EFT Methods

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The EFT algorithm

- Identify key fields $\mathbf{E}$ and $\mathbf{B}$;
- Identify low-energy scales $\omega = \lambda$
  and high-energy scales $\Delta E, 1/r_{\text{atom}}$;
- Identify symmetries $U(1)_{\text{em}}$, rotation, P, T;
- Write down all operators contributing to this process which are allowed by these symmetries; $\mathbf{E}^2, \mathbf{B}^2, \ldots$
- Organize using naive dimensional analysis;
- Determine power counting for loops in QFT;
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$\Rightarrow$ PREDICTIONS (Systematically improvable, falsifiable)

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Goal: Low-energy effective theory of QCD with nucleon and pion degrees of freedom;

Key: Effective theory must inherit low-energy symmetries of QCD.

Low-energy symmetries of QCD

$$\mathcal{L}_{QCD} = \bar{u} i \not{D} u + \bar{d} i \not{D} d - m_u \bar{u} u - m_d \bar{d} d - \frac{1}{4} G_{\mu\nu} G^{\mu\nu}$$

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Symmetry under $u_L \leftrightarrow d_L$ *and* $u_R \leftrightarrow d_R$;

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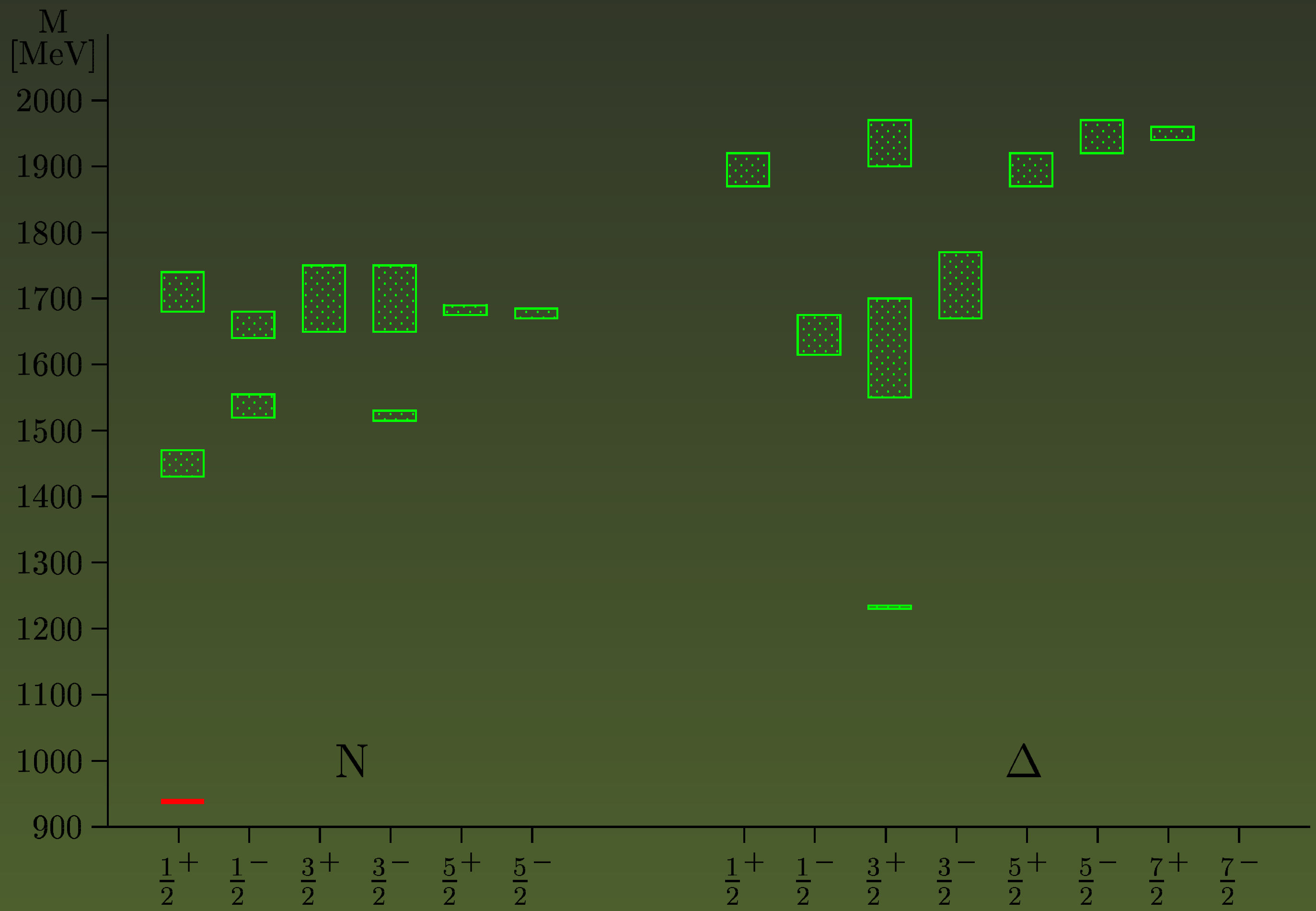
Prediction: Symmetry of QCD Hamiltonian $\Rightarrow$ for every positive parity eigenstate of H_{QCD} there should be an (almost) degenerate negative parity eigenstate.

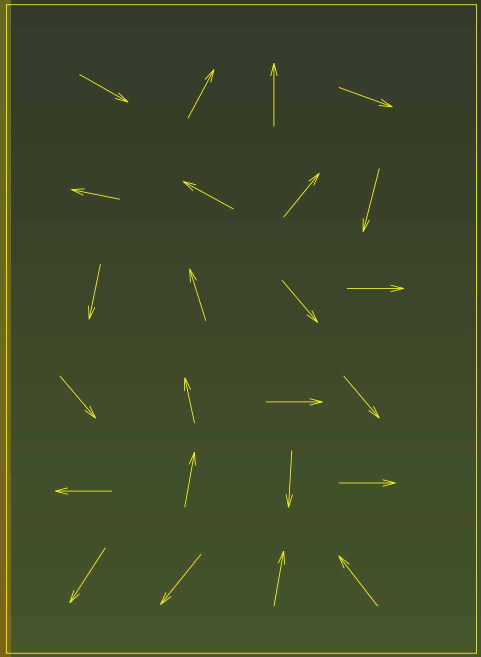
Experimental baryon spectrum



Cohen & Glozman, Int. J. Mod. Phys. **A17**, 1237 (2002)

Analogy: Ferromagnetism

Above T_c:



$\langle \mathbf{M} \rangle = 0$

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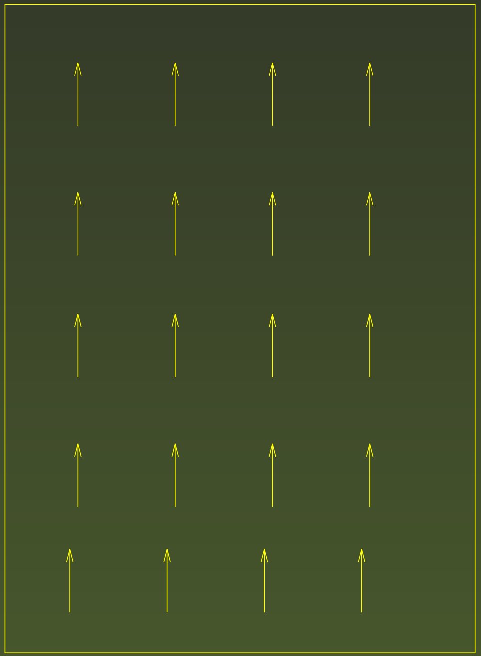

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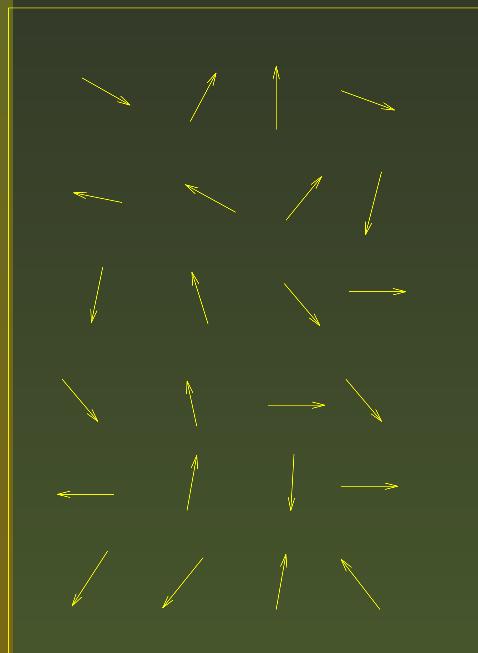

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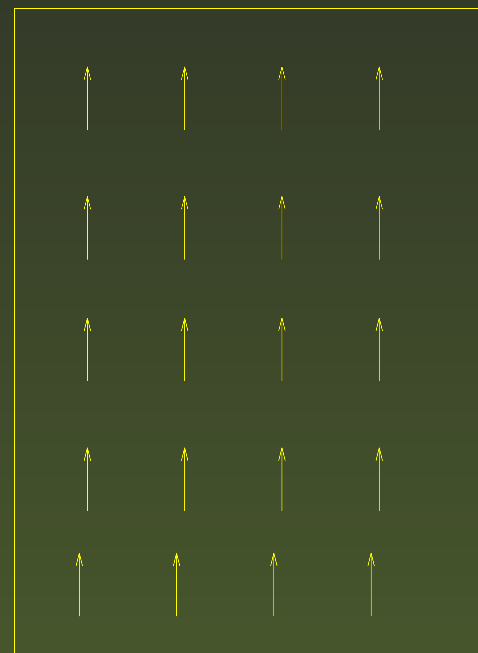

$\langle \mathbf{M} \rangle \neq 0$

H_{magnet} rotationally symmetric, so how can $\langle \mathrm{magnet} | \mathbf{M} | \mathrm{magnet} \rangle \neq 0$?

Analogy (contd.)

Spontaneous symmetry breaking: below T_c ground state of Hamiltonian does not have symmetry of Hamiltonian itself.

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Ferromagnetism	**QCD**
Ground state $\|\text{magnet}\rangle$	QCD vacuum $\|0\rangle$
$\langle\text{magnet}\|\mathbf{M}\|\text{magnet}\rangle$	$\langle 0\|\bar{q}q\|0\rangle$
$O(3)$	$SU(2)_A$
Low temperature	Low energy, also T
Magnons	Pions

Consequences for low-energy QCD

$m_q = 0$ **(chiral limit):**

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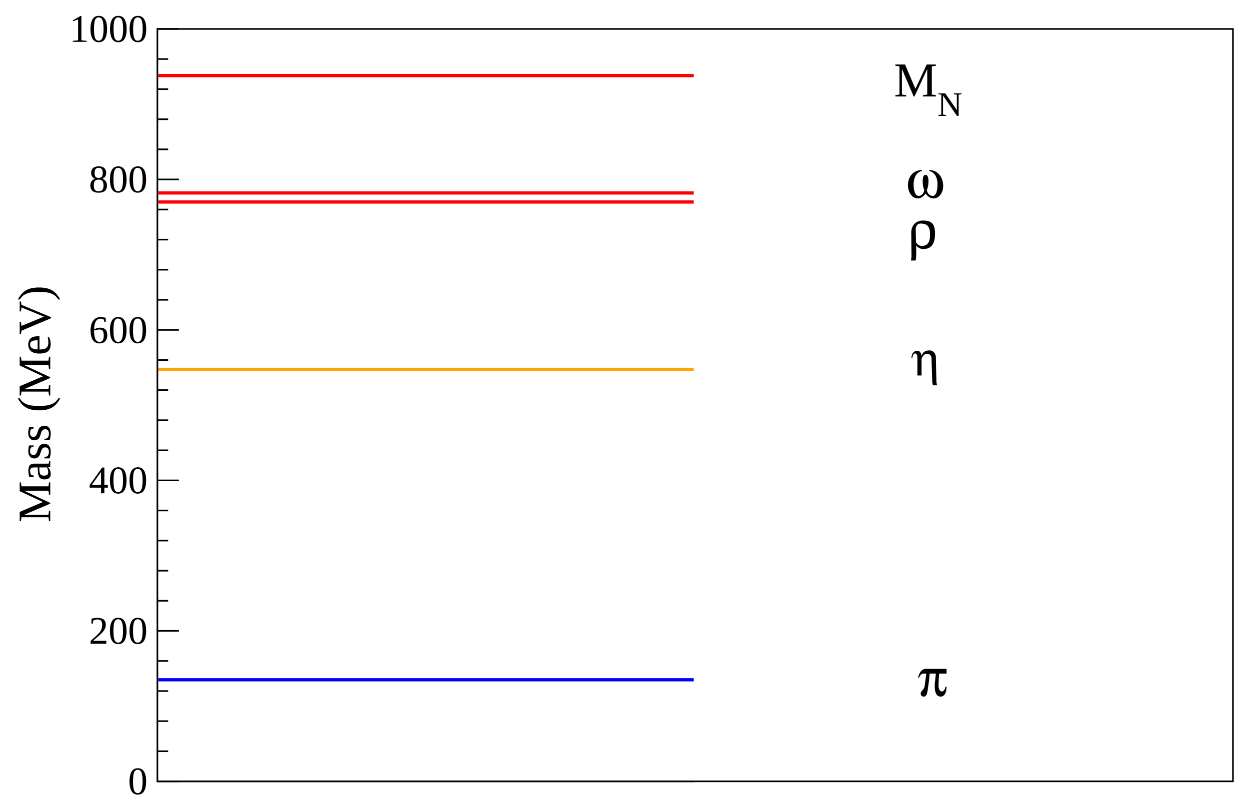
New effective theory: $m_\pi, p \ll M_N, m_\rho$

SMALL BIG

Symmetries: $U(1)_{\rm em}$, isospin, Spontaneously broken χS

Degrees of freedom: N, π

The strong-interaction mass gap



Chiral perturbation theory

Chiral perturbation theory is the most general $\mathcal{L}(N, \pi)$ consistent with the symmetries of QCD and the pattern of their breaking, up to a given order in the small expansion parameter:

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- "Short-distance physics" ($r \sim \frac{\hbar c}{m_\rho}$) expanded a la the multipole expansion $\Rightarrow$ certain number of "multipoles" need to be determined at each order;
- Pions are weakly coupled and light $\Rightarrow$ they provide the long-distance ($r \sim \frac{\hbar c}{m_\pi}$) contribution to observables.

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Resultant EFT is model-independent and systematically improvable

Weinberg, Gasser, Leutwyler, Bernard, Kaiser, Meißner,...

Power counting in χPT

Rules:

- P^n for a vertex with n powers of p or m_π: $\mathcal{L}^{(n)}$;
- P^{-2} for each pion propagator: $\frac{1}{q^2-m_\pi^2}$;
- P^{-1} for each nucleon propagator: $\frac{1}{p_0-\mathbf{p}^2/(2M)}$;
- P^4 for each loop: $\int d^4k$;

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Power counting for loops as well as for $\mathcal{L}$

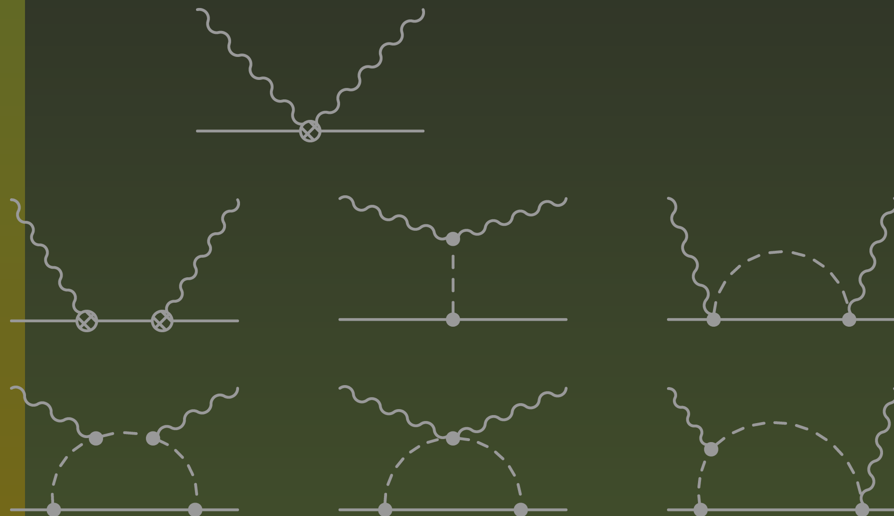
$$\Rightarrow \mathcal{A}(\pi s, \gamma s, N) = \sum_n \mathcal{F}_n\left(\frac{p}{m_\pi}\right) P^n,$$

$$\mathcal{F}_n \sim O(1)$$

Nucleon Compton Scattering in χPT

$O(e^2)$:

$O(e^2 P)$:



$$\frac{-e^2}{M}\epsilon' \cdot \epsilon$$

Powell X-Sn +

non-analyticity

from loops

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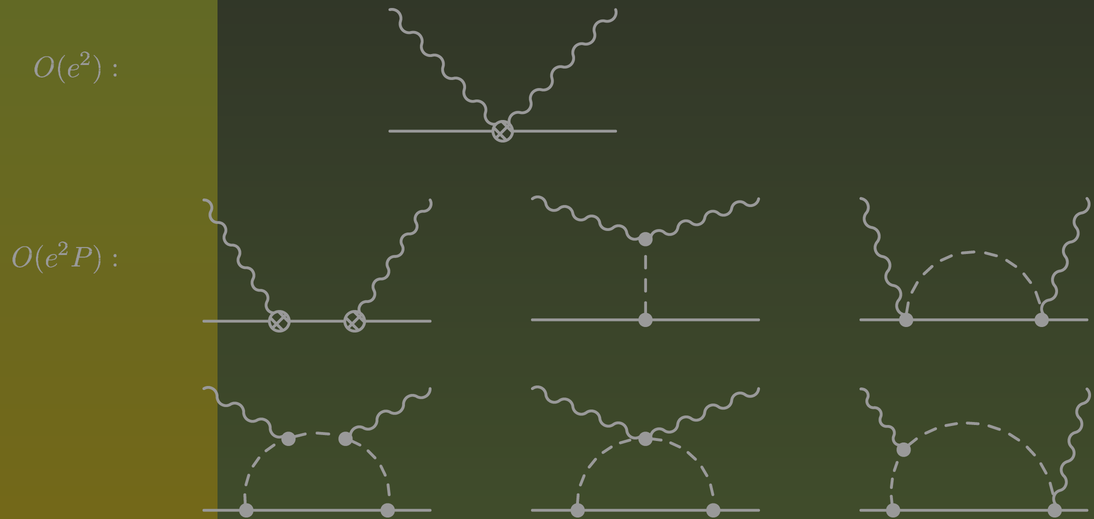

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Small ω expansion:

$$\mathcal{A}_{\gamma N}(\omega) = \left[-\frac{e^2}{M} + 4\pi\alpha_N\omega^2\right]\epsilon' \cdot \epsilon + 4\pi\beta_N\omega^2(\epsilon \times \hat{k}) \cdot (\epsilon' \times \hat{k}')$$

$$\alpha_N = \frac{5e^2 g_A^2}{384\pi^2 f_\pi^2 m_\pi} = 12.2 \times 10^{-4}\ \text{fm}^3; \quad \beta_N = 1.2 \times 10^{-4}\ \text{fm}^3.$$

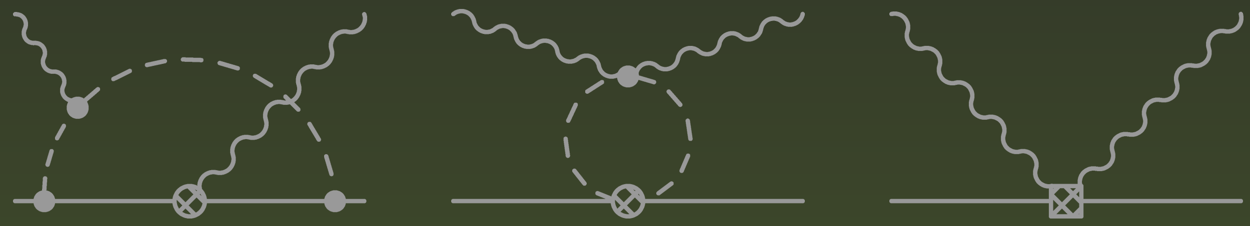
Bernard, Kaiser, Meißner (1992)

PDG average:

$$\alpha_p = (12.0 \pm 0.7) \times 10^{-4}\ \text{fm}^3;$$
$$\beta_p = (1.6 \pm 0.6) \times 10^{-4}\ \text{fm}^3.$$

N^{2}LO: $O(e^2P^2)$

γN amplitude at $O(e^2P^2)$



J. McGovern, Phys. Rev. C **63**, 064608 (2001)

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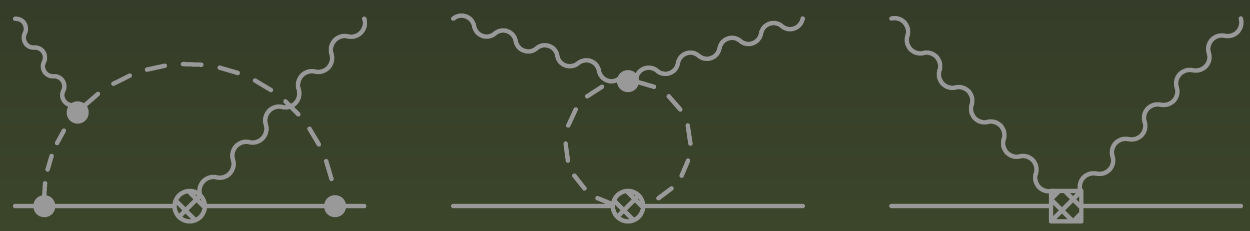

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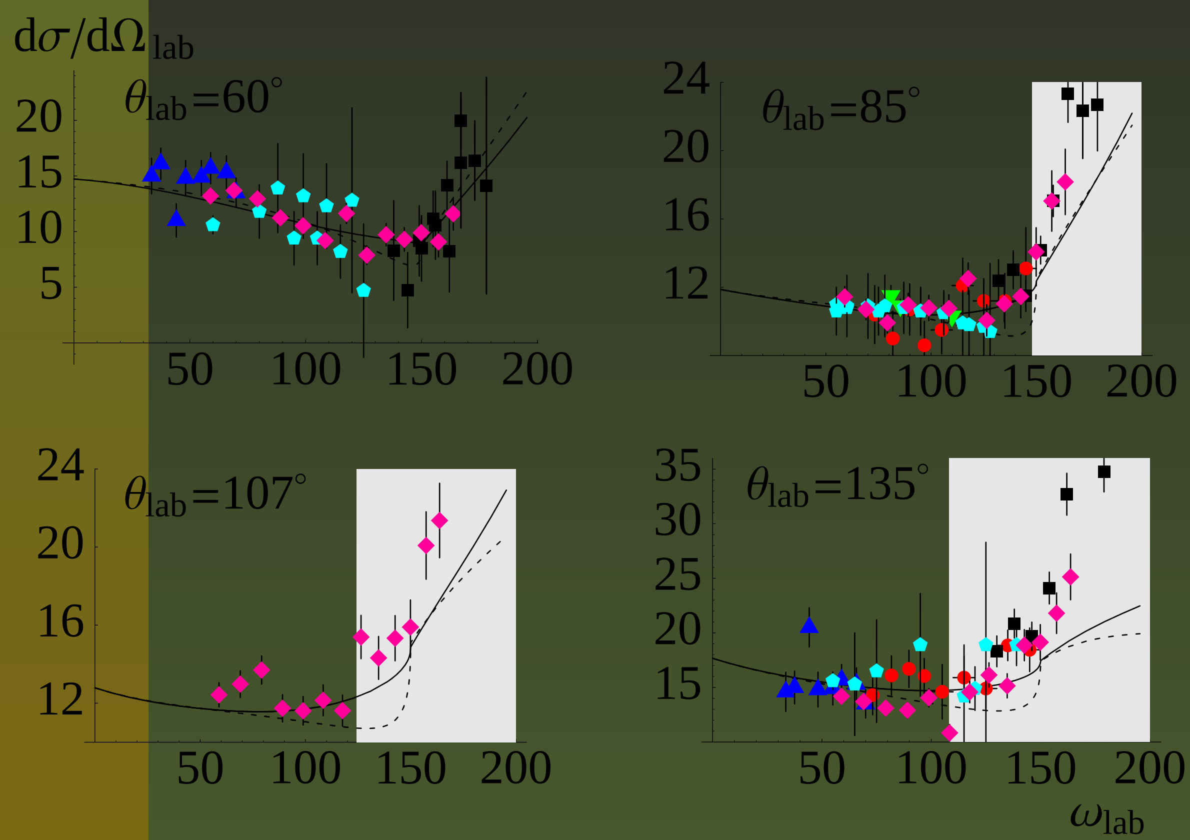
Short-distance physics via contact terms , with coefficients which should be fit to data:

$$4\pi\Delta\alpha_N\mathbf{E}^2, 4\pi\Delta\beta_N\mathbf{B}^2 \qquad \sim \omega^2 e^2$$

Experiments: SAL/Illinois, LEGS, MAMI, ...

Results



χ^2/d.o.f.=170/131

$$\alpha_p = (12.1 \pm 1.1)^{+0.5}_{-0.5} \times 10^{-4}\ \mathrm{fm}^3$$

$$\beta_p = (3.4 \pm 1.1)^{+0.1}_{-0.1} \times 10^{-4}\ \mathrm{fm}^3$$

S. R. Beane, J. McGovern, M. Malheiro, D. P., U. van Kolck, Phys. Lett. B, **567**, 200 (2003).

χPT and light nuclei

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Weinberg (1990): employ chiral expansion for NN potential and solve Schrödinger equation for nuclear wave function:

$$(E - H_0)|\psi\rangle = V|\psi\rangle$$

$$V = V^{(0)} + V^{(2)} + V^{(3)} + \dots$$

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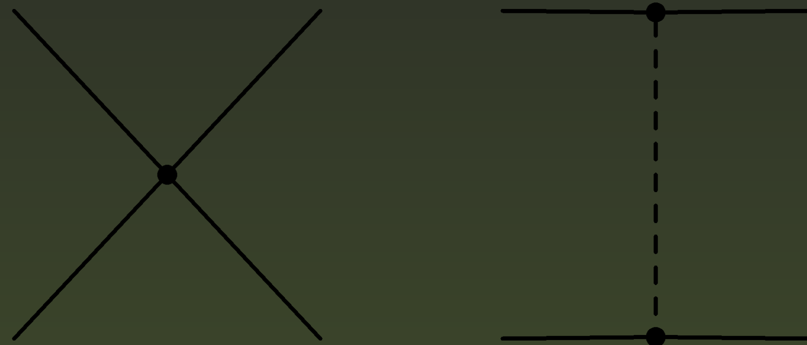
- V respects QCD pattern of chiral symmetry breaking;
- Systematic theory of NN interaction.

Leading-order potential

$$V = C + \frac{g_A^2}{4f_\pi^2}\frac{\sigma_1\cdot\mathbf{q}\;\sigma_2\cdot\mathbf{q}}{\mathbf{q}^2+m_\pi^2}(\tau_1^a\tau_2^a)$$

Leading-order potential



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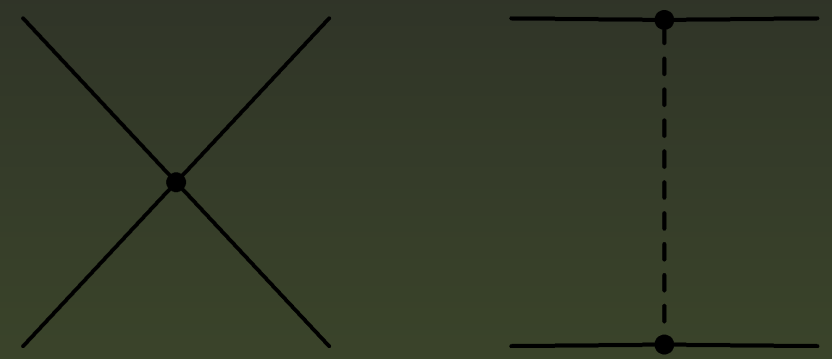

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Yukawa(1935): $\Delta E\Delta t \sim \hbar \quad\Rightarrow\quad \Delta t \sim \frac{\hbar}{m_\pi c^2}$

$$\Rightarrow \text{Range} \sim \frac{\hbar}{m_\pi c} \sim 2\text{ fm}$$

$$V(r) = C\delta^{(3)}(r) \;+\; \frac{g_A^2 m_\pi^2}{8\pi f_\pi^2}\frac{e^{-m_\pi r}}{r}$$

Leading-order χPT potential is singular, requires regularization and renormalization.

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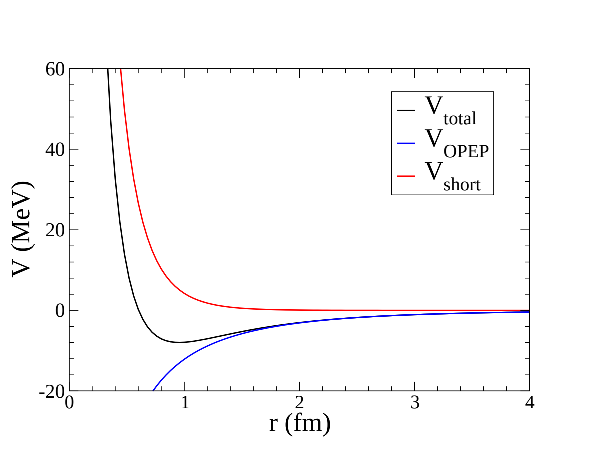

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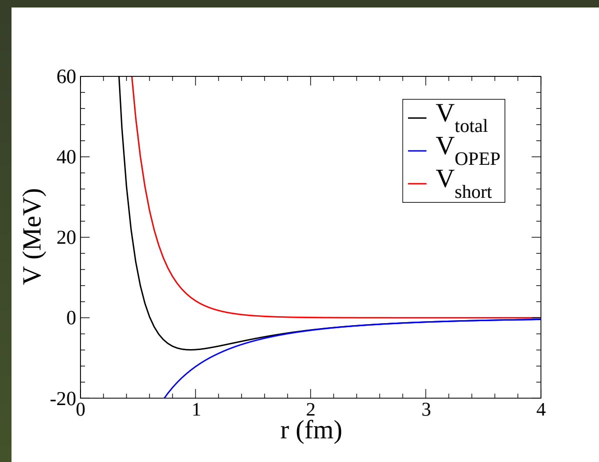

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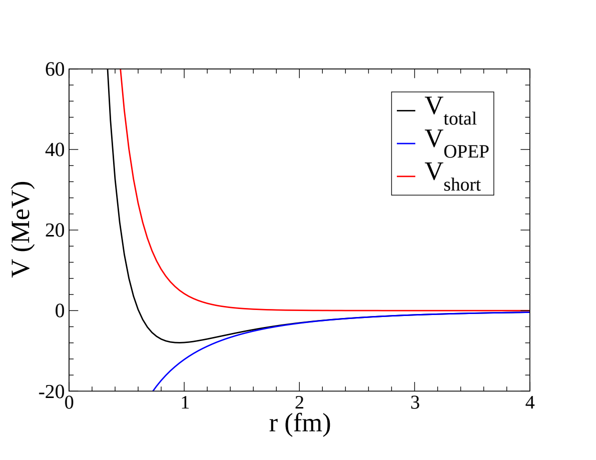

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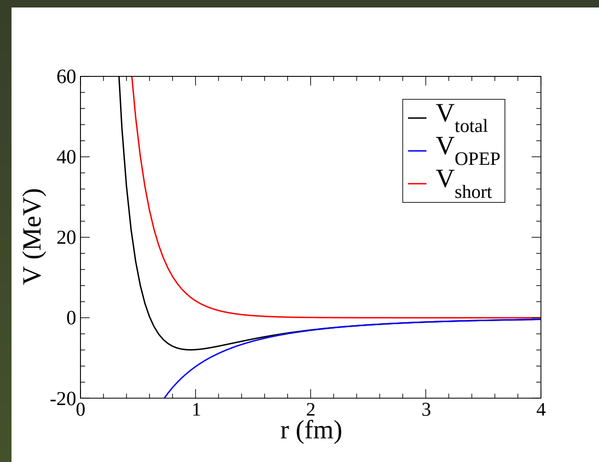

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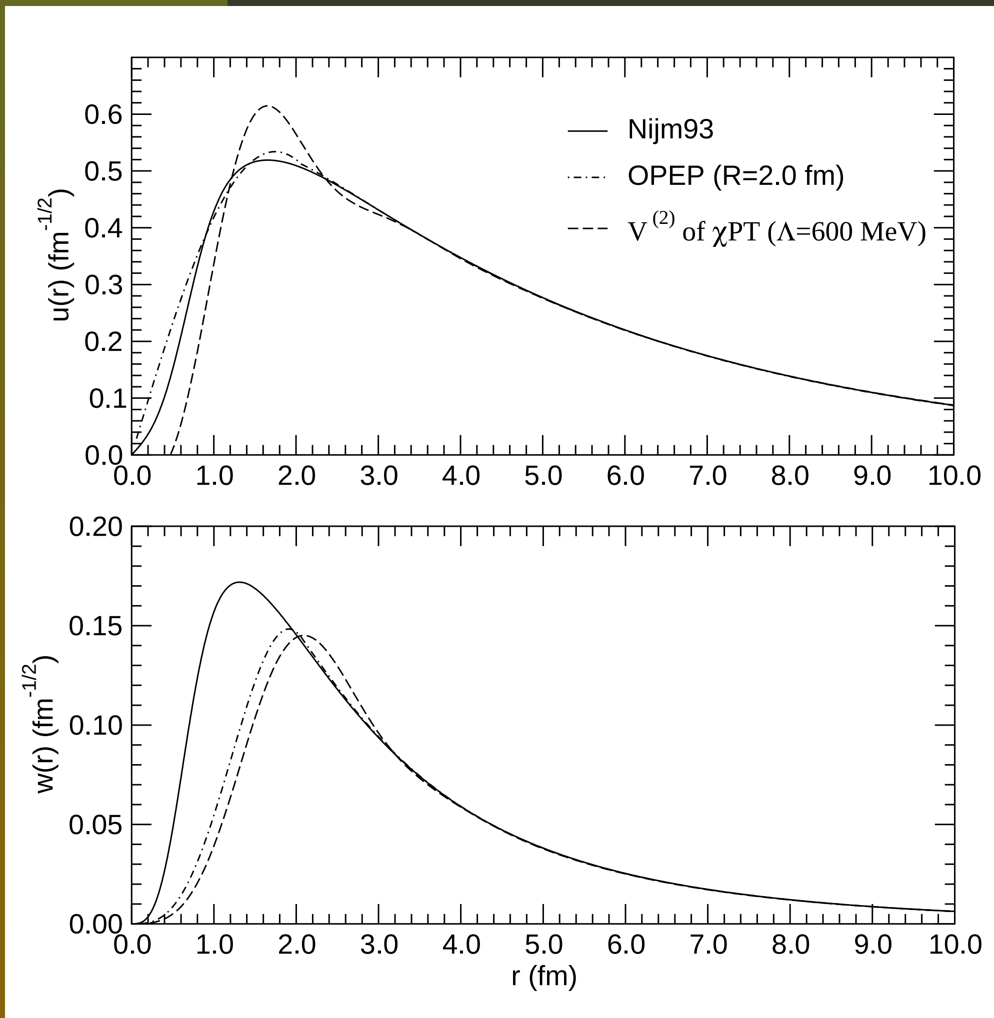
- $V_{OPEP} \rightarrow \frac{S_{12}(\hat{r})}{r^3}$ as $m_\pi \rightarrow 0$; Beane & Savage and Epelbaum *et al.*
- Corrections to LO potential due to two-pion exchange etc. can be systematically calculated in χPT.

Deuteron wave functions

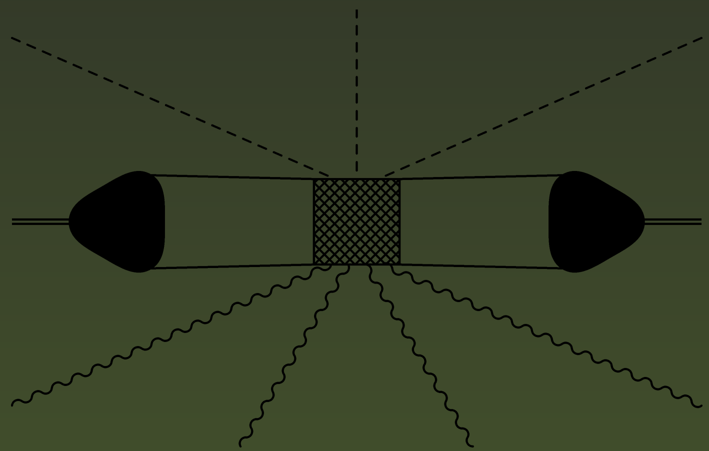
Deuteron: binding energy 2.225 MeV, (?small on scale of m_π?) fixes C.



Same at long distances: B, A_S, A_D, $f_{\pi NN}$, m_π. Some differences at two-pion range.

Reactions on deuterium

$$\langle \psi | \hat{O} | \psi \rangle$$



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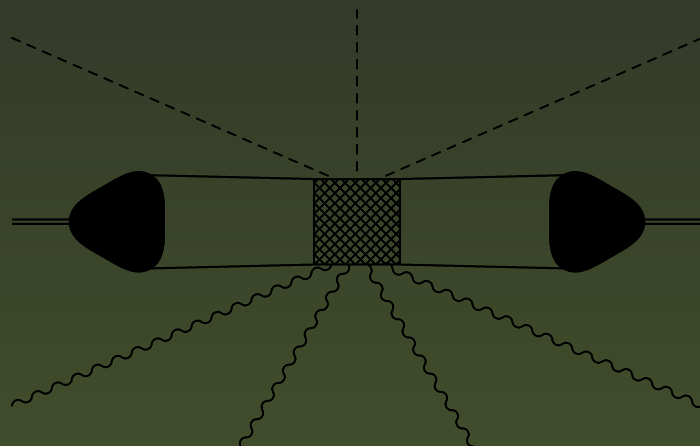

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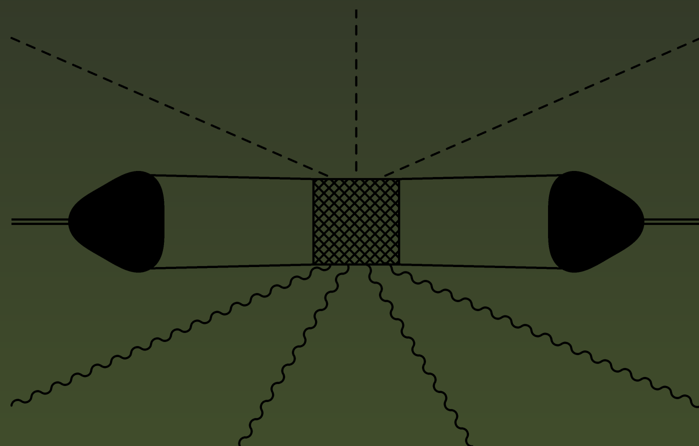

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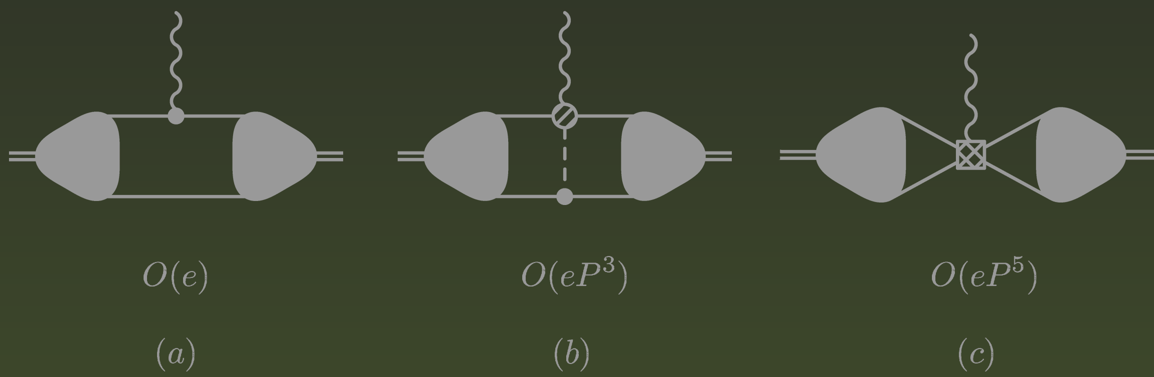
Description of observables which should be: model independent, systematically improvable, accurate at low momentum/energy transfer.

J^0 in χPT



D.P. + Cohen, Meißner + Walzl, D.P.

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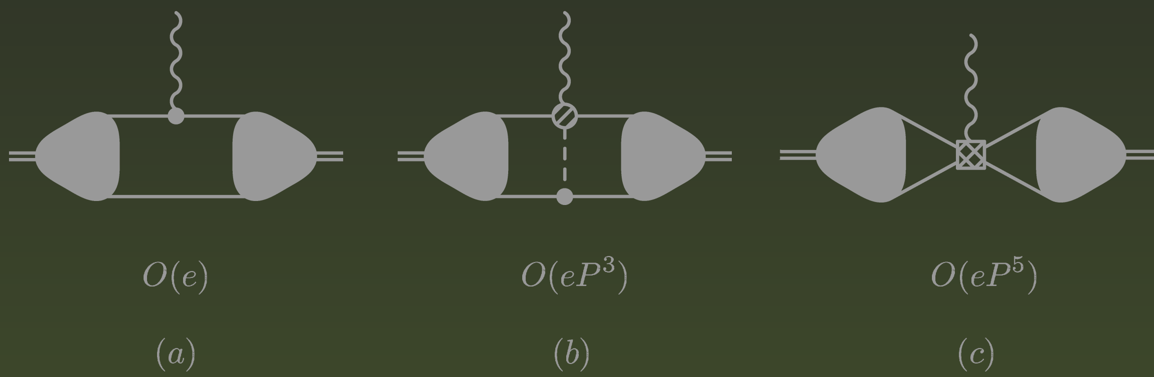
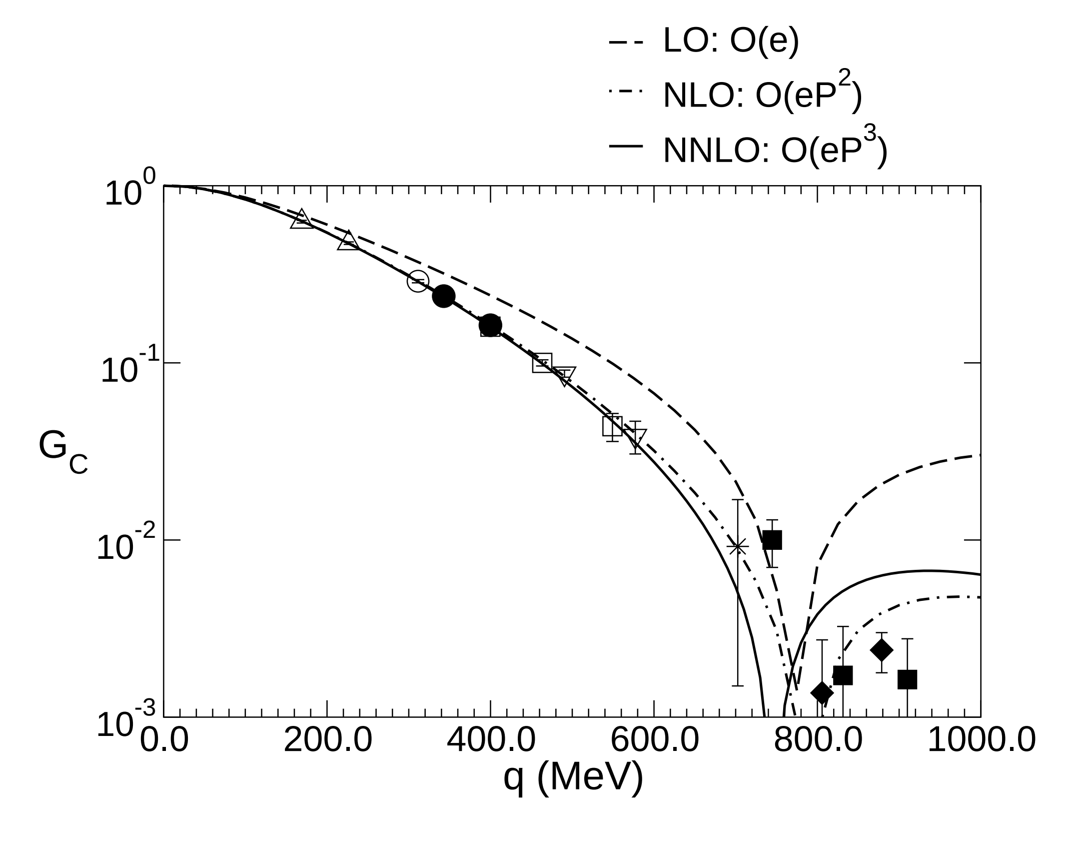


D.P. + Cohen, Meißner + Walzl, D.P.

- LO $O(e)$: structureless nucleons
- NLO $O(eP^2)$: nucleon isoscalar charge radius + relativistic effects
- NNLO $O(eP^3)$: two-body pion-exchange-charge operator
- N^3LO $O(eP^4)$: two-meson-exchange charge pieces

G_C using factorization

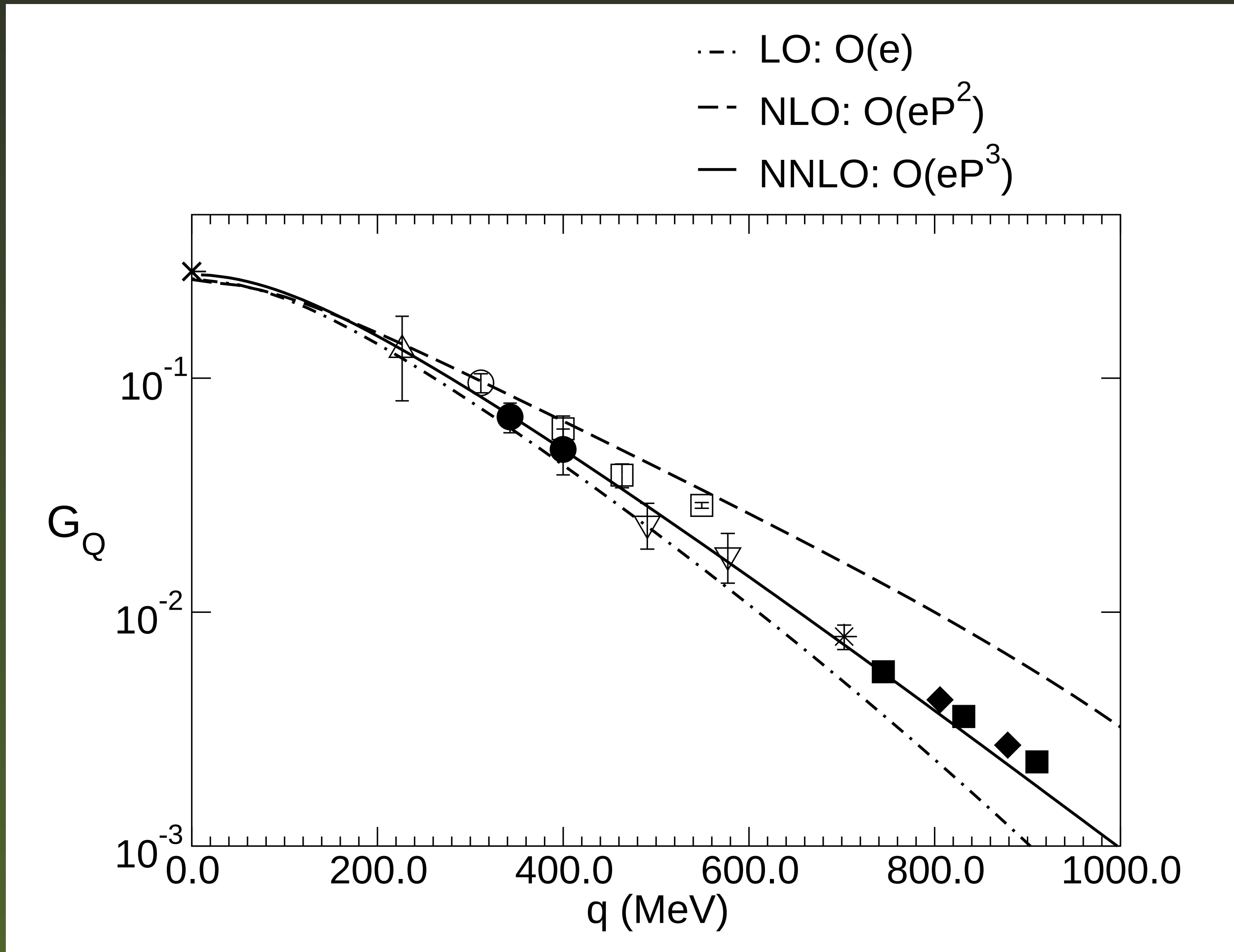
$$\frac{G_C}{G_E^{(s)}} = \langle\psi|e|\psi\rangle + \langle\psi|J_\pi^0|\psi\rangle + O(eP^4)$$



Parameter-free prediction: tests χPT's description of *deuteron*.

Data: Abbott et al., Eur. Phys. J. A **47**, 421 (2000); Theory: D.P., Phys. Lett. B **567**, 12 (2003).

G_Q



LO: O(e)
NLO: O(eP^2)
NNLO: O(eP^3)
G$_Q$
10^{-1}
10^{-2}
10^{-3}
0.0
200.0
400.0
600.0
800.0
1000.0
q (MeV)

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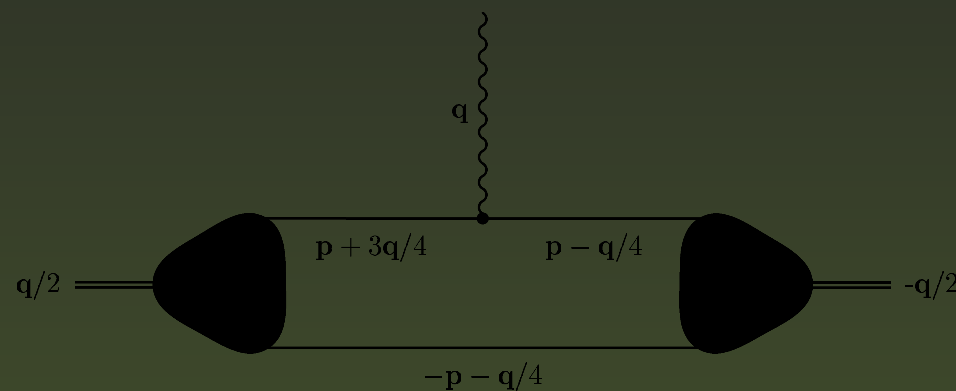
- NN, ed, γd, πd, $\gamma d \to \pi^0 d$, $np \to d\gamma$, νd, NNN, etc.

Future work

- Polarization observables in $\vec{\gamma}d$ (with D. Choudhury);
- Δ degrees of freedom in γd (with R. Hildebrandt, et al.);
- More data on γd $\rightarrow$ γd! HIγS at TUNL
- Compton scattering on Helium-3;
- $\pi^- d \rightarrow \gamma nn$ for nn scattering length (with A. Gårdestig);
- δ-expansion for πN scattering;
- Systematic n-body forces which are consistent with NN force;
- Shell model as an EFT;
- MFT, DFT, and EFT.

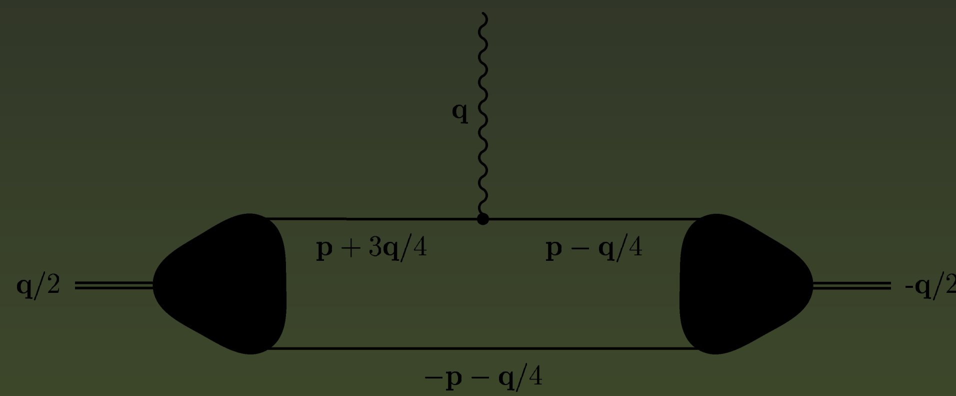
Thanks to the U.S. Department of Energy for financial support.

J^0 in χPT



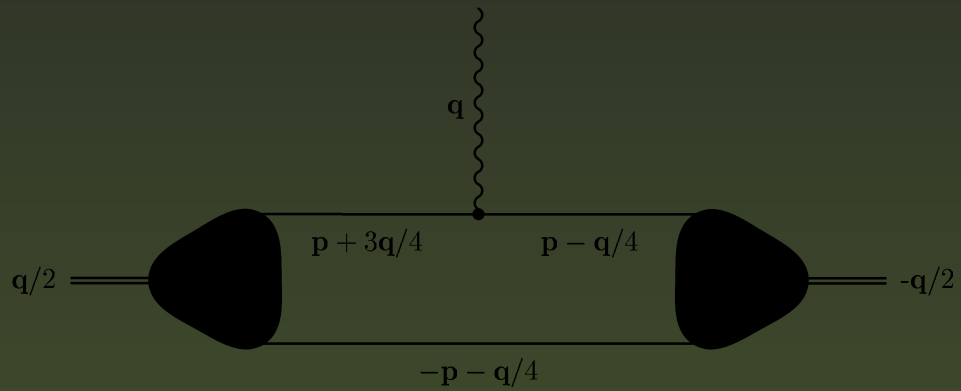
- Leading-order $O(e)$: $j_0 = e$, structureless nucleons;

J^0 in χPT



- Leading-order $O(e)$: $j_0 = e$, structureless nucleons;
- Next-to-leading order $O(eP^2)$: $j_0 = e\left(1 - \frac{1}{6}Q^2\langle r_N^2\rangle\right)$, nucleon structure;

J^0 in χPT



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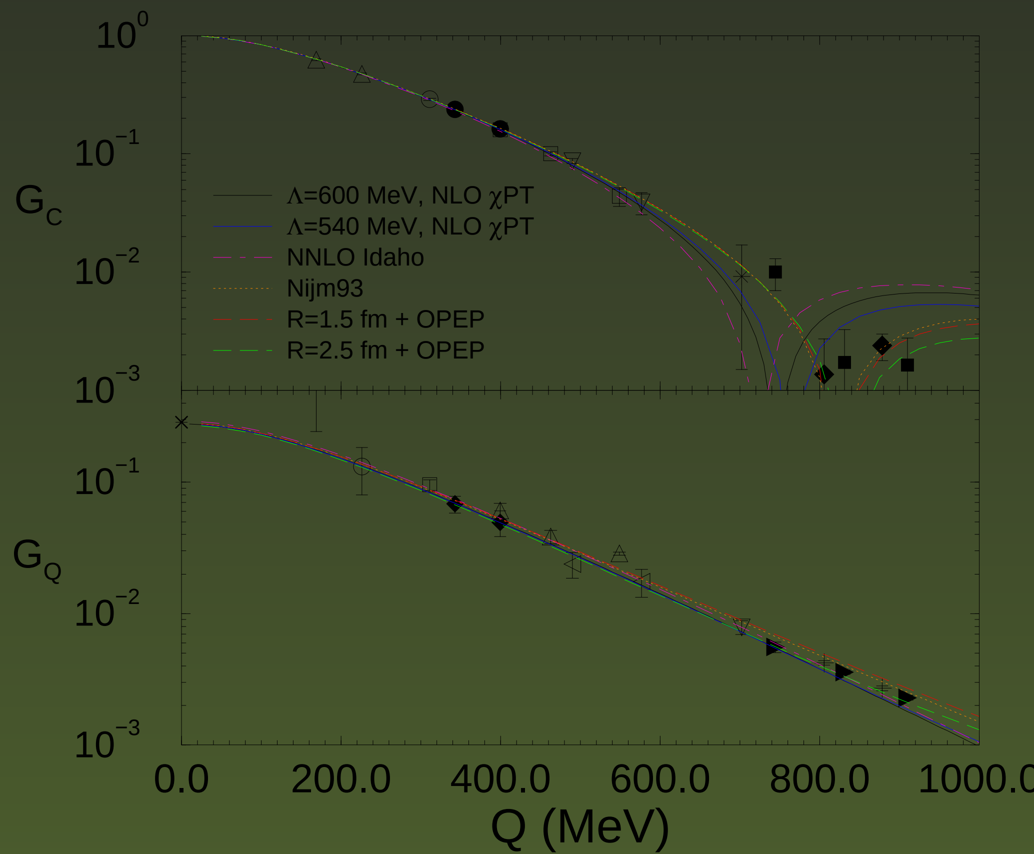
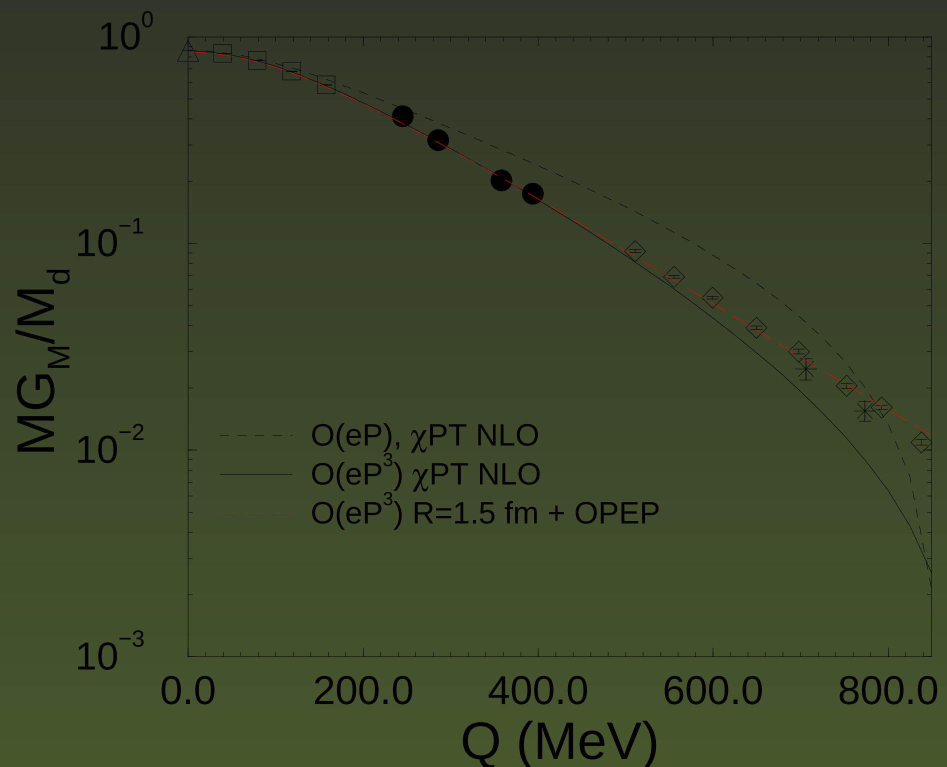
- $O(eP^2)$ also includes relativistic corrections (down by p^2/M^2).

Wave-function dependence



Wave-function sensitivity gives an estimate of higher-order effects.

G_M



J^+: more sensitive to short-distance contributions than J^0.

Higher Q^2? “Effective models”?