Strong Interactions and "Fundamental" Symmetries

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Outline

- Symmetries
- Effective field theory
- Lepton number
- Time reversal
- Baryon number
- Conclusion

in collaboration with

V. Cirigliano (Los Alamos) – L
W. Dekens (INT) – L
M. Graesser (Los Alamos) – L
W. Hockins (Blue Mountain) – T
R. Higa (USP) – T
C.-P. Liu (Dong Hua) – T
C. Maekawa (FURGS) – T
E. Mereghetti (Los Alamos) – T, L
F. Oosterhof (Groningen) – B
S. Pastore (Wash U) – L
M. Piarulli (Wash U) – L
I. Stetcu (Los Alamos) – T
J. de Vries (Amsterdam) – T, L, B
R. Timmermans (Groningen) – T, B
R. Wiringa (Argonne) – L

Symmetries

Standard Model (SM) "explains" everything, except:

- neutrino masses
  - sterile neutrinos
  - Majorana neutrinos → <u>lepton-number (L) violation</u>
- galaxy rotations, lensing
  - dark matter
  - modification of gravity
- matter-antimatter imbalance
  - <u>baryon-number (B) violation</u>
  - <u>time-reversal (T) violation</u>

neutrinoless double-beta decay: $nn \rightarrow ppee$ in nucleus

nucleon decay and neutron-antineutron oscillation: $N \rightarrow l\,X,\ n \leftrightarrow \bar{n}$ free and in nucleus

nucleon and nuclear electric dipole moments

⇒ Physics beyond the SM (BSM)

3

Q

unknown physics

$M_{\mathrm{BSM}} \sim ?$

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

~ 100 GeV

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

~ 100 MeV

...

relevant for
precision experiments
with hadrons and nuclei

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

Effective Field Theory

aka Modern S-Matrix Theory

Q

$M_{\rm hi}$ — Λ UV regulator

$M_{\rm lo}$

most general Lagrangian

$$\mathcal{L}_{\rm EFT} = \mathcal{L}^{(0)} + \frac{M_{\rm lo}}{M_{\rm hi}}\mathcal{L}^{(1)} + \frac{M_{\rm lo}^2}{M_{\rm hi}^2}\mathcal{L}^{(2)} + \ldots$$

"power counting"

most general S matrix

$$S(Q \sim M_{\rm lo} \ll M_{\rm hi}) - 1 \propto \frac{M_{\rm lo}}{M_{\rm hi}} s^{(0)}\left(\frac{Q}{M_{\rm lo}}\right) + \frac{M_{\rm lo}^2}{M_{\rm hi}^2} s^{(1)}\left(\frac{Q}{M_{\rm lo}}\right) + \ldots$$

renormalization-group invariance

$$\frac{dS(Q \sim M_{\rm lo} \ll M_{\rm hi})}{d\Lambda} = 0$$

MODEL INDEPENDENCE

CONTROLLED UNCERTAINTY

The Way of EFT

Q

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

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

~ 100 GeV

$M_{\mathrm{QCD}} \sim m_N, m_\rho, 4\pi f_\pi, \ldots$

~ 1 GeV

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

~ 100 MeV

...

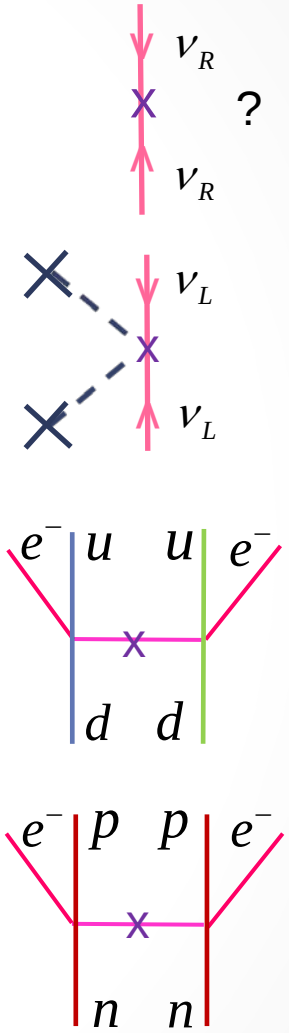
unknown physics

Standard Model
+ higher-dim
"SMEFT"

QCD + QED
+ higher-dim
"WEFT"

Chiral EFT
(χPT)

...



run
RG

match
with
lattice,
...

...

SMEFT

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

Weinberg '67
Salam '68
…

Weinberg '79

Rao + Shrock '82
…
Buchoff + Wagman '16

Weinberg '79'89
Wilczek + Zee '79
Abbott + Wise '80
Claudson, Wise + Hall '82
…
Buchmüller + Wyler '86
de Rújula *et al.* '91
…
Ng + Tulin '11

	$\Delta L = 2$	T violation	$\Delta B = 1$	$\Delta B = 2$
Examples:	neutrinoless double-beta decay	nuclear electric dipole moments	nuclear decay into mesons (+ lepton)	
illustrating	proper renormalization	chiral symmetry as a filter	systematic expansion	

Nuclei

$Q \ll m_{W,Z}$ $\qquad \mathcal{L}_{\rm SM} = \mathcal{L}_{\rm QCD} + \ldots$

Weinberg '90'91'92
Rho '91
Ordóñez + vK '92
vK '94
Ordóñez, Ray + vK '94,'96
…

$Q \sim m_\pi \ll M_{\rm QCD}$

<u>Chiral EFT:</u> nucleons and *pions (and Deltas, Ropers?)* + SM symmetries
-- including approximate chiral symmetry

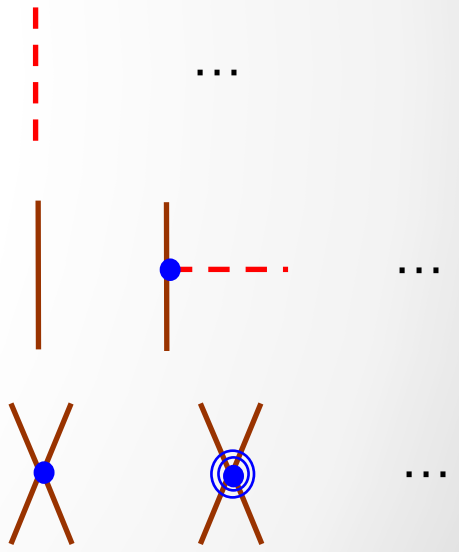
$$\mathcal{L}_{\pi\rm EFT} = \frac{1}{2}\left[(\partial_\mu \boldsymbol{\pi})^2 - m_\pi^2 \boldsymbol{\pi}^2\right] + \ldots$$

$$+ N^+\left(i\partial_0 + \frac{\nabla^2}{2m_N} + \frac{g_A}{2f_\pi}\boldsymbol{\tau}\vec{\sigma}\cdot\vec{\nabla}\boldsymbol{\pi} + \ldots\right)N$$

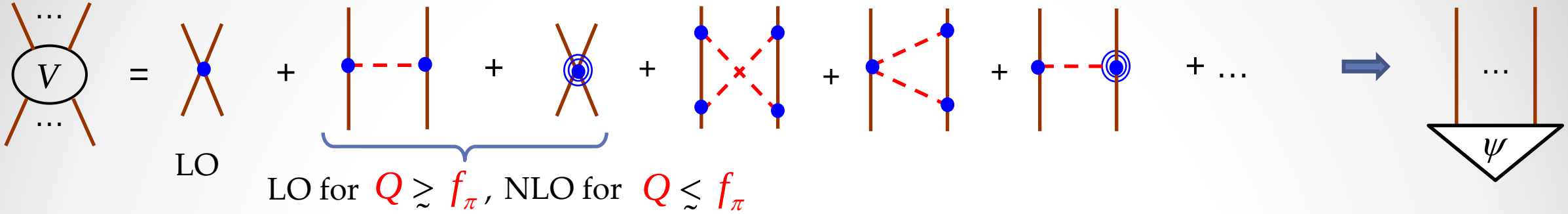
$$-\frac{1}{2}\sum_{I=0,1} N^+N^+P_2^{(I)}\left(C_{0I} + C_{2I}\nabla^2 + m_\pi^2\gamma_{0I} + \ldots\right)NN$$

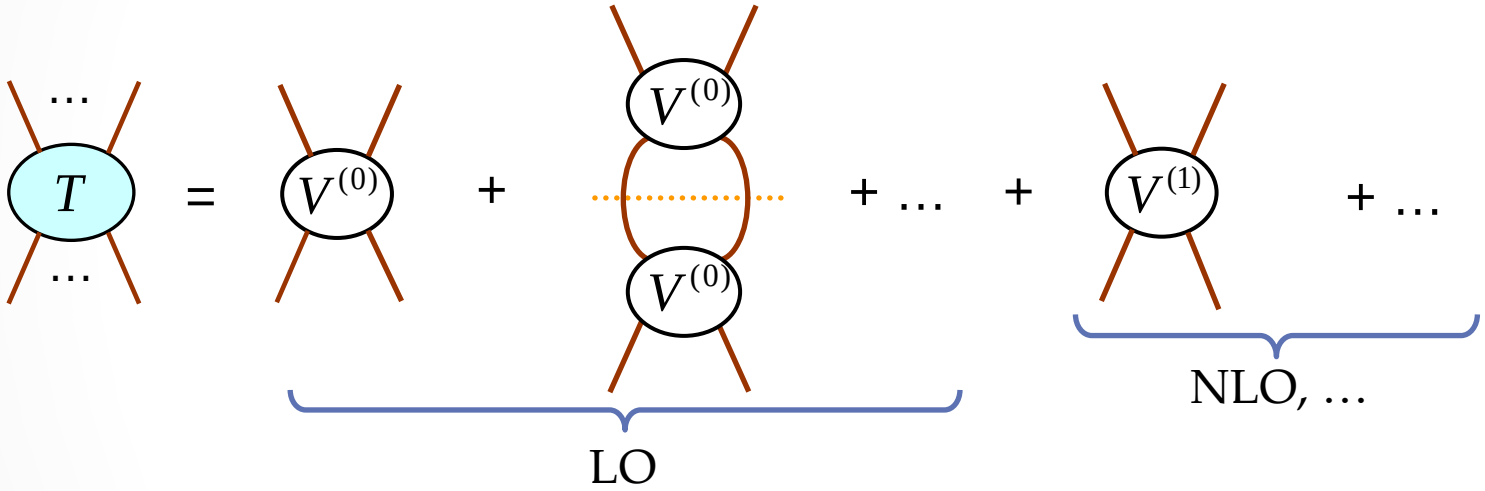
$$+\ldots$$

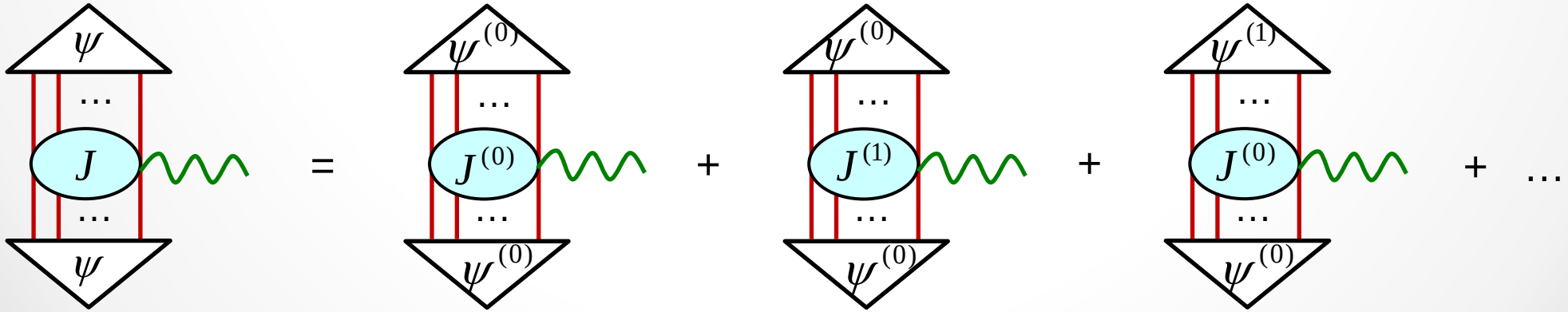
projector on isospin *I*



more derivatives,
more fields,
isospin violation


V
LO
LO for $Q \gtrsim f_\pi$, NLO for $Q \lesssim f_\pi$
ψ


T
$V^{(0)}$
$V^{(1)}$
LO
NLO, …


ψ
J
$\psi^{(0)}$
$J^{(0)}$
$J^{(1)}$
$\psi^{(1)}$

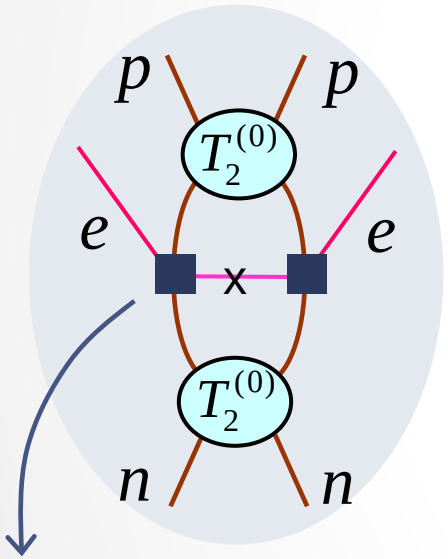
0ν2ß decay & renormalization

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

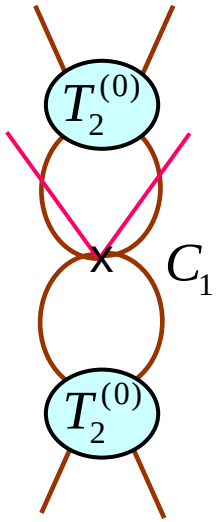
$Q \ll m_{W,Z}$

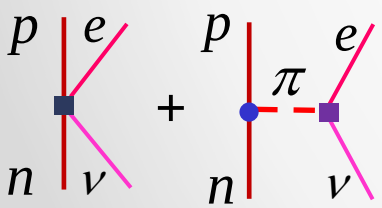
$$\mathcal{L}_{\text{dim=5}} = -\frac{m_{\beta\beta}}{2} \nu_{eL}^T C \nu_{eL} + \ldots$$

$$m_{\beta\beta} \equiv \sum_{i=1}^{3} U_{ei}^2 m_{\nu i} \propto \frac{v^2}{M_{\not L}}$$



renorm





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

bad news: unknown

calculable with lattice QCD

Davoudi + Kadan '21

good news: no new unknown parameter at NLO

0ν2ß decay & renormalization

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

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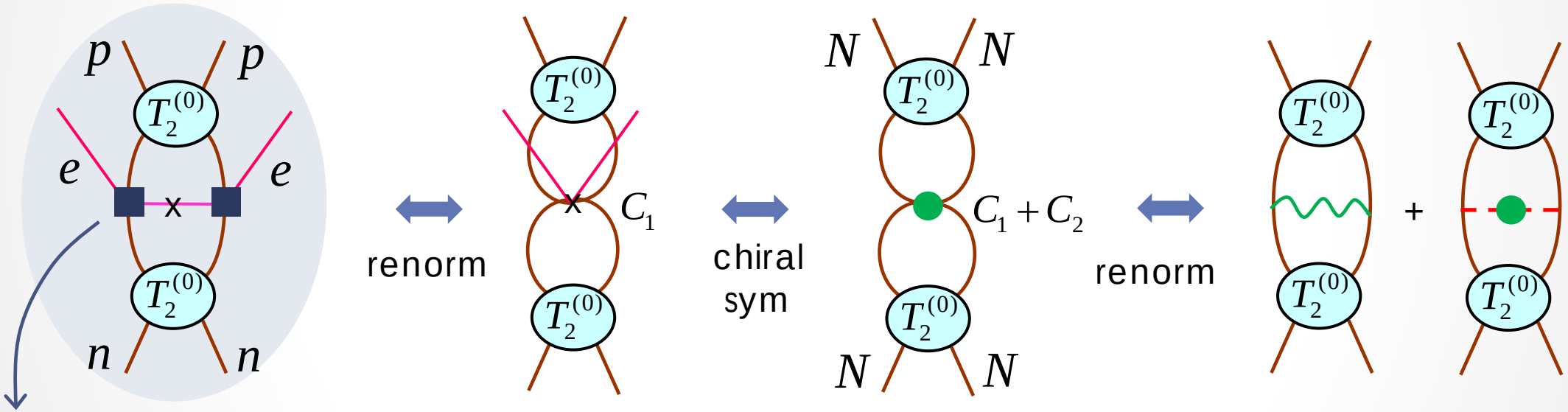
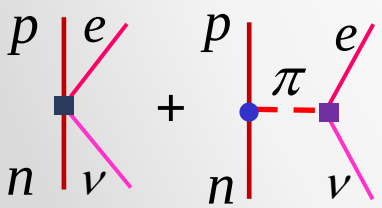
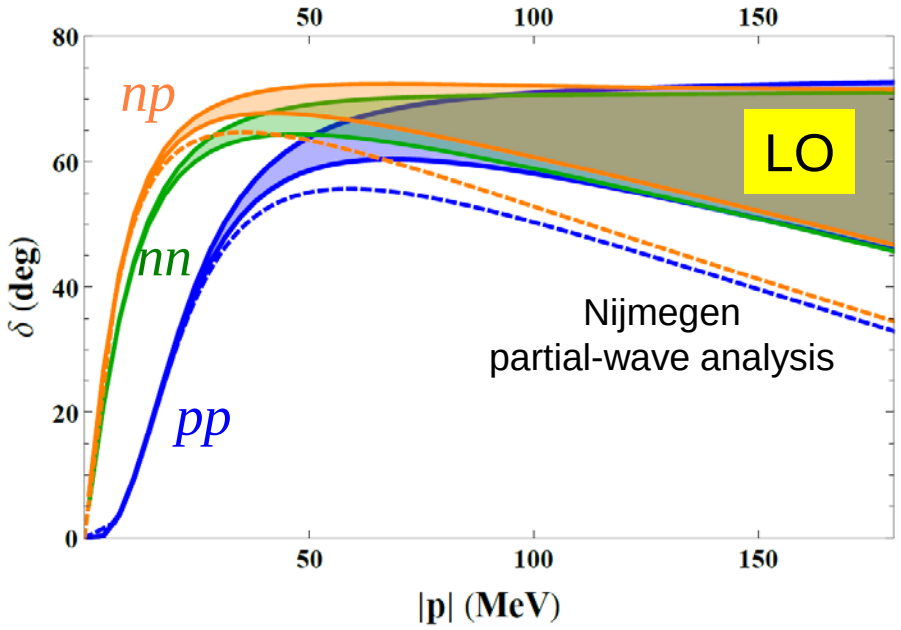




$$\propto \int d^3 l_1 \int d^3 l_2 \frac{m_N}{l_1^2} \frac{m_N}{l_2^2} \frac{1}{(l_1 - l_2)^2} \propto m_N^2 \ln \Lambda$$

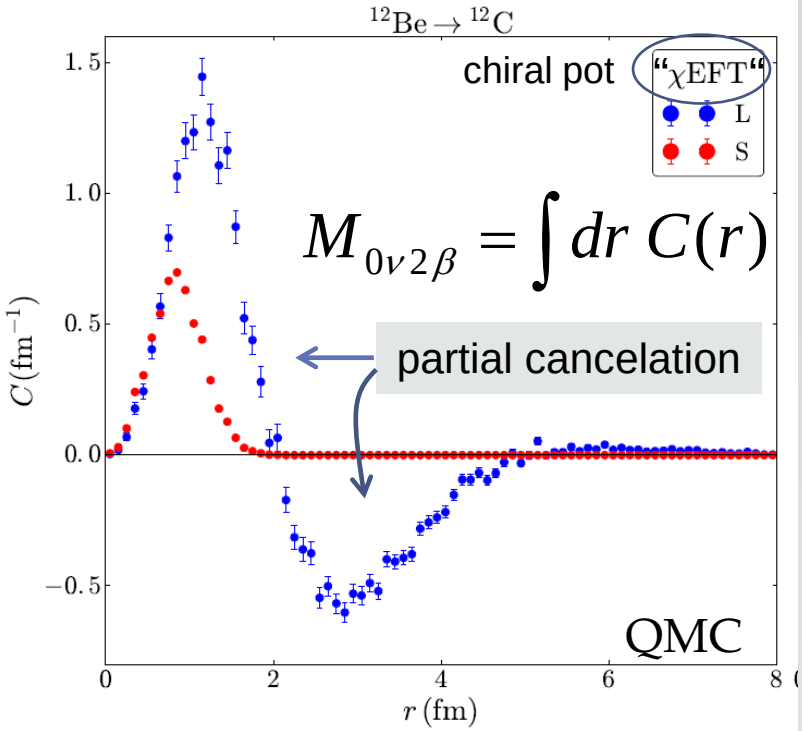


Jokiniemi, Soriano + Menéndez '21

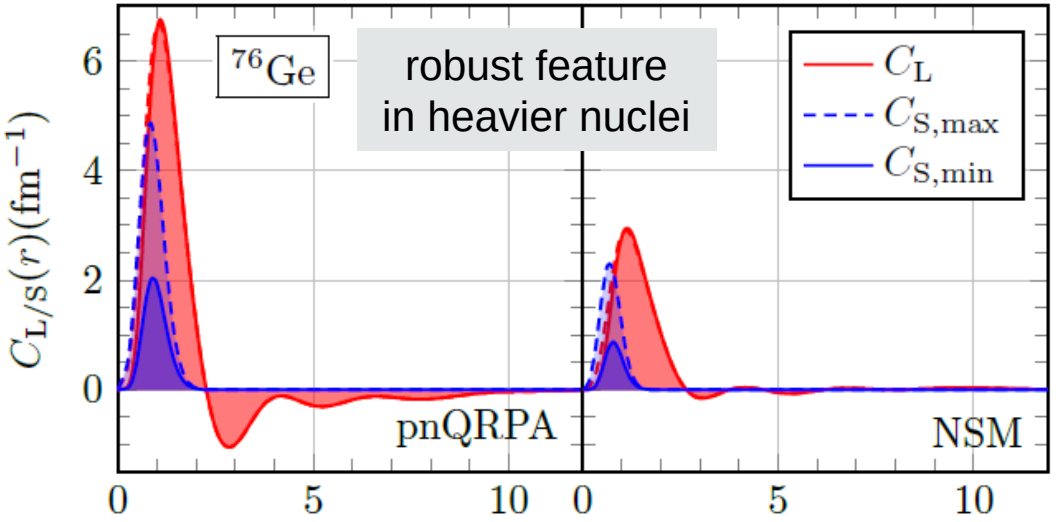
$C_1 + C_2$

assuming $C_1 \sim C_2$

other charge-independence data needed to disentangle C_1 and C_2

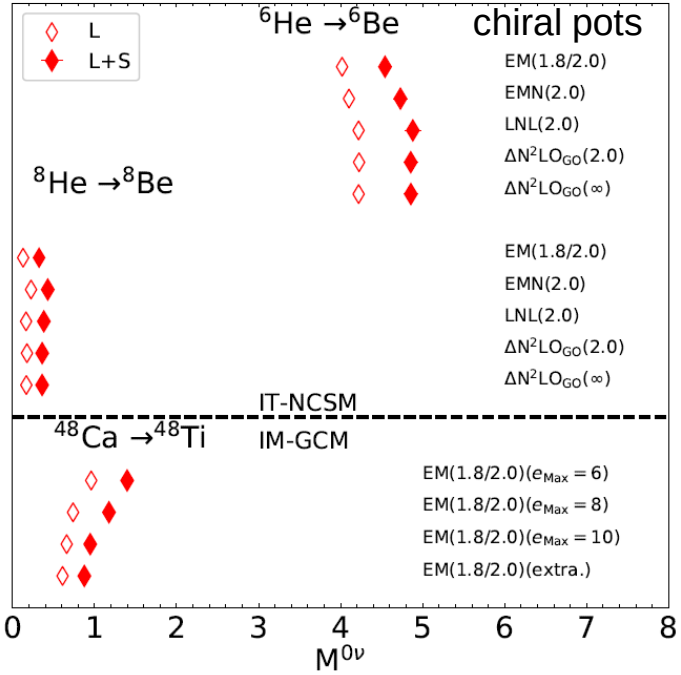


$$\frac{M_S}{M_L} \simeq 0.75$$



$$\frac{M_S}{M_L} \simeq 0.15 - 0.80$$

but *ab initio* calculations needed for heavier nuclei



Wirth, Yao+ Hergert '21

Nuclear EDMs & the "chiral filter"

Hockings + vK '05
Merehetti, Hockings + vK '10
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
…

$Q \ll m_{W,Z}$

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

θ term — qEDM — qCEDM

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

gCEDM

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

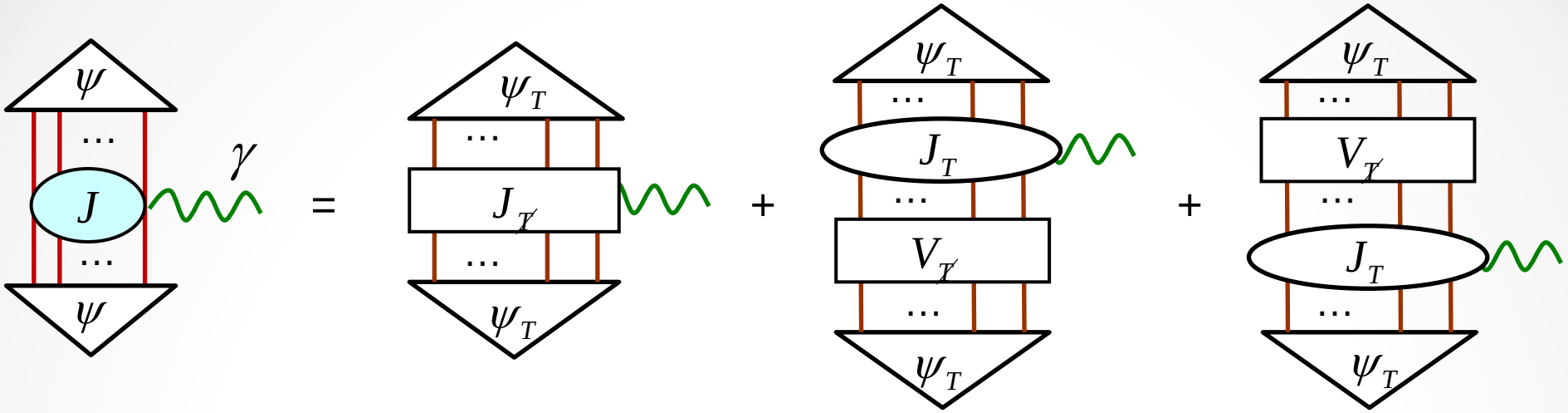
PSC

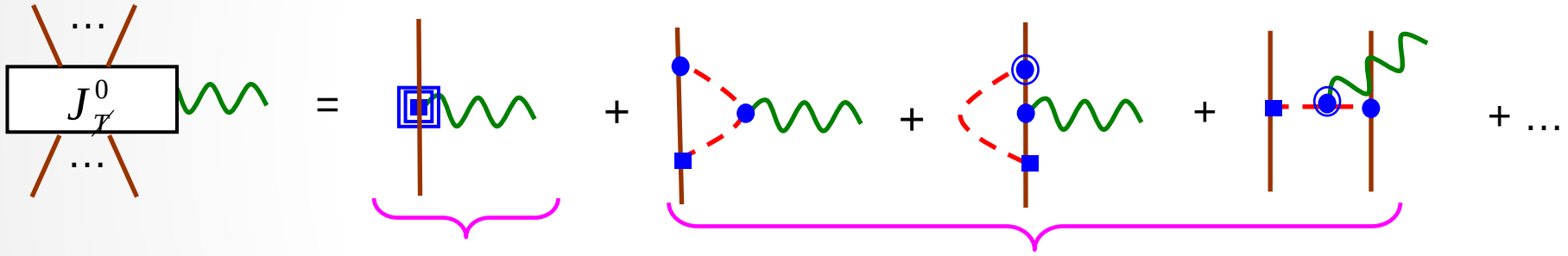
$$+ \frac{D_1}{4}\varepsilon_{3ij}\ \bar{q}\tau_i\gamma^\mu q\ \bar{q}\tau_j\gamma_\mu\gamma_5 q + \frac{D_8}{4}\varepsilon_{3ij}\ \bar{q}\tau_i\gamma^\mu\lambda^a q\ \bar{q}\tau_j\gamma_\mu\gamma_5\lambda^a q + \ldots$$

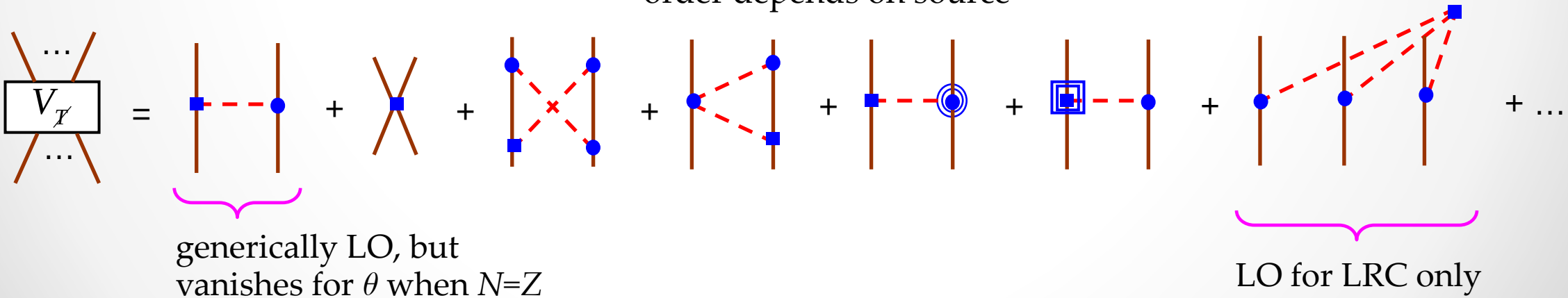
LRC

$$d_q^{(i)}, c_q^{(i)}, c_G, C_a, D_a \propto \frac{1}{M_{\not{T}}^2}$$

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


ψ
J
γ
ψ
=
ψ_T
J_T
ψ_T
+
ψ_T
J_T
V_T
ψ_T
+
ψ_T
V_T
J_T
ψ_T


J^0_T
=
+
+
+
+ …
LO for all sources
order depends on source


V_T
=
+
+
+
+
+
+
+ …
generically LO, but
vanishes for θ when N=Z
LO for LRC only

$Q \sim M_{\text{nuc}}$		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	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{\text{QCD}}^2}{Q^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{\text{QCD}}^2}{Q^2}\right)$
^{3}He	d_h/d_n	$\mathcal{O}\left(\frac{M_{\text{QCD}}^2}{Q^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{\text{QCD}}^2}{Q^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{\text{QCD}}^2}{Q^2}\right)$
^{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.

$$\begin{cases} d_h + d_t \simeq 0.84\left(d_n + d_p\right) & \text{qEDM and } \theta \text{ term} \\ d_h - d_t \simeq 0.94\left(d_n - d_p\right) & \text{qEDM} \\ d_h + d_t \simeq 3d_d & \text{qCEDM and LRC} \end{cases}$$

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

Farley *et al.* '04
…

Deuteron decay & systematic expansion (ΔB=1)

Oosterhof, De Vries, Timmermans + vK '21

$Q \ll m_{W,Z}$

$$\mathcal{L}^{(\Delta B=1)}_{\text{dim}=6} = \sum_{i=1}^{4}\sum_{d=1}^{2} \mathcal{C}_{id}\, \mathcal{Q}_d^{(i)} + \sum_{i=1}^{6}\sum_{d=1}^{2} \tilde{\mathcal{C}}_{id}\, \tilde{\mathcal{Q}}_d^{(i)} \; + \; \text{H.c.}$$

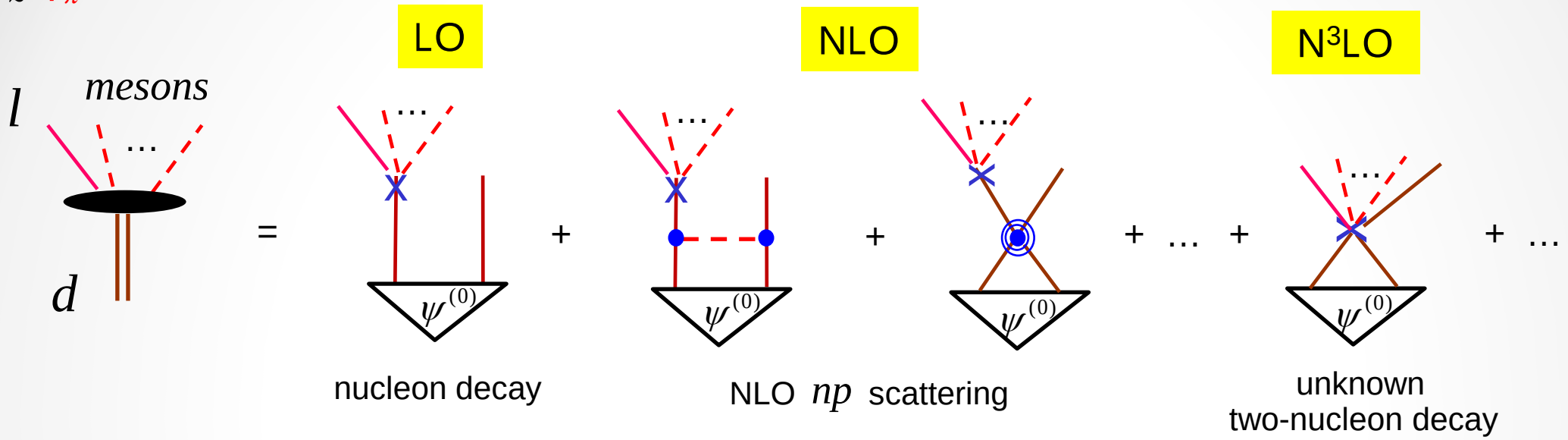
Weinberg '79'89
Wilczek + Zee '79
Abbott + Wise '80
Claudson, Wise + Hall '82

$$\mathcal{C}_{id}, \tilde{\mathcal{C}}_{id} \propto \frac{1}{M^2_{\not{B}_1}}$$

$$\mathcal{Q}_d^{(1)} = (d_{R\alpha}^T C u_{R\beta}) \left[(u_{L\gamma}^T C e_{Ld}) - (d_{L\gamma}^T C \nu_{Ld})\right] \varepsilon_{\alpha\beta\gamma} \,,$$
$$\mathcal{Q}_d^{(2)} = (d_{L\alpha}^T C u_{L\beta})(u_{R\gamma}^T C e_{Rd}) \varepsilon_{\alpha\beta\gamma} \,,$$
$$\mathcal{Q}_d^{(3)} = (d_{L\alpha}^T C u_{L\beta}) \left[(u_{L\gamma}^T C e_{Ld}) - (d_{L\gamma}^T C \nu_{Ld})\right] \varepsilon_{\alpha\beta\gamma} \,,$$
$$\mathcal{Q}_d^{(4)} = (d_{R\alpha}^T C u_{R\beta})(u_{R\gamma}^T C e_{Rd}) \varepsilon_{\alpha\beta\gamma} \,,$$

$$\tilde{\mathcal{Q}}_d^{(1)} = (s_{R\alpha}^T C u_{R\beta}) \left[(u_{L\gamma}^T C e_{Ld}) - (d_{L\gamma}^T C \nu_{Ld})\right] \varepsilon_{\alpha\beta\gamma} \,,$$
$$\tilde{\mathcal{Q}}_d^{(2)} = (s_{L\alpha}^T C u_{L\beta})(u_{R\gamma}^T C e_{Rd}) \varepsilon_{\alpha\beta\gamma} \,,$$
$$\tilde{\mathcal{Q}}_d^{(3)} = (s_{L\alpha}^T C u_{L\beta}) \left[(u_{L\gamma}^T C e_{Ld}) - (d_{L\gamma}^T C \nu_{Ld})\right] \varepsilon_{\alpha\beta\gamma} \,,$$
$$\tilde{\mathcal{Q}}_d^{(4)} = (s_{R\alpha}^T C u_{R\beta})(u_{R\gamma}^T C e_{Rd}) \varepsilon_{\alpha\beta\gamma} \,,$$
$$\tilde{\mathcal{Q}}_d^{(5)} = (d_{R\alpha}^T C u_{R\beta})(s_{L\gamma}^T C \nu_{Ld}) \varepsilon_{\alpha\beta\gamma} \,,$$
$$\tilde{\mathcal{Q}}_d^{(6)} = (d_{L\alpha}^T C u_{L\beta})(s_{L\gamma}^T C \nu_{Ld}) \varepsilon_{\alpha\beta\gamma} \,.$$

$Q \lesssim f_\pi$



$$\Gamma_d = \left(\Gamma_p + \Gamma_n\right)\left(1 \pm 0.02\right)$$

vs. $0.02 - 0.5$ in pot models

Dover, Goldhaber, Trueman + Chau '81
Alvarez-Estrada + Sánchez-Gómez '82

$$\Gamma_N = \mathcal{O}\left(\frac{M_{\text{QCD}}^5}{(4\pi)^4}\mathcal{C}^2\right) \sim 10^{-4}\mathcal{C}^2\ \text{GeV}^5$$

vs.

lattice QCD: $\Gamma_{p \to l^+ + \text{meson}} \approx 3 \cdot 10^{-4}\mathcal{C}^2\ \text{GeV}^5$ — Aoki *et al.* '17

experiment: $\Gamma^{-1}_{p \to e^+ + \pi^0} > 1.6 \cdot 10^{34}\ \text{y}$ — Abe *et al.* '17

Deuteron decay & systematic expansion (ΔB=2)

Oosterhof, Long, De Vries, Timmermans + vK '19
…

$Q \ll m_{W,Z}$

Buchoff + Wagman '16

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

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

$$\mathcal{C}_i \propto \frac{1}{M^5_{\not{B}_2}}$$

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

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

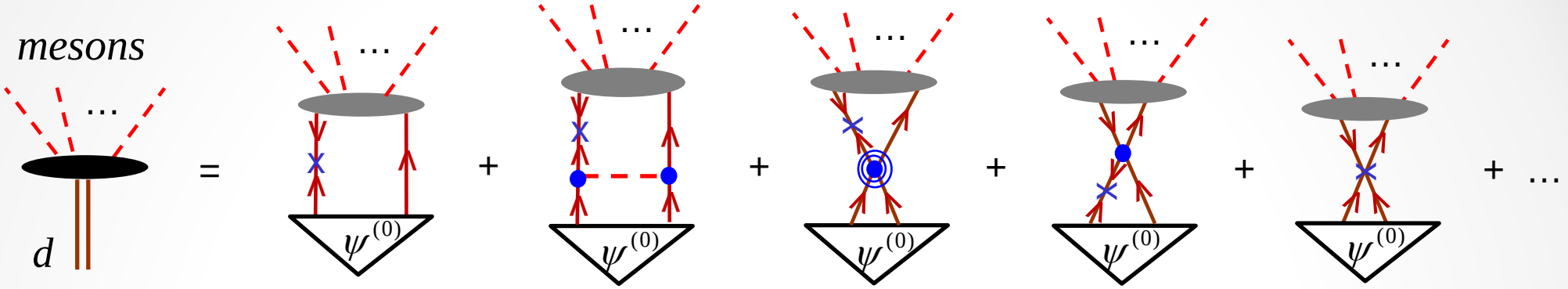
$$T^{SSS} \equiv \varepsilon_{ikm}\varepsilon_{jln} + \varepsilon_{ikn}\varepsilon_{jlm} + \varepsilon_{jkm}\varepsilon_{iln} + \varepsilon_{jkn}\varepsilon_{ilm} \,,$$

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

$Q \lesssim f_\pi$

LO NLO

$\mathcal{Q}_{1,2,3}$



plain $n\bar{n}$ oscillation NLO np scattering $\bar{n}p$ scattering unknown

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

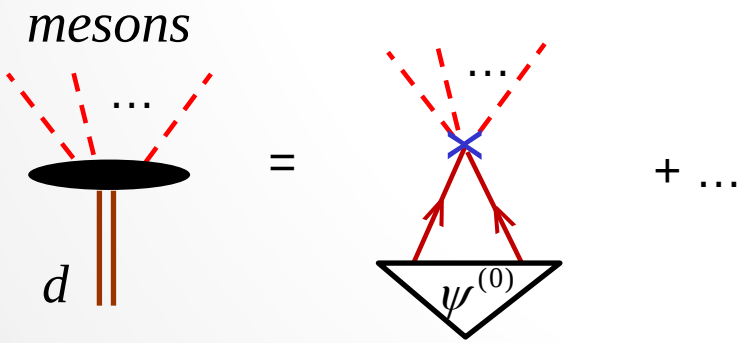
≈ 2.5 smaller than pot models

Dover, Gal + Richard '83

experiment: $\Gamma_d^{-1} > 1.18\cdot 10^{31}$ y $\Rightarrow$ $\tau_{n\bar{n}} > 1.6\cdot 10^8$ s

Aharmin *et al.* (SNO) '17 *vs.* $\tau_{n\bar{n}} > 0.86\cdot 10^8$ s Baldo-Ceolin *et al.* (ILL) '94

$\mathcal{Q}_4$



LO

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

approximately independent of $n\bar{n}$ oscillation time

can be separated

Conclusion

EFTs connect symmetry violation
beyond the Standard Model to 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