SICHUAN UNIVERSITY

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$|\Delta B| = 2$ in chiral effective field theory

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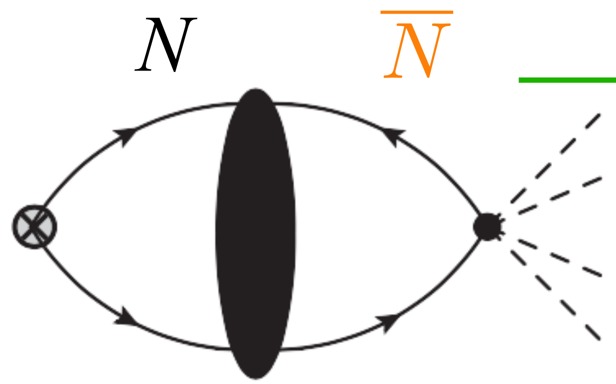
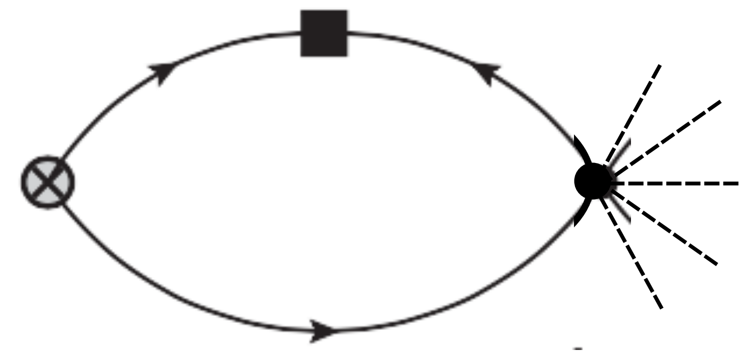
$|\Delta B| = 2$ nuclear physics

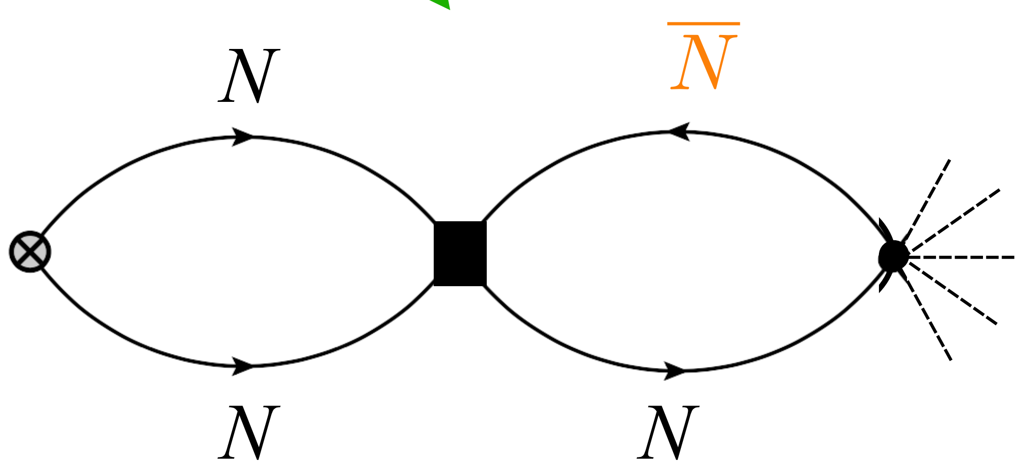
BSM	$\Lambda_{|\Delta B|=2}$	$10^?$ TeV	Mohapatra, Marshak '80 Arnold, Fornal, Wise '13 Bell, Corbett, Nee, Ramsey-Mulsolf '19
Standard M	M_{H}	100 GeV	
	Λ_χ	1 GeV	chiral sym. breaking
chiral EFT	Λ_{nuc}	$\sim$ 100 MeV	avg. nucleon momentum inside nuclei
we use this perturbative pion	Q_D	45 MeV	
	$1/a_{1S0}$	8 MeV	

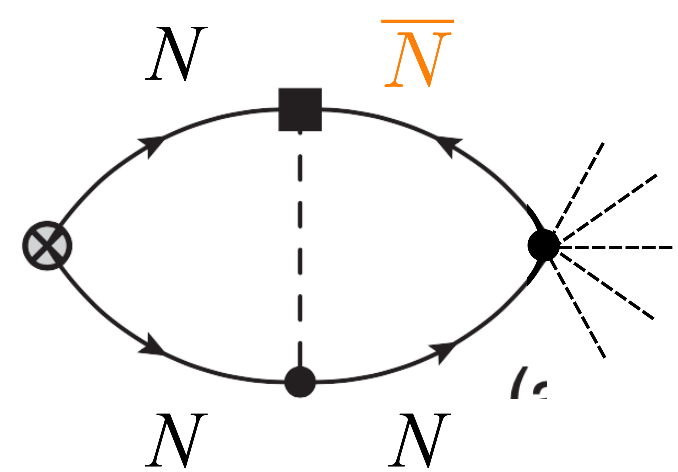
NN → NNbar





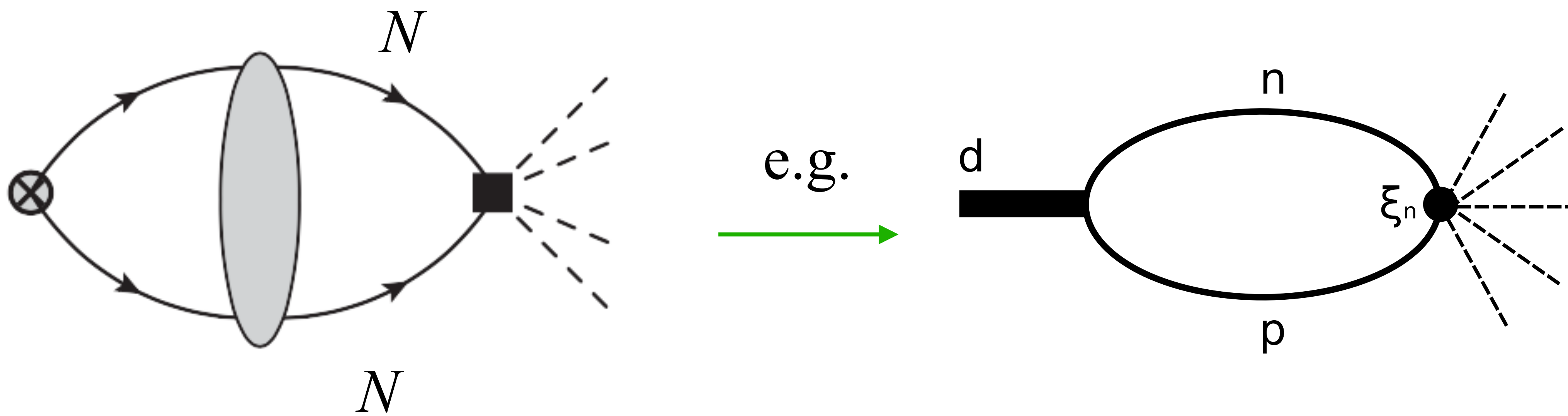
1-body





2-body

Direct *NN* annihilation



- To what extent can we disentangle these mechanisms?

Four Dim-9 operators

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

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

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

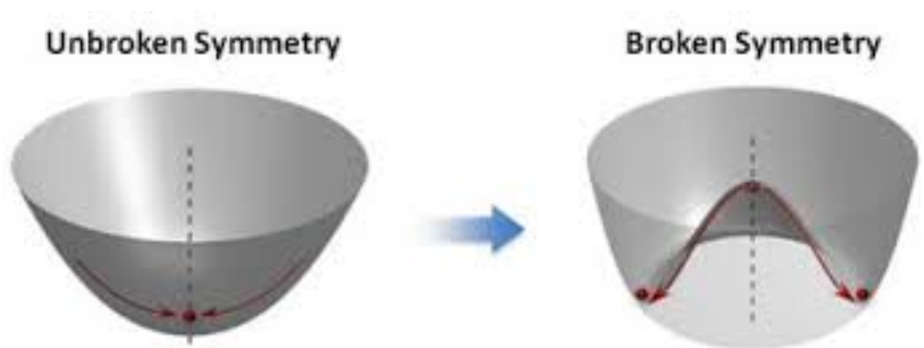
- Includes all symmetries of QCD, especially (approximate) chiral symmetry and its spontaneous breaking

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

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

- Only two flavors used in present work

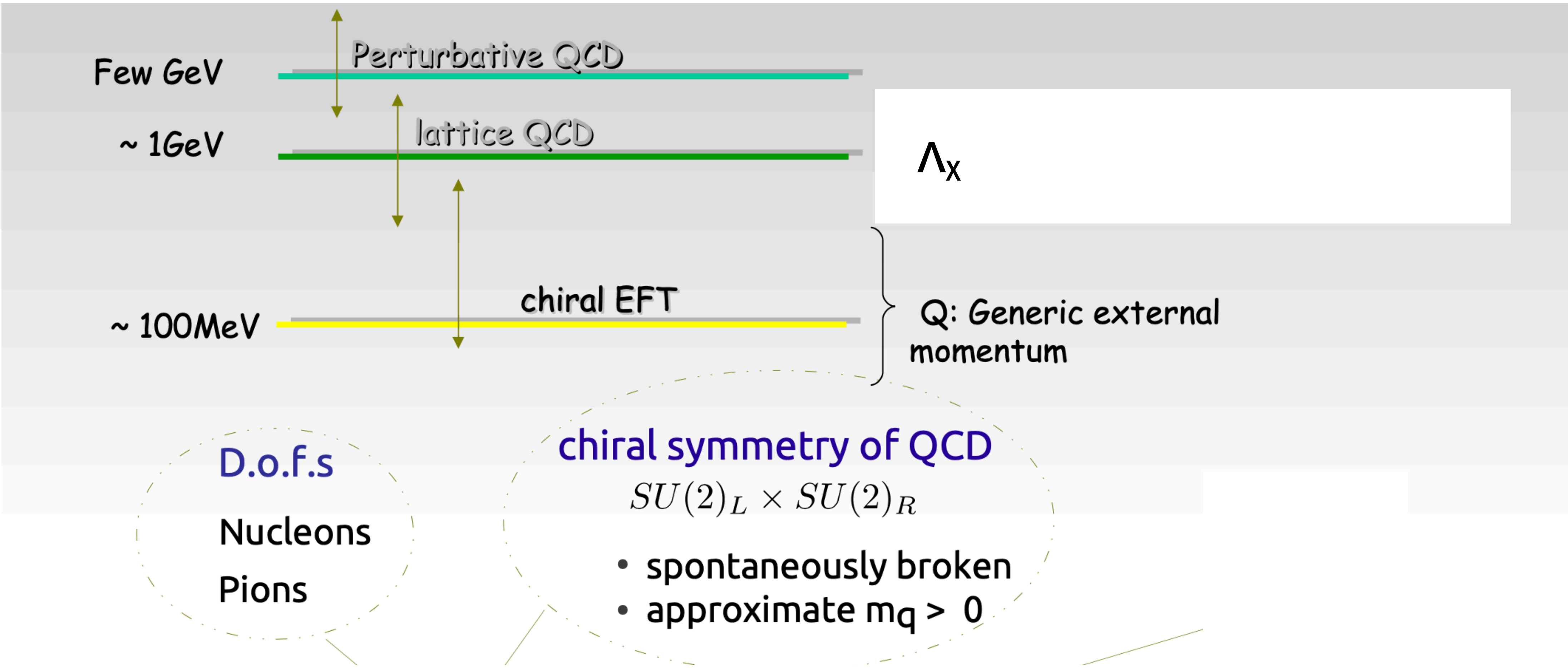
Lagrangian invariant when $m_f \to 0$, but broken by QCD ground state



CCWZ; Weinberg; …

→ chiral symmetry nonlinearly realized by hadronic Dofs

- Chiral L: a hadronic Lagrangian to respect chiral sym. and its spontaneous breaking



$$\mathcal{L}^{(2)}_{\Delta B=0} = N^\dagger\left(i\partial_0 + \frac{\nabla^2}{2m_N}\right)N + N^{c\dagger}\left(i\partial_0 + \frac{\nabla^2}{2m_N}\right)N^c$$
$$+\frac{g_A}{F_\pi}(N^\dagger\sigma_k\tau^a N + N^{c\dagger}\sigma_k\tau^{aT}N^c)\nabla_k\pi^a$$
$$-\frac{1}{2}\pi^a(\partial^2 + m_\pi^2)\pi^a + \ldots,$$

N: nucleon
N^c: anti-nucleon
π: pion

Goal

- Low-energy approximation of QCD, expansion in Q/M_hi
  Q:(small momenta), M_hi ~ 1GeV

$$\mathcal{M} = \sum_n \left(\frac{Q}{M_{hi}}\right)^n \mathcal{F}_n\left(\frac{Q}{M_{lo}}\right)$$

Q: generic external momenta,

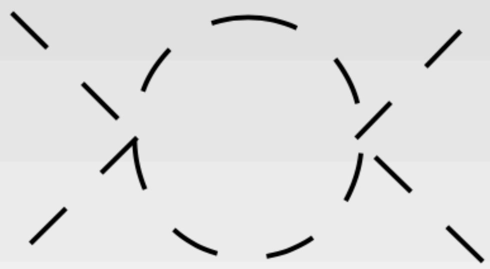
$M_{hi} = \Lambda_{SB}, m_\rho, \cdots \sim 1\mathrm{GeV}$

$M_{lo} = m_\pi, f_\pi \sim 100\mathrm{MeV}$

Systematic approximation
$\rightarrow$ able to estimate theoretical errors

Power of counting

Q: generic external momenta



+ ...

pion propagator ~ $\frac{1}{Q^2}$

pi-pi vertex~ $\frac{Q^2}{f_\pi^2}$

$$\int d^4 l \sim \frac{Q^4}{16\pi^2}$$

actual cal. $= \frac{Q^2}{f_\pi^2}\frac{\#Q^2}{16\pi^2 f_\pi^2}\ln\left(\frac{Q}{\mu}\right) + \frac{Q^4}{16\pi^2 f_\pi^4}\ln\left(\frac{\mu}{\Lambda}\right) + CQ^4$

dim. analysis

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

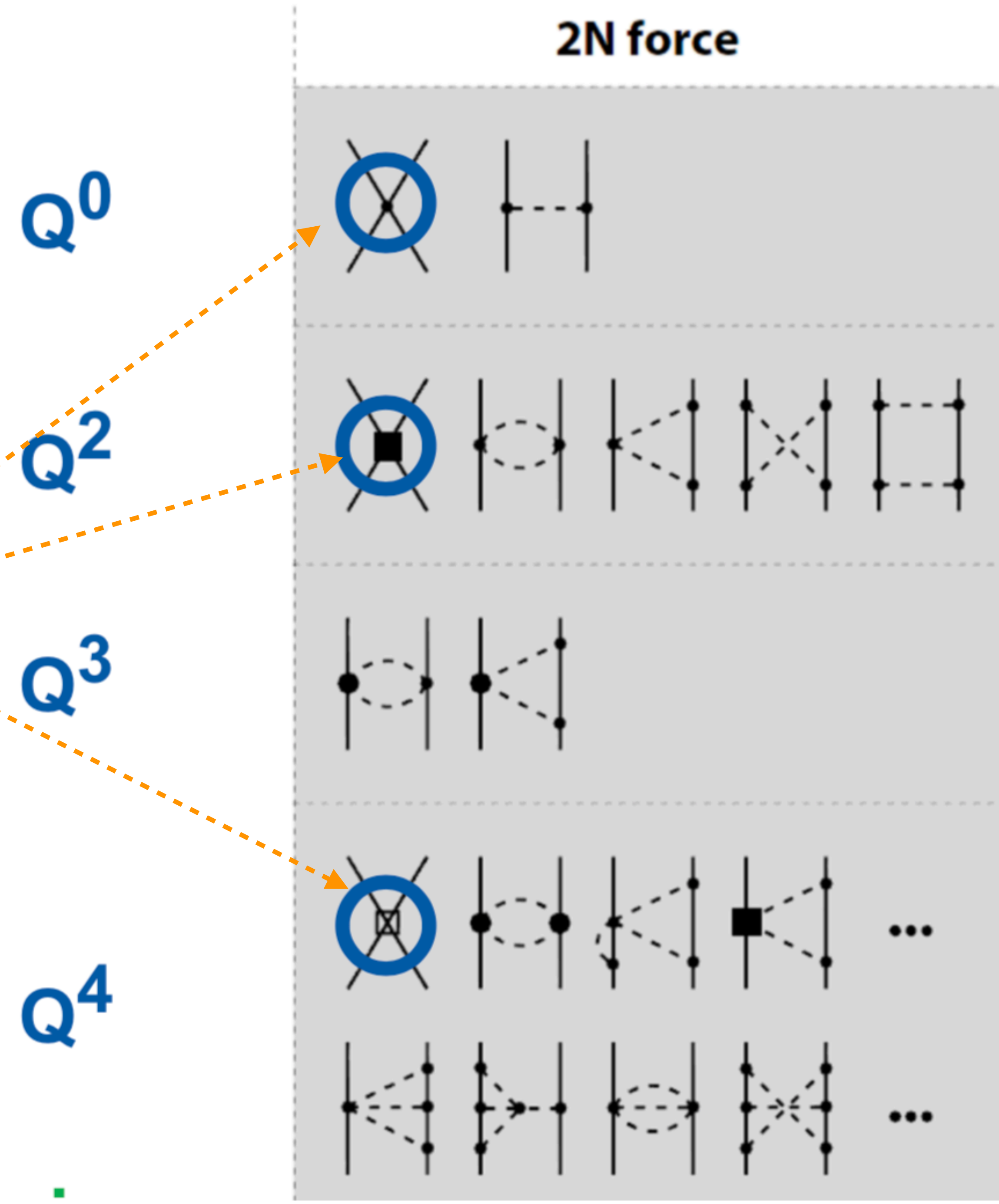
Dim. analysis captures long-range phys (non-analytic in Q) very well

Imposing naturalness → counterterms and logs contribute about the same

$$\frac{Q^2}{f_\pi^2}\frac{\#Q^2}{16\pi^2 f_\pi^2}\ln\left(\frac{Q}{\mu}\right) \simeq \frac{Q^4}{16\pi^2 f_\pi^4}\ln\left(\frac{\mu}{\Lambda}\right) + CQ^4 \qquad C \sim \frac{1}{f_\pi^2(4\pi f_\pi)^2}$$

How to count size of LECs?

24 contacts
in naive dim.
analysis up to Q^4



Renormalization group invariance

- In practice, UV cutoff Λ or ren. scale μ independence

$$C \to C(\Lambda) e^{-\frac{p'^2 + p^2}{\Lambda^2}}$$

- Start with a power counting by NDA

- If it provides enough short-range LECs to absorb UV div, then it is acceptable

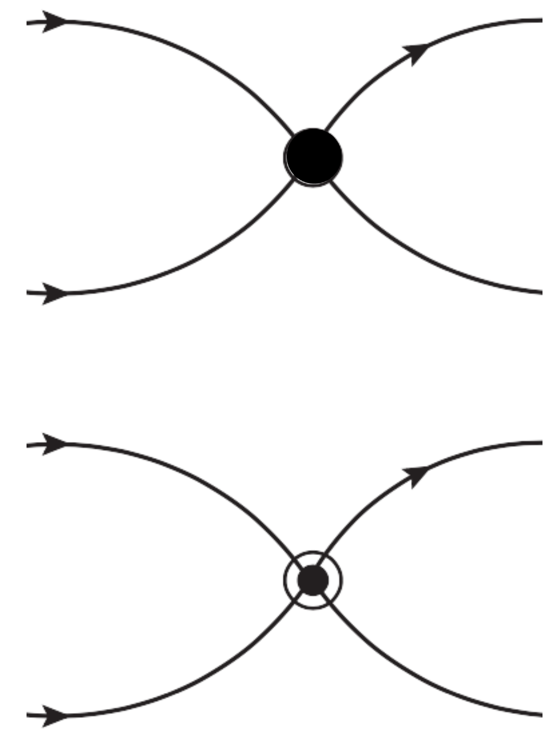
- Used to show three-body force is leading order in pionless EFT
(Bedaque, Hammer & van Kolck '99 & '00)

One more trick

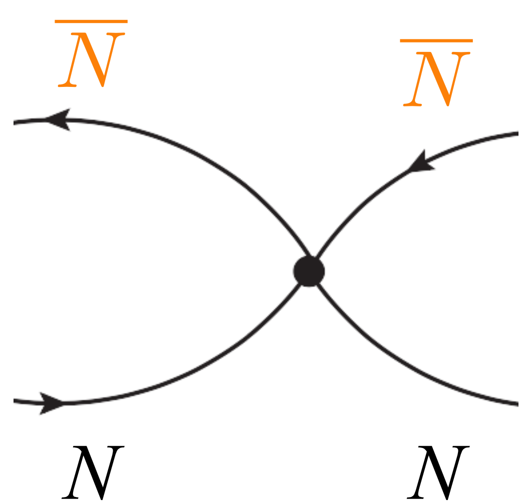
- NNbar annihilation releases 2GeV kinetic energy, way beyond chiral EFT break down scale
- To get around, calculate deuteron life time by imaginary part of deuteron self energy
- hard pions integrated out as intermediate states

More Lagrangian terms

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



NN contacts



NNbar contacts

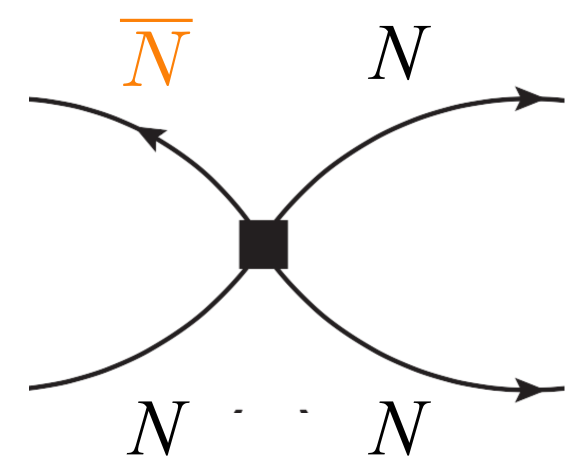
$|\Delta B| = 2$ terms

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

nnbar oscillation

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

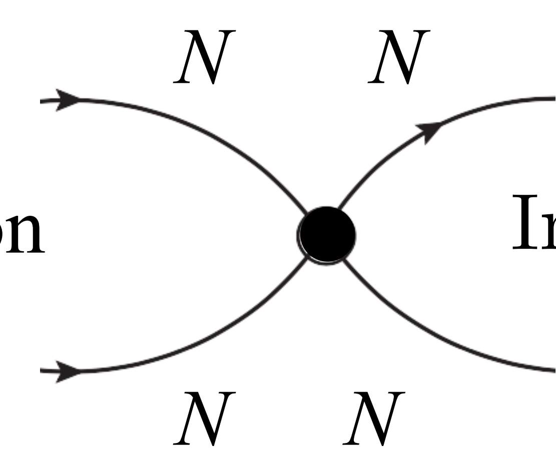
$$\tau_{n\bar{n}} = (\delta m)^{-1}[1 + \mathcal{O}(m_\pi^2/\Lambda_\chi^2)]$$



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

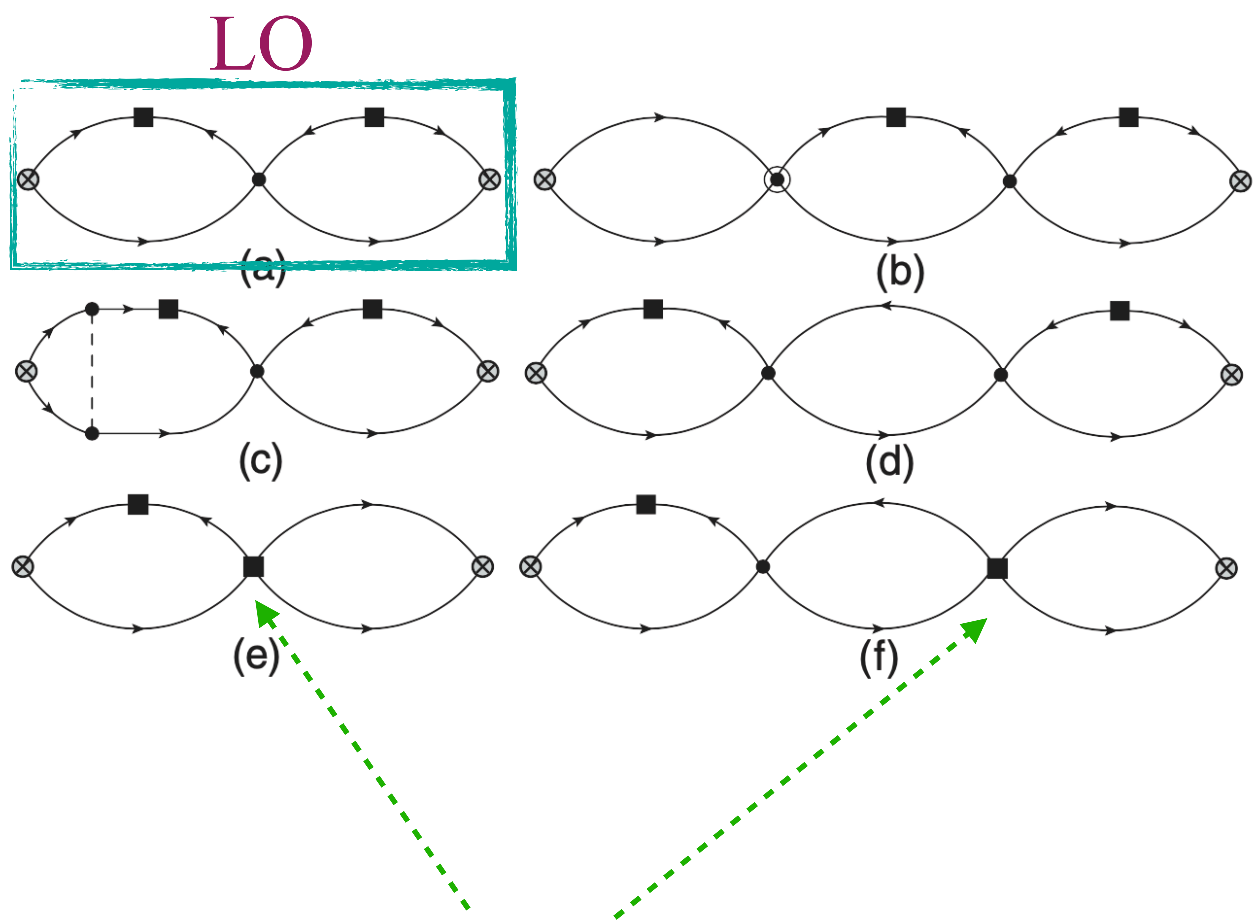
$$\mathcal{L}^{(4)}_{|\Delta B|=2} = i\tilde{B}_0[(N^T P_i N)^\dagger (N^{cT} \tau^2 Y_i^- N) - \text{H.c.}] + \ldots,$$

NN direct annihilation



$\mathrm{Im}C_0$

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)
- NNbar interaction parametrized by (anti-n p) scattering length $a_{\text{nbar-p}}$ = (0.44 - i 0.96) fm (Zhou & Timmermans '12 & '13)

Finally…

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

Re($a_{\text{nbar-p}}$)

NN range

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 (nuclei with neutron halo?)
- B_0 gives largest uncertainty
- W/ nonperturbative pion EFT, unknown LECs may have smaller impact