VIOLATION OF STANDARD MODEL SYMMETRIES IN NUCLEAR EFFECTIVE FIELD THEORY

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Supported by CNRS and US DOE

Outline

- The way of EFT
- Nuclear EFTs
- Three Symmetry Violations
- Conclusion

Work with

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Q

$M_{BSM} \sim ?$

unknown physics

$M_{EW} \sim v, m_Z, m_W$

~ 100 GeV

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

~ 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

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

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

$N^{\bar\nu}LO$

Q

M_{lo}

λ IR regulator

CONTROLLED UNCERTAINTY

renormalization-group invariance

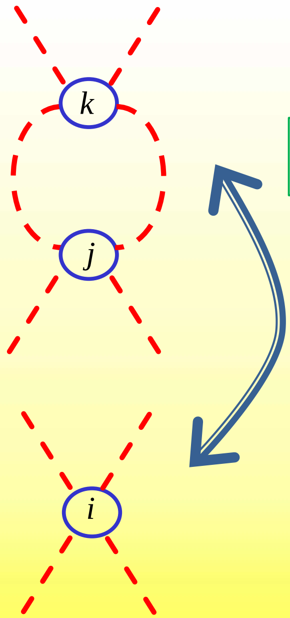
$$\begin{cases} \dfrac{\Lambda}{S^{(\bar{\nu})}} \dfrac{\partial S^{(\bar{\nu})}}{\partial \Lambda} = \mathcal{O}\left(\dfrac{Q^{\bar{\nu}+1}}{M_{hi}^{\bar{\nu}} \Lambda} \right) \\ \dfrac{\lambda}{S^{(\bar{\nu})}} \dfrac{\partial S^{(\bar{\nu})}}{\partial \lambda} = \mathcal{O}\left(\dfrac{Q^{\bar{\nu}}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

MODEL INDEPENDENCE (insensitivity to arbitrary regulators)

Want large "model space"

$\Lambda \gtrsim M_{hi}$

$\lambda \lesssim M_{lo}$



uncertainty principle

momenta $\gtrsim \Lambda$

= short-range physics

"naturalness"

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

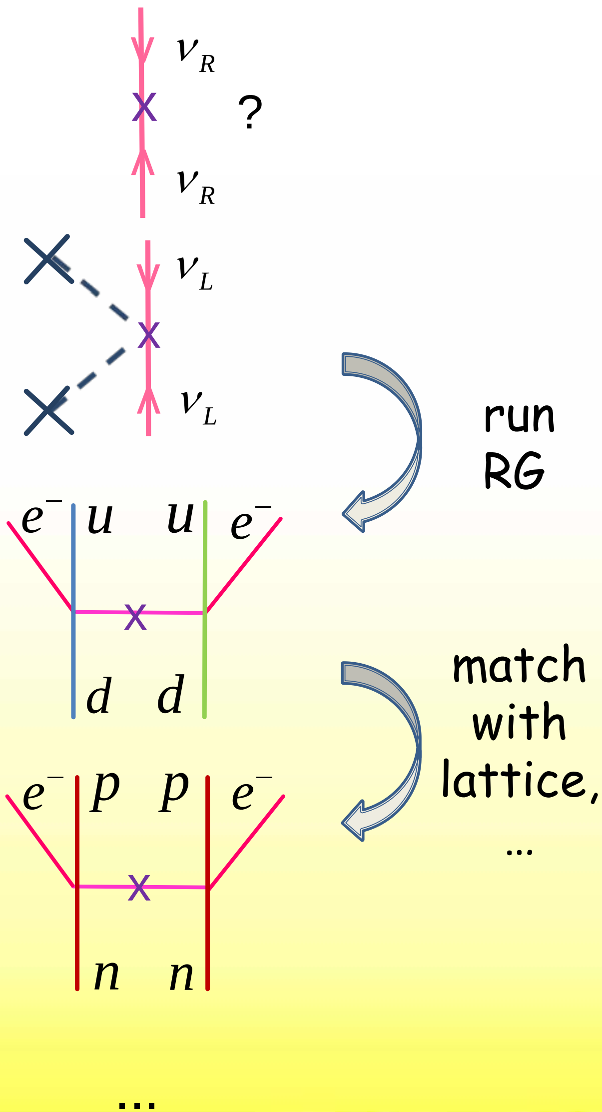
otherwise "fine tuning"

→ power counting

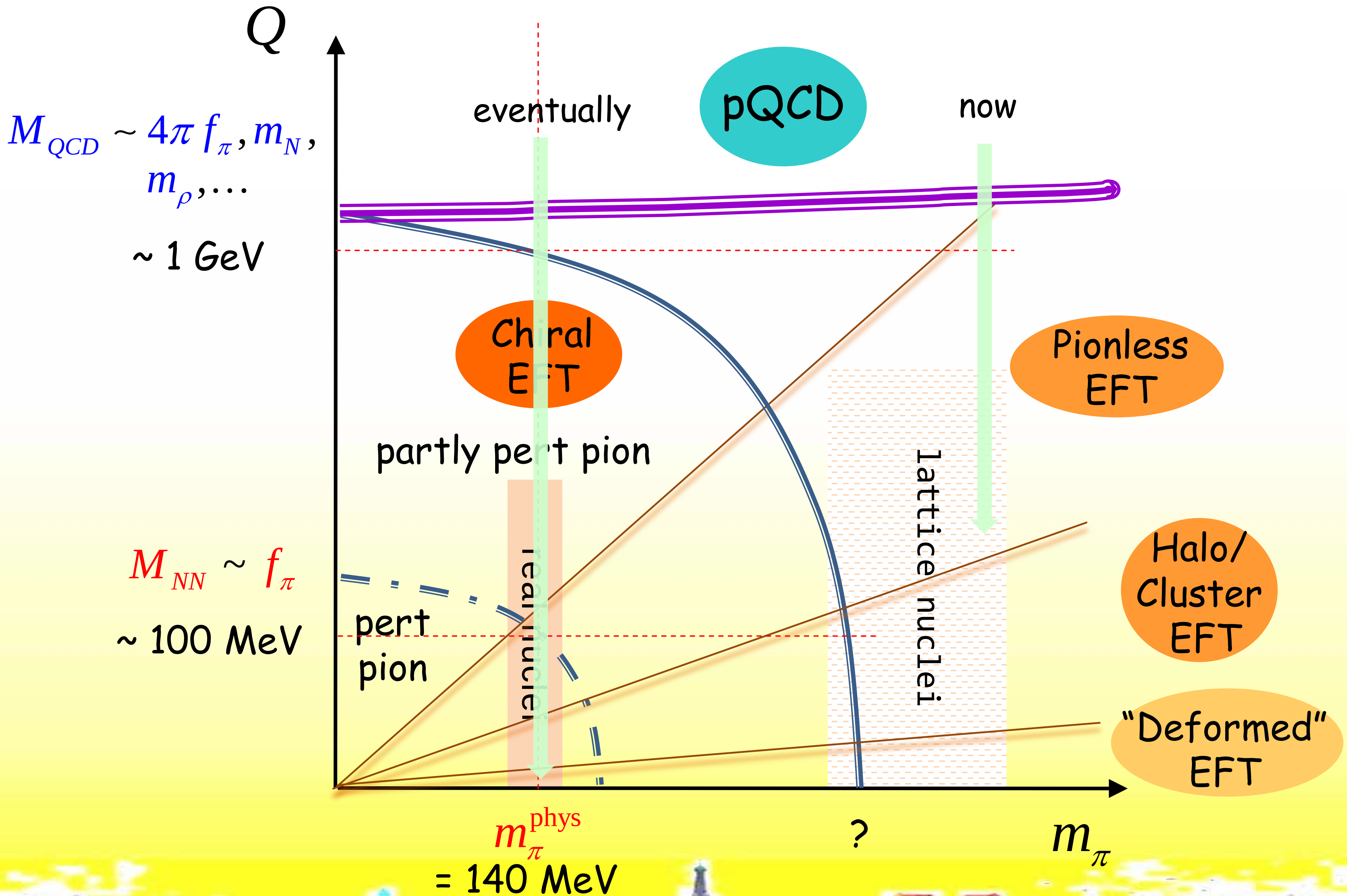
The Way of EFT

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, L, $SU(3)_c$, $U(1)_e$ (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

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

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

Pionful (or Chiral) EFT

$M_{lo} \sim m_\pi$

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

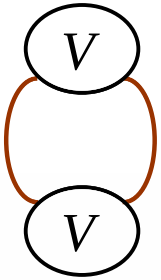
$$\mathcal{L}_\pi = \mathcal{L}_{\not\pi} + \frac{1}{2}\left[(\partial_\mu \boldsymbol{\pi})^2 - m_\pi^2 \boldsymbol{\pi}^2\right]\left(1+\mathcal{O}\left(\frac{\boldsymbol{\pi}^2}{f_\pi^2}\right)\right)$$

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

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

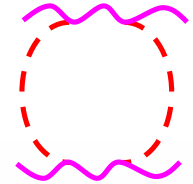
more derivatives,
more bodies,
isospin violation

Are nuclear amplitudes perturbative?



Weinberg's IR enhancement

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



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

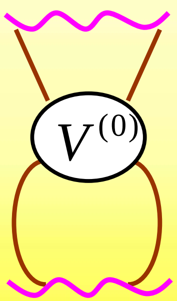
4π enhancement compared to NDA

Chiral Perturbation Theory

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

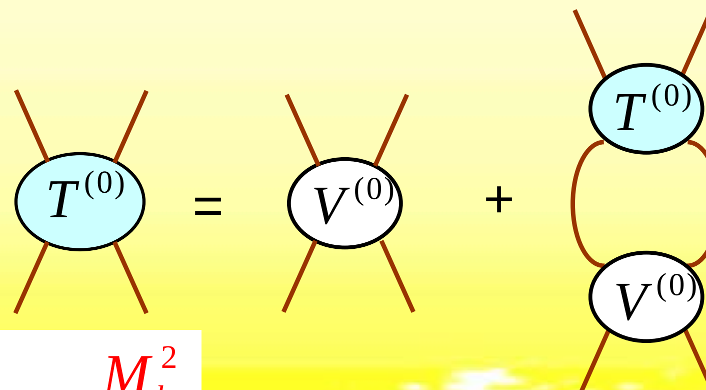
$$V^{(\mu)}(Q, M_{lo}, M_{hi}, \lambda, \Lambda)$$

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



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

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

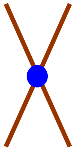
each order in potential must contain enough LECs

$\Rightarrow$ amplitude renormalization

↳ not trivial when resuming higher orders

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

Chiral EFT

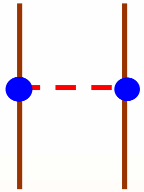


$$\sim \frac{4\pi}{m_N M_{lo}}$$ LO

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

- perturbative pions

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



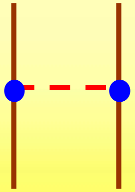
$$\sim \frac{1}{f_\pi^2} \equiv \frac{4\pi}{m_N M_{NN}} \sim \frac{4\pi}{m_N M_{hi}}$$ NLO

all pion exchanges perturbative;
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

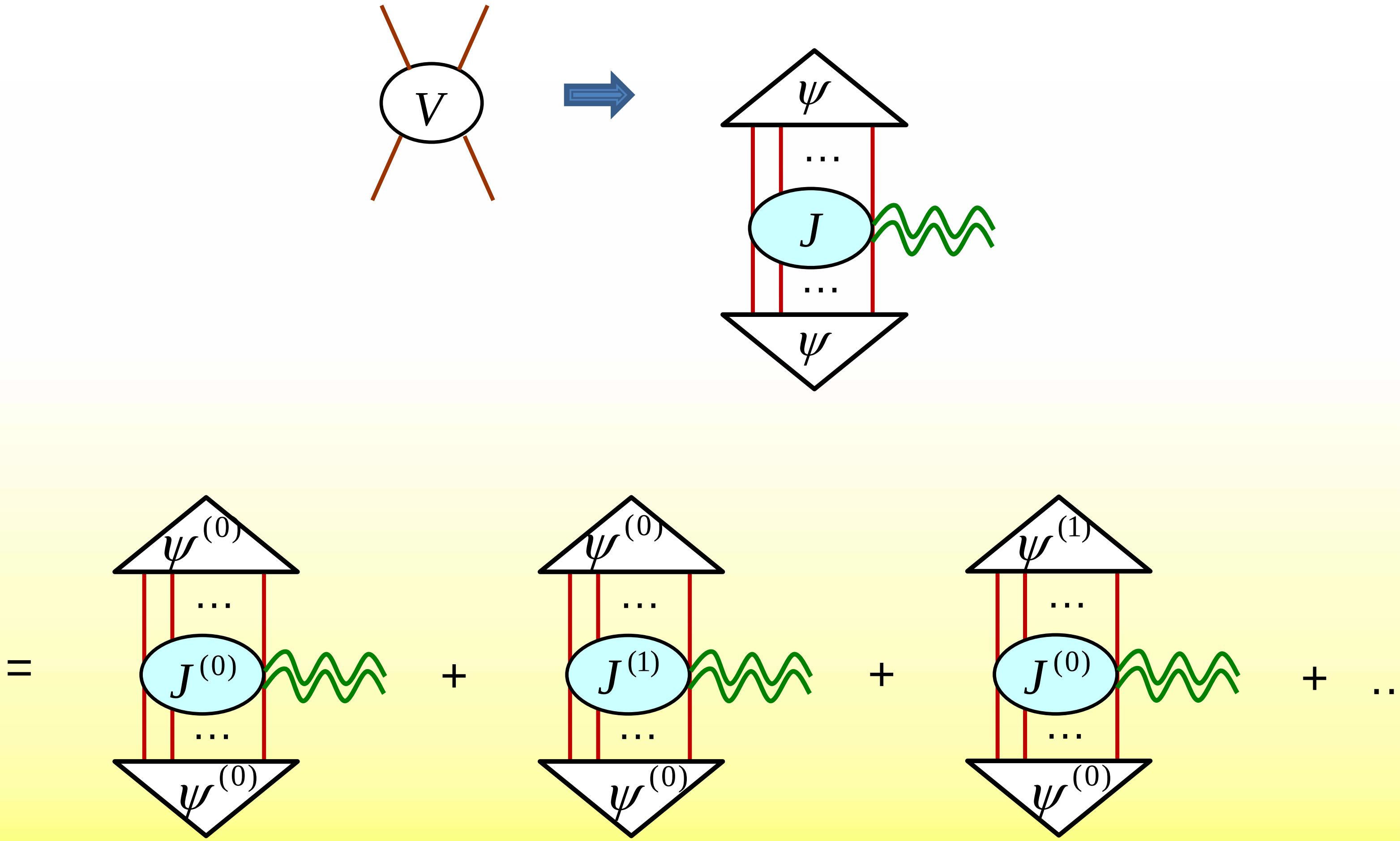
$$M_{lo} \sim M_{NN}, m_\pi$$
$$M_{hi} \sim M_{QCD} \equiv 4\pi f_\pi, m_N, \ldots$$



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

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

Processes with external probes



Point

Framework for nuclear physics exists where:

- ✓ SM symmetries are implemented properly
- ✓ Renormalized amplitudes can be calculated systematically
- ✓ Observables are model independent and can be matched to lattice QCD calculations
- ✓ Information from hadronic physics is included consistently
- ✓ Basic ingredients (potential, currents) can be used as input to nuclear "ab initio" methods *

Now: on to SM symmetry VIOLATION

* but beware that most applications use a "chiral potential" that does not yield renormalized amplitudes

Beyond the SM

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\text{dim}=5} + \mathcal{L}_{\text{dim}=6} + \ldots + \mathcal{L}_{\text{dim}=9} + \ldots$$

Weinberg '79

Rao + Shrock '82
...
Buchoff + Wagman '16

Buchmüller + Wyler '86
Weinberg '89
de Rújula *et al.* '91
...
Ng + Tulin '11

$\Delta L = 2$	T violation	$\Delta B = 2$
neutrinoless double-beta decay	nuclear electric dipole moments	nuclear decay into mesons

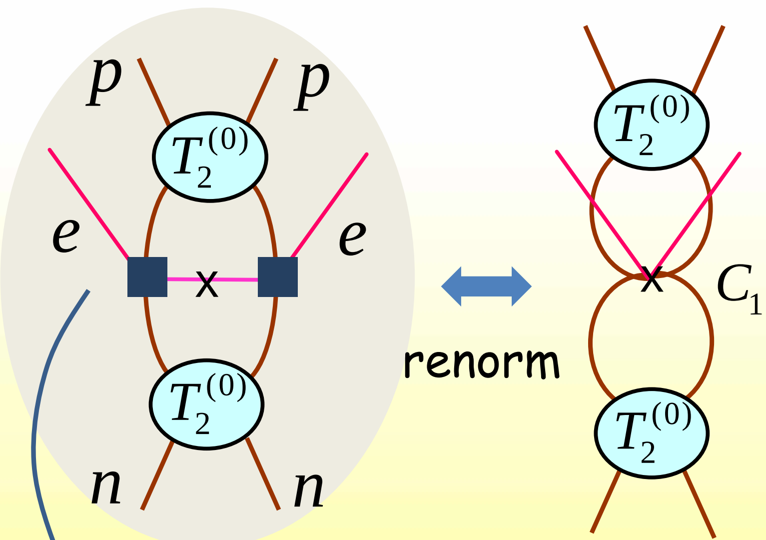
Three examples

Cirigliano, Dekens, De Vries, Graesser, Mereghetti, Pastore + vK, '18
Cirigliano, Dekens, De Vries, Graesser, Mereghetti, Pastore, Piarulli, vK + Wiringa '19

0ν2β decay & renormalization

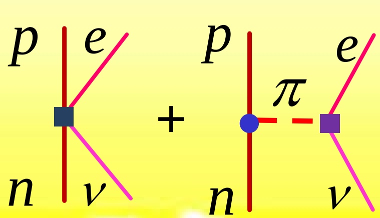
$Q \ll m_{W,Z}$

$$\mathcal{L}^{(\Delta L=2)}_{\text{dim}=5} = -\frac{m_{\beta\beta}}{2} \nu^T_{eL} C \nu_{eL} + \dots \qquad m_{\beta\beta} \equiv \sum_{i=1}^{3} U^2_{ei} m_{\nu i}$$



calculable on the lattice,
but it will take some time…

no new LEC at NLO

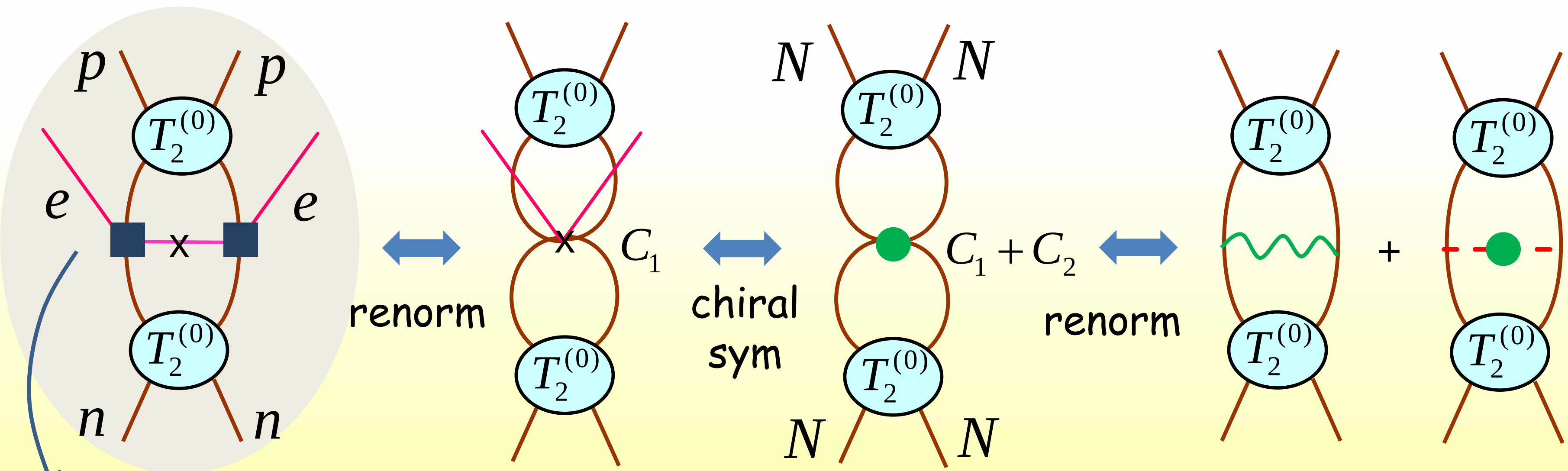


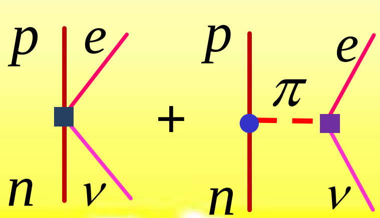
$$\propto \int d^3 l_1 \int d^3 l_2 \, \frac{m_N}{l_1^2} \frac{m_N}{l_2^2} \frac{1}{(l_1 - l_2)^2} \propto m_N^2 \ln \Lambda$$

0ν2ß decay & renormalization

$Q \ll M_{W,Z}$

$$\mathcal{L}_{\text{dim}=5} = -\frac{m_{\beta\beta}}{2} \nu_{eL}^T C \nu_{eL} + \ldots \qquad m_{\beta\beta} \equiv \sum_{i=1}^{3} U_{ei}^2 m_{\nu i}$$





$$\propto \int d^3 l_1 \int d^3 l_2 \, \frac{m_N}{l_1^2} \frac{m_N}{l_2^2} \frac{1}{(l_1 - l_2)^2} \propto m_N^2 \ln \Lambda$$

$$C_1 \propto \langle pp | \frac{1}{\vec{q}^{\,2}} | nn \rangle$$ same as electromagnetism for $I = 2$

$$\begin{cases} O_1 = N^\dagger u^\dagger Q_L u N \; N^\dagger u^\dagger Q_L u N - \frac{1}{6}\mathrm{Tr}\left(u^{\dagger 2} Q_L u^2 Q_L\right) N^\dagger \boldsymbol{\tau} N \bullet N^\dagger \boldsymbol{\tau} N + (L \leftrightarrow R) \\ O_2 = 2\left[N^\dagger u^\dagger Q_L u N \; N^\dagger u Q_R u^\dagger N - \frac{1}{6}\mathrm{Tr}\left(u^{\dagger 2} Q_L u^2 Q_R\right) N^\dagger \boldsymbol{\tau} N \bullet N^\dagger \boldsymbol{\tau} N \right] \end{cases}$$

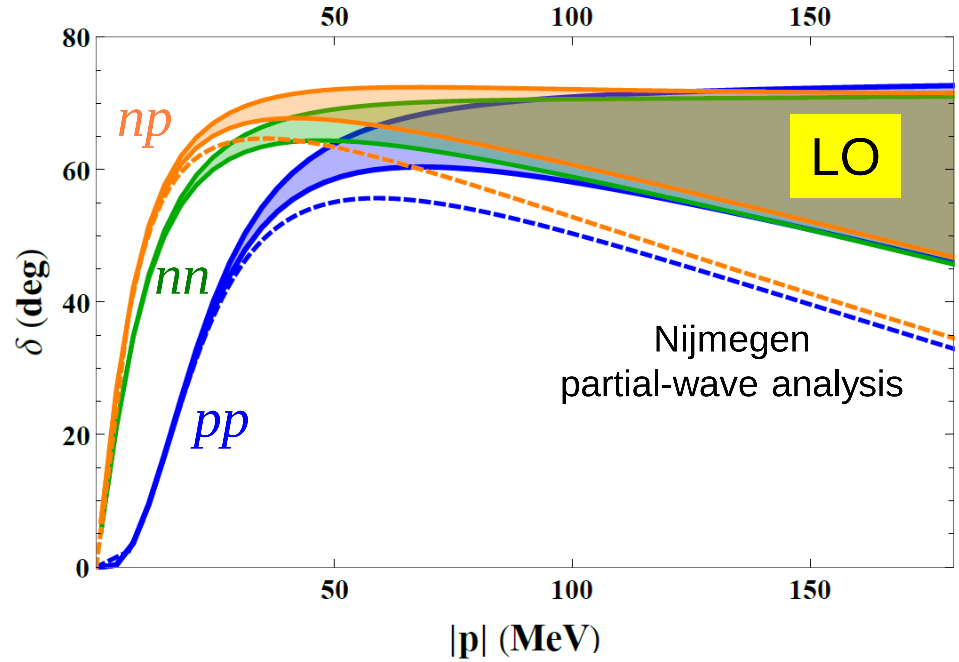
$$u = \exp\left(i \boldsymbol{\tau} \bullet \boldsymbol{\pi} / 2 f_\pi\right)$$

- E&M: $Q_L = Q_R = \frac{\tau_3}{2}$
- L violation: $Q_L = \tau^+ \quad Q_R = 0$

$$\Rightarrow \quad \mathcal{L}_{\chi EFT} = \ldots + \frac{\pi}{4}\alpha\left(C_1 + C_2\right)\left[N^\dagger \tau_3 N \; N^\dagger \tau_3 N - \frac{1}{3} N^\dagger \boldsymbol{\tau} N \bullet N^\dagger \boldsymbol{\tau} N \right]$$

$$+ G_F^2 V_{ud}^2 \, m_{\beta\beta} \, C_1 \; \bar{e}_L C \bar{e}_L^T N^\dagger \tau^+ N \; N^\dagger \tau^+ N + \ldots$$

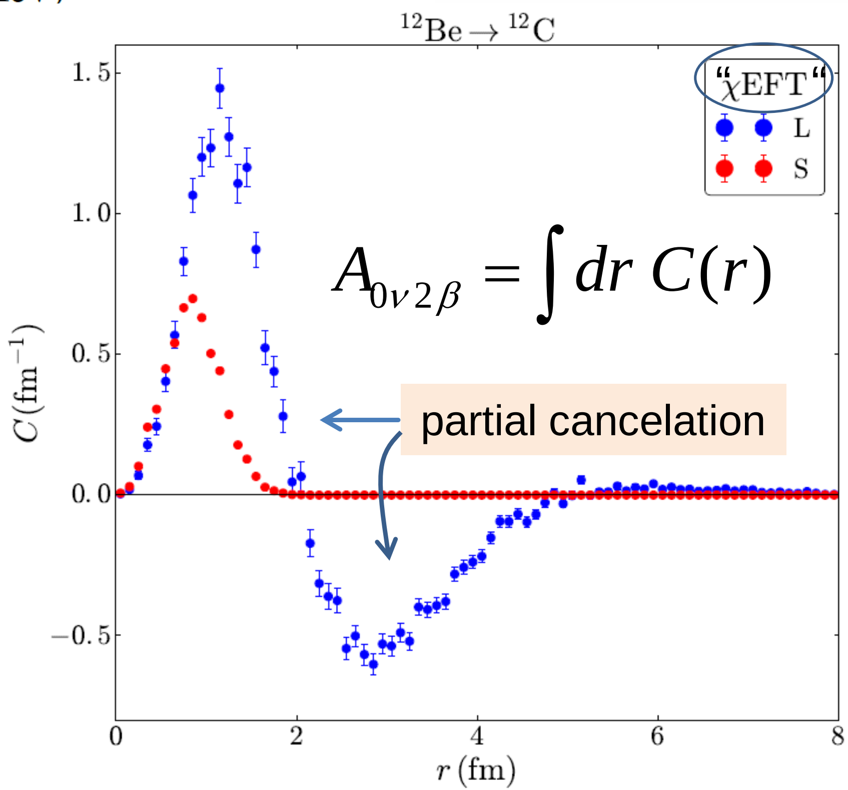
multi-pion E&M interactions can separate C_1 and C_2



$\Rightarrow$ $C_1 + C_2$

other charge-independence data needed to disentangle C_1 and C_2

assuming $C_1 \sim C_2$ $\Rightarrow$



unrenormalized chiral potential

Šimkovic *et al.* '08
Menéndez *et al.* '09

robust feature in heavier nuclei

$$\frac{A_S}{A_L} \simeq 0.75 \Leftarrow$$

but calculation of A_S needed!

Hockings + vK '05
De Vries, Timmermans, Mereghetti + vK '10
Maekawa, Mereghetti, De Vries + vK '11
De Vries, Mereghetti, Timmermans + vK '11 '12
De Vries, Higa, Liu, Mereghetti, Stetcu, Timmermans + vK '13
...

Nuclear EDMs & the "chiral filter"

$Q \ll m_{W,Z}$

θ term — qEDM — qCEDM

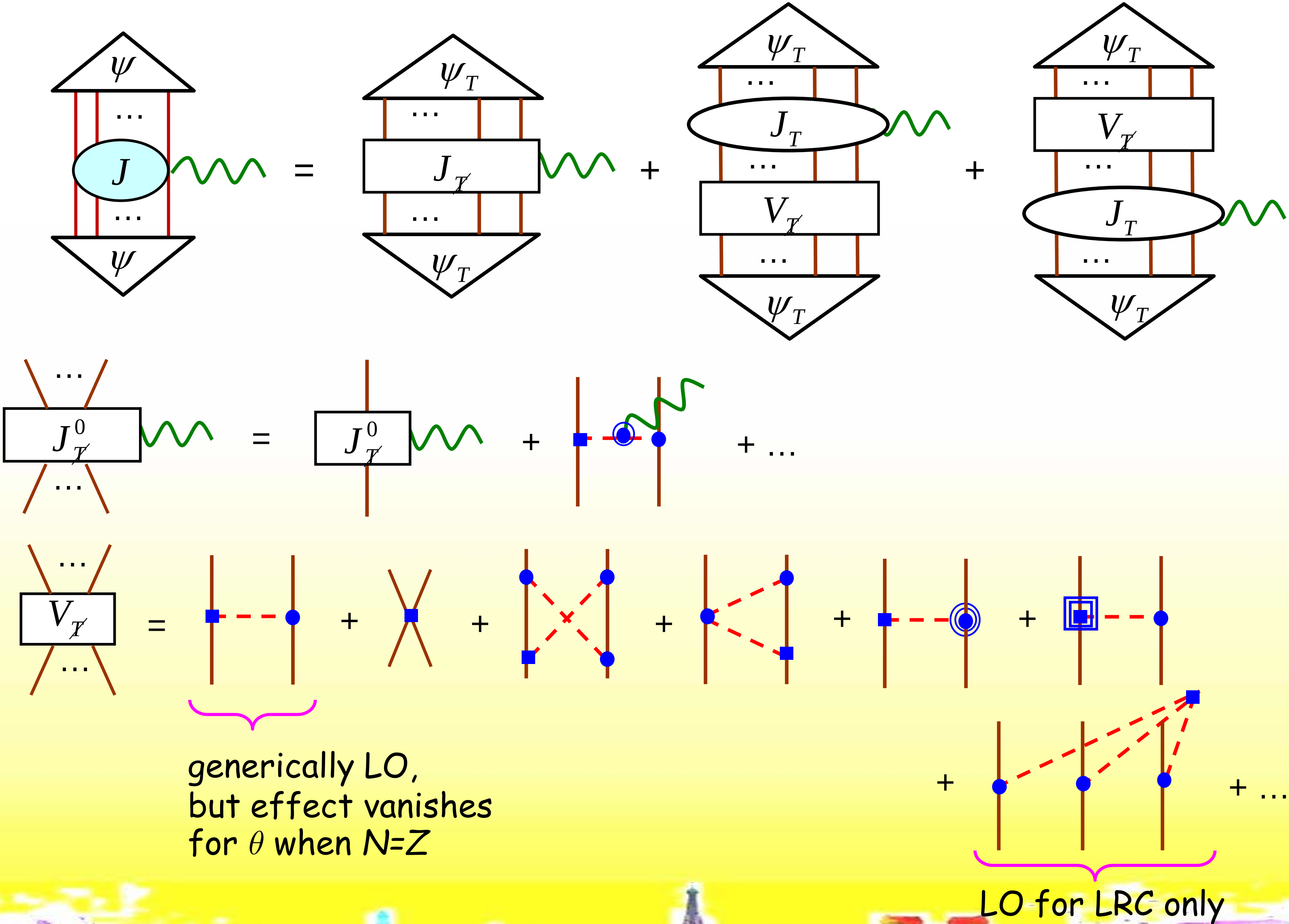
$$\mathcal{L}^{(\not T)}_{\text{dim}=4,6} = \ldots + \frac{\bar m}{2}\left(1-\varepsilon^2\right)\bar\theta\;\bar q i\gamma_5 q - \frac{1}{2}\bar q\left(d_q^{(0)}+d_q^{(1)}\tau_3\right)\sigma_{\mu\nu} q\,\tilde F^{\mu\nu} - \frac{1}{2}\bar q\left(c_q^{(0)}+c_q^{(1)}\tau_3\right)\sigma_{\mu\nu}\tilde G^{\mu\nu} q$$

$$+\frac{c_G}{6} f^{abc} G^a_{\mu\nu}\tilde G^{b\nu\rho} G^{c\,\mu}_{\rho} + \frac{C_1}{4}\left(\bar q q\;\bar q i\gamma_5 q - \bar q \boldsymbol{\tau} q\cdot \bar q i\gamma_5\boldsymbol{\tau} q\right) + \frac{C_8}{4}\left(\bar q\lambda^a q\;\bar q i\gamma_5\lambda^a q - \bar q\boldsymbol{\tau}\lambda^a q\cdot\bar q i\gamma_5\boldsymbol{\tau}\lambda^a q\right)$$

$$+\frac{D_1}{4}\varepsilon_{3ij}\;\bar q\tau_i\gamma^\mu q\;\bar q\tau_j\gamma_\mu\gamma_5 q + \frac{D_8}{4}\varepsilon_{3ij}\;\bar q\tau_i\gamma^\mu\lambda^a q\;\bar q\tau_j\gamma_\mu\gamma_5\lambda^a q + \ldots$$

gCEDM — PSC — LRC

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


generically LO,
but effect vanishes
for θ when N=Z
LO for LRC only

$Q \sim M_{NN}, m_\pi$		θ term	qEDM	qCEDM	gCEDM, PSC	LRC
^{1}H	d_p/d_n	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
^{2}H	d_d/d_n	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{Q^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{Q^2}\right)$
^{3}He	d_h/d_n	$\mathcal{O}\left(\frac{M_{QCD}^2}{Q^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{Q^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{Q^2}\right)$
^{3}H	d_t/d_h	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

+ specific relations

e.g.

$$d_h + d_t \simeq 0.84\left(d_n + d_p\right)$$ qEDM and θ term

$$d_h - d_t \simeq 0.94\left(d_n - d_p\right)$$ qEDM

$$d_h + d_t \simeq 3d_d$$ qCEDM and LRC

storage-ring measurements (COSY? CERN?) could teach us about sources!

Farley *et al.* '04

…

Deuteron decay & systematic expansion

$Q \ll m_{W,Z}$

$$\mathcal{L}^{(\Delta B=2)}_{\text{dim}=9} = \sum_{i=1}^{4} \mathcal{C}_i \, \mathcal{Q}_i$$

Buchoff + Wagman '16

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

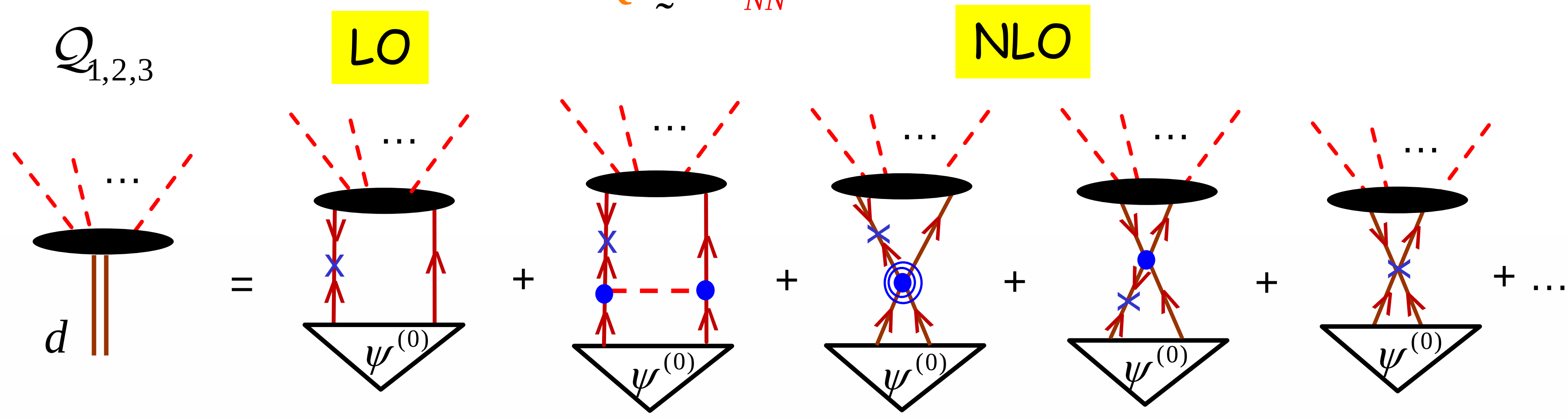
$$\mathcal{D}_{L,R} \equiv q^{iT} C P_{L,R} \, i\tau^2 q^j \, , \quad \mathcal{D}^a_{L,R} \equiv q^{iT} C P_{L,R} \, i\tau^2 \tau^a q^j \, ,$$

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

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

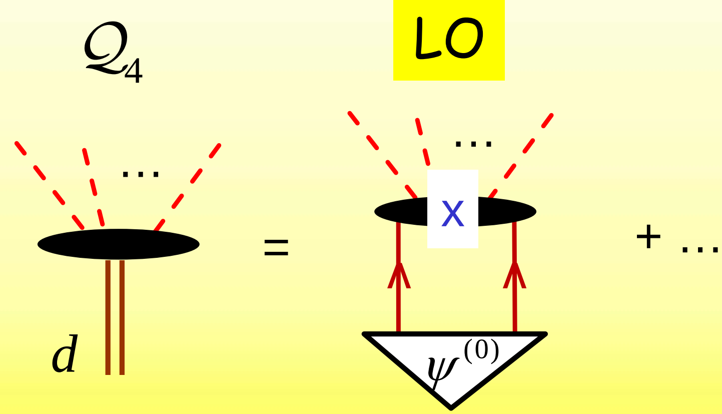
$$T^{AAS} \equiv \varepsilon_{ikm}\varepsilon_{jln} + \varepsilon_{ikn}\varepsilon_{jlm} \, .$$

$$Q \lesssim M_{NN}$$



$$R_d \equiv \left(\Gamma_d\, \tau_{n\bar{n}}^2\right)^{-1} = -\left[\sqrt{\frac{m_N}{B_2}}\,\mathrm{Im}\, a_{\bar{n}p}\,(1+0.40+0.20-0.13\pm 0.4)\right]^{-1} = (1.1\pm 0.3)\cdot 10^{22}\ \mathrm{s}^{-1}$$

≈ 2.5 smaller than pot models



can be separated

$$\Gamma_d = -4\sqrt{m_N B_d^3}\,\mathrm{Im}\, a_{np} + \ldots$$

Conclusion

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

Renormalization requires
short-range physics missed by nuclear models

Chiral symmetry allows
partial separation of symmetry-violating sources

Power counting leads to
organization of interactions in nuclear environment