JÜLICH FORSCHUNGSZENTRUM

5/7th Bethe Center Workshop **"Challenges in Strong Interaction Physics"**

Physikzentrum Bad Honnef, September 29 – October 2, 2015

Electric Dipole Moments of Light Ions

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in collaboration with
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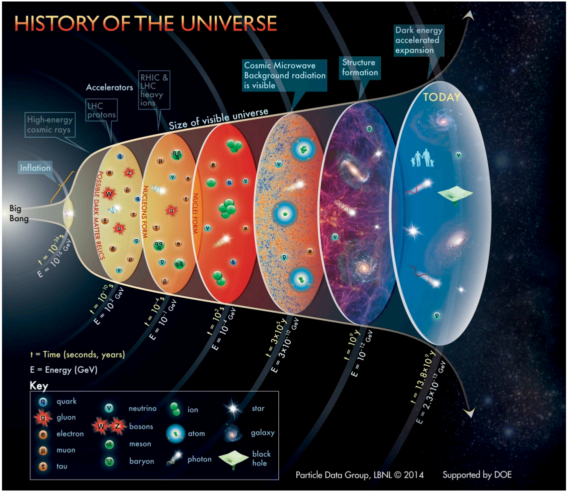
Bad Honnef | October 2, 2015

Matter Excess in the Universe



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

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

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

CP violation and the Electric Dipole Moment (EDM)

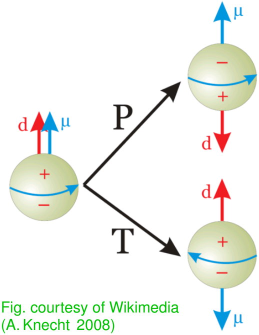


Fig. courtesy of Wikimedia
(A. Knecht 2008)

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

(polar) (axial)

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

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

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

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): $|d_n| \sim 10^{-31} e\,\text{cm}$, $|d_e| \sim 10^{-38} e\,\text{cm}$
- Current bounds: $|d_n| < 3 \cdot 10^{-26} e\,\text{cm}$, $|d_p| < 8 \cdot 10^{-25} e\,\text{cm}$, $|d_e| < 1 \cdot 10^{-28} e\,\text{cm}$

  n: Baker et al. (2006), *p* prediction: Dimitriev & Sen'kov (2003)*, *e*: Baron et al.(2013)†

  * from $|d_{^{199}\text{Hg}}| < 3.1 \cdot 10^{-29} e\,\text{cm}$ bound of Griffith et al. (2009) † from polar ThO: $|d_{ThO}| \lesssim 10^{-21} e\,\text{cm}$

Three motivations for EDM searches

Why are EDMs interesting?

- Matter/Antimatter asymmetry requires CP violation beyond SM: EDMs excellent probes
- A search for new physics (NP) which is virtually 'background free'
- Many NP models predict 'large' EDMs: Complementary to LHC searches

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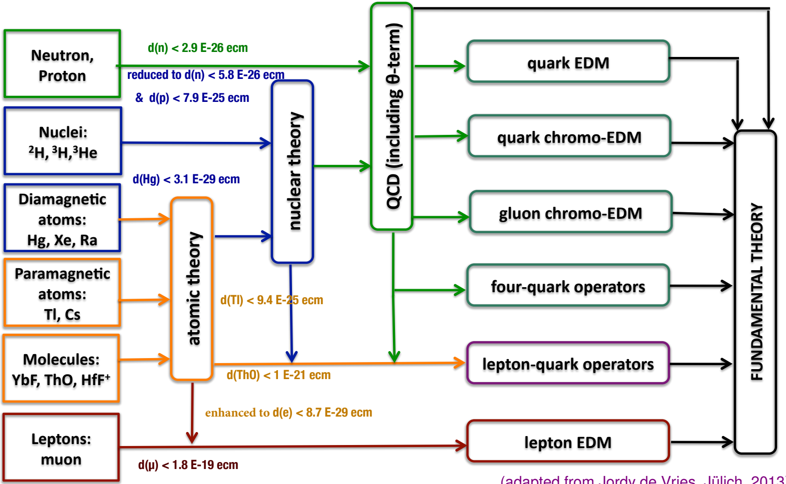
and why are EDMs of *light ions* interesting?

Road map from EDM Measurements to EDM Sources

Experimentalist's point of view → ← Theorist's point of view

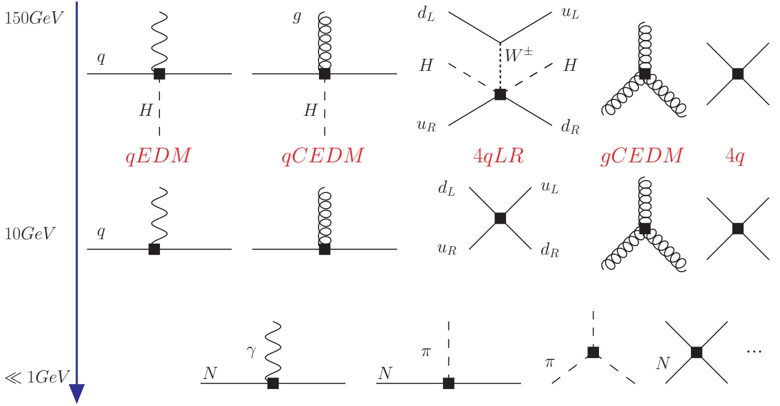


(adapted from Jordy de Vries, Jülich, 2013)

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)



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

$$= \underbrace{1(\text{dim-four}) + 8(\text{dim-six})}_{\hookrightarrow \text{ 5 discriminable classes}}\ [+3+1]$$

[Caveat: $m_s \gg m_u, m_d$ (& $m_\mu \gg m_e$) assumed]

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

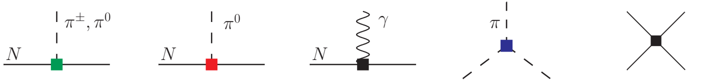
↪ Low-Energy Effective Field Theory with External Sources

i.e. Chiral Perturbation Theory (suitably extended)

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

5 discriminable classes:

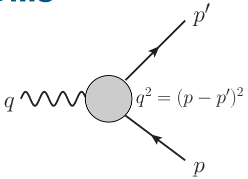
	g_0	g_1	d_0, d_1	$(m_N\Delta)$	$C_{1,2}\,(C_{3,4})$
	$\not{CP}$, I	$\not{CP}$, $\not{I}$	$\not{CP}$, I + $\not{I}$	$\not{CP}$, $\not{I}$	$\not{CP}$, I ($\not{I}$)
$\mathcal{L}^{\not{CP}}_{\text{EFT}}$:					
θ-term:	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi/m_N)$	$\mathcal{O}(M_\pi/m_N)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(M_\pi^2/m_N^2)$
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

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



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

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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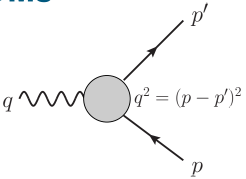


$$\Gamma^\mu(q^2) = \gamma^\mu F_1(q^2) - i\sigma^{\mu\nu} q_\nu \frac{F_2(q^2)}{2m_f} + \sigma^{\mu\nu} q_\nu \gamma_5 \frac{F_3(q^2)}{2m_f} + (\not q\, q^\mu - q^2\gamma^\mu)\gamma_5 \frac{F_a(q^2)}{m_f^2}$$

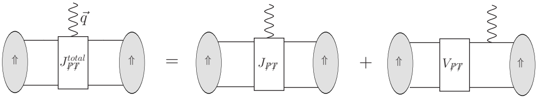
Dirac FF — Pauli FF — electric dipole FF ($\not{C}\not{P}$) — anapole FF ($\not{P}$)

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

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)

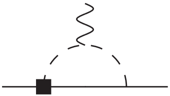
Isovector πNN coupling:

$$g_0^\theta = \frac{(m_n - m_p)^{\text{strong}}(1-\epsilon^2)}{4F_\pi \epsilon}\,\bar\theta \approx (-0.018 \pm 0.007)\bar\theta \qquad \left(\text{where } \epsilon \equiv \frac{m_u - m_d}{m_u + m_d}\right)$$

$$\hookrightarrow d_N\big|^{\text{isovector}}_{\text{loop}} \sim (2.1 \pm 0.9)\cdot 10^{-16}\,\bar\theta\,\mathrm{e\,cm}$$

Bsaisou et al., *EPJA* **49** (2013)

single nucleon EDM:

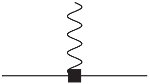


isovector

$\approx$

$\ll$

isoscalar



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

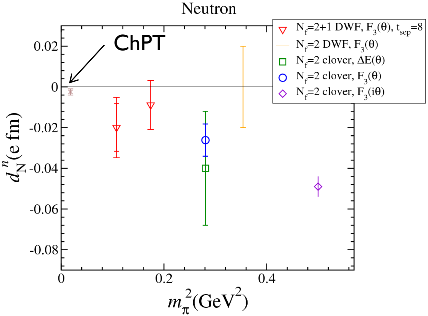
“unknown" coefficients

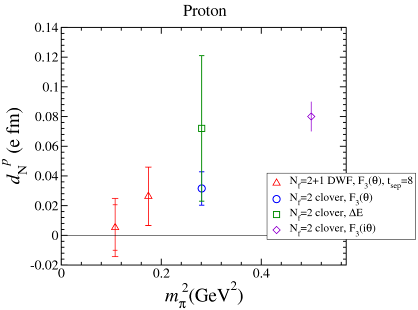
$\longrightarrow$ lattice QCD required

Guo & Meißner, *JHEP* **12** (2012)

Preliminary Lattice (full QCD) results

neutron EDM and proton EDM





$\theta \equiv 1$!

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

no systematical errors!

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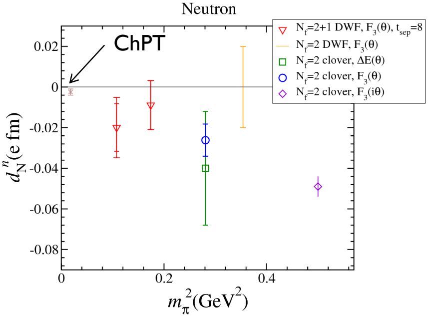

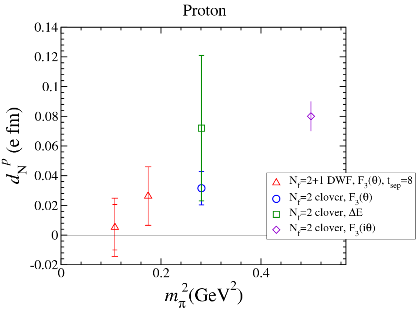

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$$\hookrightarrow d_n = \bar{\theta}\,(-2.7 \pm 1.2)\cdot 10^{-3}\cdot e\cdot fm \quad \text{and} \quad d_p = \bar{\theta}\,(2.1 \pm 1.2)\cdot 10^{-3}\cdot e\cdot fm$$

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

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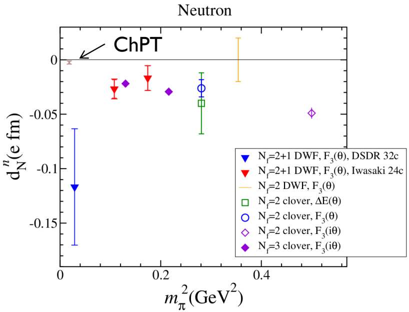
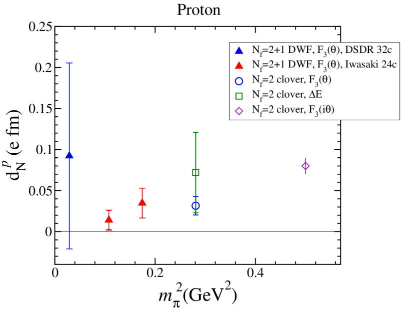


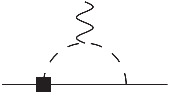


(adapted from Eigo Shintani (RIKEN-AICS), INT Program INT-15-3, Seattle, Sept. 22, 2015)

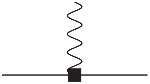
Don't mention the ... light nuclei

Single Nucleon Versus Nuclear EDM

single nucleon EDM:



isovector $\approx$ $\ll$ isoscalar



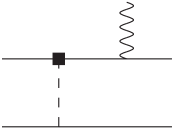
"controlled" — "unknown" coefficients

$\longrightarrow$ lattice QCD required

Guo & Meißner, *JHEP* (2012)

two nucleon EDM:

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



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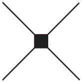
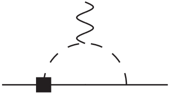


controlled — unknown coefficient

Single Nucleon Versus Nuclear EDM

single nucleon EDM:



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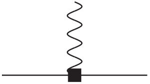

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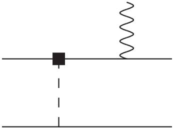

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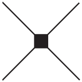
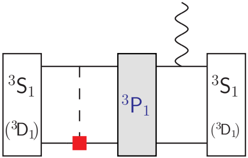


controlled — unknown coefficient

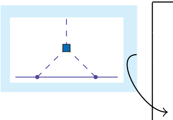
EDM of the Deuteron at LO: CP-violating π exchange

$$\mathcal{L}^{\pi N}_{\cancel{CP}} = -d_n N^\dagger(1-\tau^3)S^\mu v^\nu N F_{\mu\nu} - d_p N^\dagger(1+\tau_3)S^\mu v^\nu N F_{\mu\nu}$$
$$+ (m_N \Delta)\pi^2\pi_3 + \cancel{g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N} + g_1 N^\dagger \pi_3 N$$
$$+ \cancel{C_1 N^\dagger N \mathcal{D}_\mu (N^\dagger S^\mu N)} + \cancel{C_2 N^\dagger \vec{\tau} N \cdot \mathcal{D}_\mu (N^\dagger \vec{\tau} S^\mu N)} + \cdots .$$



LO: $\cancel{g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N}$ $(\cancel{CP}, I)$ $\rightarrow$ 0 (Isospin filter!)

NLO: $g_1 N^\dagger \pi_3 N$ $(\cancel{CP}, \cancel{I})$ $\rightarrow$ *"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 $\cancel{CP}$ sources: g_1 πNN vertex is of LO in qCEDM and 4qLR case

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

$$
\begin{aligned}
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& + (m_N \Delta)\pi^2\pi_3 + \cancel{g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N} + g_1 N^\dagger \pi_3 N \\
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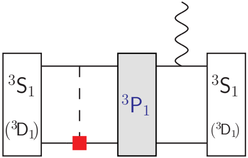
\end{aligned}
$$



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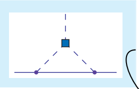
NLO: $g_1 N^\dagger \pi_3 N$ $(\not{CP}, \not{I})$ $\rightarrow$ *"LO"* in D case

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



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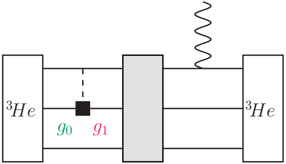


$g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N$ ($\not{CP}$, I)

LO: θ-term, qCEDM

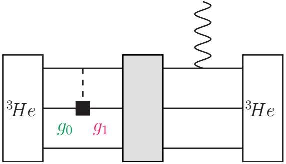
N^{2}LO: 4qLR

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

LO: qCEDM, 4qLR

NLO: θ term

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



$g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N$ $(\not{C}\not{P}, \mathrm{I})$
LO: θ-term, qCEDM
N^{2}LO: 4qLR

$g_1 N^\dagger \pi_3 N$ $(\not{C}\not{P}, \not{\mathrm{I}})$
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)

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

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

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	$\Delta\, e\,\mathrm{fm}$
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Bsaisou, dissertation, Univ. Bonn (2014); Bsaisou et al., *JHEP* **03** (2015)

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 $\tilde d_d \simeq 4d_d \simeq 20 d_W$

matched on

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

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 + $\bar\theta$

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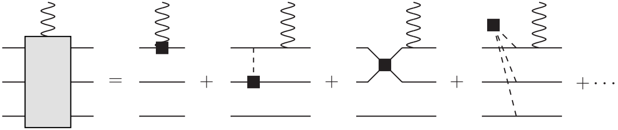
— with the hierarchy $\tilde d_d \simeq 4 d_d \simeq 20 d_W$

matched on



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

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

Extraction of $\bar{\theta}$

*includes ± 0.20 uncertainty from 2N contact terms

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

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

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Extraction of $\bar{\theta}$

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

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

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

*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)

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

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

↓

Extraction of Δ^{LR}

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

* 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)

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}

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

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

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

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

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

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

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

Measurement of the deuteron and nucleon EDMs

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

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

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

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)

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

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

Extraction of g_0

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

*includes ±0.01 uncertainty from 2N contact terms

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.)
- ^{3}He (or ^{3}H) EDM necessary for a **proper test** of $\bar{\theta}$ and LR scenarios
- Deuteron & helion work as complementary isospin filters of EDMs
- a2HDM scenario: helion *and* triton EDMs would be needed for a test
- pure qCEDM: similar to a2HDM scenario
- pure qEDM: $d_D = 0.94(d_n + d_p)$ and $d_{^3\mathrm{He}/^3\mathrm{H}} = 0.9 d_{n/p}$
- gCEDM, 4quark chiral singlet:

  controlled calculation/disentanglement 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

Traditional atomic EDMs

- Why can't we get **this info** from EDMs of Hg, Ra, Rn, ... ?

  Strong bound on atomic EDM: $|d_{^{199}\mathrm{Hg}}| < 3.1 \cdot 10^{-29} \cdot e \cdot \mathrm{fm}$

  Griffiths et al., *PRL* (2009)

- The atomic part of the calculation is well under control

  $d_{^{199}\mathrm{Hg}} = (2.8 \pm 0.6)\, S_{\mathrm{Hg}} \cdot e \cdot \mathrm{fm}^{-2}$ Dzuba et al., *PRA* (2002), (2009)

  S_{Hg}: Nuclear Schiff moment

- But the nuclear part isn't ...

  $S_{^{199}\mathrm{Hg}} = \left[(0.3 \pm 0.4) g_0 + (0.4 \pm 0.8) g_1\right]\, e \cdot \mathrm{fm}^3$ Engel et al., *PPNP* (2013)

- There is **no power counting** for nuclei with so many nucleons
- Short-range 4N contributions **not even considered**
- Hadronic uncertainties of g_0 and g_1 are **underestimated** too

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** will play a key role in **disentangling the *sources* of (flavor-diagonal) $\not{C}\not{P}$**
- 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 ^{3}He are needed
to have a realistic chance to disentangle the underlying physics

Many thanks to my colleagues

in Jülich: Jan Bsaisou, Christoph Hanhart, Susanna Liebig, Ulf-G. Meißner, David Minossi, Andreas Nogga, Jordy de Vries

in Bonn: Feng-Kun Guo, Bastian Kubis, Ulf-G. Meißner

and: Werner Bernreuther, Wouter Dekens, Bira van Kolck, Kolya Nikolaev

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Backup slides

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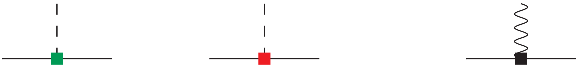
Hierachy among the sources at the hadronic EFT level

Each source transforms differently under chiral and isospin symmetry

$\not{CP}$, I $\qquad$ $\not{CP}$, $\not{I}$ $\qquad$ $\not{CP}$, I + $\not{I}$

$$\mathcal{L}^{\not{CP}}_{\rm EFT} = g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N \;+\; g_1 N^\dagger \pi_3 N \;+\; N^\dagger (d_0 + d_1 \tau_3) S^\mu v^\nu F_{\mu\nu} N \;+\cdots$$

$\Downarrow$ $\qquad$ $\Downarrow$ $\qquad$ $\Downarrow$



...

dominant for $\bar\theta$ term $\qquad$ suppressed for $\bar\theta$ term $\qquad$ suppressed by $\mathcal{O}(M_\pi^2)$

- $\mathcal{L}^{\theta}_{QCD} = \bar\theta m_q^* \sum_f \bar q_f i\gamma_5 q_f$: $\quad$ $\not{CP}$, I $\qquad$ $m_q^* = \frac{m_u m_d}{m_u + m_d}$

  ↪ $\bar\theta$ source breaks chiral symmetry ($\propto m_q^*$) but conserves the isospin one:

  ↪ $|g_0^\theta| \gg |g_1^\theta|$: NDA estimate: $g_1^\theta / g_0^\theta \sim \mathcal{O}(M_\pi^2/m_n^2)$ $\qquad$ de Vries et al. *PRC* '11

  ChPT LECs predict: $g_1^\theta / g_0^\theta \sim \mathcal{O}(M_\pi/m_n)$! $\quad$ Bsaisou et al. *EPJA* '13

Hierachy among the sources at the hadronic EFT level

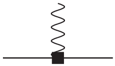
Each source transforms differently under chiral and isospin symmetry

$$\mathcal{L}^{\not{CP}}_{\text{EFT}} = \underbrace{g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N}_{\not{CP},\ \mathrm{I}} + \underbrace{g_1 N^\dagger \pi_3 N}_{\not{CP},\ \not{\mathrm{I}}} + \underbrace{N^\dagger (d_0 + d_1 \tau_3) S^\mu v^\nu F_{\mu\nu} N}_{\not{CP},\ \mathrm{I} + \not{\mathrm{I}}} + \cdots$$

$\Downarrow$

dominant for chromo qEDM source

dominant for chromo qEDM source



$\mathcal{O}(m_\pi^2)$ suppressed for chromo qEDM source

...

- chromo quark EDM: chiral symmetries are (& isospin ones may be) broken because of quark masses $\rightsquigarrow$ Goldstone theorem respected
- 4quark Left-Right EDM: **explicit** breaking of **chiral & isospin** symmetries because of underlying W boson exchange $\rightsquigarrow$ Goldstone theorem does not apply

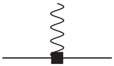
Hierachy among the sources at the hadronic EFT level

Each source transforms differently under chiral and isospin symmetry

$$\not{CP},\ \mathrm{I} \qquad\qquad \not{CP},\ \not{\mathrm{I}} \qquad\qquad \not{CP},\ \mathrm{I} + \not{\mathrm{I}}$$

$$\mathcal{L}^{\not{CP}}_{\mathrm{EFT}} = g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N \;+\; g_1 N^\dagger \pi_3 N \;+\; N^\dagger (d_0 + d_1 \tau_3) S^\mu v^\nu F_{\mu\nu} N \;+\cdots$$

$\Downarrow$ $\qquad$ $\Downarrow$ $\qquad$ $\Downarrow$



…

suppressed for quark EDM source | suppressed for quark EDM source | dominating for quark EDM source

- quark EDM: $N\pi$ (and NN) interactions are **suppressed** by $\alpha_{\mathrm{em}}/(4\pi)$
- gluon color EDM (and chiral-4quark EDM): **relative** $\mathcal{O}(M_\pi^2)$ **suppression** of $N\pi$ interactions because of Goldstone theorem

If $\bar{\theta}$-term tests fail, then effective BSM dim. 6 sources

de Vries et al.(2011)

qEDM	qCEDM	4qLR	gCEDM + 4qEDM
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

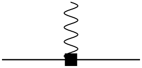
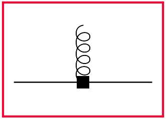
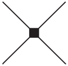
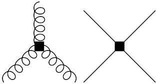
$\longrightarrow \quad g_0, \, g_1 \propto \alpha/(4\pi)$

$2N$ contribution suppressed by photon loop!

here: only absolute values considered

If $\bar{\theta}$-term tests fail, then effective BSM dim. 6 sources

de Vries et al.(2011)

			
qEDM	*qCEDM*	*4qLR*	*gCEDM + 4qEDM*
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

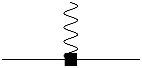
$\longrightarrow$ g_0, g_1 dominant and of the same order

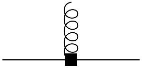
$2N$ contribution enhanced!

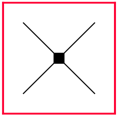
here: only absolute values considered

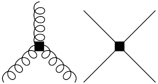
If $\bar{\theta}$-term tests fail, then effective BSM dim. 6 sources

de Vries et al.(2011)









qEDM	*qCEDM*	*4qLR*	*gCEDM* + *4qEDM*
$d_D \approx d_p + d_n$	$d_D > d_p + d_n$	$d_D > d_p + d_n$	$d_D \sim d_p + d_n$
$d_{^3He} \approx d_n$	$d_{^3He} > d_n$	$d_{^3He} > d_n$	$d_{^3He} \sim d_n$

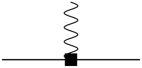
$\longrightarrow g_1 \gg g_0$; 3π-coupling (unsuppressed in ^{3}He)

isospin-breaking $2N$ contribution enhanced!

here: only absolute values considered

If $\bar{\theta}$-term tests fail, then effective BSM dim. 6 sources

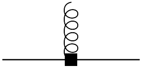
de Vries et al.(2011)



qEDM

$d_D \approx d_p + d_n$

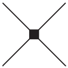
$d_{^3He} \approx d_n$



qCEDM

$d_D > d_p + d_n$

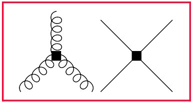
$d_{^3He} > d_n$



4qLR

$d_D > d_p + d_n$

$d_{^3He} > d_n$



gCEDM + 4qEDM

$d_D \sim d_p + d_n$

$d_{^3He} \sim d_n$

$\longrightarrow$ g_1, g_0, $4N$ – coupling on the same footing

$2N$ contribution difficult to asses!

here: only absolute values considered

θ-term: $\not{CP}$ πNN vertices determined from LECs

Leading g_0^θ coupling (from c_5)

Crewther et al. (1979);
Ottnad et al. (2010); Mereghetti et al. (2011);
de Vries et al. (2011); Bsaisou et al. (2013)

g_0^θ: $N^\dagger \vec{\pi} \cdot \vec{\tau} N$-vertex

$$\mathcal{L}_{\pi N} = \quad \ldots + \quad c_5 2B\, N^\dagger \left((m_u - m_d)\, \tau_3 + \frac{2m^* \bar{\theta}}{F_\pi} \vec{\pi} \cdot \vec{\tau} \right) N \quad + \ldots$$

$$\delta M_{np}^{str} = 4B(m_u - m_d) c_5 \quad \rightarrow \quad g_0^\theta = \bar{\theta}\, \delta M_{np}^{str}\, (1 - \epsilon^2) \frac{1}{4 F_\pi \epsilon}$$

$$\delta M_{np}^{em} \quad \rightarrow \quad \delta M_{np}^{str} = (2.6 \pm 0.5)\text{MeV}$$

Walker-Loud et al. (2012)

$$\longrightarrow \boxed{g_0^\theta = (-0.018 \pm 0.007)\bar{\theta}}$$

$$\epsilon = (m_u - m_d)/(m_u + m_d)\,, \quad 4Bm^* = M_\pi^2 (1 - \epsilon^2), \quad m^* = \frac{m_u m_d}{m_u + m_d}$$

θ-term: subleading g_1^θ coupling (from c_1 LEC)

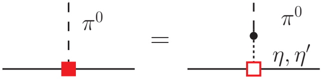
g_1^θ: $\pi_3 NN$-vertex

$\epsilon := (m_u - m_d)/(m_u + m_d)$

$$\mathcal{L}_{\pi N} = \ldots + c_1 4B\, N^\dagger \left((m_u + m_d) + \frac{(\delta M_\pi^2)_{QCD}(1-\epsilon^2)\,\bar\theta}{2BF_\pi \epsilon} \pi_3 \right) N + \ldots$$

1 $c_1 \longleftrightarrow \sigma_{\pi N}$: $c_1 = (-1.0 \pm 0.3)\ \mathrm{GeV}^{-1}$ Compilation: Baru et al. (2011)

2 $(\delta M_\pi^2)_{QCD} \approx \frac{\epsilon^2}{4} \frac{M_\pi^4}{M_K^2 - M_\pi^2}$



$\longrightarrow$ $g_1^\theta = (0.003 \pm 0.002)\bar\theta$

Bsaisou et al. (2013)

$$\frac{g_1^\theta}{g_0^\theta} = -0.20 \pm 0.13 \sim \frac{M_\pi}{m_N}$$

Bsaisou et al. (2013)

$$\gg \quad \epsilon \frac{M_\pi^2}{m_N^2} \sim -0.01 \quad \text{(NDA)}$$

de Vries et al. (2011)

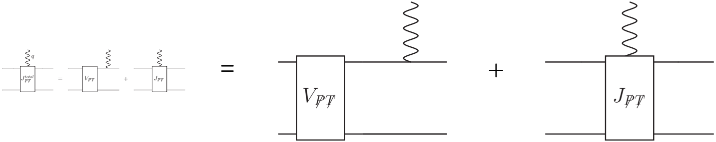
$g_0^\theta(\delta M_{np}^{str})$ is unnaturally small !

EDM of the Deuteron:

Deuteron (D) as Isospin Filter

note:  $= \frac{ie}{2}(1+\tau_3)$

2N-system: $I + S + L$=odd



total current | irred. potential | irred. current

I = 0 I = 0 | I = 0 → I = 1 → I = 0 | I = 0 I = 0

isospin selection rules!

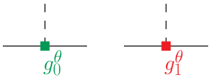
⇓

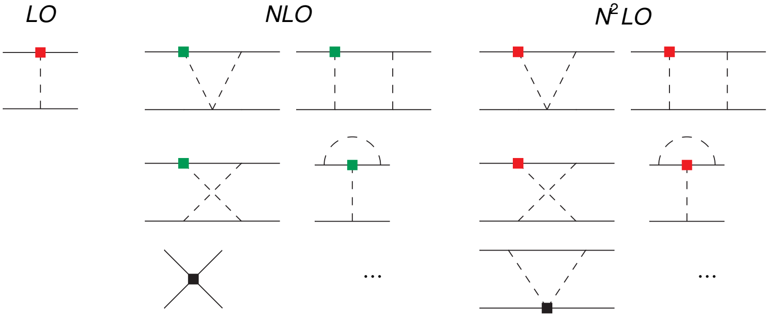
~~$g_0^\theta N^\dagger \vec\pi\cdot\vec\tau N$~~ at leading order (LO)

⇓

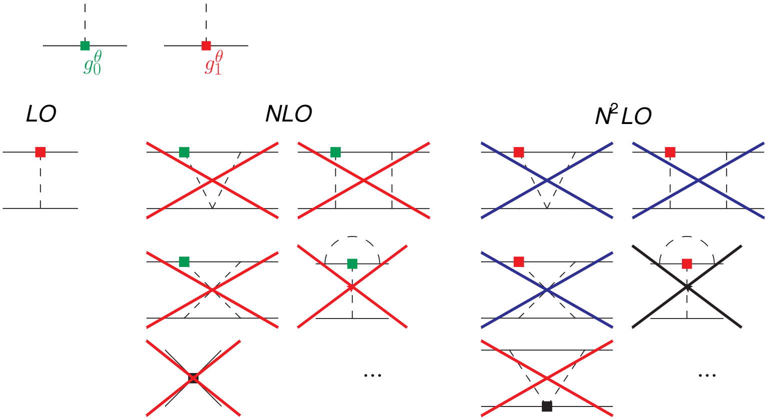
subleading (NLO) $g_1^\theta N^\dagger \pi_3 N$ acts as *'new'* leading order (LO) for D

EDM of the Deuteron: *NLO*-and N^2LO Potentials





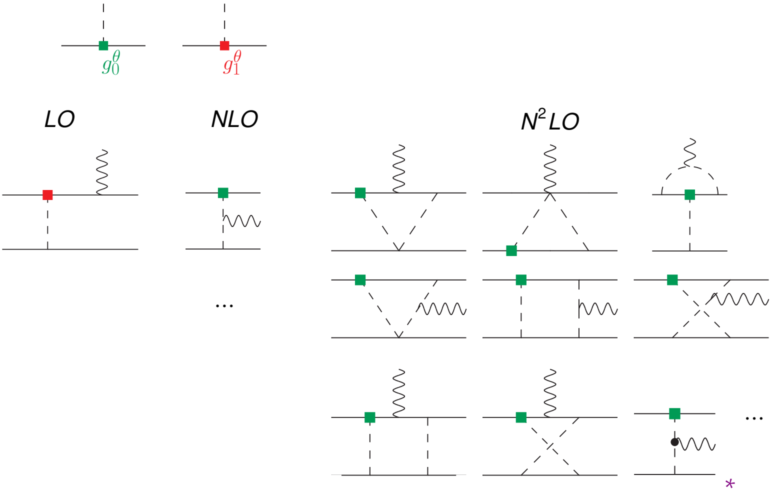
EDM of the Deuteron: *NLO*-and *N*^{2}*LO* Potentials



- ✕: vanishing by selection rules, ✕: sum of diagrams vanishes
  ✕: vertex correction

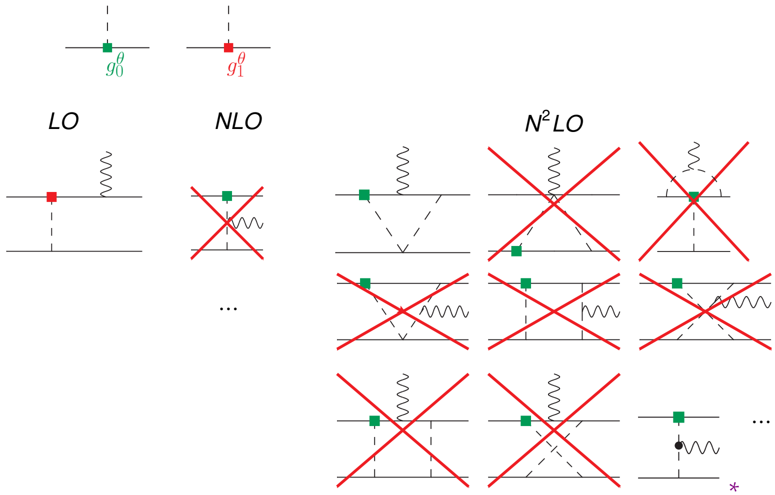
LO NLO N^{2}LO

EDM of the Deuteron: *NLO* and N^2LO Currents



$\ast$: de Vries et al. (2011), Bsaisou et al. (2013)

EDM of the Deuteron: *NLO* and N^2LO Currents



$\ast$: de Vries et al. (2011), Bsaisou et al. (2013)

- ×: vanishing by selection rules, ×: sum of diagrams vanishes

A *naive* estimate of the scale of the nucleon EDM

Khriplovich & Lamoreaux (1997); Kolya Nikolaev (2012)

- CP & P conserving magnetic moment ~ nuclear magneton μ_N

$$\mu_N = \frac{e}{2m_p} \sim 10^{-14}\, e\,\text{cm}\,.$$

- A nonzero EDM requires

  parity P violation: the price to pay is $\sim 10^{-7}$

  $\left(G_F \cdot F_\pi^2 \sim 10^{-7} \text{ with } G_F \approx 1.166 \cdot 10^{-5}\text{GeV}^{-2} \right)$,

  and **CP violation**: the price to pay is $\sim 10^{-3}$

  $\left(|\eta_{+-}| \equiv |\mathcal{A}(K_L^0 \to \pi^+\pi^-)| / |\mathcal{A}(K_S^0 \to \pi^+\pi^-)| = (2.232 \pm 0.011) \cdot 10^{-3} \right)$.

- In summary: $|d_N| \sim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24}\, e\,\text{cm}$

- In SM (without θ term): extra $G_F F_\pi^2$ factor to *undo* flavor change

$$\hookrightarrow \quad \left|d_N^{\text{SM}}\right| \sim 10^{-7} \times 10^{-24}\, e\,\text{cm} \sim 10^{-31}\, e\,\text{cm}$$

$\hookrightarrow$ *The empirical window* for search of physics BSM(θ=0) is

$$10^{-24}\, e\,\text{cm} > |d_N| > 10^{-30}\, e\,\text{cm}.$$

Chronology of upper bounds on the neutron EDM

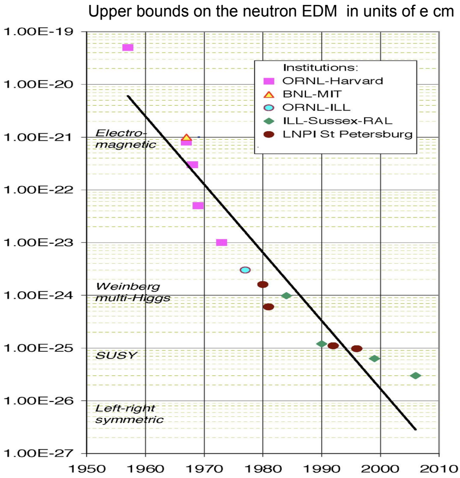


Fig. courtesy of N.N. Nikolaev

Smith, Purcell, Ramsey (1957) . . . . Baker et al. (2006)

↪ 5 to 6 orders above SM predictions which are out of reach !

Chronology of upper bounds on the neutron EDM

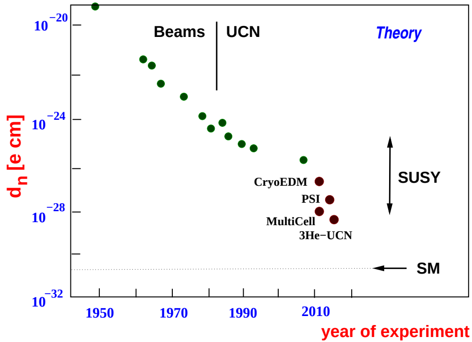


Fig. courtesy of U.-G. Meißner

Smith, Purcell, Ramsey (1957) .... Baker et al. (2006)

↪ 5 to 6 orders above SM predictions which are out of reach !

Chronology of upper bounds on the neutron EDM

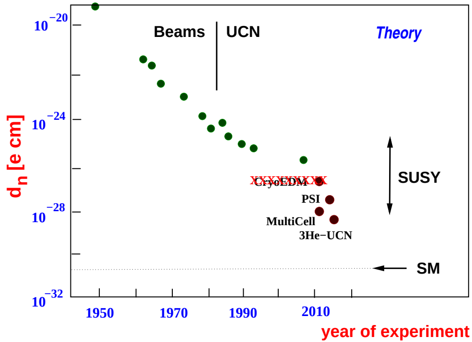


Fig. courtesy of U.-G. Meißner

Smith, Purcell, Ramsey (1957) .... Baker et al. (2006)

↪ 5 to 6 orders above SM predictions which are out of reach !

EDM bounds from neutral particles

- Modern neutron EDM experiments at ILL, SNS, PSI, TRIUMF

  current $\quad d_n = \big(0.2 \pm 1.5(\text{stat.}) \pm 0.7(\text{sys.})\big) \cdot 10^{-26}\, e\,\text{cm}$

  Baker et al. *PRL*'06 (ILL)

  proposed $\quad \sim 10^{-28}\, e\,\text{cm}$

- Proton (and neutron) EDM inferred from diamagnetic atoms

  current $\quad |d(^{199}\text{Hg})| < 3.1 \cdot 10^{-29}\, e\,\text{cm}$ (95% C.L.)

  Griffith et al. *PRL* '09 (UW)

  $\hookrightarrow |d_p| < 7.9 \cdot 10^{-25}\, e\,\text{cm}$

  Theory input from: Dimitriev & Sen'kov *PRL* '03

  ongoing experiments on Ra, Rn, Xe, . . .

- Electron EDM inferred from paramagnetic atoms or non-generate molecules:

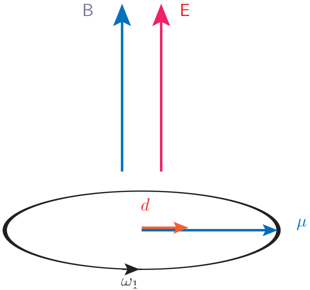
  current $\quad |d_e| < 8.7 \cdot 10^{-29}\, e\,\text{cm}$ (90% C.L.)

  from polar ThO

  Baron et al. *Science* '14 (ACME)

EDM measurement of neutral particles in a nutshell

ground state with $s = 1/2$:



$$\omega_1 = \frac{2\mu B + 2d E}{\hbar} \qquad \omega_2 = \frac{2\mu B - 2d E}{\hbar}$$

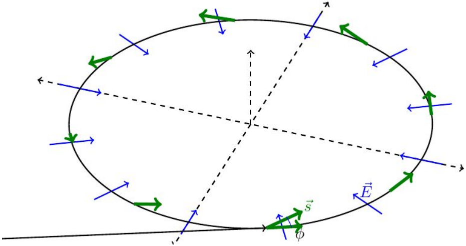
$$\omega_1 - \omega_2 = \frac{4d E}{\hbar}$$

Direct EDM searches with charged particles

in storage rings

General idea:

Farley et al. *PRL* '04



Initially longitudinally polarized particles interact with radial $\vec{E}$ field
↪ build-up of vertical polarization (measured with a polarimeter)

Limit on muon EDM: $d_\mu < 1.8 \cdot 10^{-19}\,e\,\text{cm}$ (95 % C. L.) Bennett et al. (BNL *g*-2) *PRL* '09:

Proposed storage ring experiments ($\sim 10^{-29}\,e\,\text{cm}$):

- Counter-circling proton ring at Brookhaven (srEDM) or Fermilab (Project X) ?
- All-purpose ring for proton, deuteron (and helion) in Jülich (JEDI) ?
- ↪ Precursor experiment ($\gtrsim 10^{-24}\,e\,\text{cm}$) for p or D at COSY@Jülich !

CP violation in the Standard Model

The conventional source: Kobayashi-Maskawa mechanism

Empirical facts: 3 generations of u/d quarks (& e/ν leptons)

- quarks & leptons in **mass** basis $\neq$ quarks & leptons in **weak**-int. basis
- $\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm gauge\text{-}fermion} + \mathcal{L}_{\rm gauge\text{-}Higgs} + \mathcal{L}_{\rm Higgs\text{-}fermion}$ is CP inv.,
  - with the exception of the θ term of QCD (see later)

    and the **charged-weak-current** interaction ($\subset \mathcal{L}_{\rm gauge\text{-}fermion}$)

$$\mathcal{L}_{\rm c\text{-}w\text{-}c} = -\frac{g_w}{\sqrt{2}} \sum_{ij=1}^{3} \bar{d}_{Li}\gamma^\mu V_{ij}\, u_{Lj}\, W_\mu^- - \frac{g_w}{\sqrt{2}} \sum_{ij=1}^{3} \bar{\ell}_{Li}\gamma^\mu U_{ij}\, \nu_{Lj}\, W_\mu^- + \text{h.c.}$$

  - V: 3×3 unitary quark-mixing matrix (Cabibbo-Kobayashi-Maskawa m.)

    3 angles + 1 ~~CP~~ phase δ_{KM}

    U: 3×3 unitary lepton-mixing matrix (Maki-Nakagawa-Sakata matrix)

    3 angles +1(3) ~~CP~~ phase(s) for Dirac (Majorana) ν_i's

~~CP~~ and EDMs and in the SM with $J_{\mathbf{KM}} = \mathbf{Im}(V_{tb} V_{td}^* V_{cd} V_{cb}^*) \simeq 3 \cdot 10^{-5}$

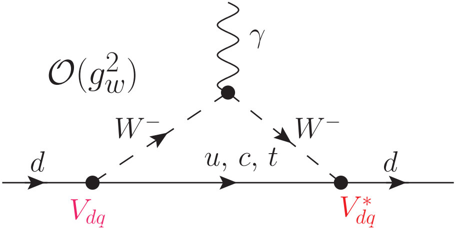
$$\propto \left(\frac{m_t^2 - m_c^2}{M_{EW}^2}\right)\left(\frac{m_c^2 - m_u^2}{M_{EW}^2}\right)\left(\frac{m_t^2 - m_u^2}{M_{EW}^2}\right) \cdot \left(\frac{m_b^2 - m_s^2}{M_{EW}^2}\right)\left(\frac{m_s^2 - m_d^2}{M_{EW}^2}\right)\left(\frac{m_b^2 - m_d^2}{M_{EW}^2}\right) \cdot J_{\mathrm{KM}} \simeq 10^{-15} J_{\mathrm{KM}},$$

Jarlskog *PRL* '85

↪ $(n_B - n_{\bar{B}})/n_\gamma|^{\mathrm{SM}}_{T\sim 20\mathrm{MeV}} \sim 10^{-20}$ and $d_n^{\mathrm{SM}} \sim 10^{-20} \cdot 10^{-14}\, e\,\mathrm{cm} \sim 10^{-34}\, e\,\mathrm{cm}$

EDM flavor-neutral ⇒ KM predictions tiny: $\mathcal{O}(G_F^2) \sim \mathcal{O}(g_W^4)$

1 loop:



↪ ~~CP~~ phase δ_{KM} cancels → prefactor real ⇒ $d_q^{\text{1-loop}} = 0$

$\not{CP}$ and EDMs and in the SM with $J_{\rm KM} = \mathrm{Im}(V_{tb} V_{td}^* V_{cd} V_{cb}^*) \simeq 3 \cdot 10^{-5}$

$$\propto \left(\frac{m_t^2 - m_c^2}{M_{EW}^2}\right)\left(\frac{m_c^2 - m_u^2}{M_{EW}^2}\right)\left(\frac{m_t^2 - m_u^2}{M_{EW}^2}\right)\cdot\left(\frac{m_b^2 - m_s^2}{M_{EW}^2}\right)\left(\frac{m_s^2 - m_d^2}{M_{EW}^2}\right)\left(\frac{m_b^2 - m_d^2}{M_{EW}^2}\right)\cdot J_{\rm KM} \simeq 10^{-15} J_{\rm KM},$$

Jarlskog *PRL* '85

$\hookrightarrow$ $(n_B - n_{\bar B})/n_\gamma|^{\rm SM}_{T\sim 20\,\rm MeV} \sim 10^{-20}$ and $d_n^{\rm SM} \sim 10^{-20} \cdot 10^{-14}\, e\,\mathrm{cm} \sim 10^{-34}\, e\,\mathrm{cm}$

EDM flavor-neutral $\Rightarrow$ KM predictions tiny: $\mathcal{O}(G_F^2) \sim \mathcal{O}(g_W^4)$

2 loops:

$$d_{\rm quark}^{\text{2-loop}} = d_{\text{chromo q}}^{\text{2-loop}} = 0$$

Shabalin *Sov.J.NP* '78

$\not{CP}$ and EDMs and in the SM with $J_{KM} = \mathrm{Im}(V_{tb} V_{td}^* V_{cd} V_{cb}^*) \simeq 3 \cdot 10^{-5}$

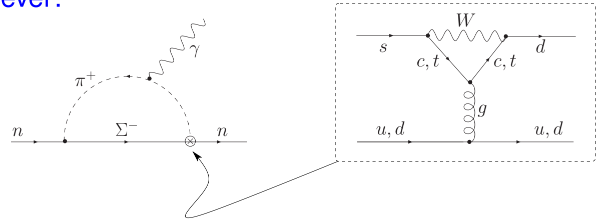
$$\propto \left(\frac{m_t^2 - m_c^2}{M_{EW}^2}\right)\left(\frac{m_c^2 - m_u^2}{M_{EW}^2}\right)\left(\frac{m_t^2 - m_u^2}{M_{EW}^2}\right) \cdot \left(\frac{m_b^2 - m_s^2}{M_{EW}^2}\right)\left(\frac{m_s^2 - m_d^2}{M_{EW}^2}\right)\left(\frac{m_b^2 - m_d^2}{M_{EW}^2}\right) \cdot J_{KM} \simeq 10^{-15} J_{KM},$$

Jarlskog *PRL* '85

$\hookrightarrow$ $(n_B - n_{\bar{B}})/n_\gamma|^{SM}_{T\sim 20 MeV} \sim 10^{-20}$ and $d_n^{SM} \sim 10^{-20} \cdot 10^{-14}\, e\,\mathrm{cm} \sim 10^{-34}\, e\,\mathrm{cm}$

EDM flavor-neutral $\Rightarrow$ KM predictions tiny: $\mathcal{O}(G_F^2) \sim \mathcal{O}(g_W^4)$

however:



$\mathcal{O}(g_W^4 g_s^2)$

$d_n^{KM} \simeq 10^{-32}\, e\,\mathrm{cm}$ because of long-range pion & 'strong penguin'

Gavela; Khriplovich & Zhitnitsky ('82)

$\not{CP}$ and EDMs and in the SM with $J_{\mathrm{KM}} = \mathrm{Im}(V_{tb}V_{td}^{*}V_{cd}V_{cb}^{*}) \simeq 3\cdot 10^{-5}$

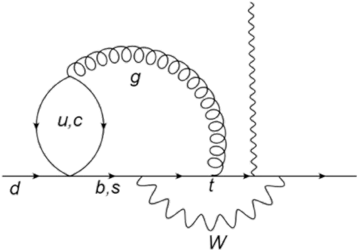
$$\propto \left(\frac{m_t^2-m_c^2}{M_{EW}^2}\right)\left(\frac{m_c^2-m_u^2}{M_{EW}^2}\right)\left(\frac{m_t^2-m_u^2}{M_{EW}^2}\right)\cdot\left(\frac{m_b^2-m_s^2}{M_{EW}^2}\right)\left(\frac{m_s^2-m_d^2}{M_{EW}^2}\right)\left(\frac{m_b^2-m_d^2}{M_{EW}^2}\right)\cdot J_{\mathrm{KM}} \simeq 10^{-15} J_{\mathrm{KM}},$$

Jarlskog *PRL* '85

$\hookrightarrow$ $(n_B - n_{\bar{B}})/n_\gamma|^{\mathrm{SM}}_{T\sim 20\mathrm{MeV}} \sim 10^{-20}$ and $d_n^{\mathrm{SM}} \sim 10^{-20}\cdot 10^{-14}\,e\,\mathrm{cm} \sim 10^{-34}\,e\,\mathrm{cm}$

EDM flavor-neutral $\Rightarrow$ KM predictions tiny: $\mathcal{O}(G_F^2) \sim \mathcal{O}(g_W^4)$

at $\geq$ 3 loops:



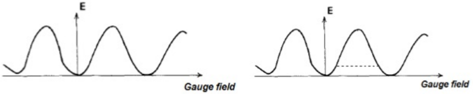
$\mathcal{O}(g_W^4 g_s^2)$

$d_n^{\mathrm{KM}} \simeq 10^{-34}\ldots 10^{-31} e\,\mathrm{cm}$ $\quad(d_e^{\mathrm{KM}} \sim 10^{-38}\ldots 10^{-40} e\,\mathrm{cm}$ since 4 loops & $\mathcal{O}(g_W^6 g_s^2))$

Khriplovich (1986); Czarnecki & Krause ('97) (Khriplovich & Pospelov (1991))

EDM sources: QCD θ-term of the SM

The topologically non-trivial vacuum structure of QCD



induces a direct $\not{P}\&\not{T} \rightsquigarrow \not{CP}$ interaction with a new parameter θ:

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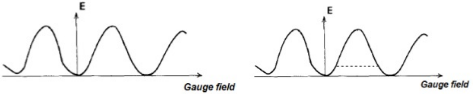
EDM sources: QCD θ-term of the SM

The topologically non-trivial vacuum structure of QCD



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$$|d_n^{\bar\theta}| \sim \bar\theta \cdot \frac{m_q^*}{m_s} \cdot \frac{e}{2m_n} \sim \bar\theta \cdot 10^{-2} \cdot 10^{-14} e\,\text{cm} \sim \bar\theta \cdot 10^{-16} e\,\text{cm} \quad \text{with } \bar\theta \sim \mathcal{O}(1).$$

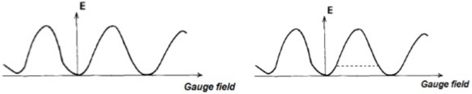
$$|d_n^{emp}| < 2.9 \cdot 10^{-26} e\,\text{cm} \rightsquigarrow |\bar\theta| < 10^{-10}$$

strong CP problem

Baker et al. *PRL* '06

EDM sources: QCD θ-term of the SM

The topologically non-trivial vacuum structure of QCD



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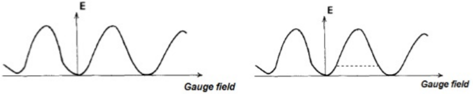
$10^{-10} > |\bar\theta| > 10^{-14}$ eventually measurable via nonzero EDM, but because of $\Lambda_{\chi SB} \ll \Lambda_{EWSB}$ it doesn't explain the cosmic matter surplus.

JÜLICH FORSCHUNGSZENTRUM

EDM sources: QCD θ-term of the SM

The topologically non-trivial vacuum structure of QCD



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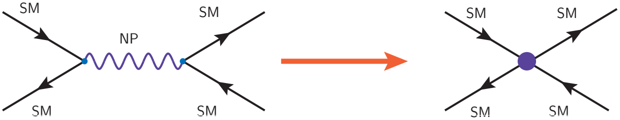
Thus $\not{CP}$ by new physics (NP) (*i.e.* dimension ≥ 6 sources beyond SM) needed to explain the cosmic matter-antimatter asymmetry.

How to handle CP-violating sources beyond the SM?

New interactions as higher dimensional operators

- Add to the SM **all possible** effective interactions



- The new interactions appear as higher dimensional operators

$$\mathcal{L}_{\text{eft}} = \mathcal{L}_{SM} + \cancel{\sum_i \frac{c_5^{(i)}}{M_{\not{T}}} \mathcal{O}_5^{(i)}} + \sum_i \frac{c_6^{(i)}}{M_{\not{T}}^2} \mathcal{O}_6^{(i)} + \ldots$$

where $M_{\not{T}}$ is the scale of the *New Physics* particles

- Only the lowest dimensional operators should be important
- Hadronic EDMs: non-leptonic CP-violating operators of dim. 6

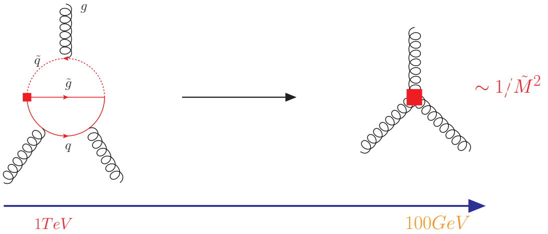
Not of dim. 5 because of Higgs insertion (chiral symm.) at high (low) scales

How to handle CP-violating sources beyond the SM?

Evaluation in Effective Field Theory (EFT) approach

▸ EFT

- All degrees of freedom *beyond NP (EW) scale* are integrated out:
  ↪ Only SM degrees of freedom remain: q, g, (H, Z, $W^{\pm}$, ...)
- Write down *all* interactions for these *active* degrees of freedom that *respect the* SM+ Lorentz *symmetries*: here dim. 6 or higher order
- Need a *power-counting scheme* to order these infinite # interactions
- Relics of eliminated BSM physics 'remembered' by the values of the low-energy constants (LECs) of the CP-violating contact terms, e.g.



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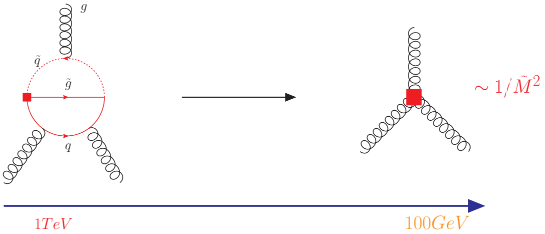

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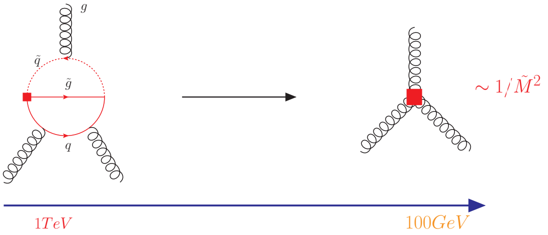

How to handle CP-violating sources beyond the SM?

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