EDMs and bounds on new physics

Martin Jung
Motivation

Quark-flavour and CP violation in the SM:

- CKM describes flavour and CP violation
- Extremely constraining, one phase
- Especially, $K$ and $B$ physics agree
- Only tensions so far ($R_K, K^*, P_5', B \rightarrow D^{(*)}\tau\nu, g_\mu - 2, \ldots$)
- Works well!
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Works too well!

We expect new physics (ideally at the (few-)TeV scale):

- Baryon asymmetry of the universe
- Hierarchy problem
- Dark matter and energy
- ...

So where is it?
The Quest for New Physics

Three of the main strategies (missing are e.g. $\nu$, DM, astro,...):

**Direct search:**
- Tevatron, LHC
- Maximal energy fixed

**Indirect search, flavour violating:**
- LHCb, Belle II, BES III, NA62, MEG, ...
- Maximal reach flexible

**Indirect search, flavour diagonal:**
- EDM experiments, g-2, ...
- Maximal reach flexible, complementary to flavour-violating searches

A new era in particle physics!
The curious case of the One-Higgs-Doublet Model

EDMs are finite in the SM... 
... but flavour-sector of the SM is special (→):

- Unique connection between Flavour- and CP-violation
- FCNCs highly suppressed, $\sim \Delta m^2 / M_W^2$
  $\Delta m^2 / M_W^2 \sim 10^{-25}$ for $\nu$ in the loop!
- FConserving NCs with CPV as well:
  $d_e^{SM} \lesssim 10^{-38}$ e cm [Khriplovich/Pospelov '91]

EDMs are quasi-nulltests of the SM!

NP models typically do not exhibit such strong cancellations

- Background-free precision-laboratories for NP
  (assuming dynamical solution for strong CP)
- EDMs $\sim CPV / \Lambda^2$ (interference with SM, e.g. LFV $\sim 1/\Lambda^4$)

Here: focus as much as possible on model-independent statements
Back to basics: EDMs

Classically: \( d = \int d^3 r \rho(r) r, \quad U = d \cdot E \)

QM: non-degenerate ground state implies \( d \sim j \)

\( d \neq 0 \) implies T- and P-violation!

CP-violation for conserved CPT

Search for linear shift \( U = d j \cdot E \)

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Non-relativistic neutral system of point-like particles:
Potential EDMs of constituents are shielded! [Schiff'63]

- Sensitivity stems from violations of the assumptions
  - Paramagnetic systems: relativistic enhancement
  - Diamagnetic systems: finite-size effects

Shielding can be reversed, e.g. \( d_A^{\text{para}} \sim \mathcal{O}(100) \times d_e \)!

[Sandars'65,'66]
Sakharov’s conditions (’67):
NP models necessarily involve new sources of CPV!

- This does not imply sizable EDMs
- However, typically (too) large EDMs in NP models
  - Generic one-loop contributions excluded
  (→ SUSY CP-problem)
  - EDMs test combination of flavour- and CPV-structure

EDMs important on two levels:
- “Smoking-gun-level”: Visible EDMs proof for NP
- Quantitative level:
  Setting limits/determining parameters
  - Theory uncertainties are important!
Flavour anomalies and EDMs

\[ b \rightarrow c\tau\nu \] [Murgui+’19]

\[ b \rightarrow s\ell^+\ell^- \] [Algueró+’19]

- Presently \( \sim 3\sigma \) and \( \sim 5\sigma \) from SM predictions
- No indication of CPV
  - Why is this relevant for EDMs?
  - Both imply lepton-flavour-non-universality (LFNU)!
  - Often implicitly assumed in NP scenarios (at least in the past)
  - Decouples \( e, \mu, \tau \) EDMs, no scaling with masses
  - Increased importance of explicit \( \mu, \tau \)-EDM measurements!
Experimental approaches [K. Jungmann’13 in Annalen der Physik]

Lines of attack towards an EDM

- Free Particles
  - neutron
  - muon
  - proton
  - deuteron
  - bare nuclei?
  - particle EDM
  - unique information
  - new insights
  - new techniques

- Atoms
  - Hg
  - Xe
  - Tl
  - Cs
  - Rb
  - Ra
  - Rn
  - Fr
  - ... (electron EDM enhancements)

- Molecules
  - YbF
  - PbO
  - PbF, ThO
  - Hff, ThF
  - WN, WC, ...

- Condensed State
  - garnets
    - (Gd₃Ga₅O₁₂, Gd₃Fe₂Fe₂O₁₂)
  - solid He?
  - liquid Xe

- systematics

- challenging technology

- electron EDM
  - strong enhancements
  - new techniques

- poor spectroscopic data
Experimental status [see talk by P. Schmidt-Wellenburg]

Neutron EDM:

- $|d_n| \leq 3.6 \times 10^{-26} \text{e cm} \ (95\% \text{CL})$ [Pendlebury+'15,Baker+'06]
- Worldwide effort aiming at $(10 \rightarrow 0.1) \times 10^{-27} \text{e cm}$
- UCN sources critical problem [P.Schmidt-Wellenburg’16]

Paramagnetic systems:

- Atomic: $|d_{\text{Tl}}| \leq 9.6 \times 10^{-25} \text{e cm} \ (95\% \text{ CL})$ [Regan+'02]
- Molecular: $|\omega_{\text{ThO}}| \leq 1.1 \text{ mrad/s} \ (95\% \text{ CL})$ [ACME’18]
- Ionic: $\text{HfF}^+, |\omega_{\text{HfF}}| \leq 7.9 \text{ mrad/s} \ (90\% \text{ CL})$ [Cairncross+'17]

Diamagnetic systems:

- $|d_{\text{Hg}}| \leq 7.4 \times 10^{-30} \text{e cm} \ (95\% \text{ CL})$ [Graner+'16]
- Ongoing: Xe, Hg, exploit octupole deformation, e.g. Ra, Rn, . . .

Solid state systems: $|d_e| \leq 6.1 \times 10^{-24} - 25 \text{e cm}$ [Eckel+'12,Kim+'15]

Storage rings: $|d_\mu| \leq 1.9 \times 10^{-19} \text{e cm}$ [Bennett+'08]

Collider: $|d_\tau| \leq 3.4 \times 10^{-17} \text{e cm}$ [Belle’03]
Relating NP parameters and experiment

- Most stringent constraints from neutron, atoms and molecules
  - Shielding typically applies

  Atomic level
  ↓
  Nuclear Level
  ↓
  Hadronic level
  ↓
  Effective Theory with (C)EDMs of fermions, $O_W, \ldots$
  ↓
  Parameters of your favourite NP model

- Each step potentially involves large uncertainties!
- 4/5 model-independent $\Rightarrow$ series of EFTs [e.g. deVries+’11]
- Limits usually displayed as allowed regions
  - Conservative uncertainty estimates important
Schematic EFT framework [Pospelov/Ritz'05, Hoecker'12]

- **Energy**
  - TeV
  - QCD

- **Fundamental CP-odd source**
  - $d_\theta, d_\mu, d_\tau$
  - $C_{q\theta}, C_{qq}$
  - $\theta, d_q, \bar{d}_q, w$

- **Muon EDM**
  - $d_e$
  - $C_{SP,T}$
  - Muon EDM bound: $< 1.9 \times 10^{-19}$

- **EDMs of paramagnetic atoms (Tl, Rb, Cs) and molecules (YbF, PbO, HfF*)**
  - Best bound: $10.5 \times 10^{-28}$ (YbF)

- **EDMs of diamagnetic atoms (Hg, Xe, Ra, Rn)**
  - Best bound: $2 \times 10^{-28}$ ($^{199}$Hg)

- **Neutron & proton EDM**
  - $d_n < 2.9 \times 10^{-26}$

- **Solid states EDMs**
  - Tilt, Rb, Cs, etc.
The EDM in heavy paramagnetic systems

Two main contributions, enhanced by $Z^3$: [Sandars’65, Flambaum’76]

- A single measurement does not restrict $d_e$ directly
  - $C_S$: CP-odd electron-nucleon interaction
  - Atoms: typically polarized in external field
  - Molecules: aligned in external field

- Exploit huge internal field

For molecules: energy shift $\Delta E = \hbar \omega$ with

$$\omega_M [\text{mrad/s}] = \alpha^{d_e}_M d_e + \alpha^{C_S}_M C_S.$$

<table>
<thead>
<tr>
<th>Molecule</th>
<th>$\alpha^{d_e}_M / 10^{-27} \text{ ecm}$</th>
<th>$\alpha^{C_S}_M / 10^7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HfF^+$</td>
<td>$34.9 \pm 1.4$</td>
<td>$32.0 \pm 1.3$</td>
</tr>
<tr>
<td>ThO</td>
<td>$120.6 \pm 4.9$</td>
<td>$181.6 \pm 7.3$</td>
</tr>
</tbody>
</table>

[Results entering: Skripnikov’17,Fleig’17,Denis/Fleig’16,Skripnikov’16

Averages: Fleig/MJ’18]
Model-independent extraction of $d_e$ and $C_S$

In principle: two unknowns, three measurements (TI,YbF,ThO)

Extract $d_e$, $C_S$ model-independently [Dzuba et al.’11, MJ’13]

Problem: Aligned constraints

weak limits
Model-independent extraction of $d_e$ and $C_S$

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2017

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- weak limits

Partial resolution: HfF$^+$ result
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Problem: Aligned constraints
- weak limits

Partial resolution: HfF$^+$ result
Mercury bound $\sim$ orthogonal!

Assumption: $C_S$, $d_e$ saturate $d_{\text{Hg}}$
- Conservative

[Fleig,MJ’18]

$$d_e \leq 3.8 \times 10^{-28} \text{e cm}$$

$$C_S \leq 2.7 \times 10^{-8}$$

Yields model-independent limit on every paramagnetic system!
Model-independent extraction of $d_e$ and $C_S$

In principle: two unknowns, three measurements (TI, YbF, ThO)

- Extract $d_e$, $C_S$ model-independently \cite{Dzuba et al.’11, MJ’13}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{chart.png}
\caption{2019}
\end{figure}

Problem: Aligned constraints
- weak limits

Partial resolution: HfF$^+$ result
Mercury bound $\sim$ orthogonal!

Assumption: $C_S$, $d_e$ saturate $d_{Hg}$

- Conservative

\begin{equation*}
\begin{aligned}
d_e &\leq 3.8 \times 10^{-28} \text{ e cm} \\
C_S &\leq 2.7 \times 10^{-8}
\end{aligned}
\end{equation*}

Yields model-independent limit on every paramagnetic system!

Future measurements aim at precision beyond present constraints!
- Help to resolve the alignment problem
- Requires precision measurements of low-Z and high-Z elements
EDMs of diamagnetic systems and nucleons

Situation more complicated than for paramagnetic systems:

- Potential SM contribution: $\bar{\theta}$ (→ strong CP puzzle)
- Contributions from $\bar{\theta}, d_q, \tilde{d}_q, w, C_{S,P,T}, C_{qq}$
  - Interpretation usually model-dependent
    (for model-independent prospects: [Chupp/Ramsey-Musolf'14])

Complementary measurements, different sources possible/likely

- $|d_{Hg}| \leq 7.4 \times 10^{-30} \text{ e cm}$ [Graner et al. '16], very constraining
  Problem: QCD and nuclear theory uncertainties ($\times 00\%$!)
  - No conservative constraint on CEDMs left! [MJ/Pich'13]

- $|d_n| \leq 3.6 \times 10^{-26} \text{ e cm}$ [Pendlebury'15]
  Theory in better shape, still $O(100\%)$ uncertainties
  [Pospelov/Ritz'01, Hisano et al'12, Demir et al'03,'04, de Vries et al'11]

Progress in theory necessary to fully exploit these measurements
Unique: orders-of-magnitude improvement w/o new measurement!
The role of Mercury in determining the electron EDM

Mercury is a diamagnetic system, many contributions

- Why is it shown in the paramagnetic global fit? [MJ'13]
  - Shielding of $C_S$ and $d_e$ effective (even vanishing at LO)
  - Schiff moment contribution expected to be dominant
  - $d_e, C_S$ only a fraction of the total EDM
  - Assuming $d_e, C_S$ to saturate the exp. limit is conservative

New calculation of the $C_S$ coefficient [Fleig/MJ’18]

LO contribution vanishes

- Triple perturbative expansion necessary:
  1. External electric field (here: included in basis set)
  2. Hyperfine splitting
  3. $d_e/C_S$

$$\alpha_{C_S} = -2.8(6) \times 10^{-22} \text{ e cm}$$

$\alpha_{d_e}$ w.i.p., so far old calculation [Martensson-Pendrill/Oster’85] + conservative error estimate
The importance of multiple measurements

Only pattern of CPV observables allows for model-differentiation! ➩ There is no single “best” measurement!

Paramagnetic systems:
- 1 significant measurement NP
- 2 determine ideally $d_e$ and $C_S$
- More for consistency (unless MQM is relevant)

Diamagnetic systems, nucleons/baryons, light nuclei:
- 1 significant measurement: $\bar{\theta}$ possible explanation
- 2 should tell $\bar{\theta}$ from other sources
- Many more to identify model-independently CPV structure

➡️ We need as many measurement as possible!
➡️ Ideally very different systems
➡️ Try to find P-, T-odd measurements besides EDMs
EDMs in NP Models

EDM constraints forbid generic CPV contributions up to two loops
- huge scales or highly specific structure!
  - hardly testable elsewhere
  - simple power-counting insufficient
    (UV sensitivity)
- Model-independent analyses difficult

EDMs unique, both blessing and curse

- some model-independent relations exist, e.g. to $\beta$ decay [Khriplovich’91, see also e.g. Dekens/Vos’15]
- strong (model-dependent) constraints
  of related observables
- Consider models or subsets of model-independent framework
EDMs in sLQ models [Dekens/de Vries/MJ/Vos’18]

Cascade of EFTs:

Example: $R_2$ LQ

Tree-level: semileptonic operators

1-loop (matching + running): Dipole operators are generated

Below $\mu_{EW}$: gluonic operators added

$\mu_{low} \sim 1 \text{ GeV}$: → hadronic operators

- enter EDM calculations
  (→ atomic + nuclear MEs)
- MEs have large uncertainties
Phenomenological consequences

Most observables constrain (mainly) real parts

* EDMs constrain complementarily imaginary parts

Flavour-dependence of constraints

* Vastly different magnitudes
* Most relevant observables differ

* Complementarity of measurements!
Relation to $R(D) - R(D^*)$ flavour anomaly

$R_2$ LQ part of NP model for flavour anomalies: [Bečirević+’18]

- Generates $C_{SL} \sim 4C_T$ ($@ \mu_{LQ}$)
- Explanation of $R(D^{(*)})$ possible, but requires imaginary part
- The same coupling combination yields $(\bar{c}\sigma^{\mu\nu}\gamma_5 c)(\bar{\tau}\sigma_{\mu\nu}\tau)$
  - Generates charm (+ $\tau$) EDMs + Weinberg operator
  - Bounds from neutron + Hg EDMs

2 effects:

1. Weinberg operator: smaller effect (outer line)
2. Charm EDM: depends on charm tensor-current neutron ME 1 calculation [Alexandrou+’17]
  - compatible with 0

Future EDM experiments or lattice can improve this
Conclusions

• EDMs unique tests of NP models
• Model-independent constraints on NP parameters difficult
  ➤ Need (at least) as many experiments as (eff.) parameters
• Quantitative results require close look at theory uncertainties
  ➤ Use conservative limits, allowing for cancellations
  ➤ For e.g. $d_n, d_{\text{Hg}}$ bottleneck! Chance for nuclear theory
• Robust, model-independent limit on electron EDM
  ($C_S$ not model-independently negligible):
  \[ |d_e| \leq 3.9 \times 10^{-28} \text{e cm} \quad (95\% \text{ CL}) \]
• Flavour anomalies killed LFU paradigm
  ➤ Increased importance of $\mu, \tau$ EDM
• EDMs in scalar LQ models
  ➤ Demonstrate this point
  ➤ Every measurement important for at least one coupling!
• Plethora of new results to come
  ➤ Might turn limits into determinations!
Backup slides

- EDM EFT framework
- 2HDM Framework
- Limits on $|d_e|$ and $|C_S|$  
- Expected limits from paramagnetic systems
Effective Lagrangian at a hadronic scale:

\[ \mathcal{L} = - \sum_{f=u,d,e} \left[ \frac{d_f^\gamma}{2} \mathcal{O}_f^\gamma + \frac{d_f^C}{2} \mathcal{O}_f^C \right] + C_W \mathcal{O}_W + \sum_{i,j=(q,l)} C_{ij} \mathcal{O}_{ij}^{4f}, \]

in the operator basis

\[ \mathcal{O}_f^\gamma = ie \bar{\psi}_f F_{\mu\nu} \sigma_{\mu\nu} \gamma_5 \psi_f, \quad \mathcal{O}_f^C = ig_s \bar{\psi}_f G_{\mu\nu} \sigma_{\mu\nu} \gamma_5 \psi_f, \]

\[ \mathcal{O}_W = + \frac{1}{3} f^{abc} G_{\mu\nu}^a \tilde{G}_{\nu, b}^\beta \sigma_{\mu, c} G_{\beta}^\mu, \quad \mathcal{O}_{ij}^{4f} = (\bar{\psi}_i \psi_i)(\bar{\psi}_j \gamma_5 \psi_j) \]

Options for matrix elements:

- Naive dimensional analysis\textsuperscript{[Georgi/Manohar '84]}: only order-of-magnitude estimates
- Baryon \( \chi PT \): not applicable for all the operators
- QCD sum rules: used here \textsuperscript{[Pospelov et al.]} , uncertainties large
Framework for 2HDM contributions

In 2HDMs, CPV in new interactions can generate EDMs!

Parametrization for $H^\pm$ Yukawas, $\varsigma_i$ complex:

$$\mathcal{L}^{H^\pm}_Y = -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[ V \varsigma_d M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L \right] d + \bar{\nu} \varsigma_l M_l \mathcal{P}_R l \right\} + \text{h.c.}$$

- General for coupling matrices $\varsigma_i$ ($M_i$ choice of normalization)
- Numbers $\varsigma_i$: Aligned 2HDM [Pich/Tuzon'09, MJ/Pich/Tuzon'10]
- Easily matched on your favourite model

For mass eigenstates $\varphi^0_i = \{h, H, A\}$, $M^2_{\text{diag}} = \mathcal{R} M^2 \mathcal{R}^T$, we have

$$\mathcal{L}^{\varphi^0_i}_Y = -\frac{1}{v} \sum_{\varphi, f} \varphi^0_i \bar{f} y^0_{f} M_f \mathcal{P}_R f + \text{h.c.},$$

$$y^0_{f} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} \pm i \mathcal{R}_{i3}) \left( \varsigma_{F(f)}^{(*)} \right)_{ff} \quad \text{for} \quad F(f) = d, l(u).$$

For neutrals: additional CPV contributions from the potential!
Why 2HDM?

Model-independent NP analysis: Too many parameters in general

EW symmetry breaking mechanism still not completely fixed:

- 1HDM minimal and elegant, but “unlikely” (SUSY, GUTs, . . .)
- 2HDM “next-to-minimal”:
  - $\rho$-parameter “implies” doublets
  - low-energy limit of more complete NP models
  - Model-independent element
  - simple structure, but interesting phenomenology
  - important effects in flavour observables

- Plethora of 2HDMs:
  - differ in their suppression mechanism for FCNCs

Could explain tensions in the flavour sector (e.g. $B \rightarrow D^{(*)}\tau\nu$)

WARNING

Not an attempt at a complete theory!
Framework for 2HDM contributions

The CPV interactions of the 2nd doublet can generate EDMs

**General parametrization for** $H^\pm$ **Yukawas, $\varsigma_i$ complex matrices:**

$$\mathcal{L}_{H^\pm} = -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[ V \varsigma_d M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L \right] d + \bar{\nu} \varsigma_l M_l \mathcal{P}_R l \right\} + \text{h.c.}$$

- Induce couplings like $W$-exchange, just with a charged Higgs ($M_{H^\pm} \gtrsim m_t$)
- Easily matched on your favourite model
  - $M_i$ only choice of normalization
- $\varsigma_i \rightarrow$ numbers: Aligned 2HDM [Pich/Tuzon'09,MJ/Pich/Tuzon'10]
  - Comparisons with flavour data in this model

Neutral Higgs exchanges: couplings $y_i^0 (\varsigma_i, V)$

- Additional CPV contributions from the potential
- Analysis depends on many unknown parameters
EDMs in 2HDMs

From necessary flavour suppression for a viable model:

- One-loop (C)EDMs: controlled (not tiny) [e.g. Buras et al. '10]
- 4-quark operators small (no $\tan^3 \beta$-enhancement)

Two-loop graphs dominant
[Weinberg '89, Dicus '90, Barr/Zee '90, Gunion/Wyler '90, ...]

- Weinberg diagram important for neutron EDM
- Barr-Zee(-like) diagrams dominate other EDMs

Paramagnetic systems: tree-level can be relevant ($C_S \times Z^3$) (light-quark mass $\times$ tree) vs. (top mass $\times$ two-loop)
Neutral Higgs contributions in general 2HDMs [MJ/Pich’13]

Contributions typically involve the following sum:
(f,f': fermions, F(f): family of the fermion)

\[
\sum_i \operatorname{Re} \left( y_{f_i}^0 \right) \operatorname{Im} \left( y_{f'_{i'}}^0 \right) = \pm \operatorname{Im} \left[ (\varsigma_{F(f)})_{ff'} (\varsigma_{F(f')})_{f'f'} \right]
\]

- R.h.s. independent of the Higgs potential
- Vanishes for equal fermions (universality: equal family)
- Modified by mass-dependent weight factors…
  - but holds for degenerate masses and decoupling limit

CPV in the potential tends to have smaller impact

Approximation for phenomenological analysis:

\[
\sum_i f(M_{\varphi_i^0}) \operatorname{Re} \left( y_{f_i}^0 \right) \operatorname{Im} \left( y_{f'_{i'}}^0 \right) \rightarrow \pm f(M_{\varphi}) \operatorname{Im} \left[ (\varsigma_{F(f)})_{ff'} (\varsigma_{F(f')})_{f'f'} \right].
\]
Bounds from the electron EDM

- Contributions via Barr-Zee diagrams [Bowser-Chao et al.'97]
- Sensitivity to $d_e \sim \text{Im}(\varsigma_{u,33}^* \varsigma_{l,11})$
- Bounds $\text{Im}(\varsigma_u^* \varsigma_l) \lesssim \mathcal{O}(0.05)$
  - Strong despite two-loop suppression and mass factors
- Implies $\text{Im}(\varsigma_l \varsigma_u^*)/M_{H^\pm}^2 \leq \times 10^{-5}\text{GeV}^{-2}$ (universal $\varsigma_i$'s)
  - A factor 1000 stronger than (semi)leptonic constraints!
Bounds from the neutron EDM

- Size of Weinberg (charged) and Barr-Zee (neutral) similar
- So far no fine-tuning necessary
- Next-generation experiments will test critical parameter space
- Constraint from Hg potentially a few times stronger
- Comparison with $b \rightarrow s\gamma$: large impact! [MJ/Pich'14, MJ/Li/Pich'12]
  - EDMs restrict CPV in other modes

![Graph](image.png)
Theory uncertainties and the EDM of Mercury

- Extremely precise atomic EDM limit: 
  \[ |d_{Hg}| \leq 3.1 \times 10^{-29} \text{ e cm} \] [Griffith et al. ’09]
- However: difficult diamagnetic system
  - Shielding efficient \( \rightarrow \) sensitivity \( \sim d_n, d_{Tl} \)

\[
d_{Hg}^{\text{Atomic}} = d_{Hg}(S, C_{S,P}^N) \quad d_{Hg}^{\text{Nuclear}}(\bar{g}_{\pi NN}, C_{S,P}^{p,n}) \\
QCD = d_{Hg}(d_f^C, C_{qq',} C_{S,P}^q)
\]

- Uncertainties:
  Atomic \( \sim 20\% \), Nuclear \( \sim x00\% \), QCD sum rules \( \sim 100 - 200\% \)
  - No conservative constraint on CEDMs left! [MJ/Pich’13]

\[
d_{Hg} = \left\{ -(1.0 \pm 0.2) \left( (1.0 \pm 0.9) \bar{g}_{\pi NN}^{(0)} + 1.1 (1.0 \pm 1.8) \bar{g}_{\pi NN}^{(1)} \right) \\
+ (1.0 \pm 0.1) \times 10^{-5} [-4.7 C_S + 0.49 C_P] \right\} \times 10^{-17} \text{ e cm ,}
\]

Progress in theory necessary to fully exploit precision measurements of diamagnetic EDMs
The EDM of the Neutron

Explicit expressions for the neutron EDM [MJ/Pich’13 (refs therein)]

$$d_n(d_q^\gamma, d_q^C)/e = \left(1.0^{+0.5}_{-0.7}\right) \left[1.4 \left(d_d^\gamma(\mu_h) - 0.25 d_u^\gamma(\mu_h)\right) + 1.1 \left(d_d^C(\mu_h) + 0.5 d_u^C(\mu_h)\right)\right] \frac{\langle \bar{q}q\rangle(\mu_h)}{(225 \text{ MeV})^3},$$

$$|d_n(C_W)/e| = \left(1.0^{+1.0}_{-0.5}\right) 20 \text{ MeV } C_W,$$

$$|d_n(C_{bd})/e| = 2.6 \left(1.0^{+1.0}_{-0.5}\right) \times 10^{-3} \text{ GeV}^2 \left(\frac{C_{bd}(\mu_b)}{m_b(\mu_b)} + 0.75 \frac{C_{db}(\mu_b)}{m_b(\mu_b)}\right).$$
Chances and challenges for nuclear theory

Some more detail:

- Measurements with neutral atoms (now) or ions (future)
- Atomic theory relates $d_A$ to P-, T-odd nuclear moments
  1. Schiff moment: typically dominant in diamagnetic systems
  2. MQM: relevant in paramagnetic systems
  3. EDM: typically shielded, but relevant for ions
- Nuclear theory relates nuclear moments to hadronic operators
  1. EDMs of neutron and proton $d_{n,p}$
  2. CP-violating pion-nucleon interactions $\bar{g}_{\pi NN}$
  3. Four-nucleon contact terms ($C_{4N}$)
- QCD relates hadronic operators to quark-level operators
  - Nuclear theory essential e.g. for world’s best EDM limit (Hg)

**Challenge:** calculate $S, M, d_N(d_{n,p}, \bar{g}_{\pi NN}, C_{4N})$ for $A \sim 200$

Hg: sign of $\bar{g}_{\pi NN}^{(1)}$ unclear $\rightarrow$ no constraint

$S(d_{n,p})$: 1. just $d_n$ 2. shell model $\rightarrow$ $S(d_{n,p})$ 3. can we do better?

Unique chance: orders of magnitude *without a new experiment!* 
Connecting high- and low-energy observables with EFTs

Example from [Cirigliano et al.’16]:
Consider chirality-flipping SMEFT operators with top and Higgs
→ Affect EDMs, Higgs observables, flavour, ...

[Cirigliano+’16]
● CPV dominated by EDMs
● collider observables complementary
→ significant progress expected for both
Turning the argument around

Other limits not relevant to global fit
- Use results to conservatively bound their EDMs

<table>
<thead>
<tr>
<th>System</th>
<th>Indirect bound</th>
<th>Present/Expected limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs</td>
<td>$[-3.1, 2.2]$</td>
<td>1400 [Murthy+’89] /1</td>
</tr>
<tr>
<td>Rb</td>
<td>$[-0.8, 0.5]$</td>
<td>$10^8$ [Ensberg+’67] /0.1</td>
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<tr>
<td></td>
<td>unpublished: (1200) [Huang-Hellinger’87]</td>
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<tr>
<td>Fr</td>
<td>$[-3.2, 4.2]$</td>
<td>—/1</td>
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</tbody>
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Bounds on $|d_X|$ in $10^{-26}$ e cm

- Several orders of magnitude below present limits!

Experiments aiming at even better sensitivity:
- Important progress to be expected
- In case of a violation of the above limits:
  Highly-tuneed cancellations or experimental problem