TIME-REVERSAL VIOLATION IN THE NUCLEON AND LIGHT NUCLEI

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with

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Supported by CNRS and US DOE

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Outline

- Time-Reversal Violation: SM and BSM
- Nucleon Electric Dipole Form Factor
- Light-Nuclear T-Violating Form Factors
- Outlook & Conclusion

For a review, including heavier nuclei and atoms,
J. Engel, M.J. Ramsey-Musolf, U. van Kolck, Prog. Part. Nucl. Phys. 71 (2013) 21

For TC PV theory,
go back in time and see M. Schindler's talk, Mon 2:30pm
For more on symmetries,
wake-up after the end of this talk…

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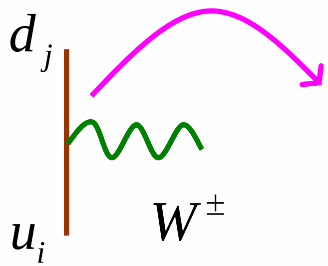
Time Reversal (T)

$$\begin{cases} t \to -t \\ \vec{r} \to \vec{r} \end{cases} \qquad i \to -i$$

$\not{T}$: little in weak interactions

Wolfenstein '83

- 

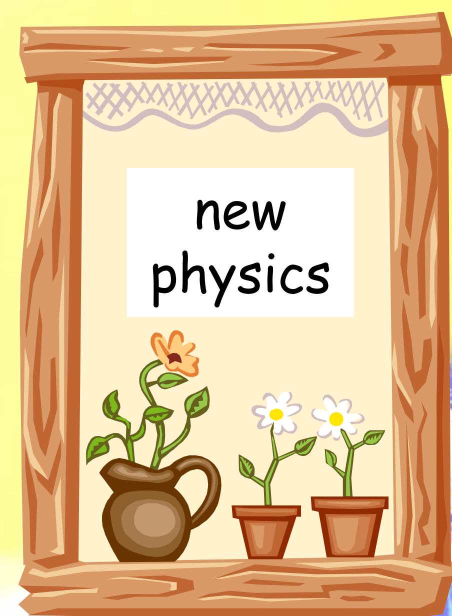
$$U_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A\left(\rho - i\eta\left(1-\lambda^2/2\right)\right) \\ -\lambda & 1-\lambda^2/2 - i\eta A^2\lambda^4 & \lambda^2 A\left(1+i\eta\lambda^2\right) \\ \lambda^3 A\left(1-\rho-i\eta\right) & -\lambda^2 A & 1 \end{pmatrix} + \dots$$

$$\lambda \cong 0.22 \qquad A, \rho, \eta = \mathcal{O}(1)$$

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

Jarlskog '85

- insufficient for electroweak baryogenesis !?



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Electric Dipole Moment (EDM)

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

Radius of EDFF: Schiff moment (SM) S'

For PCTC FFs, "see" talk by E. Cisbani, Tue 10:10am

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

e.g. Donoghue, Golowich + Holstein '92

Experiment:

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

Baker *et al* '06 (ILL)

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

Bodek *et al* (PSI) → "see" talk by V. Helaine, Tue 3:20pm
Budker *et al* (SNS)
...

$$\left|d_{Hg}\right| < 3.1\cdot 10^{-16}\, e\,\text{fm} \;\; (95\%\ \text{c.l.})$$

Griffith *et al* '09 (UW)

Nuclear Schiff moment from RPA, ...

Dmitriev + Sen'kov '03

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

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The new kid on the block: charged particle in storage ring

Bargmann, Michel + Telegdi '59

$$\frac{d\vec{S}}{dt} = \vec{S}\times\vec{\Omega}$$

charge → q; anomalous MDM → a

$$\vec{\Omega} = \frac{q}{m}\left[a\vec{B} + \left(\frac{1}{v^2} - a\right)\vec{v}\times\vec{E}\right] + 2d\left(\vec{E} + \vec{v}\times\vec{B}\right)$$

$$\left(\vec{v}\cdot\vec{B} = 0 = \vec{v}\cdot\vec{E}\right)$$

precession sensitive to EDM

e.g. $d_\mu \lesssim 10^{-6}\, e\,\mathrm{fm}$ Bennett *et al* (BNL g-2) '09

Orlov *et al* (Fermilab? COSY?)

choose radius and combination of E&M fields:

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

Proton and helion as well? How about triton?

e.g. $R \sim 10\ \mathrm{m}$

$B \sim 0.5\ \mathrm{T}$

$E \sim 17\ \mathrm{MV/m}$

Magnetic quadrupole moment (MQM) $\mathcal{M}_d$?

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Fact:
T violated in SM by a dim-4 operator,
so it should be violated also by other operators

Issue:
once a hadronic/nuclear EDM is observed,
how many/which observables do we need to
identify the source(s) of T violation?

Strategy:
use Effective Field Theory
to study various hadronic T-violating effects

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The Way of EFT

Q

$M_T \sim ?$

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

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

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

$\aleph \sim 1/a_{NN}$
$\sim 30\ \mathrm{MeV}$

$M_{at} \sim \alpha\, m_e$
$\sim 3\ \mathrm{keV}$

unknown physics

Standard Model
(incl higher dim ops)

run RG

QCD

match with
lattice, …

Chiral EFT
(χPT)

Pionless EFT

hadronic + nuclear
observables

QED

atomic
observables

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TV Sources

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

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 $\varphi_u^i = \varepsilon^{ij} \varphi_{dj}^*$ $\quad \tilde{G}_{\mu\nu} \equiv \varepsilon_{\mu\nu\rho\sigma} G^{\rho\sigma}$

θ term (dim=4)

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

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

→ 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)

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

→ gluon color-EDM (dim=6)

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

→ four-quark contact (dim=6)

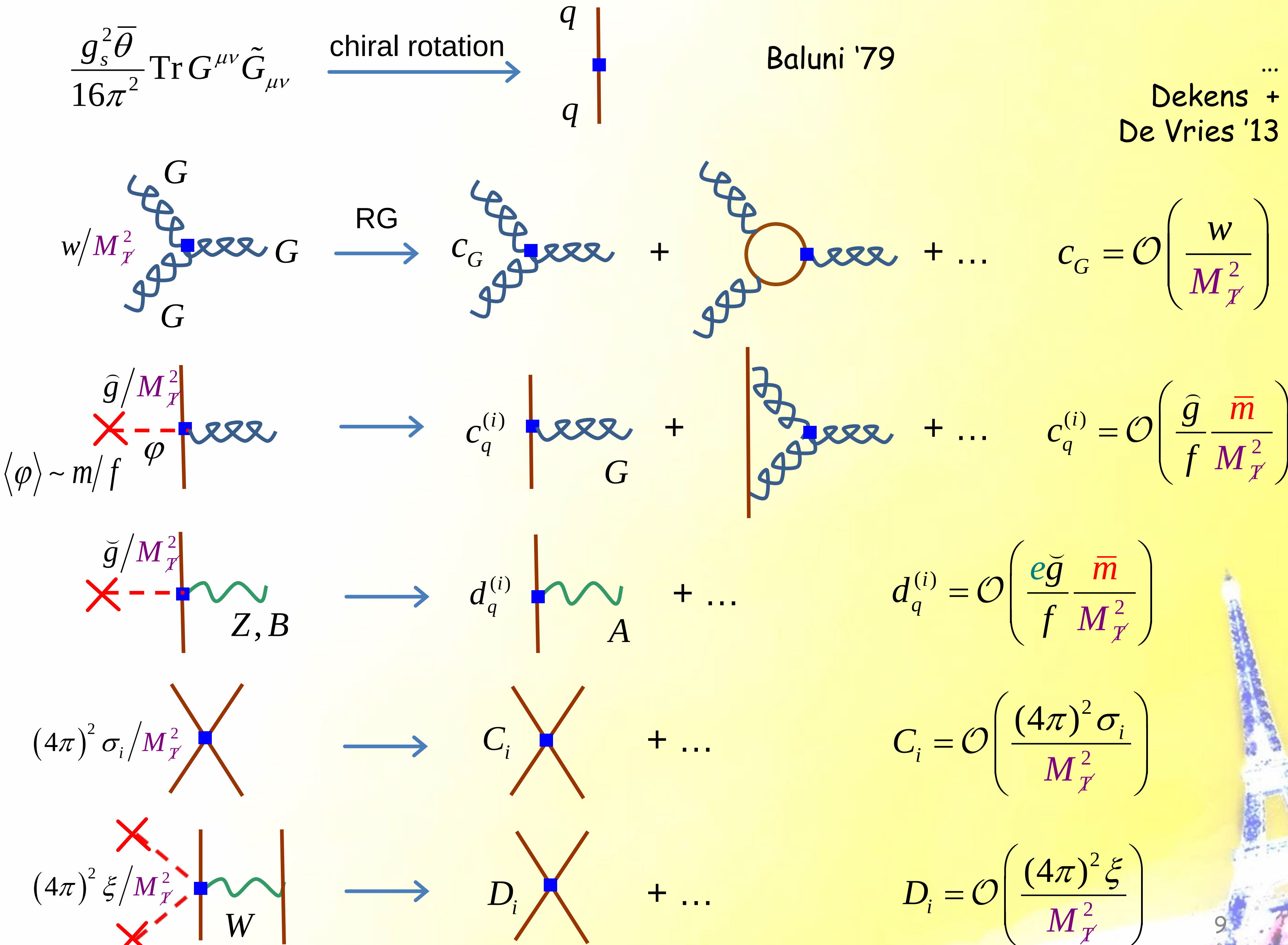
$$+ \frac{(4\pi)^2 \xi}{M_{\not{T}}^2} \bar{u}_R \gamma^\mu d_R \, \varphi_u^\dagger i D_\mu \varphi_d + \text{H.c.}$$

→ LR four-quark contact (dim=6)

$$+ \ldots$$

dimension ↓

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



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

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

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

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

qEDM

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

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

gCEDM

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

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

4QC

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

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

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

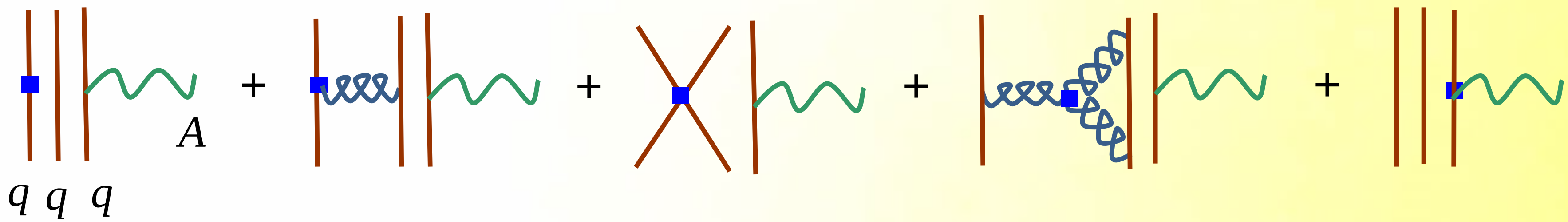
LRC

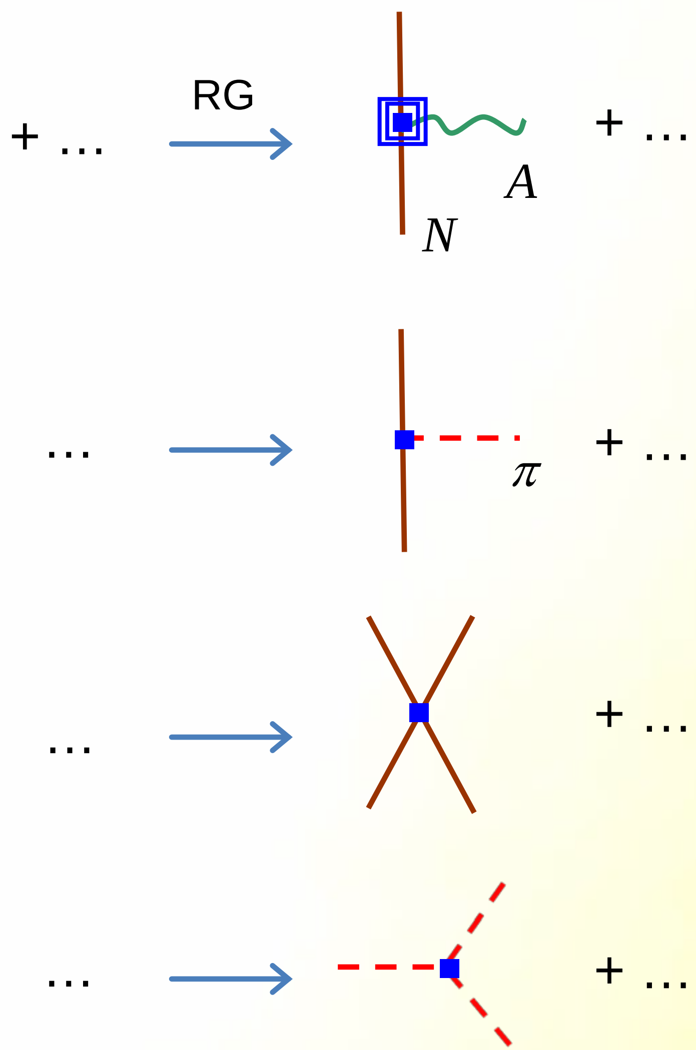
$$D_i = \mathcal{O}\left(\frac{(4\pi)^2\xi}{M_{\not{T}}^2}\right)$$

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

$$+\ldots$$

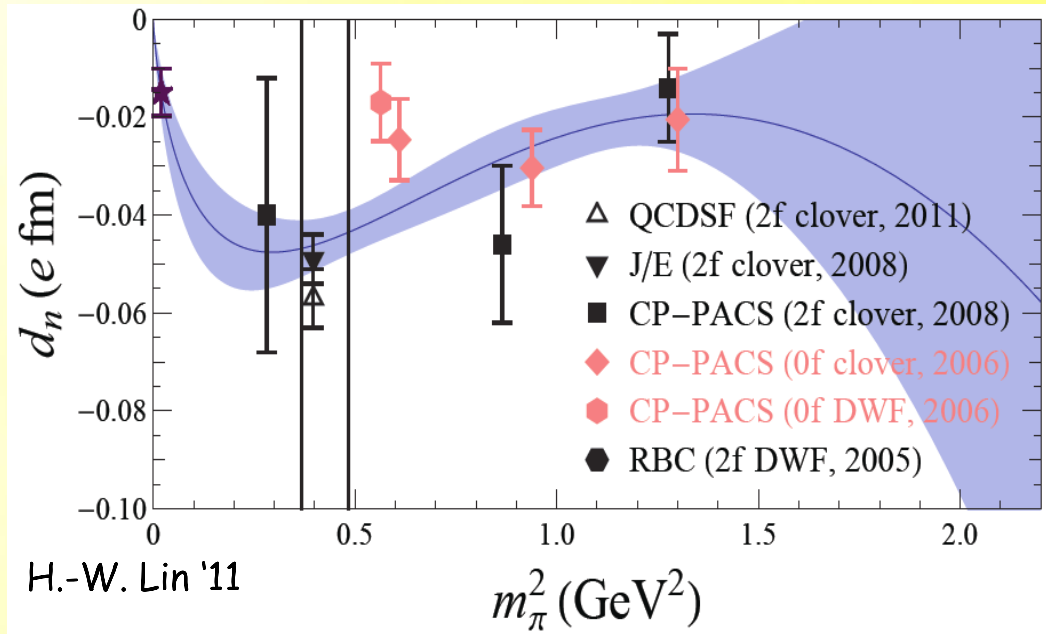
N.B. To this order, $\not{T} \to \not{P}$





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

lattice simulations:
only for nucleon EDM from θ term,
and situation unclear



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

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

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

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

chiral symmetry

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

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

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

qEDM

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

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

gCEDM

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

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

4QC

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

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

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

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, $\not{T} \rightarrow \not{P}$

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, 4QC } CI — chiral invariants: cannot be separated at low energies, $\{w, \sigma_{1,8}\} \rightarrow w$

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

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

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

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

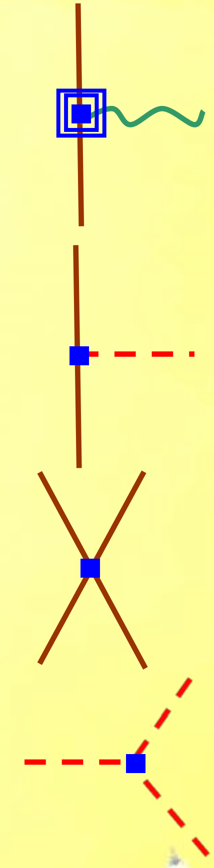
$$+\ldots$$

short-range EDM contribution

PV, TV pion-nucleon coupling

PV, TV two-nucleon contact

three-pion coupling



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?

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

2) for θ, link to CSB, *e.g.*

$$\bar{g}_0 \simeq \frac{\bar{\theta}}{2\varepsilon}\left(m_n - m_p\right)_{qm} \approx 3\,\bar{\theta}\ \mathrm{MeV}$$

Mereghetti, Hockings + v.K. '10

using lattice QCD (Beane et al '06)

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Observables

arbitrary regulator

$$T_{PT} = \sum_{\nu=\nu_{\min}}^{\infty} \sum_{i} c_{\nu,i}(\Lambda/M_{QCD}) \left[\frac{Q}{M_{QCD}}\right]^{\nu} F_{\nu,i}\left(\frac{Q}{m_\pi};\frac{\Lambda}{m_\pi}\right)$$

chiral symmetry $\nu_{\min} \geq 0$

product of P,T-conserving low-energy constants

$\ll 1$

controlled

non-analytic, from loops

$$T_{\not P \not T} = \sum_{\nu=\bar{\nu}_{\min}}^{\infty} \sum_{i} \bar{c}_{\nu,i}(\Lambda/M_{QCD}) \left[\frac{Q}{M_{QCD}}\right]^{\nu} F_{\nu,i}\left(\frac{Q}{m_\pi};\frac{\Lambda}{m_\pi}\right)$$

product of (odd number of) P,T-violating LECs, and P,T-conserving LECs

$$\frac{\partial T}{\partial \Lambda} = 0$$

RG invariance

model independent

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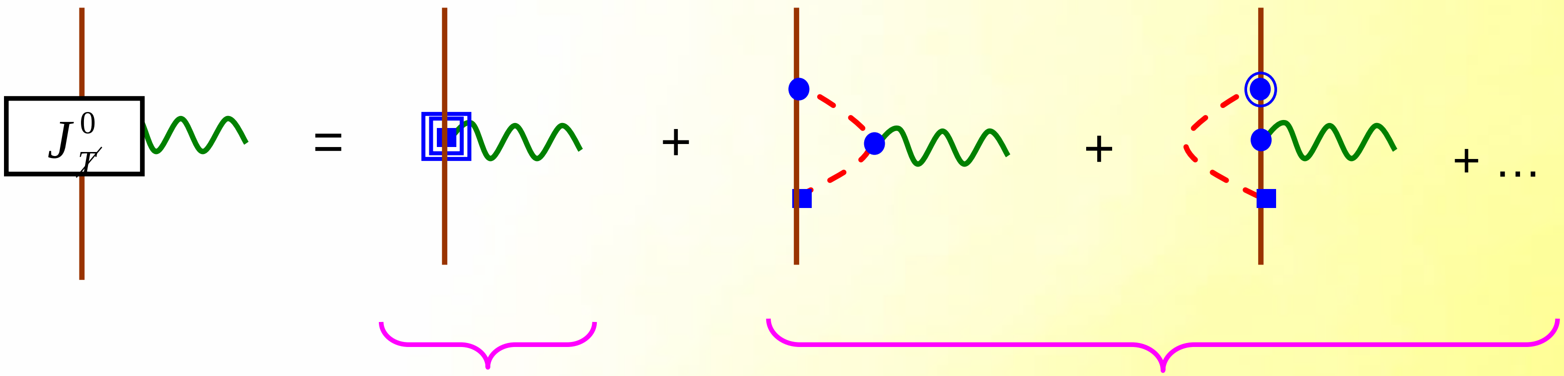
Crewther *et al* '79
Thomas '95
...
Hockings + v.K. '05
Narison '08
Ottnad *et al* '10
De Vries *et al* '10'11

Nucleon EDFF (to NLO)



short-ranged;
LO for all sources

- ensures RG invariance
- brings in two parameters

long-ranged;
order depends on source

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

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

Nucleon EDM (to NLO)

De Vries *et al* '10'11

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

- $|d_N| \gtrsim 2\cdot 10^{-3}\bar\theta\, e\,\mathrm{fm}$ from long-range contributions

- $d_n = (0.2 \pm 1.5(\mathrm{stat}) \pm 0.7(\mathrm{syst}))\cdot 10^{-13} e\,\mathrm{fm} \Rightarrow \begin{cases} \bar\theta \lesssim 10^{-10} \\ \dfrac{\tilde g}{f} M_{\not T}^{-2}, \dfrac{\breve g}{f} M_{\not T}^{-2} \lesssim (10^5\,\mathrm{GeV})^{-2} \\ w M_{\not T}^{-2}, \xi M_{\not T}^{-2} \lesssim (10^6\,\mathrm{GeV})^{-2} \end{cases}$

  Baker *et al* '06 (ILL)

- $d_n(\mathrm{CKM}) \sim \dfrac{e}{M_{QCD}}\left(G_F f_\pi^2\right)^2 J_{CP} \approx 10^{-19} e\,\mathrm{fm} \Rightarrow$ measurement much above this means new source

LHC-type scales!

- n and p EDMs can be fitted with any one source

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

Nucleon EDM (to NLO)

De Vries *et al* '10'11

	θ term	qCEDM	LRC	qEDM	CI
$m_n \frac{d_n}{e}$	$\mathcal{O}\left(\bar{\theta}\,\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{\hat{g}}{f}\,\frac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\xi\,\frac{M_{QCD}^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\frac{\breve{g}}{f}\,\frac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(w\,\frac{M_{QCD}^2}{M_{\not T}^2}\right)$
$\frac{d_p}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$(2m_\pi)^2\,\frac{S'_p}{d_p}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$
$(2m_\pi)^2\,\frac{S_N^{'(0)}}{d_n}$	$\mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{m_\pi^2}{M_{QCD}^2}\right)$

SM partially sensitive
to sources

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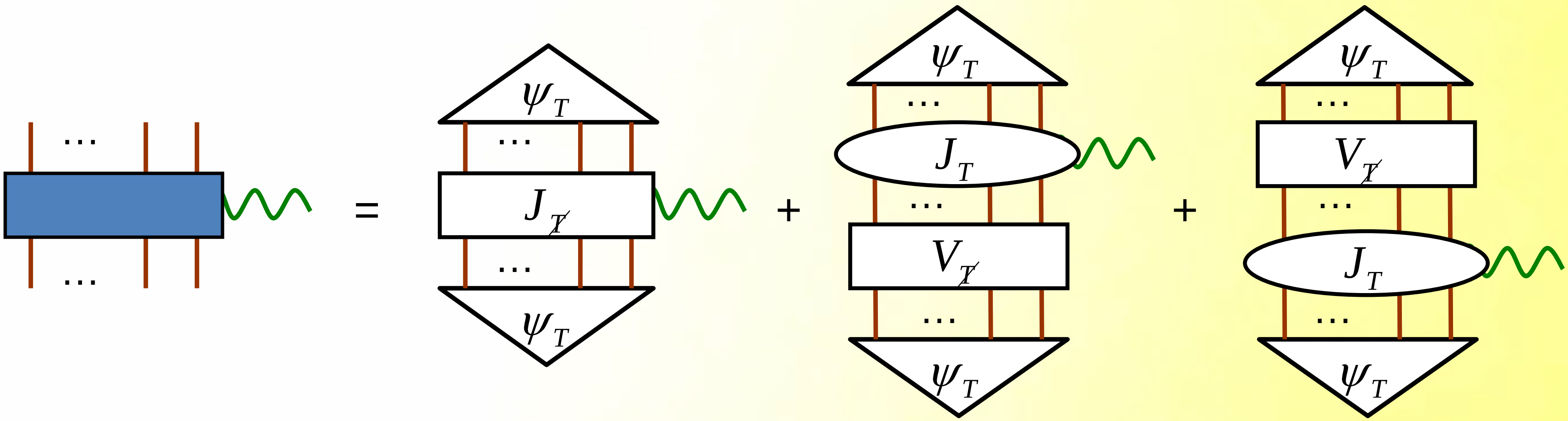
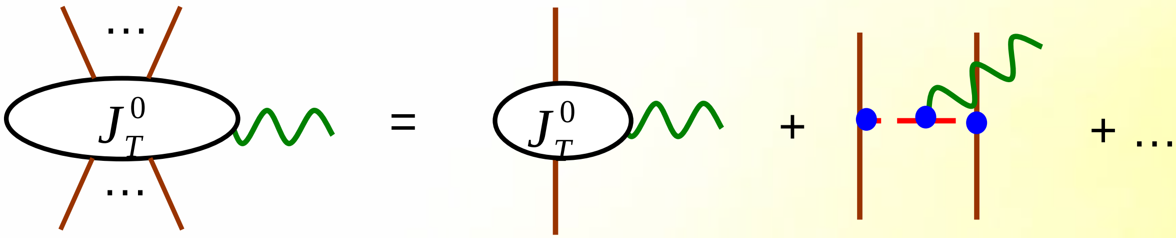
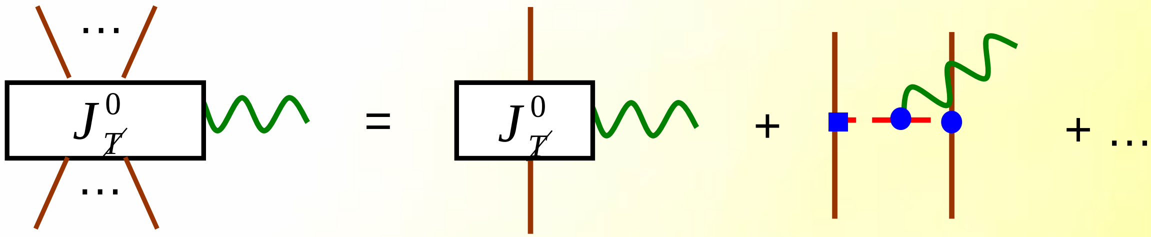
Nuclear EDFFs & MQFFs





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

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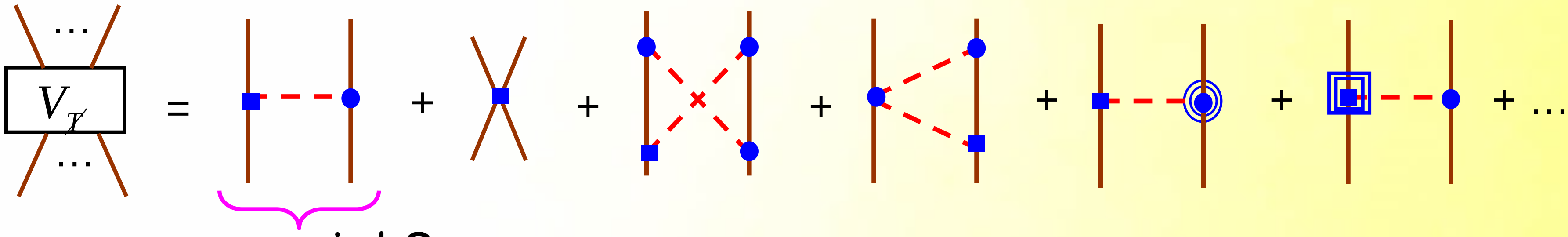
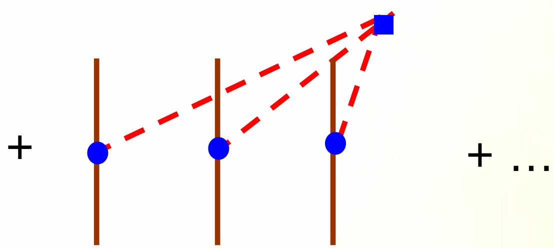


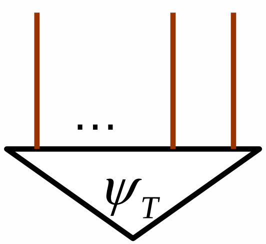
generic LO,
but effect vanishes for θ when N=Z



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

LO for LRC only

Weinberg '90, '91
Ordónez + v.K. '92
…



from solution of the Schrödinger equation

- for now, phenom pots (AV18, Reid93, Idaho: agree +/- 10%)
- eventually, consistent EFT approach

introduces dependence on binding energy B_A

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De Vries *et al* '11 '13
Bsaisou *et al* '12

Deuteron EDM (LO)

	θ term	qCEDM	LRC	qEDM	CI
$m_d \dfrac{d_d}{e}$	$\mathcal{O}\left(\bar\theta \dfrac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\dfrac{\hat g}{f}\dfrac{M_{QCD}^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\xi \dfrac{M_{QCD}^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\dfrac{\breve g}{f}\dfrac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(w \dfrac{M_{QCD}^2}{M_{\not T}^2}\right)$

- $|d_d| \gtrsim 3\cdot 10^{-4}\,\bar\theta\, e\,\mathrm{fm}$ from long-range contributions to $d_N^{(0)}$
- $|d_d| < 10^{-16} e\,\mathrm{fm}$ ⇨
$$\begin{cases} \bar\theta \lesssim 3\cdot 10^{-13} \\ \dfrac{\breve g}{f} M_{\not T}^{-2} \lesssim \left(5\cdot 10^{6}\,\mathrm{GeV}\right)^{-2} \\ \dfrac{\hat g}{f} M_{\not T}^{-2}, w M_{\not T}^{-2}, \xi M_{\not T}^{-2} \lesssim \left(3\cdot 10^{7}\,\mathrm{GeV}\right)^{-2} \end{cases}$$

  Fermilab? COSY?

Improved reach for BSM physics!

- d EDM can be fitted with any one source

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De Vries *et al* '11 '13
Bsaisou *et al* '12

Deuteron EDM (LO)

	θ term	qCEDM	LRC	qEDM	CI
$m_d \dfrac{d_d}{e}$	$\mathcal{O}\left(\bar{\theta}\,\dfrac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\dfrac{\widehat{g}}{f}\dfrac{M_{QCD}^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(\xi\,\dfrac{M_{QCD}^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(\dfrac{\breve{g}}{f}\dfrac{m_\pi^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(w\,\dfrac{M_{QCD}^2}{M_{\not{T}}^2}\right)$
$\dfrac{d_d}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}\left(\dfrac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}\left(\dfrac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

- $d_d \simeq d_n + d_p$ for θ term, qEDM, and CI
- n and d EDMs could isolate qCEDM and LRC

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Deuteron EDM (LO)

De Vries *et al* '11 '13
Bsaisou *et al* '12

	θ term	qCEDM	LRC	qEDM	CI
$m_d \frac{d_d}{e}$	$\mathcal{O}\left(\bar{\theta}\,\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{\hat{g}}{f}\,\frac{M_{QCD}^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(\xi\,\frac{M_{QCD}^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(\frac{\breve{g}}{f}\,\frac{m_\pi^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(w\,\frac{M_{QCD}^2}{M_{\not{T}}^2}\right)$
$\frac{d_d}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$16 m_N B_d \frac{S'_d}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$m_d \frac{\mathcal{M}_d}{d_d}$	$\mathcal{O}\left(\frac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{\sqrt{m_N B_d}}{m_\pi}\right)$	$\mathcal{O}(1)$

$\mathcal{M}_d \cong 2 \cdot 10^{-3}\,\bar{\theta}\, e\, \mathrm{fm}^2$
(no short-range assumptions)

can be isolated

could be isolated if MQM measured

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De Vries *et al* '11

Triton and Helion EDMs (LO)

	θ term	qCEDM	LRC	qEDM	CI
$m_h \dfrac{d_h}{e}$	$\mathcal{O}(\bar{\theta})$	$\mathcal{O}\left(\dfrac{\hat{g}}{f}\dfrac{M_{QCD}^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\xi\dfrac{M_{QCD}^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\dfrac{\breve{g}}{f}\dfrac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(w\dfrac{M_{QCD}^2}{M_{\not T}^2}\right)$
$\dfrac{d_t}{d_h}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

- t and h EDMs can be fitted with any one source

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De Vries *et al* '11

Triton and Helion EDMs (LO)

	θ term	qCEDM	LRC	qEDM	CI
$m_h \dfrac{d_h}{e}$	$\mathcal{O}(\bar{\theta})$	$\mathcal{O}\left(\dfrac{\tilde{g}}{f}\dfrac{M_{QCD}^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(\xi\dfrac{M_{QCD}^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(\dfrac{\breve{g}}{f}\dfrac{m_\pi^2}{M_{\not{T}}^2}\right)$	$\mathcal{O}\left(w\dfrac{M_{QCD}^2}{M_{\not{T}}^2}\right)$
$\dfrac{d_t}{d_h}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\dfrac{d_h}{d_n}$	$\mathcal{O}\left(\dfrac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}\left(\dfrac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}\left(\dfrac{M_{QCD}^2}{m_\pi^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

- $d_h + d_t \simeq 0.84(d_n + d_p)$ for qEDM and θ term
  $d_h - d_t \simeq 0.94(d_n - d_p)$ for qEDM
  $d_h + d_t \simeq 3d_d$ for qCEDM
  $\alpha_1 d_h + \alpha_2 d_t \simeq \beta_1 d_n + \beta_2 d_p + d_d$ for LRC

- n, p, d and h EDMs could isolate θ term, qCEDM and LRC, and adding t EDM might isolate qEDM and LRC

What's needed?

- Triton and helion for LRC $\left(\alpha_{1,2}, \beta_{1,2} = ?\right)$
- Deuteron, triton and helion at NLO to test convergence
- EDMs of larger nuclei in terms of same six LECs?

  cf. Haxton + Henley '83

  …
- Calculation of LECs for each source in lattice QCD
- Generalization to SU(3)
- Measurements…

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Conclusion

- QCD-based framework exists for calculation of nuclear T-violating observables
- Chiral symmetry properties determine form of effective T-violating interactions.
- Pattern of nucleon, deuteron, helion and triton T-violating FFs partially reflects T-violating source

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