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JÜLICH FORSCHUNGSZENTRUM

Electric Dipole Moments

of Hadrons and Light Nuclei

in chiral EFT

LEPON 2017 | Mainz | May 10, 2017 | Andreas Wirzba

CP violation and the Electric Dipole Moment (EDM)

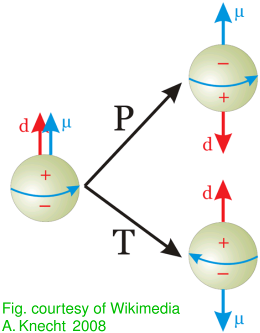


Fig. courtesy of Wikimedia
A. Knecht 2008

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-degenerate** (e.g. 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: $|d_n| < 3^{\diamond}/1.6^{*} \cdot 10^{-26} e\,\text{cm}$, $|d_p| < 2 \cdot 10^{-25} e\,\text{cm}$, $|d_e| < 1 \cdot 10^{-28} e\,\text{cm}$

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

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

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 ~ 10^{-7}

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

  and additionally **CP violation**: the price to pay is ~ 10^{-3}

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

- 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

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

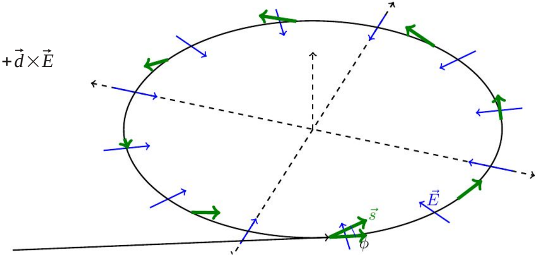
$\hookrightarrow$ *The empirical window* for search of physics BSM(θ=0) is

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

Search for EDMs of charged particles in storage rings

General idea:

$$\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$



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

The spin precession relative to the momentum direction is given by the Thomas-BMT equation (for $\vec{\beta} \cdot \vec{B} = 0,\ \vec{\beta} \cdot \vec{E} = 0,\ \vec{E} \cdot \vec{B} = 0$):

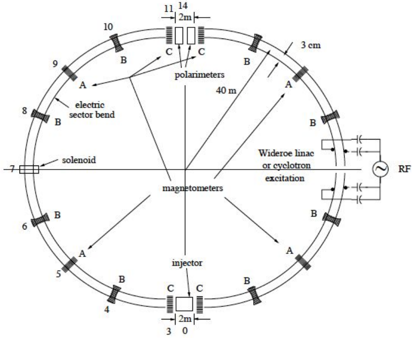
$$\frac{d\vec{S}^*}{dt} = \vec{\Omega} \times \vec{S}^* \quad \text{with} \quad \vec{\Omega} = -\frac{e}{m}\left(a\vec{B} + \left(\beta^{-2} - 1 - a\right)\vec{\beta} \times \vec{E} + \eta(\vec{E} + \vec{\beta} \times \vec{B})\right)$$

$$\text{and} \quad \vec{\mu} = (1 + a)\frac{e}{2m}\vec{S}/S \quad \text{and} \quad \vec{d} = \eta\frac{e}{2m}\vec{S}/S$$

Method 1: pure electrostatic ring

$$\vec{\Omega} = -\frac{e}{m}\left(\cancel{a\vec{B}} + \underbrace{\left(\beta^{-2} - 1 - a\right)\vec{\beta}\times\vec{E}}_{:=0,\ \text{“Frozen spin method”}} + \eta\left(\vec{E} + \cancel{\vec{\beta}\times\vec{B}}\right)\right) \longrightarrow -\frac{e}{m}\eta\vec{E}$$

only possible for $a > 0$, *i.e.* for p and ^{3}H (or ^{19}F), but not for d or ^{3}He



Advantages:

– no magnetic field

– counter rotating beams possible

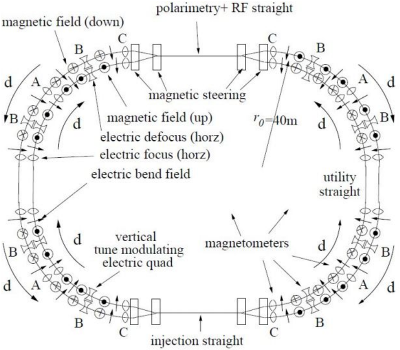
Disadvantage:

– not possible for deuterons ($a_D < 0$)

srEDM BNL / KAIST Korea ($\gtrsim$ 2000): design for E-ring for protons

Method 2: combined electric & magnetic ring

$$\vec{\Omega} = -\frac{e}{m}\left(\underbrace{a\vec{B} + \left(\beta^{-2} - 1 - a\right)\vec{\beta}\times\vec{E}}_{:=0,\ \text{“Frozen spin method”}} + \eta(\vec{E} + \vec{\beta}\times\vec{B})\right) \to -\frac{e}{m}\eta(\vec{E} + \vec{\beta}\times\vec{B})$$



Advantage:

– works for p, deuterons and ^{3}He

Disadvantages:

– requires also magnetic fields

– two beam pipes

– magnetic coils made of copper

JEDI Jülich/Aachen ($\gtrsim$ 2011): design for E/B ring

Method 3: pure magnetic ring

$$\vec{\Omega} = -\frac{e}{m}\left(\underbrace{a\vec{B}}_{\text{precession in beam plane}} + \left(\frac{1}{\beta^2} - 1 - a\right)\vec{\beta}\times\vec{E} + \eta(\vec{E} + \underbrace{\vec{\beta}\times\vec{B})}_{\text{+ Wien filter: accumulation of vertical spin}} \right)$$

polarized p and D with $p = (0.3\text{–}3.7)\ \mathrm{GeV}/c$

Advantage:

– existing COSY accelerator

↪ precursor experiment:

First attempt for *direct* measurement of an EDM of a charged hadron

Disadvantage:

– low sensitivity

$\gtrsim 10^{-21}$–$10^{-24}\,e\,\mathrm{cm}$ JEDI at COSY

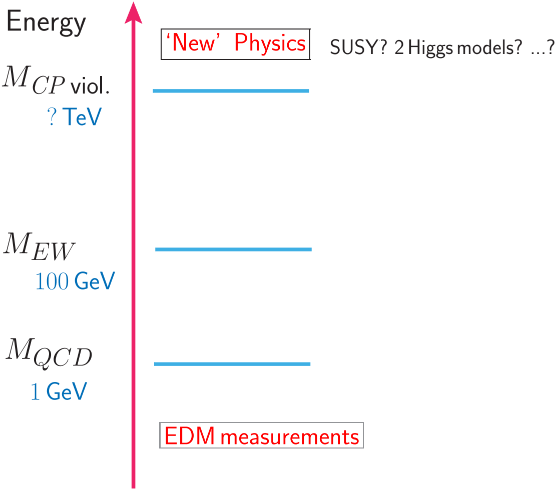
Recent Achievements PRL 115 ('15), 117 ('16):

- Spin tune $\bar{\nu}_s = -0.16097\ldots \pm 10^{-10}$ in 100 s
- Spin coherence time $\tau > 1000\,\mathrm{s}$
- Spin feedback (pol. vector within 12°)

How to handle CP-violating sources beyond the SM?

Running through the scales

W. Dekens & J. de Vries, *JHEP* '13



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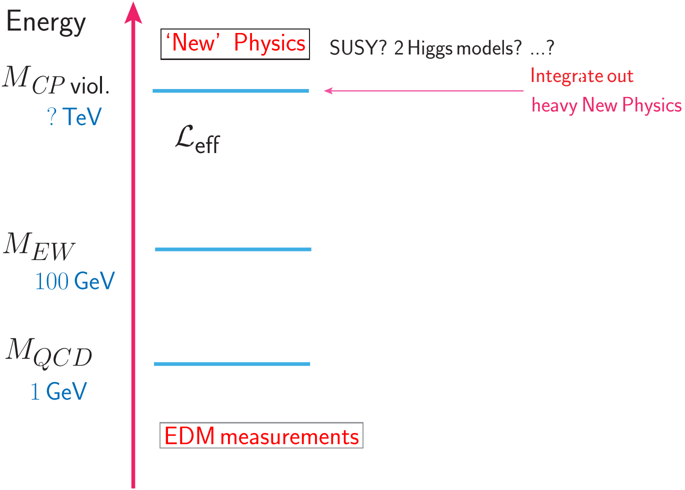

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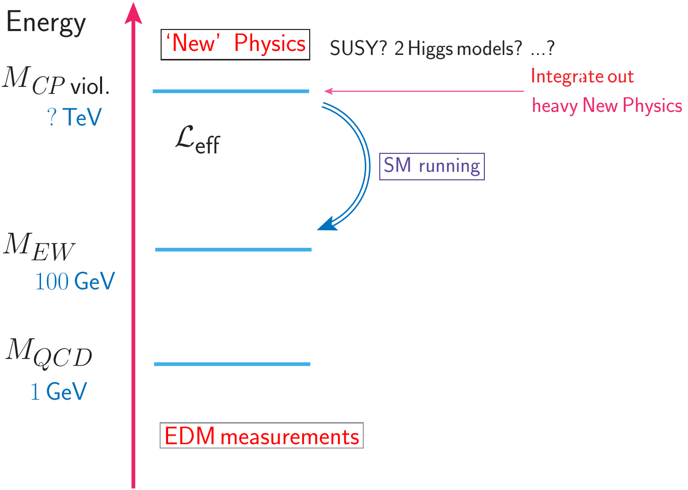

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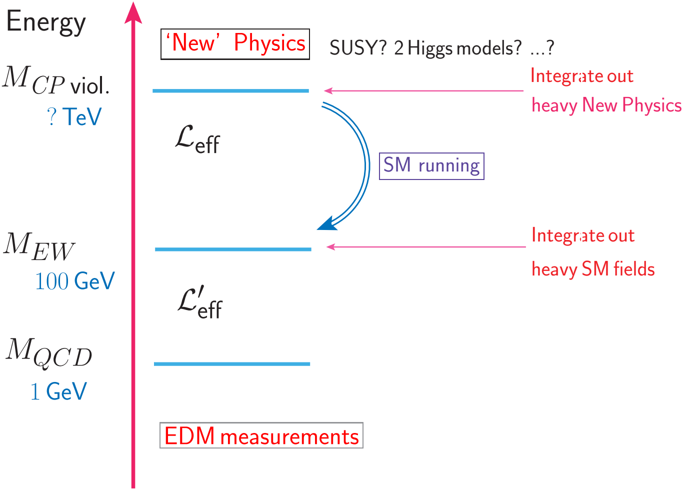

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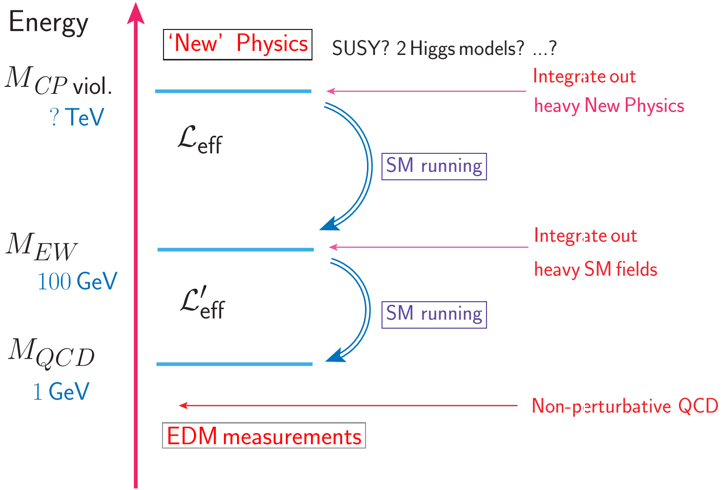

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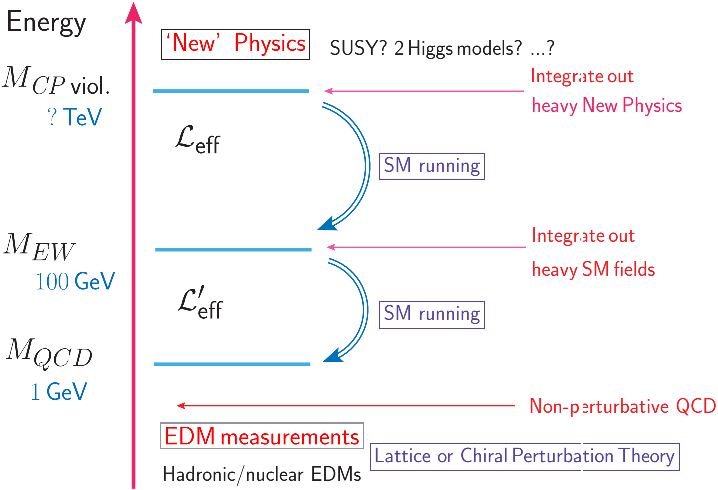
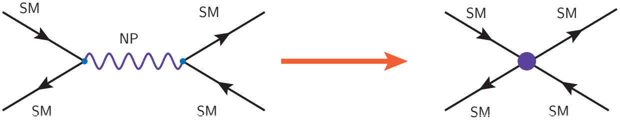


How to handle CP-violating sources beyond the SM?

New interactions as higher dimensional operators

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



- The new interactions appear as higher dimensional operators

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

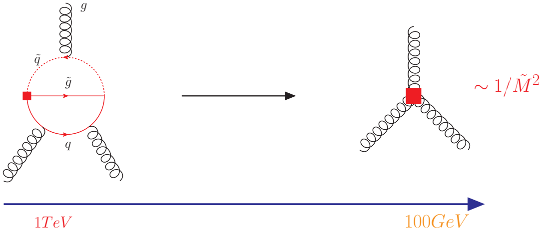
  where $M_{\not T}$ is the scale of the *New Physics* particles
- Only the lowest dimensional operators should be important
- Hadronic EDMs: non-leptonic CP-violating operators of dim. 6

  Not of dim. 5 because of Higgs insertion / chiral symm. at EW / low scales

How to handle CP-violating sources beyond the SM?

Evaluation in Effective Field Theory (EFT) approach

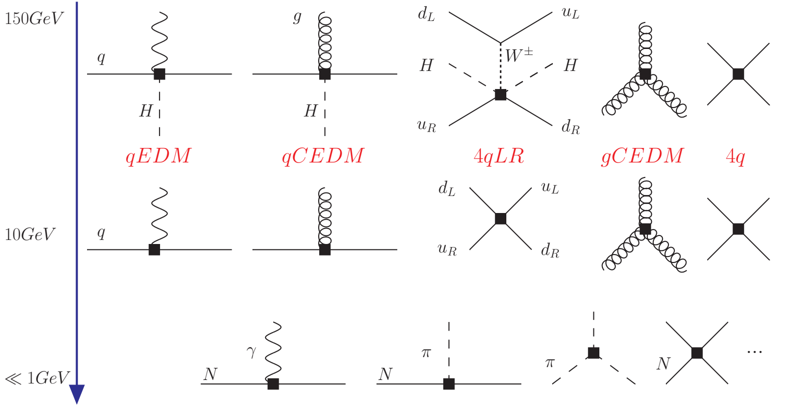
- All degrees of freedom *beyond NP (EW) scale* are integrated out:
  ↪ Only SM degrees of freedom remain: q, g, (H, Z, $W^{\pm}$, ...)
- Write down *all* interactions for these *active* degrees of freedom that *respect the* SM+ Lorentz *symmetries*: here dim. 6 or higher order
- Need a *power-counting 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.



CP-violating BSM sources of dimension 6 from above EW scale

to their hadronic equivalents below 1 GeV

W. Dekens & J. de Vries *JHEP* '13



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

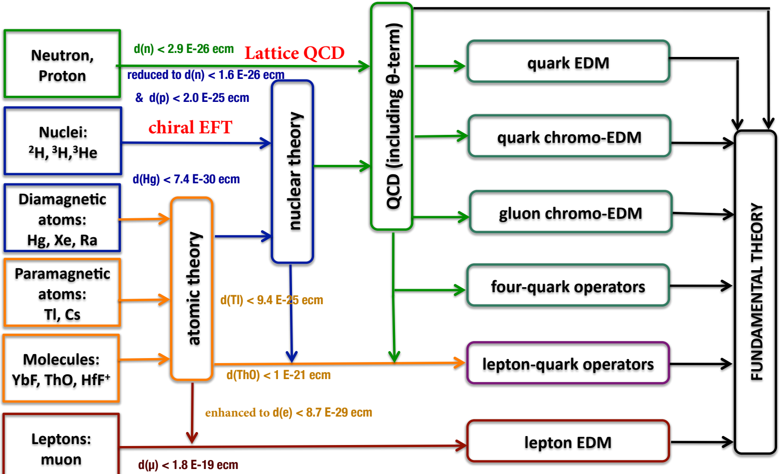
$$= 1(\text{dim-four}) + 8(\text{dim-six}) \quad [+3+1]$$

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

↪ 5 discriminable classes

Road map from EDM Measurements to EDM Sources

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



(adapted from Jordy de Vries, Jülich, March 14, 2013)

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

3-CPO & R2-D2

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

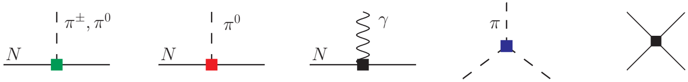
3-CPO & R2-D2

↪ 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)

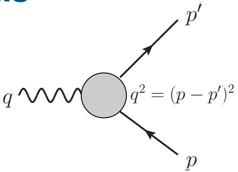
	g_0 $\not{CP}$, I	g_1 $\not{CP}$, $\not{I}$	d_0, d_1 $\not{CP}$, I + $\not{I}$	$(m_N\Delta)$ $\not{CP}$, $\not{I}$	$C_{1,2}$ $(C_{3,4})$ $\not{CP}$, I ($\not{I}$)
$\mathcal{L}^{\not{CP}}_{\text{EFT}}$:					
θ-term:	$\boldsymbol{\mathcal{O}(1)}$	$\boldsymbol{\mathcal{O}(M_\pi/m_N)}$	$\mathcal{O}(M_\pi/m_N)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(M_\pi^2/m_N^2)$
qEDM:	$\mathcal{O}(\alpha_{EM}/4\pi)$	$\mathcal{O}(\alpha_{EM}/4\pi)$	$\boldsymbol{\mathcal{O}(1)}$	$\mathcal{O}(\alpha_{EM}/4\pi)$	$\mathcal{O}(\alpha_{EM}/4\pi)$
qCEDM:	$\boldsymbol{\mathcal{O}(1)}$	$\boldsymbol{\mathcal{O}(1)}$	$\mathcal{O}(M_\pi/m_N)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(M_\pi^2/m_N^2)$
4qLR:	$\mathcal{O}(M_\pi^2/m_n^2)$	$\boldsymbol{\mathcal{O}(1)}$	$\mathcal{O}(M_\pi^3/m_N^3)$	$\boldsymbol{\mathcal{O}(M_\pi/m_n)}$	$\mathcal{O}(M_\pi^2/m_N^2)$
gCEDM:	$\mathcal{O}(M_\pi^2/m_N^2)^\star$	$\mathcal{O}(M_\pi^2/m_N^2)^\star$	$\boldsymbol{\mathcal{O}(1)}$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\boldsymbol{\mathcal{O}(1)}$
4q:	$\mathcal{O}(M_\pi^2/m_N^2)^\star$	$\mathcal{O}(M_\pi^2/m_N^2)^\star$	$\boldsymbol{\mathcal{O}(1)}$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\boldsymbol{\mathcal{O}(1)}$



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

Calculation: from form factors to EDMs

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



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

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

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

Calculation: from form factors to EDMs

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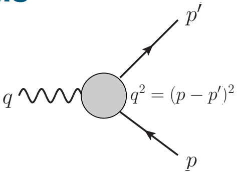


$$\Gamma^{\mu}(q^2) = \gamma^{\mu}F_1(q^2) - i\sigma^{\mu\nu}q_{\nu}\frac{F_2(q^2)}{2m_f} + \sigma^{\mu\nu}q_{\nu}\gamma_5\frac{F_3(q^2)}{2m_f} + (\not{q}\,q^{\mu} - q^2\gamma^{\mu})\gamma_5\frac{F_a(q^2)}{m_f^2}$$

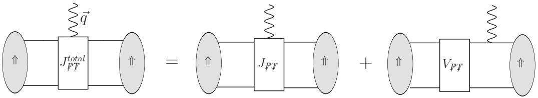
Dirac FF | Pauli FF | electric dipole FF ($\not{C}\not{P}$) | anapole FF ($\not{P}$)

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

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

Baluni, *PRD* (1979); Crewther et al., *PLB* (1979); ... Pich & de Rafael, *NPB* (1991); ... Ottnad et al., *PLB* (2010)

Isospin-conserving πNN coupling:

$$g_0^\theta = \frac{(m_n - m_p)^{\text{strong}}(1-\epsilon^2)}{4F_\pi \epsilon}\,\bar\theta \approx (-15.5 \pm 1.9)\cdot 10^{-3}\bar\theta \quad \left(\text{where } \epsilon \equiv \frac{m_u - m_d}{m_u + m_d}\right)$$

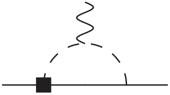
$$\hookrightarrow d_N\big|^{\text{isovector}}_{\text{loop}} \sim (1.8 \pm 0.3)\cdot 10^{-16}\,\bar\theta\, \mathrm{e\,cm}$$

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

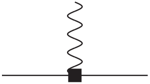
Note also: $g_1^\theta = 8c_1 m_N \Delta^\theta + (0.6 \pm 1.1)\cdot 10^{-3}\bar\theta = (3.4 \pm 1.5)\cdot 10^{-3}\bar\theta$ with the

3-pion coupling: $\Delta^\theta = \frac{\epsilon(1-\epsilon^2)}{16F_\pi m_N}\frac{M_\pi^4}{M_K^2 - M_\pi^2}\bar\theta + \cdots = (-0.37 \pm 0.09)\cdot 10^{-3}\bar\theta$

single nucleon EDM:



isovector $\approx$ $\ll$ isoscalar



$g_0^\theta/\bar\theta$ known $\rightsquigarrow$ "controlled"

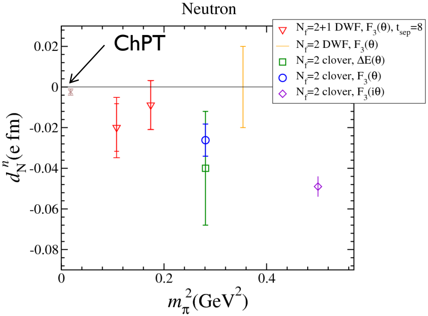
"unknown" coefficients

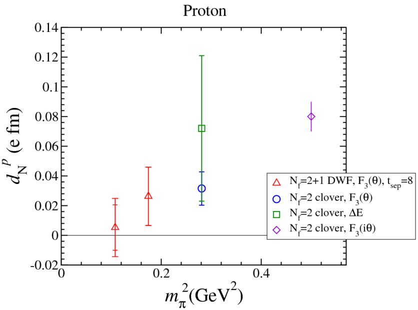
$\longrightarrow$ lattice QCD required

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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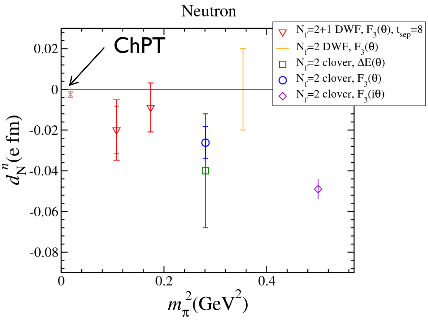

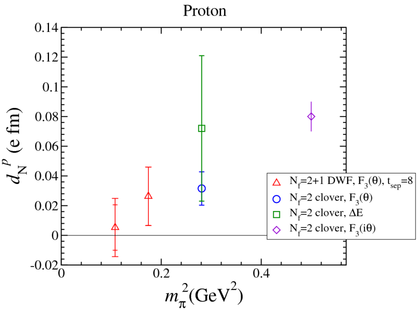

$\theta \equiv 1$! (adapted from Eigo Shintani (Mainz), *Lattice calculation of nucleon EDM*, Hirschegg, Jan. 14, 2014)

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)

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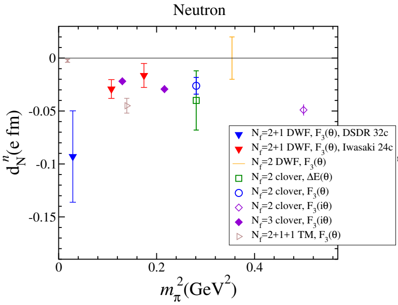

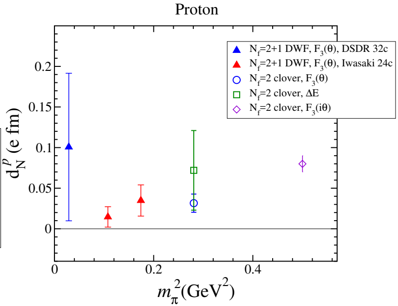

$\bar{\theta} \equiv 1$!

Eigo Shintani et al., *Phys. Rev. D* **93**, 094503 (2016) $M_\pi = 170, 330, 420, 530\,\text{MeV}$

Don't mention the ... light nuclei

Single Nucleon Versus Nuclear EDM

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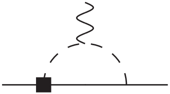
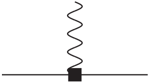


isovector

$\approx$

$\ll$

isoscalar



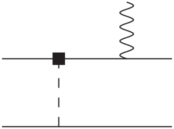
“controlled” “unknown" coefficients

$\longrightarrow$ lattice QCD required

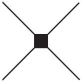
Guo, Meißner *JHEP*’12

two nucleon EDM:

Sushkov, Flambaum, Khriplovich *Sov.Phys. JETP*’84



$\gg$

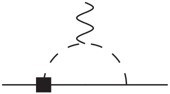


controlled unknown coefficient

Single Nucleon Versus Nuclear EDM

Baluni, *PRD* (1979); Crewther et al., *PLB* (1979); ... Pich & de Rafael, *NPB* (1991); ... Ottnad et al., *PLB* (2010)

single nucleon EDM:

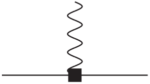


isovector

$\approx$

$\ll$

isoscalar



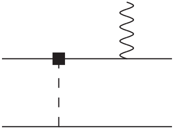
"controlled" "unknown" coefficients

$\longrightarrow$ lattice QCD required

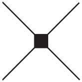
Guo, Meißner *JHEP*'12

two nucleon EDM:

Sushkov, Flambaum, Khriplovich *Sov.Phys. JETP*'84



$\gg$



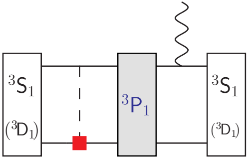
controlled

unknown coefficient

JÜLICH FORSCHUNGSZENTRUM

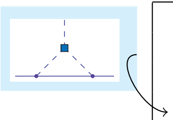
EDM of the Deuteron at LO: CP-violating π exchange

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



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

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



term	N^{2}LO χPT	N^{4}LO χPT	Av$_{18}$	CD-Bonn	units
d_n^D	0.939(9)	0.936(8)	0.914	0.927	d_n
d_p^D	0.939(9)	0.936(8)	0.914	0.927	d_p
g_1	0.183(17)	0.182(2)	0.186	0.186	$g_1\, e\,$fm
Δf_{g_1}	−0.748(138)	−0.646(23)	−0.703	−0.719	$\Delta\, e\,$fm

Bsaisou et al., *JHEP* **03** (2015); A.W., Bsaisou, Nogga, IJMP **E26** (2017)

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

new

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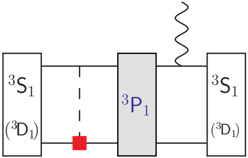

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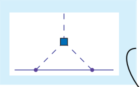
Yamanaka & Hiyama, *PRC* **91** (2015): $d_N^D = \left(1 - \frac{3}{2} P_{^3D_1}\right) d_N$



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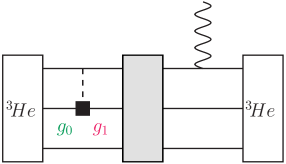
new

^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^{2}LO: 4qLR

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NLO: θ term

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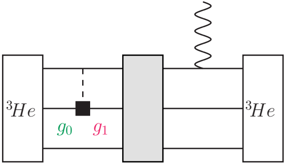

$g_0 N^\dagger \vec{\pi}\cdot\vec{\tau} N \quad (\not{CP}, \mathrm{I})$

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	$\Delta\, e\,$fm
	^{3}H	-0.017 ± 0.006	-0.015	-0.018	
g_0	^{3}He	0.111 ± 0.013	0.073	0.087	$g_0\, e\,$fm
	^{3}H	-0.108 ± 0.013	-0.073	-0.085	
g_1	^{3}He	0.142 ± 0.019	0.142	0.146	$g_1\, e\,$fm
	^{3}H	0.139 ± 0.019	0.142	0.144	
Δf_{g_1}	^{3}He	-0.608 ± 0.142	-0.556	-0.586	$\Delta\, e\,$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

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Discriminating between three 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

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

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

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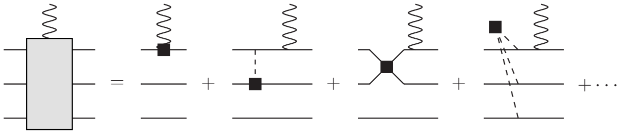

Testing strategies: SM + $\bar{\theta}$

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

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

Extraction of $\bar{\theta}$

*includes ± 0.20 uncertainty from 2N contact terms

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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): $d_D^{\mathrm{Nucl}} \approx -d_{^3\mathrm{He}}^{\mathrm{Nucl}} \approx \frac{1}{2} d_{^3\mathrm{H}}^{\mathrm{Nucl}}$

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

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

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

* 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
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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}

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

*includes ± 0.1 uncertainty from 2N contact terms

JÜLICH FORSCHUNGSZENTRUM

Testing strategies: minimal LR symmetric Model

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↓

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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): $d_D \approx d_{^3\mathrm{He}} \approx d_{^3\mathrm{H}}$

*includes ± 0.1 uncertainty from 2N contact terms

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Prediction for the helion EDM

(& triton EDM): $d_D \approx d_{^3\text{He}} \approx d_{^3\text{H}}$

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

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

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

*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)

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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

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

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

$$d_{^3\mathrm{He}} - 0.9 d_n$$
$$= \left[(0.11 \pm 0.02^{\star}) g_0 + (0.14 \pm 0.02^{\star}) g_1 - (0.61 \pm 0.14)\Delta\right] e\,\mathrm{fm}$$

Extraction of g_0

*includes ± 0.01 uncertainty from 2N contact terms

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

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Extraction of g_0

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

*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.)
- ^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**
$\hookrightarrow$ $\not{C}\not{P}$ $N\pi$ couplings g_0 & g_1 may be accessible even for dim-6 case

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Many thanks to my colleagues

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

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

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

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3. J. Bsaisou, C. Hanhart, S. Liebig, D. Minossi, U.-G. Meißner, A. Nogga and A.W.,
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4. W. Dekens, J. de Vries, J. Bsaisou, W. Bernreuther, C. Hanhart, U.-G. Meißner, A. Nogga and A.W., JHEP **07**, 069 (2014), arXiv:1404.6082 [hep-ph].
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θ-term: $\not{CP}$ πNN vertices determined from LECs

Leading g_0^θ coupling (from c_5)

Baluni (1979); 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

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

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

$$\delta M_{np}^{em} \ \rightarrow \ \delta M_{np}^{str} = (2.44 \pm 0.18)\mathrm{MeV}$$ Walker-Loud ('13); Borsányi et al.('14)

$$\& \quad m_u/m_d = 0.46 \pm 0.03$$ Flag Working Group ('14)

$$\longrightarrow \boxed{g_0^\theta = (15.5 \pm 1.9)\cdot 10^{-3}\cdot\bar{\theta}}$$ Bsaisou et al. ('15)

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

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

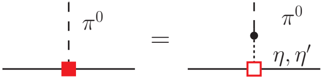
g_1^θ: $\pi_3 NN$-vertex

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

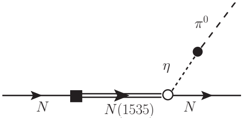
$$\mathcal{L}_{\pi N} = \ldots + c_1 4B N^\dagger \left((m_u + m_d) + \frac{(\delta M_\pi^2)_{QCD}(1-\epsilon^2)\bar\theta}{2BF_\pi \epsilon} \pi_3 \right) N + \ldots$$

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

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



$\hookrightarrow g_1^\theta(c_1) = 8 c_1 m_N \Delta^\theta$ in terms of $\underbrace{\Delta^\theta = \frac{\epsilon(1-\epsilon^2)}{4F_\pi m_N} \frac{M_\pi^4}{M_K^2 - M_\pi^2} \bar\theta}_{\not{CP}\ \text{3-pion coupling}}$



$g_1^\theta(c_1) = (2.8 \pm 1.1) 10^{-3} \bar\theta$ & $\bar g_1^\theta = (0.6 \pm 1.1) 10^{-3} \bar\theta$

$\rightsquigarrow$ $g_1^\theta = (3.4 \pm 1.5) \cdot 10^{-3} \bar\theta$

Bsaisou et al. '13, '15

$$\frac{g_1^\theta}{g_0^\theta} = -0.22 \pm 0.10 \sim \frac{M_\pi}{m_N} \gg \epsilon \frac{M_\pi^2}{m_N^2} \sim -0.01 \quad \text{(NDA)}$$

Bsaisou et al. '13, '15 — de Vries et al. (2011)

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

◂ πNN

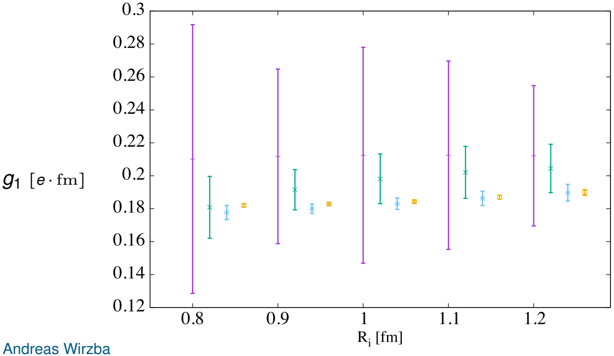
Deuteron Quantities in ChPT from NLO to N4LO

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

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

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

R_i	0.8 fm	0.9 fm	1.0 fm	1.1 fm	1.2 fm
Λ_b^i	0.6GeV	0.6GeV	0.6GeV	0.5GeV	0.4GeV



NLO, N2LO, N3LO, N4LO

$(0.183 \pm 0.017) g_1\, e$fm

$\hookrightarrow (0.1815 \pm 0.0025) g_1\, e$fm

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Deuteron Quantities in ChPT from NLO to N4LO

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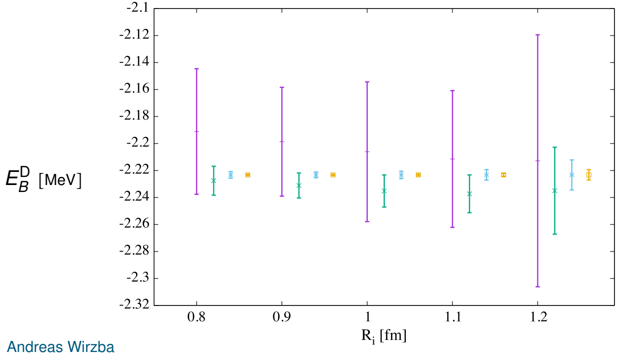
$$\Delta X^{\mathrm{N}^n\mathrm{LO}}(p) = Q^{n+2}\cdot\max\Bigg[\left|X^{\mathrm{LO}}(p)\right|, \frac{\left|X^{\mathrm{NLO}}(p)-X^{\mathrm{LO}}(p)\right|}{Q^2}, \frac{\left|X^{\mathrm{N2LO}}(p)-X^{\mathrm{NLO}}(p)\right|}{Q^3}, \frac{\left|X^{\mathrm{N3LO}}(p)-X^{\mathrm{N2LO}}(p)\right|}{Q^4}, \frac{\left|X^{\mathrm{N4LO}}(p)-X^{\mathrm{N3LO}}(p)\right|}{Q^5}\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

and

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

R_i	0.8 fm	0.9 fm	1.0 fm	1.1 fm	1.2 fm
Λ_b^i	0.6GeV	0.6GeV	0.6GeV	0.5GeV	0.4GeV



NLO, N2LO, N3LO, N4LO

(-2.2233 ± 0.0004) MeV

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Deuteron Quantities in ChPT from NLO to N4LO

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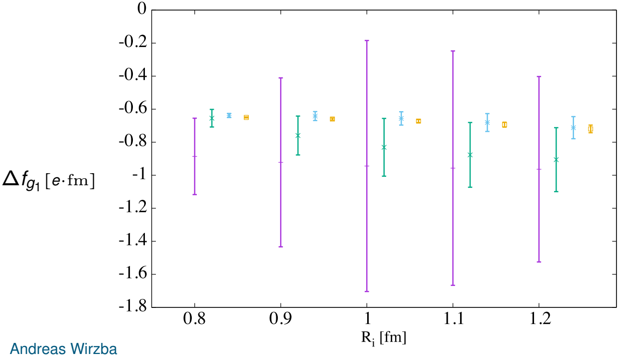
$$\Delta X^{\mathrm{N}n\mathrm{LO}}(p) = Q^{n+2}\cdot\max\left[\left|X^{\mathrm{LO}}(p)\right|, \frac{\left|X^{\mathrm{NLO}}(p)-X^{\mathrm{LO}}(p)\right|}{Q^2}, \frac{\left|X^{\mathrm{N2LO}}(p)-X^{\mathrm{NLO}}(p)\right|}{Q^3}, \frac{\left|X^{\mathrm{N3LO}}(p)-X^{\mathrm{N2LO}}(p)\right|}{Q^4}, \frac{\left|X^{\mathrm{N4LO}}(p)-X^{\mathrm{N3LO}}(p)\right|}{Q^5}\r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

and

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

with

R_i	0.8 fm	0.9 fm	1.0 fm	1.1 fm	1.2 fm
Λ_b^i	0.6GeV	0.6GeV	0.6GeV	0.5GeV	0.4GeV



NLO, N2LO, N3LO, N4LO

$(-0.748 \pm 0.138)\Delta e\mathrm{fm}$

$\hookrightarrow (-0.646 \pm 0.023)\Delta e\mathrm{fm}$

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Deuteron Quantities in ChPT from NLO to N4LO

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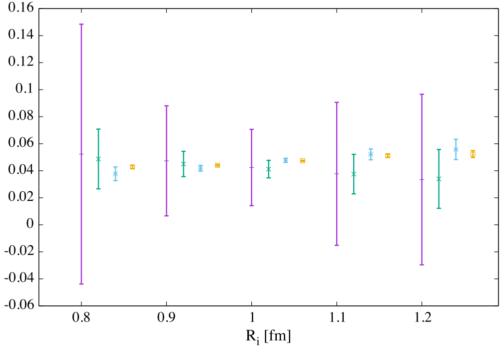
and $$f\left(\frac{r}{R_i}\right) = \left[1-\exp\left(-\frac{r^2}{R_i^2}\right)\right]^6$$ with

R_i	0.8 fm	0.9 fm	1.0 fm	1.1 fm	1.2 fm
Λ_b^i	0.6GeV	0.6GeV	0.6GeV	0.5GeV	0.4GeV



NLO, N2LO, N3LO, N4LO

$d^D_{n,p} = (0.939 \pm 0.009)\,d_n$

$\hookrightarrow d^D_{n,p} = (0.936 \pm 0.008)\,d_n$

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Deuteron Quantities in ChPT from NLO to N4LO

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

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

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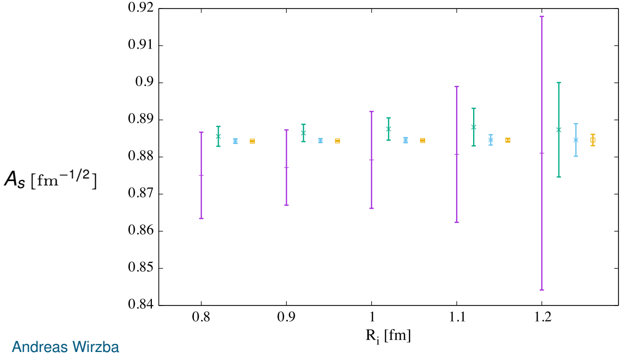
Λ_b^i	0.6GeV	0.6GeV	0.6GeV	0.5GeV	0.4GeV



NLO, N2LO, N3LO, N4LO

(0.8844 ± 0.0001) fm$^{-1/2}$

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Deuteron Quantities in ChPT from NLO to N4LO

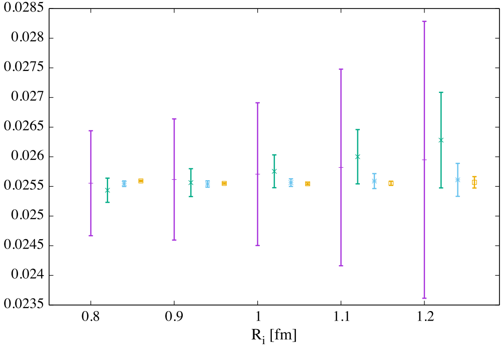
Epelbaum, Krebs, Meißner, *EPJA* **51** & *PRL* **115** (2015); Binder et al., *PRC* **93** (2016); *and* A. Nogga, *priv. comm.*

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

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

R_i	0.8 fm	0.9 fm	1.0 fm	1.1 fm	1.2 fm
Λ_b^i	0.6GeV	0.6GeV	0.6GeV	0.5GeV	0.4GeV

$\eta = D/S$



NLO, N2LO, N3LO, N4LO

(0.02555 ± 0.00001)

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