JÜLICH
FORSCHUNGSZENTRUM

Electric Dipole Moments
of Hadrons and Light Nuclei
in chiral EFT

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

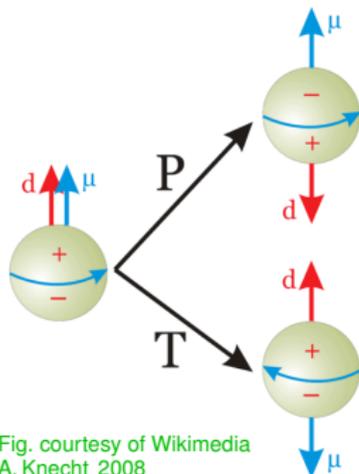# CP violation and the Electric Dipole Moment (EDM)

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

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

Any *non-vanishing EDM* of a **non-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): $|d_n| \sim 10^{-31}\,e\,\mathrm{cm}$, $|d_e| \sim 10^{-38}\,e\,\mathrm{cm}$
- Current bounds: $|d_n| < 3^\diamond/1.6^* \cdot 10^{-26}\,e\,\mathrm{cm}$, $|d_p| < 2\cdot 10^{-25}\,e\,\mathrm{cm}$, $|d_e| < 1\cdot 10^{-28}\,e\,\mathrm{cm}$

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

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

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

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

- CP & P conserving magnetic moment $\sim$ 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 $\sim 10^{-7}$

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

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

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

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

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

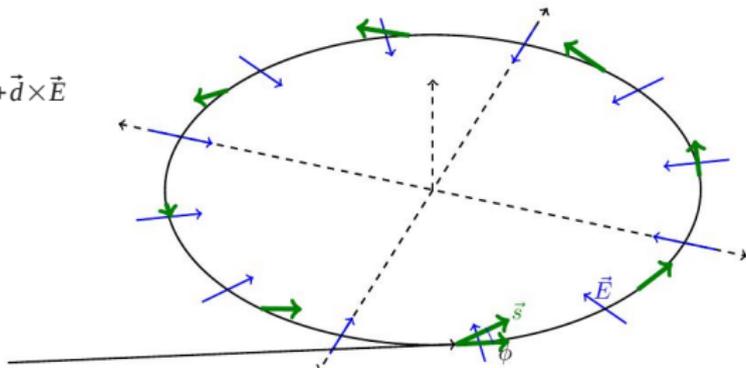 $\hookrightarrow$ $\boxed{|d_N^{\text{SM}}| \sim 10^{-7} \times 10^{-24} e\,\text{cm} \sim 10^{-31} e\,\text{cm}}$

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

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

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 $\vec{\beta} \cdot \vec{B} = 0$, $\vec{\beta} \cdot \vec{E} = 0$, $\vec{E} \cdot \vec{B} = 0$):
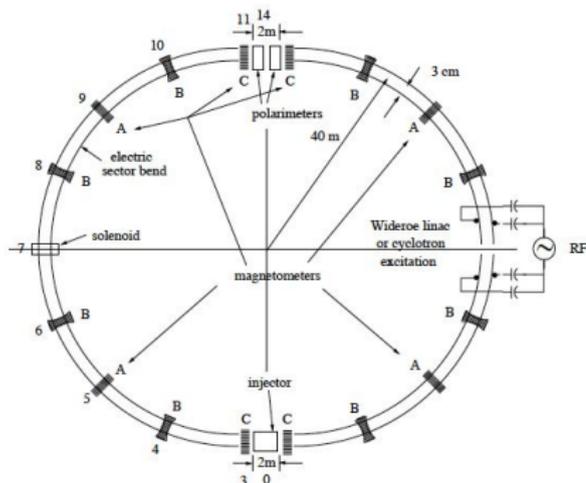
$$\frac{d\vec{S}^*}{dt} = \vec{\Omega} \times \vec{S}^* \quad \text{with} \quad \vec{\Omega} = -\frac{e}{m}\left(a\vec{B} + \left(\beta^{-2} - 1 - a\right)\vec{\beta} \times \vec{E} + \eta(\vec{E} + \vec{\beta} \times \vec{B})\right)$$

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

Method 1: pure electrostatic ring

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

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
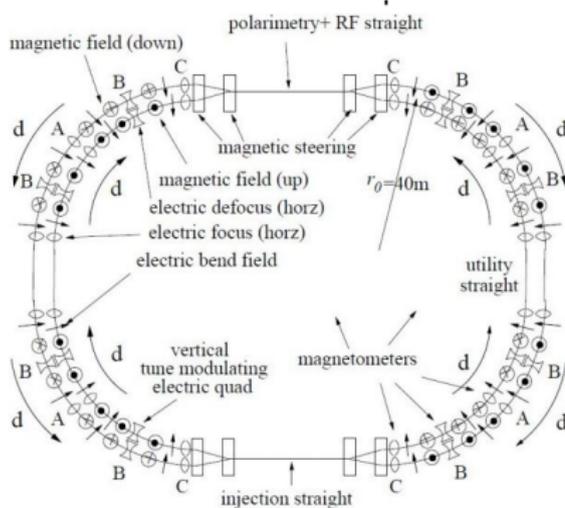– counter rotating beams possible

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

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

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

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

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

Advantage:

– existing COSY accelerator

↪ precursor experiment:

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

Disadvantage:

– low sensitivity

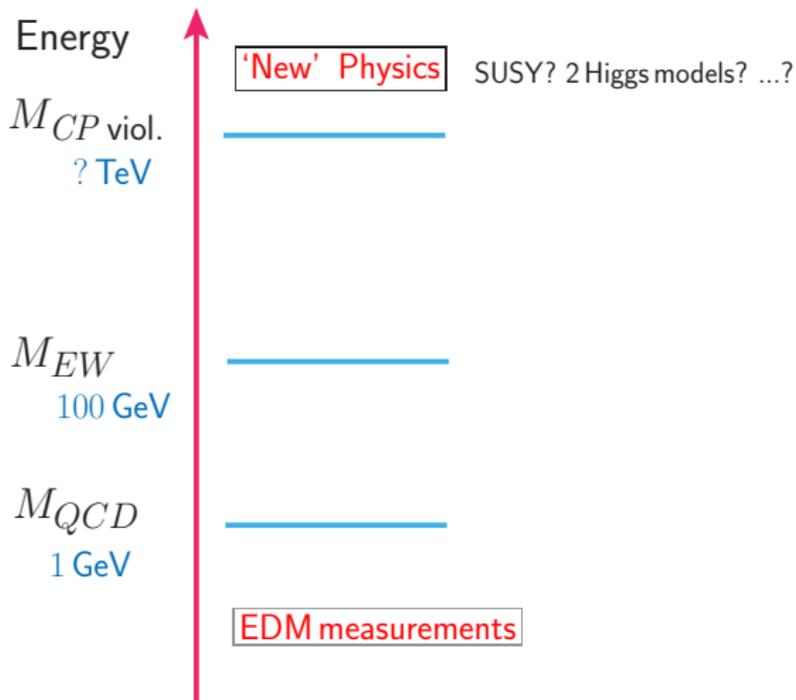$\gtrsim 10^{-21}$–$10^{-24}\,e\,\mathrm{cm}$ JEDI at COSY

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

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

How to handle CP-violating sources beyond the SM?
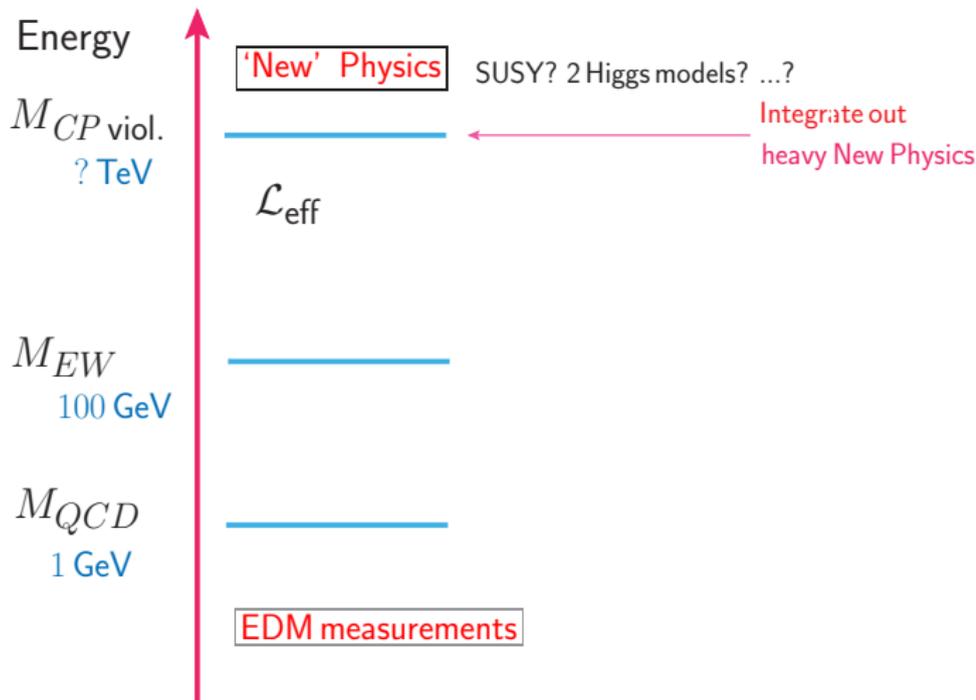
Running through the scales   W. Dekens & J. de Vries, *JHEP* '13

Energy

M_{CP} viol.
? TeV

'New' Physics   SUSY? 2 Higgs models? ...?

Integrate out
heavy New Physics
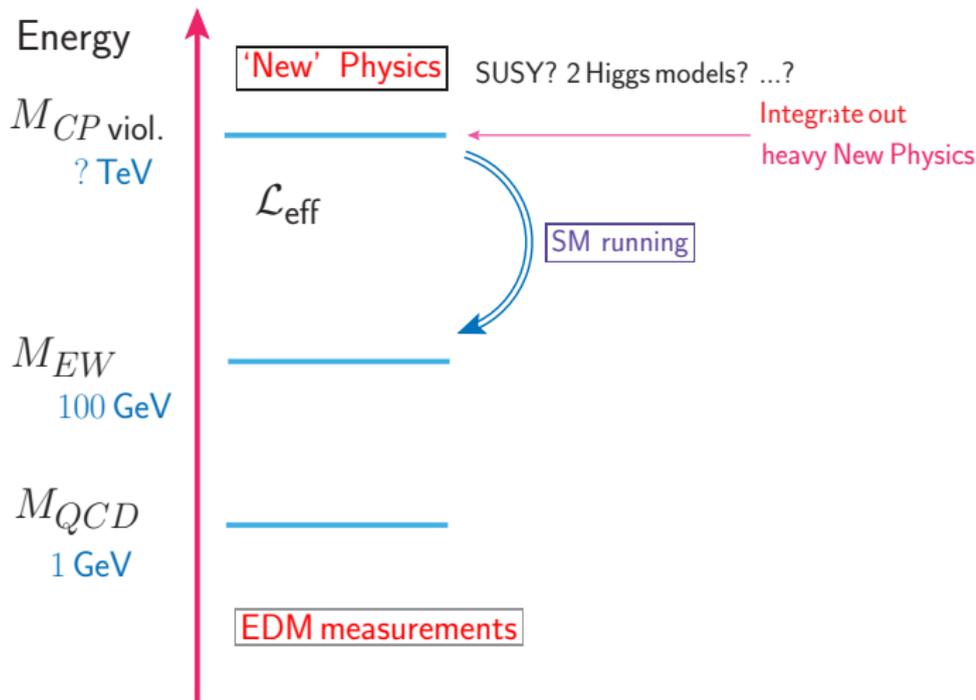
$\mathcal{L}_{\text{eff}}$

M_{EW}
100 GeV

M_{QCD}
1 GeV

EDM measurements
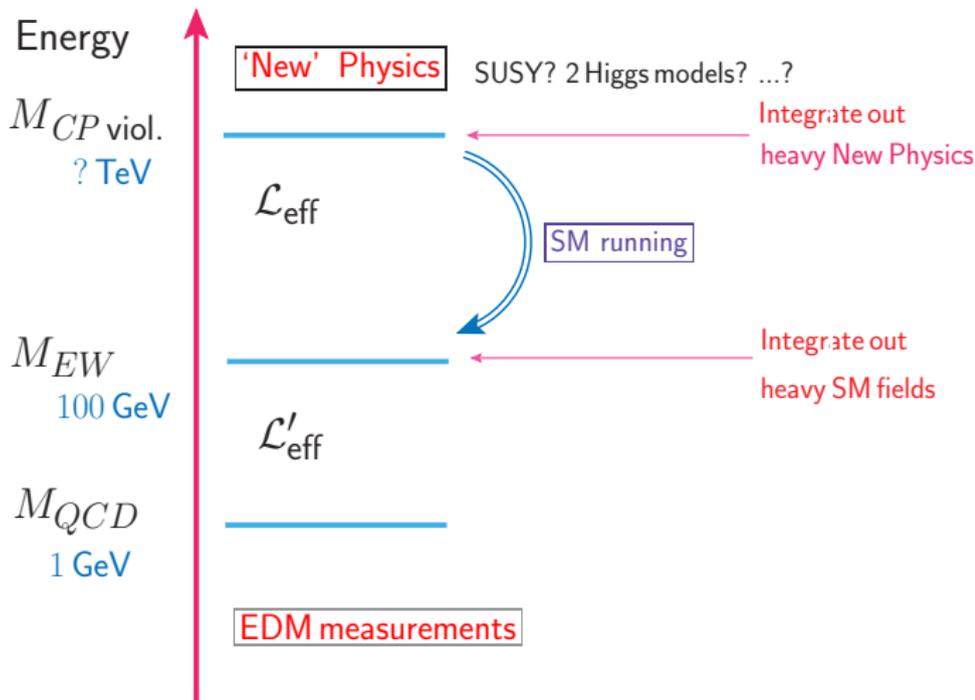
How to handle CP-violating sources beyond the SM?

Running through the scales

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

Energy

'New' Physics   SUSY? 2 Higgs models? ...?

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Integrate out
heavy New Physics

$\mathcal{L}_{\text{eff}}$

SM running

M_{EW}
100 GeV

Integrate out
heavy SM fields

$\mathcal{L}'_{\text{eff}}$

SM running

M_{QCD}
1 GeV

Non-perturbative QCD

EDM measurements
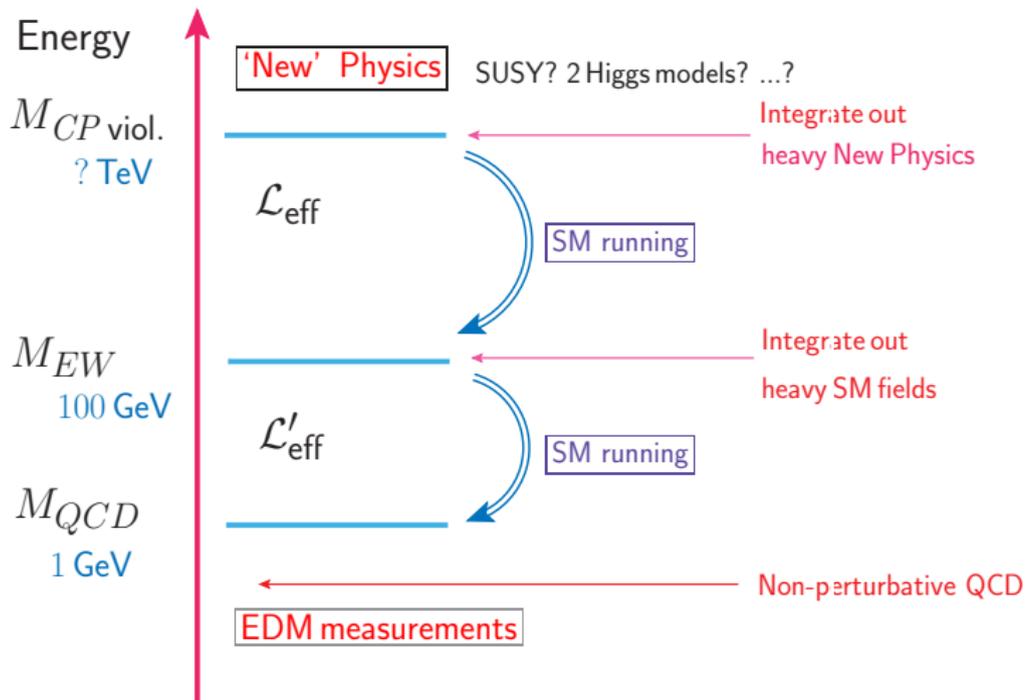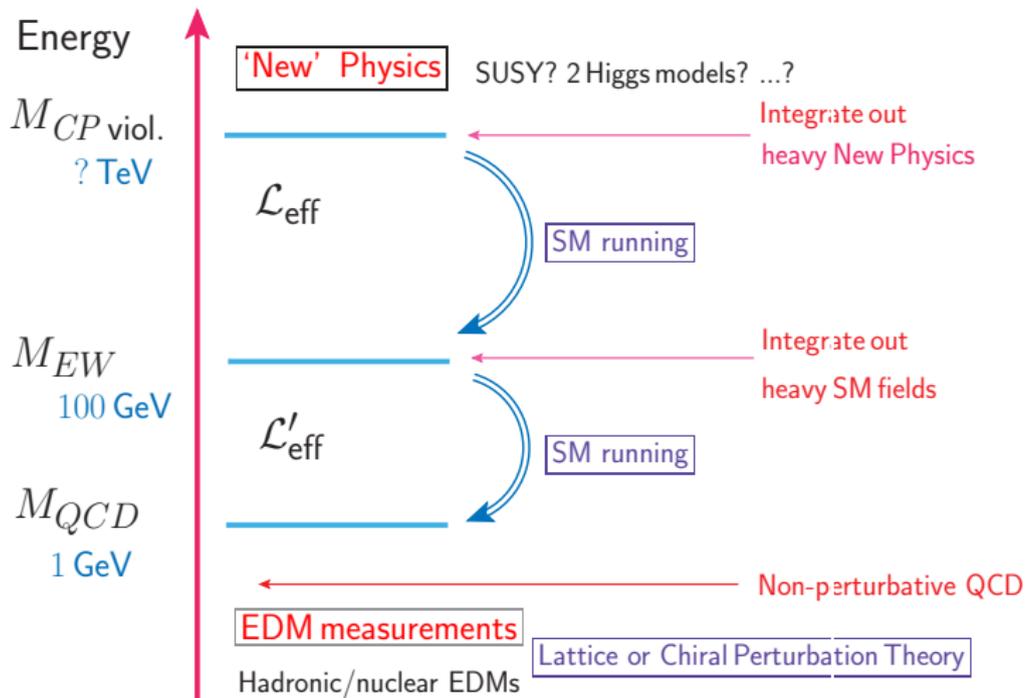
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Integrate out heavy New Physics

$\mathcal{L}_{\text{eff}}$

SM running

M_{EW}
100 GeV

Integrate out heavy SM fields

$\mathcal{L}'_{\text{eff}}$

SM running

M_{QCD}
1 GeV

Non-perturbative QCD

EDM measurements

Lattice or Chiral Perturbation Theory

Hadronic/nuclear EDMs

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

$$\mathcal{L}_{\text{eft}} = \mathcal{L}_{SM} + \sum_i \frac{c_5^{(i)}}{M_{\not{V}}} \mathcal{O}_5^{(i)} + \sum_i \frac{c_6^{(i)}}{M_{\not{V}}^2} \mathcal{O}_6^{(i)} + \dots$$
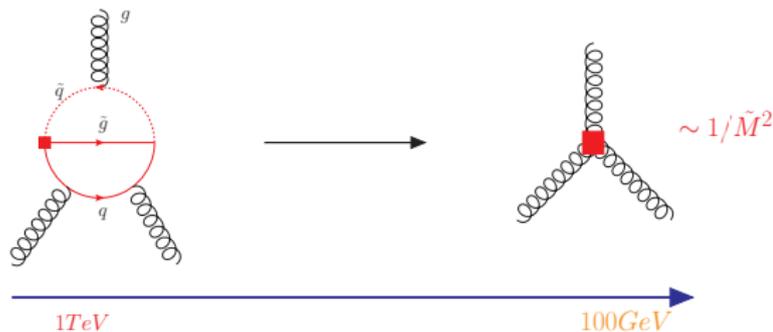
where $M_{\not{V}}$ is the scale of the *New Physics* particles

- 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

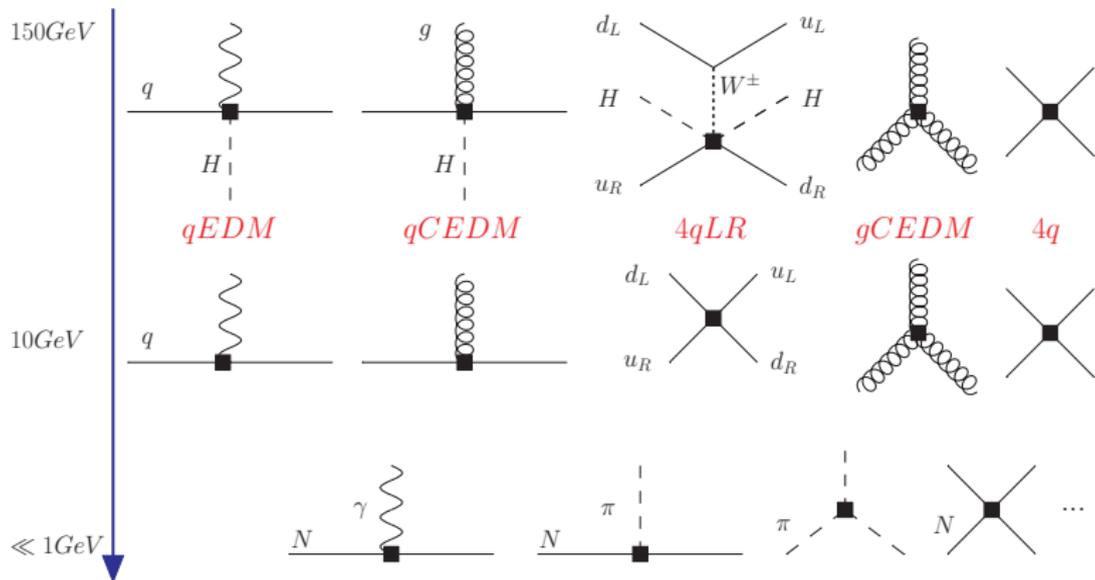# How to handle CP-violating sources beyond the SM?
Evaluation in Effective Field Theory (EFT) approach

- 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

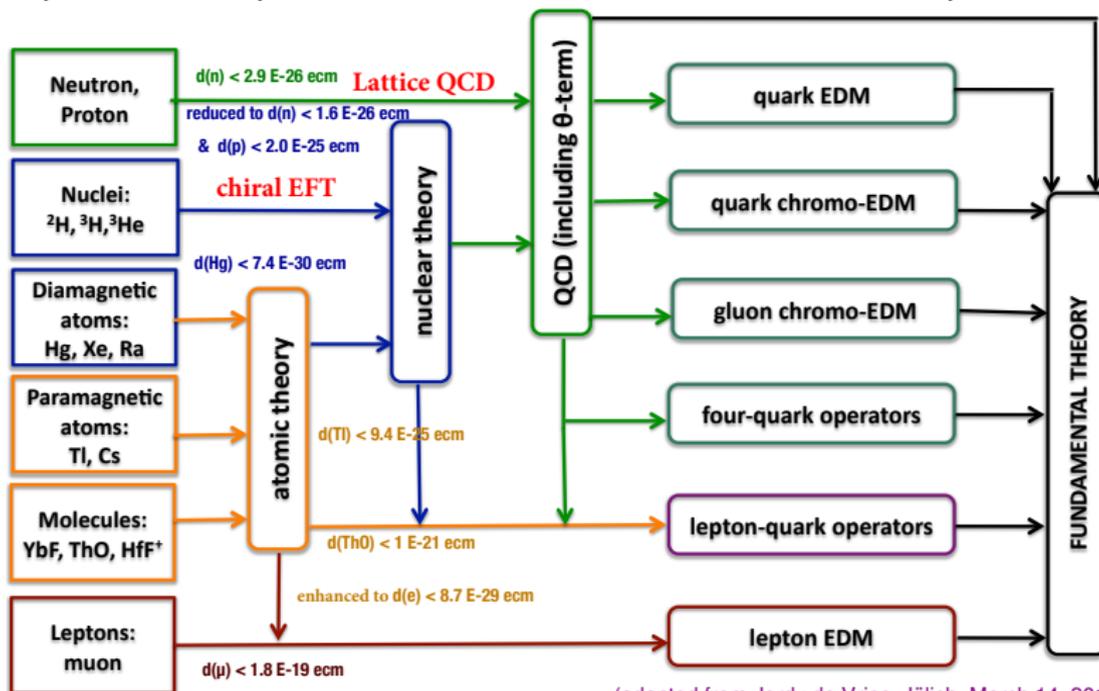## to their hadronic equivalents below 1 GeV

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

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

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

↪ 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   Dirk Vorderstraße

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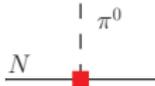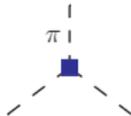

3-CPO & R2-D2 Dirk Vorderstraße

Symmetries (esp. chiral one) plus Goldstone Theorem

↪ Low-Energy Effective Field Theory with External Sources

i.e. Chiral Perturbation Theory (suitably extended)

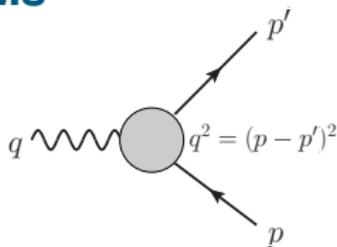# Scalings of C̶P̶ hadronic vertices – from θ to BSM sources

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

	g_0 C̶P̶, I	g_1 C̶P̶, ̶I̶	d_0, d_1 C̶P̶, I + ̶I̶	$(m_N\Delta)$ C̶P̶, ̶I̶	$C_{1,2}(C_{3,4})$ C̶P̶, I (̶I̶)
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:	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(1)$
4q:	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(M_\pi^2/m_N^2)^*$	$\mathcal{O}(1)$	$\mathcal{O}(M_\pi^2/m_N^2)$	$\mathcal{O}(1)$

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

Calculation: from form factors to EDMs

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

$$\Gamma^{\mu}(q^2) = \gamma^{\mu} F_1(q^2) - \mathrm{i}\sigma^{\mu\nu} q_{\nu} \frac{F_2(q^2)}{2m_f} + \sigma^{\mu\nu} q_{\nu} \gamma_5 \frac{F_3(q^2)}{2m_f} + (\slashed{q}\, q^{\mu} - q^2 \gamma^{\mu})\gamma_5 \frac{F_a(q^2)}{m_f^2}$$

Dirac FF   Pauli FF   electric dipole FF ($C\!\!\!/P$)   anapole FF ($P\!\!\!/$)

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

Calculation: from form factors to EDMs

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

$$\Gamma^\mu(q^2) = \gamma^\mu F_1(q^2) - i\sigma^{\mu\nu}q_\nu \frac{F_2(q^2)}{2m_f} + \sigma^{\mu\nu}q_\nu\gamma_5 \frac{F_3(q^2)}{2m_f} + (\slashed{q}\,q^\mu - q^2\gamma^\mu)\gamma_5 \frac{F_a(q^2)}{m_f^2}$$
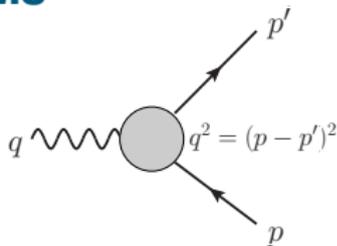
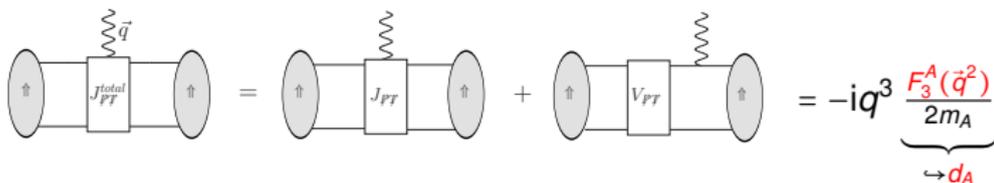Dirac FF   Pauli FF   electric dipole FF ($\cancel{CP}$)   anapole FF ($\cancel{P}$)

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

Nucleus A

$\langle \Uparrow | J_{PT}^0(q) | \Uparrow \rangle$
in Breit frame

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

θ-Term Induced Nucleon EDM

Isospin-conserving πNN coupling:

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

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

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 $\leadsto$ "controlled"

"unknown" coefficients

$\longrightarrow$ lattice QCD required

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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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!

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

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

Preliminary Lattice (full QCD) results

neutron EDM and proton EDM

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

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

Don't mention the ... light nuclei

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

Single Nucleon Versus Nuclear EDM

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

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$\gg$

controlled   unknown coefficient

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

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

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

NLO: $g_1 N^\dagger \pi_3 N$ $(\cancel{CP}, \cancel{I}) \to$ "LO" in D case

term	N²LO χPT	N⁴LO 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	Δe fm

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

BSM $\cancel{CP}$ sources: $g_1 \pi NN$ vertex is of LO in qCEDM and 4qLR case

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

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

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

NLO: $g_1 N^\dagger \pi_3 N$ $(\cancel{CP},\cancel{I}) \to$ "LO" in D case

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

term	N²LO χPT	N⁴LO 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 $\cancel{CP}$ sources: $g_1\,\pi NN$ vertex is of LO in qCEDM and 4qLR case

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

$g_0 N^\dagger \vec{\pi} \cdot \vec{\tau} N$ ($\cancel{CP}$, I)

  LO: θ-term, qCEDM

  N^{2}LO: 4qLR

$g_1 N^\dagger \pi_3 N$ ($\cancel{CP}$, $\cancel{I}$)

  LO: qCEDM, 4qLR

  NLO: θ term

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

$g_0 N^\dagger \vec\pi \cdot \vec\tau N$ ($\cancel{CP}$, I)
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$g_1 N^\dagger \pi_3 N$ ($\cancel{CP}$, $\cancel{I}$)
LO: qCEDM, 4qLR
NLO: θ term

term	A	N^2LO 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	
$\Delta_{f_{g_1}}$	^{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	$C_1\, e\,$fm^{-2}
	^{3}H	0.041 ± 0.016	0.0014	0.016	
C_2	^{3}He	0.089 ± 0.022	0.0042	0.033	$C_2\, e\,$fm^{-2}
	^{3}H	-0.087 ± 0.022	-0.0044	-0.032	

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

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

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Discriminating between three scenarios at 1 GeV

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

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

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

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

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

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

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

matched on

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

Discriminating between three scenarios at 1 GeV

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

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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 + $\bar{\theta}$

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

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

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

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

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

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

*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

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

Extraction of Δ^{LR}

* includes ± 0.1 uncertainty from 2N contact terms

Testing strategies: minimal LR symmetric Model

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

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

Extraction of Δ^{LR}

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

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

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

$$
\begin{aligned}
g_1^{LR} &= 8c_1 m_N \Delta^{LR} &&= (-7.5 \pm 2.3)\Delta^{LR}, \\
g_0^{LR} &= \frac{(m_n - m_p)^{\text{str}} m_N}{M_\pi^2} \Delta^{LR} &&= (0.12 \pm 0.02)\Delta^{LR}
\end{aligned}
$$

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

*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

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

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

Testing strategies: aligned 2-Higgs Doublet Model

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

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

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

Extraction of g_0

$\star$ includes ± 0.01 uncertainty from 2N contact terms

Testing strategies: aligned 2-Higgs Doublet Model

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

Measurement of the deuteron and nucleon EDMs

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

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

* includes ± 0.01 uncertainty from 2N contact terms

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**
  $\hookrightarrow$ $\cancel{CP}$ $N\pi$ couplings g_0 & g_1 may be accessible even for dim-6 case

Many thanks to my colleagues

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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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Int. J. Mod. Phys. E **26**, 1740031 (2017), arXiv:1610.00794.

2 J. Bsaisou, U.-G. Meißner, A. Nogga and A.W.,
P- and T-Violating Lagrangians in Chiral Effective Field Theory and Nuclear Electric Dipole Moments, Annals of Physics **359**, 317-370 (2015), arXiv:1412.5471 [hep-ph].

3 J. Bsaisou, C. Hanhart, S. Liebig, D. Minossi, U.-G. Meißner, A. Nogga and A.W.,
Electric dipole moments of light nuclei, JHEP **03**, 104 (**05**, 083) (2015), arXiv:1411.5804.

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].

5 J. Bsaisou, C. Hanhart, S. Liebig, U.-G. Meißner, A. Nogga and A.W.,
The electric dipole moment of the deuteron from the QCD θ-term,
Eur. Phys. J. A **49**, 31 (2013), arXiv:1209.6306 [hep-ph].

Jump slides

θ-term: $\cancel{CP}\ \pi NN$ 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)

$$\boxed{g_0^\theta: \quad N^\dagger \vec{\pi} \cdot \vec{\tau} N\text{-vertex}}$$

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

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

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

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

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

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

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

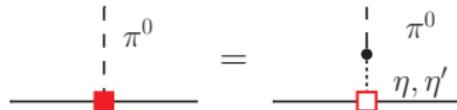g_1^θ: $\quad \pi_3 NN$-vertex $\qquad\qquad \epsilon := (m_u - m_d)/(m_u + m_d)$

$$\mathcal{L}_{\pi N} = \quad \ldots + \quad c_1 4B\, N^\dagger \left((m_u + m_d) + \frac{(\delta M_\pi^2)_{QCD}(1 - \epsilon^2)\, \bar\theta}{2BF_\pi \epsilon} \pi_3 \right) N \quad + \ldots$$
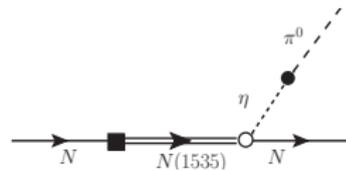
1 $\quad c_1 \longleftrightarrow \sigma_{\pi N}$: $\; c_1 = (-1.0 \pm 0.3)$ GeV^{-1} $\qquad$ Compilation: Baru et al. (2011)

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

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

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

$\rightsquigarrow \boxed{g_1^\theta = (3.4 \pm 1.5) \cdot 10^{-3}\bar\theta}$ $\qquad\qquad$ Bsaisou et al. '13, '15

$$\boxed{\frac{g_1^\theta}{g_0^\theta} = -0.22 \pm 0.10 \sim \frac{M_\pi}{m_N}}$$
Bsaisou et al. '13, '15

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

de Vries et al. (2011)

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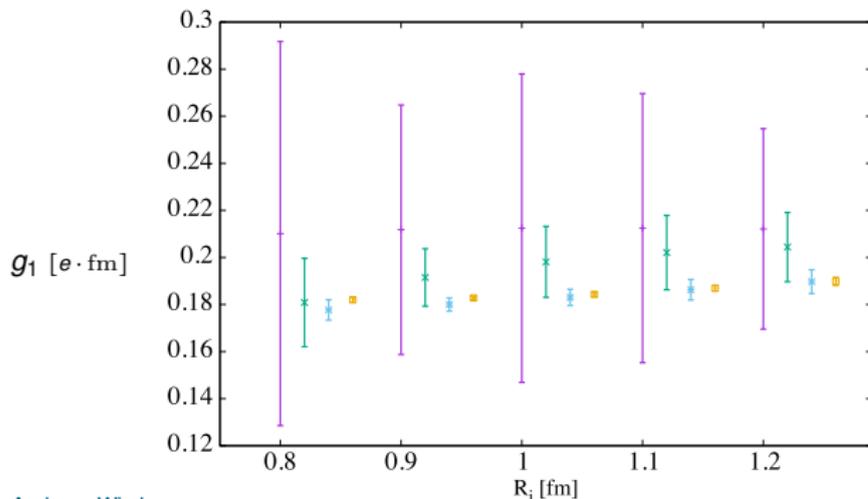
$\blacktriangleleft \pi NN$

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.*

$$\Delta x^{\mathrm{N}n\mathrm{LO}}(p) = Q^{n+2} \cdot \max\left[\left|x^{\mathrm{LO}}(p)\right|, \frac{\left|x^{\mathrm{NLO}}(p) - x^{\mathrm{LO}}(p)\right|}{Q^2}, \frac{\left|x^{\mathrm{N2LO}}(p) - x^{\mathrm{NLO}}(p)\right|}{Q^3},\right.$$

$$\left.\frac{\left|x^{\mathrm{N3LO}}(p) - x^{\mathrm{N2LO}}(p)\right|}{Q^4}, \frac{\left|x^{\mathrm{N4LO}}(p) - x^{\mathrm{N3LO}}(p)\right|}{Q^5}\right] \quad \text{with} \quad Q = \max\left(\frac{|p|}{\Lambda_b^i}, \frac{M_\pi}{\Lambda_b^i}\right)$$

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

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

NLO, N2LO, N3LO, N4LO

$(0.183 \pm 0.017)\, g_1\, e\mathrm{fm}$

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

◀ back

Deuteron Quantities in ChPT from NLO to N4LO

$$\Delta x^{\text{N}n\text{LO}}(p) = Q^{n+2} \cdot \max\left[\left|x^{\text{LO}}(p)\right|, \frac{\left|x^{\text{NLO}}(p) - x^{\text{LO}}(p)\right|}{Q^2}, \frac{\left|x^{\text{N2LO}}(p) - x^{\text{NLO}}(p)\right|}{Q^3},\right.$$

$$\left.\frac{\left|x^{\text{N3LO}}(p) - x^{\text{N2LO}}(p)\right|}{Q^4}, \frac{\left|x^{\text{N4LO}}(p) - x^{\text{N3LO}}(p)\right|}{Q^5}\right] \quad \text{with} \quad Q = \max\left(\frac{|p|}{\Lambda_b^i}, \frac{M_\pi}{\Lambda_b^i}\right)$$

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

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

E_B^{D} [MeV]

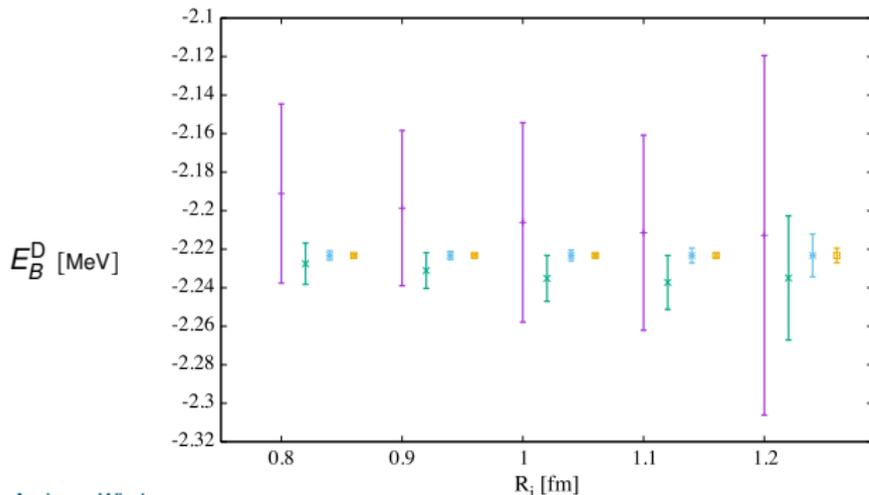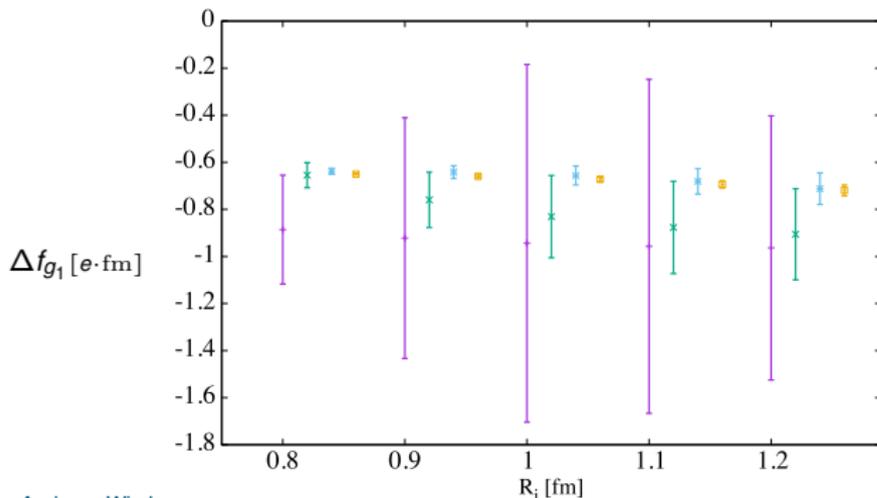NLO, N2LO, N3LO, N4LO

(-2.2233 ± 0.0004) MeV

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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.*

$$\Delta x^{\mathrm{N}n\mathrm{LO}}(p) = Q^{n+2} \cdot \max\left[\left|x^{\mathrm{LO}}(p)\right|, \frac{\left|x^{\mathrm{NLO}}(p) - x^{\mathrm{LO}}(p)\right|}{Q^2}, \frac{\left|x^{\mathrm{N2LO}}(p) - x^{\mathrm{NLO}}(p)\right|}{Q^3},\right.$$

$$\left.\frac{\left|x^{\mathrm{N3LO}}(p) - x^{\mathrm{N2LO}}(p)\right|}{Q^4}, \frac{\left|x^{\mathrm{N4LO}}(p) - x^{\mathrm{N3LO}}(p)\right|}{Q^5}\right] \quad \text{with} \quad Q = \max\left(\frac{|p|}{\Lambda_b^i}, \frac{M_\pi}{\Lambda_b^i}\right)$$

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

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

NLO, N2LO, N3LO, N4LO

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

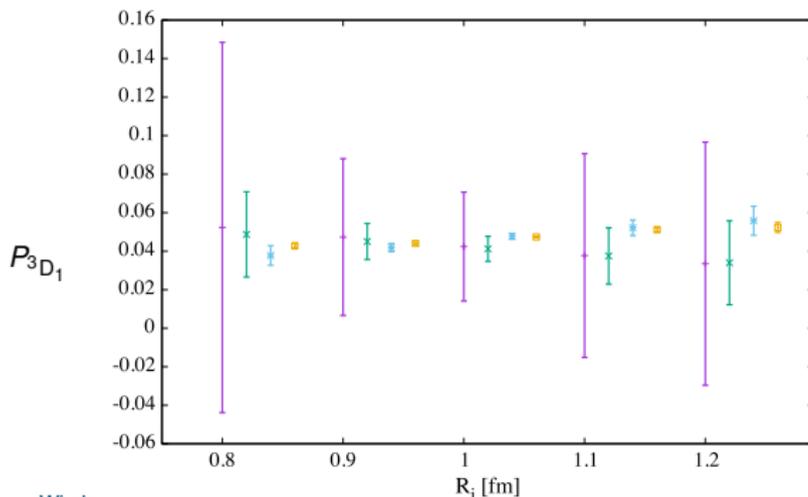$\hookrightarrow (-0.646 \pm 0.023)\,\Delta e\,\mathrm{fm}$

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Deuteron Quantities in ChPT from NLO to N4LO

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

$$\Delta x^{\mathrm{N}n\mathrm{LO}}(p) \;=\; Q^{n+2} \cdot \max\left[\left|x^{\mathrm{LO}}(p)\right|, \frac{\left|x^{\mathrm{NLO}}(p) - x^{\mathrm{LO}}(p)\right|}{Q^2}, \frac{\left|x^{\mathrm{N2LO}}(p) - x^{\mathrm{NLO}}(p)\right|}{Q^3},\right.$$

$$\left.\frac{\left|x^{\mathrm{N3LO}}(p) - x^{\mathrm{N2LO}}(p)\right|}{Q^4}, \frac{\left|x^{\mathrm{N4LO}}(p) - x^{\mathrm{N3LO}}(p)\right|}{Q^5}\right] \quad \text{with} \quad Q = \max\left(\frac{|p|}{\Lambda_b^i}, \frac{M_\pi}{\Lambda_b^i}\right)$$

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

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

NLO, N2LO, N3LO, N4LO

$$d_{n,p}^D = (0.939 \pm 0.009)\, d_n$$

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

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$P_{^3D_1}$ ... R_i [fm]

Deuteron Quantities in ChPT from NLO to N4LO

$$\Delta x^{\text{N}n\text{LO}}(p) = Q^{n+2} \cdot \max\left[\left|x^{\text{LO}}(p)\right|, \frac{\left|x^{\text{NLO}}(p) - x^{\text{LO}}(p)\right|}{Q^2}, \frac{\left|x^{\text{N2LO}}(p) - x^{\text{NLO}}(p)\right|}{Q^3},\right.$$

$$\left.\frac{\left|x^{\text{N3LO}}(p) - x^{\text{N2LO}}(p)\right|}{Q^4}, \frac{\left|x^{\text{N4LO}}(p) - x^{\text{N3LO}}(p)\right|}{Q^5}\right] \quad \text{with} \quad Q = \max\left(\frac{|p|}{\Lambda_b^i}, \frac{M_\pi}{\Lambda_b^i}\right)$$

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

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

$A_s\,[\text{fm}^{-1/2}]$ $R_i\,[\text{fm}]$

NLO, N2LO, N3LO, N4LO
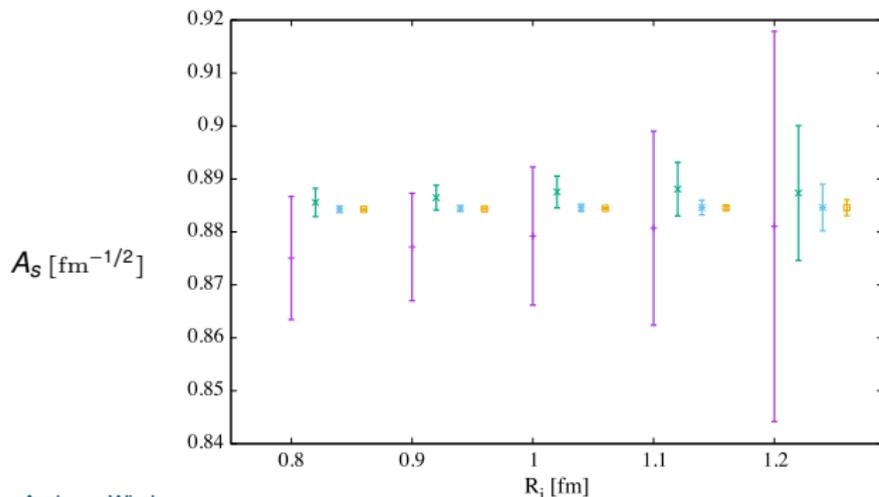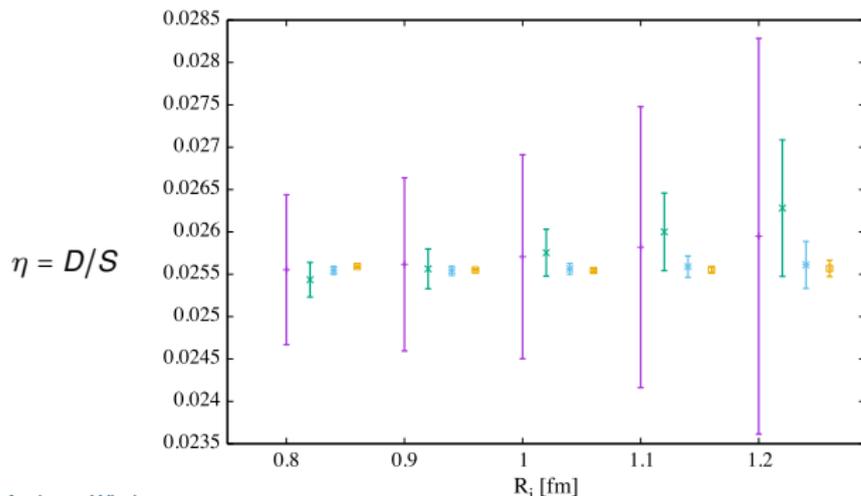
$(0.8844 \pm 0.0001)\,\text{fm}^{-1/2}$

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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.*

$$\Delta x^{\mathrm{N}n\mathrm{LO}}(p) = Q^{n+2} \cdot \max\left[\left| x^{\mathrm{LO}}(p) \right|, \frac{\left| x^{\mathrm{NLO}}(p) - x^{\mathrm{LO}}(p) \right|}{Q^2}, \frac{\left| x^{\mathrm{N2LO}}(p) - x^{\mathrm{NLO}}(p) \right|}{Q^3}, \right.$$

$$\left. \frac{\left| x^{\mathrm{N3LO}}(p) - x^{\mathrm{N2LO}}(p) \right|}{Q^4}, \frac{\left| x^{\mathrm{N4LO}}(p) - x^{\mathrm{N3LO}}(p) \right|}{Q^5} \right] \quad \text{with} \quad Q = \max\left(\frac{|p|}{\Lambda_b^i}, \frac{M_\pi}{\Lambda_b^i} \right)$$

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

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

$\eta = D/S$

NLO, N2LO, N3LO, N4LO

(0.02555 ± 0.00001)

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