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EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

EDMs from EFTs:
Next nuclear steps

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Outline

- ☐ Symmetries
- ☐ Effective field theory
- ☐ Nucleon EDFF
- ☐ Nuclear EDFFs and MQFFs
- ☐ TV NN scattering
- ☐ What’s needed?
- ☐ Conclusion

Symmetries

Standard Model (SM) “explains” everything, except:

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

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

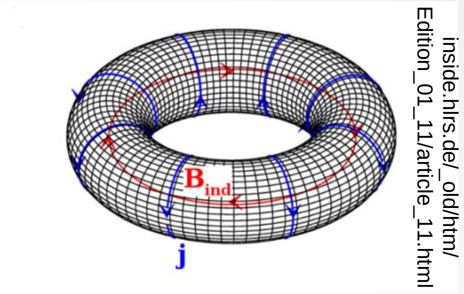
nucleon decay and neutron-antineutron oscillation:
$$N \to l\,X\,,\; n \leftrightarrow \overline{n}$$
free and in nucleus

nucleon and nuclear T-violating E&M form factors

⇒ Physics beyond the SM (BSM)

without requiring additional light degrees of freedom

Electromagnetic Form Factors



inside.hlrs.de/_old/htm/Edition_01_11/article_11.html

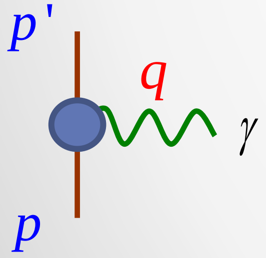
polarity	Electric	Magnetic	Toroidal
0 (monopole, charge)	P,T	$\varnothing$	$\varnothing$
1 (dipole, anapole)	$\boxed{\cancel{P},\cancel{T}}$	P,T	$\cancel{P},T$
2 (quadrupole)	P,T	$\boxed{\cancel{P},\cancel{T}}$	$\boxed{P,\cancel{T}}$

…

$S = 0$

$S = 1/2$

$S = 1$



spin

velocity

$$\langle p', j | J^\mu | p, i\rangle = \ldots - 2iS_{\sigma ij}\left[v^\mu q^\sigma - \eta^{\mu\sigma} v\cdot q + \ldots\right]F_{E1}(-q^2) + \frac{1}{4}\varepsilon^{\mu\nu\lambda\rho}\left(q_i\delta_{\lambda j} + q_j\delta_{\lambda i}\right)q_\nu\left[v_\rho + \ldots\right]F_{M2}(-q^2)$$

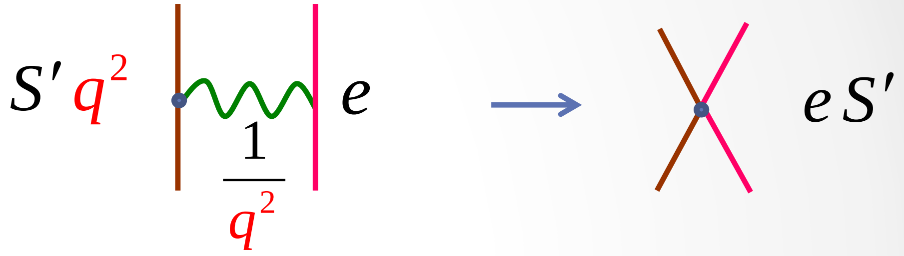
$$+\,i\left[q_i q_j q^\mu + \frac{q^2}{2}\left(\eta_i{}^\mu q_j + \eta_j{}^\mu q_i\right) + \ldots\right]F_{T2}(-q^2)$$

EDFF $$F_{E1}(-q^2) \equiv d + S' q^2 + H_{E1}(-q^2)$$

EDM

EDFF radius

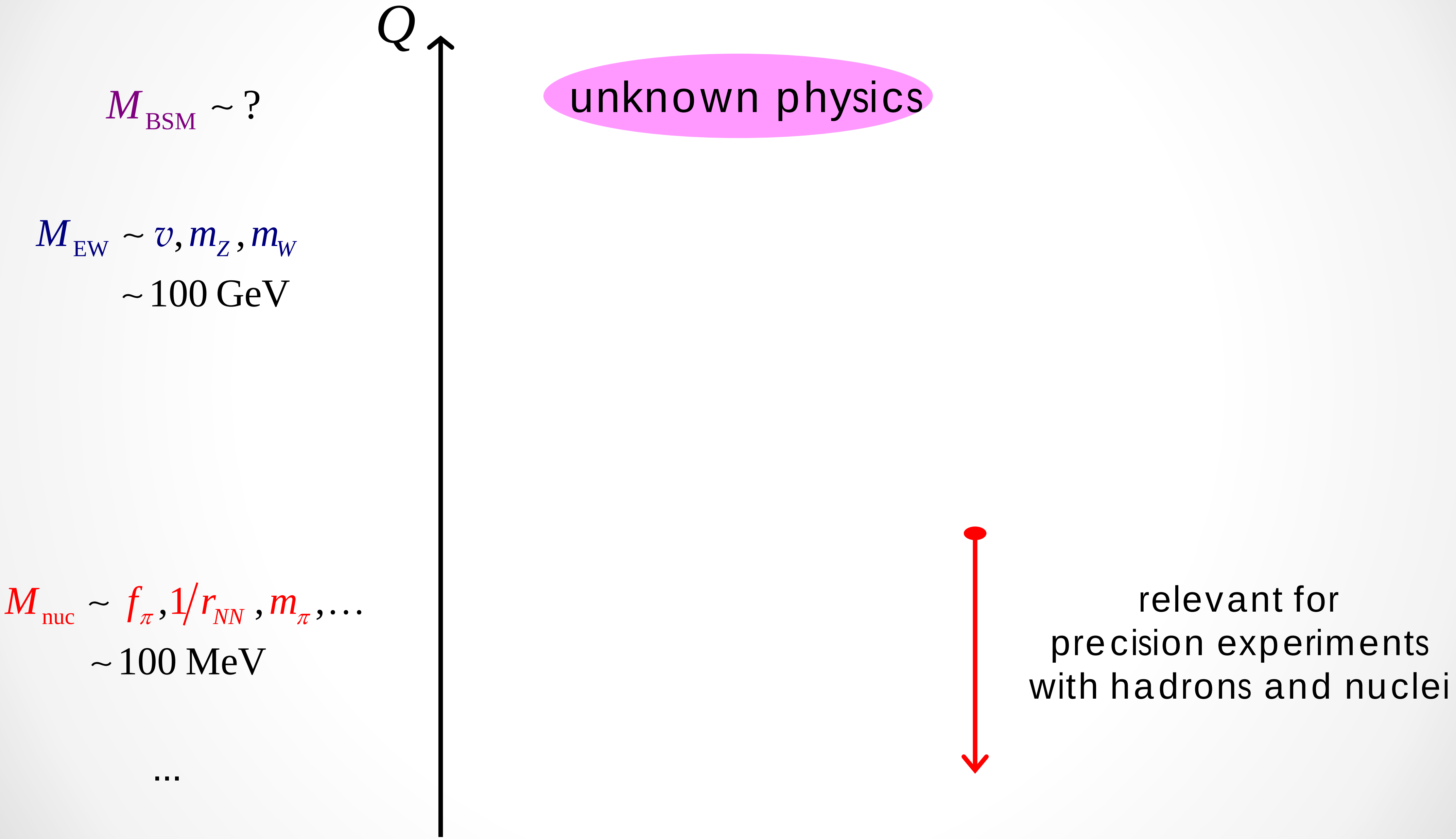
electromagnetic contribution to Schiff moment (SM)



MQFF $$F_{M2}(-q^2) \equiv \mathcal{M} + H_{M2}(-q^2)$$

MQM

- nuclear EDMs
- nuclear SMs and MQMs ⟹ atomic/molecular EDMs



Q

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

unknown physics

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

$\sim 100\ \text{GeV}$

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

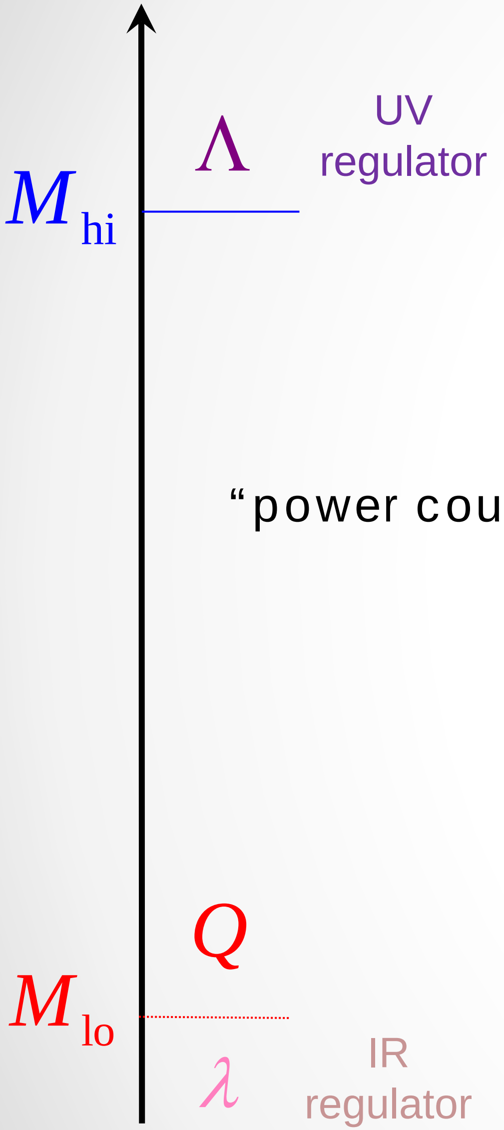
$\sim 100\ \text{MeV}$

...

relevant for
precision experiments
with hadrons and nuclei

Effective Field Theory©

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



most general Lagrangian

“power counting” ↓ $\nu=\nu(s,d,N,\dots)$

most general S matrix

$$\mathcal{L}_{\rm EFT}=\sum_{\nu=0}^{\infty}\underbrace{\gamma_i^{(\nu)}\left(\frac{M_{\rm lo}}{\Lambda},\frac{\lambda}{M_{\rm lo}}\right)\frac{M_{\rm lo}^{s}}{M_{\rm hi}^{\nu}}}_{\text{“low-energy constants”/ “Wilson coefficients”}}\underbrace{O^{(\nu)}\left(\partial^{d}\psi^{N}\right)}_{\text{operators}}$$

$$S^{(\bar\nu)}(Q\sim M_{\rm lo}\ll M_{\rm hi})-1\propto\sum_{\nu=0}^{\bar\nu}\left[\frac{Q}{M_{\rm hi}}\right]^{\nu}\overbrace{F^{(\nu)}\left(\frac{Q}{M_{\rm lo}},\frac{Q}{\Lambda},\frac{\lambda}{Q};\gamma_i^{(\le\nu)}\left(\frac{M_{\rm lo}}{\Lambda},\frac{\lambda}{M_{\rm lo}}\right)\right)}^{\text{non-analytic functions, from (finite or infinite number of) loops}}$$

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

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

CONTROLLED UNCERTAINTY

MODEL INDEPENDENCE

The Way of EFT

Example: T

Q

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

unknown physics

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

$\sim 100\ \mathrm{GeV}$

Standard Model
+ higher-dim

"SMEFT"

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

$\sim 1\ \mathrm{GeV}$

QCD + QED
+ higher-dim

"WEFT"

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

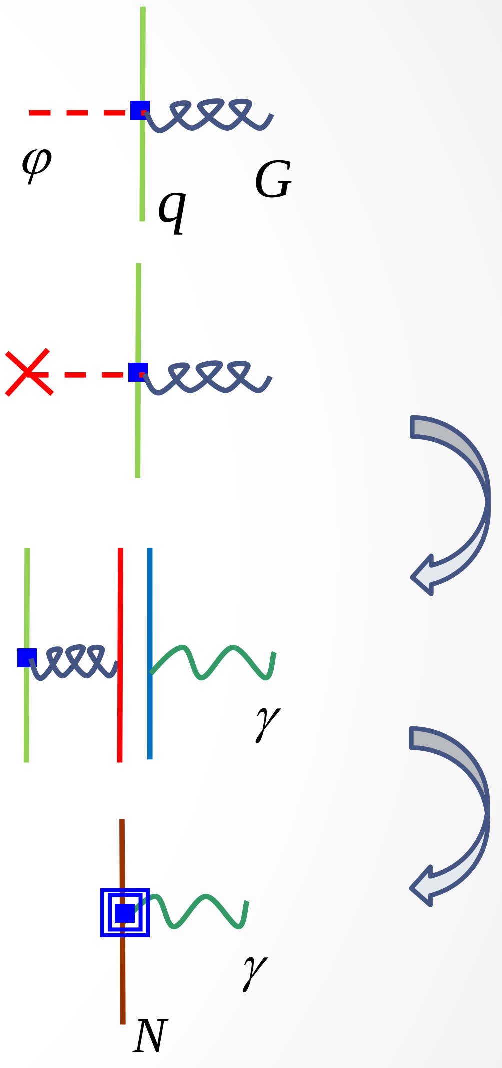
$\sim 100\ \mathrm{MeV}$

Chiral EFT

(χPT)

...

...



run
RG

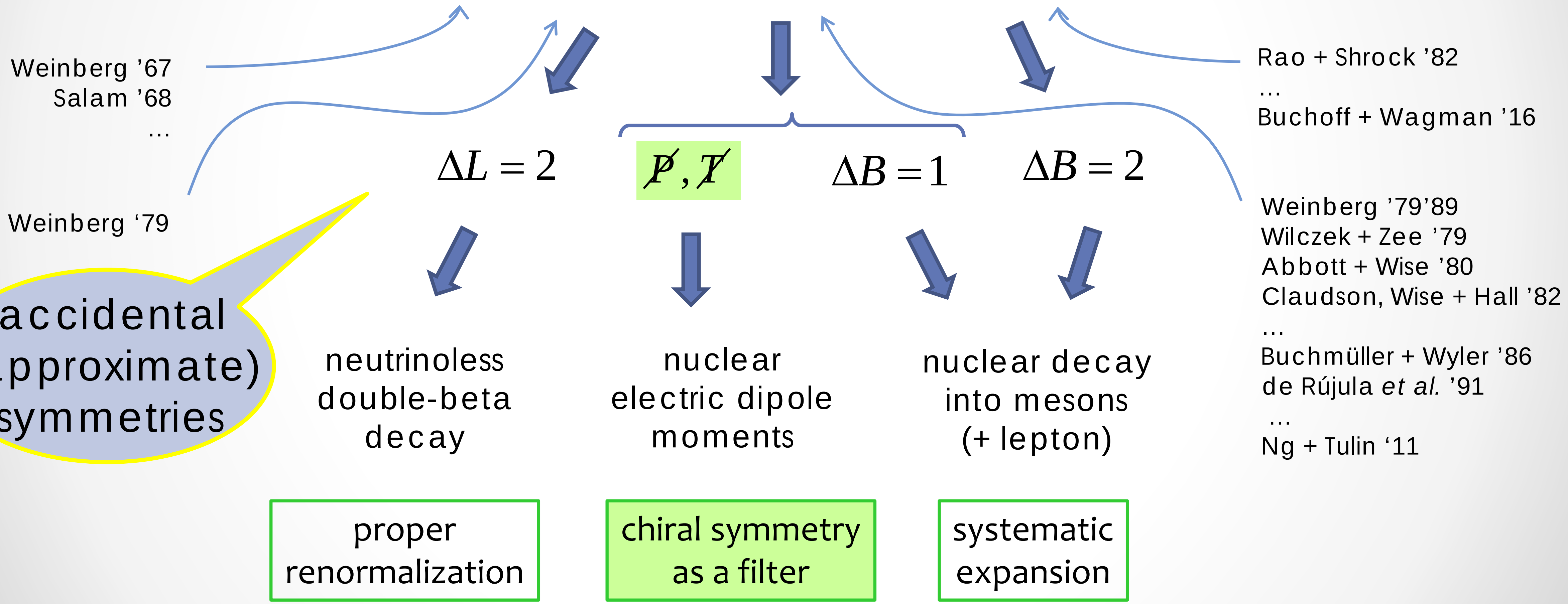
match
with
lattice,
...

...

SMEFT

$Q \sim M_{\text{EW}}$

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



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

$\Delta L = 2$ | $\not{P}, \not{T}$ | $\Delta B = 1$ | $\Delta B = 2$

accidental (approximate) symmetries

neutrinoless double-beta decay

nuclear electric dipole moments

nuclear decay into mesons (+ lepton)

proper renormalization

chiral symmetry as a filter

systematic expansion

$Q \sim M_{\rm EW}$

TV Sources

$$\mathcal{L}_{\rm SMEFT} = \bar{q}_L\,\gamma^{\mu}\left[\ldots - g_2\tau_{\pm}W_{\pm\mu}U_q\right]q_L$$

CKM matrix (dim=4) $J_{CP} \simeq 3\cdot 10^{-5}$ Jarlskog ’85

$$+\bar{q}_L\left[\,f_u\varphi_u u_R + f_d\varphi_d d_R\right] + \text{H.c.} + \frac{g_s^2\bar{\theta}}{16\pi^2}\,\text{Tr}\,G^{\mu\nu}\tilde{G}_{\mu\nu} + \ldots$$

θ term (dim=4) $\bar{\theta} \lesssim 10^{-10}$ ‘t Hooft ‘76

e.g. single Higgs $\varphi_u^i = \varepsilon^{ij}\varphi_{dj}^*$ $\tilde{G}_{\mu\nu} \equiv \varepsilon_{\mu\nu\rho\sigma}G^{\rho\sigma}$

small…

dimension

$$-\frac{1}{M_{\not{T}}^2}\,\bar{q}_L\sigma^{\mu\nu}\Big[\tilde{G}_{\mu\nu}\left(\overset{\frown}{g}_u\varphi_u u_R + \overset{\frown}{g}_d\varphi_d d_R\right)$$

→ quark color-EDM (eff dim=6)

$$+\left(\breve{g}_{Bu}\tilde{B}_{\mu\nu} + \breve{g}_{Wu}\tilde{W}_{\mu\nu}\tau_3\right)\varphi_u u_R + \left(\breve{g}_{Bd}\tilde{B}_{\mu\nu} + \breve{g}_{Wd}\tilde{W}_{\mu\nu}\tau_3\right)\varphi_d d_R\Big] + \text{H.c.}$$

→ quark EDM (eff dim=6)

$$+\frac{w}{M_{\not{T}}^2}\,f^{abc}\,G^a_{\mu\nu}\tilde{G}^{b\nu\rho}G^{c\mu}_{\rho}$$

→ gluon color-EDM (dim=6)

$$+\frac{(4\pi)^2}{M_{\not{T}}^2}\,i\varepsilon_{ij}\left(\sigma_1\,\bar{q}_L^i u_R\,\bar{q}_L^j d_R + \sigma_8\,\bar{q}_L^i\lambda^a u_R\,\bar{q}_L^j\lambda^a d_R\right) + \text{H.c.}$$

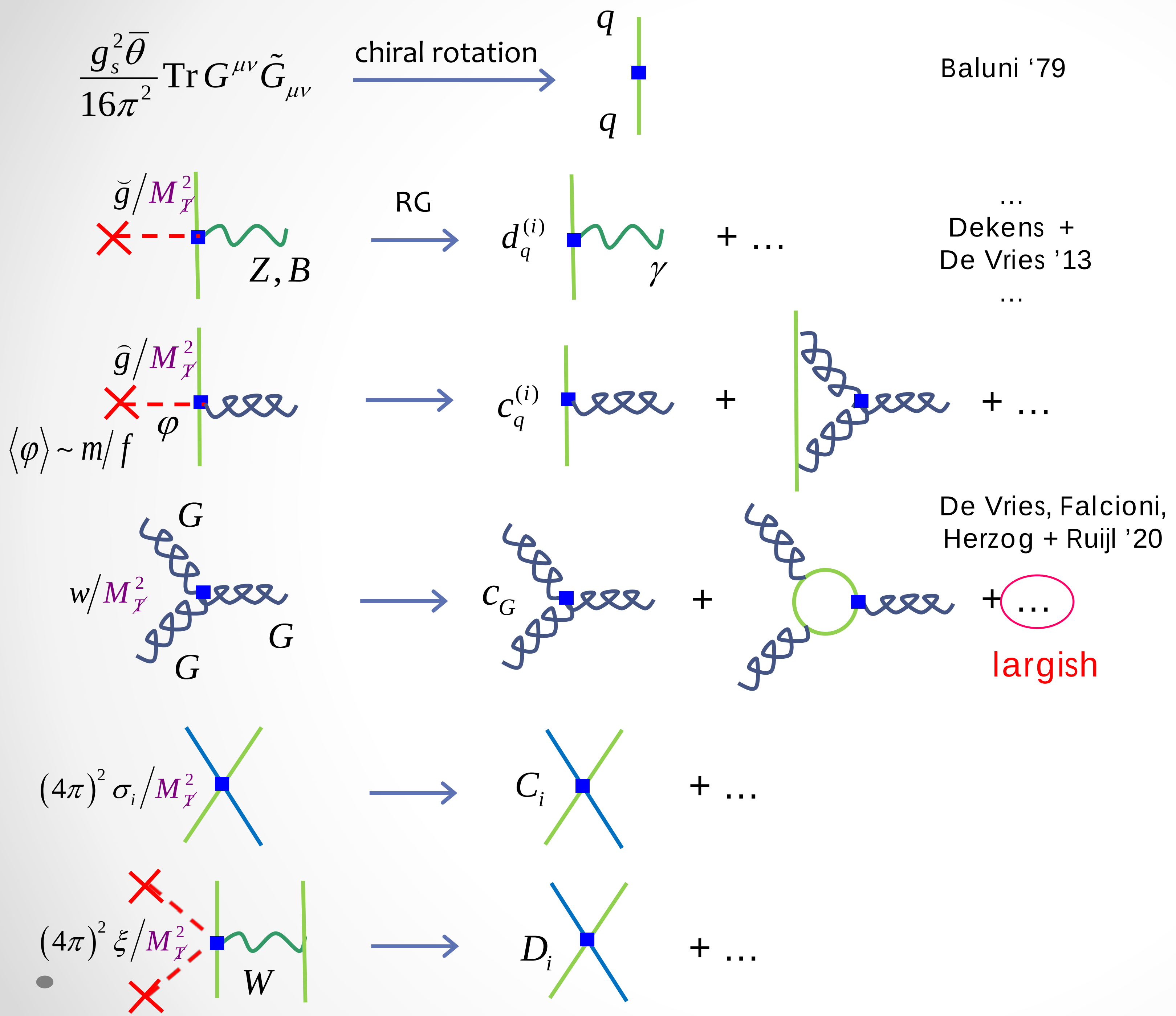
→ CI four-quark contact (dim=6)

$$+\frac{(4\pi)^2\xi}{M_{\not{T}}^2}\,\bar{u}_R\gamma^{\mu}d_R\,\varphi_u^{\dagger}\,iD_{\mu}\varphi_d + \text{H.c.}$$

→ LR four-quark contact (dim=6)

$$+\ldots$$

Buchmüller + Wyler ’86
Weinberg ’89
de Rujula *et al.* ’91
…
Ng + Tulin ‘11



largish

Baluni ‘79

…
Dekens +
De Vries ’13
…

De Vries, Falcioni,
Herzog + Ruijl ’20

θ term

$$d_q^{(i)} = \mathcal{O}\left(\frac{e\breve g}{f}\,\frac{\bar m}{M_{\not T}^2}\right)$$

qEDM

$$c_q^{(i)} = \mathcal{O}\left(\frac{\hat g}{f}\,\frac{\bar m}{M_{\not T}^2}\right)$$

qCEDM

$$c_G = \mathcal{O}\left(\frac{w}{M_{\not T}^2}\right)$$

gCEDM

$$C_i = \mathcal{O}\left(\frac{(4\pi)^2\sigma_i}{M_{\not T}^2}\right)$$

PSC

$$D_i = \mathcal{O}\left(\frac{(4\pi)^2\xi}{M_{\not T}^2}\right)$$

LRC

Buchmüller + Wyler ’86
de Rújula *et al.* ’91
...
Ng + Tulin ‘11

$Q \ll M_{\text{EW}}$

$$q = \begin{pmatrix} u \\ d \end{pmatrix}$$

θ term

$$\mathcal{L}_{\text{WEFT}} = \ldots - \bar{m}\,\bar{q}q + \varepsilon\bar{m}\,\bar{q}\tau_3 q + \boxed{\frac{\bar{m}}{2}\left(1-\varepsilon^2\right)\bar{\theta}\;\bar{q}i\gamma_5 q}$$

qCEDM

gCEDM

qEDM

$$-\boxed{\frac{1}{2}\bar{q}\left(d_q^{(0)} + d_q^{(1)}\tau_3\right)\sigma_{\mu\nu} q\,\tilde{F}^{\mu\nu}} - \boxed{\frac{1}{2}\bar{q}\left(c_q^{(0)} + c_q^{(1)}\tau_3\right)\sigma_{\mu\nu}\tilde{G}^{\mu\nu} q} + \boxed{\frac{c_G}{6}\, f^{abc}\, G^a_{\mu\nu}\tilde{G}^{b\nu\rho}G^{c\,\mu}_{\rho}}$$

$$+\boxed{\frac{C_1}{4}\left(\bar{q}q\;\bar{q}i\gamma_5 q - \bar{q}\boldsymbol{\tau}q\cdot\bar{q}i\gamma_5\boldsymbol{\tau}q\right) + \frac{C_8}{4}\left(\bar{q}\lambda^a q\;\bar{q}i\gamma_5\lambda^a q - \bar{q}\boldsymbol{\tau}\lambda^a q\cdot\bar{q}i\gamma_5\boldsymbol{\tau}\lambda^a q\right)}$$

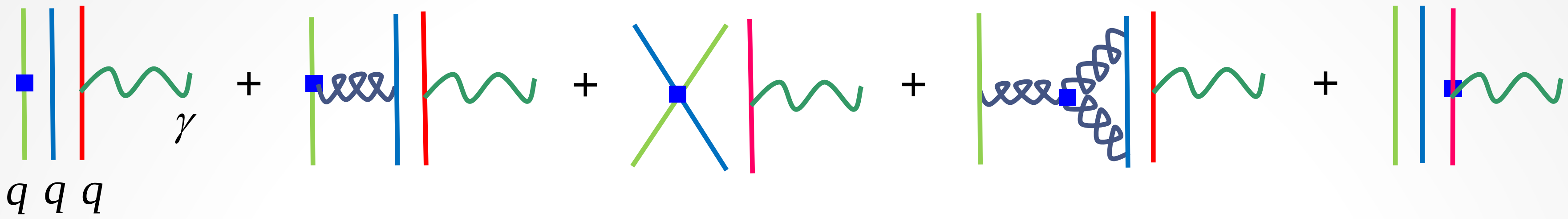
PSC

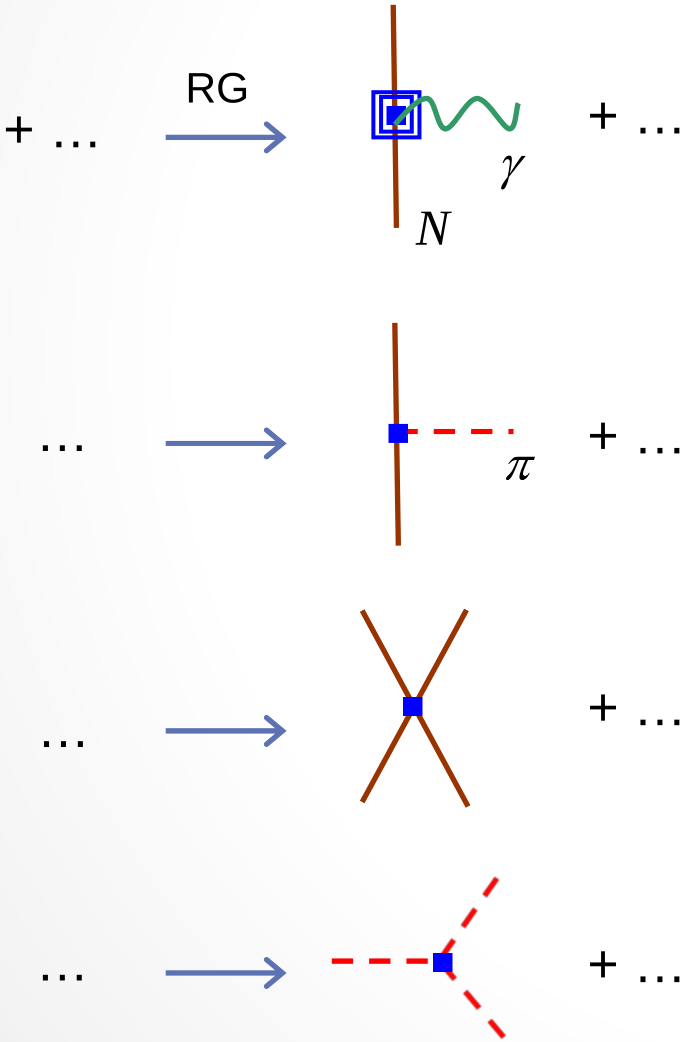
$$+\boxed{\frac{D_1}{4}\varepsilon_{3ij}\;\bar{q}\tau_i\gamma^\mu q\;\bar{q}\tau_j\gamma_\mu\gamma_5 q + \frac{D_8}{4}\varepsilon_{3ij}\;\bar{q}\tau_i\gamma^\mu\lambda^a q\;\bar{q}\tau_j\gamma_\mu\gamma_5\lambda^a q} + \ldots$$

LRC

$$d_q^{(i)}, c_q^{(i)}, c_G, C_a, D_a \propto \frac{1}{M_{\cancel{T}}^{2}}$$

To this order, $\cancel{T} \to \cancel{P}$





much work in specific models
see J. Engel *et al.*, PPNP (2013)

lattice simulations needed!

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

Chiral EFT

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

Chiral EFT

- nucleons and pions *(and Deltas, Ropers?)*
- SM symmetries (including approximate chiral symmetry)

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

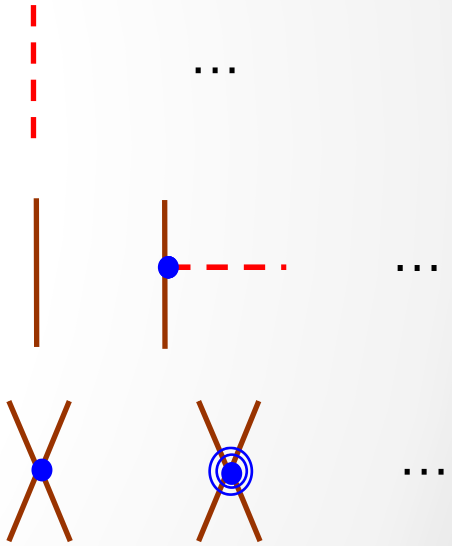
$$+ N^+\left(i\partial_0 + \frac{\nabla^2}{2m_N} + \frac{g_A}{2f_\pi}\boldsymbol{\tau}\vec{\sigma}\cdot\cdot\vec{\nabla}\boldsymbol{\pi} + \ldots\right)N$$

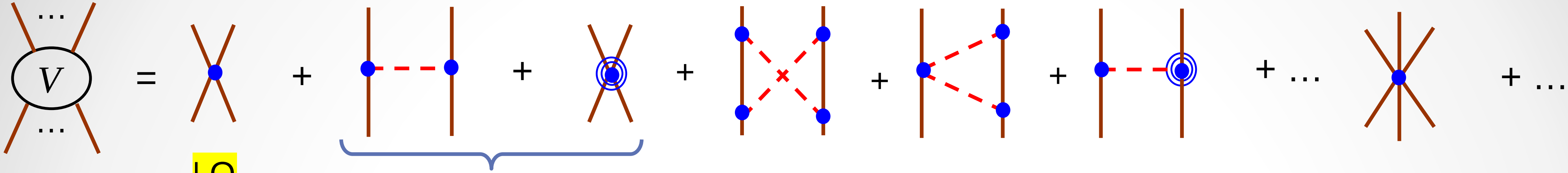
$$-\frac{1}{2}\sum_{I=0,1} N^+N^+ P_2^{(I)}\left(C_{0I} + C_{2I}\nabla^2 + m_\pi^2\gamma_{0I} + \ldots\right)NN$$

$$+\ldots$$

more derivatives,
more fields,
isospin violation

projector on isospin *I*

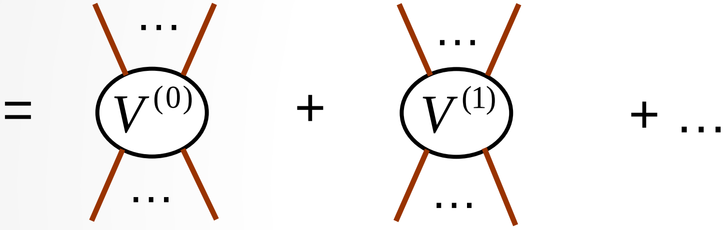




LO

LO for $Q \gtrsim M_{NN}$, NLO for $Q \lesssim M_{NN}$

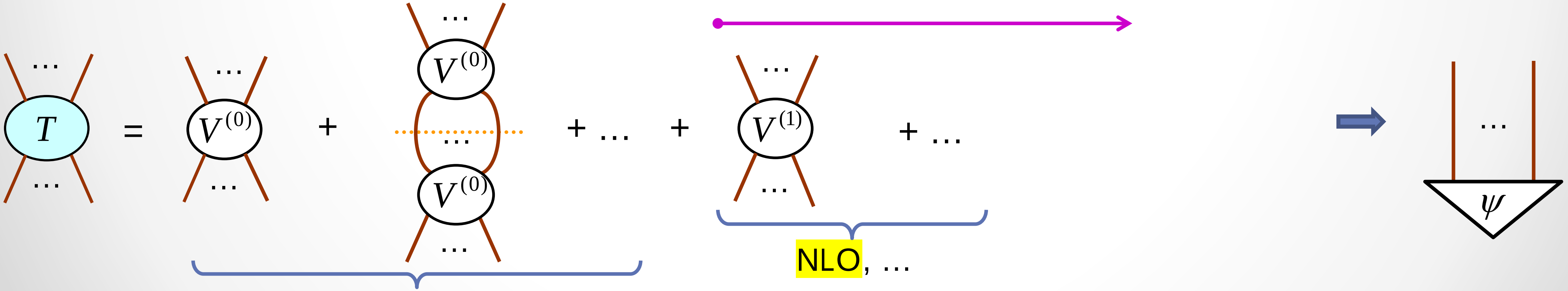
$$M_{NN} = \frac{4}{g_A^2}\frac{4\pi f_\pi}{m_N} f_\pi \simeq 300\ \text{MeV}$$



LO

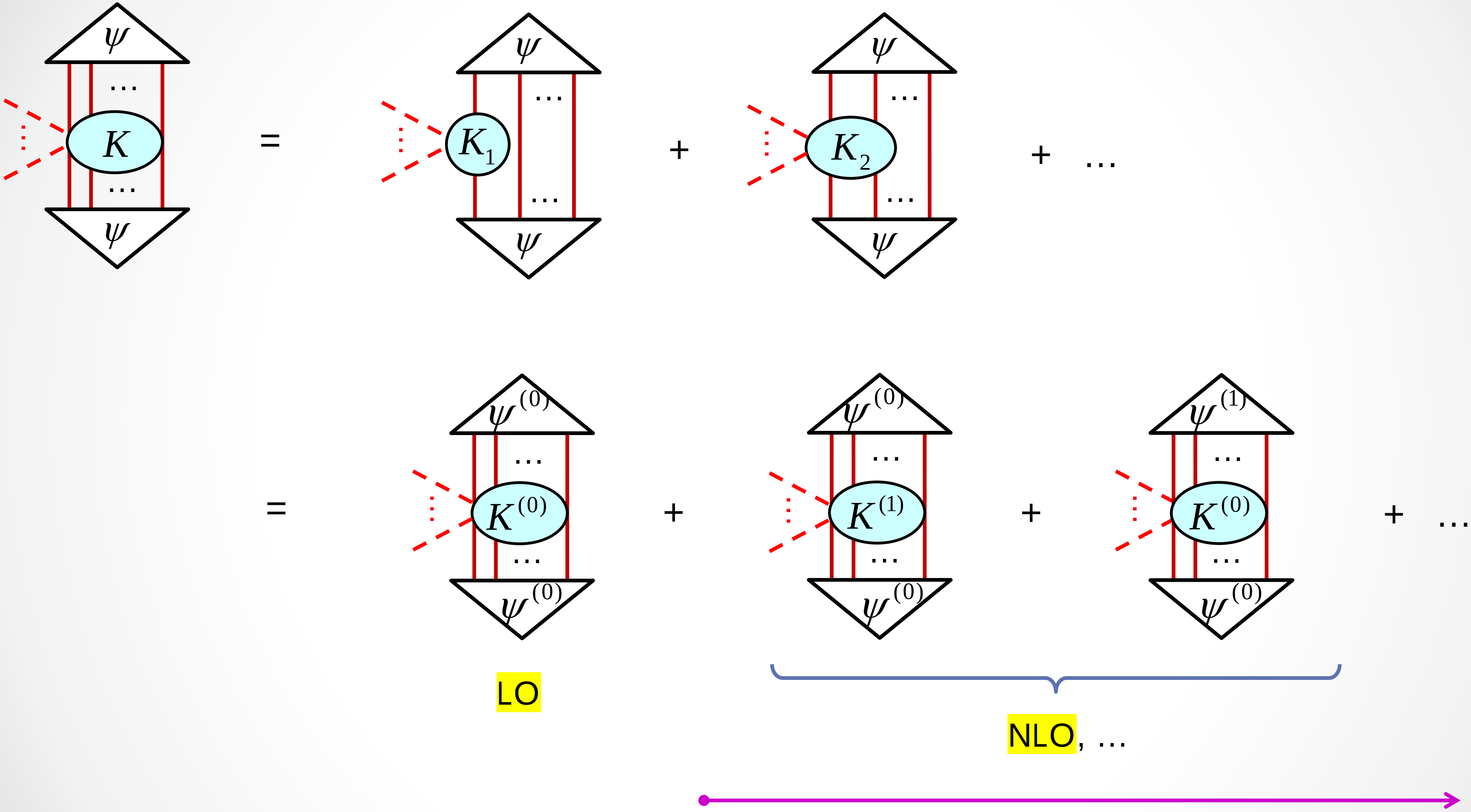
NLO

distorted-wave perturbation theory



NLO, …

LO



LO

NLO, …

DWPT

Most applications of
chiral potentials and kernels
to date
violate RG invariance

We will return
to this

Mereghetti, Hockings + v.K. '10
De Vries *et al*, '13

Key to disentangle TV sources: each breaks chiral symmetry in a particular way, and produces *different* hadronic interactions

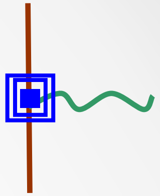
θ term	a chiral pseudo-vector: same as quark mass difference ➡ link to P,T-conserving charge symmetry breaking
qCEDM	a chiral vector
LRC	a rank-2 chiral tensor
qEDM	another rank-2 chiral tensor

gCEDM
PSC
} CI chiral invariants: cannot be separated at low energies

$$\left\{w,\sigma_{1,8}\right\}\to w$$

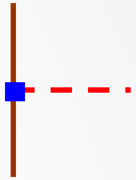
$$\mathcal{L}_{\pi\mathrm{EFT}} = \ldots - 2\,\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right)S_\mu N\, v_\nu F^{\mu\nu}$$

short-range EDM contribution



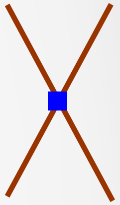
$$-\frac{1}{2f_\pi}\bar{N}\left(\bar{g}_0\boldsymbol{\tau}\cdot\boldsymbol{\pi} + \bar{g}_1\pi_3\right)N$$

PV, TV pion-nucleon coupling



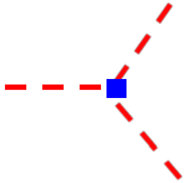
$$+\bar{C}_1\,\bar{N}N\,\partial_\mu\left(\bar{N}S^\mu N\right) + \bar{C}_2\,\bar{N}\boldsymbol{\tau}N\cdot\partial_\mu\left(\bar{N}S^\mu\boldsymbol{\tau}N\right)$$

PV, TV two-nucleon contact



$$-\frac{m_\pi^2\bar{g}_0}{2f_\pi(m_n-m_p)_{qm}}\boldsymbol{\pi}^2\pi_3$$

three-pion coupling



$$+\ldots$$

terms related by
chiral symmetry
+ higher orders

six LO couplings
for EDMs

cf. Barton ’61
and nuclear followers

$v^\mu = \left(1,\vec{0}\right)$	velocity
$S^\mu = \left(0,\frac{\vec{\sigma}}{2}\right)$	spin

Where are the differences?

There are differences!

For example,

$$\mathcal{L}_{\not{T},\pi N} = -\frac{1}{2 f_\pi D}\bar{N}\left[\bar{g}_0 \boldsymbol{\tau}\cdot\boldsymbol{\pi} + \bar{g}_1 \pi_3\right] N + \dots$$

$$\bar{g}_0 = \mathcal{O}\left(\bar{\theta}\frac{m_\pi^2}{M_{QCD}}, \frac{\hat{g}}{f}\frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}, \frac{\breve{g}}{f}\frac{\alpha}{\pi}\frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}, w\frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}, \varepsilon\xi\frac{M_{QCD}^3}{M_{\not{T}}^2}\right)$$

$$\bar{g}_1 = \mathcal{O}\left(\bar{\theta}\frac{m_\pi^4}{M_{QCD}^3}, \frac{\hat{g}}{f}\frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}, \frac{\breve{g}}{f}\frac{\alpha}{\pi}\frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}, \varepsilon w\frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}, \xi\frac{M_{QCD}^3}{M_{\not{T}}^2}\right)$$

different orders;
two-derivative interactions
also appear at higher order

pion physics
suppressed

comparable to
two-derivative
interactions

N.B.

1) $\bar{g}_2\, \bar{N}\pi_3\tau_3 N$ in high orders for *all* sources up to dim 6

2) for θ, link to CSB, *e.g.*

$$\bar{g}_0 \simeq \frac{\bar{\theta}}{2\varepsilon}\delta m_N \approx 3\,\bar{\theta}\ \text{MeV}$$

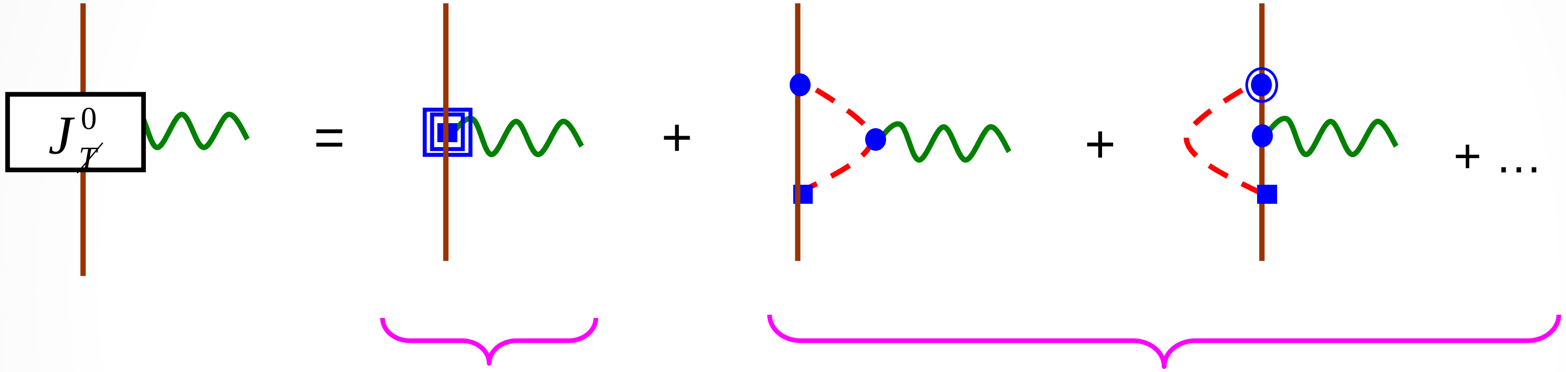
Mereghetti, Hockings + v.K. ’10

$$\delta m_N \equiv \left(m_n - m_p\right)_{\text{qm}} \longrightarrow$$

using lattice QCD (Beane et al ’06)

Crewther *et al* ’79
Thomas ’95
…
Hockings + v.K. ‘05
Narison ‘08
Ottnad *et al* ’10
De Vries *et al* ’10’11
…

Nucleon EDFF (to NLO)



short-ranged;
LO for all sources

long-ranged;
order depends on source

- ensures RG invariance
- brings in two parameters

- can provide estimates in terms of pion parameters at “reasonable” renormalization scale

Example: qCEDM

De Vries *et al* ’10’11

$$\left\{\begin{aligned} d_1 &= \bar{d}_1 + \frac{e g_A \bar{g}_0}{(4\pi f_\pi)^2}\left[\left(\bar{\Delta} + 2\ln\frac{\mu}{m_\pi}\right) + \frac{5\pi}{4}\frac{m_\pi}{m_N}\left(1+\frac{\bar{g}_1}{5\bar{g}_0}\right) - \frac{\breve{\delta} m_\pi^2}{m_\pi^2} + \mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)\right] \\ \bar{\Delta} &\equiv \frac{2}{4-d} - \gamma_E + \ln 4\pi \\ d_0 &= \bar{d}_0 + \frac{e g_A \bar{g}_0}{(4\pi f_\pi)^2}\left[0 + \frac{3\pi}{4}\frac{m_\pi}{m_N}\left(1+\frac{\bar{g}_1}{3\bar{g}_0}\right) - \frac{\delta m_N}{m_\pi} + \mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)\right] \end{aligned}\right.$$

renormalization

$$\breve{\delta} m_\pi^2 \equiv \left(m_{\pi^\pm}^2 - m_{\pi^0}^2\right)_{\text{em}}$$

$$\delta m_N \equiv \left(m_n - m_p\right)_{\text{qm}}$$

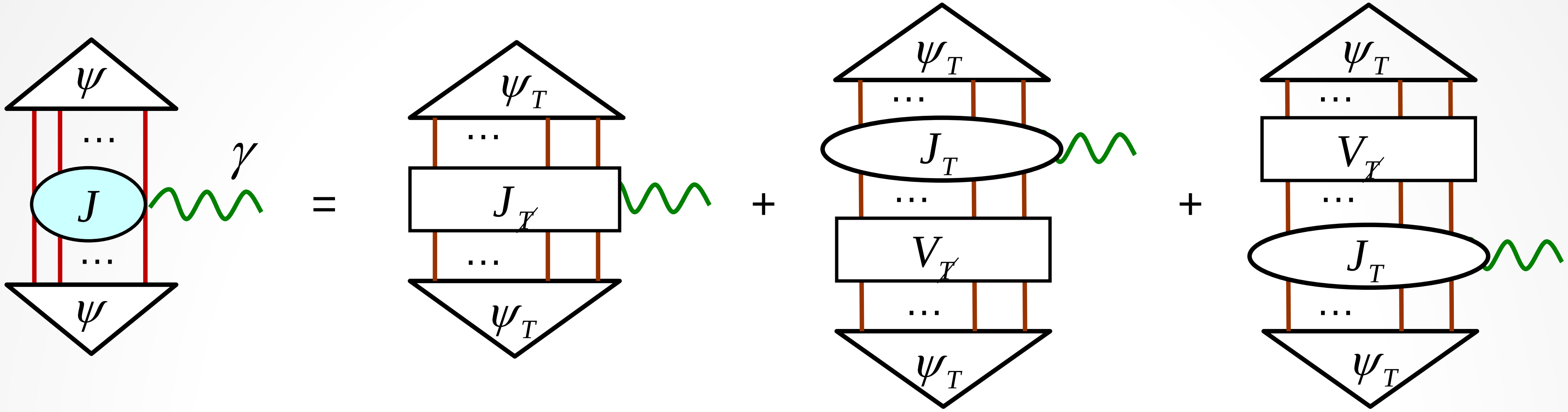
$$\left\{\begin{aligned} S_1' &= \frac{e g_A \bar{g}_0}{6(4\pi f_\pi)^2 m_\pi^2}\left[1 - \frac{5\pi}{4}\frac{m_\pi}{m_N} - \frac{\breve{\delta} m_\pi^2}{m_\pi^2} + \mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)\right] \\ S_0' &= -\frac{e g_A \bar{g}_0}{6(4\pi f_\pi)^2 m_\pi^2}\left[0 + \frac{\pi}{2}\frac{\delta m_N}{m_\pi} + \mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)\right] \end{aligned}\right.$$

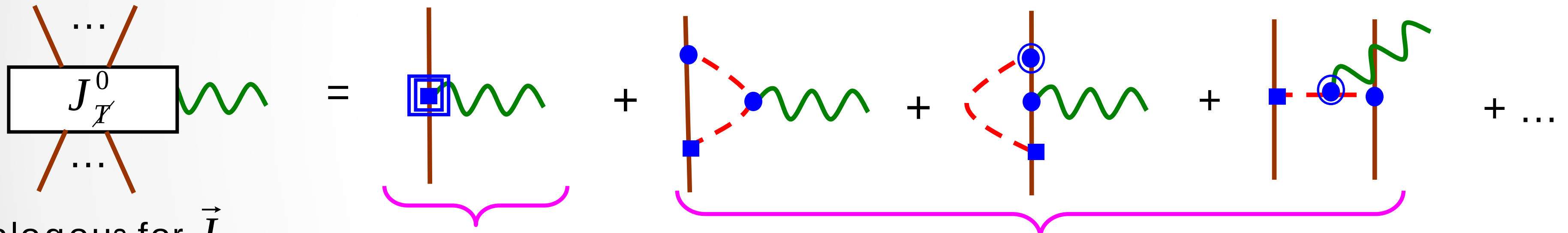
Crewther *et al* ’79
Thomas ‘95
…
Hockings + v.K. 05
Narison ‘08
Ottnad *et al* ’10
De Vries *et al* ’11

	θ term	qCEDM	LRC	qEDM	CI
$m_n \frac{d_n}{e}$	$\mathcal{O}\left(\bar{\theta}\,\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{\hat{g}}{f}\,\frac{m_\pi^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(\xi\,\frac{M_{QCD}^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(\frac{\breve{g}}{f}\,\frac{m_\pi^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(w\,\frac{M_{QCD}^2}{M_{\not{T}}^2}\right)$
$\frac{d_p}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$(2m_\pi)^2\,\frac{S'_p}{d_p}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$
$(2m_\pi)^2\,\frac{S'_0}{d_n}$	$\mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$

SM partially sensitive to sources

Nuclear EDFFs & MQFFs (at LO)





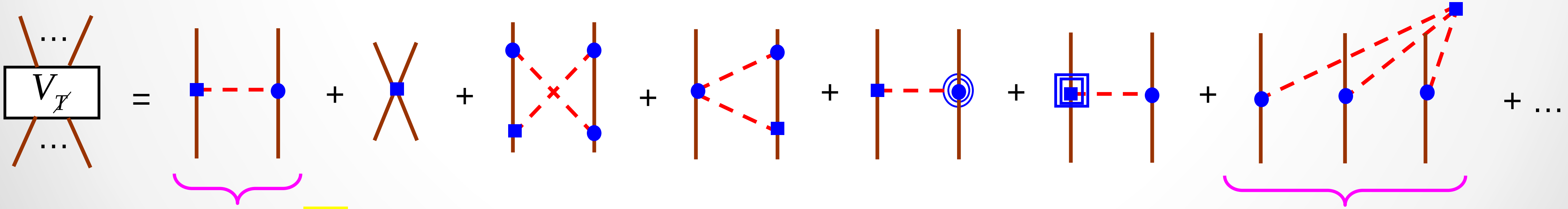
Analogous for $\vec{J}_{\not T}$

LO for all sources

order depends on source

De Vries, Mereghetti, Higa, Liu, Stetcu, Timmermans + v.K. '11

De Vries, Mereghetti, Liu, Timmermans + v.K. '12



generically LO, but vanishes for θ when N=Z

LO for LRC only

Maekawa, Mereghetti, De Vries + v.K. '11
De Vries, Mereghetti, Timmermans + v.K. '13

De Vries *et al* ’10

cf. Khriplovich + Korkin ‘00

Example: qCEDM

deuteron EDFF; pert pions – full EFT calculation

$$F_{E1,d}(-q^2) = -\frac{e g_A \bar{g}_1}{6 m_\pi}\,\boxed{\frac{m_N}{4\pi f_\pi^2}}\,\frac{1+\gamma/m_\pi}{\left(1+2\boxed{\gamma}/m_\pi\right)^2}\,F_2\left(-q^2/(4\gamma)^2\right)\left[1+\mathcal{O}\left(\frac{m_\pi}{M_{NN}}\right)\right]$$

$$\frac{m_N}{4\pi f_\pi^2} \equiv 1/M_{NN} \qquad \gamma \equiv \sqrt{m_N B_d}$$

$$F_2(x) = 1+\mathcal{O}(x)$$

scale of momentum variation $\sim 4\gamma \approx 180\ \mathrm{MeV}$

$$\Rightarrow \quad d_d \simeq -0.12\frac{\bar{g}_1}{f_\pi}\, e\ \mathrm{fm}$$

deuteron, helion, triton EDMs; non-pert pions

De Vries *et al* ’11

cf. Liu + Timmermans ’04
Gudkov, Lazauskas + Song ‘12

$$\begin{cases} d_d \simeq -0.10\dfrac{\bar{g}_1}{f_\pi}\, e\ \mathrm{fm} \\[2ex] d_h \simeq 0.83\,\bar{d}_0 - 0.93\,\bar{d}_1 - \left(0.08\dfrac{\bar{g}_0}{f_\pi} + 0.14\dfrac{\bar{g}_1}{f_\pi}\right) e\ \mathrm{fm} \\[2ex] d_t \simeq 0.85\,\bar{d}_0 - 0.95\,\bar{d}_1 + \left(0.08\dfrac{\bar{g}_0}{f_\pi} - 0.14\dfrac{\bar{g}_1}{f_\pi}\right) e\ \mathrm{fm} \end{cases}$$

“hybrid” calculations
assuming
naïve dimensional analysis

De Vries *et al* ’10
cf. Khriplovich + Korkin ‘00

deuteron MQFF; pert pions

$$F_{M2,d}(-q^2) = \left[1+\kappa_1+3(1+\kappa_0)\frac{\bar{g}_0}{\bar{g}_1}\right]\frac{F_{E1,d}(-q^2)}{m_N}\left[1+\mathcal{O}\left(\frac{m_\pi}{M_{NN}}\right)\right]$$

$$\Rightarrow \quad \frac{m_d\mathcal{M}_d}{d_d} \simeq 2\left[1+\kappa_1+3(1+\kappa_0)\frac{\bar{g}_0}{\bar{g}_1}\right]$$

anomalous mag mom $\kappa_0 \simeq -0.12$
$\kappa_1 \simeq 3.71$

De Vries *et al* ’12
cf. Liu + Timmermans ‘04

deuteron MQM; non-pert pions

$$\frac{m_d\mathcal{M}_d}{d_d} \simeq 1.6\left[1+\kappa_1+1.4(1+\kappa_0)\frac{\bar{g}_0}{\bar{g}_1}+0.4\right]$$

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

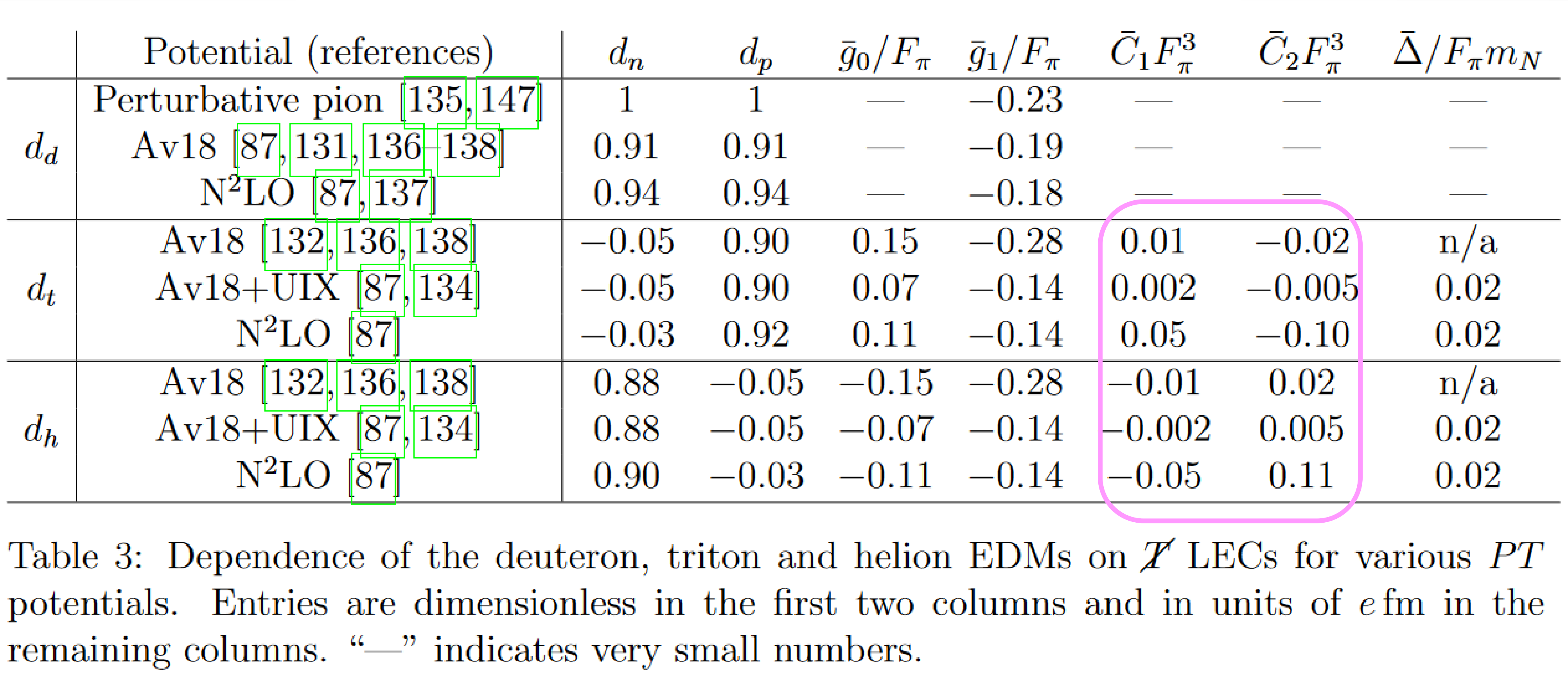
+ specific relations

e.g.

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

storage-ring measurements
could teach us about sources!

Farley *et al.* '04
…



	Potential (references)	d_n	d_p	$\bar{g}_0/F_\pi$	$\bar{g}_1/F_\pi$	$\bar{C}_1F_\pi^3$	$\bar{C}_2F_\pi^3$	$\bar{\Delta}/F_\pi m_N$
d_d	Perturbative pion [135, 147]	1	1	—	−0.23	—	—	—
	Av18 [87, 131, 136–138]	0.91	0.91	—	−0.19	—	—	—
	N^{2}LO [87, 137]	0.94	0.94	—	−0.18	—	—	—
d_t	Av18 [132, 136, 138]	−0.05	0.90	0.15	−0.28	0.01	−0.02	n/a
	Av18+UIX [87, 134]	−0.05	0.90	0.07	−0.14	0.002	−0.005	0.02
	N^{2}LO [87]	−0.03	0.92	0.11	−0.14	0.05	−0.10	0.02
d_h	Av18 [132, 136, 138]	0.88	−0.05	−0.15	−0.28	−0.01	0.02	n/a
	Av18+UIX [87, 134]	0.88	−0.05	−0.07	−0.14	−0.002	0.005	0.02
	N^{2}LO [87]	0.90	−0.03	−0.11	−0.14	−0.05	0.11	0.02

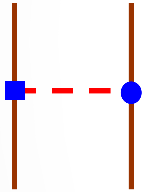
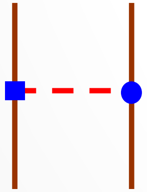
Table 3: Dependence of the deuteron, triton and helion EDMs on $\not{T}$ LECs for various PT potentials. Entries are dimensionless in the first two columns and in units of $e\,\mathrm{fm}$ in the remaining columns. "—" indicates very small numbers.

E. Mereghetti, U. van Kolck, *Ann. Rev. Nucl. Part. Sci.* **65** (2015) 215

sensitive to inconsistency

TV NN Scattering

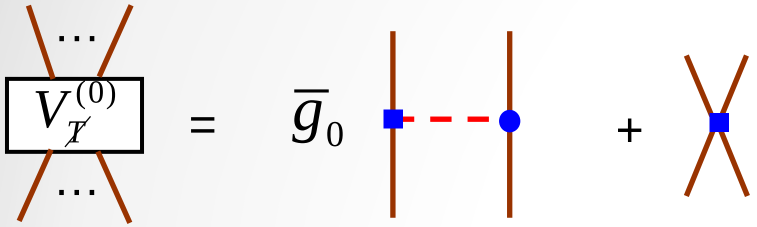
mixing of partial waves with different parity

	channels	isospin	mixing angle
$\bar{g}_0$ 	${}^1S_0 - {}^3P_0$	$I = 1$	ε_{0SP}
	${}^3\{S,D\}_1 - {}^1P_1$	$I = 0$	ε_{10SP}, ε_{10DP}
$\bar{g}_1$ 	${}^1S_0 - {}^3P_0$	$I_3 = \pm 1$	$\delta\varepsilon_{0SP}$
	${}^3S_1 - {}^3P_1$	$I_3 = 0$	ε_{11SP}

J. de Vries, A. Gnech, S. Shain,
Phys. Rev. C **103** (2021) L012501

θ term

LO

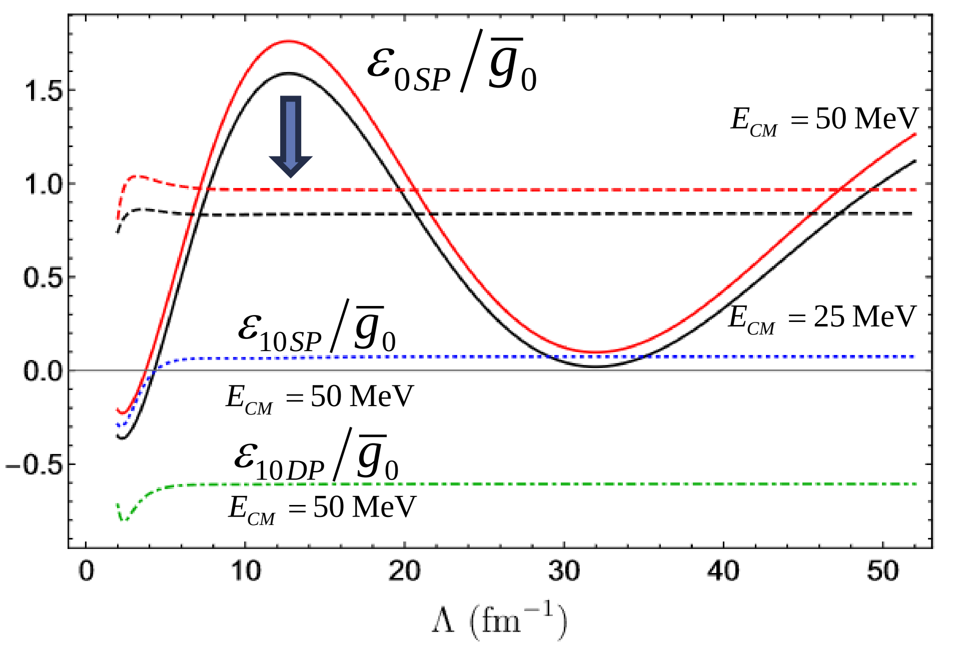


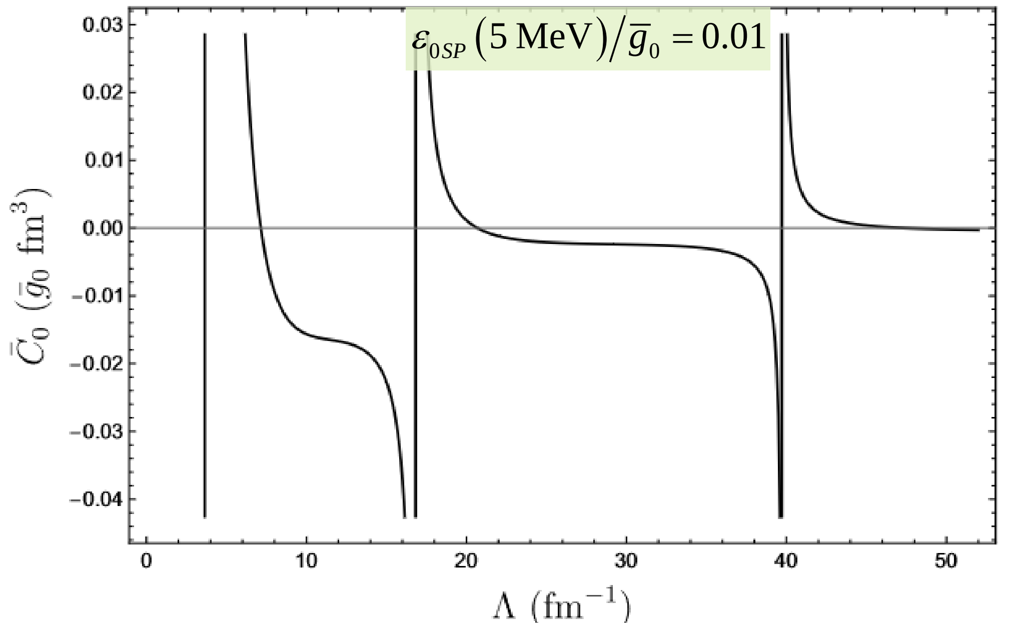
$\bar{C}_{1s} \equiv \bar{C}_1 - 3\bar{C}_2$

N^{2}LO $\mathcal{O}\left(\bar{\theta}\,\frac{m_\pi^2 Q}{f_\pi^2 M_{QCD}^3}\right)$ (NDA)

LO $\mathcal{O}\left(\bar{\theta}\,\frac{m_\pi^2}{Q\, f_\pi^2 M_{QCD}}\right)$

- appears only beyond deuteron
- in principle accessible in charge-symmetry-breaking pion production, e.g. $dd \to \alpha\pi^0$

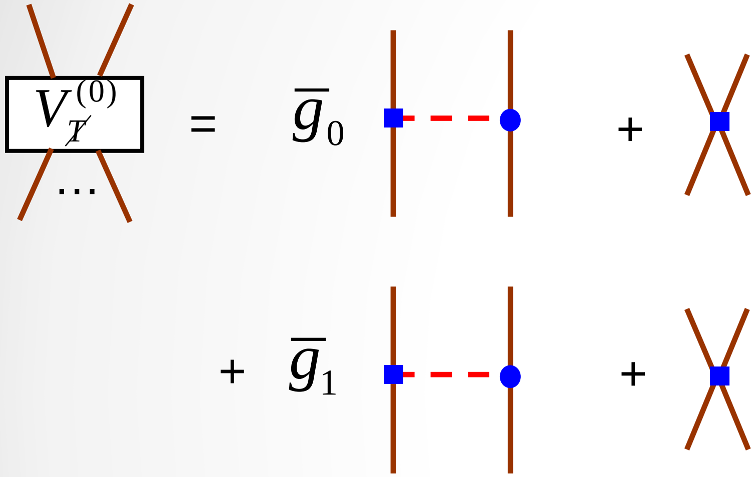




gCEDM, PSC, qEDM

potential relevant for EDMs only at subleading orders

qCEDM, LRC



$$\bar{C}_{1s} \equiv \bar{C}_1 - 3\bar{C}_2$$

$$\bar{C}_{3t} \equiv \bar{C}_{13} + \bar{C}_{31}$$

ε_{11SP} converges with cutoff

$\delta\varepsilon_{0SP}$ similar cutoff dependence

$$\mathcal{L}_{\pi\text{EFT}} = \ldots + \bar{C}_{13}\,\bar{N}N\,\partial_\mu\left(\bar{N}\,S^\mu\tau_3 N\right) + \bar{C}_{31}\,\bar{N}\tau_3 N\cdot\partial_\mu\left(\bar{N}\,S^\mu N\right) + \ldots$$

- appears beyond deuteron
- not directly obtained from other experiments

explains at least in part the dependence of matrix elements on short-range physics

What's needed?

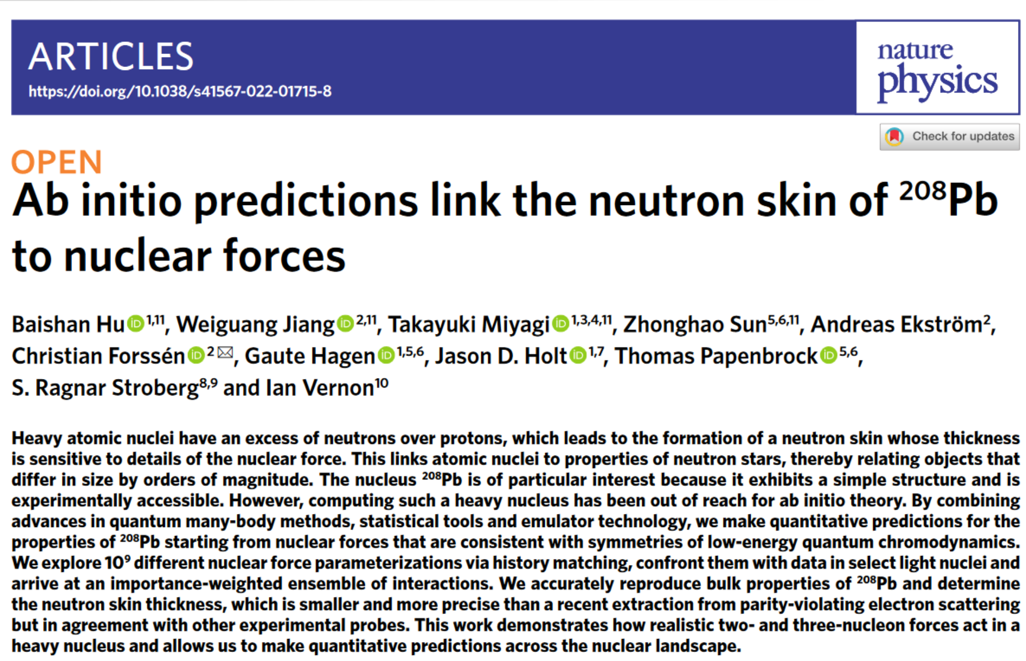
- Fully consistent triton and helion EDFFs;
  additional LECs at LO?

- Revised organization of interactions

- Other nuclear EDFFs and MQFFs in same framework;
  additional work on strong interactions and *ab initio* methods needed

cf. Yang, Ekström, Forssén, Hagen, Rupak + v.K. '23

The promise of nuclear *ab initio* methods



ARTICLES
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nature physics

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OPEN

Ab initio predictions link the neutron skin of ^{208}Pb to nuclear forces

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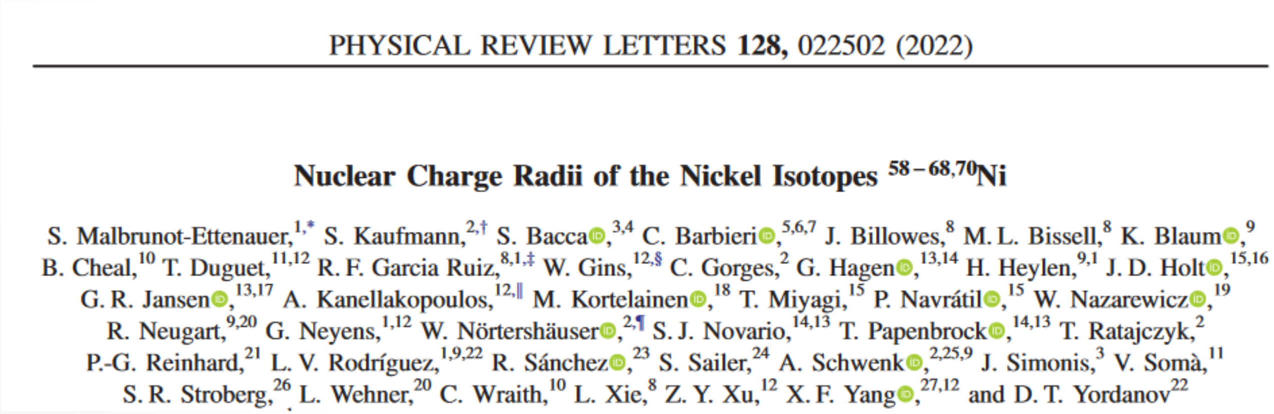
S. Ragnar Stroberg[8,9] and Ian Vernon[10]

Heavy atomic nuclei have an excess of neutrons over protons, which leads to the formation of a neutron skin whose thickness is sensitive to details of the nuclear force. This links atomic nuclei to properties of neutron stars, thereby relating objects that differ in size by orders of magnitude. The nucleus ^{208}Pb is of particular interest because it exhibits a simple structure and is experimentally accessible. However, computing such a heavy nucleus has been out of reach for ab initio theory. By combining advances in quantum many-body methods, statistical tools and emulator technology, we make quantitative predictions for the properties of ^{208}Pb starting from nuclear forces that are consistent with symmetries of low-energy quantum chromodynamics. We explore 10^9 different nuclear force parameterizations via history matching, confront them with data in select light nuclei and arrive at an importance-weighted ensemble of interactions. We accurately reproduce bulk properties of ^{208}Pb and determine the neutron skin thickness, which is smaller and more precise than a recent extraction from parity-violating electron scattering but in agreement with other experimental probes. This work demonstrates how realistic two- and three-nucleon forces act in a heavy nucleus and allows us to make quantitative predictions across the nuclear landscape.



PHYSICAL REVIEW LETTERS **128,** 022502 (2022)

Nuclear Charge Radii of the Nickel Isotopes $^{58-68,70}$Ni

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S. R. Stroberg,[26] L. Wehner,[20] C. Wraith,[10] L. Xie,[8] Z. Y. Xu,[12] X. F. Yang,[27,12] and D. T. Yordanov[22]

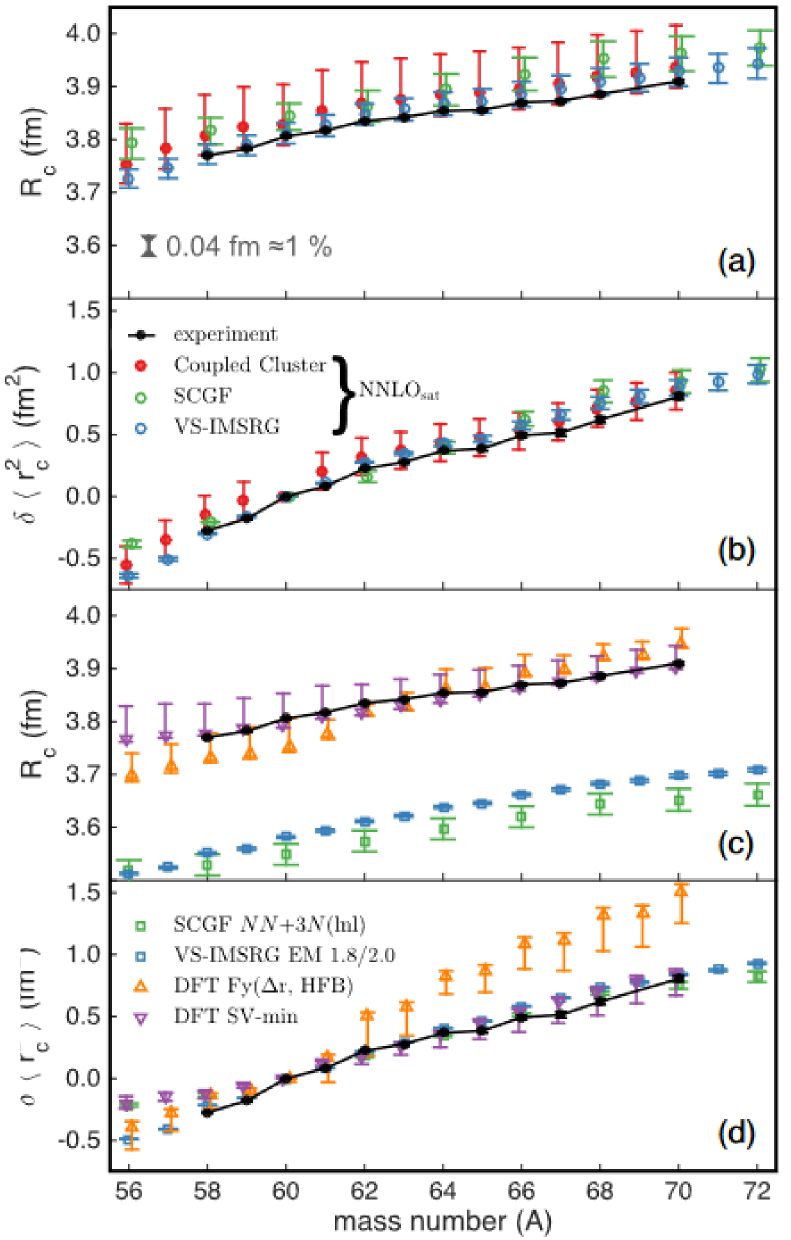

FIG. 2. Nuclear charge radii R_c (a,c) and differentials $\delta\langle r_c^2\rangle^{60,A}$ (b,d) of Ni isotopes with respect to ^{60}Ni as reference. Experimental data are compared to theoretical results. See text for details.

BUT INCONSISTENT WITH EFT…

J. Dobaczewski, J. Engel, M. Kortelainen, P. Becker, *Phys. Rev. Lett.* **121** (2018) 232501

Mean-field methods in terms of the same LECs?

cf.

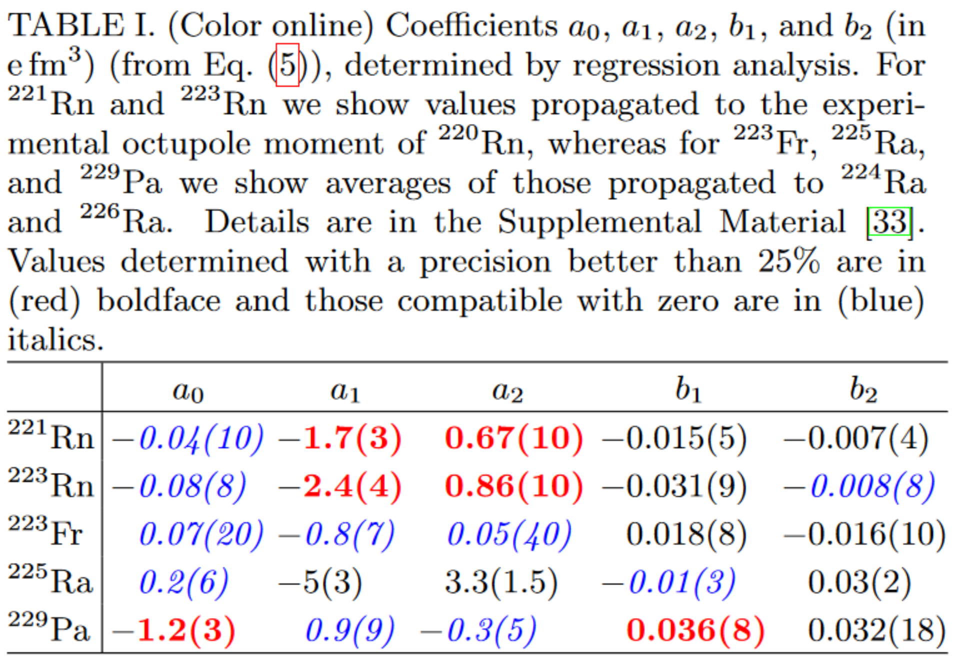

TABLE I. (Color online) Coefficients a_0, a_1, a_2, b_1, and b_2 (in e fm^3) (from Eq. (5)), determined by regression analysis. For ^{221}Rn and ^{223}Rn we show values propagated to the experimental octupole moment of ^{220}Rn, whereas for ^{223}Fr, ^{225}Ra, and ^{229}Pa we show averages of those propagated to ^{224}Ra and ^{226}Ra. Details are in the Supplemental Material [33]. Values determined with a precision better than 25% are in (red) boldface and those compatible with zero are in (blue) italics.

	a_0	a_1	a_2	b_1	b_2
^{221}Rn	*−0.04(10)*	**−1.7(3)**	**0.67(10)**	−0.015(5)	−0.007(4)
^{223}Rn	*−0.08(8)*	**−2.4(4)**	**0.86(10)**	−0.031(9)	*−0.008(8)*
^{223}Fr	*0.07(20)*	*−0.8(7)*	*0.05(40)*	0.018(8)	−0.016(10)
^{225}Ra	*0.2(6)*	−5(3)	3.3(1.5)	*−0.01(3)*	0.03(2)
^{229}Pa	**−1.2(3)**	*0.9(9)*	*−0.3(5)*	**0.036(8)**	0.032(18)

$$S=\frac{g_A m_N}{2 f_\pi^2}\left(a_0\bar{g}_0+a_1\bar{g}_1+a_2\bar{g}_2\right)+m_N^3\left(b_1\bar{C}_1+b_2\bar{C}_2\right)$$

More comprehensive analysis of SMs

Dekens, De Vries, Jung + Vos ’19

$$\mathcal{L}_{\pi\mathrm{EFT}}=\ldots+\bar{e}i\gamma_5 e\,\bar{N}\left(C_{S0}+C_{S1}\tau_3\right)N+4\,\bar{e}\sigma_{\mu\nu}e\,\bar{N}\left(C_{T0}+C_{T1}\tau_3\right)v^\mu S^\nu N+\bar{e}e\,\frac{\partial_\mu}{m_N}\left[\bar{N}\left(C_{P0}+C_{P1}\tau_3\right)S^\mu N\right]+\ldots$$

$\Uparrow$

eS'

- LECs in terms of SMEFT sources
- hierarchy for each source
- SMs for nuclei

Conclusion

EFTs connect symmetries violation
from beyond the Standard Model to nuclear physics
in a controlled and systematic way

Renormalization requires
short-range physics missed by nuclear models

Power counting leads to
organization of interactions in nuclear environment

Chiral symmetry allows
partial separation of symmetry-violating sources

But still…
plenty for PhD students to do with nuclear EDMs, MQMs, and SMs