EDMs and CP Violation (in the LHC Era)

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w/~ D. McKeen, M. Pospelov [1208.4597, 1303.1172, 1311.5537]
w/~ M. Le Dall, M. Pospelov [to appear]

Reviews: M. Pospelov & AR [hep-ph/0504231]
T. Fukuyama [1201.4252]
J. Engel, M. Ramsey-Musolf, U. van Kolck [1303.2371]
CP (or T) Violation in the Standard Model

\[ \sin(\delta_{KM}) \propto \text{Arg Det}[Y_u Y_u^\dagger, Y_d Y_d^\dagger] \]

\[ \sin(\bar{\theta}_{QCD}) \sim \text{Arg Det}[Y_u Y_d] \]

(in a basis where \(\theta_0\) rotated \(\rightarrow 0\))

\(\delta_{KM} \sim \mathcal{O}(1)\)

Explains CP-violation in K and B meson mixing and decays

\(\theta_{QCD} < 10^{-10}!\)

Constrained experimentally (strong CP problem)

Motivations for new CP-odd sources?

- Required for baryogenesis (Sakharov conditions)
- Generic with extra degrees of freedom
EDMs are powerful (amplitude-level) probes for new (T,P) violating sources, motivated e.g. by baryogenesis.

Best current limits from neutrons, para- and dia-magnetic atoms and molecules.

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Negligible SM (CKM) background - contribution is (at least) 4-5 orders of magnitude below the current neutron sensitivity, and lower for the atomic EDMs.
Experimental EDM Limits

- EDMs are powerful (amplitude-level) probes for new (T,P) violating sources, motivated e.g. by baryogenesis.
- Best current limits from neutrons, para- and dia-magnetic atoms and molecules

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Negligible SM (CKM) background - contribution is (at least) 4-5 orders of magnitude below the current neutron sensitivity, and lower for the atomic EDMs
Schematic view of the bounds

\[ \log(\Delta E/\epsilon_{\text{ext}} \ [\text{e cm}]) \]

-22 ThO
-24
-26 n
-28 Hg
-30
-32
-34

Difference of 7 orders of magnitude is very misleading!

Real sensitivity to underlying sources of CP violation, depends on significant enhancement and suppression factors to be discussed shortly...
EDM Sensitivity to (short distance) CP-violation

Fundamental CP phases

- Electron EDM
- Semi-leptonic $qqee$
- $\theta$-term, quark EDMs, CEDMs etc.
- Pion-nucleon $\pi NN$ and NNNN
- Nucleon EDMs ($n,p$)
- EDMs of nuclei and ions (deuteron, etc)
- EDMs of diamagnetic atoms (Hg, Xe, Ra, Rn, ...)
- EDMs of paramagnetic atoms and molecules (Tl, YbF, ThO, HfF$^+$, ...)
- Atoms in traps (Rb, Cs, Fr) solid state

Energy

- TeV
- QCD

Nuclear

Atomic
EDM Sensitivity to (short distance) CP-violation

Fundamental CP phases

- Electron EDM
- Semi-leptonic $\mu$ EDM
- Semi-leptonic $NN_{\mu\mu}$
- EDMs of paramagnetic atoms and molecules ($Tl,YbF, ThO, HfF^+,...$)
  Atoms in traps (Rb,Cs,Fr) solid state

- Pion-nucleon $\tauNN$ and $NNNN$

- EDMs of nuclei and ions (deuteron, etc)

- EDMs of diamagnetic atoms ($Hg,Xe,Ra,Rn,...$)

- $\theta$-term, quark EDMs, CEDMs etc.

- Nucleon EDMs ($n,p$)

Energy

- TeV
- QCD
- Nuclear
- Atomic
Choose to start by parametrizing new (flavor-diagonal) CP-violating new physics with an operator expansion at \( \sim 1 \text{GeV} \)

\[
\mathcal{L}_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}_d^{(n)}
\]

NB: (ii) Basis at \( \sim 1 \text{GeV} \) simpler than EW scale, after integrating out \( W, Z, h \), assuming L-R chirality structure of the Standard Model

(i) *Assumes* new physics is heavier than \( \sim 1 \) GeV

Will return to this later, as empirical evidence for new physics (dark matter, neutrino mass) does not necessarily suggest a particular mass scale...
(Flavor-diagonal) CP-violating operators at $\sim 1\text{GeV}$

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}^{(n)}_d$$

$$\mathcal{L}_{\text{dim} \ 4} \supset \bar{\theta} \alpha_s G \tilde{G}$$

$$\bar{\theta} = \theta_0 - \text{ArgDet}(M_u M_d) \equiv \theta_0 - \theta_q$$
CP-odd operator expansion (at $\sim 1\text{GeV}$)

(Flavor-diagonal) CP-violating operators at $\sim 1\text{GeV}$

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}^{(n)}_d$$

$$\mathcal{L}_{\text{dim 4}} \supset \bar{\theta} \alpha_s G \tilde{G}$$

$$\mathcal{L}^{\text{"dim 6"}} \supset \sum_{q=u,d,s} \left( d_q \bar{q} F \sigma \gamma_5 q + \tilde{d}_q \bar{q} G \sigma \gamma_5 q \right) + \sum_{l=e,\mu} d_l \bar{l} F \sigma \gamma_5 l$$

$$\mathcal{L}_{\text{dim 6}} \supset w g_s^3 G G \tilde{G}$$
(Flavor-diagonal) CP-violating operators at ~1GeV

\[ \mathcal{L}_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}_d^{(n)} \]

\[ \mathcal{L}_{\text{dim} \ 4} \supset \bar{\theta} \alpha_s G \tilde{G} \]

\[ \mathcal{L}^{\text{“dim} \ 6\text{”}} \supset \sum_{q=u,d,s} \left( d_q \bar{q} F \sigma \gamma_5 q + \tilde{d}_q \bar{q} G \sigma \gamma_5 q \right) + \sum_{l=e,\mu} d_l \bar{l} F \sigma \gamma_5 l \]

\[ \mathcal{L}_{\text{dim} \ 6} \supset w g_s^3 G G \tilde{G} + \sum_{f,f',\Gamma} C_{f,f'}^\prime (\bar{f} \Gamma f')_{LL} (\bar{f} \Gamma f')_{RR} \]

Suppressed without new sources of LR mixing
(Flavor-diagonal) CP-violating operators at ∼1GeV

\[ L_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^{d-4}} O^{(n)}_d \]

\[ L_{\text{dim }4} \supset \bar{\theta} \alpha_s G \tilde{G} \]

\[ L^{\text{“dim 6”}} \supset \sum_{q=u,d,s} \left( d_q \bar{q} F \sigma \gamma_5 q + \tilde{d}_q \bar{q} G \sigma \gamma_5 q \right) + \sum_{l=e,\mu} d_l \bar{l} F \sigma \gamma_5 l \]

\[ L_{\text{dim }6} \supset w g_s^3 G G \tilde{G} + \sum_{f,f',\Gamma} C'_{ff'} (f \Gamma f')_{LL} (\bar{f} \Gamma f')_{RR} \]

\[ L^{\text{“dim 8”}} \supset \sum_{q,\Gamma} C_{qq} \bar{q} \Gamma qq \bar{q} \Gamma i \gamma_5 q + C_{qe} \bar{q} \Gamma qe \bar{\Gamma} i \gamma_5 e + \cdots \]

\[ C_{ij} \sim cY_i Y_j \frac{v^2}{\Lambda^4} \]
CP-odd operator expansion (at $\sim 1$GeV)

(Flavor-diagonal) CP-violating operators at $\sim 1$GeV

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}_d^{(n)}$$

$\mathcal{L}_{\text{dim 4}} \supset \bar{\theta} \alpha_s \tilde{G} \tilde{G}$

$\mathcal{L}_{\text{"dim 6"}} \supset \sum_{q=u,d,s} \left( d_q \bar{q} F \sigma \gamma_5 q + \tilde{d}_q \bar{q} G \sigma \gamma_5 q \right) + \sum_{l=e,\mu} d_l \bar{l} F \sigma \gamma_5 l$

$\mathcal{L}_{\text{dim 6}} \supset w g_s^3 G G \tilde{G} + \sum_{f,f',\Gamma} C'_{ff'} (\bar{f} \Gamma f')_{LL} (\bar{f} \Gamma f')_{RR}$

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CP-odd operator expansion (at \(\sim 1\text{GeV}\))

(Flavor-diagonal) CP-violating operators at \(\sim 1\text{GeV}\)

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\)

[Blue arrow pointing to nuclear scales]

\[d_{(n,p)} \bar{N} F \sigma_{5} N + \bar{g}_{\pi N N}^{(1)} \bar{N} \pi^0 N + \bar{g}_{\pi N N}^{(0)} \bar{N} \sigma \cdot \pi N + \cdots
\]

\[d_{e} \bar{e} F \sigma_{5} e + C_S^{(0)} \bar{N} N \bar{e} i \sigma_{5} e + \cdots
\]
EFT hierarchy

Fundamental CP phases

- $d_e$
- $C_{qe}, C_{qq}$
- $\theta, d_q, \tilde{d}_q, w$

Pion-nucleon couplings ($\tilde{g}_{\pi NN}$)

Nucleon EDMs (n,p)

EDMs of nuclei and ions (deuteron, etc)

EDMs of paramagnetic atoms and molecules (Tl, YbF, ThO, HfF+, ...)

Atoms in traps (Rb, Cs, Fr) solid state

EDMs of diamagnetic atoms (Hg, Xe, Ra, Rn, ...)

Energy

- TeV
- QCD

atomic

nuclear
Paramagnetic EDMs - “Schiff enhancement”

**Atoms (e.g. Tl [Berkeley])** [Regan et al '02]

( relativistic violation of Schiff screening which naively implies $d_{\text{neutral atom}}(d_e) = 0$ at the non-rel level)

\[ \alpha^2 Z^3 \vec{E} \] [Salpeter ‘58; Sandars ‘65]

\[ d_{\text{Tl}} \sim -20\alpha^2 Z^3 d_e + \mathcal{O}(C_S) \]

\[ \mathcal{O}(500 - 600) \] for Tl [e.g. Liu & Kelly '92]
Polar molecules (e.g. ThO [Harvard/Yale], YbF [Imperial])
[Baron et al ‘13, Hudson et al ’11]

\[ \Delta E_{\text{ThO}} \sim \mathcal{E}_{\text{eff}}(E_{\text{ext}})d_e + \mathcal{O}(C_S) \]

Nonlinear function of \( E_{\text{ext}} \)

\[ \frac{\Delta E_{\text{ThO}}}{E_{\text{ext}}} \equiv "d_{\text{ThO}}" \sim 10\alpha^2 Z^3 \frac{\mu_{\text{nuc}}}{m_e} d_e + \mathcal{O}(C_S) \]

[Sandars; Sushkov & Flambaum, ’78]
**Paramagnetic EDMs - “Schiff enhancement”**

**Polar molecules (e.g. ThO [Harvard/Yale], YbF [Imperial])**

[Baron et al ‘13, Hudson et al ’11]

\[\Delta E_{\text{ThO}} \sim -84 \text{ GeV} \left( \frac{d_e}{e \text{ cm}} \right) + \mathcal{O}(C_S(C_{qe}))\]

\[\Delta E_{\text{YbF}} \sim -15 \text{ GeV} \left( \frac{d_e}{e \text{ cm}} \right) + \mathcal{O}(C_S(C_{qe}))\]

[Kozlov et al. 94-98; Quiney et al ’98; Parpia ’98; Chaudhuri & Nayak ’08, Meyer & Bohn ’08; Dzuba et al ’11; Skripnikov et al ’13]
Diamagnetic EDMs - “Schiff suppression”

**Atoms (e.g. Hg [Washington], also Xe)**

[Griffith et al '09]

- Charge distribution (finite size violation of Schiff screening, which implies $d_{\text{neutral atom}}(d_{\text{nuc}})=0$)

- Nuclear dipole

\[
d_{Hg} \sim 10Z^2 \left( R_N/R_A \right)^2 d_{\text{nuc}}
\]

\[
O(10^{-3})
\]

\[
d_{Hg} \sim -3 \times 10^{-17} S[e \text{ fm}^2] + O(d_e, C_{qe}, C_{qq})
\]

Schiff moment [Schiff '63]

\[
\vec{S} = S \frac{\vec{I}}{I} = \frac{1}{10} \left[ \int e\rho(\vec{r})\vec{r}r^2 d^3r - \frac{5}{3Z} \vec{d} \int \rho(\vec{r})r^2 d^3r \right]
\]

Schiff moment is dominant CP-odd source for large atoms (magnetic quadrupole important for small nuclei)

[Flambaum et al '86; Dzuba et al. '02]
Diamagnetic EDMs - “Schiff suppression”

Atoms (e.g. Hg [Washington], also Xe)

charge distribution (finite size violation of Schiff screening)

\[ d_{\text{Hg}} \sim -3 \times 10^{-17} S[e \text{ fm}^2] + \mathcal{O}(d_e, C_{q_e}, C_{qq}) \]

[Flambaum et al ’86; Dzuba et al. ’02]

\[ S = S(\bar{g}_{\pi NN}^{(i)} d_N, \ldots) \sim -g_{\pi NN} \left( \mathcal{O}(0.1) \bar{g}_{\pi NN}^{(0)} + \mathcal{O}(0.1) \bar{g}_{\pi NN}^{(1)} + \cdots \right) \text{ fm}^3 + \cdots \]

[Flambaum et al. ’86; Dmitriev & Senkov ’03; de Jesus & Engel ’05; Ban et al ’10]

NB: concerns over precision for Hg

\[ \bar{g}_{\pi NN}^{(1)} \sim (3 \pm 2)(\tilde{d}_u - \tilde{d}_d) + \mathcal{O}(\tilde{d}_u + \tilde{d}_d, \tilde{d}_s, w) \]

[Pospelov ’01]

• Octopole enhancements (e.g. Ra, Rn)

- Schiff moment \( O(100-1000) \) larger than Hg

[Flambaum et al.]
Nuclear EDMs - avoiding Schiff screening

- Neutron EDM via UCN bottles [....., PSI, SNS, PNPI, TRIUMF, TUM, J-PARC...]
  (Calculations using: chiralPT, NDA, QCD sum rules, ...)

\[ d_n(\bar{\theta}) \sim 3 \times 10^{-16} \bar{\theta} \text{ ecm} \quad \Rightarrow \quad |\theta| < 10^{-10} \]
\[ d_n^{(PQ)} \sim (0.4 \pm 0.2)[4d_d - d_u + 2.7e(\tilde{d}_d + 0.5\tilde{d}_u) + \cdots] + \mathcal{O}(d_s, w, C_{qq}) \]

- Nuclear EDMs (e.g. p,D,^3\text{He},...) in storage rings [BNL, FNAL? COSY/Julich]
  - proton - similar sensitivity to the neutron (d \leftrightarrow u)
  - deuteron

\[ d_D = (d_n + d_p)(\bar{\theta}, d_q, \tilde{d}_q) + d_D^{\pi NN}[\bar{g}_{\pi NN}^{(1)}(\bar{\theta}, d_q), \cdots] \sim -5e(\tilde{d}_d - \tilde{d}_u) + \cdots \]

via \(\eta-\pi\) mixing [Lebedev, Olive, Pospelov, AR ‘04]

- extended to other light nuclei (e.g. ^3\text{H}, ^3\text{He}) in recent work [Stetcu et al ’08, de Vries et al ’11]

[hadronic EDMs covered in next talk by Rob Timmermans]
**EFT hierarchy**

- **Energy**
- **TeV**
- **QCD**
- **Fundamental CP phases**
  - $d_e$
  - $C_{qe}, C_{qq}$
  - $\theta, d_q, \tilde{d}_q, w$
  - pion-nucleon coupling ($\tilde{g}_{\pi NN}$)

- **EDMs of paramagnetic atoms and molecules**
  - (Tl, YbF, ThO, HfF$^+$, ...)
  - Atoms in traps (Rb, Cs, Fr) solid state

- **EDMs of diamagnetic atoms**
  - (Hg, Xe, Ra, Rn, ...)

- **EDMs of nuclei and ions**
  - (deuteron, etc)

- **Nucleon EDMs**
  - (n, p)

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Constraints on CP-violation

EDM constraints

Fundamental CP phases

Energy

TeV

QCD

nuclear

atomic
## Resulting Bounds on fermion EDMs & CEDMs

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<tr>
<td>n EDM [±50%?]</td>
<td>$</td>
<td>e(\tilde{d}_d + 0.5\tilde{d}_u) + 1.3(d_d - 0.25d_u) + O(\tilde{d}<em>s, w, C</em>{qq})</td>
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<td>Hg EDM [±O(few)?]</td>
<td>$e</td>
<td>\tilde{d}_d - \tilde{d}<em>u + O(d_e, \tilde{d}<em>s, C</em>{qq}, C</em>{qe})</td>
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**Generic scaling:**

$$d_f \sim (\text{couplings}) \times \frac{m_f}{\Lambda_{CP}^2}$$

**See also recent compilation of limits:** [Engel, Ramsey-Musolf, van Kolck ’13]
### Resulting Bounds on fermion EDMs & CEDMs

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<td>(&lt; 8.7 \times 10^{-29} \text{ e cm} )</td>
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<td>YbF “EDM”</td>
<td>( d_e + e(21 \text{ MeV})^2 \left( 3 \frac{C_{ed}}{m_d} + 11 \frac{C_{es}}{m_s} + 5 \frac{C_{eb}}{m_b} \right) )</td>
<td>(&lt; 1.1 \times 10^{-27} \text{ e cm} )</td>
</tr>
<tr>
<td>TI EDM</td>
<td>( d_e + e(26 \text{ MeV})^2 \left( 3 \frac{C_{ed}}{m_d} + 11 \frac{C_{es}}{m_s} + 5 \frac{C_{eb}}{m_b} \right) )</td>
<td>(&lt; 1.6 \times 10^{-27} \text{ e cm} )</td>
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<td>n EDM [±20%?]</td>
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<td>(&lt; 2 \times 10^{-26} \text{ e cm} )</td>
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<td>Hg EDM [±O(few)?]</td>
<td>( e</td>
<td>\tilde{d}_d - \tilde{d}<em>u + O(d_e, \tilde{d}<em>s, C</em>{qq}, C</em>{qe})</td>
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**Generic scaling:** \( d_f \sim \text{(couplings)} \times \frac{m_f}{\Lambda_{CP}^2} \)

**See also recent compilation of limits:** [Engel, Ramsey-Musolf, van Kolck ’13 ]
Summary of the bounds

\[ \log(\Delta E/\varepsilon_{\text{ext}} \ [\text{e cm}]) \]

Difference of 7 orders of magnitude is very misleading!

Real sensitivity to underlying sources of CP violation, depends on significant enhancement and suppression factors to be discussed shortly...
Summary of the bounds

\[ \log(d [e \text{ cm}]) \]

-22
-24
-26
-28
-30
-32
-34

\(d_q\) and \(\tilde{d}_q\) from the neutron

\(\tilde{d}_q\) from Hg

\(d_e\) from ThO

The generic sensitivity to new physics follows from taking \(d_f \propto m_f\)

impact of recent order of magnitude improvement in paramagnetic EDM sensitivity
EDMs in the Standard Model (CKM phase)

\[ d(\text{CKM}) \propto J \sim \text{Im}(VVVV) \]

Next generation sensitivity?

\[ d_n(\text{CKM}) \propto C_{qq}(J) \propto JG_F^2 \]

[Khriplovich & Zhitnitsky ’82; McKellar et al ’87; Mannel & Uraltsev ’12]
EDMs in the Standard Model (CKM phase)

\[ d(CKM) \propto J \sim \text{Im}(VVVV) \]

\[ d_{Hg}(CKM) \propto C_{qq}(J) \propto JG_F^2 \]

[Flambaum et al '84; Donoghue et al '87]
EDMs in the Standard Model (CKM phase)

\[ d(\text{CKM}) \propto J \sim \text{Im}(VVVV) \]

Paramagnetic EDMs in the SM determined by \( C_S \) rather than \( d_e \)

\[ "d_{\text{ThO}}(\text{CKM})" \propto C_S(J) \propto JG_F^2 \]

[Postelov & AR '13]
LHC-era tests of CP-violating new physics

Expectation of new EW-scale physics is (or was) primarily associated with stabilizing the Higgs sector...

\[ h \quad y_t \quad y_t \quad h \]

- This predominantly suggests new physics coupling strongly to the Higgs, 3rd generation, ...
  \[ \Rightarrow \text{EDMs at 2-loops} \]
**Example 1 - CP-odd Higgs couplings**

- Hints in 2012 that $\text{Br}(h\to\gamma\gamma) > \text{Br}_{\text{SM}}$ (have since dissipated)
- EDMs significantly constrain any CP-odd contribution to $h\to\gamma\gamma$

$$\Delta \mathcal{L} = \frac{1}{e^2\tilde{\Lambda}^2} H^\dagger H \left( a_h g_1^2 B_{\mu\nu} \tilde{B}^{\mu\nu} + b_h g_2^2 W_{\mu\nu} \tilde{W}^{\mu\nu} \right) \rightarrow \frac{\tilde{c}_h \nu}{\tilde{\Lambda}^2} h F_{\mu\nu} \tilde{F}^{\mu\nu} + \cdots$$

This interaction shifts $\text{Br}(h\to\gamma\gamma)$, but also generates EDMs!

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\text{SM}}} \simeq 1 + \left| \frac{\tilde{c}_h \nu^2}{\tilde{\Lambda}^2} \frac{8\pi}{\alpha A_{\text{SM}}} \right|^2$$

Current bound on $d_e$ limits $\Delta \text{Br}(h\to\gamma\gamma)/\text{Br}_{\text{SM}} < O(10^{-5})$ from this CP-odd operator!

[McKeen, Pospelov & AR ’12]
[Harnik et al ’12; Fan & Reece ’13]
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  ⇒ EDMs at 2-loops

- SUSY provides new physics with strong coupling to 1st generation
  ⇒ EDMs at 1-loop!

SUSY CP problem!
Example 2a - (LHC era) SUSY CP Problem

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**(pre-LHC)**

\[ M_{\text{susy}} = 500 \text{ GeV} \]

![Diagram showing (pre-LHC) MV parameter space with \( d_{YbF}, d_{Hg}, d_n \).]

**(2012/13)**

\[ M_{\text{susy}} = 2 \text{ TeV} \]

![Diagram showing (2012/13) MV parameter space with \( d_{YbF}, d_{Hg}, d_n \).]

1st gen squarks excluded by direct searches at ~1 TeV

EDMs have for many years required (tuned) \( O(10^{-3}) \) CP-odd phases for “generic” weak-scale SUSY. The LHC appears to have “resolved” this by pushing mass limits on 1st generation sfermions above a TeV.
Example 2a - (LHC era) SUSY CP Problem

(pre-LHC)

\[ M_{\text{susy}} = 500 \text{ GeV} \]

(now)

\[ M_{\text{susy}} = 2 \text{ TeV} \]

EDMs have for many years required (tuned) \(O(10^{-3})\) CP-odd phases for "generic" weak-scale SUSY. The LHC appears to have "resolved" this by pushing mass limits on 1st generation sfermions above a TeV. Now tuning (at a TeV) being re-introduced via ThO limit on \(d_e\).
• Within minimal SUSY, $m_h >> m_Z$ points to PeV-scale s-partners (⇒ tuning, no soln to “little hierarchy” problem) [e.g. Arkani-Hamed et al ’12]

$$m_h^2 \sim M_Z^2 + \frac{3}{\sqrt{2}\pi^2} G_F m_t^4 \ln \frac{m_t^2}{v^2}$$

Need a large log correction
⇒ $m_{\text{squark}} > 100$-1000 TeV
Example 2b - PeV-scale SUSY sensitivity

- Within minimal SUSY, $m_h >> m_Z$ points to PeV-scale s-partners
- The PeV scale allows a generic flavour structure and, with TeV gauginos, EDMs are one of the few observables able to probe this scale via log-enhanced quark CEDMs

[McKeen, Pospelov & AR; Altmannshofer et al '13; Fuyuto et al ’13]

\[ |m_{\tilde{B}}| = |m_{\tilde{W}}| = 3 \text{ TeV}, \quad |m_{\tilde{g}}| = 10 \text{ TeV} \]
Expectation of new EW-scale physics is (or was) primarily associated with stabilizing the Higgs sector...

- This predominantly suggests new physics coupling strongly to the Higgs, 3rd generation, ...
  \[ \Rightarrow \text{EDMs at 2-loops} \]
- SUSY provides new physics with strong coupling to 1st generation
  \[ \Rightarrow \text{EDMs at 1-loop!} \]
LHC-era tests of CP-violating new physics

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  \[ \Rightarrow \text{EDMs at 1-loop!} \]
- Hidden sectors with light (sub-GeV) states
  \[ \Rightarrow \text{EDMs at 2-loops} \]
EFT hierarchy can be modified if new CP-violating physics is light (sub-GeV)
Mediating (IR) CP-violation - Portals

- Empirical evidence for new physics (neutrino mass, dark matter) points to very weak interactions, but not to a specific mass scale...
- EFT parametrization of couplings to neutral hidden sector

![Diagram showing Standard Model and Hidden Sector](diagram.png)

- Only a small number of new (light) dofs can couple via relevant or marginal interactions (given SM SU(2)xU(1) structure), e.g.

Vector portal (V)  
[Okun ’82, Holdom ’86]

\[ \mathcal{O}_4 = -\frac{\kappa}{2} V^{\mu\nu} B_{\mu\nu} \quad \rightarrow \quad \kappa V_\mu J^\mu_{em} \]

(also shifts muon g-2)

- Can mediate IR hidden sector CP-violation \(\rightarrow\) observable EDMs
Example 3 - EDM Sensitivity to hidden sectors

Would a nonzero EDM *necessarily* imply new short distance physics? **No!**

\[
\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{portals}}(\mathcal{O}_3, \mathcal{O}_4) + \mathcal{L}_{\text{hid}}
\]

\[
\mathcal{O}_4 = -\frac{\kappa}{2} V^{\mu \nu} B_{\mu \nu} \rightarrow \kappa V^\mu J^\mu_{\text{em}}
\]

\[
\mathcal{O}_3 = A S H^\dagger H \rightarrow \left( \theta = \frac{A v}{m_h^2} \right) S (m_q \langle \bar{q} q \rangle + \cdots )
\]

\[
\mathcal{L}_{\text{hid}}^{\text{CP}} = \bar{\psi} i \gamma^\mu D^V_\mu \psi + \bar{\psi} (m_\psi + S(Y_S + i \tilde{Y}_S \gamma_5)) \psi
\]

\[
|d_e| \sim 4.4 \times 10^{-29} \, e \cdot \text{cm} \times \left( \frac{1 \text{GeV}}{m_\psi} \right) \left( \frac{\kappa}{10^{-2}} \right)^2 \left( \frac{\theta}{10^{-3}} \right)
\]

EDMS are also competitive probes of weakly coupled hidden sectors
EDMs are an important class of flavour-diagonal CP-odd observables, probing new physics (motivated by the need for baryogenesis)

Disentangling CP-odd operators at 1 GeV requires multiple EDM observables

• Useful complementarity between EDM constraints and precision LHC tests of CP-odd Higgs couplings

• The SUSY CP problem, hinted at by (1-loop) EDMs for more than 20 years, has been “confirmed” by the LHC, with no squarks seen near the weak scale (thus far). EDMs probe the very high (PeV) sfermion scales characteristic of the “large” observed Higgs mass

• Baryogenesis requires new CP-odd physics, but are the new states at or above the weak scale? EDMs can also probe light (CP-violating) hidden sectors

[NB: Also MHz EDMs from light axion DM ▶ \(d_n \propto \theta_{\text{eff}}(\rho_{\text{DM}})\cos(m_{\text{at}})\) ]

[Graham, Rajendran, Budker et al]