Electric dipole moments of the nucleon and light nuclei

Jülich-Bonn Collaboration (JBC)

Schleching | February 20, 2014 | Andreas Wirzba
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+COBE (2012): $n_B/n_\gamma|_{\text{CMB}} = (6.08 \pm 0.09) \times 10^{-10}$

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. non-equilibrium to escape $(B) = 0$ if CPT holds

\[ 2J^{\text{CKM}}_{\text{Jarlskog}} (m_t^2 - m_d^2) (m_t^2 - m_u^2) (m_c^2 - m_d^2) (m_b^2 - m_d^2) (m_s^2 - m_d^2) (m_s^2 - m_d^2) \sim 10^{-18} M_{\text{EW}}^{12} \]
The Electric Dipole Moment (EDM)

**EDM:**

\[ \vec{d} = \sum_i \vec{r}_i e_i \]

(subatomic particles)

\[ d \cdot \vec{S}/|\vec{S}| \]

(axes)

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

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

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

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

- Assuming CPT to hold, CP is violated as well
- subatomic EDMs: “rear window” to CP violation in early universe
- Strongly suppressed in SM (CKM-matrix):
  \[ |d_n| \approx 10^{-31} \text{e cm}, \ |d_e| \approx 10^{-38} \text{e cm} \]
- Current bounds:
  \[ |d_n| < 3 \cdot 10^{-26} \text{ e cm}, \ |d_p| < 8 \cdot 10^{-25} \text{ e cm}, \ |d_e| < 1 \cdot 10^{-28} \text{ e cm} \]

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

* from \( |d_{199 \text{Hg}}| < 3.1 \cdot 10^{-29} \text{ e cm} \) bound of Griffith et al. (2009)

† from polar ThO: \( |d_{\text{ThO}}| \lesssim 10^{-21} \text{ e cm} \)
A naive estimate of the scale of the nucleon EDM

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

- CP & P conserving magnetic moment ~ nuclear magneton $\mu_N$
  $$\mu_N = \frac{e}{2m_p} \sim 10^{-14} \text{e cm}.$$  

- A nonzero EDM requires
  
  parity P violation: the price to pay is $\sim 10^{-7}$
  ( $G_F \cdot F_{\pi}^2 \sim 10^{-7}$ with $G_F \approx 1.166 \cdot 10^{-5} \text{GeV}^{-2}$ ),

  and CP violation: the price to pay is $\sim 10^{-3}$
  ( $|\eta_{+-}| \equiv |\Delta A(K^0_L \rightarrow \pi^+ \pi^-)| / |\Delta A(K^0_S \rightarrow \pi^+ \pi^-)| = (2.232 \pm 0.011) \cdot 10^{-3}$ ).

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

- In SM (without $\theta$ term): extra $G_F F_{\pi}^2$ factor to undo flavor change
  $$\Rightarrow |d_N^{SM}| \sim 10^{-7} \times 10^{-24} \text{e cm} \sim 10^{-31} \text{e cm}$$

  $\Rightarrow$ The empirical window for search of physics BSM($\theta=0$) is
  $$10^{-24} \text{e cm} > |d_N| > 10^{-30} \text{e cm}.$$
Chronology of upper bounds on the neutron EDM

Upper bounds on the neutron EDM in units of e cm

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

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

→ 5 to 6 orders above SM predictions which are out of reach!
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
\( \rightarrow \) build-up of vertical polarization (measured with a polarimeter)

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

- Counter-circling proton ring at Brookhaven (srEDM) or Fermilab (Project X) ?
- All-purpose ring for proton, deuteron (and helion) in Jülich (JEDI) ?
- \( \rightarrow \) Precursor experiment (\( \gtrsim 10^{-25} \) e cm) for \( p \) or \( D \) at COSY@Jülich !
Road map from EDM Measurements to EDM Sources

Experimentalist’s point of view → Theorist’s point of view

- Neutron, Proton
- Nuclei: $^2$H, $^3$H, $^3$He
- Diamagnetic atoms: Hg, Xe, Ra
- Paramagnetic atoms: Tl, Cs
- Molecules: YbF, ThO, HfF$^+$
- Leptons: muon

d(n) < 2.9 E-26 ecm

d(p) < 7.9 E-25 ecm

d(Hg) < 3.1 E-29 ecm

d(H) < 9.4 E-25 ecm

d(ThO) < 1 E-21 ecm

d(e) < 8.7 E-29 ecm

d(mu) < 1.8 E-19 ecm

QCD (including $\theta$-term)
- quark EDM
- quark chromo-EDM
- gluon chromo-EDM
- four-quark operators
- lepton-quark operators
- lepton EDM

(Adapted from Jordy de Vries, Jülich, March 14, 2013)
CP-conserving and -violating form factors and EDMs

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

\[ \Gamma^\mu(q^2) = \gamma^\mu F_1(q^2) - i\sigma^{\mu\nu} q_\nu \frac{F_2(q^2)}{2m_f} + \sigma^{\mu\nu} q_\nu \gamma_5 \frac{F_3(q^2)}{2m_f} + (q^\mu - q^2 \gamma^\mu) \gamma_5 \frac{F_a(q^2)}{m^2_f} \]

Dirac FF \hspace{1cm} Pauli FF \hspace{1cm} electric dipole FF (CP) \hspace{1cm} anapole FF (P)

\[ \leftrightarrow d_f := \lim_{q^2 \to 0} \frac{F_3(q^2)}{2m_f} \quad \text{for } s = 1/2 \text{ fermion} \]
CP-conserving and -violating form factors and EDMs

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- Dirac FF
- Pauli FF
- electric dipole FF (CP)
- anapole FF (P)

\[ \lim_{q^2 \to 0} \frac{F_3(q^2)}{2m_f} \]

for \( s = 1/2 \) fermion

Nucleus A

\[ \langle \uparrow \uparrow | J_{\text{PF}}^0(q) | \uparrow \uparrow \rangle \]

in Breit frame

\[ = -i q^3 \frac{F_A^3(q^2)}{2m_A} \]

Andreas Wirzba
EDM sources: QCD $\theta$-term of the SM

QCD has topologically non-trivial vacuum $\to$ $\mathcal{P}$ & $\mathcal{T}$ term in $\mathcal{L}_{QCD}$:

$$\mathcal{L} = \mathcal{L}_{QCD}^{CP} + \theta \frac{g_S^2}{64\pi^2} \epsilon_{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\sigma}^a \quad (\text{of dimension 4})$$

$$... + \theta \frac{g_S^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}_{a,\mu\nu} \xrightarrow{U_A(1)} ... - \bar{\theta} m_q^* \sum_{f=u,d} \bar{q}_f i\gamma_5 q_f$$

with $\bar{\theta} = \theta + \arg \Det \mathcal{M}$, $\mathcal{M}$: quark mass matrix, $m_q^* \equiv \frac{m_u m_d}{m_u + m_d}$

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

$$\left| d_n^{\text{emp}} \right| < 2.9 \cdot 10^{-26} \text{ e cm} \sim |\bar{\theta}| \lesssim 10^{-10} \quad \text{strong CP problem}$$

Note: $\mathcal{P} \cdot \mathcal{T}_{\text{emp}}^{CPT} = \mathcal{P} \cdot \mathcal{CP}_{\text{emp}} \sim 10^{-10} (??)$
More sources: **New Physics (Beyond the Standard Model)**

SUSY, multi-Higgs, Left-Right-Symmetric models, ...

Evaluated in Effective Field Theory (EFT) approach:

- All degrees of freedom *beyond NP (EW) scale* are integrated out:
  - Only SM degrees of freedom remain: $q, g, (H, W^\pm, ...)$

- 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.

\[
\sim \frac{1}{\tilde{M}^2}
\]
All possible (BSM) $T$ and $P$ contact interactions of dimension 6 above/below the EW scale and their $\mathcal{CP}$ hadronic equivalents

W. Dekens & J. de Vries (2013)
EDM Translator
from ‘quarkish/machine’ to ‘hadronic/human’ language?

Symmetries (esp. chiral one) and Goldstone Theorem

\[ \leftrightarrow \]
Low-Energy Effective Field Theory with External Sources

i.e. Chiral Perturbation Theory (suitably extended)
\( \theta \)-Term on the Hadronic Level (non-perturbative QCD regime!)

\[
\mathcal{L}_{QCD}^\theta = -\bar{\theta} m_q^* \sum_f \bar{q}_f i \gamma_5 q_f: \quad \text{CP, I} \quad \Leftrightarrow \quad \mathcal{M} \to \mathcal{M} + \bar{\theta} m_q^* i \gamma_5 \quad m_q^* = \frac{m_u m_d}{m_u + m_d}
\]

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

\[
\begin{align*}
\text{CP, I} & \quad \quad \text{CP, I} & \quad \text{CP, I + I} \\
\mathcal{L}_{\text{ChPT}}^\theta = & \quad g_0^\theta N^\dagger \vec{\tau} \cdot \vec{\pi} N + g_1^\theta N^\dagger \tau_3 N + N^\dagger \left( b_0^\theta + b_1^\theta \tau_3 \right) S^\mu \nu \nu F_{\mu \nu} N + \cdots \quad \downarrow \downarrow \quad \downarrow \downarrow \quad \downarrow \downarrow \quad \downarrow \downarrow \\
& \quad g_0^\theta \quad \text{dominating for } n, p \text{ \& } ^3\text{He} \quad g_1^\theta \quad \text{suppressed but imp. for } D \quad \text{important for } n, p
\end{align*}
\]

Lebedev et al. (2004), Mereghetti et al. (2010), Bsaisou et al. (2013)

\[ |g_0^\theta| \gg |g_1^\theta| \quad \text{: NDA estimate predicts: } g_1^\theta / g_0^\theta \sim \mathcal{O}(m_\pi / m_n^2) \quad \text{de Vries et al. (2011)} \]

ChPT LECs predict: \[ g_1^\theta / g_0^\theta \sim \mathcal{O}(m_\pi / m_n) \] !

Bsaisou et al. (2013)
**θ-Term Induced EDM of a Single Nucleon**

 isovector

 \[ \sim \]

 \( \ll \)

 isoscalar

 two "unknown" coefficients

 Guo & Meißner (2012): also in SU(3) case

 \[
 d_N^{\text{isovector}}_{\text{loop}} = -e \frac{g_{\pi NN} g_0^\theta}{4\pi^2} \frac{\ln\left(\frac{M_N^2}{m^2}\right)}{2M_N} \sim \bar{\theta} m_N^2 \ln m_N^2 \quad (e > 0)
 \]

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

 \[
 g_0^\theta = \frac{(m_n - m_p)^{\text{strong}}(1 - \epsilon^2)}{4F_\pi \epsilon} \bar{\theta} \sim (-0.018 \pm 0.007)\bar{\theta} \quad (\text{where } \epsilon \equiv \frac{m_u - m_d}{m_u + m_d})
 \]

 \( \leftrightarrow d_N^{\text{isovector}}_{\text{loop}} \sim (2.1 \pm 0.9) \cdot 10^{-16} \bar{\theta} \text{ e cm} \)

 Ottnad et al. (2010); Bsaisou et al. (2013)

 But what about the two "unknown" coefficients of the contact terms?
We’ll always have ... the lattice

Don’t mention the ... light nuclei
We’ll always have ... the lattice
However, It’s a long way to Tipperary ...

Results from full QCD calculations (no systematical errors!) for the

neutron EDM and proton EDM

\[ \theta \equiv 1 \] (adapted from Eigo Shintani (Mainz), Lattice calculation of nucleon EDM, Hirschegg, Jan. 14, 2014)
We’ll always have ... the lattice

However, It’s a long way to Tipperary ...

Results from full QCD calculations (no systematical errors!) for the neutron EDM and proton EDM

Figure 29: \( dN \) for neutron and proton

Don’t mention the ... light nuclei

(adapted from Taku Izubuchi (BNL), Lattice-QCD calculations for EDMs, Fermilab, Feb. 14, 2013)
Single Nucleon Versus Nuclear EDM of the $\theta$-Term

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

single nucleon EDM:

\[
\begin{align*}
\text{isovector} & \approx \frac{1}{u^2 a} \\
\text{isoscalar} & \ll \frac{1}{u a} 
\end{align*}
\]

“controlled” \rightarrow lattice QCD required

\[
\begin{align*}
\text{“controlled”} \\
\text{lattice QCD required} \\
\text{Guo, Meißner (2012)}
\end{align*}
\]

two nucleon EDM:

\[
\begin{align*}
\text{controlled} \\
\text{unknown coefficient} \\
\text{Sushkov, Flambaum, Khriplovich (1984)}
\end{align*}
\]
Single Nucleon Versus Nuclear EDM of the $\theta$-Term

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

single nucleon EDM:

iso vector $\approx \frac{\text{unknown}}{\text{controlled}}$

isoscalar $\ll\ll$

→ lattice QCD required

Guo, Meißner (2012)

two nucleon EDM:

controlled

$\gg$

unknown coefficient

Sushkov, Flambaum, Khriplovich (1984)
EDM of the Deuteron at LO: CP-violating $\pi$ exchange

LO: $g_0^\theta N^\dagger \pi \cdot \pi N \quad (\mathbb{C}\mathbb{P}, I) \to 0$ (Isospin filter!)

NLO: $g_1^\theta N^\dagger \pi_3 N \quad (\mathbb{C}\mathbb{P}, I) \to "LO"$ in D case

<table>
<thead>
<tr>
<th>Reference</th>
<th>potential</th>
<th>result $[g_1 g_{\pi NN} \text{ e fm}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liu &amp; Timmermans (2004)</td>
<td>$A_{\nu 18}$</td>
<td>$1.43 \times 10^{-2}$</td>
</tr>
<tr>
<td>Afnan &amp; Gibson (2010)</td>
<td>Reid 93</td>
<td>$1.53 \times 10^{-2}$</td>
</tr>
<tr>
<td>Song et al. (2013)</td>
<td>$A_{\nu 18}$</td>
<td>$1.45 \times 10^{-2}$</td>
</tr>
<tr>
<td>JBC (2014)*</td>
<td>$A_{\nu 18}$</td>
<td>$1.45 \times 10^{-2}$</td>
</tr>
<tr>
<td>Bsaisou et al. (2013)*</td>
<td>CD Bonn</td>
<td>$1.52 \times 10^{-2}$</td>
</tr>
<tr>
<td>JBC (2014)*</td>
<td>ChPT ($N^2$LO)</td>
<td>$(1.43 \pm 0.13) \times 10^{-2}$</td>
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</table>


BSM $\mathbb{C}\mathbb{P}$ sources: $g_1 \pi NN$ vertex is of LO in qCEDM and 4qLR case
$^3$He EDM: results for CP-violating $\pi$ exchange

\[ g_0 N^+ \bar{\pi} \cdot \bar{\tau} N \quad (\text{CP, I}) \]
LO: $\theta$-term, qCEDM
N\(^2\)LO: 4qLR

\[ g_1 N^+ \pi N \quad (\text{CP, I}) \]
LO: qCEDM, 4qLR
NLO: $\theta$ term

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<tbody>
<tr>
<td>Stetcu et al. (2008)</td>
<td>$A_{18} \ UIX$</td>
<td>$1.20 \times 10^{-2}$ /2(\dag)</td>
<td>$2.20 \times 10^{-2}$ /2(\dag)</td>
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<tr>
<td>Song et al. (2013)</td>
<td>$A_{18} \ UIX$</td>
<td>$0.55 \times 10^{-2}$</td>
<td>$1.06 \times 10^{-2}$</td>
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<tr>
<td>JBC (2014)(\dag)</td>
<td>$A_{18} \ UIX$</td>
<td>$0.57 \times 10^{-2}$</td>
<td>$1.11 \times 10^{-2}$</td>
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<td>JBC (2014)(\dag)</td>
<td>CD BONN TM</td>
<td>$0.68 \times 10^{-2}$</td>
<td>$1.14 \times 10^{-2}$</td>
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<tr>
<td>JBC (2014)(\dag)</td>
<td>ChPT ((N^2)LO)</td>
<td>((0.86 \pm 0.11) \times 10^{-2})</td>
<td>((1.11 \pm 0.14) \times 10^{-2})</td>
</tr>
</tbody>
</table>

\(\dag\) unpublished

Results for $^3H(g_i) \approx (-1)^{1+i} \times ^3He(g_i)$ ones
Testing Strategies in the $\theta$ EDM scenario

**EDM results**  
(with $\tilde{d}_n = 0.88d_n - 0.047d_p$)  
(de Vries et al. (2011))

$$d_D = d_n + d_p + (0.54 \pm 0.39) \cdot 10^{-16} \bar{\theta} \text{ e cm}$$  
(Bsaisou et al. (2013))

$$d_{3He} = \tilde{d}_n - (1.35 \pm 0.88) \cdot 10^{-16} \bar{\theta} \text{ e cm}$$  
(JBC (2014))

Uncertainties dominated by the *hadronic* ones:

$$g_{\theta}^0 = \frac{(m_n-m_p)^{\text{strong}} (1-\epsilon^2)}{4F_{\pi} \epsilon} \bar{\theta} \quad \text{and} \quad \frac{g_1^0}{g_0^0} \approx \frac{8c_1 (M_{\pi^0}^2 - M_{\pi^+}^2)^{\text{strong}}}{(m_n-m_p)^{\text{strong}}} \quad \text{with} \quad \epsilon = \frac{m_u-m_d}{m_u+m_d}$$

**Testing strategies:**

- **plan A:** measure $d_n$, $d_p$, and $d_D$  
  $\quad d_D(2N) \rightarrow \bar{\theta} \rightarrow d_{3He}$

- **plan A':** measure $d_n$, ($d_p$), and $d_{3He}$  
  $\quad d_{3He}(2N) \rightarrow \bar{\theta} \rightarrow d_D$

- **plan B:** measure $d_n$ (or $d_p$) + Lattice QCD  
  $\quad \sim \bar{\theta} \rightarrow d_D$

- **plan B':** measure $d_n$ (or $d_p$) + Lattice QCD  
  $\quad \sim \bar{\theta} \rightarrow d_p$ (or $d_n$)
If $\bar{\theta}$-term tests fail, then effective BSM dim. 6 sources

de Vries et al.(2011)

\[
d_{D} \approx d_{p} + d_{n}
\]
\[
d_{3}\text{He} \approx d_{n}
\]

\[
g_{0}, g_{1} \propto \alpha/(4\pi)
\]

2N contribution suppressed by photon loop!

here: only absolute values considered
If $\bar{\theta}$-term tests fail, then effective BSM dim. 6 sources

$\approx d_p + d_n$

$\approx d_n$

$d_D > d_p + d_n$

$d_{3He} > d_n$

$g_{0}, g_{1}$ 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

\[ d_D \approx d_p + d_n \]
\[ d_{3\text{He}} \approx d_n \]

\[ d_D > d_p + d_n \]
\[ d_{3\text{He}} > d_n \]

\[ d_D \sim d_p + d_n \]
\[ d_{3\text{He}} \sim d_n \]

\[ \to g_1 \gg g_0; \quad 3\pi\text{-coupling (unsuppressed in } ^3\text{He)} \]

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)

\[ q\text{EDM} \quad q\text{CEDM} \quad 4q\text{LR} \quad g\text{CEDM} + 4q\text{EDM} \]

\[
\begin{align*}
d_D & \approx d_p + d_n \\
d_{\text{He}}^3 & \approx d_n \\
d_D & > d_p + d_n \\
d_{\text{He}}^3 & > d_n \\
d_D & > d_p + d_n \\
d_{\text{He}}^3 & > d_n \\
d_D & \sim d_p + d_n \\
d_{\text{He}}^3 & \sim d_n
\end{align*}
\]

\[ \longrightarrow g_1, \; g_0, \; 4N \; - \; \text{coupling on the same footing} \]

2N contribution difficult to assess!

here: only absolute values considered
Conclusions

- 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 $\mathcal{CP}$

- EDM measurements are characteristically of low-energy nature:
  - non-leptonic predictions have to be in the language of hadrons
  - only reliable methods: ChPT/EFT and Lattice QCD because of their inherent & systematical uncertainty estimates

- EDMs of light nuclei provide independent information to nucleon ones and may be even larger and, moreover, even simpler

- Deuteron & helion work as independent isospin filters of EDMs

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, and Jordy de Vries

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

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


