INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

ELECTRIC DIPOLE MOMENTS OF LIGHT NUCLEI

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with

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Outline

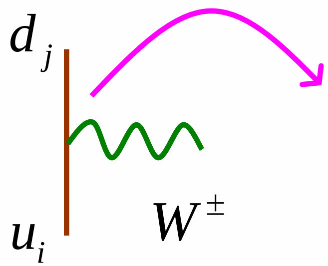
- Time-Reversal Violation
- Nucleon Electric Dipole Form Factor
- Light-Nuclear T-Violating Form Factors
- Outlook & Conclusion

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

- 

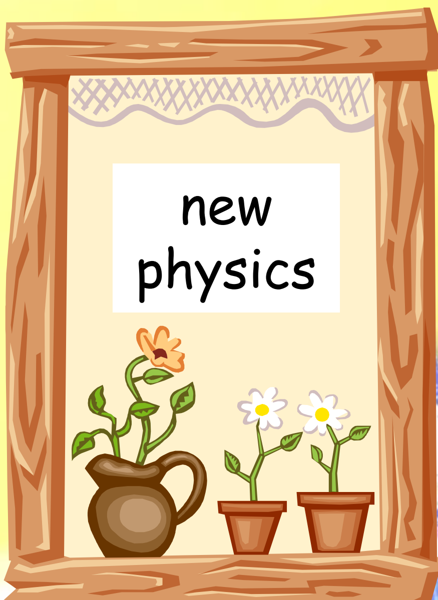
$$U_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A\left(\rho - i\eta\left(1-\lambda^2/2\right)\right) \\ -\lambda & 1-\lambda^2/2 - i\eta A^2\lambda^4 & \lambda^2 A\left(1+i\eta\lambda^2\right) \\ \lambda^3 A\left(1-\rho-i\eta\right) & -\lambda^2 A & 1 \end{pmatrix} + \ldots$$

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

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

Jarlskog '85

- insufficient for electroweak baryogenesis !?



Electric Dipole Moment (EDM)

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

Radius of corresponding FF: Schiff moment (SM) S'

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), Budker *et al* (SNS), …

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

Griffith *et al* '09 (UW)

Nuclear Schiff moment from RPA, …

Dmitriev + Sen'kov '03

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

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

Bargmann, Michel + Telegdi '59

charge → q; anomalous MDM → a

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

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

precession sensitive to EDM

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

choose radius and combination of E&M fields:

Orlov *et al* (Fermilab? COSY?)

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

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

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

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

Proton and helion as well? How about triton?

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

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

EFT Game Plan

Q ↑

$M_T \sim ?$ — unknown physics

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

$\sim 100\ \mathrm{GeV}$ — Standard Model (incl higher dim ops)

run RG

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

$\sim 1\ \mathrm{GeV}$ — QCD

match with lattice, …

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

$\sim 100\ \mathrm{MeV}$ — Pionful EFT (χPT)

$\aleph \sim 1/a_{NN}$

$\sim 30\ \mathrm{MeV}$ — Pionless EFT

hadronic + nuclear observables

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

$\sim 3\ \mathrm{keV}$ — QED

atomic observables

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

θ term (dim=4)

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

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

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

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

→ 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

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

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

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

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

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

4QC

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

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

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

LRC

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

$$+ \ldots$$

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

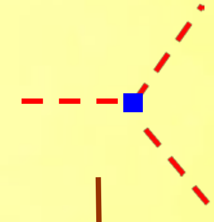
Mereghetti, Hockings + v.K. '10
De Vries *et al*, in preparation

Each breaks chiral symmetry in a particular way, and produces different hadronic interactions.

chiral invariants (CI}: cannot be separated at low energies, $\{w, \sigma_1, \sigma_8\} \to w$

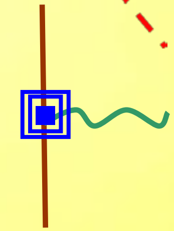
$$\mathcal{L}_{\chi PT} = -\frac{m_\pi^2 \bar{g}_0}{2 f_\pi (m_n - m_p)_{qm}} \boldsymbol{\pi}^2 \pi_3$$

three-pion coupling



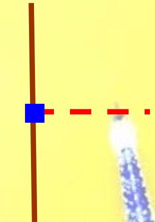
$$-2 \bar{N} \left(\bar{d}_0 + \bar{d}_1 \tau_3 \right) S_\mu N \, v_\nu F^{\mu\nu}$$

short-range EDM contribution



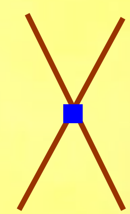
$$-\frac{1}{2 f_\pi} \bar{N} \left(\bar{g}_0 \boldsymbol{\tau} \cdot \boldsymbol{\pi} + \bar{g}_1 \pi_3 \right) N$$

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



$$+ \ldots$$

terms related by chiral symmetry + higher orders

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

2) for θ, link to CSB, *e.g.*

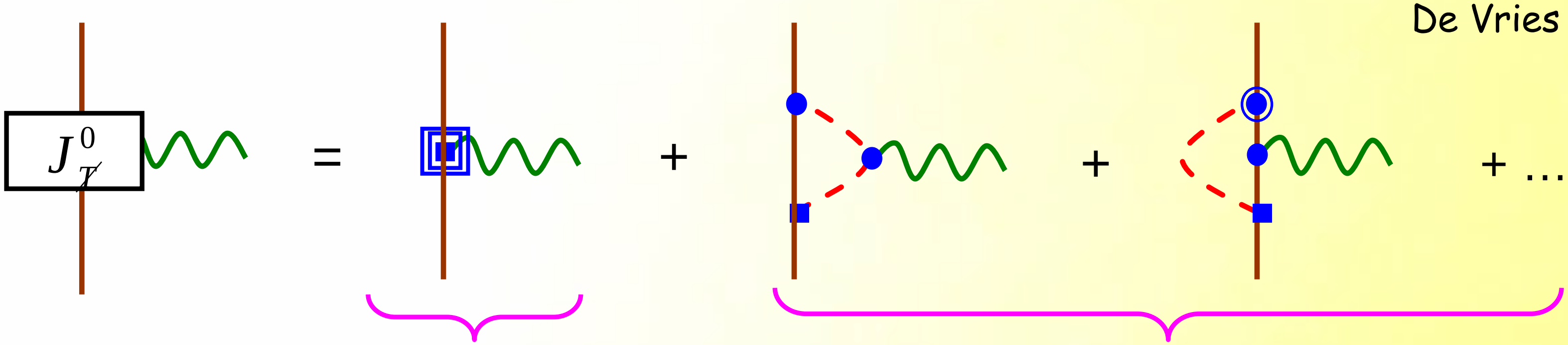
$$\bar{g}_0 \simeq \frac{\bar{\theta}}{2\varepsilon}\left(m_n - m_p\right)_{qm} \approx 3\,\bar{\theta}\ \text{MeV}$$

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)



LO for all sources

- ensures RG invariance
- brings in two parameters

order depends on source

- can provide estimates using reasonable renormalization scale

cf. lattice simulations, only for θ term and situation unclear:

quenched, $\frac{m_\pi}{m_\rho} = 0.63$: signal 10x larger than NDA! Shintani *et al* (CP-PACS) '05

full, $\frac{m_u, m_d}{m_s} \approx 1$: no signal at same level Berruto et al (RBC) '05

...

A few details

$$\langle p', s' | J_N^\mu | p, s \rangle = \bar{u}_{s'}(p') \Big[\gamma^\mu \, F_1(-q^2) - i\sigma^{\mu\nu} q_\nu \, F_2(-q^2)$$

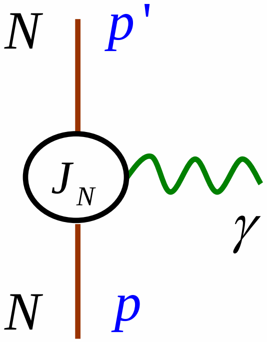
$$+ \left(\gamma^\mu \gamma_5 \, q^2 + 2 m_N \gamma_5 \, q^\mu \right) F_A(-q^2)$$

$$+ \frac{i}{2} \varepsilon^{\mu\nu\rho\sigma} \sigma_{\rho\sigma} q_\nu \, F_{E1}(-q^2) \Big] u_s(p)$$

Bernard *et al.* '92 '98

Maekawa + v.K. '00
Maekawa, Veiga + v.K. '00

Hockings + v.K. '05
De Vries *et al.* '10'12



$$\xrightarrow{|\vec{p}|, |\vec{p}\,'| \ll m_N} \chi_{s'}^\dagger(k - q/2) \; J_{E1}^\mu(q, k) \; \chi_s(k + q/2)$$

$q = p - p'$

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

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

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

rest frame

$$J_{E1}^\mu(q, k) = -2 \left(\eta^{\mu\rho} q^\sigma - \eta^{\mu\sigma} q^\rho \right) S^\nu$$

$$\times \left[\left(v_\rho + \frac{k_\rho}{m_N} \right) \eta_{\nu\sigma} + v_\rho \frac{k_\nu k_\sigma}{2 m_N^2} + \ldots \right]$$

EDFF

$$\times \left(F_{E1}^{(0)}(-q^2) + F_{E1}^{(1)}(-q^2) \, \tau_3 \right)$$

(similar for 3He and 3H)

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

De Vries *et al* '10'11

Example: qCEDM

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

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

renormalization

θ

$$|d_n| \gtrsim \frac{2 e g_A \delta m_N}{(4\pi f_\pi)^2}\frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta}\ln\frac{m_N}{m_\pi}$$

$$\approx 2.0\cdot 10^{-3}\,\bar{\theta}\, e\,\text{fm}$$

cf. Crewther *et al* \`79

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

θ

$$|d^{(0)}| \gtrsim \frac{e g_A \delta m_N}{(4\pi f_\pi)^2}\frac{1-\varepsilon^2}{2\varepsilon}\bar{\theta}\left[\frac{3\pi}{4}\frac{m_\pi}{m_N} - \frac{\delta m_N}{m_\pi}\right]$$

$$\approx 1.4\cdot 10^{-4}\,\bar{\theta}\, e\,\text{fm}$$

Thomas '95

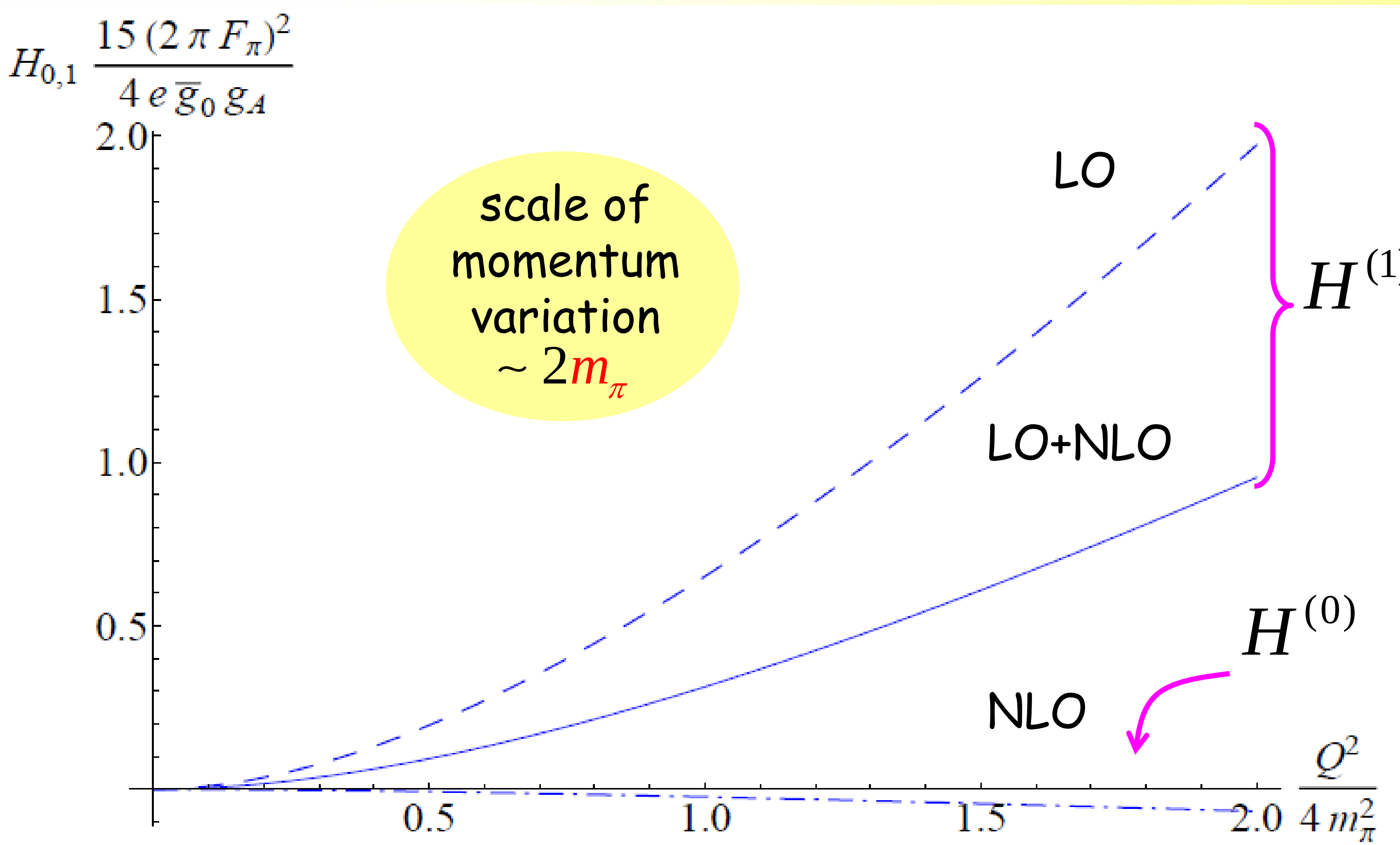
$$\begin{cases} S'^{(1)} = \dfrac{e g_A \bar{g}_0}{6(4\pi f_\pi)^2 m_\pi^2}\left[1 - \dfrac{5\pi}{4}\dfrac{m_\pi}{m_N} - \dfrac{\breve{\delta} m_\pi^2}{m_\pi^2} + \mathcal{O}\left(\dfrac{m_\pi^2}{M_{QCD}^2}\right)\right] \\ S'^{(0)} = -\dfrac{e g_A \bar{g}_0}{6(4\pi f_\pi)^2 m_\pi^2}\left[0 + \dfrac{\pi}{2}\dfrac{\delta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

θ

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

θ

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



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
$m_n \frac{d_n}{e}$	$\mathcal{O}\left(\bar{\theta}\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{\hat{g}}{f}\frac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\xi\frac{M_{QCD}^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\frac{\breve{g}}{f}\frac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(w\frac{M_{QCD}^2}{M_{\not T}^2}\right)$
$\frac{d_p}{d_n}$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

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

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

  Baker *et al* '06 (ILL)

LHC-type scales!

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

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

Crewther *et al* '79
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...
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Nucleon EDM (to NLO)

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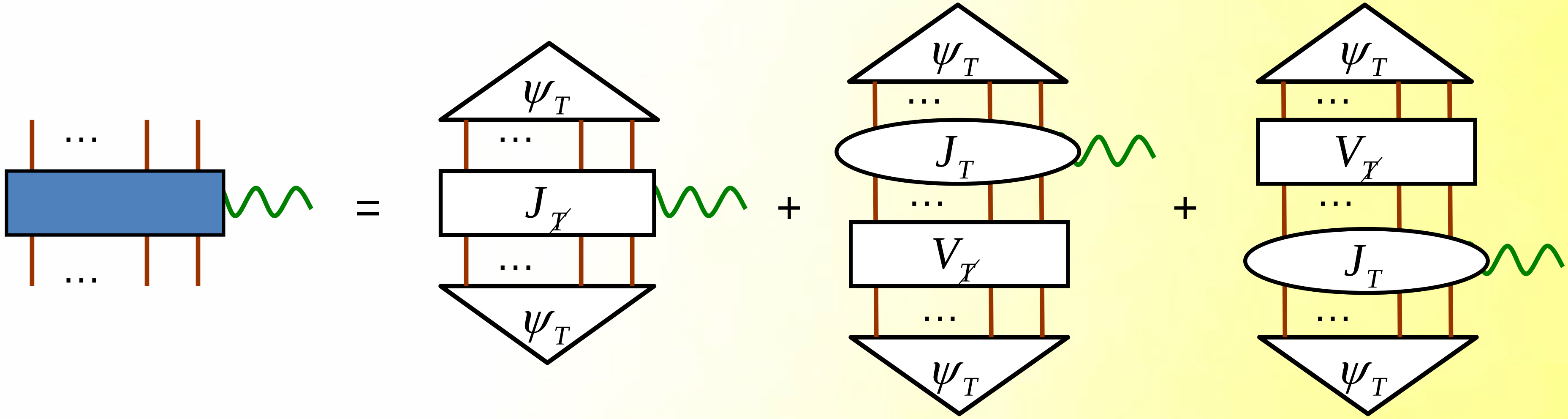
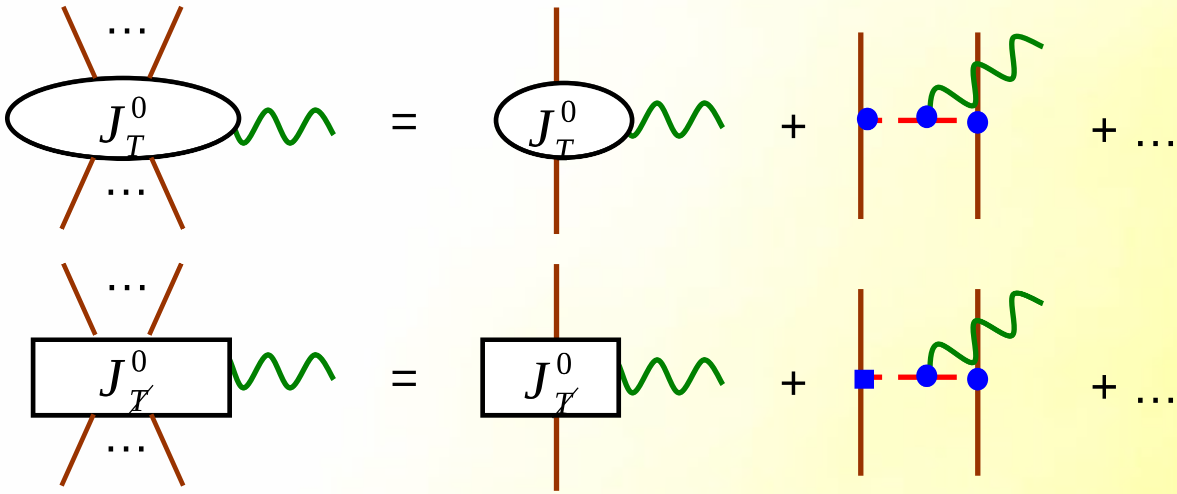
	θ term	qCEDM	LRC	qEDM	CI
$m_n \frac{d_n}{e}$	$\mathcal{O}\left(\bar{\theta}\frac{m_\pi^2}{M_{QCD}^2}\right)$	$\mathcal{O}\left(\frac{\hat{g}}{f}\frac{m_\pi^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\xi\frac{M_{QCD}^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\frac{\breve{g}}{f}\frac{m_\pi^2}{M_{\not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

SM partially sensitive
to sources

Nuclear EDFFs & MQFFs





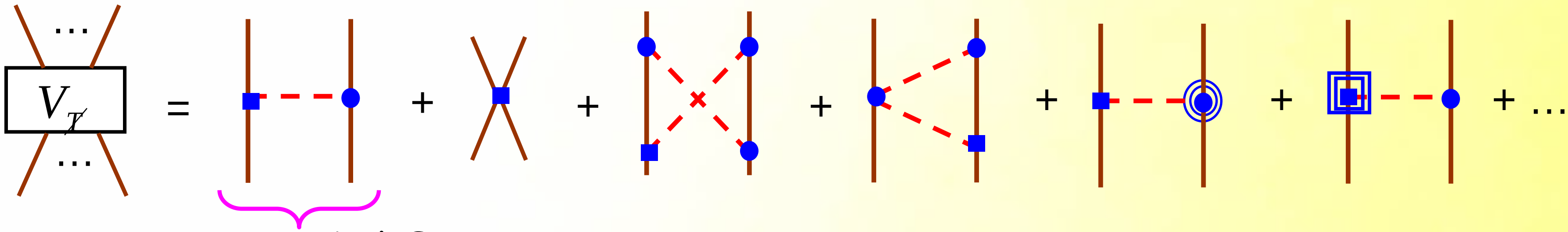
Park, Min + Rho '95

…

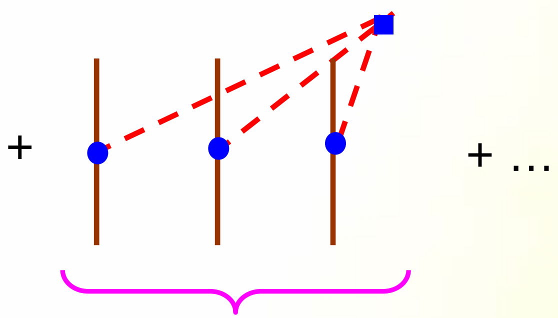
De Vries, Mereghetti, Higa, Liu, Stetcu, Timmermans + v.K.'11

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

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



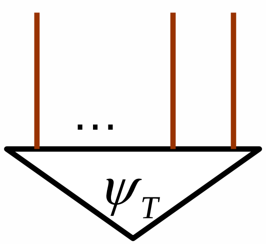
generic LO,
but effect vanishes for θ when N=Z



LO for LRC only

Maekawa, Mereghetti, De Vries + v.K. '11
De Vries *et al*, in preparation

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

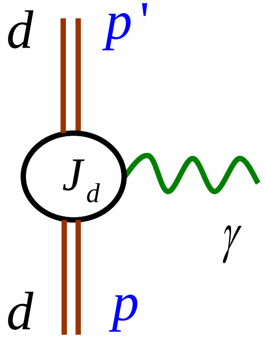
A few details

(perturbative pions)

$$\langle p', j | J_d^\mu | p, i \rangle = e\delta_{ij}\left[v^\mu + \frac{k^\mu}{m_d} + \ldots \right] F_{E0}(-q^2)$$

$$+ ieS_{\sigma ij}\left[\varepsilon^{\mu\sigma\nu\rho} q_\nu v_\rho + \ldots \right] F_{M1}(-q^2)$$

Kaplan, Savage + Wise '98



$$+ e\left(q_i q_i - \frac{q^2}{3}\delta_{ij} \right)\left[v^\mu + \ldots \right] F_{E2}(-q^2)$$

$$+ S_{\sigma ij}\left[\eta^{\mu\sigma} q^2 - q^\mu q^\sigma + \ldots \right] F_A(-q^2)$$

Savage + Springer '01

$$- 2iS_{\sigma ij}\left[v^\mu q^\sigma - \eta^{\mu\sigma} v \cdot q + \ldots \right] F_{E1}(-q^2)$$

EDFF

$$+ \frac{1}{4}\varepsilon^{\mu\nu\lambda\rho}\left(q_i \delta_{\lambda j} + q_j \delta_{\lambda i} \right) q_\nu \left[v_\rho + \ldots \right] F_{M2}(-q^2)$$

MQFF

$$F_{M2}(-q^2) = \mathcal{M}\left[1 + K(-q^2) \right]$$

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

$q = p - p'$

$k = \frac{1}{2}\left[p + p' - m_d v \right]$

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

$S_{ij}^\mu = (0, i\varepsilon_{ijk})$ spin

rest frame

Example: qCEDM

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

deuteron EDFF; pert pions

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

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

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

scale of momentum variation $\sim 4\gamma$

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

deuteron, helion, triton EDMs; non-pert pions

De Vries *et al* '11
cf. Liu + Timmermans '04

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

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

deuteron MQFF; pert pions

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

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

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

deuteron MQM; non-pert pions

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

De Vries *et al* '11
and in preparation
Bsaisou *et al* '12

Deuteron EDM (LO)

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

- $|d_d| \gtrsim 3\cdot 10^{-4}\bar{\theta}\, e\,\text{fm}$ from long-range contributions to $d_N^{(0)}$
- $|d_d| < 10^{-16} e\,\text{fm}$ $\Rightarrow$

  Fermilab? COSY?

$$\begin{cases} \bar{\theta} \lesssim 3\cdot 10^{-13} \\ \dfrac{\breve{g}}{f} M_{\not{T}}^{-2} \lesssim \left(5\cdot 10^{6}\,\text{GeV}\right)^{-2} \\ \dfrac{\hat{g}}{f} M_{\not{T}}^{-2}, w M_{\not{T}}^{-2}, \xi M_{\not{T}}^{-2} \lesssim \left(3\cdot 10^{7}\,\text{GeV}\right)^{-2} \end{cases}$$

Improved reach for BSM physics!

- d EDM can be fitted with any one source

Deuteron EDM (LO)

De Vries *et al* '11
and in preparation
Bsaisou *et al* '12

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

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

Deuteron EDM (LO)

De Vries *et al* '11
and in preparation
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

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

Triton and Helion EDMs (LO)

De Vries *et al* '11

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

- $d_h + d_t \simeq 0.84(d_n + d_p)$ 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
- Runnings from SM scale to QCD scale
- Measurements…

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