EDM Complementarity and the Inter-frontier Interface

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CERN EDM Workshop, Geneva, March 2018
Goals for This Talk

• Illustrate the interplay of EDM searches with baryogenesis and collider searches

• Illustrate the complementarity of EDM searches on different systems

• Put the opportunities for a proton EDM search in a broader context
Outline

I. EDM Interpretation: The SM & BSM context
II. The Cosmic Matter-Antimatter Asymmetry
III. The Higgs Boson & Top Quark Portals
IV. EDM Complementarity: Model Independent
V. Outlook
I. Interpretation: The SM & BSM Context
EDMs & SM Physics

\[ d_n^{SM} \sim (10^{-16} \, \text{e cm}) \times \theta_{QCD} + d_n^{CKM} \]
EDMs & SM Physics

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\[ d_n^{CKM} = (1 - 6) \times 10^{-32}\ e\ cm \]

C. Seng arXiv: 1411.1476
EDMs & SM Physics

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\[ d_n^{CKM} = (1 - 6) \times 10^{-32} \text{ e cm}^* \]

* 3.3 x 10^{-33} \text{ e cm} < d_p < 3.3 \times 10^{-32} \text{ e cm}

C. Seng arXiv: 1411.1476
EDMs & BSM Physics

\[ d \sim (10^{-16} \text{ e cm}) \times \left( \frac{\nu}{\Lambda} \right)^2 \times \sin \phi \times y_f F \]
EDMs & BSM Physics

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CPV Phase: large enough for baryogenesis?
EDMs & BSM Physics

\[ d \sim (10^{-16} \text{ e cm}) \times \left( \frac{\nu}{\Lambda} \right)^2 \times \sin\phi \times y_f F \]

BSM mass scale: TeV ? Much higher ?
EDMs & BSM Physics

\[ d \sim (10^{-16} \text{ e cm}) \times \left(\frac{\nu}{\Lambda}\right)^2 \times \sin\phi \times y_f F \]

BSM dynamics: perturbative? Strongly coupled? Dependence on other parameters?
EDMs & BSM Physics

\[ d \sim (10^{-16} \text{ e cm}) \times \left(\frac{\nu}{\Lambda}\right)^2 \times \sin\phi \times y_f F \]

Need information from at least three “frontiers”
EDMs & BSM Physics

\[ d \sim (10^{-16} \, \text{e cm}) \times \left( \frac{\nu}{\Lambda} \right)^2 \times \sin \phi \times y_f F \]

Need information from at least three “frontiers”

- Baryon asymmetry  
  Cosmic Frontier
- High energy collisions  
  Energy Frontier
- EDMs  
  Intensity Frontier
II. The Matter-Antimatter Asymmetry
Baryogenesis Scenarios

Energy Scale (GeV)

$10^{12}$

$10^9$

$10^2$

$10^{-1}$

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- Standard thermal lepto
- Affleck Dine
- Electroweak, resonant lepto, WIMPY baryo, ARS lepto...
- Post-sphaleron, cold…
Baryogenesis Scenarios

Era of EWSB: \( t_{\text{univ}} \sim 10 \text{ ps} \)
Electroweak Baryogenesis

Was $Y_B$ generated in conjunction with electroweak symmetry-breaking?
EWBG: MSSM & Beyond

- **Strong first order EWPT:** LHC → Excluded for the MSSM → Possible w/ extensions (e.g., NMSSM)

- **CPV:** Sources same as in MSSM + possible additional
**EDMs & EWBG: MSSM & Beyond**

Heavy sfermions: LHC consistent & suppress 1-loop EDMs

Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases
EDMs & EWBG: MSSM & Beyond

Heavy sfermions: LHC consistent & suppress 1-loop EDMs

Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU

Next gen $d_n$

$d_n = 10^{-27}$ e cm

$d_n = 10^{-28}$ e cm

$d_n = 10^{-29}$ e cm

$\text{Li, Profumo, RM '09-'10}$
**EDMs & EWBG: MSSM & Beyond**

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EDMs & EWBG: MSSM & Beyond

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Next gen $d_n = 10^{-28} \text{ e cm}$

PROTON EDM: SIMILAR TO NEUTRON FOR GIVEN EXPT’L SENSITIVITY

$Li, \text{ Profumo, RM ‘09-’10}$

$Compressed \text{ spectrum}$

$Next \text{ gen} \ d_e$

$ACME: \text{ ThO}$

$d_e = 10^{-28} \text{ e cm}$

$d_e = 10^{-29} \text{ e cm}$
Two-Step EW Baryogenesis

St’d Model Scalar Sector: $H_j$

BSM Scalar Sector: at least one SU(2)$_L$ non-singlet plus possibly gauge singlets: “partially secluded sector CPV”

Conventional one step EWSB

Two step EWSB

BSM CPV in $\phi H$ interactions: baryogenesis during step 1

Inoue, Ovanesyan, R-M: 1508.05404; Patel & R-M: 1212.5652; Blinov, Kozaczuk, Morrissey: 1504.05195
Two-Step EW Baryogenesis

Illustrative Model:

New sector: “Real Triplet” $\Sigma$
Gauge singlet $S$

$H \rightarrow$ Set of “SM” fields: 2 HDM

(SUSY: “TNMSSM”, Coriano…)

Two CPV Phases:

$\delta_{\Sigma}$ : Triplet phase
$\delta_{S}$ : Singlet phase

Inoue, Ovanesyan, R-M: 1508.05404
Two-Step EW Baryogenesis & EDMs

EDMs are Two Loop

Two CPV Phases:

\[ \delta_\Sigma : \text{Triplet phase} \]

\[ \delta_S : \text{Singlet phase} \]

Insensitive to \( \delta_S \): electrically neutral → “partially secluded”

Inoue, Ovanesyan, R-M: 1508.05404
Two-Step EW Baryogenesis

Two cases: (A) $\delta_S = 0$ (B) $\delta_\Sigma = 0$

Inoue, Ovanesyan, R-M: 1508.05404
CPV for EWBG
III. Portals: The BSM Mass Scale & CP
The Higgs Portal
What is the CP Nature of the Higgs Boson?

- Interesting possibilities if part of an extended scalar sector

- Two Higgs doublets?

\[ H \rightarrow H_1, H_2 \]

- New parameters:

  \[ \tan \beta = \frac{<H_1>}{<H_2>} \]
  \[ \sin \alpha_b \]
What is the CP Nature of the Higgs Boson?

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• New parameters:

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  \[ \sin \alpha_b \]

  CPV: scalar-pseudoscalar mixing from \( V(H_1, H_2) \)
work, only the scalar loop could contribute to $C_{12}$ and eventually to EDMs. A representative diagram is shown in the right panel of Fig. 12. It is proportional to $\text{Im}(\bar{v}_1 v_2) = 5 m_{H^\pm}^2 / v^2 \sin 2\beta$.

Using the relation in Eq. (13), the above quantity is indeed related to the unique CPV source in the model. The fermionic loops do not contribute because the physical charge Higgs and quark couplings have the structure proportional to the corresponding CKM element. As a result, the coefficients $C_{ij}$ are purely real and $\tilde{C}_{ij}$ are purely imaginary. They contribute to magnetic dipole moments instead of EDMs.

\[
H^0 / H^+ \\
W^\pm \\
\gamma
\]

\[f \rightarrow f' \rightarrow f\]
Higgs Portal CPV: EDMs

CPV & 2HDM: Type II illustration

$\lambda_{6,7} = 0$ for simplicity

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Figure 10: Current and prospective future constraints from electron EDM (blue), neutron EDM (green), Mercury EDM (red) and Radium (yellow) in flavor conserving 2HDMs.

First row: Type I model; Second row: Type-II model. The model parameters used are the same as Fig. 6. Central values of the hadronic and nuclear matrix elements are used.

Left: Combined current limits.

Middle: combined future limits if the Mercury and neutron EDMs are both improved by one order of magnitude. Also shown are the future constraints if electron EDM is improved by another order of magnitude (in blue dashed curves).

Right: combined future limits if the Mercury and neutron EDMs are improved by one and two orders of magnitude, respectively.

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matrix elements, there is guidance from naïve dimensional analysis, which takes into account the chiral structures of the operators in question. However, the precise value of matrix elements involving quark CEDMs and the Weinberg three-gluon operator are only known to about an order of magnitude, and dimensional analysis does not tell us the signs of the matrix elements. We highlight two places where these uncertainties can change our results.

- In Figs. 7 and 8, we see that the Weinberg three-gluon operator is always subdominant as a contribution to the neutron and mercury EDMs. It is possible, though, that the actual matrix element may be an order of magnitude larger than the current best value. Then, the Weinberg operator would make the largest contribution to the neutron and mercury EDMs at large $\tan \beta$ in the type-II model.

- In the left panel of Fig. 7, the quark EDM and CEDM contributions to $n$EDM in the type-I model are shown to be nearly equal, but with opposite signs, suppressing the total neutron EDM in the type-I model. If overall sign of the CEDM matrix element is opposite to that used here, the two effects would add constructively, making the neutron EDM limit much stronger.

In the absence of hadronic and nuclear matrix element uncertainties, improvements in neutron and diamagnetic atom searches will make them competitive with present ThO result when in constraining CPV in 2HDM. At present, however, theoretical uncertainties are significant, making it difficult to draw firm quantitative conclusions regarding the impact of the present and prospective neutron and diamagnetic EDM results.

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Present:

$\sin \alpha_b$: CPV scalar mixing

Future:

- $d_n \times 0.1$
- $d_{A(Hg)} \times 0.1$
- $d_{ThO} \times 0.1$
- $d_{A(Ra)} [10^{-27} \text{ e cm}]$

Future:

- $d_n \times 0.01$
- $d_{A(Hg)} \times 0.1$
- $d_{ThO} \times 0.1$
- $d_{A(Ra)}$

Inoue, R-M, Zhang: 1403.4257
Higgs Portal CPV: EDMs

CPV & 2HDM: Type II illustration

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Inoue, R-M, Zhang: 1403.4257
Higgs Portal CPV: EDMs & LHC

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- \( \sin \alpha_b : CPV \)
- scalar mixing

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Chen, Lewis, Dawson: 1503.01114

Inoue, R-M, Zhang: 1403.4257
Higgs Portal CPV: EDMs & LHC

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Inoue, R-M, Zhang: 1403.4257

Chen, Li, R-M: 1708.00435
**Higgs Portal CPV: EDMs & LHC**

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**Uncertainties in Matrix Elements:**

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**Chen, Li, R-M: 1708.00435**

**Inoue, R-M, Zhang: 1403.4257**
The Top Quark Portal
CPV Top Quark Interactions?

• 3rd generation quarks often have a special role in BSM scenarios, given $m_t \gg$ all other $m_f$

• If BSM CPV exists, $d_t$ may be enhanced

• Top EDMs difficult to probe experimentally

• Light fermion EDMs to the rescue!
CPV Top Quark Interactions?

Cordero-Cid et al ’08, Kamenik et al ‘12, Cirigliano et al ‘16, Fuyuto & MRM in 1706.08548

Model-indep: independent SU(2)_L & U(1)_Y dipole operators: C_{tB}, C_{tW} →

Tree level d_t & loop level d_e , d_{light q}

Induced d_e , d_{light quark}  

Fuyuto & MRM ‘17
IV. Complementarity: Model Independent
Why Multiple Systems?

Multiple sources & multiple scales
Paramagnetic Systems: Two Sources

Electron EDM

(Scalar q) x (PS e⁻)

Tl, YbF, ThO…
Paramagnetic Systems: Two Sources

Electron EDM

(Scalar q) x (PS e⁻)

Tl, YbF, ThO…
Paramagnetic Systems: Two Sources

Electron EDM

(Scalar q) x (PS e⁻)

\[ \Lambda \gtrsim (1.5 \text{ TeV}) \times \sqrt{\sin \phi_{\text{CPV}}} \quad \text{Electron EDM (global)} \]

\[ \Lambda \gtrsim (1300 \text{ TeV}) \times \sqrt{\sin \phi_{\text{CPV}}} \quad C_S \text{ (global)} \]

TL, YbF, ThO…
Paramagnetic Systems: Two Sources

Electron EDM

(Scalar q) x (PS e⁻)

TL, YbF, ThO...

\[ \Lambda \gtrsim (1.5 \text{ TeV}) \times \sqrt{\sin \phi_{\text{CPV}}} \quad \text{Electron EDM (global)} \]

\[ \Lambda \gtrsim (1300 \text{ TeV}) \times \sqrt{\sin \phi_{\text{CPV}}} \quad C_S \text{ (global)} \]

LHC inaccessible

Chupp & R-M: 1407.1064
**Paramagnetic Systems: Two Sources**

Electron EDM

(Scalar q) x (PS e⁻)

Chupp, Fierlinger, R-M, Singh 1710.02504; Fleig & Jung 1802.02171

Inclusion of HfF⁺: ~ 6 times stronger bounds on \( d_e \) & \( C_S \) \( \rightarrow \) 2.5 higher on \( \Lambda \)

Tl, YbF, ThO, HfF⁺
Illustrative Example: Leptoquark Model

(3, 2, 7/6)

\[ \mathcal{L} \equiv -\lambda_u^{ab} \bar{u}_R^a X^T \ell L^b - \lambda_e^{ab} \bar{e}_R^a X^\dagger Q^b + \text{h.c.} \]
Illustrative Example: Leptoquark Model

Electron EDM

$e^- \gamma e^- N e^- e^- gamma$

Fuyuto, R-M, Shen 1804.XXXX

$\mathcal{L} \equiv -\lambda_{u}^{ab} \bar{u}_{R} X^{T} L^{b} - \lambda_{e}^{ab} \bar{e}_{R} X^{\dagger} Q^{b} + h.c.$
Diamagnetic Systems: LR Sym Model
**TVPV Hadronic & Nuclear Interactions**

\[
\mathcal{L}_{N\pi}^{PTPV} = -2\bar{N} \left( \bar{d}_0 + \bar{d}_1 \tau_3 \right) S_\mu N \nu \bar{v} F^{\mu\nu} + \bar{N} \left[ \bar{g}_\pi^{(0)} \tau \cdot \pi + \bar{g}_\pi^{(1)} \pi_0 \pi + \bar{g}_\pi^{(2)} \left( 3\tau_3 \pi_0 - \tau \cdot \pi \right) \right] N
\]

\[
+ \bar{C}_1 \bar{N} N \partial_\mu \left( \bar{N} S^\mu N \right) + \bar{C}_2 \bar{N} \tau N \partial_\mu \left( \bar{N} S^\mu \tau N \right) + \cdots
\]

\( I = 0, 1, 2 \)

**PVTV \( \pi N \)** interaction

Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)
Left-Right Symmetric Model

Four quark operator:

\[ \frac{\text{Im} C_{\varphi ud}}{\Lambda^2} = \frac{2\sqrt{2}}{3} G_F K^{(-)} \sin \xi \text{ Im} \left( e^{-i\alpha} V_{uq}^L V_{uq}^{R*} \right) \]

\[ \bar{g}_{\pi}^{(1)} \approx -10^{-4} \left( 1 - \frac{M_1^2}{M_2^2} \right) \sin \xi \cos \theta_L \cos \theta_R \sin \alpha. \]
**Left-Right Symmetric Model**

Four quark operator:

\[ d_L u_L W^+ u_R d_R \]

\[
\tilde{g}_{\pi}^{(1)} \approx -10^{-4} \left(1 - \frac{M_1^2}{M_2^2}\right) \sin \xi \cos \theta_L \cos \theta_R \sin \alpha.
\]

\[
|d_A(^{199}\text{Hg})| \lesssim (1.1 \times 10^{-11}\text{ e fm}) \left(1 - \frac{M_1^2}{M_2^2}\right) \cos \theta_L \cos \theta_R \sin \alpha
\]

Caveat: large nuclear theory uncertainty!
Left-Right Symmetric Model

Four quark operator:

\[ \bar{g}^{(1)}_\pi \approx -10^{-4} \left( 1 - \frac{M_1^2}{M_2^2} \right) \sin \xi \cos \theta_L \cos \theta_R \sin \alpha. \]

\[
\begin{align*}
 d_n &= \bar{d}_n - \frac{eg_A}{4\pi^2F_\pi} \left\{ \bar{g}^{(0)}_\pi \left( \ln \frac{m_N^2}{m_N^2} - \frac{\pi m_\pi}{2m_N} \right) \\
 &+ \frac{\bar{g}^{(1)}_\pi}{4} (\kappa_1 - \kappa_0) \frac{m_\pi^2}{m_N^2} \ln \frac{m_\pi^2}{m_N^2} \right\}, \\
 d_p &= \bar{d}_p + \frac{eg_A}{4\pi^2F_\pi} \left\{ \bar{g}^{(0)}_\pi \left( \ln \frac{m_N^2}{m_N^2} - \frac{2\pi m_\pi}{m_N} \right) \\
 &- \frac{\bar{g}^{(1)}_\pi}{4} \left[ \frac{2\pi m_\pi}{m_N} + \left( \frac{5}{2} + \kappa_0 + \kappa_1 \right) \frac{m_\pi^2}{m_N^2} \ln \frac{m_\pi^2}{m_N^2} \right] \right\},
\end{align*}
\]

C. Seng et al 1401.1046
Left-Right Symmetric Model

Four quark operator:

\[
\mathcal{L} = d_L^d L W^+ u_R^u R + \phi \phi C.
\]

C. Seng et al 1401.1046
IV. Outlook

• Searches for permanent EDMs of atoms, molecules, hadrons and nuclei provide powerful probes of BSM physics at the TeV scale and above and constitute important tests of weak scale baryogenesis

• Studies on complementary systems is essential for first finding and then disentangling new CPV

• There exists a rich interplay between EDM searches and the quest to discover BSM physics at the Energy and Cosmic frontiers

• Exciting opportunities exist for a proton EDM search with sensitivity of $d_p \sim 10^{-29}$ e cm
Back Up Slides
Higgs Portal CPV

CPV & 2HDM: Type I & II

$$V = \frac{\lambda_1}{2}(\phi_1^+\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^+\phi_2)^2 + \lambda_3(\phi_1^+\phi_1)(\phi_2^+\phi_2) + \lambda_4(\phi_1^+\phi_2)(\phi_2^+\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^+\phi_2)^2 + \text{h.c.}\right] - \frac{1}{2}\left\{m_{11}^2(\phi_1^+\phi_1) + \left[m_{12}^2(\phi_1^+\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^+\phi_2)\right\}.$$ 

$$\delta_1 = \text{Arg}\left[\lambda_5^*(m_{12}^2)^2\right],$$

$$\delta_2 = \text{Arg}\left[\lambda_5^*(m_{12}^2)v_1v_2^*\right]$$ 

$\delta_2 \approx \frac{1 - \left|\frac{\lambda_5v_1v_2}{m_{12}^2}\right|}{1 - 2\left|\frac{\lambda_5v_1v_2}{m_{12}^2}\right|}\delta_1$

$h, H^0, A^0 \rightarrow h_{1,2,3}$

$$\begin{pmatrix}
-s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_\alpha \\ s_\alpha s_{\alpha_b} c_{\alpha_c} - c_\alpha s_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\ s_\alpha s_{\alpha_b} s_{\alpha_c} + c_\alpha c_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} s_{\alpha_c}
\end{pmatrix}$$

$\lambda_{6,7} = 0$ for simplicity

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**Higgs Portal CPV**

**CPV & 2HDM: Type I & II**

$$V = \frac{\lambda_1}{2}(\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger \phi_2)^2 + \lambda_3(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4(\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \frac{1}{2} \left[ \lambda_5(\phi_1^\dagger \phi_2)^2 + \text{h.c.} \right]$$

$$- \frac{1}{2} \left\{ m_{11}^2(\phi_1^\dagger \phi_1) + [m_{12}^2(\phi_1^\dagger \phi_2) + \text{h.c.}] + m_{22}^2(\phi_2^\dagger \phi_2) \right\}.$$  

$$\delta_1 = \text{Arg} \left[ \lambda_5^* (m_{12}^2)^2 \right],$$  

$$\delta_2 = \text{Arg} \left[ \lambda_5^* (m_{12}^2) v_1 v_2^* \right].$$

**EWSB**

$$\delta_2 \approx \frac{1 - \left| \frac{\lambda_5 v_1 v_2}{m_{12}} \right|}{1 - 2 \left| \frac{\lambda_5 v_1 v_2}{m_{12}} \right|} \delta_1$$

**h, H^0, A^0 \to h_{1,2,3}**

**CP mixing: \( \alpha_b \) & \( \alpha_c \) not independent**
Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

$\lambda_{6,7} = 0$ for simplicity

$\sin \alpha_b$: CPV scalar mixing

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Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

$\lambda_{6,7} = 0$ for simplicity

Present

$\sin \alpha_b :$ CPV scalar mixing

Challenge

$\sin \alpha_b :$ CPV scalar mixing

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EDMs generally arise at one-loop order and may entail strongly interacting virtual particles, we may translate the "single-source" assumption. Similarly, for the dimensionless, isoscalar quark chromo-EDM, the $\bar{a}$ constraint considerably weaker than the order $10^{-4}$, as shown in Fig. 1, that narrowing the experimental bounds imply, owing, in the latter case, to the constraints from chiral symmetry as discussed in Ref. [1].

From a theoretical perspective, it is interesting to consider the theoretical implications of the present and prospective improvement of up to two orders of magnitude for the neutron-EDM [21–26].

We note, however that given the considerable uncertainty in the hadronic matrix element computation these bounds may be considerably weaker than under the "single-source" assumption. For example, from the limit on $\bar{a}$ in Table I and the "reasonable" global analysis results. Perhaps, not surprisingly, the resulting constraints on various underlying CPV sources are tighter. Similarly, a result in an octupole-deformed system, for example with a cooled molecular beam [45] or another molecule will, of course, enhance the prospects.

For example, ThO provides such a tight correlation of degree of freedom and over-constrain the the set of parameters that tightening the bounds. Similarly, a result in an octupole-deformed system, $\text{Xe}$ (not octupole-deformed) would again make the one-loop assumption for illustrative purposes, taking into account, as well as on $\text{Hg}$ EDM under $\text{Ra} [29]$ and $\text{Rn} / \text{Fr}$.

Some scenarios for improved experimental sensitivity and their impact are presented in Table VIII. In the first line of one or more experiments with the improved sensitivity noted in the third column, assuming a central value of zero. We summarize the current upper limits on the parameters at the 95% CL. The remainder of the table lists the impact of one or more experiments with the improved sensitivity noted in the third column, assuming a central value of zero.

From Eq. (IV.40) into a range on the BSM mass scale $\tau^2 < 10^6$. Plan to develop storage-ring experiments to measure the EDMs of the proton and light nuclei would improve of experimental bounds in systems with current results.

Table VIII

<table>
<thead>
<tr>
<th>Source</th>
<th>$CT \times 10^7$</th>
<th>$\bar{g}_\pi^{(0)}$</th>
<th>$\bar{g}_\pi^{(1)}$</th>
<th>$\bar{a}_n$ (e-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exact solution</td>
<td>1.265</td>
<td>$-6.687 \times 10^{-10}$</td>
<td>$1.4308 \times 10^{-10}$</td>
<td>$9.878 \times 10^{-24}$</td>
</tr>
<tr>
<td>Range from best values of $\alpha_{ij}$</td>
<td>$(-7.6 - 9.5)$</td>
<td>$(-5.0 - 4.0) \times 10^{-9}$</td>
<td>$(-0.2 - 0.4) \times 10^{-9}$</td>
<td>$(-5.9 - 7.4) \times 10^{-23}$</td>
</tr>
<tr>
<td>Range from best values</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with $\alpha_{q_1} (\text{Hg}) = -4.9 \times 10^{-17}$</td>
<td>$(-7.6 - 8.4)$</td>
<td>$(-7.0 - 4.0) \times 10^{-9}$</td>
<td>$(0 - 0.2) \times 10^{-9}$</td>
<td>$(5.9 - 10.4) \times 10^{-23}$</td>
</tr>
<tr>
<td>Range from best values</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with $\alpha_{q_1} (\text{Hg}) = +1.6 \times 10^{-17}$</td>
<td>$(-9.2 - 12.4)$</td>
<td>$(-4.0 - 4.0) \times 10^{-9}$</td>
<td>$(0.4 - 0.8) \times 10^{-9}$</td>
<td>$(5.9 - 5.9) \times 10^{-23}$</td>
</tr>
<tr>
<td>Range from full variation of $\alpha_{ij}$</td>
<td>$(-10.8 - 15.6)$</td>
<td>$(-10.0 - 8.1) \times 10^{-9}$</td>
<td>$(-0.6 - 1.2) \times 10^{-9}$</td>
<td>$(12.0 - 14.8) \times 10^{-23}$</td>
</tr>
</tbody>
</table>

Isoscalar CEDM

$\delta_q^{(+)} \left( \frac{\nu}{\Lambda} \right)^2 \lesssim 0.01 \quad \Lambda \gtrsim (2 \text{ TeV}) \times \sqrt{\sin \phi_{\text{CPV}}}$

Caveat: Large hadronic uncertainty

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