FUNDAMENTAL SYMMETRIES AND CHIRAL EFFECTIVE FIELD THEORY

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Workshop on The Nuclear Interaction: Modern developments, ECT*, summer 1999

Outline

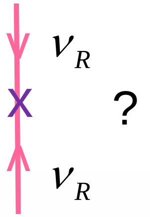
- The way of EFT
- Nuclear EFTs
- Role of chiral symmetry
- Conclusion

H.-W. Hammer, S. König, and U. van Kolck,
"Nuclear Effective Field Theory: Status and perspectives",
arXiv:1906.12122 [nucl-th]

Q

$M_{\not{L}} \sim ?$

unknown physics



$M_{nuc} \sim f_\pi, 1/r_{NN}, m_\pi, \ldots$

~ 100 MeV

$\aleph \sim 1/a_{NN}$

~ 30 MeV

relevant for precision experiments with nuclei

EFFECTIVE FIELD THEORY aka Modern S-Matrix Theory

Euler + Heisenberg '36
Weinberg '67 … '79
…

Λ UV regulator

M_{hi}

most general Lagrangian

$$\mathcal{L}_{EFT} = \sum_{\nu=0}^{\infty} \gamma_i^{(\nu)}\left(\frac{M_{lo}}{\Lambda}, \frac{\lambda}{M_{lo}}\right) \frac{M_{lo}^{s}}{M_{hi}^{\nu}}\, O^{(\nu)}\left(\partial^d \psi^N\right)$$

"low-energy constants"/ "Wilson coefficients"

"power counting" $\nu = \nu(s, d, N, \ldots)$

most general S matrix

non-analytic functions, from (finite or infinite number of) loops

$$S^{(\bar{\nu})}(Q \sim M_{lo} \ll M_{hi}) - 1 \propto \sum_{\nu=0}^{\bar{\nu}} \left[\frac{Q}{M_{hi}}\right]^{\nu} F^{(\nu)}\left(\frac{Q}{M_{lo}}, \frac{Q}{\Lambda}, \frac{\lambda}{Q}; \gamma_i^{(\le\nu)}\left(\frac{M_{lo}}{\Lambda}, \frac{\lambda}{M_{lo}}\right)\right)$$

$$\times\left\{1 + \mathcal{O}\left(\frac{Q^{\bar{\nu}+1}}{M_{hi}^{\bar{\nu}+1}}, \frac{Q^{\bar{\nu}+1}}{M_{hi}^{\bar{\nu}}\Lambda}, \frac{\lambda Q^{\bar{\nu}}}{M_{hi}^{\bar{\nu}+1}}\right)\right\}$$

$\mathrm{N}^{\bar{\nu}}\mathrm{LO}$

CONTROLLED UNCERTAINTY

Q

M_{lo}

λ IR regulator

Want large "model space"

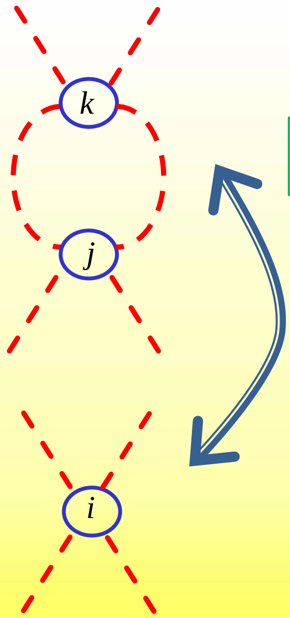
renormalization-group invariance

$$\begin{cases} \dfrac{\Lambda}{S^{(\bar{\nu})}} \dfrac{\partial S^{(\bar{\nu})}}{\partial \Lambda} = \mathcal{O}\left(\dfrac{Q^{\bar{\nu}+1}}{M_{hi}^{\bar{\nu}} \Lambda} \right) \\ \dfrac{\lambda}{S^{(\bar{\nu})}} \dfrac{\partial S^{(\bar{\nu})}}{\partial \lambda} = \mathcal{O}\left(\dfrac{Q^{\bar{\nu}} \lambda}{M_{hi}^{\bar{\nu}+1}} \right) \end{cases}$$

MODEL INDEPENDENCE (insensitivity to arbitrary regulators)

$$\Lambda \gtrsim M_{hi}$$

$$\lambda \lesssim M_{lo}$$



uncertainty principle

momenta $\gtrsim \Lambda$

= short-range physics

"naturalness"

$$\gamma_i(\alpha\Lambda) \sim \gamma_i(\Lambda) \quad \begin{cases} \Lambda \sim M_{hi} \\ \alpha = \mathcal{O}(1) \end{cases}$$

otherwise "fine tuning"

→ power counting

renormalization of perturbative amplitudes

Georgi + Manohar '86

arbitrary diagram

naturalness

$(4\pi)^{-2}$ per loop

number of fields in operator

$$\gamma_i = \mathcal{O}\left(\frac{(4\pi)^{N-2}}{M_{hi}^{D-4}} \gamma_i^{\text{red}} \right)$$

dimension of operator

NDA: naïve dimensional analysis

$$\gamma_i^{\text{red}} = \mathcal{O}\left(\left(g^{\text{red}} \right)^{\#} \right)$$

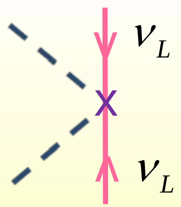
reduced coupling

reduced underlying theory parameter

insertions

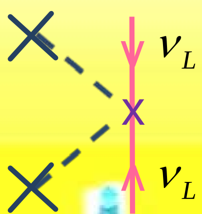
example:

Weinberg '79
Weldon + Zee '80
...



$$\mathcal{L}_5 = c_5 \left[\left(\ell^T C \tilde{\varphi} \right)\left(\tilde{\varphi}^T \ell \right) + \text{H.c.} \right]$$

$$= \frac{c_5 v^2}{2} \left(\bar{\nu}_L \nu_R^c + \text{H.c.} \right) + \ldots$$



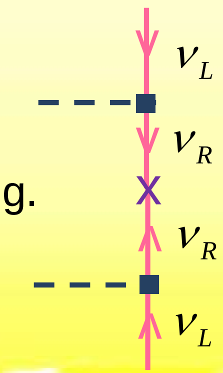
$|\Delta L| = 2$

$$c_5 = \mathcal{O}\left(\frac{(4\pi)^2}{M_{\not L}} c_5^{\text{red}} \right)$$

$$= \mathcal{O}\left(\frac{(4\pi)^2}{M_{\not L}} \left(\frac{e}{4\pi} \right)^2 \right)$$

$$= \mathcal{O}\left(\frac{e^2}{M_{\not L}} \right)$$

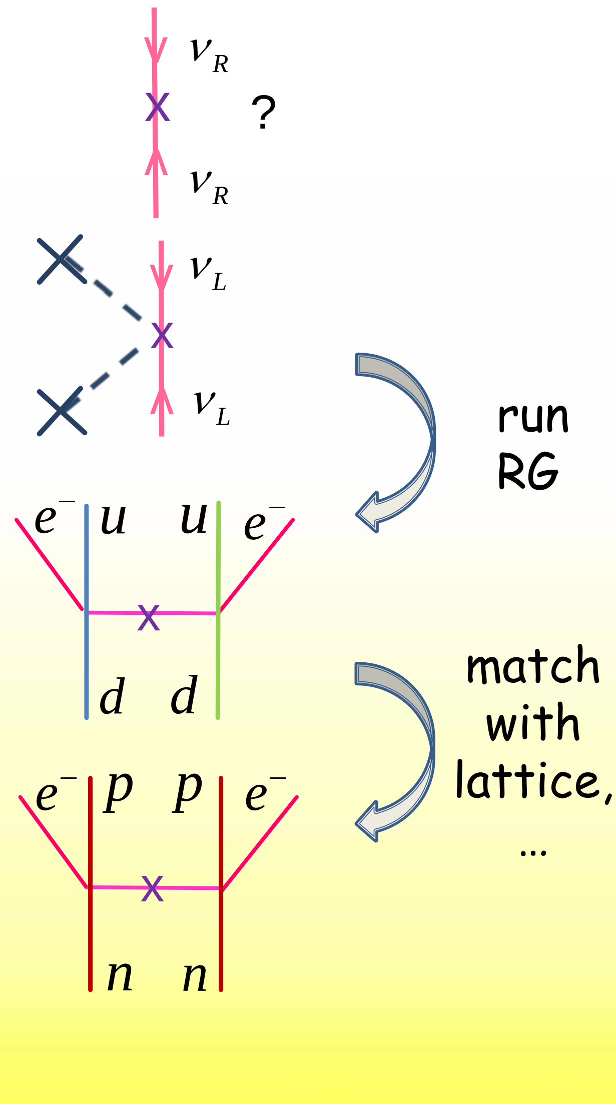
e.g.



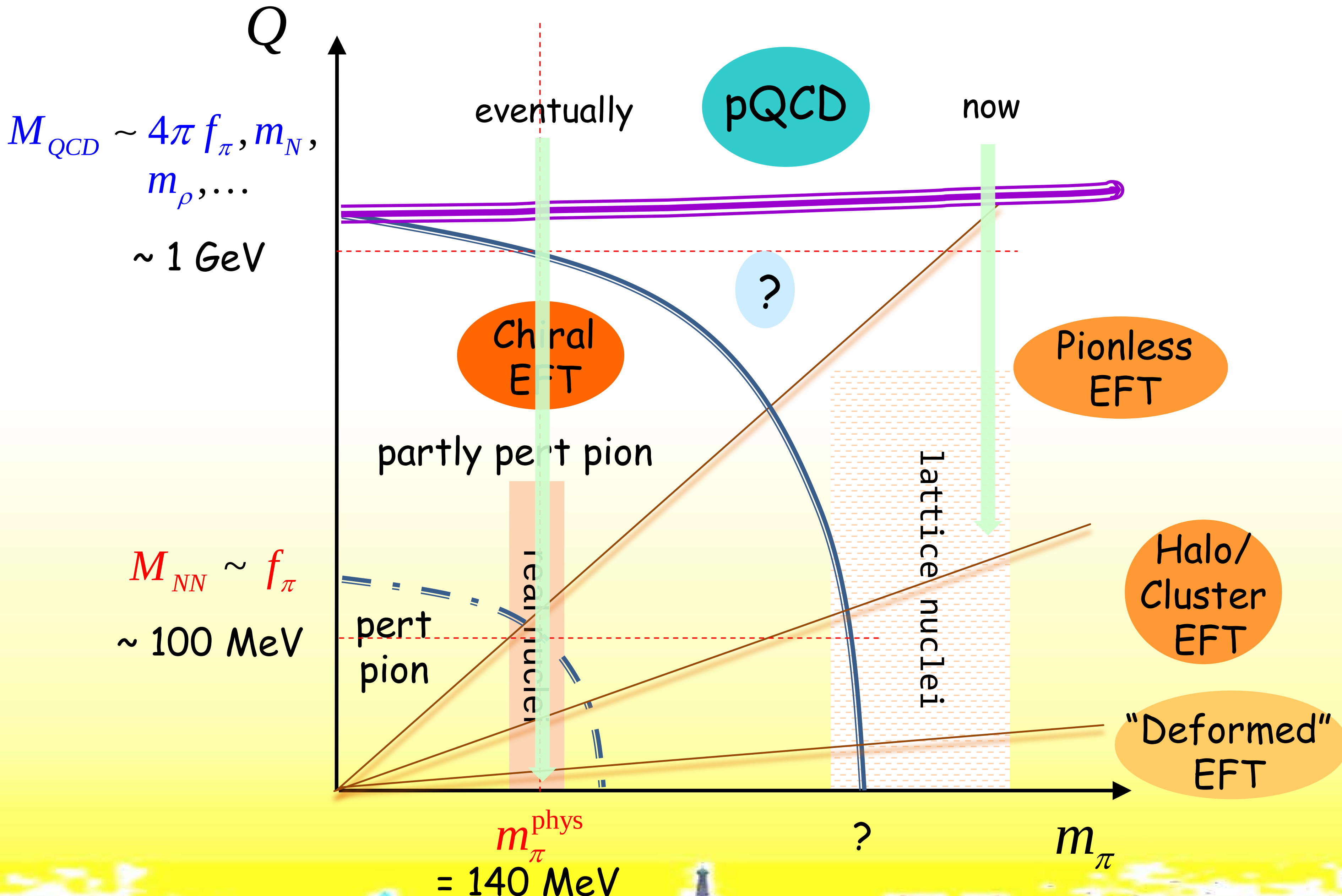
The Way of EFT

Q ↑

$M_{\not L} \sim ?$	unknown physics
$M_{EW} \sim v, m_Z, m_W$ ~ 100 GeV	Standard Model + higher-dim
$M_{QCD} \sim m_N, m_\rho, 4\pi f_\pi, \ldots$ ~ 1 GeV	QCD
$M_{nuc} \sim f_\pi, 1/r_{NN}, m_\pi, \ldots$ ~ 100 MeV	Chiral EFT (χPT)
$\aleph \sim 1/a_{NN}$ ~ 30 MeV	Pionless EFT



The Nuclear EFT Landscape



Pionless (or Contact) EFT

$$M_{lo} \sim \sqrt{2m_N B_3/3}$$
$$M_{hi} \sim m_\pi$$

- d.o.f.: nucleons
- symmetries: SO(3,1), P, T, B, $SU(3)_c$, $U(1)_e$ (trivial)

projector on isospin *I*

$$\mathcal{L}_{\not\pi} = N^+\left(i\partial_0 + \frac{\vec{\nabla}^2}{2m_N}\right)N - \frac{1}{2}\sum_{I=0,1} C_{0I}\; N^+N^+P_I NN - \frac{D_0}{3}N^+N^+N^+\;NNN$$
$$-\frac{1}{2}\sum_{I=0,1} C_{2I}\; N^+N^+P_I\vec{\nabla}^2 NN - \frac{E_0}{4}N^+N^+N^+N^+\;NNNN + \ldots$$

more derivatives,
more bodies,
isospin violation

Universality: first orders apply also to neutral atoms

$$m_\pi \to 1/l_{\rm vdW} \quad \textit{where} \quad V(r) = -\frac{l_{\rm vdW}^4}{2mr^6} + \ldots$$

Bedaque, Hammer + v.K. '99'00
Bedaque, Braaten + Hammer '01
...

Pionful (or Chiral) EFT

- d.o.f.: nucleons, *pions, and Deltas*
- symmetries: ~~SO(3,1)~~, ~~P~~, ~~T~~, ~~B~~, SU(3)$_c$, U(1)$_e$, ~~SU(2)$_L$xSU(2)$_R$~~
  (trivial)

$$\mathcal{L}_{\pi} = \mathcal{L}_{\not\pi} + \frac{1}{2}\left[(\partial_{\mu}\boldsymbol{\pi})^2 - m_{\pi}^2\boldsymbol{\pi}^2\right]\left(1+\mathcal{O}\left(\frac{\boldsymbol{\pi}^2}{f_{\pi}^2}\right)\right)$$

$$+\frac{g_A}{2f_{\pi}}N^{+}\boldsymbol{\tau}\vec{\sigma}N\cdot\vec{\nabla}\boldsymbol{\pi}\left(1+\mathcal{O}\left(\frac{\boldsymbol{\pi}^2}{f_{\pi}^2}\right)\right)+\ldots$$

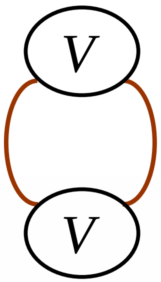
$$+D_2 m_{\pi}^2\sum_{I=0,1}N^{+}N^{+}P_I NN\left(1+\mathcal{O}\left(\frac{\boldsymbol{\pi}^2}{f_{\pi}^2}\right)\right)+\ldots$$

$$+\Delta^{+}\left[i\partial_0-(m_{\Delta}-m_N)\right]\Delta\left(1+\mathcal{O}\left(\frac{\boldsymbol{\pi}^2}{f_{\pi}^2}\right)\right)$$

$$+\frac{h_A}{2f_{\pi}}\left(N^{+}\mathbf{T}\vec{S}\Delta+\text{H.c.}\right)\cdot\vec{\nabla}\boldsymbol{\pi}\left(1+\mathcal{O}\left(\frac{\boldsymbol{\pi}^2}{f_{\pi}^2}\right)\right)+\ldots$$

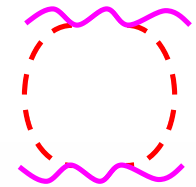
more derivatives,
more bodies,
isospin violation

Are nuclear amplitudes perturbative?



Weinberg's IR enhancement

$$\sim \frac{m_N Q}{4\pi}$$ (after renormalization) vs.



$$\sim \frac{Q^2}{(4\pi)^2}$$

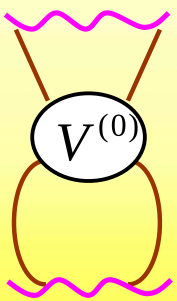
4π enhancement compared to NDA

Chiral Perturbation Theory

$$V(Q, M_{lo}, M_{hi}, \lambda, \Lambda) \propto \sum_{\mu=\mu_{\min}}^{\infty} \left[\frac{Q}{M_{hi}}\right]^{\mu} \tilde{F}^{(\mu)}\left(\frac{Q}{M_{lo}}, \frac{Q}{\Lambda}, \frac{\lambda}{Q}; \gamma_i^{(\leq\mu)}\left(\frac{M_{lo}}{\Lambda}, \frac{\lambda}{M_{lo}}\right)\right)$$

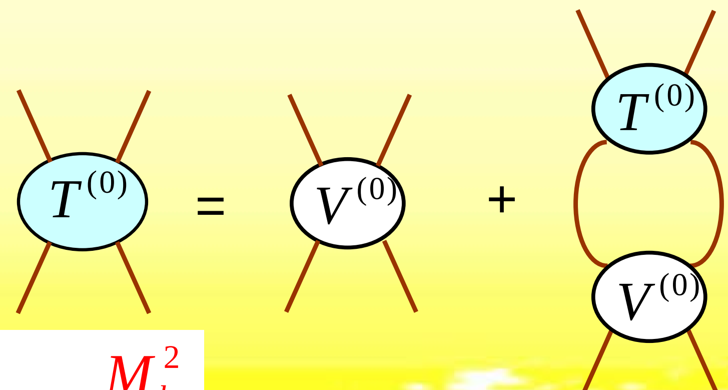
$$V^{(\mu)}(Q, M_{lo}, M_{hi}, \lambda, \Lambda)$$

$$V^{(0)} \sim \frac{4\pi}{m_N M_{lo}}$$ (after renormalization)



$$\sim \frac{Q}{M_{lo}}$$

expansion in Q/M_{lo}



b.s. at $B \sim \frac{M_{lo}^2}{m_N}$

but still keep perturbative expansion in Q/M_{hi}

CANNOT JUST COUNT POWERS OF Q

$$V^{(\mu)}(Q \sim M_{lo}) \sim \frac{4\pi}{m_N M_{lo}} \left(\frac{Q}{M_{hi}} \right)^{\mu}$$

various orders in the potential $\xrightarrow{\text{DWBA}}$ same order in amplitude

e.g. $V^{(1)2}, V^{(2)}$ in $T^{(2)}$

potential **must** depend on regulator

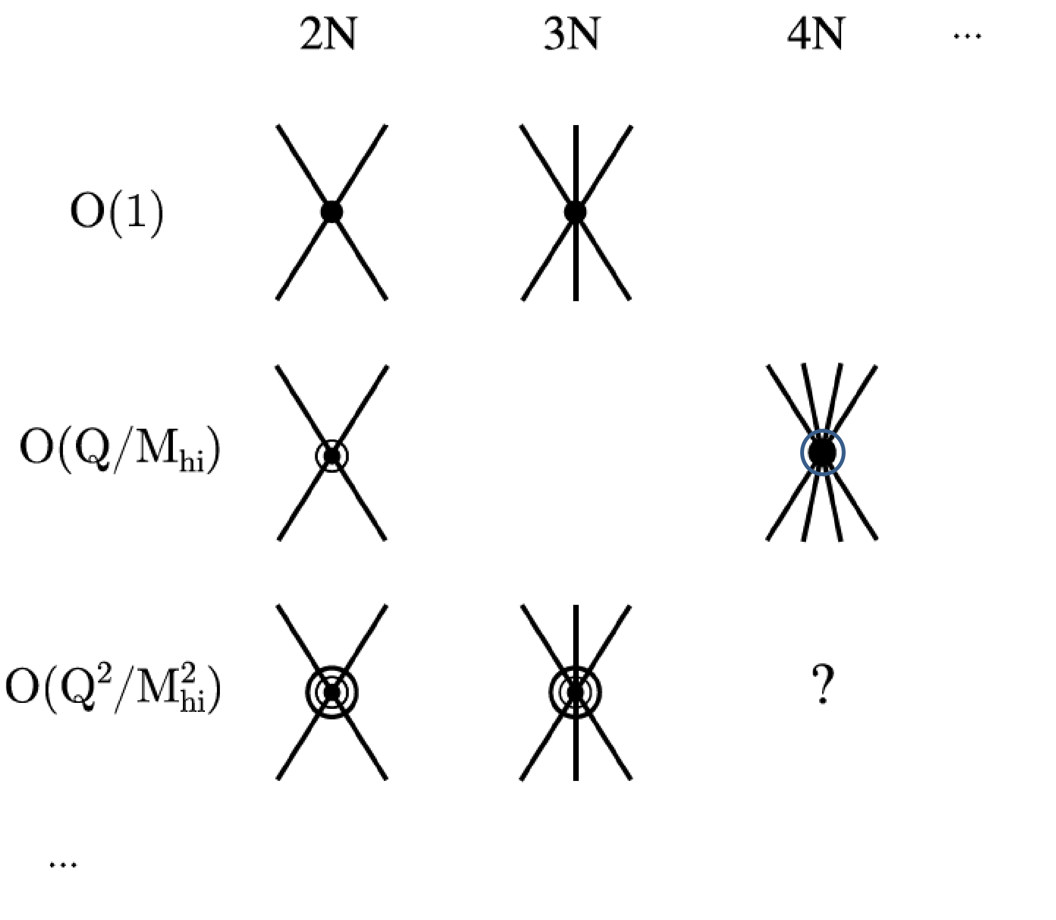
each order in potential **must** contain enough LECs

→ amplitude renormalization

↳ not trivial when resuming higher orders

e.g. $V^{(1)\infty}$

Pionless EFT

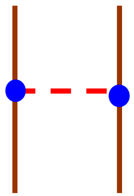


- very little to do with NDA
- enhancements required by renormalization

v.K. '97
Kaplan, Savage
+ Wise '98
...

Bedaque, Hammer
+ v.K. '99 '00
Hammer
+ Mehen '00
...

Bazak, Kirscher, König
Pavón Valderrama,
Barnea + v.K. '18

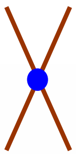


$$\sim \frac{1}{f_\pi^2} \equiv \frac{4\pi}{m_N M_{NN}} \Rightarrow B \sim \frac{M_{NN}^2}{m_N} \approx 10\ \text{MeV}$$

suggests

$$M_{NN} = \frac{4\pi f_\pi}{m_N} f_\pi \sim M_{lo}$$

Weinberg '90
...

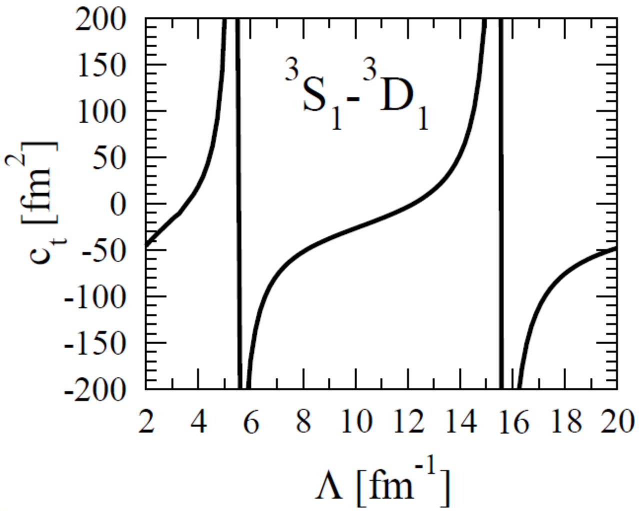


~~dim. anal. $\sim \frac{1}{M_{QCD}^2}$~~

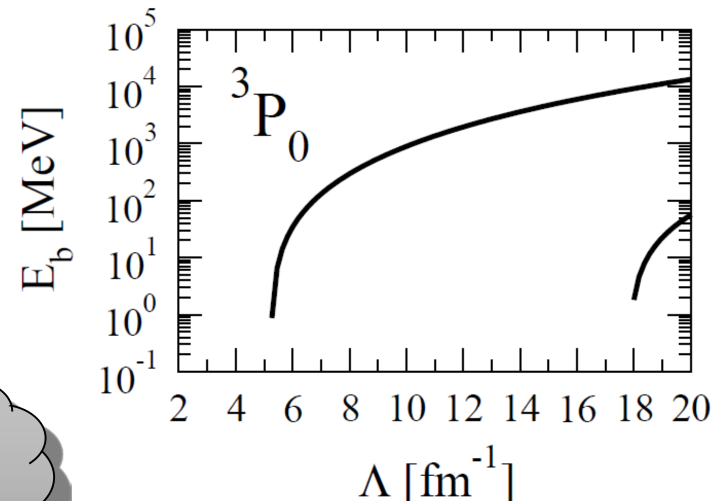
NDA $\sim \frac{1}{f_\pi^2} = \frac{4\pi}{m_N M_{NN}}$

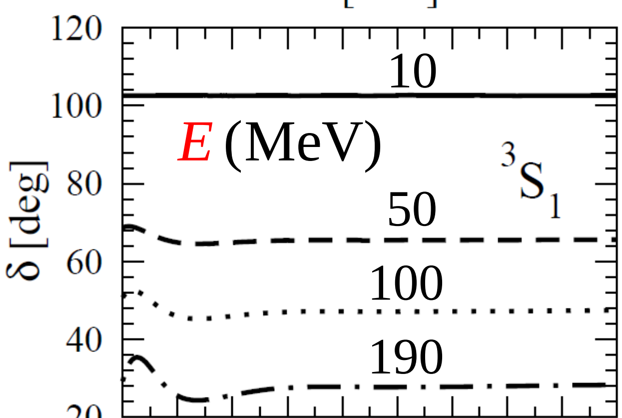
Chiral EFT

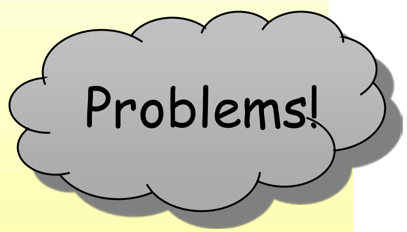
Other attractive-tensor channels



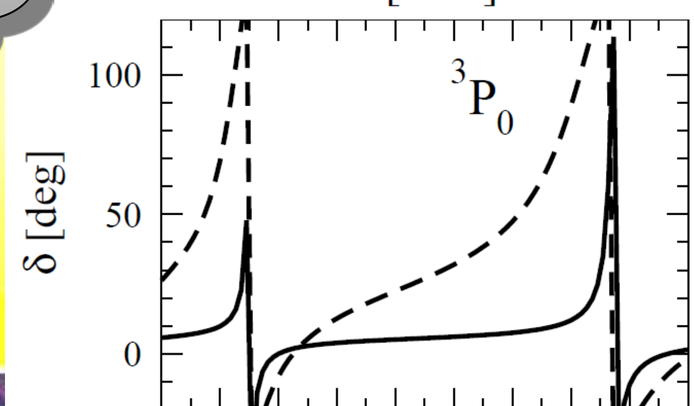
Frederico, Timóteo
+ Tomio '99
Beane, Bedaque,
Savage + v.K. '02
Nogga, Timmermans
+ v.K. '05
...



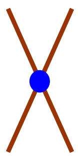




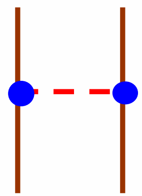
Nogga, Timmermans
+ v.K. '05
Pavón Valderrama
+ Ruiz-Arriola '06
...



- perturbative pions



$$\sim \frac{4\pi}{m_N M_{lo}}$$ LO



$$\sim \frac{4\pi}{m_N M_{hi}}$$ NLO

$$M_{lo} \sim \sqrt{2m_N B_3/3}, m_\pi$$
$$M_{hi} \sim M_{NN}$$

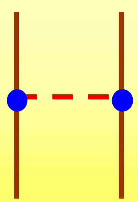
Kaplan, Savage
+ Wise '98
...
Fleming, Mehen
+ Stewart '01
...

all pion exchanges perturbative;
contact ordering and
LO same as Pionless EFT

for physical pion masses does not seem to converge in lower spin-triplet waves much beyond regime of Pionless EFT

- *partly* perturbative pions

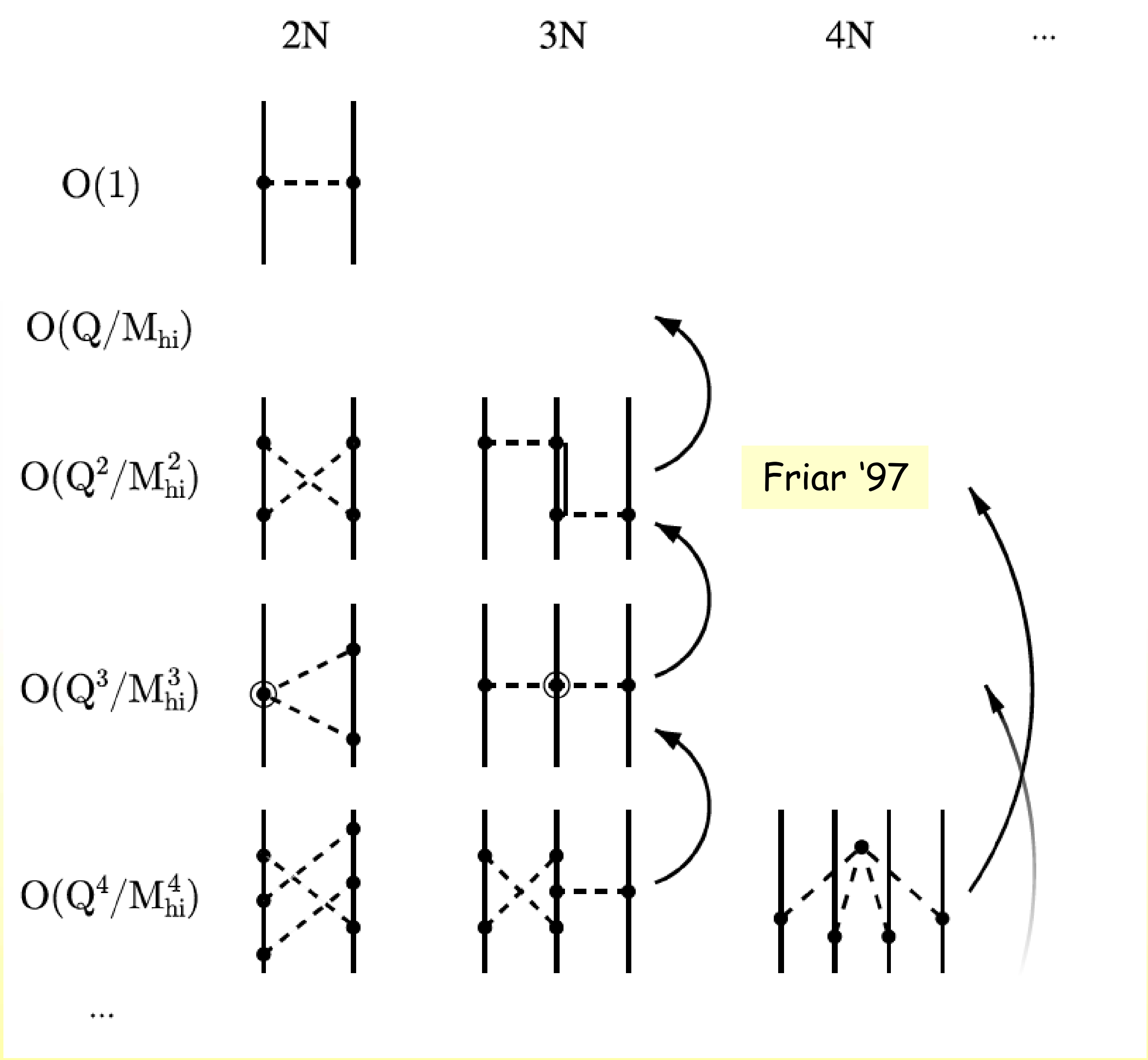
$$M_{lo} \sim M_{NN}, m_\pi$$
$$M_{hi} \sim M_{QCD} \equiv 4\pi f_\pi, m_N, \ldots$$



$$\sim \frac{4\pi}{m_N \alpha_l M_{NN}} \begin{cases} \sim \dfrac{4\pi}{m_N M_{lo}} & \text{low waves} \quad \text{LO} \\ \sim \dfrac{4\pi}{m_N M_{hi}} \left(\dfrac{M_{lo}}{M_{hi}}\right)^{n_l \geq 0} & \text{high waves} \quad \text{N}^{1+n}\text{LO} \end{cases}$$

Nogga, Timmermans
+ v.K. '05
Birse '06
Pavón Valderrama '11'11
Long + Yang '11'12'12
...

Chiral EFT



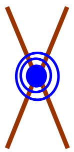
Weinberg '91
Ordóñez + v.K. '92
Ordóñez, Ray + v.K. '94'96
Kaiser '00'01'02'15
...

Ordóñez + v.K. '92
v.K. '94
Epelbaum *et al.* '02
...

Epelbaum '06'07
...

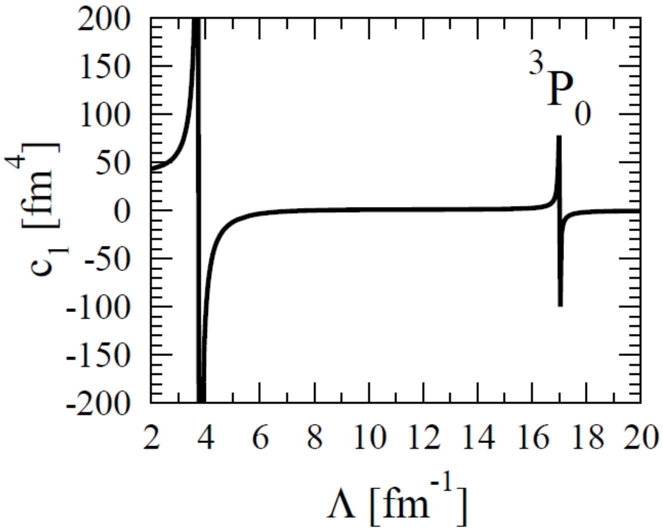
- NDA + counting 4πs as in Pionless EFT and m_N as M_{QCD} (Friar)
- long-range pot only

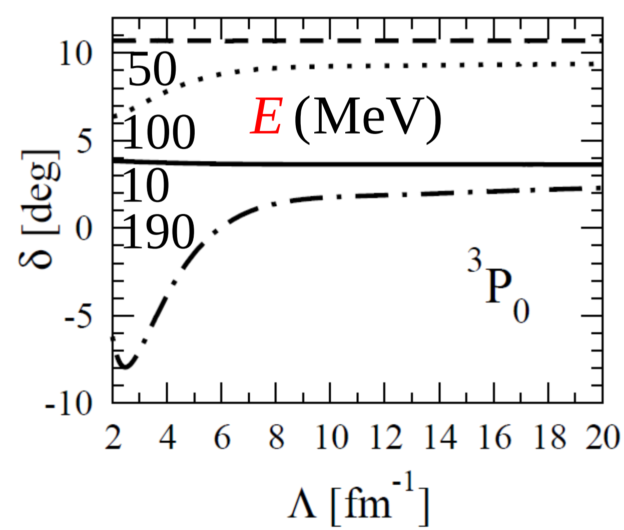
short-range pot
obeying NDA
except when running
dominated by pions,
i.e. low waves where
the one-pion-exchange
tensor force
is attractive



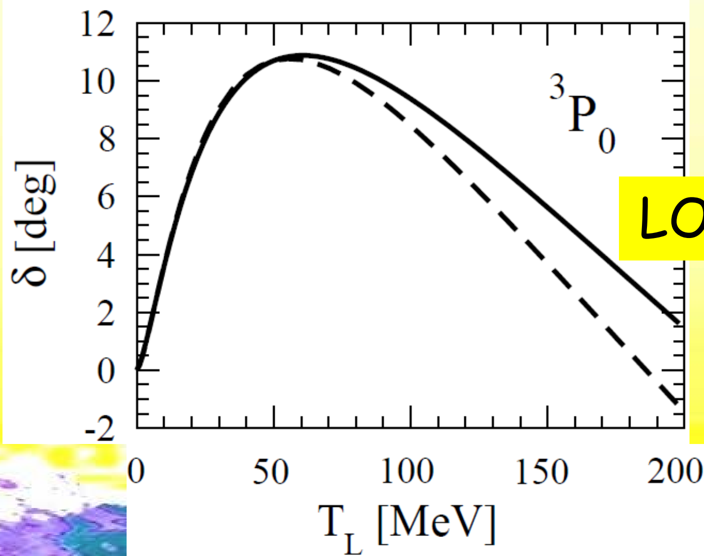
$\sim \frac{Q^2}{f_\pi^4}$ **LO** $\longleftrightarrow$ cf. NDA $\sim \frac{Q^2}{f_\pi^2 M_{QCD}^2}$ W's N²LO

renormalization of non-perturbative amplitudes





Nogga, Timmermans + v.K. '05

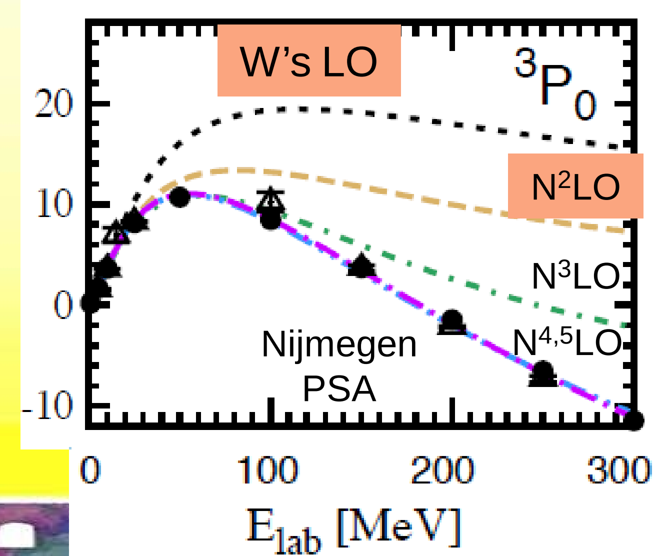


$\Lambda = 4$ GeV

Nijmegen PSA

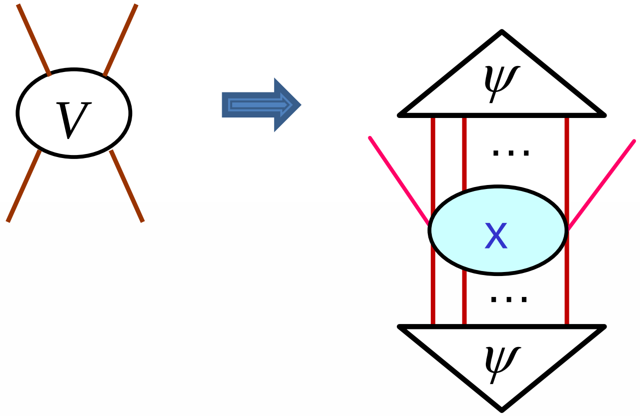
$\longleftrightarrow$ cf.

$\Lambda = 450$ MeV



Reinert, Krebs + Epelbaum '18

Processes with external probes



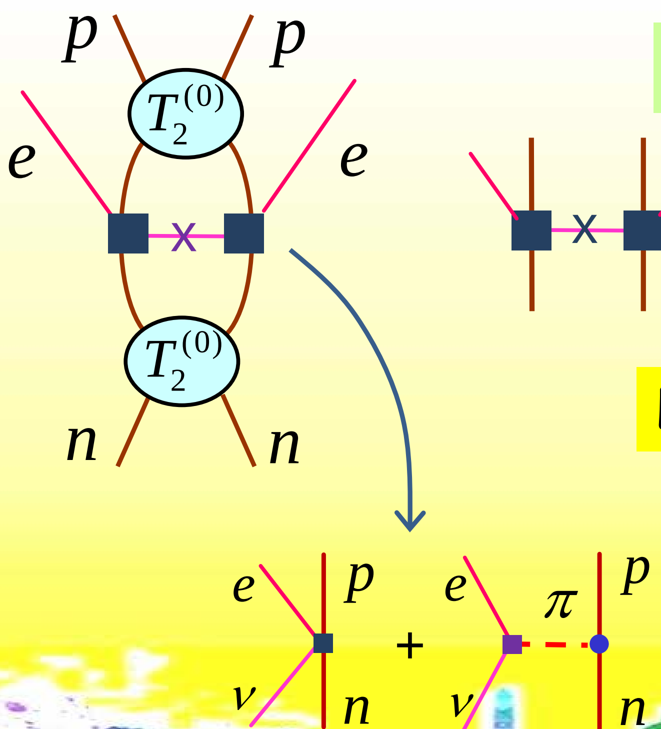
similar renormalization issues

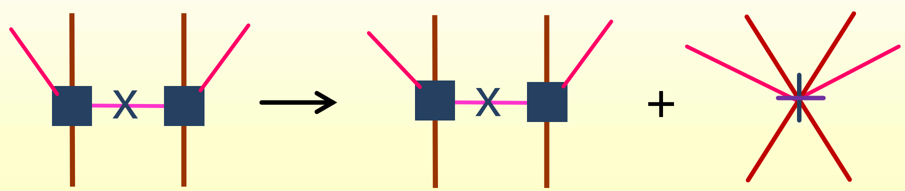
Pavón Valderrama + Phillips '15

0ν2ß decay

$|\Delta L| = 2$

Cirigliano, Dekens, De Vries, Graesser, Mereghetti, Pastore + v.K '18





See talks by De Vries, Dekens

LO

counterterm needed!

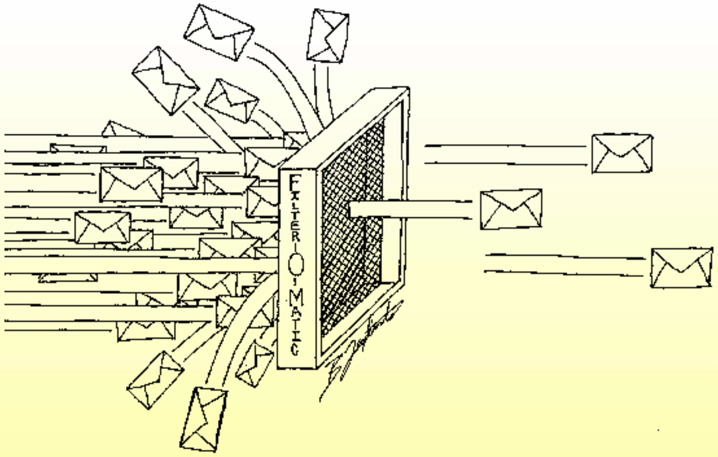
$$g_\nu = \mathcal{O}\left(\frac{1}{M_{lo}^2}\right) \gg \mathcal{O}\left(\frac{1}{M_{hi}^2}\right)$$

NDA

in Pionless and Chiral EFTs (partly or fully perturbative pions)

An advantage of Chiral EFT

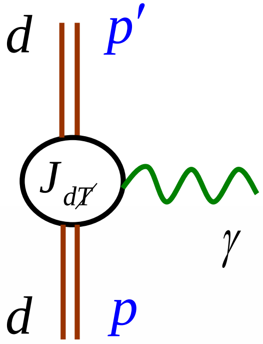
Possibility to disentangle symmetry-violating sources:
each breaks chiral symmetry in a particular way,
and thus produces *different* hadronic interactions



(For Pionless EFT, only isospin is left…)

Deuteron Electric Dipole Form Factor

De Vries, Mereghetti, Timmermans + v.K. '11



$\not{T}$

$$\left\langle p', j \middle| J^{\mu}_{d\not{T}} \middle| p, i \right\rangle = -2iS_{\sigma ij}\left[v^{\mu}q^{\sigma} - \eta^{\mu\sigma} v\cdot q + \ldots\right] F_{E1}\left(|\vec{q}|/4\kappa\right) + \ldots$$

$q = p - p'$

$v^{\mu} = (1, \vec{0})$

$S^{\mu}_{ij} = (0, i\varepsilon_{ijk})$

rest frame

$\kappa = \sqrt{mB_d}$

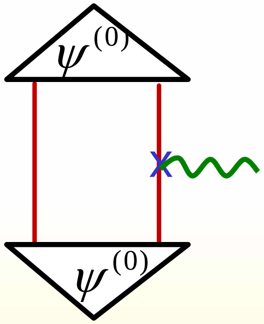
$\xi = \kappa / m_{\pi}$

perturbative pions

LO

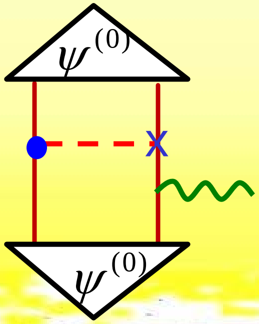
$$F_{E1}(x) = \left(d_n + d_p\right)\frac{\arctan x}{x}$$

θ term, qEDM, gCEDM, CIC



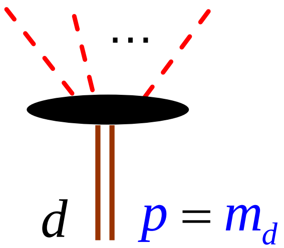
$$-\frac{eg_A\bar{g}_1}{6m_{\pi}}\frac{m_N}{4\pi f_{\pi}^2}\frac{1+\xi}{(1+2\xi)^2}\left[1 - x^2\frac{10+65\xi+144\xi^2+73\xi^3}{30(1+\xi)(1+2\xi)^2} + \ldots\right]$$

qCEDM, LRC



	θ term, qEDM, gCEDM, CIC	qCEDM, LRC
$\frac{d_d}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_{\pi}M_{NN}}\right)$

Deuteron Lifetime



$\kappa = \sqrt{mB_d}$

$\xi = \kappa / m_\pi$

$$\tau_d = \frac{1}{\Gamma_d}$$

$|\Delta B| = 2$

perturbative pions

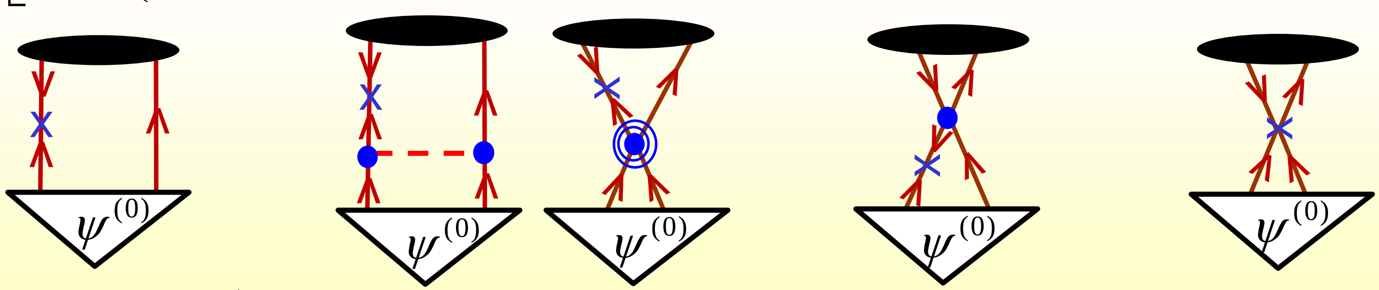
Oosterhof, De Vries, Timmermans + v.K. '19

LO

NLO

$$\Gamma_d = -\frac{m_N}{\kappa \tau_{n\bar{n}}^2} \mathrm{Im}\, a_{\bar{n}p} \left[1 + \kappa \left(r_{np} - \frac{g_A^2}{3} \frac{m_N}{4\pi f_\pi^2} \frac{2 - 2\xi - 5\xi^2 + 6\xi^3}{1 + 2\xi} + 2\,\mathrm{Re}\, a_{\bar{n}p} - \frac{\tau_{n\bar{n}} (\kappa - \mu)\, \mathrm{Im}\, B_0(\mu)}{\sqrt{2}\pi\, \mathrm{Im}\, a_{\bar{n}p}} \right) \right]$$

≈ 2.5 larger than pot models



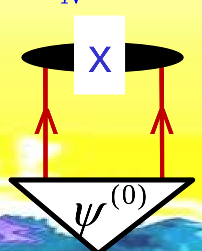
Rao + Shrock '82

...

Buchoff + Wagman '16

LO

$$\Gamma_d = -\frac{4\kappa^3}{m_N} \mathrm{Im}\, a_{np}$$



could be separated

combo's of diquarks

	Operator	Notation of Ref. [16]	Chiral irrep
$\mathcal{Q}_1$	$-\mathcal{D}_R\mathcal{D}_R\mathcal{D}_R^+ T^{AAS}/4$	$\mathcal{O}^3_{RRR}$	$(\mathbf{1}_L, \mathbf{3}_R)$
$\mathcal{Q}_2$	$-\mathcal{D}_L\mathcal{D}_R\mathcal{D}_R^+ T^{AAS}/4$	$\mathcal{O}^3_{LRR}$	$(\mathbf{1}_L, \mathbf{3}_R)$
$\mathcal{Q}_3$	$-\mathcal{D}_L\mathcal{D}_L\mathcal{D}_R^+ T^{AAS}/4$	$\mathcal{O}^3_{LLR}$	$(\mathbf{1}_L, \mathbf{3}_R)$
$\mathcal{Q}_4$	$-\mathcal{D}_R^{33+} T^{SSS}/4$	$\left(\mathcal{O}^1_{RRR} + 4\mathcal{O}^2_{RRR}\right)/5$	$(\mathbf{1}_L, \mathbf{7}_R)$

Conclusion

EFTs connect symmetry violation
beyond the Standard Model and nuclear physics
in a controlled and systematic way

Nonperturbative renormalization
in nuclear EFTs
generically leads to violation of NDA

Chiral symmetry allows the
partial separation of symmetry-violating sources

P.S.

Response to a question of E. Epelbaum:

(paraphrasing)

What is wrong with the argument against taking the cutoff to infinity in the case of the EFT for the toy model in

Epelbaum + Gegelia, arXiv:0906.3822 [nucl-th]

(I had no access to printed version when preparing this answer)

but still keep perturbative expansion in Q/M_{hi}

CANNOT JUST COUNT POWERS OF Q

$$V^{(\mu)}(Q \sim M_{lo}) \sim \frac{4\pi}{m_N M_{lo}} \left(\frac{Q}{M_{hi}} \right)^{\mu}$$

various orders in the potential $\xrightarrow{\text{DWBA}}$ same order in amplitude

e.g. $V^{(1)2}, V^{(2)}$ in $T^{(2)}$

potential must depend on regulator

each order in potential must contain enough LECs

$\Rightarrow$ amplitude renormalization

↳ not trivial when resuming higher orders

e.g. $V^{(1)\infty}$

In other words,

Different orders in the potential contribute to the same order in amplitudes

Observables are properties of amplitudes

If you iterate subleading terms in the potential,
in general there will be problems

(Well understood in EFT; example:
$1/m_Q$ effects in heavy quark EFT -- treated exactly, prevent continuum limit)

eg Sommer '10 for pedagogical explanation

if, nevertheless, you insist to iterate subleading terms in the potential,

i) you should first make sure that lower orders have been renormalized properly;
ii) the burden is on YOU to show that you don't run into problems
– and please do not blame me if you do

Epelbaum + Gegelia, arXiv:0906.3822 [nucl-th]

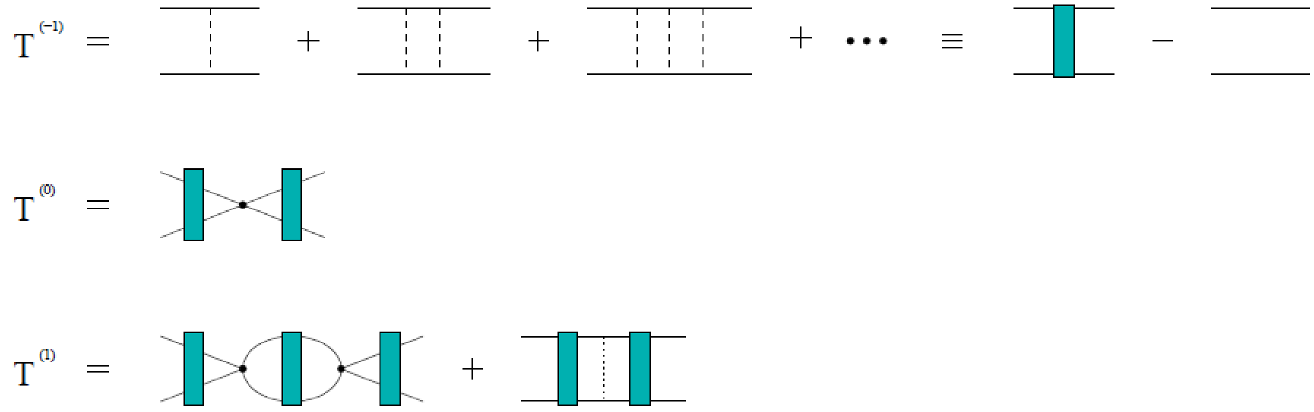
Toy model:

completely removing (or taking very large values of) the cutoff. To that aim, we construct effective theory for an exactly solvable quantum mechanical model with long- ($r_l \sim m_l^{-1}$) and short-range ($r_s \sim m_s^{-1} \ll m_l^{-1}$) interactions of a separable type valid for momenta of the order $k \sim m_l$. This can be viewed as a toy-model for pionful EFT. We explain the meaning

$$V(p, p') = v_l\, F_l(p)\, F_l(p') + v_s\, F_s(p)\, F_s(p')\,, \quad F_l(p) \equiv \frac{\sqrt{p^2 + m_s^2}}{p^2 + m_l^2}\,, \quad F_s(p) \equiv \frac{1}{\sqrt{p^2 + m_s^2}}$$ (3

specific form of the interaction potential. We fine tune the strengths of the long- and short-range interactions in such a way that they generate scattering lengths of a natural size. More

Perturbative-contact approach :



It is then easy to verify that the scattering amplitude $T^{(-1)} + T^{(0)} + T^{(1)}$ is μ-independent up to terms of order Q^2. Further, the effective range function is given at this order by

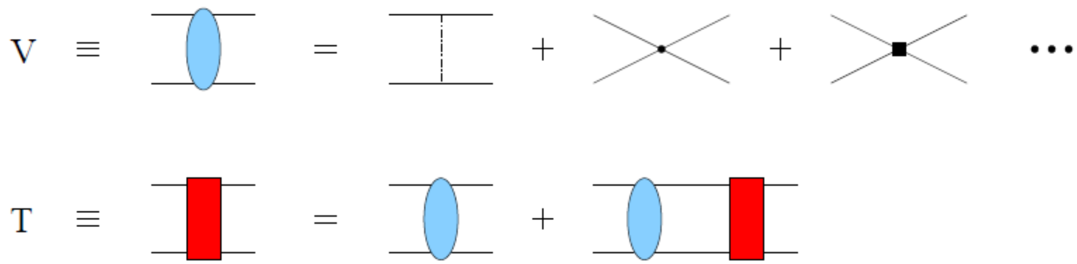
where $Q = \{m_l,\ \mu\}$. As expected, the first three terms in the "chiral" expansion of *all* ERE coefficients are reproduced correctly at NNLO. Notice further that the contributions beyond the order of accuracy of the calculation are explicitly renormalization-scale dependent, see section II for a general discussion. The above results reveal the meaning of the LETs in the present context. All i-th terms $\alpha_x^{(i)}$ in the "chiral" expansion of the coefficients in the ERE, $x = \{a,\ r,\ v_2,\ \ldots\}$ are correlated with each other due to the long-range interaction and its interplay with the short-range interaction in the underlying model. The knowledge of $\alpha_{x_j}^{(i)}$ for one particular x_j is sufficient to predict $\alpha_{x_k}^{(i)}$ for all $k \neq j$. In an EFT, short-range physics is incorporated in a systematic way by taking into account contact interactions with an increasing number of derivatives. Matching the strengths of the corresponding LECs to the first n terms in the "chiral" expansion of some of the ERE coefficients allows to correctly describe the "chiral" expansion of *all* ERE coefficients up to order m_l^n/m_s^n. It should be emphasized that at low energies and in the absence of external sources, the appearance of the above mentioned correlations is *the only* signature of the long-range interaction in the 2N system.

My conclusion:

The power counting in this situation is one
in which the contact interactions
should be treated perturbatively

which, btw, is consistent with:
the scattering length is natural
and
the long-range potential is not singular

Nonperturbative-contact approach:



the characteristic hard scale in the problem, $\Lambda \sim m_s$. Taking values $\Lambda \gg m_s$ artificially enhances certain higher-order contributions in the "chiral" expansion of the ERE coefficients spoiling the predictive power of the theory.

My conclusion:

A good example of the statement in my talk that

each order in potential
must contain enough LECs

not trivial when resuming higher orders

e.g. $V^{(1)\infty}$

My answer:

The argument is consistent with the fact that, in general, you cannot take the cutoff to infinity when iterating subsets of subleading interactions. It does not contradict the view that what matters is renormalization of the amplitude at each order in the appropriate power counting.
If X (where X is a short- or long-range interaction) is perturbative, renormalize in perturbation theory.
If Y (where Y is a short- or long-range interaction) is non-perturbative, renormalize nonperturbatively.
(Not very profound, I know.)

While at it:

Epelbaum, Gasparyan, Gegelia + Meißner, arXiv:1810.02646 [nucl-th]

Let us consider the potential

$$V(r) = \frac{\alpha\left(e^{-m_1 r} - e^{-Mr}\right)}{r^3} + \frac{\alpha\,(m_1 - M)\,e^{-m_1 r}}{r^2} + \frac{\alpha\,(M - m_1)^2 e^{-m_2 r}}{2r} - \frac{1}{6}\alpha\,(2m_1 - 3m_2 + M)\,(M - m_1)^2 e^{-m_1 r}, \quad (14)$$

where the light mass M is the small scale and the heavy masses m_1, m_2 are the large scales. Our choice of parameters is $\alpha = -36\,\text{GeV}^{-2}$, $M = 0.1385$ GeV, $m_1 = 0.75$ GeV and $m_2 = 1.15$ GeV. The factor α sets the strength of the interaction. This strength is taken equal for all terms, so that the potential $V(r)$ vanishes for $r \to 0$ and it behaves as $-\alpha\, e^{-Mr}/r^3$ for large r. In Fig. 2 we show the full potential and its long range part extended to small values of r.

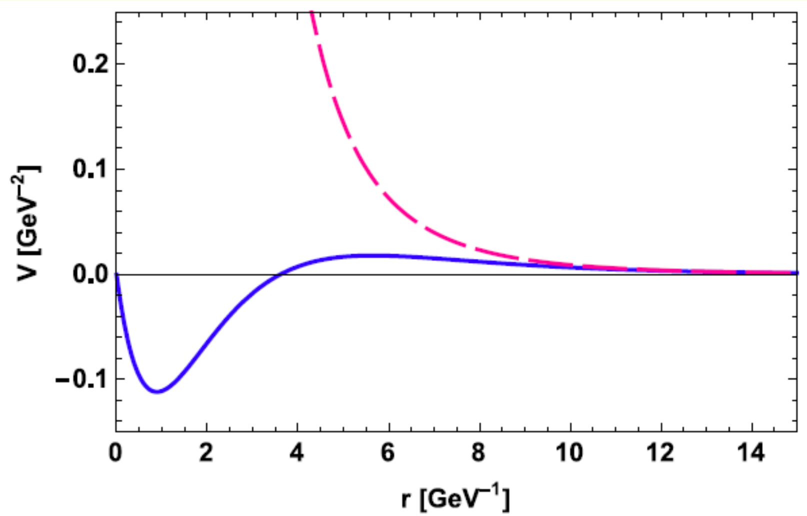


FIG. 2: Exact and approximate potentials as discussed in the text. The solid (blue) and the long-dashed (magenta) lines corresponds to the exact and the approximate potentials, respectively.

Considering the expression of Eq. (14) as an "underlying fundamental" potential, we can construct the corresponding EFT. The LO EFT potential consists of a constant contact interaction corresponding to the delta potential in coordinate space and the long range part $-\alpha\, e^{-Mr}/r^3$, which is singular if extended to the small r region. The coupling constant $\alpha = -36$ GeV^{-2} $\approx -1/(0.167$ GeV$)^2$ is chosen such that the full LO potential as well as its long range part are non-perturbative for the momenta $k \sim M = 0.1385$ GeV. A simple UV analysis shows that the

are reasonably well described by the LO EFT potential. For increasing cutoff, the region where the phase shifts are well described at LO decreases eventually vanishing in the removed cutoff limit. Note further that the phase shifts

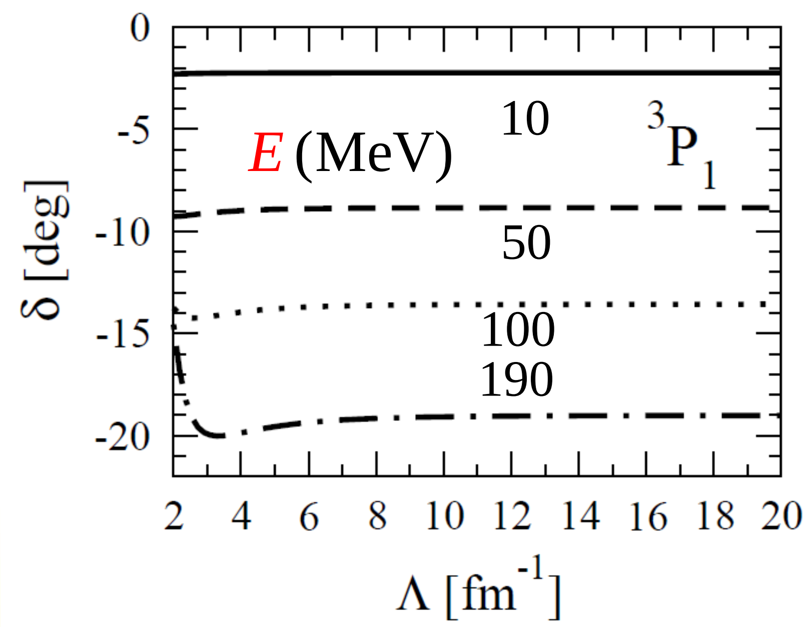
My conclusion:

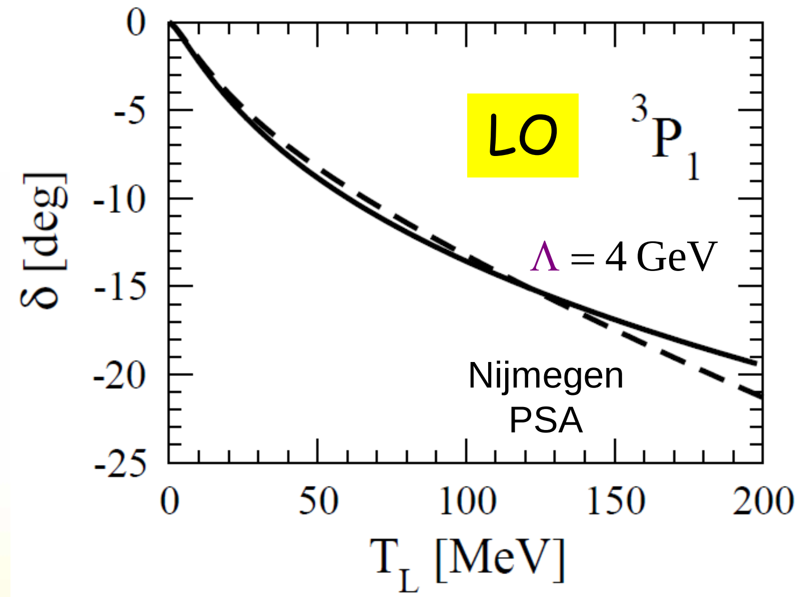
The power counting in this situation is one
in which the contact interactions
should be treated perturbatively

which, btw, is consistent with
the repulsive singular potential being properly renormalized
without a contact interaction

nonperturbative one-pion exchange alone:

Nogga, Timmermans+ v.K. '05

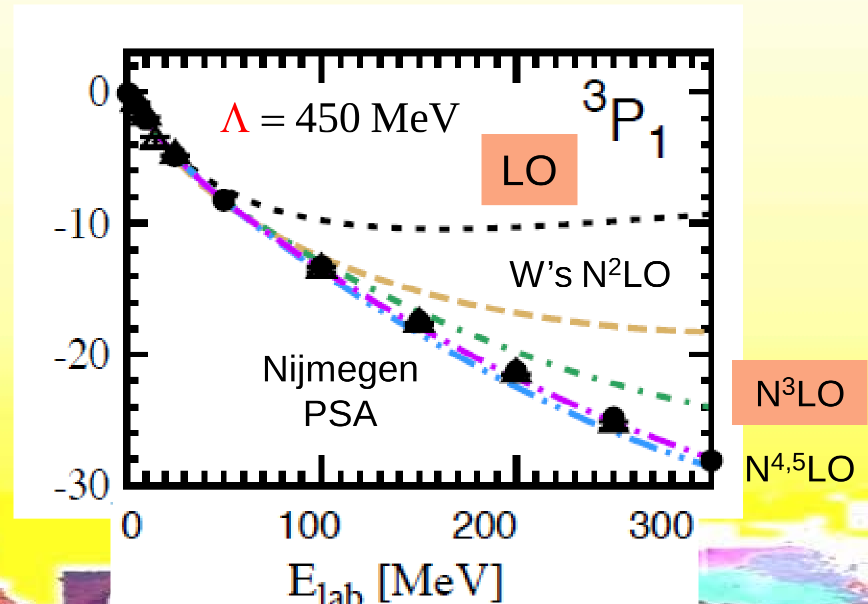




I.e. no need to revise NDA on the basis of RG invariance in this channel

cf.

Reinert, Krebs + Epelbaum '18



well described at LO decreases eventually vanishing in the removed cutoff limit. Note further that the phase shifts corresponding to a repulsive long-range singular potential without adding a strong attractive contact interaction have a well defined removed cutoff limit which strongly deviates from the data as seen in Fig. 3. One might be tempted to try to reproduce the data by treating the higher order contact interactions perturbatively. However, and on top to the conceptual problems discussed above, such a perturbative treatment would be questionable due to the large discrepancy between the data and the LO phase shifts, see also Ref. [74] for a related discussion. Thus, as mentioned

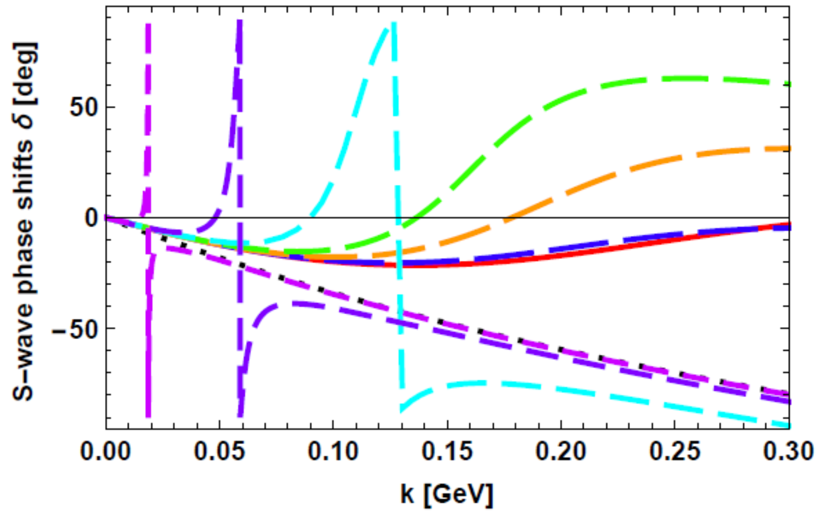
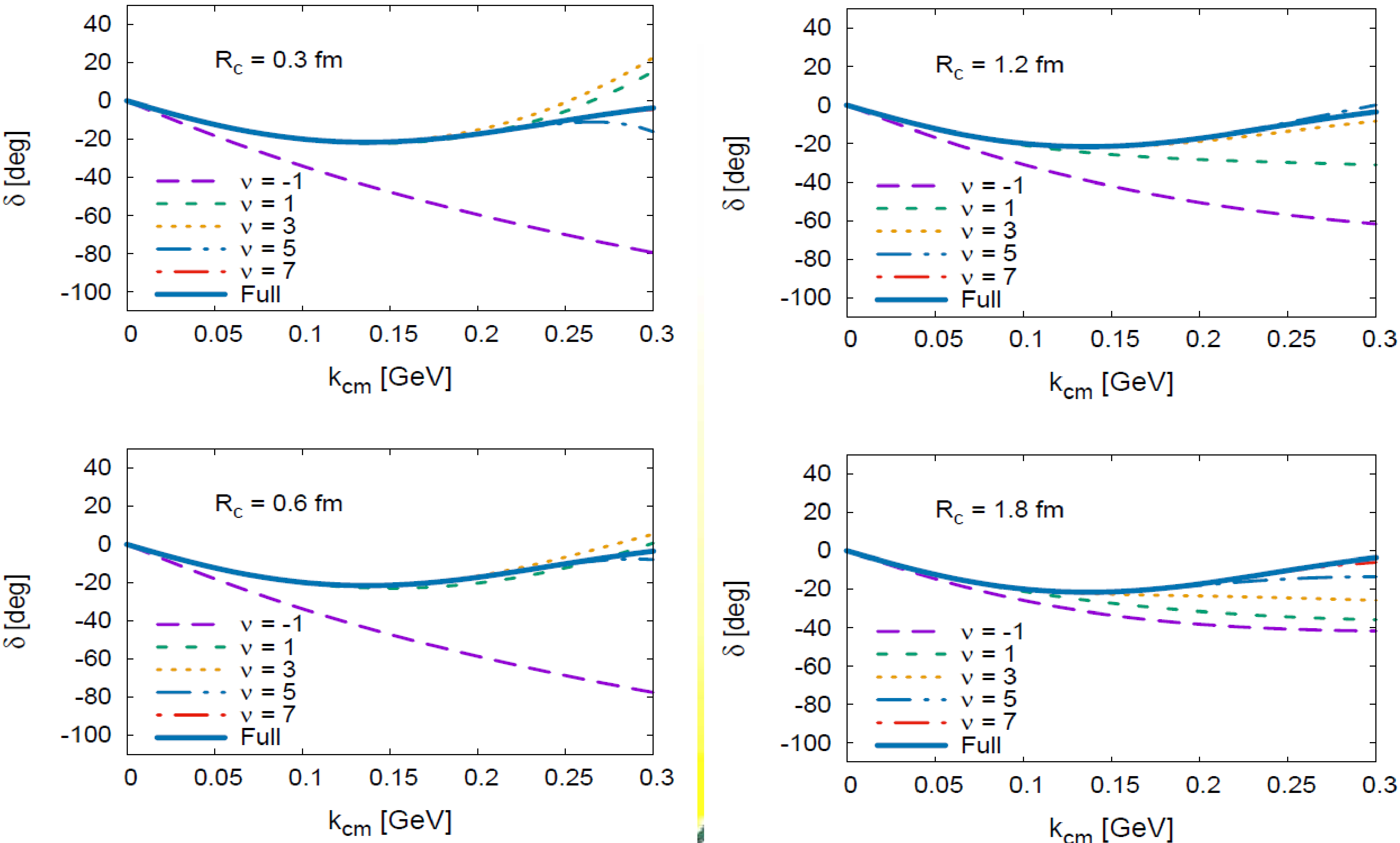


FIG. 3: S-wave phase shifts versus the particle momentum in the center-of-mass frame. The solid (red) line corresponds to the underlying potential and the dashed lines with decreasing length of dashes are phase shifts for the cutoff $\Lambda = 0.6, 0.8, 1.0, 1.4, 2.0$ and 3.0 GeV, respectively. The constant contact interaction term is fitted to reproduce the scattering length. The dotted (black) line represents the phase shifts corresponding to the singular long range potential in the infinite cutoff limit.

Valderrama, arXiv:1901.10398 [nucl-th]



plus similar expressions for its derivatives, where a local contact-range potential is used: $C_{2n} q^{2n}$. The regularization is slightly different than in the original manuscript, but it is certainly simpler and nonetheless equivalent. The details of the calculation are analogous to those of Ref. [8], but extended to higher orders. The C_{2n} couplings are determined by fitting to the toy model phase shifts in the $20 - 80\,\text{MeV}$ ($80 - 200\,\text{MeV}$) range for $\nu = 1, 3$ ($\nu = 5, 7$). Calculations are shown for the cutoffs $R_c = 0.3, 0.6, 1.2$ and $1.8\,\text{fm}$ up to order Q^7 (N^8LO) in the EFT expansion. The conclusion is that the standard EFT approach of Ref. [2] is perfectly able to describe the physics of the toy model of Epelbaum et al. [1]. In addition it improves over the proposal of Ref. [1] (namely, a purely non-perturbative approach with a judiciously chosen cutoff), in the sense that there are no strong restrictions on the cutoff (besides the numerical ones, $R_c \geq 0.3\,\text{fm}$ in this case), which can be taken harder than the breakdown scale if one wishes to. Notice that even though the existence of the $R_c \to 0$ limit has not been proven, this is not a necessary condition for the present approach to be useful.

1. E. Epelbaum, A. M. Gasparyan, J. Gegelia, and U.-G. Meißner, Eur. Phys. J. **A54**, 186 (2018), arXiv:1810.02646 [nucl-th] .
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8. M. Pavon Valderrama, Phys.Rev. **C84**, 064002 (2011), arXiv:1108.0872 [nucl-th] .

And for the record:

Epelbaum + Gegelia, arXiv:1207.2420 [nucl-th]

the $1/m$-expansion. When pions are treated non-perturbatively as suggested in the Weinberg scheme, the formulation we propose, being renormalizable, offers the appealing possibility to remove the UV cutoff in the way compatible with the principles of EFT. We have analyzed two-nucleon scattering at LO in the modified Weinberg approach. We found that the integral equation does not possess a unique solution in the $^3P_0$ partial wave similarly to the Skornyakov–Ter-Martirosyan equation for spin-doublet nucleon-deuteron scattering. One possible way to fix the solution in this channel is to include the corresponding contact interaction whose strength is tuned to reproduce the low-energy data [37]. The obtained cutoff-independent results for phase shifts at LO in the modified Weinberg scheme are in a reasonably good agreement with the Nijmegen PWA. The LETs for the coefficients in the ef-

[37] P. F. Bedaque, H. W. Hammer and U. van Kolck, Phys. Rev. Lett. **82**, 463 (1999) [nucl-th/9809025].

as claimed earlier by

A. Nogga, R.G.E. Timmermans and U.van Kolck,
Phys. Rev. C 72 (2005) 054006 [nucl-th/0506005]