

Symmetry Preserving Regularization of Nuclear Forces and Currents

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Progress in Ab Initio Techniques in Nuclear Physics

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Outline

- Nuclear forces and currents in chiral EFT
- Regularization of NN force
- Violation of chiral symmetry by regulator in 3NF
- Higher-derivative regularization in pion-sector
 - Respects all symmetries by construction
 - Application to 3NF and current operators
- Deuteron form factors

Chiral Expansion of the Nuclear Forces

Two-nucleon force

Three-nucleon force

Four-nucleon force

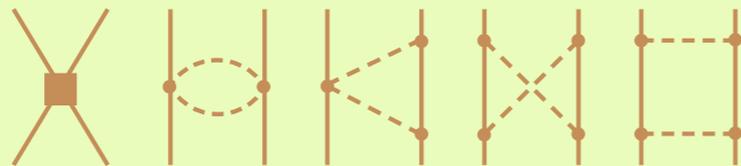
LO (Q^0)



Weinberg '90



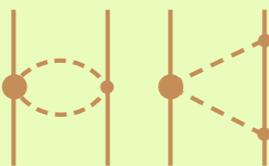
NLO (Q^2)



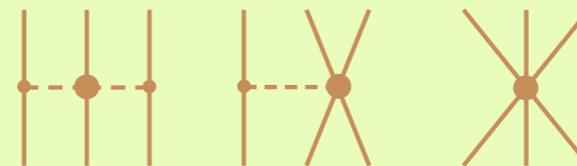
Ordonez, van Kolck '92



N^2 LO (Q^3)



Ordonez, van Kolck '92



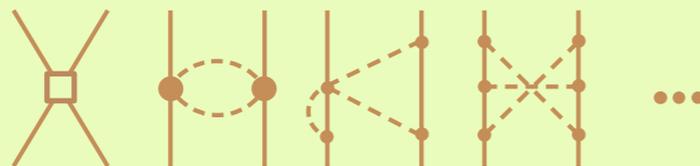
van Kolck '94; Epelbaum et al. '02



Available matrix elements
LENPIC '19



N^3 LO (Q^4)



Kaiser '00 - '02



Bernard, Epelbaum, HK, Meißner, '08, '11

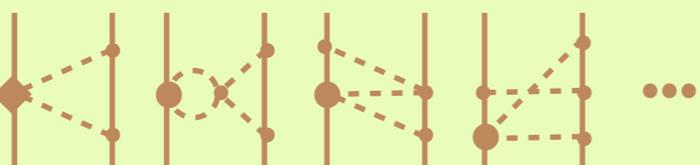
[parameter-free]



[parameter-free]

Epelbaum '06

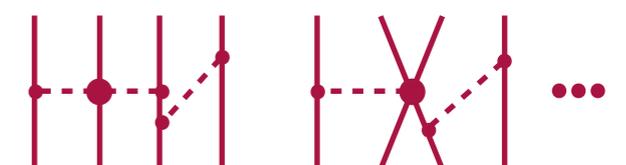
N^4 LO (Q^5)



Entem, Kaiser, Machleidt, Nosyk '15
Epelbaum, HK, Meißner '15



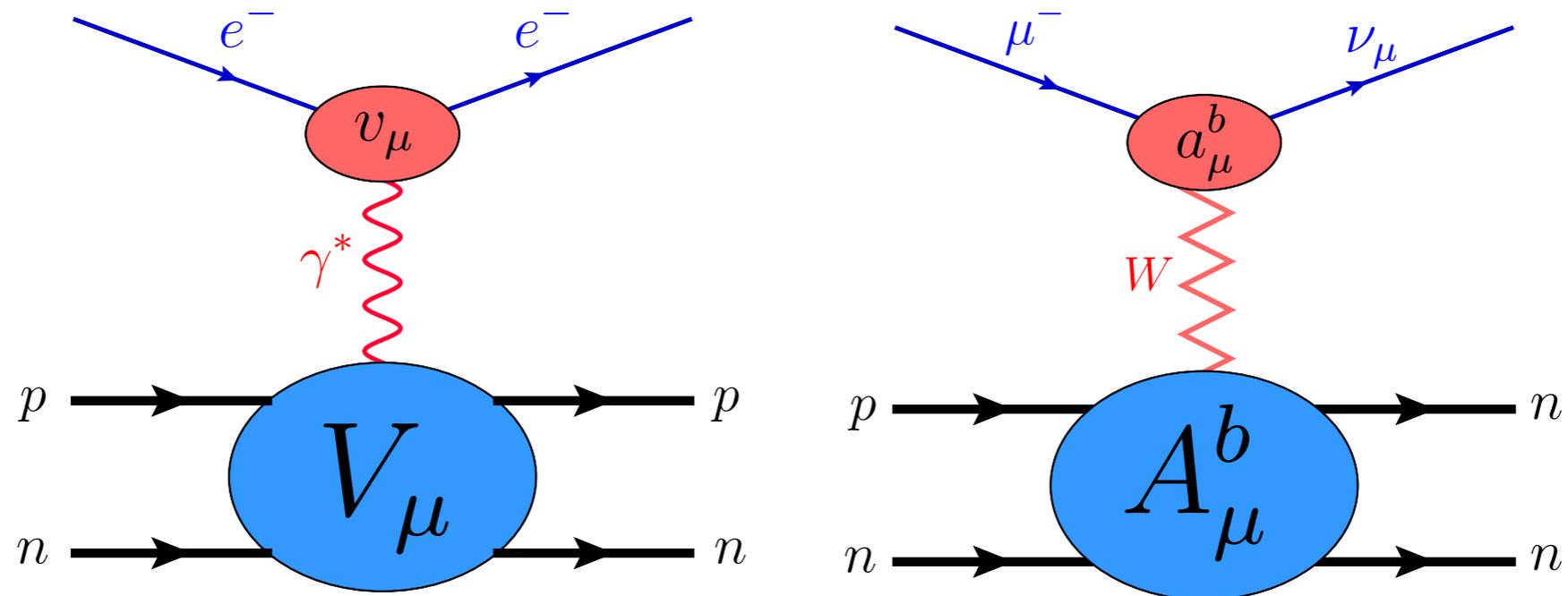
Girlanda, Kievsky, Viviani '11
HK, Gasparyan, Epelbaum '12, '13
(short-range loop contrib. still missing)



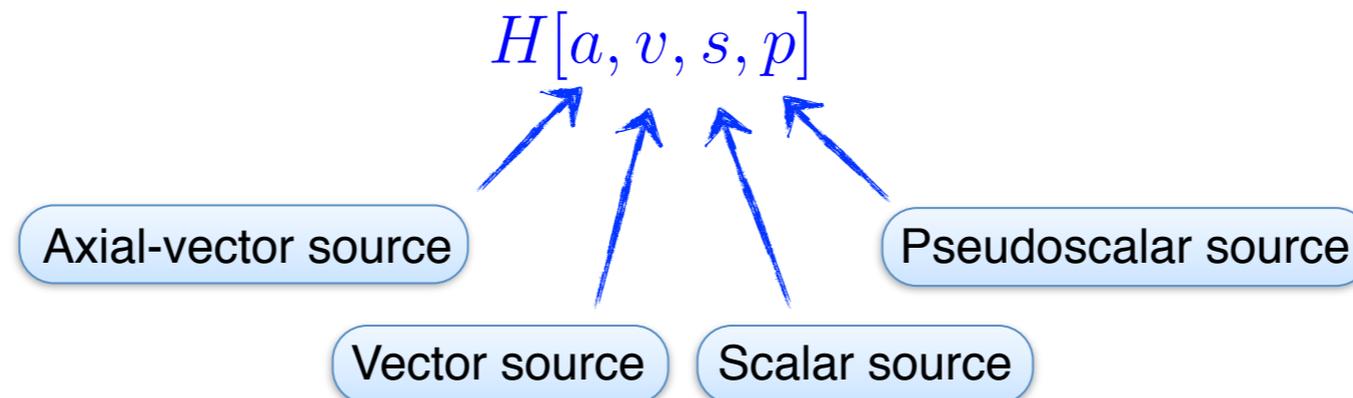
still have to be worked out

Nuclear currents in chiral EFT

Electroweak probes on nucleons and nuclei can be described by current formalism



Chiral EFT Hamiltonian depends on external sources



Vector currents in chiral EFT

Chiral expansion of the electromagnetic **current** and **charge** operators

	single-nucleon	two-nucleon	three-nucleon
Q^{-3}			
Q^{-1}			
Q^0			
Q^1		<p>depend on $d_8, d_9, d_{18}, d_{21}, d_{22}$, no $1/m$ corrections...</p> <p>parameter-free</p> <p>parameter-free static two-pion exchange</p> <p>depend on $C_2, C_4, C_5, C_7 + L_1, L_2$; no loop corrections</p> <p>depend on C_T</p>	<p>depend on C_T</p> <p>HK, Epelbaum, Meißner (UT) arXiv:1902.06839 [nucl-th]</p>

Up to order Q only
single-nucleon current
operator does depend
on energy-transfer k_0

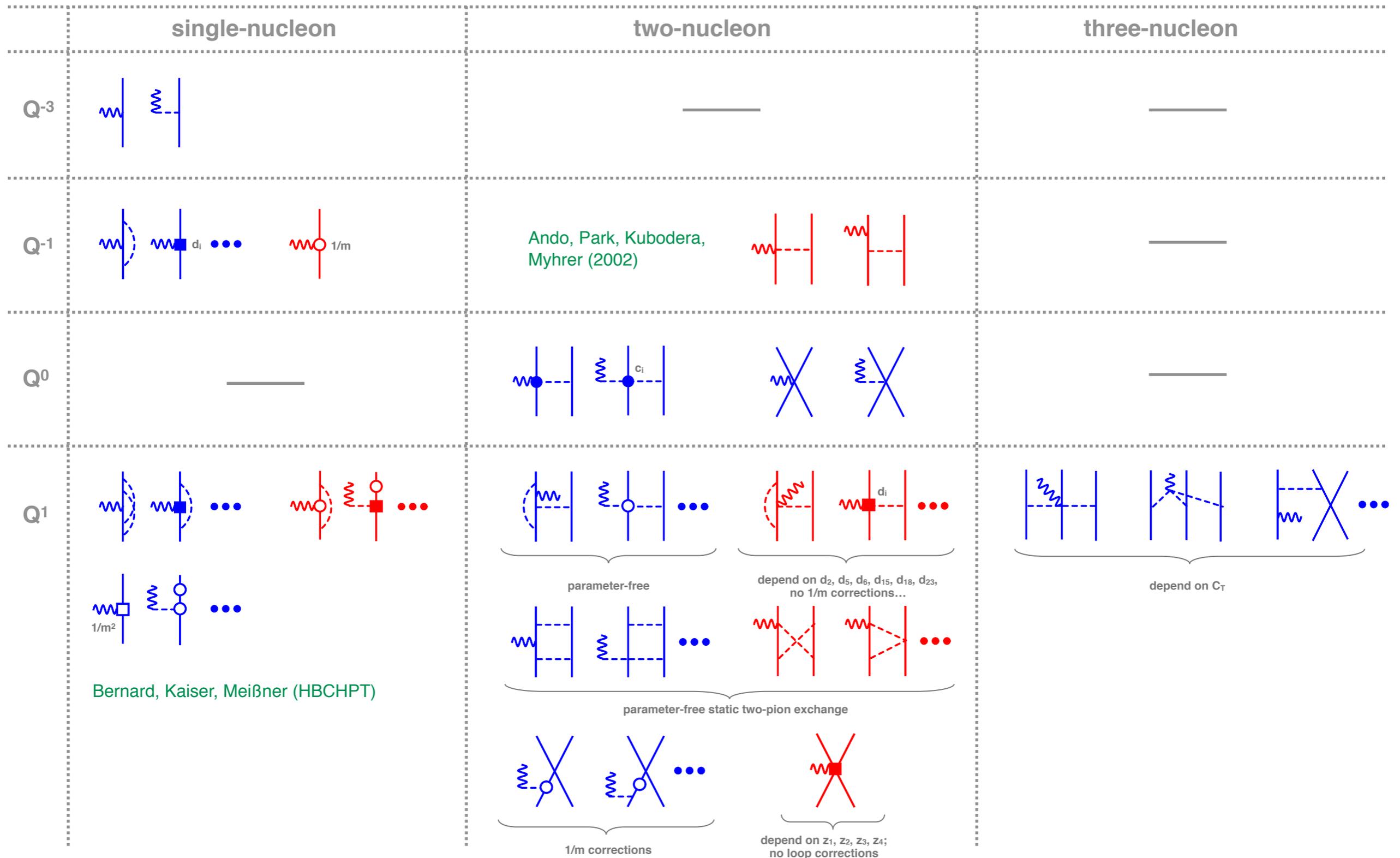


Needed for verification
of continuity equation
for OPE part

Park, Min, Rho, Kubodera, Song, Lazauskas (earlier works, incomplete, TOPT)
Pastore, Schiavilla et al. (TOPT), Kölling, Epelbaum, HK, Meißner (UT)

Axial vector operators in chiral EFT

Chiral expansion of the axial vector **current** and **charge** operators



Bernard, Kaiser, Meißner (HBCHPT)

Park, Min, Rho (earlier works, incomplete, TOPT)
Baroni et al. (TOPT), HK, Epelbaum, Meißner (UT)

Regularization of NN Force

- Regularize one-pion-exchange propagator: *Reinert, HK, Epelbaum '17 (inspired by Rijken '91)*

$$\frac{1}{q^2 + M_\pi^2} \rightarrow \frac{\exp\left(-\frac{q^2 + M_\pi^2}{\Lambda^2}\right)}{q^2 + M_\pi^2} = \frac{1}{q^2 + M_\pi^2} - \frac{1}{\Lambda^2} + \frac{q^2 + M_\pi^2}{2\Lambda^4} + \dots$$

all $1/\Lambda$ -corrections are short-range interactions

- Implement similar regularization for two-pion exchange

$$V(q) = \frac{2}{\pi} \int_{2M_\pi}^{\infty} d\mu \mu \frac{\rho(\mu)}{q^2 + \mu^2} \rightarrow V_\Lambda(q) = \frac{2}{\pi} \int_{2M_\pi}^{\infty} d\mu \mu \frac{\rho(\mu)}{q^2 + \mu^2} \exp\left(-\frac{q^2 + \mu^2}{2\Lambda^2}\right)$$

- Compared to simple gaussian regulator $\exp\left(-\frac{q^2}{\Lambda^2}\right)$ π N-coupling gets quenched

$$g_A \rightarrow g_A \exp\left(-\frac{M_\pi^2}{2\Lambda^2}\right) < g_A$$

SMS Regulator & Chiral Symmetry

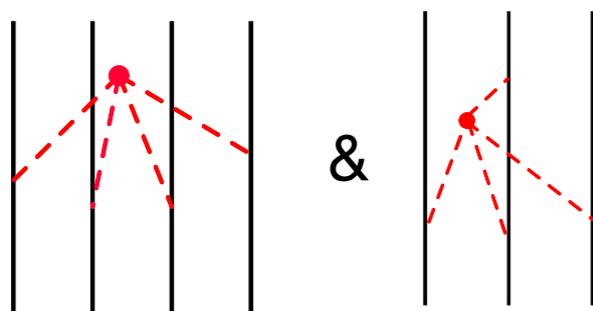
- Chiral Symmetry is preserved by SMS regulator in NN force

NN contact LECs are not constrained by chiral symmetry

- Chiral Symmetry is preserved by SMS regulator in 3N force at N²LO

There are no vertices with three or more pions at this order

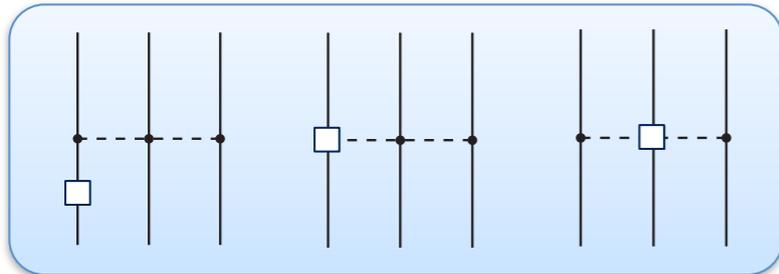
- Chiral Symmetry is violated by SMS regulator in 3N and 4N forces at N³LO



Without modification of four-pion vertex nuclear forces start to depend on chiral parametrization

Call for Consistent Regularization

Violation of chiral symmetry due to different regularizations: Dim. reg. vs cutoff reg.



← 1/m - corrections to pion-pole OPE current proportional to g_A

$$V_{2\pi,1/m}^{g_A^2} = i \frac{g_A^2}{32mF_\pi^4} \frac{\vec{\sigma}_1 \cdot \vec{q}_1 \vec{\sigma}_3 \cdot \vec{q}_3}{(q_1^2 + M_\pi^2)(q_3^2 + M_\pi^2)} \tau_1 \cdot (\tau_2 \times \tau_3) (2\vec{k}_1 \cdot \vec{q}_3 + 4\vec{k}_3 \cdot \vec{q}_3 + i [\vec{q}_1 \times \vec{q}_3] \cdot \vec{\sigma}_2)$$

Naive local cut-off regularization of the current and potential

$$V_{2\pi,1/m}^{g_A^2,\Lambda} = V_{2\pi,1/m}^{g_A^2} \exp\left(-\frac{q_1^2 + M_\pi^2}{\Lambda^2}\right) \exp\left(-\frac{q_3^2 + M_\pi^2}{\Lambda^2}\right) \quad \& \quad V_{1\pi}^{Q^0,\Lambda} = -\frac{g_A^2}{4F_\pi^2} \tau_1 \cdot \tau_2 \frac{\vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_2}{q_1^2 + M_\pi^2} \exp\left(-\frac{q_1^2 + M_\pi^2}{\Lambda^2}\right)$$

First iteration with OPE NN potential

$$V_{2\pi,1/m}^{g_A^2,\Lambda} \frac{1}{E - H_0 + i\epsilon} V_{1\pi}^{Q^0,\Lambda} + V_{1\pi}^{Q^0,\Lambda} \frac{1}{E - H_0 + i\epsilon} V_{2\pi,1/m}^{g_A^2,\Lambda} = \Lambda \frac{g_A^4}{128\sqrt{2}\pi^{3/2}F_\pi^6} (\tau_2 \cdot \tau_3 - \tau_1 \cdot \tau_3) \frac{\vec{q}_2 \cdot \vec{\sigma}_2 \vec{q}_3 \cdot \vec{\sigma}_3}{q_3^2 + M_\pi^2} + \dots$$

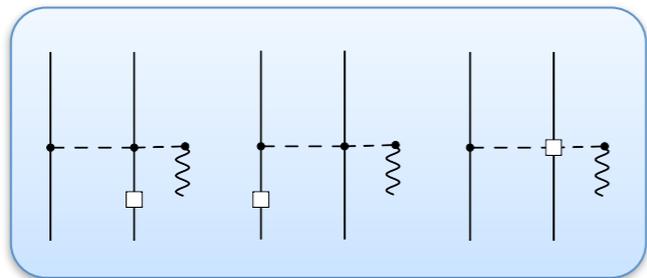
No such D-like term in chiral Lagrangian 

To be compensated by two-pion-one-pion-exchange $V_{2\pi-1\pi}$ if calculated via cutoff regularization

In dim. reg. $V_{2\pi-1\pi}$ is finite

Call for Consistent Regularization

Violation of chiral symmetry due to different regularizations: Dim. reg. vs cutoff reg.



← 1/m - corrections to pion-pole OPE current proportional to g_A

$$\vec{A}_{2N:1\pi,1/m}^{a,(Q:g_A)} = i [\tau_1 \times \tau_2]^a \frac{g_A}{8F_\pi^2 m} \frac{\vec{k}}{(k^2 + M_\pi^2)(q_1^2 + M_\pi^2)} \left(\vec{k}_2 \cdot (\vec{k} + \vec{q}_1) - \vec{k}_1 \cdot \vec{q}_1 + i \vec{k} \cdot (\vec{q}_1 \times \vec{\sigma}_2) \right) + 1 \leftrightarrow 2$$

Naive local cut-off regularization of the current and potential

$$\vec{A}_{2N:1\pi,1/m}^{a,(Q:g_A,\Lambda)} = \vec{A}_{2N:1\pi,1/m}^{a,(Q:g_A)} \exp\left(-\frac{q_1^2 + M_\pi^2}{\Lambda^2}\right) \quad \& \quad V_{1\pi}^{Q^0,\Lambda} = -\frac{g_A^2}{4F_\pi^2} \tau_1 \cdot \tau_2 \frac{\vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_2}{q_1^2 + M_\pi^2} \exp\left(-\frac{q_1^2 + M_\pi^2}{\Lambda^2}\right)$$

First iteration with OPE NN potential

$$\vec{A}_{2N:1\pi,1/m}^{a,(Q:g_A,\Lambda)} \frac{1}{E - H_0 + i\epsilon} V_{1\pi}^{O^0,\Lambda} + V_{1\pi}^{O^0,\Lambda} \frac{1}{E - H_0 + i\epsilon} \vec{A}_{2N:1\pi,1/m}^{a,(Q:g_A,\Lambda)} = \Lambda \frac{g_A^3}{32\sqrt{2}\pi^{3/2} F_\pi^4} ([\tau_1]^a - [\tau_2]^a) \frac{\vec{k}}{k^2 + M_\pi^2} \vec{q}_1 \cdot \vec{\sigma}_1 + \dots$$

No such counter term in chiral Lagrangian

To be compensated by two-pion-exchange current $\vec{A}_{2N:2\pi}^{a(Q)}$ if calculated via cutoff regularization

In dim. reg. $\vec{A}_{2N:2\pi}^{a(Q)}$ is finite

Higher Derivative Regularization

Based on ideas: Slavnov, NPB31 (1971) 301;
Djukanovic et al. PRD72 (2005) 045002; Long and Mei PRC93 (2016) 044003

- Change leading order pion - Lagrangian (modify free part)

$$S_{\pi}^{(2)} = \int d^4x \frac{1}{2} \vec{\pi}(x) (-\partial^2 - M_{\pi}^2) \vec{\pi}(x) \rightarrow S_{\pi, \Lambda}^{(2)} = \int d^4x \frac{1}{2} \vec{\pi}(x) (-\partial^2 - M_{\pi}^2) \exp\left(\frac{\partial^2 + M_{\pi}^2}{\Lambda^2}\right) \vec{\pi}(x)$$

$$\frac{1}{q^2 + M_{\pi}^2} \rightarrow \frac{\exp\left(-\frac{q^2 + M_{\pi}^2}{\Lambda^2}\right)}{q^2 + M_{\pi}^2}$$

$\mathcal{L}_{\pi, \Lambda}^{(2)}$ has to be invariant under $SU(2)_L \times SU(2)_R \times U(1)_V$

- Every derivative should be covariant one
- Lagrangian $\mathcal{L}_{\pi, \Lambda}^{(2)}$ should be formulated in terms of $U(\vec{\pi}(x)) \in SU(2)$

Gasser, Leutwyler '84, '85; Bernard, Kaiser, Meißner '95

Building blocks $\chi = 2B(s + ip)$

$$\nabla_{\mu} U = \partial_{\mu} U - i(v_{\mu} + a_{\mu})U + iU(v_{\mu} - a_{\mu})U$$

Higher Derivative Regularization

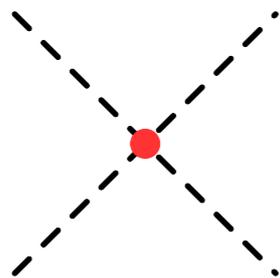
- Regularization of pion - Lagrangian will not affect nucleon Green function
 - Schrödinger or LS-equations get not modified
 - Only nuclear forces get affected

We are not going to change pion-nucleon Lagrangian

- Not every chiral symmetric higher derivative extension of pion - Lagrangian leads to a regularized theory

$$\mathcal{L}_\pi^{(2)} = \frac{F^2}{4} \text{Tr} [\partial_\mu U^\dagger \partial^\mu U] \rightarrow \frac{F^2}{4} \text{Tr} \left[\partial_\mu U^\dagger \exp \left(-\vec{\partial}^2 / \Lambda^2 \right) \partial^\mu U \right]$$

$$\text{---} = \frac{i}{q^2} \exp \left(-q^2 / \Lambda^2 \right) \checkmark$$



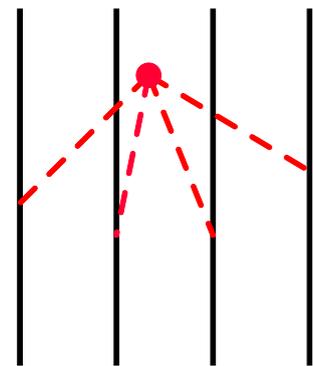
$$= \exp \left((\vec{q}_1 + \vec{q}_2)^2 / \Lambda^2 \right) \text{Polynomial}(q_i') + \dots \times$$



Unregularization of two propagators

Higher Derivative Regularization

Four-nucleon force as a regularization test



$$= \exp \left[\left(-\vec{q}_1^2 - \vec{q}_2^2 - \vec{q}_3^2 - \vec{q}_4^2 + (\vec{q}_1 + \vec{q}_2)^2 \right) / \Lambda^2 \right] \frac{1}{q_1^2 q_1^2 q_3^2 q_4^2} \cdots$$

$$= \exp \left[\left(-(\vec{q}_1 + \vec{q}_3)^2 - (\vec{q}_1 + \vec{q}_4)^2 \right) / \Lambda^2 \right] \frac{1}{q_1^2 q_2^2 q_3^2 q_4^2} \cdots$$

Only two linear combinations of momenta get regularized \rightarrow Unregularized 4NF

Which additional constrain is needed to construct a regularized theory?

- All higher derivative terms of the non-linear sigma model Lagrangian in *Slavnov, NPB31 (1971) 301* are proportional to equation of motion

Generalize this idea to chiral EFT: all additional terms \sim EOM

$$\text{EOM} = - [D_\mu, u^\mu] + \frac{i}{2} \chi_- - \frac{i}{4} \text{Tr} (\chi_-)$$

$$\text{EOM} = 0 \leftarrow \text{classical equation of motion for pions}$$

Higher Derivative Lagrangian

- To construct a parity-conserving regulator it is convenient to work with building-blocks

$$u_\mu = i u^\dagger \nabla_\mu U u^\dagger, \quad D_\mu = \partial_\mu + \Gamma_\mu, \quad \Gamma_\mu = \frac{1}{2} [u^\dagger, \partial_\mu u] - \frac{i}{2} u^\dagger r_\mu u - \frac{i}{2} u l_\mu u^\dagger$$

$$\chi_\pm = u^\dagger \chi u^\dagger \pm u \chi^\dagger u, \quad \chi = 2B(s + ip), \quad u = \sqrt{U}, \quad \text{ad}_A B = [A, B]$$

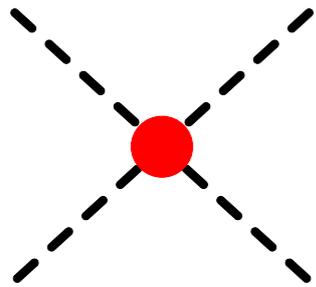
Possible ansatz for higher derivative pion Lagrangian

$$\mathcal{L}_{\pi, \Lambda}^{(2)} = \mathcal{L}_\pi^{(2)} + \frac{F^2}{4} \text{Tr} \left[\text{EOM} \frac{1 - \exp\left(\frac{\text{ad}_{D_\mu} \text{ad}_{D^\mu} + \frac{1}{2} \chi_+}{\Lambda^2}\right)}{\text{ad}_{D_\mu} \text{ad}_{D^\mu} + \frac{1}{2} \chi_+} \text{EOM} \right]$$

$$\mathcal{L}_\pi^{(2)} = \frac{F^2}{4} \text{Tr} [u_\mu u^\mu + \chi_+] \quad \text{EOM} = -[D_\mu, u^\mu] + \frac{i}{2} \chi_- - \frac{i}{4} \text{Tr} (\chi_-)$$

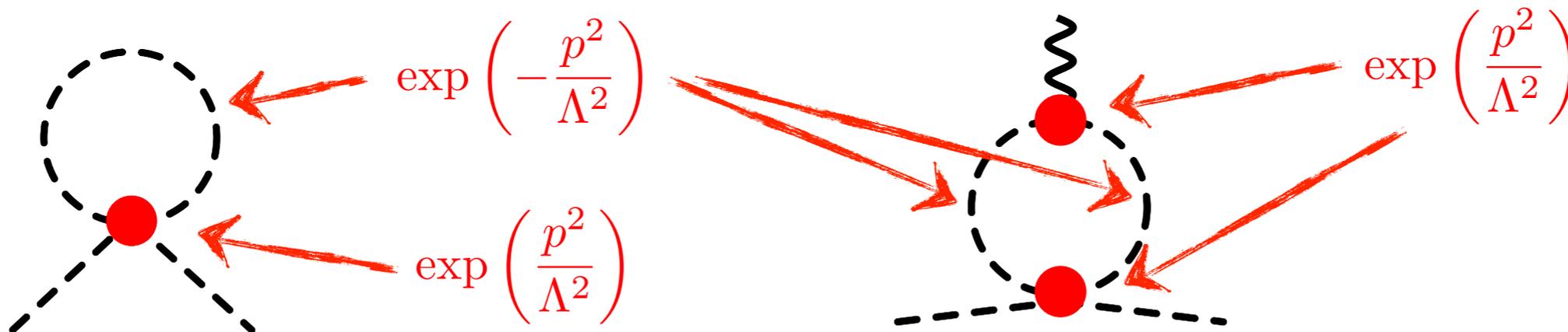
Expand $\mathcal{L}_{\pi, \Lambda}^{(2)}$ in $D_0 \rightarrow$ Lorentz-invariance only perturbatively

Modified Vertices



- Enhanced by $\exp\left(\frac{p^2}{\Lambda^2}\right)$
- Every propagator is suppressed by $\exp\left(-\frac{p^2}{\Lambda^2}\right)$

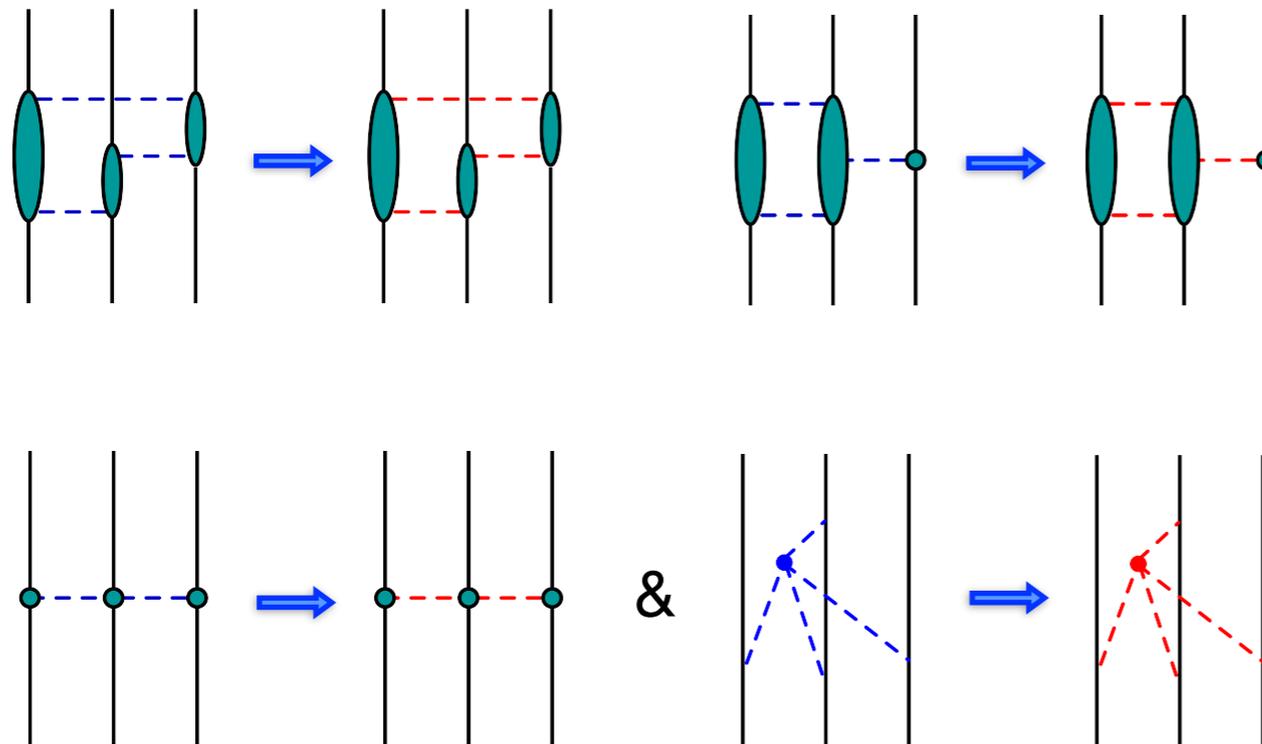
Pionic sector becomes unregularized



- Use dimensional on top of high derivative regularization
- Dimensional regularization will not affect effective potential and Schrödinger or LS equations but will regularize pionic sector

Regularization of 3NF at N³LO

- Modify pion-propagators in all 3NF diagrams
- Recalculate 3NF diagrams with four-pion vertices



- No four-pion vertices in ring and $2\pi-1\pi$ topologies
- Modified four-pion vertex leads to exponential increase in momenta
- 3NF's do not depend on chiral parametrization of U -fields by construction

Large cut-off limit of the 3NF: we see linear divergence which we can not be absorbed by rescale of c_i 's and C_D LECs

→ Non-renormalizable 3NF at N³LO

Renormalizable 3NF at N³LO

- Introduce additional unitary transformations $\sim 1/\Lambda^2$ to renormalize 3NF at N³LO

$$U = \exp\left(S^{(1/\Lambda^2)}\right) \quad \text{with} \quad S^{(1/\Lambda^2)} = \frac{\alpha^{(1/\Lambda^2)}}{\Lambda^2} \eta H_{21}^{(1)} \frac{\lambda_1}{E_\pi^2} H_{22}^{(2)} \lambda_1 E_\pi H_{21}^{(1)} \eta - \text{h.c.}$$

$$U^\dagger V_{3N} U \quad \text{becomes renormalizable for} \quad \alpha^{(1/\Lambda^2)} = 24$$

- Introduced unitary transformation modifies relativistic corrections

$$\delta V_{1/m}^{(1/\Lambda^2)} = i \vec{\sigma}_1 \cdot \vec{q}_1 \vec{\sigma}_3 \cdot \vec{q}_3 \tau_1 \cdot (\tau_2 \times \tau_3) \frac{3g_A^2}{8F_\pi^4 m \Lambda^2} (\vec{k}_1 \cdot (\vec{q}_1 - \vec{q}_2) + \vec{k}_3 \cdot (\vec{q}_3 - \vec{q}_2)) \frac{\exp\left(-\frac{q_1^2 + q_3^2 + 2M_\pi^2}{\Lambda^2}\right)}{q_3^2 + M_\pi^2}$$

From naive dimensional analysis this D-like term is of order Q^3 (N⁵LO)

Neglecting this term, however, will lead to divergent iteration with OPE in $\Lambda \rightarrow \infty$ limit which *can not* be absorbed by LECs at any order

Regularization of Vector Current

- Modify pion-propagators in a vector current

$$\text{---} = \frac{1}{q^2 + M^2} \rightarrow \frac{\exp\left(-\frac{q^2 + M^2}{\Lambda^2}\right)}{q^2 + M^2} = \text{---}$$

- Modify two-pion-photon vertex

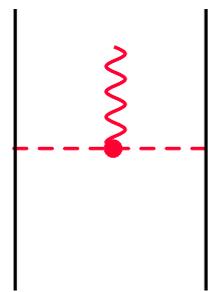
$$\text{---} \bullet \text{---} = e \epsilon_\mu (q_2^\mu - q_1^\mu) \epsilon_{3,a_1,a_2}$$

Modified two-pion-photon vertex leads to exponential increase in momenta

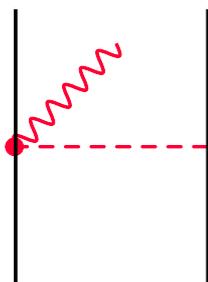
$$\text{---} \bullet \text{---} = e \epsilon_\mu (q_2^\mu - q_1^\mu) \epsilon_{3,a_1,a_2} \times \frac{1}{q_1^2 - q_2^2} \left[(q_1^2 + M^2) \exp\left(\frac{q_1^2 + M^2}{\Lambda^2}\right) - (q_2^2 + M^2) \exp\left(\frac{q_2^2 + M^2}{\Lambda^2}\right) \right]$$

Regularization of Vector Current

Regularization of pion-exchange vector current



$$= \frac{i e g_A^2}{4F^2} \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_2 \cdot \vec{\sigma}_2 [\tau_1 \times \tau_2]_3 \frac{\vec{\epsilon} \cdot (\vec{q}_2 - \vec{q}_1)}{q_1^2 - q_2^2} \left[\frac{\exp\left(-\frac{q_2^2 + M^2}{\Lambda^2}\right)}{q_2^2 + M^2} - \frac{\exp\left(-\frac{q_1^2 + M^2}{\Lambda^2}\right)}{q_1^2 + M^2} \right]$$



$$= -\frac{i e g_A^2}{4F^2} \vec{\epsilon} \cdot \vec{\sigma}_1 \vec{q}_2 \cdot \vec{\sigma}_2 [\tau_1 \times \tau_2]_3 \frac{\exp\left(-\frac{q_1^2 + M^2}{\Lambda^2}\right)}{q_1^2 + M^2} + (1 \leftrightarrow 2)$$

Riska prescription: longitudinal part of the current can be derived from continuity equation (Siegert theorem)

Riska, Prog. Part. Nucl. Phys. 11 (1984) 199

$$\left[H_{\text{strong}}, \rho \right] = \vec{k} \cdot \vec{J}$$

Higher orders  work in progress

Application to Electromagnetic Charge

Electromagnetic charge operators in chiral EFT

- 1N charge operator is parametrized in terms of em form factors

HK, Epelbaum, Meißner arXiv:1902.06839 [nucl-th]

$$V_{1N:\text{static}}^0 = eG_E(Q^2),$$

$$V_{1N:1/m}^0 = \frac{ie}{2m^2} \mathbf{k} \cdot (\mathbf{k}_1 \times \boldsymbol{\sigma}) G_M(Q^2),$$

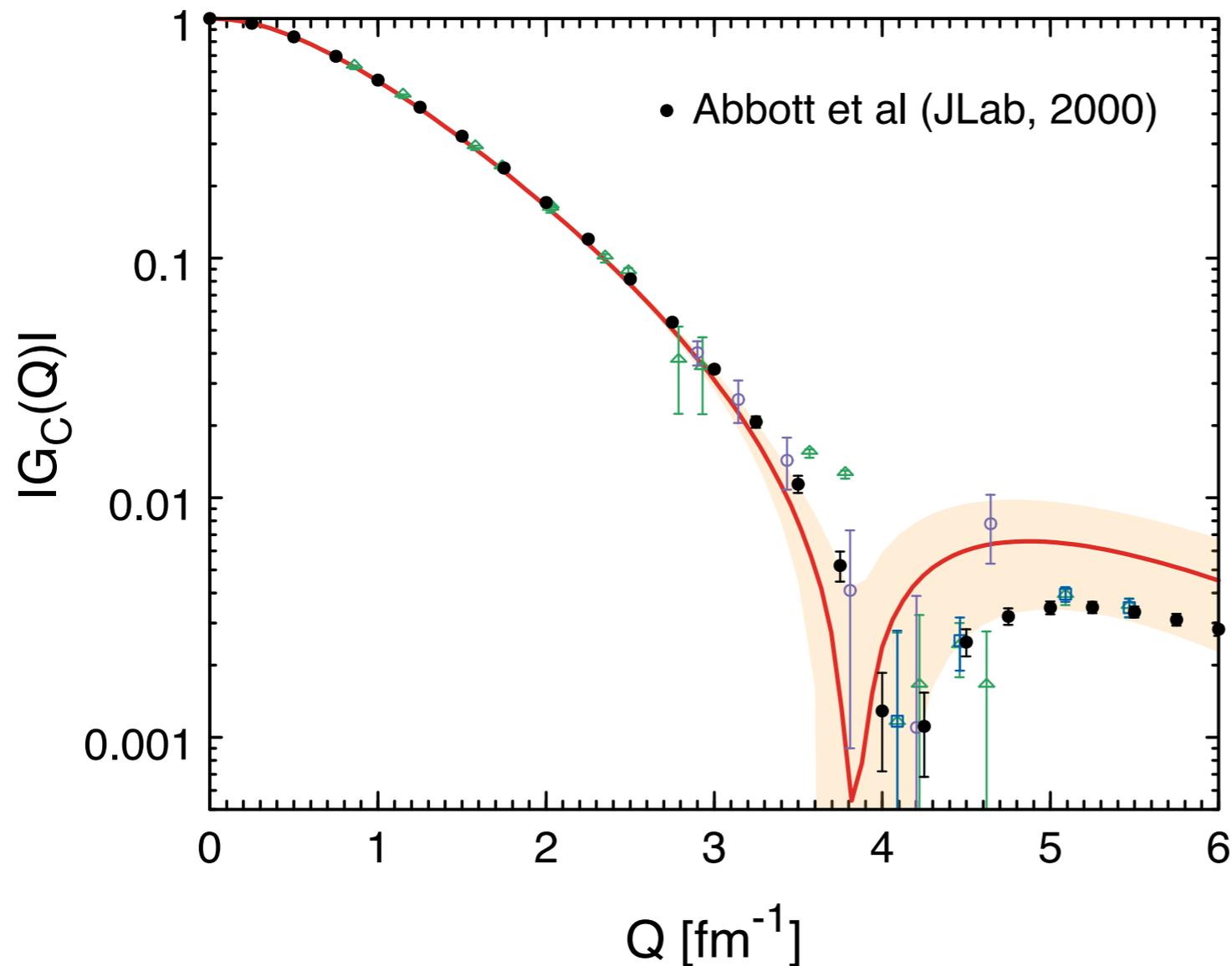
$$V_{1N:1/m^2}^0 = -\frac{e}{8m^2} [Q^2 + 2i \mathbf{k} \cdot (\mathbf{k}_1 \times \boldsymbol{\sigma})] G_E(Q^2)$$

- Static 2N charge operator does not contribute to deuteron form factors

$$\begin{aligned}
 V_{2N:1\pi,1/m}^{0,(Q)} &= \frac{eg_A^2}{16F_\pi^2 m_N} \frac{1}{q_2^2 + M_\pi^2} \left\{ (1 - 2\bar{\beta}_9) \right. \\
 &\times ([\boldsymbol{\tau}_2]^3 + \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2) \boldsymbol{\sigma}_1 \cdot \mathbf{k} \boldsymbol{\sigma}_2 \cdot \mathbf{q}_2 - i(1 + 2\bar{\beta}_9) [\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2]^3 \\
 &\times \left[\boldsymbol{\sigma}_1 \cdot \mathbf{k}_1 \boldsymbol{\sigma}_2 \cdot \mathbf{q}_2 - \boldsymbol{\sigma}_2 \cdot \mathbf{k}_2 \boldsymbol{\sigma}_1 \cdot \mathbf{q}_2 - 2 \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{q}_1}{q_1^2 + M_\pi^2} \boldsymbol{\sigma}_2 \cdot \mathbf{q}_2 \right. \\
 &\times \left. \mathbf{q}_1 \cdot \mathbf{k}_1 \right] \left. \right\} + \frac{eg_A^2}{16F_\pi^2 m_N} \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{q}_2 \boldsymbol{\sigma}_2 \cdot \mathbf{q}_2}{(q_2^2 + M_\pi^2)^2} \left[(2\bar{\beta}_8 - 1) \right. \\
 &\times ([\boldsymbol{\tau}_2]^3 + \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2) \mathbf{q}_2 \cdot \mathbf{k} + i [\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2]^3 ((2\bar{\beta}_8 - 1) \mathbf{q}_2 \cdot \mathbf{k}_1 \\
 &\left. - (2\bar{\beta}_8 + 1) \mathbf{q}_2 \cdot \mathbf{k}_2) \right] + 1 \leftrightarrow 2. \quad (59)
 \end{aligned}$$

Apply higher derivative regularization to relativistic correction of the charge

Charge Form Factor of Deuteron



Preliminary

Semilocal momentum space (SMS)
regularized NN force

Reinert, HK, Epelbaum '17

1N electromagnetic form factors

Belushkin, Hammer, Meißner '07

Cutoff 450 MeV

Truncation error band from
Bayesian analysis: *Furnstahl et al. '15*
68% DoB, $\Lambda_b = 600$ MeV

- Excellent description of the data for regularized charge even at higher momentum transfer Q

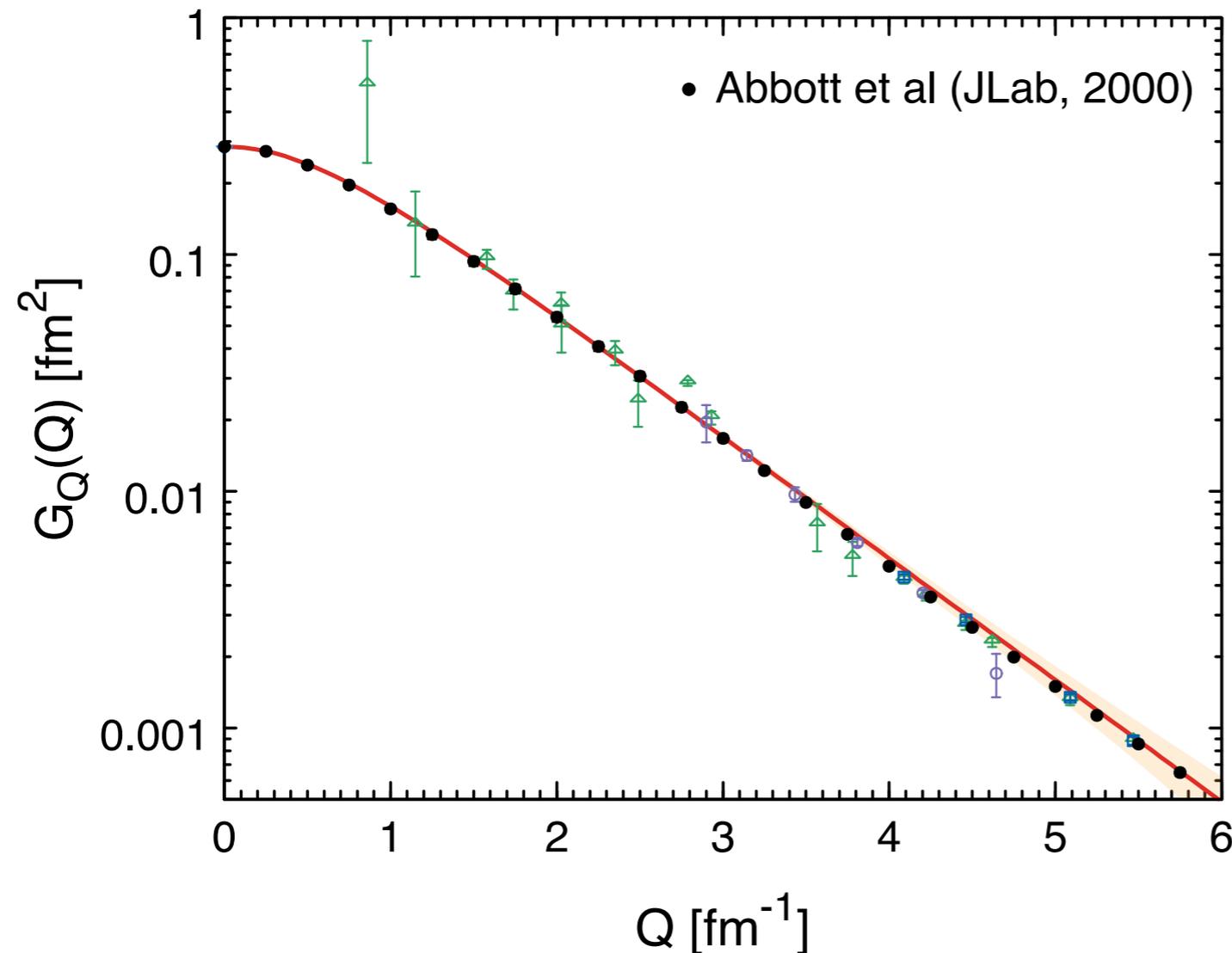
More on this in Evgeny's talk

Summary

- Local regulator in momentum space chosen not to affect analytic structure of NN force *at any* order in $1/\Lambda$ -expansion
- Naive application of the same regulator violates chiral symmetry in 3NF's
- Higher derivative in combination with dimensional regularization in pion-sector regularizes 3NF's and currents respecting all symmetries
- Appearance of modified four-pion and pion-current vertices
- First applications to deuteron form factors

Quadrupole Form Factor of Deuteron

Preliminary



Semilocal momentum space (SMS)
regularized NN force

Reinert, HK, Epelbaum '17

1N electromagnetic form factors

Belushkin, Hammer, Meißner '07

Cutoff 450 MeV

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