SOME NUCLEAR ASPECTS OF THE SAKHAROV CONDITIONS

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Outline

- Matter vs Antimatter
- EFT and the Role of Nuclear Physics
- T Violation
- B Violation
- Conclusion

$$\eta \equiv \left.\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}\right|_{T \gtrsim 1\,\mathrm{GeV}} \sim \left.\frac{N_B - N_{\bar{B}}}{N_\gamma}\right|_{T \simeq 3\,\mathrm{K}} \sim \left.\frac{N_B}{N_\gamma}\right|_{T \simeq 3\,\mathrm{K}} \simeq 6 \cdot 10^{-10}$$

↰ $$\left.\frac{N_{\bar{B}}}{N_B}\right|_{T \simeq 3\,\mathrm{K}} \lesssim 10^{-6}$$

I. B ≠ 0 as an initial condition. Difficulty: washed out by inflation

II. B = 0 as initial condition but B ≠ 0 from “baryogenesis” (after inflation)

Requirements? Sakharov '67

☐ B violation:
ΔB ≠ 0 processes

Second part

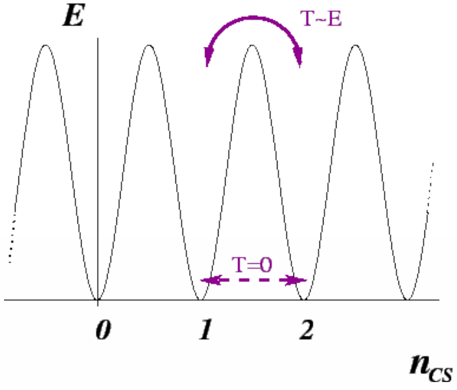
☐ deviation from thermal (and chemical) equilibrium:
ΔB > 0 and ΔB < 0 processes not to occur at the same rate

☐ C and CP violation:
B = 0 (B ≠ 0) state (not) invariant under C and CP

First part

In Standard Model, all conditions fulfilled but not sufficient:

- B violation:
  violated by non-perturbative quantum effects from non-Abelian electroweak gauge group --- sphaleron processes, efficient only at temperatures above M_{EW} ~ 100 GeV.



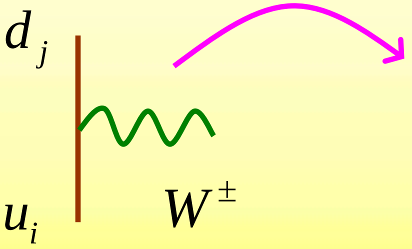
http://www-cdf.lbl.gov/~jmuelmen/www/Microphysical_mechanisms.html

- deviation from thermal (and chemical) equilibrium:
  provided by expansion of the universe,
  but much too slow above M_{EW} ~ 100 GeV.

- C and CP violation:
  both violated by weak interaction, but $\cancel{CP}$ too small.

Kobayashi + Maskawa '73

Wolfenstein '83



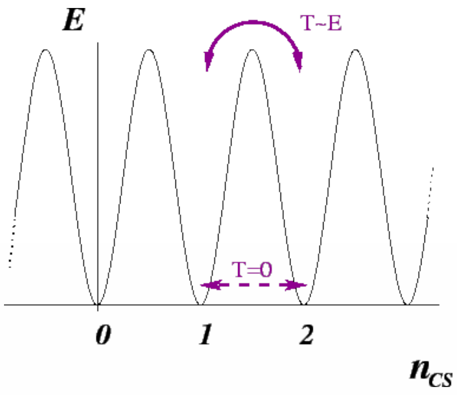
$$U_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho - \enclose{circle}{i\eta}) \\ -\lambda & 1-\lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1-\rho-\enclose{circle}{i\eta}) & -\lambda^2 A & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda \cong 0.23 \qquad A \cong 0.8 \qquad \rho \cong 0.1 \qquad \enclose{circle}{\eta} \cong 0.3$$

$$J_{CP} = A^2 \lambda^6 \enclose{circle}{\eta} + \mathcal{O}(\lambda^8) \simeq 3 \cdot 10^{-5}$$

Jarlskog '85

In Standard Model, all conditions fulfilled but not sufficient:



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- B violation:
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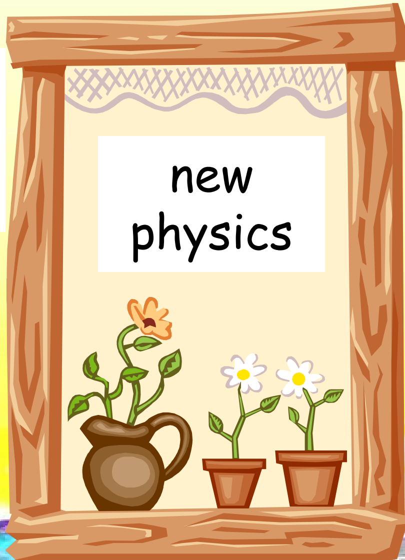
- deviation from thermal (and chemical) equilibrium:
  provided by expansion of the universe, but much too slow above $M_{EW} \sim 100$ GeV.
- C and CP violation:
  both violated by weak interaction, but $\cancel{CP}$ too small.

$$J_{CP}\left(m_t^2-m_b^2\right)\left(m_t^2-m_u^2\right)\left(m_c^2-m_u^2\right)\left(m_b^2-m_s^2\right)\left(m_b^2-m_d^2\right)\left(m_s^2-m_d^2\right)\Big/M_{EW}^{12}$$

$$\sim 10^{-20} \ll \eta$$

e.g. Canetti, Drewes + Shaposhnikov '12



> "Every disadvantage has its advantage."
> J. Cruijff (b. 1947), Dutch ~~soccer player~~ philosopher

Opportunity:
any new signal of $\not{T}$, $\not{B}$
is likely to represent new physics

Issue:
once a signal is observed,
how many/which observables do we need to
identify the new source(s) of $\not{T}$, $\not{B}$?

Strategy:
use Effective Field Theory
to study various $\not{T}$, $\not{B}$ effects

The Way of EFT

Q

$M_T, M_{|\Delta B|=1}, M_{|\Delta B|=2}, \ldots \sim ?$

unknown physics

$M_{EW} \sim \langle \varphi \rangle, m_Z, m_W$

$\sim 100\ \mathrm{GeV}$

Standard Model
(incl higher dim ops)

quarks, gluons,
leptons, photon,
weak bosons, Higgs
(+dark matter)

$SO(3,1), SU(3)_c \times SU(2)_L \times U(1)_Y$

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

$\sim 1\ \mathrm{GeV}$

QCD

up + down quarks, gluons,
electron, …, photon

$SO(3,1), SU(3)_c \times U(1)_{em}$

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

$\sim 100\ \mathrm{MeV}$

hadronic
+ nuclear
physics

Chiral EFT
(χPT)

nucleons, pions,
electron, …, photon

$SO(3,1), U(1)_{em},$

$\cancel{SU_L(2) \times SU_R(2)}$

$M_{at} \sim \alpha\, m_e$

$\sim 3\ \mathrm{keV}$

atomic
physics

QED

nuclei,
electron, …, photon

$SO(3,1), U(1)_{em}$

Main Idea

Q

$M_{EW} \sim \langle \varphi \rangle, m_Z, m_W$

$\sim 100\ \text{GeV}$

Standard Model (incl higher dim ops)

quarks, gluons,
leptons, photon,
weak bosons, Higgs
(+dark matter)

$SO(3,1), SU(3)_c \times SU(2)_L \times U(1)_Y$

$$\mathcal{L}_{SM} = \mathcal{L}_S(q,G) + \sum_i O_{\not{S}\, i}(q,G)$$

preserves symmetry S

violate S and transform in specific ways under χ symmetry

hadronic + nuclear physics

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

$\sim 100\ \text{MeV}$

Chiral EFT

(χPT)

nucleons, pions,
electron, …, photon

$SO(3,1), U(1)_{em},$

χ symmetry $\cancel{SU_L(2) \times SU_R(2)}$

$$\mathcal{L}_{\chi EFT} = \mathcal{L}_S(\pi, N) + \sum_i \sum_\Delta O^{(\Delta)}_{\not{S}\, i}(\pi, N)$$

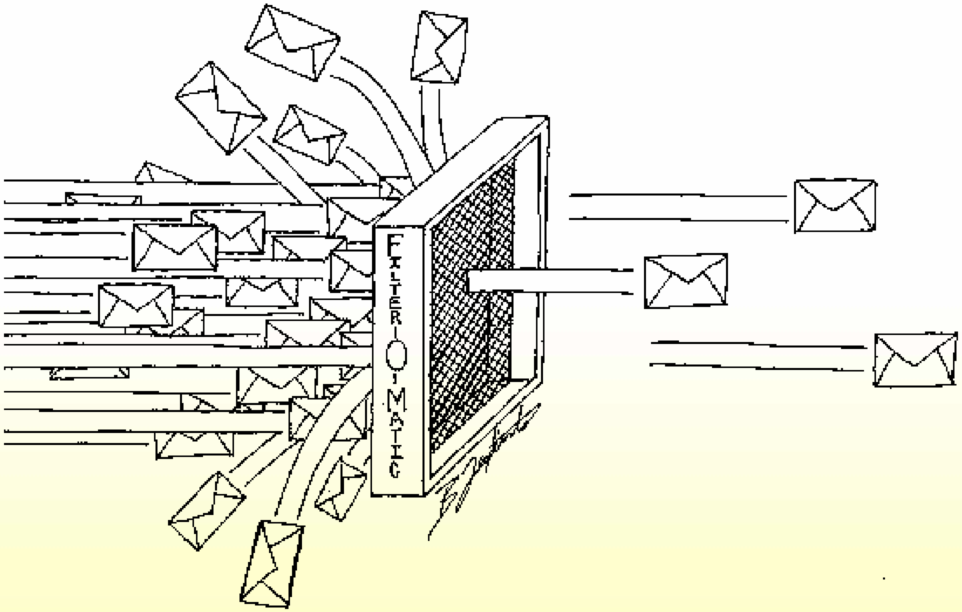
preserves symmetry S

give rise to specific relations among S-violating observables

Chiral Nuclear Filter

BSM models

source of
S violation



low-energy symmetry (violation)

chiral symmetry

T VIOLATION

following

Effective Field Theory and Time-Reversal Violation in Light Nuclei

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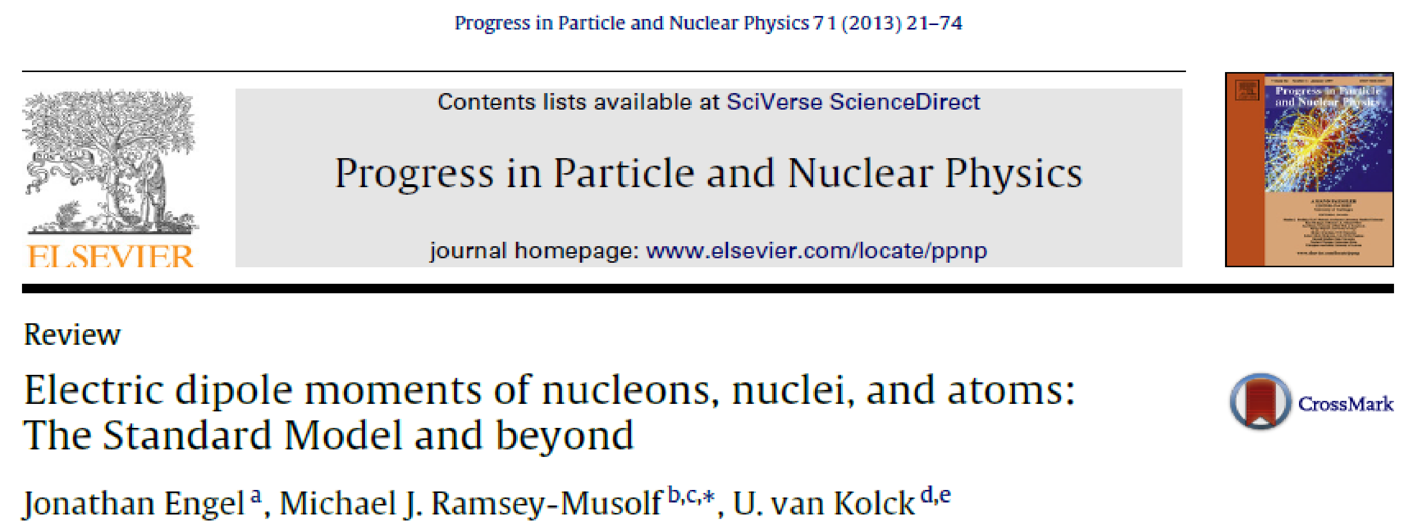
Keywords

fundamental symmetries, electric dipole moments, Standard Model and beyond, strong interactions, few-nucleon systems



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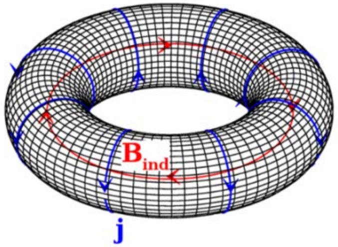
Review

Electric dipole moments of nucleons, nuclei, and atoms: The Standard Model and beyond

Jonathan Engel[a], Michael J. Ramsey-Musolf[b,c,*], U. van Kolck[d,e]

for much more …

Electromagnetic Form Factors



polarity	Electric	Magnetic	Toroidal
0 (charge, mono)	P,T	$\varnothing$	$\varnothing$
1 (di, ana)	$\cancel{P},\cancel{T}$	P,T	$\cancel{P},T$
2 (quadru)	P,T	$\cancel{P},\cancel{T}$	$P,\cancel{T}$
etc.			

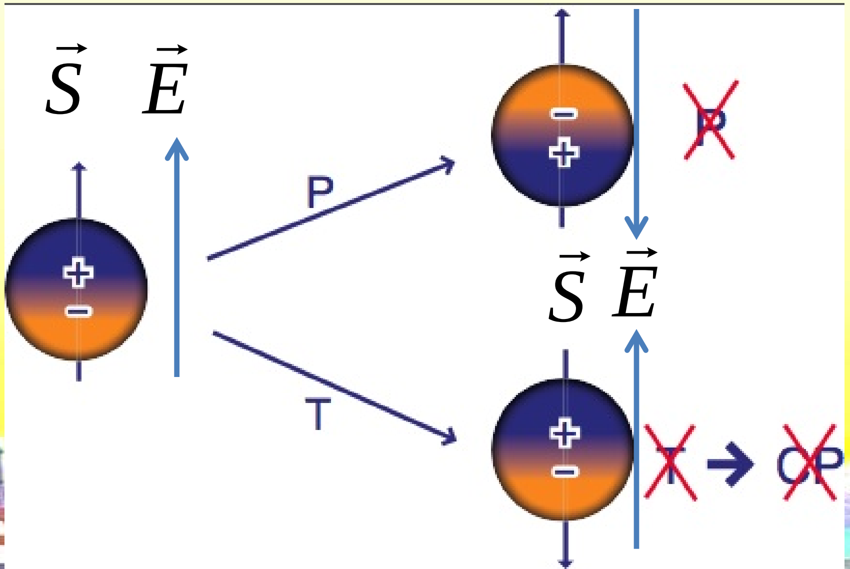
$S=0$

$S=1/2$

$S=1$

(Permanent) Electric Dipole Moment (EDM)

$$H_{edm} = -\underbrace{d\,\vec{S}}_{\vec{d}}\cdot\vec{E}\;\begin{cases}\xrightarrow{P} -d\,\vec{S}\cdot\left(-\vec{E}\right) = -H_{edm}\\[2ex] \xrightarrow{T} -d\left(-\vec{S}\right)\cdot\vec{E} = -H_{edm}\end{cases}$$



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

Weak interactions: $d_n \sim e \frac{G_F^2}{(4\pi)^4} \left(\frac{m_t}{M_W} \right)^2 J_{CP} \left(4\pi f_\pi \right)^3 \approx 10^{-19} e\,\mathrm{fm}$

e.g. Donoghue, Golowich + Holstein '92

Experiment:

$d_n = \left(0.2 \pm 1.5(\mathrm{stat}) \pm 0.7(\mathrm{syst}) \right) \cdot 10^{-13} e\ \mathrm{fm}$

Baker *et al* '06 (ILL)

$\sim\!\triangleright 10^{-15} e\ \mathrm{fm}$ (UCN, proposed)

Bodek *et al* (ILL+PSI)
Budker *et al* (SNS)

$\left| d_{Hg} \right| < 3.1 \cdot 10^{-16} e\ \mathrm{fm}$ (95% c.l.) Griffith *et al* '09 (UW)

Nuclear Schiff moment from RPA, …

Dmitriev + Sen'kov '03

$\left| d_p \right| < 7.9 \cdot 10^{-12} e\ \mathrm{fm}$

$\left| d_d \right| \sim\!\triangleright 10^{-16} e\ \mathrm{fm}$ (storage ring, proposed)

Orlov *et al* (BNL? COSY?)

Proton and 3He as well? How about 3H?

The Way of EFT

Q

$M_T \sim ?$

$M_{EW} \sim \langle \varphi \rangle, m_Z, m_W$

$\sim 100\ \text{GeV}$

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

$\sim 1\ \text{GeV}$

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

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unknown physics

Standard Model
(incl higher dim ops)

quarks, gluons,
leptons, photon,
weak bosons, Higgs
(+dark matter)

$SO(3,1), SU(3)_c \times SU(2)_L \times U(1)_Y$

neglected here

$M_{EW} \sim \langle \varphi \rangle, m_Z, m_W \sim 100\ \text{GeV}$

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

CKM matrix (dim=4)

Jarlskog '85

$J_{CP} \simeq 3 \cdot 10^{-5}$

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

small...

't Hooft '76

e.g. single Higgs $\varphi_u^i = \varepsilon^{ij} \varphi_{dj}^*$

$\tilde{G}_{\mu\nu} \equiv \varepsilon_{\mu\nu\rho\sigma} G^{\rho\sigma}$

θ term (dim=4)

$\bar{\theta} \lesssim 10^{-10}$

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

→ quark color-EDM (eff dim=6)

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

→ quark EDM (eff dim=6)

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

→ gluon color-EDM (dim=6)

dimension ↓

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

→ four-quark contact (dim=6)

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

$$+ \ldots$$

→ LR four-quark contact (dim=6)

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

The Way of EFT

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

$\sim 100\ \mathrm{MeV}$

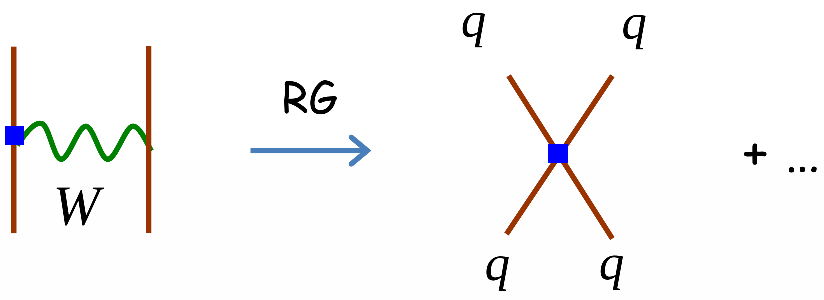
$M_{at} \sim \alpha\, m_e$

$\sim 3\ \mathrm{keV}$

QCD

up + down quarks, gluons,
electron, …, photon
$SO(3,1), SU(3)_c \times U(1)_{em}$

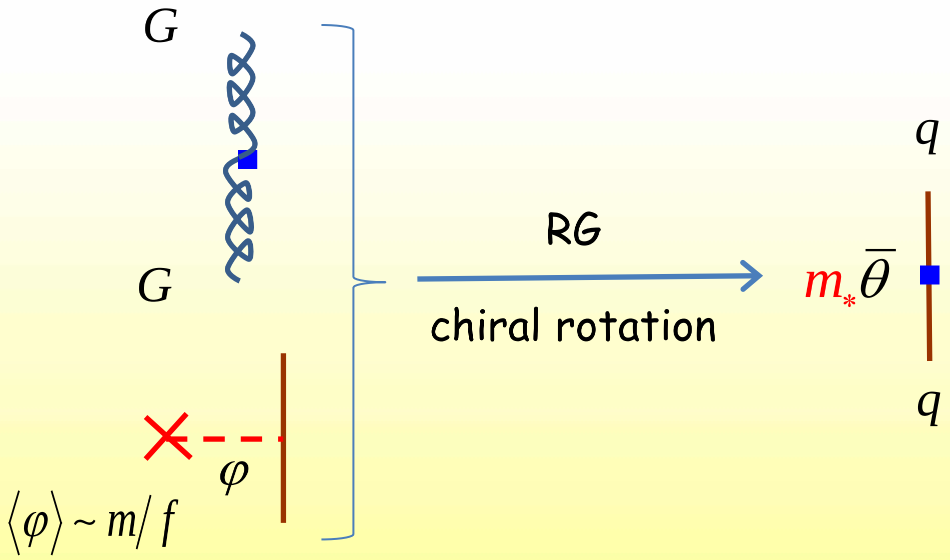
$$M_{QCD} \sim m_N, m_\rho, 4\pi f_\pi, \ldots \sim 1\,\mathrm{GeV}$$



up/down quarks

very small...

neglected from now on...



imaginary mass term

Baluni '79

$$m_* \bar{\theta} = \frac{\bar{m}}{2}\left(1-\varepsilon^2\right)\bar{\theta}$$

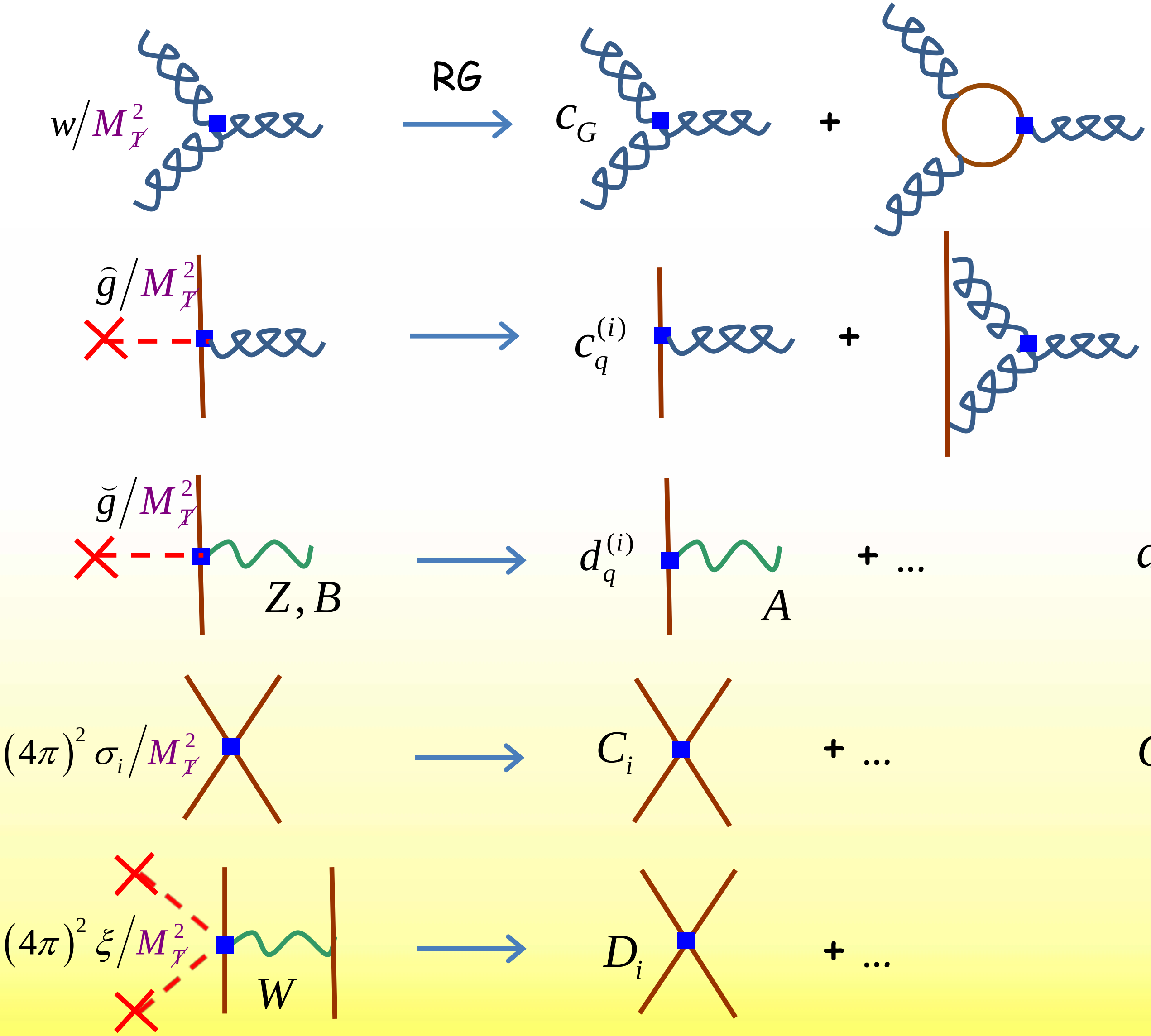
$$\bar{m} \equiv \frac{m_u + m_d}{2} \approx 4\,\mathrm{MeV}$$

average quark mass

$$\varepsilon \equiv \frac{m_d - m_u}{m_u + m_d} \simeq \frac{1}{3}$$

mass splitting

…
Dekens + De Vries '13



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

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

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

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

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

generically, RG brings in effects of $\mathcal{O}(1)$

$$\mathcal{L}_{QCD} = \bar{q}\left(i\not{\partial} + g_s \not{G}\right)q - \frac{1}{2}\mathrm{Tr}\, G^{\mu\nu}G_{\mu\nu}$$

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

$$-\bar{m}\ \bar{q}q + \varepsilon \bar{m}\ \bar{q}\tau_3 q + \frac{\bar{m}}{2}\left(1-\varepsilon^2\right)\bar{\theta}\ \ \bar{q}i\gamma_5 q$$

θ

$$-\frac{1}{2}\bar{q}\left(c_q^{(0)} + c_q^{(1)}\tau_3\right)\sigma_{\mu\nu}\tilde{G}^{\mu\nu}q$$

qCEDM

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

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

$$+\frac{c_G}{6}\ f^{abc}\,G_{\mu\nu}^{a}\tilde{G}^{b\nu\rho}G_{\rho}^{c\,\mu}$$

gCEDM

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

$$+\frac{C_1}{4}\left(\bar{q}q\ \bar{q}i\gamma_5 q - \bar{q}\boldsymbol{\tau}q\cdot\bar{q}i\gamma_5\boldsymbol{\tau}q\right)$$

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

CIC

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

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

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

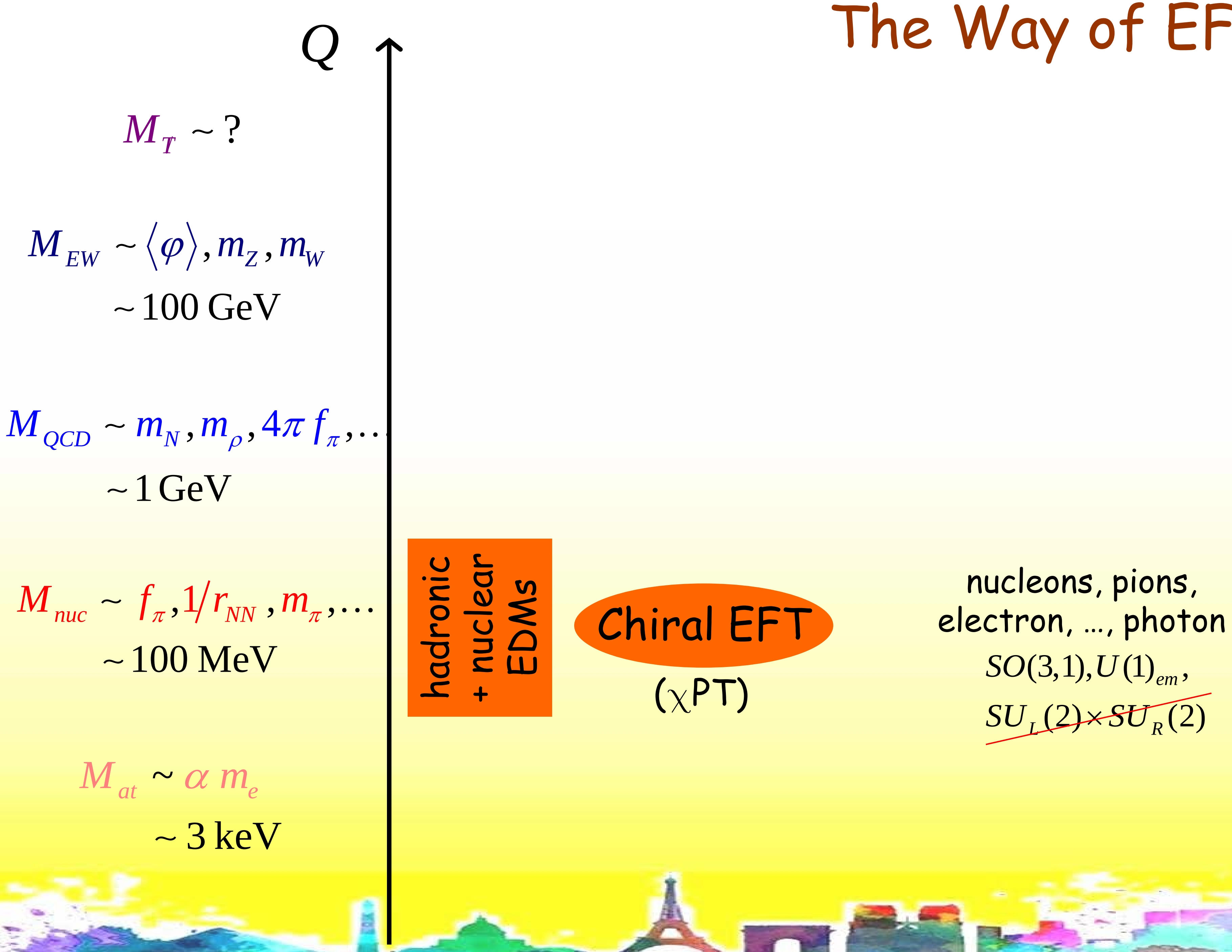
LRC

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

$$+\ldots$$

N.B. To this order, $\not{T} \to \not{P}$

The Way of EFT



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hadronic
+ nuclear
EDMs

Chiral EFT

(χPT)

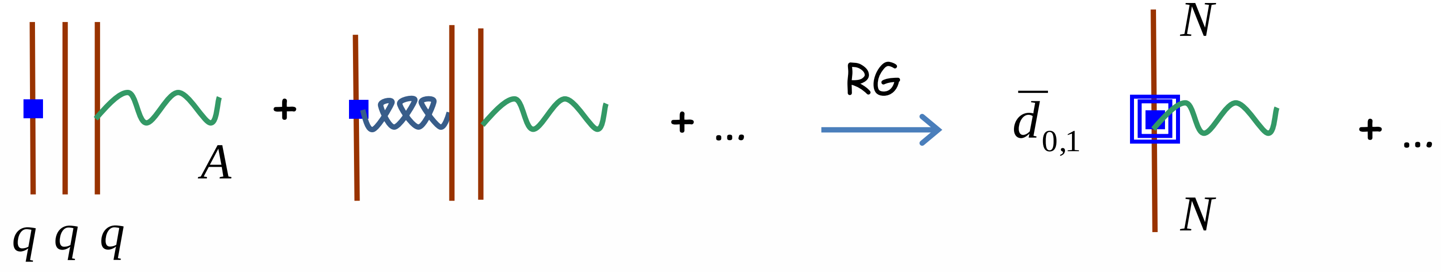
nucleons, pions,
electron, …, photon

$SO(3,1), U(1)_{em},$

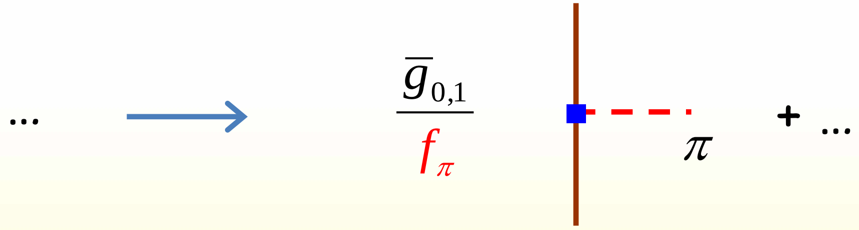
$\cancel{SU_L(2)\times SU_R(2)}$

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

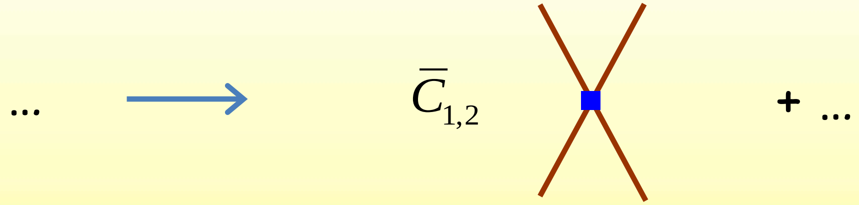
$M_{nuc} \sim f_\pi, 1/r_{NN}, m_\pi, \ldots \sim 100\ \text{MeV}$



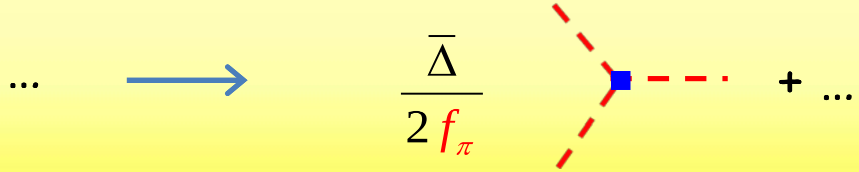
short-range
isoscalar
and isovector
(-> proton
and neutron)
EDMs



isoscalar and isovector
$\cancel{P}, \cancel{T}$
pion-nucleon couplings



isoscalar and isovector
(derivative) $\cancel{P}, \cancel{T}$
2-nucleon contacts



three-pion coupling

$$\mathcal{L}_{QCD} = \bar{q}\left(i\not{\partial} + g_s \not{G}\right)q - \frac{1}{2}\mathrm{Tr}\, G^{\mu\nu}G_{\mu\nu}$$

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

$$\longrightarrow \quad SU_L(2)\times SU_R(2) \sim SO(4)$$

chiral symmetry

$$- \bar{m}\,\bar{q}q + \varepsilon \bar{m}\,\bar{q}\tau_3 q + \frac{\bar{m}}{2}\left(1-\varepsilon^2\right)\bar{\theta}\;\bar{q}i\gamma_5 q$$

θ

$$-\frac{1}{2}\bar{q}\left(c_q^{(0)} + c_q^{(1)}\tau_3\right)\sigma_{\mu\nu}\tilde{G}^{\mu\nu}q$$

qCEDM

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

$$-\frac{1}{2}\bar{q}\left(d_q^{(0)} + d_q^{(1)}\tau_3\right)\sigma_{\mu\nu}q\;\tilde{F}^{\mu\nu}$$

qEDM

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

$$+\frac{c_G}{6}\;f^{abc}\,G^a_{\mu\nu}\tilde{G}^{b\nu\rho}G_\rho^{c\,\mu}$$

gCEDM

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

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

CIC

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

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

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

LRC

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

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

$$+\ldots$$

N.B. To this order, $\not{T} \to \not{P}$

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

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

θ 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
CIC
} CI chiral invariants: cannot be separated at low energies, $\{w, \sigma_{1,8}\} \rightarrow w$

$$\mathcal{L}_{\chi PT} = N^\dagger\left(iv\cdot\mathcal{D}+\frac{\mathcal{D}^2}{2m_N}\right)N+\ldots$$

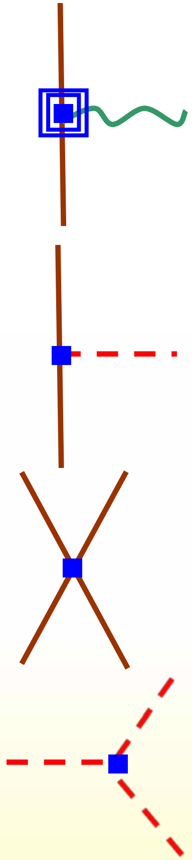
$$-2\,N^\dagger\left(\bar{d}_0+\bar{d}_1\tau_3\right)S_\mu N\,v_\nu F^{\mu\nu}$$

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

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

$$-\frac{\bar{\Delta}}{2\,f_\pi}\boldsymbol{\pi}^2\pi_3$$

$$+\ldots$$



short-range EDM contribution

PV, TV pion-nucleon coupling

PV, TV two-nucleon contact

three-pion coupling

$$\bar{\Delta}=\frac{m_\pi^2\bar{g}_0}{(m_n-m_p)_{\mathrm{qm}}}$$

only for LRC

terms related by chiral symmetry + higher orders

$v^\mu=\left(1,\vec{0}\right)$ velocity

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

six LO couplings for EDMs

cf. Barton '61 and nuclear followers

Where are the differences?

There are differences!   For example,

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

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

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

different orders;
two-derivative interactions
important 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.*

$$\bar{g}_0 \simeq \frac{\bar{\theta}}{2\varepsilon}\left(m_n - m_p\right)_{\text{qm}}$$

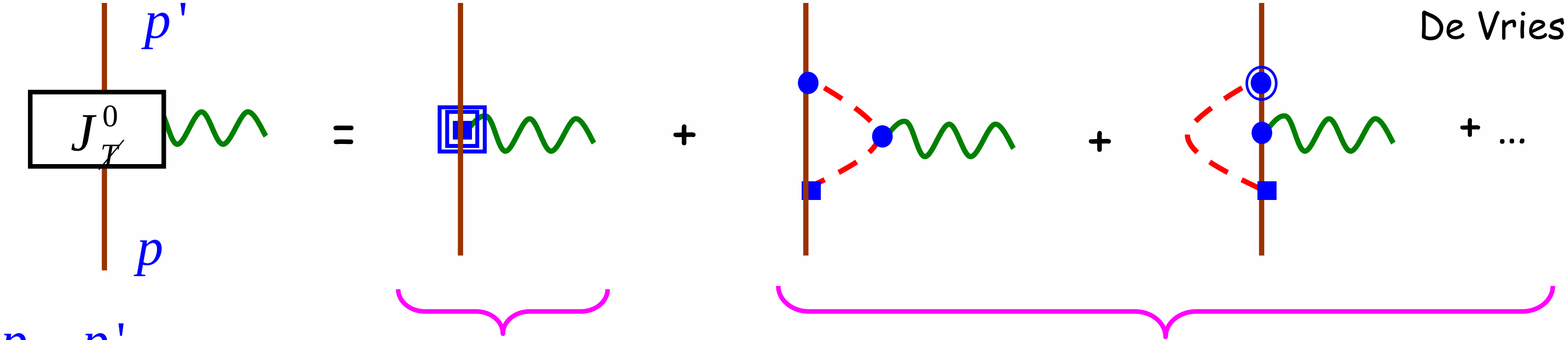
$$\approx 3\,\bar{\theta}\ \text{MeV}$$

Mereghetti,
Hockings + v.K. '10

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)



$q = p - p'$

$k = \frac{1}{2}(p + p') - m_N v$

short-ranged;

LO for all sources

- ensures RG invariance
- brings in two parameters

long-ranged;

order depends on source

- provides estimates in terms of pion parameters at "reasonable" renormalization scale

$$J_T^\mu(q,k) = -2\left(\eta^{\mu\rho}q^\sigma - \eta^{\mu\sigma}q^\rho\right)S^\nu\left[\left(v_\rho + \frac{k_\rho}{m_N}\right)\eta_{\nu\sigma} + \ldots\right]\left(F_{E1}^{(0)}(-q^2) + F_{E1}^{(1)}(-q^2)\,\tau_3\right)$$

$$F_{E1}^{(i)}(-q^2) = d^{(i)} + S'^{(i)}\, q^2 + H^{(i)}(-q^2)$$

EDM + Schiff moment + ...

$$d^{(1)} = \bar{d}^{(1)} + \frac{e g_A \bar{g}_0}{(4\pi f_\pi)^2}\left[L + 2\ln\frac{\mu}{m_\pi} + \frac{5\pi}{4}\frac{m_\pi}{m_N}\left(1+\frac{\bar{g}_1}{5\bar{g}_0}\right) - \frac{\left(m_{\pi^\pm}^2 - m_{\pi^0}^2\right)_{\mathrm{em}}}{m_\pi^2} + \mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)\right]$$

$$L \equiv \frac{2}{4-d} - \gamma_E + \ln 4\pi$$

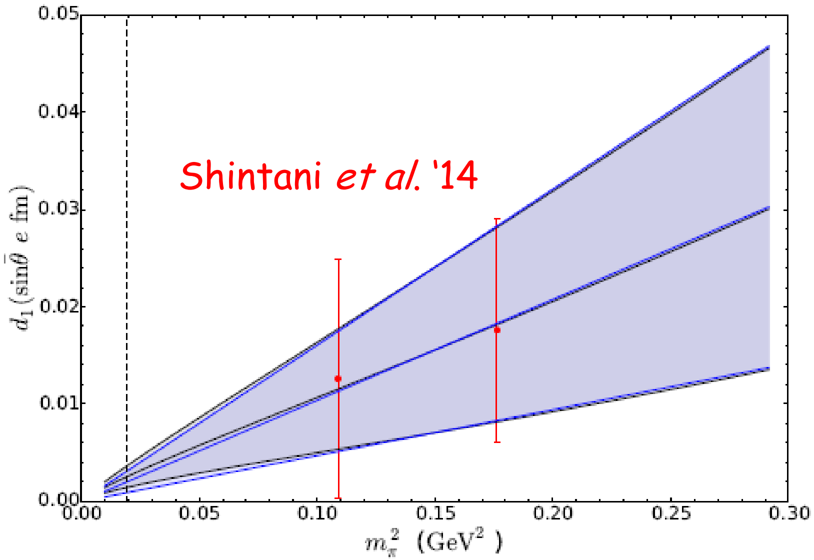
renormalization

$$\theta \quad |d_n| \gtrsim \frac{2 e g_A \delta m_N}{(4\pi f_\pi)^2}\frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta}\ln\frac{m_N}{m_\pi} \approx 2.0\cdot 10^{-3}\,\bar{\theta}\, e\, \mathrm{fm}$$

cf. Crewther *et al*`79

$$d^{(0)} = \bar{d}^{(0)} + \frac{\pi e g_A \bar{g}_0}{(4\pi f_\pi)^2}\left[0 + \frac{3 m_\pi}{4 m_N}\left(1+\frac{\bar{g}_1}{3\bar{g}_0}\right) - \frac{\left(m_n - m_p\right)_{\mathrm{qm}}}{m_\pi} + \mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)\right]$$

$$\theta \quad |d^{(0)}| \gtrsim \frac{e g_A \delta m_N}{(4\pi f_\pi)^2}\frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta}\left[\frac{3\pi}{4}\frac{m_\pi}{m_N} - \frac{\delta m_N}{m_\pi}\right] \approx 1.4\cdot 10^{-4}\,\bar{\theta}\, e\, \mathrm{fm}$$



Example from lattice

Mereghetti + vK '15

no sign of chiral loop, but

consistent with naïve estimate

$$\bar{d}_0(\mu) = (-0.04 \pm 0.45)\,\frac{m_\pi^2}{(2\pi F_\pi)^3}\, e \sin\bar{\theta}$$

$$\bar{d}_1(\mu) = (0.05 \pm 0.45)\,\frac{m_\pi^2}{(2\pi F_\pi)^3}\, e \sin\bar{\theta}$$

Thomas '95

$$S'^{(1)} = \frac{e g_A \bar{g}_0}{6(4\pi f_\pi)^2 m_\pi^2}\left[1-\frac{5\pi}{4}\frac{m_\pi}{m_N}-\frac{\left(m_{\pi^\pm}^2-m_{\pi^0}^2\right)_{\text{em}}}{m_\pi^2}+\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)\right]$$

only parameter!

θ

$\simeq 6.8\cdot 10^{-5}\,\bar{\theta}\,e\,\text{fm}^3$

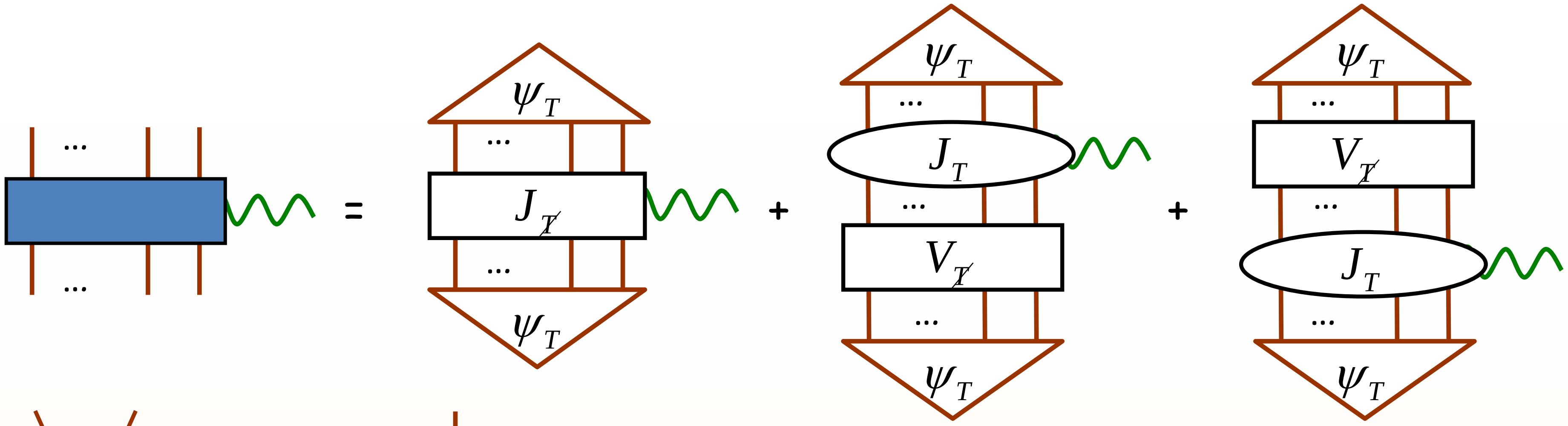
$$S'^{(0)} = -\frac{e g_A \bar{g}_0}{6(4\pi f_\pi)^2 m_\pi^2}\left[0+\frac{\pi}{2}\frac{\left(m_n-m_p\right)_{\text{qm}}}{m_\pi}+\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)\right]$$

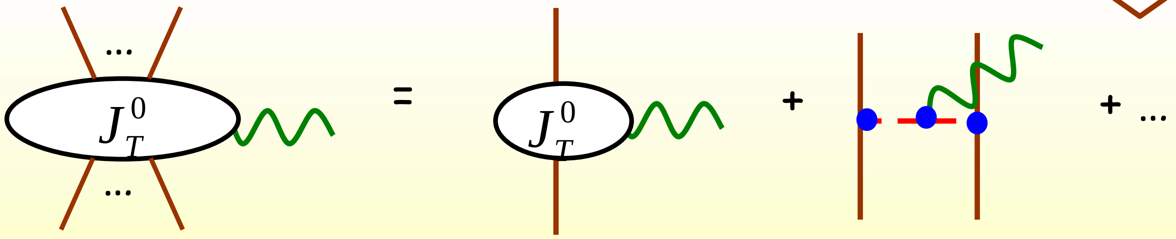
θ

$\simeq -5.0\cdot 10^{-6}\,\bar{\theta}\,e\,\text{fm}^3$

momentum dependence of EDFF from lattice would isolate $\bar{g}_0$

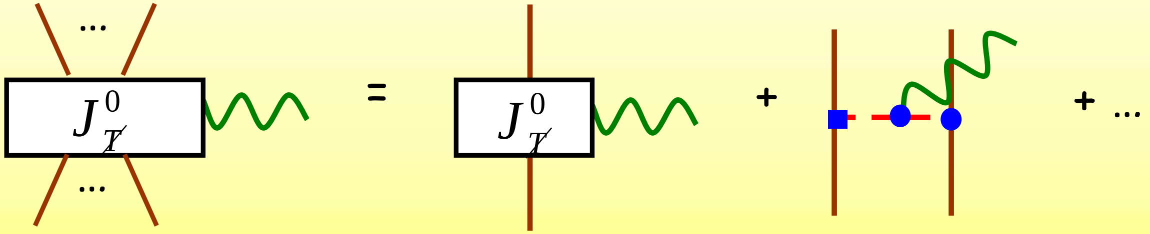
Nuclear EDMs, MQMs, …





Park, Min + Rho '95

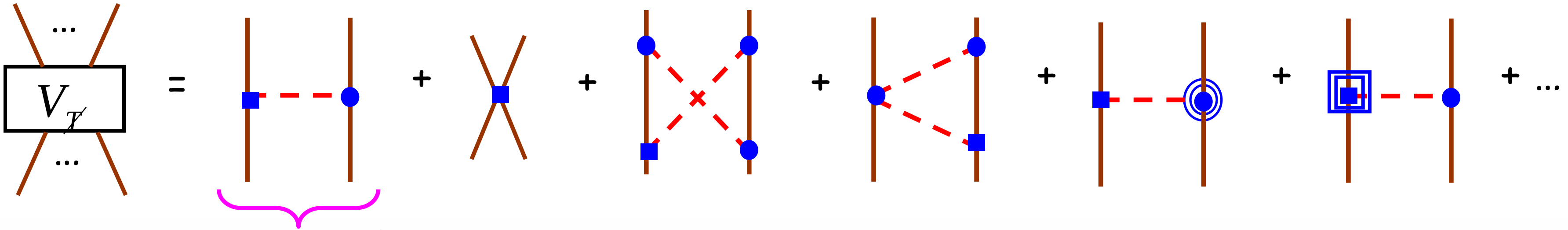
…



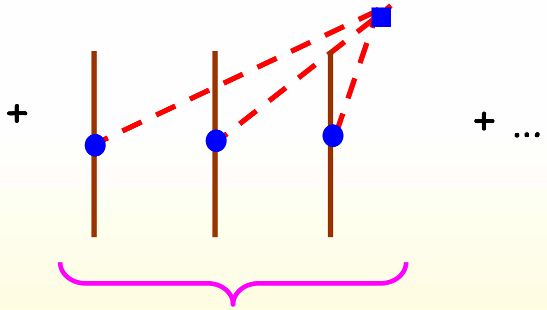
De Vries, Mereghetti,
Higa, Liu, Stetcu,
Timmermans + v.K. '11

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

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



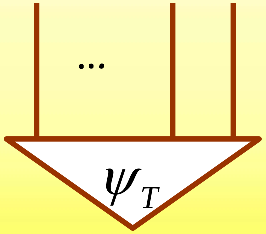
generic LO,
but effect vanishes for θ when N=Z



LO for LRC only

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

Weinberg ’90, ‘91
Ordónez + v.K. ‘92
…



from solution of the Schrödinger equation

introduces dependence on binding energy B_A

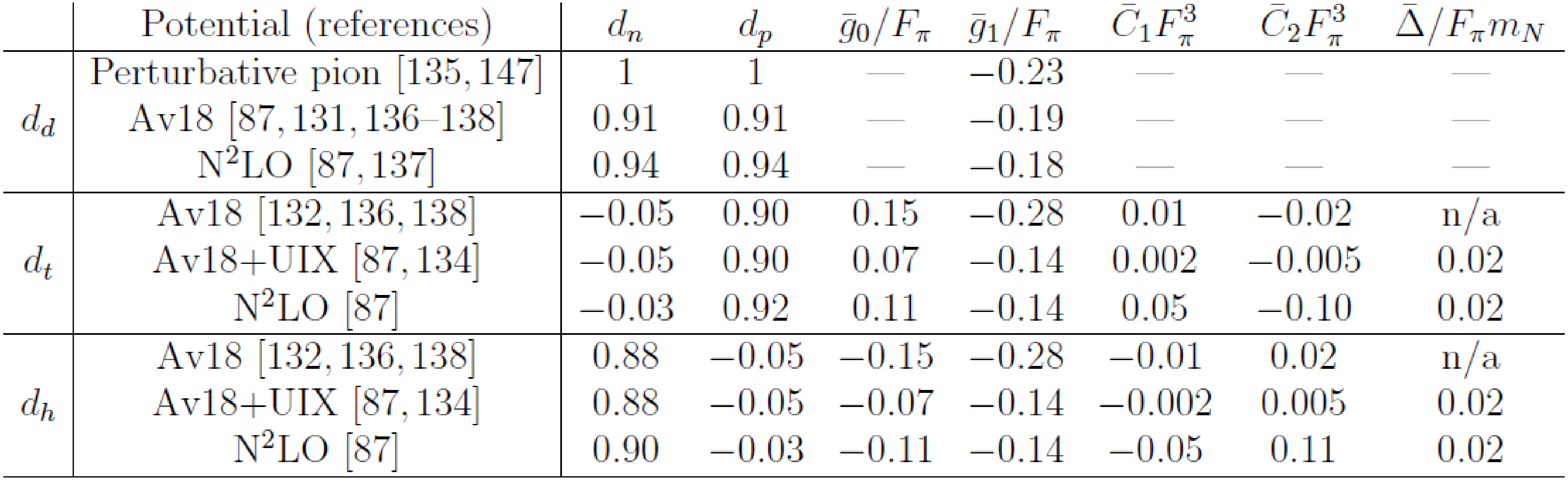
Crewther *et al.* '79
Thomas '95
…
De Vries *et al.* '10'11

Light-Nuclear EDMs (LO)

De Vries *et al* '11 '13
Bsaisou *et al* '13 '14 '15

	θ term	qCEDM	LRC	qEDM	gCEDM, CIC
$m_n \frac{d_n}{e}$	$\mathcal{O}\left(\bar\theta \frac{M_{nuc}^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{\widehat{g}}{f} \frac{M_{nuc}^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\xi \frac{M_{QCD}^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\frac{\breve{g}}{f} \frac{M_{nuc}^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(w \frac{M_{QCD}^2}{M_{\not T}^2}\right)$
$\frac{d_p}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\frac{d_d}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{M_{nuc}^2}\right)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{M_{nuc}^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\frac{d_h}{d_n}$	$\mathcal{O}\left(\frac{M_{QCD}^2}{M_{nuc}^2}\right)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{M_{nuc}^2}\right)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{M_{nuc}^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\frac{d_t}{d_h}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

Mereghetti + vK '15



	Potential (references)	d_n	d_p	$\bar{g}_0/F_\pi$	$\bar{g}_1/F_\pi$	$\bar{C}_1 F_\pi^3$	$\bar{C}_2 F_\pi^3$	$\bar{\Delta}/F_\pi m_N$
d_d	Perturbative pion [135, 147]	1	1	—	-0.23	—	—	—
	Av18 [87, 131, 136–138]	0.91	0.91	—	-0.19	—	—	—
	N^2LO [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^2LO [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^2LO [87]	0.90	-0.03	-0.11	-0.14	-0.05	0.11	0.02

[135] De Vries *et al* '11

[131] Liu + Timmermans '04

[138] Yamanaka + Hiyama '15

[147] Khriplovich + Korkin '00

[136] De Vries *et al* '11

[132] Stetcu *et al* '08

[87] Bsaisou *et al* '15

[137] Bsaisou *et al* '13

[134] Song *et al* '13

all agree to 10% or better

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

some separation of sources possible

B VIOLATION

in progress,
with
Bingwei Long (Sichuan)
and
Jan Bakker (Groningen),
Rob Timmermans (Groningen),
Jordy de Vries (NIKHEF)

Weinberg '79
Wiczek + Zee '79
Abbott + Wise '82
…

Chang + Chang '80
Kuo + Love '80
Rao + Shrock '82
…

$$\mathcal{L}_{\mathcal{SM}} = \mathcal{L}_B(q,G) + \sum_i \frac{C^{(i)}_{|\Delta B|=1}}{M^2_{|\Delta B|=1}}[qqql]_i + \ldots + \sum_i \frac{C^{(i)}_{|\Delta B|=2}}{M^5_{|\Delta B|=2}}\left[q^T C q\, q^T C q\, q^T C q\right]_i + \ldots$$

dim=6

$$|\Delta B| = 1,\ \Delta L = \Delta B$$

dim=9

$$|\Delta B| = 2,\ \Delta L = 0$$

interesting only if

$$\begin{cases} B - L \text{ not exact} & \text{(why would it be?)} \\ M_{|\Delta B|=2} \ll M_{|\Delta B|=1} & \text{(true in some models)} \end{cases}$$

RG ↓

Abbott + Wise '82
…

Özer '82
Caswell, Milutinović + Senjanović '83
…
Buchoff + Wagman '15

Conclusion

- Baryon asymmetry in the universe suggests that new sources of $\not{B}$, $\not{T}$ might be important, but they must exist anyway because B, T broken already in SM
- EFT provides a model-independent framework for $\not{B}$, $\not{T}$ in the SM and beyond
- Chiral symmetry provides a handle to (partially) distinguish $\not{B}$, $\not{T}$ sources at low energies
- Light-nuclear EDM measurements could provide the needed data to isolate $\not{T}$ sources
- $\not{B}$ in progress
- Stronger conclusions possible with
  - lattice QCD calculations for various $\not{B}$, $\not{T}$ sources
  - heavy nuclear EFT formulation.