Electric Dipole Moments of Light Ions

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in collaboration with
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Susanna Liebig, David Minossi, Werner Bernreuther and Wouter Dekens

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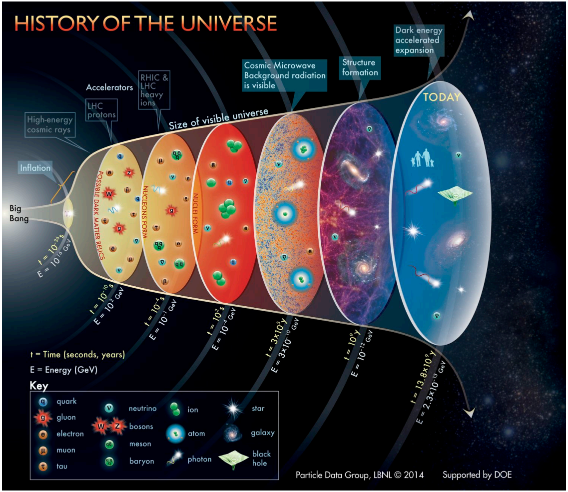
Contents

Matter Excess in the Universe



1. End of inflation: $n_B = n_{\bar{B}}$

2. Cosmic Microwave Bkgr.
   - SM(s) *prediction:* *
     $(n_B - \cancel{n_{\bar{B}}})/n_\gamma|_{CMB} \sim 10^{-18}$
   - WMAP+PLANCK ('13):
     $n_B/n_\gamma|_{CMB} = (6.05 \pm 0.07) 10^{-10}$

Sakharov conditions ('67)
for dyn. generation of net B:

1. B violation to depart from initial B=0
2. C & CP violation
   to distinguish B and $\bar{B}$ production rates
3. out of thermal equilibrium
   to dist. B production from back reaction
   and to escape $\langle B \rangle$=0 *if* CPT holds

(*) $2J^{CKM}_{Jarlskog}(m_t^2-m_u^2)(m_t^2-m_c^2)(m_c^2-m_u^2)(m_b^2-m_d^2)(m_b^2-m_s^2)(m_s^2-m_d^2)/M_{EW}^{12} \sim 10^{-18}$

CP violation and the Electric Dipole Moment (EDM)

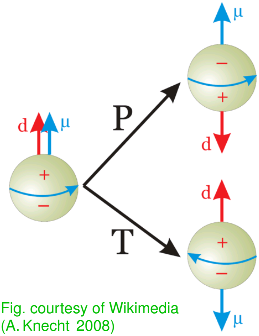


Fig. courtesy of Wikimedia
(A. Knecht 2008)

EDM: $\vec{d} = \sum_i \vec{r}_i\, e_i \xrightarrow[\text{particles}]{\text{subatomic}} d \cdot \vec{S}/|\vec{S}|$

(polar) (axial)

$$\mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} - d \frac{\vec{S}}{S} \cdot \vec{E}$$

$$\text{P:} \quad \mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{E}$$

$$\text{T:} \quad \mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{E}$$

Any *non-vanishing EDM* of a non-deg. (subatomic) particle violates **P** & **T**

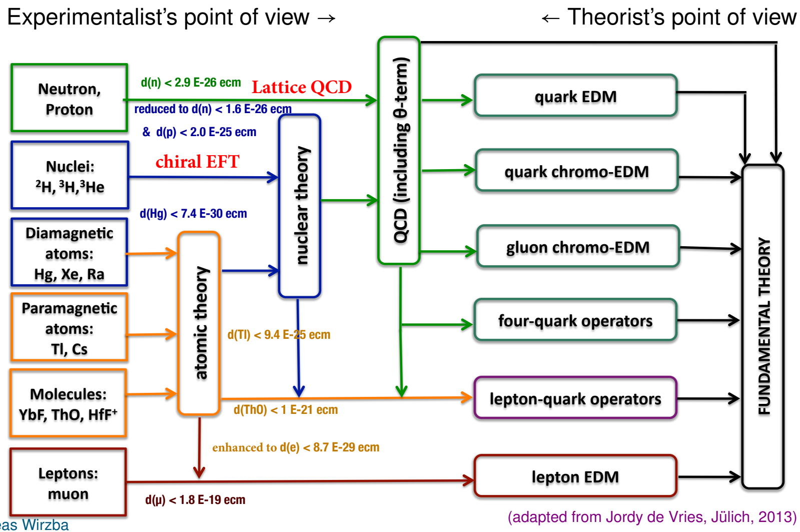
- Assuming CPT to hold, CP is violated as well (flavor-diagonally)
  ↪ subatomic EDMs: "rear window" to CP violation in early universe
- Strongly suppressed in SM (CKM-matrix): $|d_n| \sim 10^{-31} e\,\mathrm{cm}$, $|d_e| \sim 10^{-38} e\,\mathrm{cm}$
- Current bounds: $|d_n| < 3^{\diamond}/1.6^{*} \cdot 10^{-26} e\,\mathrm{cm}$, $|d_p| < 2 \cdot 10^{-25} e\,\mathrm{cm}$, $|d_e| < 1 \cdot 10^{-28} e\,\mathrm{cm}$

  n: Baker et al. (2006)$^{\diamond}$, *p* prediction: Dimitriev & Sen'kov (2003)*, *e*: Baron et al. (2013)†

* from $|d_{^{199}\mathrm{Hg}}| < 7.4 \cdot 10^{-30} e\,\mathrm{cm}$ bound of Graner et al. (2016) † from polar ThO: $|d_{\mathrm{ThO}}| \lesssim 10^{-21} e\,\mathrm{cm}$

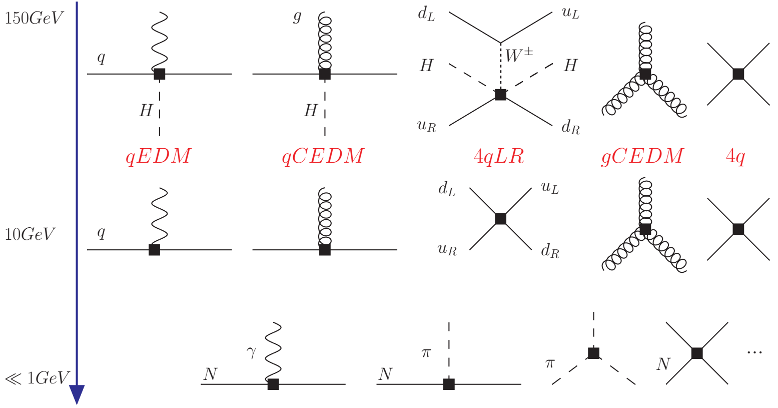
Why are EDMs of light ions interesting?

Road map from EDM Measurements to EDM Sources



CP-violating BSM sources of dimension 6 from above EW scale
to their hadronic equivalents below 1 GeV

W. Dekens & J. de Vries, *JHEP* **05** (2013)



Total # $=$ 1$(\bar{\theta})$ + 2*(qEDM)* + 2*(qCEDM)* + 1*(4qLR)* + 1*(gCEDM)* + 2*(4q)* [+3(semi)+1(lept)]

$=$ 1(dim-four) + 8(dim-six) [+3+1] [Caveat: $m_s \gg m_u, m_d$ (& $m_\mu \gg m_e$) assumed]

↪ 5 discriminable classes

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EDM Translator
from ‘quarkish/machine’ to ‘hadronic/human’ language?

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from 'quarkish/machine' to 'hadronic/human' language?

Symmetries (esp. chiral one) plus Goldstone Theorem

↪ Low-Energy Effective Field Theory with External Sources

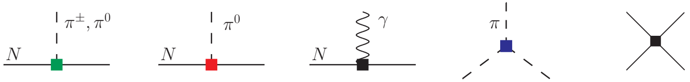
i.e. Chiral Perturbation Theory (suitably extended)

Scalings of $\not{CP}$ hadronic vertices – from θ to BSM sources

5 discriminable cases: Mereghetti et al., *AP* **325** ('10); de Vries et al., *PRC* **84** ('11); Bsaisou et al., *EPJA* **49** ('13)

	g_0	g_1	d_0, d_1	$(m_N \Delta)$	$C_{1,2}\ (C_{3,4})$
	$\not{CP}$, I	$\not{CP}$, $\not{I}$	$\not{CP}$, I + $\not{I}$	$\not{CP}$, $\not{I}$	$\not{CP}$, I ($\not{I}$)

$\mathcal{L}^{\not{CP}}_{\text{EFT}}$:

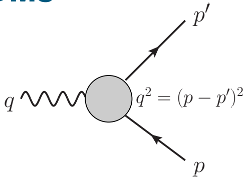


	g_0	g_1	d_0, d_1	$(m_N \Delta)$	$C_{1,2}\ (C_{3,4})$
θ-term:	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi/m_N)$	$\mathcal{O}(M_\pi/m_N)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(M_\pi^2/m_N^2)$
qEDM:	$\mathcal{O}(\alpha_{EM}/4\pi)$	$\mathcal{O}(\alpha_{EM}/4\pi)$	$\mathcal{O}(1)$	$\mathcal{O}(\alpha_{EM}/4\pi)$	$\mathcal{O}(\alpha_{EM}/4\pi)$
qCEDM:	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi/m_N)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(M_\pi^2/m_N^2)$
4qLR:	$\mathcal{O}(M_\pi^2/m_n^2)$	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi^3/m_N^3)$	$\mathcal{O}(M_\pi/m_n)$	$\mathcal{O}(M_\pi^2/m_N^2)$
gCEDM:	$\mathcal{O}(M_\pi^2/m_N^2)^\star$	$\mathcal{O}(M_\pi^2/m_N^2)^\star$	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(1)$
4q:	$\mathcal{O}(M_\pi^2/m_N^2)^\star$	$\mathcal{O}(M_\pi^2/m_N^2)^\star$	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(1)$

$^{\star)}$ Goldstone theorem → relative $\mathcal{O}(M_\pi^2/m_n^2)$ suppression of $N\pi$ interactions

Calculation: from form factors to EDMs

$$\langle f(p')|J^\mu_{\rm em}|f(p)\rangle = \bar{u}_f(p')\,\Gamma^\mu(q^2)\,u_f(p)$$



$$\Gamma^\mu(q^2) = \gamma^\mu F_1(q^2) - i\sigma^{\mu\nu} q_\nu \frac{F_2(q^2)}{2m_f} + \sigma^{\mu\nu} q_\nu \gamma_5 \frac{F_3(q^2)}{2m_f} + (\not{q}\, q^\mu - q^2\gamma^\mu)\gamma_5 \frac{F_a(q^2)}{m_f^2}$$

Dirac FF Pauli FF electric dipole FF ($\not{CP}$) anapole FF ($\not{P}$)

$$\hookrightarrow \quad d_f := \lim_{q^2\to 0} \frac{F_3(q^2)}{2m_f} \qquad \text{for } s = 1/2 \text{ fermion}$$

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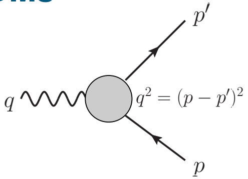

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Dirac FF — Pauli FF — electric dipole FF ($\not{C}\not{P}$) — anapole FF ($\not{P}$)

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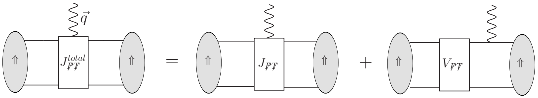
Nucleus A

$\langle \Uparrow | J^0_{\not{P}\not{T}}(q) | \Uparrow \rangle$

in Breit frame



$$= -iq^3 \underbrace{\frac{F_3^A(\vec q^{\,2})}{2m_A}}_{\hookrightarrow d_A}$$

θ-Term Induced Nucleon EDM

Crewther, di Vecchia, Veneziano & Witten, *PLB* (1979); Pich & de Rafael, *NPB* (1991); Ottnad et al., *PLB* (2010)

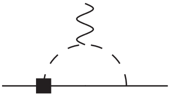
Isovector πNN coupling:

$$g_0^\theta = \frac{(m_n - m_p)^{\text{strong}}(1-\epsilon^2)}{4F_\pi\epsilon}\,\bar\theta \approx (-0.016 \pm 0.002)\bar\theta \quad \left(\text{where } \epsilon \equiv \frac{m_u - m_d}{m_u + m_d}\right)$$

$$\hookrightarrow d_N\big|^{\text{isovector}}_{\text{loop}} \sim (1.8 \pm 0.3)\cdot 10^{-16}\,\bar\theta\,\mathrm{e\,cm}$$

Bsaisou et al., *EPJA* **49** (2013), *JHEP* **03** (2015)

single nucleon EDM:

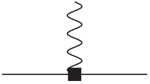


isovector

$\approx$

$\ll$

isoscalar



$g_0^\theta/\bar\theta$ known $\rightsquigarrow$ “controlled”

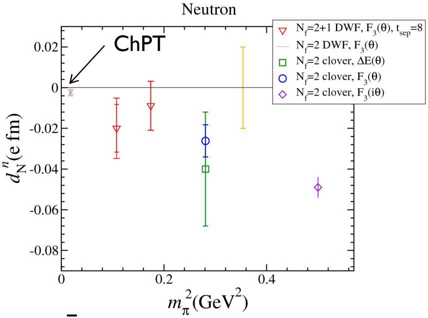
“unknown" coefficients

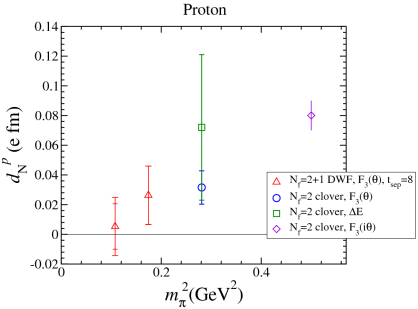
$\longrightarrow$ lattice QCD required

Guo & Meißner, *JHEP* **12** (2012)

Preliminary Lattice (full QCD) results

neutron EDM and proton EDM





$\bar{\theta} \equiv 1$!

(adapted from Eigo Shintani, *Lattice calculation of nucleon EDM*, Hirschegg, Jan. 14, 2014)

no systematical errors!

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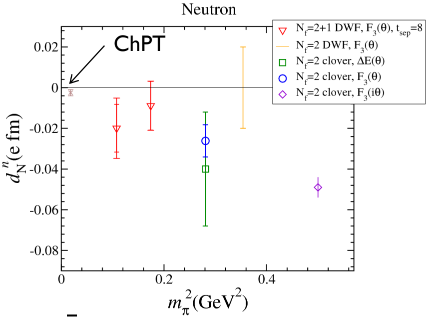

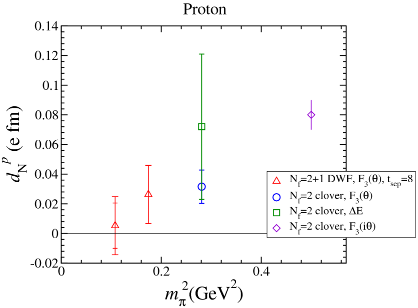

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(adapted from Eigo Shintani, *Lattice calculation of nucleon EDM*, Hirschegg, Jan. 14, 2014)

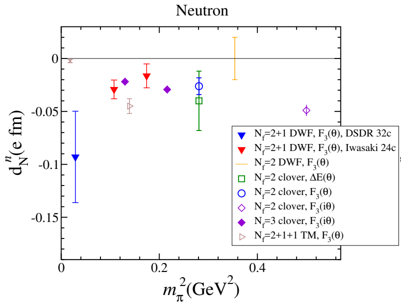
no systematical errors!

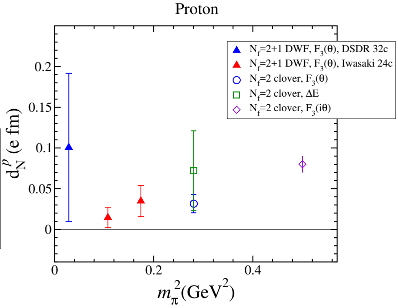
$$\hookrightarrow d_n = \bar{\theta}\,(-2.7 \pm 1.2)\cdot 10^{-3}\cdot e\,\mathrm{fm} \quad \text{and} \quad d_p = \bar{\theta}\,(2.1 \pm 1.2)\cdot 10^{-3}\cdot e\,\mathrm{fm}$$

Akan, Guo & Meißner, *PLB* **736** (2014); see also $d_n = \bar{\theta}(-3.9 \pm 0.2 \pm 0.9)10^{-3}\,e\,\mathrm{fm}$ Guo et al., *PRL* **115** (2015)

Preliminary Lattice (full QCD) results

neutron EDM and proton EDM





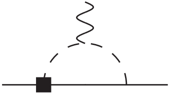
$\bar{\theta} \equiv 1$!

Eigo Shintani et al., *Phys. Rev. D* **93**, 094503 (2016)

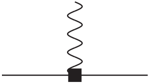
Don't mention the ... light nuclei

Single Nucleon Versus Nuclear EDM

single nucleon EDM:



isovector
$\approx$
$\ll$
isoscalar



"controlled"

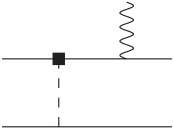
"unknown" coefficients

$\longrightarrow$ lattice QCD required

Guo & Meißner, *JHEP* (2012)

two nucleon EDM:

Sushkov, Flambaum & Khriplovich, *Sov.Phys. JETP* (1984)



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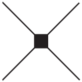

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Single Nucleon Versus Nuclear EDM

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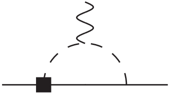
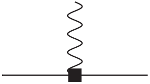


isovector $\approx$ $\ll$ isoscalar



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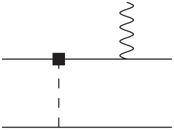

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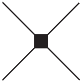
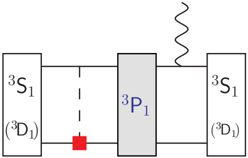


controlled unknown coefficient

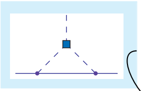
EDM of the Deuteron at LO: CP-violating π exchange

$$\mathcal{L}^{\pi N}_{\not{CP}} = -d_n N^\dagger(1-\tau^3)S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger(1+\tau_3)S^\mu v^\nu N F_{\mu\nu}$$
$$+ (m_N \Delta)\pi^2\pi_3 + \cancel{g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N} + g_1 N^\dagger \pi_3 N$$
$$+ \cancel{C_1 N^\dagger N \mathcal{D}_\mu (N^\dagger S^\mu N)} + \cancel{C_2 N^\dagger \vec{\tau} N \cdot \mathcal{D}_\mu (N^\dagger \vec{\tau} S^\mu N)} + \cdots .$$



LO: $\cancel{g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ $(\not{CP}, \text{I})$ $\to$ 0 (Isospin filter!)

NLO: $g_1 N^\dagger \pi_3 N$ $(\not{CP}, \not{\text{I}})$ $\to$ *"LO"* in D case



term	N^2LO ChPT	Av_{18}	CD-Bonn	units
d_n^D	0.939 ± 0.009	0.914	0.927	d_n
d_p^D	0.939 ± 0.009	0.914	0.927	d_p
g_1	0.183 ± 0.017	0.186	0.186	$g_1\, e\,\mathrm{fm}$
Δf_{g_1}	-0.748 ± 0.138	-0.703	-0.719	$\Delta\, e\,\mathrm{fm}$

Bsaisou, dissertation, Univ. Bonn (2014); Bsaisou et al., *JHEP* **03** (2015)

BSM $\not{CP}$ sources: g_1 πNN vertex is of LO in qCEDM and 4qLR case

 $(\Lambda_{LS}, \Lambda_{SFR}) = \{(0.45, 0.5); (0.6, 0.5); (0.55, 0.6); (0.45, 0.7); (0.6, 0.7)\}$ GeV

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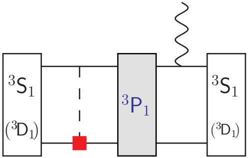
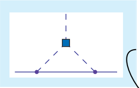


LO: $\cancel{g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ $(\not{CP}, \mathrm{I})$ → 0 (Isospin filter!)

NLO: $g_1 N^\dagger \pi_3 N$ $(\not{CP}, \not{I})$ → *"LO"* in D case

Yamanaka & Hiyama, *PRC* **91** (2015): $d_N^D = \left(1 - \frac{3}{2} P_{^3D_1}\right) d_N$



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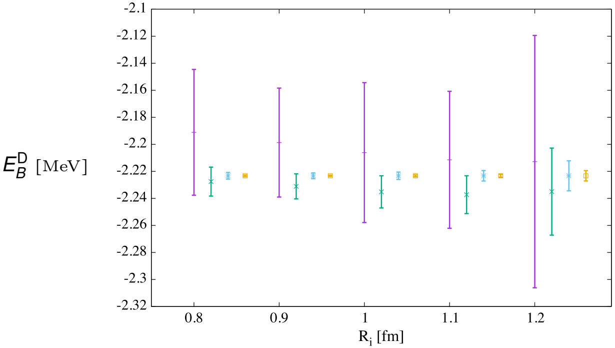
Deuteron Quantities in ChPT from NLO to N4LO

Epelbaum, Krebs, Meißner, *EPJA* **51** & *PRL* **115** (2015); Binder et al., *PRC* **93** (2016); *and* A. Nogga, *priv. comm.*

$$\Delta X^{\mathrm{N}n\mathrm{LO}}(p) = Q^{n+2}\cdot\max\left[\left|X^{\mathrm{LO}}(p)\right|, \frac{\left|X^{\mathrm{NLO}}(p)-X^{\mathrm{LO}}(p)\right|}{Q^2}, \frac{\left|X^{\mathrm{N2LO}}(p)-X^{\mathrm{NLO}}(p)\right|}{Q^3}, \frac{\left|X^{\mathrm{N3LO}}(p)-X^{\mathrm{N2LO}}(p)\right|}{Q^4}, \frac{\left|X^{\mathrm{N4LO}}(p)-X^{\mathrm{N3LO}}(p)\right|}{Q^5}\right] \quad \text{with} \quad Q=\max\left(\frac{|p|}{\Lambda_b},\frac{M_\pi}{\Lambda_b}\right)$$

and $f\left(\frac{r}{R}\right) = \left[1-\exp\left(-\frac{r^2}{R^2}\right)\right]^6$ with

R	0.8 fm	0.9 fm	1.0 fm	1.1 fm	1.2 fm
Λ_b	0.6GeV	0.6GeV	0.6GeV	0.5GeV	0.4GeV



NLO, N2LO, N3LO, N4LO

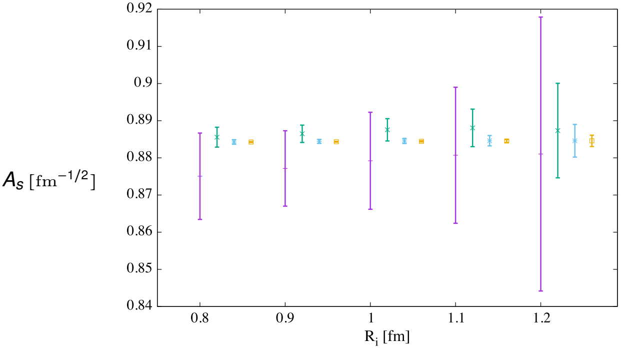
Deuteron Quantities in ChPT from NLO to N4LO

Epelbaum, Krebs, Meißner, *EPJA* **51** & *PRL* **115** (2015); Binder et al., *PRC* **93** (2016); *and* A. Nogga, *priv. comm.*

$$\Delta X^{\mathrm{N}n\mathrm{LO}}(p) = Q^{n+2}\cdot\max\left[\left|X^{\mathrm{LO}}(p)\right|, \frac{\left|X^{\mathrm{NLO}}(p)-X^{\mathrm{LO}}(p)\right|}{Q^2}, \frac{\left|X^{\mathrm{N2LO}}(p)-X^{\mathrm{NLO}}(p)\right|}{Q^3}, \frac{\left|X^{\mathrm{N3LO}}(p)-X^{\mathrm{N2LO}}(p)\right|}{Q^4}, \frac{\left|X^{\mathrm{N4LO}}(p)-X^{\mathrm{N3LO}}(p)\right|}{Q^5}\right] \quad \text{with} \quad Q=\max\left(\frac{|p|}{\Lambda_b},\frac{M_\pi}{\Lambda_b}\right)$$

and $f(\frac{r}{R}) = \left[1-\exp\left(-\frac{r^2}{R^2}\right)\right]^6$ with

R	0.8 fm	0.9 fm	1.0 fm	1.1 fm	1.2 fm
Λ_b	0.6GeV	0.6GeV	0.6GeV	0.5GeV	0.4GeV



NLO, N2LO, N3LO, N4LO

Deuteron Quantities in ChPT from NLO to N4LO

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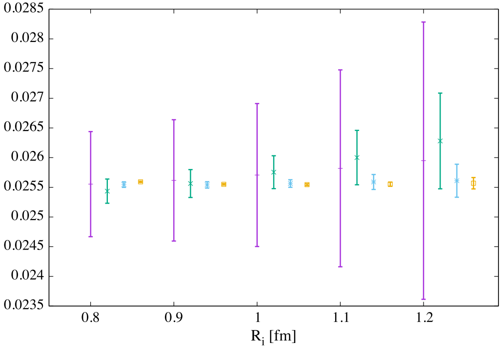
$\eta = D/S$



NLO, N2LO, N3LO, N4LO

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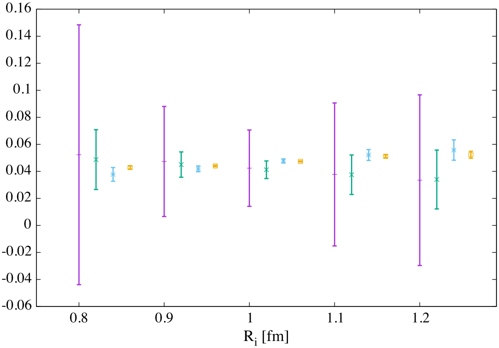
$P_{^3D_1}$



NLO, N2LO, N3LO, N4LO

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with $Q = \max\left(\frac{|p|}{\Lambda_b}, \frac{M_\pi}{\Lambda_b}\right)$

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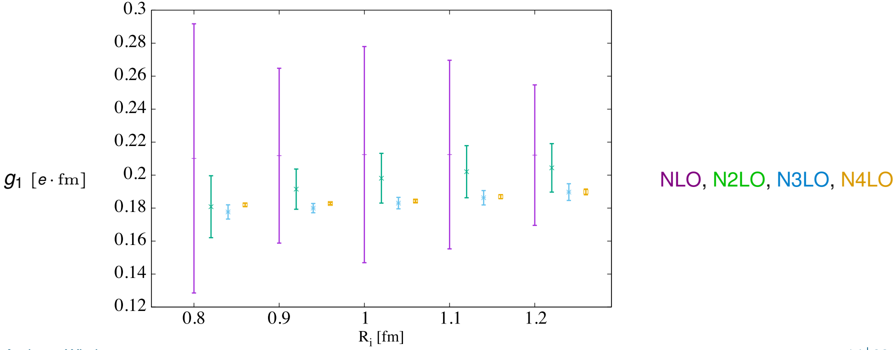

Deuteron Quantities in ChPT from NLO to N4LO

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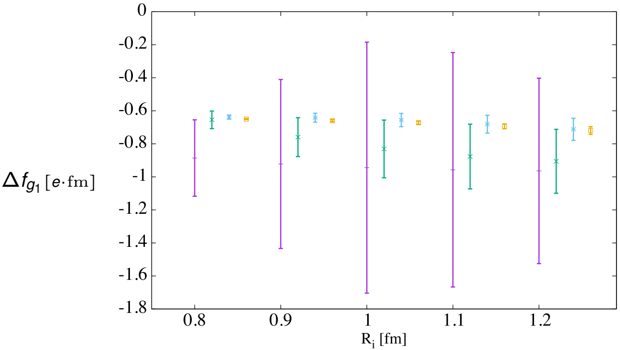
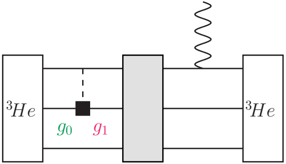


NLO, N2LO, N3LO, N4LO

^3He EDM: results for CP-violating π exchange



$g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N$ ($\not{CP}$, I)

LO: θ-term, qCEDM

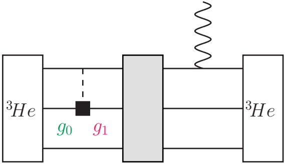
N^2LO: 4qLR

$g_1 N^\dagger \pi_3 N$ ($\not{CP}$, $\not{I}$)

LO: qCEDM, 4qLR

NLO: θ term

^3He EDM: results for CP-violating π exchange



$g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N \quad (\not{CP}, \mathrm{I})$

LO: θ-term, qCEDM

N^{2}LO: 4qLR

$g_1 N^\dagger \pi_3 N \quad (\not{CP}, \not{\mathrm{I}})$

LO: qCEDM, 4qLR

NLO: θ term

term	A	N^{2}LO ChPT	Av$_{18}$+UIX	CD-Bonn+TM	units
d_n	^{3}He	0.904 ± 0.013	0.875	0.902	d_n
	^{3}H	−0.030 ± 0.007	−0.051	−0.038	
d_p	^{3}He	−0.029 ± 0.006	−0.050	−0.037	d_p
	^{3}H	0.918 ± 0.013	0.902	0.876	
Δ	^{3}He	−0.017 ± 0.006	−0.015	−0.019	$\Delta\, e\,\mathrm{fm}$
	^{3}H	−0.017 ± 0.006	−0.015	−0.019	
g_0	^{3}He	0.111 ± 0.013	0.073	0.087	$g_0\, e\,\mathrm{fm}$
	^{3}H	−0.108 ± 0.013	−0.073	−0.085	
g_1	^{3}He	0.142 ± 0.019	0.142	0.146	$g_1\, e\,\mathrm{fm}$
	^{3}H	0.139 ± 0.019	0.142	0.144	
Δf_{g_1}	^{3}He	−0.608 ± 0.142	−0.556	−0.586	$\Delta\, e\,\mathrm{fm}$
	^{3}H	−0.598 ± 0.141	−0.564	−0.576	
C_1	^{3}He	−0.042 ± 0.017	−0.0014	−0.016	$C_1\, e\,\mathrm{fm}^{-2}$
	^{3}H	0.041 ± 0.016	0.0014	0.016	
C_2	^{3}He	0.089 ± 0.022	0.0042	0.033	$C_2\, e\,\mathrm{fm}^{-2}$
	^{3}H	−0.087 ± 0.022	−0.0044	−0.032	

Bsaisou, dissertation, Univ. Bonn (2014); Bsaisou et al., *JHEP* **03** (2015)

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^{3}*He* EDM: results for CP-violating π exchange

$$\begin{aligned}\mathcal{L}^{\pi N}_{\not{CP}} &= -d_n N^\dagger(1-\tau^3)S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger(1+\tau_3)S^\mu v^\nu N F_{\mu\nu} \\ &+ (m_N\Delta)\pi^2\pi_3 + g_0 N^\dagger\vec{\pi}\cdot\vec{\tau}N + g_1 N^\dagger\pi_3 N \\ &+ C_1 N^\dagger N\mathcal{D}_\mu(N^\dagger S^\mu N) + C_2 N^\dagger\vec{\tau}N\cdot\mathcal{D}_\mu(N^\dagger\vec{\tau}S^\mu N) + \cdots .\end{aligned}$$

term	A	N^2LO ChPT	Av_{18}+UIX	CD-Bonn+TM	units
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$(\Lambda_{LS}, \Lambda_{SFR}) = \{(0.45, 0.5); (0.6, 0.5); (0.55, 0.6); (0.45, 0.7); (0.6, 0.7)\}$ GeV

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Discriminating between three $\not{CP}$ scenarios at 1 GeV

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

1. The Standard Model + $\bar{\theta}$

$$\mathcal{L}^{\theta}_{\rm SM} = \mathcal{L}_{\rm SM} + \bar{\theta} m_q^* \bar{q} i \gamma_5 q$$

2. The left-right symmetric model — with two 4-quark operators:

$$\mathcal{L}_{LR} = -\mathrm{i}\,\Xi \left[1.1(\bar{u}_R \gamma_\mu u_R)(\bar{d}_L \gamma^\mu d_L) + 1.4(\bar{u}_R t^a \gamma_\mu u_R)(\bar{d}_L t^a \gamma^\mu d_L)\right] + \text{h.c.}$$

3. The aligned two-Higgs-doublet model — with the dipole operators:

$$\mathcal{L}_{a2HM} = -e\frac{d_d}{2}\,\bar{d}\,\mathrm{i}\sigma_{\mu\nu}\gamma_5 d\,F^{\mu\nu} - \frac{\tilde{d}_d}{4}\,\bar{d}\,\mathrm{i}\sigma_{\mu\nu}\gamma_5 \lambda^a d\,G^{a\,\mu\nu} + \frac{d_W}{3}\,f_{abc}\tilde{G}^{a\,\mu\nu}G^b_{\mu\rho}G^{c\rho}{}_{\nu}$$

— with the hierarchy $\tilde{d}_d \simeq 4 d_d \simeq 20 d_W$

matched on

$$\begin{aligned}\mathcal{L}^{\pi N}_{\not{CP}\,\rm EFT} = & -d_n N^\dagger(1-\tau^3)S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger(1+\tau_3)S^\mu v^\nu N F_{\mu\nu} \\ & + (m_N\Delta)\pi^2\pi_3 + g_0 N^\dagger \vec{\pi}\cdot\vec{\tau}N + g_1 N^\dagger \pi_3 N \\ & + C_1 N^\dagger N \mathcal{D}_\mu(N^\dagger S^\mu N) + C_2 N^\dagger \vec{\tau} N \cdot \mathcal{D}_\mu(N^\dagger \vec{\tau} S^\mu N) + \cdots .\end{aligned}$$

see also talk by *Jordy de Vries*

Discriminating between three $\not{CP}$ scenarios at 1 GeV

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

1. The Standard Model + $\bar\theta$

$$\mathcal{L}^{\theta}_{\rm SM} = \mathcal{L}_{\rm SM} + \bar\theta m_q^* \bar q i\gamma_5 q$$

2. The left-right symmetric model — with two 4-quark operators:

$$\mathcal{L}_{LR} = -\mathrm{i}\,\Xi\left[1.1(\bar u_R\gamma_\mu u_R)(\bar d_L\gamma^\mu d_L) + 1.4(\bar u_R t^a\gamma_\mu u_R)(\bar d_L t^a\gamma^\mu d_L)\right] + \text{h.c.}$$

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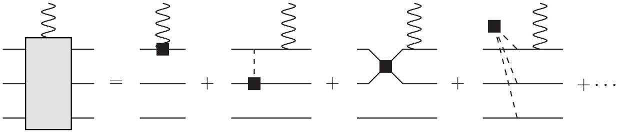
$$\mathcal{L}_{a2HM} = -e\frac{d_d}{2}\,\bar d\,\mathrm{i}\sigma_{\mu\nu}\gamma_5 d\,F^{\mu\nu} - \frac{\tilde d_d}{4}\,\bar d\,\mathrm{i}\sigma_{\mu\nu}\gamma_5\lambda^a d\,G^{a\,\mu\nu} + \frac{d_W}{3}\,f_{abc}\tilde G^{a\,\mu\nu}G^b_{\mu\rho}G^{c\rho}_{\ \ \nu}$$

— with the hierarchy $\tilde d_d \simeq 4d_d \simeq 20 d_W$

matched on



see also talk by *Jordy de Vries*

Testing strategies: SM + $\bar{\theta}$

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

Measurement of the helion
and neutron EDMs

Testing strategies: SM + $\bar{\theta}$

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

Measurement of the helion and neutron EDMs

↓

Extraction of $\bar{\theta}$

$$d_{^3\mathrm{He}} - 0.9 d_n = -\bar{\theta}\left(1.01 \pm 0.31_{\mathrm{had}} \pm 0.29^{\star}_{\mathrm{nucl}}\right) \cdot 10^{-16}\, e\,\mathrm{cm}$$

*includes ± 0.20 uncertainty from 2N contact terms

Testing strategies: SM + $\bar{\theta}$

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

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Extraction of $\bar{\theta}$

$$d_D - 0.94(d_n + d_p) = \bar{\theta}\left(0.89 \pm 0.29_{\mathrm{had}} \pm 0.08_{\mathrm{nucl}}\right) \cdot 10^{-16}\, e\,\mathrm{cm}$$

Prediction for $d_D - 0.94(d_n + d_p)$
(& triton EDM): $d_D^{\mathrm{Nucl}} \approx -d_{^3\mathrm{He}}^{\mathrm{Nucl}} \approx \frac{1}{2} d_{^3\mathrm{H}}^{\mathrm{Nucl}}$

*includes ± 0.20 uncertainty from 2N contact terms

Testing strategies: SM + $\bar{\theta}$

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

Measurement of the helion and neutron EDMs

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Prediction for $d_D - 0.94(d_n + d_p)$

(& triton EDM): $d_D^{\rm Nucl} \approx -d_{^3\mathrm{He}}^{\rm Nucl} \approx \frac{1}{2} d_{^3\mathrm{H}}^{\rm Nucl}$

$$g_0^\theta = \frac{(m_n - m_p)^{\rm strong}(1-\epsilon^2)}{4F_\pi\,\epsilon}\,\bar{\theta} = (-16 \pm 2)10^{-3}\,\bar{\theta}$$

$$\frac{g_1^\theta}{g_0^\theta} \approx \frac{8c_1(M^2_{\pi^\pm} - M^2_{\pi^0})^{\rm strong}}{(m_n - m_p)^{\rm strong}}, \quad \epsilon \equiv \frac{m_u - m_d}{m_u + m_d}$$

$g_1^\theta / g_0^\theta \approx -0.2$

*includes ± 0.20 uncertainty from 2N contact terms

Testing strategies: minimal LR symmetric Model

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

Measurement of the deuteron
and nucleon EDMs

Testing strategies: minimal LR symmetric Model

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

$$d_D - 0.94(d_n+d_p) \simeq d_D = -\left(2.1 \pm 0.5^{\star}\right)\Delta^{LR} e\,\mathrm{fm}$$

Extraction of Δ^{LR}

*includes ± 0.1 uncertainty from 2N contact terms

Testing strategies: minimal LR symmetric Model

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

$$d_D - 0.94(d_n + d_p) \simeq d_D = -\big(2.1 \pm 0.5^{\star}\big)\Delta^{LR} e\,\mathrm{fm}$$

Extraction of Δ^{LR}

$$d_{^3\mathrm{He}} - 0.9 d_n \simeq d_{^3\mathrm{He}} = -(1.7 \pm 0.5^{\star})\Delta^{LR} e\,\mathrm{fm}$$

Prediction for the helion EDM (& triton EDM): $d_D \approx d_{^3\mathrm{He}} \approx d_{^3\mathrm{H}}$

*includes ± 0.1 uncertainty from 2N contact terms

Testing strategies: minimal LR symmetric Model

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

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Extraction of Δ^{LR}

$$d_{^3\mathrm{He}} - 0.9 d_n \simeq d_{^3\mathrm{He}} = -(1.7 \pm 0.5^{\star})\Delta^{LR} e\,\mathrm{fm}$$

Prediction for the helion EDM (& triton EDM): $d_D \approx d_{^3\mathrm{He}} \approx d_{^3\mathrm{H}}$

$$g_1^{LR} = 8 c_1 m_N \Delta^{LR} = (-7.5 \pm 2.3)\Delta^{LR},$$

$$g_0^{LR} = \frac{(m_n - m_p)^{\mathrm{str}} m_N}{M_\pi^2} \Delta^{LR} = (0.12 \pm 0.02)\Delta^{LR}$$

$-g_1^{LR}/g_0^{LR} \gg 1$ (!)

*includes ± 0.1 uncertainty from 2N contact terms

Testing strategies: aligned 2-Higgs Doublet Model

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

Testing strategies: aligned 2-Higgs Doublet Model

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

$$d_D - 0.94(d_n + d_p) = \left[(0.18\pm0.02)g_1 - (0.75\pm0.14)\Delta\right] e\,\mathrm{fm}$$

Extraction of g_1^{eff} (including Δ correction)

Testing strategies: aligned 2-Higgs Doublet Model

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

$$d_D - 0.94(d_n + d_p) = \left[(0.18 \pm 0.02)g_1 - (0.75 \pm 0.14)\Delta\right] e\,\text{fm}$$

Extraction of g_1^{eff} (including Δ correction)

+ Measurement of $d_{^3\text{He}}$ (or $d_{^3\text{H}}$)

Testing strategies: aligned 2-Higgs Doublet Model

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

$$d_D - 0.94(d_n + d_p) = \left[(0.18\pm0.02)g_1 - (0.75\pm0.14)\Delta\right] e\,\mathrm{fm}$$

Extraction of g_1^{eff} (including Δ correction)

+ Measurement of $d_{^3\mathrm{He}}$ (or $d_{^3\mathrm{H}}$)

$$d_{^3\mathrm{He}} - 0.9 d_n$$
$$= \left[(0.11\pm0.02^{\star})g_0 + (0.14\pm0.02^{\star})g_1 - (0.61\pm0.14)\Delta\right] e\,\mathrm{fm}$$

Extraction of g_0

*includes ±0.01 uncertainty from 2N contact terms

Testing strategies: aligned 2-Higgs Doublet Model

Dekens et al., *JHEP* **07** (2014); Bsaisou et al., *JHEP* **03** (2015)

Measurement of the deuteron and nucleon EDMs

$$d_D - 0.94(d_n + d_p) = \left[(0.18\pm0.02)g_1 - (0.75\pm0.14)\Delta\right] e\,\mathrm{fm}$$

Extraction of g_1^{eff} (including Δ correction)

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$$d_{^3\mathrm{He}} - 0.9 d_n$$
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Extraction of g_0

Prediction of $d_{^3\mathrm{H}}$ (or $d_{^3\mathrm{He}}$)

*includes ±0.01 uncertainty from 2N contact terms

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Summary

- D EDM might **distinguish** between $\bar{\theta}$ and other scenarios and allows **extraction** of the g_1 coupling constant via $d_D - 0.94(d_n + d_p)$.
  (The prefactor of $(d_n + d_p)$ stands for a 4% probability of the $^3D_1$ state.)
- ^3He (or ^3H) EDM necessary for a **proper test** of $\bar{\theta}$ and LR scenarios:
- Deuteron & helion work as complementary isospin filters of EDMs
- 2N contact terms **cannot be neglected** for nuclei beyond D
- a2HDM case: ^3He and ^3H EDMs would be needed for a proper test
- pure qCEDM: similar to a2HDM scenario
- pure qEDM: $d_D = 0.94(d_n + d_p)$ and $d_{^3He/^3H} = 0.9 d_{n/p}$
- gCEDM, 4quark χ singlet: controlled calculation difficult (lattice ?)
- Ultimate progress may eventually come from **Lattice QCD**
  $\hookrightarrow$ $\not{CP}$ $N\pi$ couplings g_0 & g_1 may be accessible even for dim-6 case

Conclusions

- EDMs **probe** *New CP-odd Physics* (at similar energy scales as LHC)
- The **first** non-vanishing EDM might be detected in a charge-neutral case: *neutrons* or *dia-/ paramagnetic atoms* or *molecules* ⋯

  However, measurements of **light ion EDMs** can play a key role in **disentangling the *sources* of (flavor-diagonal) $\not{CP}$**
- EDM measurements are of **low-energy nature:**
  ↪ non-leptonic predictions have to be in the *language of hadrons*
  ↪ only systematical methods: *ChPT/EFT* and *Lattice QCD*
- EDMs of light nuclei give independent information to nucleon ones and may be even larger and, moreover, even **simpler**

At least the EDMs of *p*, *n*, *D*, and ^3He would be needed
to have a **realistic** chance to disentangle the underlying physics

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References:

1. J. Bsaisou, U.-G. Meißner, A. Nogga and A.W., *P- and T-Violating Lagrangians in Chiral Effective Field Theory and Nuclear Electric Dipole Moments*, Annals of Physics **359**, 317-370 (2015), arXiv:1412.5471[hep-ph].
2. J. Bsaisou, C. Hanhart, S. Liebig, D. Minossi, U.-G. Meißner, A. Nogga and A.W., *Electric dipole moments of light nuclei*, JHEP **03**,104 (**05**, 083) (2015), arXiv:1411.5804.
3. A.W., *Electric dipole moments of the nucleon and light nuclei* Nuclear Physics A **928**, 116-127 (2014), arXiv:1404.6131 [hep-ph].
4. W. Dekens, J. de Vries, J. Bsaisou, W. Bernreuther, C. Hanhart, U.-G. Meißner, A. Nogga and A.W., *Unraveling models of CP violation through electric dipole moments of light nuclei,* JHEP **07**, 069 (2014), arXiv:1404.6082 [hep-ph].
5. J. Bsaisou, C. Hanhart, S. Liebig, U.-G. Meißner, A. Nogga and A.W., *The electric dipole moment of the deuteron from the QCD θ-term,* Eur. Phys. J. A **49**, 31 (2013), arXiv:1209.6306 [hep-ph].