\vec{\sigma}_2\right]\tau_1^3\right]\delta(\vec{x}_{20})\,\frac{K_1(2x_{10})}{x_{10}^2} + (1\leftrightarrow 2)\,,$$

$$\vec{J}_{c2}(\vec{r}_{10},\vec{r}_{20}) = -\,e\,\frac{g_A^4 M_\pi^7}{256\pi^3 F_\pi^4}\left(3\nabla_{10}^2 - 8\right)\left[\vec{\nabla}_{10}[\vec{\tau}_1\times\vec{\tau}_2]^3 + 2\left[\vec{\nabla}_{10}\times\vec{\sigma}_2\right]\tau_1^3\right]\delta(\vec{x}_{20})\,\frac{K_0(2x_{10})}{x_{10}}$$
$$+\,e\,\frac{g_A^4 M_\pi^7}{32\pi^3 F_\pi^4}\left[\vec{\nabla}_{10}\times\vec{\sigma}_1\right]\tau_2^3\,\delta(\vec{x}_{20})\,\frac{K_1(2x_{10})}{x_{10}^2} + (1\leftrightarrow 2)\,,$$

$$\vec{J}_{c3}(\vec{r}_{10},\vec{r}_{20}) = -\,e\,\frac{M_\pi^7}{512\pi^4 F_\pi^4}[\vec{\tau}_1\times\vec{\tau}_2]^3\left(\vec{\nabla}_{10}-\vec{\nabla}_{20}\right)\frac{K_2(x_{10}+x_{20}+x_{12})}{(x_{10}\,x_{20}\,x_{12})(x_{10}+x_{20}+x_{12})} + (1\leftrightarrow 2)\,,$$

$$\vec{J}_{c5}(\vec{r}_{10},\vec{r}_{20}) = -\,e\,\frac{g_A^2 M_\pi^7}{256\pi^4 F_\pi^4}\left(\vec{\nabla}_{10}-\vec{\nabla}_{20}\right)\left[[\vec{\tau}_1\times\vec{\tau}_2]^3\,\vec{\nabla}_{12}\cdot\vec{\nabla}_{20} - 2\tau_1^3\vec{\sigma}_2\cdot\left[\vec{\nabla}_{12}\times\vec{\nabla}_{20}\right]\right]$$
$$\times\,\frac{K_1(x_{10}+x_{20}+x_{12})}{(x_{10}\,x_{20}\,x_{12})} + (1\leftrightarrow 2)\,,$$

$$\vec{J}_{c7}(\vec{r}_{10},\vec{r}_{20}) = e\,\frac{g_A^4 M_\pi^7}{512\pi^4 F_\pi^4}\left(\vec{\nabla}_{10}-\vec{\nabla}_{20}\right)\left[[\vec{\tau}_1\times\vec{\tau}_2]^3\,\vec{\nabla}_{12}\cdot\vec{\nabla}_{10}\,\vec{\nabla}_{12}\cdot\vec{\nabla}_{20} + 4\tau_2^3\vec{\sigma}_1\cdot\left[\vec{\nabla}_{12}\times\vec{\nabla}_{10}\right]\right.$$
$$\left.\times\,\vec{\nabla}_{12}\cdot\vec{\nabla}_{20}\right]\frac{x_{10}+x_{20}+x_{12}}{x_{10}\,x_{20}\,x_{12}}K_0(x_{10}+x_{20}+x_{12}) + (1\leftrightarrow 2)$$

$$\vec{J}_{c4}(\vec{r}_{10},\vec{r}_{20}) = \vec{J}_{c6}(\vec{r}_{10},\vec{r}_{20}) = 0\,,$$

with $\vec{r}_{1/2/0}$ the positions of the first/second nucleon/the photon, and $\vec{x}_{10} = M_\pi\,(\vec{r}_1-\vec{r}_0)$, $\vec{x}_{20} = M_\pi\,(\vec{r}_2-\vec{r}_0)$, $\vec{x}_{12} = M_\pi\,(\vec{r}_1-\vec{r}_2)$ and $\vec{\nabla}_{ij} \equiv \partial/\partial x_{ij}$ and $x_{ij} \equiv |\vec{x}_{ij}|$.
All derivatives have to be evaluated as if the variables were independent.

Two-Pion exchange currents in configuration-space Ctd.

$$\rho_{c1}(\vec r_{10},\vec r_{20}) = \rho_{c2}(\vec r_{10},\vec r_{20}) = \rho_{c3}(\vec r_{10},\vec r_{20}) = 0\,,$$

$$\rho_{c4}(\vec r_{10},\vec r_{20}) = e\,\frac{g_A^2\,M_\pi^7}{256\pi^2 F_\pi^4}\,\tau_1^3\,\delta(\vec x_{20})\left(\nabla_{10}^2-2\right)\frac{e^{-2x_{10}}}{x_{10}^2} + (1\leftrightarrow 2)\,,$$

$$\rho_{c5}(\vec r_{10},\vec r_{20}) = -\,e\,\frac{g_A^2\,M_\pi^7}{256\pi^2 F_\pi^4}\,\tau_2^3\,\delta(\vec x_{20})\left(\nabla_{10}^2-2\right)\frac{e^{-2x_{10}}}{x_{10}^2} + (1\leftrightarrow 2)\,,$$

$$\begin{aligned}\rho_{c6}(\vec r_{10},\vec r_{20}) = &-\,e\,\frac{g_A^4\,M_\pi^7}{256\pi^2 F_\pi^4}\,\delta(\vec x_{20})\left[\tau_1^3\left(2\nabla_{10}^2-4\right)+\tau_2^3\,\vec\sigma_1\cdot\vec\nabla_{10}\,\vec\sigma_2\cdot\vec\nabla_{10}\;-\tau_2^3\vec\sigma_1\cdot\vec\sigma_2\right]\frac{e^{-2x_{10}}}{x_{10}^2}\\ &-\,e\,\frac{g_A^4\,M_\pi^7}{128\pi^2 F_\pi^4}\,\delta(\vec x_{20})\,\tau_1^3\left(3\nabla_{10}^2-11\right)\frac{e^{-2x_{10}}}{x_{10}} + (1\leftrightarrow 2)\,,\end{aligned}$$

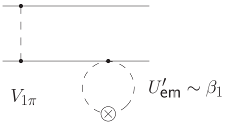
$$\begin{aligned}\rho_{c7}(\vec r_{10},\vec r_{20}) = &-\,e\,\frac{g_A^4\,M_\pi^7}{512\pi^3 F_\pi^4}\left[(\tau_1^3+\tau_2^3)\left(\vec\nabla_{12}\cdot\vec\nabla_{10}\vec\nabla_{12}\cdot\vec\nabla_{20}+\vec\nabla_{12}\cdot\left[\vec\nabla_{10}\times\vec\sigma_1\right]\vec\nabla_{12}\cdot\left[\vec\nabla_{20}\times\vec\sigma_2\right]\right)\right.\\ &\left.+\,[\vec\tau_1\times\vec\tau_2]^3\,\vec\nabla_{12}\cdot\vec\nabla_{10}\,\vec\nabla_{12}\cdot\left[\vec\nabla_{20}\times\vec\sigma_2\right]\right]\frac{e^{-x_{10}}}{x_{10}}\,\frac{e^{-x_{20}}}{x_{20}}\,\frac{e^{-x_{12}}}{x_{12}} + (1\leftrightarrow 2)\,.\end{aligned}$$

- Results also available in momentum-space, expressed in standard loop-function $L(q)$, $A(q)$ and three-point functions[S.K. et al. '09].
- Can be easily treated numerically.
- Continuity-equation is fulfilled $\rightarrow$ Current is consistent with potential obtained within the method of unitary transformation

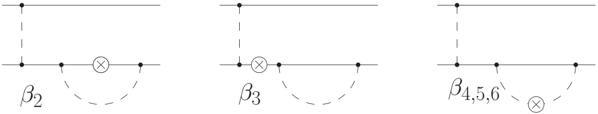
Additional transformations for the em current

- U is only the minimal unitary transformation, can choose additional transformations $U'_{\rm em}$

$$
\begin{aligned}
U'_{\rm em} &= e^{S'}\,, \quad \text{with} \quad S'(\mathcal{A}) \to 0 \quad \text{for} \quad \mathcal{A} \to 0\,, \\
U'_{\rm em} & \qquad \text{s.t. transformed Hamiltonian is block-diagonal} \\
\eta V_{\rm eff} \eta &\to \eta U'^{\dagger}_{\rm em} \eta \underbrace{U^{\dagger}\; H\; U \eta U'_{\rm em} \eta - H_0}_{\text{contains } V_{1\pi}} \supset J_{\rm eff},
\end{aligned}
$$

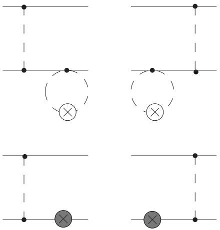


$$
S'_1 = \beta_1 \eta \left[J_{02}^{-1} \frac{\lambda^2}{E_\pi^2} H_{22}^2 - H_{22}^2 \frac{\lambda^2}{E_\pi^2} J_{02}^{-1} \right] \eta,
$$



Determination of βs

- Constraints by renormalizability!



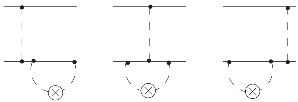
- These diagrams receive contributions from S_1'.

$$\vec{J}_{c5} = e \frac{g_A^2 i}{16 F_\pi^4} (\beta_1 - 1) [\vec{\tau}_1 \times \vec{\tau}_2]^3 \frac{\vec{\sigma}_1 \cdot \vec{q}_1 \, \vec{\sigma}_2 \cdot \vec{q}_2}{q_2^2 + M_\pi^2} \times \int \frac{d^3 l}{(2\pi)^3} \vec{l} \frac{\omega_+ - \omega_-}{\omega_+ \omega_- (\omega_+ + \omega_-)^2} + (1 \leftrightarrow 2)$$

$$\omega_\pm^2 = \left(\vec{l} \pm \vec{k}\right)^2 + 4 M_\pi^2 \,, \quad \vec{k} = \text{Photon-momentum} \,.$$

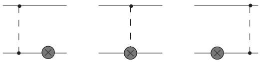
- The divergent part of the diagrams has to be absorbed into LECs.
- The divergent part (β-functions) of the LECs is already known[Gasser et al. '02].
- Contributions from LECs vanish in this case.
- Have to choose $\beta_1 = 1$ to guarantee renormalizability.

Determination of βs Ctd.



$$\vec{J}_{c7\ \mathrm{div}} =$$
$$-e\frac{i\,g_A^4}{32F_\pi^4\pi^2}[\vec{\tau}_1\times\vec{\tau}_2]^3\frac{\vec{\sigma}_2\cdot\vec{q}_2}{q_2^2+M_\pi^2}\left[\vec{k}\times[\vec{q}_2\times\vec{\sigma}_1]\right]\frac{1}{d-4}$$
$$+e\frac{5i\,g_A^4}{192F_\pi^4\pi^2}[\vec{\tau}_1\times\vec{\tau}_2]^3\frac{\vec{\sigma}_2\cdot\vec{q}_2}{q_2^2+M_\pi^2}(\beta-1)\vec{k}\vec{q}_2\cdot\vec{\sigma}_1\frac{1}{d-4}+(1\leftrightarrow 2)\,,$$

Where we choose $\beta_4=\beta_5=\beta_6=\beta$



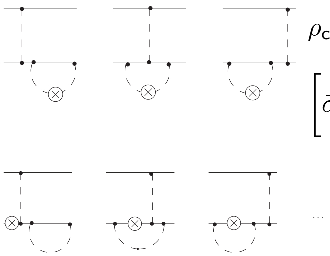
- Left and right diagram do not contribute.
- The diagram in the middle contributes among other things the following LECs

$$\vec{J} = -2e\frac{i\,g_A}{F_\pi^2}\left(d_8\tau_2^3+d_9\left(\vec{\tau}_1\cdot\vec{\tau}_2\right)\right)\frac{\vec{\sigma}_2\cdot\vec{q}_2}{q_2^2+M_\pi^2}\left[\vec{q}_2\times\vec{k}\right]$$
$$-e\frac{i\,g_A}{4F_\pi^2}(2d_{21}+d_{22})[\vec{\tau}_1\times\vec{\tau}_2]^3\frac{\vec{\sigma}_2\cdot\vec{q}_2}{q_2^2+M_\pi^2}\left[\vec{k}\times[\vec{q}_2\times\vec{\sigma}_1]\right]$$
$$+e\frac{i\,g_A\,d_{22}}{4F_\pi^2}[\vec{\tau}_1\times\vec{\tau}_2]^3\frac{\vec{\sigma}_2\cdot\vec{q}_2}{q_2^2+M_\pi^2}\left(\vec{\sigma}_2k^2-\vec{q}_2\vec{\sigma}_2\cdot\vec{k}\right)+(1\leftrightarrow 2)$$

We have to choose $\beta=1$!

Determination of βs Ctd.

These diagrams have also a (*finite*) contribution to the charge density



$$\rho_{c7} = -e\frac{g_A^4}{8F_\pi^4}\frac{\vec{\sigma}_2\cdot\vec{q}_2}{q_2^2+M_\pi^2}\tau_2^3\int d^3l\frac{1}{\omega_+^2\omega_-^2}$$
$$\left[\vec{\sigma}_1\cdot\vec{l}\,\vec{l}\cdot\vec{q}_2-\vec{\sigma}_1\cdot\vec{k}\,\vec{k}\cdot\vec{\sigma}_2\right]+(1\leftrightarrow 2)\,.$$

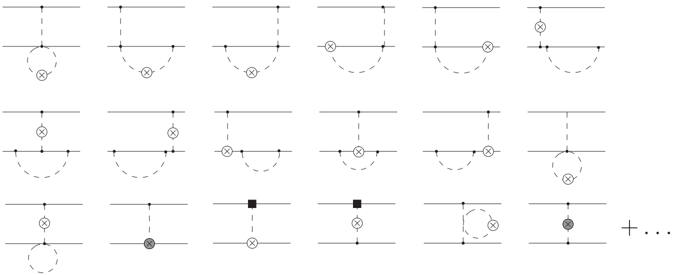
- Omitted most of the diagrams for brevity (in the figure).
- S_2' and S_3' could potentially contribute, but do not.

$$\rho_{c6} = e\frac{g_A^4}{4F_\pi^4}\tau_2^3\frac{\vec{\sigma}_2\cdot\vec{q}_2}{q_2^2+M_\pi^2}\vec{\sigma}_1\cdot\vec{q}_2\frac{1}{3}\int\frac{d^3l}{(2\pi)^3}\frac{l^2}{\omega_l^4}+(1\leftrightarrow 2).$$

Partial Summary

By choosing $\beta_1=\beta_4=\beta_5=\beta_6=1$ we can get rid of divergencies. β_2 and β_3 remain undetermined.

Additional loop contributions Ctd



- Plus the contributions from δZ_π and $\delta(g_A/F_\pi)$.
- LECs d_{16}, l_3 and l_4 disappear, only remaining term

The remaining divergence can be absorbed in l_6.

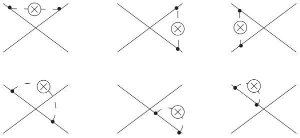
Summary OPE Ctd.

One-Pion Exchange current

- All divergencies can be canceled by additional unitary transformations
- or by LECs with predetermined β-functions
- Contributions from LECs d_8, d_9, d_{18}, d_{21}, d_{22} and l_6
- Continuity equation is fulfilled.

One-Pion exchange with LO contact potential

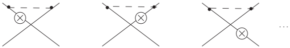
Diagrams with C_S and C_T



$$\vec{J} = e\,\frac{g_A^2\, i}{16F_\pi^2\,\pi^2}\,C_T\,\left(\tau_1^3 - \tau_2^3\right)\left[(\vec{\sigma}_1 - \vec{\sigma}_2)\times\vec{k}\right](2L(k) - 1)\,,$$

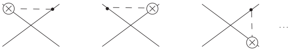
$$\rho = -e\,\frac{g_A^2}{32F_\pi^4\,\pi}\,C_T\,\left(\tau_1^3 + \tau_2^3\right)\Bigg[\vec{\sigma}_1\cdot\vec{\sigma}_2\,(3M_\pi + (3k^2 + 4M_\pi^2)A(k)) + \vec{\sigma}_1\cdot\vec{k}\;\vec{\sigma}_2\cdot\vec{k}\left(\frac{M_\pi - (4M_\pi^2 + k^2)A(k)}{k^2} + 2A(k)\right)\Bigg]\,.$$

- Contributions from additional unitary transformations cancel!
- Divergent part can be absorbed in contact currents.



$$\rho = e\,\frac{g_A^2}{8F_\pi^4\pi}\,C_T\,\left(\tau_1^3 + \tau_2^3\right)\vec{\sigma}_1\cdot\vec{\sigma}_2\,M_\pi\,.$$

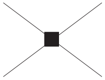
Only dependent on C_T.



$\rightarrow$ These diagrams vanish.

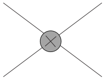
Contact currents

- Seven contact contributions to the potential.



$$\begin{aligned} V_{\text{contact}} &= C_1 q^2 + C_2 k'^2 + \left(C_3 q^2 + C_4 k'^2\right)(\vec{\sigma}_1 \cdot \vec{\sigma}_2) + iC_5 \frac{\vec{\sigma}_1 + \vec{\sigma}_2}{2} \cdot \left[\vec{k}\,' \times \vec{q}\right] \\ &\quad + C_6 (\vec{q} \cdot \vec{\sigma}_1)(\vec{q} \cdot \vec{\sigma}_2) + C_7 \left(\vec{k}\,' \cdot \vec{\sigma}_1\right)\left(\vec{k}\,' \cdot \vec{\sigma}_2\right) , \\ \vec{k}\,' &= \frac{\vec{p} + \vec{p}\,'}{2} , \qquad \vec{q} = \vec{p}\,' - \vec{p} . \end{aligned}$$

- Via a gauge transformation and a Fierz-reshuffling, we obtain

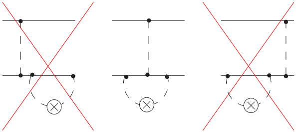


$$\begin{aligned} \vec{J}_{\text{contact}} &= +i\,(C_2 + 3C_4 + C_7)\, \frac{e}{16}\, [\vec{\tau}_1 \times \vec{\tau}_2]^3\, (\vec{q}_1 - \vec{q}_2) \\ &\quad - i\,(-C_2 + C_4 + C_7)\, \frac{e}{16}\, [\vec{\tau}_1 \times \vec{\tau}_2]^3\, (\vec{q}_1 - \vec{q}_2)\, \vec{\sigma}_1 \cdot \vec{\sigma}_2 \\ &\quad - C_5 i\, \frac{e}{16}\, (\tau_1^3 - \tau_2^3)\, [(\vec{\sigma}_1 + \vec{\sigma}_2) \times (\vec{q}_1 - \vec{q}_2)] \\ &\quad + iC_7 \frac{e}{16}\, [\vec{\tau}_1 \times \vec{\tau}_2]^3 \left[\vec{\sigma}_1 \quad \vec{\sigma}_2 \cdot (\vec{q}_1 - \vec{q}_2) + \vec{\sigma}_2 \quad \vec{\sigma}_1 \cdot (\vec{q}_1 - \vec{q}_2)\right] . \end{aligned}$$

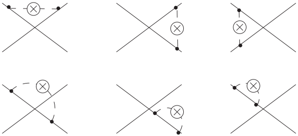
Plus two contact currents that cannot be obtained from gauge transformations

$$\vec{J}_{\text{contact}} = -e\, i\, \tilde{C}_1 \left[(\vec{\sigma}_1 + \vec{\sigma}_2) \times \vec{k}\right] - e\, i\, \tilde{C}_2 (\tau_1^3 - \tau_2^3) \left[(\vec{\sigma}_1 - \vec{\sigma}_2) \times \vec{k}\right] .$$

Comparison with Pastore et al.



- Pastore et al. (2009) do not take into account these two diagrams.
- In our formalism, however, the contribution from the middle diagram is exactly canceled from the left and right diagrams.
- ⇒ Different isospin structure of the loop contributions!
- Different contributions from LECs?

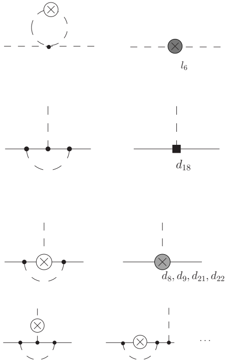


- Loops with leading-order contact interaction depend on C_S.
- This is similar to the situation with the potential.
- Again a different isospin structure!

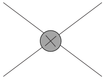
- Contact terms agree with ours.

Determining the LECs

- In the NLO pion exchange current unknown 8 LECs appear:



- l_6 is related to pion vector form factor $\longrightarrow$ well known.
- d_{18} is related to Goldberger-Treiman discrepancy $g_{\pi N}/m_N = g_A/F_\pi(1 - 2M_\pi^2 d_{18}/g_A) \longrightarrow$ relatively well known.
- d_8, d_9, d_{21} and d_{22} are related to pion-photoproduction on one nucleon, poorly known.
- Calculate full pion-photoproduction amplitude and fix these constants to data!



- $\tilde{C}_1$ can contribute to elastic *ed*-scattering, contribution to *d*-magnetic moment.
- $\tilde{C}_2$ from *d*-breakup reaction at threshold.

Conclusion and outlook

Conclusion

- We derived the full NLO em-current including two-pion exchange, one-pion exchange and contact terms.
- An explicit check of renormalizability of the one- and two-pion exchange contributions was performed.
- Expressions are given in momentum-space in terms of loop-functions $L(q)$, $A(q)$ and three-point functions.
- We analytically carried out the Fourier-transform to arrive at very compact expressions in configuration-space.
- The current fulfills the continuity-equation, i.e. is consistent with the potential.
- The two-pion exchange current corresponds to the result of Pastore et al.
- The one-loop current is different.

Outlook

- Calculation of pion-photoproduction off nucleons to determine LECs.
- Calculation of *ed*-scattering observables.
- Inclusion of Δ-degrees of freedom.
- Going to the sub-leading loop-order.