n-nbar oscillation and deuteron life time

— |ΔB| = 2 in chiral effective field theory

Bingwei Long
Sichuan University

In collaboration with Femke Oosterhof, Jordy de Vries, Rob Timmermans, Bira van Kolck (1902.05342)

$|\Delta B| = 2$ nuclear physics

Mohapatra, Marshak ’80
Arnold, Fornal, Wise ’13
Bell, Corbett, Nee, Ramsey-Mulsolf ’19

BSM — $\Lambda_{|\Delta B|=2}$ — $10^{?}$ TeV

Standard M — $M_{\rm H}$ — 100 GeV

Λ_χ — 1 GeV — chiral sym. breaking

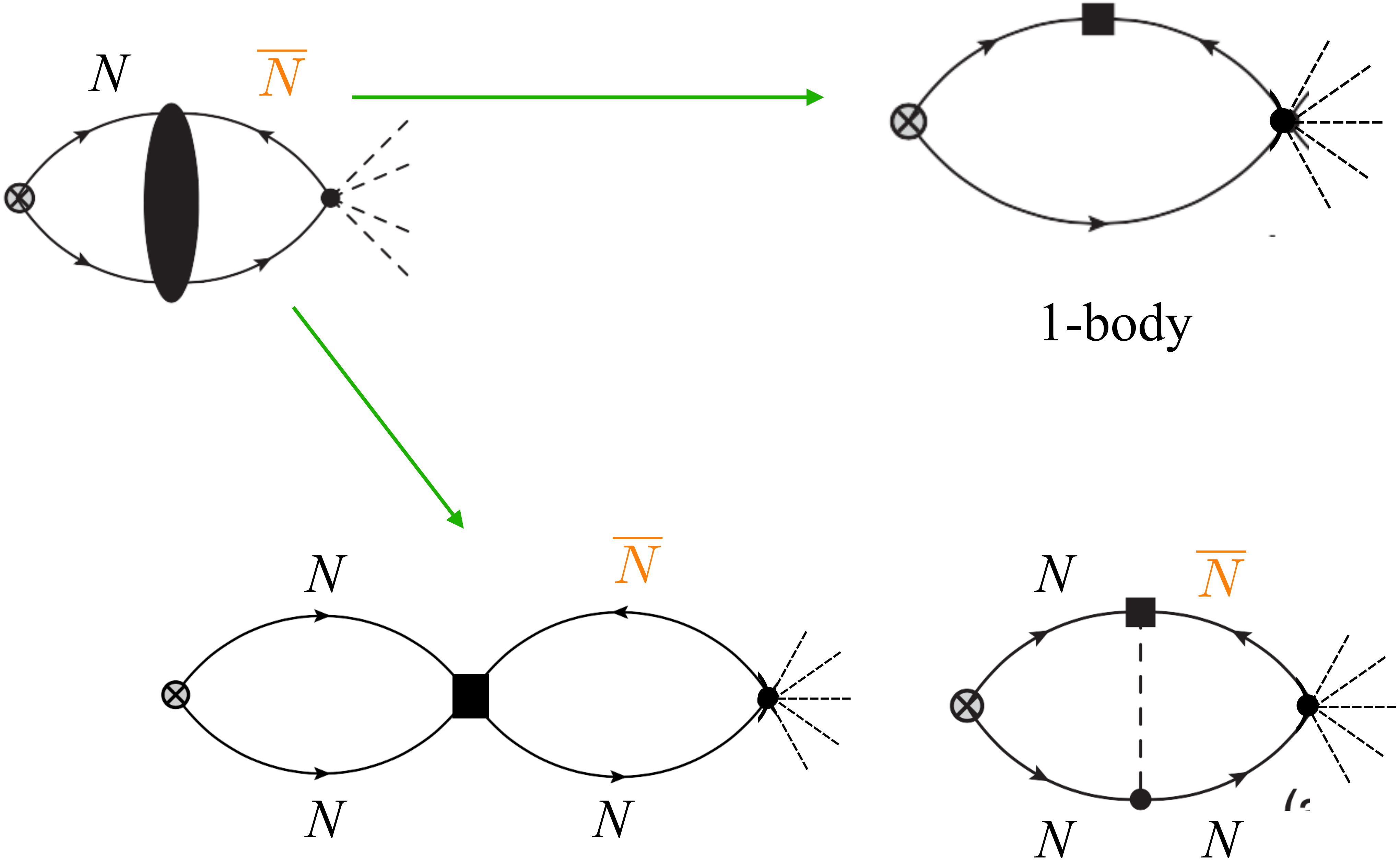
chiral EFT — Λ_{NN} — $F_\pi \sim 200$ MeV — KSW breaks down

we use this
perturbative pion — κ — 45 MeV

$1/a_{1S0}$ — 8 MeV

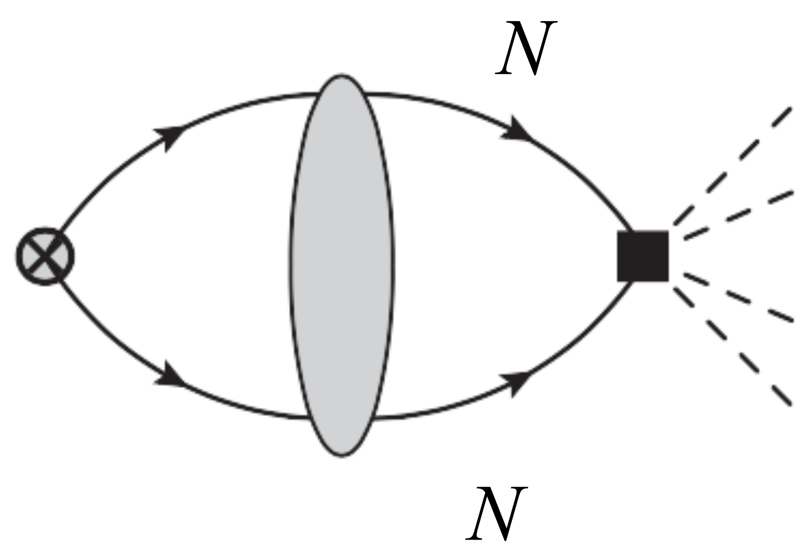
$NN \rightarrow NNbar$

$$R_d \equiv \Gamma_d^{-1} / \tau_{n\bar{n}}^2$$



2-body

Direct *NN* annihilation



- To what extent can we disentangle these mechanisms?

Four Dim-9 operators

- SM gauge invariant $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
- 6-quark operators to produce |ΔB| = 2

	Operator	Chiral irrep
$\mathcal{Q}_1$	$-\mathcal{D}_R\mathcal{D}_R\mathcal{D}_R^{+}T^{AAS}/4$	$(\mathbf{1}_L, \mathbf{3}_R)$
$\mathcal{Q}_2$	$-\mathcal{D}_L\mathcal{D}_R\mathcal{D}_R^{+}T^{AAS}/4$	$(\mathbf{1}_L, \mathbf{3}_R)$
$\mathcal{Q}_3$	$-\mathcal{D}_L\mathcal{D}_L\mathcal{D}_R^{+}T^{AAS}/4$	$(\mathbf{1}_L, \mathbf{3}_R)$
iso-breaking $\mathcal{Q}_4$	$-\mathcal{D}_R^{33+}T^{SSS}/4$	$(\mathbf{1}_L, \mathbf{7}_R)$

Important for building hadronic operators in chiral Lagrangian

Kuo & Love ’80
Rao & Shrock ’82
Caswell et al. ’83
Basecq & Wolfenstein ’83
Buchoff & Wagman ’16

$$\mathcal{D}_{L,R} \equiv q^{iT} C P_{L,R} i\tau^2 q^j, \qquad \mathcal{D}^a_{L,R} \equiv q^{iT} C P_{L,R} i\tau^2 \tau^a q^j,$$

$$\mathcal{D}^{abc}_{L,R} \equiv \mathcal{D}^{\{a}_{L,R}\mathcal{D}^{b}_{L,R}\mathcal{D}^{c\}}_{L,R} - \frac{1}{5}(\delta^{ab}\mathcal{D}^{\{d}_{L,R}\mathcal{D}^{d}_{L,R}\mathcal{D}^{c\}}_{L,R} + \delta^{ac}\mathcal{D}^{\{d}_{L,R}\mathcal{D}^{b}_{L,R}\mathcal{D}^{d\}}_{L,R} + \delta^{bc}\mathcal{D}^{\{a}_{L,R}\mathcal{D}^{d}_{L,R}\mathcal{D}^{d\}}_{L,R}),$$

$$T^{SSS} \equiv \varepsilon_{ikm}\varepsilon_{jln} + \varepsilon_{ikn}\varepsilon_{jlm} + \varepsilon_{jkm}\varepsilon_{iln} + \varepsilon_{jkn}\varepsilon_{ilm},$$

$$T^{AAS} \equiv \varepsilon_{ikm}\varepsilon_{jln} + \varepsilon_{ikn}\varepsilon_{jlm}.$$

Chiral EFT

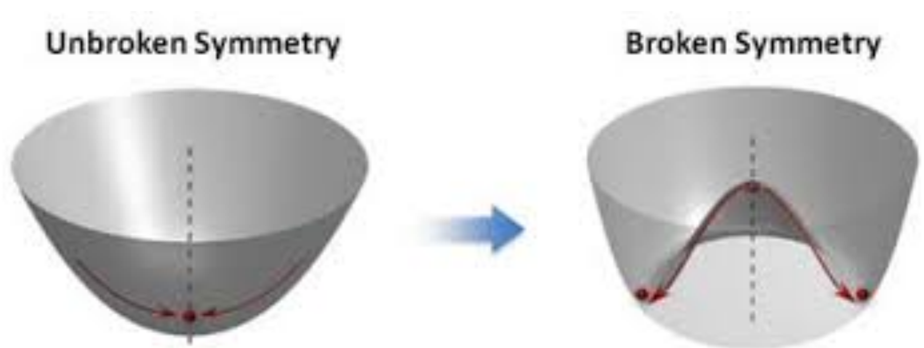
- Includes all symmetries of QCD, especially (approximate) chiral symmetry and its spontaneous breaking

$$\mathcal{L}_{\rm QCD} = \sum_{f=u,d,s,\dots} \bar{q}_f (i\not{D} - m_f) q_f - \frac{1}{4}\mathcal{G}_{a\mu\nu}\mathcal{G}_a^{\mu\nu}$$

$$q_L \equiv \begin{pmatrix} u_L \\ d_L \\ s_L \end{pmatrix} \mapsto \left(\mathbf{SU(3)}_L\right)\begin{pmatrix} u_L \\ d_L \\ s_L \end{pmatrix} \qquad q_R \equiv \begin{pmatrix} u_R \\ d_R \\ s_R \end{pmatrix} \mapsto \left(\mathbf{SU(3)}_R\right)\begin{pmatrix} u_R \\ d_R \\ s_R \end{pmatrix}$$

- Only two flavors used in present work

Lagrangian invariant when $m_f \to 0$, but broken by QCD ground state

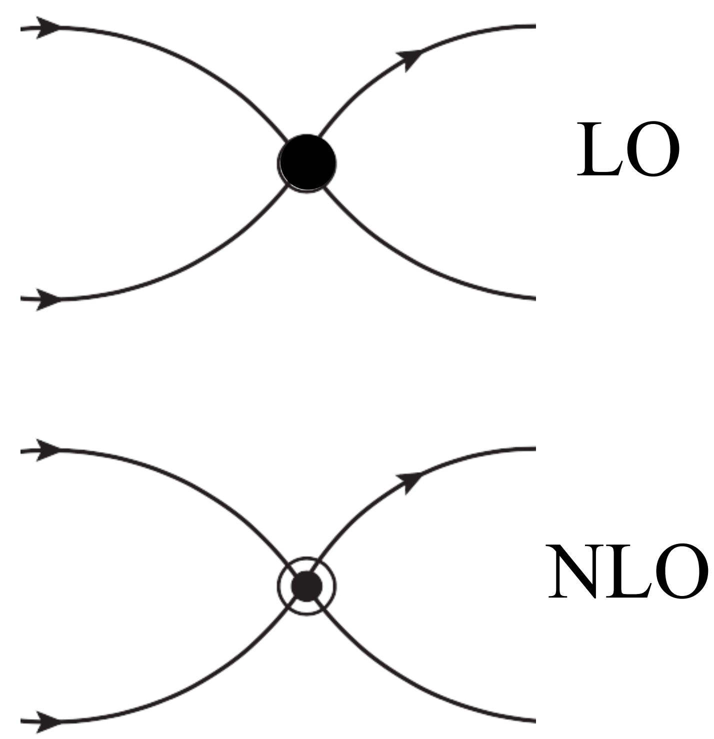


CCWZ; Weinberg; ...

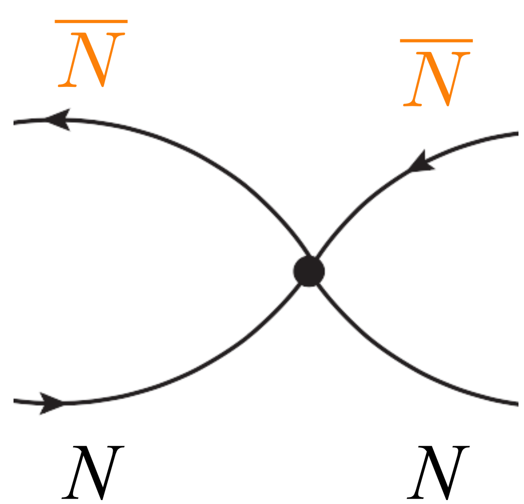
→ chiral symmetry nonlinearly realized by hadronic Dofs

More Lagrangian terms

$$\mathcal{L}^{(4)}_{\Delta B=0} = -(C_0 + D_2 m_\pi^2)(N^T P_i N)^\dagger (N^T P_i N) + \frac{C_2}{8}\left[(N^T P_i N)^\dagger (N^T P_i (\overrightarrow{\nabla} - \overleftarrow{\nabla})^2 N) + \text{H.c.}\right] - H_0 (N^{cT} \tau^2 Y_i^a N)^\dagger (N^{cT} \tau^2 Y_i^a N) + \ldots,$$



NN contacts



NNbar contacts

suppressed by

$$\frac{\kappa_d}{F_\pi} \simeq 0.24$$

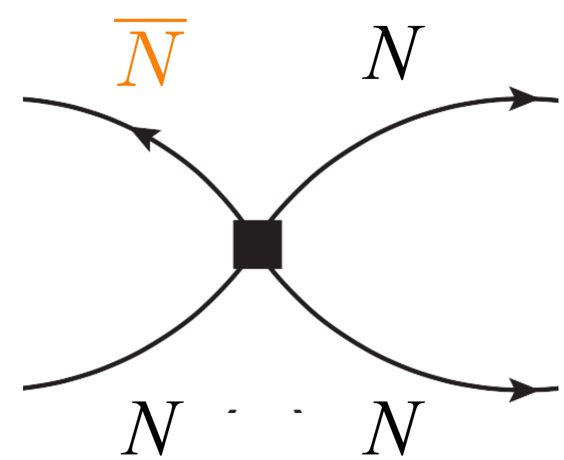
|ΔB| = 2 terms

(For LQCD calculation on delta m, Rinaldi et al. ’18 & ’19)

nnbar oscillation

$$\mathcal{L}^{(2)}_{|\Delta B|=2} = -\delta m\, n^{c\dagger} n + \text{H.c.} + \ldots,$$

$$\tau_{n\bar{n}} = (\delta m)^{-1}[1 + \mathcal{O}(m_\pi^2/\Lambda_\chi^2)]$$

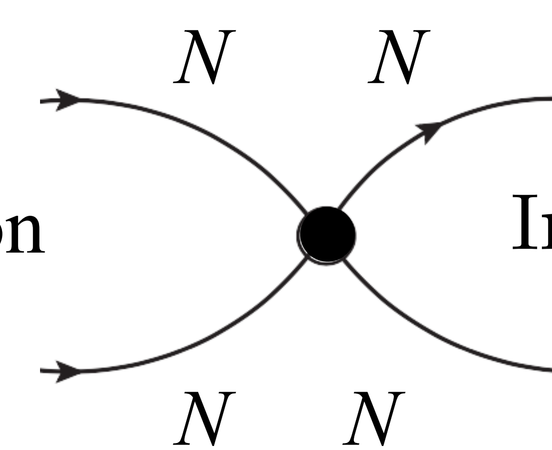


$NN \leftrightarrow N\bar{N}$ interactions

$$\mathcal{L}^{(4)}_{|\Delta B|=2} = i\tilde{B}_0[(N^T P_i N)^\dagger (N^{cT}\tau^2 Y_i^- N) - \text{H.c.}] + \ldots,$$

$$\text{Re}\tilde{B}_0 = \mathcal{O}(4\pi\,\delta m/\kappa^2\Lambda_{NN})$$

NN direct annihilation

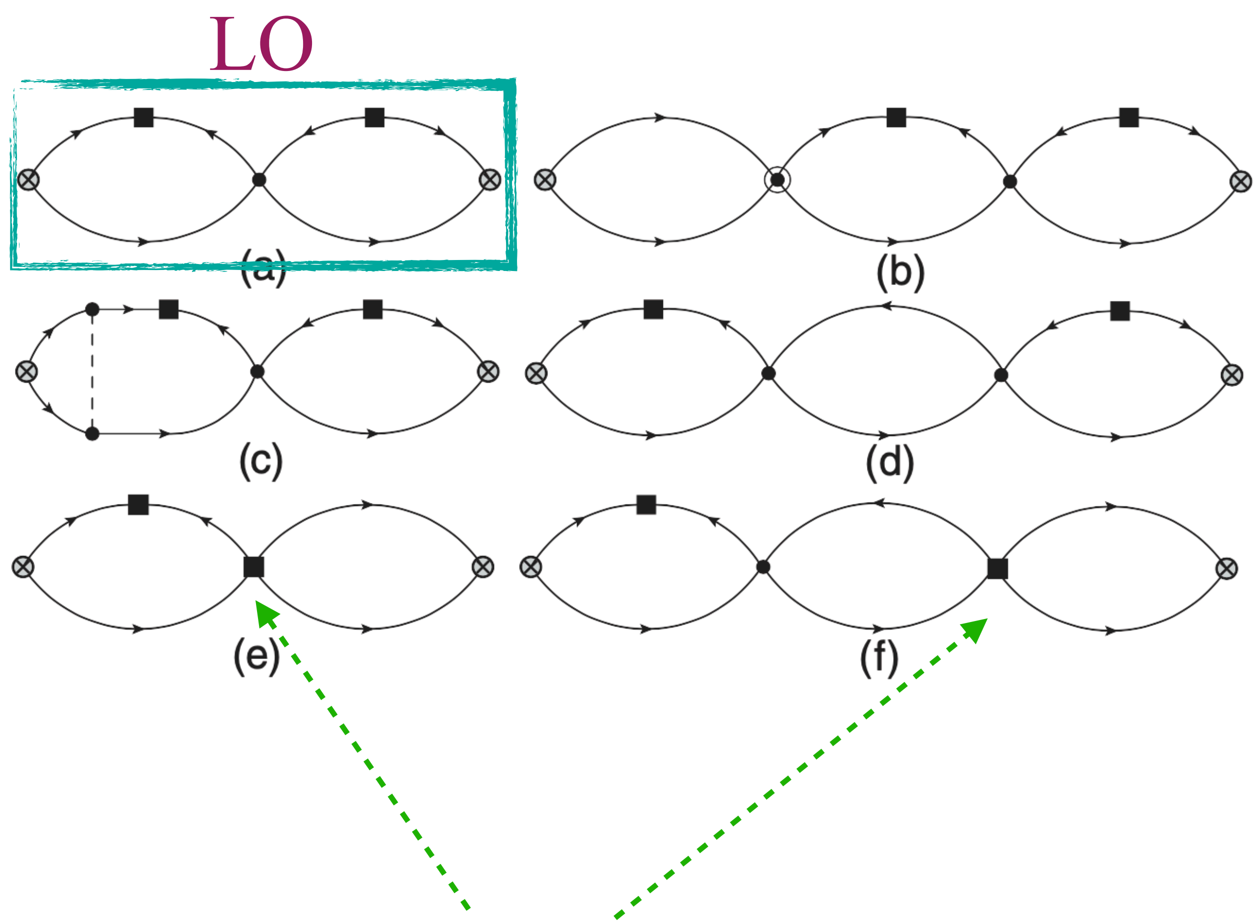


$\text{Im}C_0$ $\mathcal{O}(\delta m^2\Lambda_\chi^2/\kappa^2\Lambda_{NN}^4)$

One more trick

- NNbar annihilation releases 2GeV kinetic energy, way beyond chiral EFT break down scale
- To get around, calculate deuteron life time by imaginary part of deuteron self energy
- Hard pions as intermediate states are integrated out

Deuteron self energy up to NLO



Perturbative pion counting rule
(Kaplan, Savage & Wise PLB 424, 390 (98))

expansion parameter
$\rightarrow \quad \frac{\kappa_d}{F_\pi} \simeq 0.24$

κ_d : deuteron binding mometum ~ 45 MeV

- By RG analysis, *NN* → *NNbar* appears at NLO → $\tilde{B}_0$
- Range correction of *NN* interaction (B-conserving)

$$\mathrm{Re}\tilde{B}_0 = -m_N \delta m \, \mathrm{Re} C_2/\sqrt{2} + \ldots$$

- NNbar interaction parametrized by (anti-n p) scattering length $a_{\text{nbar-p}}$ = (0.44 - i 0.96) fm (Zhou & Timmermans '12 & '13)
- pion-exchange transition and direct annihilation at N2LO

Finally…

See also calculation by Haidenbauer & Meissner, CPC, 44, 033101

$$R_d \equiv \Gamma_d^{-1}/\tau_{n\bar{n}}^2$$

NN range

Re(a_{nbar-p})

pion

$NN \leftrightarrow N\bar{N}$ w/ unknown B_0

$$R_d = -\left[\frac{m_N}{\kappa}\mathrm{Im}a_{\bar{n}p}(1 + 0.40 + 0.20 - 0.13 \pm 0.4)\right]^{-1}$$
$$= (1.1 \pm 0.3) \times 10^{22}\ \mathrm{s}^{-1}.$$

- Perturbative pion allows for analytic expression
- Loosely bound neutron helps sensitivity (nbar-n potential energy diff. smaller if further out)
- B_0 gives largest uncertainty
- With nonperturbative pion EFT, unknown LECs may have smaller impact